PROPERTIES OF THE HIGGS BOSON WE CANNOT "UNSEE"

André David (CERN)

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]

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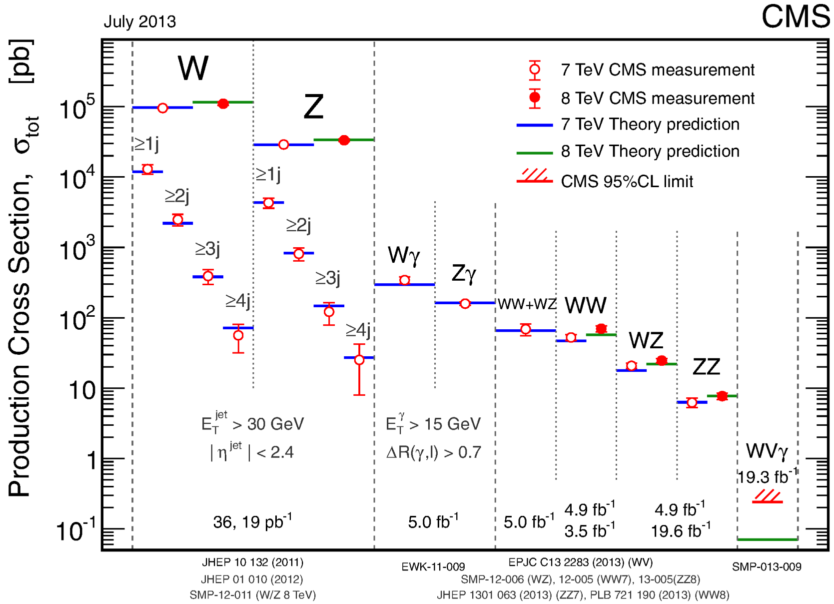
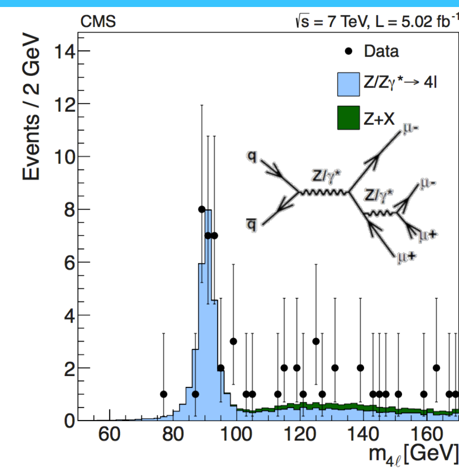
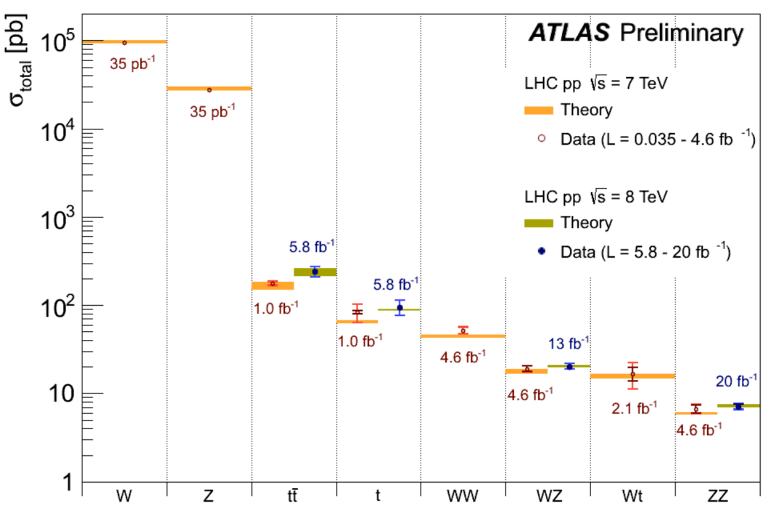
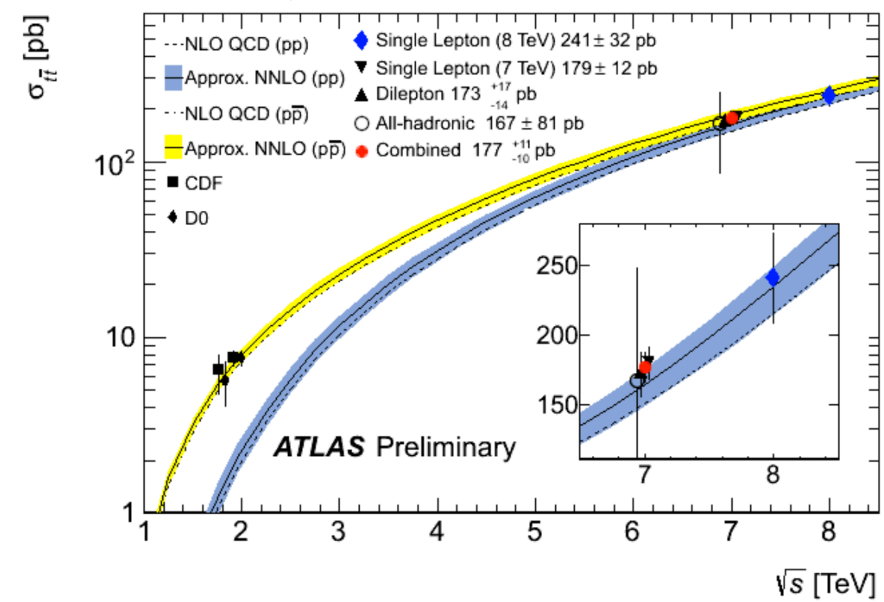
A tribute to those doing SM calculations

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









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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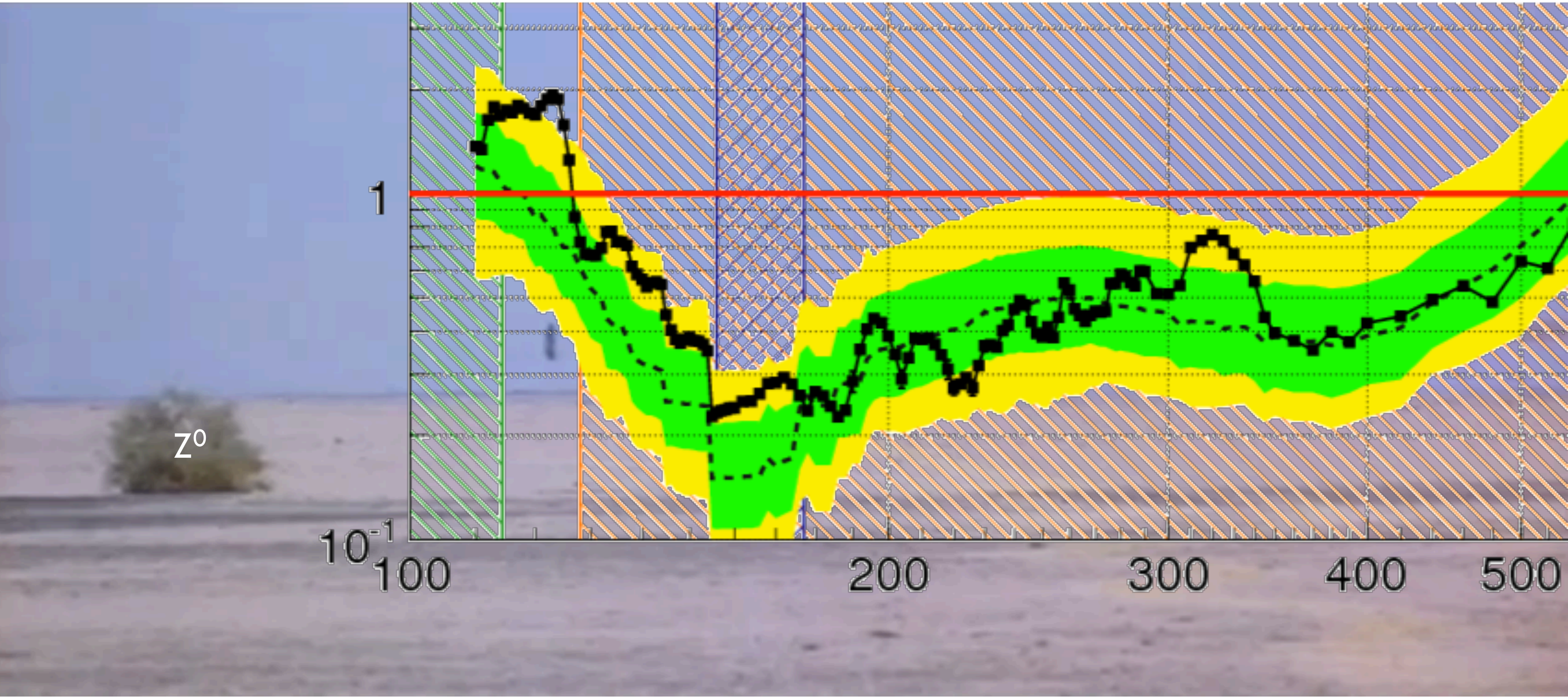


2012: a rider!

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

- We discovered a peak rising from the background.

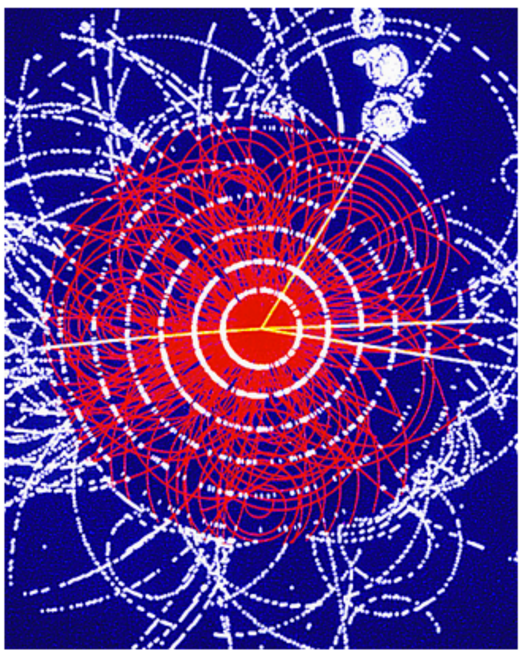
Who Should Be TIME's Person of the Year 2012?

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

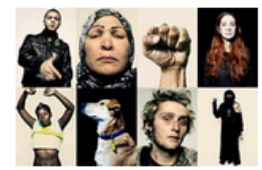
VOTE

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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1 Who Should Be TIME's Person of the Year 2012?
2 LIFE Behind the Picture: The Photo That Changed the Face of AIDS
3 Nativity-Scene Battles: Score One for the Atheists
4 The $7 Cup of Starbucks: A Logical Extension of the Coffee Chain's Long-Term Strategy

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2012 2011 2010 2009 2008

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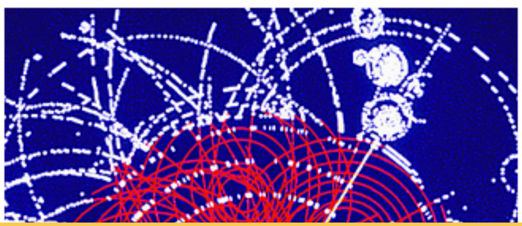
Like 1.5k | Tweet 536 | +1 20 | Share 7

THE CANDIDATES

The Higgs Boson

18 of 40

By Jeffrey Kluger | Monday, Nov. 26, 2012



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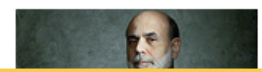

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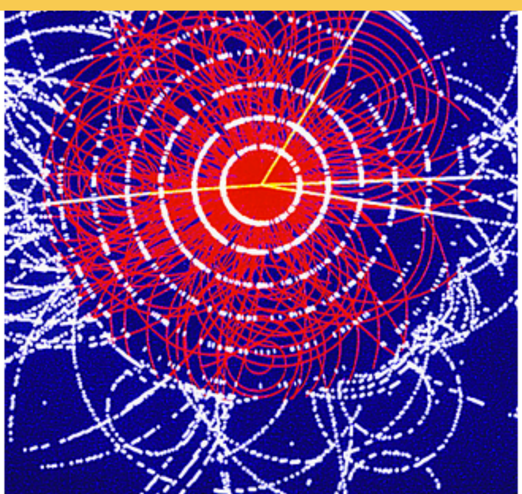

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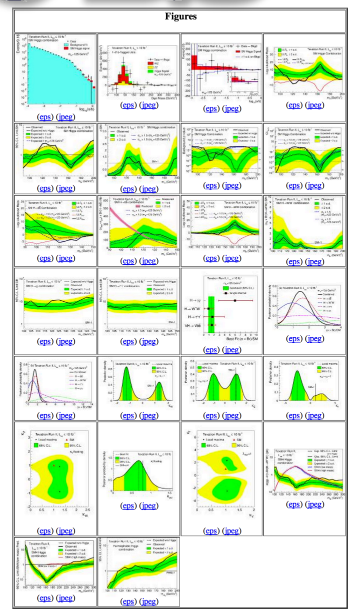
2013: a rider with a gun

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

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

(self-inflicted) Mission: impossible



Channel	Conference note	L	Date
Charged Higgs tau nu + jets	ATLAS-CONF-2013-090	20 fb-1	27/09/2013
High Mass WW(lvlv)	ATLAS-CONF-2013-067	21 fb-1	18/07/2013
Higgs to Diphoton differential cross sections	ATLAS-CONF-2013-072	21 fb-1	18/07/2013
Higgs in VH(WW)	ATLAS-CONF-2013-075	25 fb-1	18/07/2013
Higgs in VH(bb)	ATLAS-CONF-2013-079	25 fb-1	18/07/2013
ttH (diphoton)	ATLAS-CONF-2013-080	20 fb-1	25/07/2013
FCNC top to Higgs (diphoton) Charm	ATLAS-CONF-2013-081	25 fb-1	25/07/2013

Channel	Conference note	L	Date
Spin Combination	ATLAS-CONF-2013-040	up to 25 fb-1	[illegible]
Couplings Combination	ATLAS-CONF-2013-034	[illegible]	[illegible]
Higgs to Diphoton spin	ATLAS-CONF-2013-029	[illegible]	[illegible]
Higgs to WW(lvlv) spin	ATLAS-CONF-2013-031	[illegible]	11/03/2013
Higgs to WW(lvlv)	ATLAS-CONF-2013-030	25 fb-1	11/03/2013
2HDM WW(lvlv)	ATLAS-CONF-2013-027	13 fb-1	11/03/2013
Combined of Mass	ATLAS-CONF-2013-014	up to 25 fb-1	05/03/2013
Higgs to Diphoton	ATLAS-CONF-2013-012	25 fb-1	05/03/2013
Higgs to 4 leptons	ATLAS-CONF-2013-013	25 fb-1	05/03/2013
ZH (invisible decays)	ATLAS-CONF-2013-011	18 fb-1	05/03/2013
Higgs to dimuon	ATLAS-CONF-2013-010	21 fb-1	05/03/2013
Higgs to Zgamma	ATLAS-CONF-2013-009	25 fb-1	05/03/2013

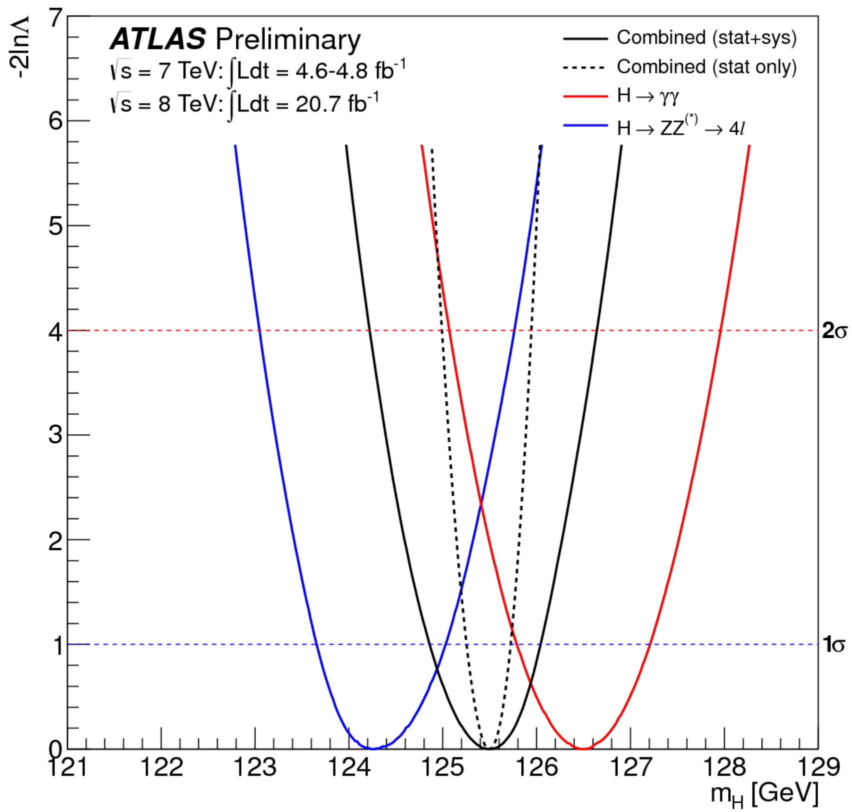
+ Moriond 2014

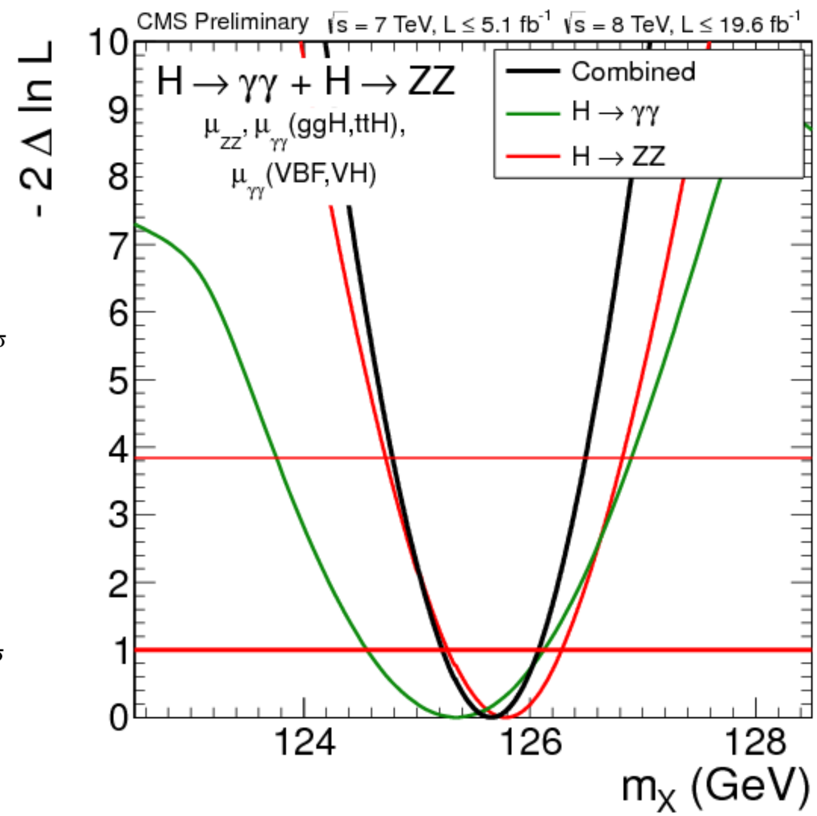
Oct-2013	Z(bb)H, H -> invisible	TWiki, PAS
Oct-2013	SM H -> mumu	TWiki, PAS
Oct-2013	ttH Combination	TWiki
Sep-2013	Full 8 TeV dataset: ttH, H -> multi-leptons	TWiki, PAS
Aug-2013	Full 8 TeV dataset: VBF H -> invisible	TWiki, PAS
Aug-2013	Full 7+8 TeV dataset: VBF H -> WW	TWiki, PAS
Jul-2013	Full 8 TeV dataset: ttH, H -> bb or tautau	TWiki, PAS
Jul-2013	[illegible] dataset: H -> ZZ -> 2l2j	TWiki, PAS
[illegible]	[illegible] dataset: h -> 2a + X -> 4mu + X	TWiki, PAS
[illegible]	[illegible] dataset: VH, H -> invisible	TWiki, PAS
[illegible]	[illegible] dataset: VH, H -> WW(2l2nu) + V -> jj	TWiki, PAS
[illegible]	[illegible] 7+8 TeV dataset: Higgs properties from H -> gamma gamma	TWiki, PAS

May-2013	Full 8 TeV dataset: VBF H, H -> bb	TWiki, PAS
May-2013	Full 8 TeV dataset: ttH, H -> gamma gamma	TWiki, PAS
May-2013	Full 7+8 TeV dataset: VH, H -> bb	TWiki, PAS
May-2013	Full 8 TeV dataset: H -> WW -> lnuJ	TWiki, PAS
May-2013	Full 7+8 TeV dataset: H -> ZZ -> 2l2nu	TWiki, PAS
Apr-2013	Moriond Higgs Combination	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> gamma gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> ZZ -> 4l	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> WW -> 2l2nu	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> tau tau	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> Z gamma	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: H -> WWW -> 3l3nu	TWiki, PAS
Mar-2013	Full 7+8 TeV dataset: VH -> tau tau	TWiki, PAS

- Present a coherent view of present-day results of Higgs properties from the LHC and Tevatron experiments.
  - Any omission or mistake are the speaker's fault.

First things first: the mass

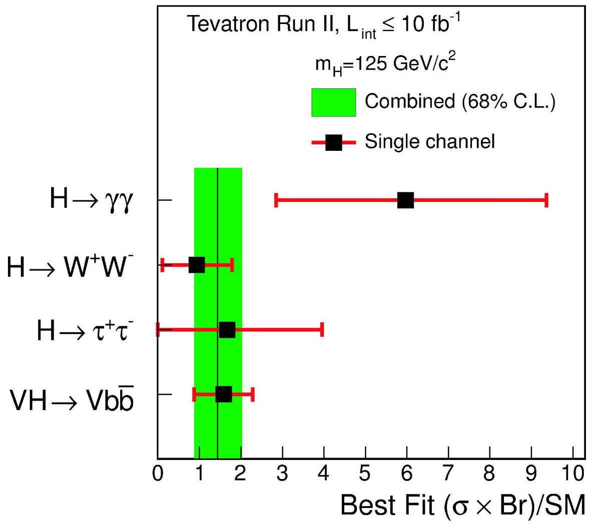


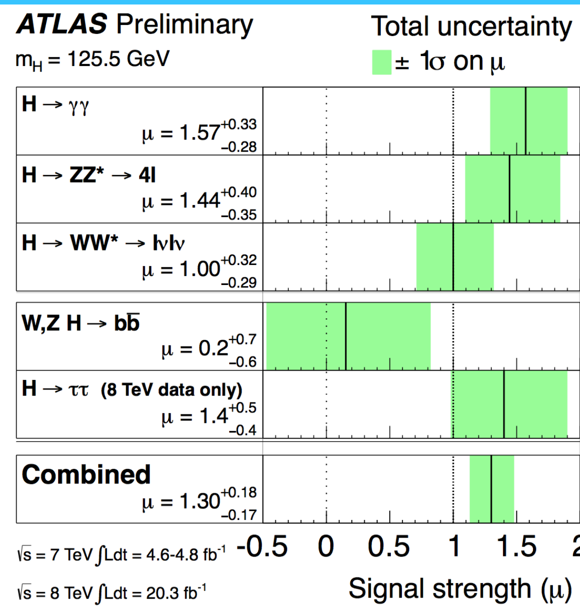


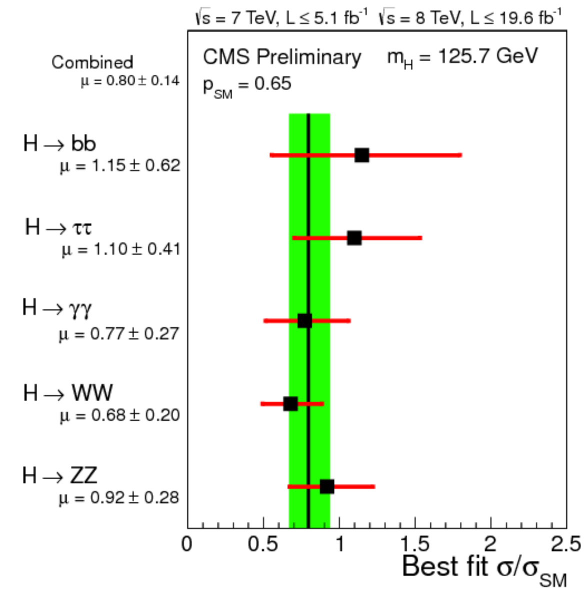
	ATLAS	CMS
m_X	125.5 ±0.2 (stat.) $^{+0.5}_{-0.6}$ (syst.) GeV	125.7 ±0.3 (stat.) ±0.3 (syst.) GeV
Naïve average: 125.6 ±0.4 GeV		

Relative signal strengths

[arXiv:1303.6346] [ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





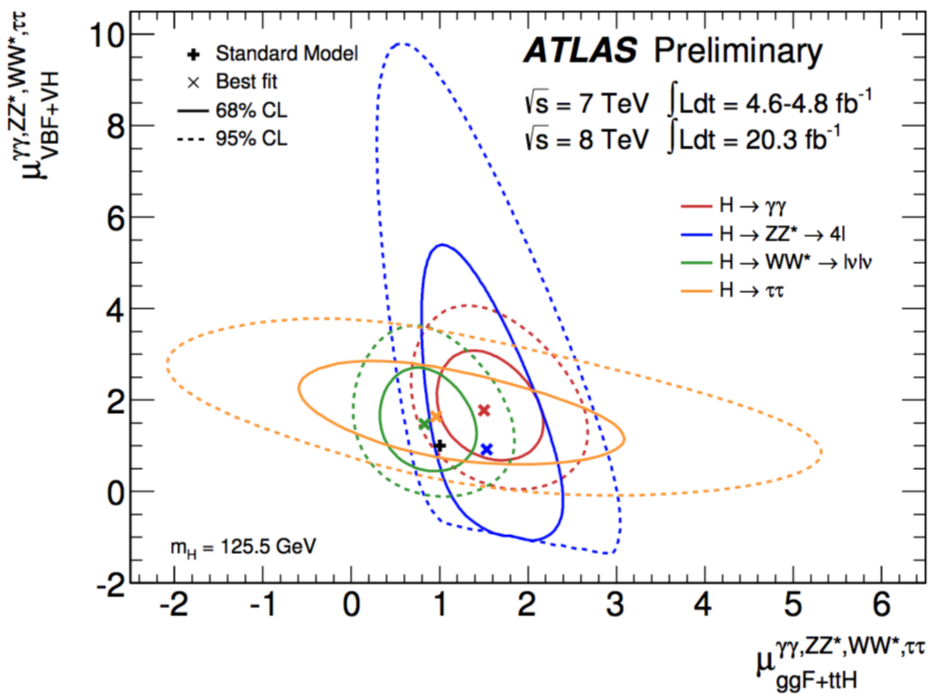


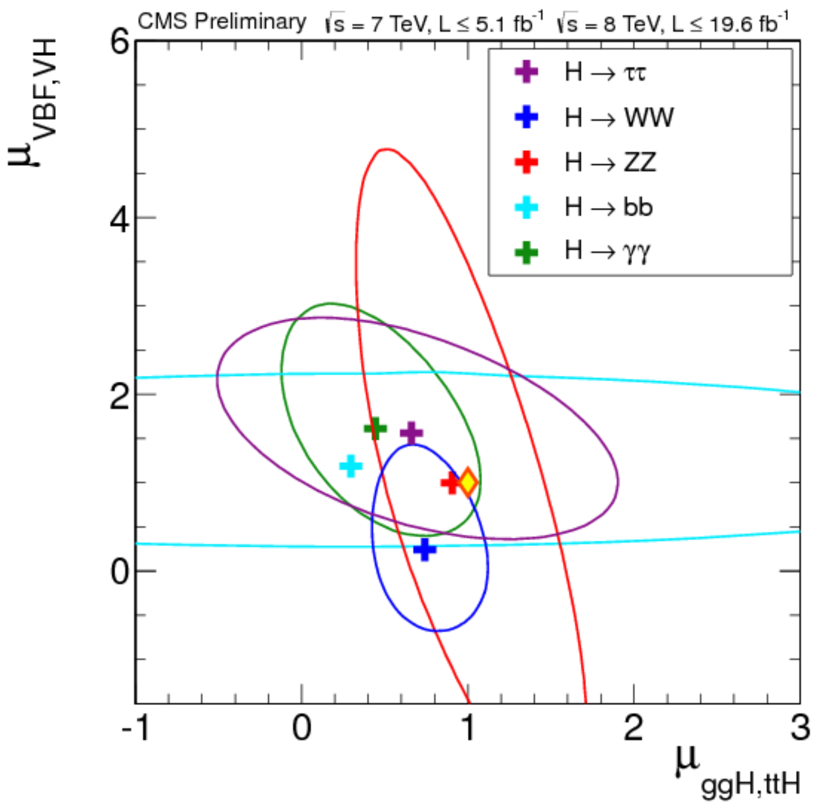
	Tevatron	ATLAS	CMS
m_H	125 GeV	125.5 GeV	125.7 GeV
$\mu = \sigma/\sigma_{SM}$	$1.44\,^{+0.59}_{-0.56}$	1.30 ±0.18	0.80 ±0.14

Naïve average: 0.98 ±0.11

Production mechanisms

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]

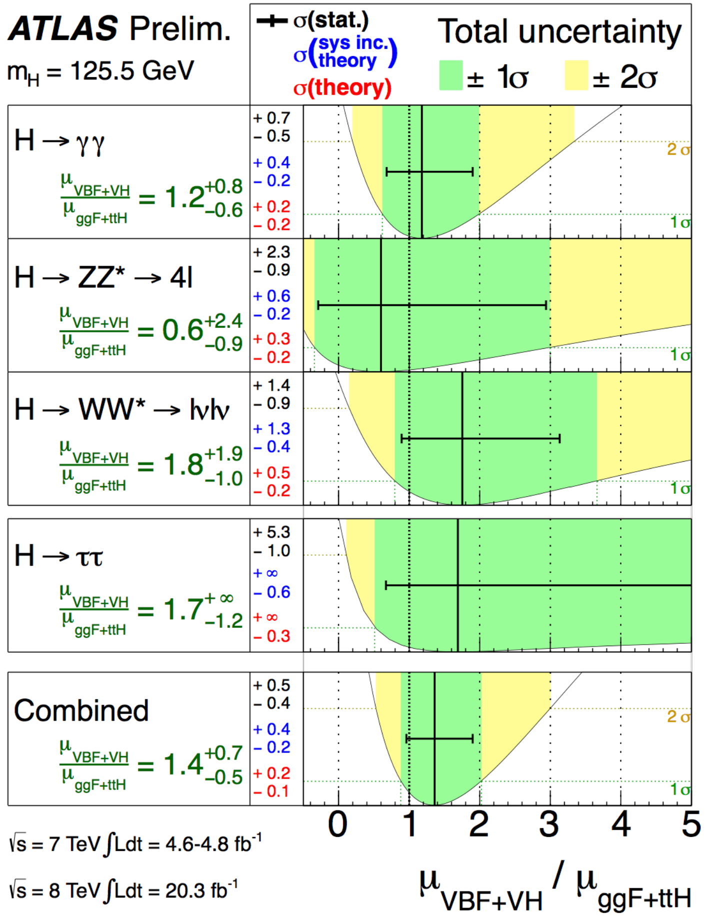


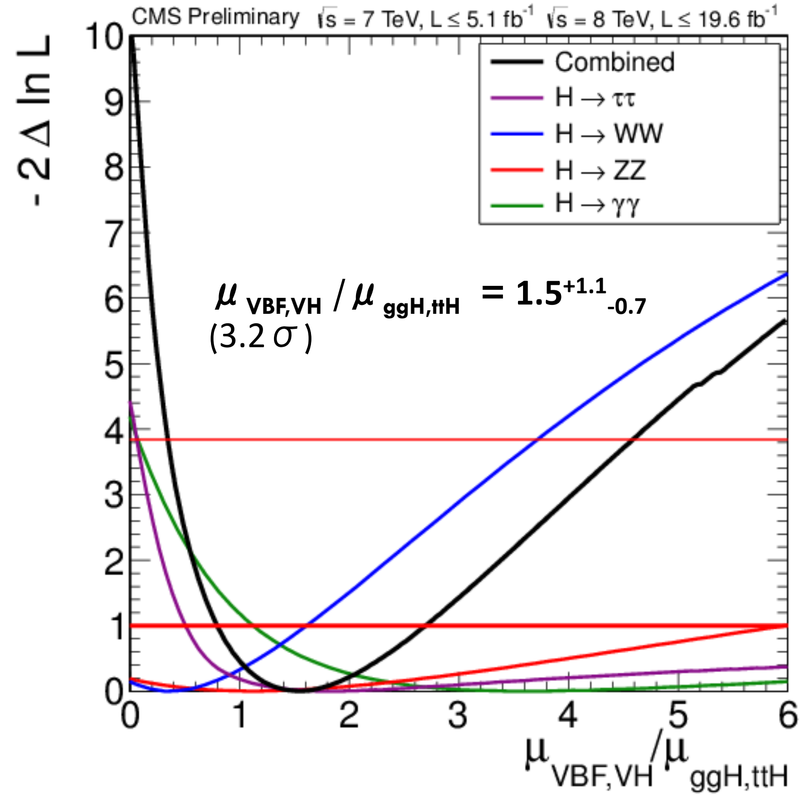


- Scale fermion-mediated (ggH & ttH) and vector-boson-mediated (VBF & VH) together.

Production mechanisms

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]



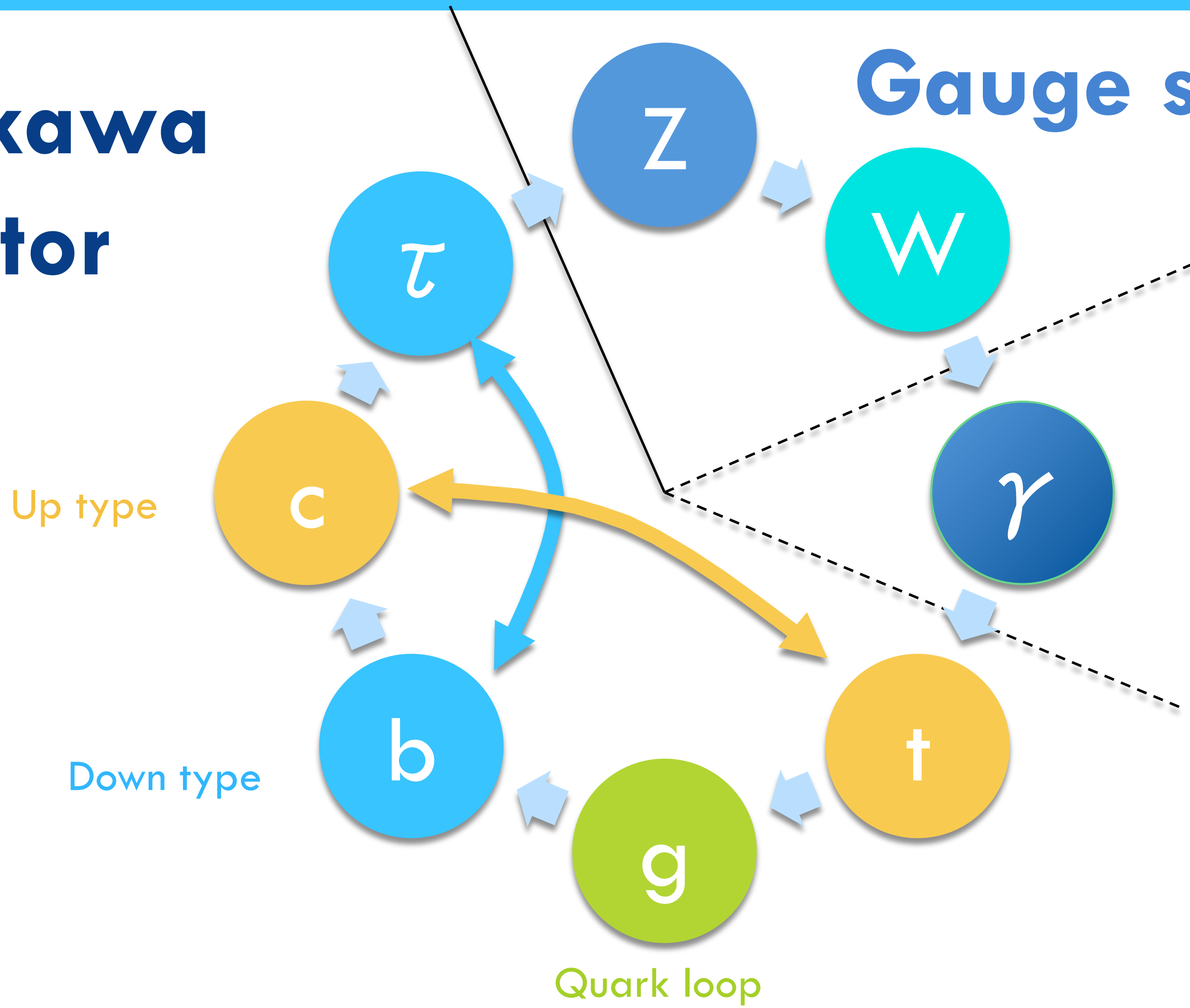


- Ratio of production scaling factors does not depend on decay mode.
  - **> 3 σ evidence for $\mu_{VBF,VH} / \mu_{ggH,ttH}$ > 0 in both experiments.**

Scalar coupling structure

Yukawa sector

Gauge sector



Mixed sector

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

Couplings deviations

[arXiv:1209.0040]

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

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

- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Couplings deviations

[arXiv:1209.0040]

Production modes

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

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

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Total width

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

- Contributions resolved at NLO QCD and LO EWK.
- Peg the as-of-yet unmeasured to "closest of kin".

Weak bosons and fermions

 [arXiv:1209.0040]

Boson and fermion scaling assuming no invisible or undetectable widths

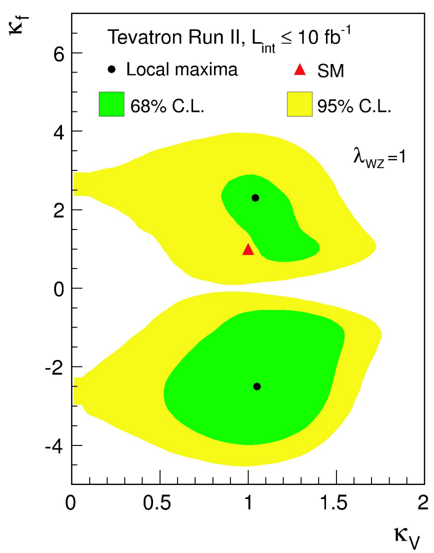
Free parameters: $\kappa_V (= \kappa_W = \kappa_Z), \kappa_f (= \kappa_t = \kappa_b = \kappa_\tau)$.

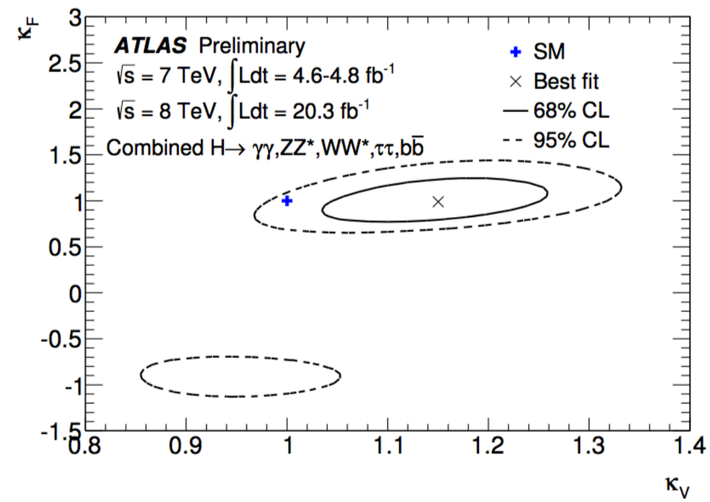
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\frac{\kappa_f^2 \cdot \kappa_\gamma^2(\kappa_f, \kappa_f, \kappa_f, \kappa_V)}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_f^2 \cdot \kappa_V^2}{\kappa_H^2(\kappa_i)}$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

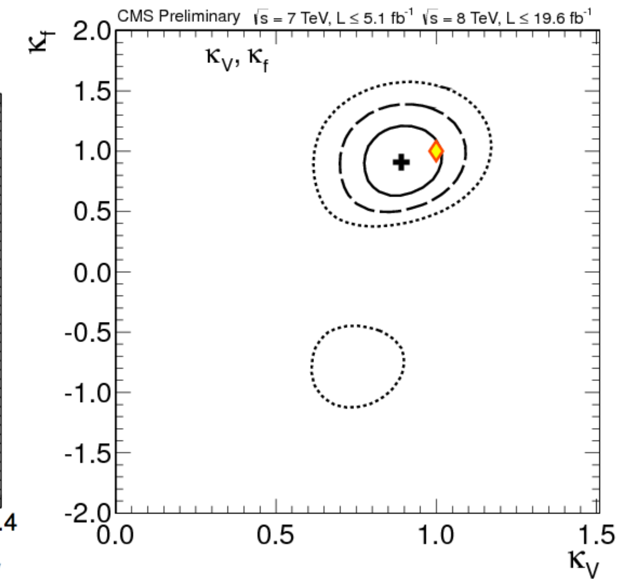
$H \to \gamma\gamma$ resolved into top-loop, b-loop, τ-loop, and W-loop.

Weak bosons and fermions

[arXiv:1303.6346] [ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]







	Tevatron	ATLAS	CMS
p(SM)	**-**	**10%**	**< 1 σ**

Composite (R.Contino)

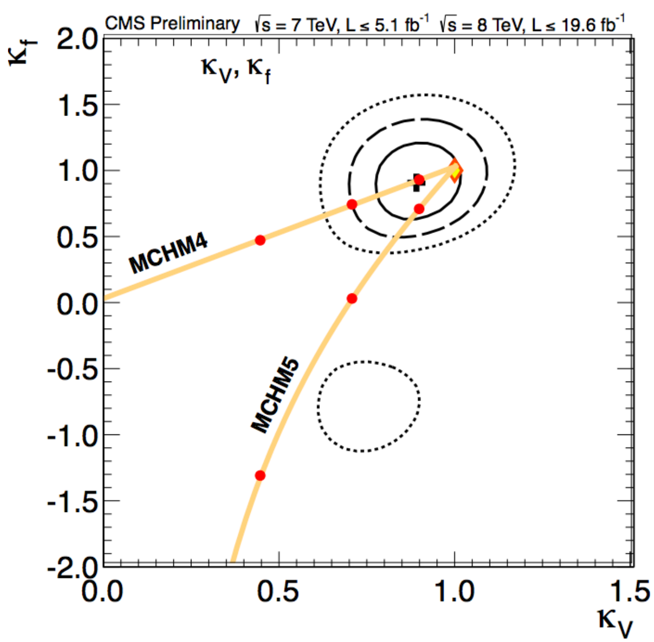
[http://cern.ch/go/W96V]

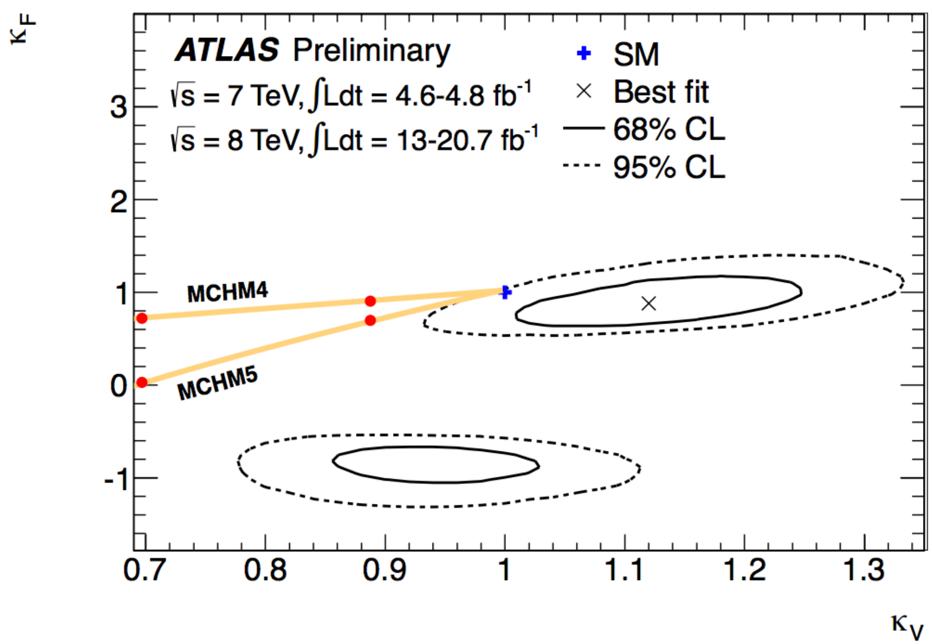
- Leading effects in tree-level couplings and Zγ rate

$$c_V, c_u, c_d = 1 + O\left(\frac{v^2}{f^2}\right) \qquad \frac{\Gamma(h \to Z\gamma)}{\Gamma_{SM}} = 1 + O\left(\frac{v^2}{f^2}\right)$$

f = Higgs decay constant

$$m_{\text{new}} = g_* f \lesssim 4\pi f$$

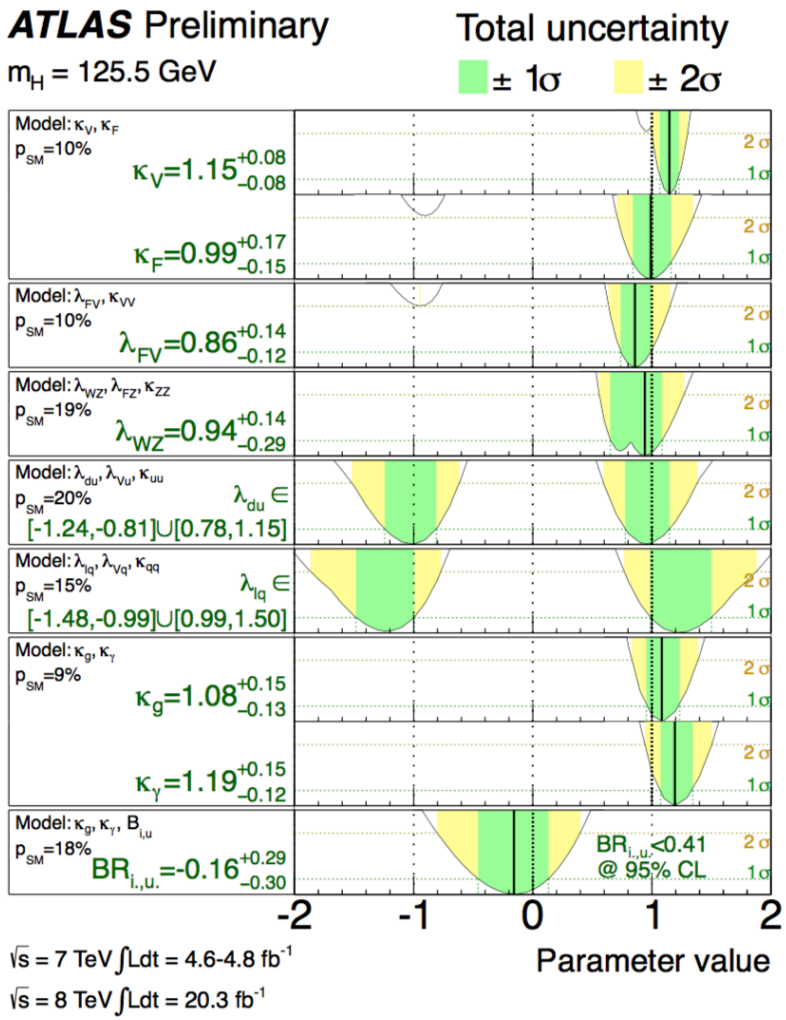


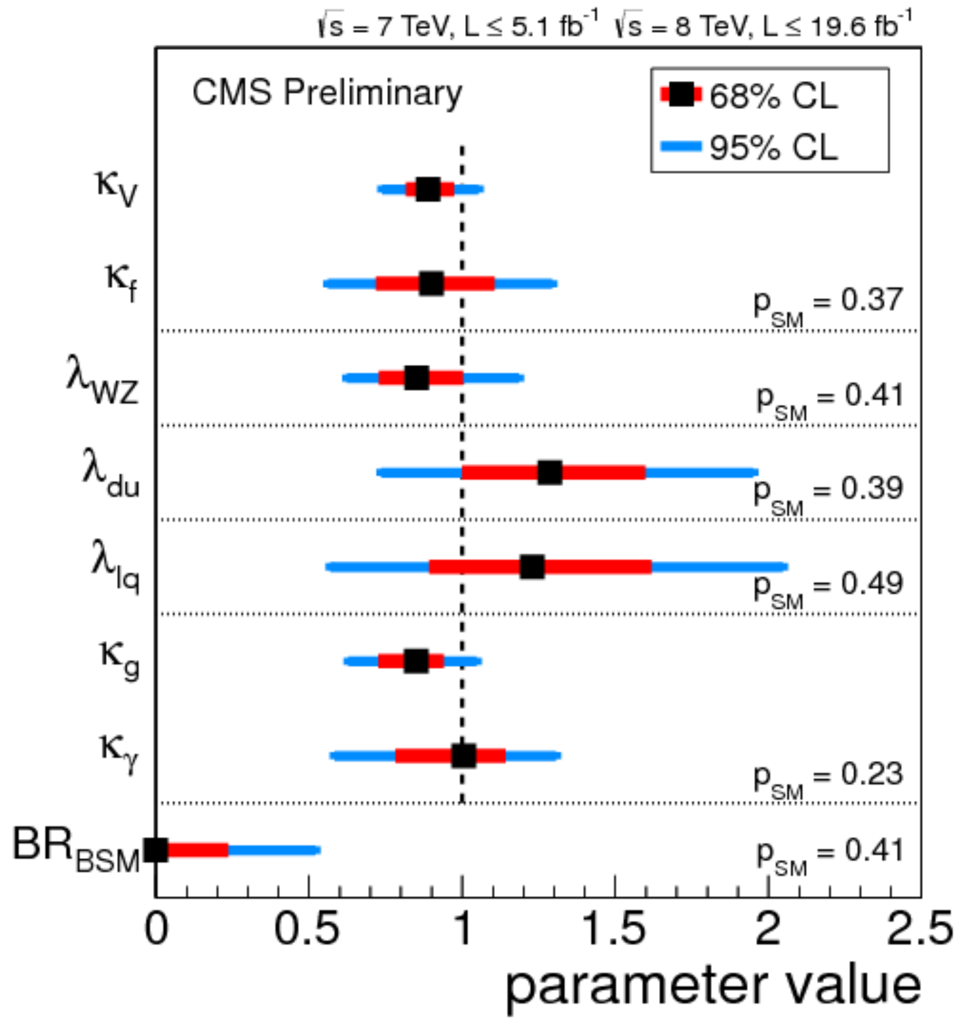


Red points at $(v/f)^2 = 0.2,\ 0.5,\ 0.8$

The deviations that we do not (yet) see

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





Spin is so much more than a number

[arXiv:1208.4018]

- The spin-2 amplitude has many (higher-order) terms:

$$
\begin{aligned}
A(X \to V_1 V_2) = \Lambda^{-1} \Big[& 2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu} \frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)} \frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu} \left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha} \right) \\
& + g_4^{(2)} \frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2 \left(2g_5^{(2)} t_{\mu\nu} \epsilon_1^{*\mu} \epsilon_2^{*\nu} + 2g_6^{(2)} \frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu} \left(\epsilon_1^{*\nu} \epsilon_2^{*\alpha} - \epsilon_1^{*\alpha} \epsilon_2^{*\nu} \right) + g_7^{(2)} \frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu} \epsilon_1^* \epsilon_2^* \right) \\
& + g_8^{(2)} \frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} \tilde{f}^{*(2)}_{\alpha\beta} + m_V^2 \left(g_9^{(2)} \frac{t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^2} \epsilon_{\mu\nu\rho\sigma} \epsilon_1^{*\nu} \epsilon_2^{*\rho} q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha} \tilde{q}^\alpha}{\Lambda^4} \epsilon_{\mu\nu\rho\sigma} q^\rho \tilde{q}^\sigma \left(\epsilon_1^{*\nu} (q\epsilon_2^*) + \epsilon_2^{*\nu} (q\epsilon_1^*) \right) \right) \Big] ,
\end{aligned}
\tag{18}
$$

Spin is so much more than a number

[arXiv:1208.4018]

- The spin-2 amplitude has many (higher-order) terms:

$$A(X \to V_1 V_2) = \Lambda^{-1}\Big[2g_1^{(2)} t_{\mu\nu} f^{*(1)\mu\alpha} f^{*(2)\nu\alpha} + 2g_2^{(2)} t_{\mu\nu}\frac{q_\alpha q_\beta}{\Lambda^2} f^{*(1)\mu\alpha} f^{*(2)\nu\beta} + g_3^{(2)}\frac{\tilde{q}^\beta \tilde{q}^\alpha}{\Lambda^2} t_{\beta\nu}\left(f^{*(1)\mu\nu} f^{*(2)}_{\mu\alpha} + f^{*(2)\mu\nu} f^{*(1)}_{\mu\alpha}\right)$$
$$+ g_4^{(2)}\frac{\tilde{q}^\nu \tilde{q}^\mu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta} f^{*(2)}_{\alpha\beta} + m_V^2\left(2g_5^{(2)} t_{\mu\nu}\epsilon_1^{*\mu}\epsilon_2^{*\nu} + 2g_6^{(2)}\frac{\tilde{q}^\mu q_\alpha}{\Lambda^2} t_{\mu\nu}\left(\epsilon_1^{*\nu}\epsilon_2^{*\alpha} - \epsilon_1^{*\alpha}\epsilon_2^{*\nu}\right) + g_7^{(2)}\frac{\tilde{q}^\mu \tilde{q}^\nu}{\Lambda^2} t_{\mu\nu}\epsilon_1^*\epsilon_2^*\right)$$
$$+ g_8^{(2)}\frac{\tilde{q}_\mu \tilde{q}_\nu}{\Lambda^2} t_{\mu\nu} f^{*(1)\alpha\beta}\tilde{f}^{*(2)}_{\alpha\beta} + m_V^2\left(g_9^{(2)}\frac{t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^2}\epsilon_{\mu\nu\rho\sigma}\epsilon_1^{*\nu}\epsilon_2^{*\rho}q^\sigma + \frac{g_{10}^{(2)} t_{\mu\alpha}\tilde{q}^\alpha}{\Lambda^4}\epsilon_{\mu\nu\rho\sigma}q^\rho\tilde{q}^\sigma\left(\epsilon_1^{*\nu}(q\epsilon_2^*) + \epsilon_2^{*\nu}(q\epsilon_1^*)\right)\right)\Big], \quad (18)$$

- Keep only dim-4 terms ($g_1 = g_5 \neq 0$):
  - Graviton-like "couplings" (2^+_m).

J^P: a simplified picture

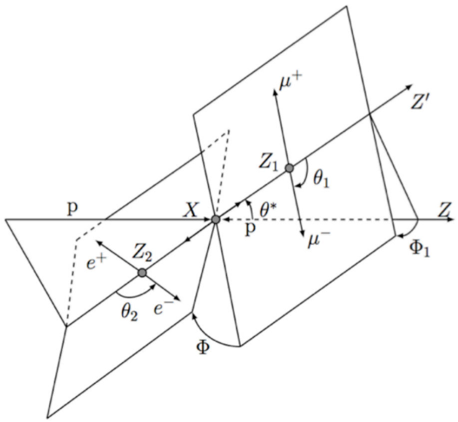
[arXiv:1208.4018]

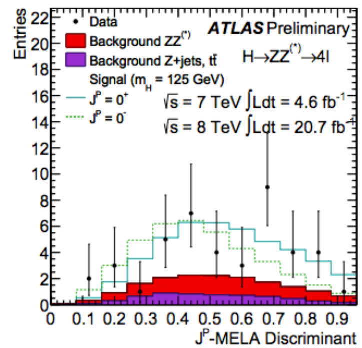
- **Until there is enough data, perform pairwise hypothesis tests against SMH (0^+).**
- Select models using simplifying assumptions on amplitudes:
  - 0^- (parity) "from" ZZ.
  - 2^+_m (graviton-like minimal couplings) also "from" WW and $\gamma\gamma$.

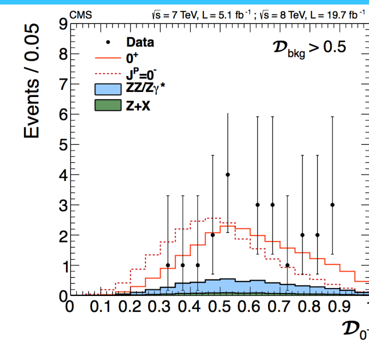
scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$
0^+_m vs background	5.0	5.0	5.0
0^+_m vs 0^+_h	1.7	1.1	0.0
0^+_m vs 0^-	2.9	1.2	0.0
0^+_m vs 1^+	1.9	2.0	–
0^+_m vs 1^-	2.6	3.2	–
0^+_m vs 2^+_m	1.5	2.8	2.4
0^+_m vs 2^+_h	∼5	1.1	3.1
0^+_m vs 2^-_h	∼5	2.5	3.1

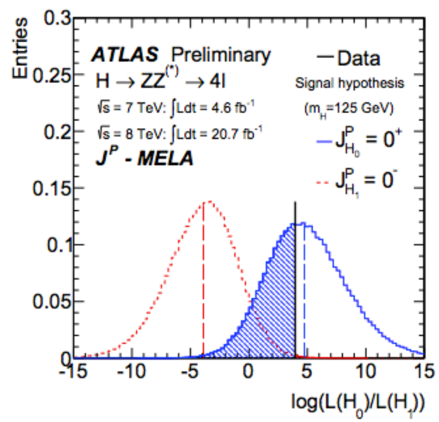
Parity: H⟶ZZ⟶4ℓ

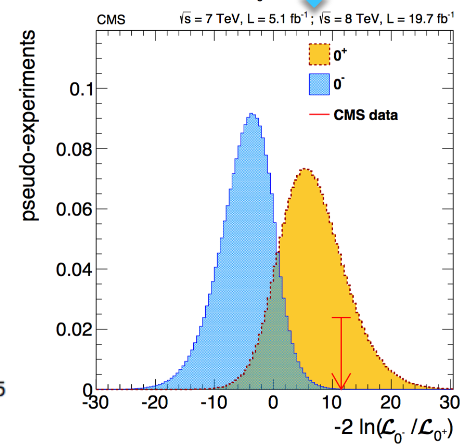
[ATLAS-CONF-2013-013] [arXiv:1312.5353]









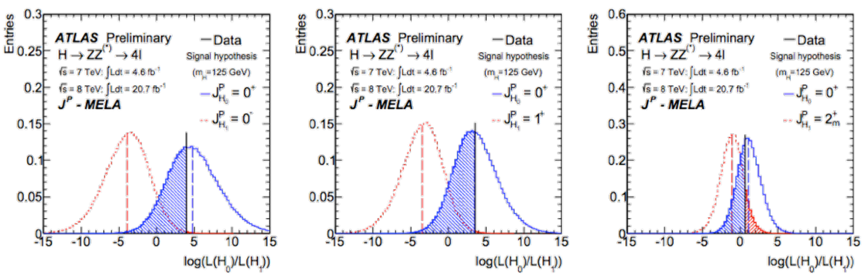


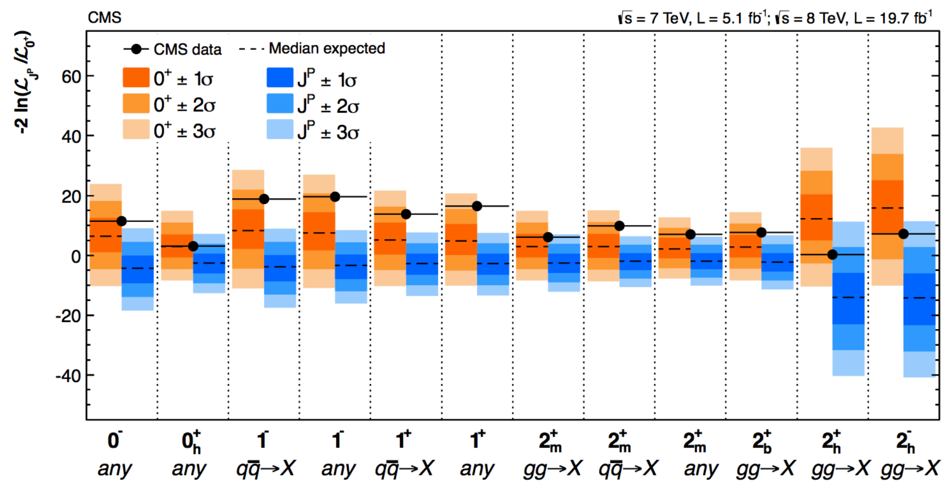
- Discriminants built from decay angles and invariant masses.
- Profiled likelihood ratio test statistic.
  - CL_S criterion protects against fluctuations from null hypothesis.

	ATLAS	CMS
CL_S	**0.37%**	**0.09%**
P(obs.|0^+)	0.2 σ	-0.9 σ
P(obs.|0^-)	2.8σ	3.6 σ

Other J^P in $H \longrightarrow ZZ \longrightarrow 4\ell$

[ATLAS-CONF-2013-013] [arXiv:1312.5353]





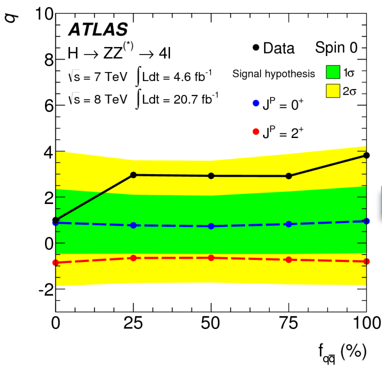
		J^P-MELA analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_s
		expected	observed	observed*	
0^-	p_0	0.0011	0.0022	0.40	0.004
1^+	p_0	0.0031	0.0028	0.51	0.006
1^-	p_0	0.0010	0.027	0.11	0.031
2^+_m	p_0	0.064	0.11	0.38	0.182
2^-	p_0	0.0032	0.11	0.08	0.116

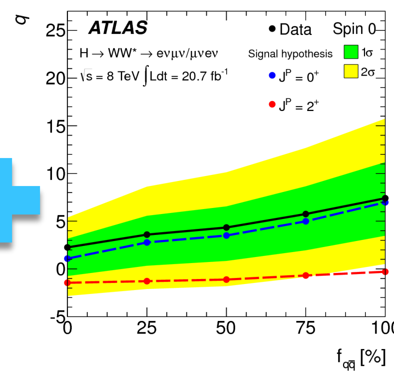
J^P model	J^P production	Expected ($\mu = 1$)	Obs. 0^+	Obs. J^P	CL_s
0^-	any	2.4σ (2.7σ)	-0.9σ	$+3.6\sigma$	0.09%
0^+_h	any	1.7σ (1.9σ)	-0.0σ	$+1.8\sigma$	7.1%
1^-	$q\bar{q} \to X$	2.6σ (2.7σ)	-1.4σ	$+4.8\sigma$	0.001%
1^-	any	2.6σ (2.6σ)	-1.7σ	$+4.9\sigma$	0.001%
1^+	$q\bar{q} \to X$	2.1σ (2.3σ)	-1.5σ	$+4.1\sigma$	0.03%
1^+	any	2.0σ (2.1σ)	-1.9σ	$+4.5\sigma$	0.01%
2^+_m	$gg \to X$	1.7σ (1.8σ)	-0.8σ	$+2.6\sigma$	1.9%
2^+_m	$q\bar{q} \to X$	1.6σ (1.7σ)	-1.6σ	$+3.6\sigma$	0.03%
2^+_m	any	1.5σ (1.5σ)	-1.3σ	$+3.0\sigma$	1.4%
2^+_b	$gg \to X$	1.6σ (1.8σ)	-1.2σ	$+3.1\sigma$	0.9%
2^+_h	$gg \to X$	3.7σ (4.0σ)	$+1.8\sigma$	$+1.9\sigma$	3.1%
2^-_h	$gg \to X$	4.0σ (4.5σ)	$+1.0\sigma$	$+3.0\sigma$	1.7%

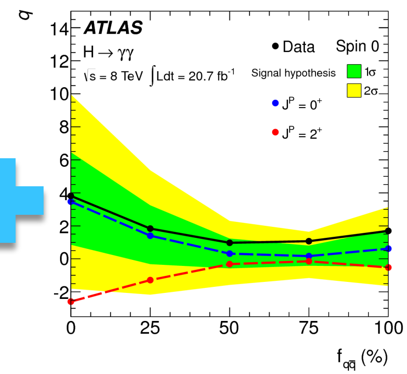
	ATLAS	CMS
Worse CL_s for $J \neq 0$	< 18.2%	< 3.1%

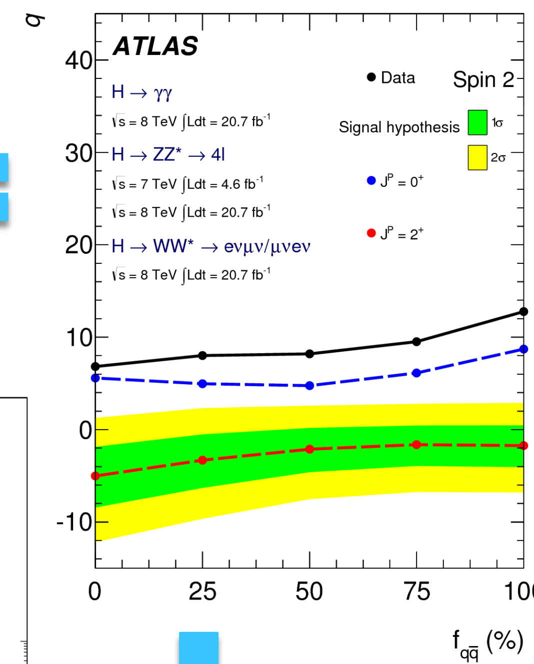
ATLAS: combination against 2^+_m

[arXiv:1307.1432]

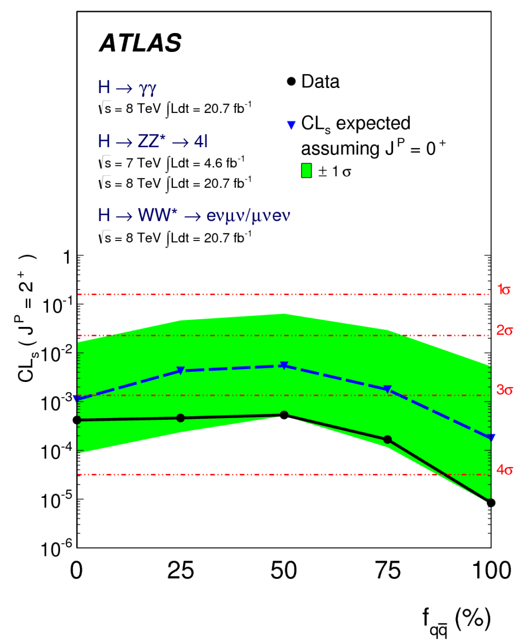








- Combined H⟶ZZ, WW, and $\gamma\gamma$.
- Scan for fraction of $(gg/q\bar{q})\longrightarrow 2^+_m$:
  - **CL_s < 0.06% ∀ $f_{q\bar{q}}$.**



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

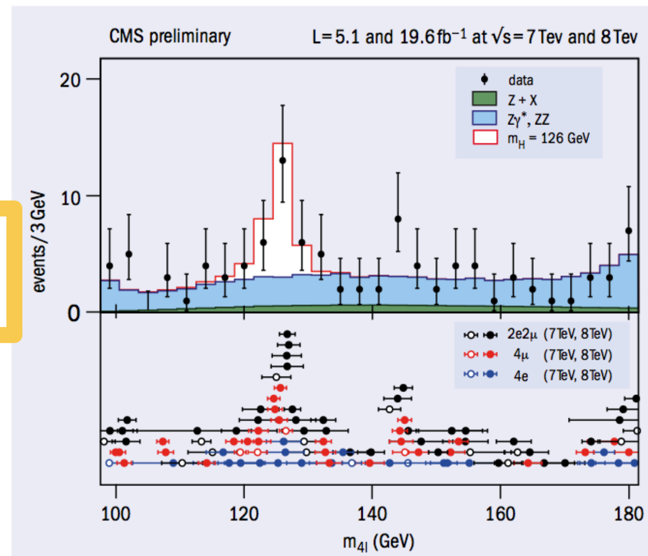
March, giving the particle-physics community enough evidence to name this new boson "a Higgs boson".

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			
$125.8 \pm 0.4 \pm 0.4$	CHATRCHYAN [1]	2013J	CMS	pp , 7 and 8 TeV
$126.0 \pm 0.4 \pm 0.4$	AAD [2]	2012AI	ATLS	pp , 7 and 8 TeV
*** We do not use the following data for averages, fits, limits, etc ***				
$126.2 \pm 0.6 \pm 0.2$	CHATRCHYAN [3]	2013J	CMS	pp , 7 and 8 TeV
$125.3 \pm 0.4 \pm 0.5$	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.

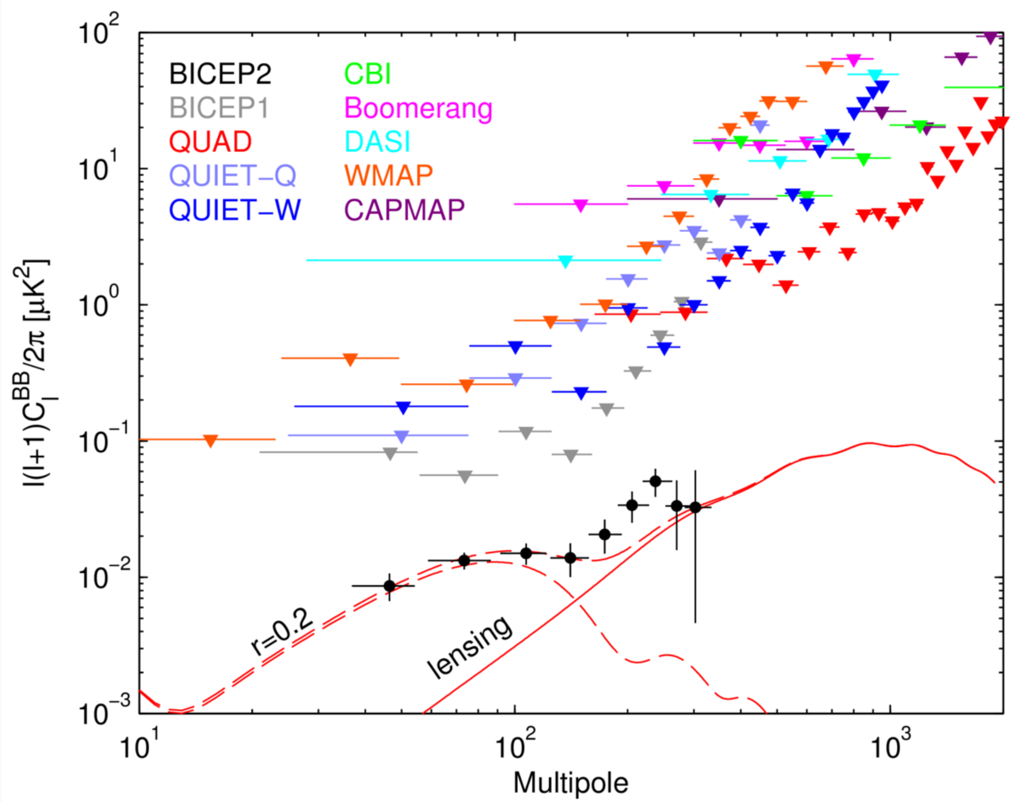
2013: “killer” news

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

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

Flexing your BICEP2 muscles

[arXiv:1403.3985]



Is Higgs Inflation Dead?. (arXiv:1403.4971v1 [astro-ph.CO])

12 hep-ph updates on arXiv.org by Jessica L. Cook, Lawrence M. Krauss, Andrew J. Long, Subir Sabharwal / 1d // keep unread // hide

We consider the status of Higgs Inflation in light of the recently announced detection of B-

... y the BICEP2 ... y BICEP2, the ... ion generally ... al to ask if Higgs ... s essentially no, ... eyond the ... of the original

The Gravitational Wave Background and Higgs False Vacuum Inflation. (arXiv:1403.5244v1 [astro-ph.CO])

1 hep-ph updates on arXiv.org by Isabella Masina / 1d // keep unread // hide

For a narrow band of values of the top quark and Higgs boson masses, the Standard Model Hi... where pr... that banc... is an ass... the tensc... collabora...

Higgs inflation still alive. (arXiv:1403.5043v1 [hep-ph])

5 hep-ph updates on arXiv.org by Yuta Hamada, Hikaru Kawai, Kin-ya Oda, Seong Chan Park / 1d // keep unread // hide

Higgs Chaotic Inflation and the Primordial B-mode Polarization Discovered by BICEP2. (arXiv:1403.4132v2 [hep-ph] UPDATED)

33 hep-ph updates on arXiv.org by Kazunori Nakayama, Fuminobu Takahashi / 4d // keep unread // hide

... ial becomes small ... onsider the Higgs ... ut that the non- ... aller than ten. For ... ich is consistent with

We show that the standard model Higgs field can realize the quadratic chaotic inflation, if the kinetic term is significantly modified at large field values. This is a simple realization of the so-called running kinetic inflation. The point is that the Higgs field respects an approximate shift symmetry at high energy scale. The tensor-to-scalar ratio is predicted to be $r \simeq 0.13 - 0.16$, which nicely explains the primordial B-mode polarization, $r = 0.20^{+0.07}_{-0.05}$, recently discovered by the BICEP2 experiment. In particular, allowing small modulations induced by the shift symmetry breaking, the negative running spectral index can also be induced. The reheating temperature is expected to be so high that successful thermal leptogenesis is possible. The suppressed quartic coupling of the Higgs field at high energy scales may be related to the Higgs chaotic inflation.

- Who knows ?

Who ordered 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

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}	$Z \to b\bar{b}b\bar{b}$	$(3.6 \pm 1.3) \times 10^{-4}$		

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 future in a nutshell

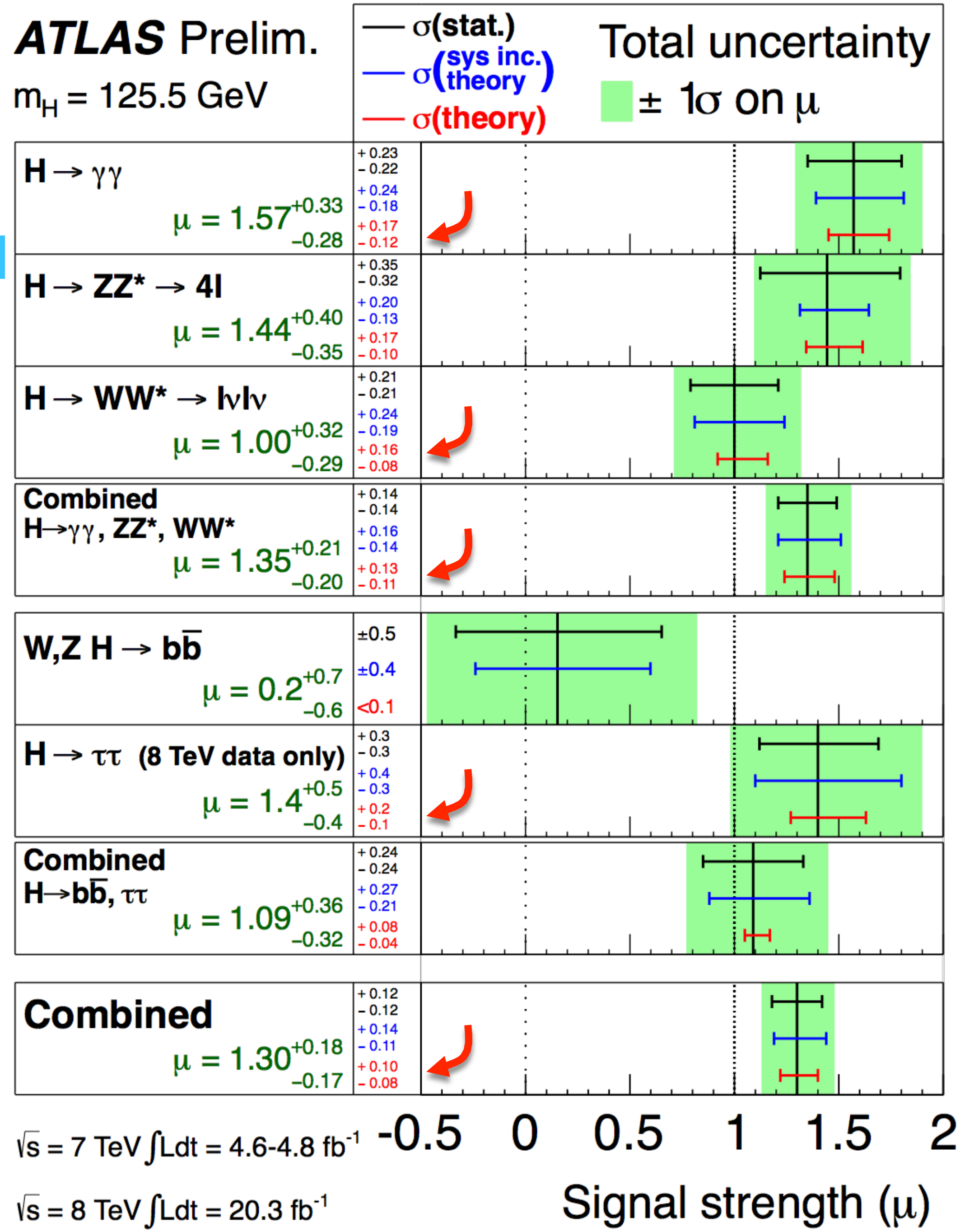
- Boson “solo gigs”:
  - Beyond spin hypotheses tests.
  - Theory uncertainties and ratios.
  - The adventure of unfolding: going differential.
  - Statistics-limited: ttH, tH, invisible.
  - Total width interferometry.
  - Loops and rare decays: $Z\gamma$, $\gamma\gamma$, full Dalitz, $\mu\mu$.
  - Weird decays: vector mesons, t→cH FCNC, etc.
- Boson & friends:
  - Small deviations: from the κ-framework to Wilson coefficients.
  - Global electroweak picture: EWPD, Higgs, and aTGCs.

- **Caveats:**
  - Not directly discussing beyond-one-doublet alternatives: extra singlet, MSSM, 2HDM, nMSSM, triplet and double charged, etc.
    - **They need searching as well !**
  - Not discussing parity, which is a definitely not a closed case.

Theory uncertainties

[ATLAS-CONF-2014-009]

- PDFs not dominating on μ .
  - ggH vs VBF+VH.
  - PDF4LHC prescription too conservative?
  - PDG $\sigma(\alpha_s)$ too aggressive?
- NNLO+NNLL not enough to tame large QCD corrections in gluon-fusion?



Theory uncertainties: MHOU

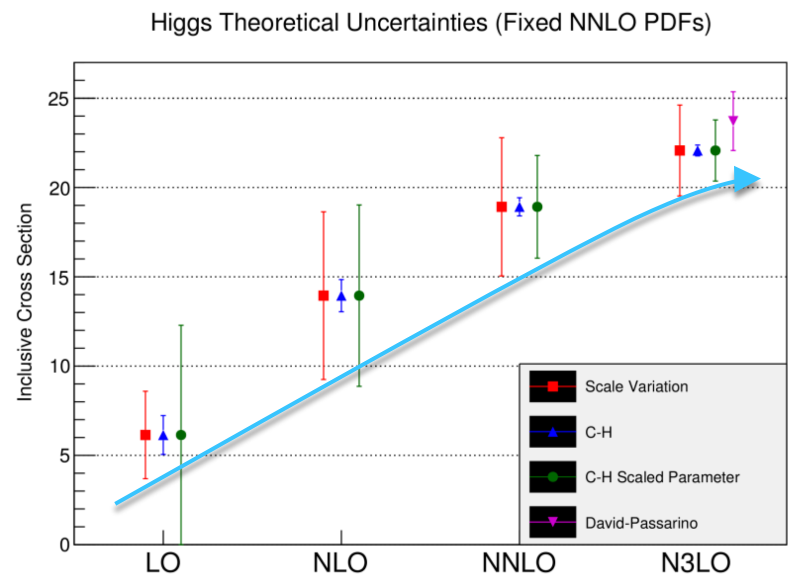
[arXiv:1307.1843] [http://cern.ch/go/V8xJ]

- Scale variations are not theory uncertainties.
- **The uncertainty is due to missing higher orders.**

$$\frac{\sigma_{gg}(\sqrt{s}, M_H)}{\sigma^{\mathrm{LO}}_{gg}(\sqrt{s}, M_H)} = 1 + \sum_{n=1}^{\infty} \alpha_s^n(\mu_R)\, K^n_{gg}(\sqrt{s}, \mu = M_H)$$

8 TeV	$\mu = M_H/2$	$\mu = M_H$	$\mu = 2M_H$
K^1_{gg}		11.879	
K^2_{gg}		72.254	
K^3_{gg}	168.98 ± 30.87	377.20 ± 30.78	681.72 ± 29.93

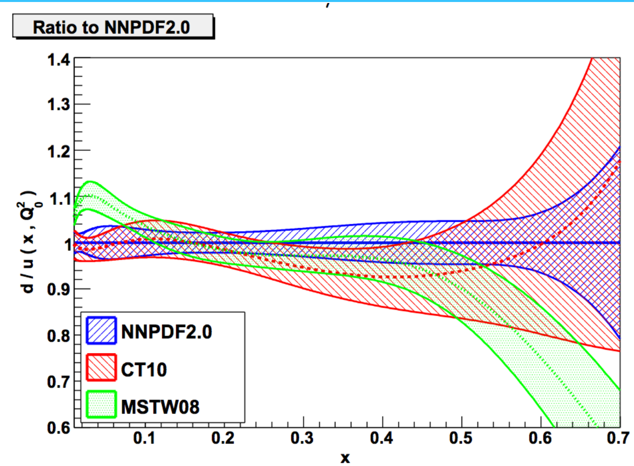
- Take gluon-gluon fusion:
  - All series terms are positive.
  - We can try and complete the series instead of **always** being off.

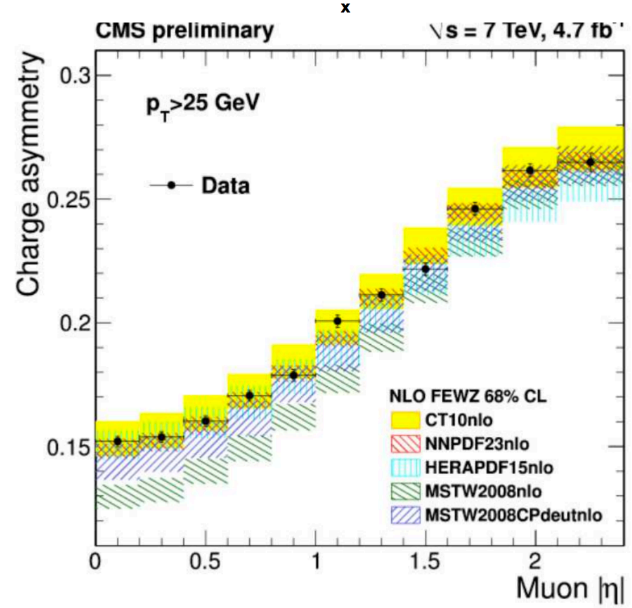


Theory uncertainties: a tale of PDFs

[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.

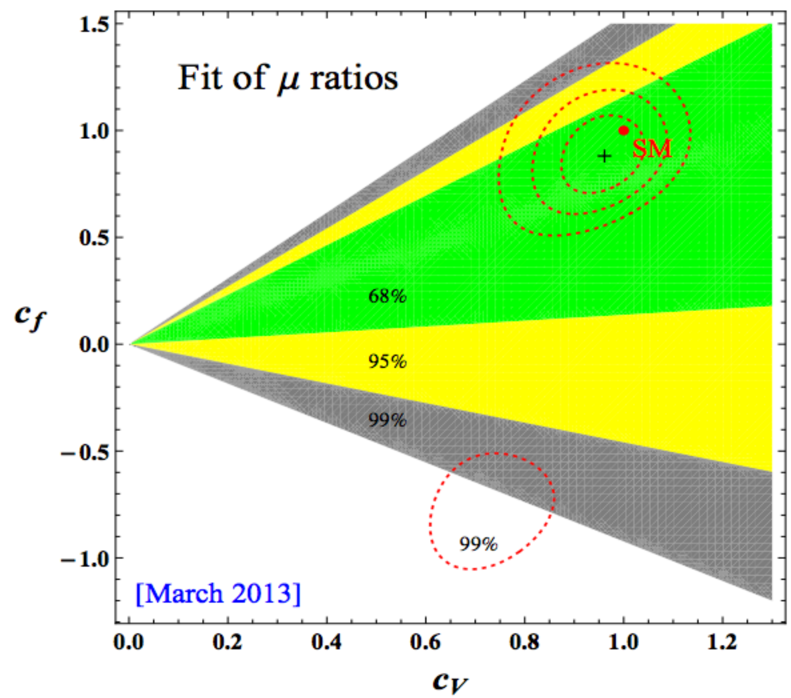
- Or you can try to dodge them with ratios…

Ratios to the rescue?

[arXiv:1303.6591] [http://cern.ch/go/gLP9]

- Total width not accessible at the LHC
  - More on that later.
- Idea: take ratios and cancel out the TH uncertainties.
- But this is naïve:
  THU only cancel if the phase-space probed is exactly the same.
- **More statistics allows for exactly matched kinematics.**

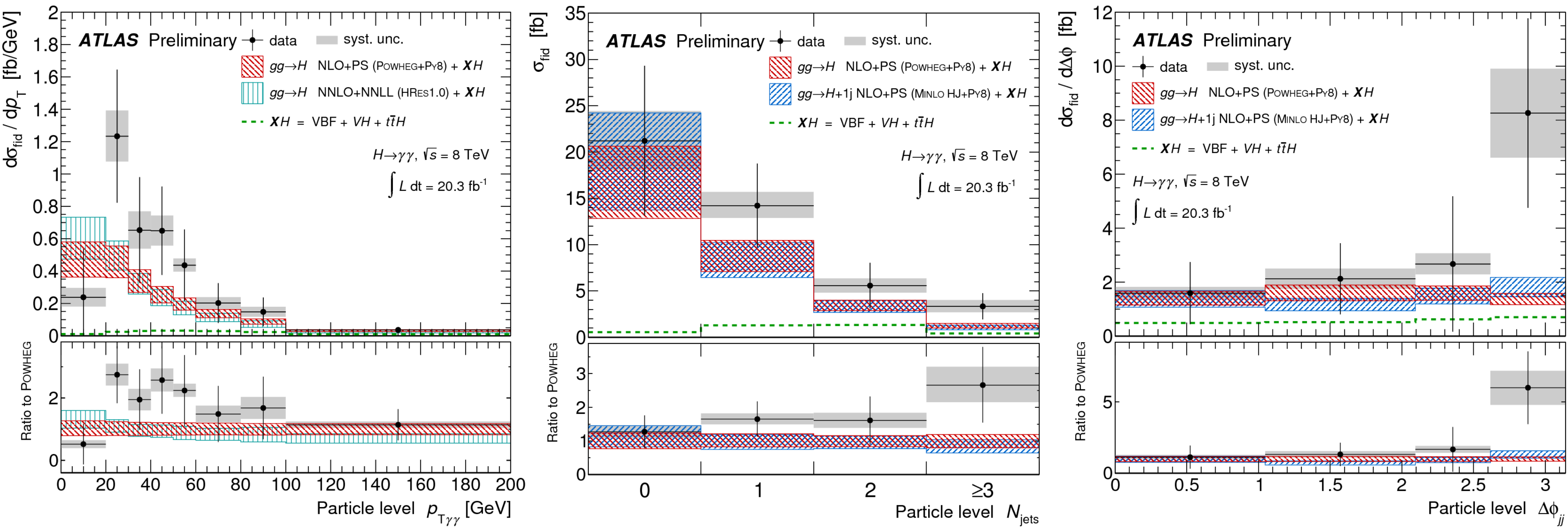
$$D_{XX} \hat{=} \frac{\mu_{XX}}{\mu_{VV}} \simeq \frac{\frac{\sigma(pp\to H)\times \mathrm{BR}(H\to XX)}{\sigma(pp\to H)|_{\mathrm{SM}}\times \mathrm{BR}(H\to XX)|_{\mathrm{SM}}}}{\frac{\sigma(pp\to H)\times \mathrm{BR}(H\to VV)}{\sigma(pp\to H)|_{\mathrm{SM}}\times \mathrm{BR}(H\to VV)|_{\mathrm{SM}}}} = \frac{\frac{\mathrm{BR}(H\to XX)}{\mathrm{BR}(H\to XX)|_{\mathrm{SM}}}}{\frac{\mathrm{BR}(H\to VV)}{\mathrm{BR}(H\to VV)|_{\mathrm{SM}}}} = \frac{\frac{\Gamma(H\to XX)}{\Gamma(H\to XX)|_{\mathrm{SM}}}}{\frac{\Gamma(H\to VV)}{\Gamma(H\to VV)|_{\mathrm{SM}}}} = \frac{|c_X|^2}{|c_V|^2}$$



Differential distributions

[ATLAS-CONF-2013-072]

- 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→$\gamma\gamma$ result and the adventure of unfolding.
  - Illustrates the power of having more statistics (signal-like excess).



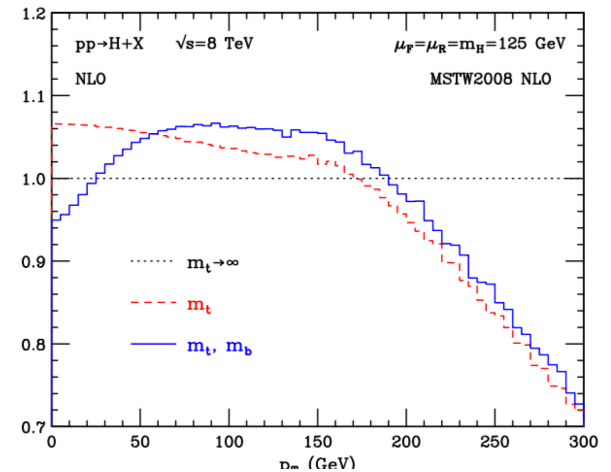
Boosted Higgs + Ratios

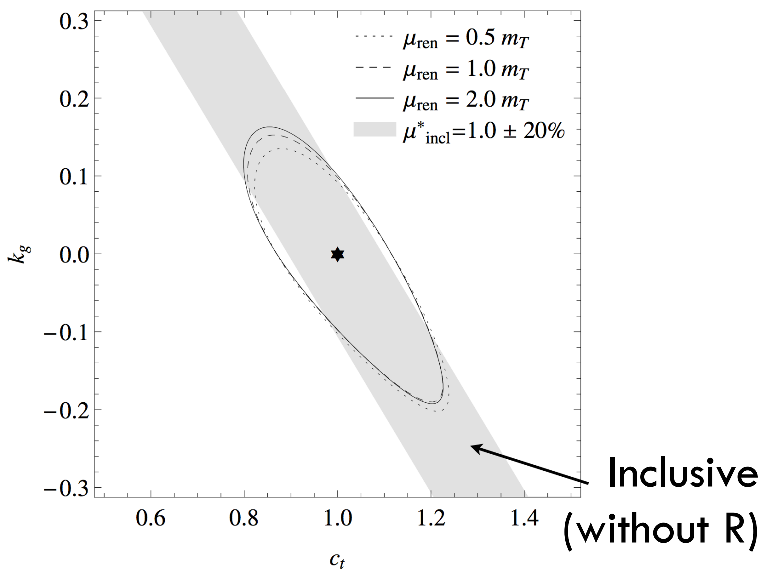
[arXiv:1306.4581] [http://cern.ch/go/lqB8]

- $p_T(H)$ sensitive to the loop particle masses.
  - m_b intrinsically ill-defined.
- Idea: check $p_T(H)$ in H+j and use THU "cancelling":

$$\mathcal{R}(c_t, k_g) = \frac{\sigma_{650\,\text{GeV}}}{\sigma_{150\,\text{GeV}}}(c_t, k_g)\frac{K_{650}}{K_{150}}$$

  - But it's a 3000/fb venture.





Oversimplified big picture

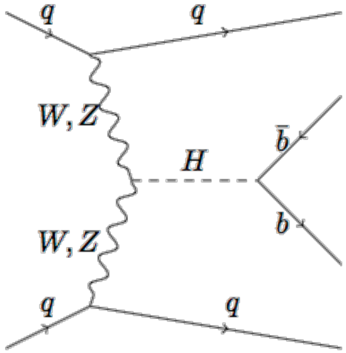
T – Tevatron; A – ATLAS; C – CMS; recent results in red.

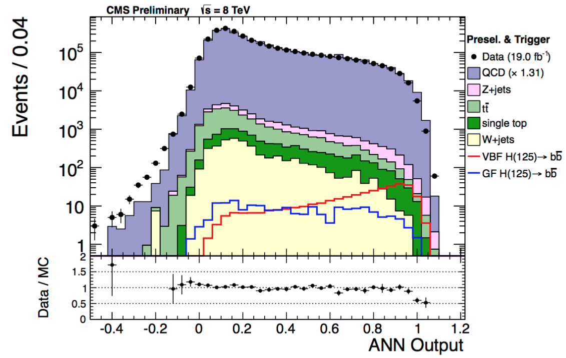
★ "seen" ☆ "tried" - "impossible"	H→bb̄			H→ττ			H→WW			H→ZZ			H→γγ			H→Zγ			H→inv.			H→μμ			H→cc̄ H→HH		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	☆	★	☆	★	★	☆	★	★	☆	★	★	-	☆	☆ (red)	-	-	-	-	☆	☆ (red)	-		
VBF			☆ (red)	☆	☆	★		★	★		★	☆		★	☆	-		☆ (red)			☆ (red)	-		☆ (red)	-		
VH	★	☆ (red)	★	☆		☆	☆	☆ (red)	☆		☆			☆	☆	-				☆ (red)	☆ (red)	-			-		
ttH		☆	☆	☆		☆ (red)	☆		☆ (red)			☆ (red)		☆ (red)	☆ (red)	-						-			-		

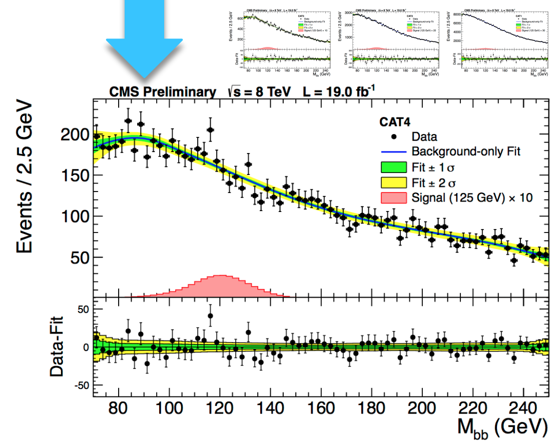
- **Still much to explore on the rarer ends.**
  (to the right and to the bottom) (and outside this picture ☳)

☆ VBF, $H \rightarrow b\bar{b}$

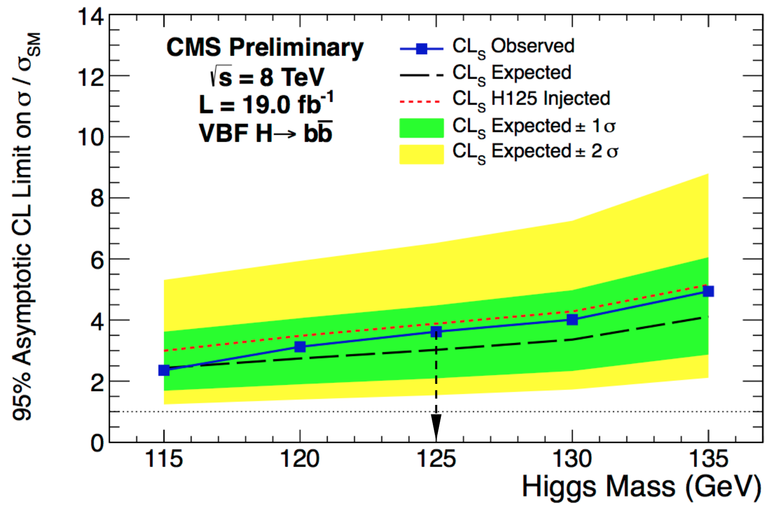
[CMS-PAS-HIG-13-011]







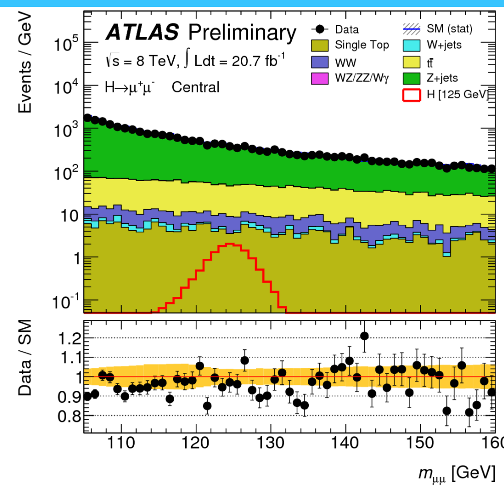
- Neural network event classifier.
- Simultaneous $m_{b\bar{b}}$ fits to 4 ANN categories.
- At m_H=125 GeV, μ **< 3.6 (3.0)** (95%CL), obs.(exp.) or μ **= 0.7 ±1.4.**

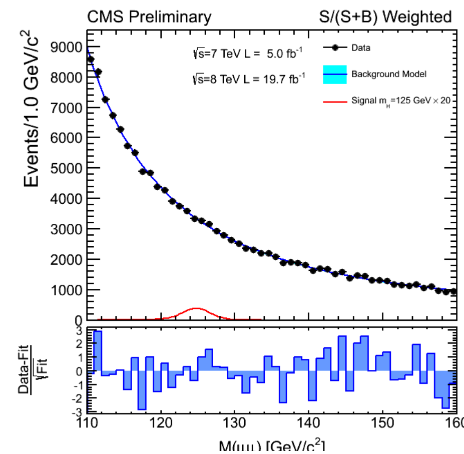


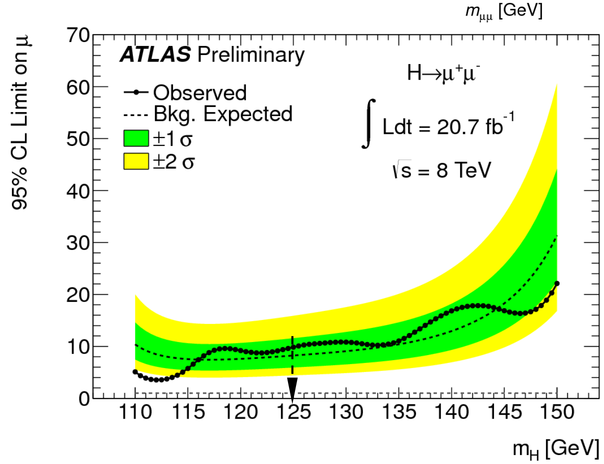
☆ $H \rightarrow \mu\mu$

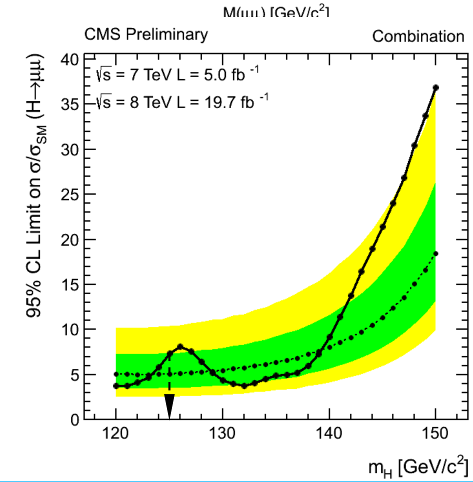
[ATLAS-CONF-2013-010] [CMS-PAS-HIG-13-007]

- Probe coupling to second-generation fermions.
- Very clean final state.
  - CMS also uses dijet category.
- BR < 10^{-4} in the search range.





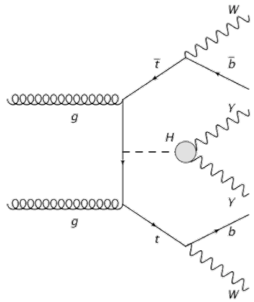




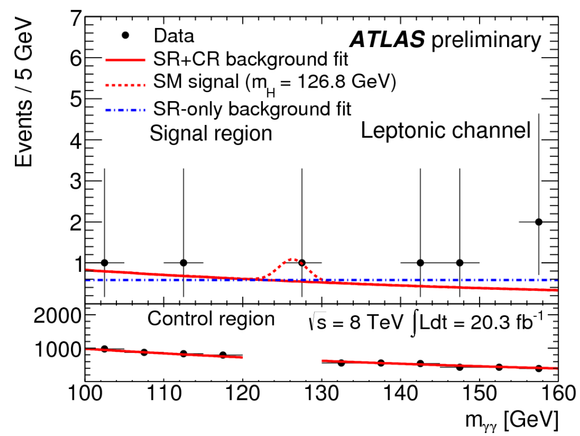
Obs. (exp.)	ATLAS	CMS
μ at 125 GeV (95% CL)	< 9.8 (8.2)	< 7.5 (5.1)

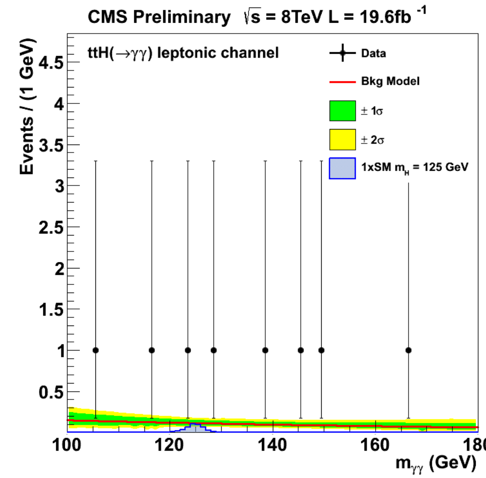
☆ ttH, H→ γ γ

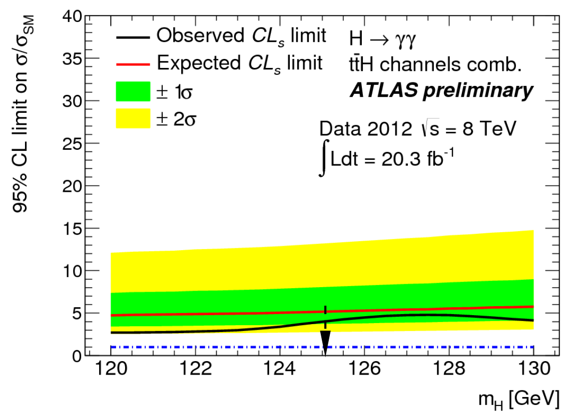
 [ATLAS-CONF-NOTE-2013-080] [CMS-PAS-HIG-13-015]

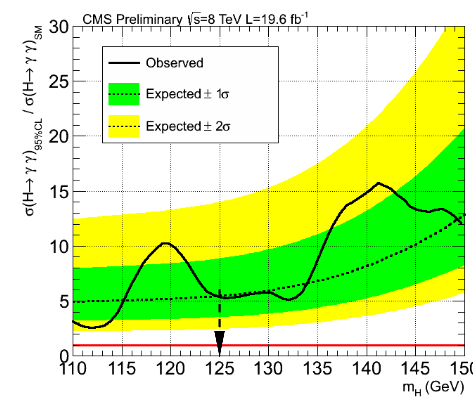


- Tagging of **leptonic** and **hadronic** W decays from top (anti-)quarks.
- Direct access to the top-Higgs coupling.





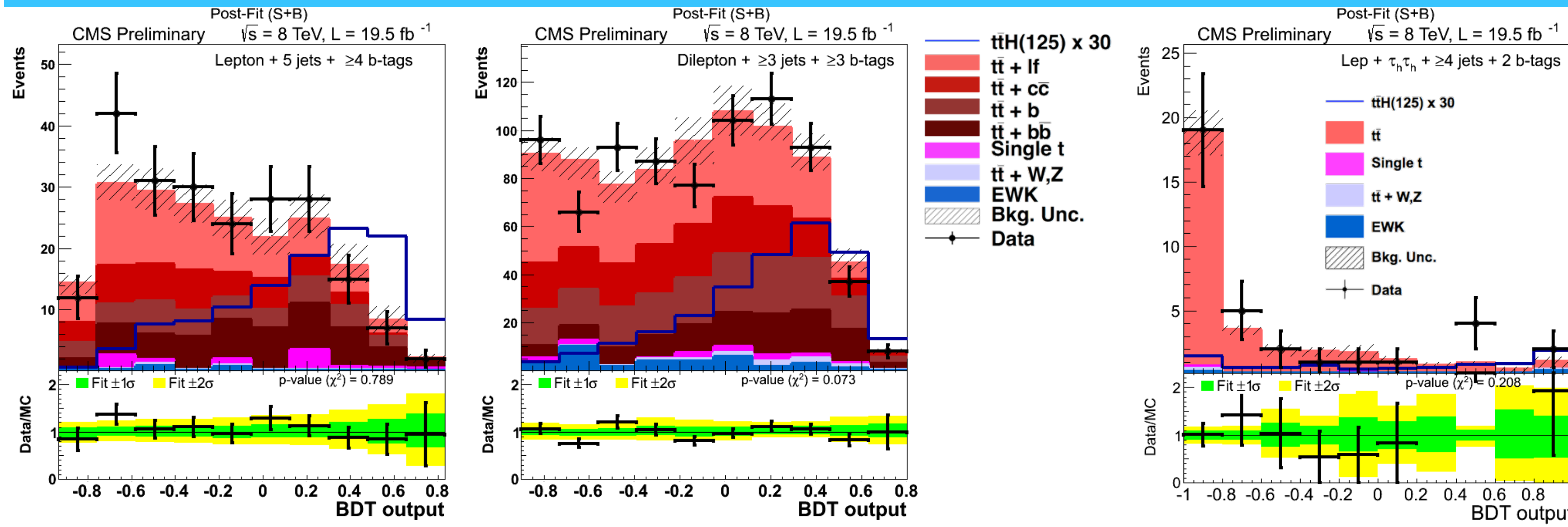




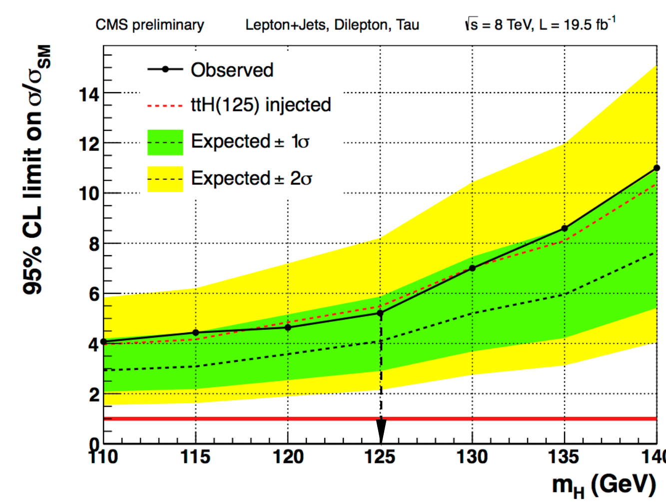
Obs. (exp.)	ATLAS	CMS
μ at 125 GeV (95% CL)	**< 5.3 (6.4)**	**< 5.4 (5.3)**

☆ $t\bar{t}$H, H⟶$b\bar{b}$ or $\tau\ \tau$

[CMS-PAS-HIG-13-019]

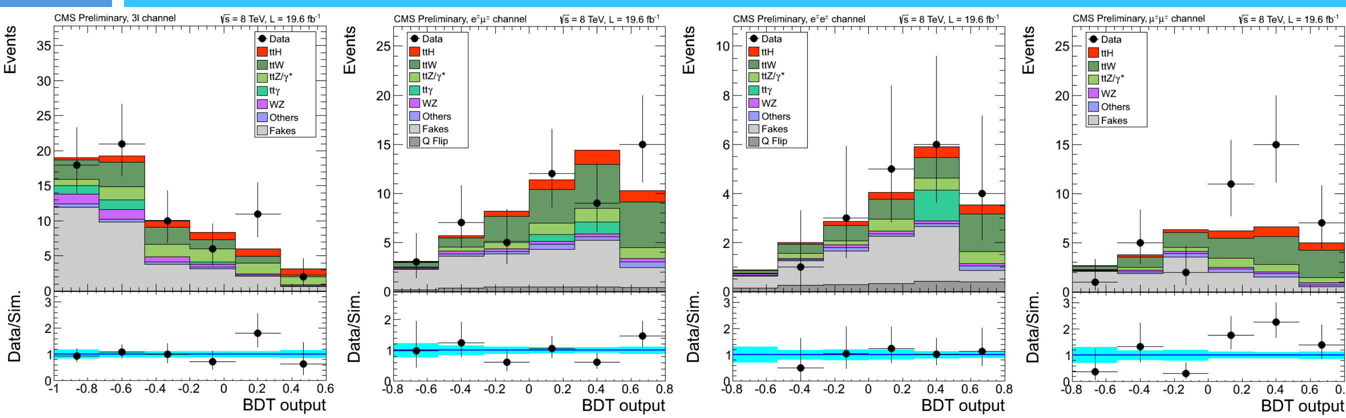


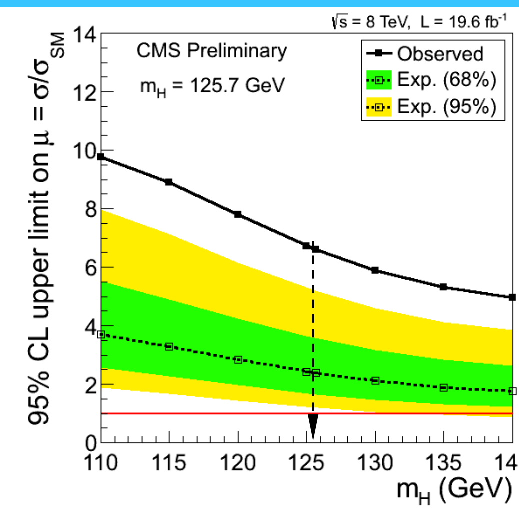
- Three channels:
  - **Lepton+jets:** $t\bar{t} \rightarrow \ell^{\pm}\nu\ qq\ b\bar{b}$, H → $b\bar{b}$.
  - **Dilepton:** $t\bar{t} \rightarrow \ell^{+}\nu\ \ell^{-}\nu\ b\bar{b}$, H → $b\bar{b}$.
  - **Hadronic tau:** $t\bar{t} \rightarrow \ell^{\pm}\nu\ qq\ b\bar{b}$, H → $\tau^{+}\tau^{-}$.
- Categories on number of number of jets and b-tags.
  - Fit to BDT classifier.
- At m_H=125 GeV,
  μ **< 5.2 (4.1)** (95%CL), obs.(exp.) or
  μ **= 0.85 ±2.5.**

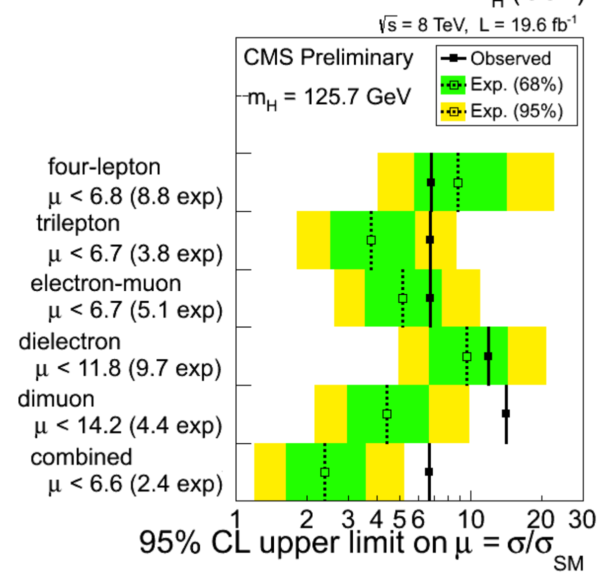


☆ ttH, H⟶multi-leptons

[CMS-PAS-HIG-13-020]





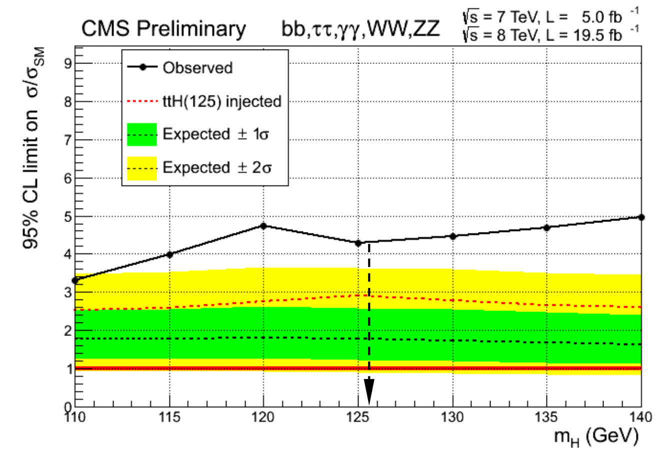


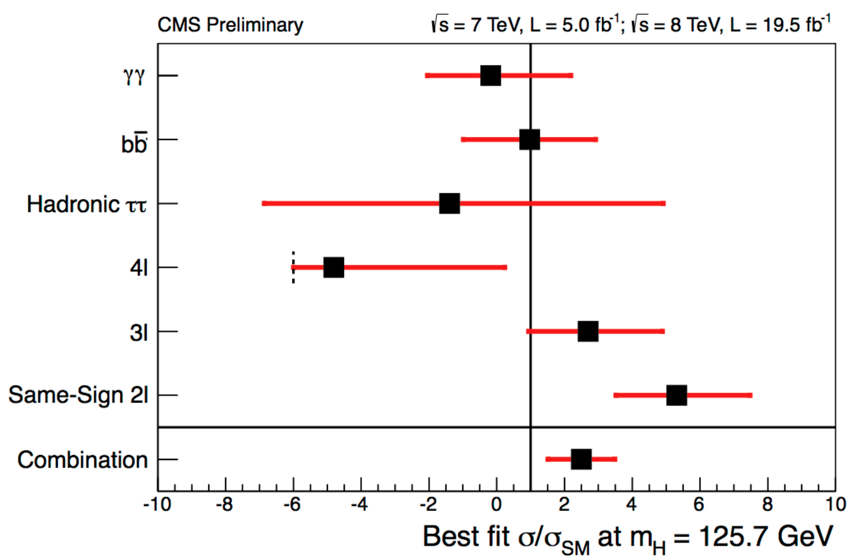
- 4ℓ, 3ℓ, and same-sign 2ℓ.
  - BDT discriminant.
- At m_H=125.7 GeV,
  ***μ* < 6.6 (2.4)** (95%CL), obs.(exp.) or
  ***μ* = 3.7 ±1.6.**
  - *One excess out of how many measurements?*

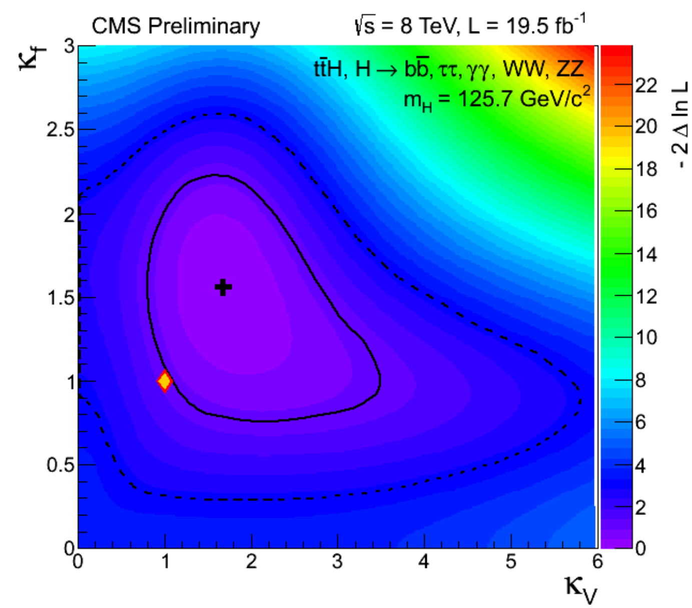
☆ CMS ttH combination

[http://cern.ch/go/vf8d]

- Combine all the channels: $\gamma\gamma$, $b\bar{b}$, $\tau\tau$, and multi-leptons.
- At m_H=125.7 GeV, μ **< 4.3 (1.8)** (95%CL), obs.(exp.) or μ **= 2.5** $^{+1.1}_{-1.0}$.
  - (κ_V, κ_f) compatible with SMH.



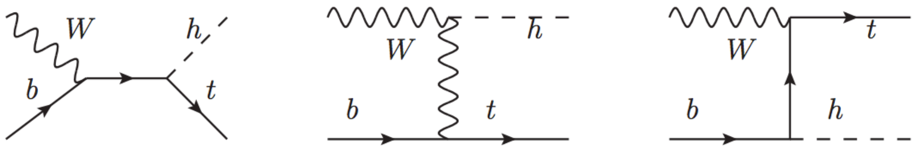




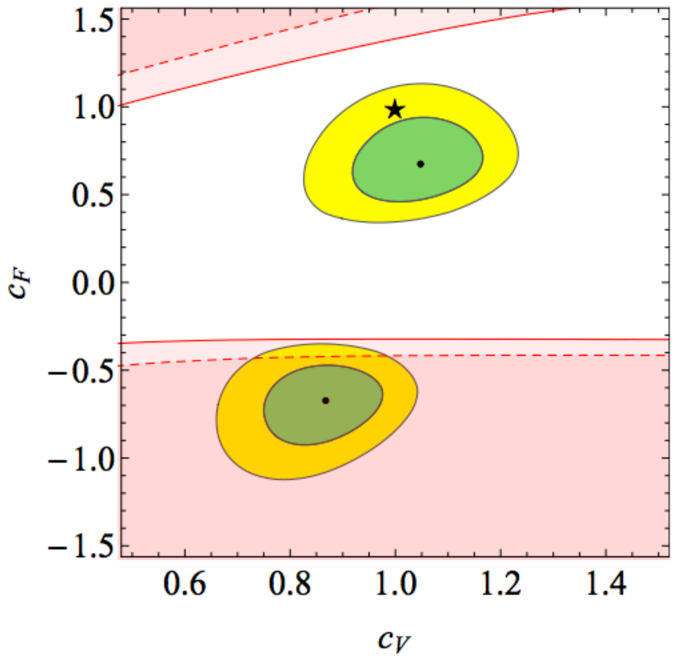
Statistics-limited: tH

[arXiv:1211.3736]

- Interesting added value to the couplings fit.
  - Esp. in the presence of a diphoton excess.

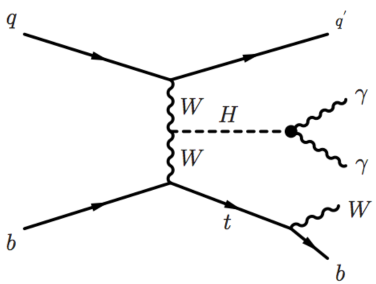


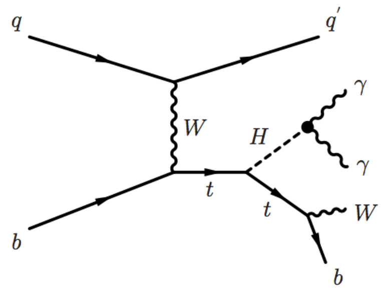
- At the top-Higgs border.
  - TH projection for 14 TeV and 50/fb looks promising.



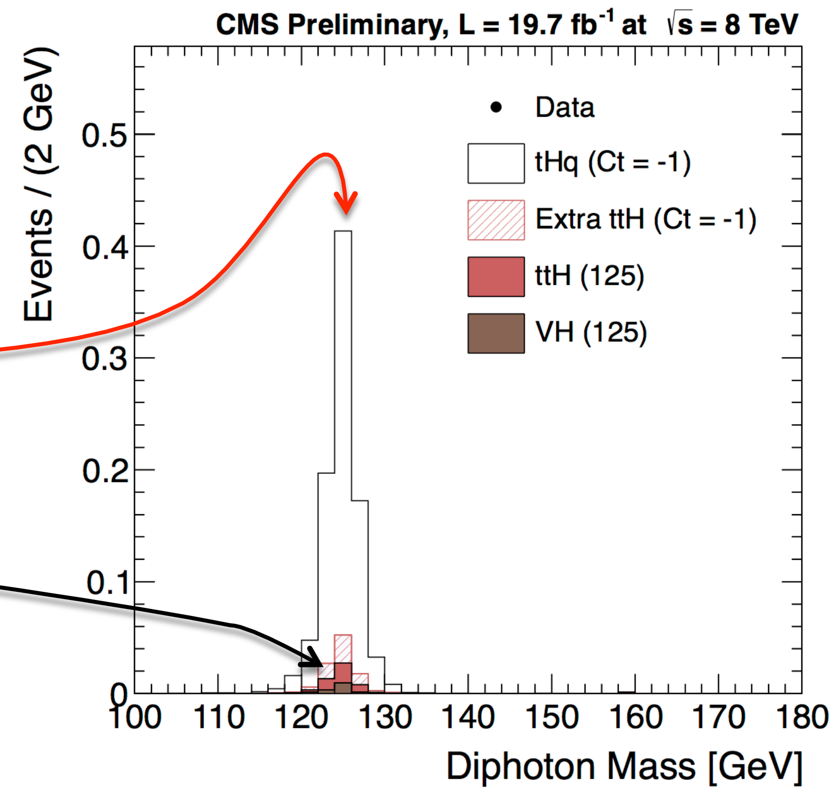
tHq and flipped couplings

[CMS-PAS-HIG-14-001]





- Interference gives sensitivity to sign of $\kappa_t \kappa_W$:
  - In tHq production: **15x SM if flipped**.
  - In $H \longrightarrow \gamma\gamma$ decay: **2x SM if flipped**.
- **SMH now a background !**
- Tight selection against ttH.
  - **No data survives selection.**

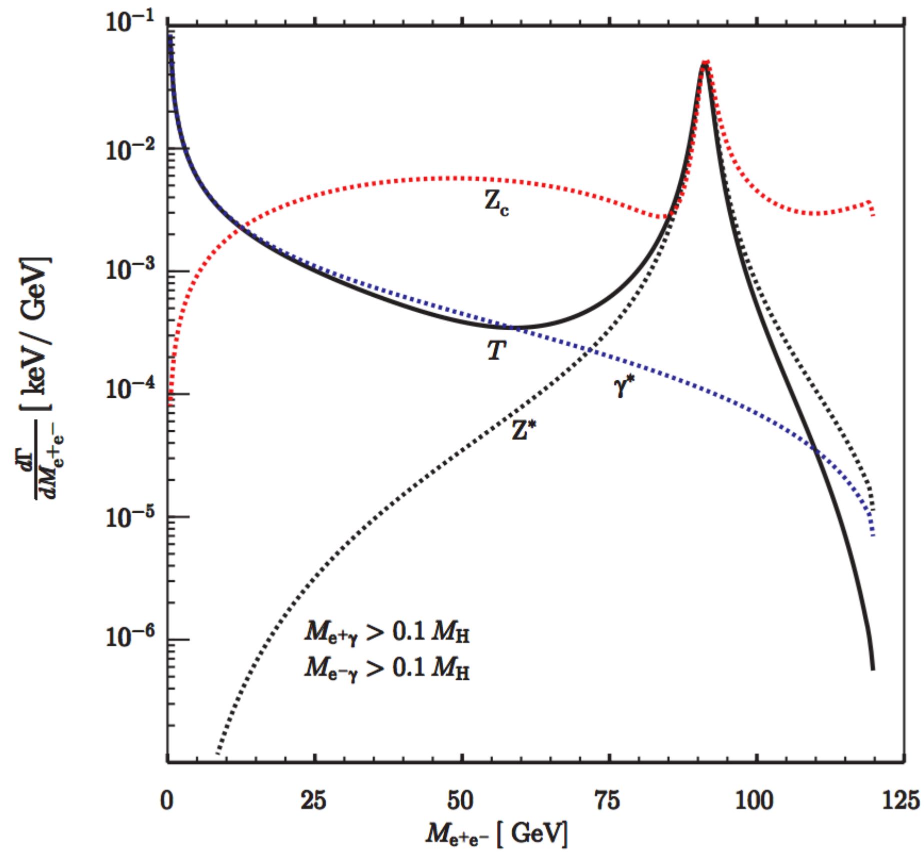


Obs. (exp.)	CMS
μ (κ_t = -1) at 125 GeV (95% CL)	**< 4.1 (4.1)**

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.

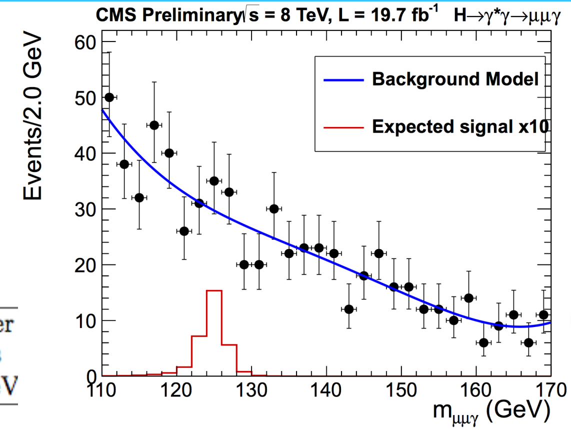


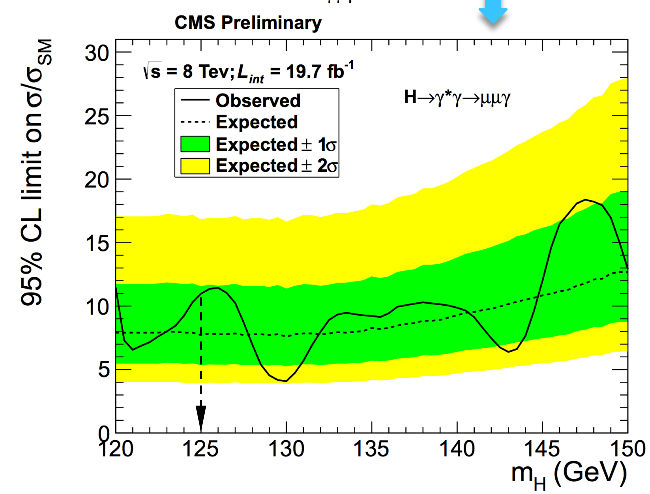
$H \to \gamma^* \gamma \to \ell\ell\gamma$

[CMS-PAS-HIG-14-003]

- $m_{\mu\mu} < 20$ GeV.
- Veto 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

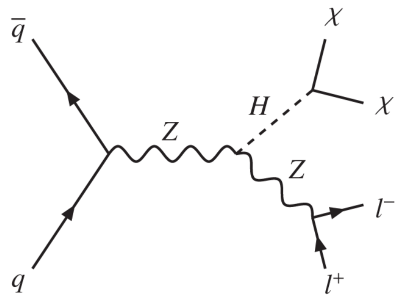




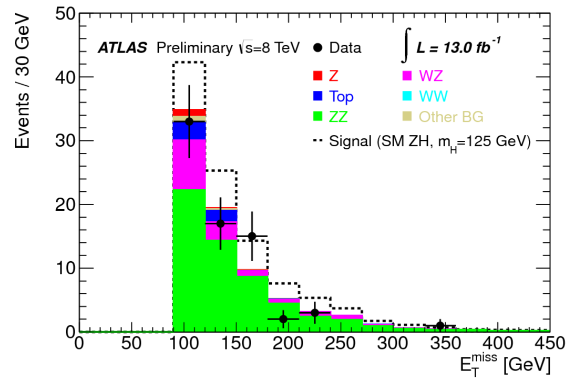
Obs. (exp.)	CMS
μ at 125 GeV (95% CL)	< 11 (8)

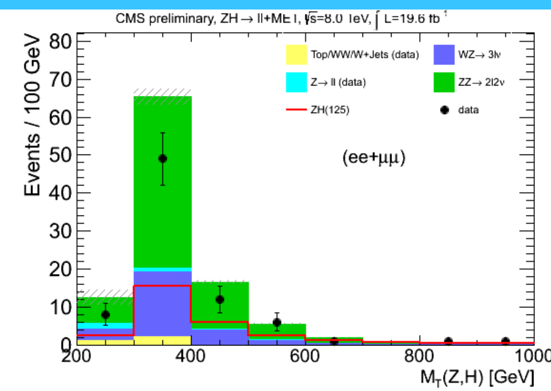
☆ ZH⟶ℓℓ+invisible

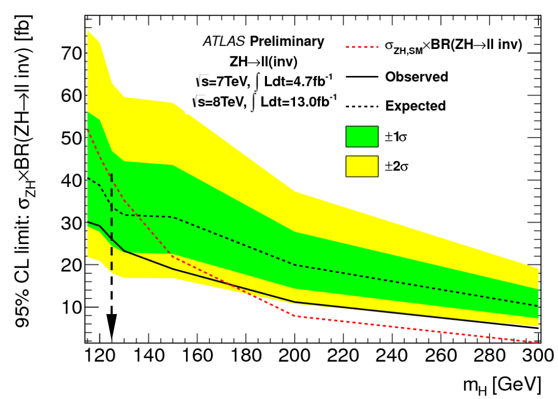
[ATLAS-CONF-2013-011] [CMS-PAS-HIG-13-018]

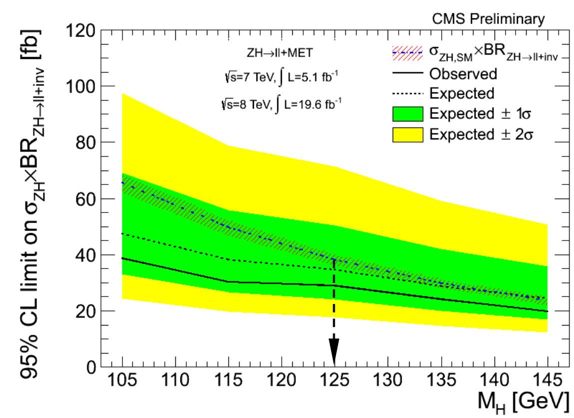


- What if?
- Disentangles *invisible* from *undetectable*.
- Cosmic connection via limits on Dark Matter.
- Also VBF and Z⟶$b\bar{b}$ in CMS.





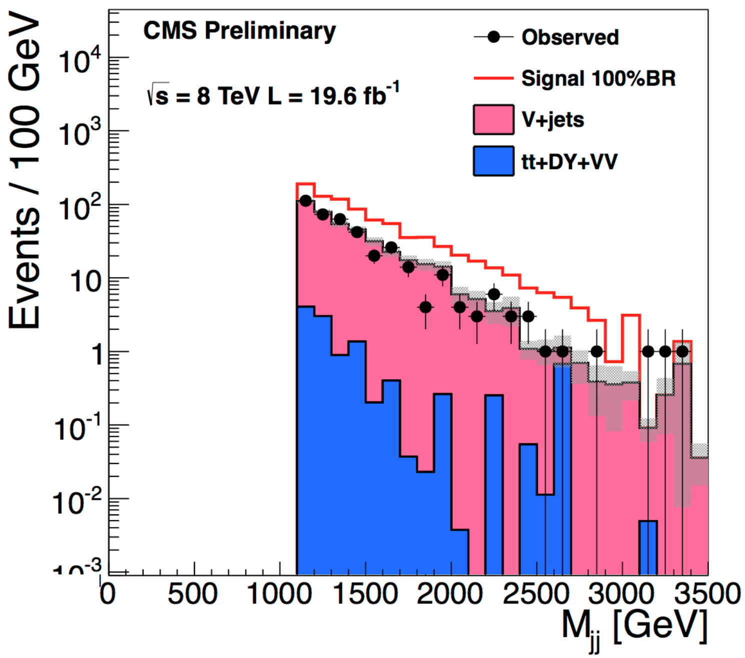


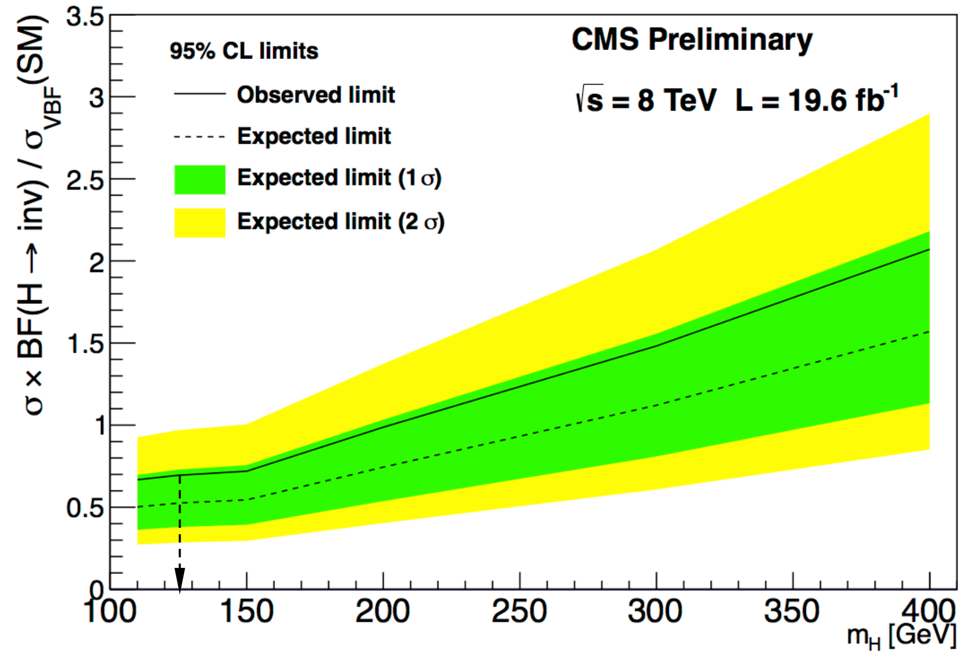


Obs. (exp.)	ATLAS	CMS
$BR_{inv.}$ at 125 GeV (95% CL)	**< 0.65 (0.84)**	**< 0.75 (0.91)**

☆ VBF, H⟶invisible

[CMS-PAS-HIG-13-013]



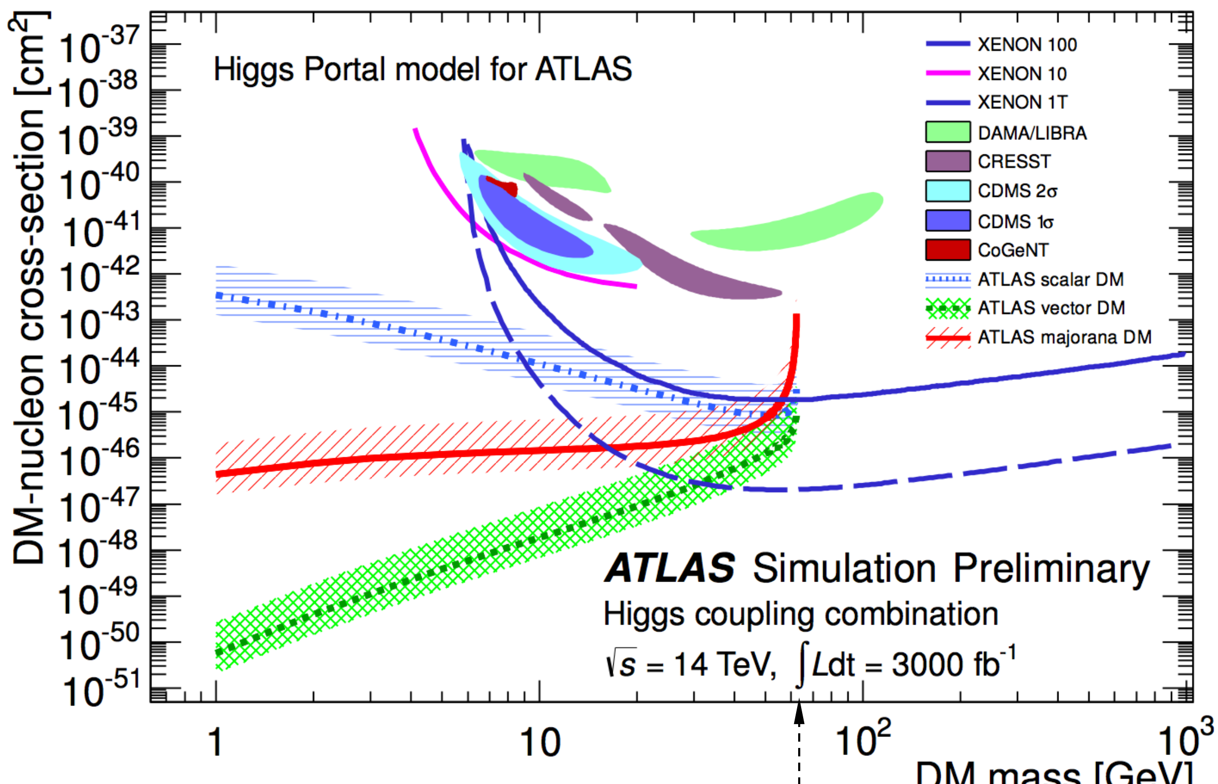


- At m_H=125 GeV, **$BR_{inv.}$ < 0.69 (0.53)** (95%CL), obs.(exp.).

Statistics-limited: invisible

[ATL-PHYS-PUB-2013-015]

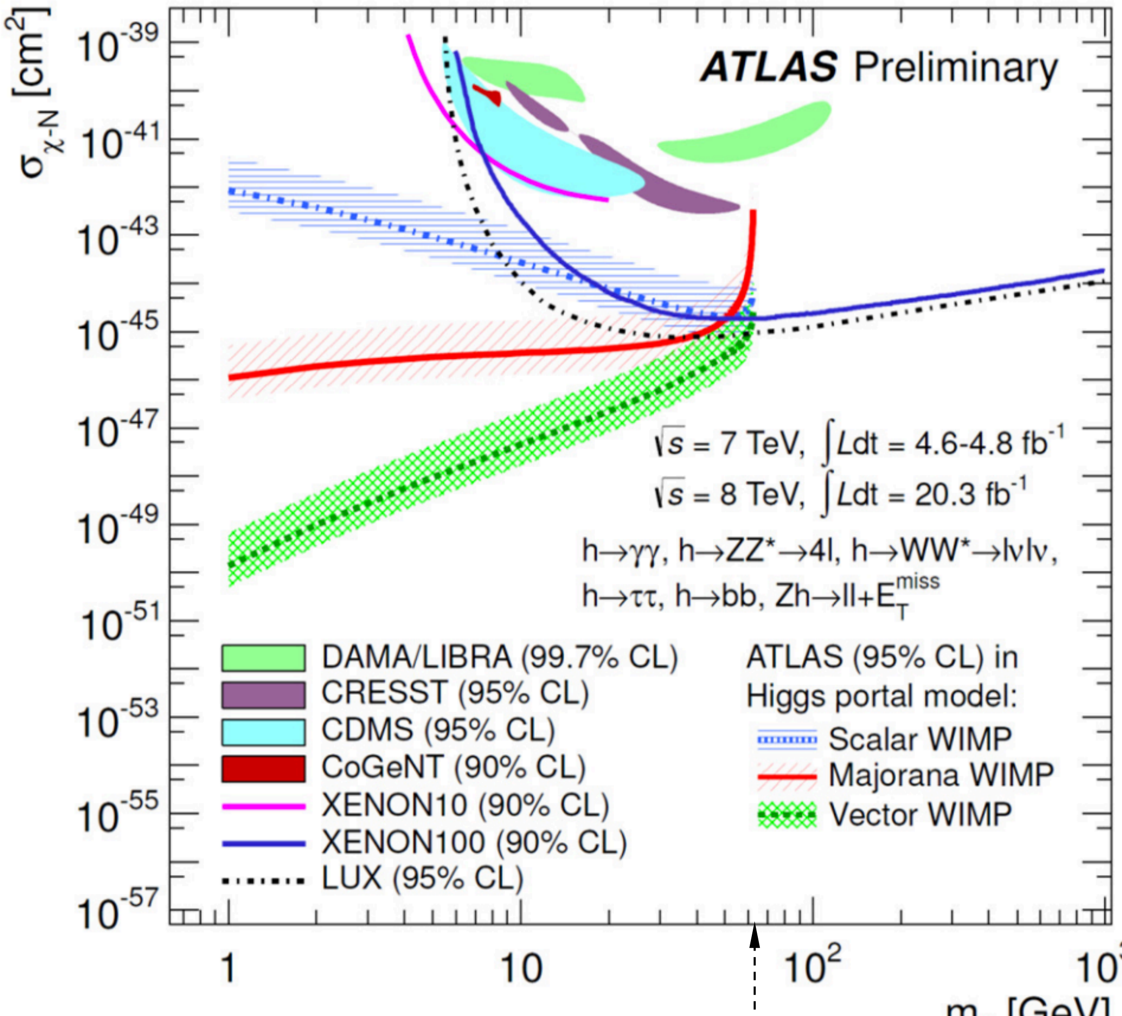
- Cosmic connection at the HL-LHC.
  - Direct bounds for massive dark particles with $m_\chi < m_H/2$.



Direct and indirect combined

[ATLAS-CONF-2014-010] [http://cern.ch/go/bL8M]

- Shown by ATLAS at Moriond 2014.
- Combination
  - **BR_{inv} < 0.37 (0.39) (95% CL), obs.(exp.)**
  - Dominated by constraints from the visible decays.



Probing the Higgs total width: Γ_H

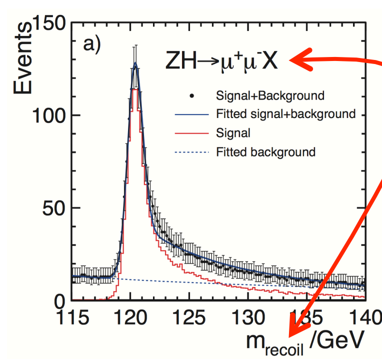
Hadron collider (LHC)

- All rates are proportional to $\sigma_i \times BR_i = \sigma_i \times \Gamma_i / \Gamma_H$
- Deemed impossible to access Γ_H...

$$f(E) = \frac{k}{(E^2 - M^2)^2 + M^2\Gamma^2}.$$

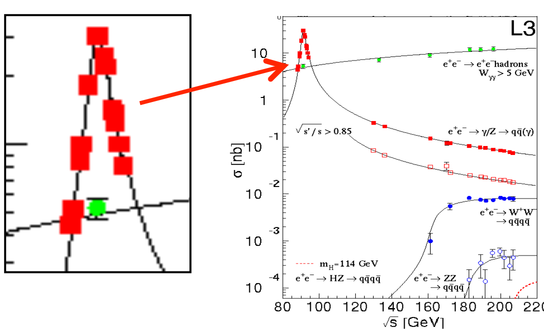
Linear collider (ILC)

- $e^+e^- \to ZH$ with $Z \to \ell^+\ell^-$ and $H \to X$(recoil).
  - Get σ_{ZH} from recoil.
  - Get $\sigma_{ZH} \times BR_{ZZ}$ from rates like LHC.
  - Get Γ_{ZZ} from σ_{ZH}.
  - Get $\Gamma_H = \Gamma_{ZZ}/BR_{ZZ}$.



Muon collider (?)

- Scan the muon energy and measure the resonance shape directly.
- Cf. LEP $e^+e^- \to Z$ (below).

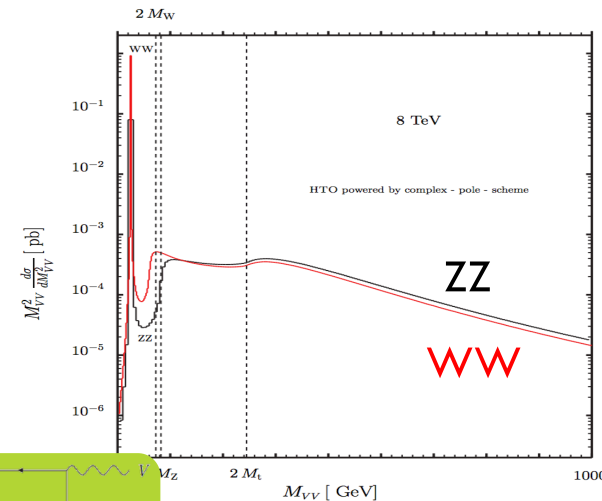


Total width: interferometry

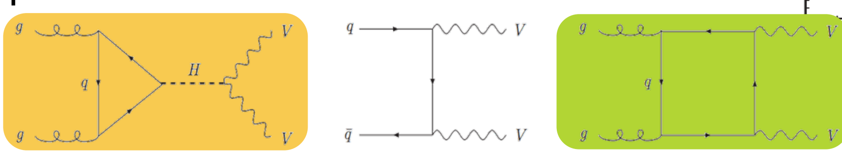
[arXiv:1206.4803] [arXiv:1211.3736] [arXiv:1305.3854]

- Kauer-Passarino note that:

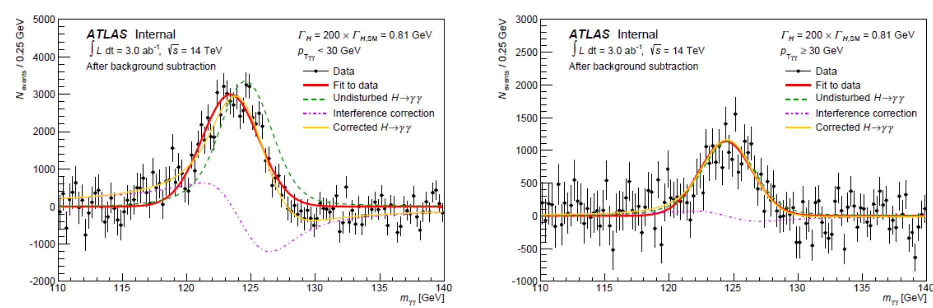
$$\left(\frac{d\sigma}{dM_{VV}}\right)_{\rm ZWA} = \sigma_{H,\rm ZWA}\,\frac{M_H\Gamma_H}{\pi}\,\frac{2M_{VV}}{\left(M_{VV}^2-M_H^2\right)^2+(M_H\Gamma_H)^2}$$



- **σ above ZZ threshold is independent of the on-shell total width.**
- Caola-Melnikov propose analysis in ZZ→4ℓ and estimate **Γ_H<90 MeV for LHC Run1.**
- gg→H*→VV off-shell production interferes with gg→non-H→VV.



- Dixon-Siu show how total width affects signal-background interference in $\gamma\gamma$.
  - **ATLAS HL-LHC projection: Γ_H<100 MeV.**



H*: constraining the width of H

[CMS-PAS-HIG-14-002]

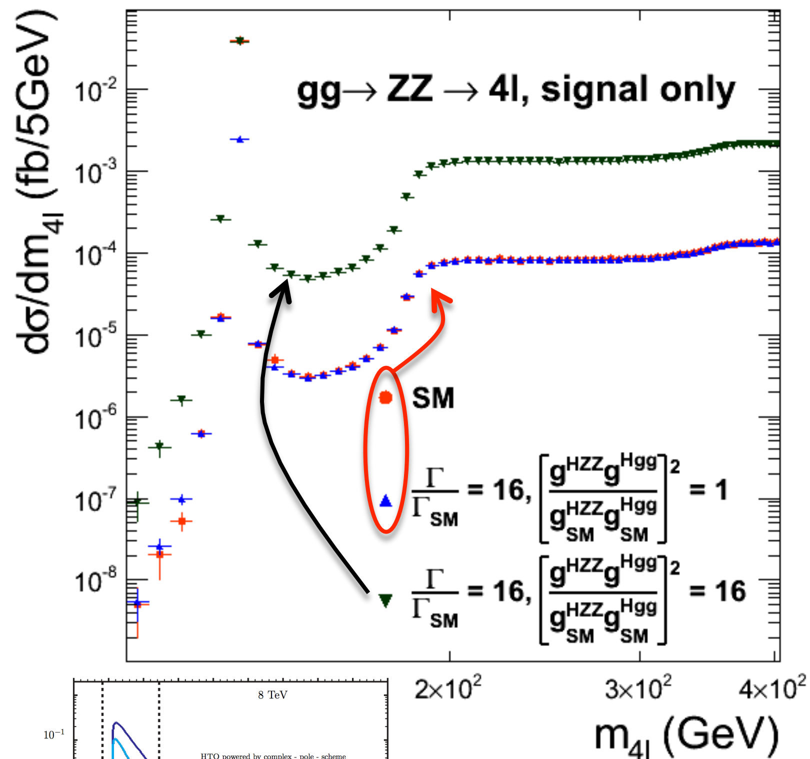
- Define $r = \Gamma_H / \Gamma_H^{SM}$
- On-mass-shell we have

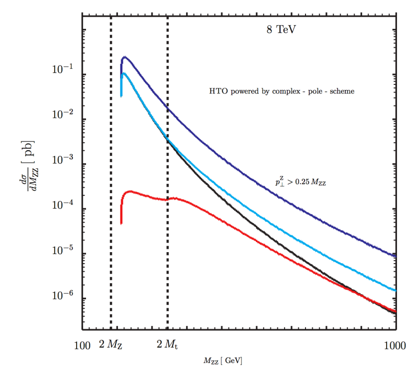
$$\sigma^{on-peak}_{gg \to H \to ZZ} = \frac{\kappa_g^2 \kappa_Z^2}{r} (\sigma \cdot \mathcal{B})_{SM} \equiv \mu (\sigma \cdot \mathcal{B})_{SM}$$

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

$$\frac{d\sigma^{off-peak}_{gg \to H \to ZZ}}{dm_{ZZ}} = \kappa_g^2 \kappa_Z^2 \cdot \frac{d\sigma^{off-peak,SM}_{gg \to H \to ZZ}}{dm_{ZZ}} = \mu r \frac{d\sigma^{off-peak,SM}_{gg \to H \to ZZ}}{dm_{ZZ}}$$

- Can make inference on ***r*** **assuming:**
  - μ =0.93±0.25 (arXiv:1312.5353)
  - Only SM processes ⟶ZZ:
    - gg⟶H*
    - **gg** = |gg⟶H* + gg⟶non-H|^2
    - |gg⟶H*|^2 + |gg⟶non-H|^2
    - **Total** = **gg** + $q\bar{q}$

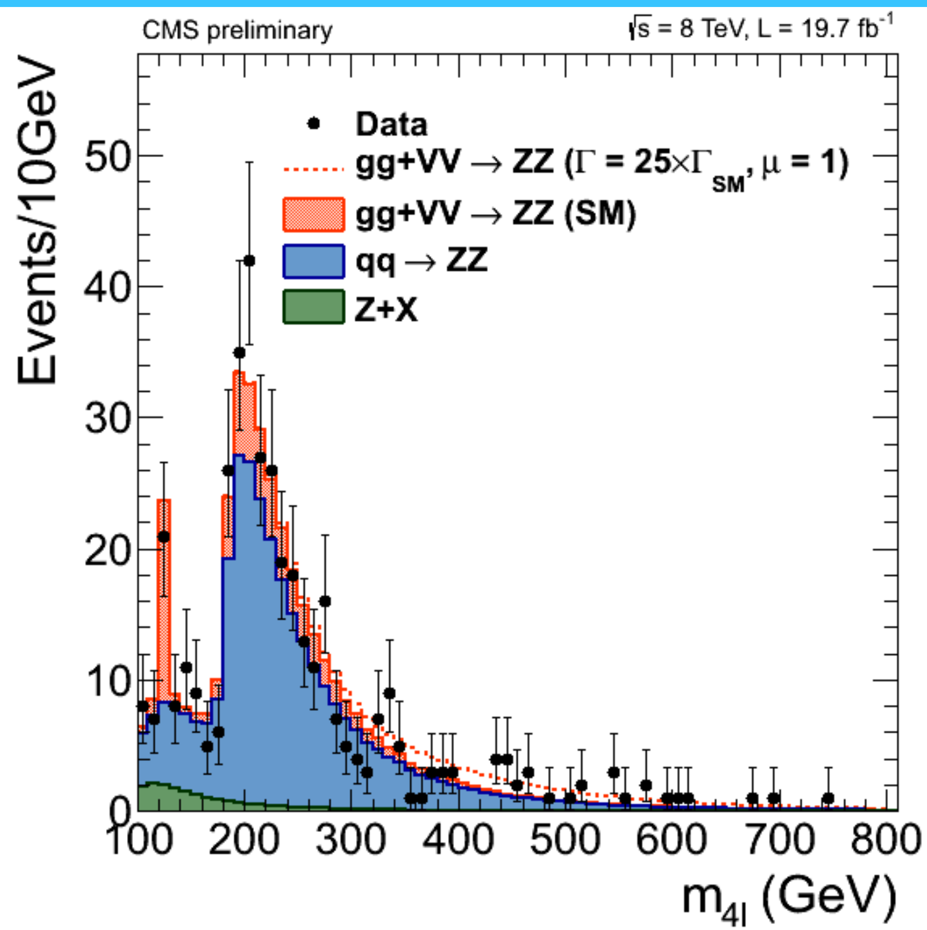




H*: constraining the width of H

[CMS-PAS-HIG-14-002]

- Two channels exploited:
  - ZZ⟶4ℓ
    - 2D: m4ℓ + MELA(gg vs. $q\bar{q}$)



H*: constraining the width of H

[CMS-PAS-HIG-14-002]

- Two channels exploited:
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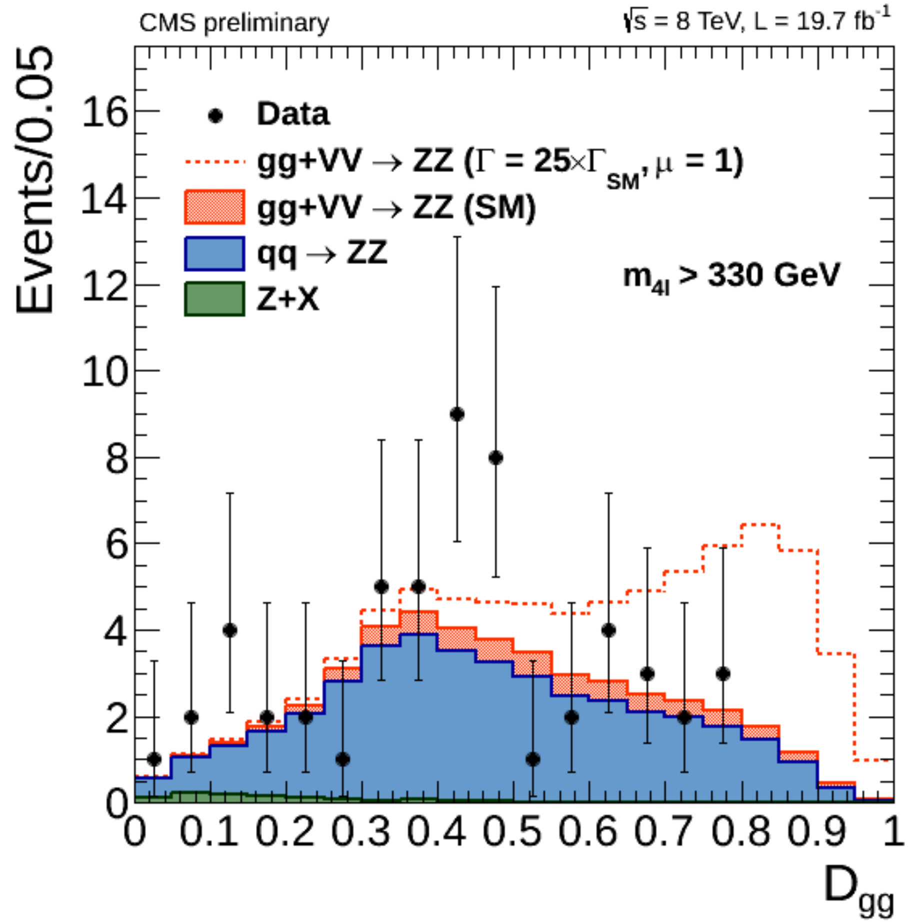
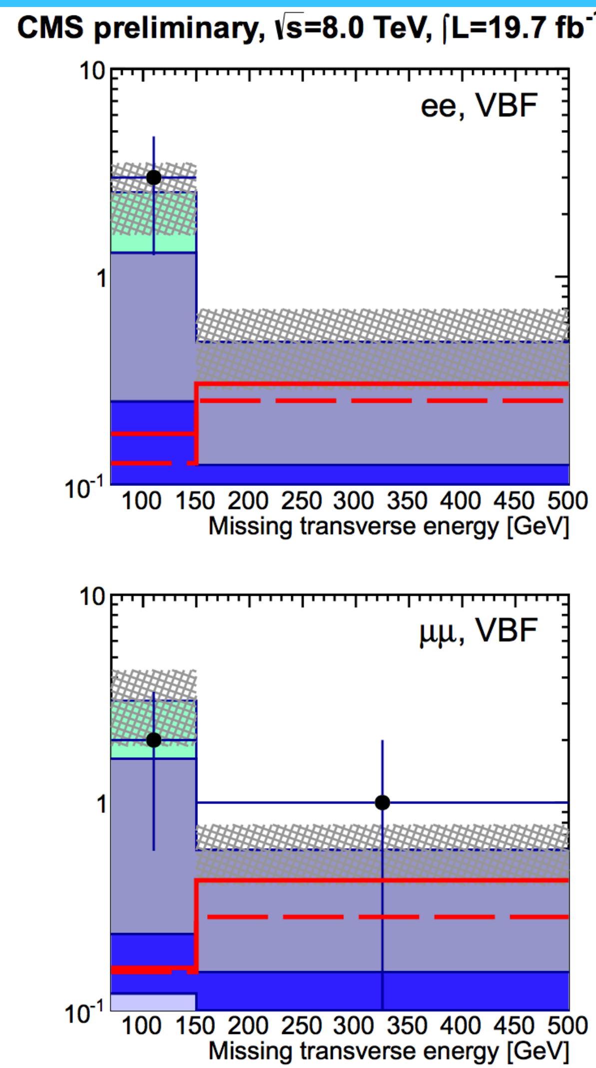


H*: constraining the width of H

[CMS-PAS-HIG-14-002]

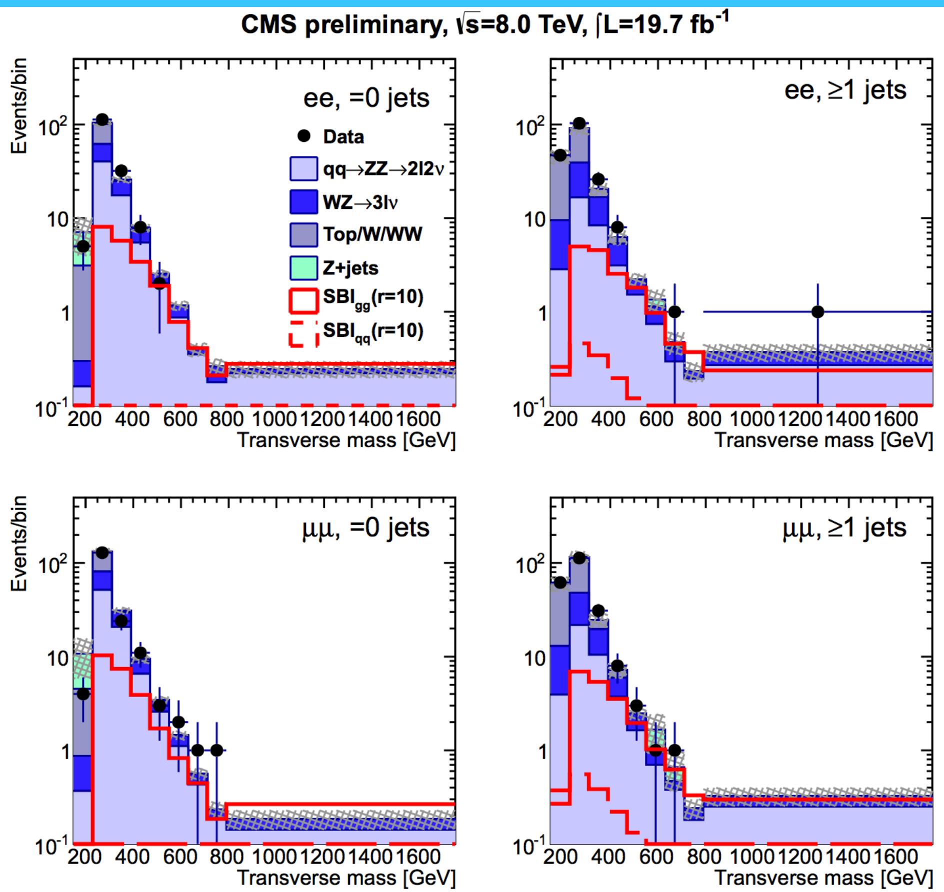
- Two channels exploited:
  - ZZ⟶4ℓ
    - 2D: m4ℓ + MELA(gg vs. $q\bar{q}$)
  - ZZ⟶2ℓ2ν
    - MET shape in 2j-VBF,
    - m_T shape in 0 jet, and ≥1 jet



H*: constraining the width of H

[CMS-PAS-HIG-14-002]

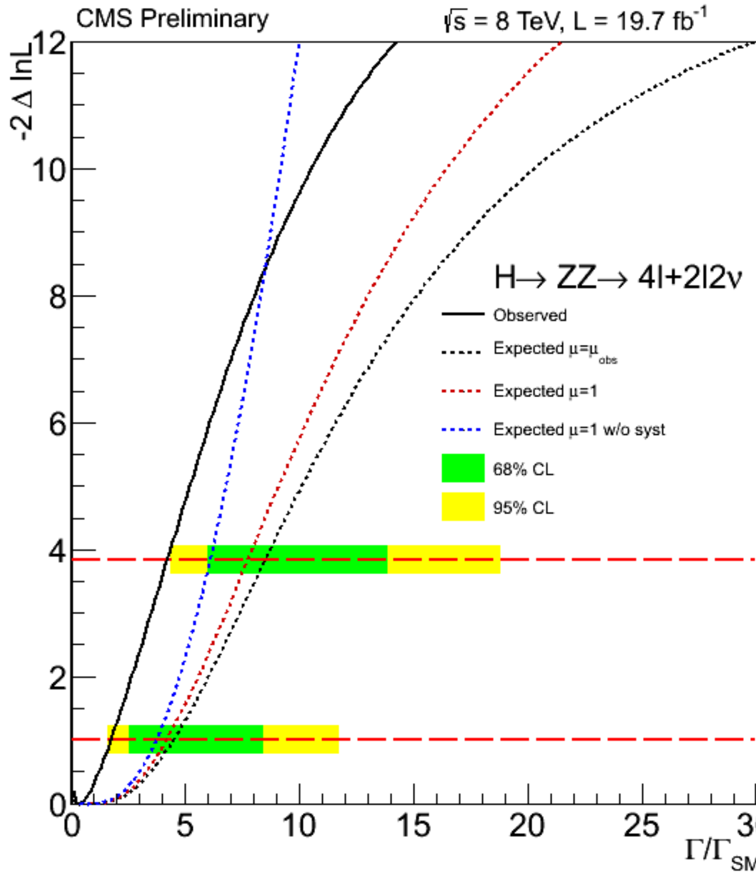
- Two channels exploited:
  - $ZZ \longrightarrow 4\ell$
    - 2D: $m4\ell$ + MELA(gg vs. $q\bar{q}$)
  - $ZZ \longrightarrow 2\ell 2\nu$
    - MET shape in 2j-VBF,
    - m_T shape in 0 jet, and ≥1 jet



H*: constraining the width of H

[CMS-PAS-HIG-14-002]

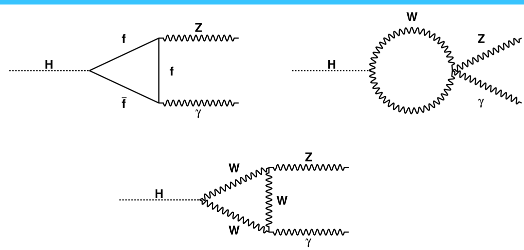
- Two channels exploited:
  - ZZ⟶4ℓ
    - 2D: m4ℓ + MELA(gg vs. $q\bar{q}$)
  - ZZ⟶2ℓ2ν
    - MET shape in 2j-VBF,
    - m_T shape in 0 jet, and ≥1 jet
- Observed limit lower than expected (p=0.02)



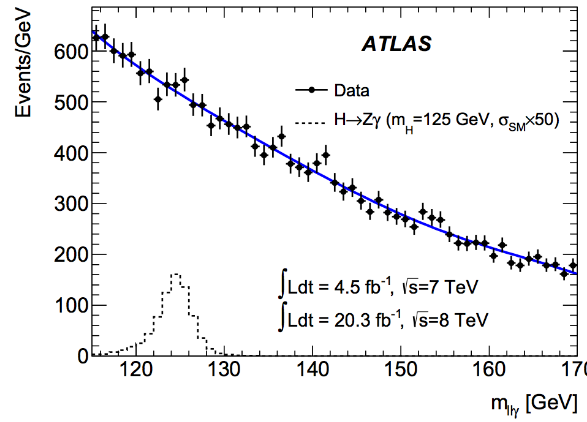
Obs. (exp.)	4ℓ	2ℓ2ν	Combined
Γ_H/Γ_H^{SM} (95% CL)	< 6.6 (11.5)	< 6.4 (10.7)	< 4.2 (8.5)

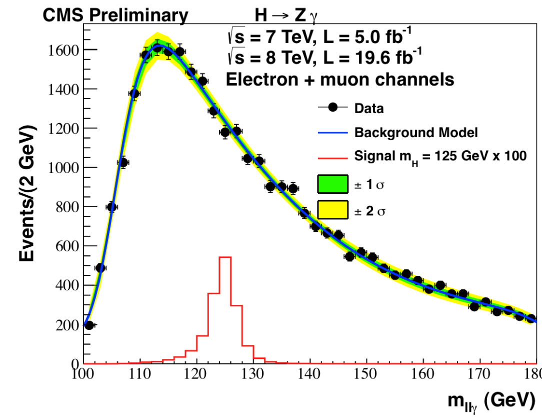
☆ $H \to Z\gamma \to \ell\ell\gamma$

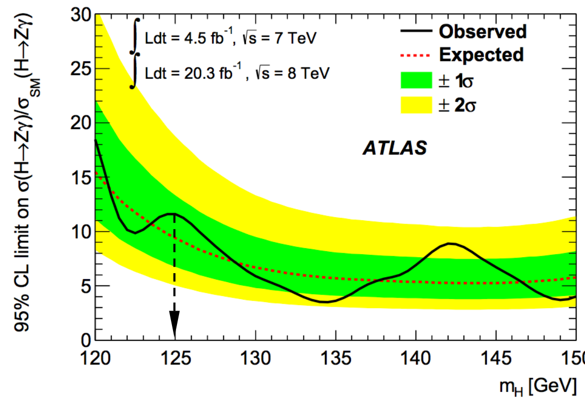
[arXiv:1402.3051] [CMS-PAS-HIG-13-006]

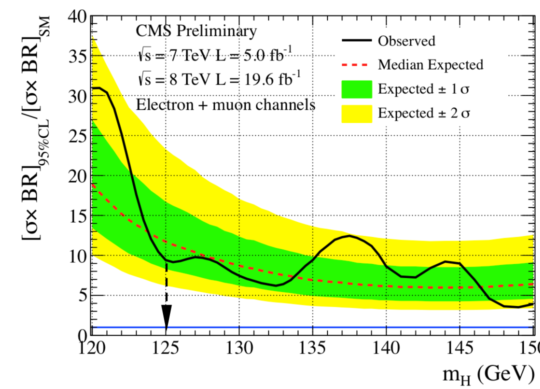


- Loop-mediated decay: sensitive to BSM.
- Both analyses on full 7 and 8 TeV data sets.







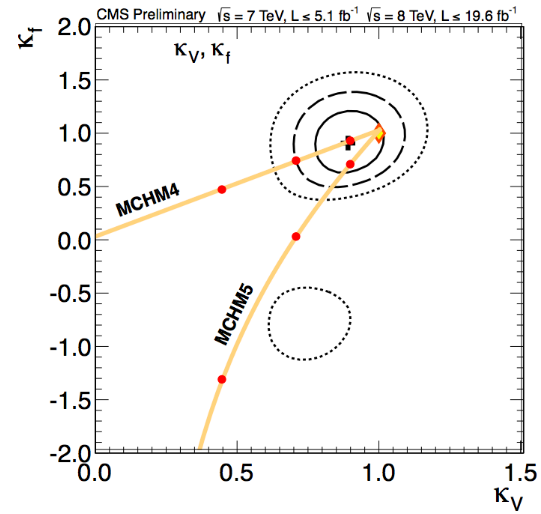


Obs. (exp.)	ATLAS	CMS
μ at 125 GeV (95% CL)	**< 11 (9)**	**< 9 (12)**

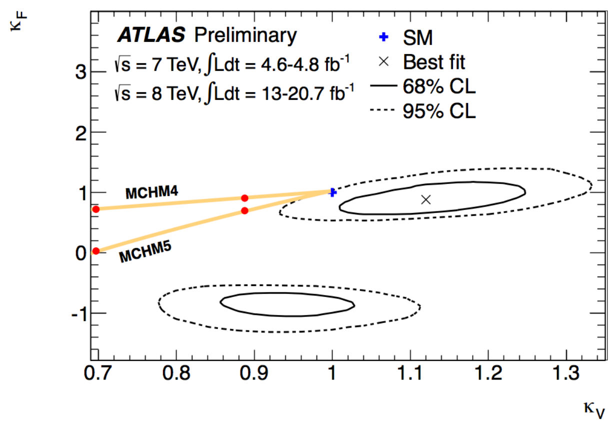
From deviations to EFTs

 [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.



And 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: $$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$$

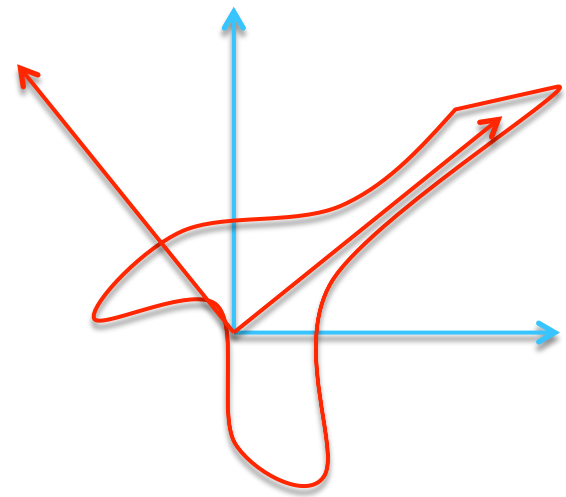
Effective field theory (EFT): the idea

[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?**



EFT: a possible basis?

 [http://cern.ch/go/lgT8]

- Multiple sectors affected:
  - Electroweak precision data.
  - Anomalous triple gauge couplings.
  - Higgs only.
- Global fit should be possible.

19= 8+3+8

change Higgs kin. term: VV→h

$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$

$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$

$\mathcal{O}_6 = \lambda |H|^6$

Affects h^3: It can be measured in the far future by GG→hh

$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$

$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$

$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$

$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$

KHW-KHB → h→Zγ

h→γγ: $\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$

GG→h: $\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$

$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_\mu W^b_{\nu\rho} W^{c\,\rho\mu}$

h→ff

$\mathcal{O}_{y_u} = y_u |H|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d |H|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e |H|^2 \bar{L}_L H e_R$
$\mathcal{O}_R^u = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$ $\mathcal{O}_L^q = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$ $\mathcal{O}_L^{(3)\,q} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \sigma^a \gamma^\mu Q_L)$	$\mathcal{O}_R^d = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
		$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)(\bar{L}_L \sigma^a \gamma_\mu L_L)$

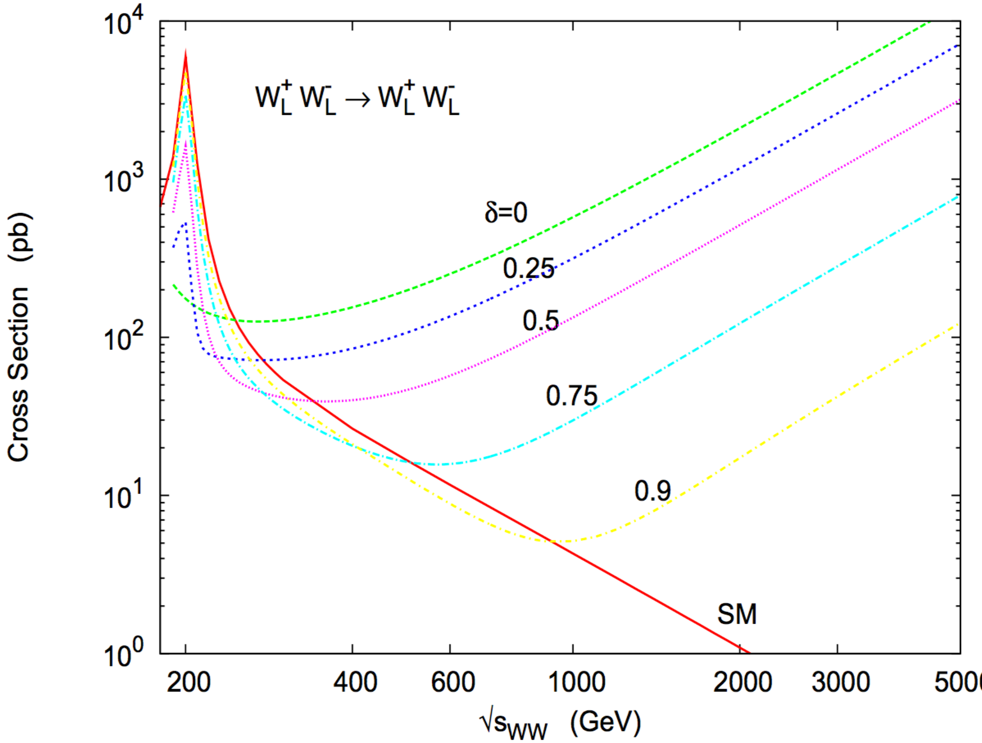
CP-even: **8 (precision test) + 3 (TGC) + 8 (Higgs physics)**

CP-odd: **+ 2 (TGC) + 3 (Higgs physics)**

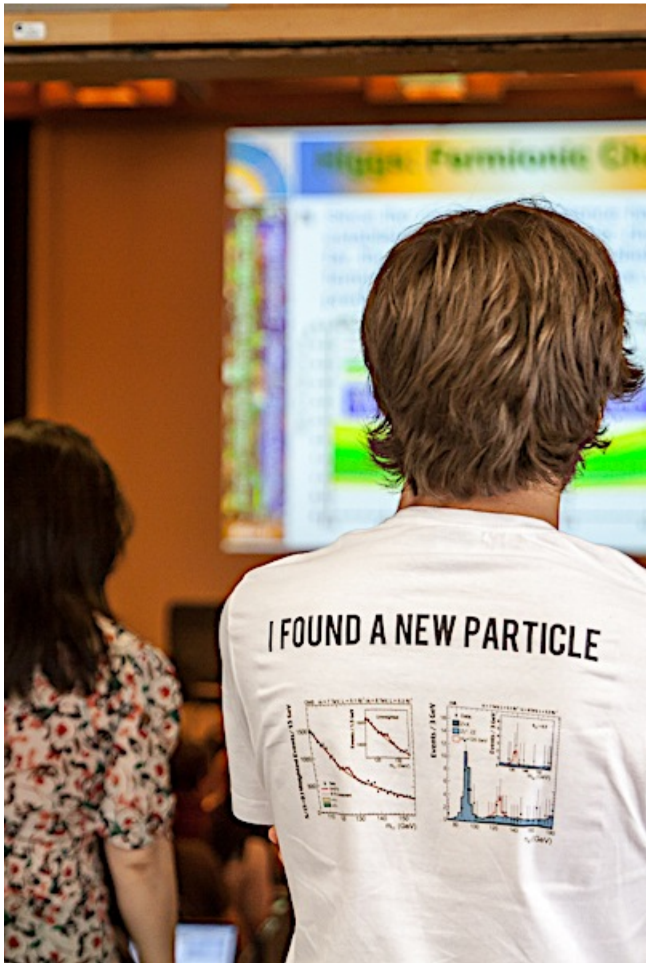
Delayed unitarization: until when?

 [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.**



Summary

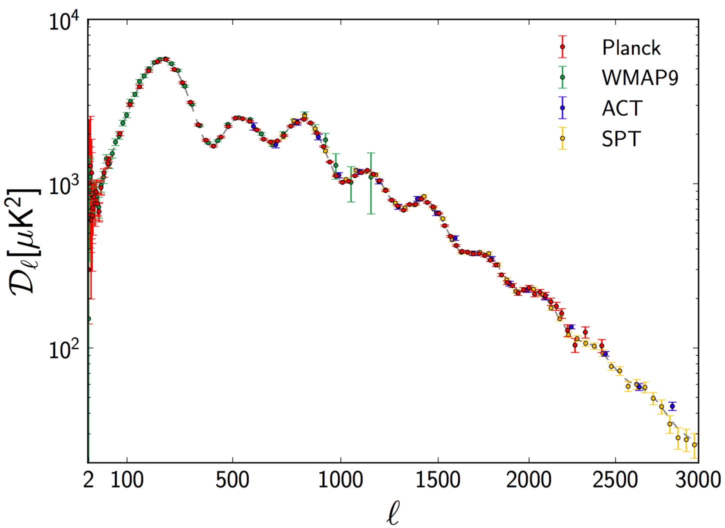


- **LHC13: last chance before a "BSM desert".**
  - Tevatron: Run I → top discovery, Run II → SM precision.
  - LHC 2010: early SUSY and EXO exclusions.
- **Higgs, one way out of the "SM oasis":**
  - From O(10%) to differential.
  - From "seen" to O(%) measurements.
  - From limits on rare things to 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.

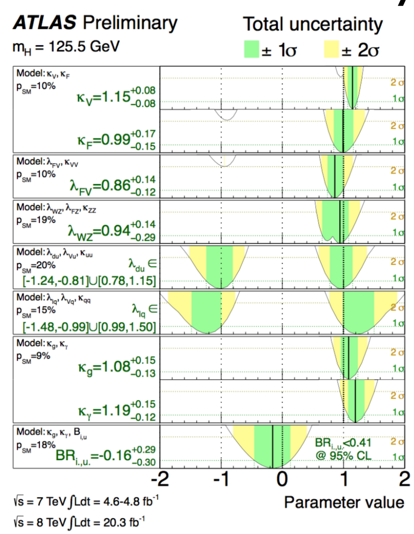
The ~~beautiful~~ ~~boring~~ 2014 Universe

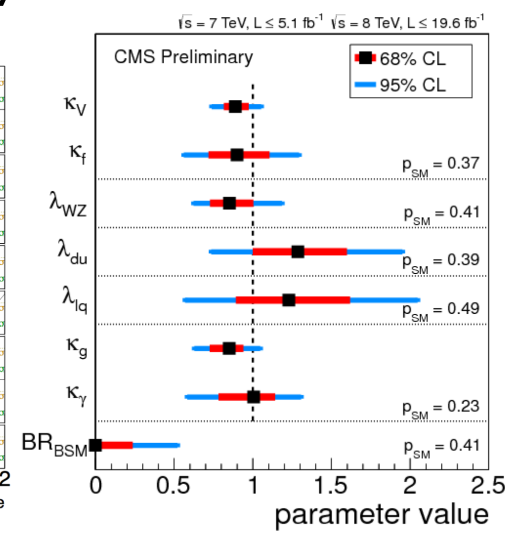
[arXiv:1303.5062]

- **Up above:** "Simple six-parameter ΛCDM".



- **Down below:** (Not-as-simple) ~20-parameter Standard Model of Particle Physics.





Looking forward to LHC combination and surprises at higher energy: PeV neutrinos, LHC 13 TeV, …

References

“…and references therein.”

- 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

- 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

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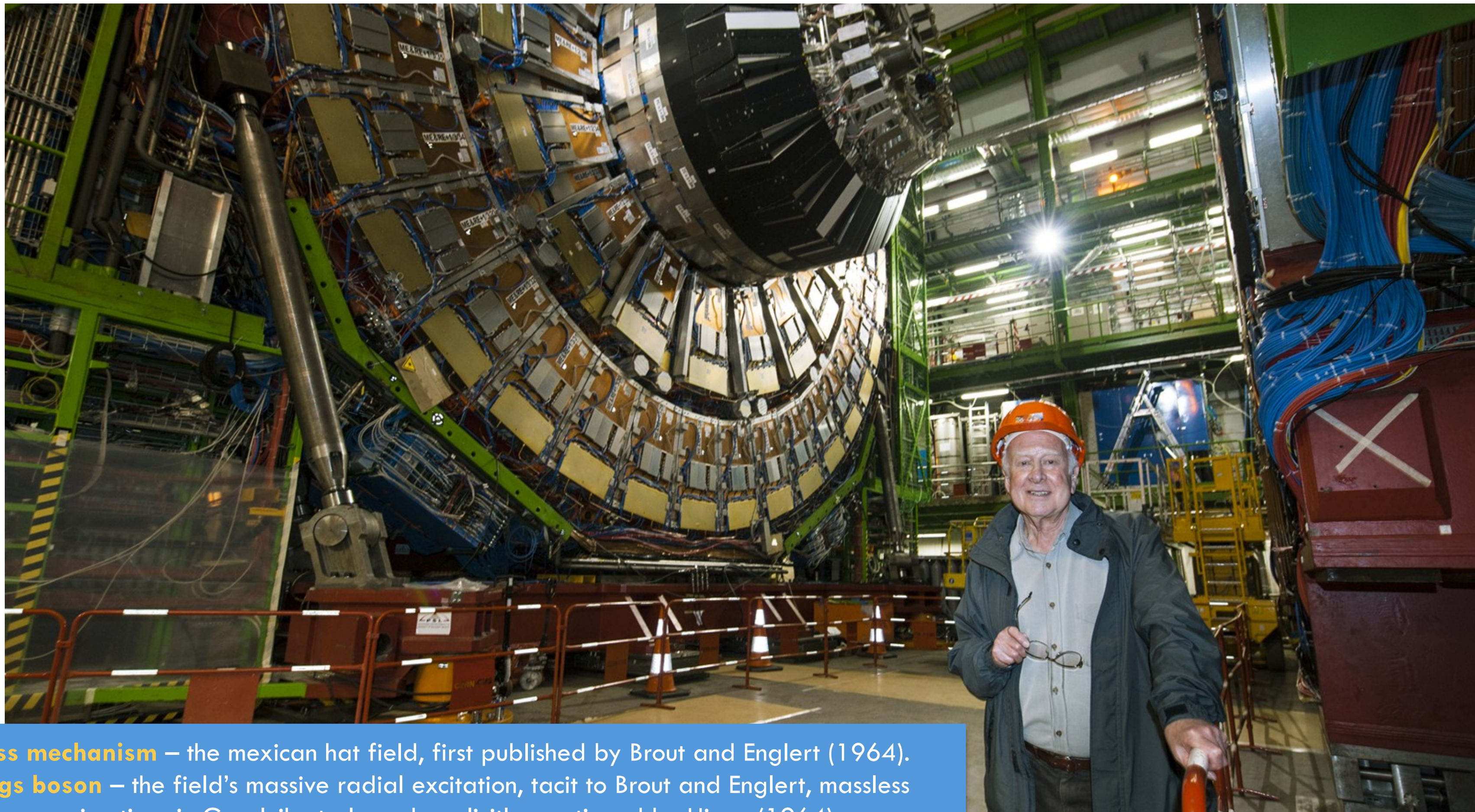
For discussion

Higgs in CMS – ca. 2008

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

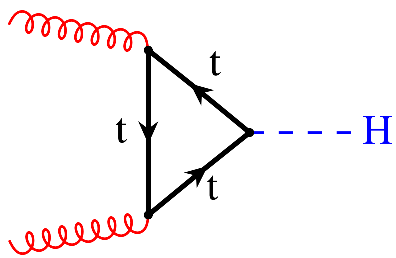


- **Mass mechanism** – the mexican hat field, first published by Brout and Englert (1964).
- **Higgs boson** – the field's massive radial excitation, tacit to Brout and Englert, massless via approximations in Guralnik et al., and explicitly mentioned by Higgs (1964).
- **Viability** – photons and massive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

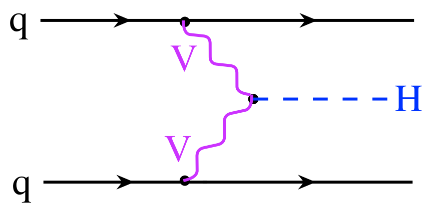
How SM Higgses are born

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

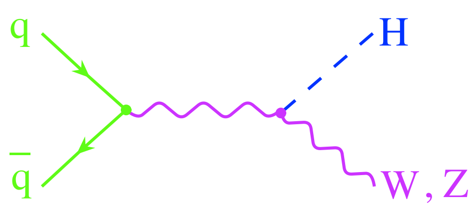
- **Gluon fusion**



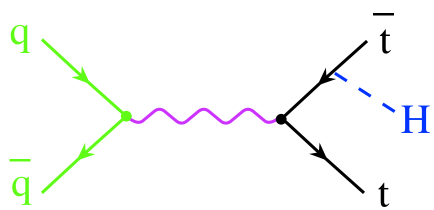
- **VBF**

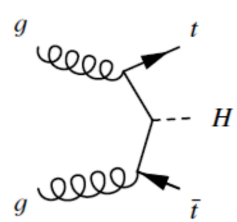


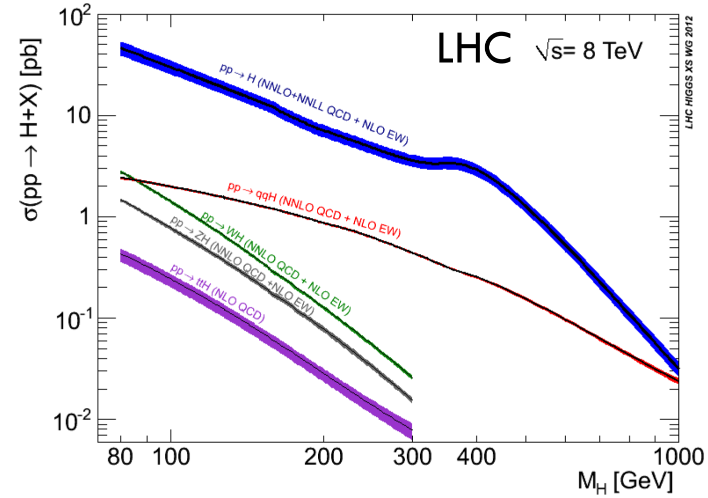
- **VH**

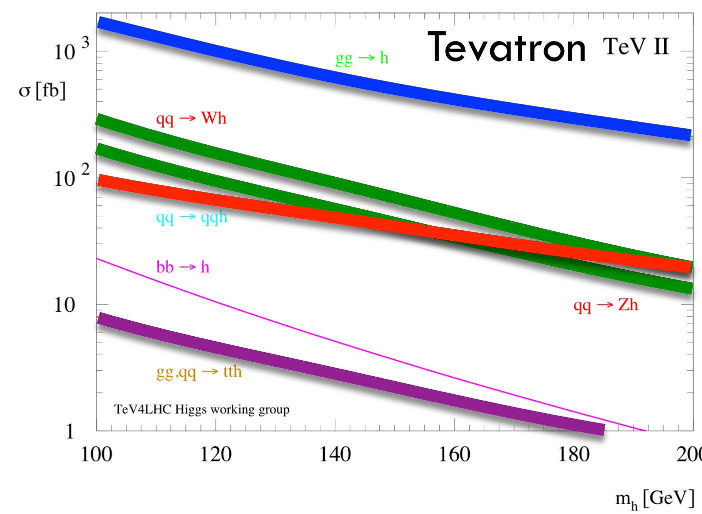


- **ttH**





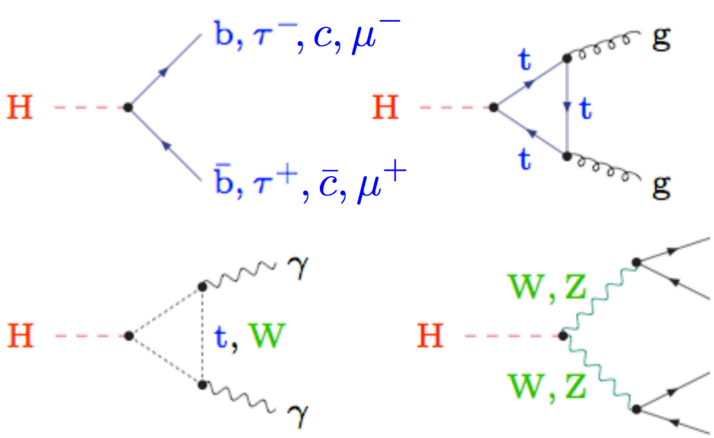




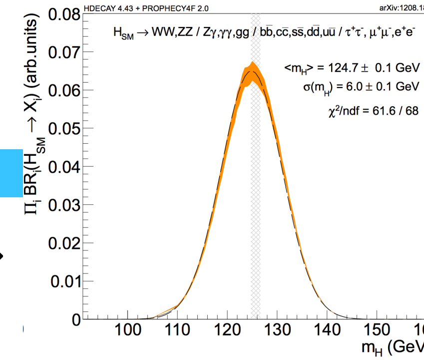
How SM Higgses die

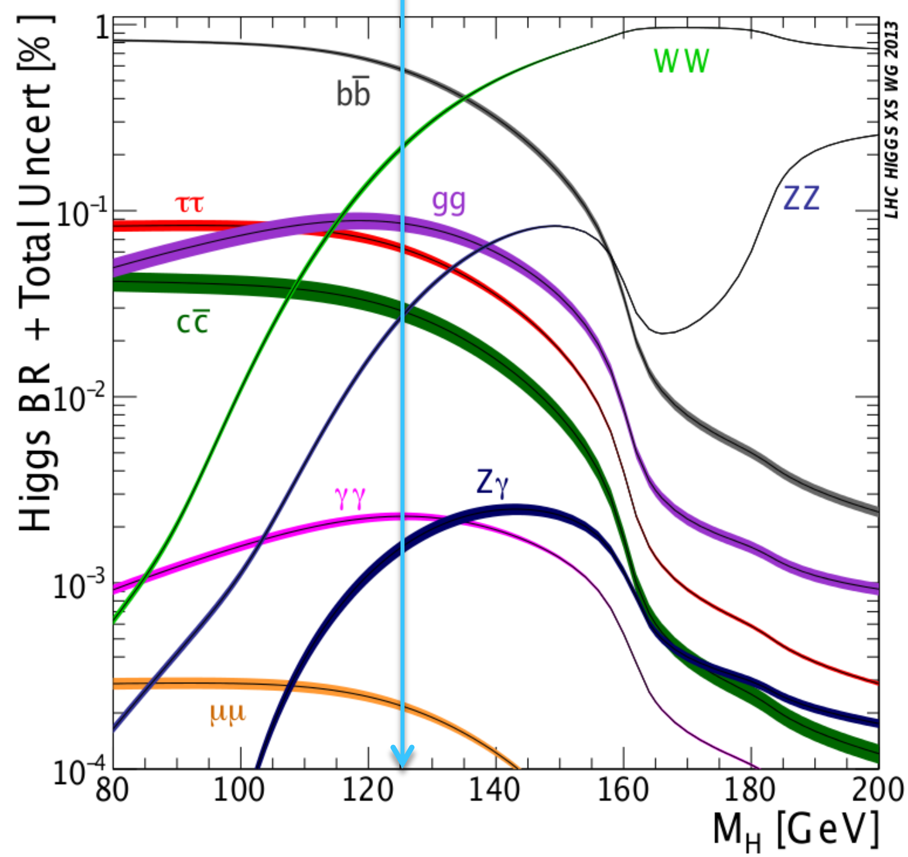
[http://cern.ch/go/qkh6] [arXiv:1208.1993]

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



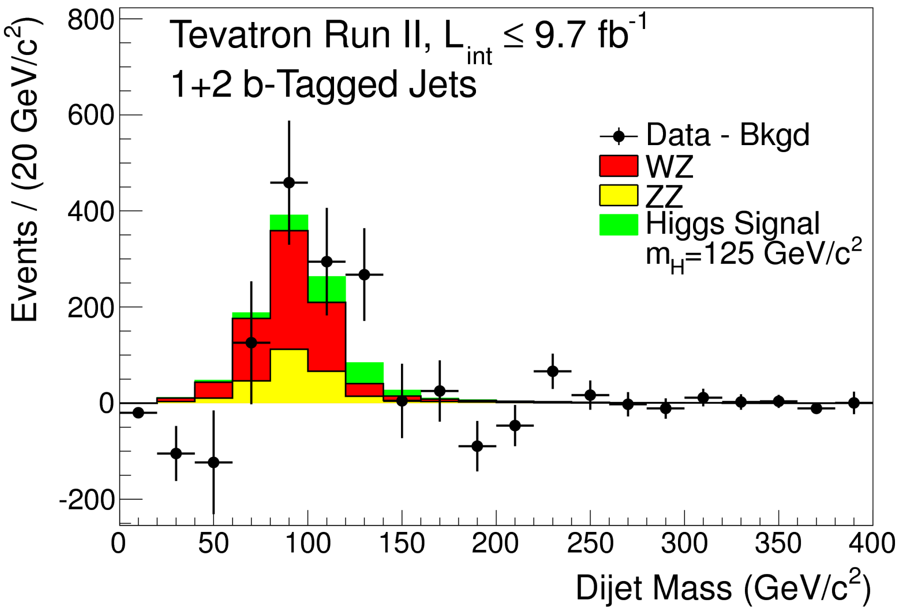
Near to maximal ΠBR_i ⟶

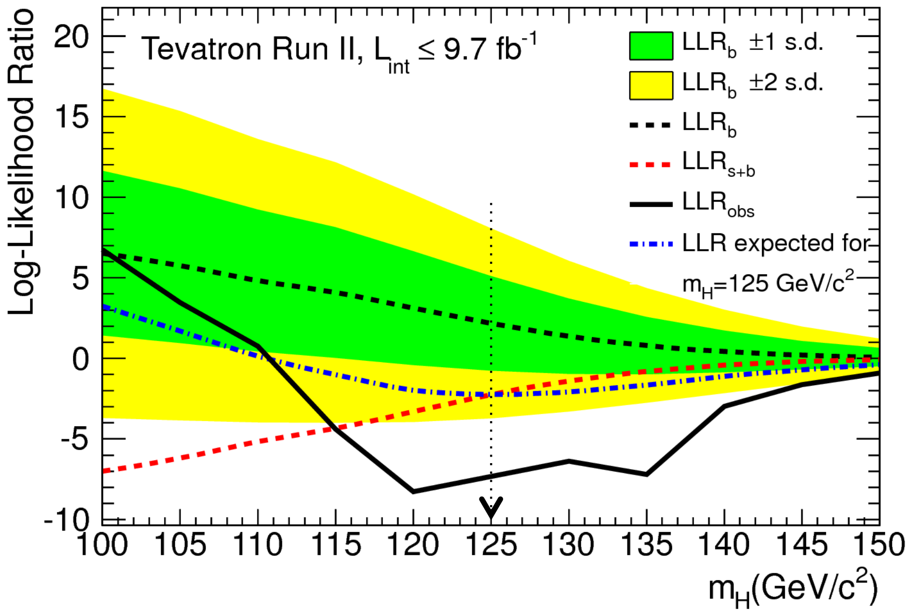




From the other side of the pond

[arXiv:1207.6436]

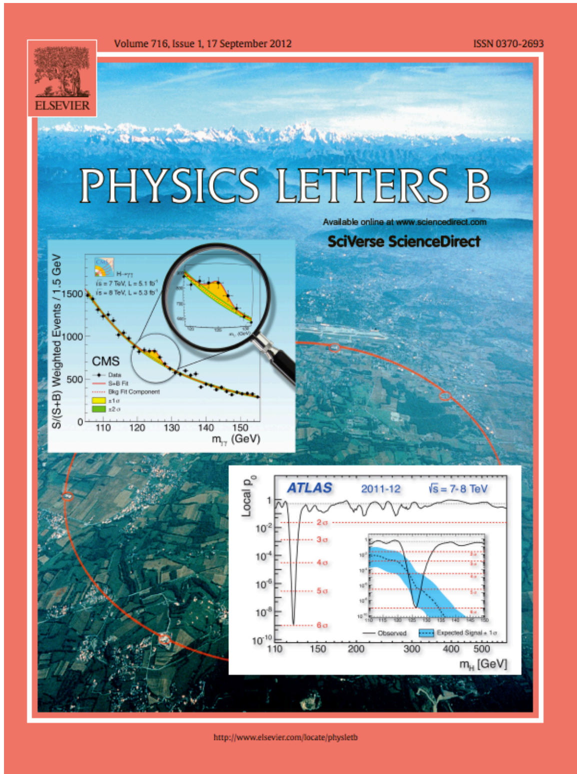




- Combination of Tevatron VH⟶$b\bar{b}$ searches, in July 2012:
  - **2.8 σ local significance at m_H=125 GeV.**

Looking up to a new boson

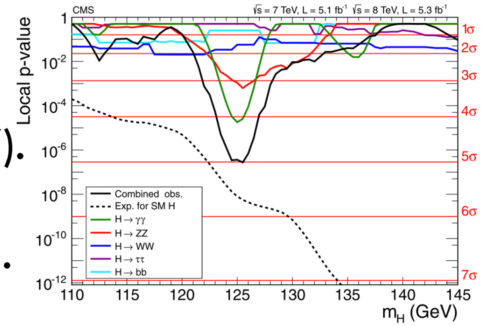
[http://cern.ch/go/q8jx]

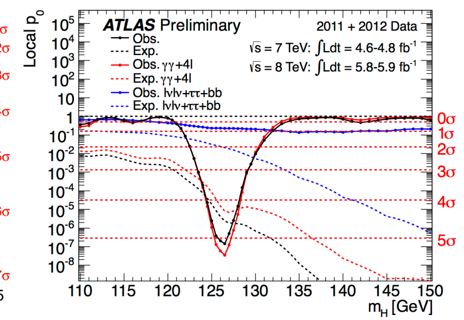


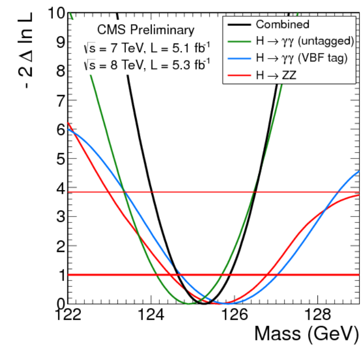
Higgsdependence day recap

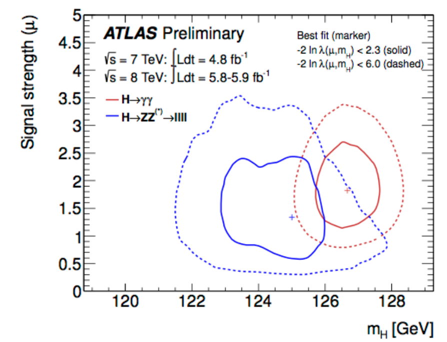
[http://cern.ch/go/q8jx]

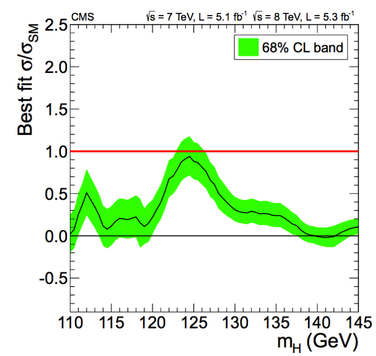
- **Both experiments at 5.0 σ.**
  - One above expectations… **$\sigma_{ATLAS}/\sigma_{SM}$ = 1.2 ±0.3** (at 126.5 GeV).
  - …the other one below. **σ_{CMS}/σ_{SM} = 0.80 ±0.20** (at 125 GeV).
- Mass
  - ATLAS: min. p-value at 126.5 GeV.
  - CMS: m_X = 125.3 ±0.6 GeV.
- "Proto-couplings" compatible with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

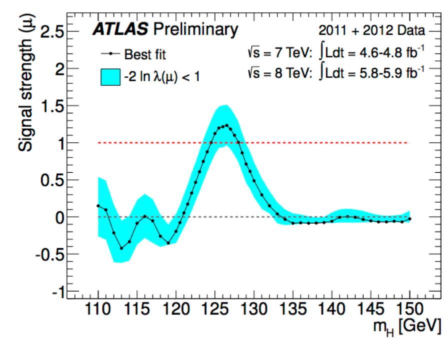


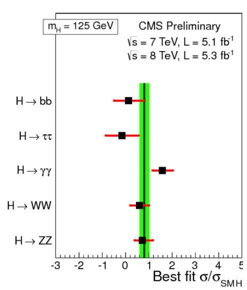


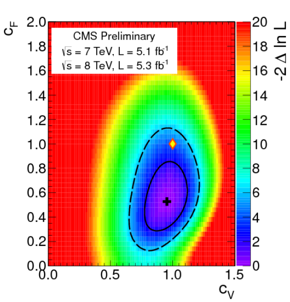


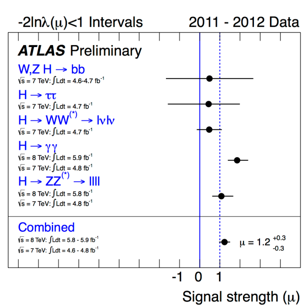












A 2012 hit

[http://goo.gl/49c0c] [http://goo.gl/suJzZ] [http://goo.gl/ShJJG]

symmetry dimensions of particle physics

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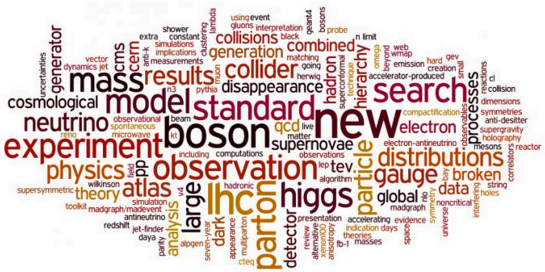

signal to background

May 12, 2013

The top 40 physics hits of 2012

The Higgs boson is a popular subject among the most-cited physics papers of 2012, but a particle simulation manual takes the top spot.

2012 reports for eprints

1. 568 citations in 2012
   Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC
   ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Jul 2012. 24 pp.
   Published in **Phys.Lett. B716 (2012) 1-29**
   CERN-PH-EP-2012-218
   DOI: 10.1016/j.physletb.2012.08.020
   e-Print: **arXiv:1207.7214 [hep-ex]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   ADS Abstract Service; Link to all figures including auxiliary figures

2. 558 citations in 2012
   Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC
   CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Jul 2012.
   Published in **Phys.Lett. B716 (2012) 30-61**
   CMS-HIG-12-028, CERN-PH-EP-2012-220
   DOI: 10.1016/j.physletb.2012.08.021
   e-Print: **arXiv:1207.7235 [hep-ex]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; ADS Abstract Service; Link to PRESSRELEASE

3. 433 citations in 2012
   Combined results of searches for the standard model Higgs boson in pp collisions at $\sqrt{s}=7$ TeV
   CMS Collaboration (Serguei Chatrchyan (Yerevan Phys. Inst.) *et al.*). Feb 2012.
   Published in **Phys.Lett. B710 (2012) 26-48**
   CMS-HIG-11-032, CERN-PH-EP-2012-023
   DOI: 10.1016/j.physletb.2012.02.064
   e-Print: **arXiv:1202.1488 [hep-ex]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
   CERN Document Server ; ADS Abstract Service

4. 381 citations in 2012
   Combined search for the Standard Model Higgs boson using up to 4.9 fb^{-1} of pp collision data at $\sqrt{s}=7$ TeV with the ATLAS detector at the LHC
   ATLAS Collaboration (Georges Aad (Freiburg U.) *et al.*). Feb 2012. 8 pp.
   Published in **Phys.Lett. B710 (2012) 49-66**
   CERN-PH-EP-2012-019
   DOI: 10.1016/j.physletb.2012.02.044
   e-Print: **arXiv:1202.1408 [hep-ex]** | PDF
   References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
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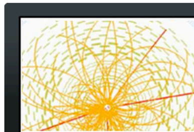
Home > Collections > Online Extras > Special Issues 2012 > Breakthrough of the Year, 2012

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

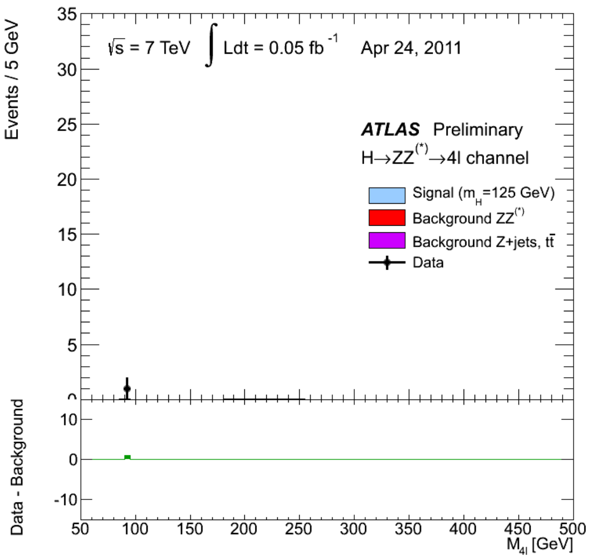
Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably 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.

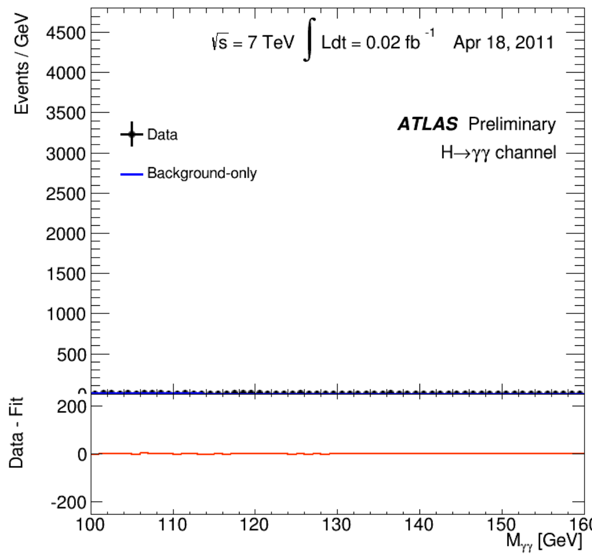
Read more about the Higgs boson from the research teams at CERN.

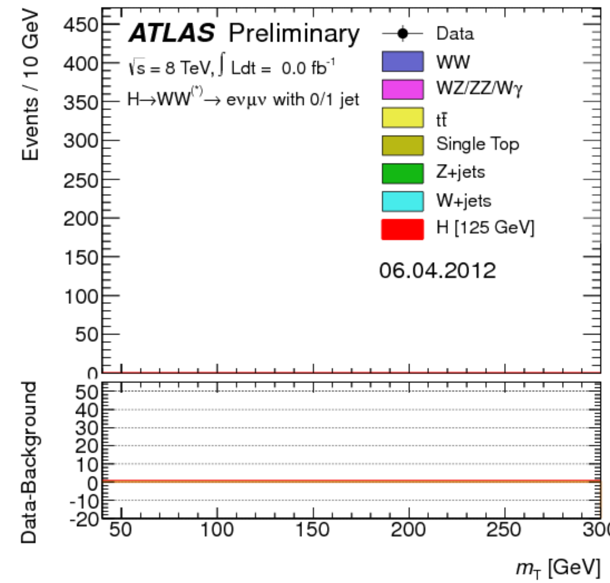
Runners-Up FREE WITH REGISTRATION

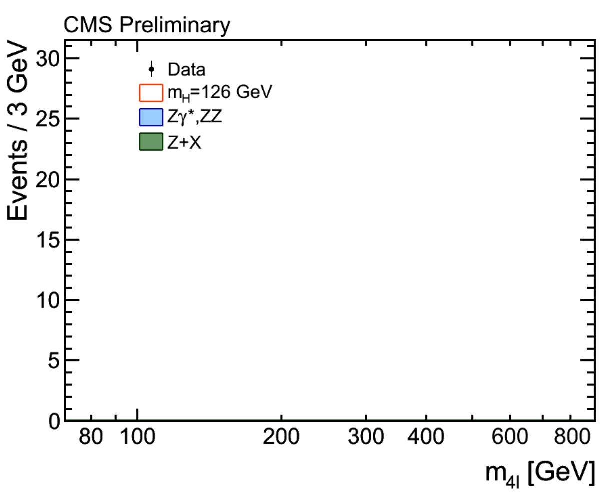
This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

The build up of a signal









- Thanks to the excellent performance of the LHC !
  - >15 fb^{-1} delivered after July 2012.

Timeline of the results

2012

- ICHEP
  - 5 σ per LHC experiment.
- HCP
  - First properties.

2013

- Moriond
  - Some full LHC dataset updates.
  - More properties measurements.
- LHCP
  - More full dataset analyses.

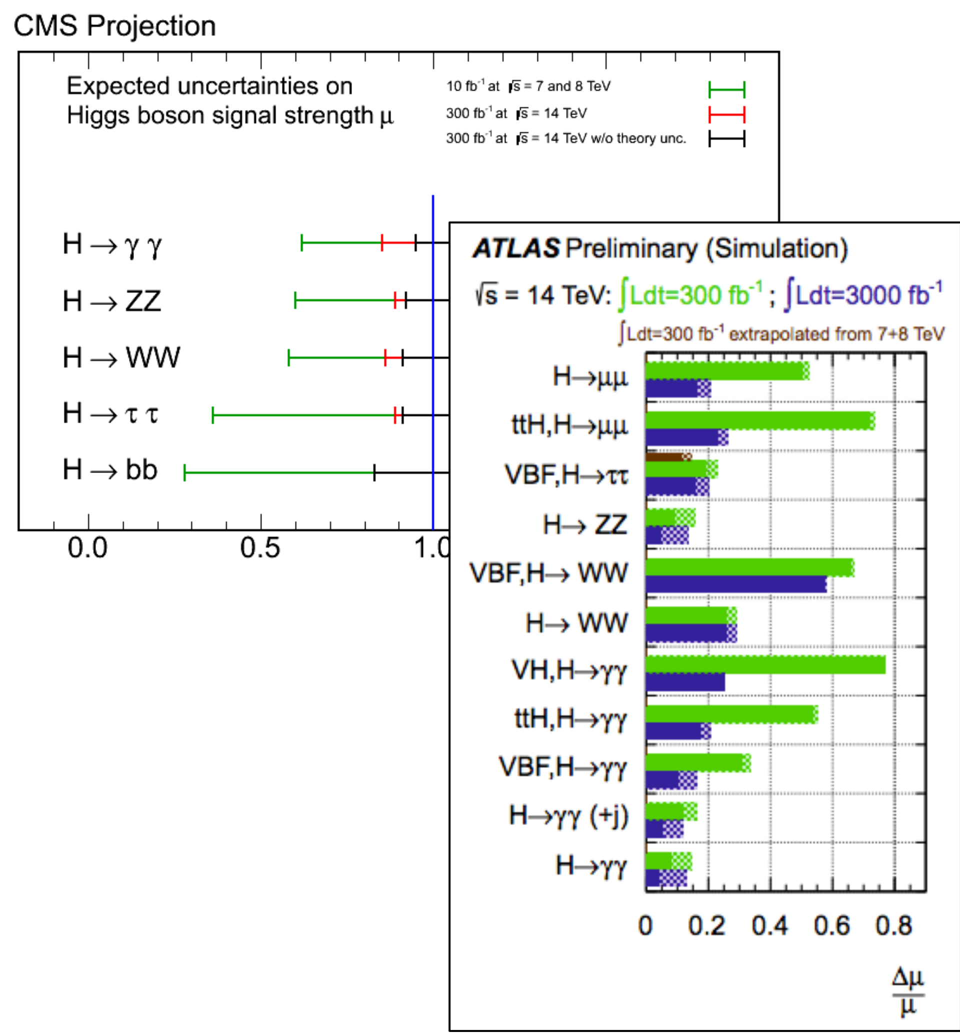
Today

The Future

Looking well ahead

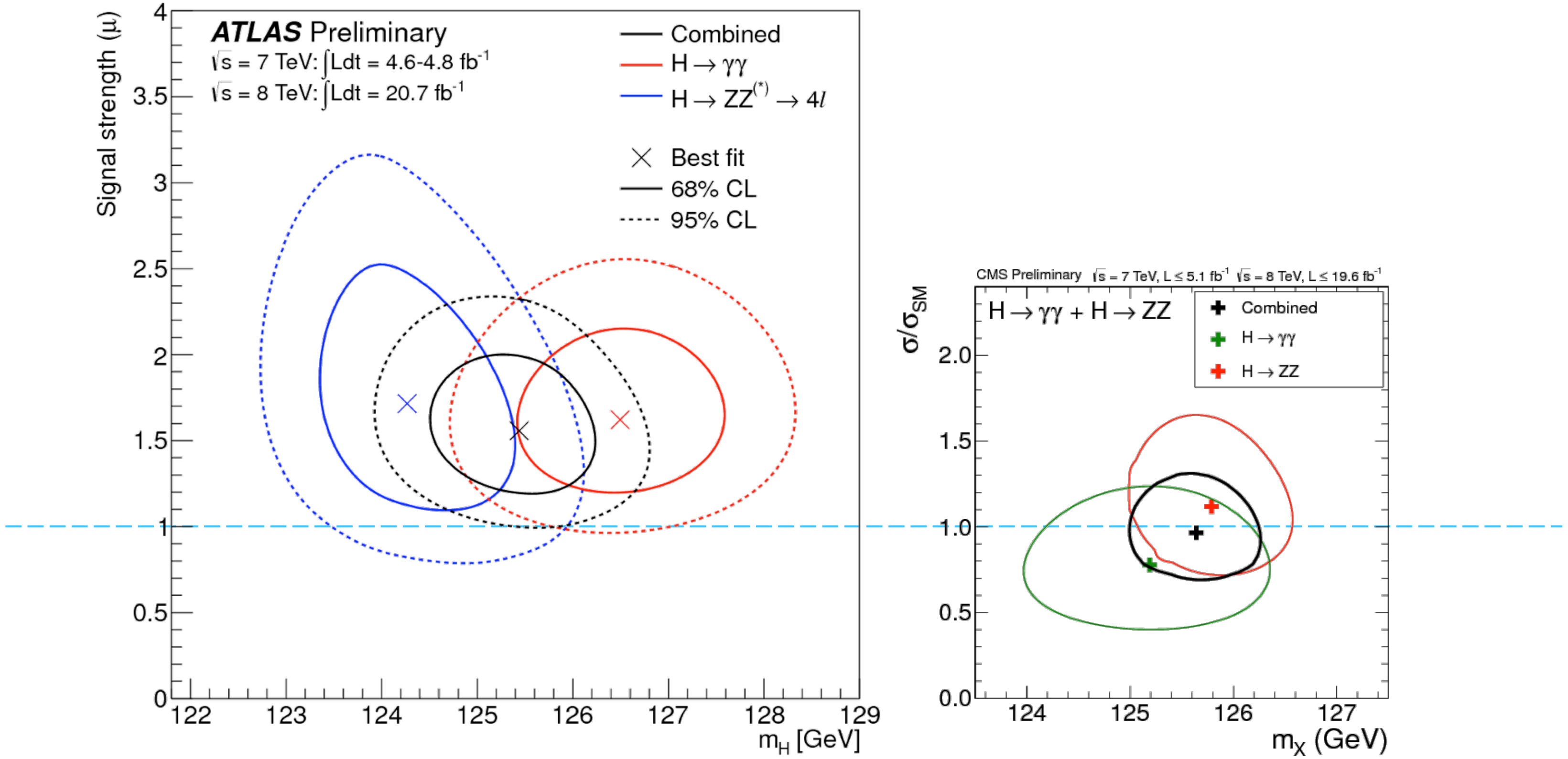
[http://cern.ch/go/P8Tn] [http://cern.ch/go/l7RZ]

- 300/fb at 14 TeV:
  - Vast improvement over present datasets.
  - **Room for theory improvements.**
- For (HL-LHC) 3 ab^{-1}:
  - self-coupling seems feasible with $\lambda_{HH} \sim 3\sigma$/expt.



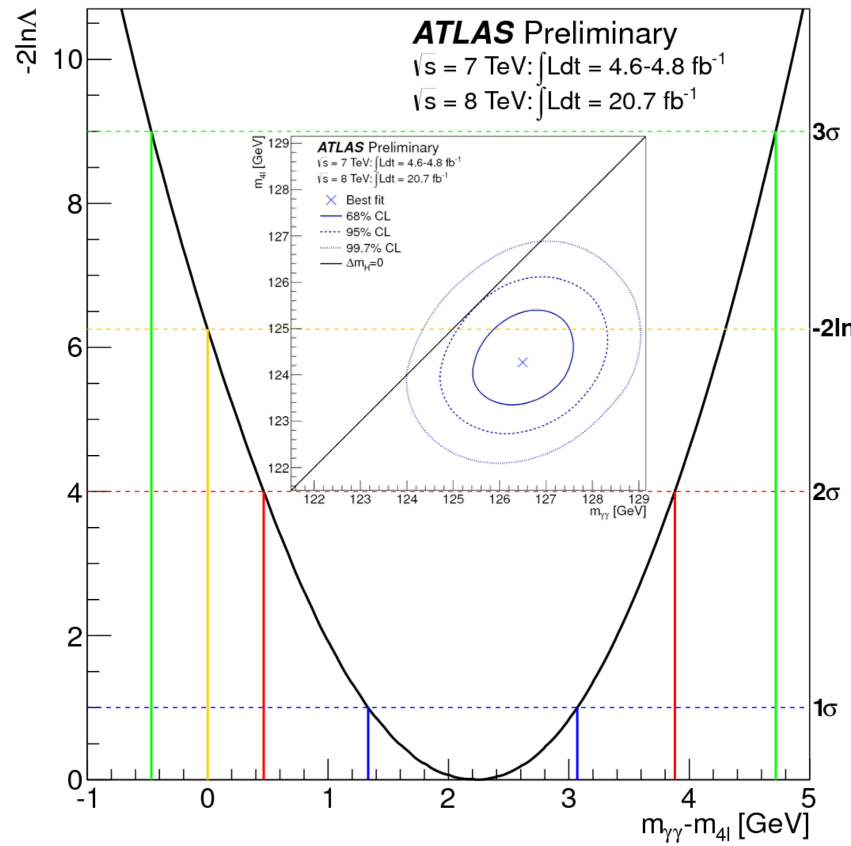
More on mass

Measuring the mass



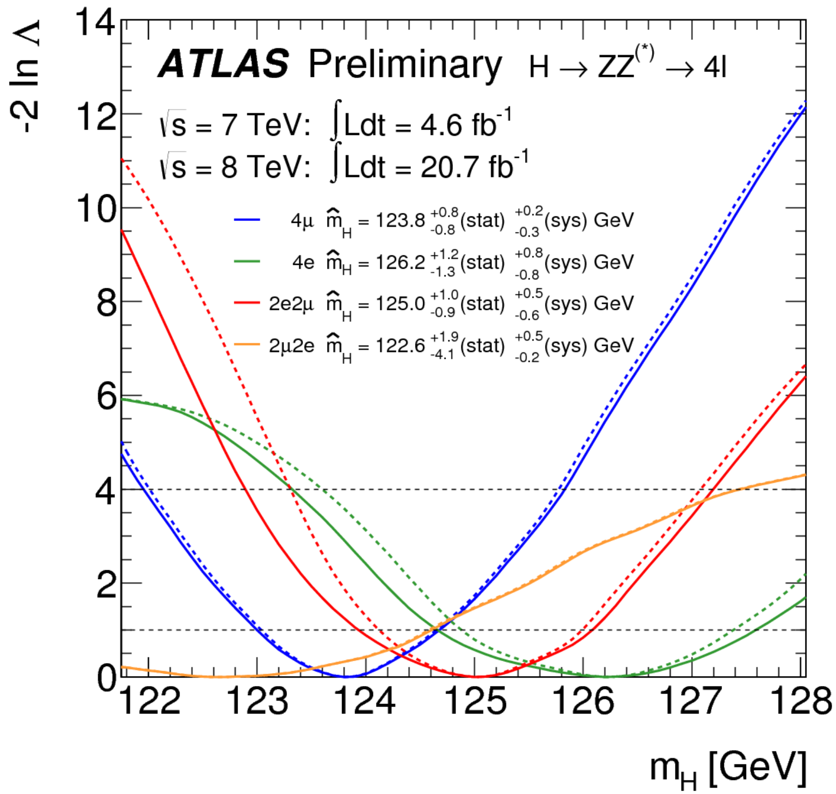
- Combinations of the high-resolution channels.

More on ATLAS mass

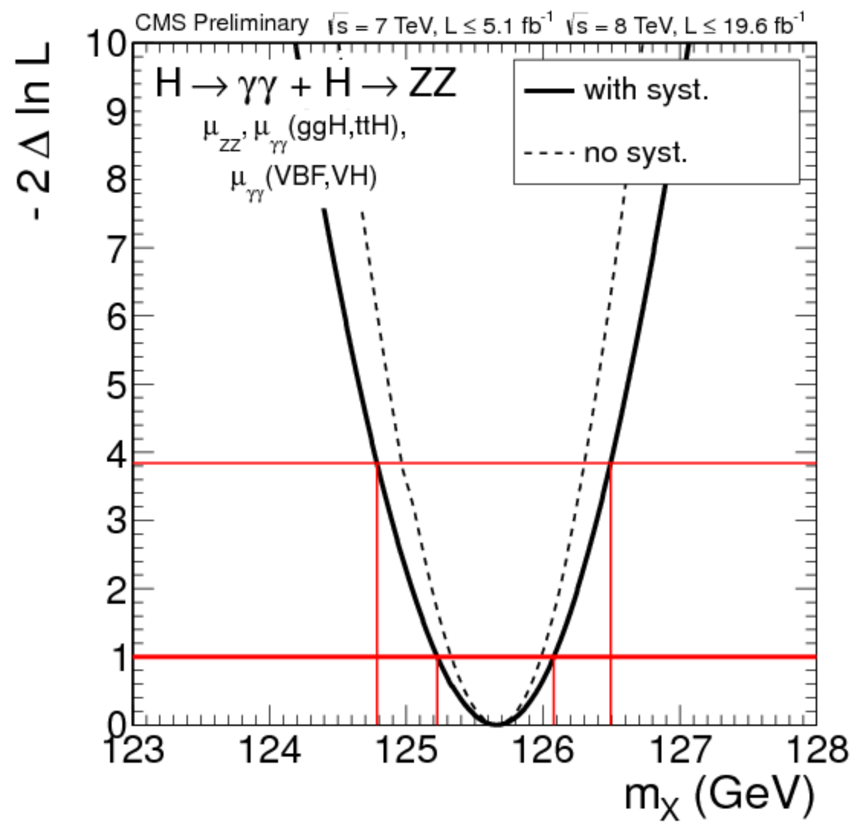


- Slight difference in ATLAS results:
  - $\Delta m = 2.3\ ^{+0.6}_{-0.7}$(stat.) ±0.6(syst.) GeV
  - 2.4σ (p=1.5%)
- Using more conservative energy scale uncertainties: **1.8σ (p=8%).**

More on mass



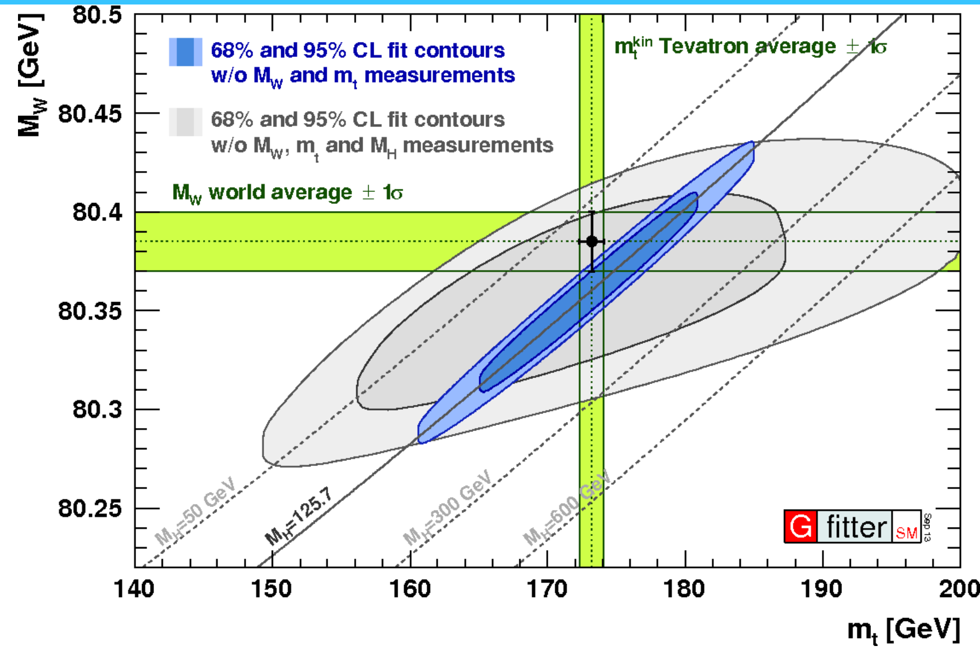
ATLAS Preliminary H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.6 fb-1
√s = 8 TeV: ∫Ldt = 20.7 fb-1
4μ m̂H = 123.8 +0.8 -0.8 (stat) +0.2 -0.3 (sys) GeV
4e m̂H = 126.2 +1.2 -1.3 (stat) +0.8 -0.8 (sys) GeV
2e2μ m̂H = 125.0 +1.0 -0.9 (stat) +0.5 -0.6 (sys) GeV
2μ2e m̂H = 122.6 +1.9 -4.1 (stat) +0.5 -0.2 (sys) GeV
-2 ln Λ
mH [GeV]



CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
H → γγ + H → ZZ
μZZ, μγγ(ggH,ttH), μγγ(VBF,VH)
with syst.
no syst.
- 2 Δ ln L
mX (GeV)

One measurement, three masses?

- Green rectangle?
- There are correlations !
  - m_W: leptons, MET.
  - m_t: MET, b-tag, leptons.
  - m_H: leptons, photons.
  - Theory.

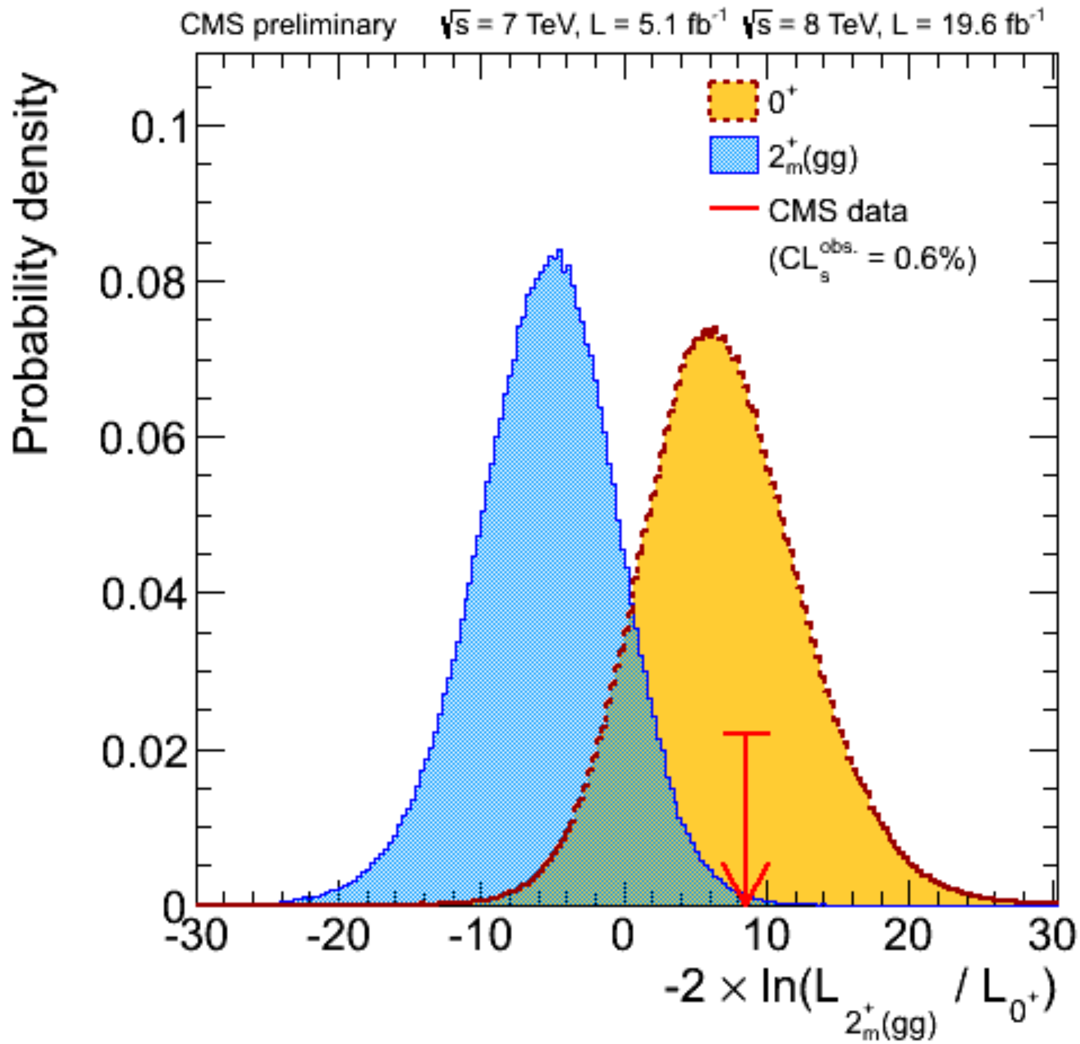


- **But what do the m_X mean?**

More on spin 2

CMS: 2^{+}_{m} combination

- Combination of $H \longrightarrow ZZ$, WW:
  - p(obs.|0^+) = -0.34 σ
  - p(obs.|2^{+}_{m}(gg)) = 2.84 σ
  - **CL_S = 0.6%**



Miscellaneous

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.**

100

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

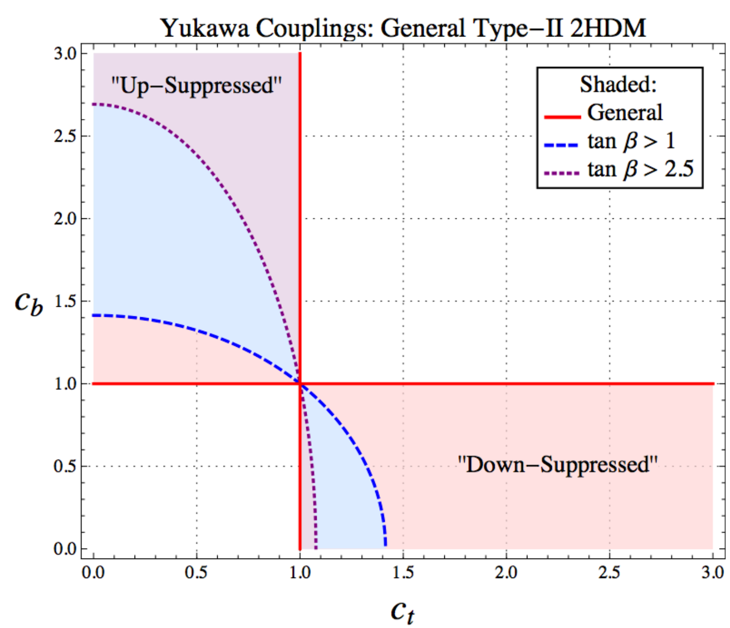
if $c_t > 1$ then $c_b < 1$ and viceversa

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

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

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

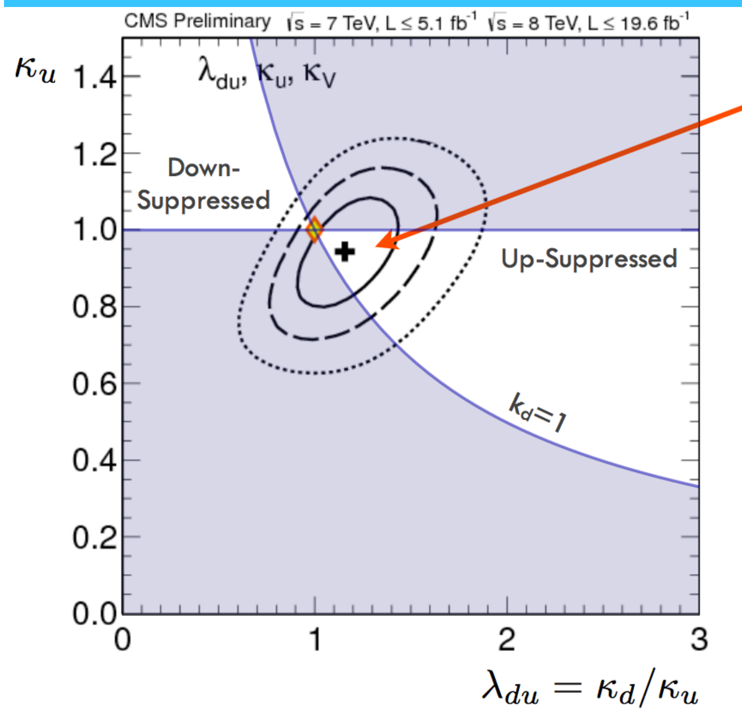
Down-Suppressed region almost *not accessible* in the MSSM for $\tan\beta > 1$



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

MSSM (R.Contino)

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

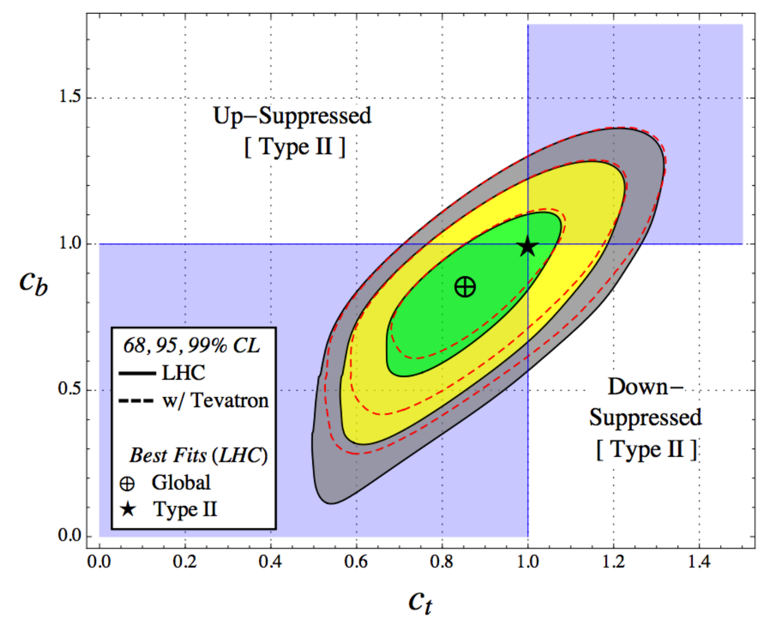


the current fit by CMS seems to favor the MSSM region, though errors are large

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:

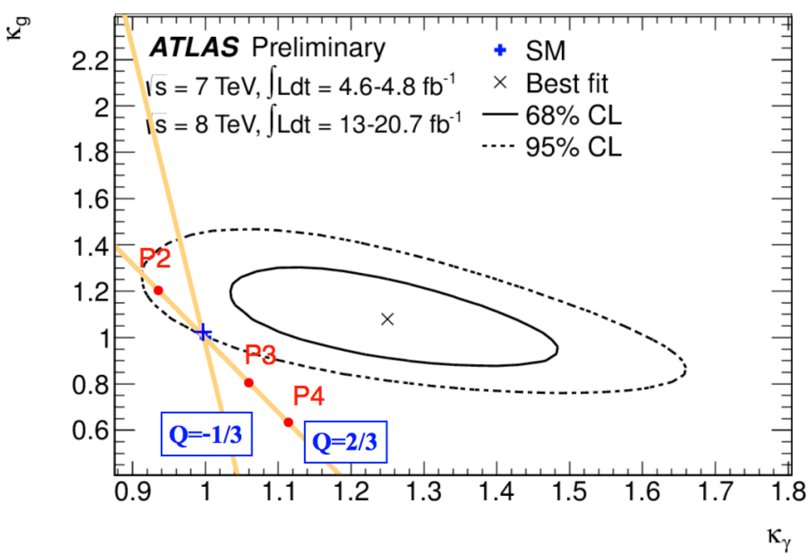
from: Azatov, Galloway Int. J. Mod. Phys. A28 (2013) 1330004

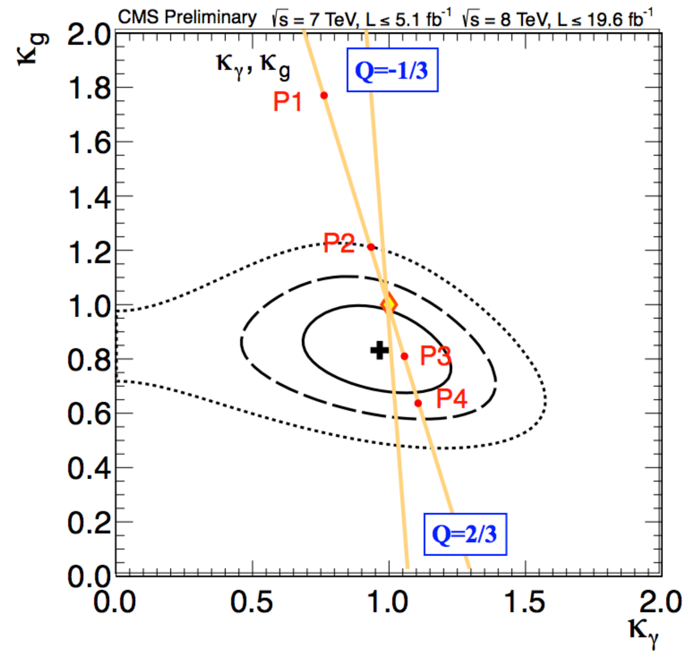


MSSM (R.Contino)

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

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

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

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

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

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

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:

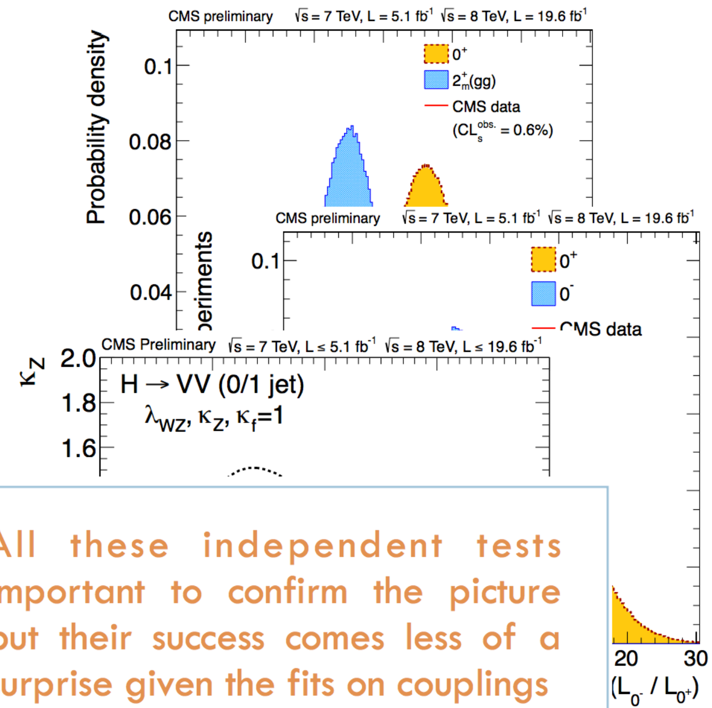
- h has spin 0 ✓
- h is (mostly) CP=+ ✓
- There exists a correlation among processes with 0,1,2 Higgs bosons

  Ex: custodial symmetry ✓

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

- 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

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

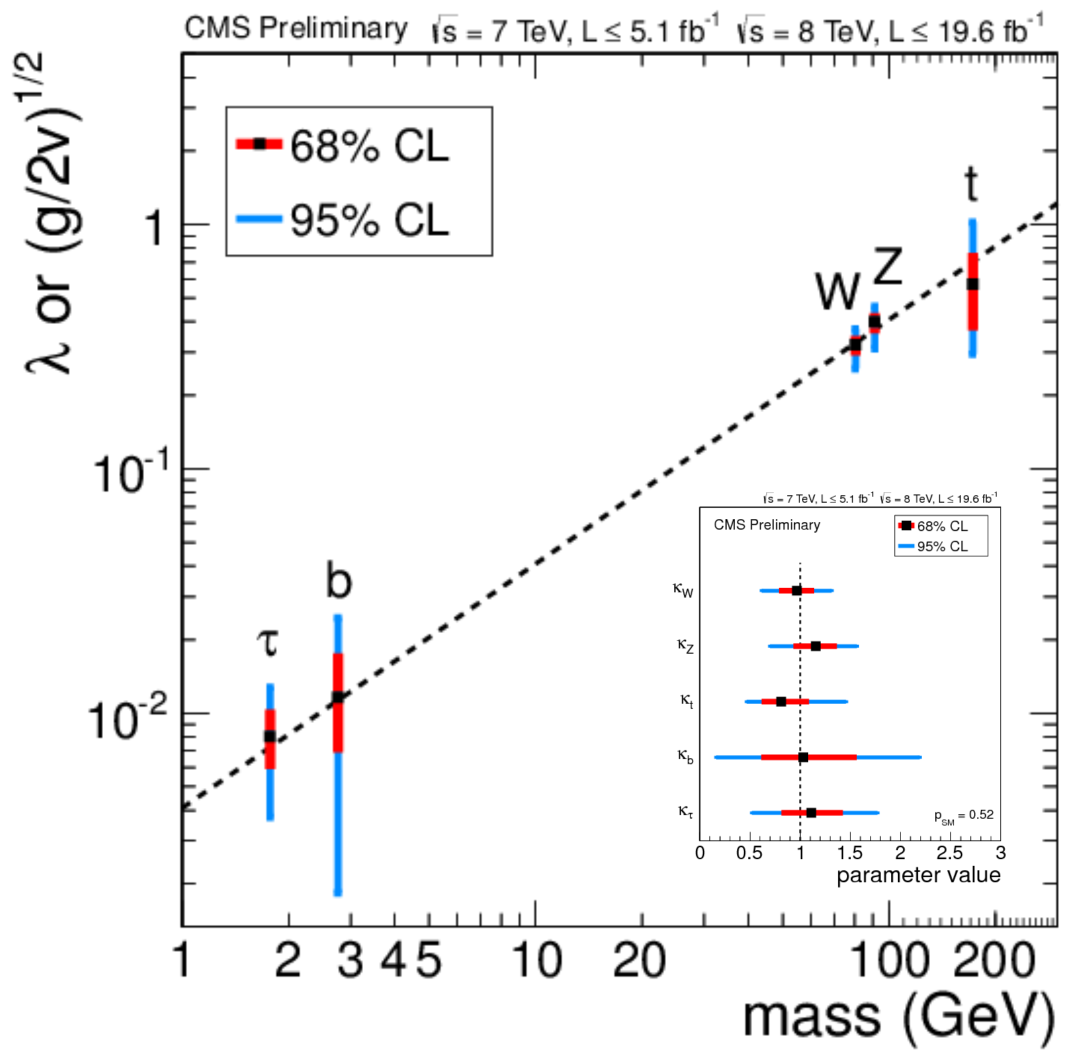
As a function of masses

Resolving SM contributions

[CMS-PAS-HIG-13-005]

- 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.

- **P(SM)=0.52.**
- "Reduced" couplings as function of "mass":
  - $\lambda_f = \kappa_f (m_f/vev)$
  - $(g_V/2vev)^{1/2} = \kappa_V^{1/2} (m_V/vev)$



"C6" vs "resolved C6"

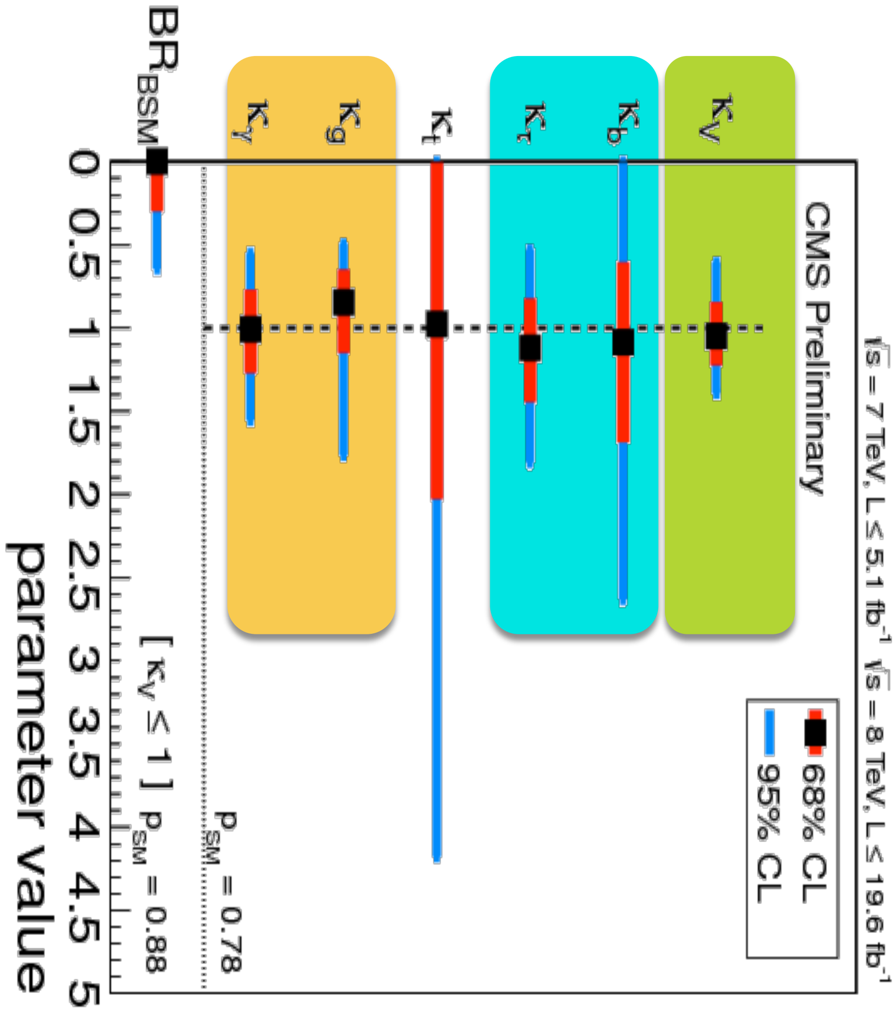
Generic coupling fit

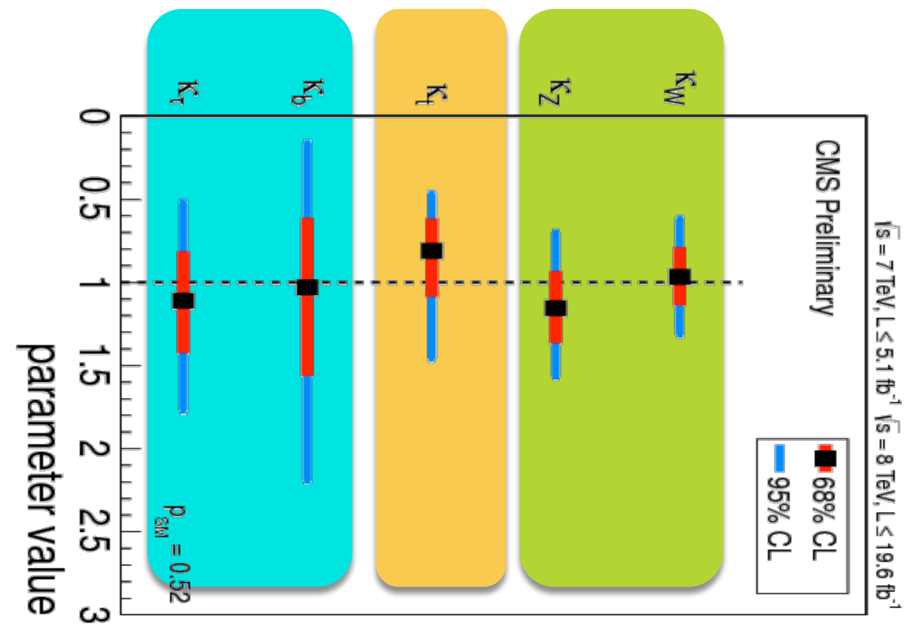
- Assume custodial symmetry ($\kappa_V = \kappa_W = \kappa_Z$).
- Loops treated effectively (κ_γ, κ_g).
- Option to allow BSM decays, forcing $\kappa_V \leq 1$.

Resolved coupling fit

- Keep W and Z separate.
- Loops assuming SM structure:
  - κ_g (κ_b, κ_t).
  - κ_γ (κ_W, κ_b, κ_t, κ_τ).
- Only SM-like decays.

"C6" vs "resolved C6"

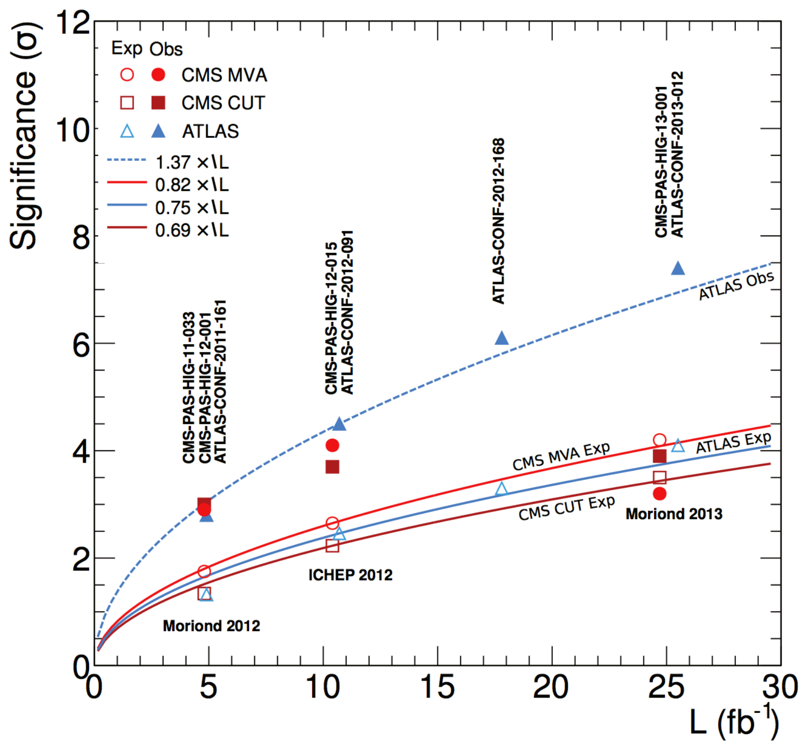


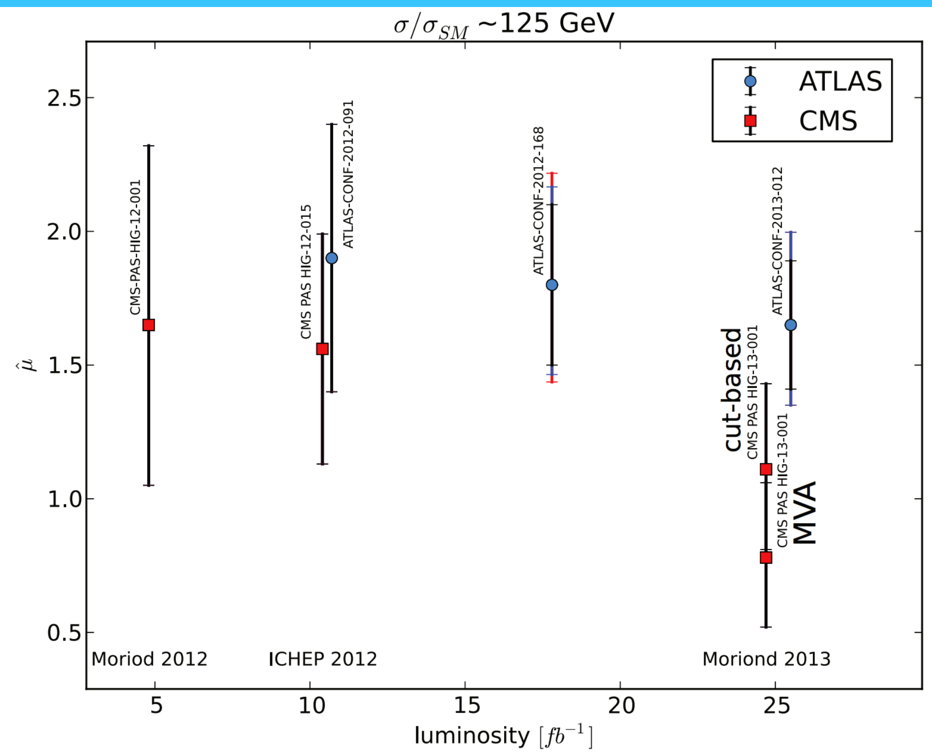


$H \rightarrow \gamma\gamma$ evolution

Interesting H→ $\gamma\ \gamma$ comparisons

[http://cern.ch/go/lc9j]

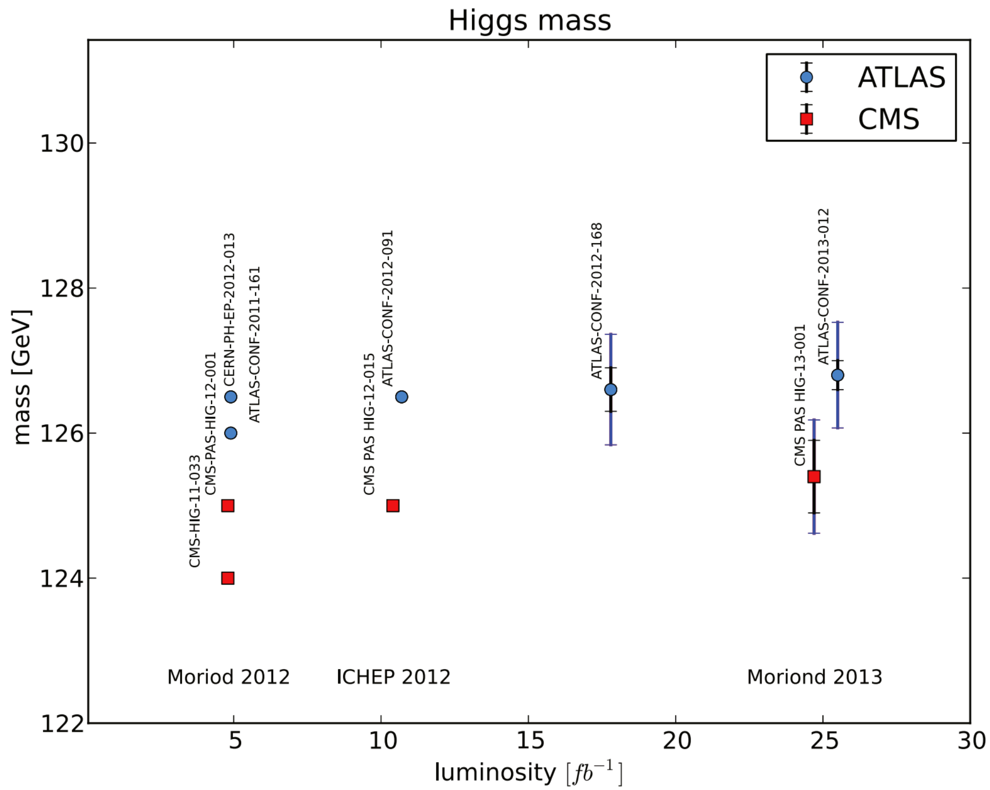




- VI Workshop Italiano sulla Fisica p-p a LHC

Interesting H→ $\gamma\gamma$ comparisons

[http://cern.ch/go/lc9j]



- VI Workshop Italiano sulla Fisica p-p a LHC

More on scalar couplings

Oversimplified big picture

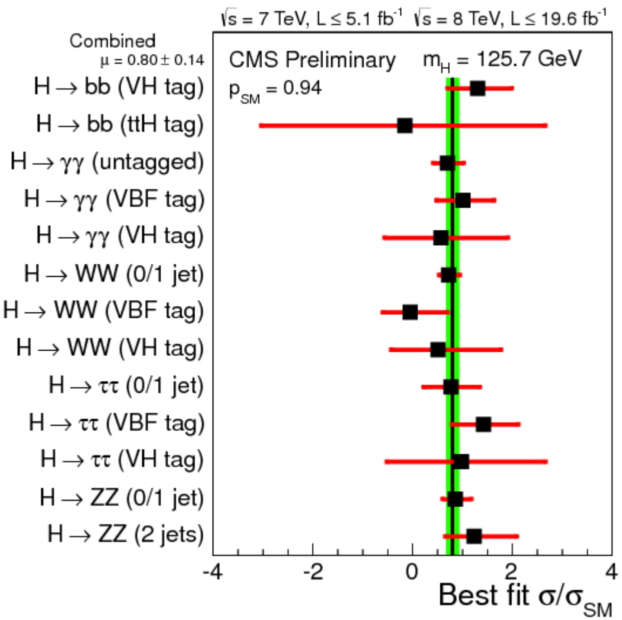
T – Tevatron; A – ATLAS; C – CMS; combination drivers in red.

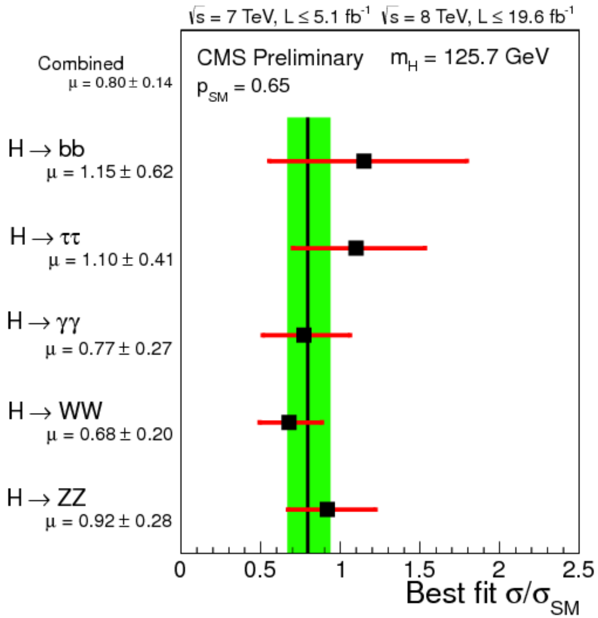
★ "seen" ☆ "tried" - "impossible"	H→bb̄			H→ττ			H→WW			H→ZZ			H→γγ			H→Zγ			H→inv.			H→μμ			H→cc̄ H→HH		
	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C	T	A	C
ggH	-	-	-	☆	☆	★ (red)	☆	★ (red)	★ (red)	☆	★ (red)	★ (red)	☆	★ (red)	★ (red)	-	☆	☆				-	☆	☆	-		
VBF			☆	☆	☆	★ (red)		★ (red)	★ (red)		★ (red)	☆		★ (red)	☆	-		☆			☆	-		☆	-		
VH	★ (red)	☆	★ (red)	☆		☆	☆	☆	☆		☆			☆	☆	-				☆	☆	-			-		
ttH		☆	☆	☆			☆							☆	☆	-						-			-		

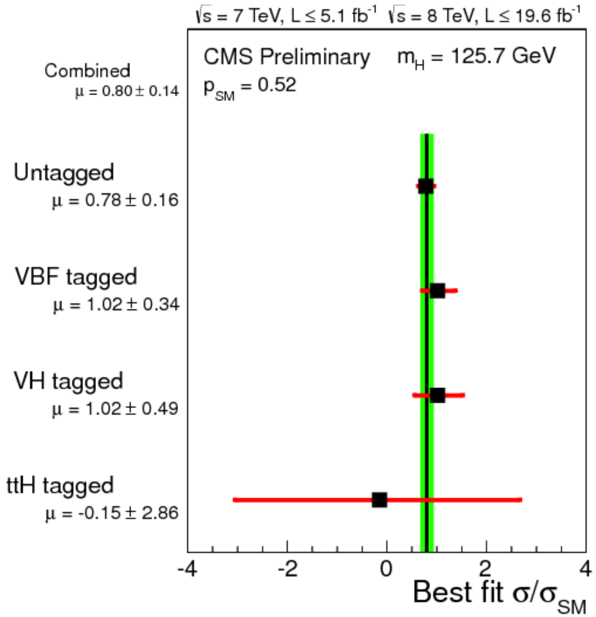
- **Still much to explore on the rarer ends.**

(to the right and to the bottom)

CMS: channel compatibility





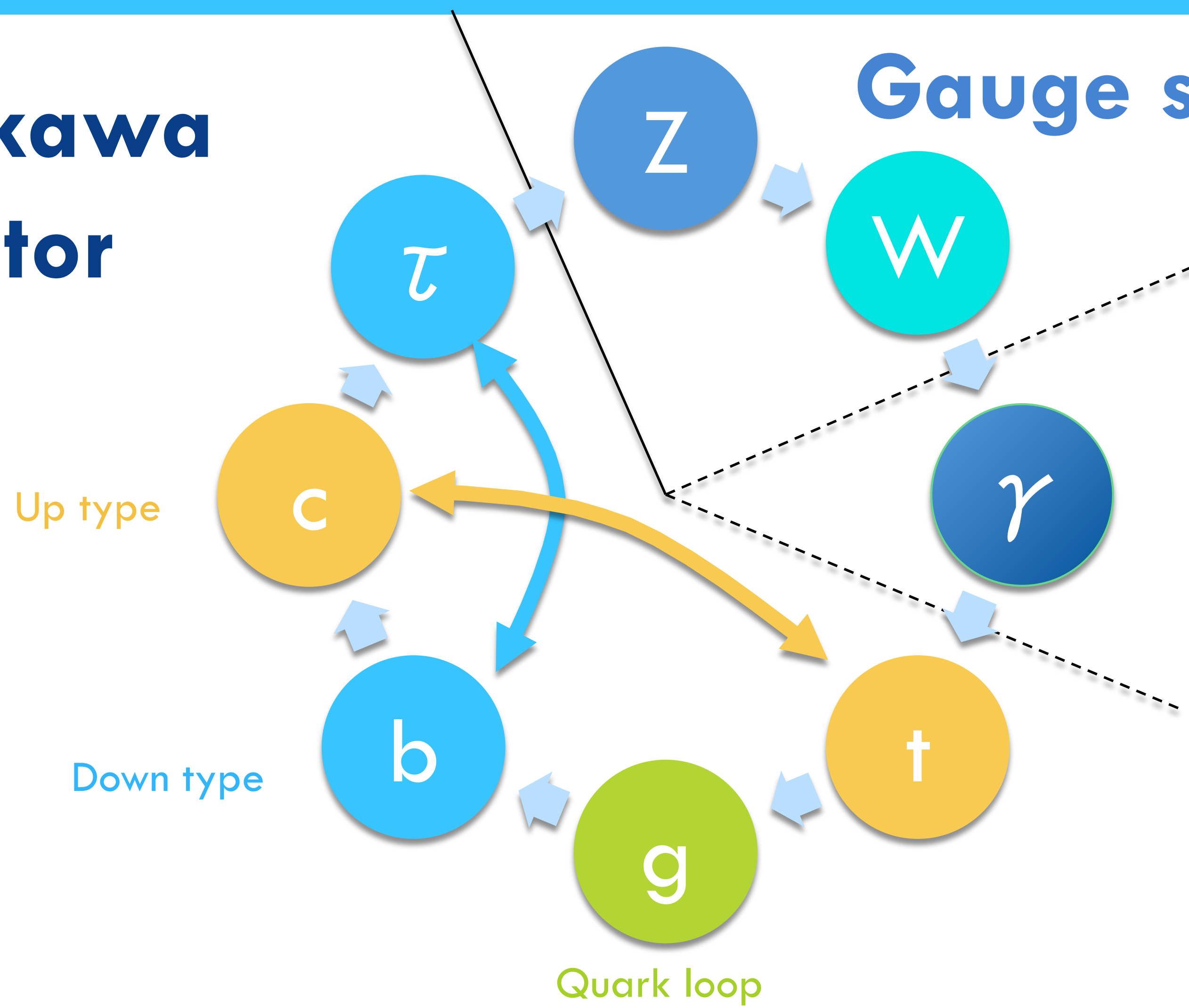


Scalar coupling structure

Yukawa sector

Gauge sector

Mixed sector



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

Interim scalar coupling deviations framework

[arXiv:1209.0040]

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

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

- Narrow-width approximation: $(\sigma \times BR) = \sigma \cdot \Gamma / \Gamma_H$

Interim scalar coupling deviations framework

[arXiv:1209.0040]

Production modes

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

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

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

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

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

Detectable decay modes

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

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

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

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

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

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

Currently undetectable decay modes

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

$\frac{\Gamma_{gg}}{\Gamma^{SM}_{gg}}$: 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

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

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

Probing custodial symmetry

 [arXiv:1209.0040]

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	$\frac{\kappa_Z^2 \cdot \kappa_\gamma^2(\kappa_f,\kappa_f,\kappa_f,\kappa_Z\lambda_{WZ})}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_Z^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot (\kappa_Z\lambda_{WZ})^2}{\kappa_H^2(\kappa_i)}$	$\frac{\kappa_Z^2 \cdot \kappa_f^2}{\kappa_H^2(\kappa_i)}$	

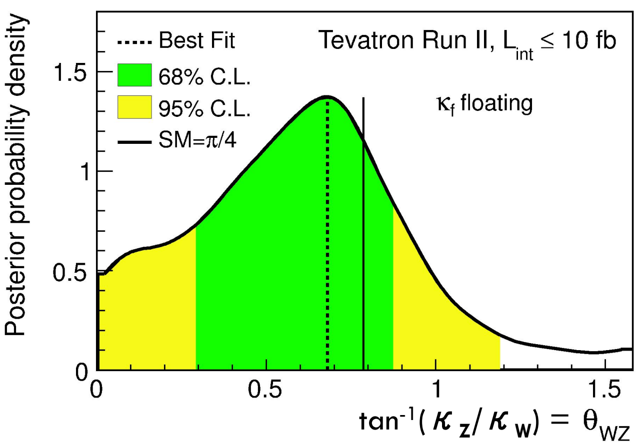
Probing custodial symmetry without assumptions on the total width

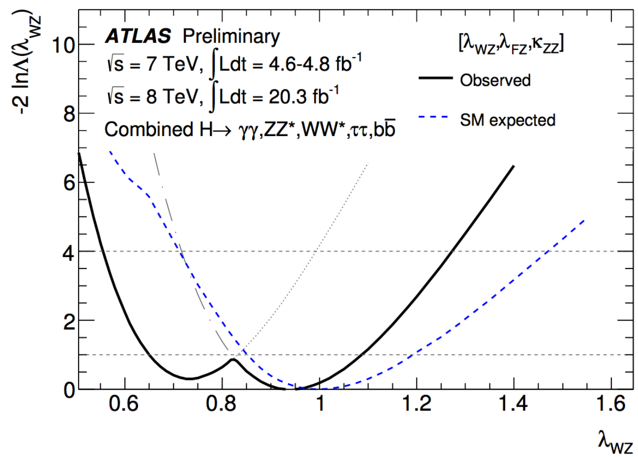
Free parameters: $\kappa_{ZZ} (= \kappa_Z \cdot \kappa_Z/\kappa_H)$, $\lambda_{WZ} (= \kappa_W/\kappa_Z)$, $\lambda_{FZ} (= \kappa_f/\kappa_Z)$.

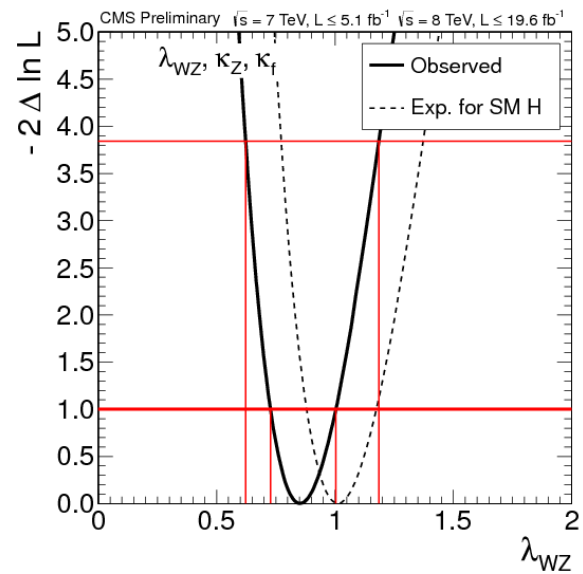
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH $t\bar{t}H$	$\kappa_{ZZ}^2\lambda_{FZ}^2 \cdot \kappa_\gamma^2(\lambda_{FZ},\lambda_{FZ},\lambda_{FZ},\lambda_{WZ})$	$\kappa_{ZZ}^2\lambda_{FZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2 \cdot \lambda_{WZ}^2$	$\kappa_{ZZ}^2\lambda_{FZ}^2 \cdot \lambda_{FZ}^2$	
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-2013-034] [CMS-PAS-HIG-13-005]



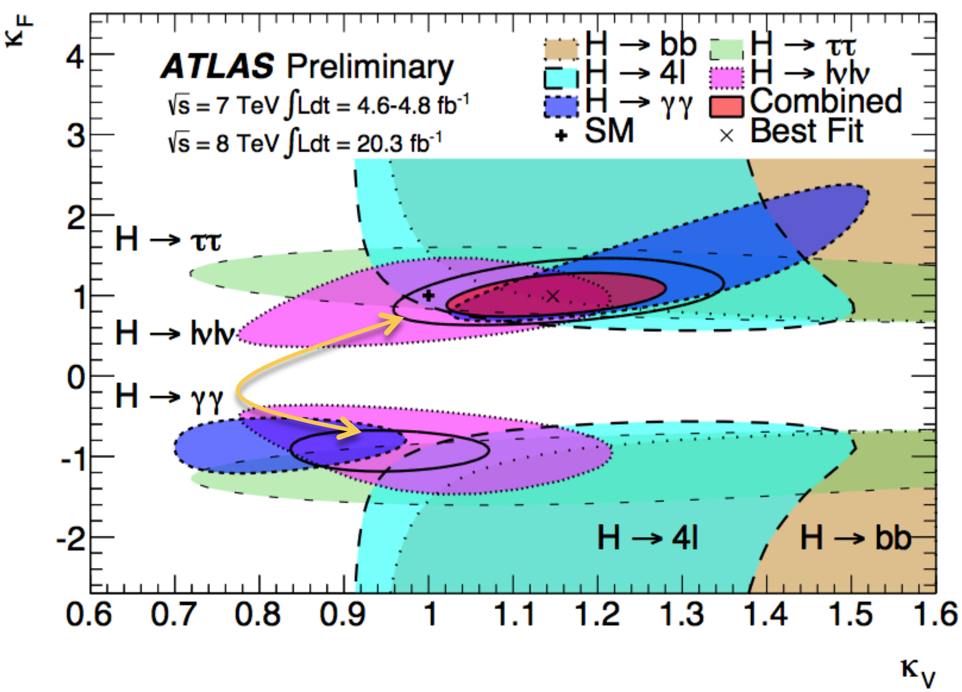


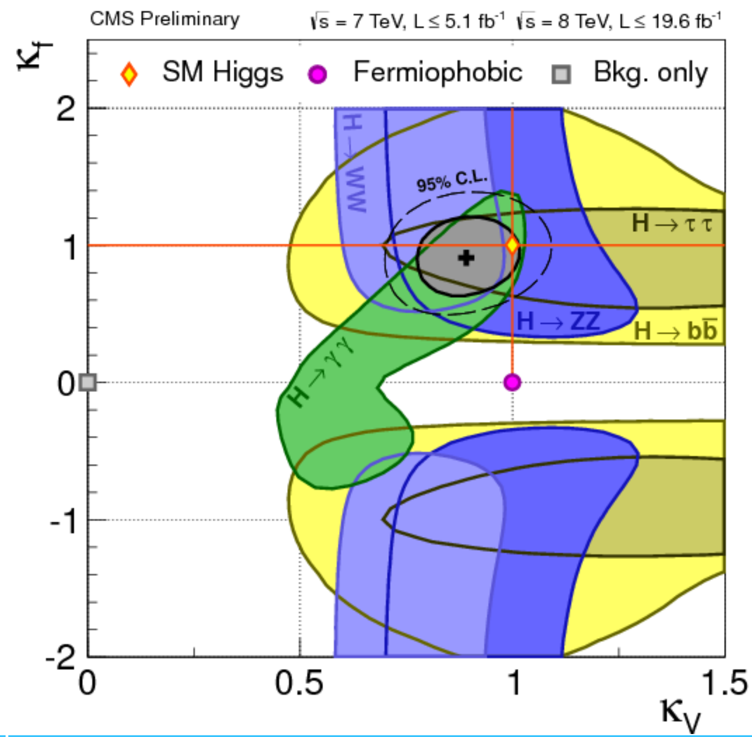


	Tevatron [κ_W, κ_Z, κ_f]	ATLAS [λ_{WZ}, λ_{FZ}, κ_{ZZ}]	CMS [λ_{WZ}, κ_Z, κ_f]
λ_{WZ}	$1.24^{+2.34}_{-0.42}$	$0.94^{+0.14}_{-0.29}$	0.86 ± 0.13

Weak bosons and fermions

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]





	ATLAS	CMS
P(SM)	**10%**	**< 1 σ**

Looking for new particles

[arXiv:1209.0040]

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

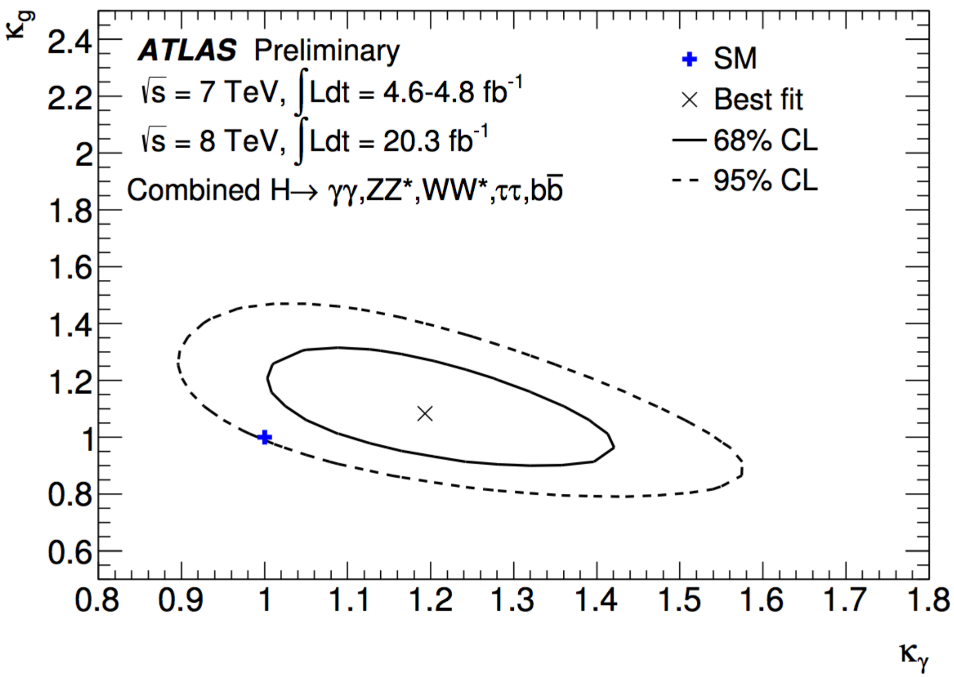
Free parameters: $\kappa_g, \kappa_\gamma, BR_{inv.,undet.}$.

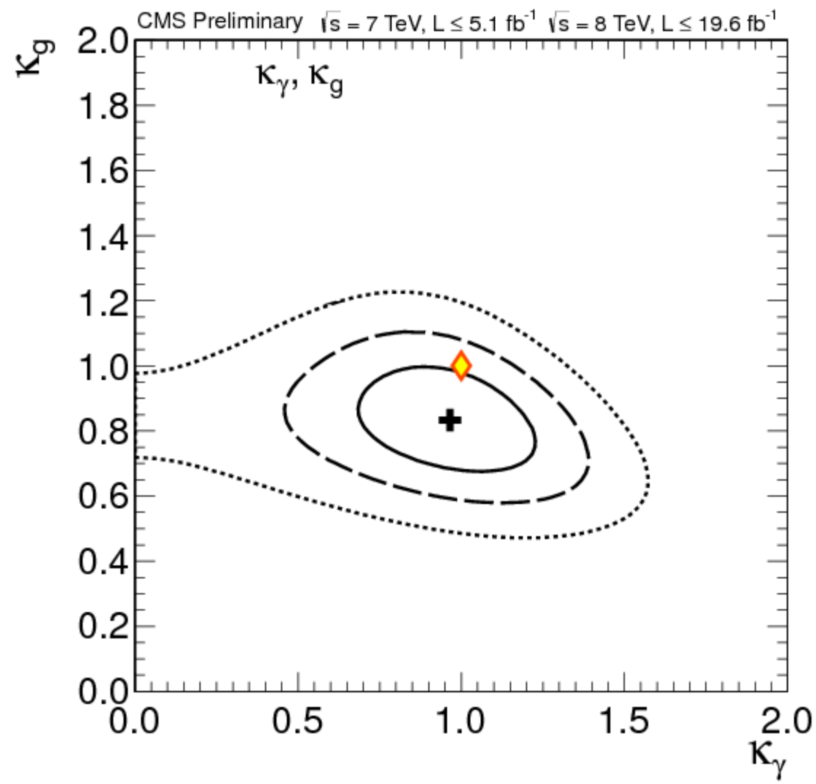
	$H \to \gamma\gamma$	$H \to ZZ^{(*)}$	$H \to WW^{(*)}$	$H \to b\bar{b}$	$H \to \tau^-\tau^+$
ggH	$\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$	$\frac{\kappa_g^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$			
$t\bar{t}H$ VBF WH ZH	$\frac{\kappa_\gamma^2}{\kappa_H^2(\kappa_i)/(1-BR_{inv.,undet.})}$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

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

Looking for new particles in loops

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]



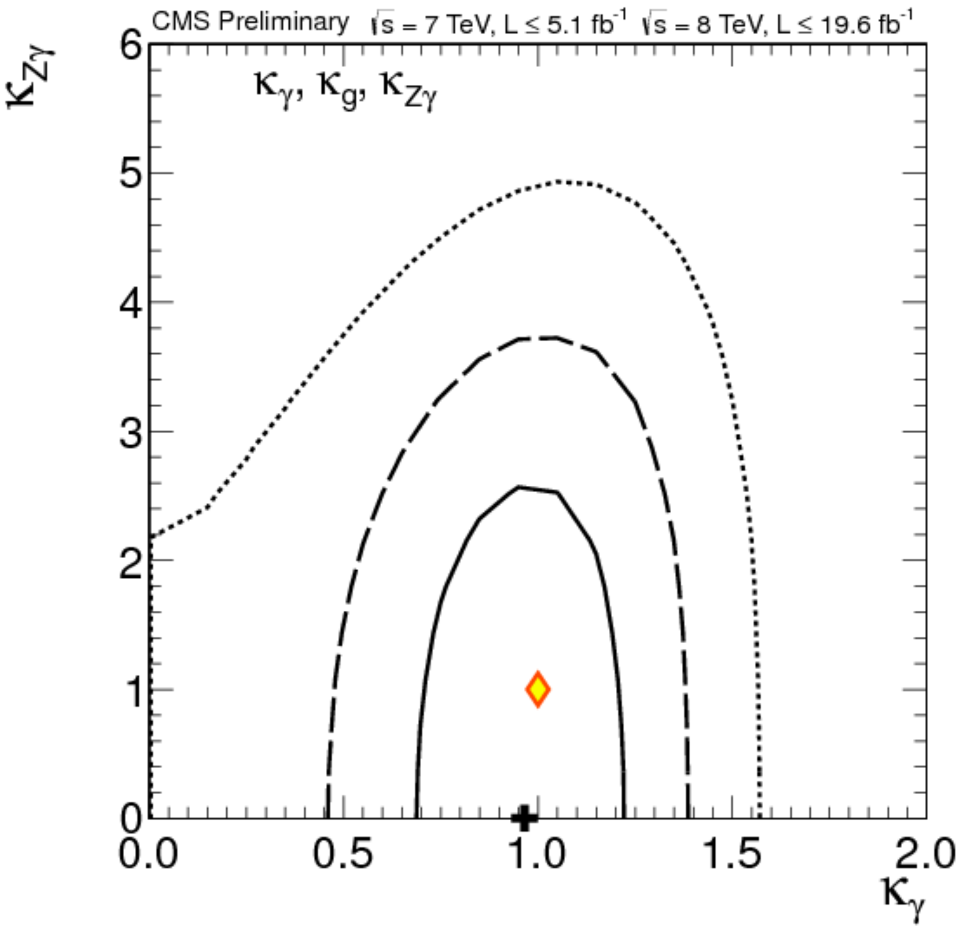


	ATLAS	CMS
κ_γ	$1.19^{+0.15}_{-0.12}$	0.97 ±0.18
κ_g	1.08 ±0.14	0.83 ±0.11

A further take on loops

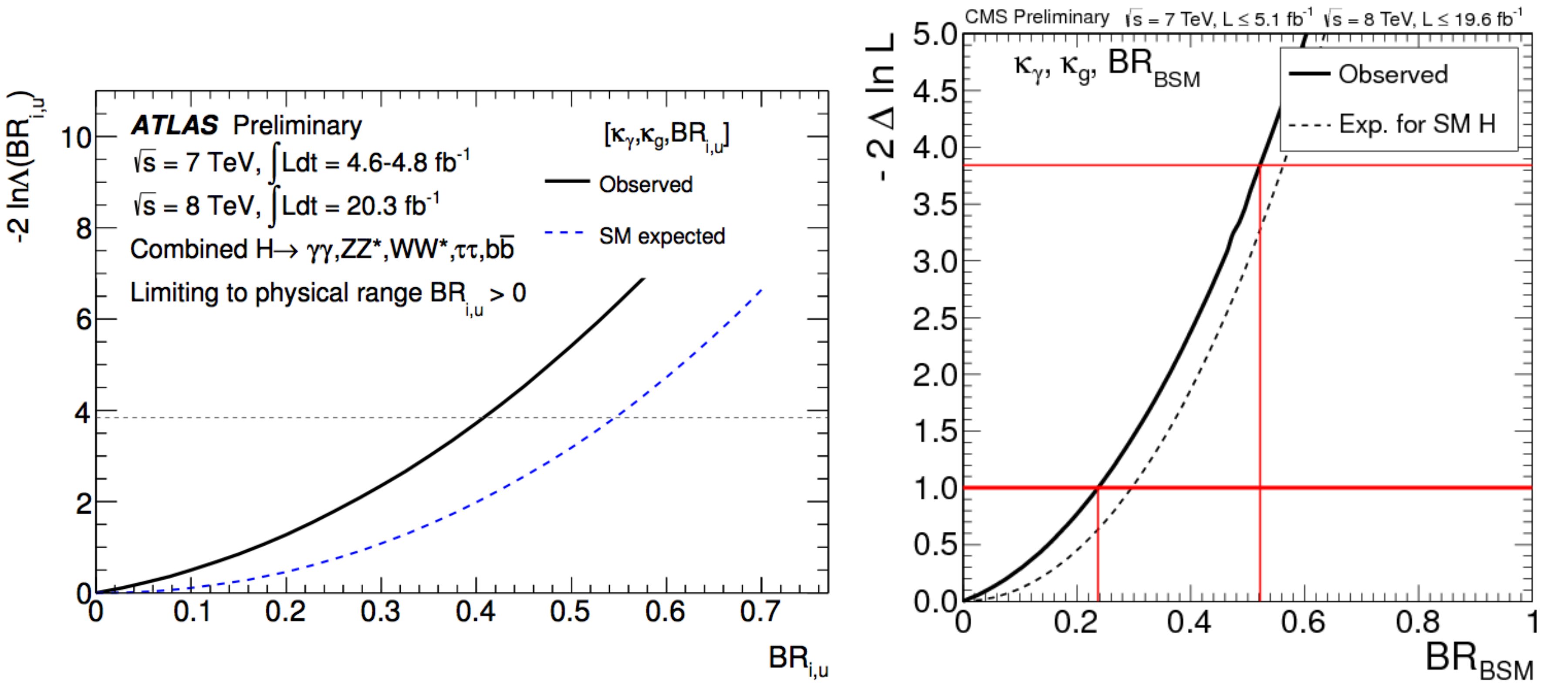
[CMS-PAS-HIG-13-005]

- Resolve the H⟶$\gamma\gamma$, H⟶Zγ, and ggH loops.



Looking for new particles

[ATLAS-CONF-2014-009] [CMS-PAS-HIG-13-005]



	ATLAS	CMS
BR_{BSM}	< 0.41 (95% CL)	< 0.52 (95% CL)

Probing the fermion sector

[arXiv:1209.0040]

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'	$\frac{\cos\alpha}{\sin\beta}$	$\frac{-\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

SM-like

CMS

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

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

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

CMS

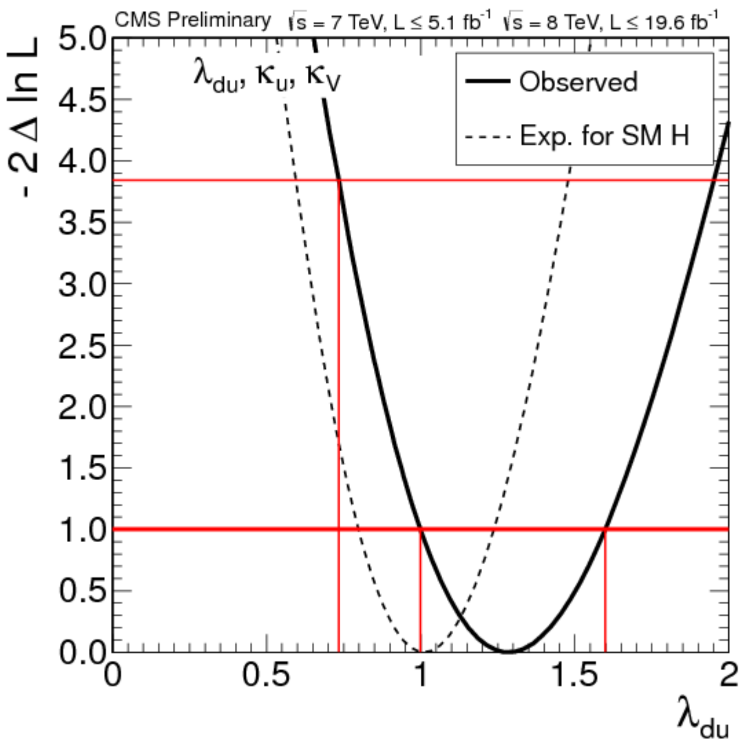
Probing quark and lepton fermion symmetry assuming no invisible or undetectable widths

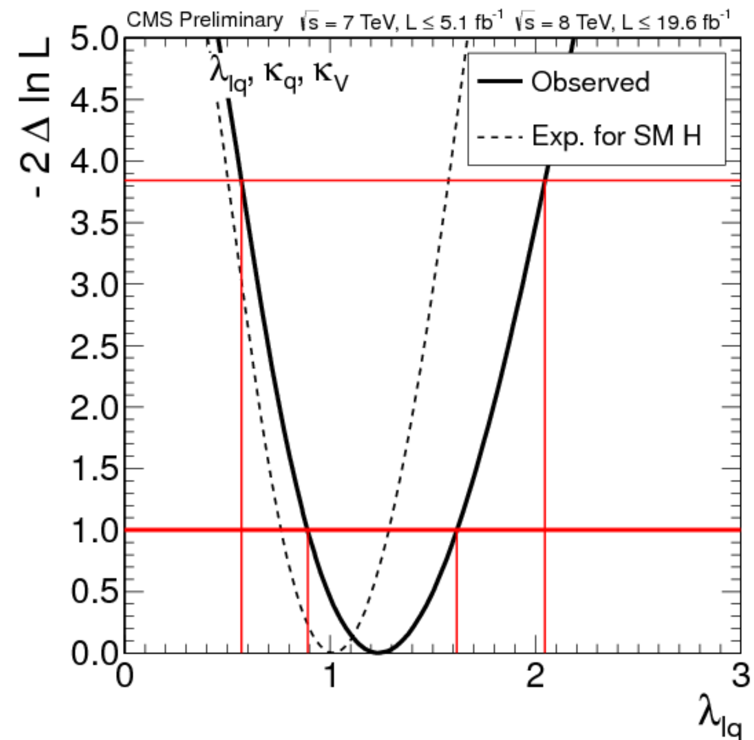
Free parameters: $\kappa_V(=\kappa_Z=\kappa_W)$, $\lambda_{lq}(=\kappa_l/\kappa_q)$, $\kappa_q(=\kappa_t=\kappa_b)$.

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

Probing the fermion sector

[CMS-PAS-HIG-13-005]

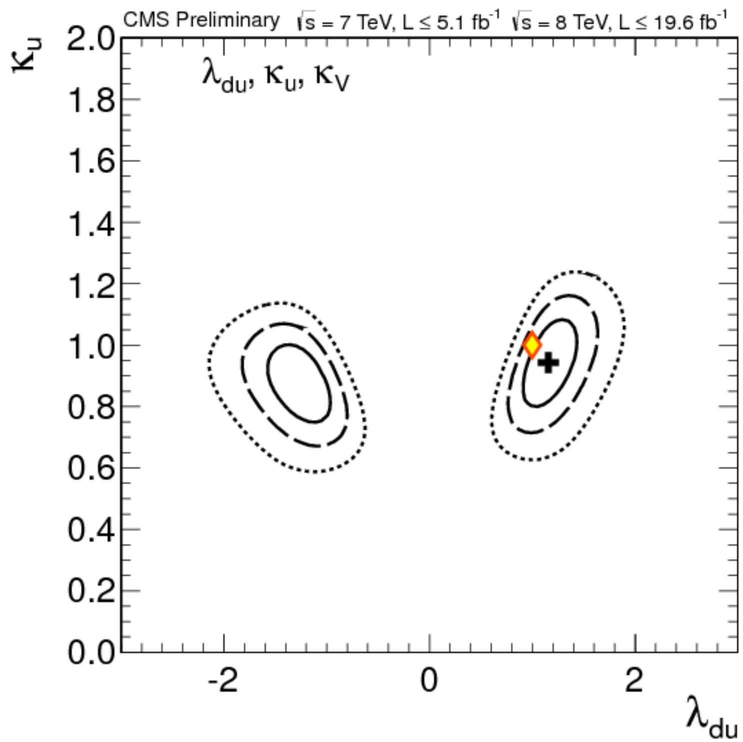


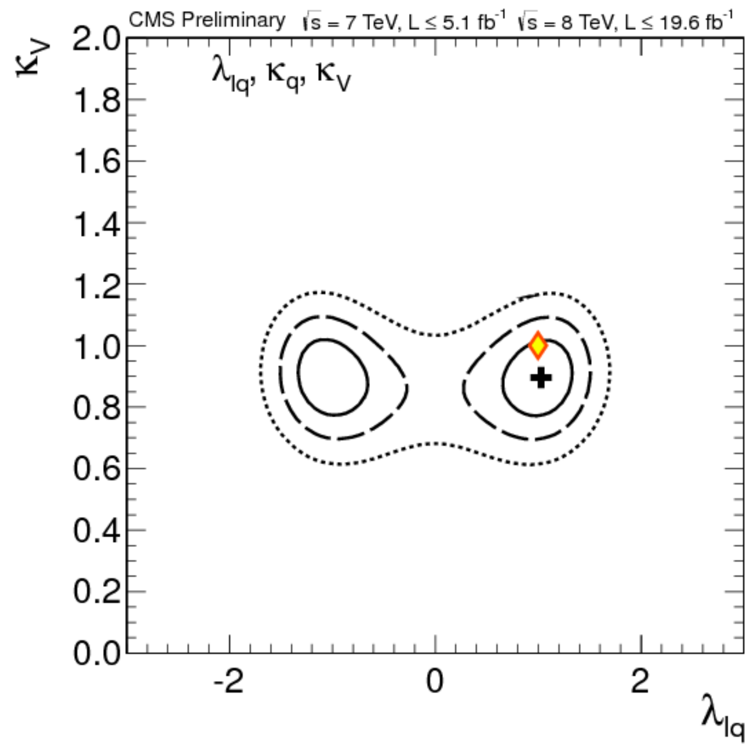


	λ_{du}	λ_{lq}
CMS	**[0.74, 1.95] (95% CL)**	**[0.57, 2.05] (95% CL)**

Probing possible 2HDM

[CMS-PAS-HIG-13-005]





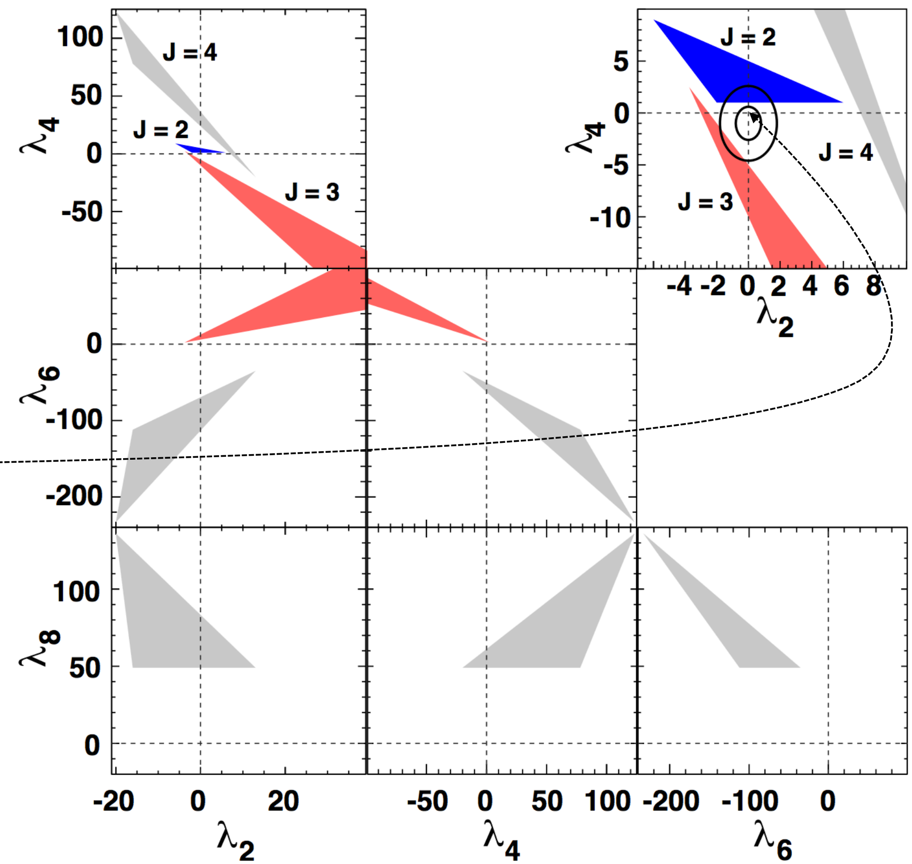
	λ_{du}	λ_{lq}
CMS	**[0.74, 1.95] (95% CL)**	**[0.57, 2.05] (95% CL)**

A way out the spin quandary?

 [arXiv:1307.7121]

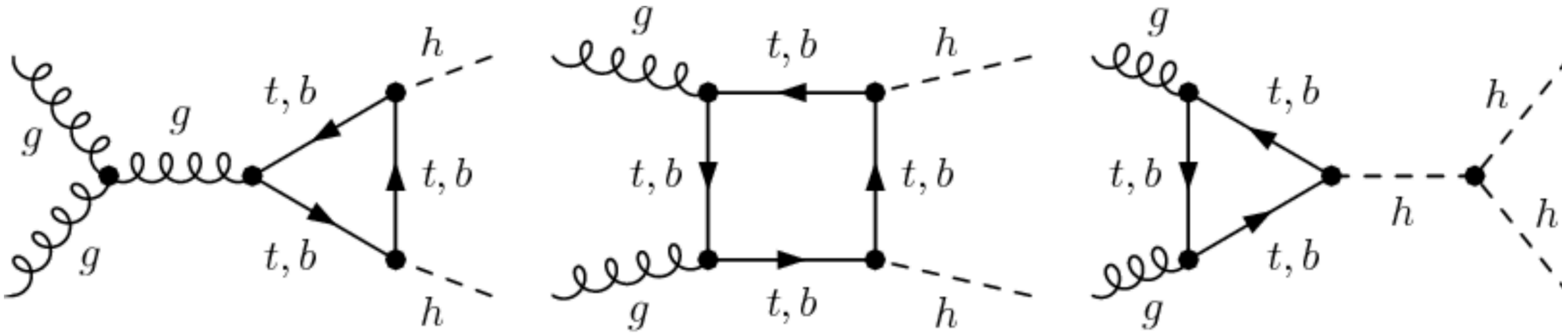
- It's not easy to kill all possible non-spin-0 alternatives.
- gg→H→ γ γ holds promise:
  - J≠0 allowed areas do not contain **J=0 point.**
  - But gluons and photons must be real…

$$w(\cos\vartheta \mid \vec{\lambda}) = \frac{1}{2} \frac{1 + \sum_{i=1}^{2J} \lambda_i (\cos\vartheta)^i}{1 + \sum_{j=1}^{J} \frac{\lambda_{2j}}{2j+1}}$$



Statistics-limited: HH and self-coupling

[http://cern.ch/go/7smd]



- Among main objectives for HL-LHC.
  - Tiny cross-section.
  - Diagrams interfere destructively…
  - Problematic even in e^+e^-.
- Experimental projections not finalized.

Estimated yields for 3000/fb	
$b\bar{b}WW$	30'000
$b\bar{b}\tau\tau$	9'000
WWWW	6'000
$\gamma\gamma b\bar{b}$	320
$\gamma\gamma\gamma\gamma$	1

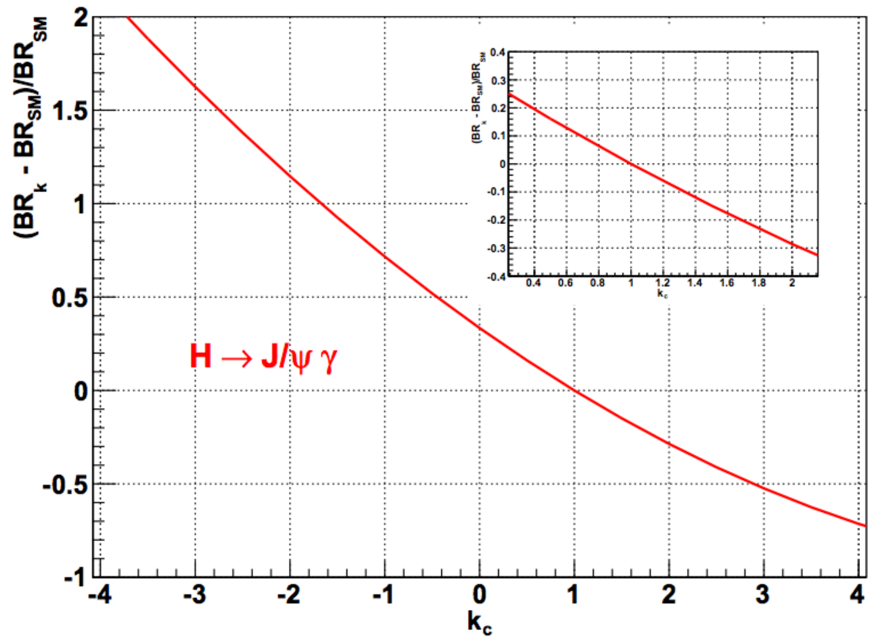
Weird decays: $H \to Q\bar{Q} + \gamma$

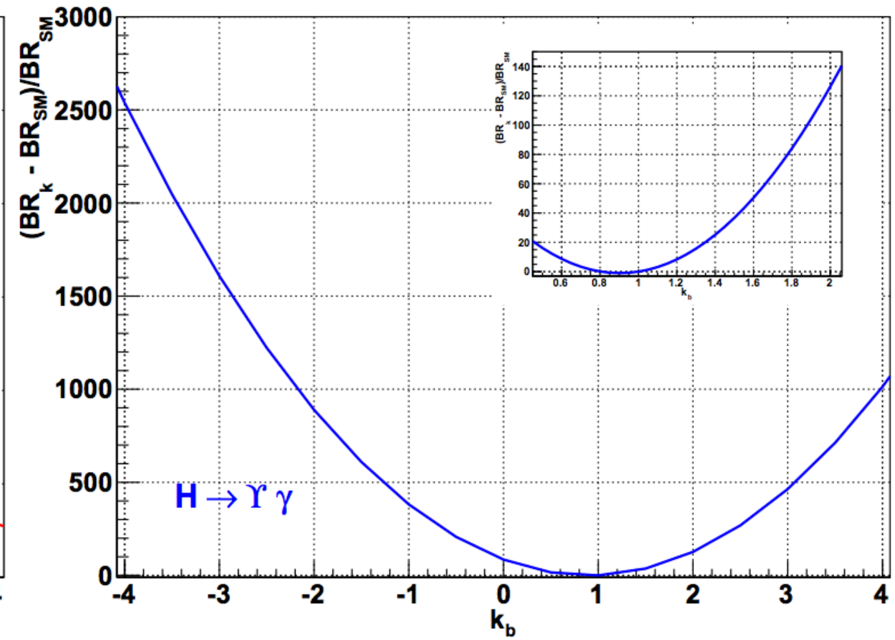
[arXiv:1306.5770]

- Complementary way to get to the bottom.
- A way to get to charm?

$$\mathrm{BR_{SM}}(H \to J/\psi\,\gamma) = (2.46^{+0.26}_{-0.25}) \times 10^{-6}$$

$$\mathrm{BR_{SM}}(H \to \Upsilon(1S)\,\gamma) = (1.41^{+2.03}_{-1.14}) \times 10^{-8}$$

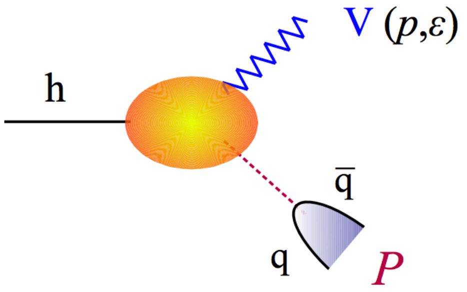




Weird decays: H$\longrightarrow$VP

[http://cern.ch/go/8gXr]

- Accessible due to small m_H.
- Relatively clean.
- Can bear O(1) BSM changes.

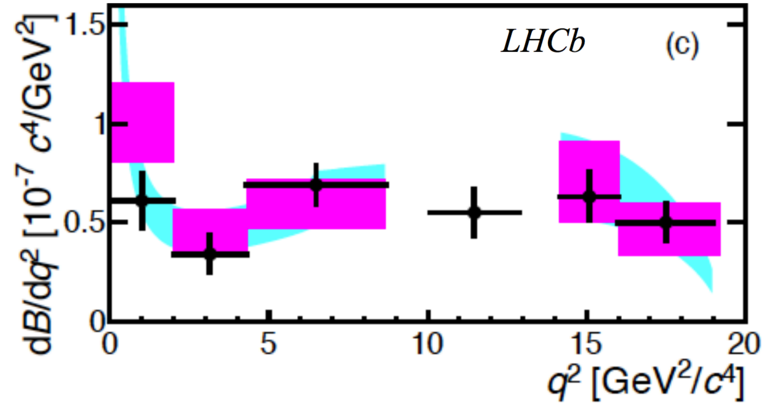


VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	0.4×10^{-5}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	0.4×10^{-5}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	1.4×10^{-5}

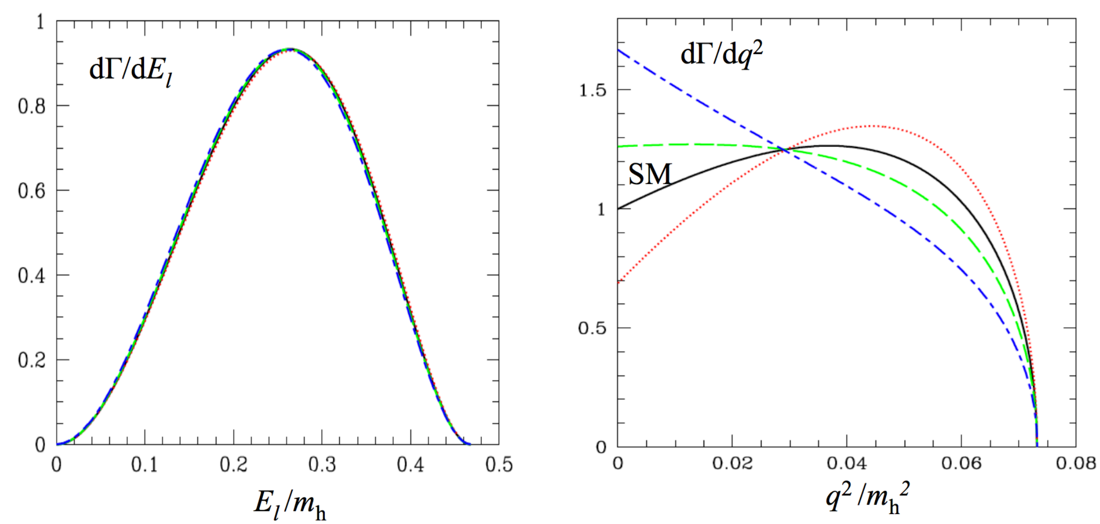
Weird form factors: H→Zℓℓ

[http://cern.ch/go/8gXr]

- Analogous to the LHCb analysis of B→K*ℓℓ.



- Can be done in the 4ℓ channel.
- Complementary to spin-CP analyses.

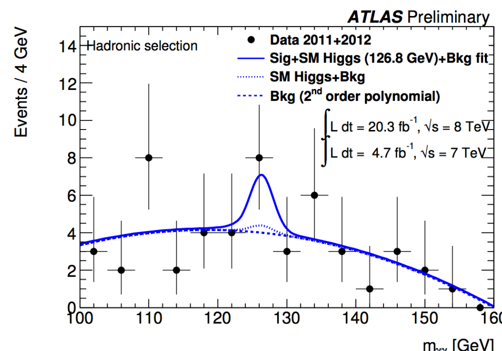


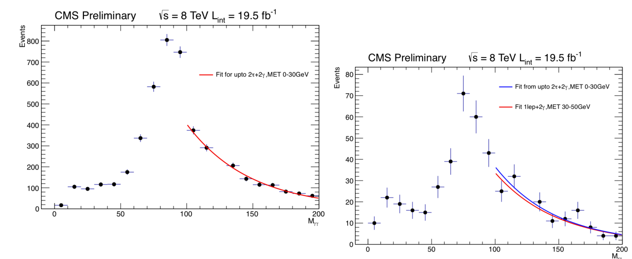
Weird decays: t→cH FCNC

[ATLAS-CONF-2013-081] [CMS-PAS-HIG-13-034]

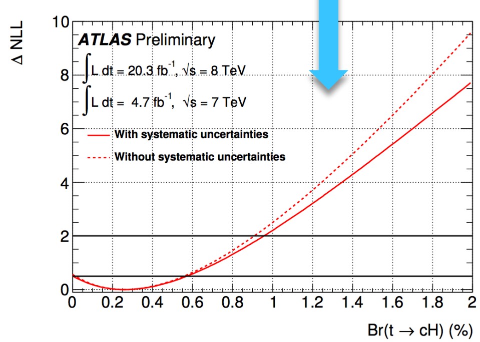
Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}

- Tree-level in BSM.
- SMH now a background:
  - ATLAS H→γγ.
  - CMS H→γγ & multileptons.





OSSF pair	$N_{\tau_{had}}$	E_T^{miss} [GeV]	H_T [GeV]	$N_{b\text{-jets}}$	data	background	signal	efficiency [10^{-5}]
below Z	0	50–100	0–200	≥ 1	48	48 ± 23	9.5 ± 2.3	10.3 ± 2.5
n/a	0	50–100	0–200	≥ 1	29	26 ± 13	5.9 ± 1.3	6.4 ± 1.4
below Z	0	0–50	0–200	≥ 1	34	42 ± 11	5.9 ± 1.2	6.4 ± 1.3
n/a	0	0–50	0–200	≥ 1	29	23 ± 10	4.3 ± 1.1	4.7 ± 1.2
below Z	0	50–100	> 200	≥ 1	10	9.9 ± 3.7	3.0 ± 1.1	3.3 ± 1.2
below Z	0	0–50	> 200	≥ 1	5	10 ± 2.5	2.8 ± 0.8	3.1 ± 0.9
below Z	0	50–100	0–200	0	142	125 ± 27	9.7 ± 2.1	10.6 ± 2.3
n/a	1	0–50	0–200	≥ 1	237	240 ± 113	13.1 ± 2.6	14.3 ± 2.8
n/a	0	50–100	0–200	0	35	38 ± 15	4.3 ± 1.1	4.7 ± 1.2
above Z	0	0–50	0–200	≥ 1	17	18 ± 6.7	2.8 ± 0.8	3.1 ± 0.9



Higgs Decay Mode	observed	expected	1σ range
$H \to WW^*$ ($\mathcal{B} = 23.1\,\%$)	1.58 %	1.57 %	(1.02–2.22) %
$H \to \tau\tau$ ($\mathcal{B} = 6.15\,\%$)	7.01 %	4.99 %	(3.53–7.74) %
$H \to ZZ^*$ ($\mathcal{B} = 2.89\,\%$)	5.31 %	4.11 %	(2.85–6.45) %
combined multileptons ($WW^*, \tau\tau, ZZ^*$)	1.28 %	1.17 %	(0.85–1.73) %
$H \to \gamma\gamma$ ($\mathcal{B} = 0.23\,\%$)	0.69 %	0.81 %	(0.60–1.17) %
combined multileptons + diphotons	0.56 %	0.65 %	(0.46–0.94) %

Obs. (exp.)	ATLAS	CMS
BR(t→cH) (95% CL)	< 0.83% (0.53%)	< 0.56% (0.65%)