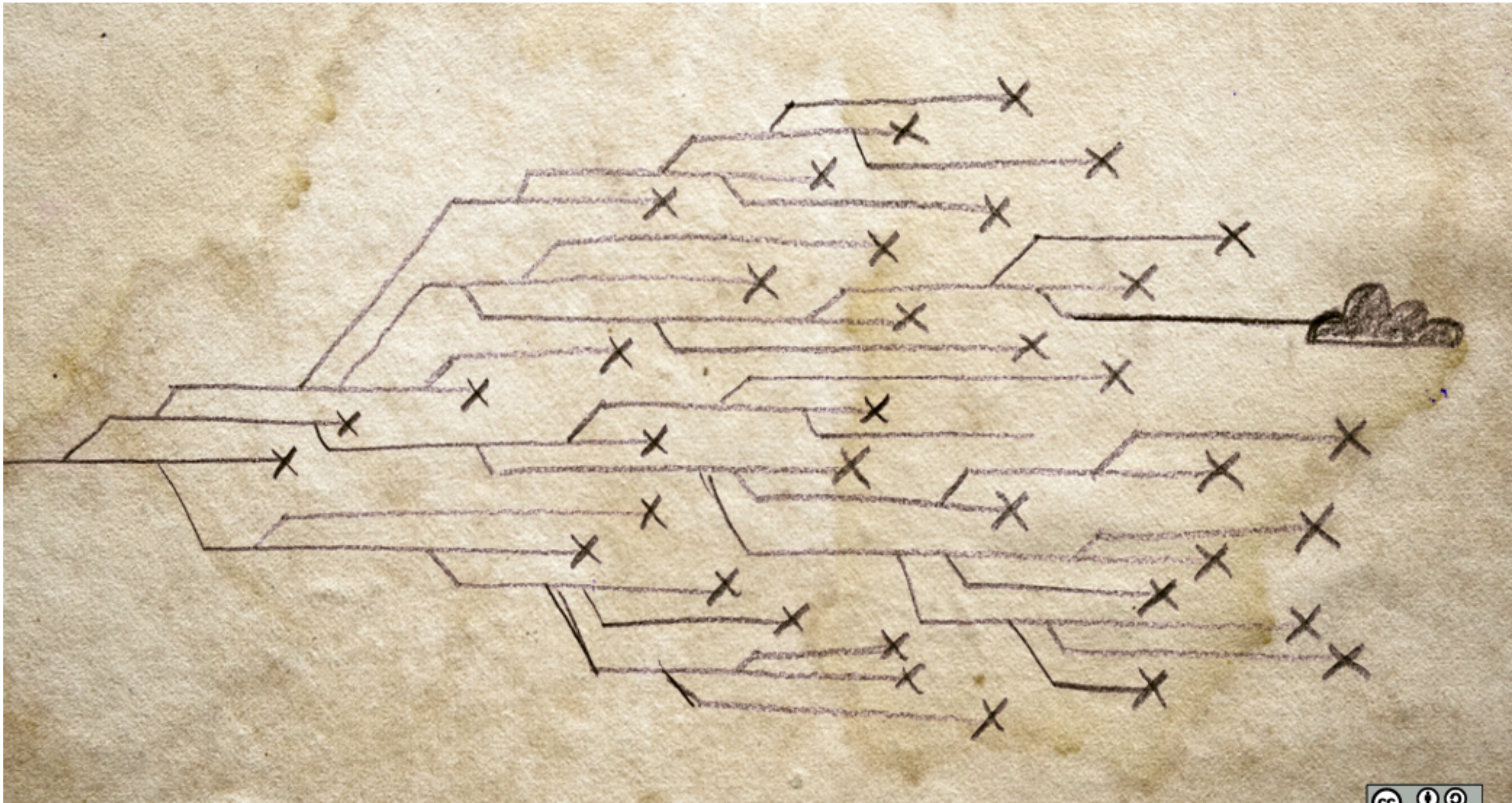
PROPERTIES OF THE HIGGS BOSON WE CANNOT "UNSEE"

André David (CERN)

The experimental method

falsifying theories since the dawn of reason

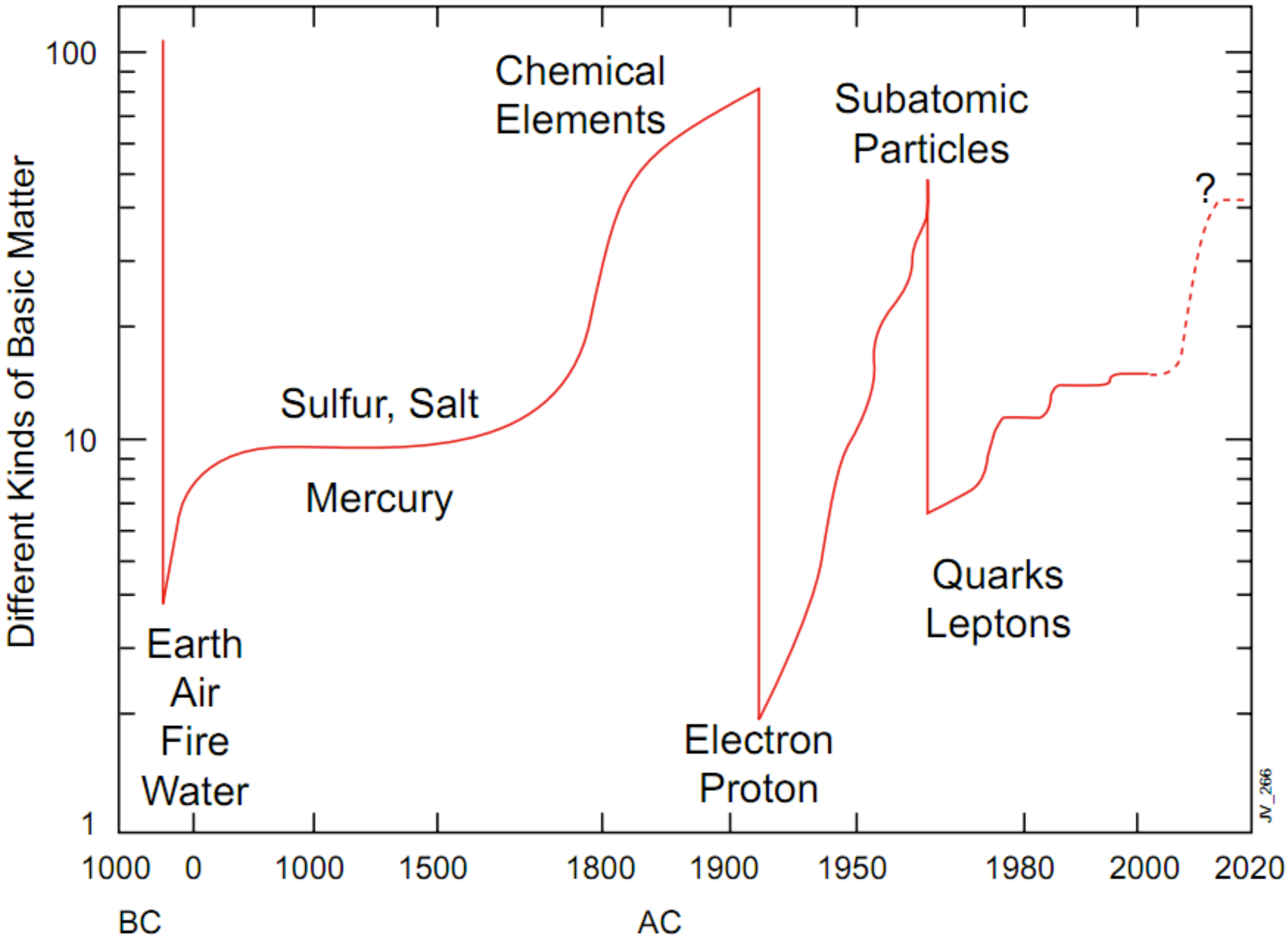
[opensource.com]



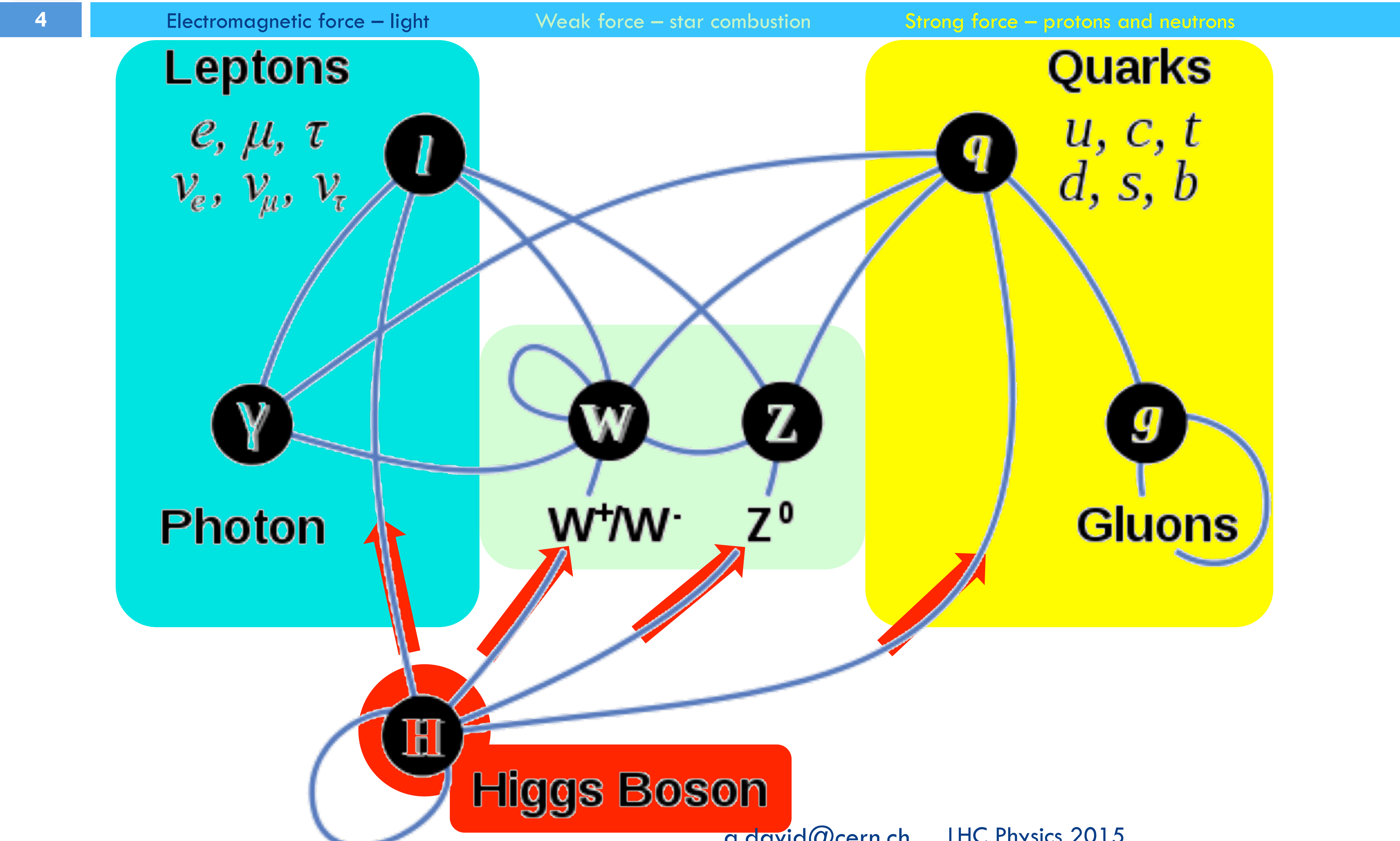
Crosses: experimental results pushing humans to track back and rethink their models.

Evolutions & revolutions of the elements

[Plot courtesy of Jim Virdee]

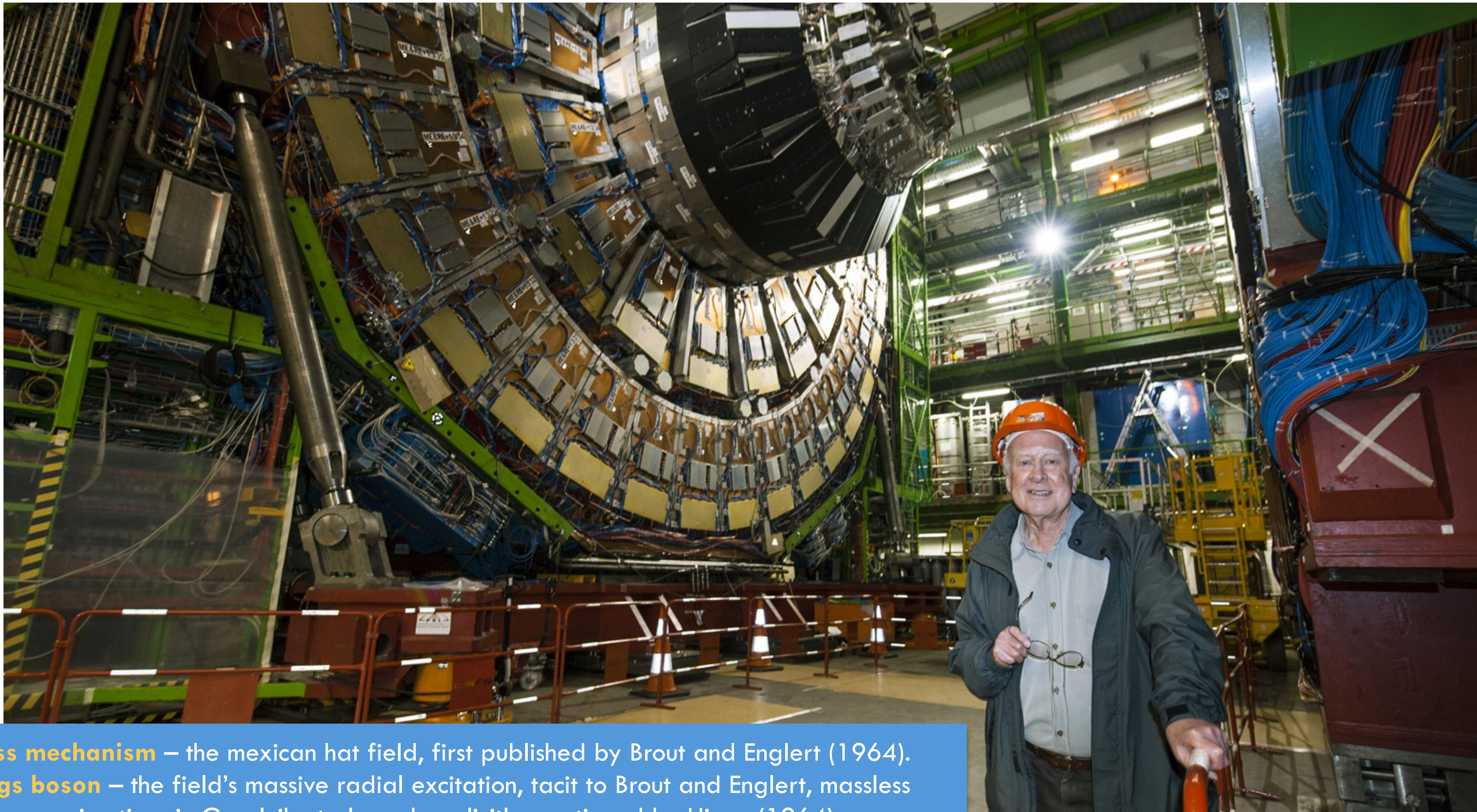


The Standard Model of Particle Physics



Higgs in CMS – ca. 2008

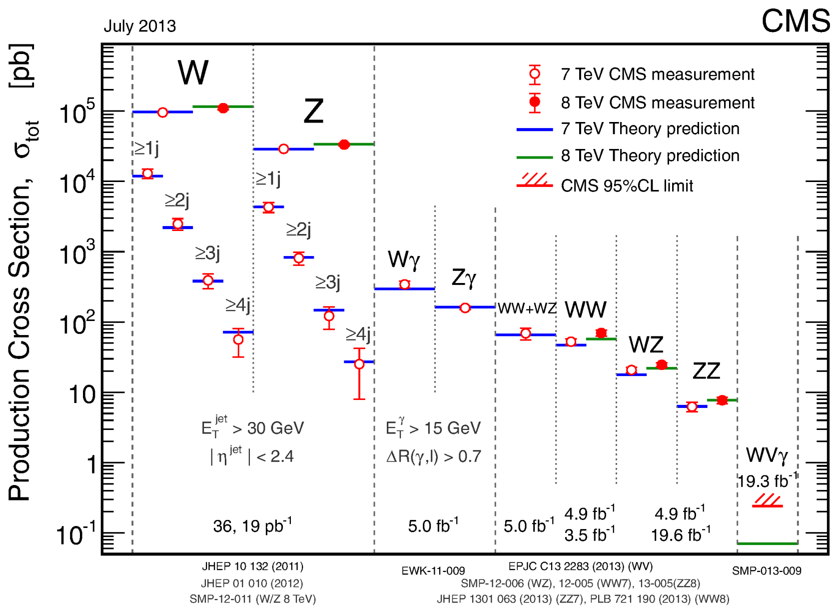
[http://cern.ch/go/dJf7] [http://cern.ch/go/Sx8m]

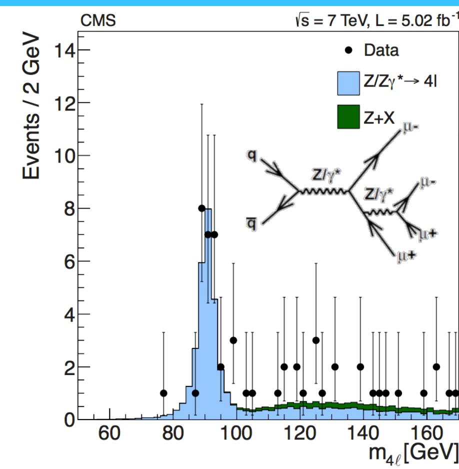


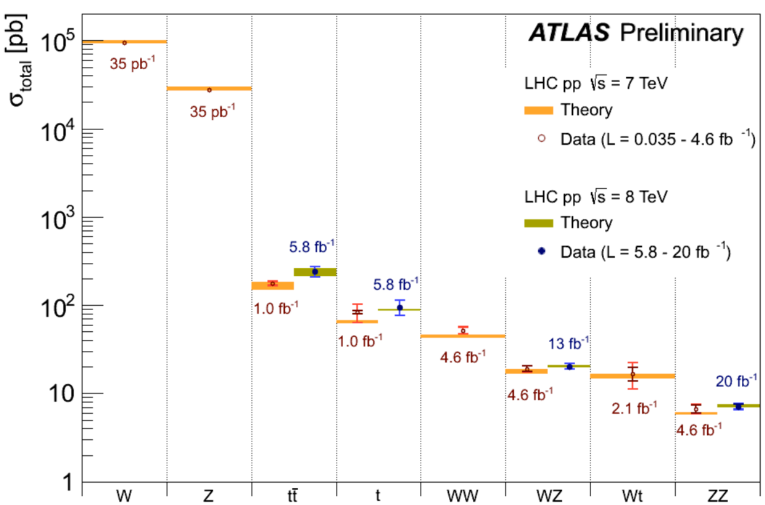
- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive weak bosons can coexist was shown by Kibble (1967).

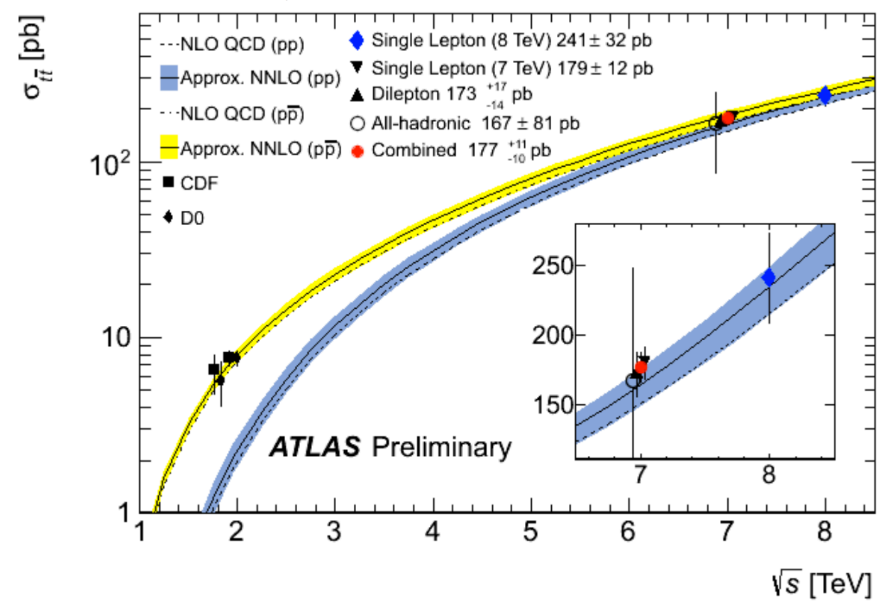
A tribute to those doing SM calculations

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi





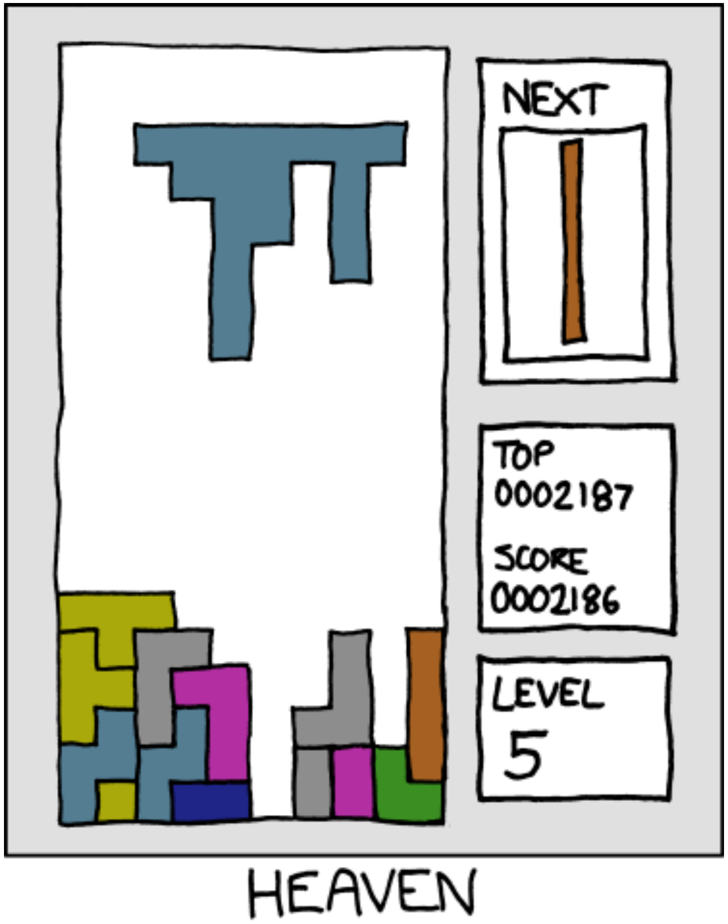




LHC Higgs Cross Section WG

[http://xkcd.com/888/]

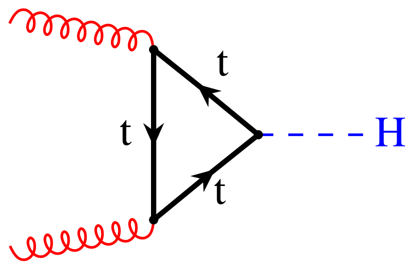
- **Experimentalists and theorists.**
  - Together since 2010.
  - Produce the best pieces for a common Higgs puzzle. ➘



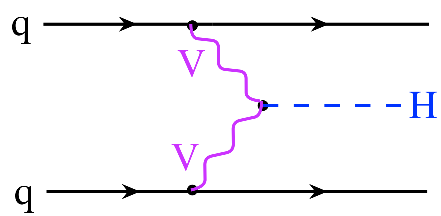
How SM Higgses are born

[http://cern.ch/go/cWH8][http://cern.ch/go/SnJ8]

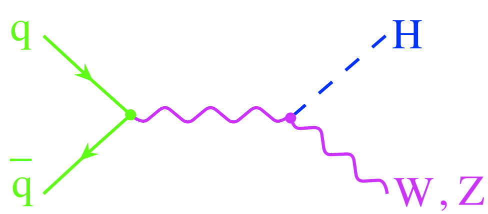
- **Gluon fusion**



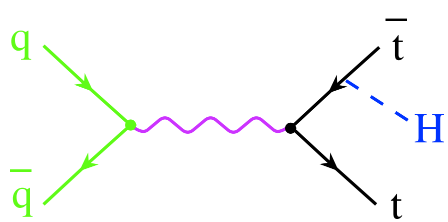
- **VBF**

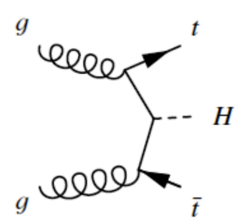


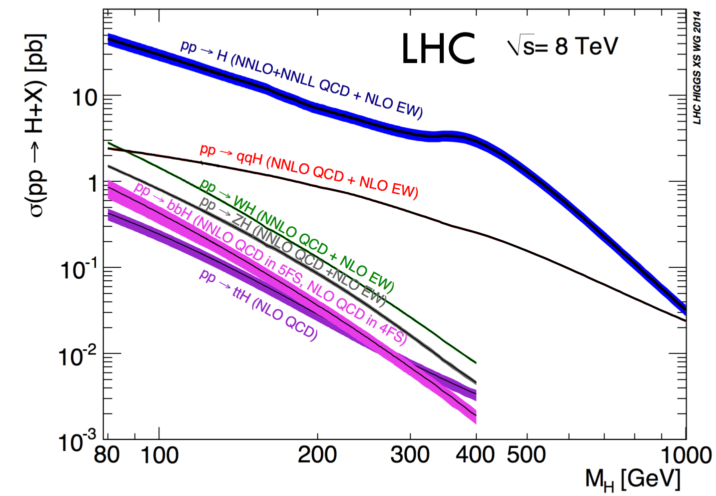
- **WH, ZH**

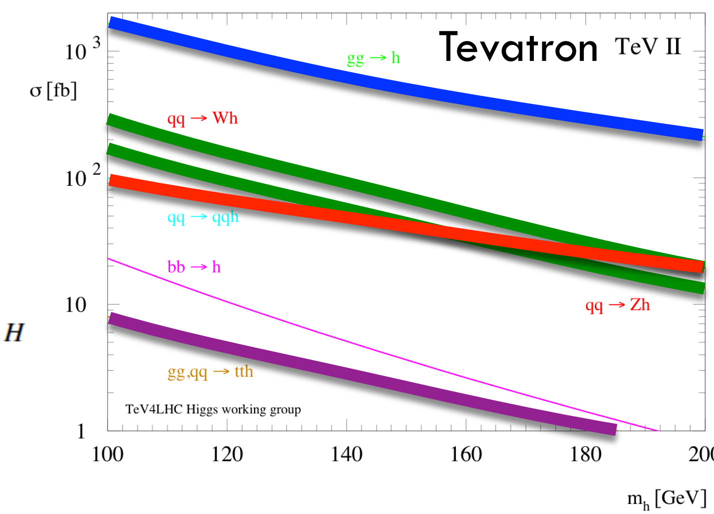


- **bbH, ttH**





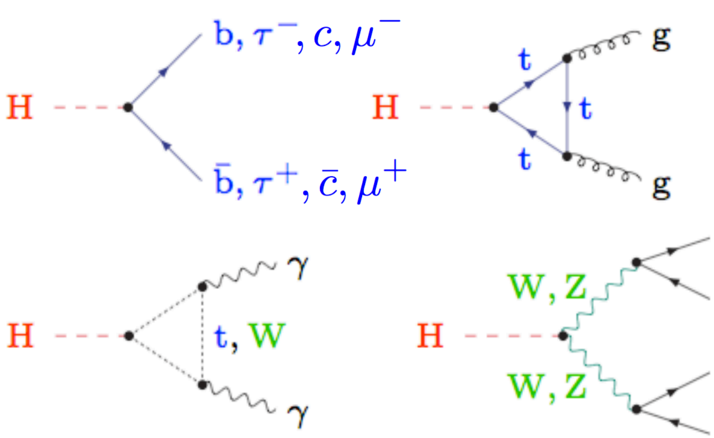




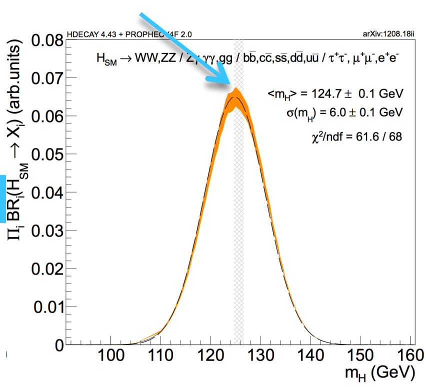
How SM Higgses die

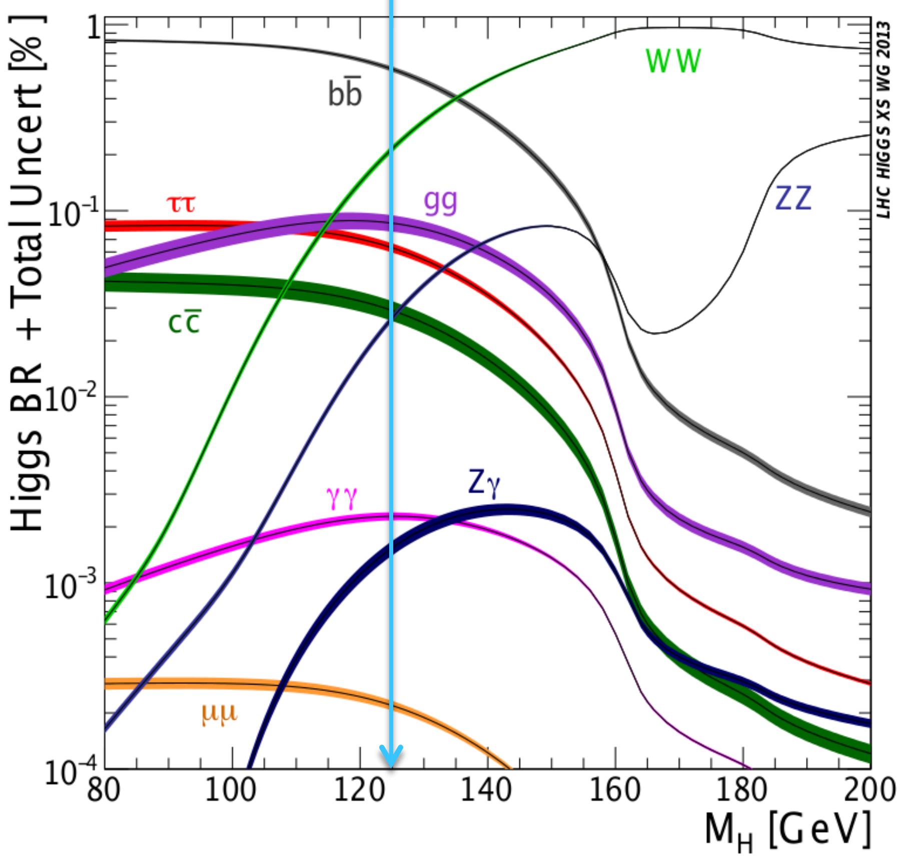
[http://cern.ch/go/qkh6][arXiv:1208.1993][arXiv:1408.0827]

- Couplings and kinematics drive BR ($b\bar{b}$, WW, $\tau\tau$, ZZ).
  - Decays with photons ($\gamma\gamma$, $Z\gamma$) through loops.



Near to maximal ΠBR_i ⟶





2011: nothing else in the horizon

["Lawrence of Arabia" idea from C. Grojean]

- We first saw that we could not exclude a narrow range.

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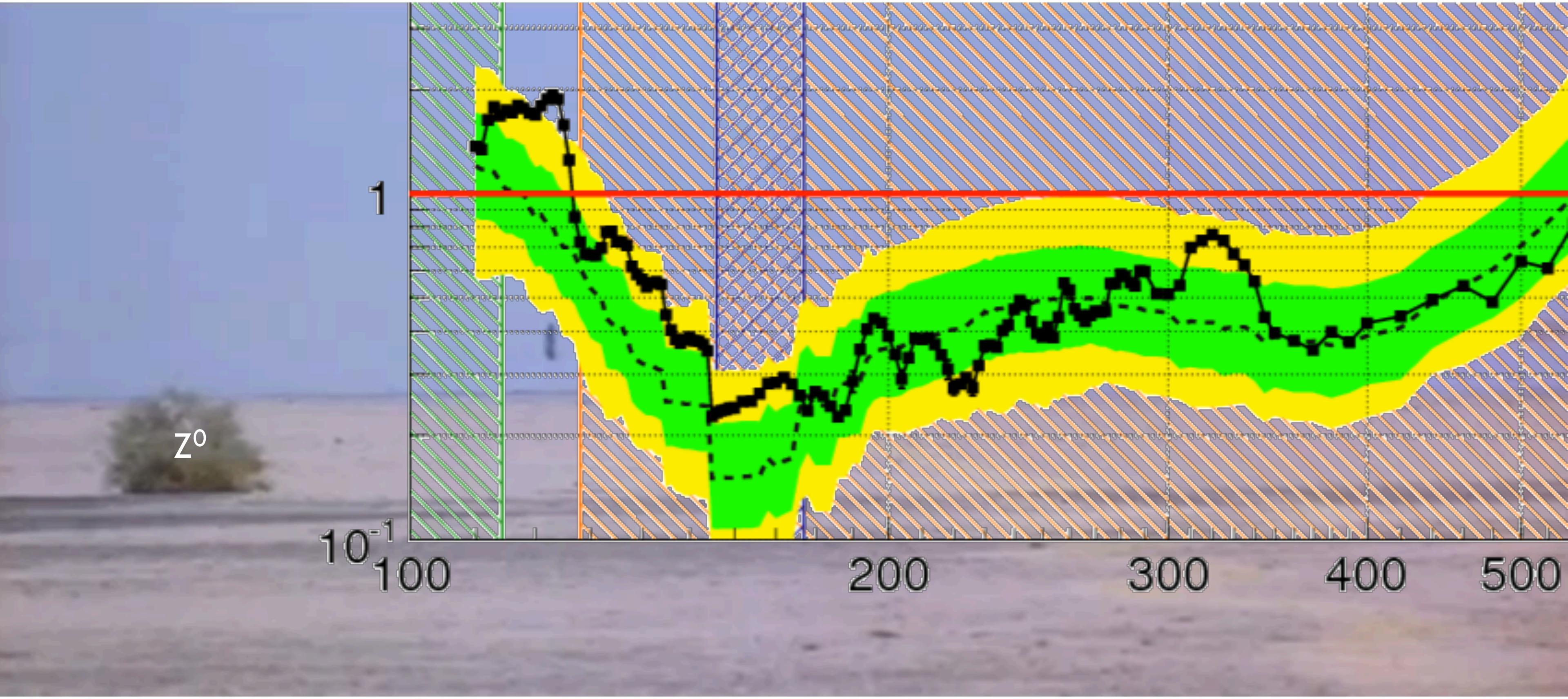
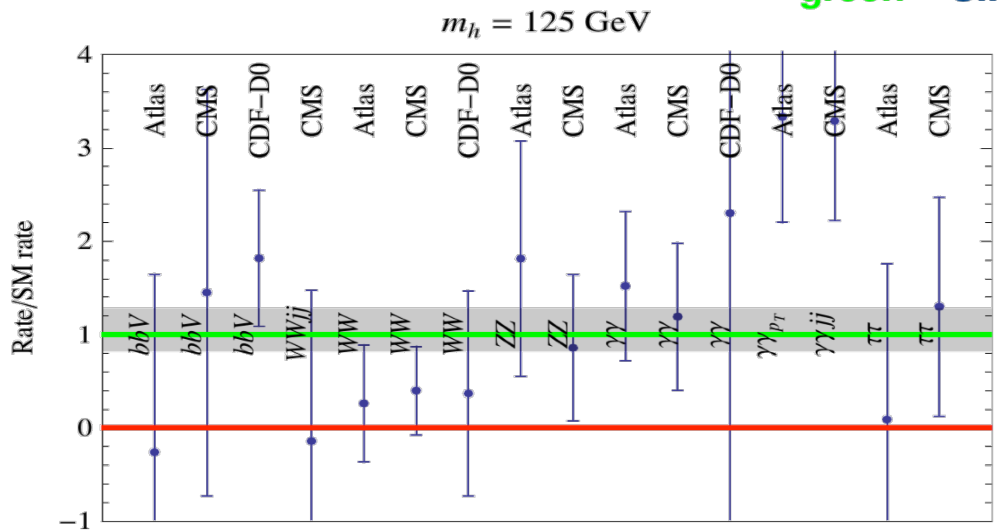


In 2012 some theorists speculated…

[http://goo.gl/CVm6s]

- After Moriond 2012, new fits disfavor the SM and motivate for New Physics

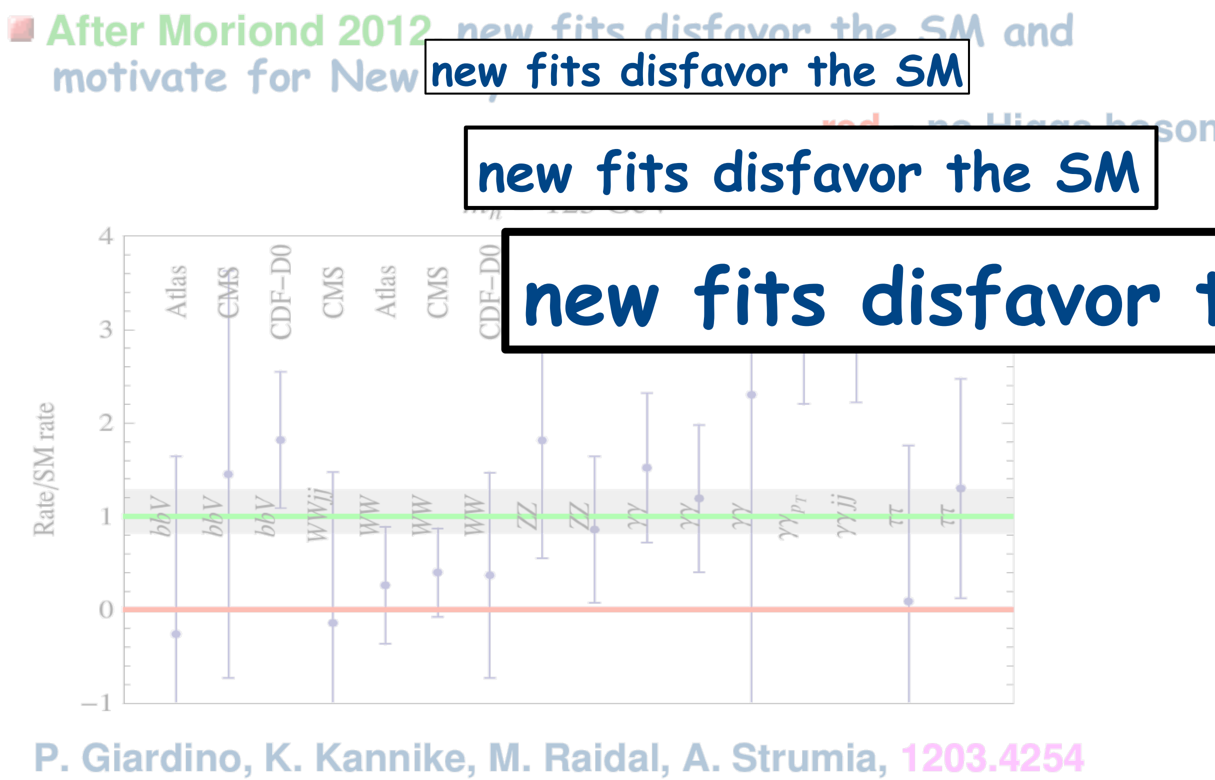
red = no Higgs boson
green = SM



P. Giardino, K. Kannike, M. Raidal, A. Strumia, 1203.4254

In 2012 some theorists speculated…

[http://goo.gl/CVm6s]



new fits disfavor the SM

new fits disfavor the SM

new fits disfavor the SM

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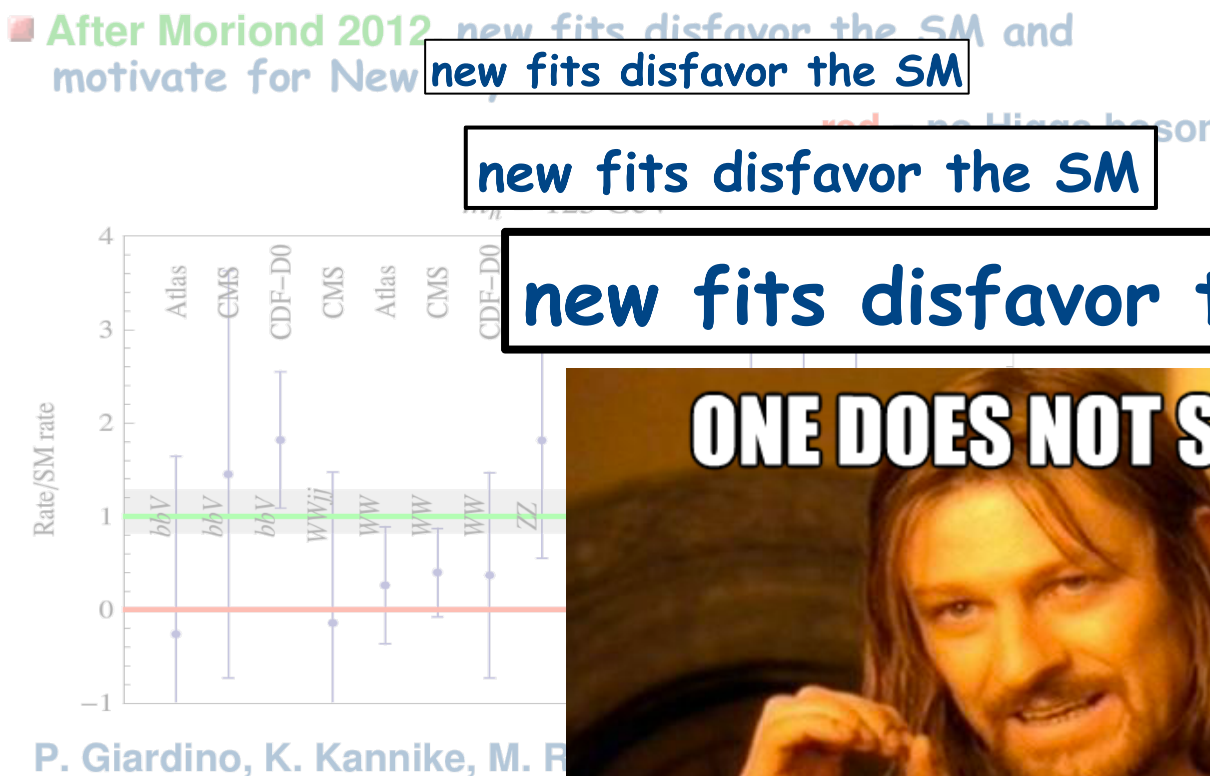

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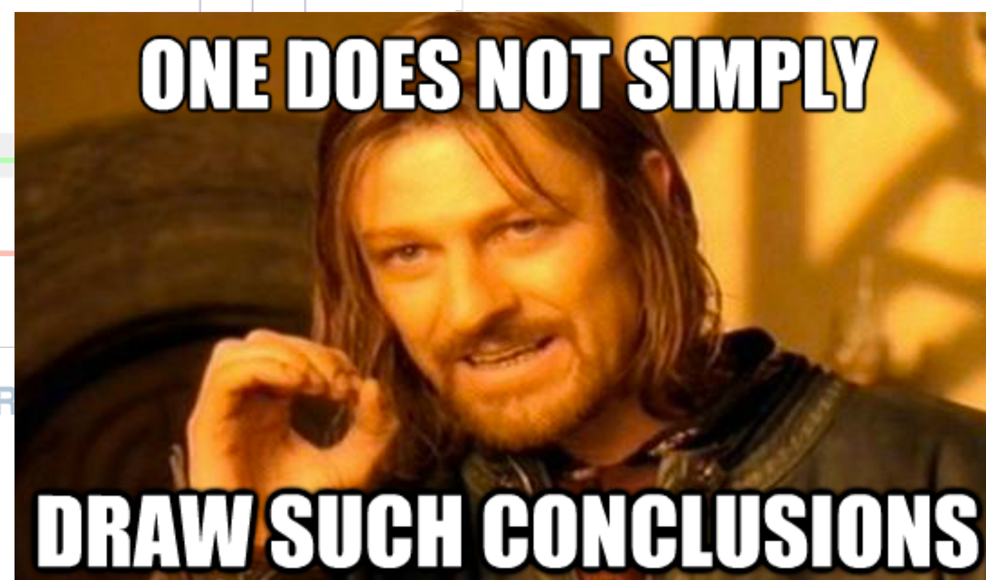


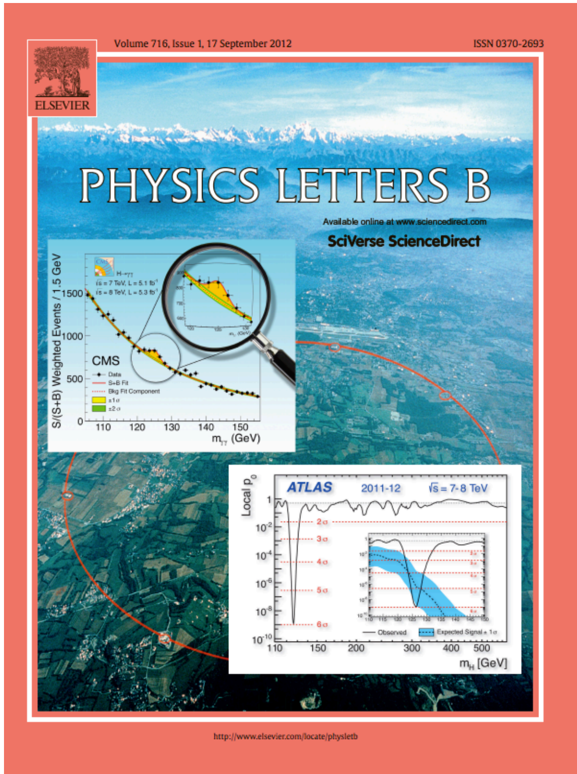
2012: a rider!

["Lawrence of Arabia" idea from C. Grojean]

- We discovered a peak rising from the background.

July 4, 2012
Looking up to a new boson

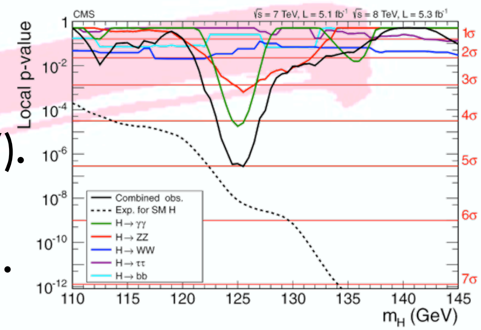
[http://cern.ch/go/q8jx]

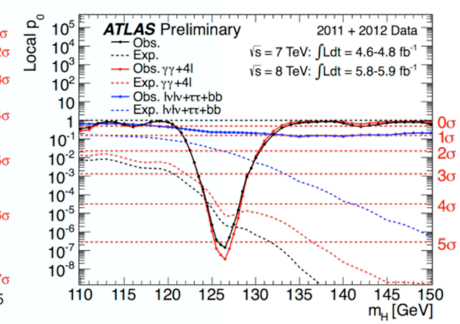


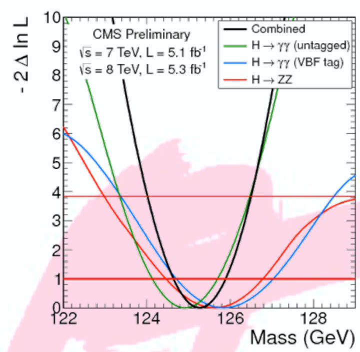
Higgsdependence day recap

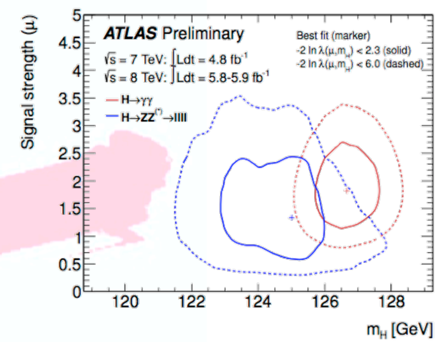
[http://cern.ch/go/q8jx]

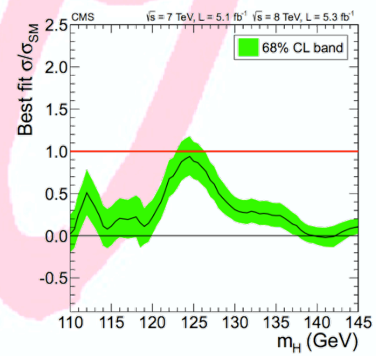
- **Both experiments at 5.0 σ.**
  - One above SM expectations… $\sigma_{ATLAS}/\sigma_{SM}$ = **1.2 ±0.3** (at 126.5 GeV).
  - …the other one below. σ_{CMS}/σ_{SM} = **0.80 ±0.20** (at 125 GeV).
- Mass
  - ATLAS: min. p-value at 126.5 GeV.
  - CMS: m_X = 125.3 ±0.6 GeV.
- "Proto-couplings" compatible with SM.
- ***"More data needed…"***

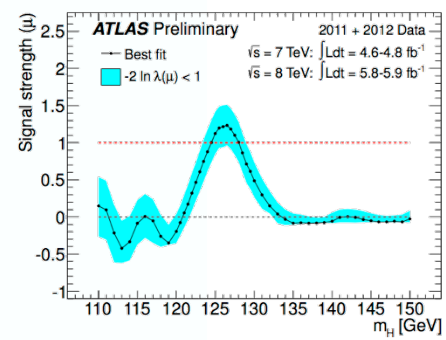


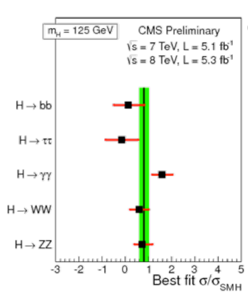


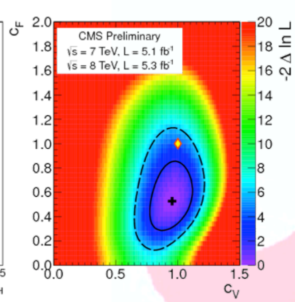


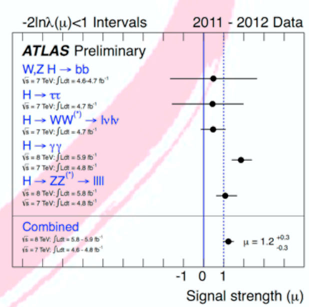












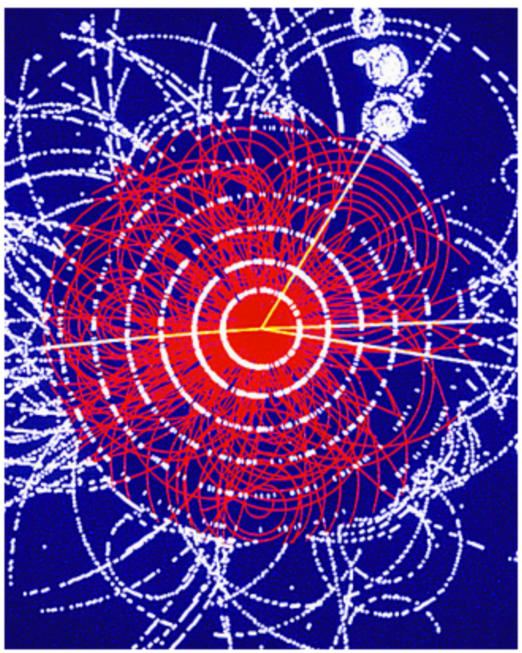
Who Should Be TIME's Person of the Year 2012?

As always, TIME's editors will choose the Person of the Year, but that doesn't mean readers shouldn't have their say. Cast your vote for the person you think most influenced the news this year for better or worse. Voting closes at 11:59 p.m. on Dec. 12, and the winner will be announced on Dec. 14.

THE CANDIDATES

The Higgs Boson

By Jeffrey Kluger | Monday, Nov. 26, 2012



SSPL/GETTY IMAGES

Simulation of a Higgs-Boson decaying into four muons, CERN, 1990.

What do you think?

Should **The Higgs Boson** be TIME's Person of the Year 2012?

Definitely No Way

VOTE

Take a moment to thank this little particle for all the work it does, because without it, you'd be just inchoate energy without so much as a bit of mass. What's more, the same would be true for the entire universe. It was in the 1960s that Scottish physicist Peter Higgs first posited the existence of a particle that causes energy to make the jump to matter. But it was not until last summer that a team of researchers at Europe's Large Hadron Collider — Rolf Heuer, Joseph Incandela and Fabiola Gianotti — at last sealed the deal and in so doing finally fully confirmed Einstein's general theory of relativity. The Higgs — as particles do — immediately decayed to more-fundamental particles, but the scientists would surely be happy to collect any honors or awards in its stead.

Photos: Step inside the Large Hadron Collider.

WHO SHOULD BE TIME'S PERSON OF THE YEAR 2012?

The Candidates

Video

Poll Results

PAST PERSONS OF THE YEAR

2011: The Protester

2010: Facebook's Mark Zuckerberg

2009: Ben Bernanke

2008: Barack Obama

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18 of 40

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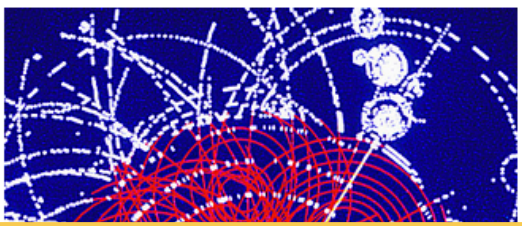

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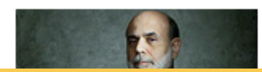

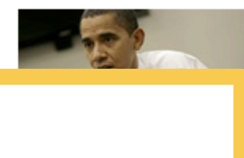

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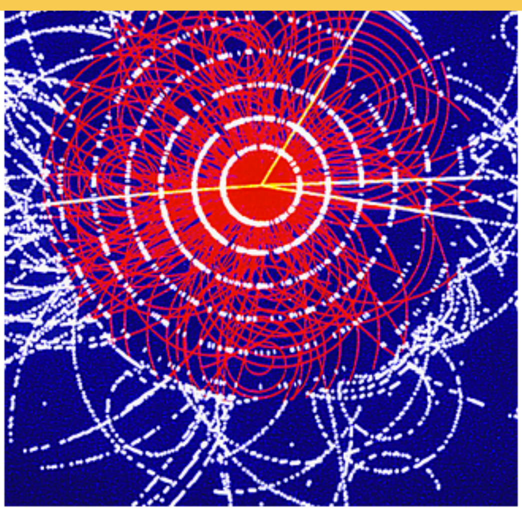

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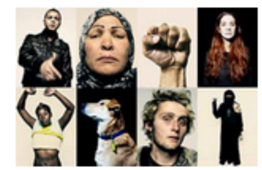

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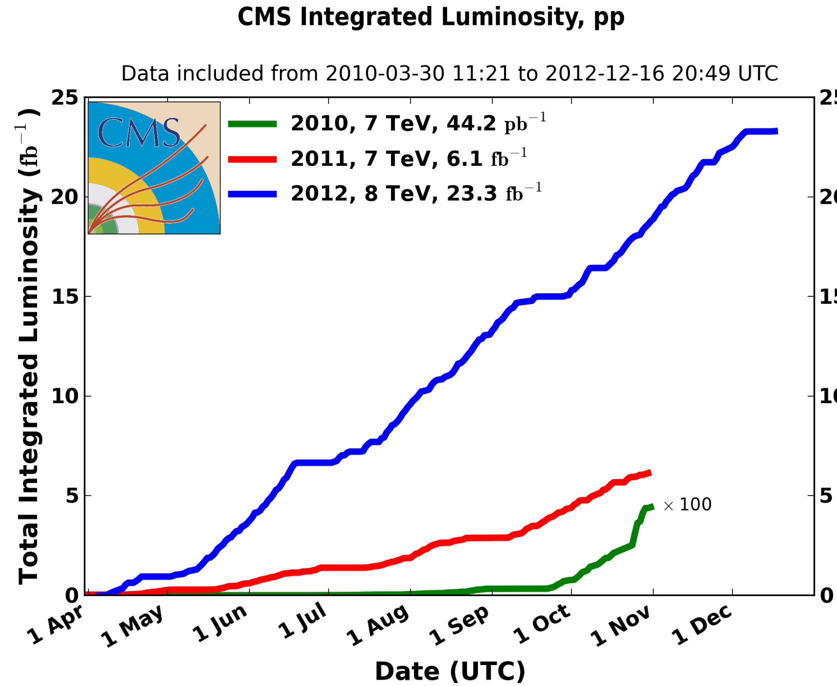
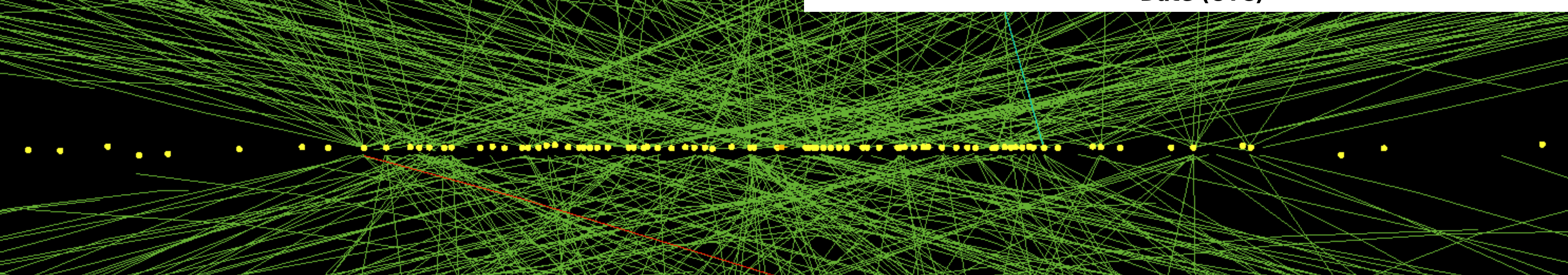
The LHC Run 1: a bountiful harvest

[http://cern.ch/go/K8Tj] [http://cern.ch/go/ZW9S]

- LHC delivered ~30 fb^{-1}.
- **Challenge:** precision physics with ~20 simultaneous proton-proton collisions.





Event with 78 reconstructed vertices along ~10 cm.

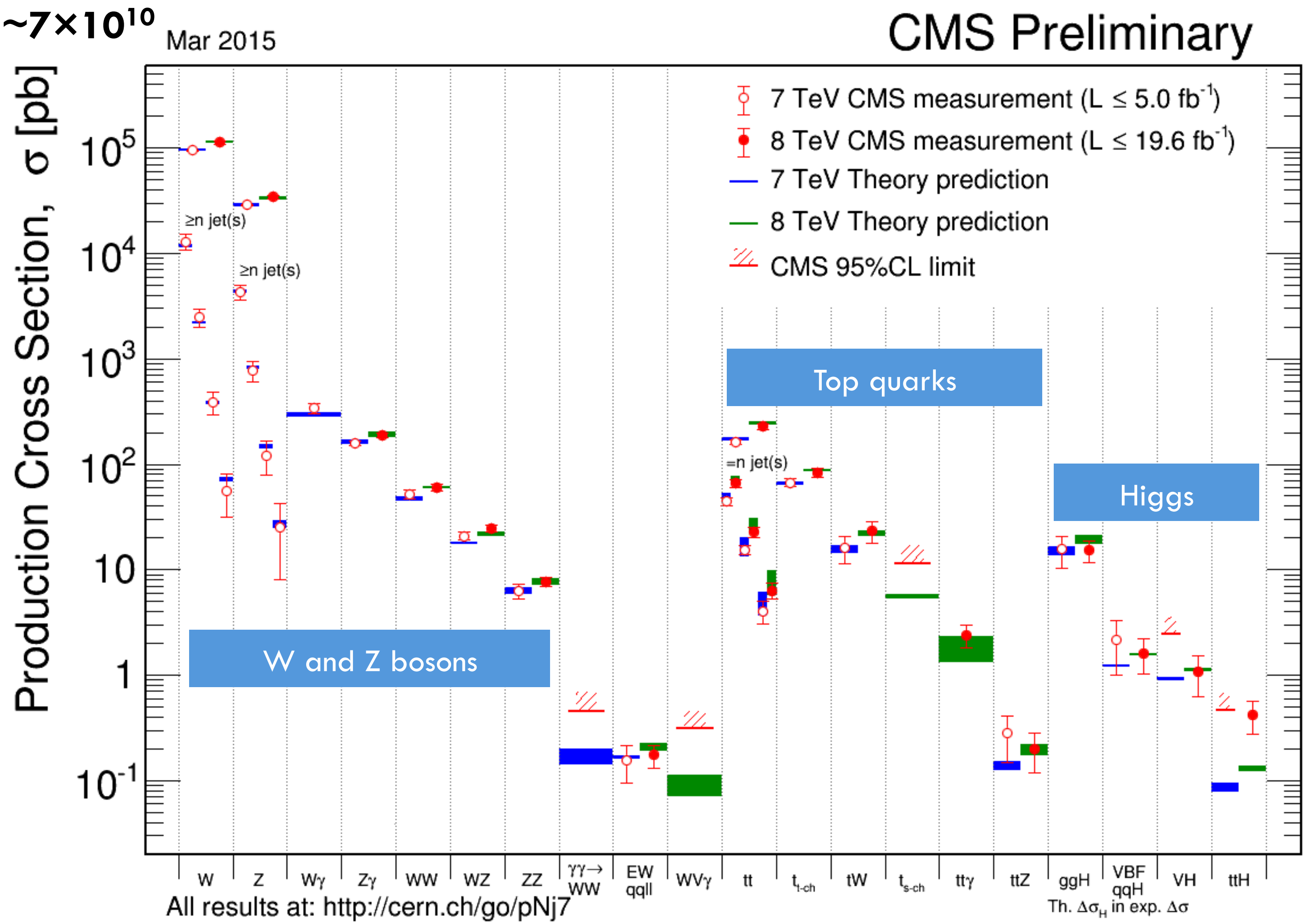
On the shoulders of giants

detector makers & theory calculators

"Yesterday's discovery is today's calibration, and tomorrow's background." – V. L. Telegdi [http://cern.ch/go/lf9C][http://cern.ch/go/KD8D]

Inelastic collisions: ~7×10^{10}

Six orders of magnitude of EWK, top, and Higgs Physics

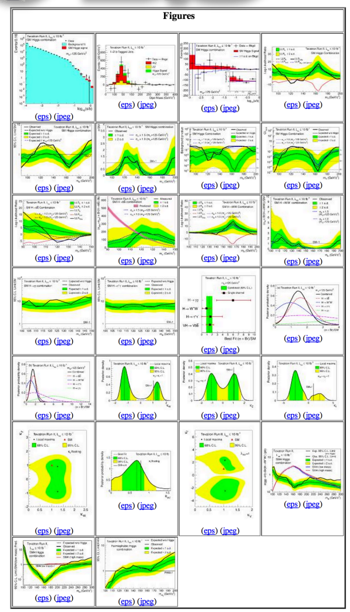


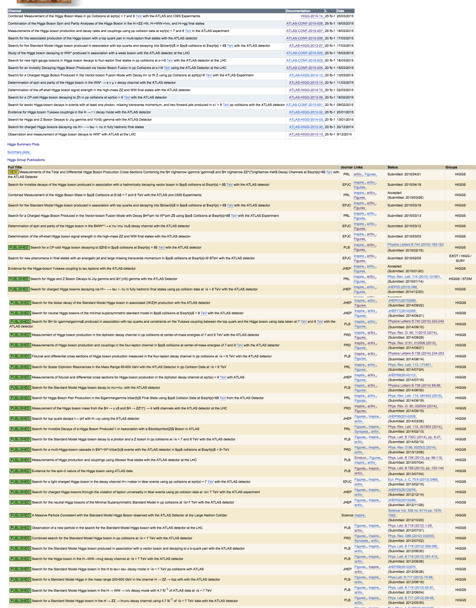
2013: a rider with a gun

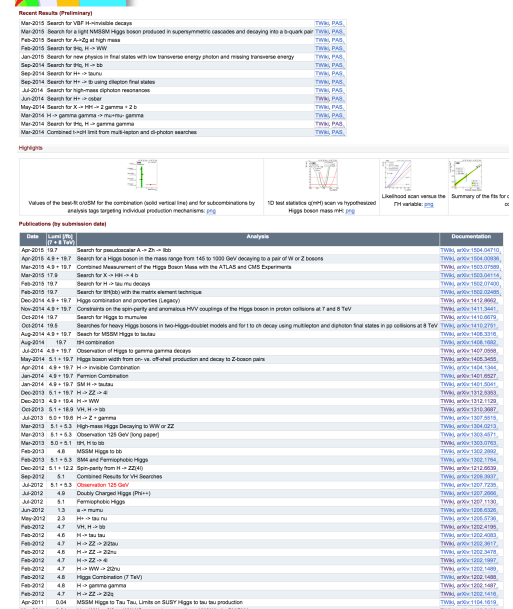
["Lawrence of Arabia" idea from C. Grojean]

- By early 2013 a clear Higgs-like picture emerged.

(self-inflicted) Mission: impossible







- Present a coherent view of present-day results of Higgs couplings from the LHC (and Tevatron) experiments.
  - Any mistake is the speaker's fault (send email).

Oversimplified big picture

T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

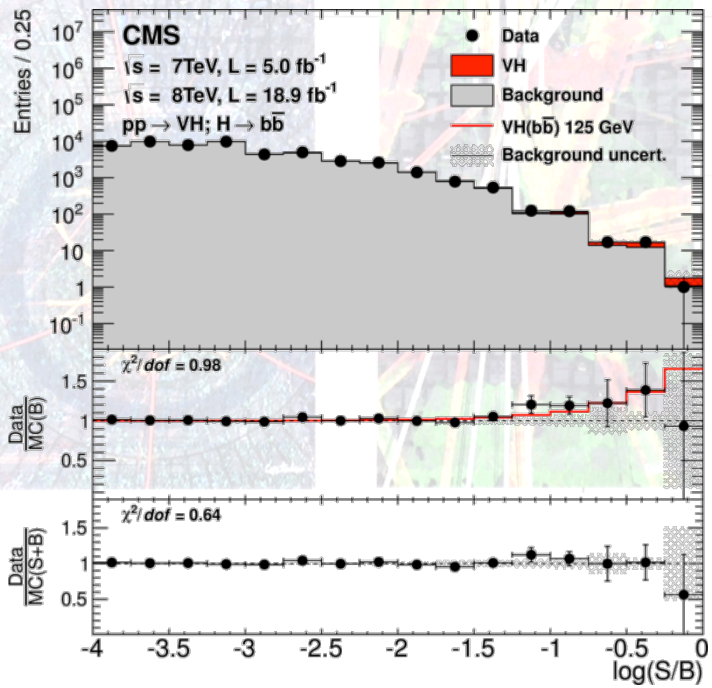
★ "seen" ☆ "tried" - "impossible"	$H\to b\bar{b}$			$H\to\tau\tau$			H→WW			H→ZZ			$H\to\gamma\gamma$			$H\to Z\gamma$			H→inv.			$H\to\mu\mu$			$H\to c\bar{c}$ H→HH		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

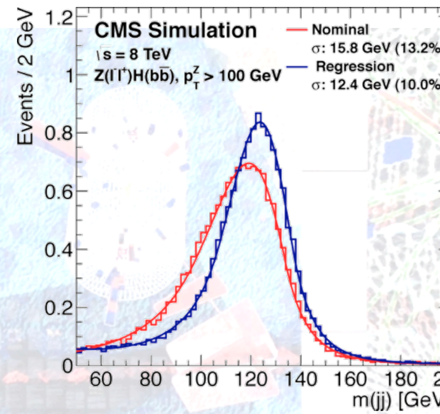
- **Still much to explore on the rarer ends.**
  (to the right and to the bottom) (and outside this picture)

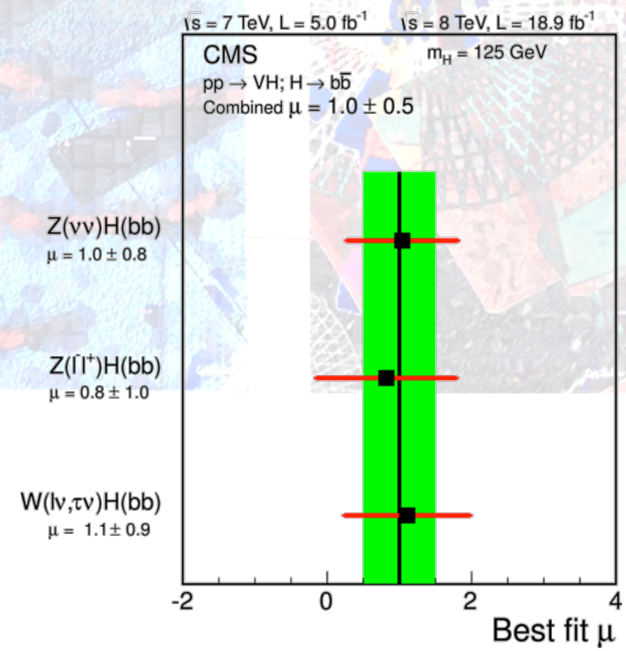
VH, $H\to b\bar{b}$ vignettes

PRD 89 (2014) 012003

- 2.1σ (2.3σ exp.)
- σ/σ_{SM} = 1.0 ±0.5



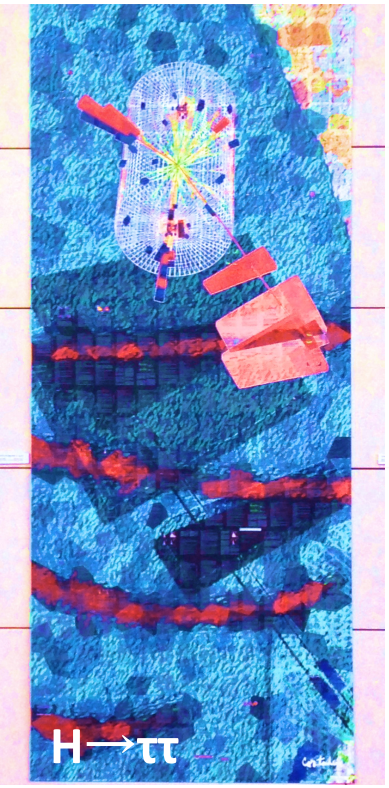




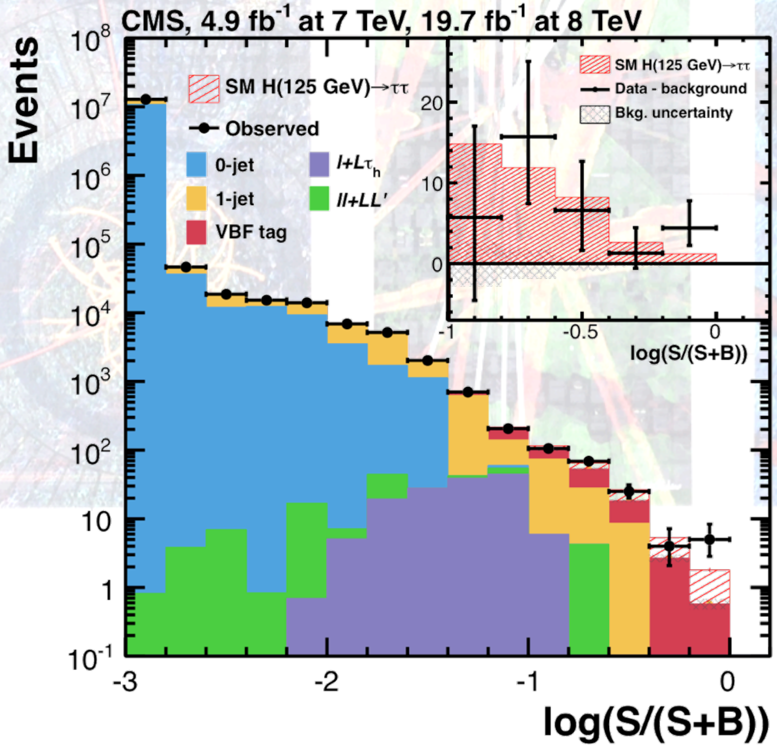
H→ττ vignettes

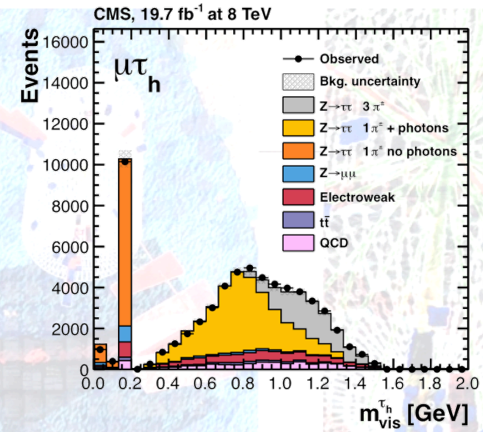
[JHEP 05 (2014) 104]

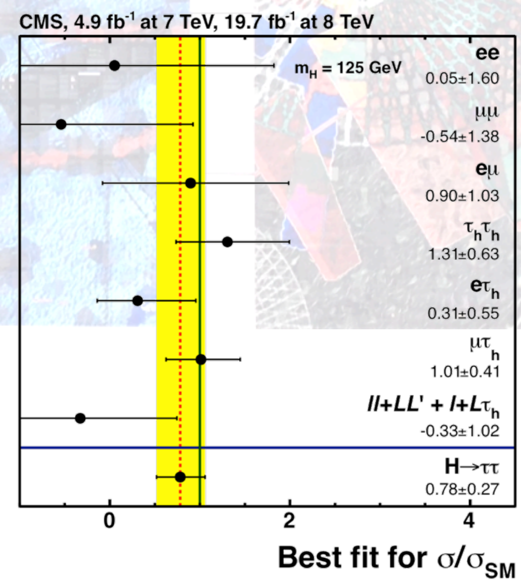
- 3.2σ (3.7σ exp.)
- $\sigma/\sigma_{SM} = 0.78 \pm 0.27$



JHEP 05 (2014) 104

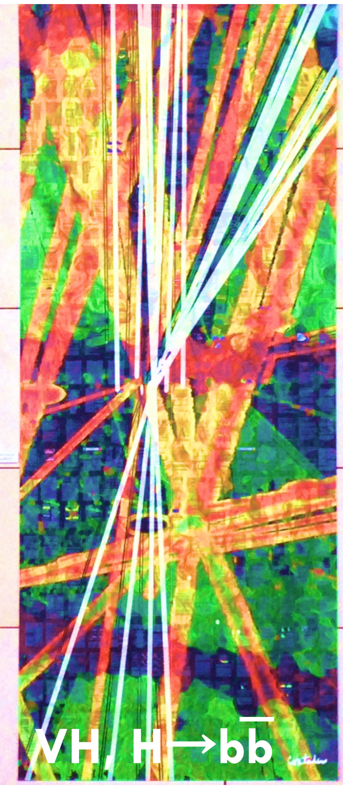


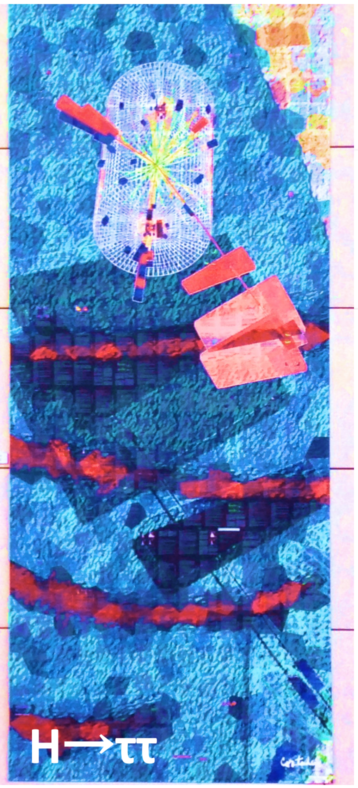




Fermion decay combination vignette

[Nature Physics 10 (2014) 557]

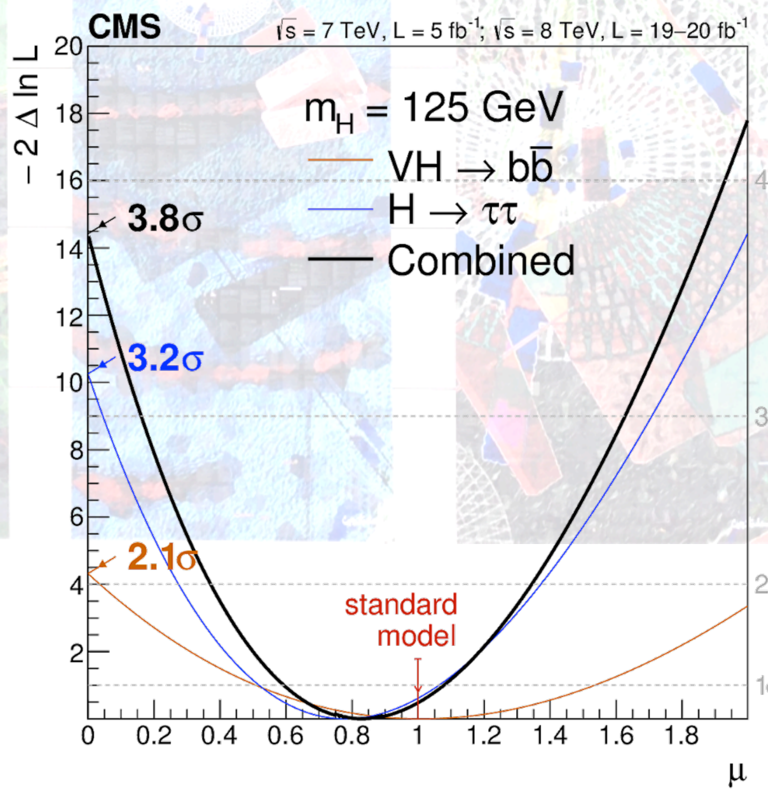




PRD 89 (2014) 012003

JHEP 05 (2014) 104

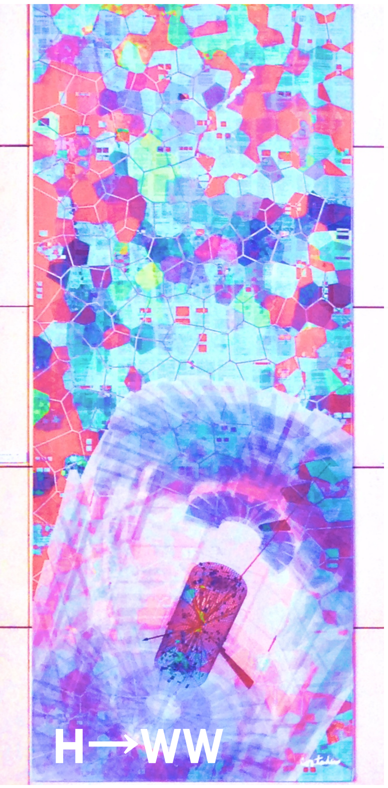
- 3.8σ (4.4σ exp.)
- $\sigma/\sigma_{SM} = 0.83 \pm 0.24$



Fermion decay combination
3.8σ obs. (4.4σ exp.)
Nature Physics 10 (2014) 557

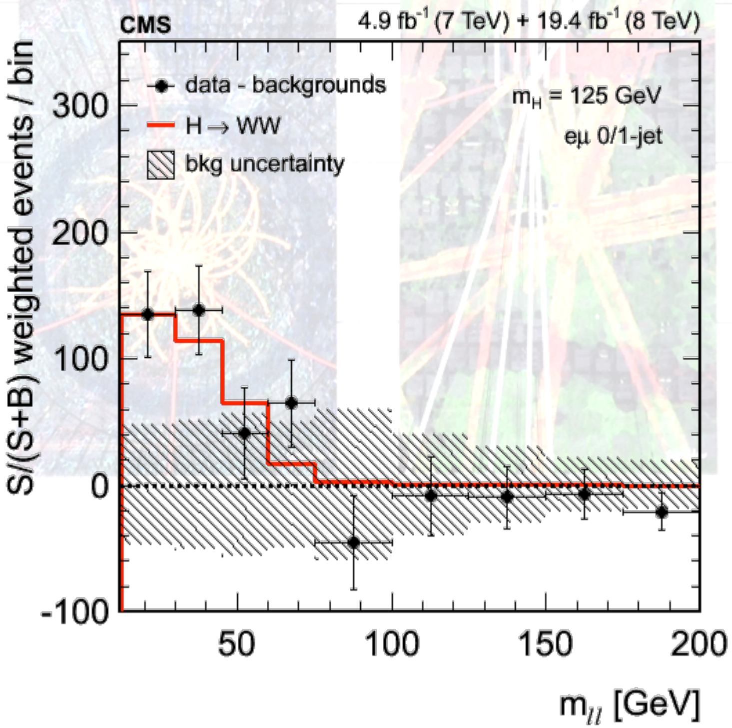
H→WW→2ℓ2ν vignettes

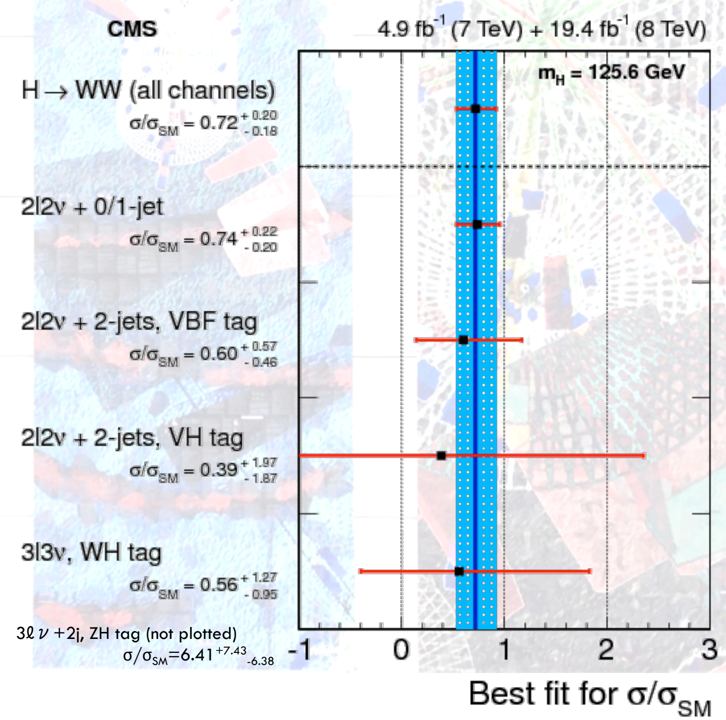
[JHEP 01 (2014) 096]



JHEP 01 (2014) 096

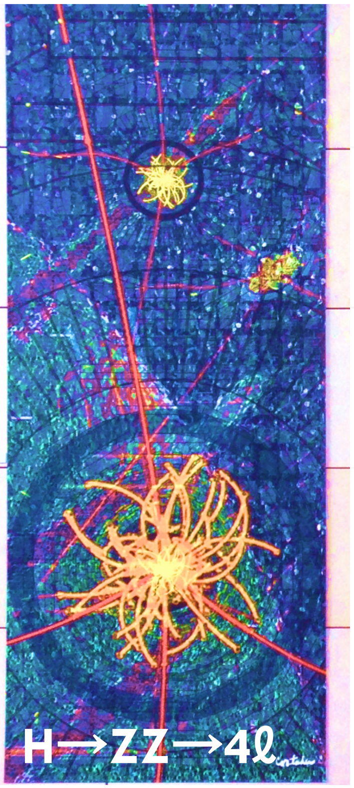
- 4.3σ (5.8σ exp.)
- σ/σ_{SM} = 0.72 ±0.19





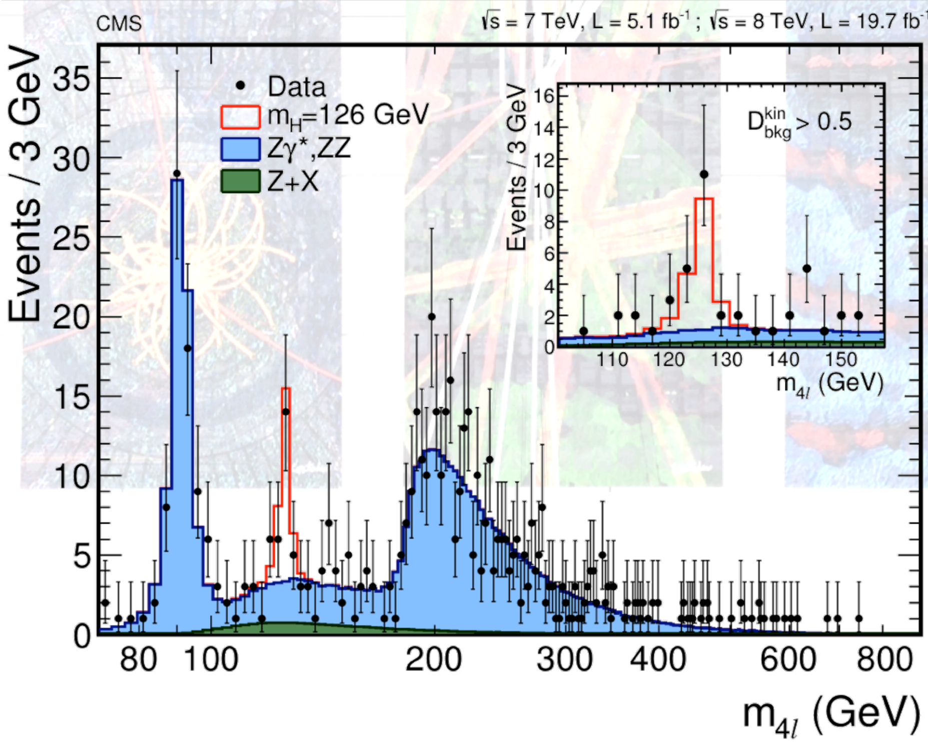
$H \rightarrow ZZ \rightarrow 4\ell$ vignettes

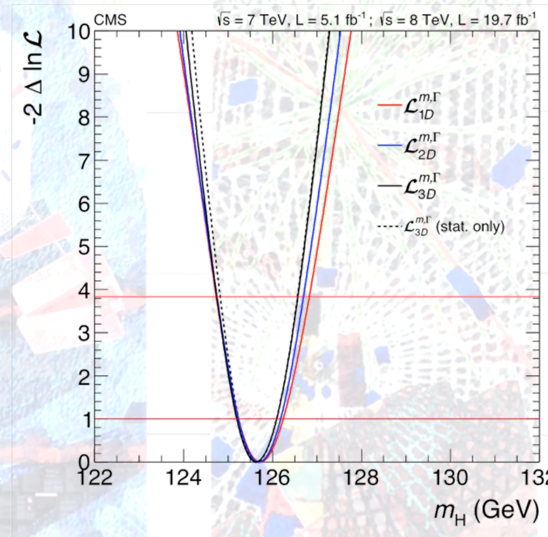
[PRD 89 (2014) 092007]

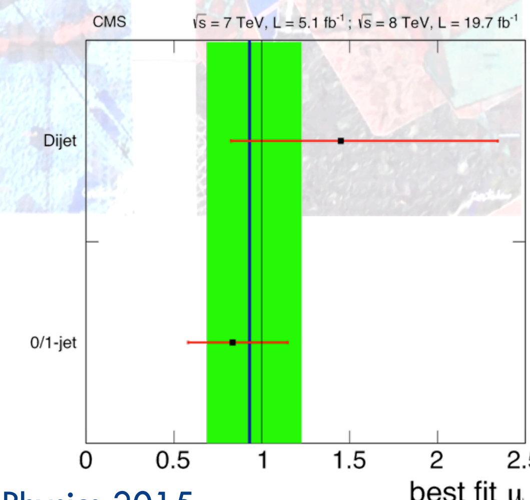


PRD 89 (2014) 092007

- 6.8σ (6.7σ exp.)
- m_H = 125.63 ±0.42 (stat.) ±0.16 (syst.) GeV
- σ/σ_{SM} = 0.93 ±0.25 (stat.) ±0.13 (syst.)





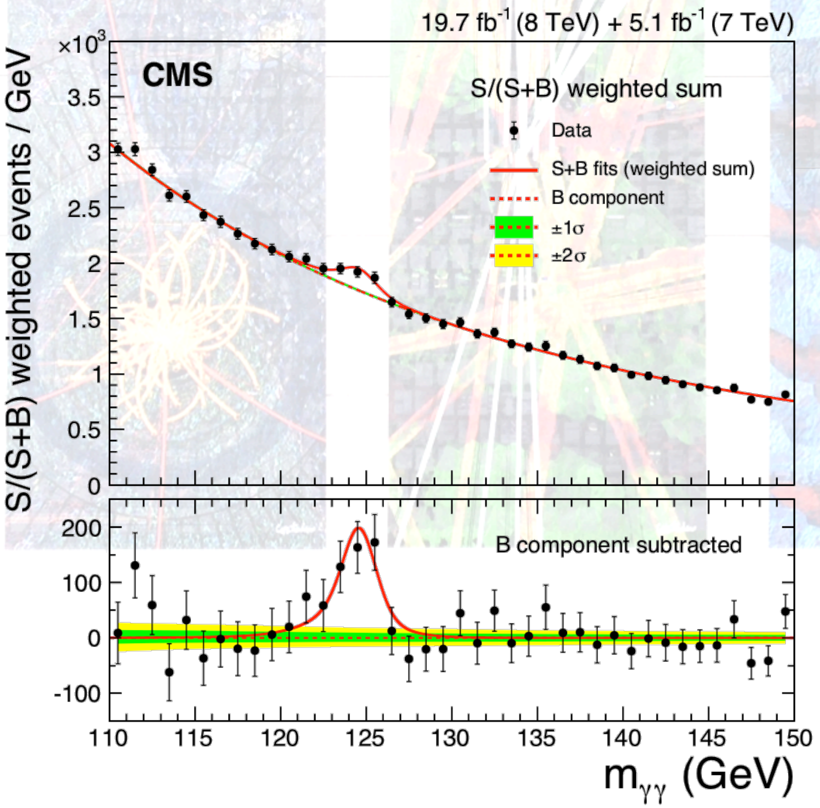


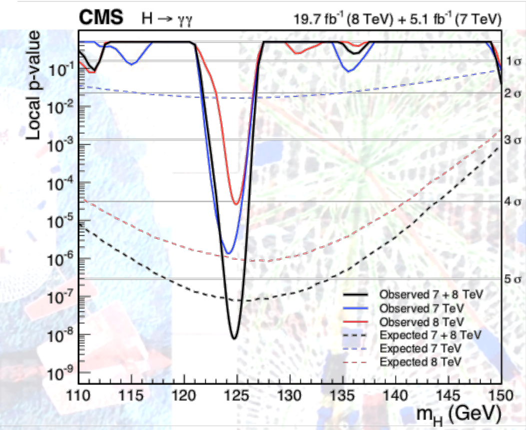
H→γγ vignettes

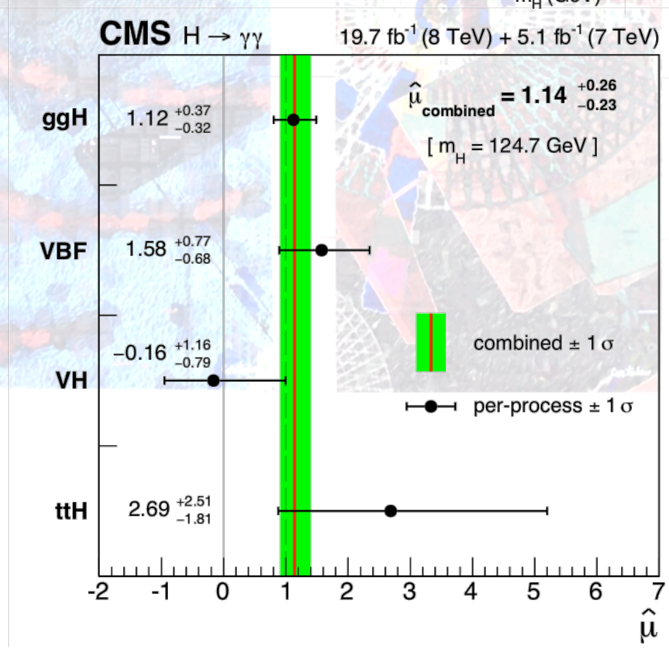
[EPJC 74 (2014) 3076]

EPJC 74 (2014) 3076

- 5.7σ (5.2σ exp.)
- m_H= 124.70 ±0.31 (stat.) ±0.15 (syst.) GeV
- σ/σ_{SM} = 1.14 ±0.21 (stat.) ±0.11 (theo.) ±0.07 (syst.)







Birth of a Higgs boson

Results from ATLAS and CMS now provide enough evidence to identify the new particle of 2012 as 'a Higgs boson'.

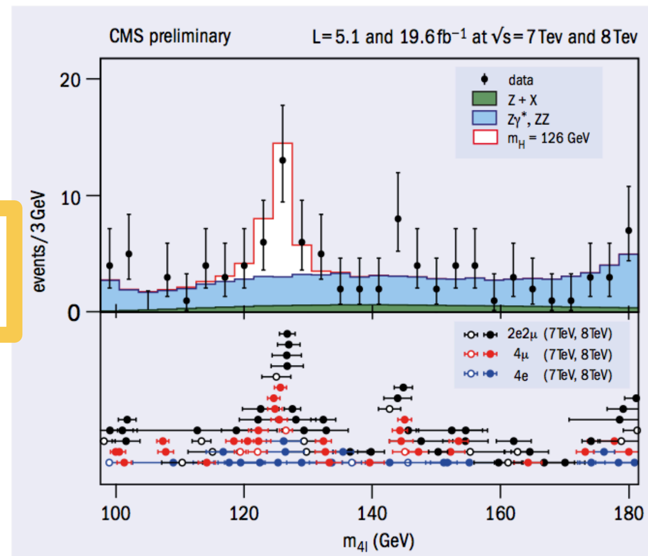
In the history of particle physics, July 2012 will feature prominently as the date when the ATLAS and CMS collaborations announced that they had discovered a new particle with a mass near 125 GeV in studies of proton–proton collisions at the LHC. The discovery followed just over a year of dedicated searches for the Higgs boson, the particle linked to the Brout-Englert-Higgs mechanism that endows elementary particles with mass. At this early stage, the phrase "Higgs-like boson" was the recognized shorthand for a boson whose properties were yet to be fully investigated (*CERN Courier* September 2012 p43 and p49). The outstanding performance of the LHC in the second half of 2012 delivered four times as much data at 8 TeV in the centre of mass as were used in the "discovery" analyses. Thus equipped, the experiments were able to present new results at the 2013 Rencontres de Moriond in March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

results that further elucidate the nature of the particle discovered just eight months earlier. The collaborations find that the new particle is looking more and more like a Higgs boson. However, it remains an open question whether this is *the* Higgs boson of the Standard Model of particle physics, or one of several such bosons predicted in theories that go beyond the Standard Model. Finding the answer to this question will require more time and data.

This brief summary provides an update of the measurements

Observed CL_s compared with $J^P=0^+$		0^- (gg) pseudo-scalar	2^+_m (gg) minimal couplings	2^+_m ($q\bar{q}$) minimal couplings	1^- ($q\bar{q}$) exotic vector	1^+ ($q\bar{q}$) exotic pseudo-vector
$ZZ^{(*)}$	ATLAS	2.2%	6.8%	16.8%	6.0%	0.2%
	CMS	0.16%	1.5%	<0.1%	<0.1%	<0.1%
$WW^{(*)}$	ATLAS	–	5.1%	1.1%	–	–
	CMS	–	14%	–	–	–
$\gamma\gamma$	ATLAS	–	0.7%	12.4%	–	–

Table 1. Summary of preliminary results of the hypothesis tests compared with the Standard Model hypothesis of no spin, positive parity ($J^P=0^+$). All alternatives are disfavoured using the CL_s ratio of probabilities that takes into account how the observation relates to both the Standard Model and the alternative hypotheses.



Entry in the PDG

H^0 (Higgs Boson)

The observed signal is called a Higgs Boson in the following, although its detailed properties and in particular the role that the new particle plays in the context of electroweak symmetry breaking need to be further clarified. The signal was discovered in searches for a Standard Model (SM)-like Higgs. See the following section for mass limits obtained from those searches.

H^0 MASS

INSPIRE search

Value (GeV)	Document ID		TECN	Comment
125.9 ±0.4	OUR AVERAGE			
125.8 ±0.4 ±0.4	CHATRCHYAN [1]	2013J	CMS	pp , 7 and 8 TeV
126.0 ±0.4 ±0.4	AAD [2]	2012AI	ATLS	pp , 7 and 8 TeV
*** We do not use the following data for averages, fits, limits, etc ***				
126.2 ±0.6 ±0.2	CHATRCHYAN [3]	2013J	CMS	pp , 7 and 8 TeV
125.3 ±0.4 ±0.5	CHATRCHYAN [4]	2012N	CMS	pp , 7 and 8 TeV

[1] Combined value from ZZ and $\gamma\gamma$ final states.

[2] AAD 2012AI obtain results based on $4.6 - 4.8$ fb^{-1} of pp collisions at E_{cm} = 7 TeV and $5.8 - 5.9$ fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.9 σ is observed at m_{H^0} = 126 GeV. See also AAD 2012DA.

[3] Result based on final states in 5.1 fb^{-1} of pp collisions at E_{cm} = 7 TeV and 12.2 fb^{-1} at E_{cm} = 8 TeV.

[4] CHATRCHYAN 2012N obtain results based on $4.9 - 5.1$ fb^{-1} of pp collisions at E_{cm} = 7 TeV and $5.1 - 5.3$ fb^{-1} at E_{cm} = 8 TeV. An excess of events over background with a local significance of 5.0 σ is observed at about m_{H^0} = 125 GeV. See also CHATRCHYAN 2012BY.

References

Document Id		Journal Name
CHATRCHYAN	2013J	PRL 110 081803
AAD	2012AI	PL B716 1
CHATRCHYAN	2012N	PL B716 30

NB: the mass measurement alone "cleared up" a huge chunk of BSM space.

2013: “killer” news

[“Lawrence of Arabia” idea from C. Grojean]

- SM-like: the Swedish academy shot the prize at Englert and Higgs.

Nobel prizes…

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

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The Nobel Prize in Physics 2013

Photo: A. Mahmoud
François Englert
Prize share: 1/2

Photo: A. Mahmoud
Peter W. Higgs
Prize share: 1/2

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

...and knighthoods.

Eminent physicists receive royal honours

by Deborah Evanson, Colin Smith, Gail Wilson
16 June 2014

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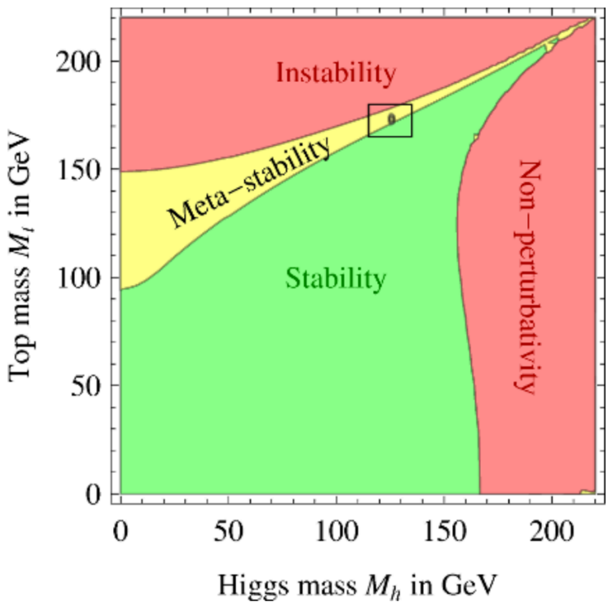
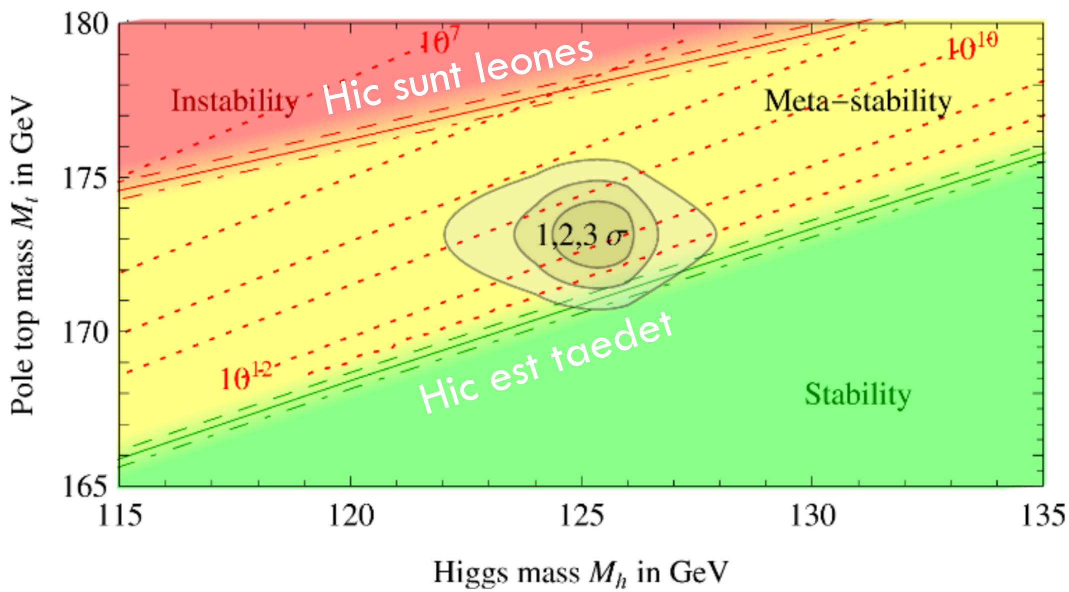
Two of Imperial's physicists, best known for predicting and finding the Higgs boson, have been knighted in this year's Queen's Birthday honours list.

The fate/character of the Universe

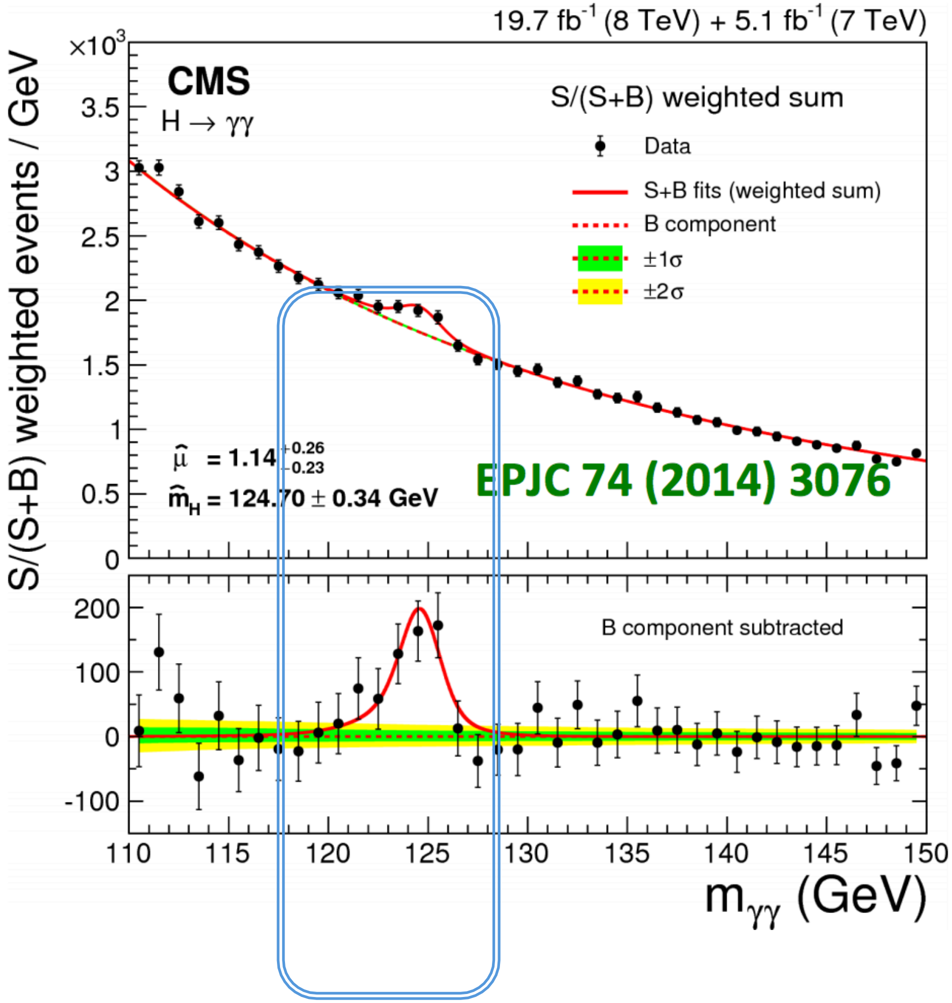
[JHEP 08 (2012) 098]

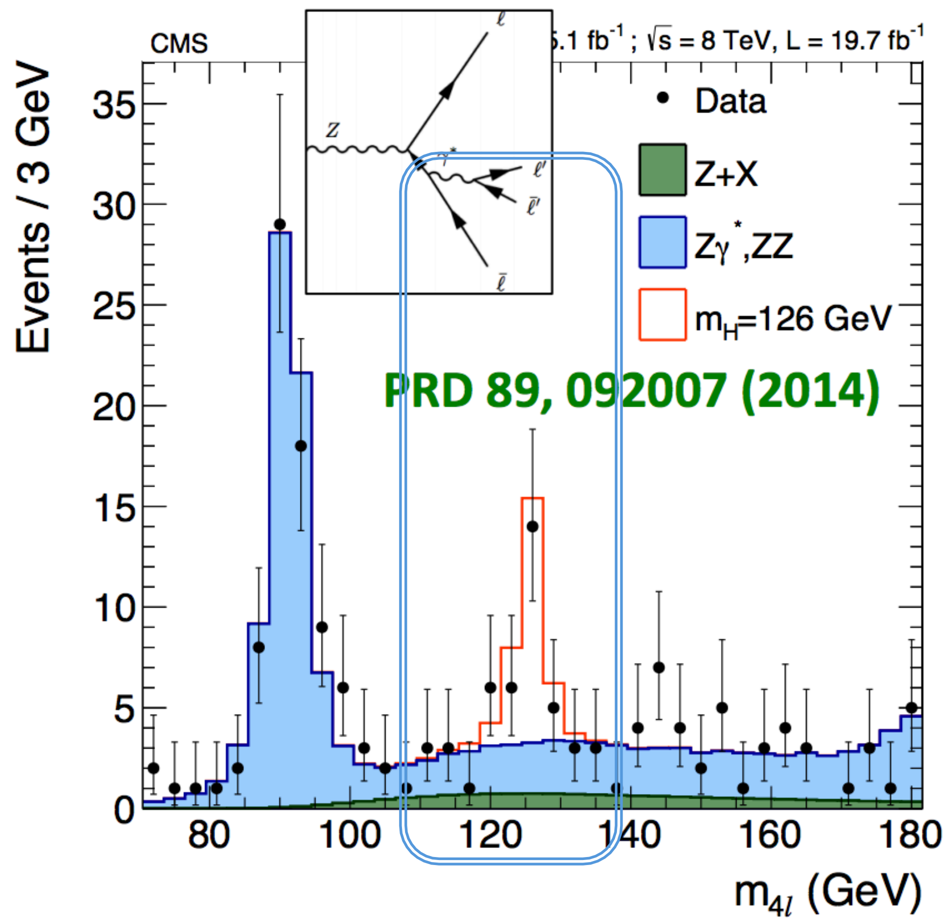




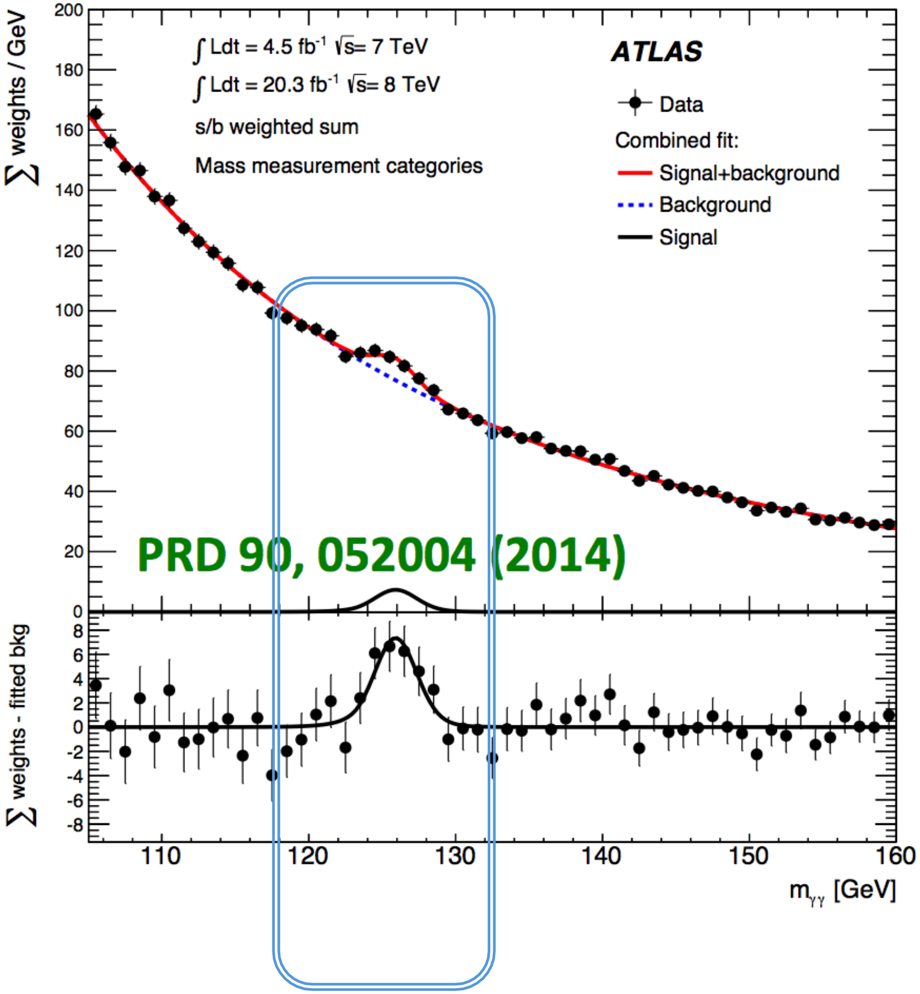
- The SM vacuum stability depends crucially on the masses of the top quark and Higgs boson.

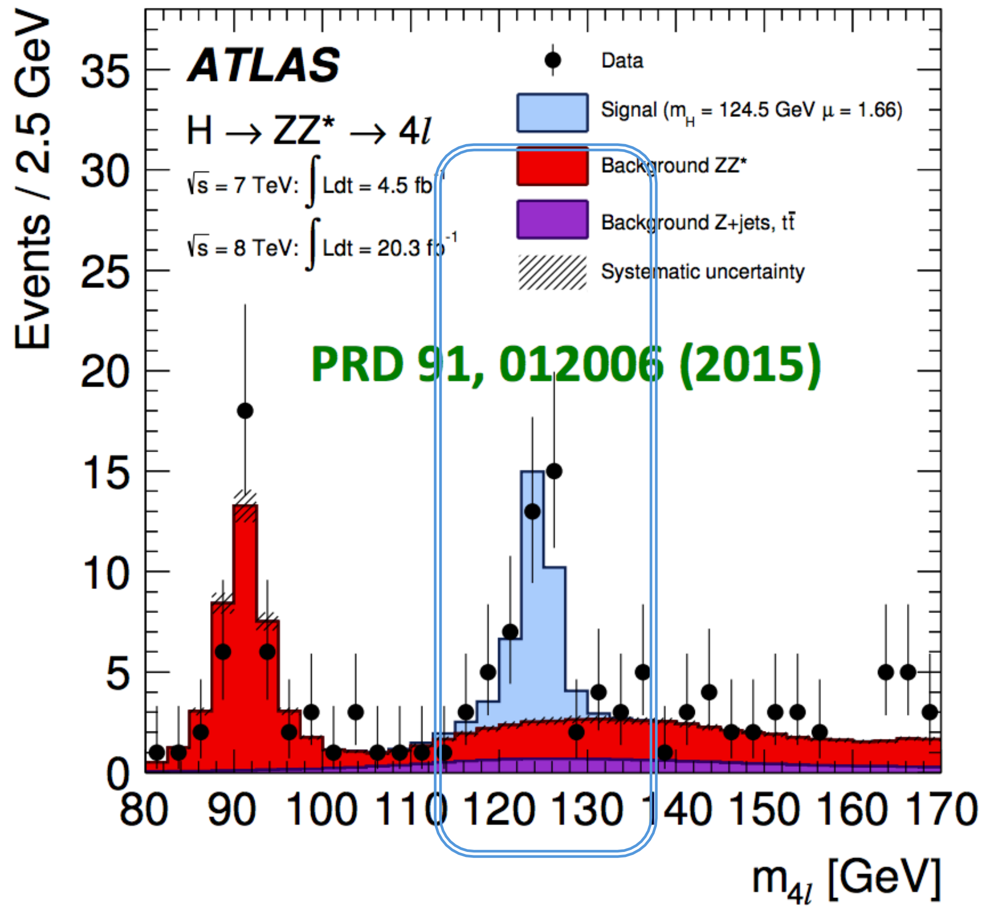
Mass peaks: mass measurements





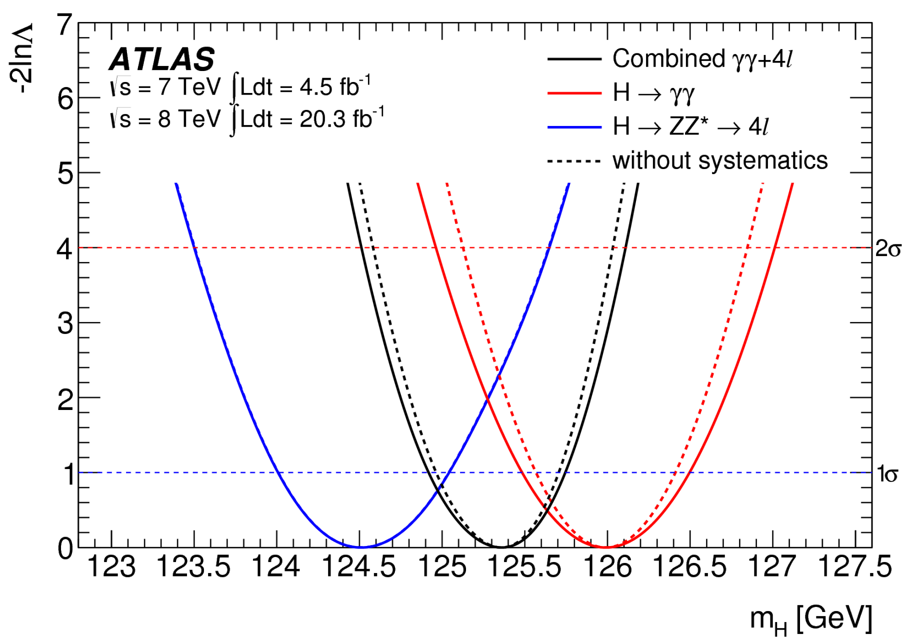
Mass peaks: mass measurements

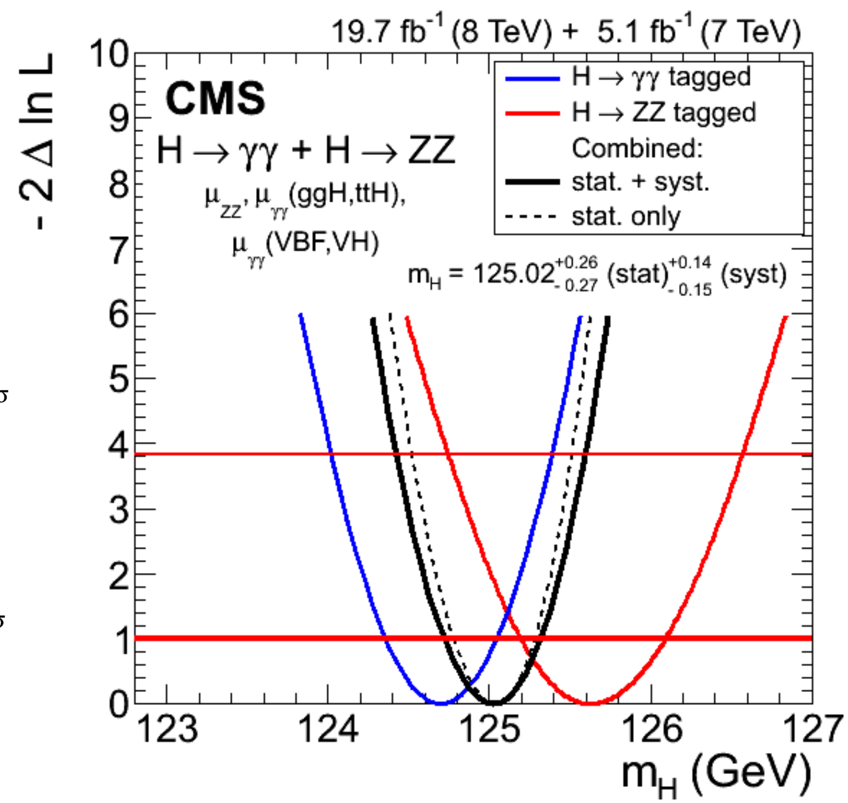




Mass measurement

[arXiv:1406.3827][arXiv:1412.8662]

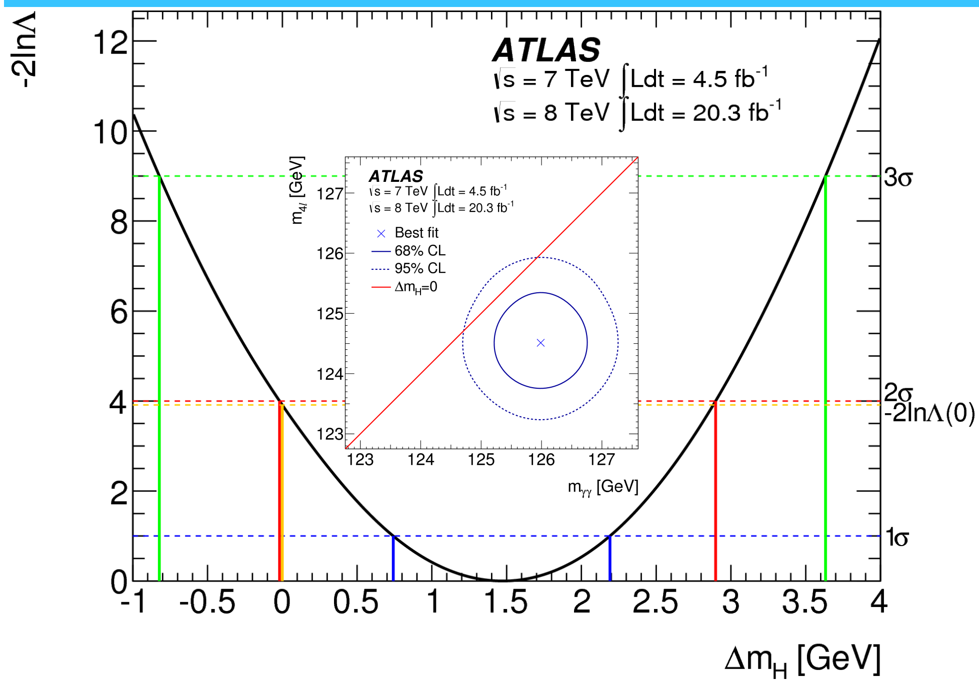


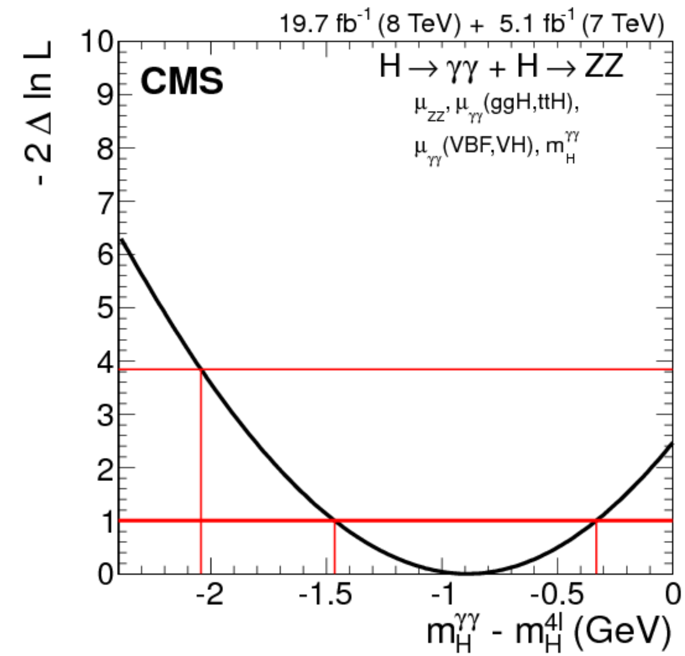


	ATLAS	CMS
m_X	125.36 ±0.37 (stat.) ±0.18 (syst.) GeV	125.02 ±0.27 (stat.) ±0.15 (syst.) GeV
Naïve average: 125.15 ±0.25 GeV		

More on mass

[arXiv:1406.3827][arXiv:1412.8662]

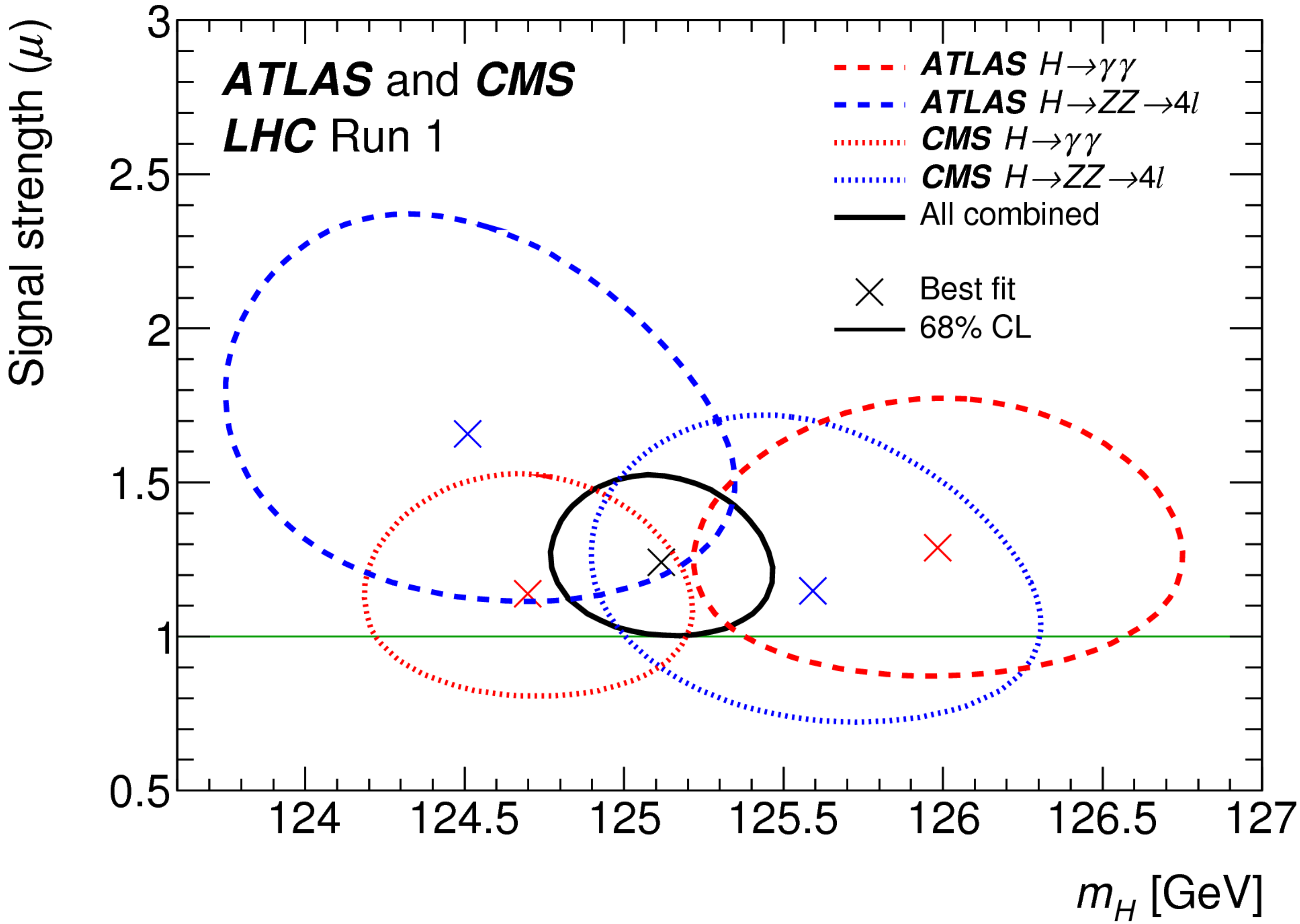




- Slight difference in ATLAS results:
  - $m_H^{\gamma\gamma} - m_H^{ZZ} =$ 1.47 ±0.67(stat.) ±0.28(syst.) GeV
  - **1.97σ (p=4.9%).**
  - Using more conservative energy scale uncertainties: 1.8σ (p=7.5%).
- In CMS, less significant and with **opposite sign:**
  - $m_H^{\gamma\gamma} - m_H^{ZZ} = -0.9 \pm 0.6$ GeV
  - 1.6σ.

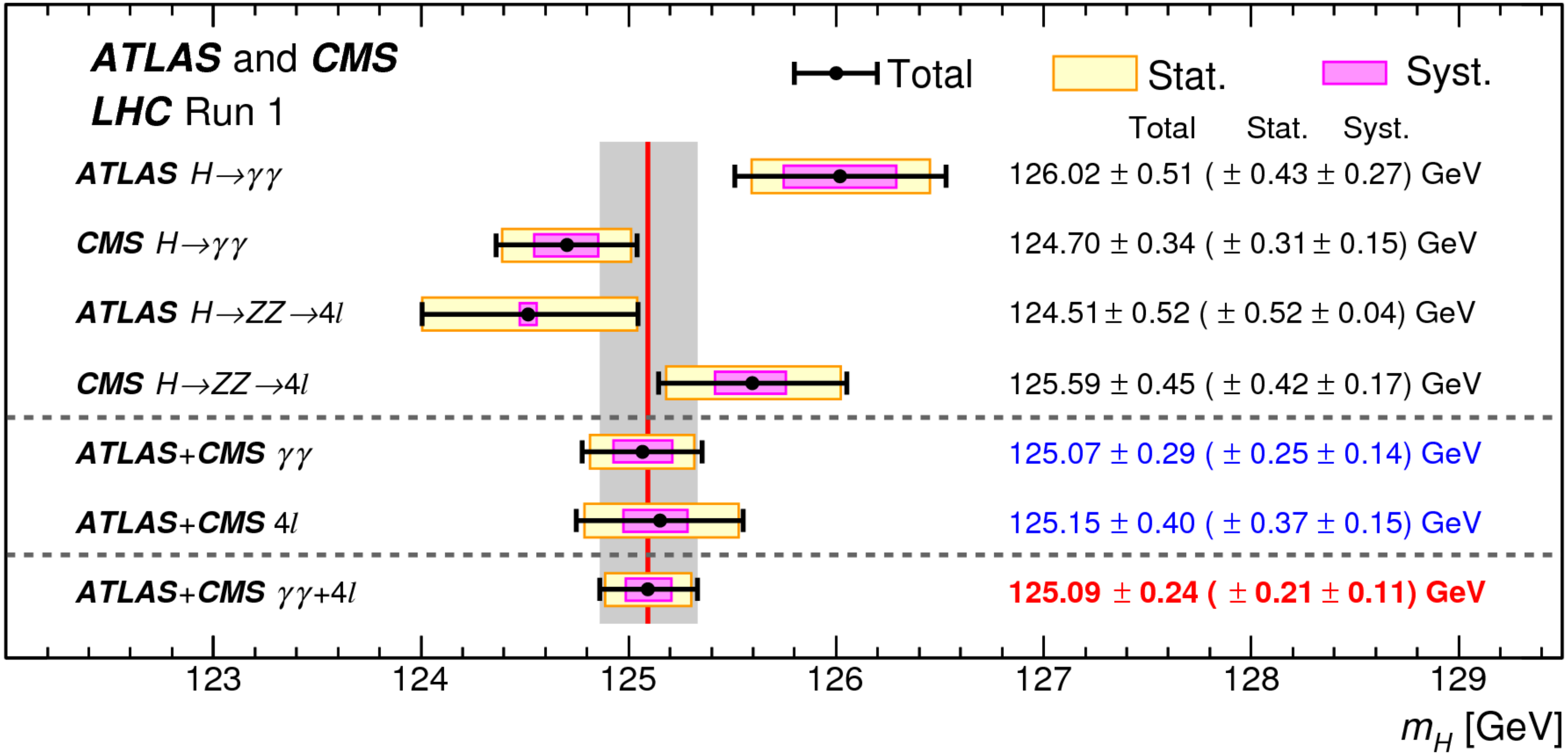
Combined LHC mass measurement

[arXiv:1503.07589]



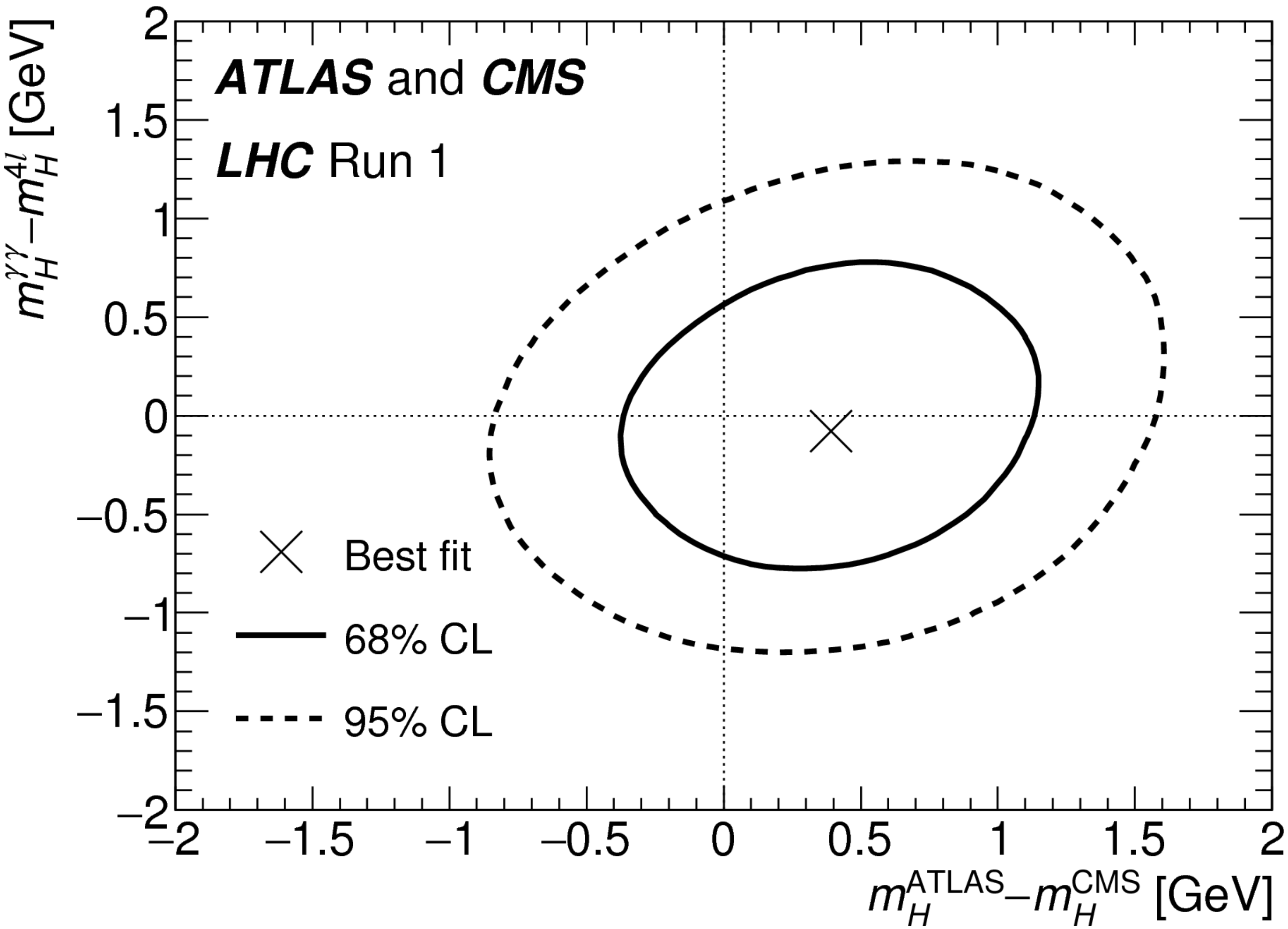
Combined LHC mass measurement

[arXiv:1503.07589]



Combined LHC mass measurement

[arXiv:1503.07589]

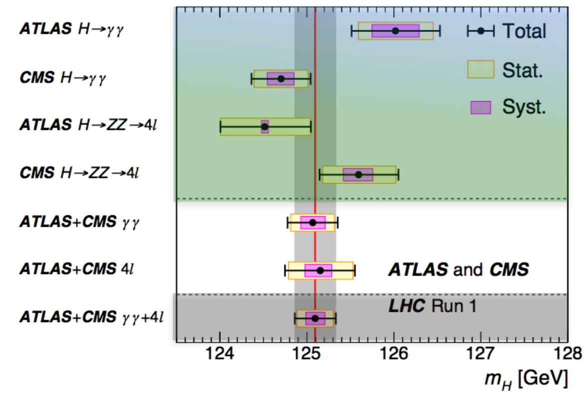


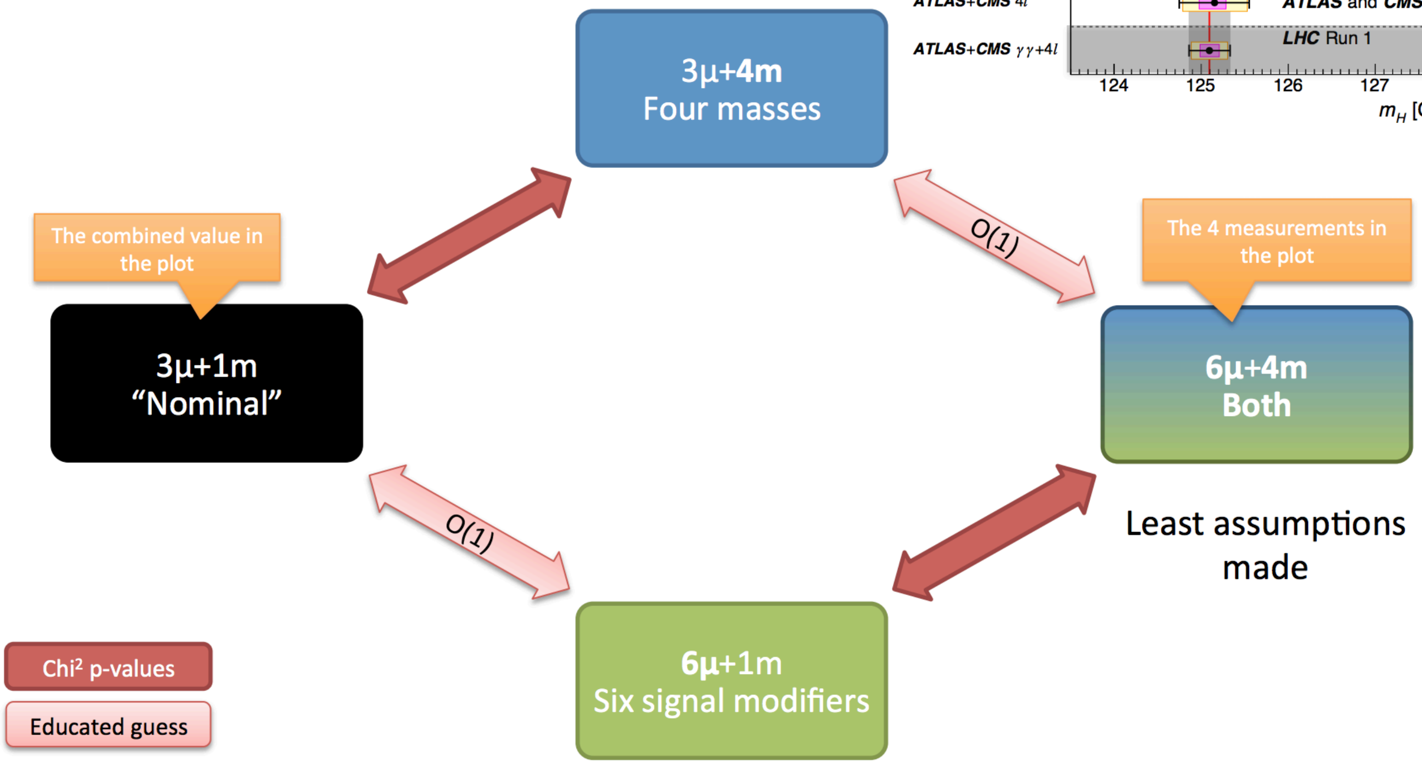
Combined LHC mass measurement

[arXiv:1503.07589]

Compatibility

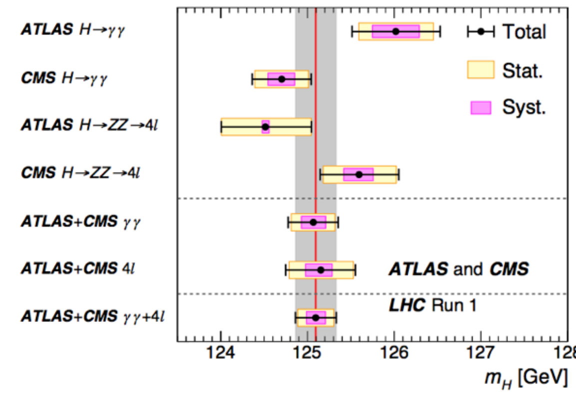
A number of different models to check compatibility of the result …





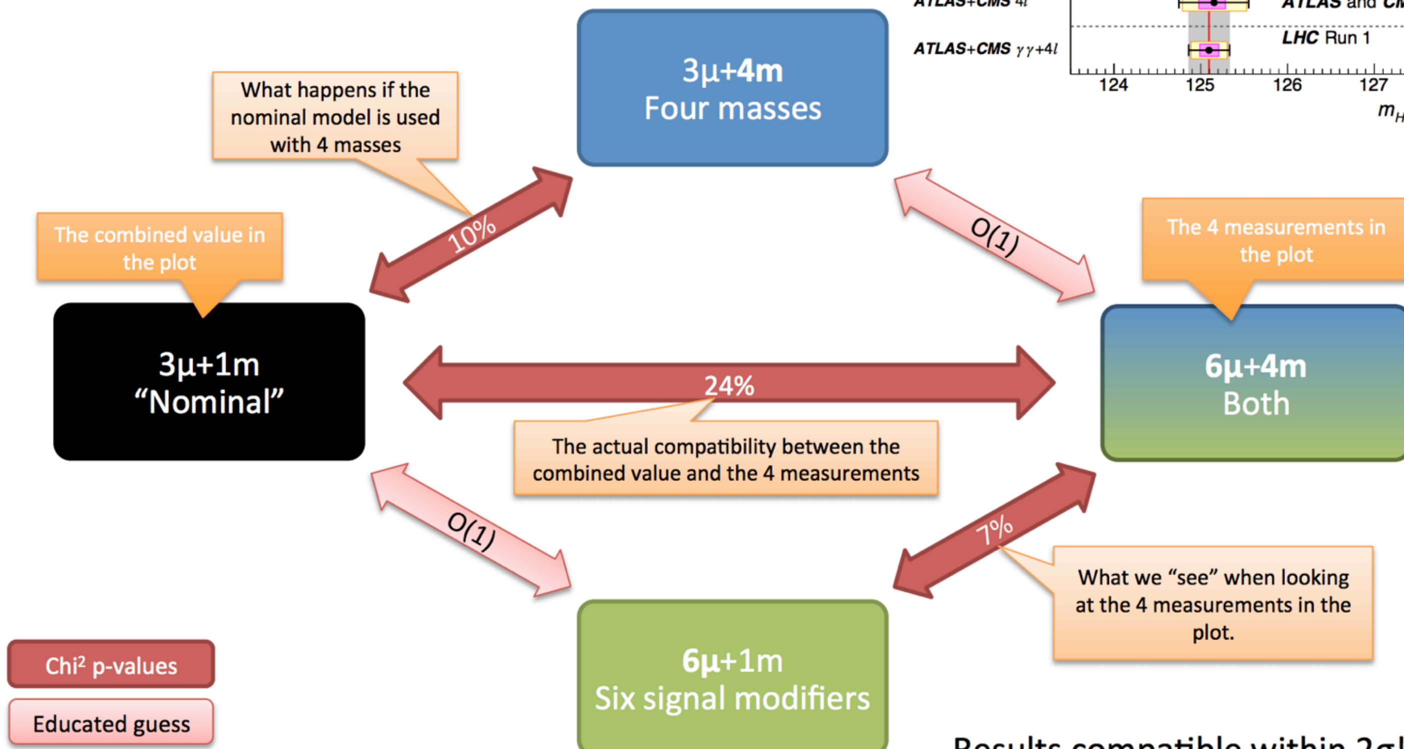
Combined LHC mass measurement

[arXiv:1503.07589]



Compatibility

A number of different models to check compatibility of the result …



Results compatible within 2σ!

Combined LHC mass measurement

[arXiv:1503.07589]

$$m_H = 125.09 \pm 0.21 \ (\text{stat})$$
$$\pm 0.11 \ (\text{scale})$$
$$\pm 0.02 \ (\text{other})$$
$$\pm 0.01 \ (\text{theory}^*)$$
$$\text{GeV}$$

Uncertainty is mostly statistical

Scale uncertainties dominate systematic

→ But we can expect that to improve with more data!

One model

One model

One model


Fiat 124


Fiat 126

One model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125 ±0.2
a very
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594 ELIZABETH STREET, MELBOURNE. Phone 34-1519


Fiat 124


CB 29070
Fiat 126

Deviations of H(125)

- **Heavy New Physics**
  - Concern of LHC HXSWG WG2
  - Decoupling of heavy d.o.f.
  - Indirect effects, loops, dim-6 operators, etc.

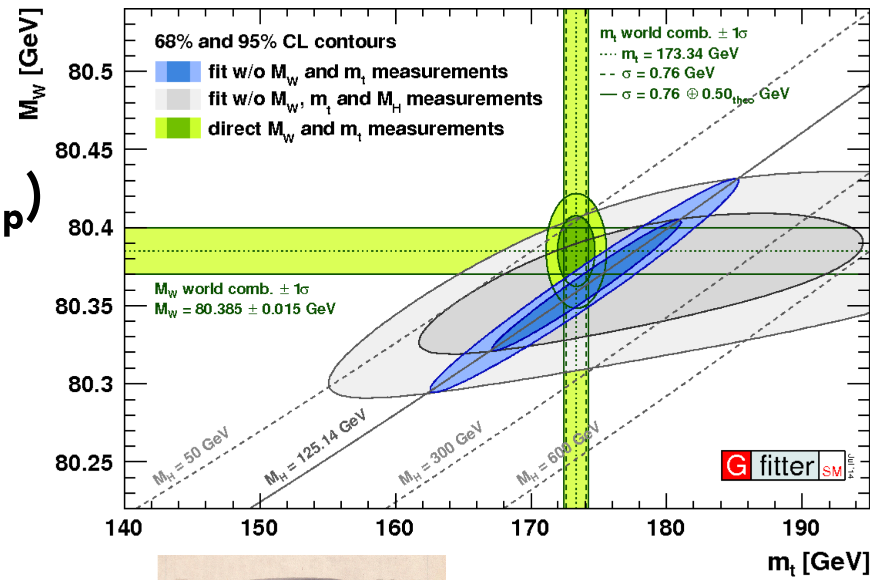
- **Light New Physics**
  - Benchmarks from LHC HXSWG WG3
  - Other states, degenerate states, etc.

Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

An actual measurement

- **Mass**
  - **Exp. Uncertainties**
  - **SM consistency: (m_H, m_W, m_{top})**
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT



Handles on deviations

- Mass
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  - SM consistency: (m_H, m_W, m_{top})
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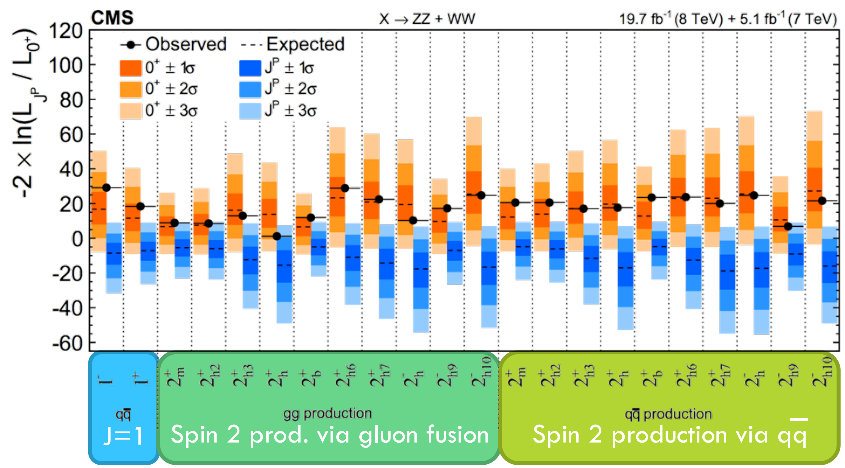

Handles on deviations

- Mass
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  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- **Charge**
  - **Zero. (That was easy.)**
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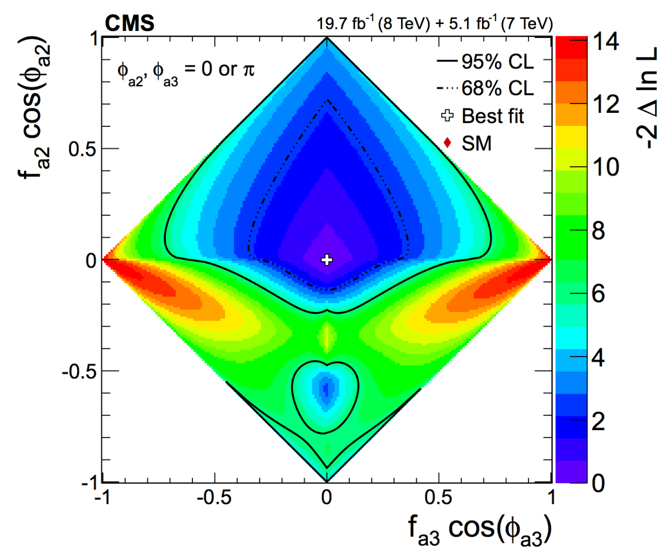
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

0

Handles on deviations

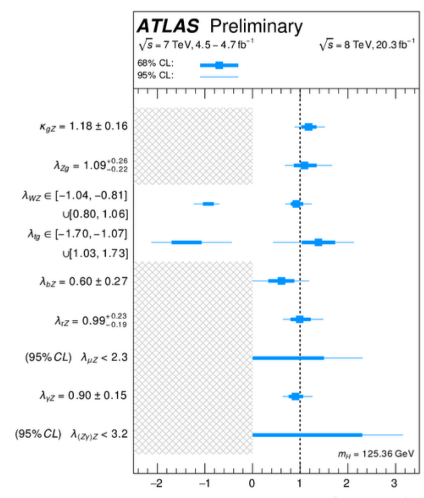
- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- **Parity**
  - **Amplitude decomposition → EFT**
- Scalar couplings
  - $\kappa \rightarrow \kappa(q) \rightarrow f(q) \rightarrow$ EFT

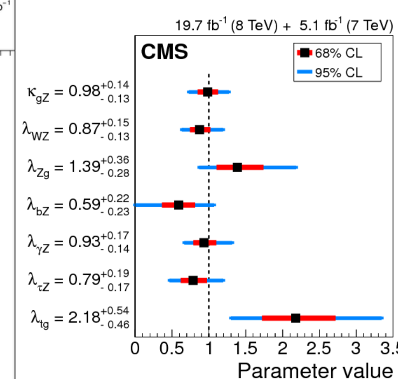
$$
\begin{aligned}
A(X_{J=0} \rightarrow V_1 V_2) \sim\ & v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}}\frac{q^2_{Z_1}+q^2_{Z_2}}{(\Lambda_1)^2}\right] m_Z^2 \epsilon^*_{Z_1}\epsilon^*_{Z_2}\right.\\
& + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu}\\
& + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}\\
& \left. + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu}\right)
\end{aligned}
$$



Handles on deviations

- Mass
  - Exp. Uncertainties
  - SM consistency: (m_H, m_W, m_{top})
- Spin
  - Are we happy now?
- Charge
  - Zero. (That was easy.)
- Parity
  - Amplitude decomposition → EFT
- **Scalar couplings**
  - **κ → κ (q) → f(q) → EFT**





Oversimplified big picture

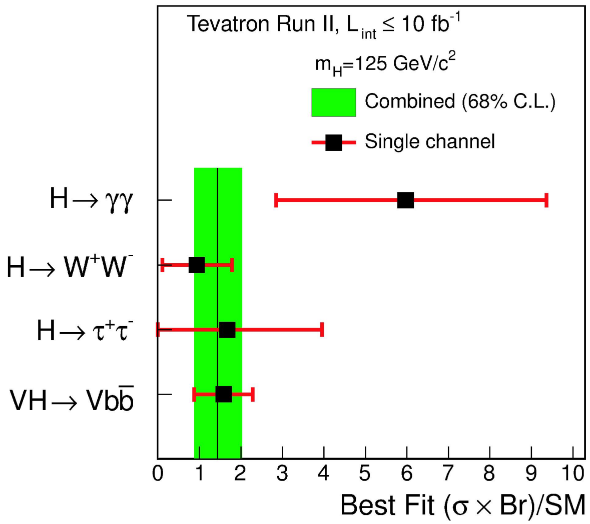
T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

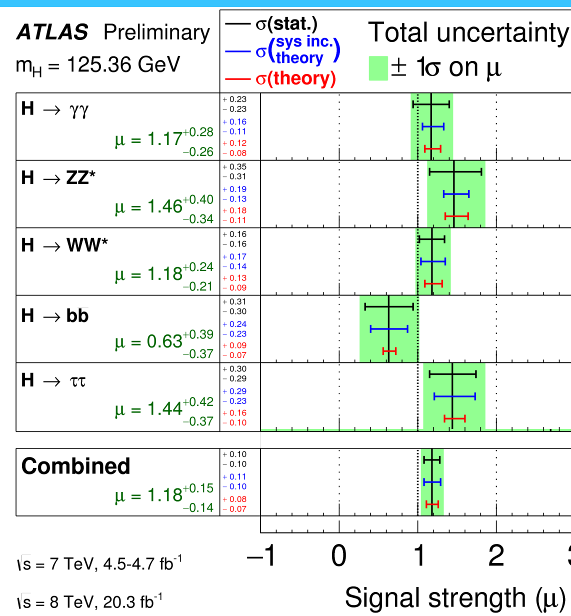
★ "seen" ☆ "tried" - "impossible"	$H\to b\bar{b}$			$H\to\tau\tau$			$H\to WW$			$H\to ZZ$			$H\to\gamma\gamma$			$H\to Z\gamma$			$H\to$inv.			$H\to\mu\mu$			$H\to c\bar{c}$ $H\to HH$		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	★	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	★	★		★	★		★	☆		★	☆	-		☆			☆	-		☆	-		
VH	★	☆	★	☆		☆	☆	☆	☆		☆	☆		☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆		☆	☆							☆	☆	-						-			-		

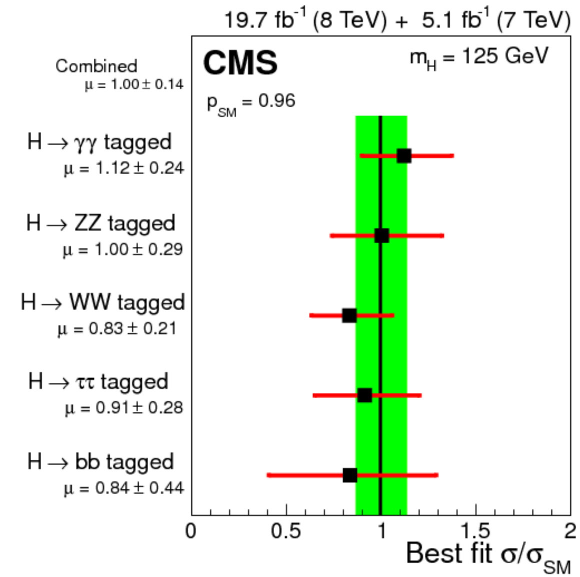
- **Still much to explore on the rarer ends.**
  (to the right and to the bottom) (and outside this picture ☲)

Relative signal strengths

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]







What's in a "signal strength"?

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

- Deviations are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Production

Decay

- Deviations are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

- **Deviations** are searched relative to SM expectation.
- *Conclusions are only as good as the accuracy and precision of the numerator and denominator.*

Anatomy of deviations

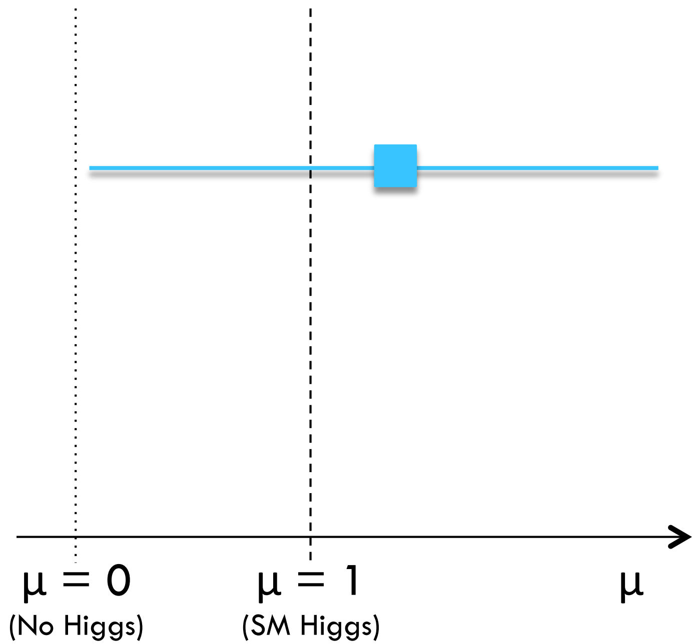
$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{observed}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{expected}}}$$

Data

Standard Model

- **Deviations** are searched **relative to SM expectation.**
- *Conclusions are only as good as the* ***accuracy and precision*** *of the* ***numerator and denominator.***

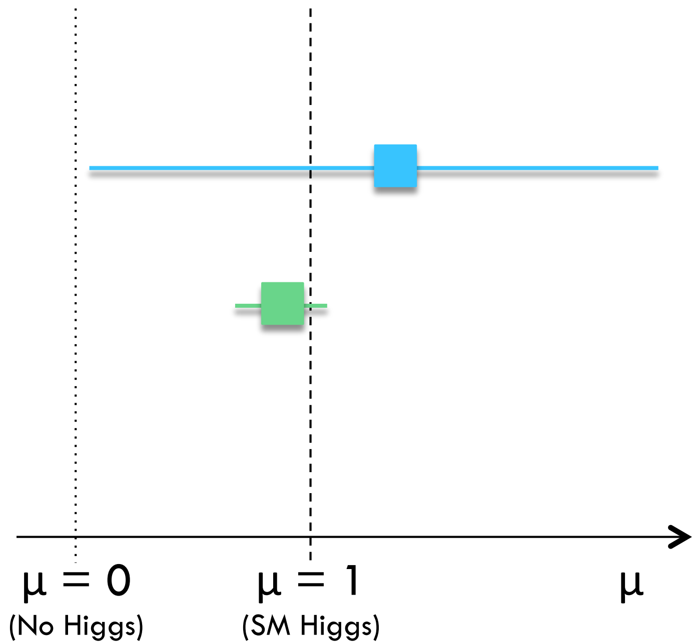
The anatomy of deviations



Imprecise measurement compatible with 0 and 1.
Inconclusive, "more data needed".

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - **$\mu = 1.3 \pm 1.2$ is inconclusive and "more data is needed"**, but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

The anatomy of deviations

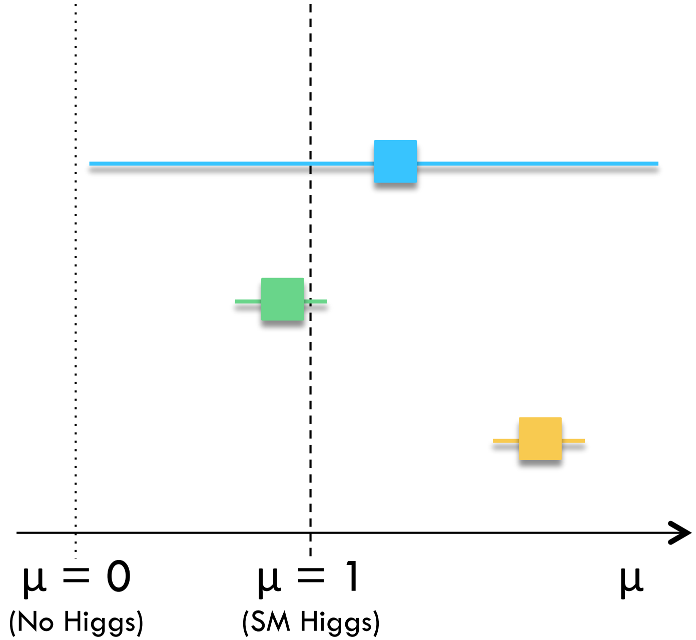


Imprecise measurement compatible with anything.
Inconclusive, "more data needed".

Precise measurement **compatible** with the SM.
Large deviations excluded!

- **$\mu = 1$ means that the data match the SM.**
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 1.3 \pm 1.2$ usually means "more data needed", but
    - $\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, “more data needed”.

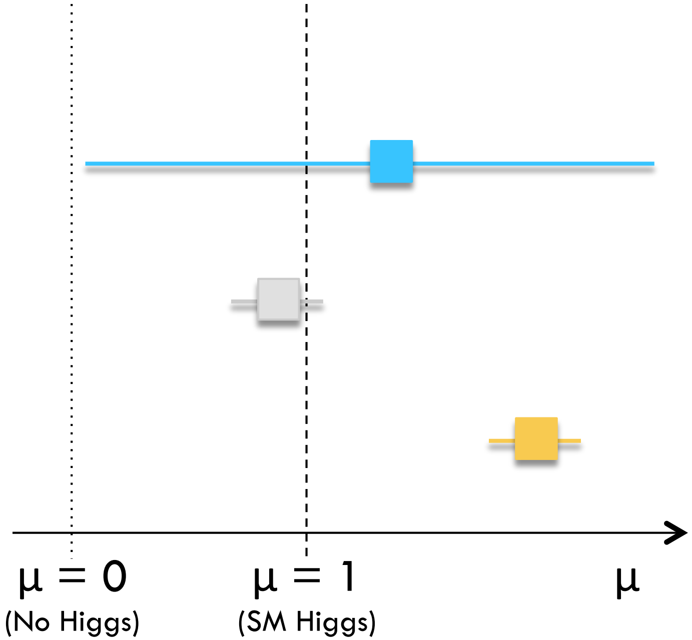
Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation.

“New Physics ⇒ Deviation” but “Deviation ⇏ New Physics”
See, e.g., http://cern.ch/go/W8wW

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$ usually means “more data needed”, but
    - **$\mu = 2.0 \pm 0.2$ could mean New Physics (or a systematic effect).**

The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, “more data **or better theory** needed”.

Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation **or exp./theory bias.**

“New Physics ⇒ Deviation” but “Deviation ⇏ New Physics”
See, e.g., http://cern.ch/go/W8wW

- $\mu = 1$ means that the data match the SM.
  - Uncertainty on μ quantifies the compatibility with the SM:
    - $\mu = 3 \pm 5$ usually means “more data needed”, but
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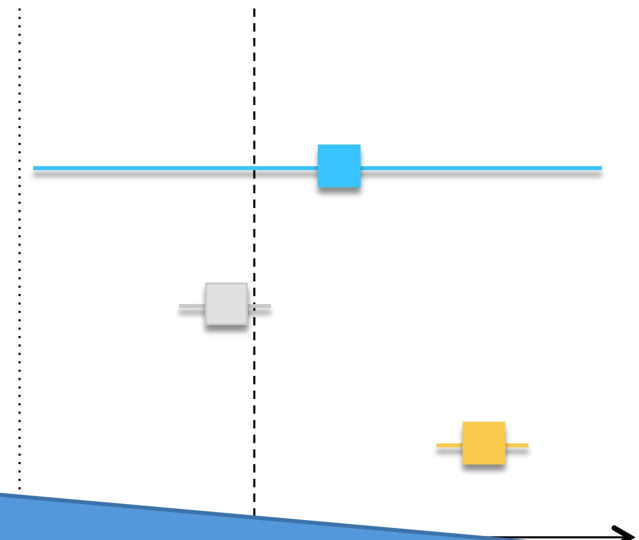
The anatomy of deviations



Imprecise measurement compatible with anything.
Inconclusive, “more data **or better theory** needed”.

Precise measurement **compatible** with the SM.
Large deviations excluded!

Precise measurement **incompatible** with the SM!
Evidence of a deviation **or exp./theory bias.**

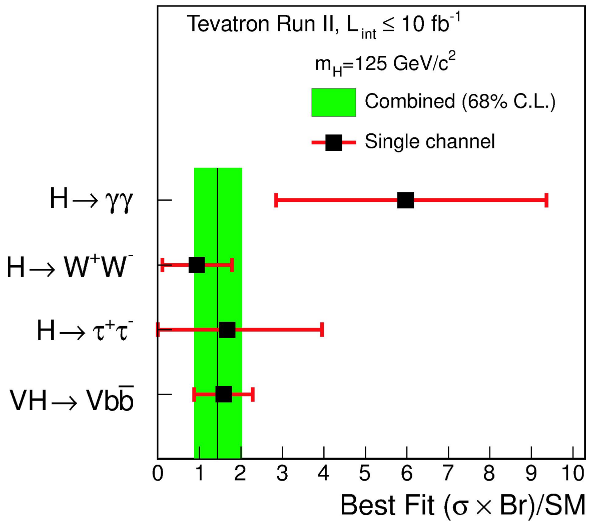
“New Physics ⇒ Deviation” but “Deviation ⇏ New Physics”
See, e.g., http://cern.ch/go/W8wW

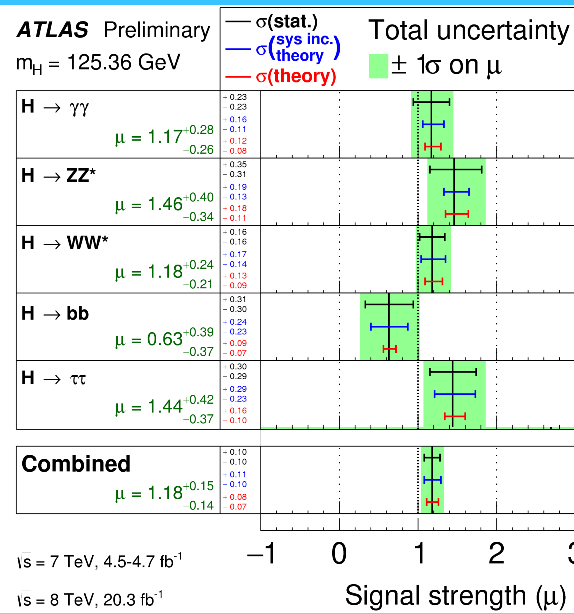
Theory contributes as much to the conclusions as experiments !

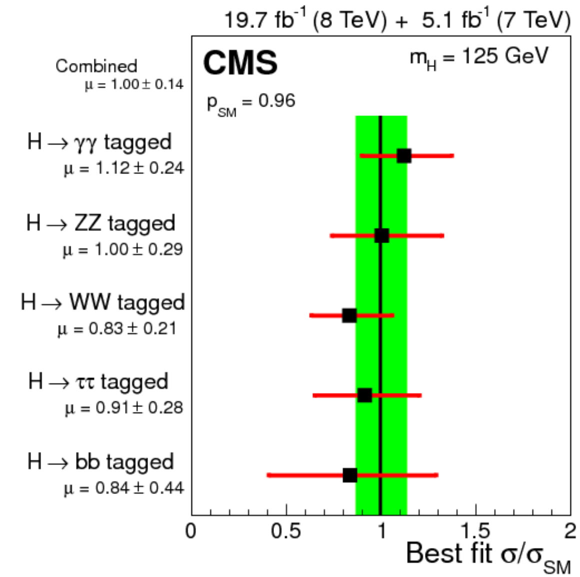
- μ = 2.0 ±0.2 **could mean New** ...

Relative signal strengths

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]







	Tevatron	ATLAS	CMS
m_H	125 GeV	125.4 GeV	125.0 GeV
$\mu = \sigma/\sigma_{SM}$	$1.44^{+0.59}_{-0.56}$	1.18 ±0.15	1.00 ±0.14

Naïve LHC average: 1.1 ±0.1

So small that you need a pipette

Particles smaller than the Higgs boson exist?

By PTI | 23 Mar, 2014, 01.52PM IST — 1 comments | Post a Comment

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LONDON: There are unknown particles floating around the universe that may be even smaller than the Higgs boson, the 'God particle' discovered in 2012, scientists say.

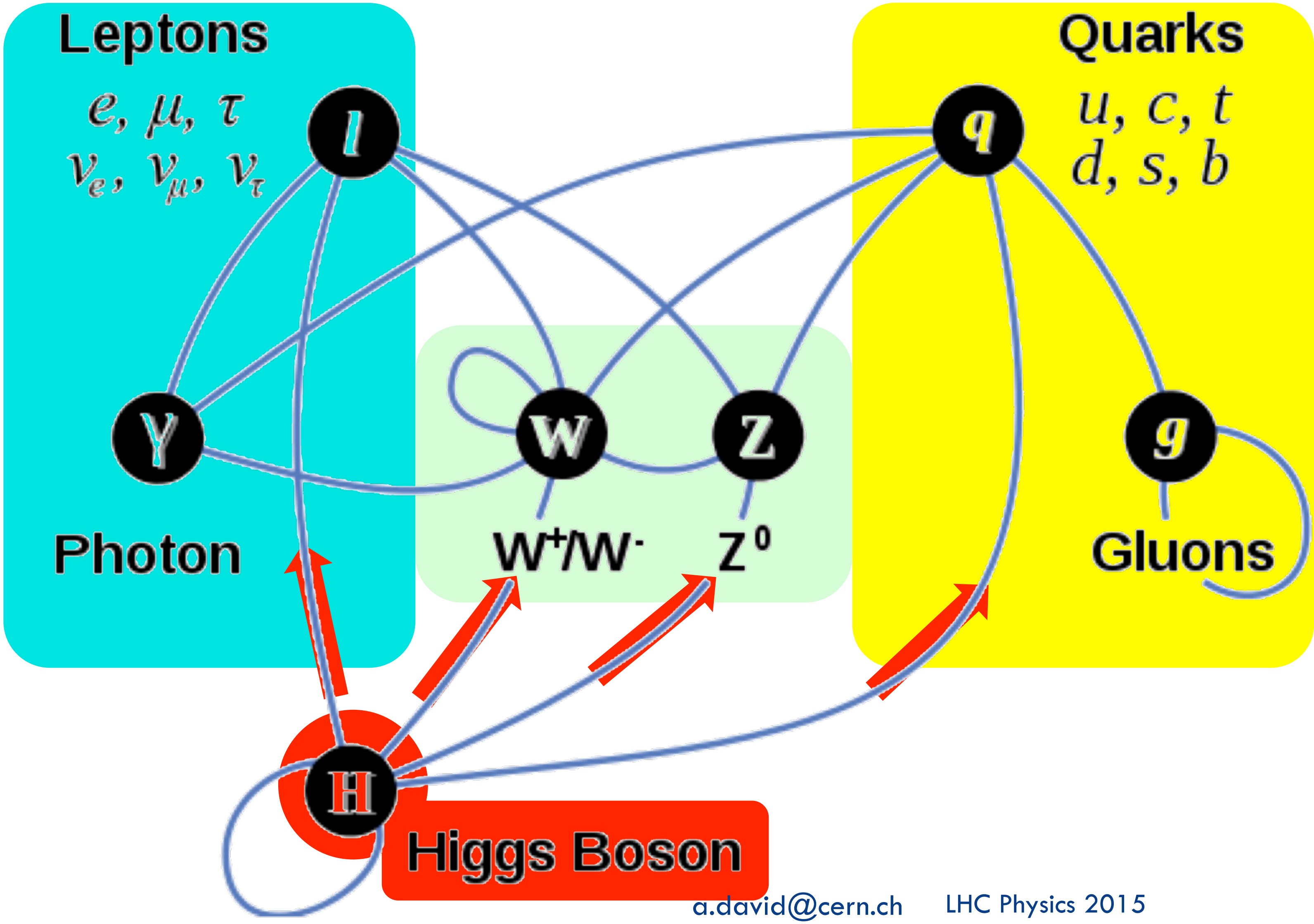
Ryttov referred to the theories that have been put forward over the last five years for the existence of particles in the universe that are smaller than the Higgs particle.

The so-called techni-quarks can be the yet unseen particles, smaller than the Higgs particle that will form a natural extension of the Standard Model which includes three generations of quarks and leptons.

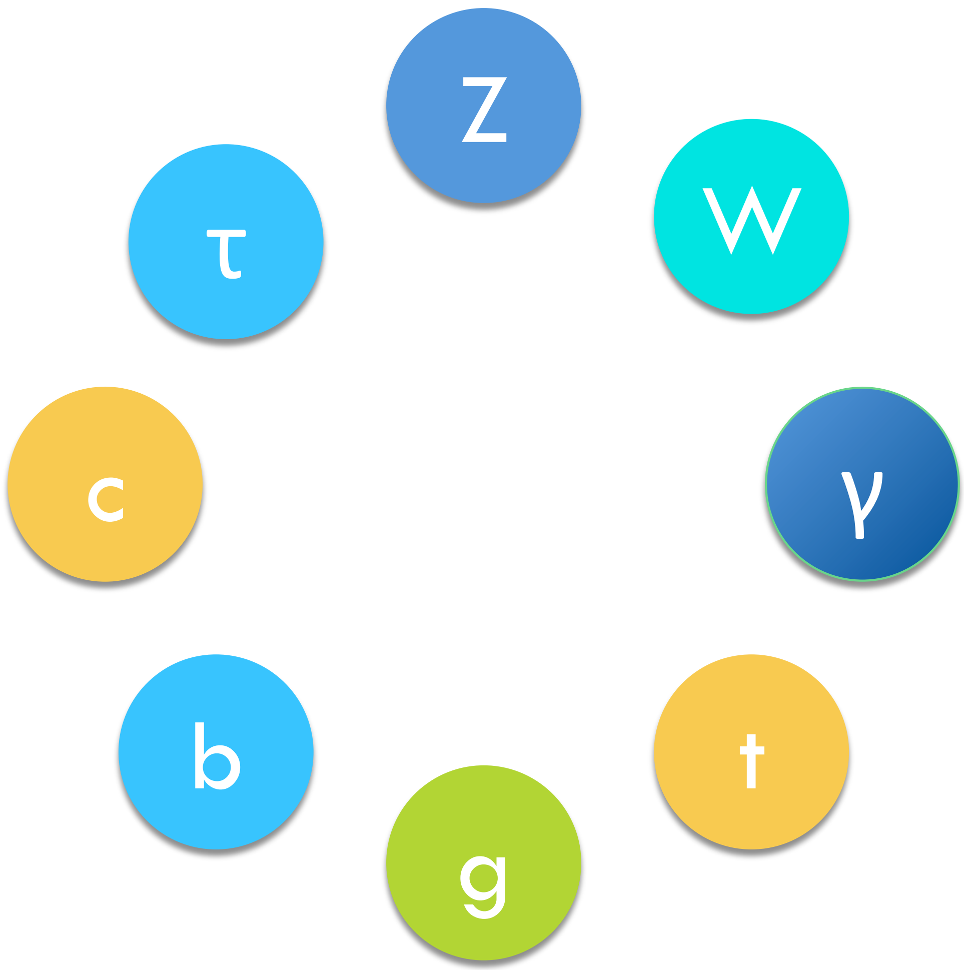
These particles together with the

The Standard Model of Particle Physics

Electromagnetic force – light   Weak force – star combustion   Strong force – protons and neutrons

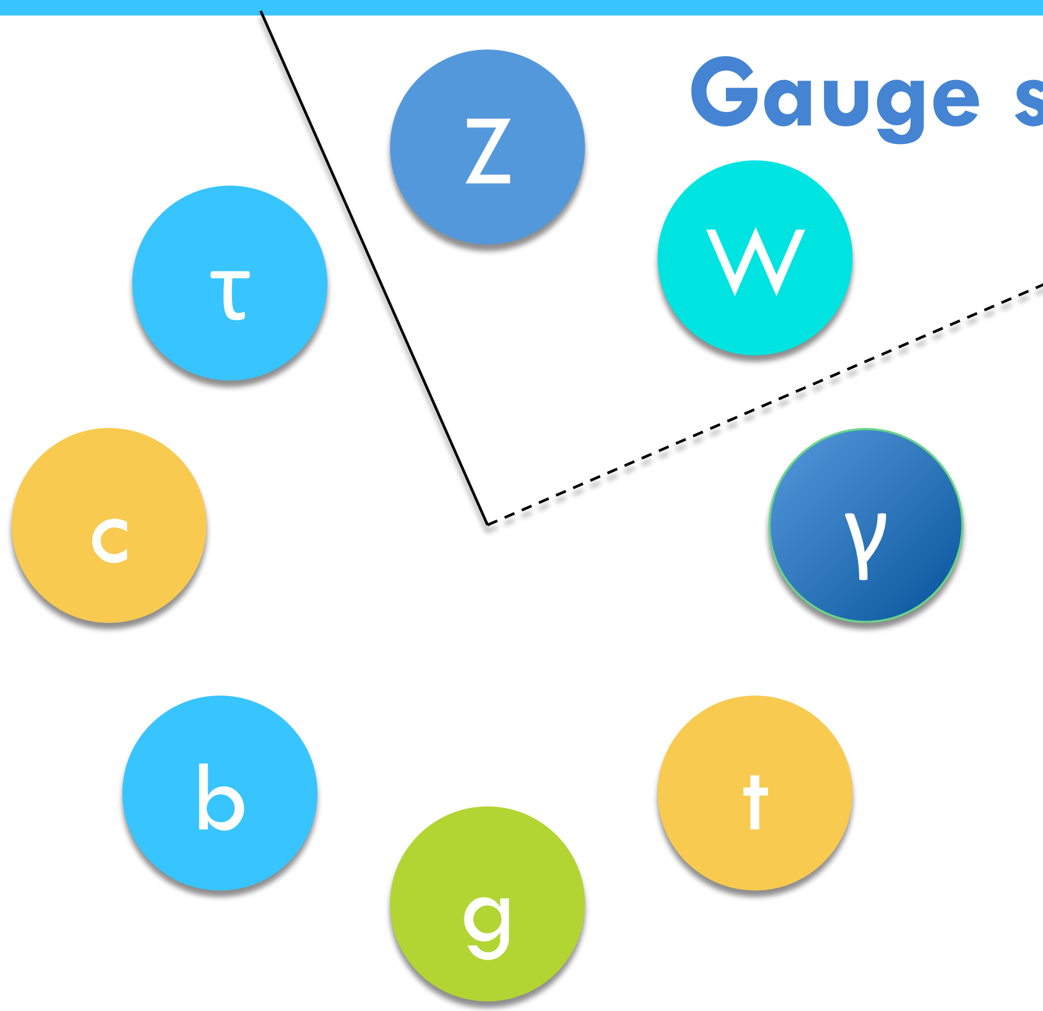


Scalar coupling structure



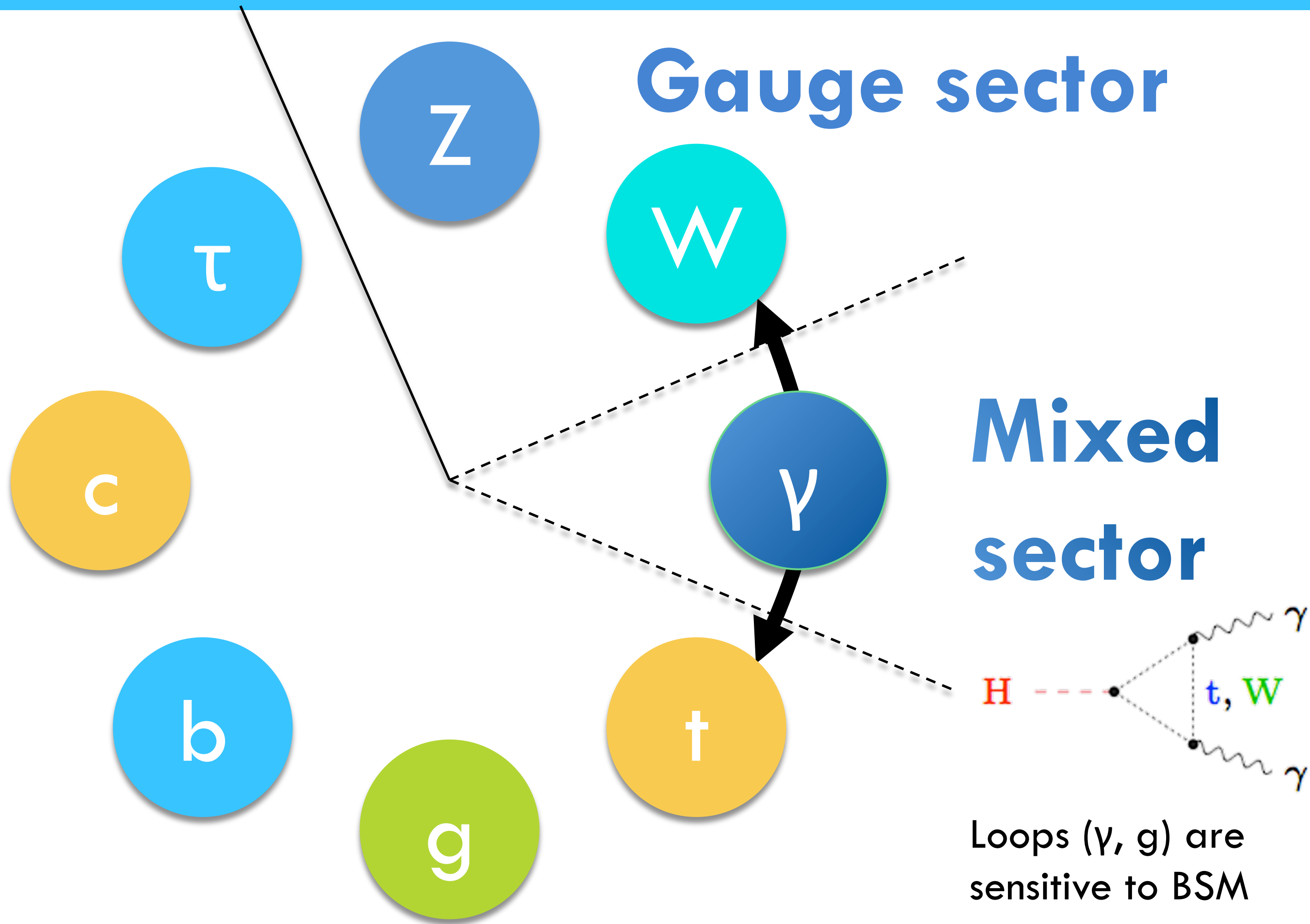
Scalar coupling structure

Gauge sector



Hic est electroweak symmetry breaking

Scalar coupling structure

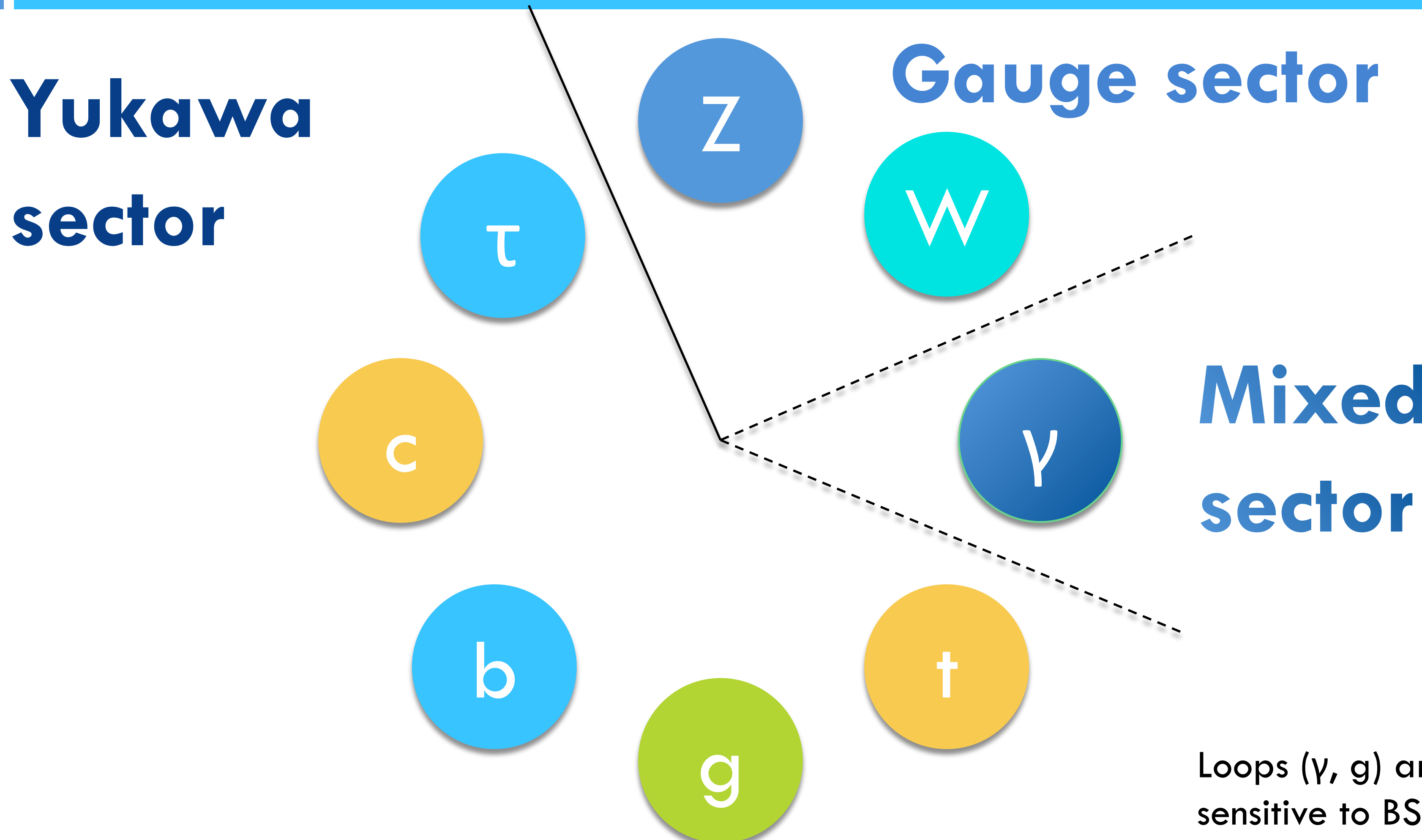


Gauge sector

Mixed sector

Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure



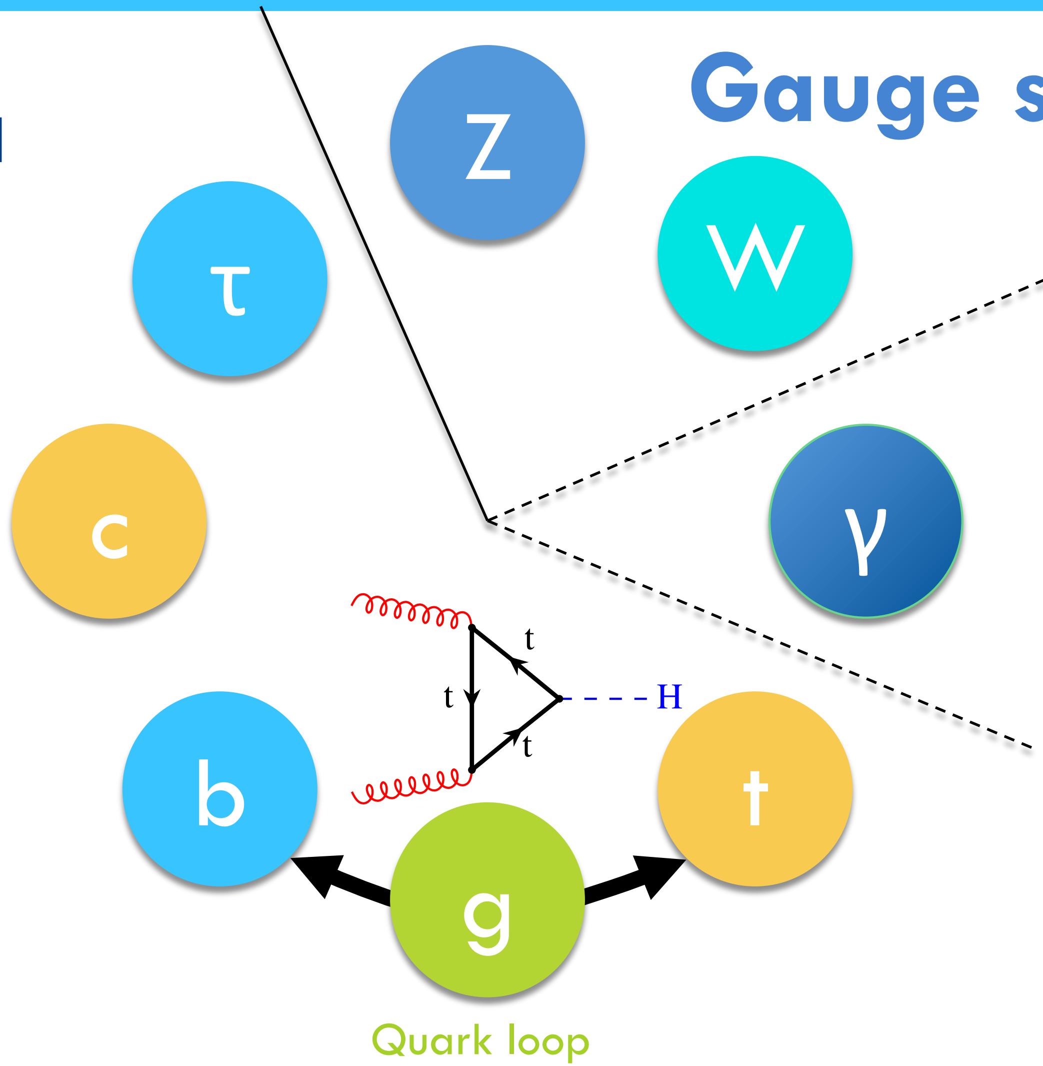
Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure

Yukawa sector

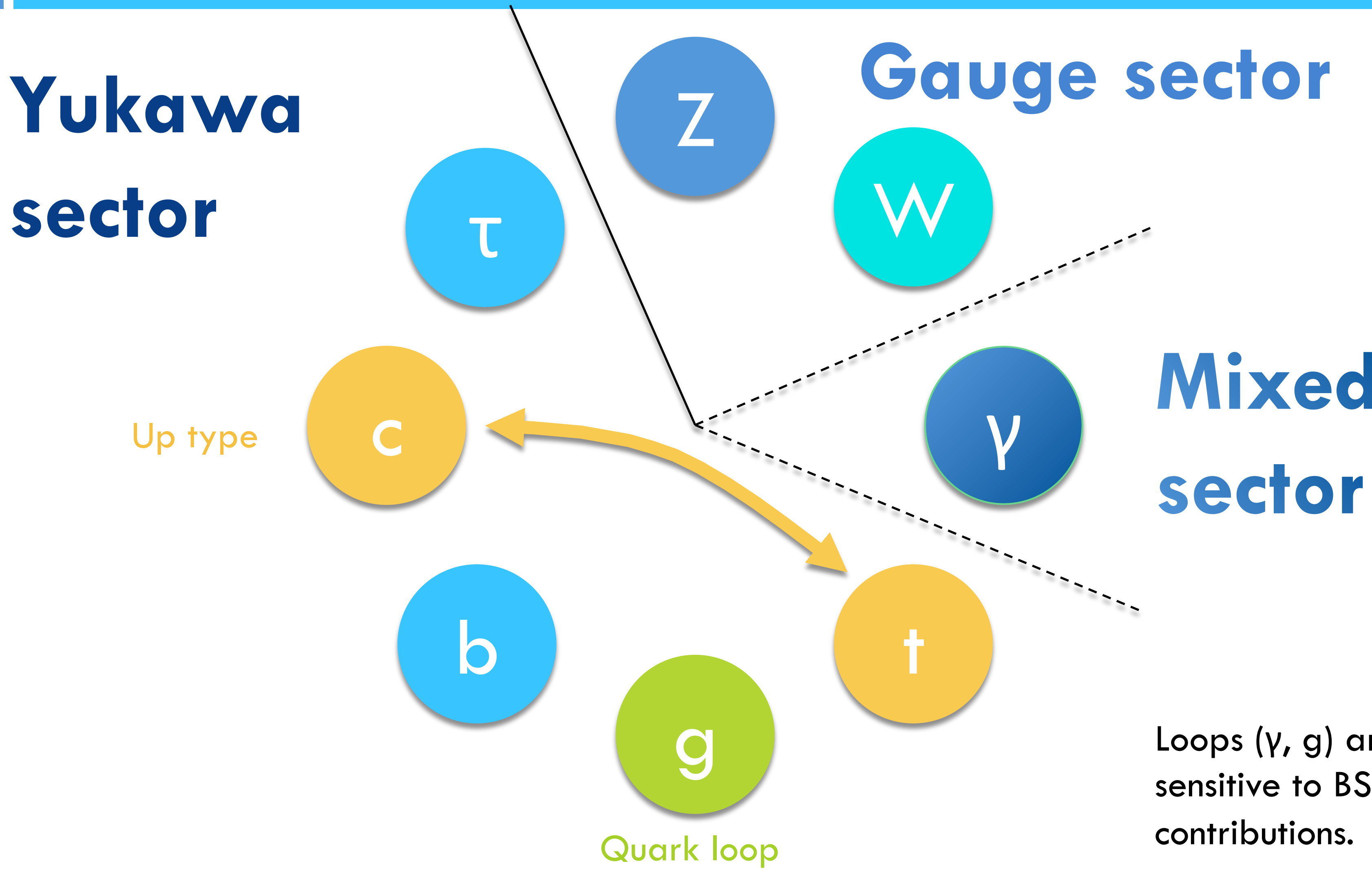
Gauge sector

Mixed sector



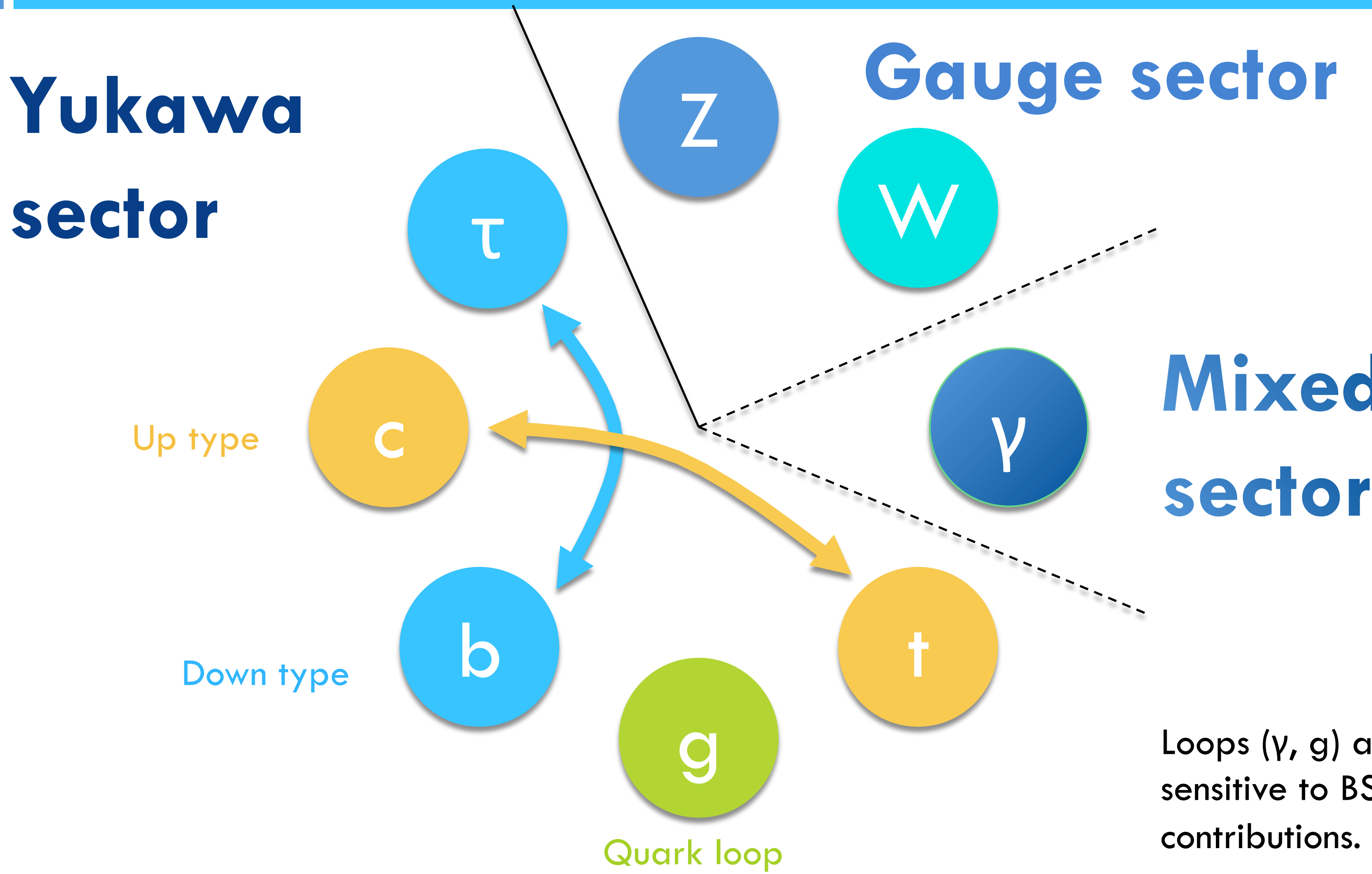
Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure



Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling structure



Loops (γ, g) are sensitive to BSM contributions.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa^2_g(\kappa_b, \kappa_t, m_H) \\ \kappa^2_g \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa^2_W$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa^2_Z$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa^2_t$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa^2_W$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa^2_Z$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa^2_b$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa^2_\tau$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa^2_\gamma(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_\gamma \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa^2_t$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa^2_t$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa^2_b$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa^2_\tau$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa^2_H(\kappa_i, m_H) \\ \kappa^2_H \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to “closest of kin”.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{\mathrm{ggH}}}{\sigma_{\mathrm{ggH}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{g}}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, m_{\mathrm{H}}) \\ \kappa_{\mathrm{g}}^2 \end{cases}$$

$$\frac{\sigma_{\mathrm{VBF}}}{\sigma_{\mathrm{VBF}}^{\mathrm{SM}}} = \kappa_{\mathrm{VBF}}^2(\kappa_{\mathrm{W}}, \kappa_{\mathrm{Z}}, m_{\mathrm{H}})$$

$$\frac{\sigma_{\mathrm{WH}}}{\sigma_{\mathrm{WH}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\sigma_{\mathrm{ZH}}}{\sigma_{\mathrm{ZH}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\sigma_{\mathrm{t\bar{t}H}}}{\sigma_{\mathrm{t\bar{t}H}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

Detectable decay modes

$$\frac{\Gamma_{\mathrm{WW}^{(*)}}}{\Gamma_{\mathrm{WW}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{W}}^2$$

$$\frac{\Gamma_{\mathrm{ZZ}^{(*)}}}{\Gamma_{\mathrm{ZZ}^{(*)}}^{\mathrm{SM}}} = \kappa_{\mathrm{Z}}^2$$

$$\frac{\Gamma_{\mathrm{b\bar{b}}}}{\Gamma_{\mathrm{b\bar{b}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{\gamma}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{\gamma}^2 \end{cases}$$

$$\frac{\Gamma_{\mathrm{Z}\gamma}}{\Gamma_{\mathrm{Z}\gamma}^{\mathrm{SM}}} = \begin{cases} \kappa_{(\mathrm{Z}\gamma)}^2(\kappa_{\mathrm{b}}, \kappa_{\mathrm{t}}, \kappa_{\tau}, \kappa_{\mathrm{W}}, m_{\mathrm{H}}) \\ \kappa_{(\mathrm{Z}\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{\mathrm{t\bar{t}}}}{\Gamma_{\mathrm{t\bar{t}}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

$$\frac{\Gamma_{\mathrm{gg}}}{\Gamma_{\mathrm{gg}}^{\mathrm{SM}}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{\mathrm{c\bar{c}}}}{\Gamma_{\mathrm{c\bar{c}}}^{\mathrm{SM}}} = \kappa_{\mathrm{t}}^2$$

$$\frac{\Gamma_{\mathrm{s\bar{s}}}}{\Gamma_{\mathrm{s\bar{s}}}^{\mathrm{SM}}} = \kappa_{\mathrm{b}}^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{\mathrm{SM}}} = \kappa_{\tau}^2$$

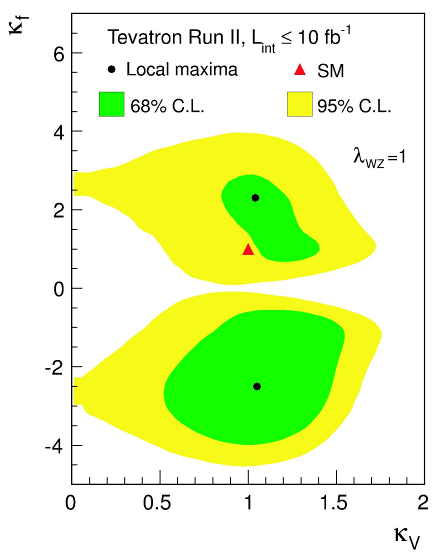
Total width

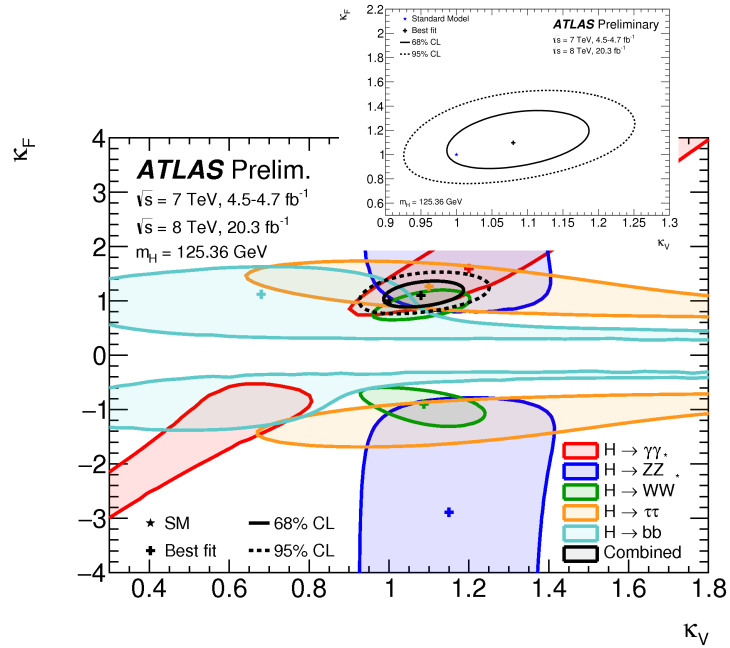
$$\frac{\Gamma_{\mathrm{H}}}{\Gamma_{\mathrm{H}}^{\mathrm{SM}}} = \begin{cases} \kappa_{\mathrm{H}}^2(\kappa_i, m_{\mathrm{H}}) \\ \kappa_{\mathrm{H}}^2 \end{cases}$$

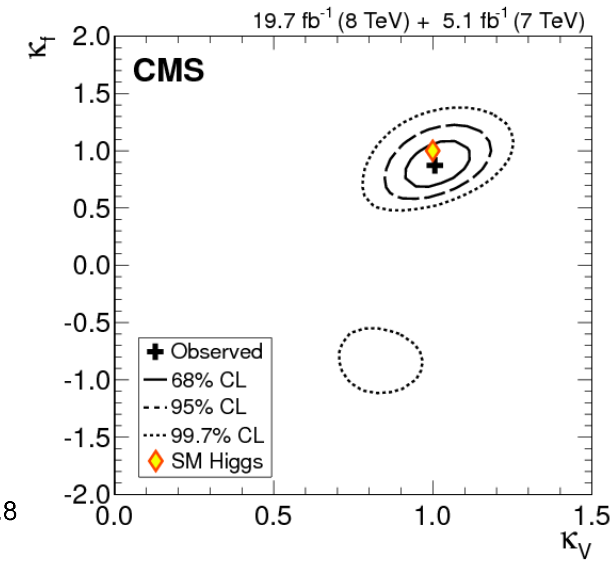
- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H.

Weak bosons and fermions

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]



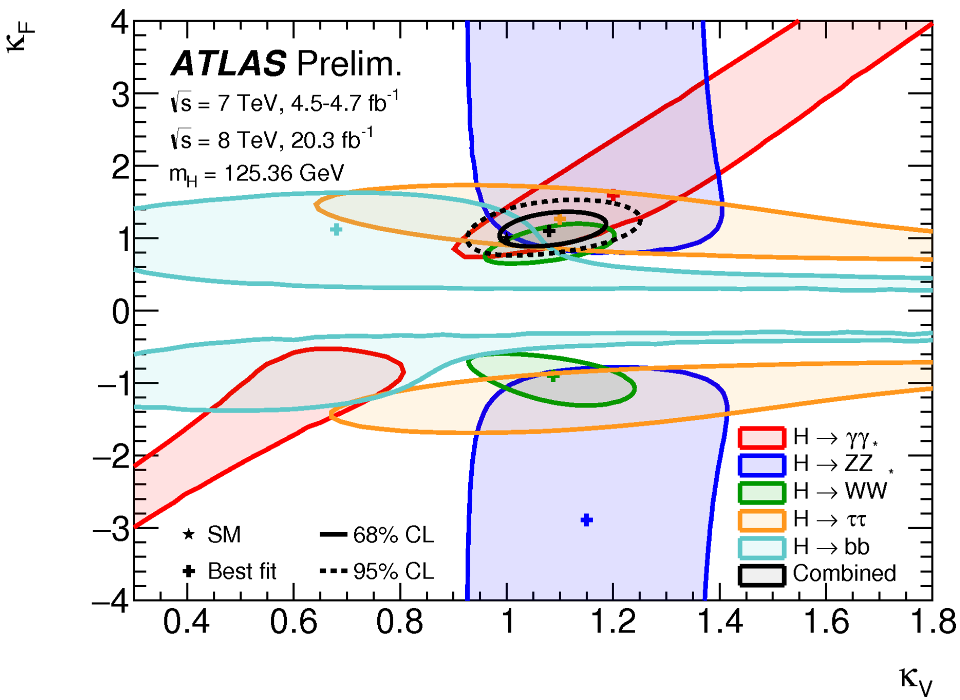


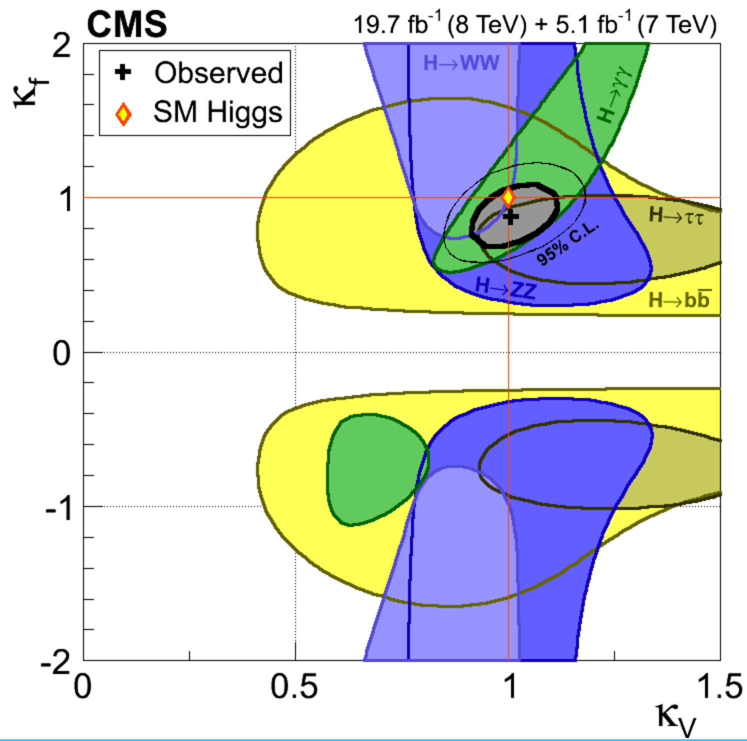


	Tevatron	ATLAS	CMS
p(SM)	-	41%	< 1 σ

Weak bosons and fermions

[ATLAS-CONF-2015-007][arXiv:1412.8662]

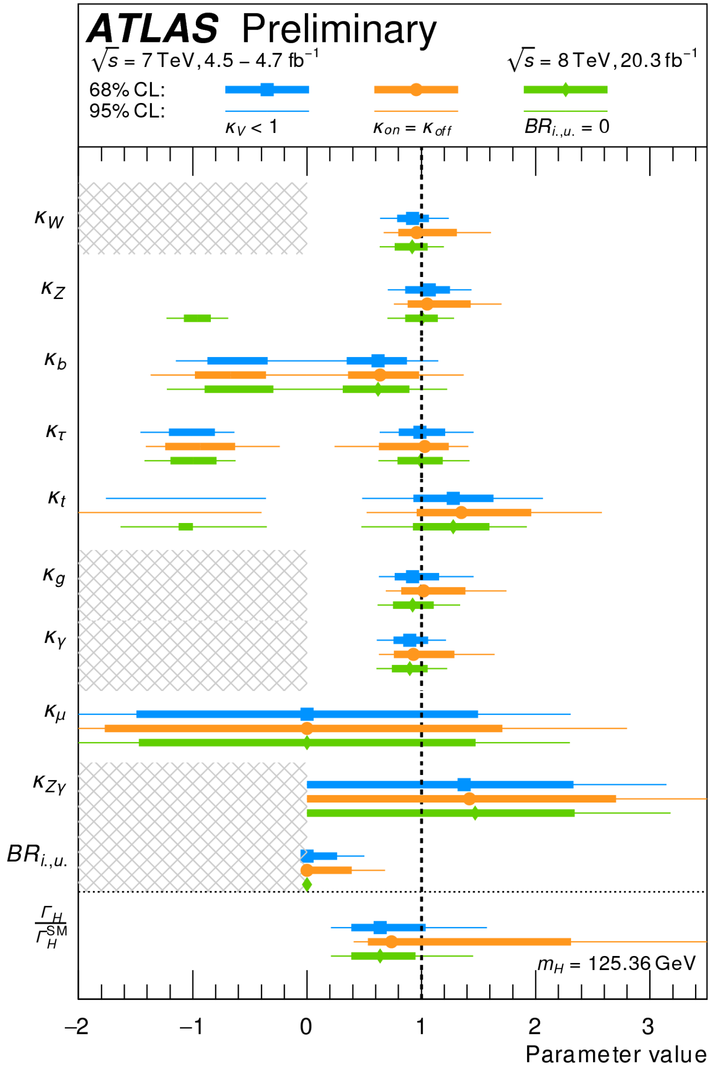


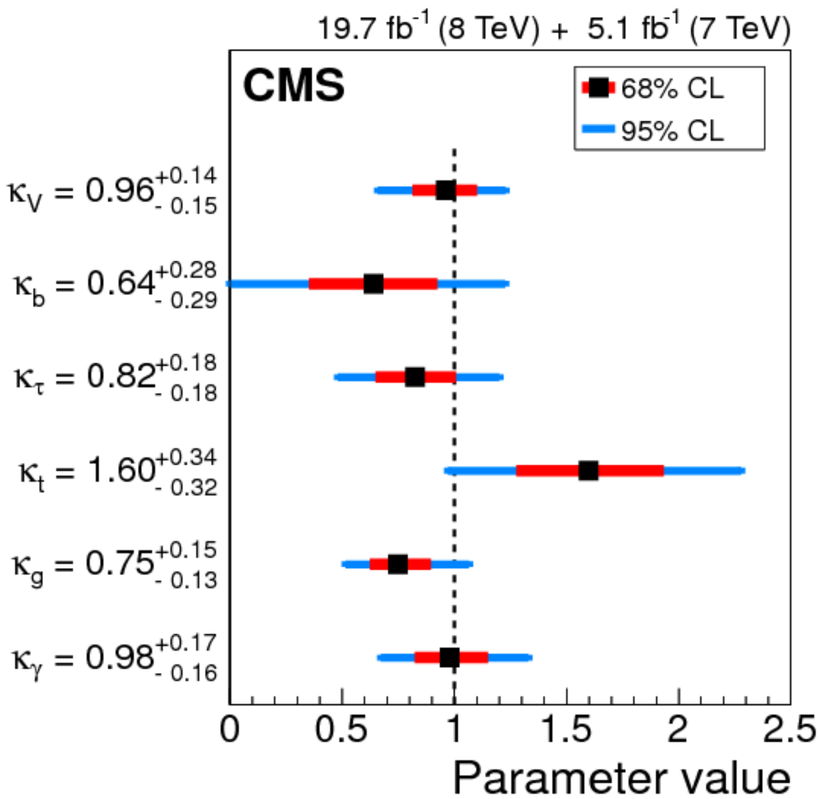


	ATLAS	CMS
P(SM)	10%	$< 1\,\sigma$

The deviations that we do not (yet) see

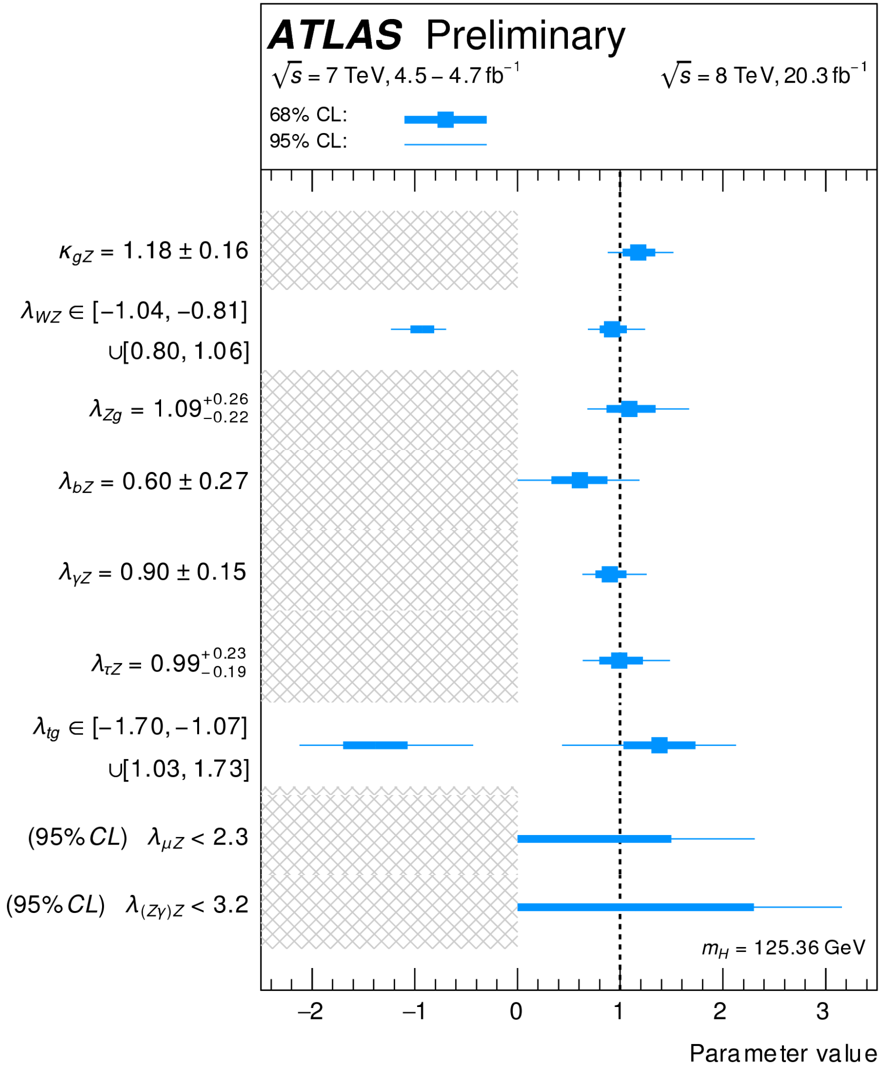
[ATLAS-CONF-2015-007][arXiv:1412.8662]

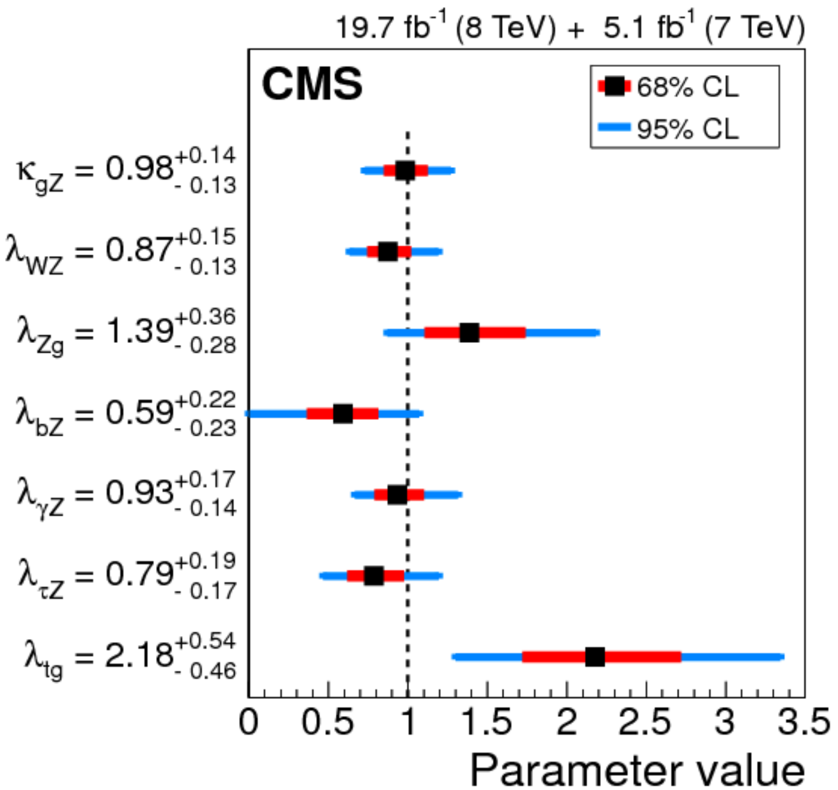




The deviations that we do not (yet) see

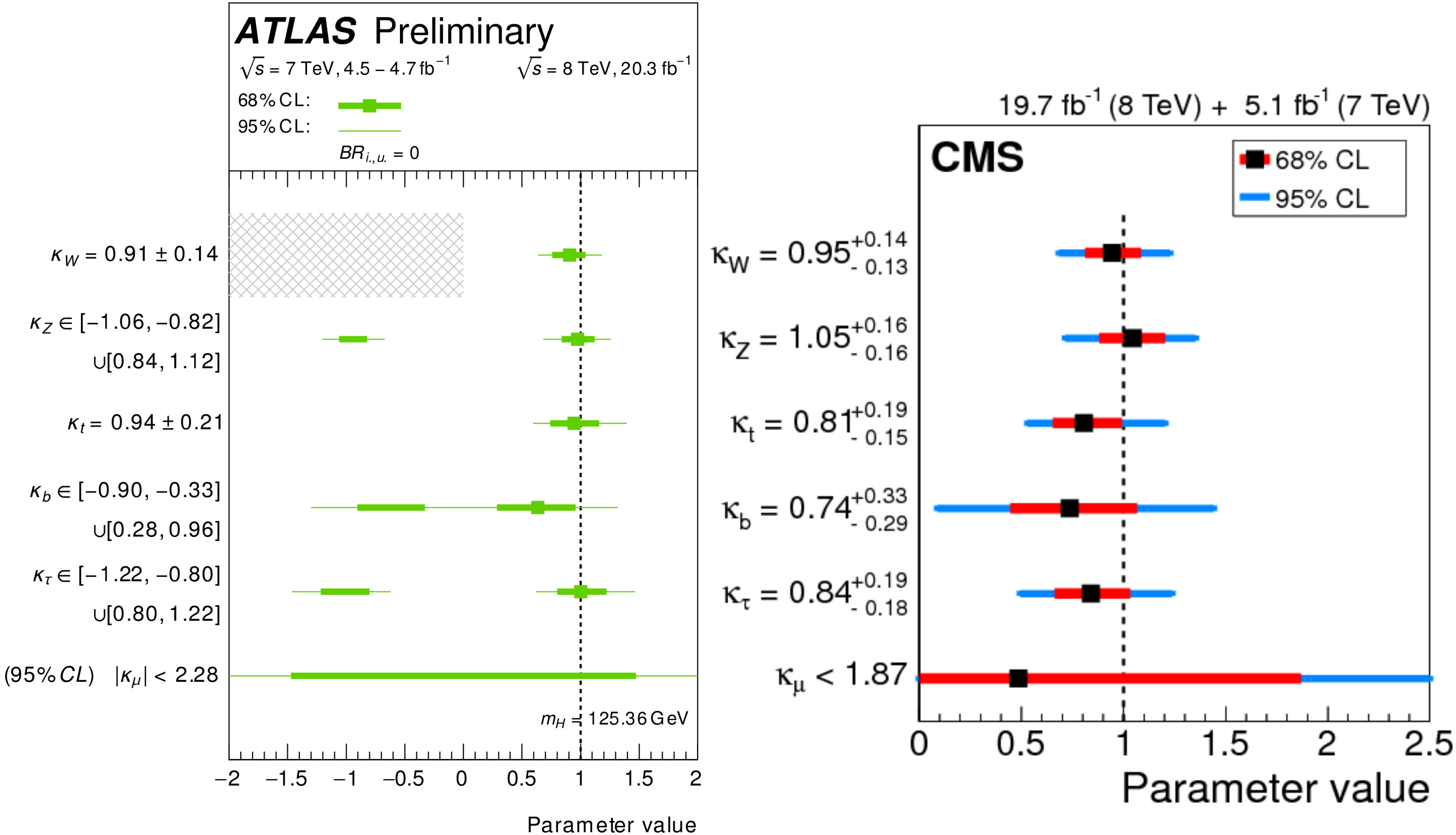
[ATLAS-CONF-2015-007][arXiv:1412.8662]





Resolving SM contributions

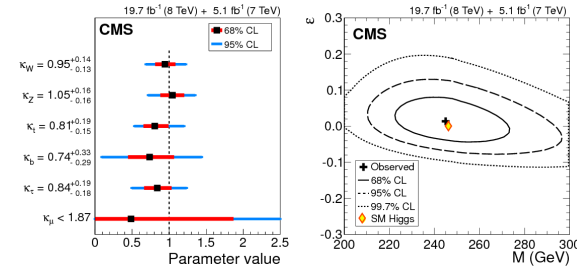
[ATLAS-CONF-2015-007][arXiv:1412.8662]

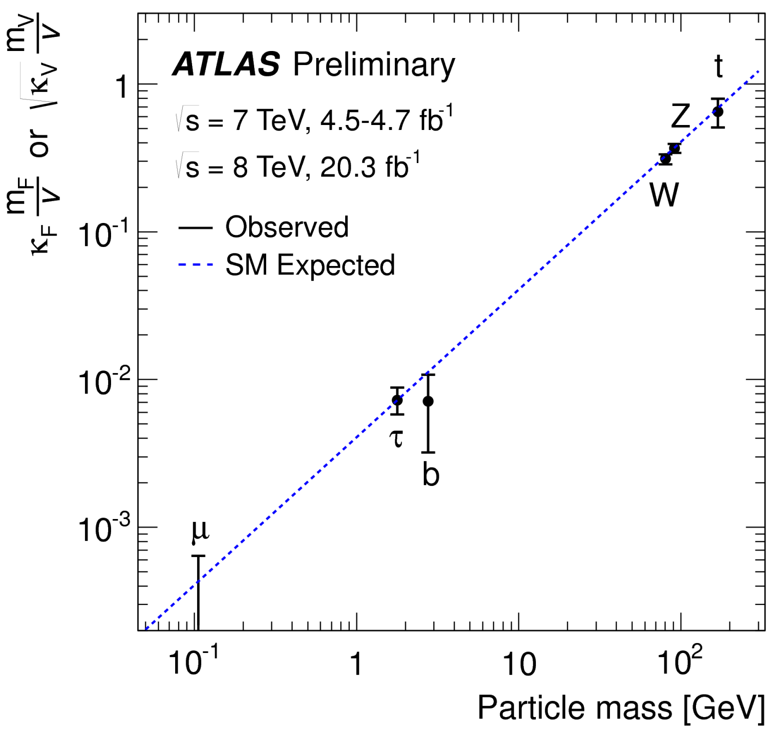


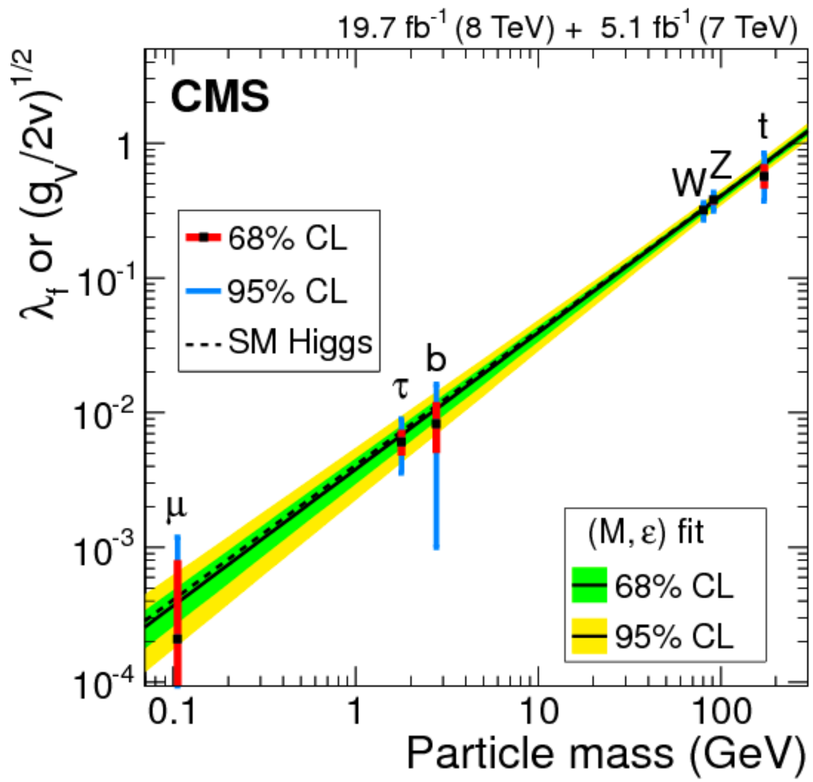
Coupling deviations summaries

[ATLAS-CONF-2015-007][arXiv:1412.8662][arxiv:1207.1693][arxiv:1303.3570]

- Assuming no BSM particles.







A very long way to go…

Decay Modes

Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$H^0 \to WW^*$	seen		
Γ_2	$H^0 \to ZZ^*$	seen		
Γ_3	$H^0 \to \gamma\gamma$	seen		
Γ_4	$H^0 \to b\bar{b}$	possibly seen		
Γ_5	$H^0 \to \tau^+\tau^-$	possibly seen		

H^0 SIGNAL STRENGTHS IN DIFFERENT CHANNELS

Combined Final States	1.07 ± 0.26	(S = 1.4)
WW^* Final State	0.88 ± 0.33	(S = 1.1)
ZZ^* Final State	$0.89^{+0.30}_{-0.25}$	
$\gamma\gamma$ Final State	1.65 ± 0.33	
$b\bar{b}$ Final State	$0.5^{+0.8}_{-0.7}$	
$\tau^+\tau^-$ Final State	0.1 ± 0.7	

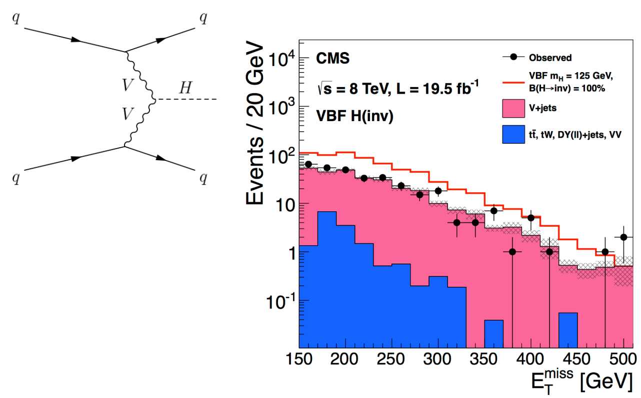
Decay Modes

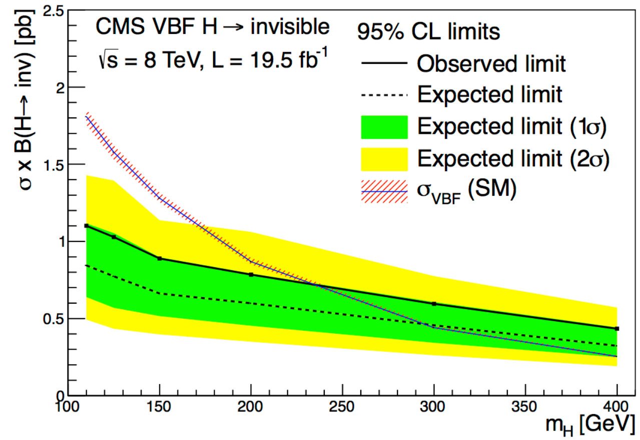
Γ_i	Mode	Fraction (Γ_i / Γ)	Scale Factor/ Confidence Level	P (MeV/c)
Γ_1	$Z \to e^+e^-$	3.363 ± 0.004 %		45594
Γ_2	$Z \to \mu^+\mu^-$	3.366 ± 0.007 %		45594
Γ_3	$Z \to \tau^+\tau^-$	3.370 ± 0.008 %		45559
Γ_4	$Z \to \ell^+\ell^-$	3.3658 ± 0.0023 %		
Γ_5	$Z \to \ell^+\ell^-\ell^+\ell^-$	$(4.2^{+0.9}_{-0.8}) \times 10^{-6}$		45594
Γ_6	$Z \to$ invisible	$(2.000 \pm .006) \times 10^{-1}$		
Γ_7	$Z \to$ hadrons	$(6.991 \pm .006) \times 10^{-1}$		
Γ_8	$Z \to (u\bar{u} + c\bar{c})/2$	$.116 \pm .006$		
Γ_9	$Z \to (d\bar{d} + s\bar{s} + b\bar{b})/3$	$.156 \pm .004$		
Γ_{10}	$Z \to c\bar{c}$	$(1.203 \pm .021) \times 10^{-1}$		
Γ_{11}	$Z \to b\bar{b}$	$(1.512 \pm .005) \times 10^{-1}$		
Γ_{12}	$Z \to b\bar{b}b\bar{b}$	$(3.6 \pm 1.3) \times 10^{-4}$		

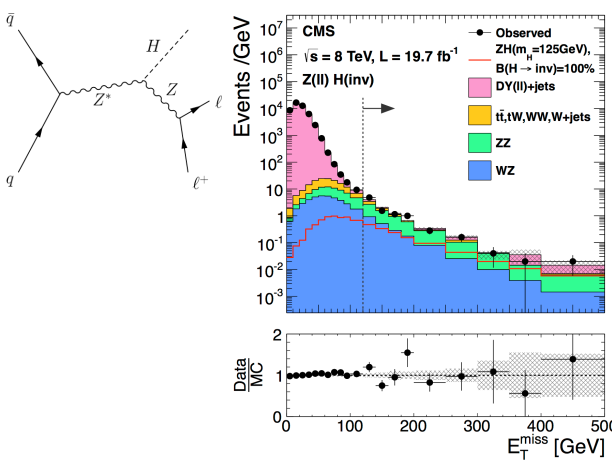
Dark matter: invisible Higgs decay search

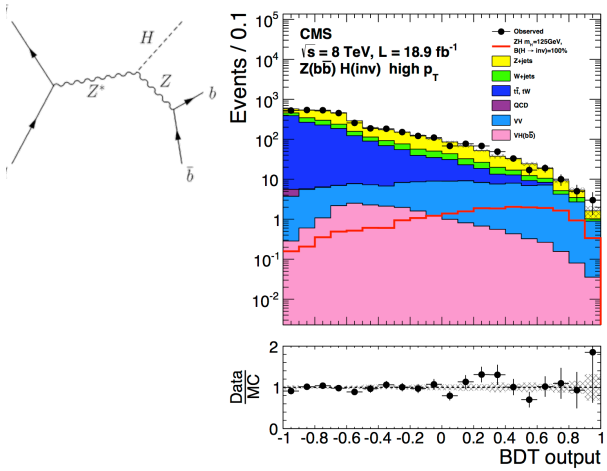
[EPJC 74 (2014) 2980]

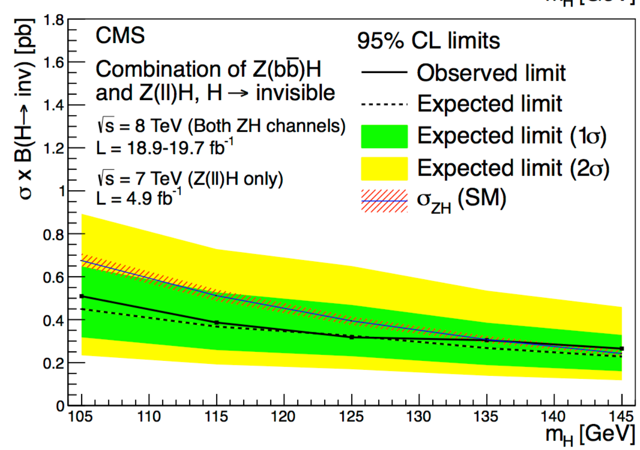
- VBF and ZH topologies combined; $Z \to \ell\ell$ and $Z \to b\bar{b}$.
- **BR(H→inv.) < 0.58 (0.44 exp.) at 95% CL**







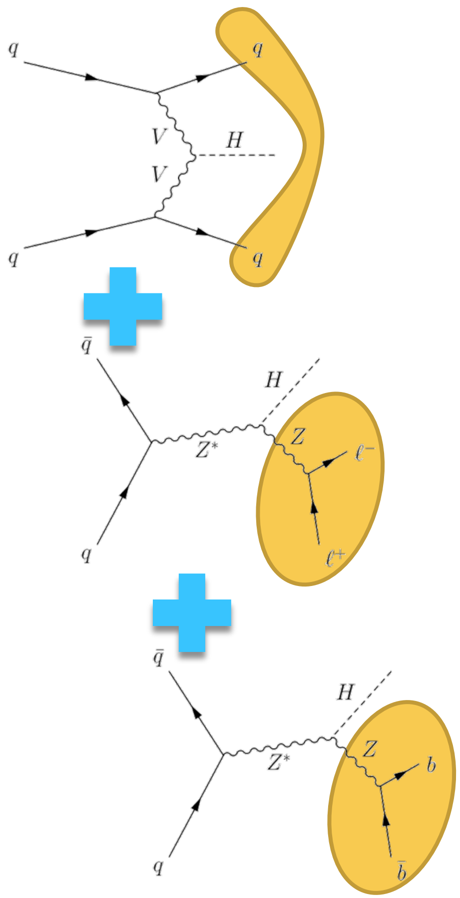




Invisible Higgs search combination

[EPJC 74 (2014) 2980]

- Combination of **VBF, Z(ℓℓ)H, and Z($b\bar{b}$)H** searches: **BR(H→inv) < 0.58** (0.44 exp.) at 95% CL.
-



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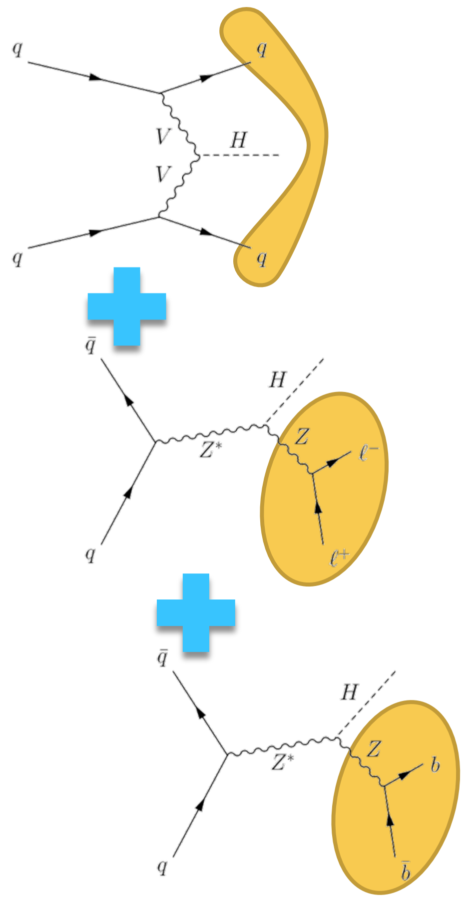
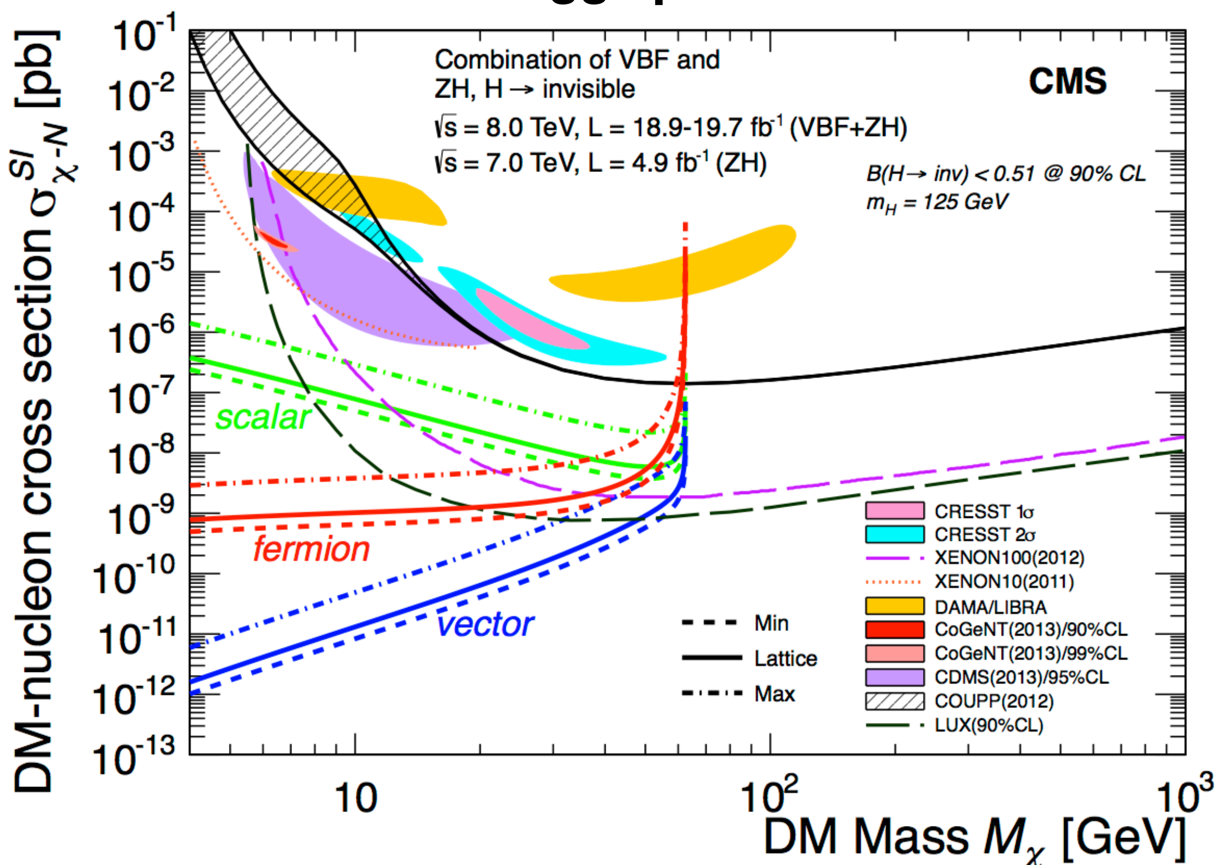
[EPJC 74 (2014) 2980]

- Combination of **VBF, Z(ℓℓ)H, and Z($b\bar{b}$)H** searches: **BR(H→inv) < 0.58** (0.44 exp.) at 95% CL.
- **Competitive limits for low mass DM in "Higgs portal" models.**





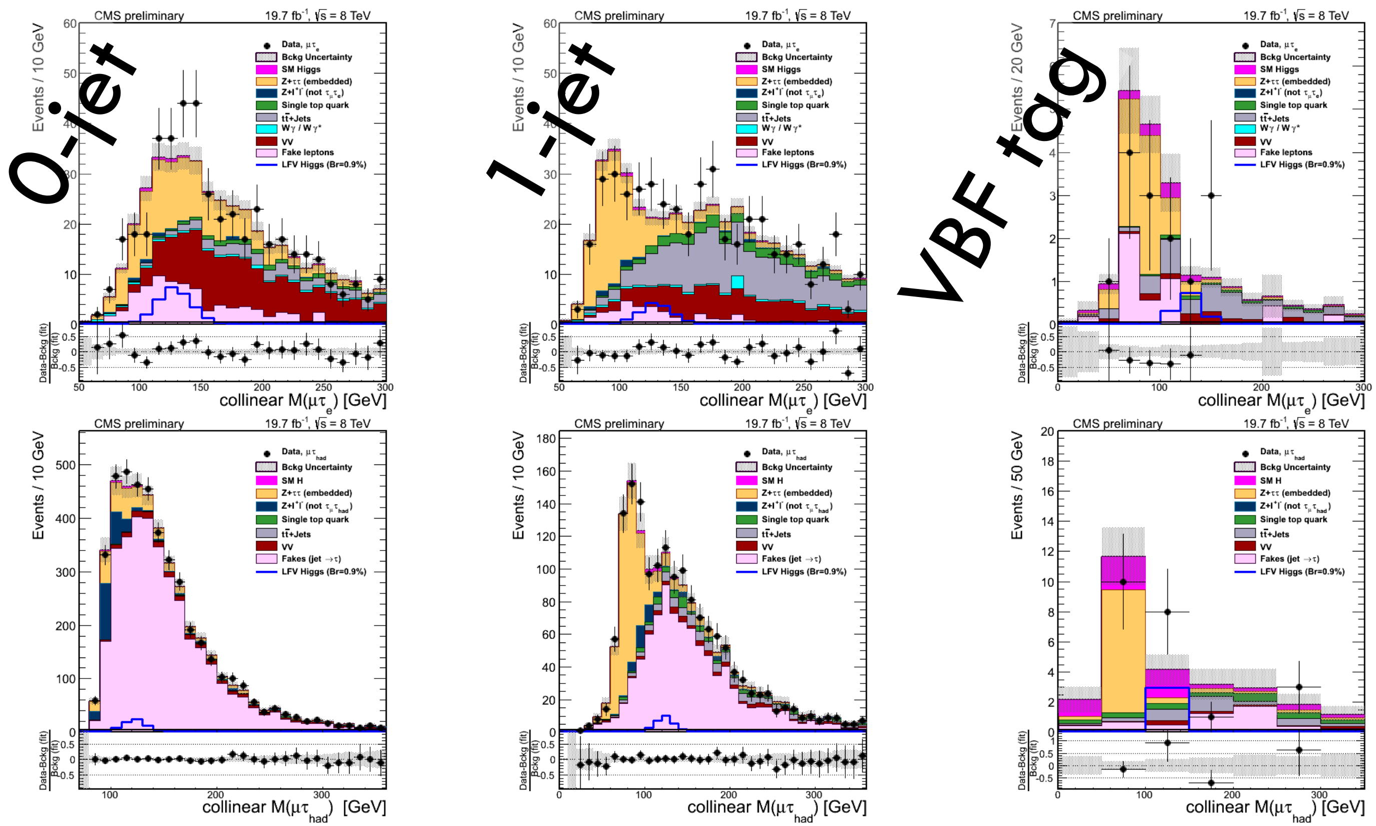
Lepton flavor violation: search for H→μτ

[CMS-PAS-HIG-14-005]

- **τ lepton flavor violation not as well constrained as μe (MEG).**
- Based on SM H→ττ analysis. **Different kinematics allows good SM H rejection.**
  - **BR(H→μτ) < 1.57%** at 95%CL (expected limit of 0.75%)

$\mu\tau_e$

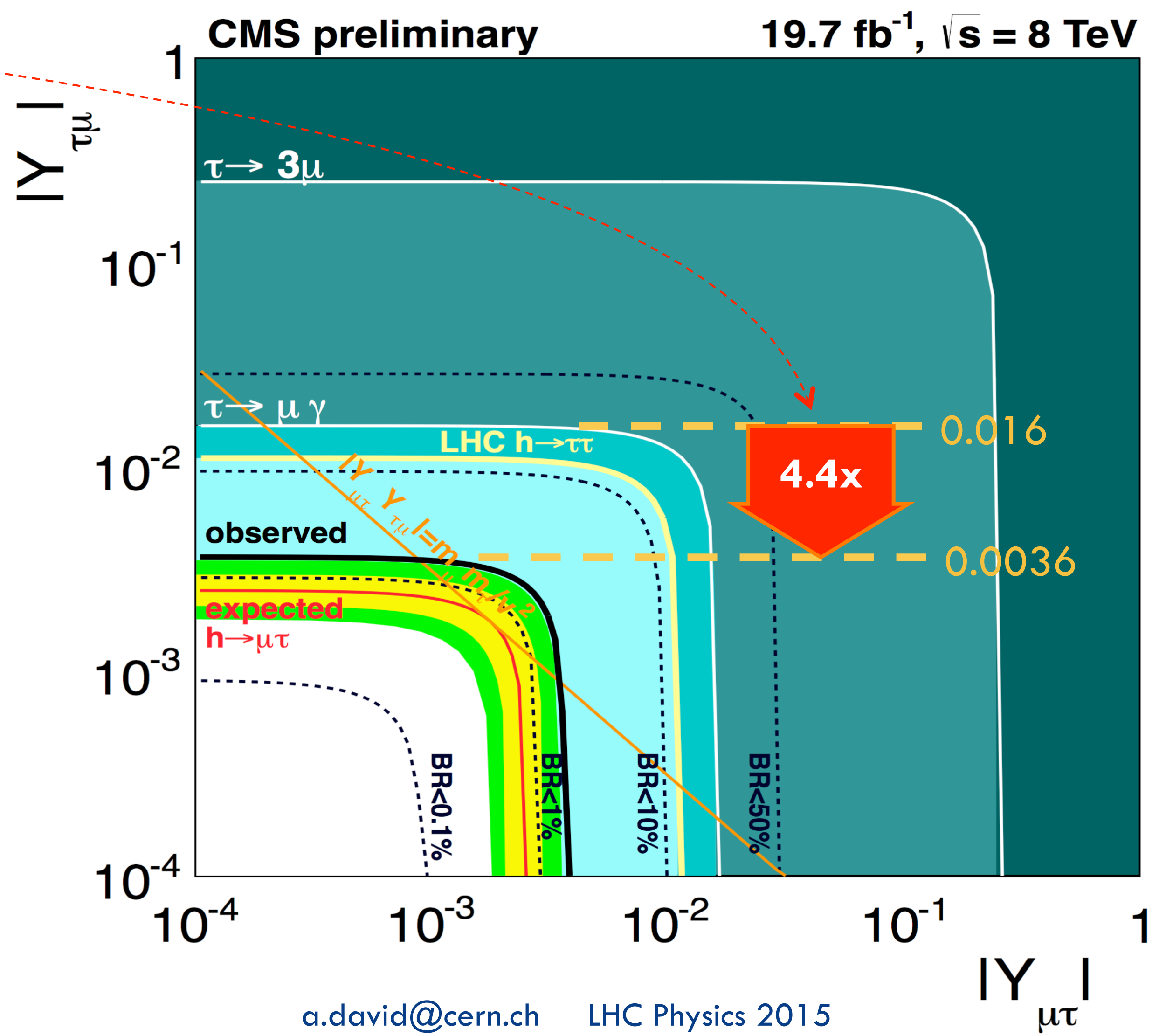
$\mu\tau_{had}$



Search for H→μτ

[CMS-PAS-HIG-14-005]

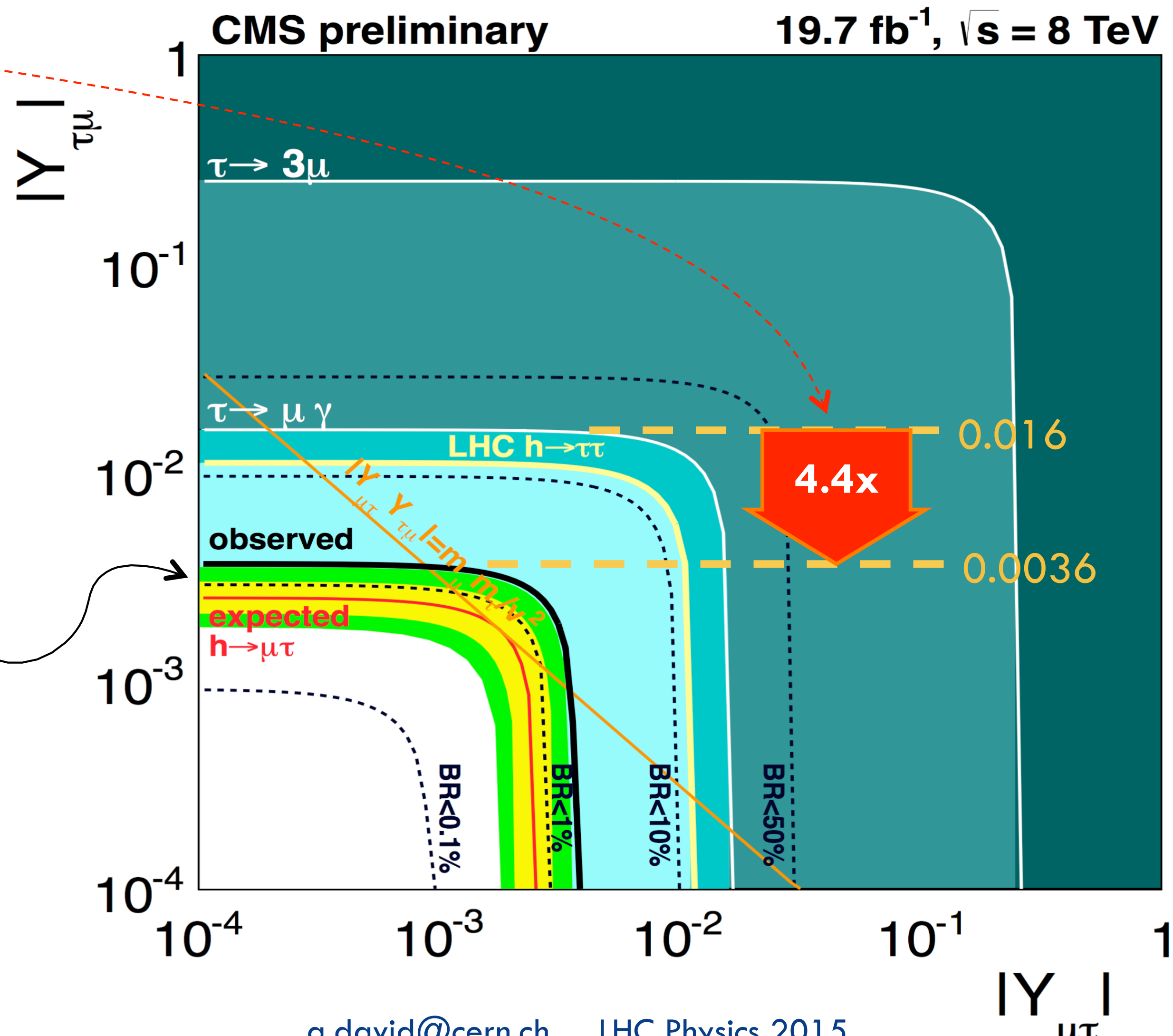
- **Best limits on τ anomalous Yukawa couplings.**



Search for H⟶μτ

[CMS-PAS-HIG-14-005]

- **Best limits on τ anomalous Yukawa couplings.**
  - Higgs flavor sector could hold surprises.

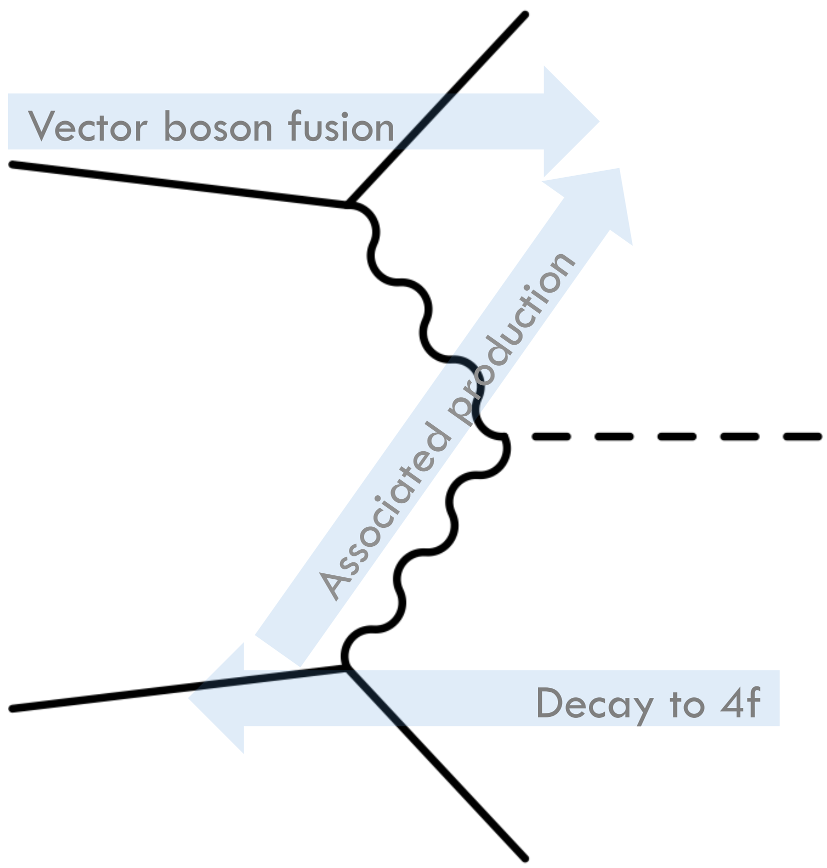


The future

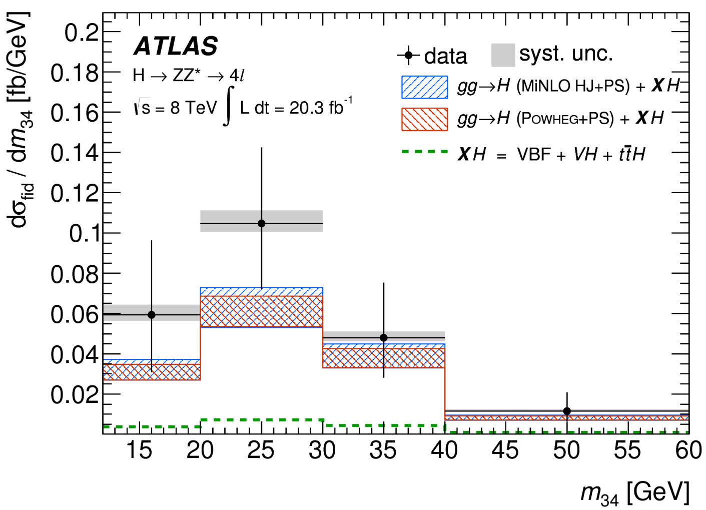
["Lawrence of Arabia" idea from C. Grojean]

- We must examine this Higgs to the fullest extent !
  - It may be the only clue to leave the SM oasis and cross the desert.

The many facets of HVV



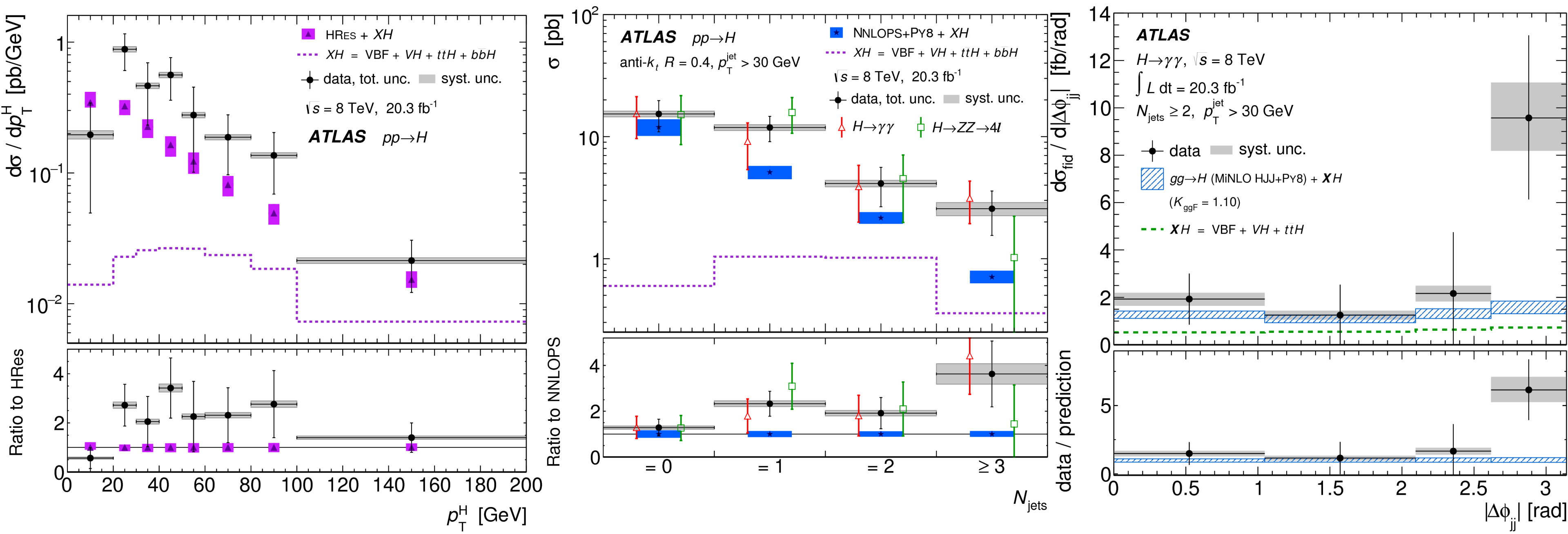
Decay	γ	γ*/Z*	Z
γ	✓	✓	✓
γ*/Z*		? (VBF)	✓ (VH)
Z			✓ (H*)



Differential distributions

[arXiv:1407.4222][arXiv:1408.3226][arXiv:1504.05833]

- Differential picture directly touches fundamental aspects:
  - The loop structure where new particles may be running (p_T shape).
  - The QCD structure of the calculations (N_{jets}).
- ATLAS $H \rightarrow \gamma\gamma$ and ZZ results and the adventure of unfolding.
  - Illustrates the power of having more statistics (signal-like excess).



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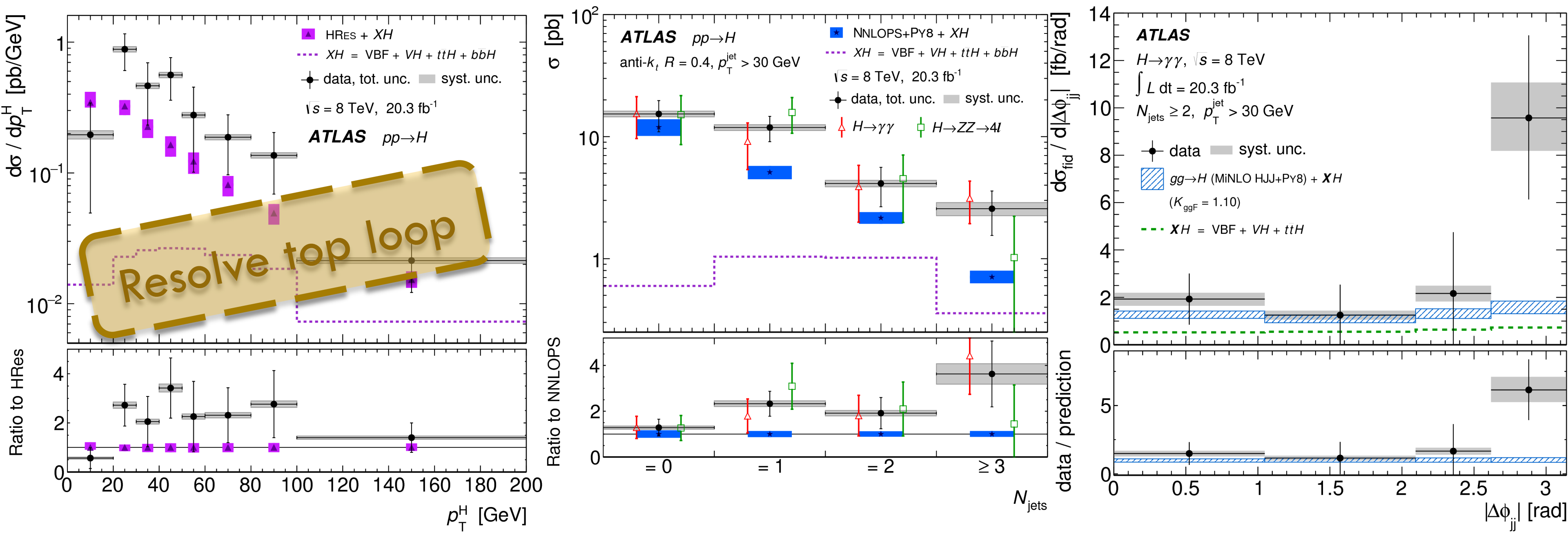

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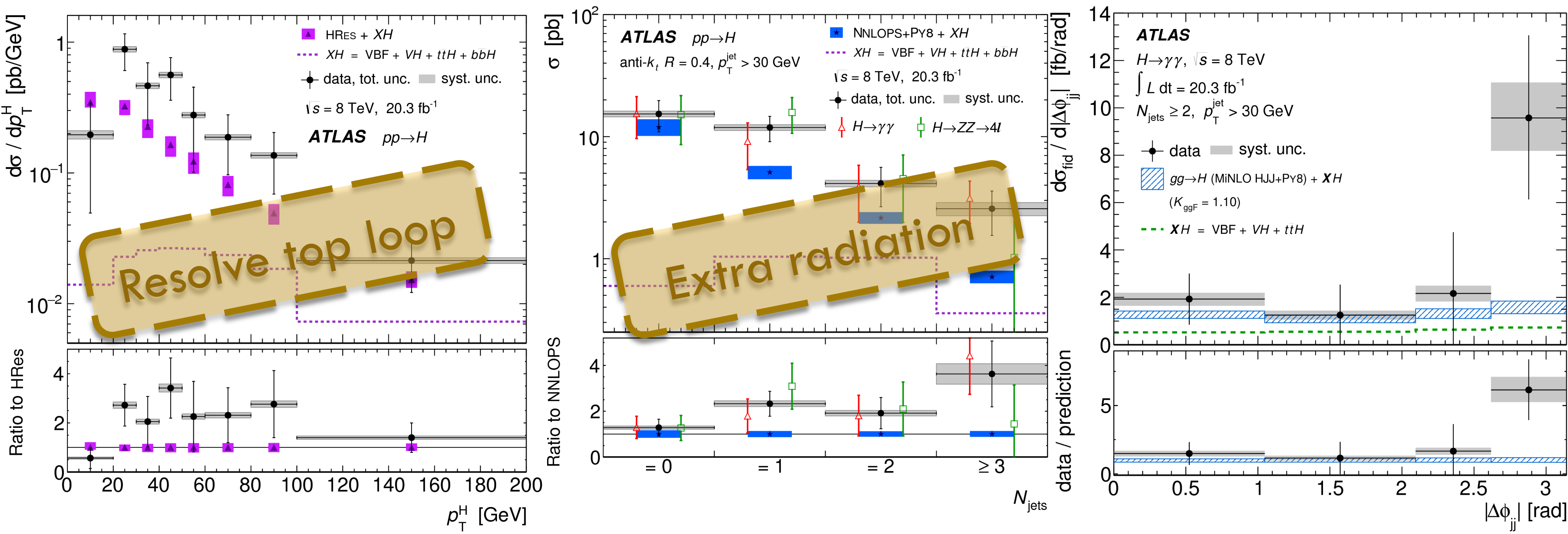

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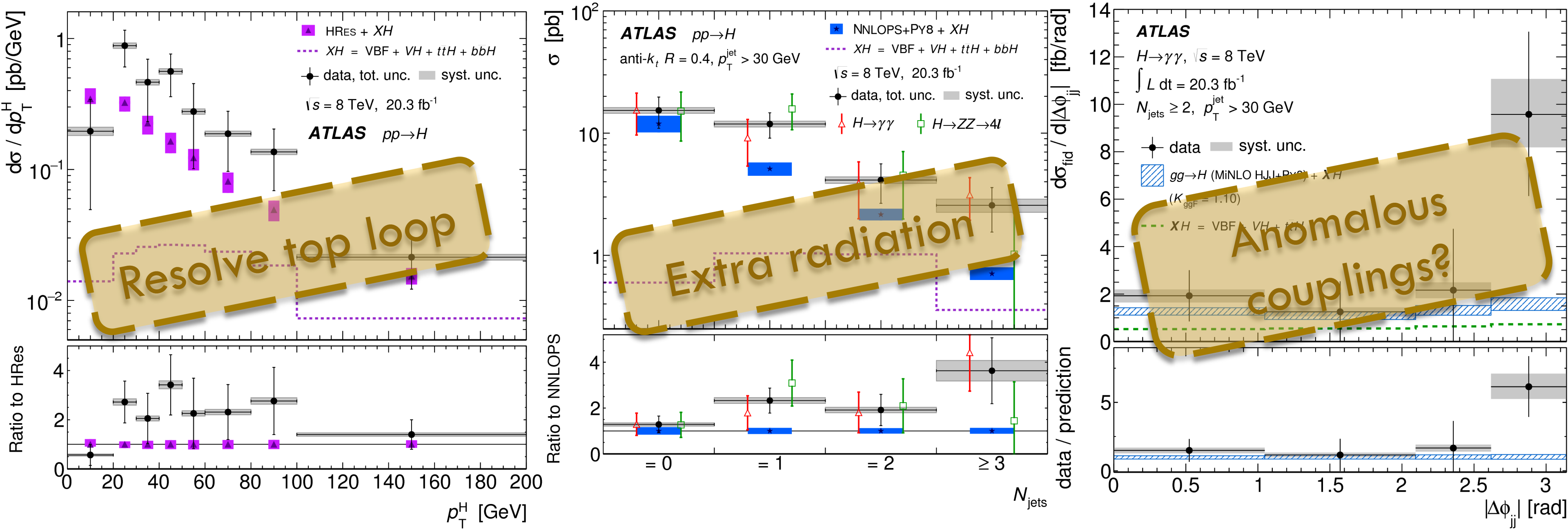
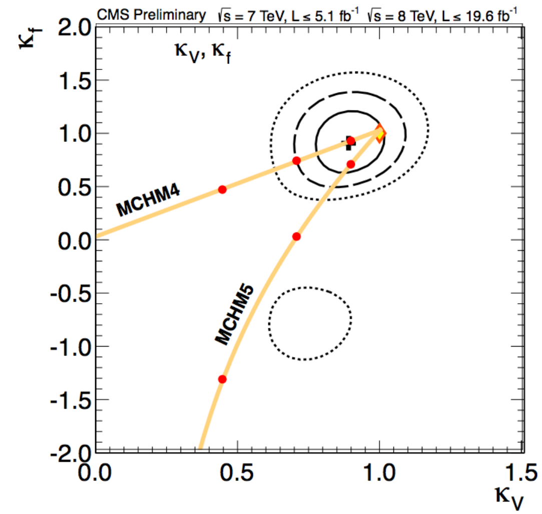
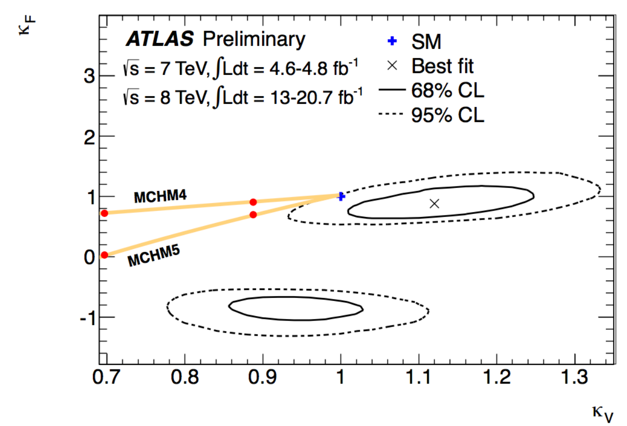


From deviations to EFTs

[http://cern.ch/go/W96V]

- Today we talk about deviations from the SMH.
  - arXiv:1209.0040 or equivalent.
  - **Draw/exclude your own theory. ➔**





- **One (single) nice feature: κ =1 recovers best SMH calculations.**
  - But that's it: we can find deviations, but only roughly fathom their meaning.

Deviations are on a diet

[arXiv:1306.6352]

- SUSY ($\tan\beta$ =5): $$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$
- Composite Higgs: $$\frac{g_{hff}}{g_{h_{SM}ff}} \simeq \frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$
- Top partners: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$$

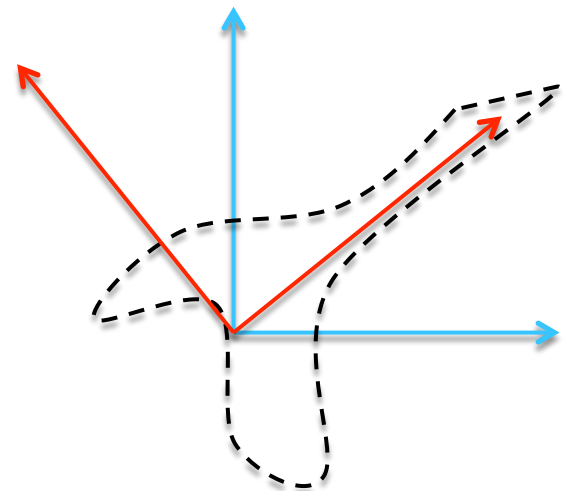
Effective field theory (EFT): the idea

[NPB 268 (1986) 621]

- Instead of an **experimentally-driven basis of parameters** use a **basis of QFT operators** that may be more aligned with the **BSM physics**.

- EFT allows to perform accurate calculations.
  - NLO EWK effects, etc.
  - More sensitive interpretation.

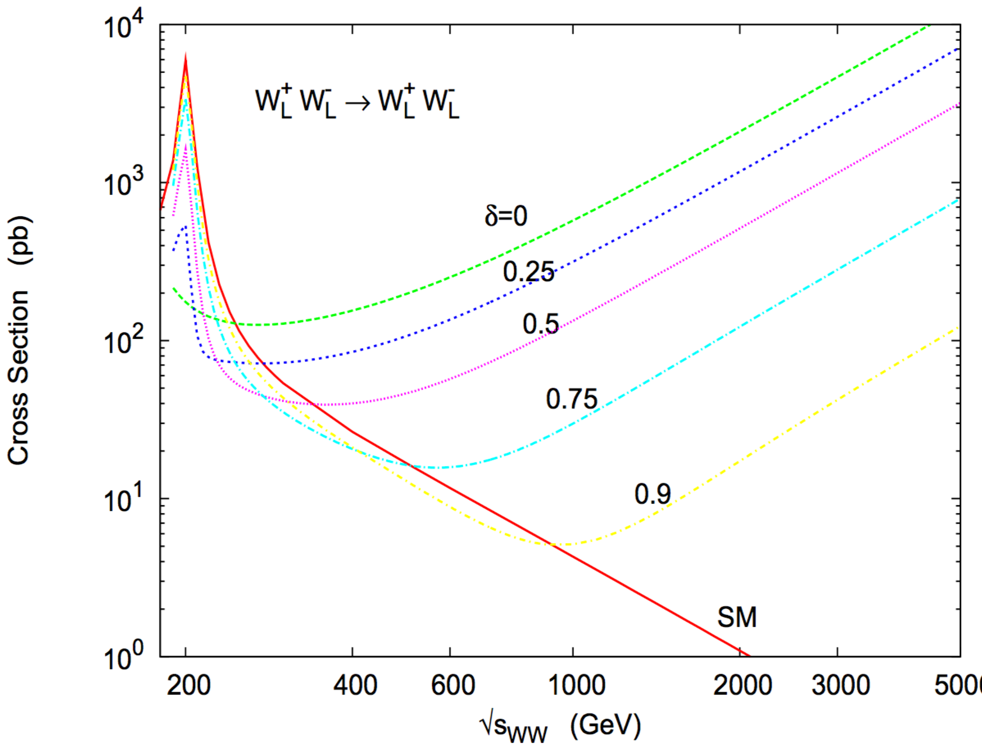
- 59 dim-6 operators already mapped out in 1986.
  - **Which operators to keep?**
  - **What about dim-8?**
  - **What about loop processes?**



Delayed unitarization: until when?

[http://cern.ch/go/q8Gq]

- Assume that WW scattering is $\delta^{-1/2}$ that of SM.
- Things can look like the SM for a long time.
  - **Time ~ Energy.**



Things you can't "unseen"

[http://cern.ch/go/Dxh7]

TOBLERONE®

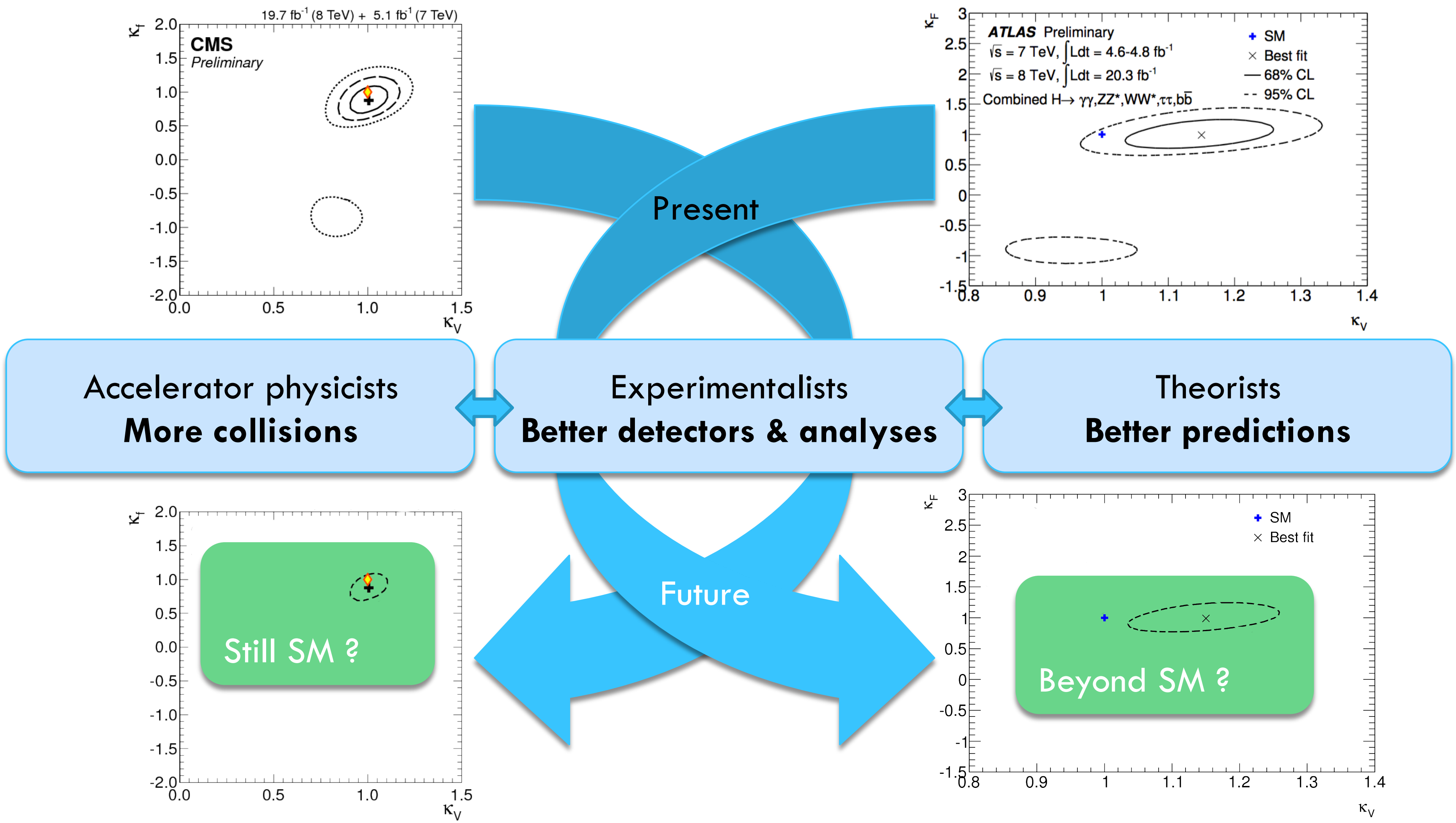
Things you can't "unsee"

[http://cern.ch/go/Dxh7]

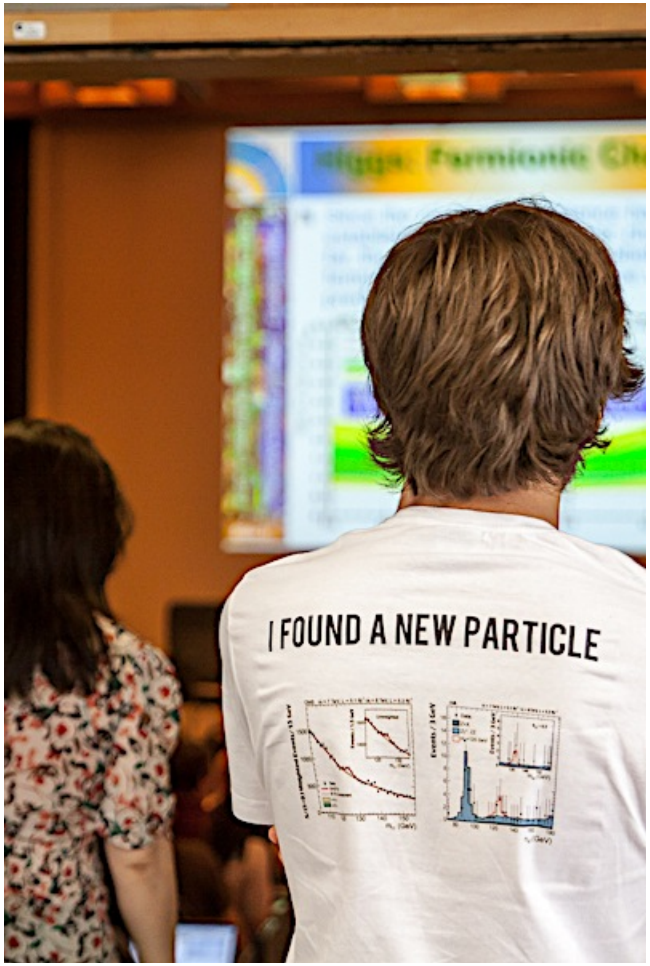
Things you can't "unsee"

[http://cern.ch/go/Dxh7]

The future is in precision and accuracy



Outlook



- **LHC13: last chance before a "BSM desert".**
  - Tevatron: Run I → top discovery, Run II → SM precision.
  - LHC 2010: early SUSY and EXO exclusions.
- **Higgs, one way out of the "SM oasis":**
  - From O(10%) to differential.
  - From "seen" to O(%) measurements.
  - From limits on rare things to observations.
  - From conjectures on weird things, to putting limits on them.
  - From ad-hoc κ fits to global EWK EFT fits.
- **We have a long way to go.**
  All it takes is one deviation.

References

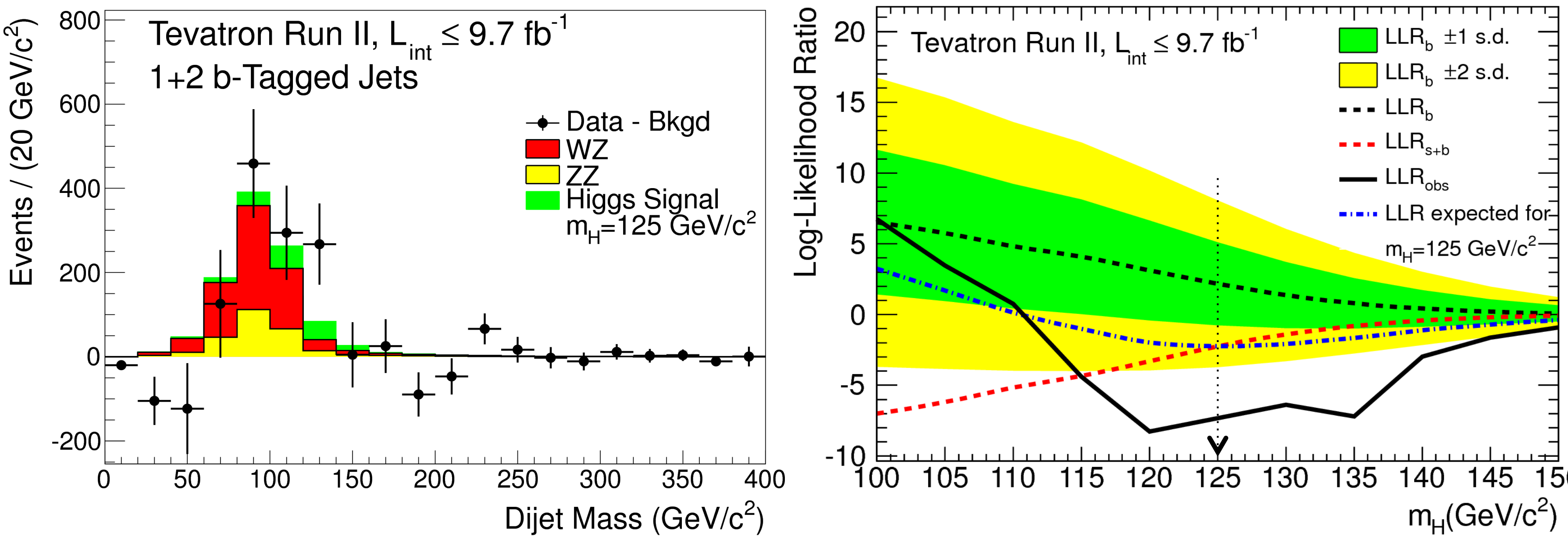
"...and references therein."

- Experiments' pages on Higgs results:
  - ATLAS: http://cern.ch/go/7IDT
  - CMS: http://cern.ch/go/6qmZ
  - Tevatron: http://cern.ch/go/h9jX
    - CDF: http://cern.ch/go/q8NV
    - D0: http://cern.ch/go/9Djq
- Partial list of conferences and workshops:
  - Higgs Days 2013: http://cern.ch/go/6zBp
  - ECFA HL-LHC workshop: http://cern.ch/go/SFW6
  - Higgs EFT 2013: http://cern.ch/go/bR7w
  - Higgs Couplings 2013: http://cern.ch/go/THp9
  - Moriond 2014: http://cern.ch/go/k8FP
  - Bernasque 2014: http://cern.ch/go/Pz7I
  - ICHEP 2014: http://cern.ch/go/8Btf
  - Rencontres du Vietnam 2014: http://cern.ch/go/9ZJJ
  - Zuoz Summer School 2014: http://cern.ch/go/9SHw
  - Higgs Days 2014: http://cern.ch/go/IfP6
  - Higgs Couplings 2014: http://cern.ch/go/HMm6

For discussion

From the other side of the pond

[arXiv:1207.6436]



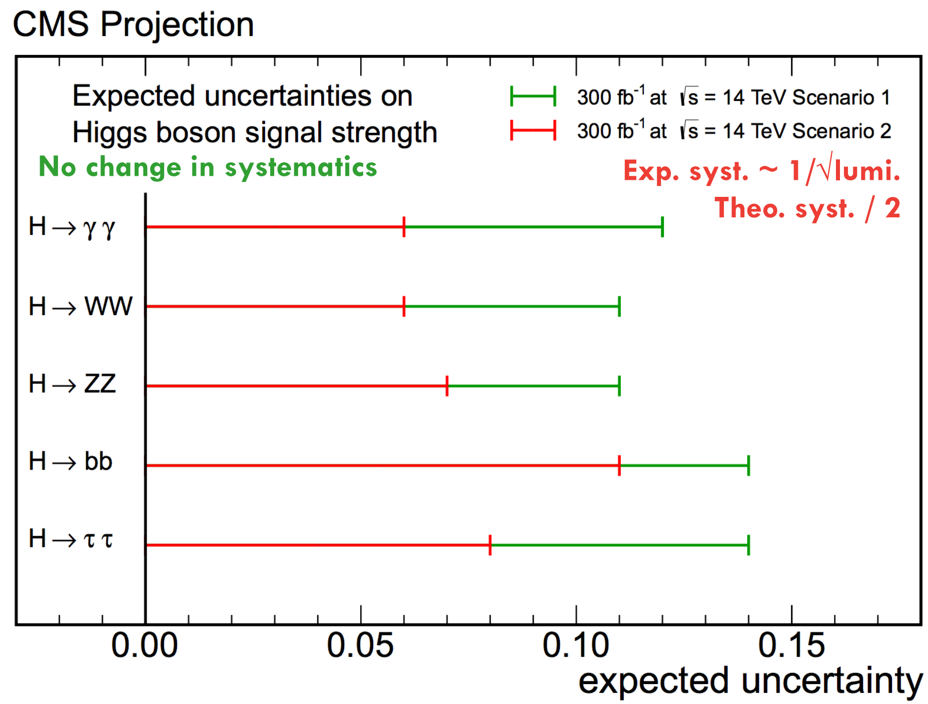
- Combination of Tevatron VH⟶$b\bar{b}$ searches, in July 2012:
  - **2.8 σ local significance at m_H=125 GeV.**

The Future

Looking ahead

[arXiv:1307.7135][CMS-PAS-HIG-13-007]

- 300 fb^{-1} at 14 TeV:
  - Vast improvement over present datasets.
  - **Room for theory improvements.**



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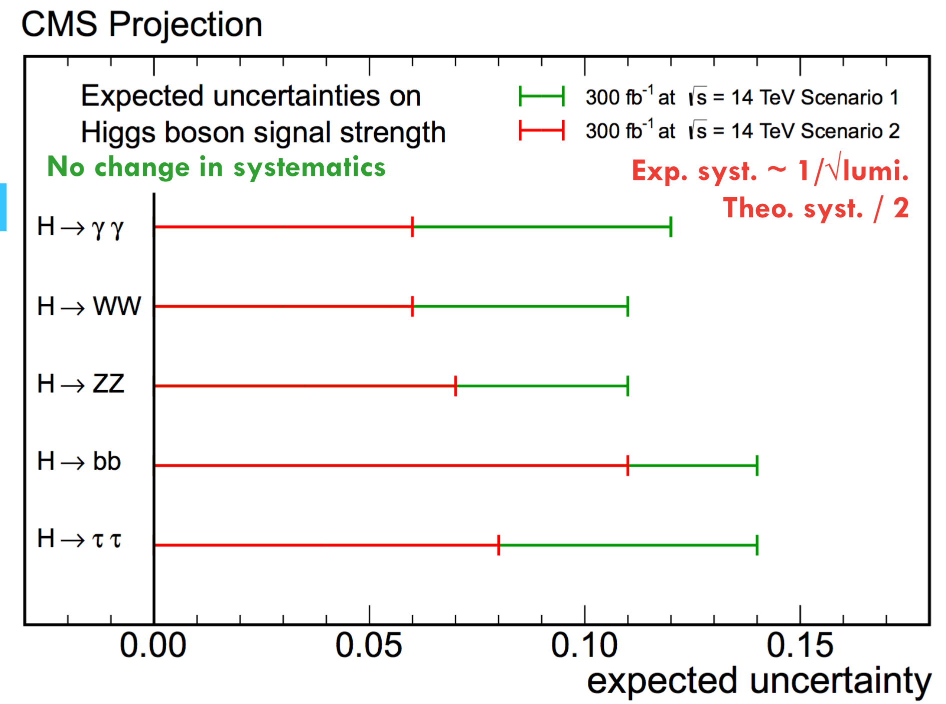
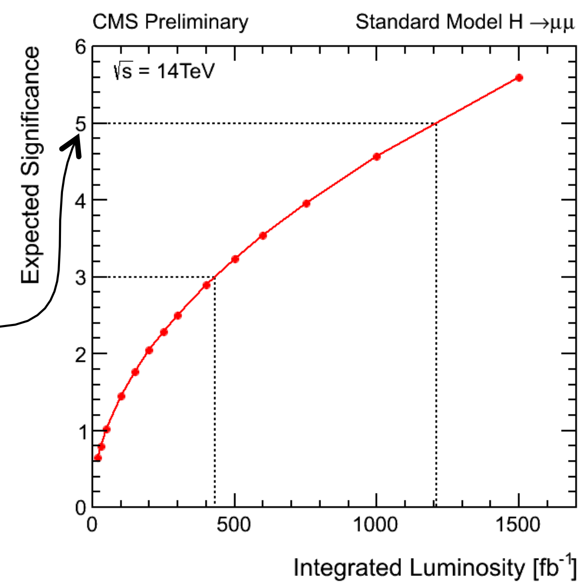


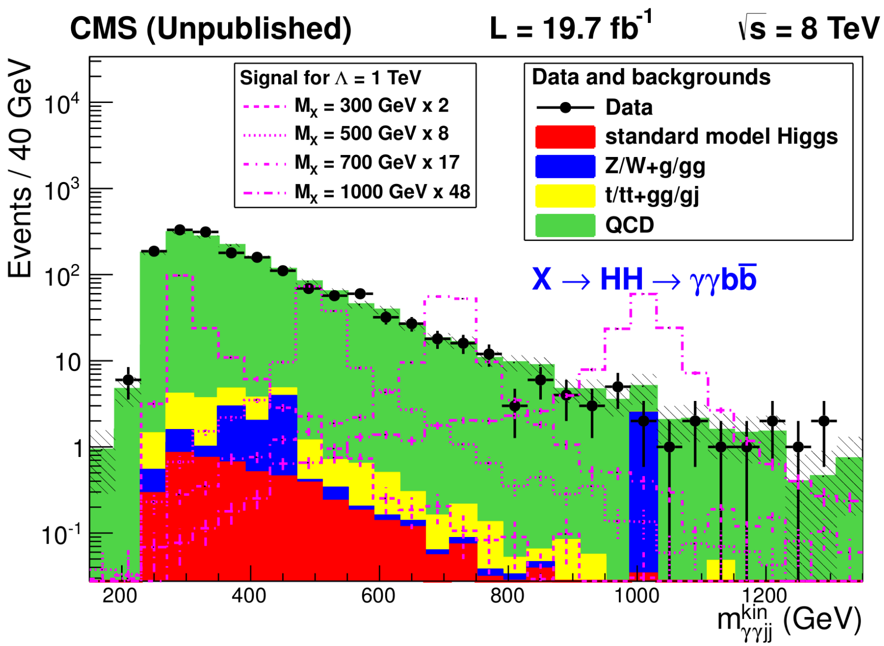
- For (HL-LHC) 3000 fb^{-1}:
  - **H→μμ at > 5σ.**
  - Can we get to the Higgs self-coupling?

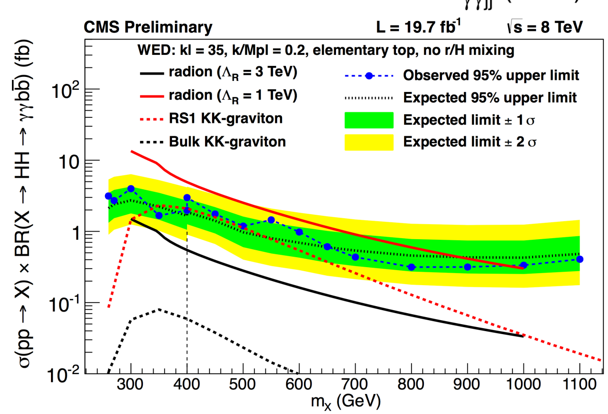


X→HH→$b\bar{b}\gamma\gamma$ and the future

[CMS-PAS-HIG-13-032]

- **First step towards two-Higgs measurements at the HL-LHC.**
- For now setting limits on radion production from warped extra dimensions.





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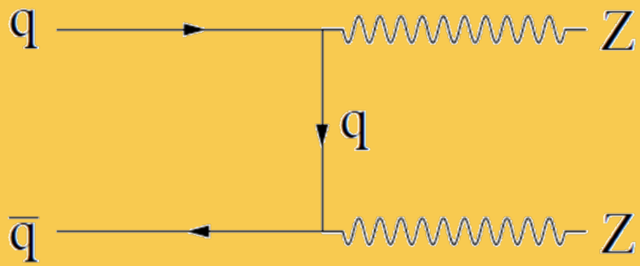
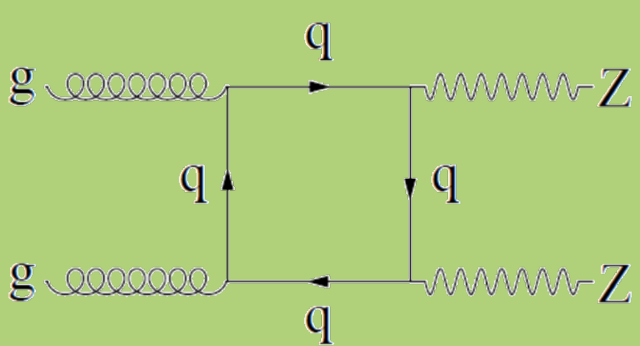
Going off-shell

Off-shell – involved processes

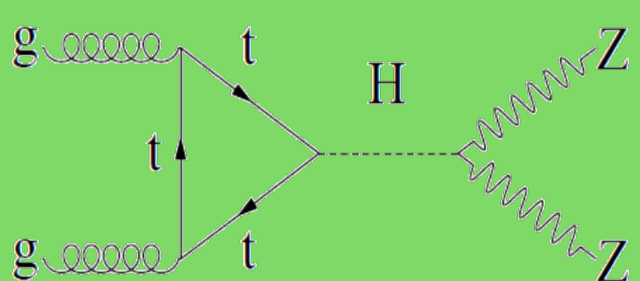


Backgrounds



Strong interference

NNLO/LO k-factors depend on m_{ZZ}
[G. Passarino, arXiv:1312.2397]
Use the same k-factors for signal and gg continuum
[M. Bonvini et al., PRD 88 2013]



Signal

H^* – off-shell

[PLB 736 (2014) 64][JHEP 08 (2012) 116][PRD 88 (2013) 054024][arXiv:1311.3589]

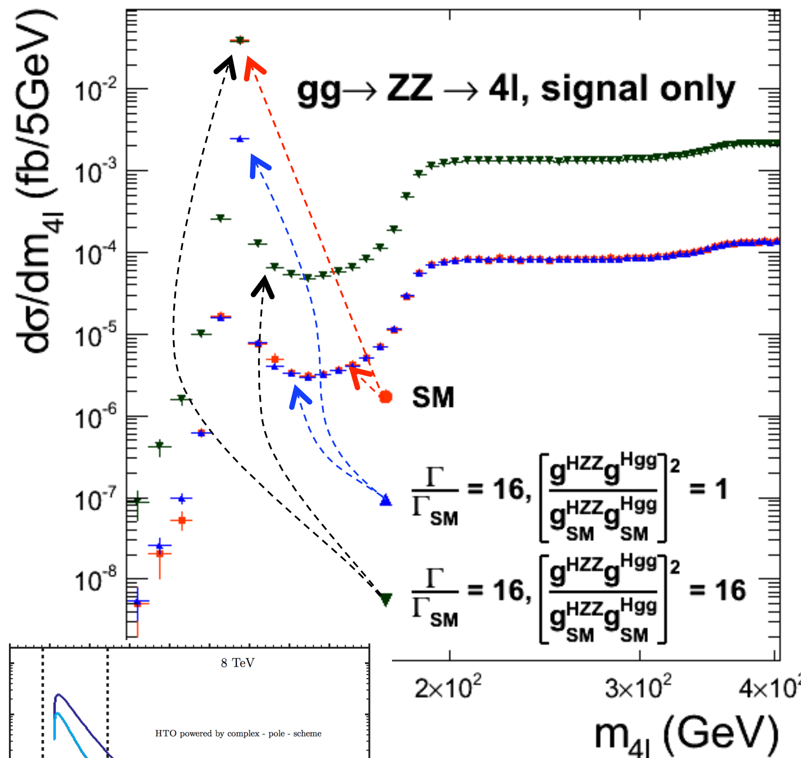
- Define $r = \Gamma_{\mathrm{H}} / \Gamma_{\mathrm{H}}^{\mathrm{SM}}$
- On-mass-shell we have

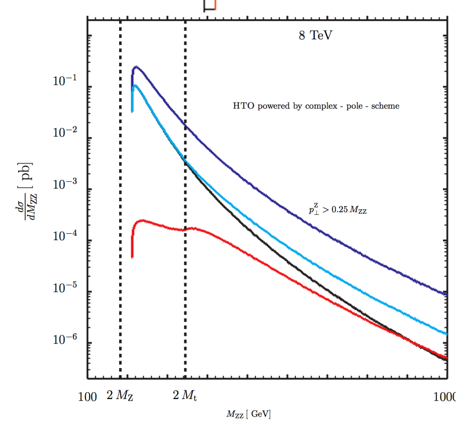
$$\sigma_{gg \to H \to ZZ}^{\text{on-peak}} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{\mathrm{SM}}$$

- Off-mass-shell there is no ***r***:

$$\frac{d\sigma_{gg \to H \to ZZ}^{\text{off-peak}}}{dm_{ZZ}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma_{gg \to H \to ZZ}^{\text{off-peak,SM}}}{dm_{ZZ}}$$

- Can make inference on ***r*** from on- **and** off-shell **assuming:**
  - $\mu_{\text{on-shell}} = \mu_{\text{off-shell}}$
  - Only SM processes → ZZ:
    - gg→H*
    - **gg** = |gg→H* + gg→non-H|²
    - |gg→H*|² + |gg→non-H|²
    - **Total** = **gg** + $q\bar{q}$

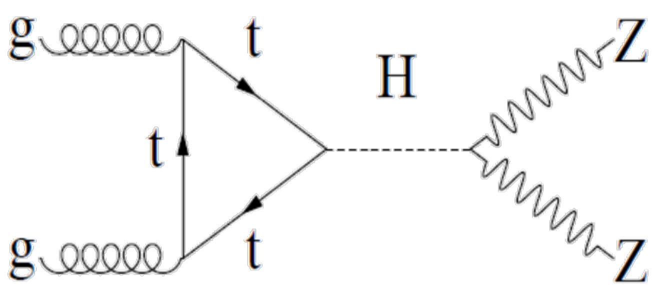


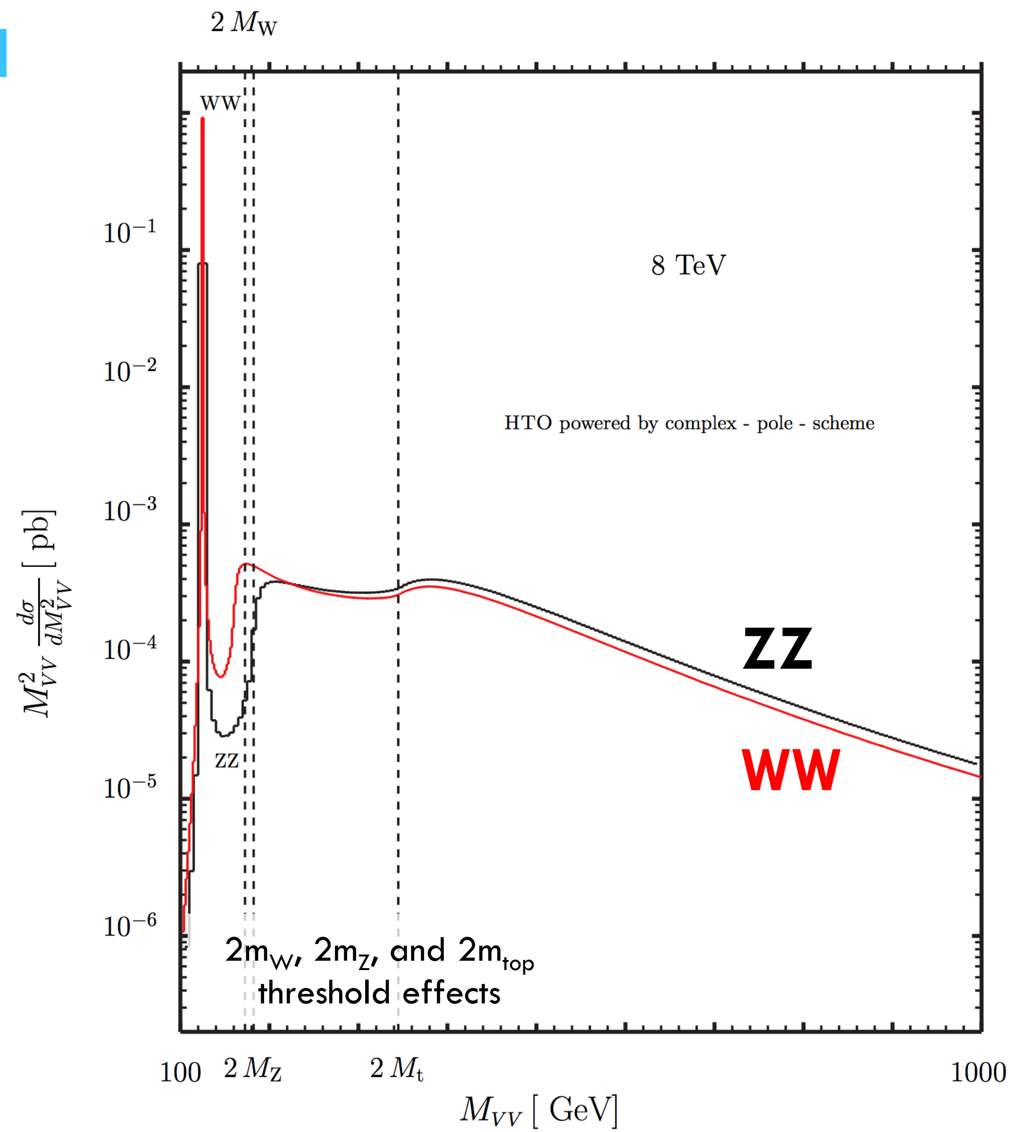


H* – going off-shell

[PLB 736 (2014) 64][arXiv:1206.4803]

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH} g^2_{HZZ}}{(m^2_{ZZ} - m^2_{H})^2 + m^2_{H}\Gamma^2_{H}}$$





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[PLB 736 (2014) 64][arXiv:1206.4803]

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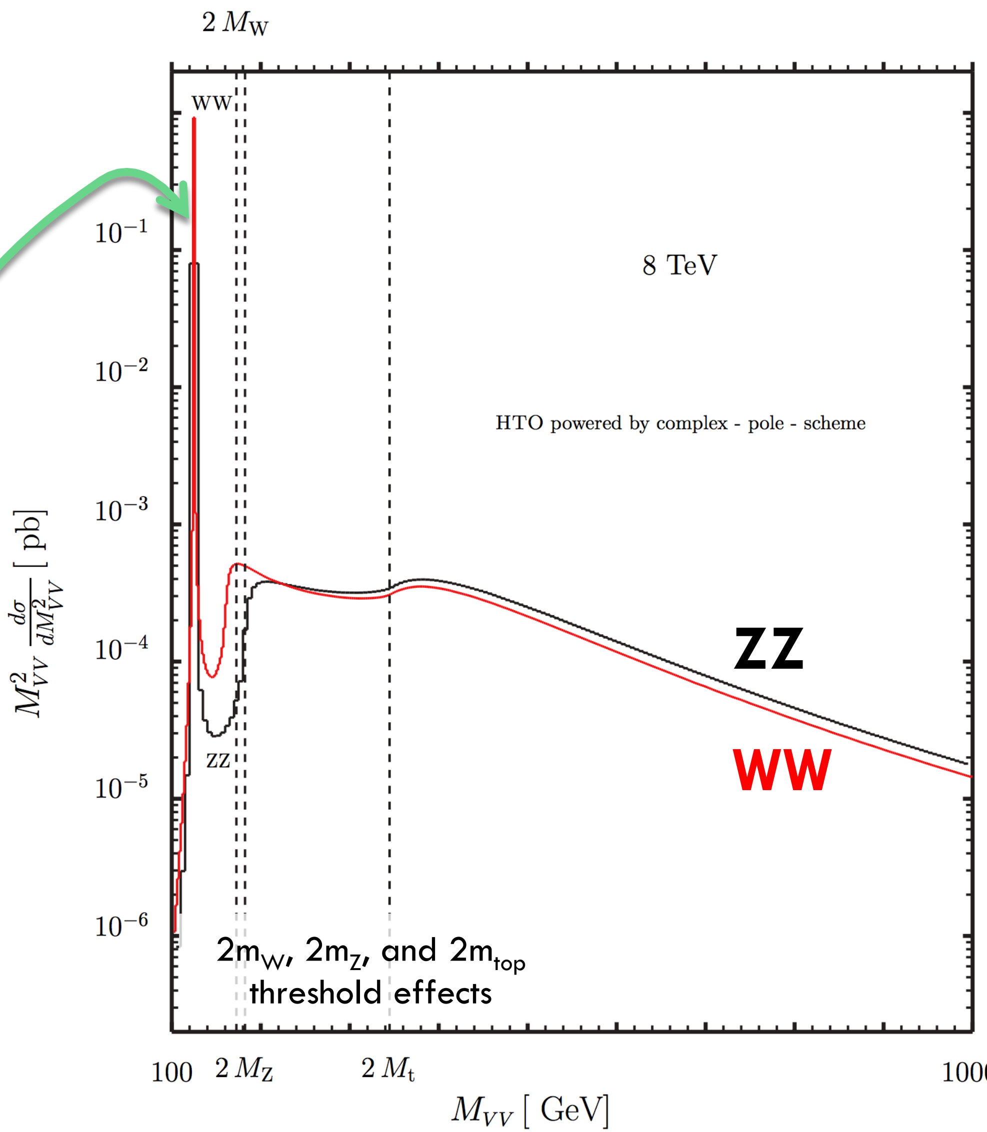
$m_{ZZ} \sim m_H$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}$$



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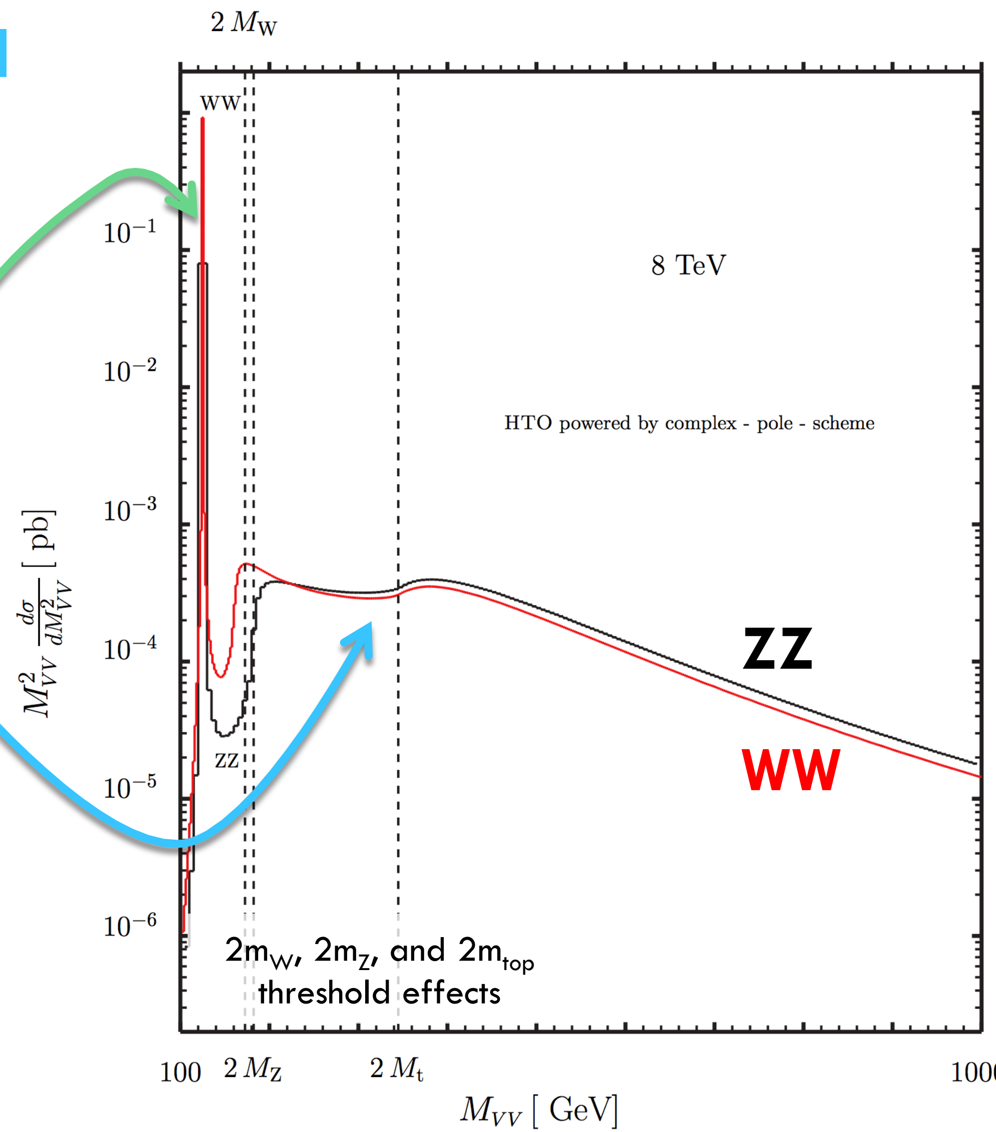
$m_{ZZ} \sim m_H$

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$$

$m_{ZZ} \gg m_H$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$$



$2m_W$, $2m_Z$, and $2m_{top}$ threshold effects

H* – going off-shell

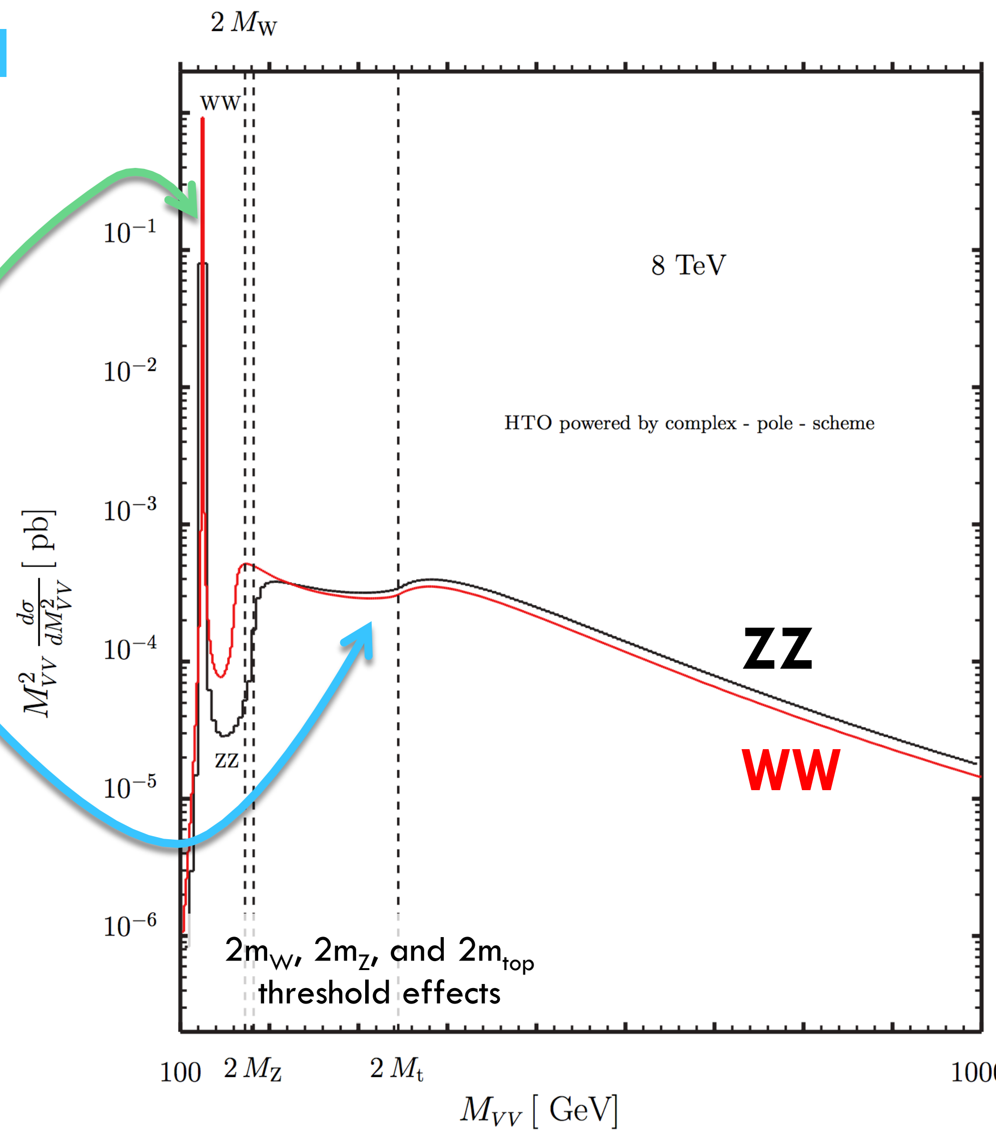
[PLB 736 (2014) 64][arXiv:1206.4803]

$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$

$m_{ZZ} \sim m_H$: $\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$

$m_{ZZ} \gg m_H$: $\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$

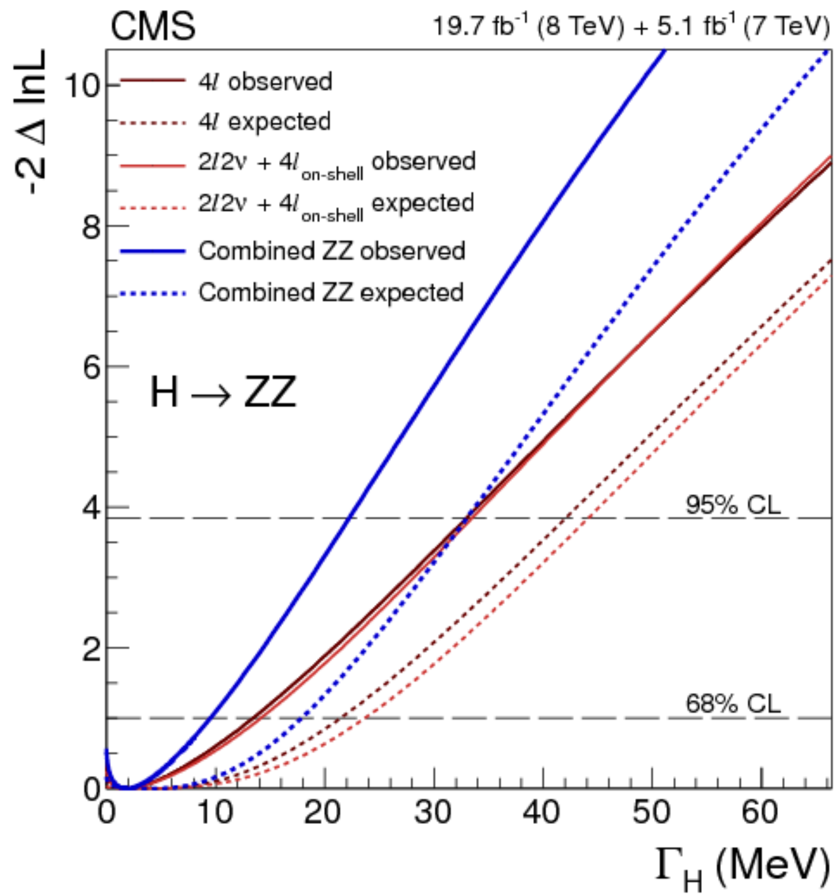
$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$



H* – off-shell decay to ZZ

[PLB 736 (2014) 64]

- Two channels exploited:
  - ZZ→4ℓ
    - 2D: $m_{4\ell}$ and gg vs. $q\bar{q}$ discriminant.
  - ZZ→2ℓ2ν
    - Jet-inclusive m_T shape.
- Observed limit lower than expected.



Obs. (exp.)	4ℓ	2ℓ2ν	Combined
Γ_H/Γ_H^{SM} (95% CL)	< 8.0 (10.1)	< 8.1 (10.6)	< 5.4 (8.0)

More on theory

MSSM (R.Contino)

[http://cern.ch/go/W96V]

- Shifts to tree-level couplings due to mixing with heavier Higgs

$$c_V = \sin(\beta - \alpha) \qquad c_t = \frac{\cos\alpha}{\sin\beta} \qquad c_b = -\frac{\sin\alpha}{\cos\beta}$$

c_V always reduced

if $c_t > 1$ then $c_b < 1$ and viceversa

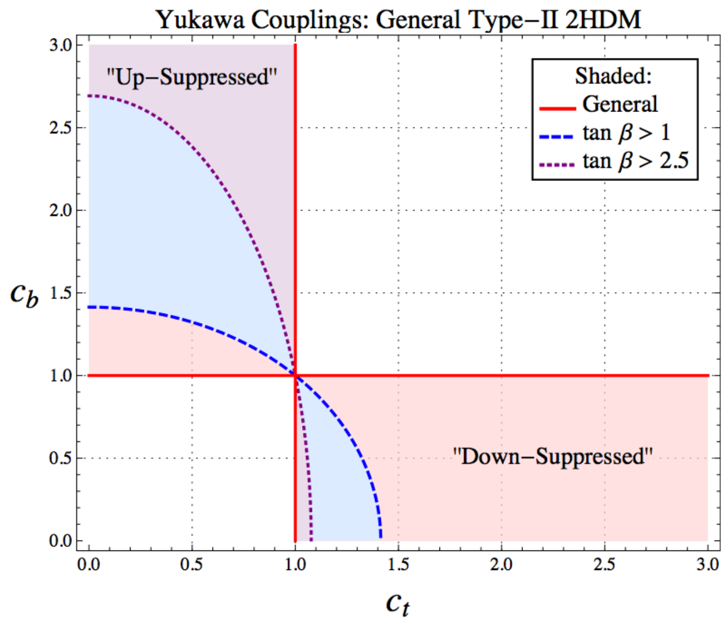
$$\begin{pmatrix} h^0 \\ H^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \mathrm{Re}\, H_u^0 \\ \mathrm{Re}\, H_d^0 \end{pmatrix}$$

$$\tan\beta = \frac{v_u}{v_d}$$

Only two regions in the (c_t, c_b) plane accessible in a *generic* Type-II 2HDM

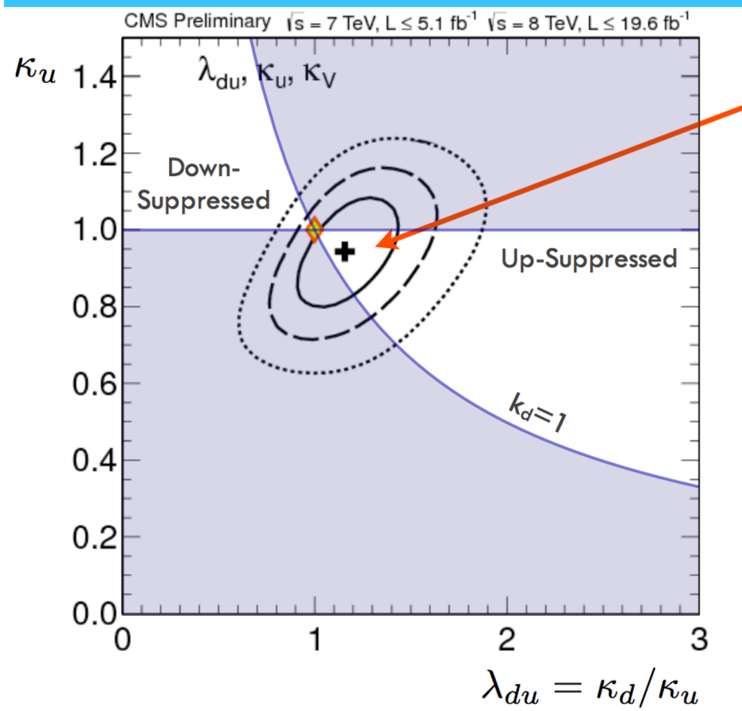
Down-Suppressed region almost *not accessible* in the MSSM for $\tan\beta > 1$

see: Azatov, Chang, Craig, Galloway PRD 86 (2012) 075033



MSSM (R.Contino)

[http://cern.ch/go/W96V]

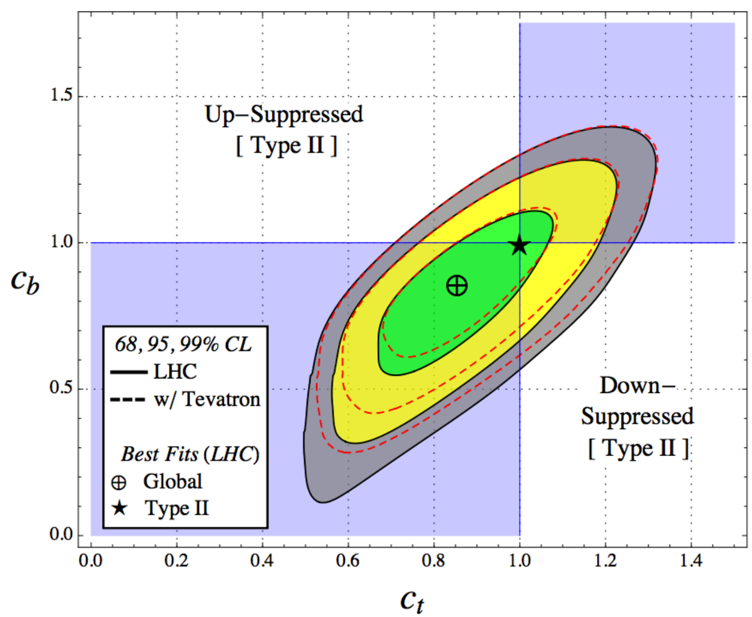


the current fit by CMS seems to favor the MSSM region, though errors are large

It would be nice to see the same plot by ATLAS and even nicer to see plot in the plane (κ_u, κ_d)

For the impatient ones here is a theorist's combination of ATLAS+CMS+Tevatron:

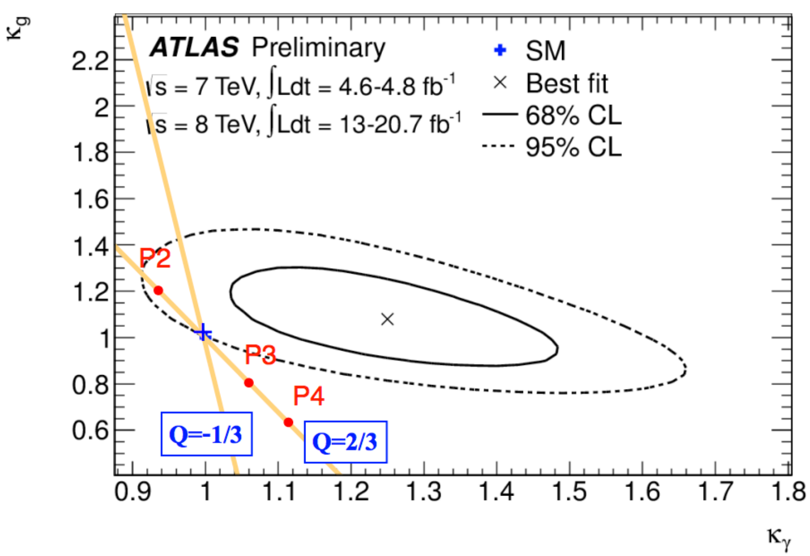
from: Azatov, Galloway Int. J. Mod. Phys. A28 (2013) 1330004

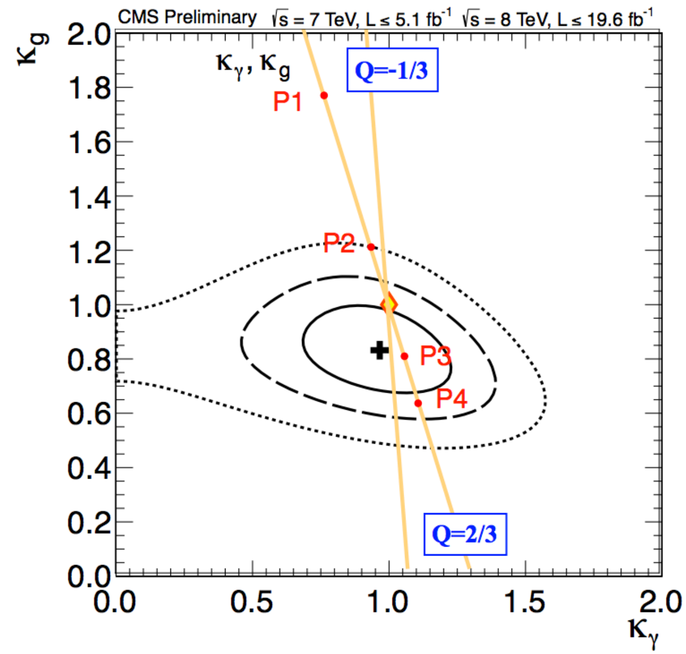


MSSM (R.Contino)

[http://cern.ch/go/W96V]

- Shifts to loop-induced couplings due to squarks





Small mixing: ➡ $\Gamma(gg \to h)$ enhanced
$\Gamma(h \to \gamma\gamma)$ suppressed

Large mixing: ➡ $\Gamma(gg \to h)$ suppressed
$\Gamma(h \to \gamma\gamma)$ enhanced

P1: $m_{\tilde{t}_1} = 100\,\text{GeV},\ m_{\tilde{t}_2} = 300\,\text{GeV},\ \theta_t = 0$

P2: $m_{\tilde{t}_1} = 200\,\text{GeV},\ m_{\tilde{t}_2} = 500\,\text{GeV},\ \theta_t = 0$

P3: $m_{\tilde{t}_1} = 400\,\text{GeV},\ m_{\tilde{t}_2} = 1000\,\text{GeV},\ \theta_t = \pi/4$

P4: $m_{\tilde{t}_1} = 500\,\text{GeV},\ m_{\tilde{t}_2} = 1500\,\text{GeV},\ \theta_t = \pi/4$

MSSM (R.Contino)

[http://cern.ch/go/W96V]

- Implications on the masses of the heavier Higgses

In the decoupling limit: $\alpha \to \beta - \pi/2$

$$c_V = 1 - \Delta^2 \frac{1}{\tan^2\beta} + O(\Delta^3)$$

starts at $O(m_H^{-4})$

$$c_t = 1 - \Delta \frac{1}{\tan^2\beta} + O(\Delta^2)$$

$$c_b = 1 + \Delta + O(\Delta^2)$$

$$\Delta = O\left(\frac{m_Z^2}{m_H^2}\right)$$

c_b most sensitive probe of spectrum of Heavy Higgses

$$\frac{\delta c_b}{c_b} > 0.1 \quad \Rightarrow \quad m_H > 300-400\,\text{GeV}$$

Notice:

masses of Heavy Higgses are *not* linked to naturalness of m_h anyway

Lighter masses (up to m_H ~200 GeV) however simple to obtain in explicit models (ex: NMSSM) with mild tuning of Δ

see for example: Barbieri et al. arXiv:1304.3670

The case for the SMH (R.Contino)

[http://cern.ch/go/W96V]

If one assumes that

1. The new boson is part of an $SU(2)_L$ doublet
2. There is a gap between the NP scale and m_H

then it must follow:

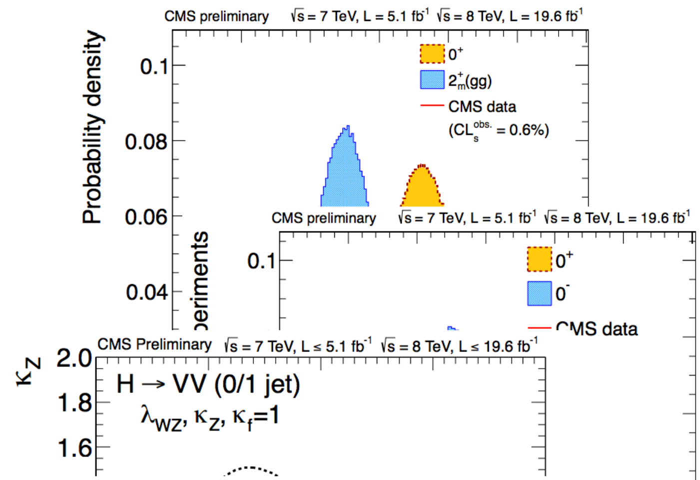
- h has spin 0 ✓
- h is (mostly) CP=+ ✓
- There exists a correlation among processes with 0,1,2 Higgs bosons

  Ex: custodial symmetry ✓

  $$\frac{m_W}{m_Z \cos\theta_W} = 1 \Rightarrow \lambda_{WZ} = \frac{c_W}{c_Z} = 1$$

- There are no new light states to which the Higgs boson can decay

  Ex: Invisible width=0 ✓



All these independent tests important to confirm the picture but their success comes less of a surprise given the fits on couplings

Ex: there's no reason why a $J^P=0^-$ boson should have SM coupling strength

$$|D_\mu H|^2 \quad \text{vs} \quad \frac{\tilde{c}_{WW}}{M^2} W_{\mu\nu}\tilde{W}^{\mu\nu} H^\dagger H$$

To loop or not to loop

To loop or not to loop

Generic coupling fit

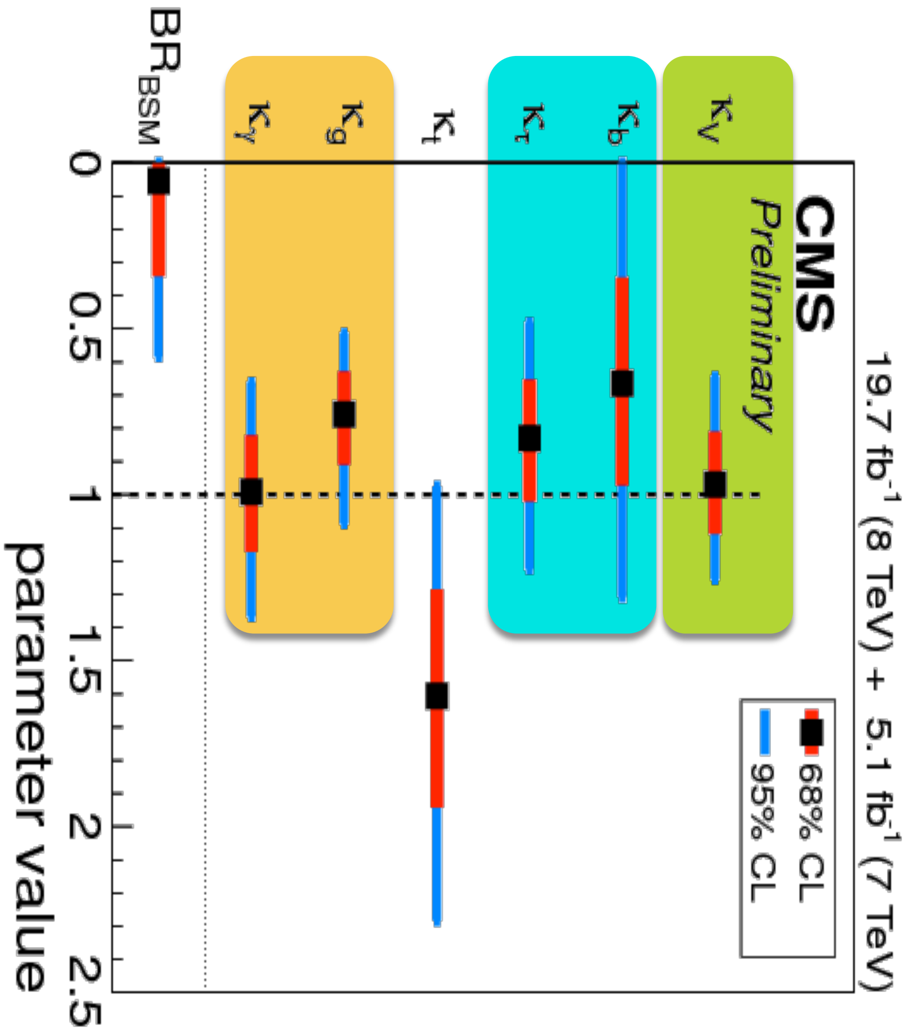
- Assume custodial symmetry ($\kappa_V = \kappa_W = \kappa_Z$).
- Loops treated effectively (κ_γ, κ_g).
- Option to allow BSM decays, forcing $\kappa_V \leq 1$.

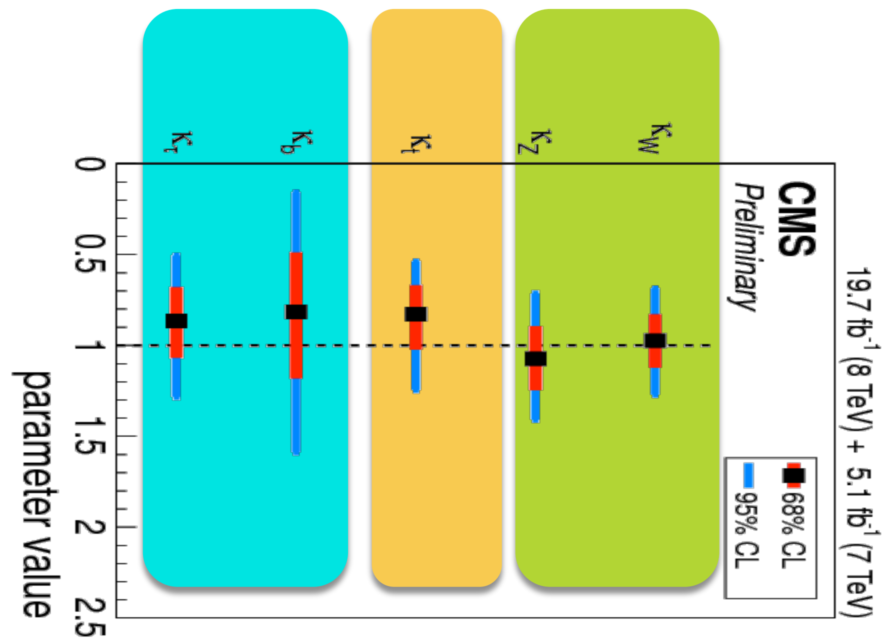
Resolved coupling fit

- Keep W and Z separate.
- Loops assuming SM structure:
  - $\kappa_g(\kappa_b, \kappa_t)$.
  - $\kappa_\gamma(\kappa_W, \kappa_b, \kappa_t, \kappa_\tau)$.
- Only SM-like decays.

To loop or not to loop

[arXiv:1412.8662]





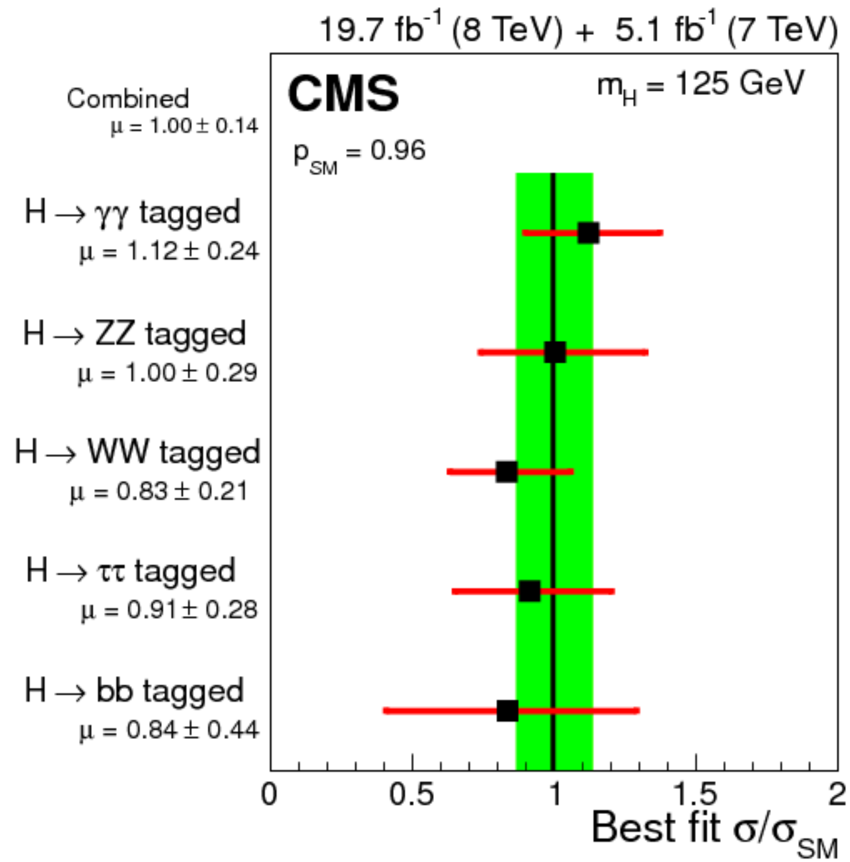
More on scalar couplings

Signal strength

[arXiv:1412.8662]

$$1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

- Grouped by dominant decay:
  - $\chi^2/\text{dof} = 1.0/5$
  - p-value = 0.96 (asymptotic)

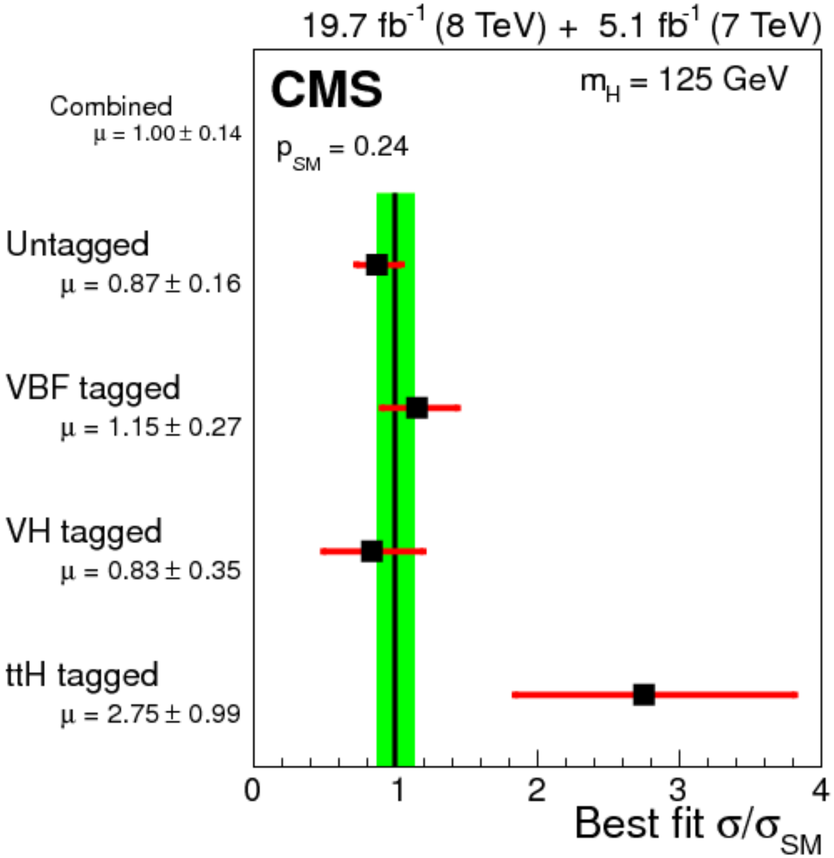


Signal strength

[arXiv:1412.8662]

$$1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

- Grouped by production tag:
  - $\chi^2/\text{dof} = 5.5/4$
  - p-value = 0.24 (asymptotic)
- **ttH-tagged 2.0σ above SM.**

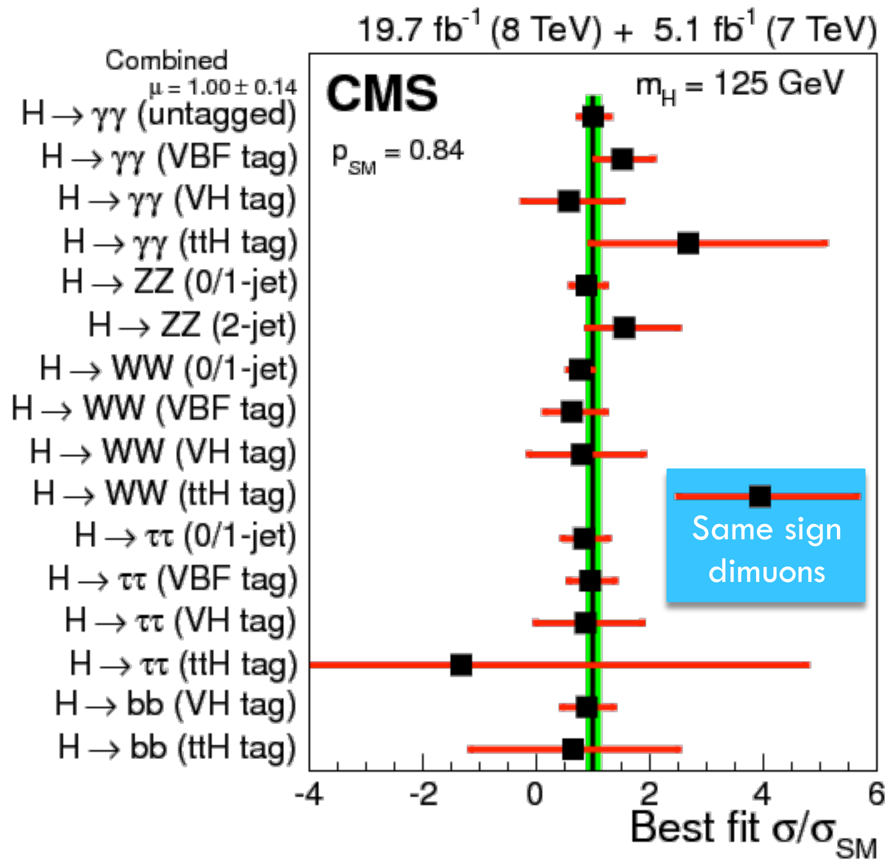


Signal strength

[arXiv:1412.8662]

$$1.00 \pm 0.09\,(\text{stat.})\,^{+0.08}_{-0.07}\,(\text{theo.}) \pm 0.07\,(\text{syst.})$$

- Grouped by production tag and dominant decay:
  - $\chi^2/\text{dof} = 10.5/16$
  - p-value = 0.84 (asymptotic)
- ttH-tagged 2.0σ above SM.
  - **Driven by one channel.**



Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

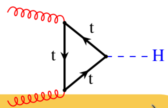
$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Single state, spin 0, and CP-even.
- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes



$$\frac{\sigma_{ggH}}{\sigma^{SM}_{ggH}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma^{SM}_{VBF}} = \kappa^2_{VBF}(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma^{SM}_{WH}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma^{SM}_{ZH}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma^{SM}_{t\bar{t}H}} = \kappa_t^2$$

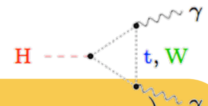
Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma^{SM}_{WW^{(*)}}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma^{SM}_{ZZ^{(*)}}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma^{SM}_{b\bar{b}}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma^{SM}_{\tau^-\tau^+}} = \kappa_\tau^2$$



$$\frac{\Gamma_{\gamma\gamma}}{\Gamma^{SM}_{\gamma\gamma}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma^{SM}_{Z\gamma}} = \begin{cases} \kappa^2_{(Z\gamma)}(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa^2_{(Z\gamma)} \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma^{SM}_{t\bar{t}}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}} \quad : \quad \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma^{SM}_{c\bar{c}}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma^{SM}_{s\bar{s}}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma^{SM}_{\mu^-\mu^+}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma^{SM}_H} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

- Loops resolved at NLO QCD and LO EWK accuracy.
- Peg the as-of-yet unmeasured to “closest of kin”.

Scalar coupling deviations framework

[arXiv:1307.1347]

Production modes

$$\frac{\sigma_{ggH}}{\sigma_{ggH}^{SM}} = \begin{cases} \kappa_g^2(\kappa_b, \kappa_t, m_H) \\ \kappa_g^2 \end{cases}$$

$$\frac{\sigma_{VBF}}{\sigma_{VBF}^{SM}} = \kappa_{VBF}^2(\kappa_W, \kappa_Z, m_H)$$

$$\frac{\sigma_{WH}}{\sigma_{WH}^{SM}} = \kappa_W^2$$

$$\frac{\sigma_{ZH}}{\sigma_{ZH}^{SM}} = \kappa_Z^2$$

$$\frac{\sigma_{t\bar{t}H}}{\sigma_{t\bar{t}H}^{SM}} = \kappa_t^2$$

Detectable decay modes

$$\frac{\Gamma_{WW^{(*)}}}{\Gamma_{WW^{(*)}}^{SM}} = \kappa_W^2$$

$$\frac{\Gamma_{ZZ^{(*)}}}{\Gamma_{ZZ^{(*)}}^{SM}} = \kappa_Z^2$$

$$\frac{\Gamma_{b\bar{b}}}{\Gamma_{b\bar{b}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\tau^-\tau^+}}{\Gamma_{\tau^-\tau^+}^{SM}} = \kappa_\tau^2$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{\gamma\gamma}^{SM}} = \begin{cases} \kappa_\gamma^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_\gamma^2 \end{cases}$$

$$\frac{\Gamma_{Z\gamma}}{\Gamma_{Z\gamma}^{SM}} = \begin{cases} \kappa_{(Z\gamma)}^2(\kappa_b, \kappa_t, \kappa_\tau, \kappa_W, m_H) \\ \kappa_{(Z\gamma)}^2 \end{cases}$$

Currently undetectable decay modes

$$\frac{\Gamma_{t\bar{t}}}{\Gamma_{t\bar{t}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{gg}}{\Gamma_{gg}^{SM}} : \text{see Section 3.1.2}$$

$$\frac{\Gamma_{c\bar{c}}}{\Gamma_{c\bar{c}}^{SM}} = \kappa_t^2$$

$$\frac{\Gamma_{s\bar{s}}}{\Gamma_{s\bar{s}}^{SM}} = \kappa_b^2$$

$$\frac{\Gamma_{\mu^-\mu^+}}{\Gamma_{\mu^-\mu^+}^{SM}} = \kappa_\tau^2$$

Total width

$$\frac{\Gamma_H}{\Gamma_H^{SM}} = \begin{cases} \kappa_H^2(\kappa_i, m_H) \\ \kappa_H^2 \end{cases}$$

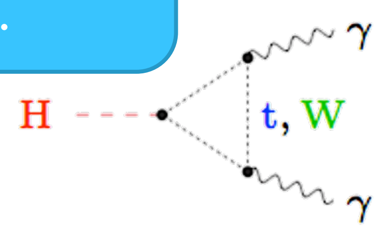
- Total width as dependent function of all κ_i.
- Total width scaled as free parameter: κ_H. (invisible decays)

Weak bosons and fermions

[arXiv:1307.1347]

Boson and fermion scaling assuming no invisible or undetectable widths Free parameters: $\kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.					
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}$H	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF WH ZH	$\frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_V^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$		$\frac{\kappa_V^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

H→ $\gamma\gamma$ resolved into top-loop, b-loop, τ-loop, and W-loop.



Probing custodial symmetry

[arXiv:1307.1347]

Probing custodial symmetry assuming no invisible or undetectable widths

Free parameters: κ_Z, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\kappa_f(=\kappa_t=\kappa_b=\kappa_\tau)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot (\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
VBF	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ}) \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ}) \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ}) \cdot (\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_{VBF}^2(\kappa_Z,\kappa_Z\lambda_{WZ}) \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
WH	$\frac{(\kappa_Z\lambda_{WZ})^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2 \cdot (\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{(\kappa_Z\lambda_{WZ})^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	
ZH	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot (\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

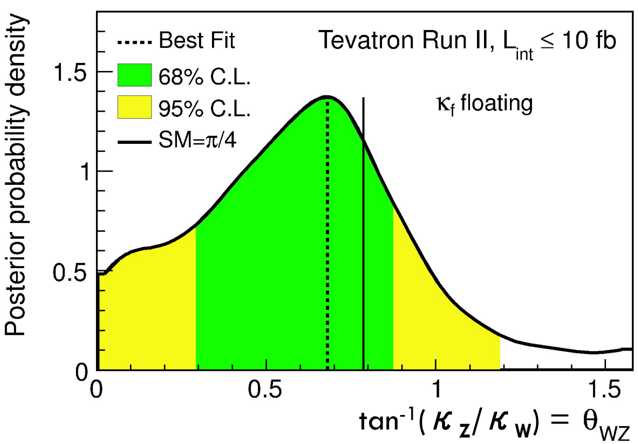
Probing custodial symmetry without assumptions on the total width

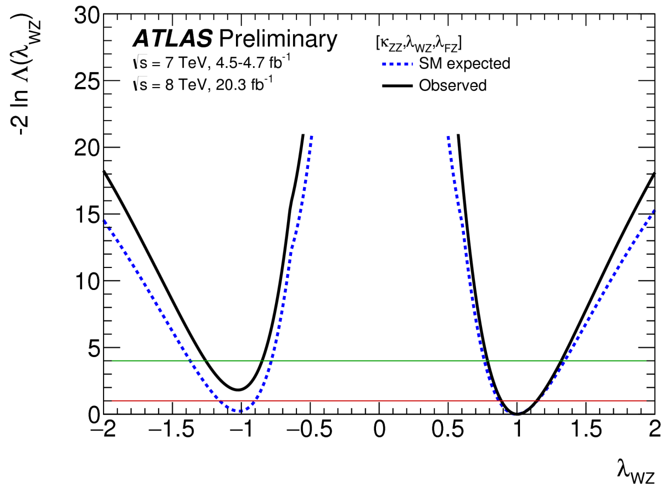
Free parameters: $\kappa_{ZZ}(=\kappa_Z \cdot \kappa_Z/\kappa_H)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{FZ}(=\kappa_f/\kappa_Z)$.

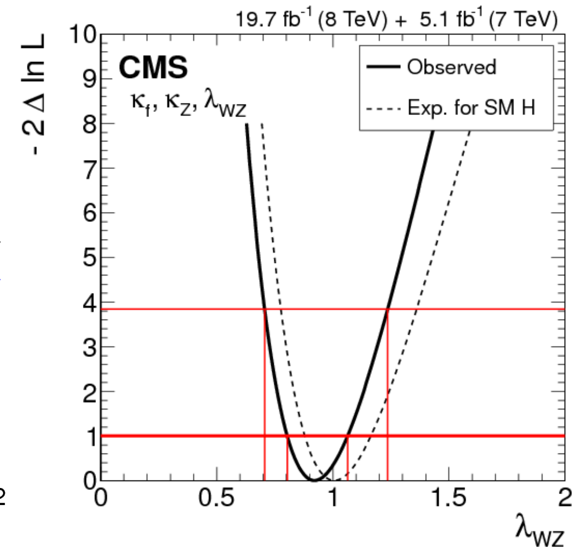
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2 \cdot \lambda_{FZ}^2$	
VBF	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2) \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2)$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2) \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2\kappa_{VBF}^2(1,\lambda_{WZ}^2) \cdot \lambda_{FZ}^2$	
WH	$\kappa_{ZZ}^2\lambda_{WZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{WZ}^2 \cdot \lambda_{FZ}^2$	
ZH	$\kappa_{ZZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	κ_{ZZ}^2	$\kappa_{ZZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2 \cdot \lambda_{FZ}^2$	

Probing custodial symmetry

[arXiv:1303.6346][ATLAS-CONF-2015-007][arXiv:1412.8662]







	Tevatron [κ_W, κ_Z, κ_f]	ATLAS [λ_{WZ}, λ_{FZ}, κ_{ZZ}]	CMS [λ_{WZ}, κ_Z, κ_f]
λ_{WZ}	$1.24^{+2.34}_{-0.42}$	$1.00^{+0.15}_{-0.11}$	$0.92^{+0.14}_{-0.12}$

Looking for new particles

[arXiv:1307.1347]

Probing loop structure assuming no invisible or undetectable widths

Free parameters: κ_g, κ_γ.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)}$	$\frac{1}{\kappa_H^2(\kappa_i)}$			

Probing loop structure allowing for invisible or undetectable widths

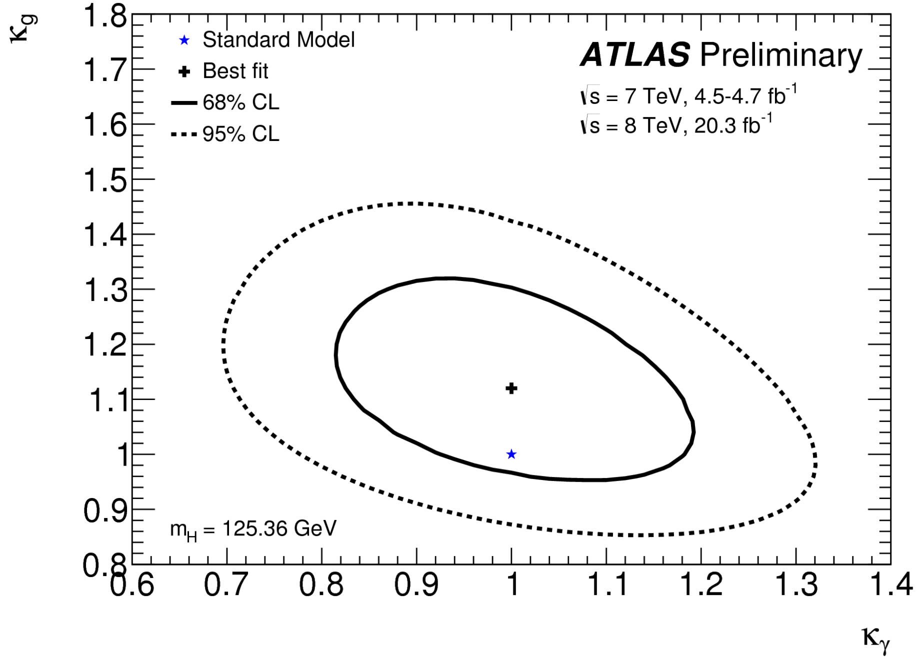
Free parameters: $\kappa_g, \kappa_\gamma, BR_{\text{inv.,undet.}}$.

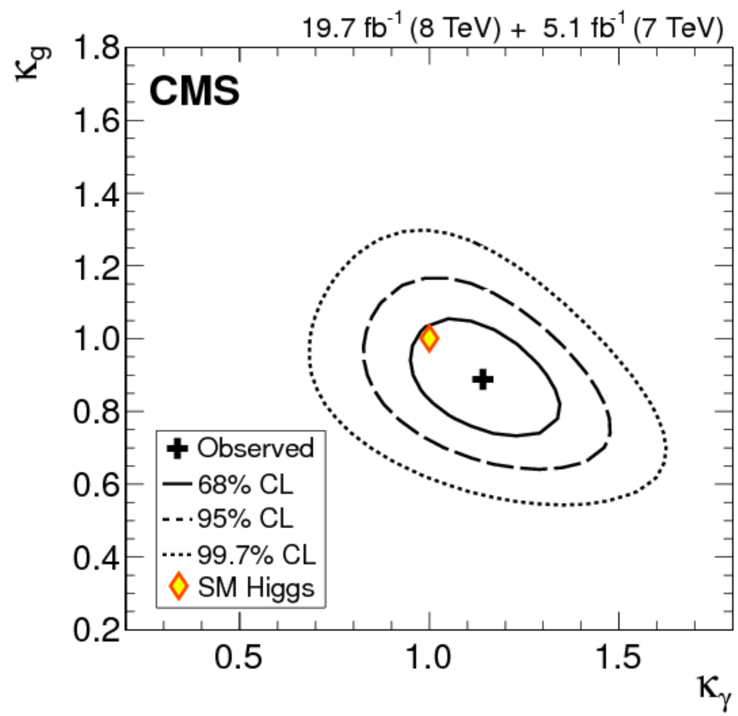
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{\text{inv.,undet.}})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-BR_{\text{inv.,undet.}})}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{\text{inv.,undet.}})}$	$\frac{1}{\kappa_H^2(\kappa_i)/(1-BR_{\text{inv.,undet.}})}$			

$$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$$

Looking for new particles in loops

[ATLAS-CONF-2015-007][arXiv:1412.8662]

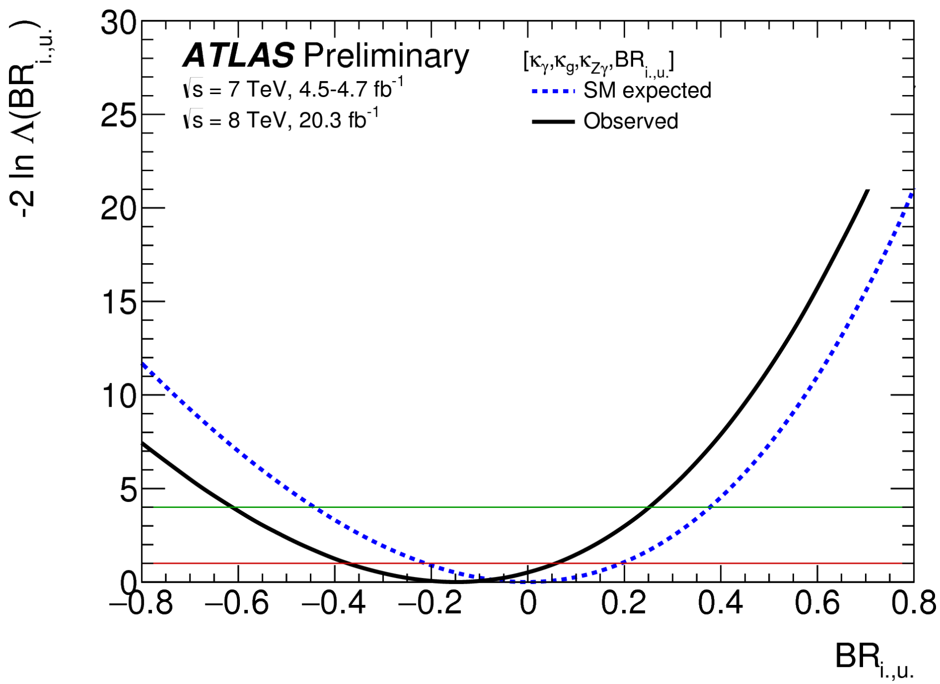


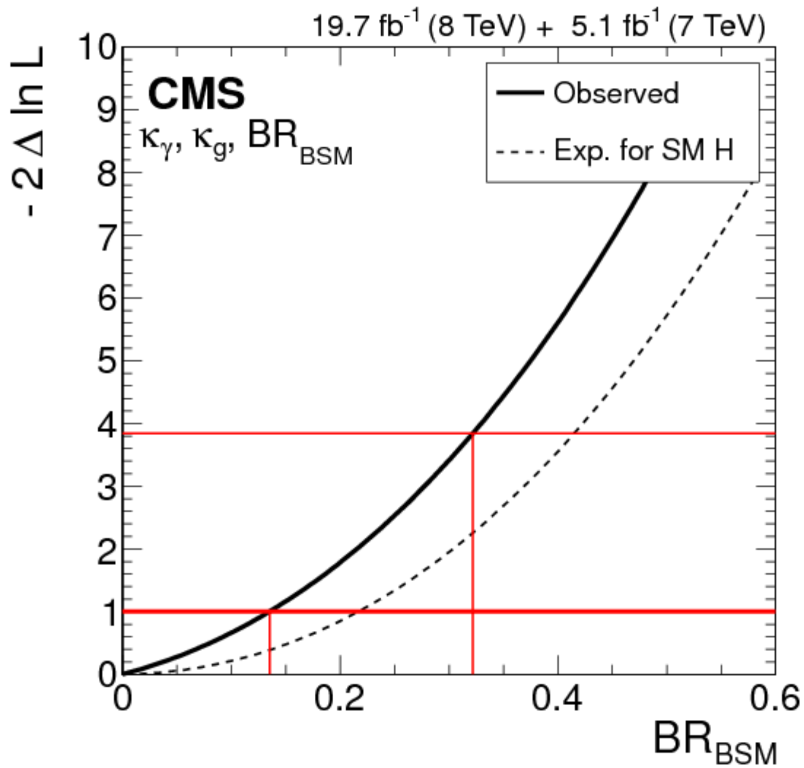


	ATLAS	CMS
κ_γ	**1.00 ±0.12**	$\mathbf{1.14^{+0.12}_{-0.13}}$
κ_g	**1.12 ±0.12**	$\mathbf{0.89^{+0.11}_{-0.10}}$

Looking for new particles

[ATLAS-CONF-2015-007][arXiv:1412.8662]





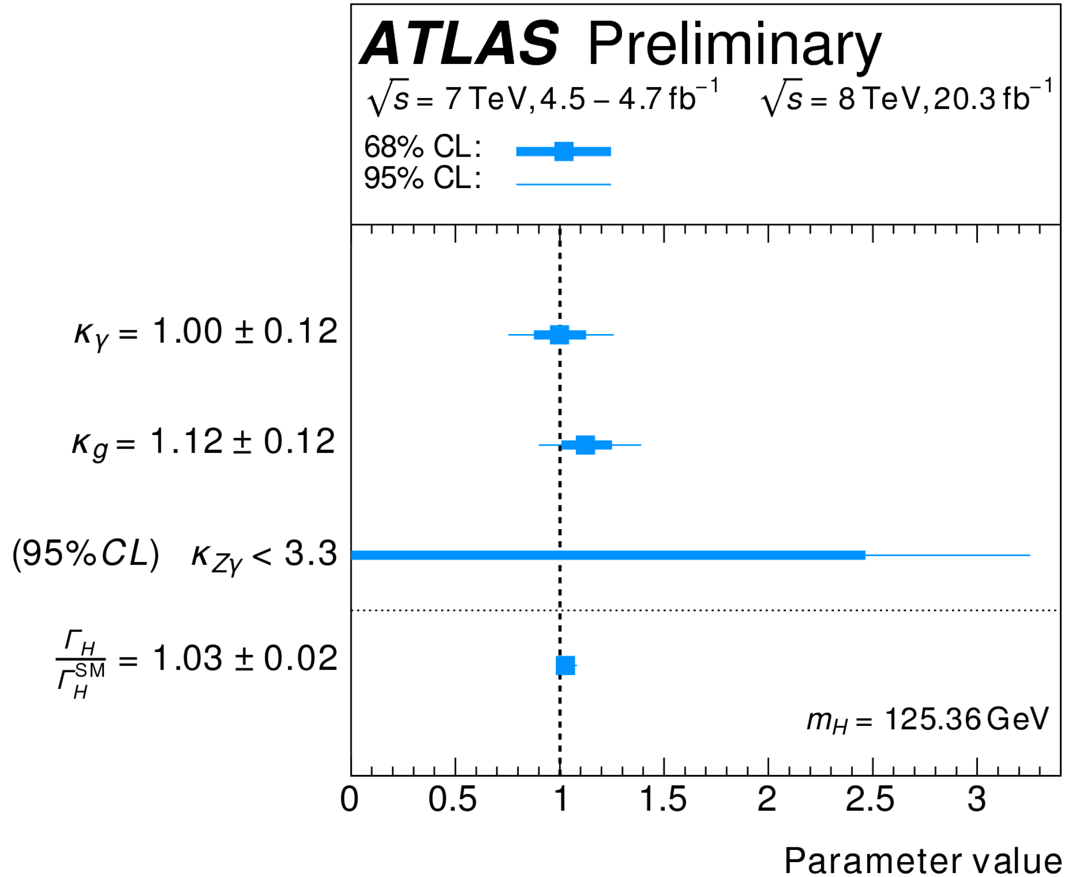
	ATLAS	CMS
BR_{BSM}	< 0.27 (95% CL, BR_{BSM}>0)	< 0.32 (95% CL)

A further take on loops

[ATLAS-CONF-2015-007]

Effective H⟶$\gamma\gamma$, H⟶Zγ, and ggH loops.

- Waiting for more data.



Probing the fermion sector

[arXiv:1307.1347]

2HDM

	u-type	d-type	lepton	
I	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	SM-like
I’	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	
II	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	
II’	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	

Probing up-type and down-type fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_Z = \kappa_W), \lambda_{du} (= \kappa_d/\kappa_u), \kappa_u (= \kappa_t)$.

Probing up-type and down-type fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{uu} (= \kappa_u \cdot \kappa_u/\kappa_H), \lambda_{du} (= \kappa_d/\kappa_u), \lambda_{Vu} (= \kappa_V/\kappa_u)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{Vu}^2$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{Vu}^2$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{du}^2$	$\kappa_{uu}^2\kappa_g^2(\lambda_{du},1)\cdot\lambda_{du}^2$
ttH	$\kappa_{uu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$	$\kappa_{uu}^2\cdot\lambda_{Vu}^2$	$\kappa_{uu}^2\cdot\lambda_{du}^2$	$\kappa_{uu}^2\cdot\lambda_{du}^2$
VBF WH ZH	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\kappa_\gamma^2(\lambda_{du},1,\lambda_{du},\lambda_{Vu})$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{Vu}^2$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{Vu}^2$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{du}^2$	$\kappa_{uu}^2\lambda_{Vu}^2\cdot\lambda_{du}^2$

Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

Free parameters: $\kappa_V (= \kappa_Z = \kappa_W), \lambda_{lq} (= \kappa_l/\kappa_q), \kappa_q (= \kappa_t = \kappa_b)$.

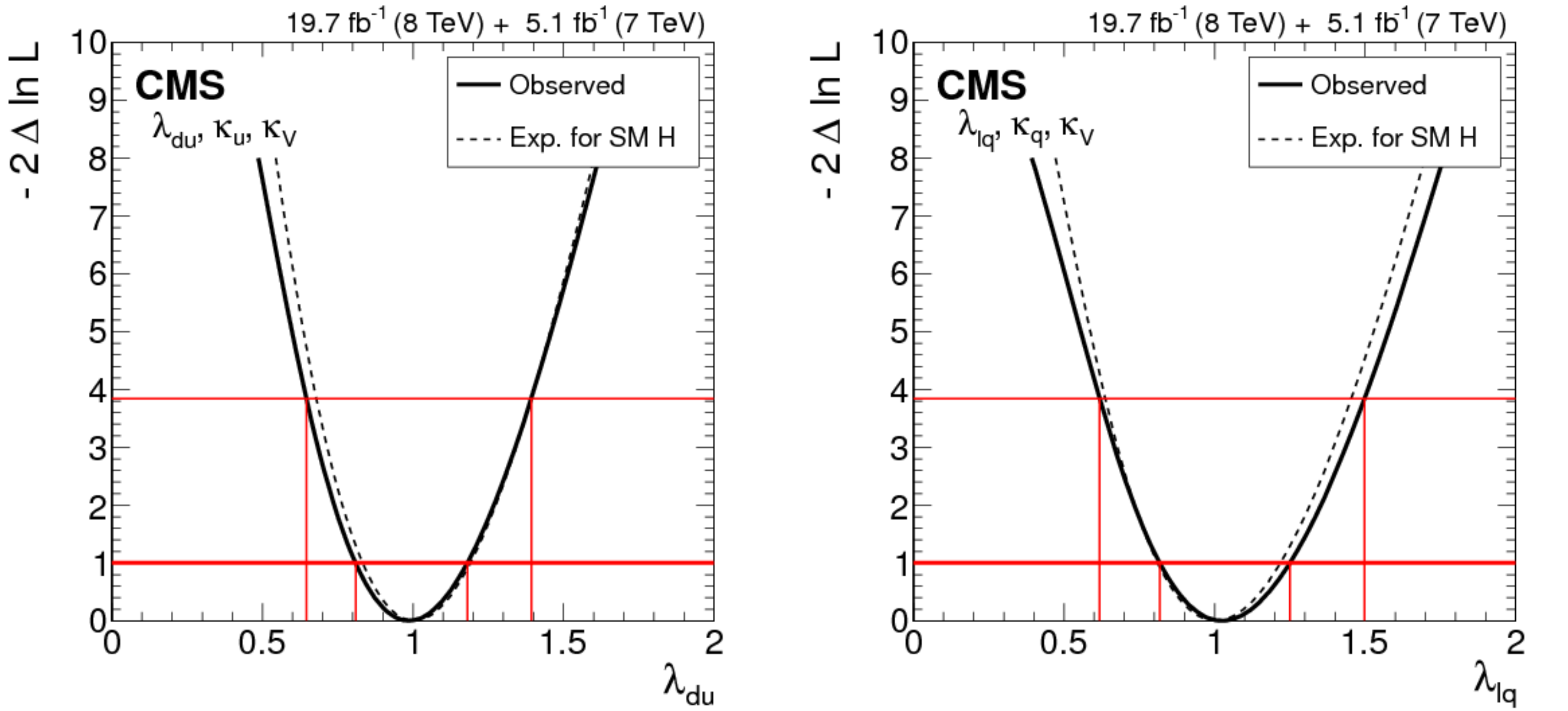
Probing quark and lepton fermion symmetry without assumptions on the total width

Free parameters: $\kappa_{qq} (= \kappa_q \cdot \kappa_q/\kappa_H), \lambda_{lq} (= \kappa_l/\kappa_q), \lambda_{Vq} (= \kappa_V/\kappa_q)$.

	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH ttH	$\kappa_{qq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	κ_{qq}^2	$\kappa_{qq}^2\cdot\lambda_{lq}^2$
VBF WH ZH	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\kappa_\gamma^2(1,1,\lambda_{lq},\lambda_{Vq})$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\cdot\lambda_{Vq}^2$	$\kappa_{qq}^2\lambda_{Vq}^2\cdot\lambda_{lq}^2$

Probing the fermion sector

[arXiv:1412.8662]

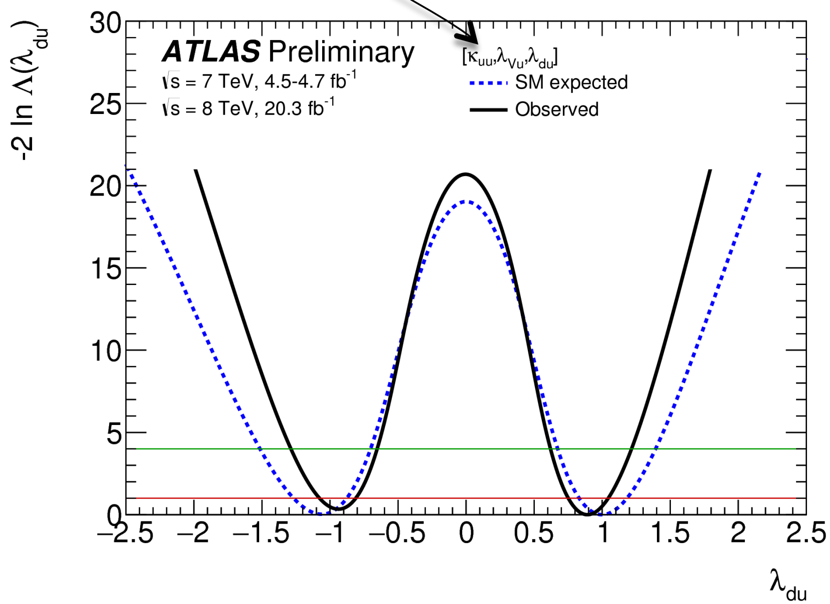


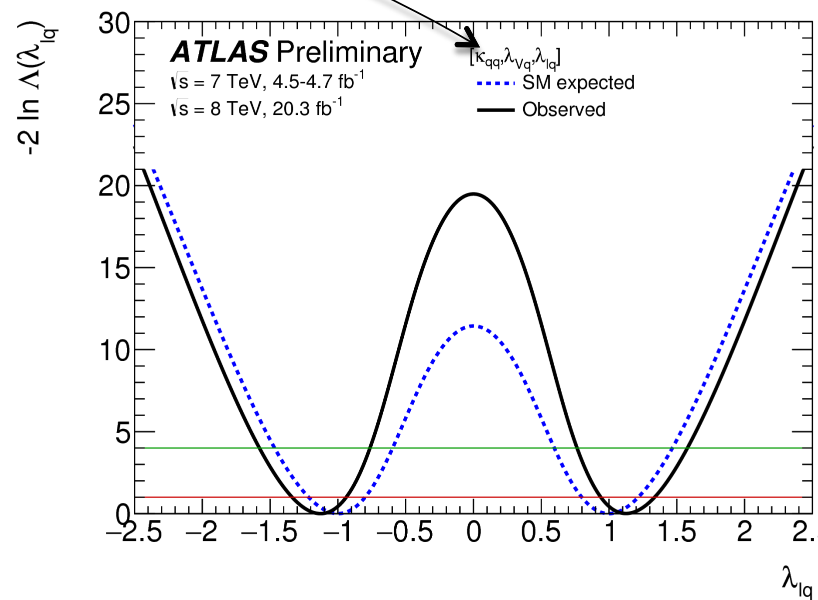
	λ_{du}	λ_{lq}
CMS	$0.99^{+0.19}_{-0.18}$	$1.03^{+0.23}_{-0.21}$

Probing the fermion sector

[ATLAS-CONF-NOTE-2015-007]

Floating total width





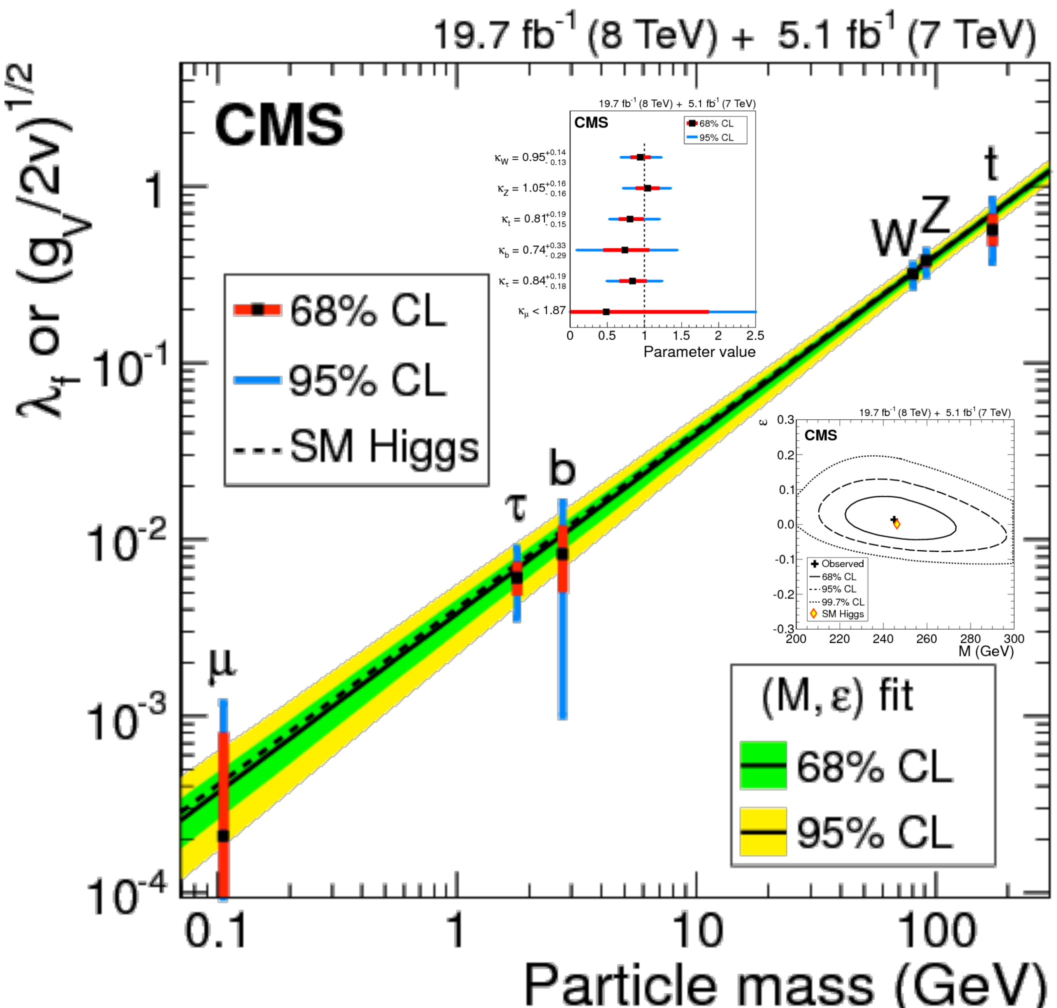
	λ_{du}	λ_{lq}
ATLAS	**[-1.08, -0.81] ∪ [0.75, 1.04] (68% CL)**	**[-1.34, -0.94] ∪ [0.94, 1.34] (68% CL)**

Resolving SM contributions

[arXiv:1412.8662][arxiv:1303.3570]

- Individual coupling scaling factors:
  - κ_W, κ_Z, κ_b, κ_t, κ_τ.
  - All loops resolved:
    - $\kappa_\gamma(\kappa_W, \kappa_t)$
    - $\kappa_g(\kappa_t, \kappa_b)$
  - SMH width scaled.

- "Reduced" couplings as function of "mass":
  - $\lambda_f = \kappa_f\,(m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2}\,(m_V/vev)$

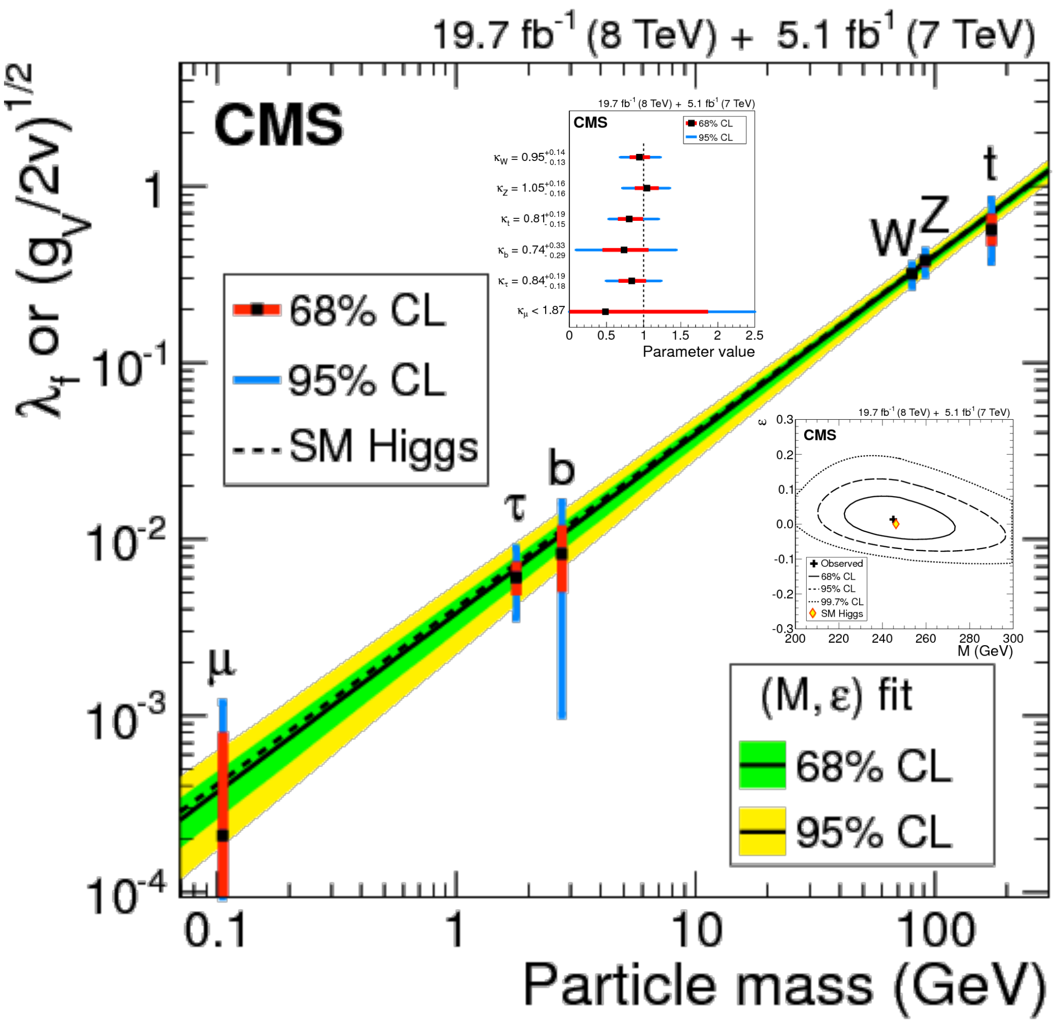


Mass power parametrization

[arXiv:1412.8662][arxiv:1207.1693]

- *Vev* modifier and power of coupling to mass:
  - Gauge bosons: $\kappa_V = vev \times m_V^{2\varepsilon} / M^{1+2\varepsilon}$
  - Fermions: $\kappa_f = vev \times m_f^{\varepsilon} / M^{1+\varepsilon}$

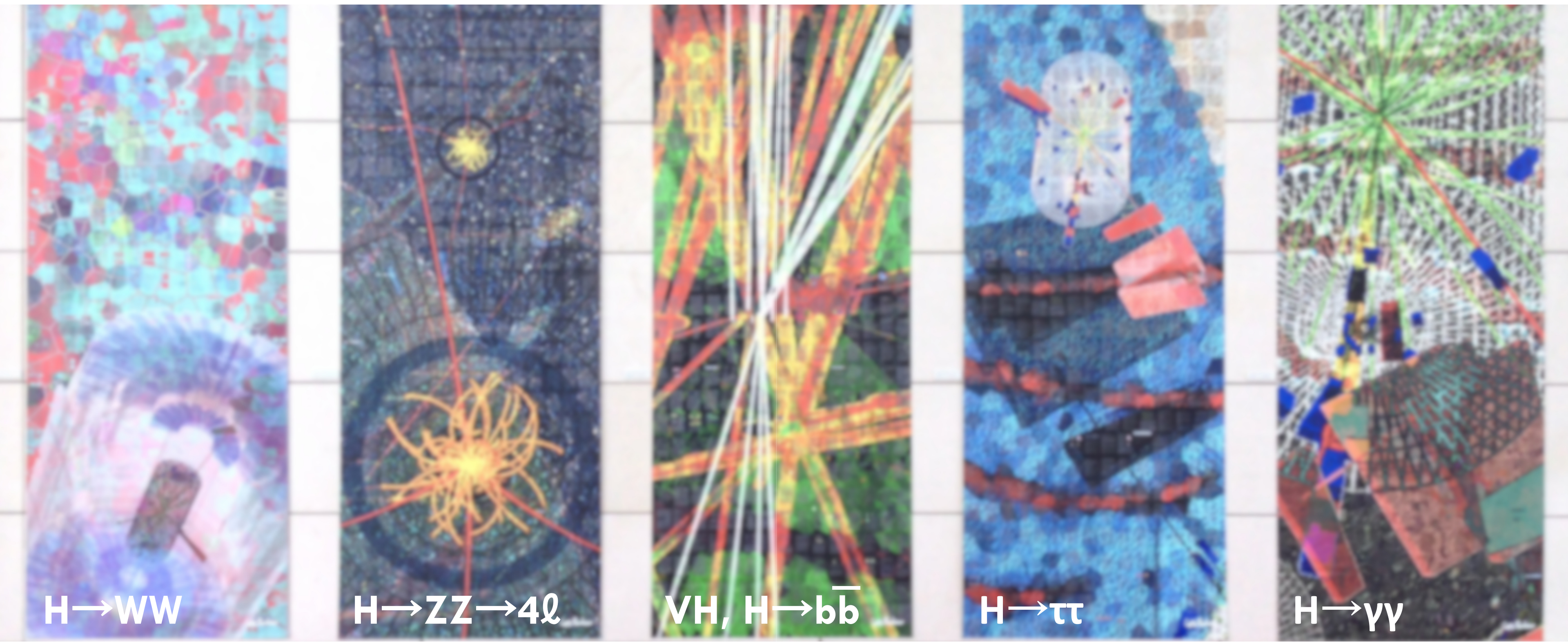
- For SMH, $M = vev = 246.22$ GeV and $\varepsilon = 0$.



More on the CMS combination

Bringing it all together in CMS

[arXiv:1412.8662]



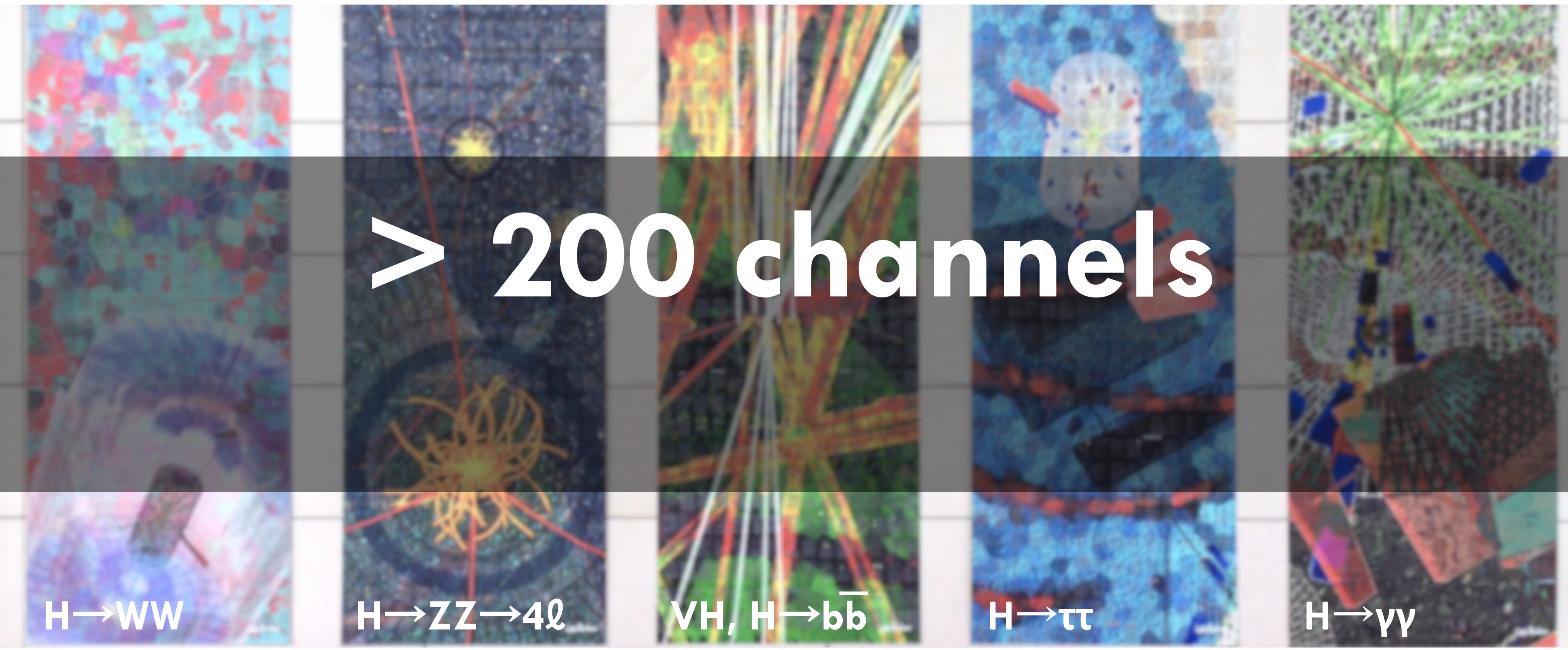
JHEP 01(2014) 096 | PRD 89 (2014) 092007 | PRD 89 (2014) 012003 | JHEP 05 (2014) 104 | EPJC 74 (2014) 3076

Also include further ttH searches:

- JHEP 05(2013)145 – ttH, H→bb̄ (7 TeV).
- arXiv:1408.1682 (subm. to JHEP) – ttH, H→bb̄, H→ττ, and H decaying to multiple leptons (8 TeV).

Bringing it all together in CMS

[arXiv:1412.8662]



JHEP 01(2014) 096 | PRD 89 (2014) 092007 | PRD 89 (2014) 012003 | JHEP 05 (2014) 104 | arXiv:1407.0558 (subm. to EPJC)

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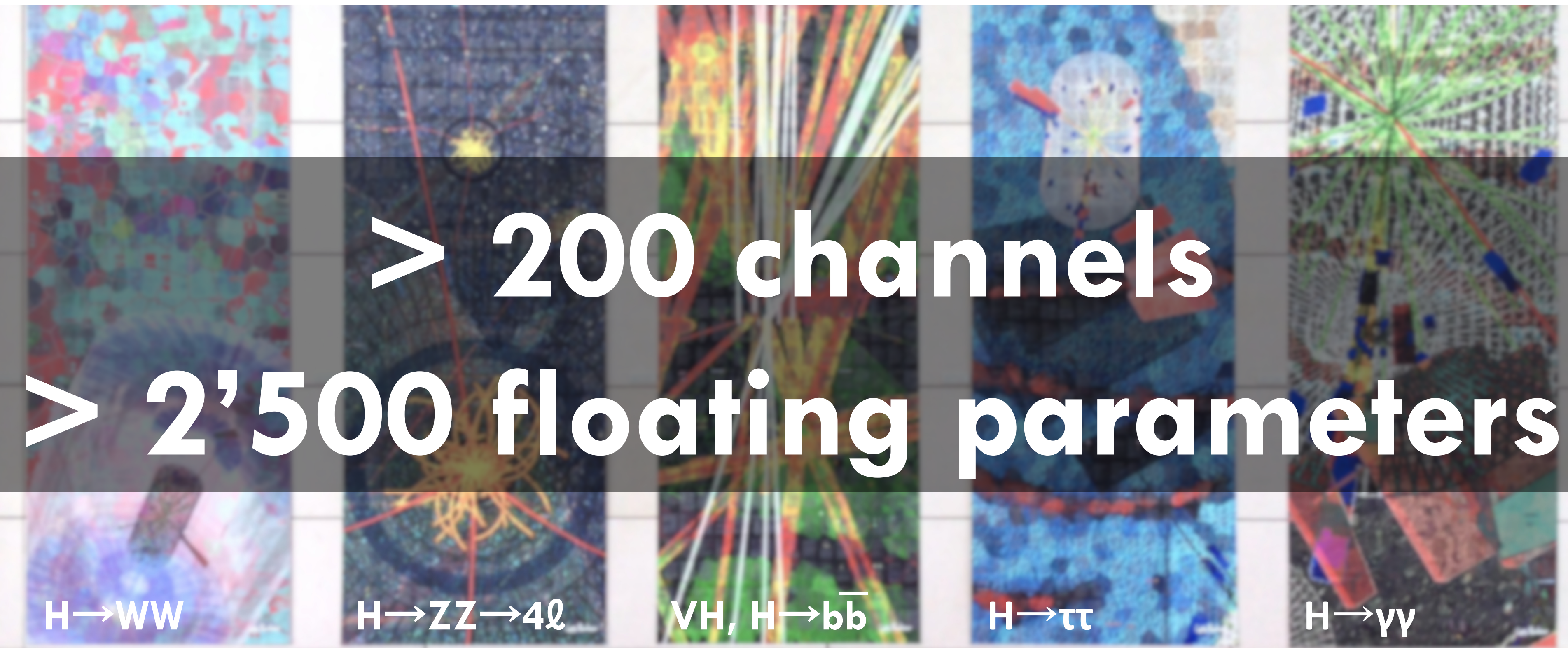
Bringing it all together in CMS

[arXiv:1412.8662]



JHEP 01(2014) 096	**PRD 89 (2014) 092007**	**PRD 89 (2014) 012003**	**JHEP 05 (2014) 104**	**arXiv:1407.0558 (subm. to EPJC)**

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The challenge of combining

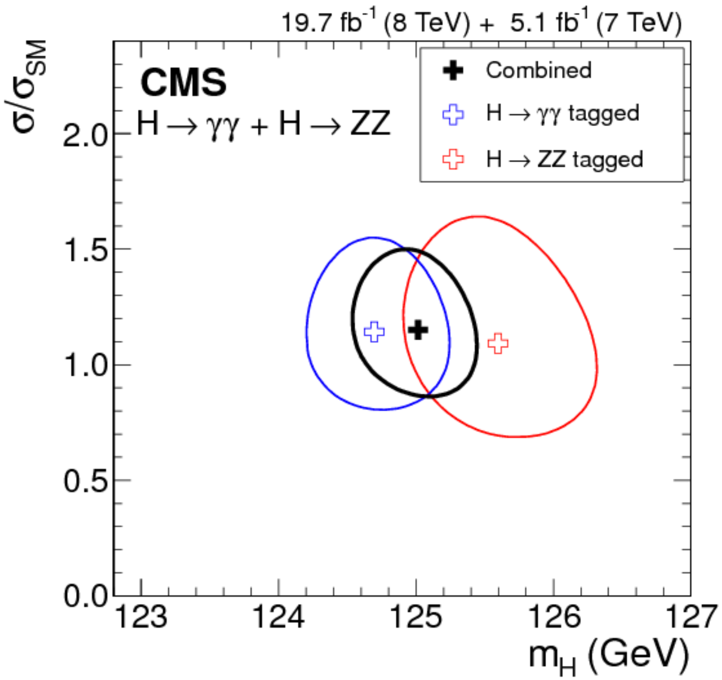
[arXiv:1412.8662]

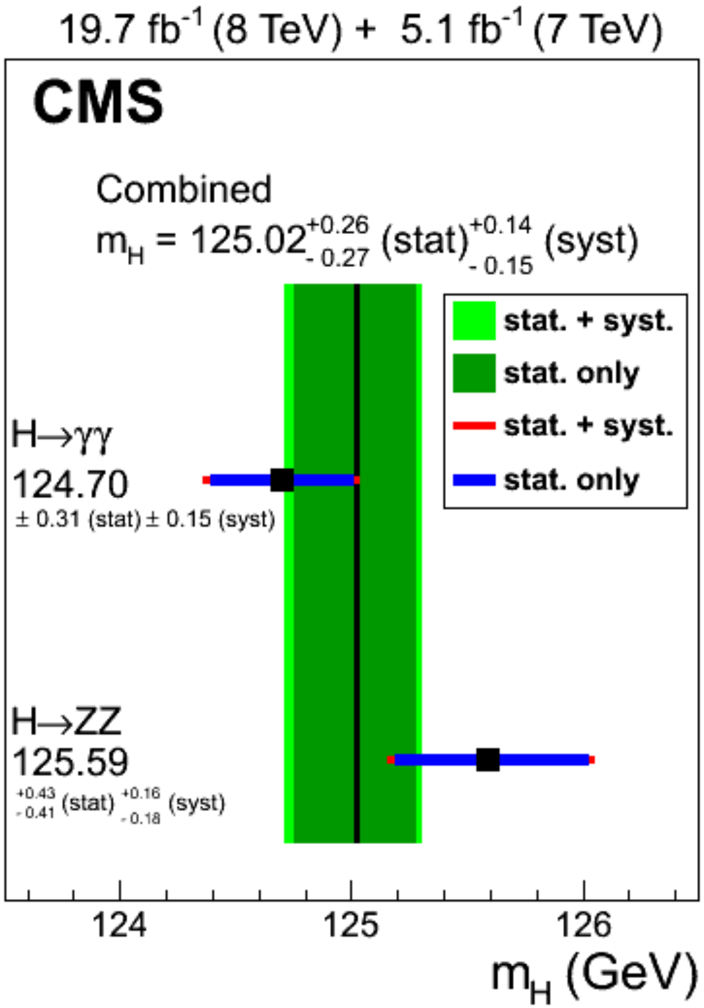
- Include **five main decays** and searches for **ttH production.**
- **207 channels.**
- **2519 parameters.**
  - 219 H→γγ background parameters.

Decay tag and production tag		Expected signal composition	σ_{m_H}/m_H	Luminosity (fb^{-1}) No. of categories 7 TeV	8 TeV
$H \to \gamma\gamma$ [20], Section 2.1				*5.1*	*19.7*
$\gamma\gamma$	Untagged	76–93% ggH	0.8–2.1%	4	5
	2-jet VBF	50–80% VBF	1.0–1.3%	2	3
	Leptonic VH	≈95% VH (WH/ZH ≈ 5)	1.3%	2	2
	E_T^{miss} VH	70–80% VH (WH/ZH ≈ 1)	1.3%	1	1
	2-jet VH	≈65% VH (WH/ZH ≈ 5)	1.0–1.3%	1	1
	Leptonic $t\bar{t}H$	≈95% $t\bar{t}H$	1.1%	$1^{\dagger}$	1
	Multijet $t\bar{t}H$	>90% $t\bar{t}H$	1.1%		1
$H \to ZZ^{(*)} \to 4\ell$ [18], Section 2.2				*5.1*	*19.7*
4μ, $2e2\mu$, $4e$	2-jet	42% VBF + VH	1.3, 1.8, 2.2%‡	3	3
	Other	≈90% ggH		3	3
$H \to WW^{(*)} \to \ell\nu\ell\nu$ [17], Section 2.3				*4.9*	*19.4*
$ee + \mu\mu$, $e\mu$	0-jet	96–98% ggH	$e\mu$: 16%‡	2	2
	1-jet	82–84% ggH	$e\mu$: 17%‡	2	2
	2-jet VBF	78–86% VBF		2	2
	2-jet VH	31–40% VH		2	2
$3\ell 3\nu$ WH	SF-SS, SF-OS	≈100% WH, up to 20% $\tau\tau$		2	2
$\ell\ell + \ell'\nu jj$ ZH	eee, $ee\mu$, $\mu\mu\mu$, $\mu\mu e$	≈100% ZH		4	4
$H \to \tau\tau$ [19], Section 2.4				*4.9*	*19.7*
$e\tau_h$, $\mu\tau_h$	0-jet	≈98% ggH	11–14%	4	4
	1-jet	70–80% ggH	12–16%	5	5
	2-jet VBF	75–83% VBF	13–16%	2	4
$\tau_h\tau_h$	1-jet	67–70% ggH	10–12%	-	2
	2-jet VBF	80% VBF	11%	-	1
$e\mu$	0-jet	≈98% ggH, 23–30% WW	16–20%	2	2
	1-jet	75–80% ggH, 31–38% WW	18–19%	2	2
	2-jet VBF	79–94% VBF, 37–45% WW	14–19%	1	2
ee, $\mu\mu$	0-jet	88–98% ggH		4	4
	1-jet	74–78% ggH, ≈17% WW *		4	4
	2-jet CJV	≈50% VBF, ≈45% ggH, 17–24% WW *		2	2
$\ell\ell + LL'$ ZH	$LL' = \tau_h\tau_h, \ell\tau_h, e\mu$	≈15% (70%) WW for $LL' = \ell\tau_h$ ($e\mu$)		8	8
$\ell + \tau_h\tau_h$ WH		≈96% VH, ZH/WH ≈ 0.1		2	2
$\ell + \ell'\tau_h$ WH		ZH/WH ≈ 5%, 9–11% WW		2	4
VH with $H \to bb$ [16], Section 2.5				*5.1*	*18.9*
$W(\ell\nu)bb$	$p_T(V)$ bins	≈100% VH, 96–98% WH	≈10%	4	6
$W(\tau_h\nu)bb$		93% WH		-	1
$Z(\ell\ell)bb$	$p_T(V)$ bins	≈100% ZH		4	4
$Z(\nu\nu)bb$	$p_T(V)$ bins	≈100% VH, 62–76% ZH		2	3
$t\bar{t}H$ with $H \to$ hadrons [14, 28], Section 2.6				*5.0*	*19.3*
$H \to bb$	$t\bar{t}$ lepton+jets	≈90% bb but ≈24% WW in ≥6j + 2b		7	7
	$t\bar{t}$ dilepton	45–85% bb, 8–35% WW, 4–14% $\tau\tau$		2	3
$H \to \tau_h\tau_h$	$t\bar{t}$ lepton+jets	68–80% $\tau\tau$, 13–22% WW, 5–13% bb		-	6
$t\bar{t}H$ with $H \to$ leptons [29], Section 2.6				-	*19.6*
2ℓ-SS		$WW/\tau\tau \approx 3$		-	6
3ℓ		$WW/\tau\tau \approx 3$		-	2
4ℓ		$WW : \tau\tau : ZZ \approx 3:2:1$		-	1

Combined m_H measurement

[arXiv:1412.8662]

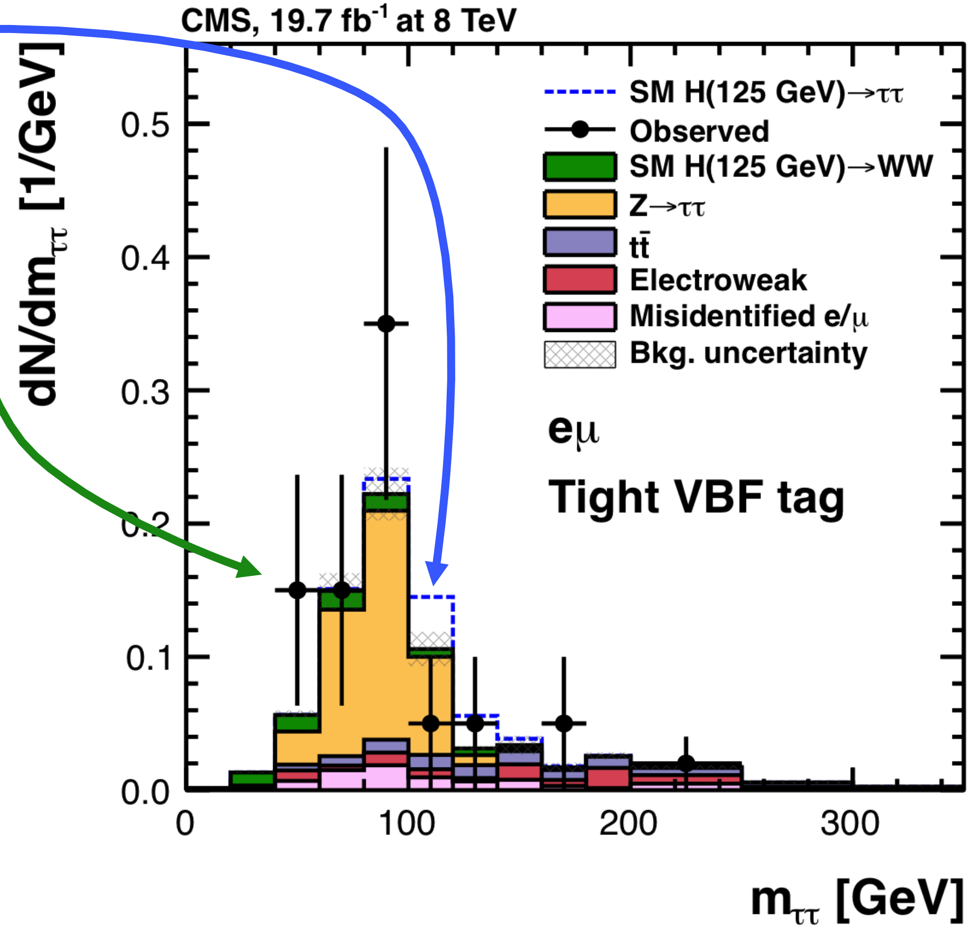




Extra Higgs sensitivity in $H \to \tau\tau$ analysis

[JHEP 05 (2014) 104][arXiv:1412.8662]

- $H \to \tau\tau$ analysis has **sensitivity** to:
  - **$H \to \tau\tau$ decays**, and
  - **$H \to WW$ decays.**
- $H \to WW$ treatment:
  - **In combination: signal.**
    - 3.9σ obs. (3.9σ exp.)
  - **In $H \to \tau\tau$ paper: SM background.**
    - 3.2σ obs. (3.7σ exp.)



H→VV results in combination

[JHEP 01 (2014) 096][PRD 89 (2014) 092007][arXiv:1412.8662]

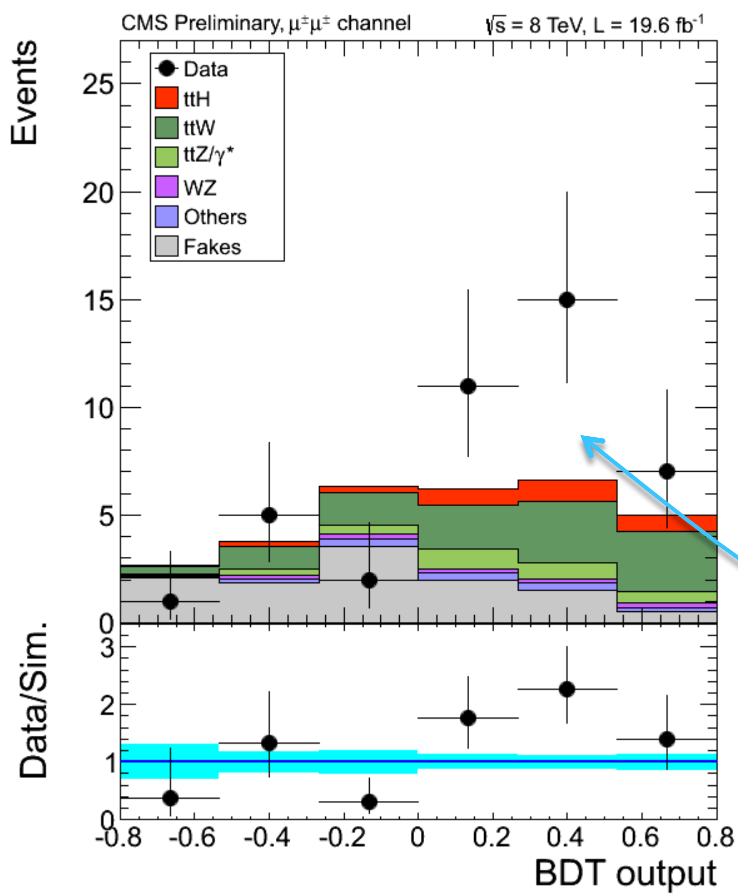
- What changed?
  - **BR(H→VV) changes by 4 – 5%.**
    - H→WW and H→ZZ paper results evaluated at H→ZZ m_H result: **m_H = 125.6 GeV.**
    - Combined mass slightly lower: **m_H = 125.0 GeV.**
  - In the combination **H→WW includes the ttH, H decaying to multi-lepton result:** $\sigma/\sigma_{SM} = 3.7 \pm 1.5$.

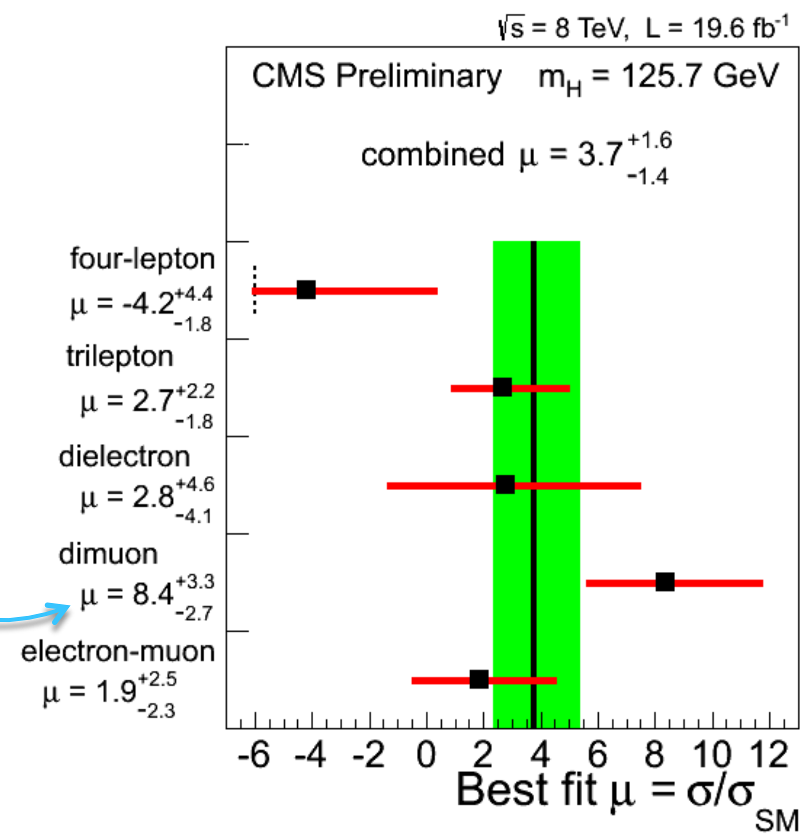
σ/σ_{SM}	Individual publication	Combination
H→ZZ	0.93	1.00
H→WW	0.72	0.83

ttH multi-leptons

[CMS-PAS-HIG-13-020][http://cern.ch/go/FKr9]

- Very extensive cross-checks performed: http://cern.ch/go/Xv8S





Significance of excesses

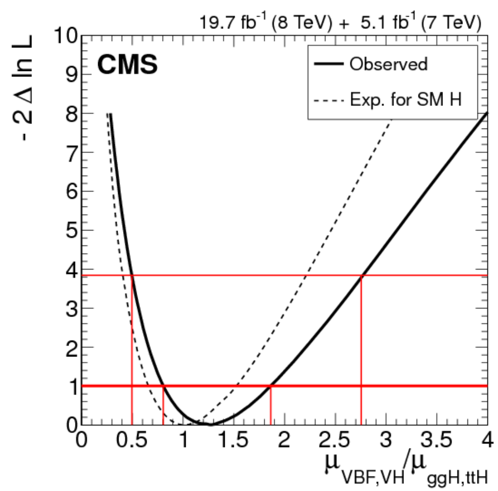
[arXiv:1412.8662]

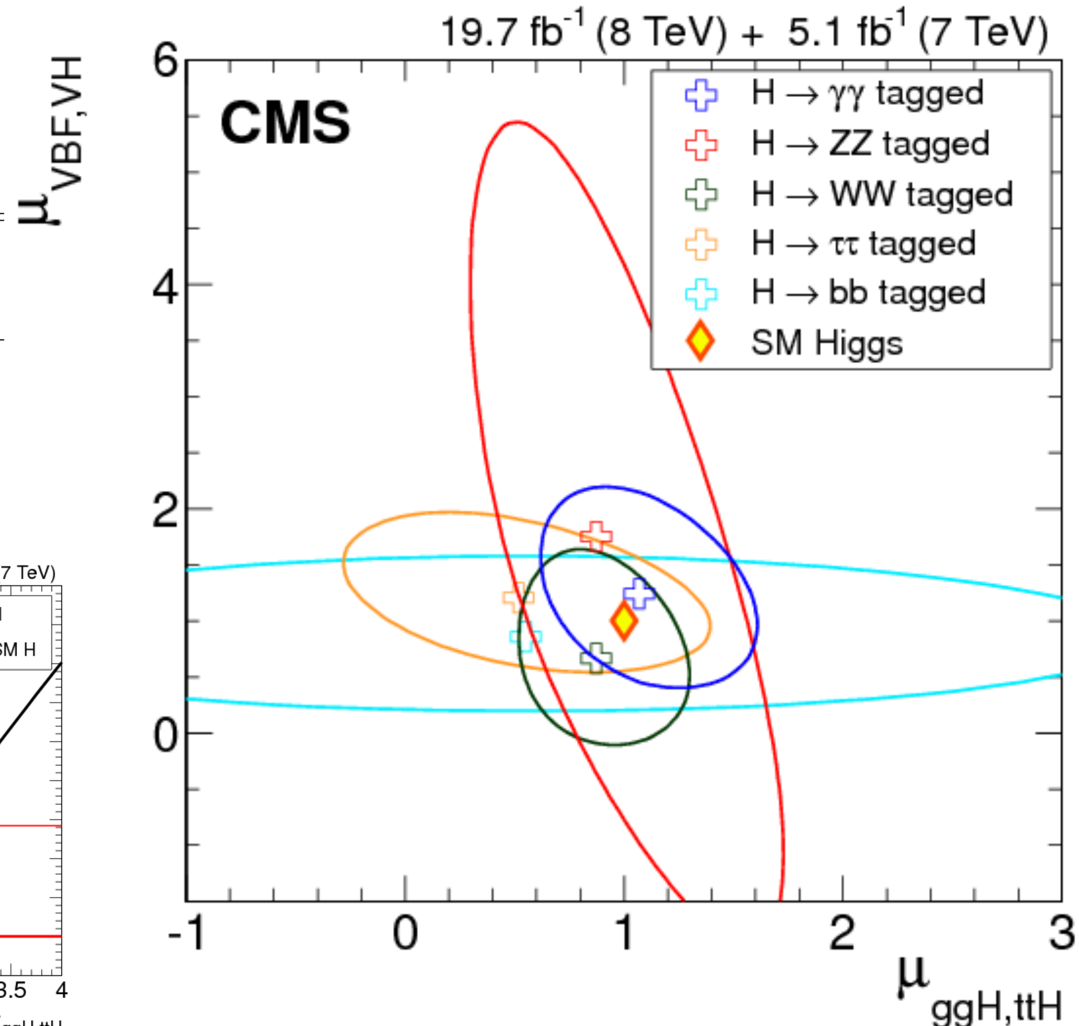
Channel grouping	Significance (σ) Observed	Expected
$H \to ZZ$ tagged	6.5	6.3
$H \to \gamma\gamma$ tagged	5.6	5.3
$H \to WW$ tagged	4.7	5.4
Grouped as in Ref. [22]	*4.3*	*5.4*
$H \to \tau\tau$ tagged	3.8	3.9
Grouped as in Ref. [23]	*3.9*	*3.9*
$H \to bb$ tagged	2.0	2.6
Grouped as in Ref. [21]	*2.1*	*2.5*
$H \to \mu\mu$ tagged	< 0.1	0.4

Combined production measurement

[arXiv:1412.8662]

Channel grouping	Best fit $(\mu_{ggH,ttH}, \mu_{VBF,VH})$
$H \to \gamma\gamma$ tagged	$(1.07, 1.24)$
$H \to ZZ$ tagged	$(0.88, 1.75)$
$H \to WW$ tagged	$(0.87, 0.66)$
$H \to \tau\tau$ tagged	$(0.52, 1.21)$
$H \to bb$ tagged	$(0.55, 0.85)$
Combined best fit $\mu_{VBF,VH}/\mu_{ggH,ttH}$	Observed (expected)
	$1.25^{+0.62}_{-0.44}$ $(1.00^{+0.49}_{-0.35})$



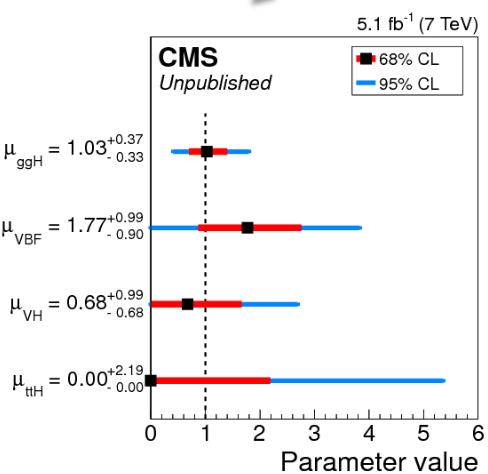


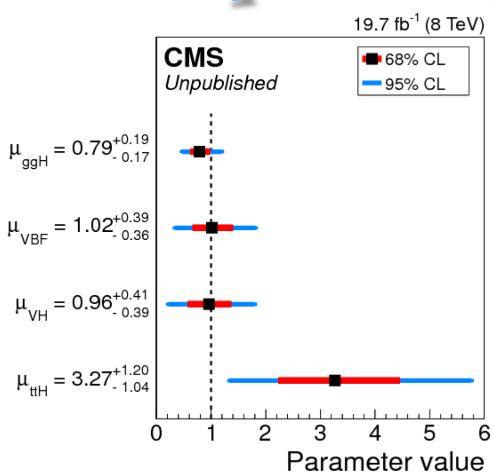
Production mode scaling assuming SM BR structure

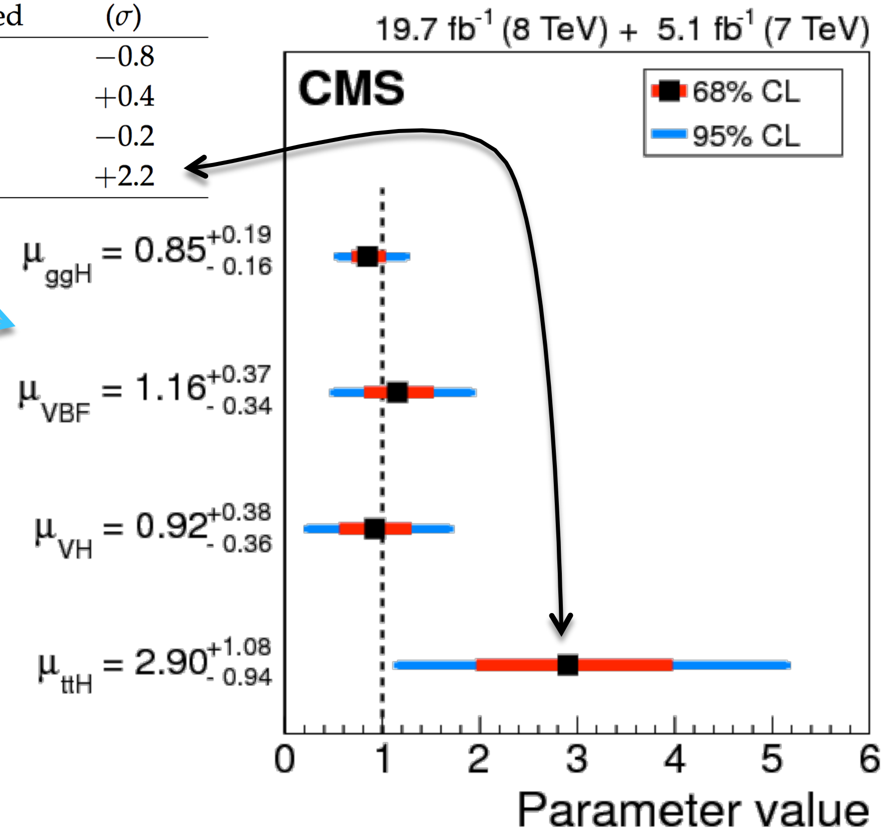
[arXiv:1412.8662]

- $\mu_{ggH} = 0.85\,^{+0.11}_{-0.09}\,(\text{stat.})\,^{+0.11}_{-0.08}\,(\text{theo.})\,^{+0.10}_{-0.09}\,(\text{syst.})$

Parameter	Best-fit result (68% CL)			Significance (σ)		Pull to SM
	7 TeV	8 TeV	Combined	Observed	Expected	(σ)
μ_{ggH}	$1.03^{+0.37}_{-0.33}$	$0.79^{+0.19}_{-0.17}$	$0.85^{+0.19}_{-0.16}$	6.6	7.4	-0.8
μ_{VBF}	$1.77^{+0.99}_{-0.90}$	$1.02^{+0.39}_{-0.36}$	$1.16^{+0.37}_{-0.34}$	3.7	3.3	$+0.4$
μ_{VH}	$0.68^{+0.99}_{-0.68}$	$0.96^{+0.41}_{-0.39}$	$0.92^{+0.38}_{-0.36}$	2.7	2.9	-0.2
μ_{ttH}	< 2.19	$3.27^{+1.20}_{-1.04}$	$2.90^{+1.08}_{-0.94}$	3.5	1.2	$+2.2$



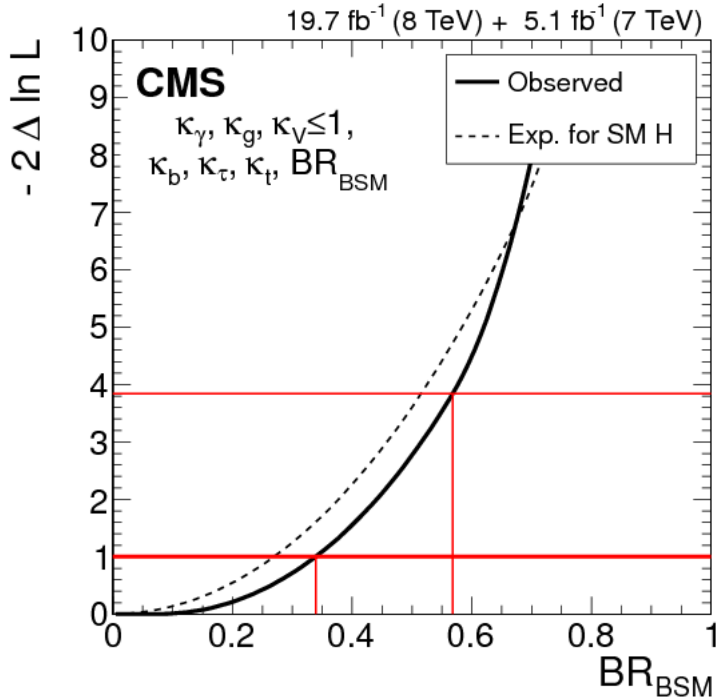


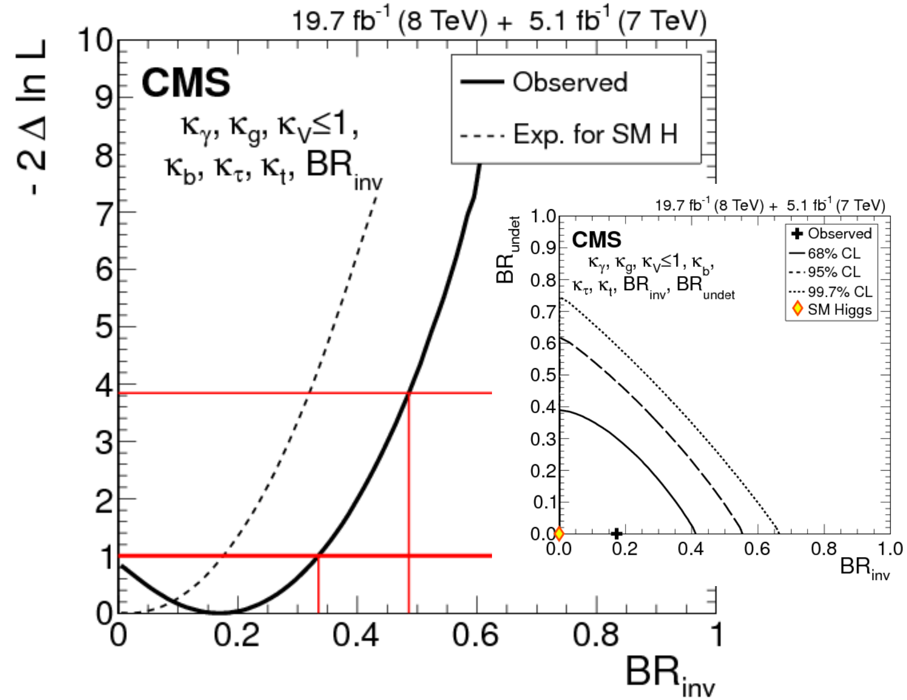


Coupling deviations summaries

[arXiv:1412.8662][arXiv:1307.1347]

- Visible searches can constrain $BR_{BSM}=BR_{inv}+Br_{undet}$.
- Combine with H(inv) searches, assuming $BR_{undet}=0$.
  - Can then scan BR_{inv} vs. BR_{undet}.





Coupling deviations

[arXiv:1412.8662][arXiv:1307.1347]

Model parameters	Table in Ref. [169]	Parameter	Best-fit result 68% CL	Best-fit result 95% CL	Comment
κ_Z, λ_{WZ} (κ_f =1)	—	λ_{WZ}	$0.94^{+0.22}_{-0.18}$	$[0.61, 1.45]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from ZZ and 0/1-jet WW channels.
$\kappa_Z, \lambda_{WZ}, \kappa_f$	44 (top)	λ_{WZ}	$0.92^{+0.14}_{-0.12}$	$[0.71, 1.24]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$ from full combination.
κ_V, κ_f	43 (top)	κ_V	$1.01^{+0.07}_{-0.07}$	$[0.87, 1.14]$	κ_V scales couplings to W and Z bosons.
		κ_f	$0.87^{+0.14}_{-0.13}$	$[0.63, 1.15]$	κ_f scales couplings to all fermions.
$\kappa_V, \lambda_{du}, \kappa_u$	46 (top)	λ_{du}	$0.99^{+0.19}_{-0.18}$	$[0.65, 1.39]$	$\lambda_{du} = \kappa_u/\kappa_d$, relates up-type and down-type fermions.
$\kappa_V, \lambda_{\ell q}, \kappa_q$	47 (top)	$\lambda_{\ell q}$	$1.03^{+0.23}_{-0.21}$	$[0.62, 1.50]$	$\lambda_{\ell q} = \kappa_\ell/\kappa_q$, relates leptons and quarks.
$\kappa_W, \kappa_Z, \kappa_t,$	Extends 51	κ_W	$0.95^{+0.14}_{-0.13}$	$[0.68, 1.23]$	
		κ_Z	$1.05^{+0.16}_{-0.16}$	$[0.72, 1.35]$	
		κ_t	$0.81^{+0.19}_{-0.15}$	$[0.53, 1.20]$	Up-type quarks (via t).
$\kappa_b, \kappa_\tau, \kappa_\mu$		κ_b	$0.74^{+0.33}_{-0.29}$	$[0.09, 1.44]$	Down-type quarks (via b).
		κ_τ	$0.84^{+0.19}_{-0.18}$	$[0.50, 1.24]$	Electron and tau lepton (via τ).
		κ_μ	$0.49^{+1.38}_{-0.49}$	$[0.00, 2.77]$	κ_μ scales the coupling to muons.
M, ϵ	Ref. [202]	M (GeV)	245 ± 15	$[217, 279]$	$\kappa_f = v\frac{m_f^\epsilon}{M^{1+\epsilon}}$ and $\kappa_V = v\frac{m_V^{2\epsilon}}{M^{1+2\epsilon}}$
		ϵ	$0.014^{+0.041}_{-0.036}$	$[-0.054, 0.100]$	(Section 7.4)
κ_g, κ_γ	48 (top)	κ_g	$0.89^{+0.11}_{-0.10}$	$[0.69, 1.11]$	Effective couplings to
		κ_γ	$1.14^{+0.12}_{-0.13}$	$[0.89, 1.40]$	gluons (g) and photons (γ).
κ_g, κ_γ, BR_{BSM}	48 (middle)	BR_{BSM}	≤ 0.14	$[0.00, 0.32]$	Allows for BSM decays.
with H(inv) searches	—	BR_{inv}	$0.03^{+0.15}_{-0.03}$	$[0.00, 0.32]$	H(inv) use implies BR_{undet} =0.
with H(inv) and $\kappa_i = 1$	—	BR_{inv}	$0.06^{+0.11}_{-0.06}$	$[0.00, 0.27]$	Assumes $\kappa_i = 1$ and uses H(inv).
κ_{gZ},	50 (bottom)	κ_{gZ}	$0.98^{+0.14}_{-0.13}$	$[0.73, 1.27]$	$\kappa_{gZ} = \kappa_g\kappa_Z/\kappa_H$, i.e. floating κ_H.
		λ_{WZ}	$0.87^{+0.15}_{-0.13}$	$[0.63, 1.19]$	$\lambda_{WZ} = \kappa_W/\kappa_Z$.
		λ_{Zg}	$1.39^{+0.36}_{-0.28}$	$[0.87, 2.18]$	$\lambda_{Zg} = \kappa_Z/\kappa_g$.
$\lambda_{WZ}, \lambda_{Zg}, \lambda_{bZ},$		λ_{bZ}	$0.59^{+0.22}_{-0.23}$	≤ 1.07	$\lambda_{bZ} = \kappa_b/\kappa_Z$.
		$\lambda_{\gamma Z}$	$0.93^{+0.17}_{-0.14}$	$[0.67, 1.31]$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$.
$\lambda_{\gamma Z}, \lambda_{\tau Z}, \lambda_{tg}$		$\lambda_{\tau Z}$	$0.79^{+0.19}_{-0.17}$	$[0.47, 1.20]$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$.
		λ_{tg}	$2.18^{+0.54}_{-0.46}$	$[1.30, 3.35]$	$\lambda_{tg} = \kappa_t/\kappa_g$.
$\kappa_V, \kappa_b, \kappa_\tau,$	Similar to 50 (top)	κ_V	$0.96^{+0.14}_{-0.15}$	$[0.66, 1.23]$	
		κ_b	$0.64^{+0.28}_{-0.29}$	$[0.00, 1.23]$	Down-type quarks (via b).
		κ_τ	$0.82^{+0.18}_{-0.18}$	$[0.48, 1.20]$	Charged leptons (via τ).
$\kappa_t, \kappa_g, \kappa_\gamma$		κ_t	$1.60^{+0.34}_{-0.32}$	$[0.97, 2.28]$	Up-type quarks (via t).
		κ_g	$0.75^{+0.15}_{-0.13}$	$[0.52, 1.07]$	
		κ_γ	$0.98^{+0.17}_{-0.16}$	$[0.67, 1.33]$	
with $\kappa_V \leq 1$ and BR_{BSM}	—	BR_{BSM}	≤ 0.34	$[0.00, 0.57]$	Allows for BSM decays.
with $\kappa_V \leq 1$ and H(inv)	—	BR_{inv}	0.17 ± 0.17	$[0.00, 0.49]$	H(inv) use implies $BR_{undet} = 0$.
with $\kappa_V \leq 1$, H(inv),	—	BR_{inv}	0.17 ± 0.17	$[0.00, 0.49]$	Separates BR_{inv} from BR_{undet},
BR_{inv}, and BR_{undet}	—	BR_{undet}	≤ 0.23	$[0.00, 0.52]$	$BR_{BSM} = BR_{inv} + BR_{undet}$.

Spin zero amplitude in H→VV

[arXiv:1411.3441]

- Parameterization in terms of cross-section fractions:

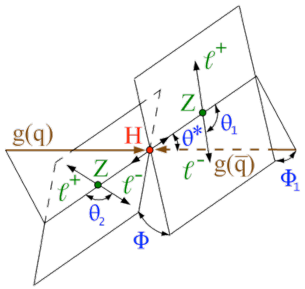
$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

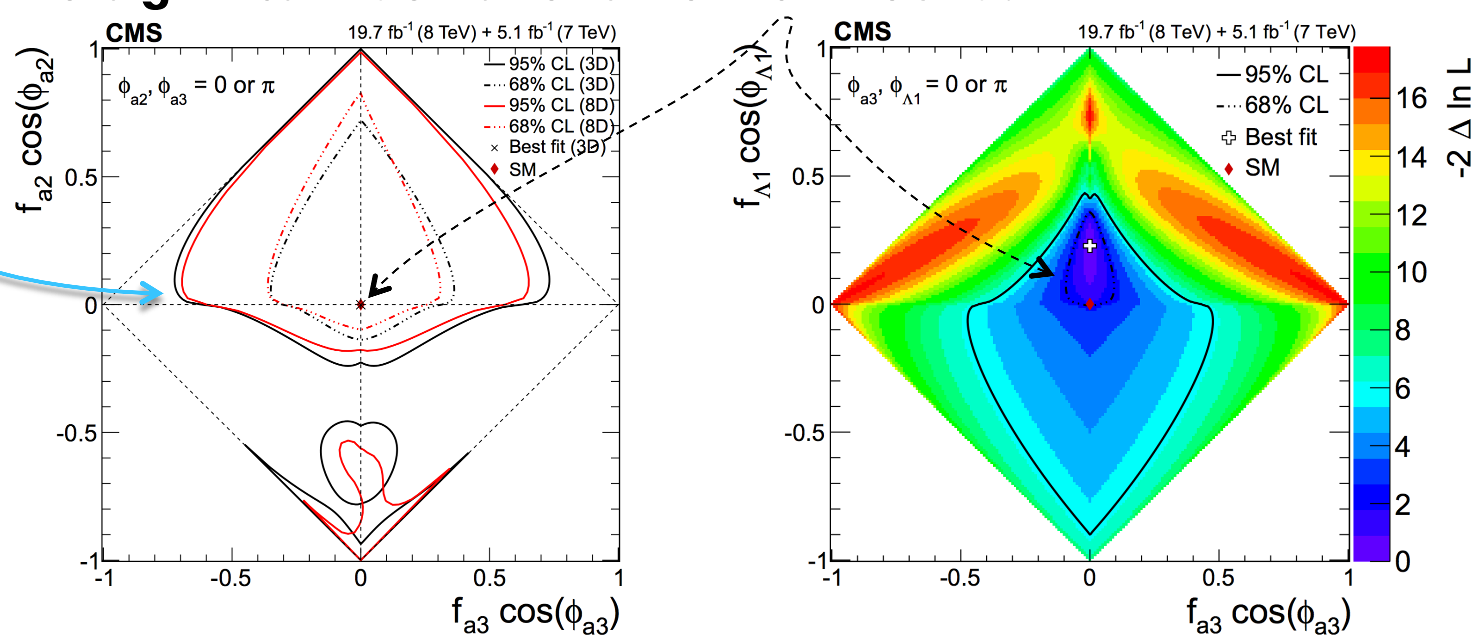
$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1} / (\Lambda_1)^4} \qquad \phi_{\Lambda 1},$$

Spin zero amplitude in H→ZZ→4ℓ

[arXiv:1411.3441]



- Full final state available:
  - **Kinematic discriminants** reducing to 2D or 3D.
  - **8D likelihood** fit.
- 2D scans of anomalous coupling fractions (real phases).
  - But also done profiling over the phases.
- **No significant deviations from SM found.**



Spin zero amplitude in H→VV

[arXiv:1411.3441]

- Anomalous couplings formalism:
  - a_1 is the SM amplitude.
  - Λ_1 is a higher-term of an expansion in momentum.
  - a_2 and a_3 control the CP-even and CP-odd amplitudes.
- Parameterized using fractions of cross-sections: f_{a1}, f_{a2}, f_{a3}, $f_{\Lambda 1}$.

$$\begin{aligned} A(X_{J=0} \to V_1 V_2) \sim\ & v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\ & + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\ & + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\ & \left. + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right) \end{aligned}$$

Spin zero amplitude in H→VV

[arXiv:1411.3441]

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$$
\begin{aligned}
A(X_{J=0} \to V_1 V_2) \sim\ & v^{-1} \left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon_{Z_1}^* \epsilon_{Z_2}^* \right. \\
& + a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu} \\
& + a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu} \\
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\end{aligned}
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$$
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& + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu} \\
& + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} \\
& + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \Bigg)
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$$

Spin zero amplitude in H→VV

[arXiv:1411.3441]

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$$+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu}$$
$$+ a_2^{Z\gamma} f_{\mu\nu}^{*(Z)} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f_{\mu\nu}^{*(Z)} \tilde{f}^{*(\gamma),\mu\nu}$$
$$\left. + a_2^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f_{\mu\nu}^{*(\gamma_1)} \tilde{f}^{*(\gamma_2),\mu\nu} \right)$$

a_2 terms
CP-even (scalar)

Spin zero amplitude in H→VV

[arXiv:1411.3441]

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  - **Λ_1 is a higher-term of an expansion in momentum.**
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$$+ a_2 f_{\mu\nu}^{*(Z_1)} f^{*(Z_2),\mu\nu} + a_3 f_{\mu\nu}^{*(Z_1)} \tilde{f}^{*(Z_2),\mu\nu}$$
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a_2 terms
CP-even (scalar)

a_3 terms
CP-odd
(pseudoscalar)

Spin zero amplitude in H→VV

[arXiv:1411.3441]

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  - **Λ_1 is a higher-term of an expansion in momentum.**
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$$A(X_{J=0} \to V_1 V_2) \sim v^{-1} \Bigg(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q_{Z_1}^2 + q_{Z_2}^2}{(\Lambda_1)^2} \right] m_Z^2 \epsilon^*_{Z_1} \epsilon^*_{Z_2}$$

ZZ, WW
$$+ a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu}$$

Zγ*
$$+ a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu}$$

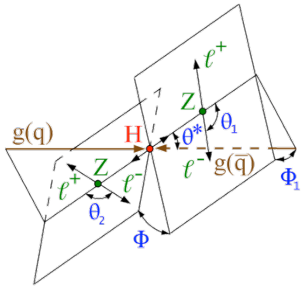
γ*γ*
$$+ a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu} \Bigg)$$

a_2 terms
CP-even (scalar)

a_3 terms
CP-odd
(pseudoscalar)

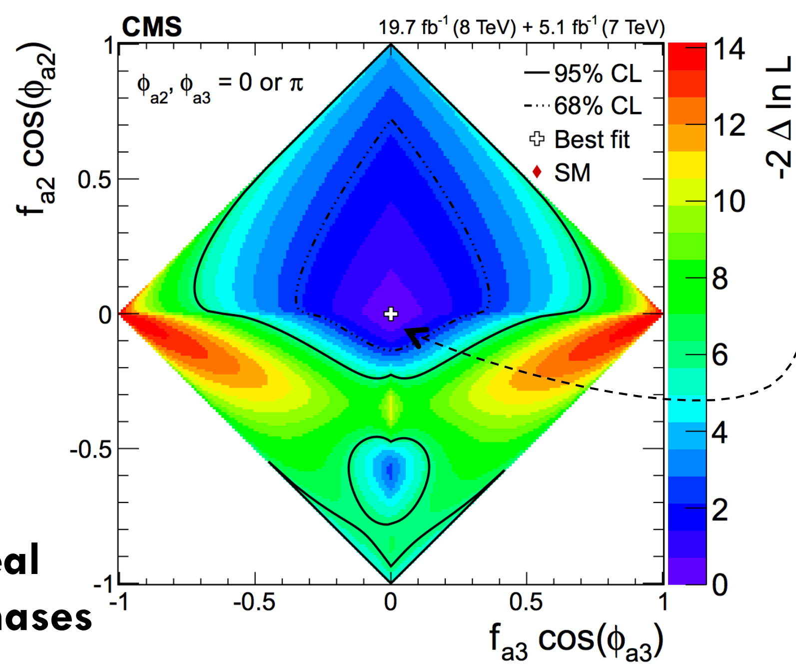
Spin zero amplitude in H→ZZ→4ℓ

[arXiv:1411.3441]

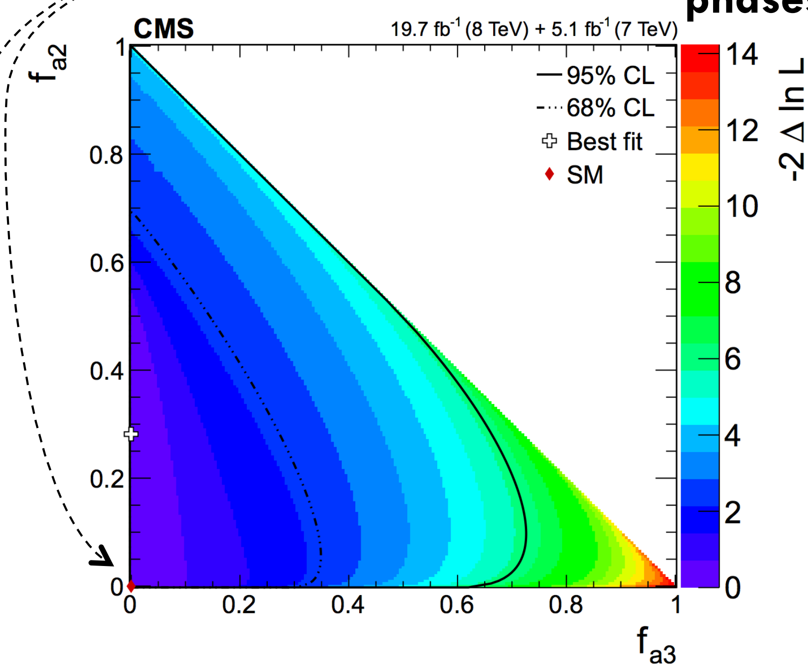


- Full final state available:
  - **Kinematic discriminants** reduce 8D to 2D or 3D.
- 2D scans of anomalous coupling fractions.
  - Assuming real phases and floating the phases.
- **No significant deviations from SM found.**

Floating phases



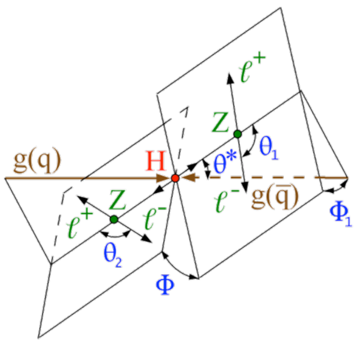
Real phases

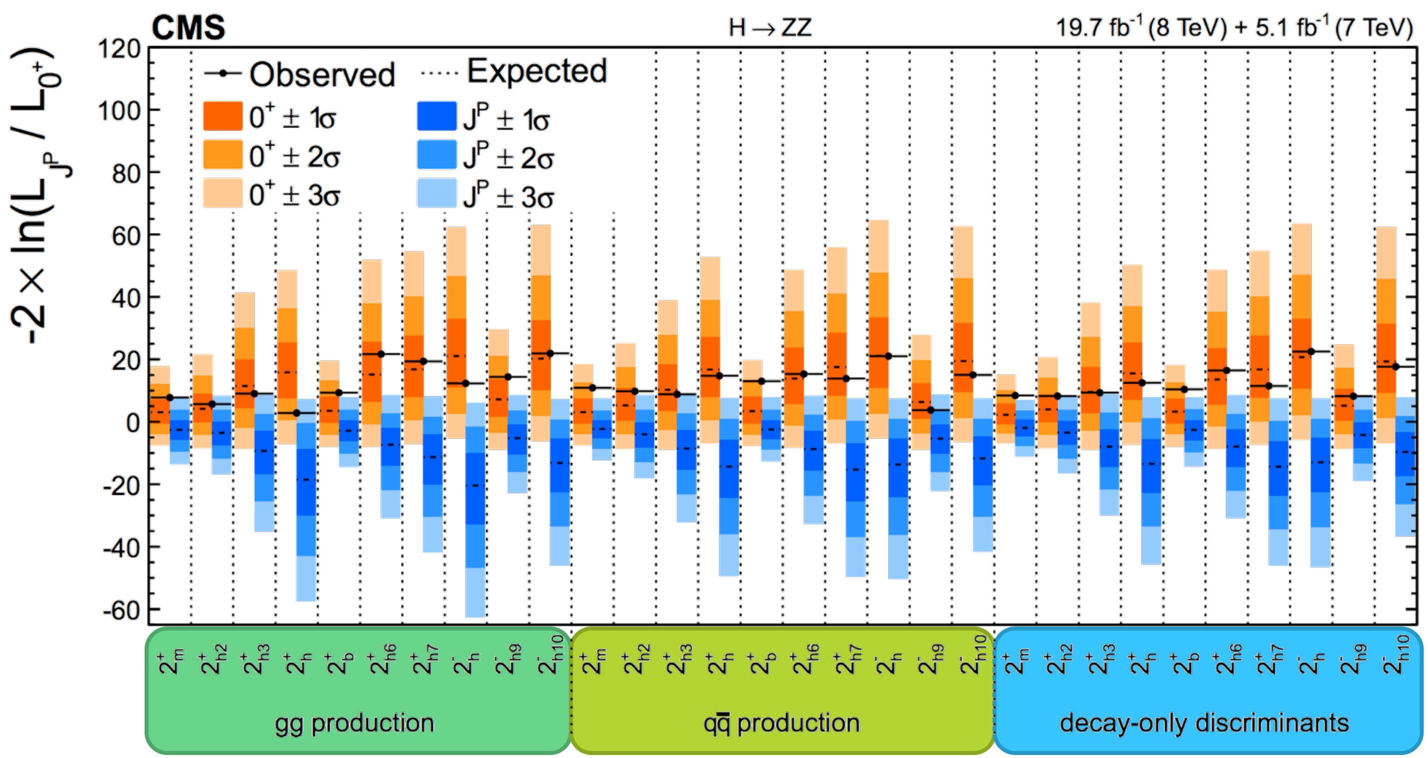


H→ZZ→4ℓ – J=2 states

[arXiv:1411.3441]

- Broad range of hypothesis tests based on the observables optimized for each case.

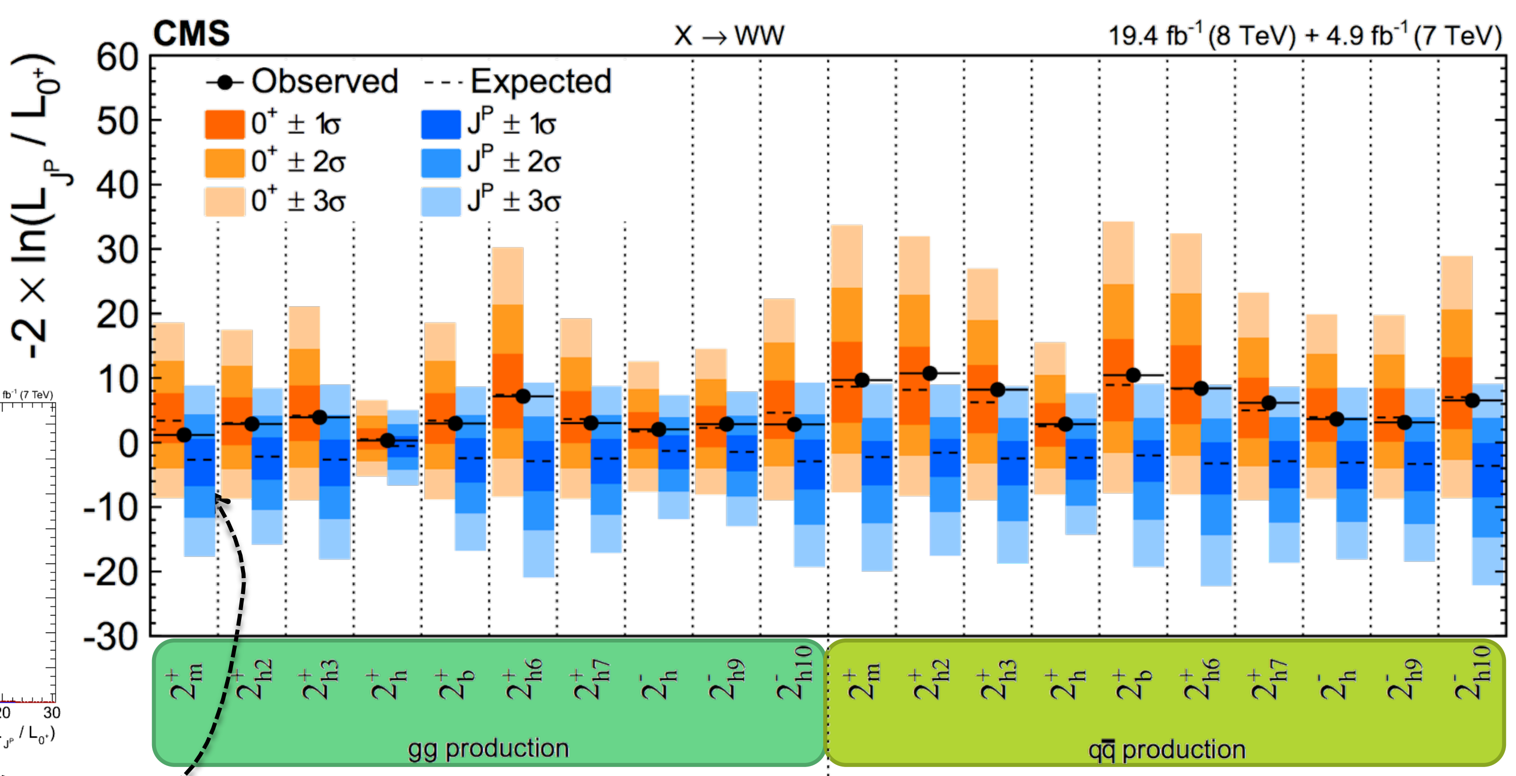


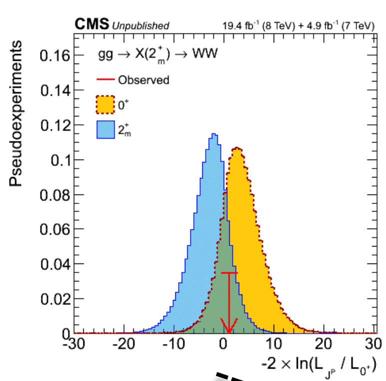


H→WW→2ℓ2ν – J>0 states

[CMS-PAS-HIG-14-012]

- Broad range of hypothesis tests based on the observables used for the SM measurements.

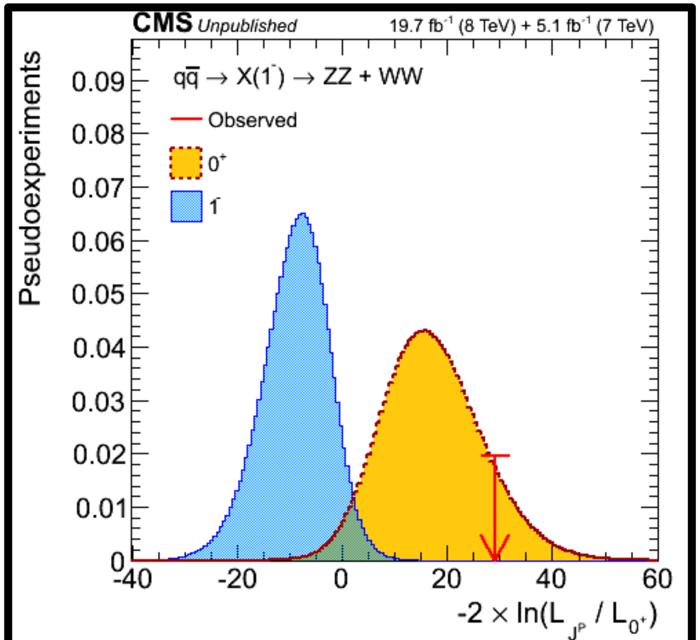




H→VV combination on J>0 states

[CMS-PAS-HIG-14-012][arXiv:1411.3441]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
-

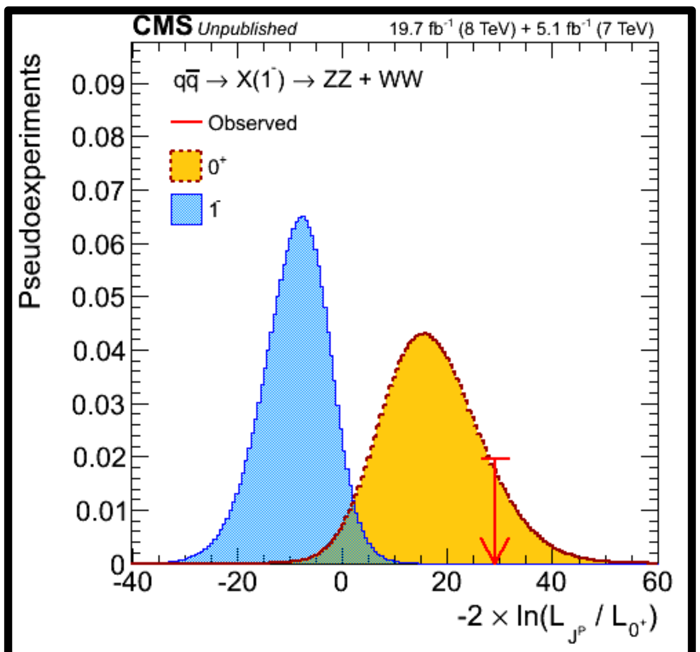


Hypothesis test for 0^+ vs. 1^-

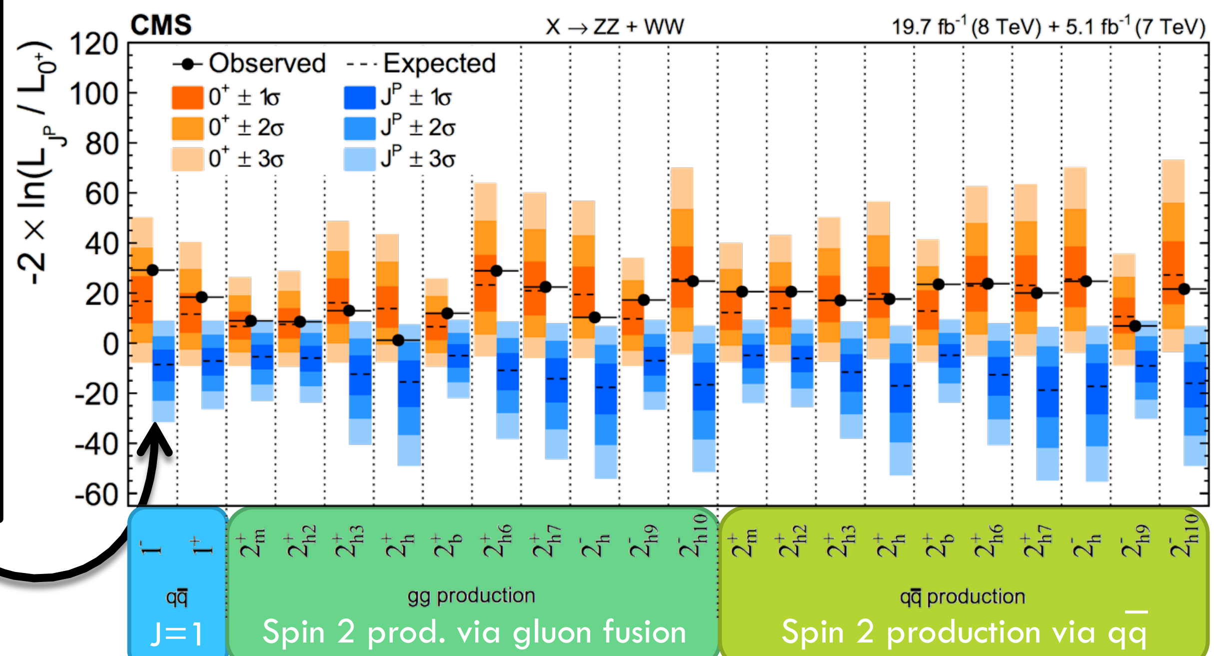
H→VV combination on J>0 states

[CMS-PAS-HIG-14-012][arXiv:1411.3441]

- Combination of H→WW→2ℓ2ν and H→ZZ→4ℓ.
- All tested hypotheses excluded at more than 99.9% CL_S.



Hypothesis test for 0^+ vs. 1^-



Direct searches

Other models?

[http://cern.ch/go/r8kv]

Fiat Turbina

Other models?

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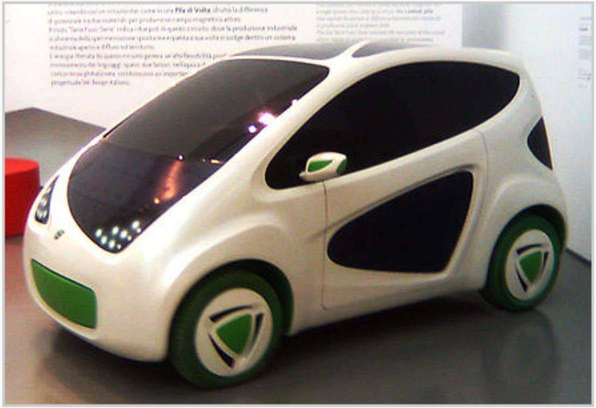
Fiat Turbina

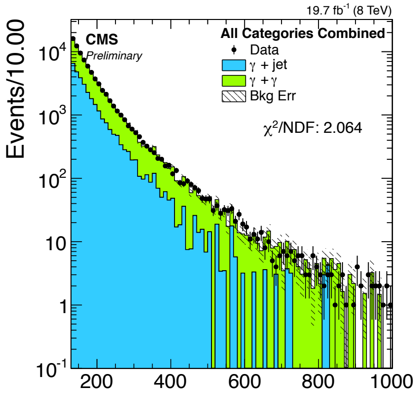


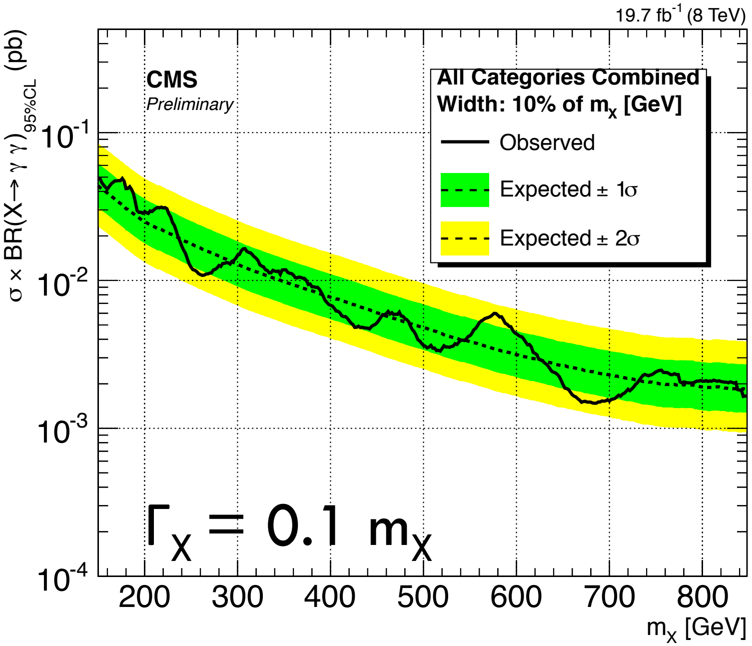
Fiat Phylla at Triennale Design Museum (Milan), 2009.

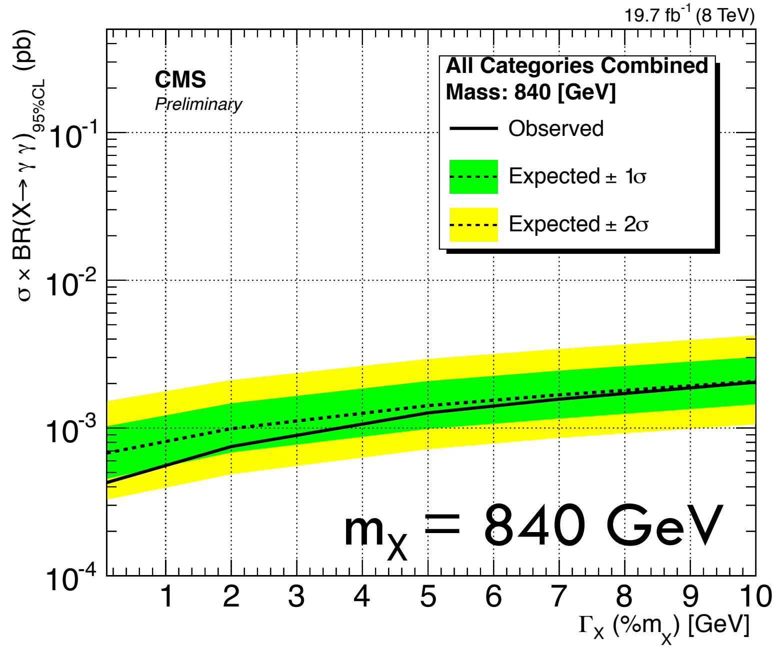
High-mass diphoton searches

[CMS-PAS-HIG-14-006]

- Simplified cut-based selection.
- Signal model: double Crystal-Ball ⊗ Breit-Wigner.
  - Signal width and mean scale appropriately with m_H.
- **Limits on σ×BR as a function of Γ_X and m_X.**

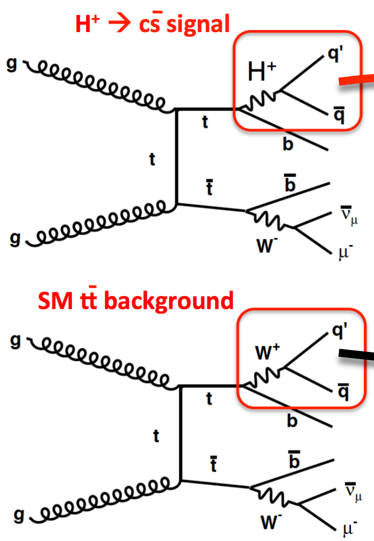


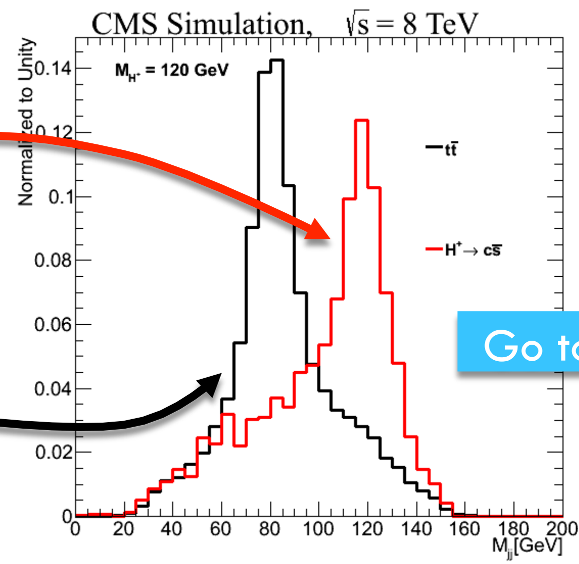


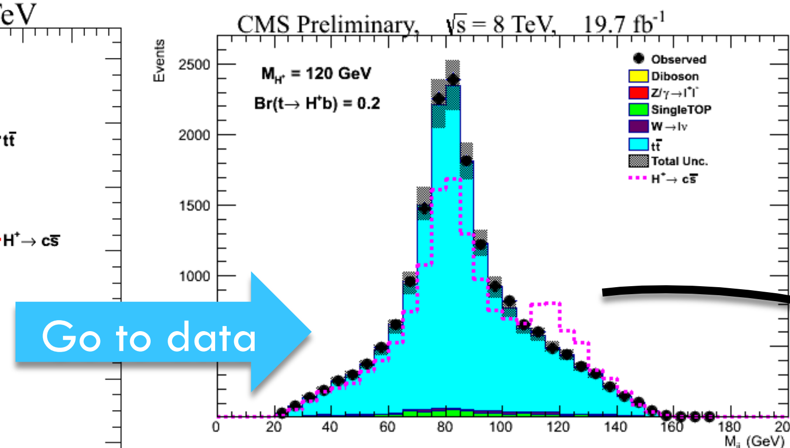


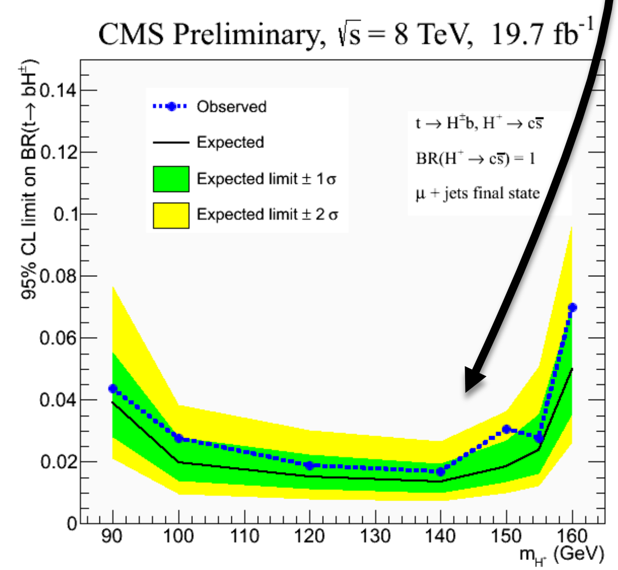
$H^+ \rightarrow cs$ in decays of $t \rightarrow H^+ + b$

[CMS-PAS-HIG-13-035]









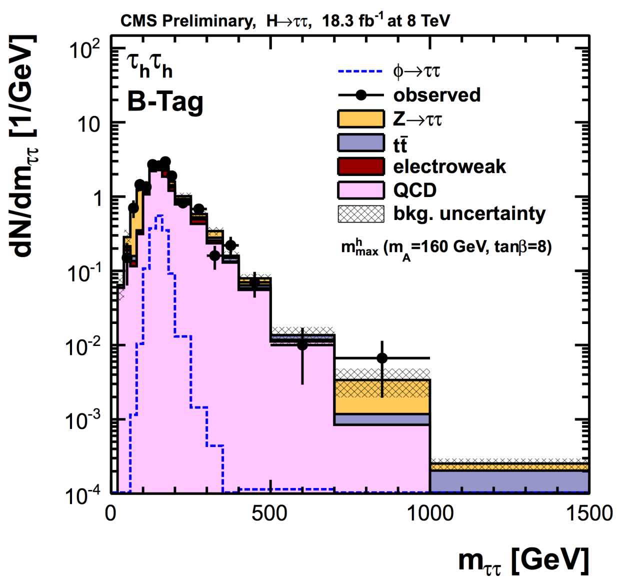
- 2 jets + 2 b-tagged jets + lepton and MET.
- Mass reconstructed using m_W and m_t constraints and likelihood fit.

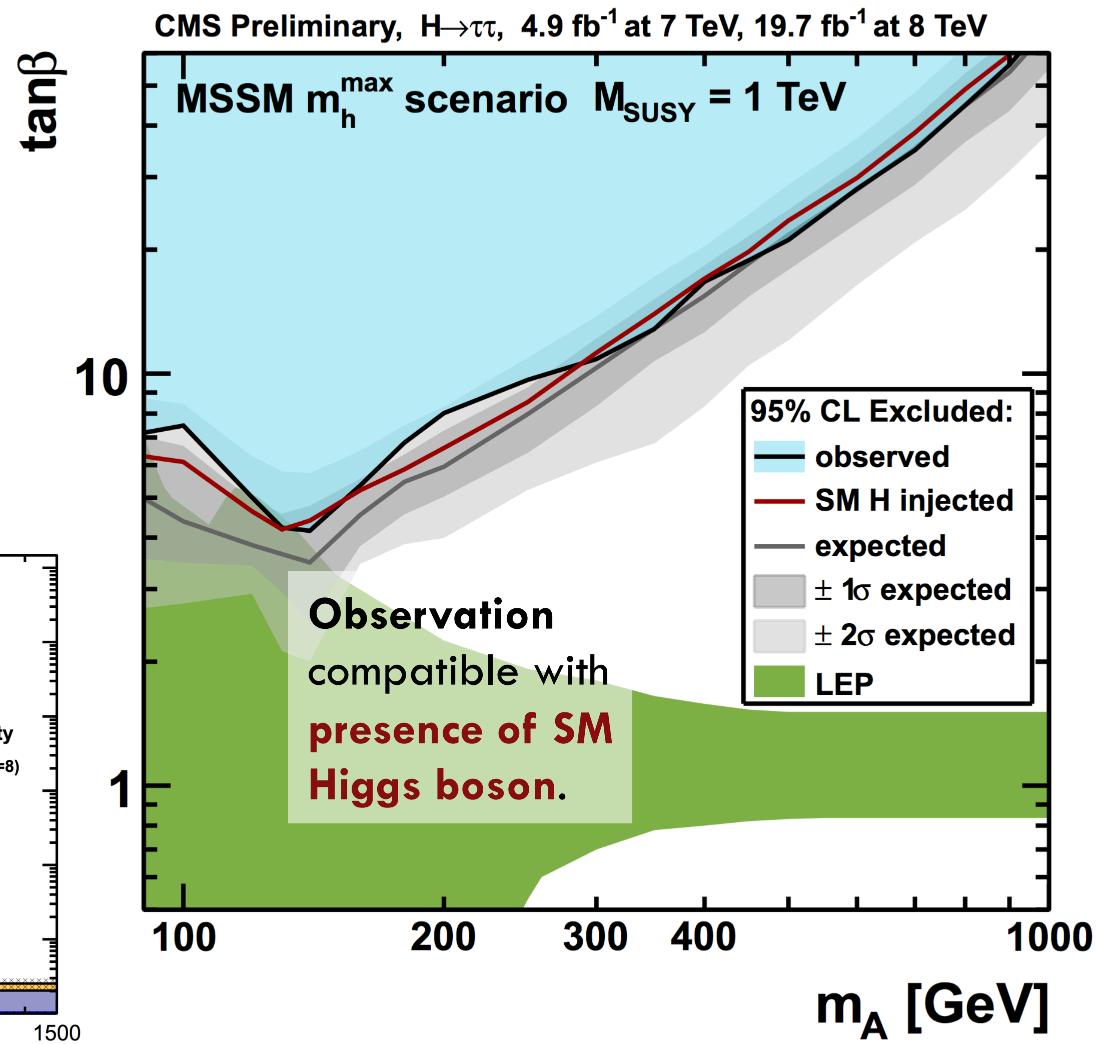
Search for MSSM $\Phi \to \tau\tau$

[CMS-PAS-HIG-13-021]

Not shown: model-independent limits on $gg \to \Phi$ and $gg \to \Phi b\bar{b}$.

- Minimal SuperSymmetric Model predicts:
  - **h^0, H^0, A^0: generically Φ.**
  - H^+ and H^-.
- Based on SM analysis but:
  - **Using extra b-tags (production).**
  - **Extended to up to $m_{\tau\tau}$ = 1.5 TeV:**



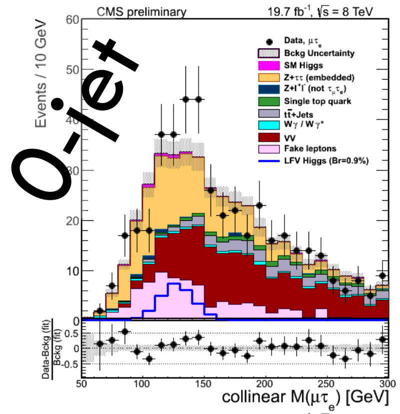


Search for H→μτ

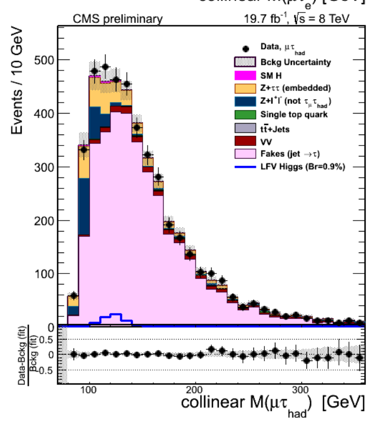
[CMS-PAS-HIG-14-005]

- **τ lepton flavor violation not as well constrained as μe (MEG).**
- Based on SM H→ττ analysis. **Different kinematics allows good SM H rejection.**
  - **BR(H→μτ) < 1.57%** at 95%CL (expected limit of 0.75%)

$\mu\tau_e$



$\mu\tau_{had}$



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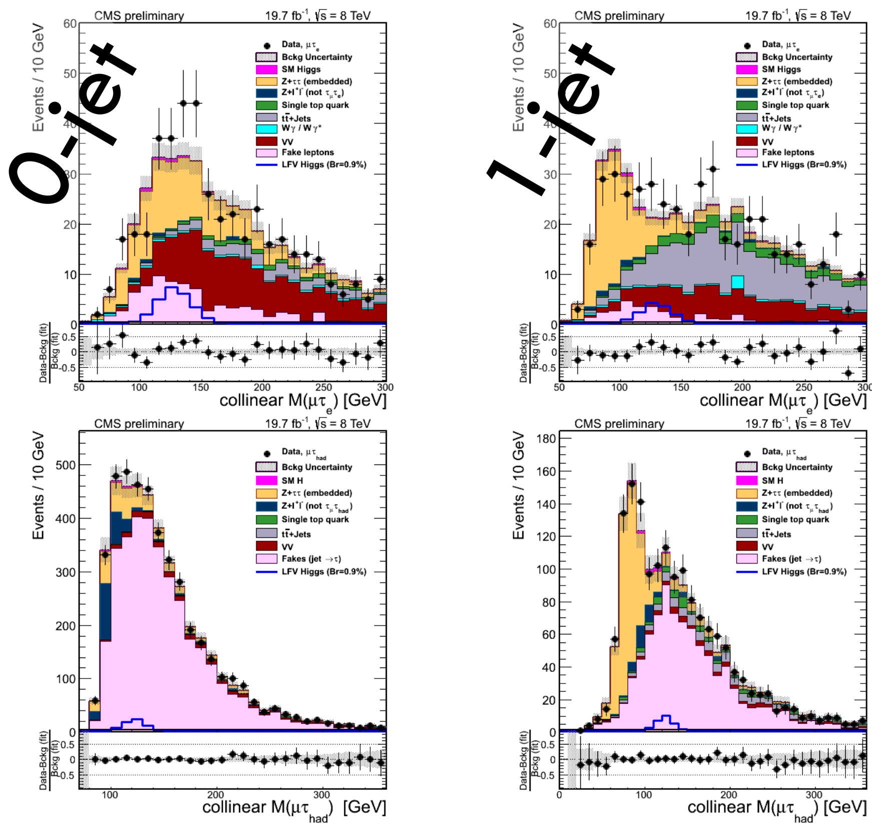
$\mu\tau_e$

$\mu\tau_{had}$



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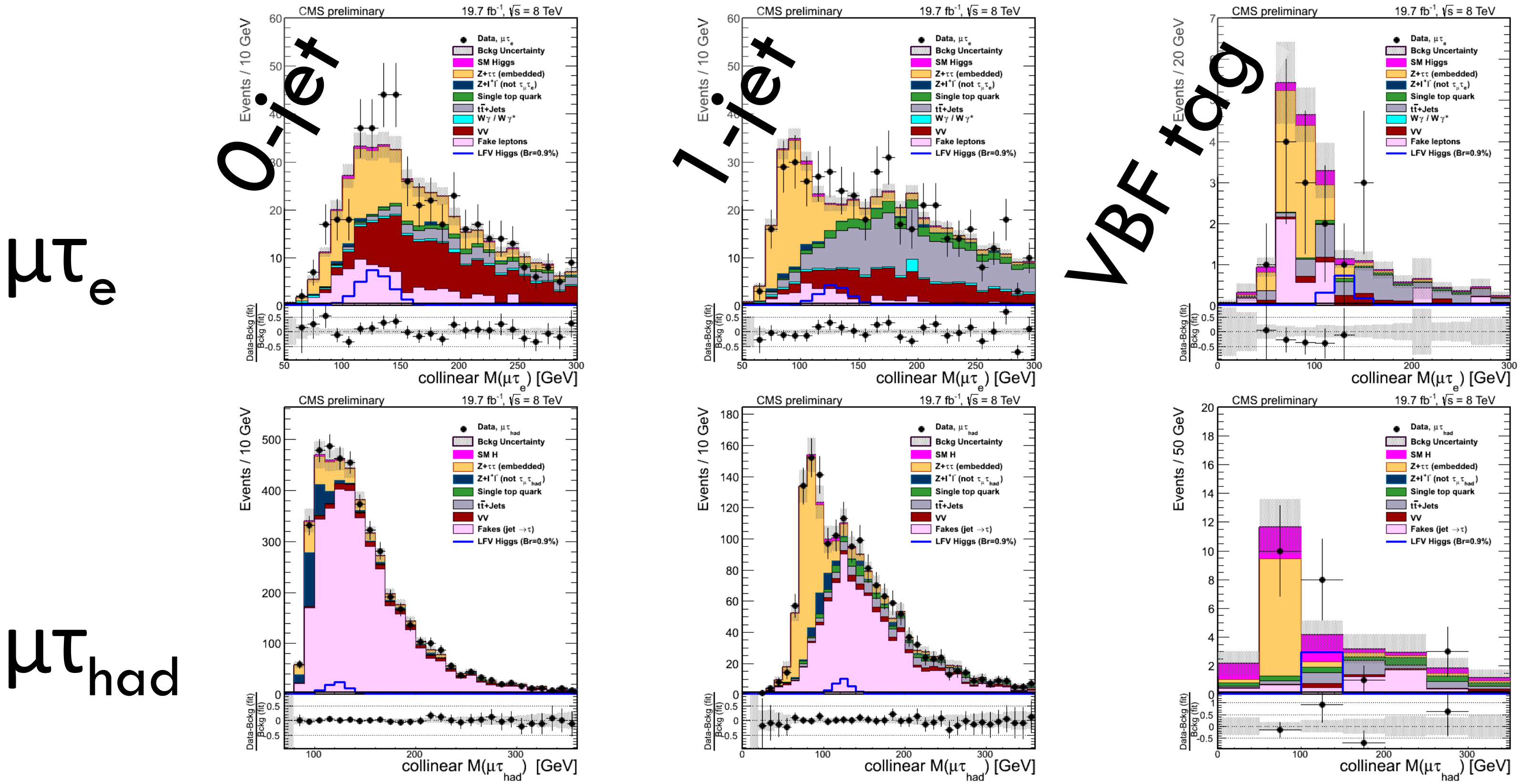
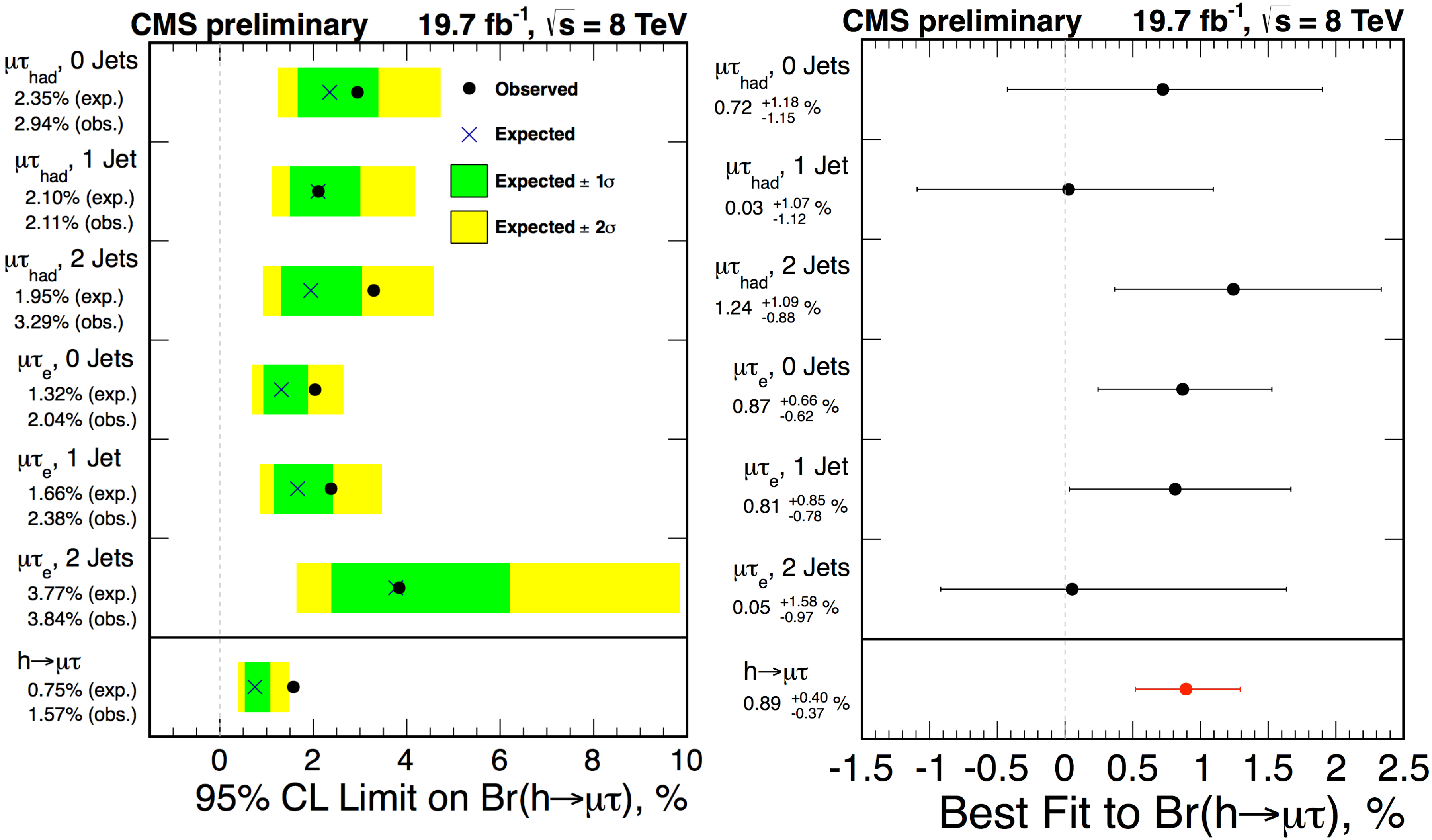


Search for H⟶μτ

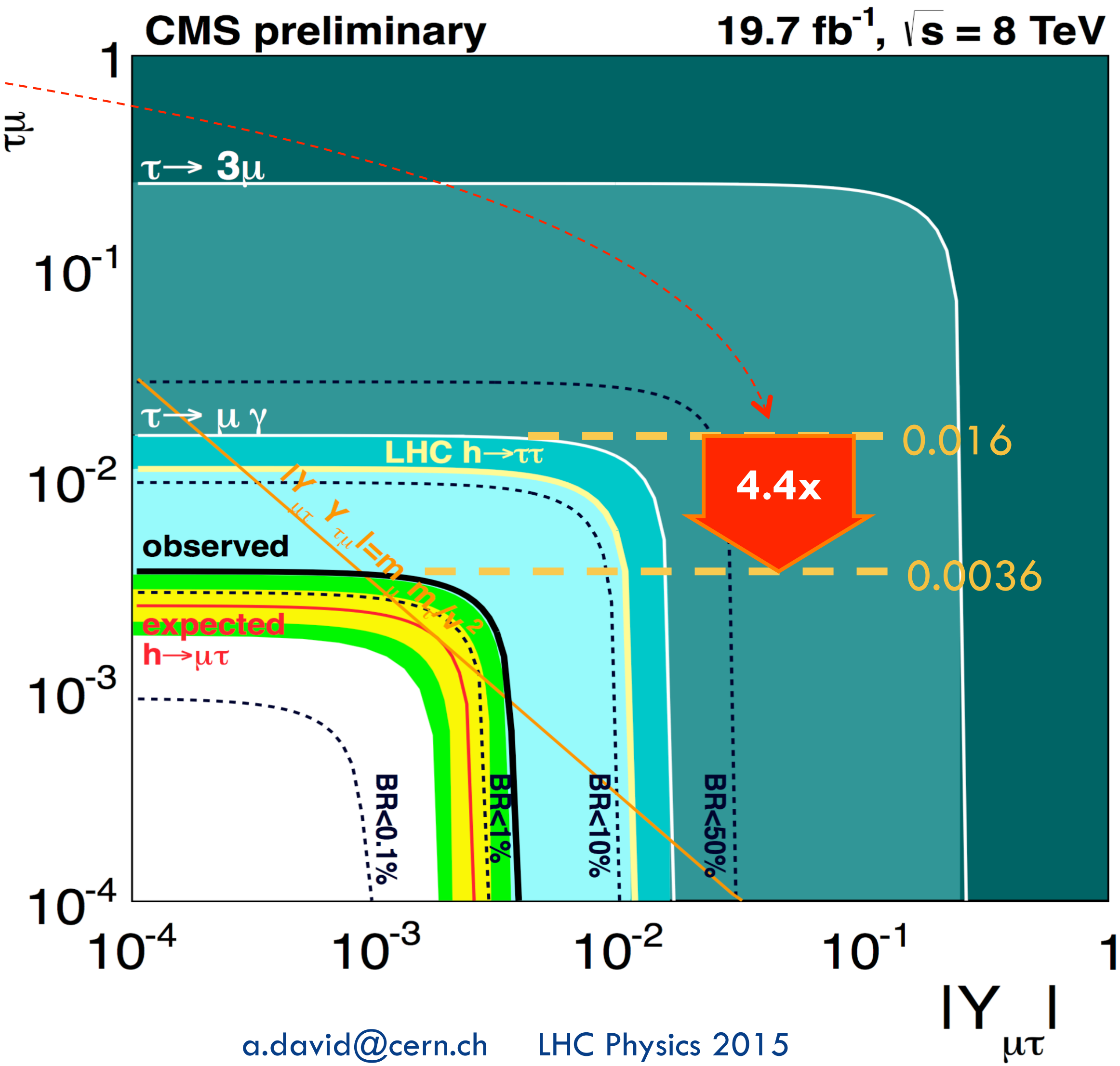
[CMS-PAS-HIG-14-005]



Search for H→μτ

[CMS-PAS-HIG-14-005]

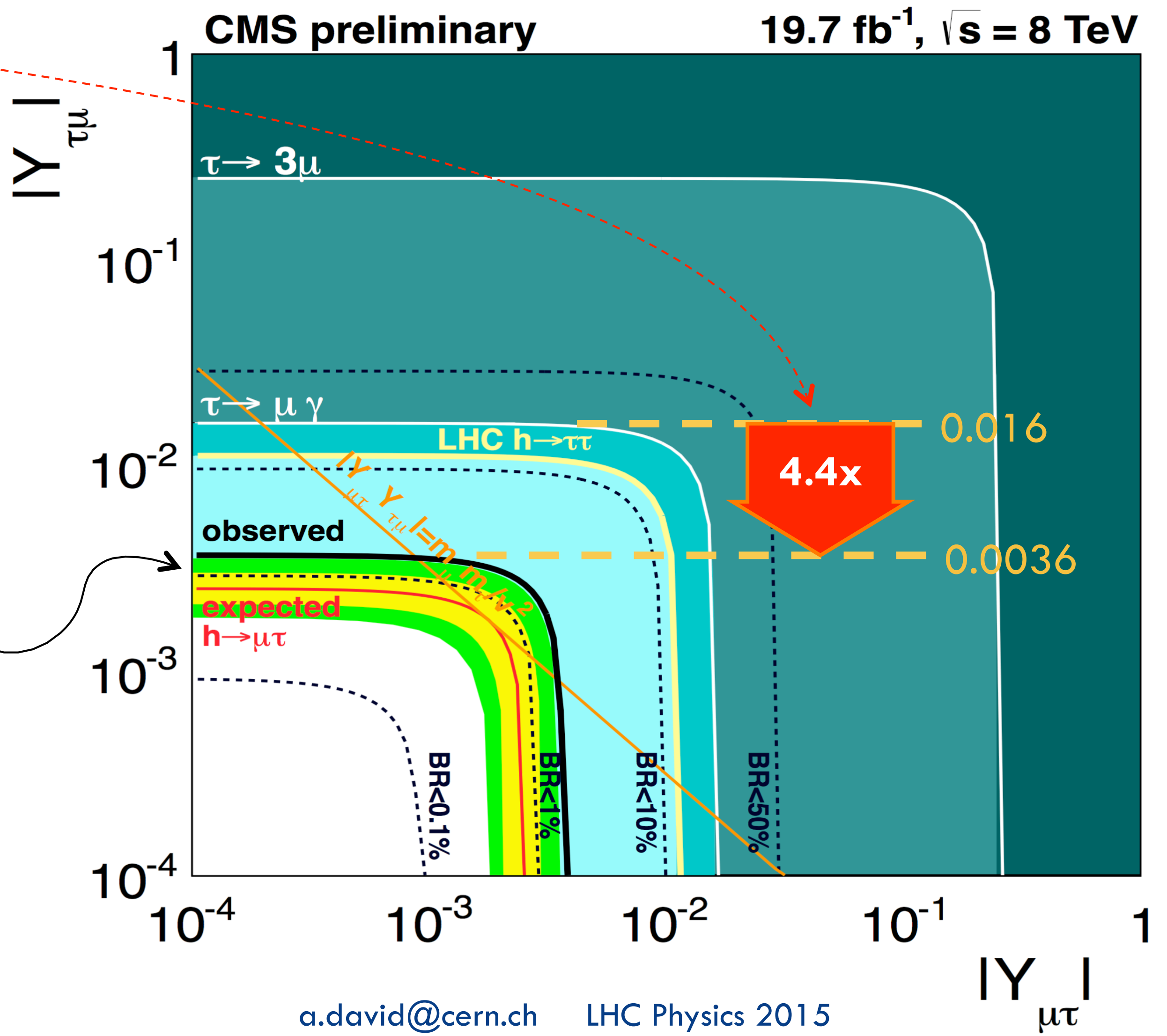
- **Best limits on τ anomalous Yukawa couplings.**



Search for H→μτ

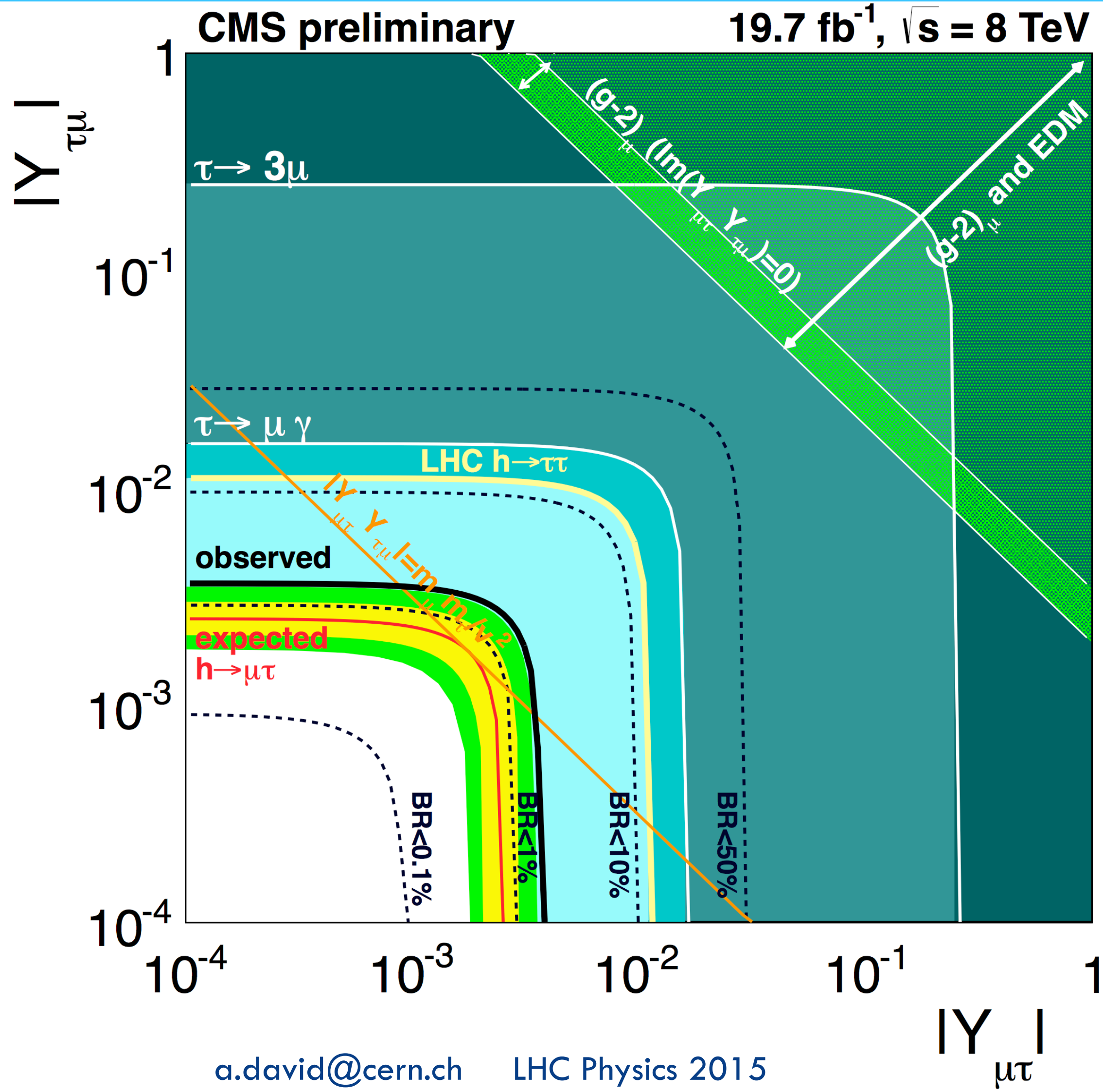
[CMS-PAS-HIG-14-005]

- **Best limits on τ anomalous Yukawa couplings.**
  - Higgs flavor sector could hold surprises.



Search for H→μτ

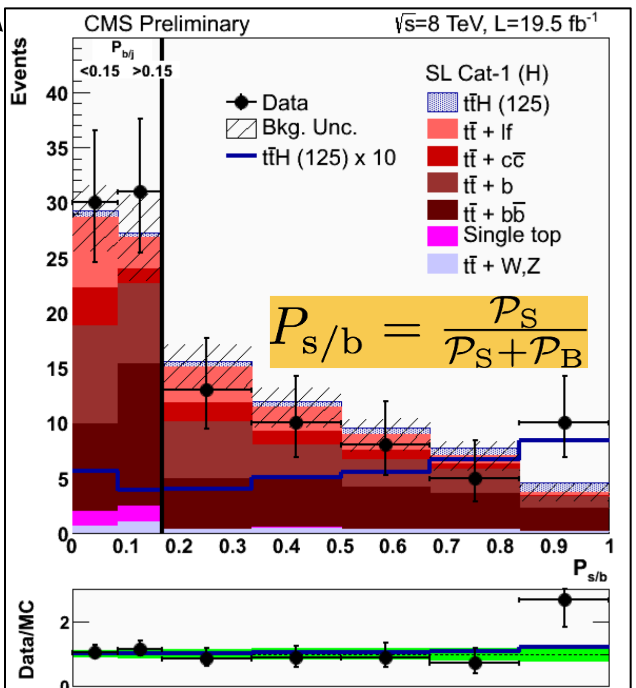
[CMS-PAS-HIG-14-005]



New search for ttH with H→$b\bar{b}$

[CMS-PAS-HIG-14-010]

- Improved performance:
  - Event probability ($P_{s/b}$) based on matrix element probabilities.
  - Single lepton (SL) and di-lepton (DL) topologies.
    - Best with identified W→jj (**SL Cat-1**).
  - Reduced dependency on tt+HF modeling.
- **Clearly a hot topic for Run 2.**



New search for ttH with H→$b\bar{b}$

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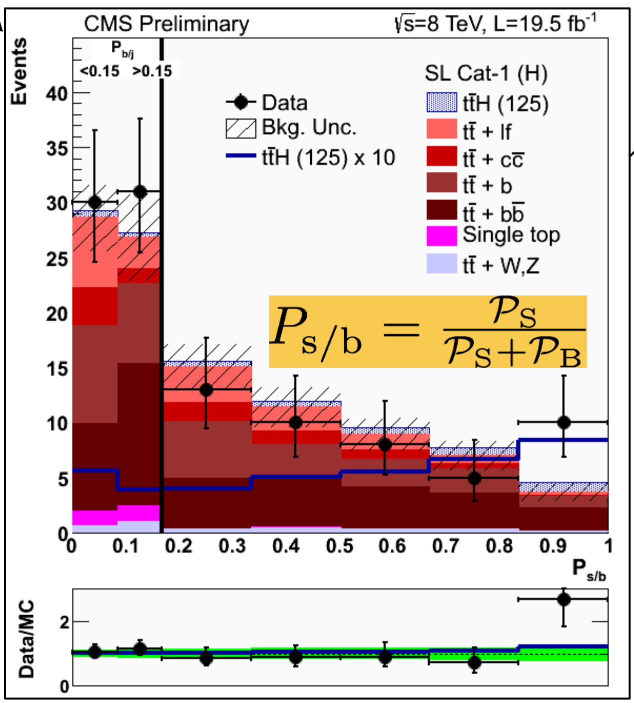

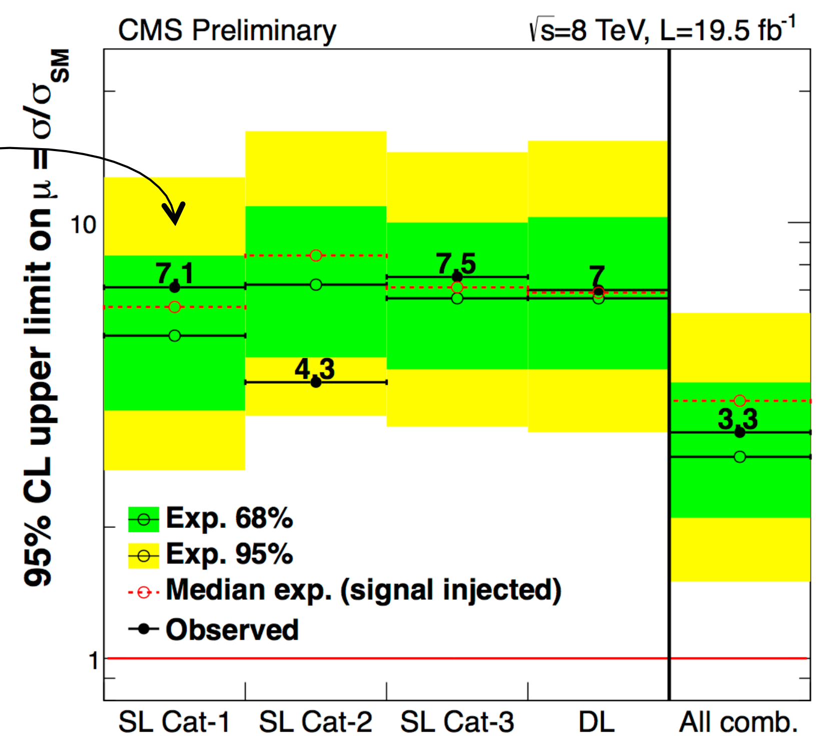

New search for ttH with H→b$\bar{b}$

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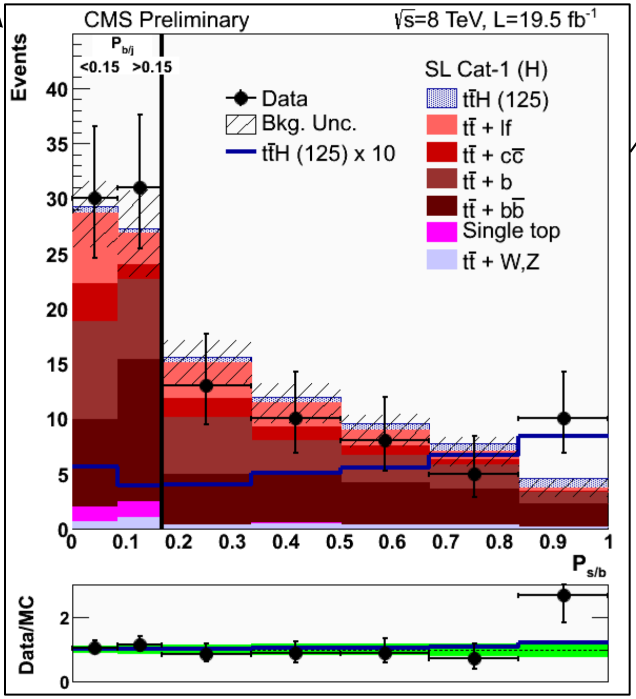

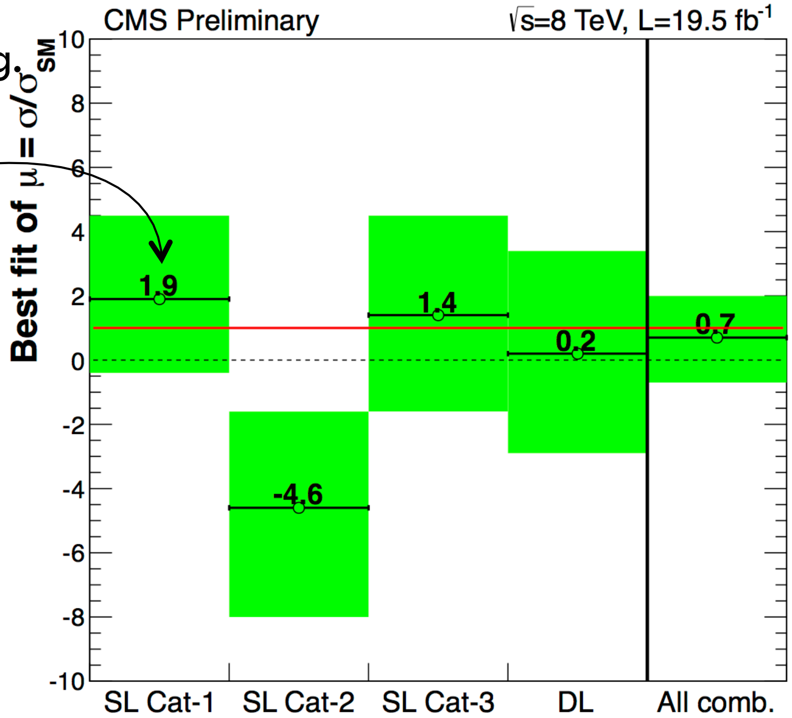

$$P_{s/b} = \frac{\mathcal{P}_{S(bbbb)}}{\mathcal{P}_{S(bbbb)} + \lambda \mathcal{P}_{B(bbbb)} + (1-\lambda)\mathcal{P}_{B(bbjj)}}$$

Statistics

Statistics interlude

[ATL-PHYS-PUB-2011-11, CMS NOTE-2011/005]

	Test statistic	Profiled?	Test statistic sampling
LEP	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\tilde{\theta})}{\mathcal{L}(data\|0,\tilde{\theta})}$	no	Bayesian-frequentist hybrid
Tevatron	$q_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|0,\hat{\theta}_0)}$	yes	Bayesian-frequentist hybrid
LHC	$\tilde{q}_\mu = -2 \ln \frac{\mathcal{L}(data\|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data\|\hat{\mu},\hat{\theta})}$	yes $(0 \leq \hat{\mu} \leq \mu)$	frequentist

- **LEP**: nuisances parameters (θ) kept at nominal values (~).
- **Tevatron**: maximise likelihood against nuisances (^).
  - Denominator considers **background-only hypothesis** (μ=0).
- **LHC**: frequentist profiled likelihood.
  - Denominator considers **global best-fit likelihood** with **floating signal strength**.
  - **Nice asymptotic properties, savings in computational power.**

Breaking down uncertainties

- Nuisances grouped into **stat, theo, other.**
  - **stat** includes $H\rightarrow\gamma\gamma$ background parameters.
  - **theo** includes QCD scales, PDF+α_s, UEPS, and BR.
  - **syst** = **theo** $\cup$ **other.**
- Procedures:
  - For (**stat**)+(**syst**):
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{syst} = \sigma_{all} \ominus \sigma_{stat}$.
  - For (**stat**)+(**theo**)+(**other**)
    - σ_{all} from scan floating all nuisances.
    - σ_{stat} from scan floating **stat** group only.
    - $\sigma_{stat+other}$ from scan floating **stat** and **other**.
    - $\sigma_{theo} = \sigma_{all} \ominus \sigma_{stat+other}$.
    - $\sigma_{other} = \sigma_{all} \ominus \sigma_{stat} \ominus \sigma_{theo}$.

Odds and ends

A 2012 hit

203 [http://goo.gl/ShJJG]

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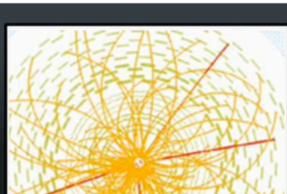
Home > Collections > Online Extras > Special Issues 2012 > Breakthrough of the Year, 2012

Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



FREE ACCESS

The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

Runners-Up FREE WITH REGISTRATION

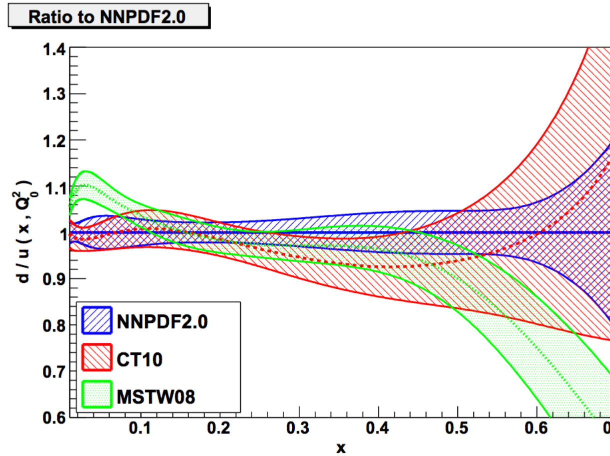
This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

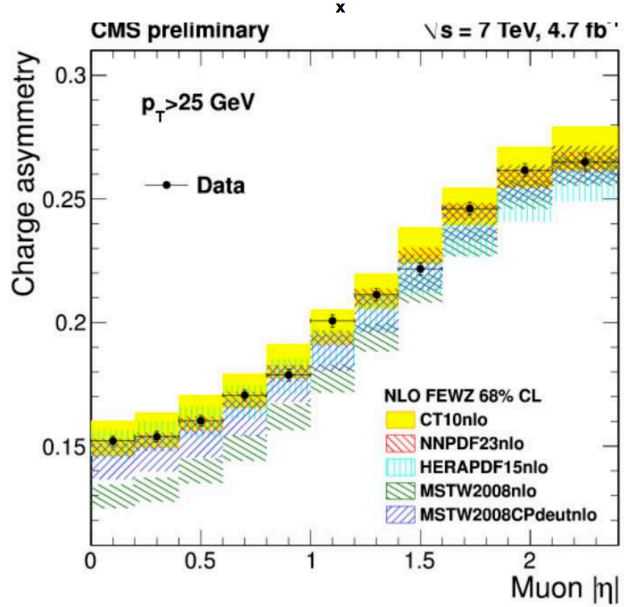
Oct 2013: boson becomes Nobel

Theory uncertainties: a tale of PDFs

[http://cern.ch/go/V8xJ]

- Long-standing difference in d/u ratio between MSTW and others.
- Neatly resolved by CMS W asymmetry measurements.
- MSWT made parameterization more flexible: case closed.



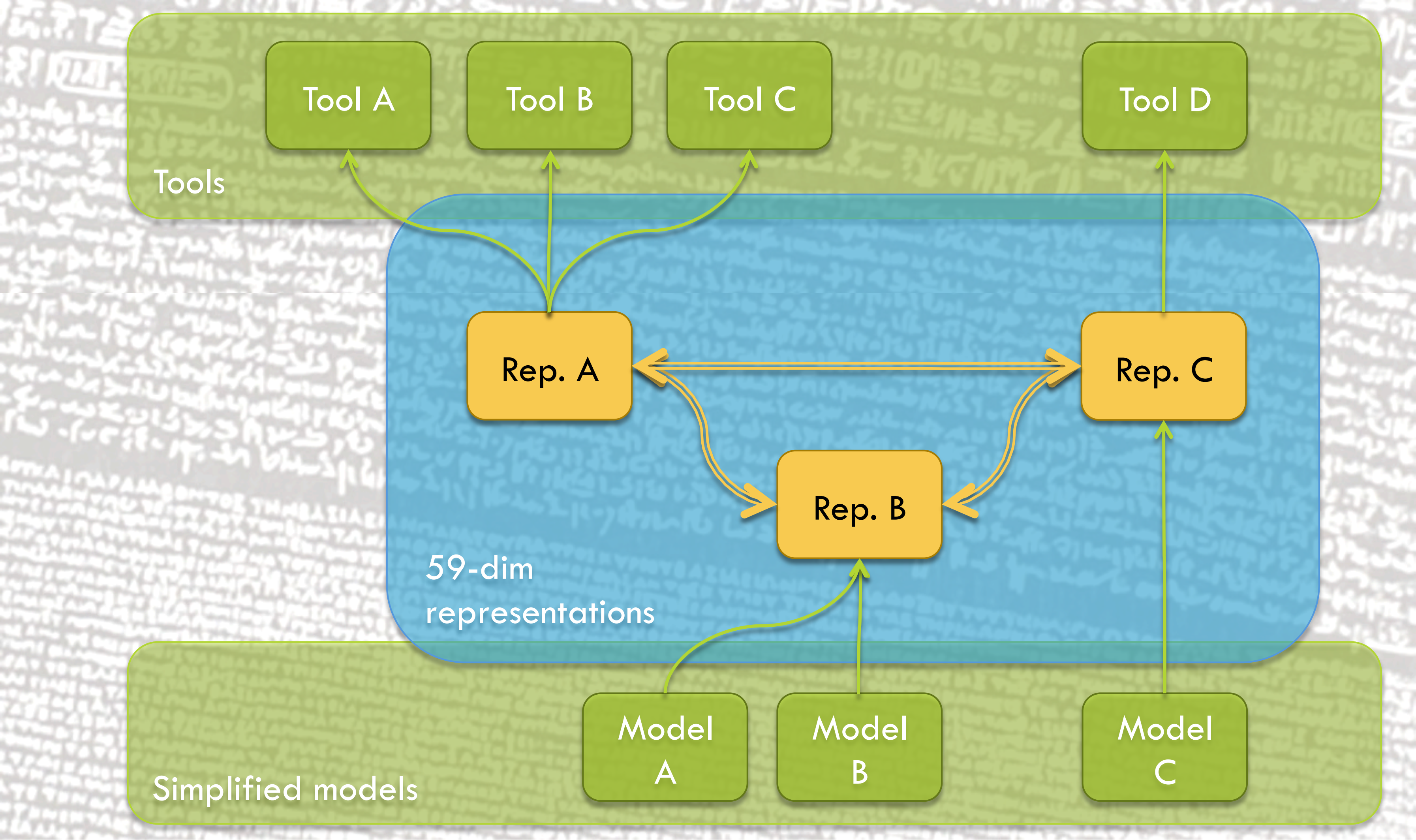


Theory uncertainties

- Bottom-line for Run2:
  - Consider measurements that constrain PDF fits.
  - For higher orders, more than precision, also a matter of accuracy.
    - Need to work with theorists to get these right, also differentially.

- Or you can try to dodge them with p_T ratios…
  - …but end up needing a lot of data.

A Rosetta stone for Higgs EFT



First steps in YR3

[arXiv:1307.1347]

Table 52: Dimension-6 operators involving Higgs doublet fields or gauge-boson fields. For all $\psi^2\Phi^3$, $\psi^2 X\Phi$ operators and for $\mathcal{O}_{\Phi \mathrm{ud}}$ the hermitian conjugates must be included as well.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}_{\Phi} = (\Phi^\dagger\Phi)^3$	$\mathcal{O}_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi\Box} = (\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi)$	$\mathcal{O}_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}_{\Phi D} = (\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi)$	$\mathcal{O}_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{d}}\mathrm{d}\Phi)$	$\mathcal{O}_{\mathrm{W}} = \varepsilon^{IJK} \mathrm{W}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK} \widetilde{\mathrm{W}}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}_{\Phi G} = (\Phi^\dagger\Phi) G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) G^A_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu \mathrm{l})$
$\mathcal{O}_{\Phi\widetilde{G}} = (\Phi^\dagger\Phi) \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) G^A_{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I \mathrm{l})$
$\mathcal{O}_{\Phi\mathrm{W}} = (\Phi^\dagger\Phi) \mathrm{W}^I_{\mu\nu} \mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^I\Phi) \mathrm{W}^I_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu \mathrm{e})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}} = (\Phi^\dagger\Phi) \widetilde{\mathrm{W}}^I_{\mu\nu} \mathrm{W}^{I\mu\nu}$	$\mathcal{O}_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^I\widetilde{\Phi}) \mathrm{W}^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu \mathrm{q})$
$\mathcal{O}_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi) \mathrm{B}_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\tau^I\Phi) \mathrm{W}^I_{\mu\nu}$	$\mathcal{O}^{(3)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I \mathrm{q})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi) \widetilde{\mathrm{B}}_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{eB}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\Phi) \mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu \mathrm{u})$
$\mathcal{O}_{\Phi\mathrm{WB}} = (\Phi^\dagger\tau^I\Phi) \mathrm{W}^I_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) \mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu \mathrm{d})$
$\mathcal{O}_{\Phi\widetilde{\mathrm{W}}\mathrm{B}} = (\Phi^\dagger\tau^I\Phi) \widetilde{\mathrm{W}}^I_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) \mathrm{B}_{\mu\nu}$	$\mathcal{O}_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$

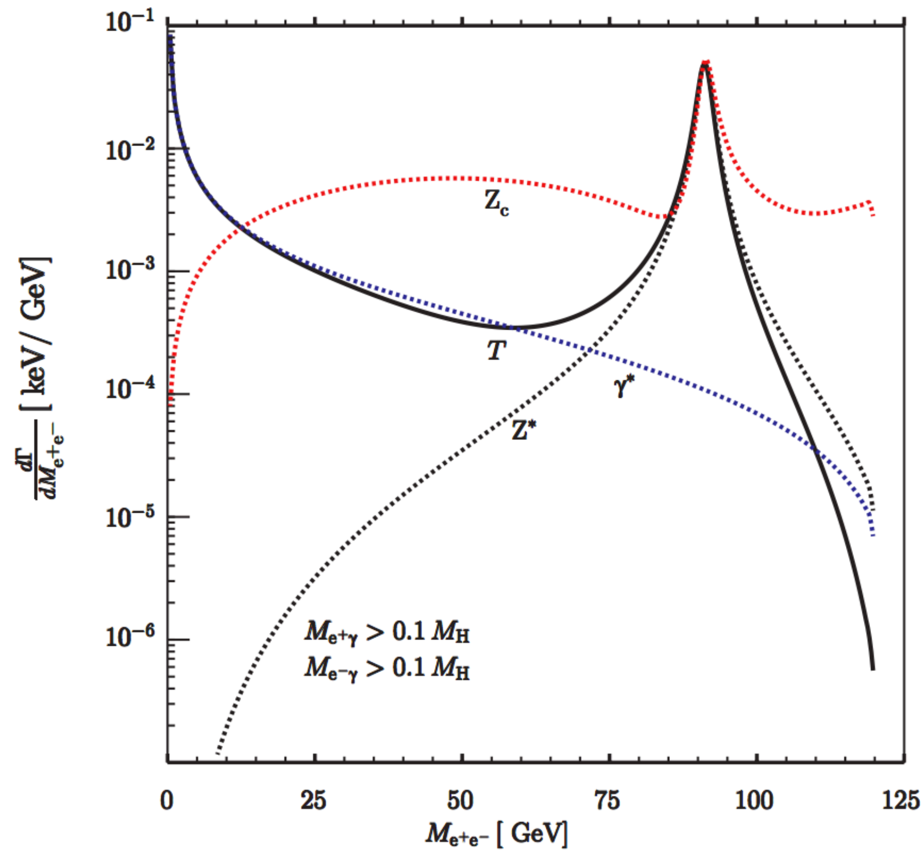
Table 53: Alternative basis of dimension-6 operators involving Higgs doublet fields or gauge-boson fields.

Φ^6 and $\Phi^4 D^2$	$\psi^2\Phi^3$	X^3
$\mathcal{O}'_6 = (\Phi^\dagger\Phi)^3$	$\mathcal{O}'_{\mathrm{e}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{l}}\,\Gamma_{\mathrm{e}}\mathrm{e}\Phi)$	$\mathcal{O}'_G = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}'_\Phi = \partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$	$\mathcal{O}'_{\mathrm{u}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi})$	$\mathcal{O}'_{\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$\mathcal{O}'_{\mathrm{T}} = (\Phi^\dagger\overleftrightarrow{D}_\mu\Phi)(\Phi^\dagger\overleftrightarrow{D}^\mu\Phi)$	$\mathcal{O}'_{\mathrm{d}\Phi} = (\Phi^\dagger\Phi)(\bar{\mathrm{q}}\,\Gamma_d d\Phi)$	$\mathcal{O}'_{\mathrm{W}} = \varepsilon^{IJK} \mathrm{W}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
		$\mathcal{O}'_{\widetilde{\mathrm{W}}} = \varepsilon^{IJK} \widetilde{\mathrm{W}}_\mu^{I\nu} \mathrm{W}_\nu^{J\rho} \mathrm{W}_\rho^{K\mu}$
$X^2\Phi^2$	$\psi^2 X\Phi$	$\psi^2\Phi^2 D$
$\mathcal{O}'_{\mathrm{DW}} = \left(\Phi^\dagger\tau^I \mathrm{i}\overleftrightarrow{D}^\mu\Phi\right)(D^\nu \mathrm{W}_{\mu\nu})^I$	$\mathcal{O}'_{\mathrm{u}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) G^A_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu \mathrm{l})$
$\mathcal{O}'_{\mathrm{DB}} = \left(\Phi^\dagger \mathrm{i}\overleftrightarrow{D}^\mu\Phi\right)(\partial^\nu \mathrm{B}_{\mu\nu})$	$\mathcal{O}'_{\mathrm{d}G} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\frac{\lambda^A}{2}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) G^A_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{l}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{l}}\gamma^\mu\tau^I \mathrm{l})$
$\mathcal{O}'_{D\Phi\mathrm{W}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'_{\mathrm{eW}} = (\bar{\mathrm{l}}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\tau^I\Phi) \mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{e}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{e}}\gamma^\mu \mathrm{e})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{W}}} = \mathrm{i}(D^\mu\Phi)^\dagger\tau^I(D^\nu\Phi)\widetilde{\mathrm{W}}^I_{\mu\nu}$	$\mathcal{O}'_{\mathrm{uW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\tau^I\widetilde{\Phi}) \mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'^{(1)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu \mathrm{q})$
$\mathcal{O}'_{D\Phi\mathrm{B}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{dW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\tau^I\Phi) \mathrm{W}^I_{\mu\nu}$	$\mathcal{O}'^{(3)}_{\Phi\mathrm{q}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}^I_\mu\Phi)(\bar{\mathrm{q}}\gamma^\mu\tau^I \mathrm{q})$
$\mathcal{O}'_{D\Phi\widetilde{\mathrm{B}}} = \mathrm{i}(D^\mu\Phi)^\dagger(D^\nu\Phi)\widetilde{\mathrm{B}}_{\mu\nu}$	$\mathcal{O}'_{\mathrm{eB}} = (\bar{l}\sigma^{\mu\nu}\Gamma_{\mathrm{e}}\mathrm{e}\Phi) B_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{u}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu \mathrm{u})$
$\mathcal{O}'_{\Phi\mathrm{B}} = (\Phi^\dagger\Phi) B_{\mu\nu} \mathrm{B}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{uB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{u}}\mathrm{u}\widetilde{\Phi}) \mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{d}} = (\Phi^\dagger \mathrm{i}\overleftrightarrow{D}_\mu\Phi)(\bar{\mathrm{d}}\gamma^\mu \mathrm{d})$
$\mathcal{O}'_{\Phi\widetilde{\mathrm{B}}} = (\Phi^\dagger\Phi) \mathrm{B}_{\mu\nu} \widetilde{\mathrm{B}}^{\mu\nu}$	$\mathcal{O}'_{\mathrm{dB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\Gamma_{\mathrm{d}}\mathrm{d}\Phi) \mathrm{B}_{\mu\nu}$	$\mathcal{O}'_{\Phi\mathrm{ud}} = \mathrm{i}(\widetilde{\Phi}^\dagger D_\mu\Phi)(\bar{\mathrm{u}}\gamma^\mu\Gamma_{\mathrm{ud}}\mathrm{d})$
$\mathcal{O}'_{\Phi G} = \Phi^\dagger\Phi G^A_{\mu\nu} G^{A\mu\nu}$		
$\mathcal{O}'_{\Phi\widetilde{G}} = \Phi^\dagger\Phi G^A_{\mu\nu} \widetilde{G}^{A\mu\nu}$		

Rare decays: full Dalitz analysis

[arXiv:1308.0422]

- $\gamma\gamma$ and $Z\gamma$ loops sensitive to different physics because of V-A structure for Z.
- More information from full $m_{\ell\ell}$ spectrum.
  - Need to clearly define the phase-space used in analysis.

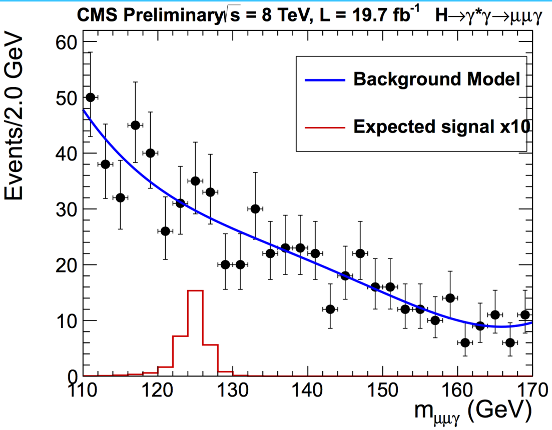


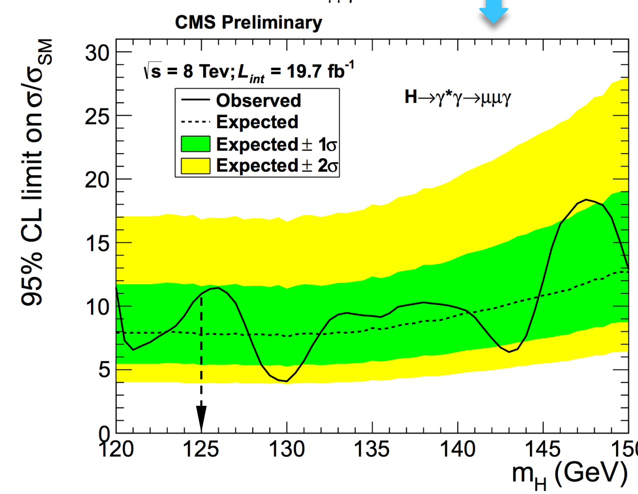
$H \to \gamma^* \gamma \to \ell\ell\gamma$

[CMS-PAS-HIG-14-003]

- $m_{\mu\mu} < 20$ GeV.
- Veto out J/ψ and Υ.

Requirement	Observed event yield	Expected number of signal events for $m_H = 125$ GeV
Trigger, photon selection, $p_T^\gamma > 25$ GeV	0.6M	6.2
Muon selection, $p_T^{\mu 1} > 23$ GeV and $p_T^{\mu 2} > 4$ GeV	55836	4.7
110 GeV $< m_{\mu\mu\gamma} <$170 GeV	7800	4.7
$m_{\mu\mu} < 20$ GeV	1142	3.9
$\Delta R(\gamma, \mu) > 1$	1138	3.9
Removal of resonances	1020	3.7
$p_T^\gamma / m_{\mu\mu\gamma} > 0.3$ and $p_T^{\mu\mu} / m_{\mu\mu\gamma} > 0.3$	665	3.3
122 GeV $< m_{\mu\mu\gamma} <$ 128 GeV	99	2.9



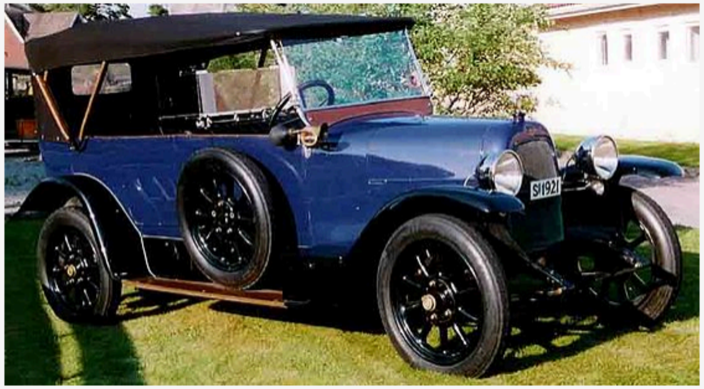


Obs. (exp.)	CMS
μ at 125 GeV (95% CL)	< 11 (8)

Other models?

[http://cern.ch/go/X6rC]

Fiat 505

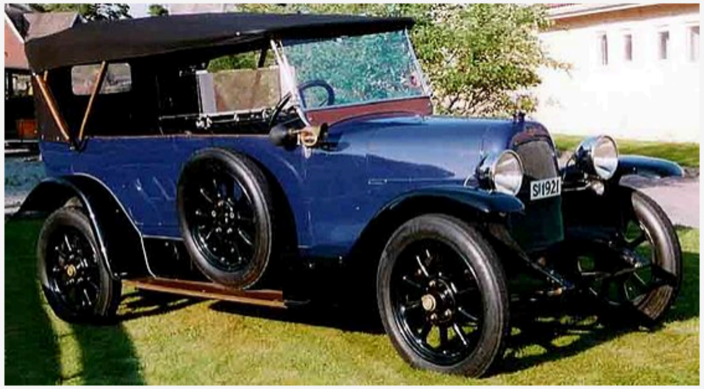


Other models?

212 [http://cern.ch/go/X6rC]

Fiat 1400/1900

Fiat 505



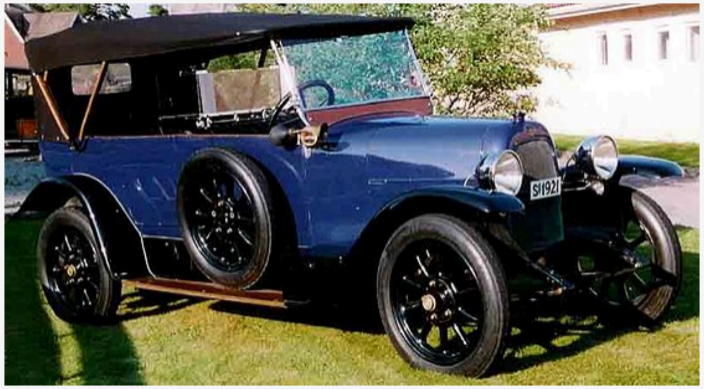
Other models?

[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 505



Other models?

[http://cern.ch/go/X6rC]

Fiat 850

Fiat 1400/1900

Fiat 2300

Fiat 505

Other models?

[http://cern.ch/go/X6rC]