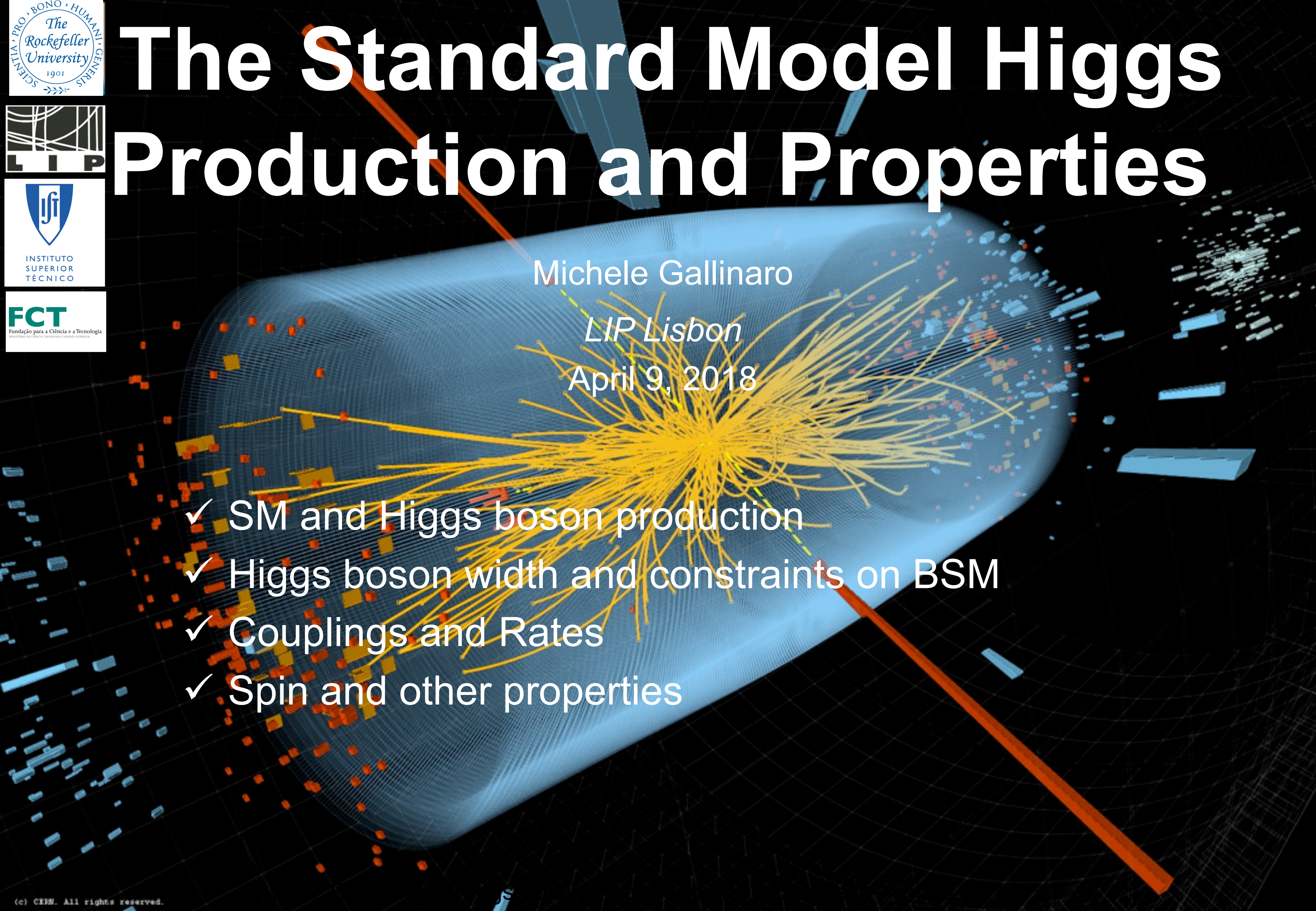
The Standard Model Higgs Production and Properties



Michele Gallinaro

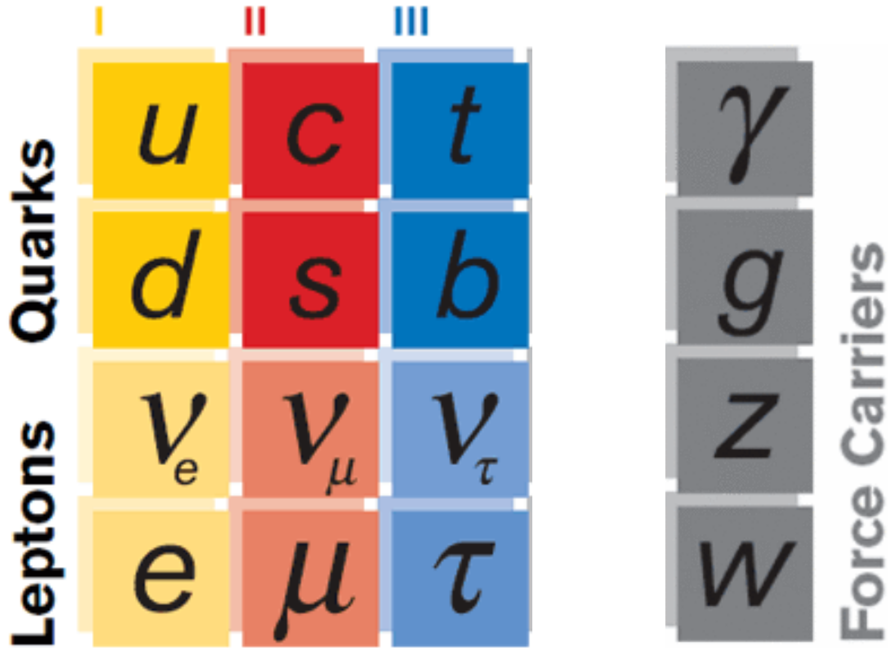
LIP Lisbon

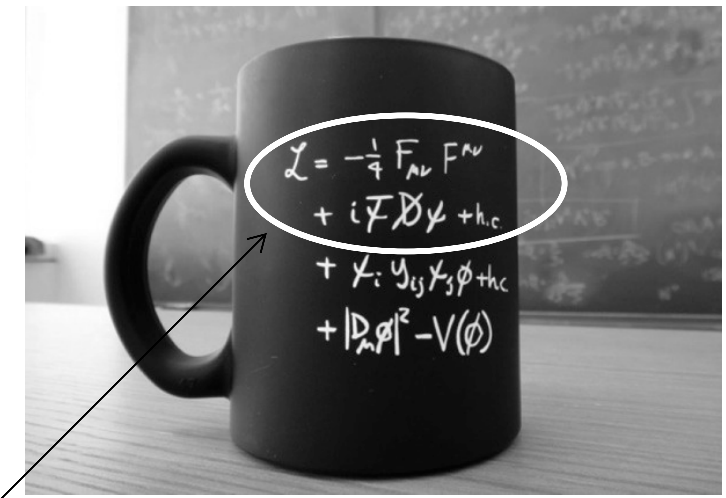
April 9, 2018

- ✓ SM and Higgs boson production
- ✓ Higgs boson width and constraints on BSM
- ✓ Couplings and Rates
- ✓ Spin and other properties

The Standard Model...

Building blocks: matter (fermions), forces (bosons)

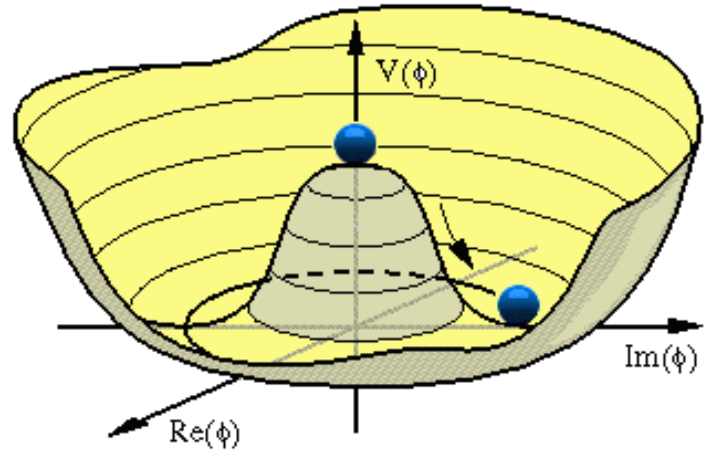




- Electroweak theory is based on underlying symmetry between the two interactions
- Simple Lagrangian formalism describes this very well but only for massless particles....

…and the Higgs boson

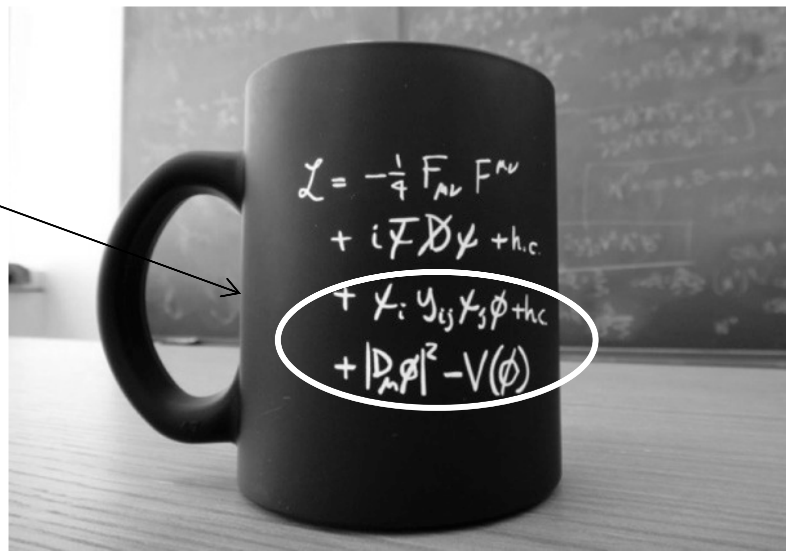
How do particles acquire their masses?



- Hand inserted mass terms destroy gauge invariance (local)
- Need gauge invariant mechanism to generate mass terms
- Higgs mechanism is simplest way to do it

The Higgs mechanism

- Introduce additional scalar field
- Additional terms with mass appear
- Vacuum expectation value ≠0
- Particles move through field which gives them mass



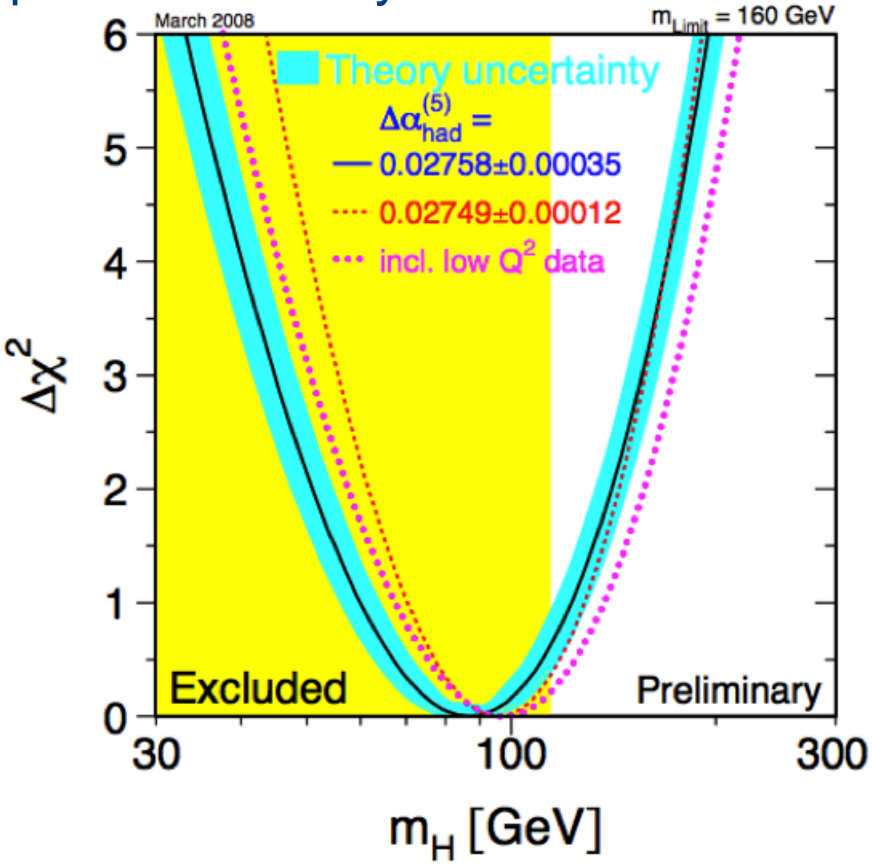
massive

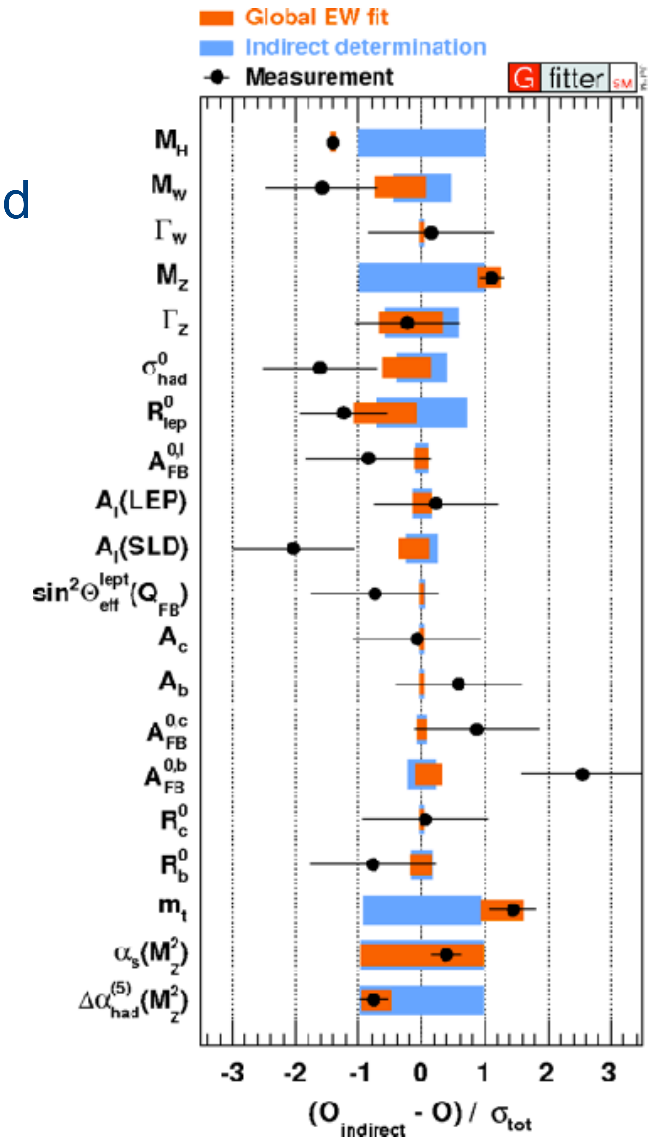
"what makes everything ~~solid~~"

Bruce Springsteen

Testing the SM

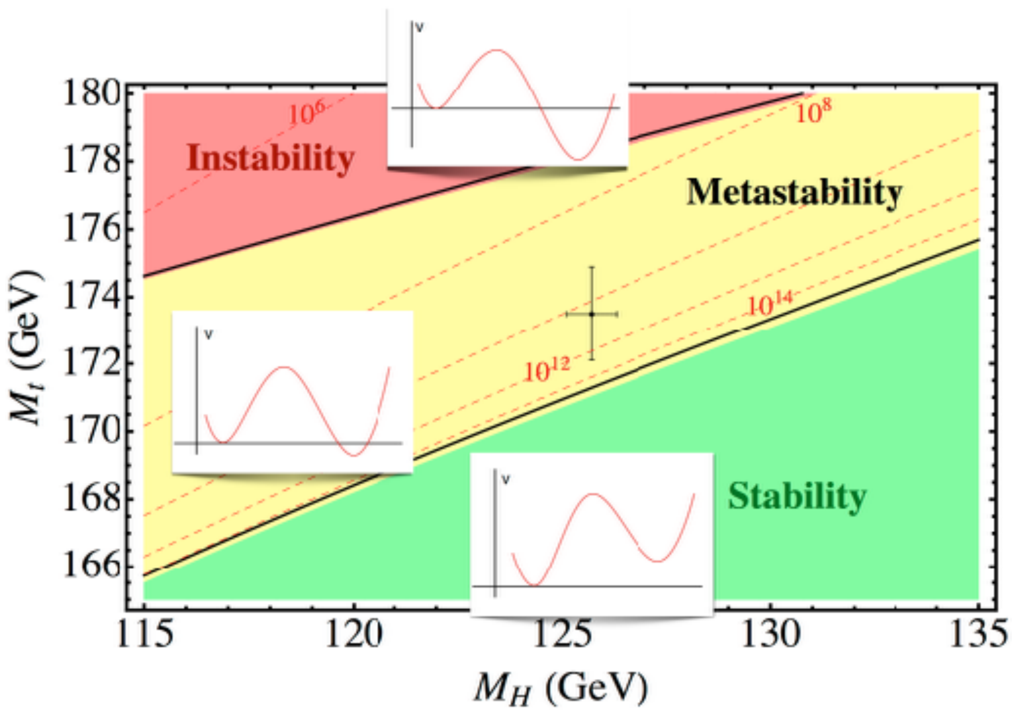
- Measured to incredible precision
- Largest deviations to 3%
- After LEP: scale of the “missing piece” accurately predicted
- SM is a predictive theory

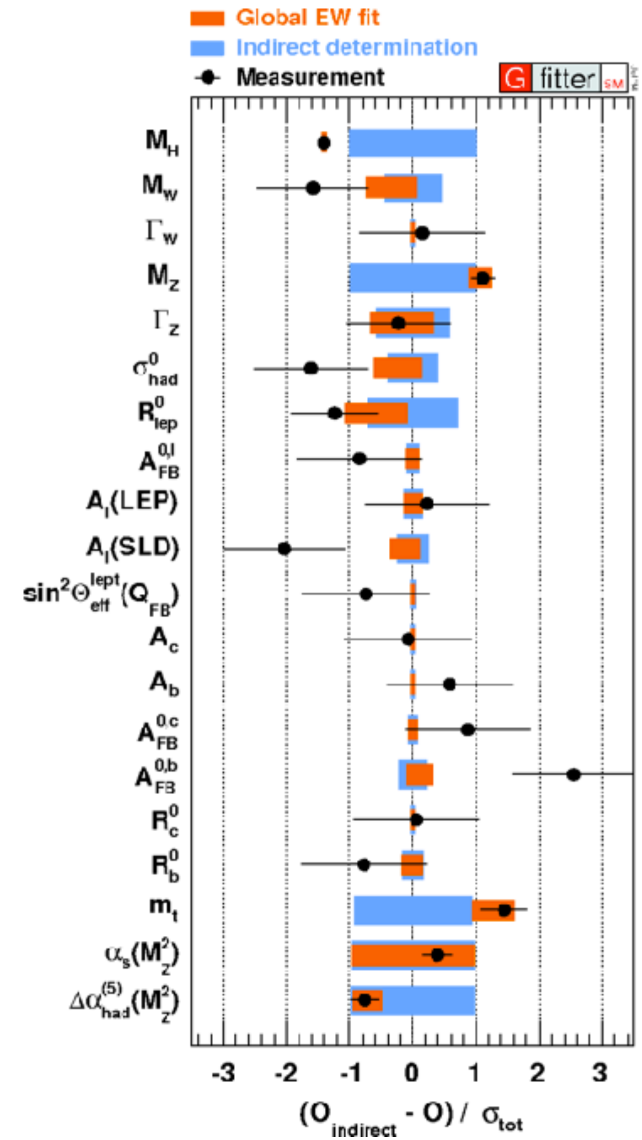




Testing the SM

- Is the SM really consistent?
- p-value currently estimated at ~0.22 (GFitter)
- If Higgs mass @300GeV, p-value ~3×10^{-5}
- Are corrections to the mass fine-tuned?
- How stable is vacuum generated by Higgs field?

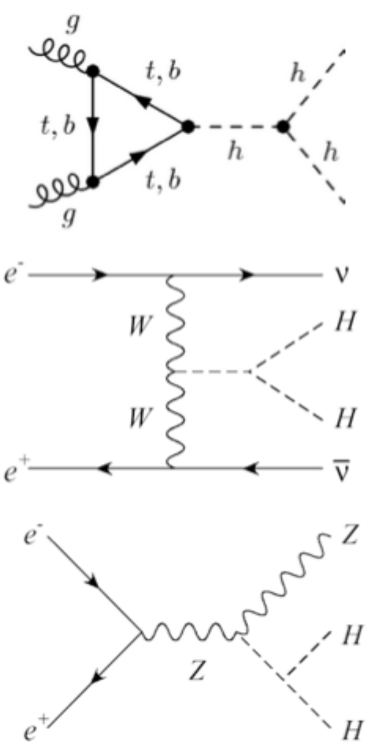




Higgs "self-coupling"

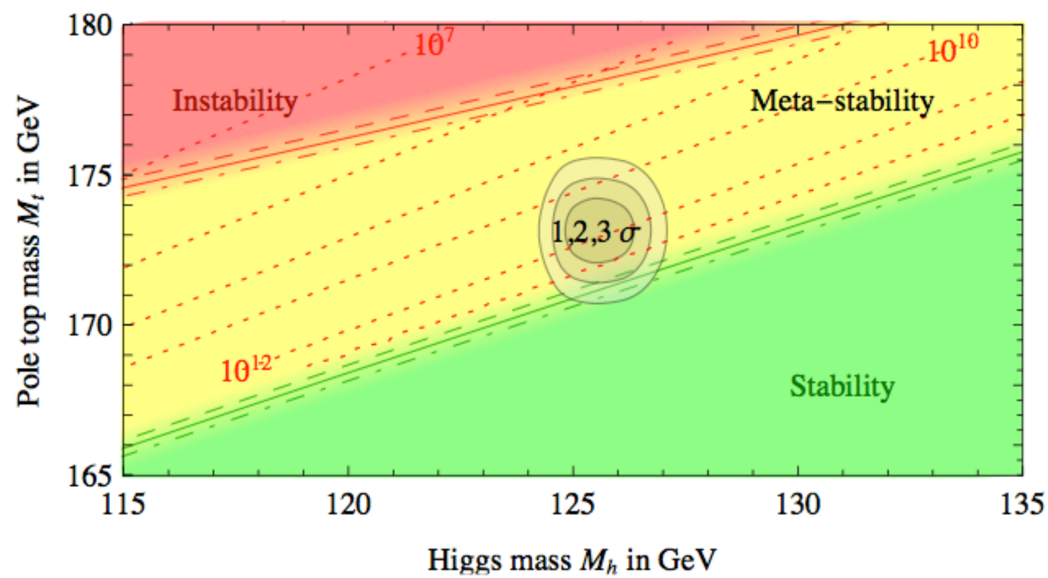
Drives the stability of the Higgs potential

- We can measure self-coupling through rare processes, eg h→hh



- Alternatively, test if SM is consistent at higher scales

⇒ Depending on the top mass, Universe may be unstable



Outline

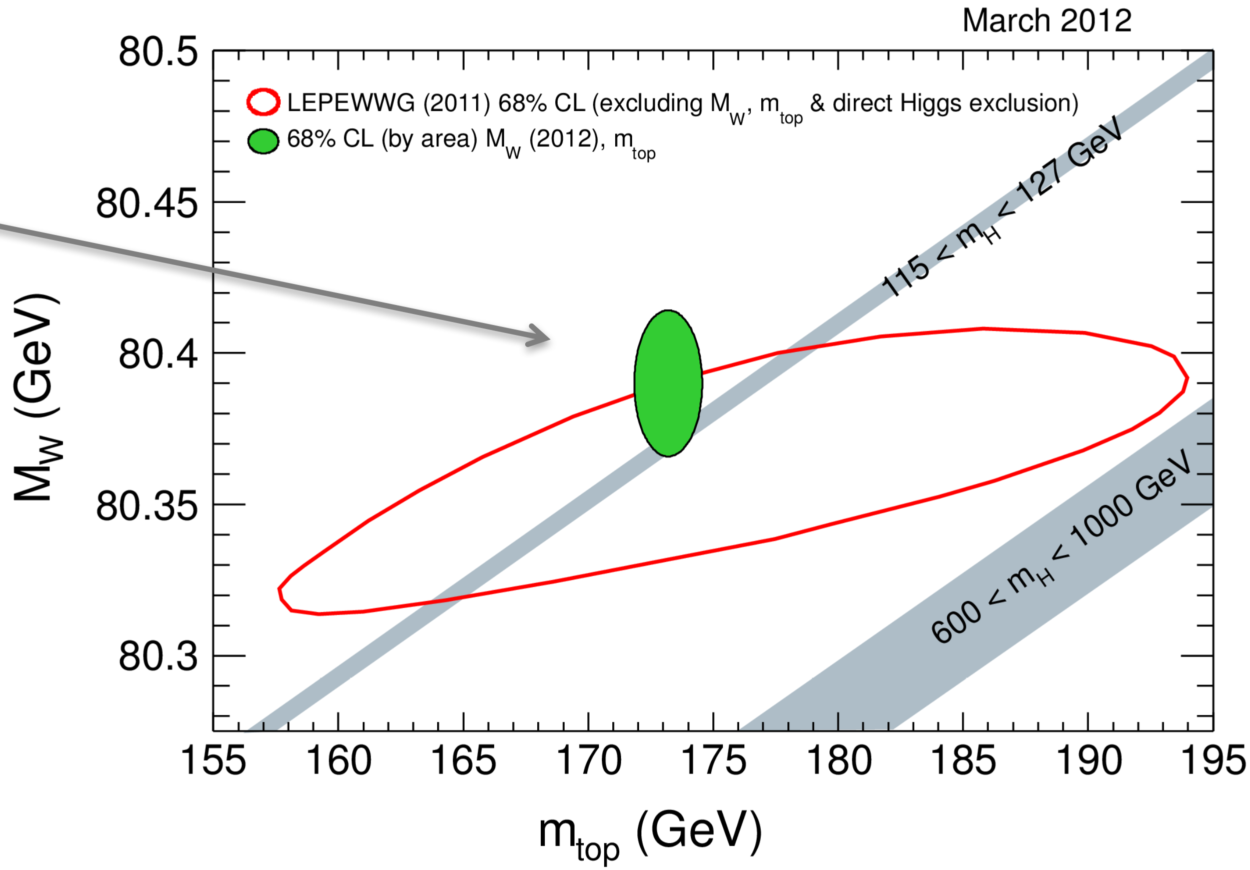
- From rates to couplings
- Models, properties, interpretation
- Results: mass, charge, spin and parity, couplings

Situation in early 2012

Very precise measurement of M_W = 80.390 ± 0.016 GeV, driven mainly by the Tevatron.

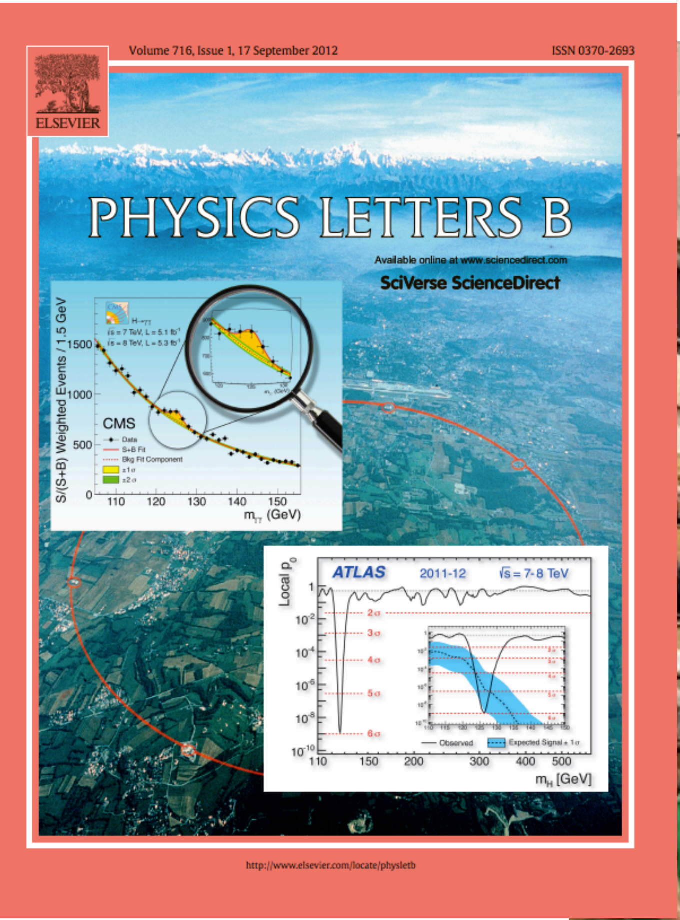
Much of the SM Higgs range had been ruled out by 2011 LHC running.

Excess of events in the low mass region seen in ATLAS and CMS



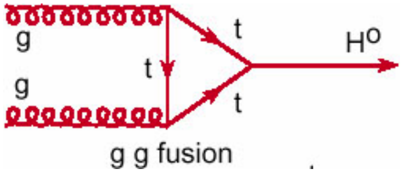
Exclusions of M_H:
- LEP < 114 GeV (arXiv:0602042v1)
- Tevatron [156,177] GeV (arXiv:1107.5518)
- LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS) arXiv:1202.1488 (CMS)

2012: A new boson discovery

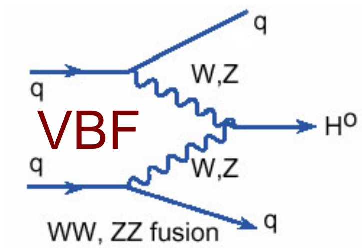


Higgs production

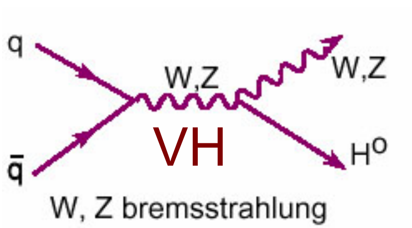
87%



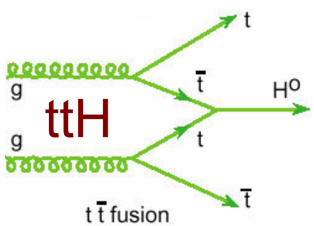
7.1%

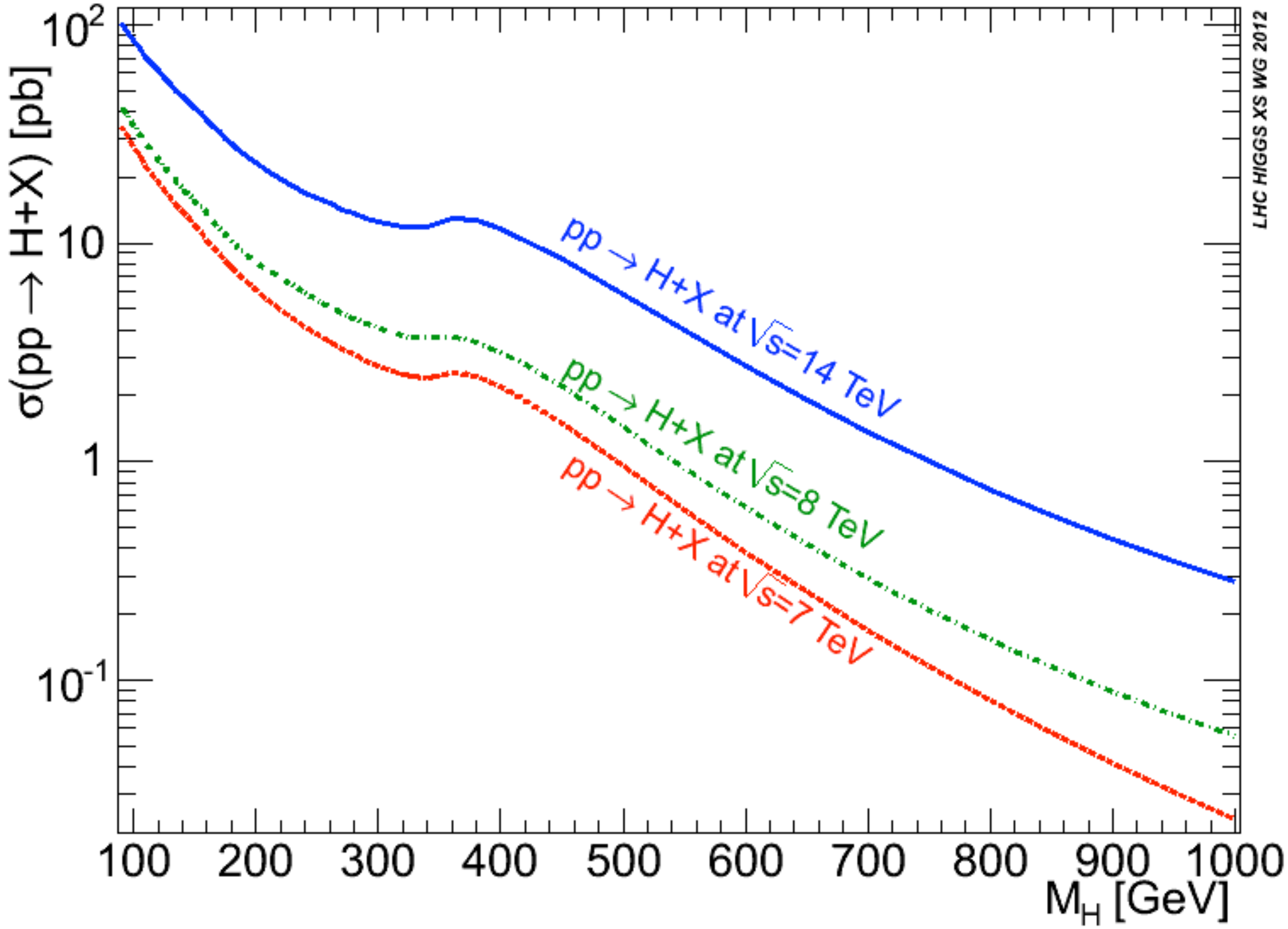


4.9%



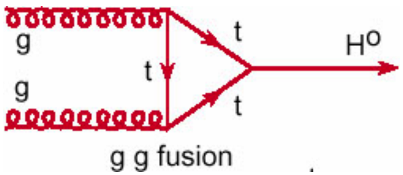
0.6%





Higgs production

87%



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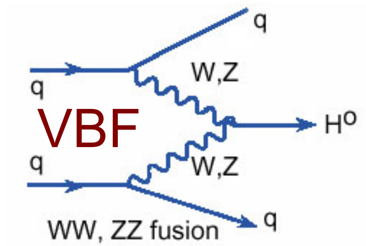

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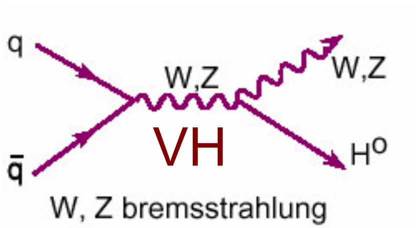
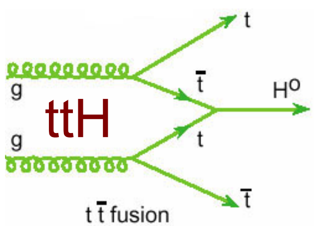
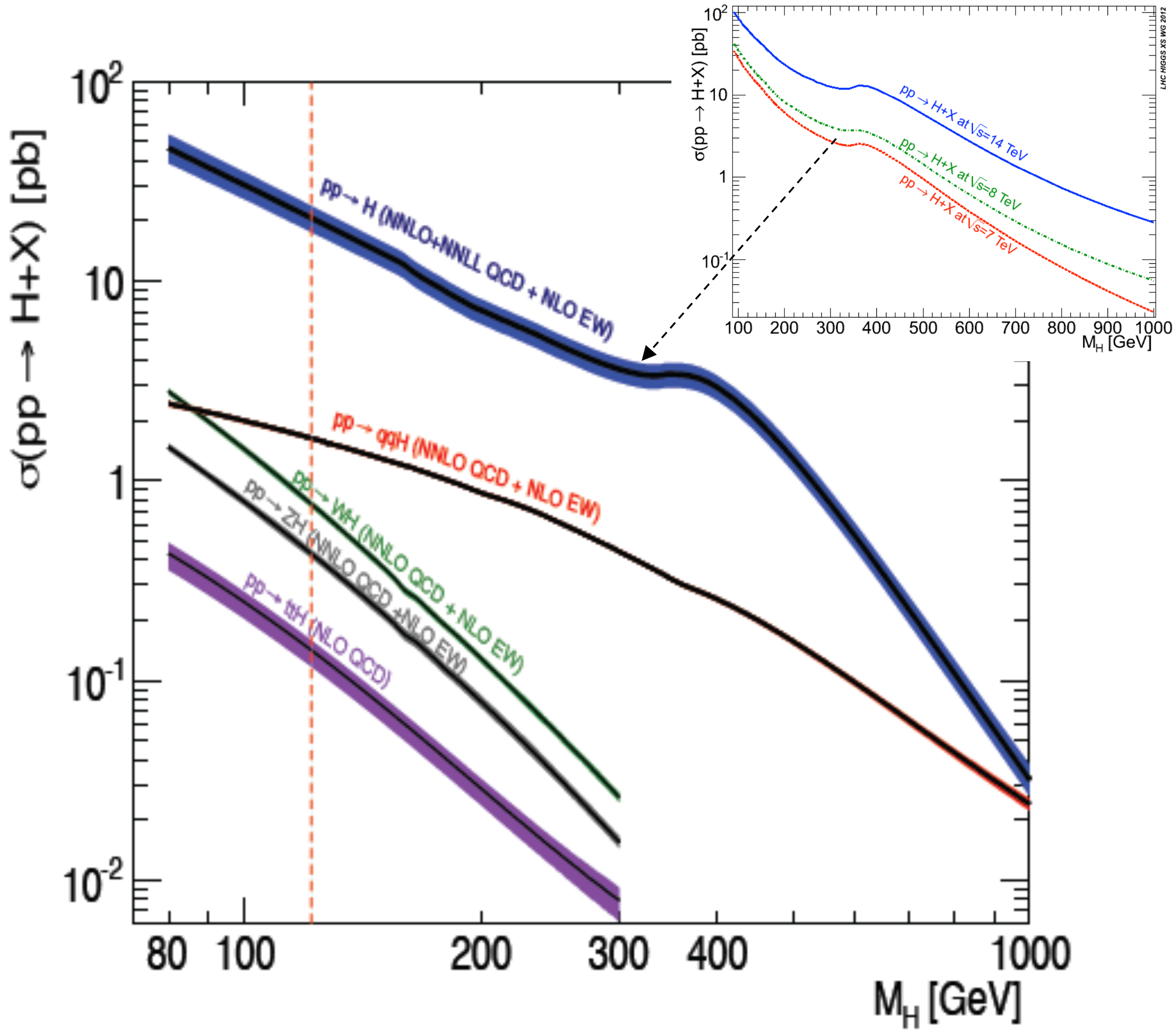


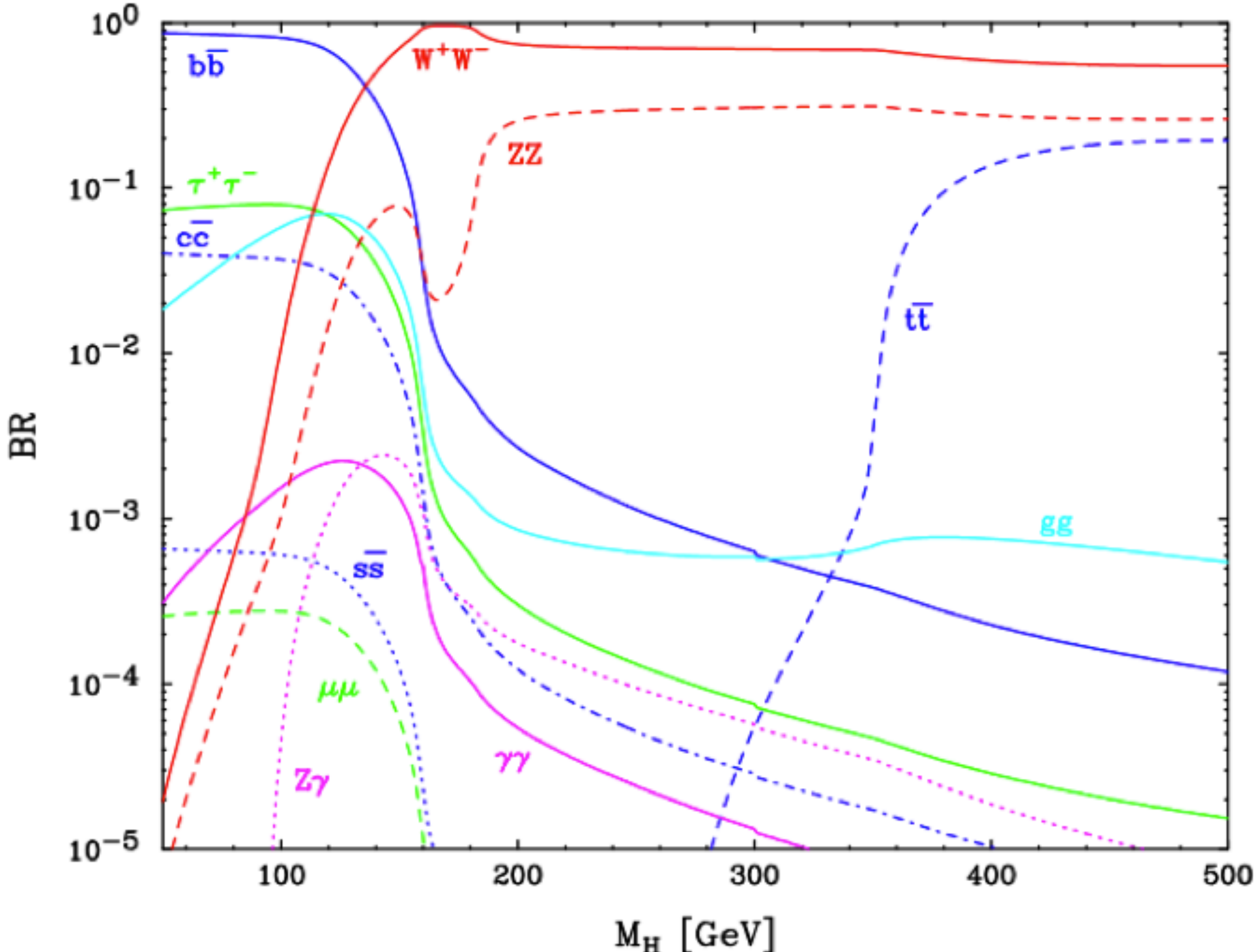
0.6%





Look for all possible decays

- Window of maximum opportunity (most “democratic”) at ~125 GeV
- Couplings to gluons and photons available through top and W loops

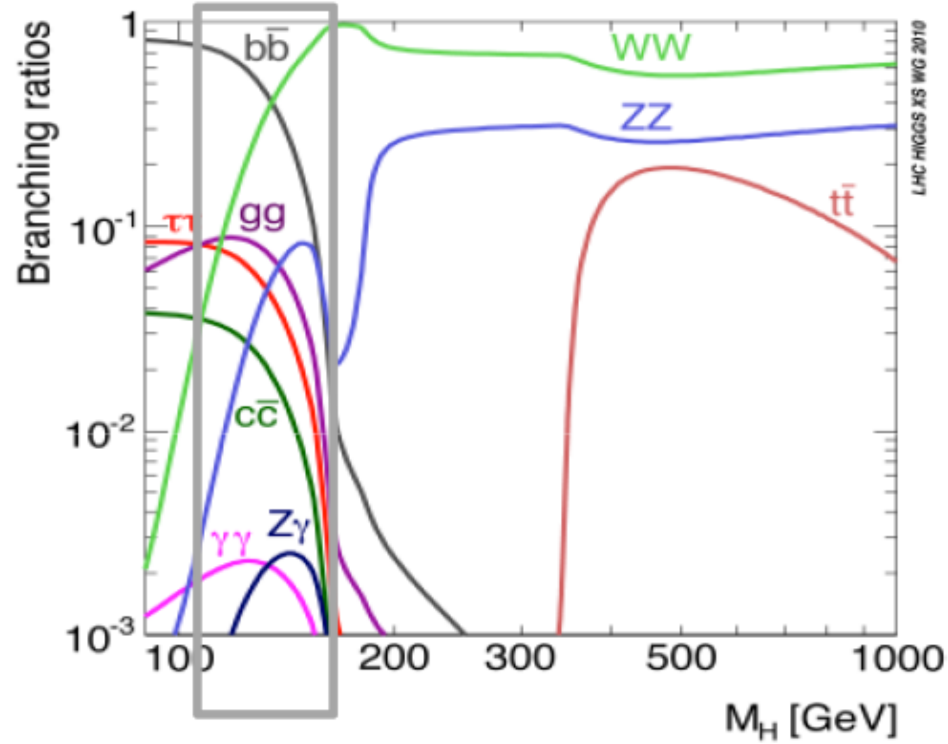


Higgs decays

5 decay modes studied:

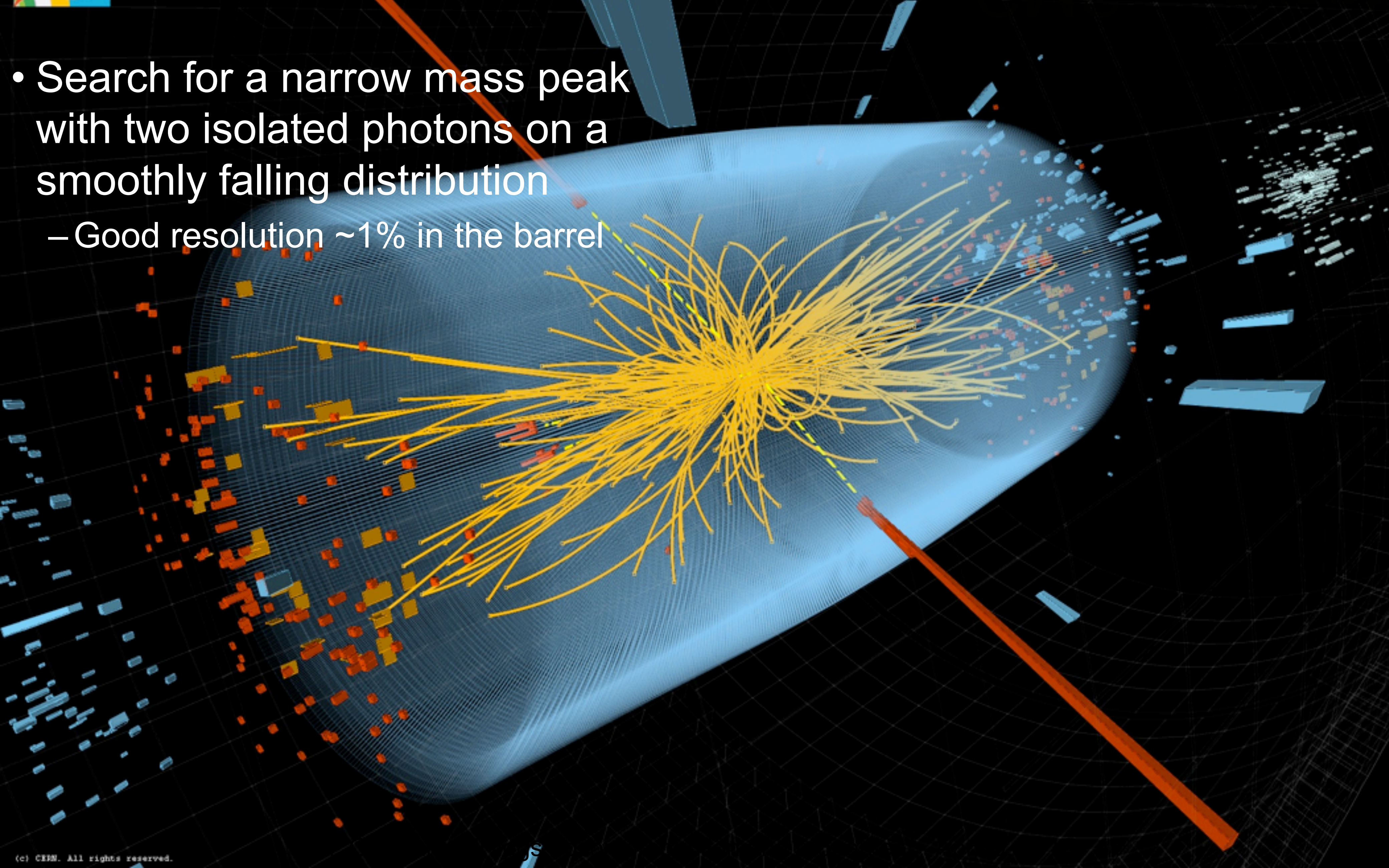
- High mass: WW, ZZ
- Low mass: bb, $\tau\tau$, WW, ZZ, $\gamma\gamma$
- Low mass region is very challenging
- Very good mass resolution ~1% ($\gamma\gamma$, 4l)

Decay mode	Production tagging	No. of subchannels	m_H range (GeV)	Int. Lum. (fb^{-1}) 7 TeV	8 TeV
$\gamma\gamma$	untagged dijet (VBF)	4 1 or 2	110–150	5.1	5.3
ZZ	untagged	3	110–600	5.1	5.3
WW	untagged dijet (VBF)	4 1 or 2	110–600	4.9	5.1
$\tau\tau$	untagged dijet (VBF)	16 4	110–145	4.9	5.1
bb	lepton, E_T^{miss} (VH)	10	110–135	5.0	5.1



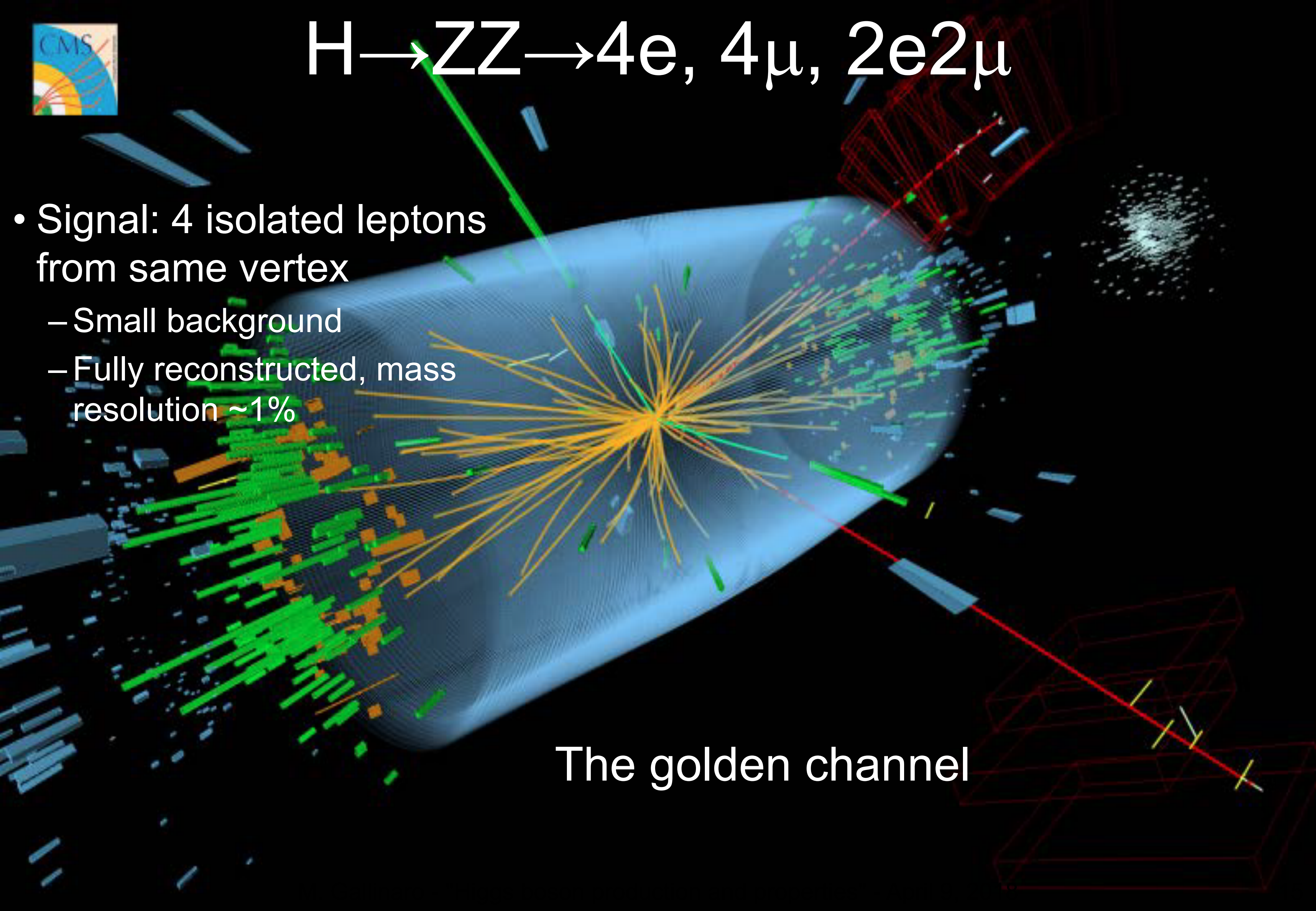
CMS $\gamma\gamma$ event

- Search for a narrow mass peak with two isolated photons on a smoothly falling distribution
  - Good resolution ~1% in the barrel



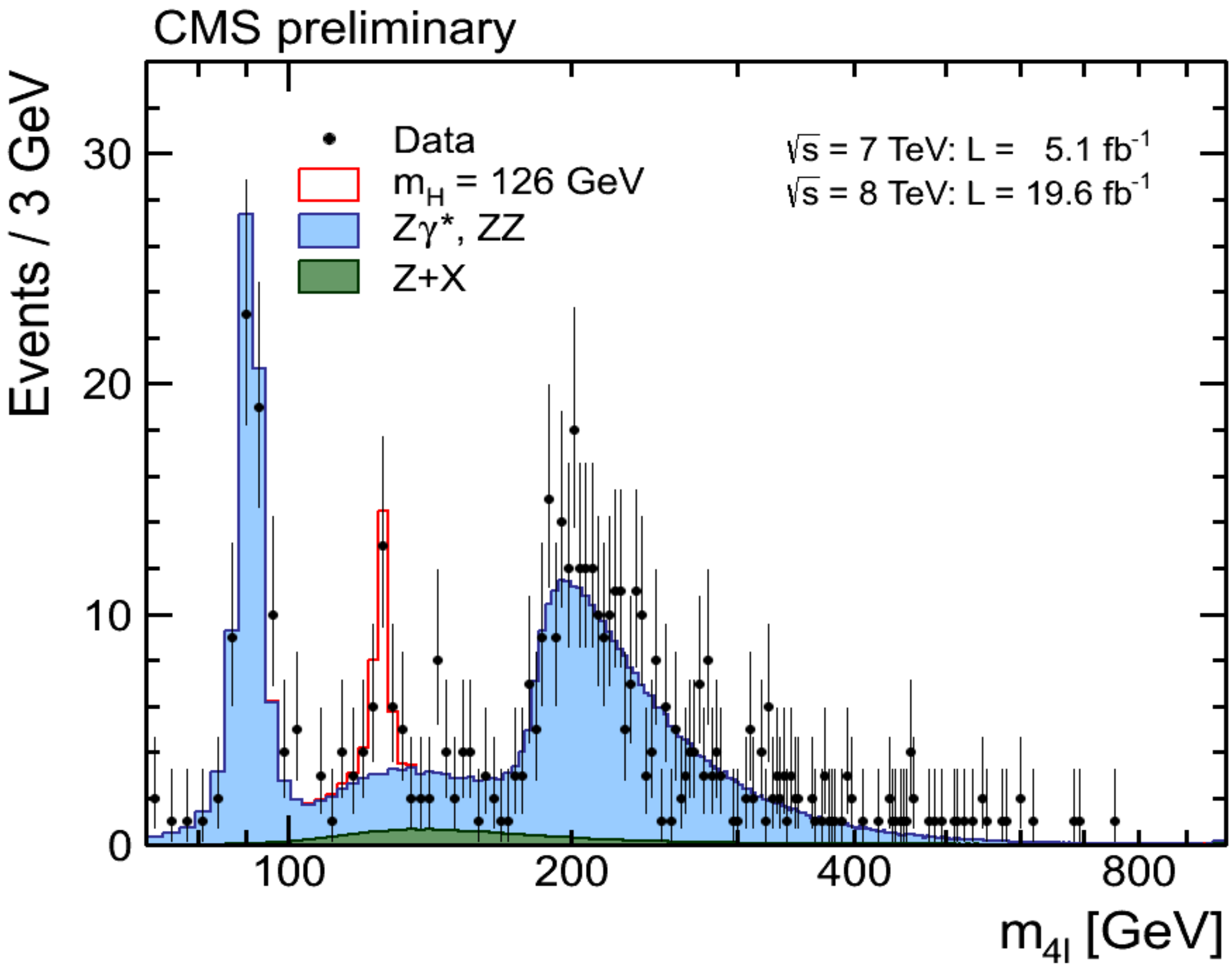
$H \to ZZ \to 4e,\ 4\mu,\ 2e2\mu$

- Signal: 4 isolated leptons from same vertex
  - Small background
  - Fully reconstructed, mass resolution ~1%

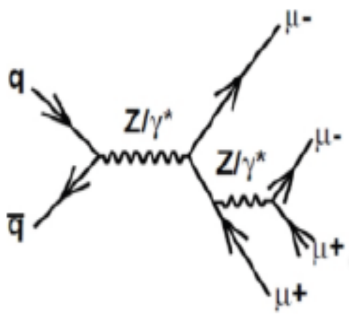


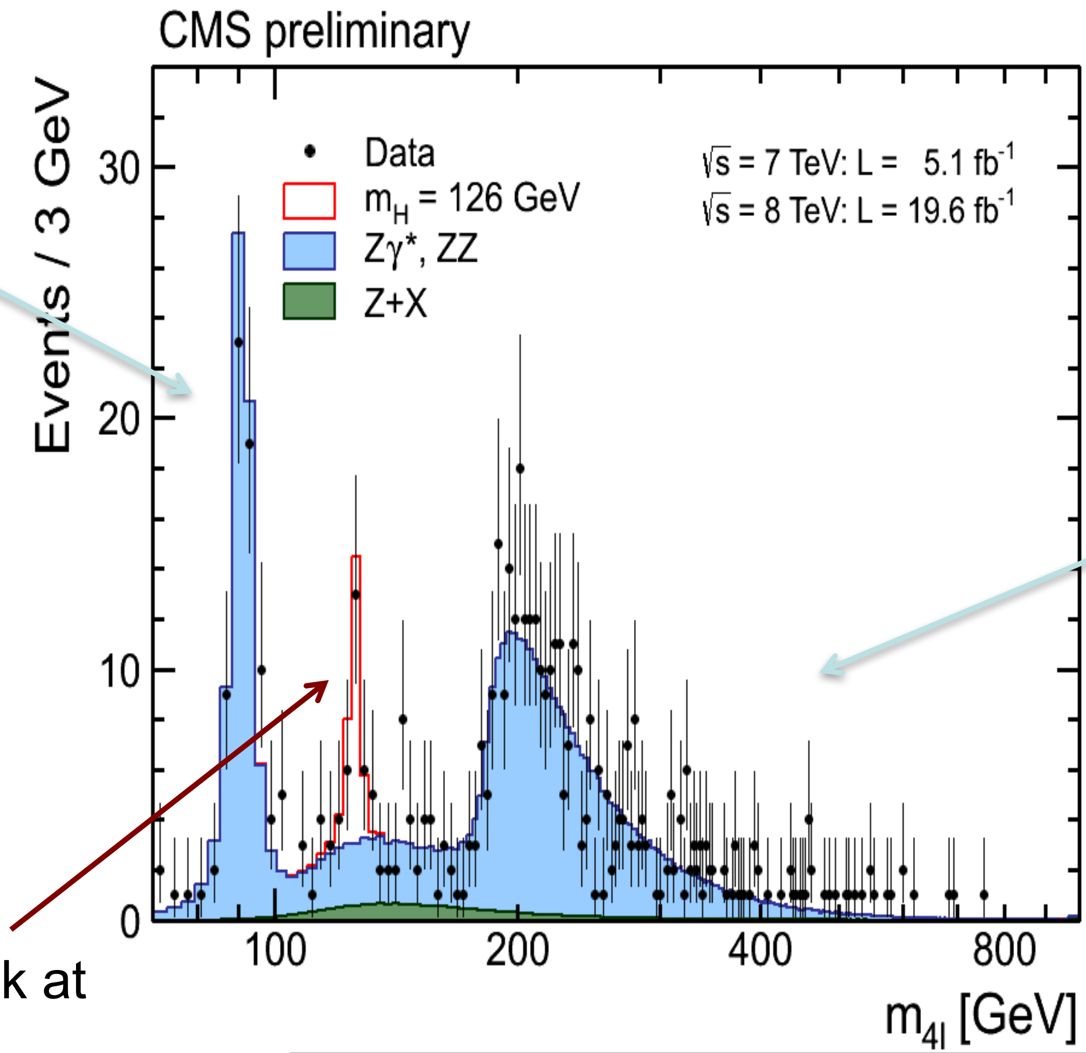
The golden channel

A beautiful peak



Mass spectrum





Very good control of the dominant ZZ background

Offline selection cuts:
5 (7) GeV for μ (e) in |η| < 2.4 (2.5).

M(4l)>160 GeV
Data 380
MC 364.5

Clean signal peak at ~126 GeV

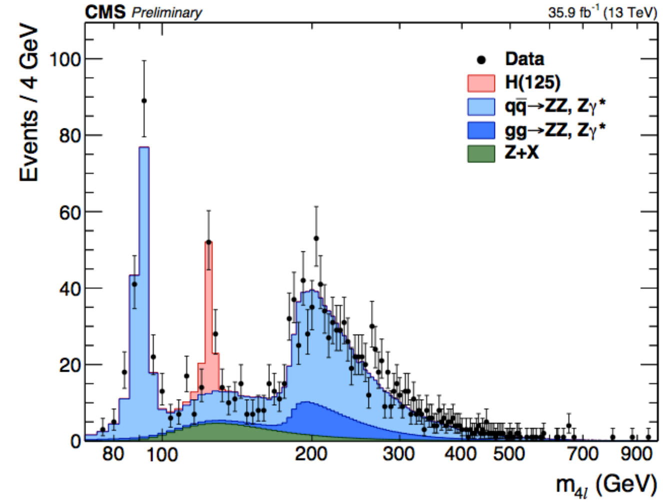
σ_{SM}(th) = 7.8 ± 0.6 pb

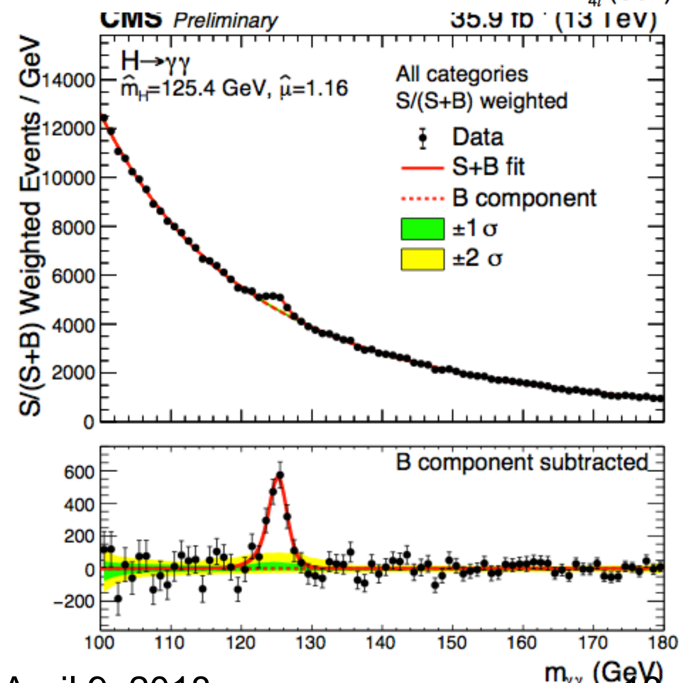
σ(pp →ZZ, 8TeV) = 8.4±1.0 (stat.) ± 0.7 (syst.) ± 0.4(lum.) pb

Higgs boson

PRD 89 (2014) 092007, PLB726(2013)088, HIG-16-040, HIG-16-041

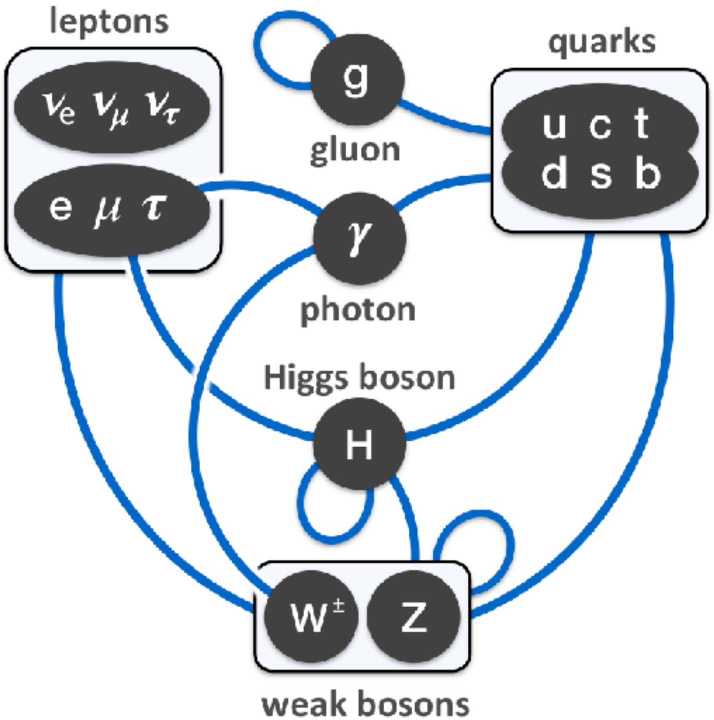
- Progress since Higgs discovery (July 2012)
  - Observation in boson channels
  - Evidence for fermion couplings
  - Precision mass measurement (~125 GeV)
  - Spin determined
- It looks like the SM Higgs boson





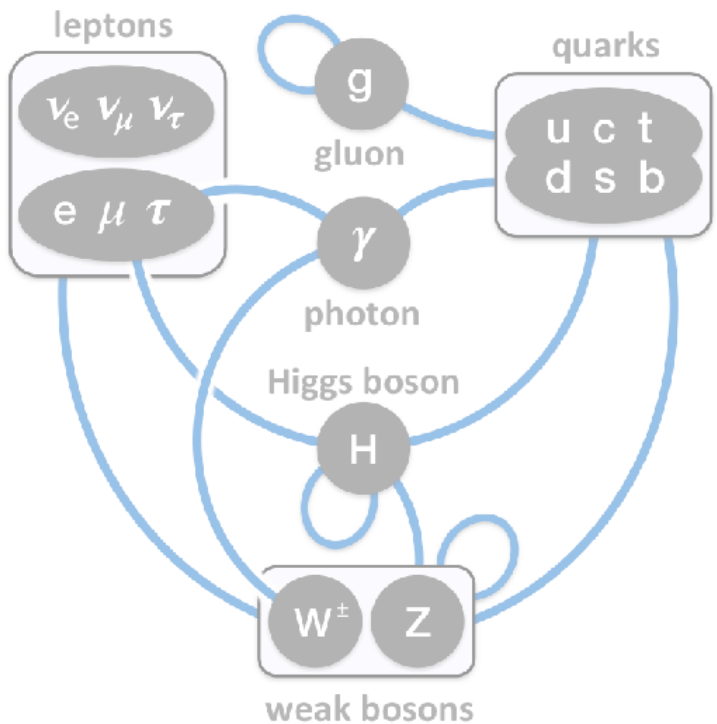
Rates and Couplings

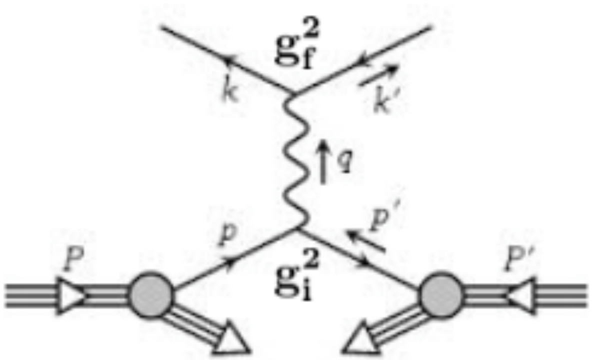
- Higgs gives mass to fermions and vector bosons
- Different couplings at production and decay
- Can we disentangle them?



Rates and Couplings

- Higgs gives mass to fermions and vector bosons
- Different couplings at production and decay
- Can we disentangle them?
- Observed production rate (cross section) and total width (Γ)
- Depends on the couplings





$$\sigma \propto \int \frac{g_i^2 \cdot g_f^2}{(s - m_0^2)^2 + \Gamma^2 m^2} ds$$

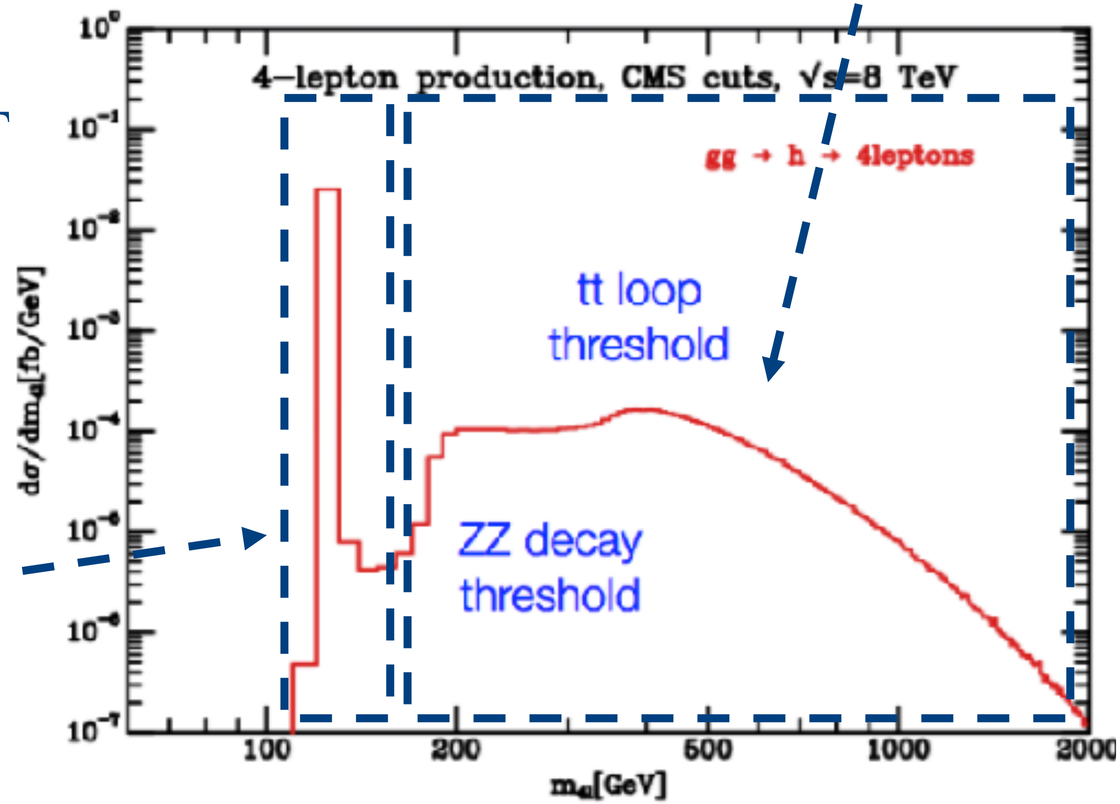
Couplings and Width

- Observed production rate holds as well as the information on the total width Γ

$$\sigma_{\text{off-shell}} \propto g_i^2 \cdot g_f^2$$

- On-shell production

$$\sigma_{\text{on-shell}} \propto \frac{g_i^2 \cdot g_f^2}{\Gamma}$$



- Lineshape limited by detector resolution
- Width determined from BRs and cross section

$$\frac{\sigma_{\text{off-shell}}}{\sigma_{\text{on-shell}}} \propto \Gamma$$

Constraining Higgs width

PLB 736(2014)64

obs.(exp.) @95%CL:
$\Gamma_H < 5.4 (8.0) \Gamma_H^{SM}$
$\Gamma_H < 22(33)$MeV

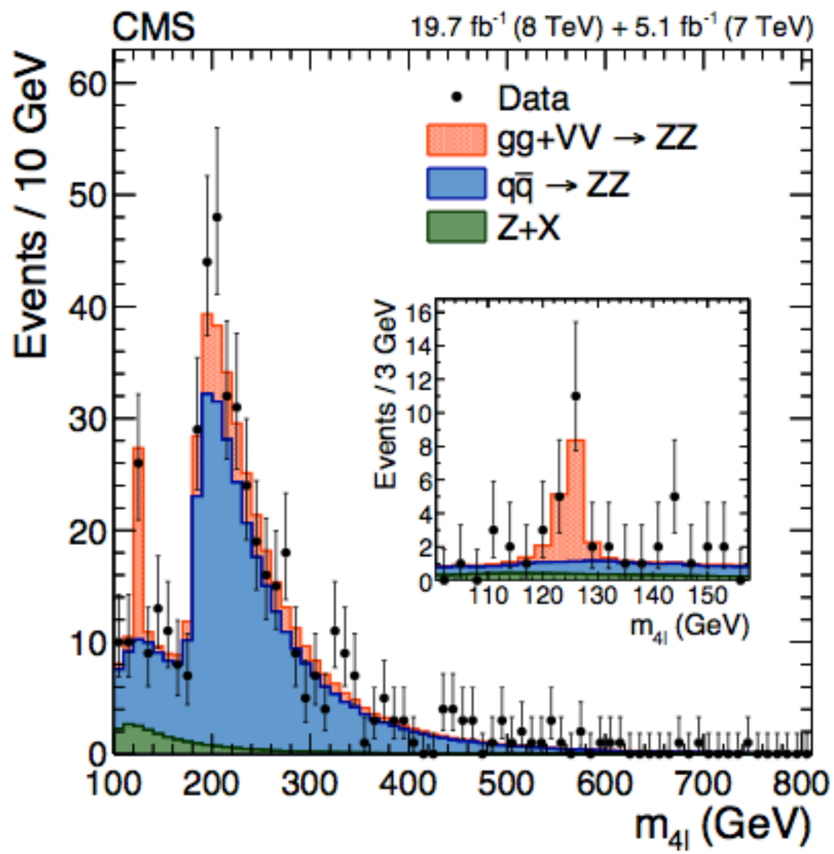
- couplings and width sensitive probes to BSM
- indirectly constrained in coupling fits
- off-peak to on-peak ratio proportional to Γ_H
- constrain Higgs boson width by using off-shell production/decay
- measure ratio of $\sigma^{\text{off-peak}}$ to $\sigma^{\text{on-peak}}$

$$\boxed{\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \propto \frac{g^2_{ggH} g^2_{HZZ}}{\Gamma_H}, \qquad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \propto g^2_{ggH} g^2_{HZZ}}$$

F. Caola, K. Melnikov PRD88(2013)054024
J. Campbell et al. arXiv:1311.3589

  – g_{ggH} and g_{HZZ}: couplings to gluons and bosons

- measurement of Γ_H



Rates and Couplings

- How to convert signal rates into couplings?
- Expected rates in a given channel depend on integrated luminosity, cross section, BR, overall selection efficiency

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \text{BR}^f \right\}$$

- Production modes are precisely predicted in the SM

Rates and Couplings (cont.)

- Uncertainties ~2-3% (EWK production, VH) to 10% (strong production, ggH)

$$n_{\mathrm{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}^f \right\}$$

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+APP.NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.357 ± 0.015	0.446 ± 0.019	NNLO(QCD)+NLO(EW)
ZH: $gg \to ZH$			LO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

- New Physics can alter SM expectations:

$$\sigma_i = \mu_{\mathrm{i}} \cdot \sigma_{\mathrm{SM}}$$

Final states

- SM Higgs branching ratios determined to 1-3% precision

$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \{\sigma_i \times A_i^f(k) \times \epsilon_i^f(k) \times \text{BR}^f\}$$

Decay channel	Branching ratio [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

- New decay channels may appear, e.g. H→ dark matter

Signal strength

- Deviations relative to SM expectations

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

Production

Decay

μ is called "signal strength"

Other factors

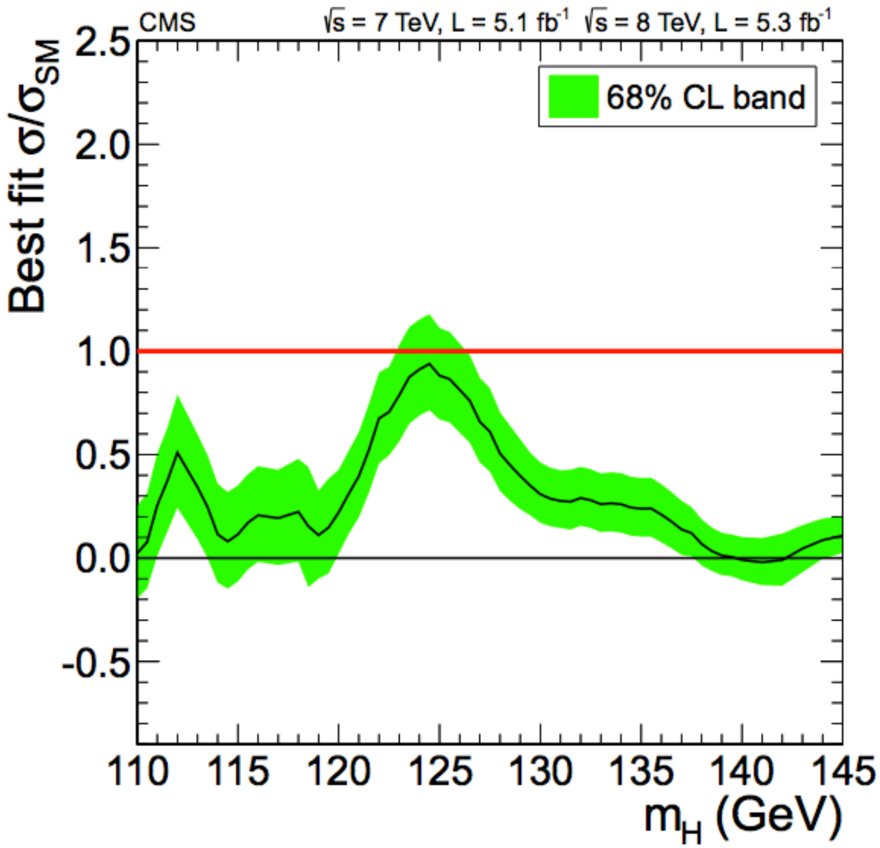
- Determined from data or from simulation

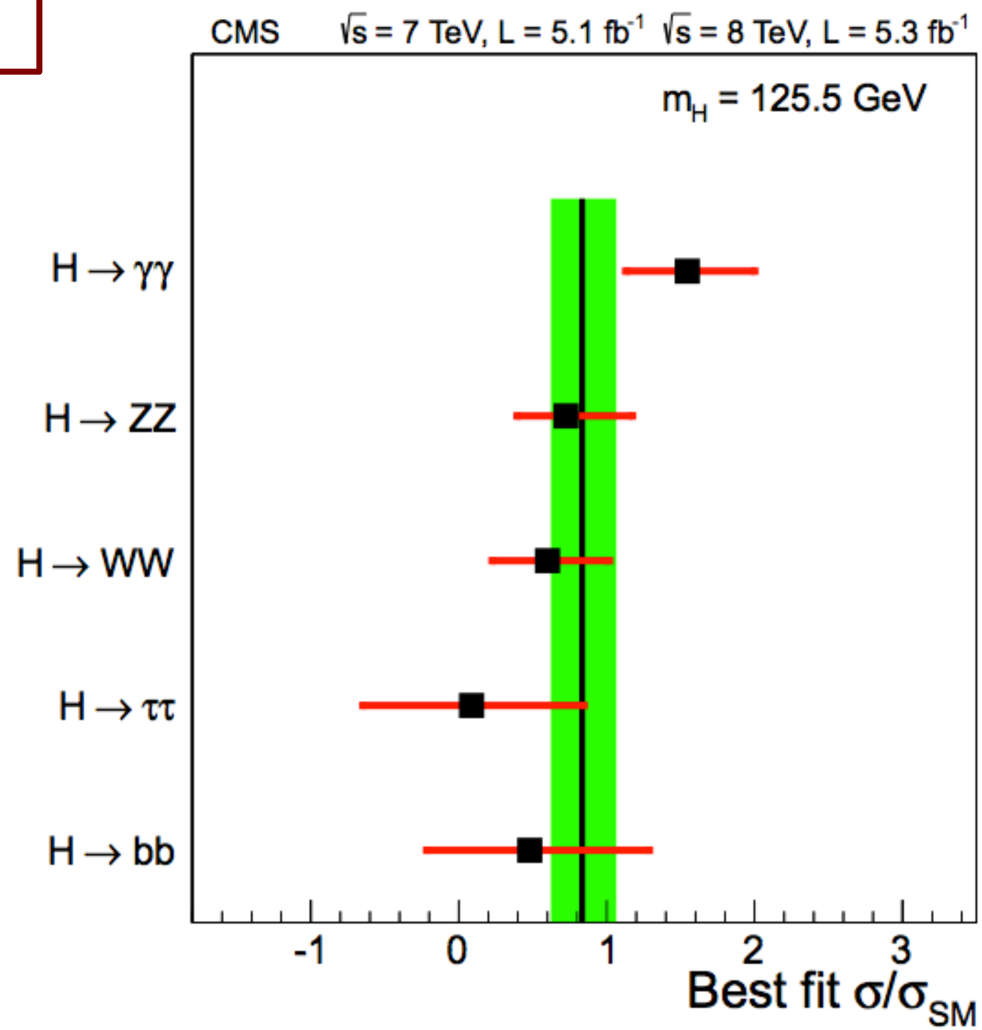
$$n_{\text{signal}}(k) = \mathcal{L}(k) \times \sum_i \sum_f \left\{ \sigma_i \times A_i^f(k) \times \varepsilon_i^f(k) \times \mathrm{BR}^f \right\}$$

- Integrated luminosity (L): from Van-der-Meer scans
- Efficiencies (ε): from control regions
- Acceptance (A): due to geometry and trigger requirements, etc.
- Uncertainties: theoretical and experimental

Combined results (early)

Overall strength: σ/σ_{SM}=0.87±0.23



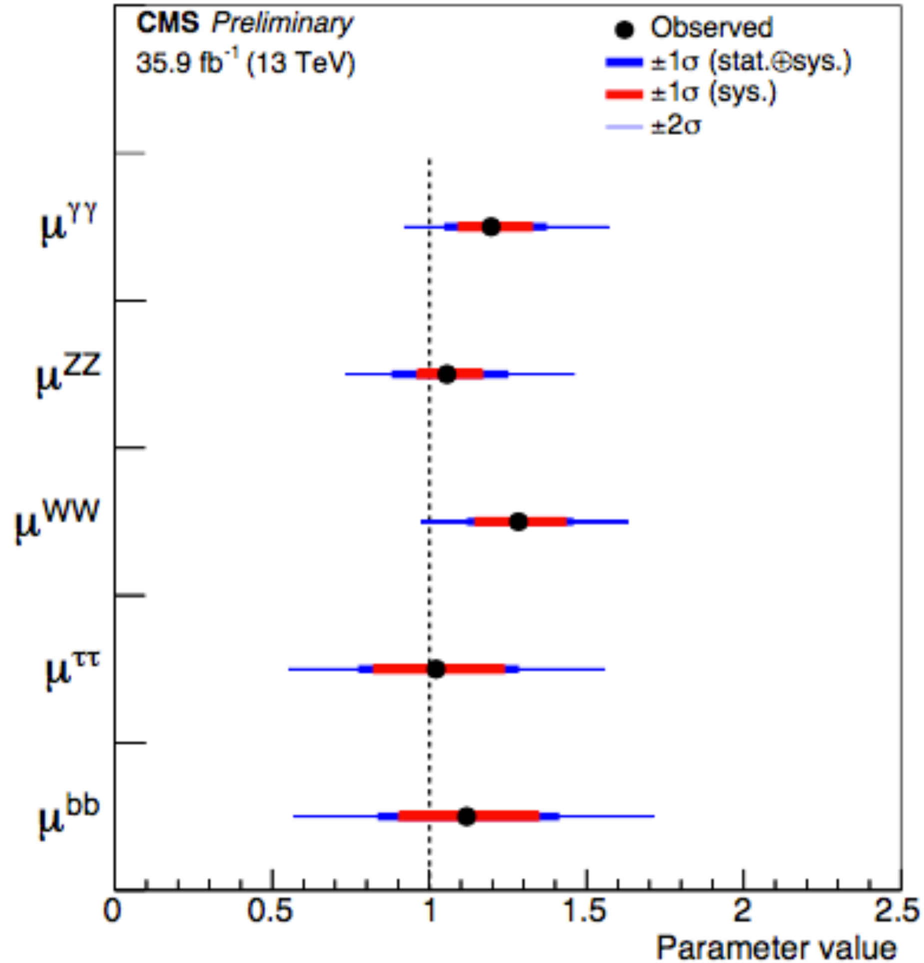


Combined Results (decay)

CMS-HIG-17-031

- If μ~1, observations are close to SM predictions
- Compatibility with expectations depends on experimental and theoretical uncertainties

$$\boxed{\mu = 1.17^{+0.10}_{-0.10}}$$



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CMS-HIG-17-031

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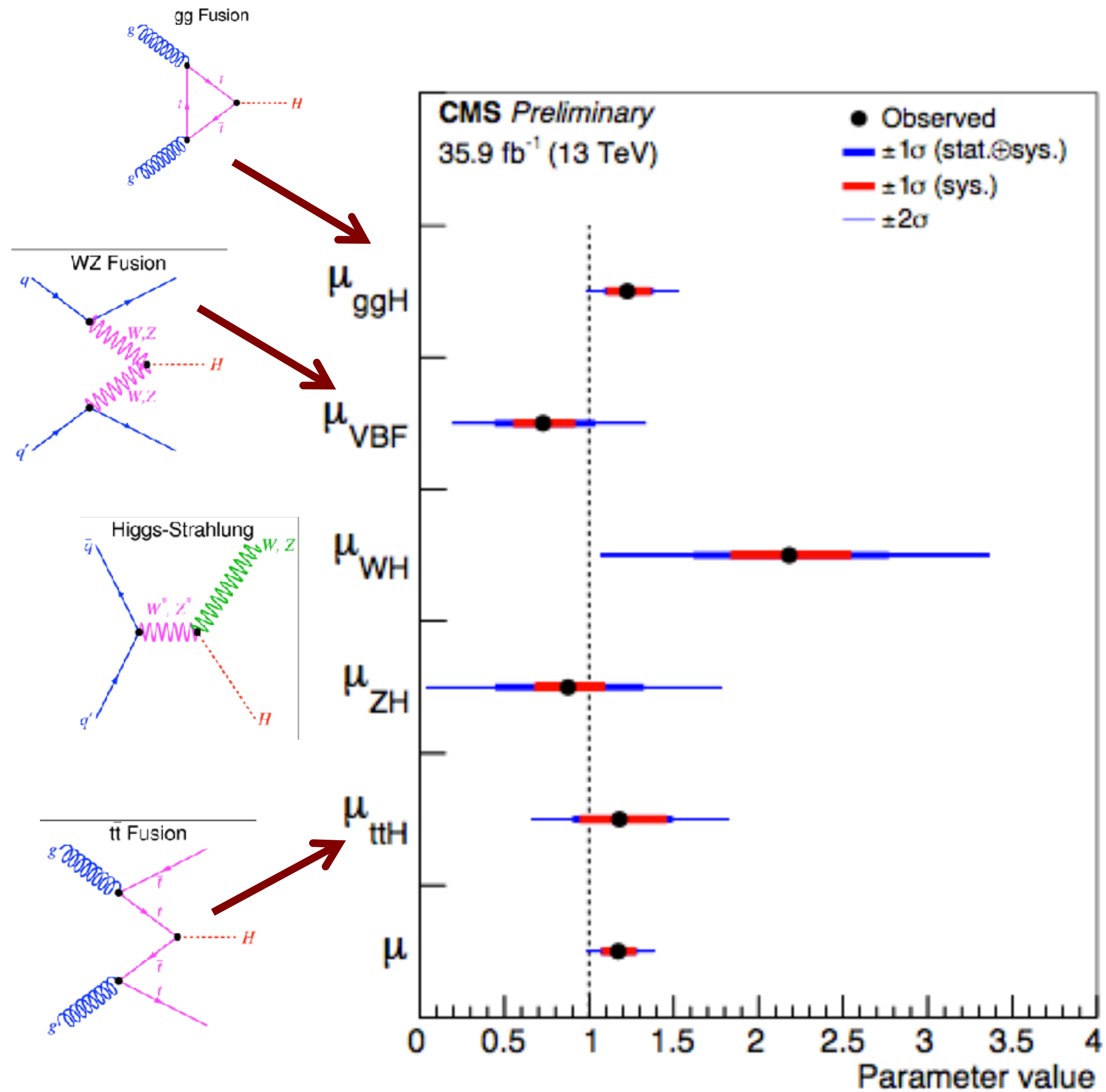

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CMS-HIG-17-031

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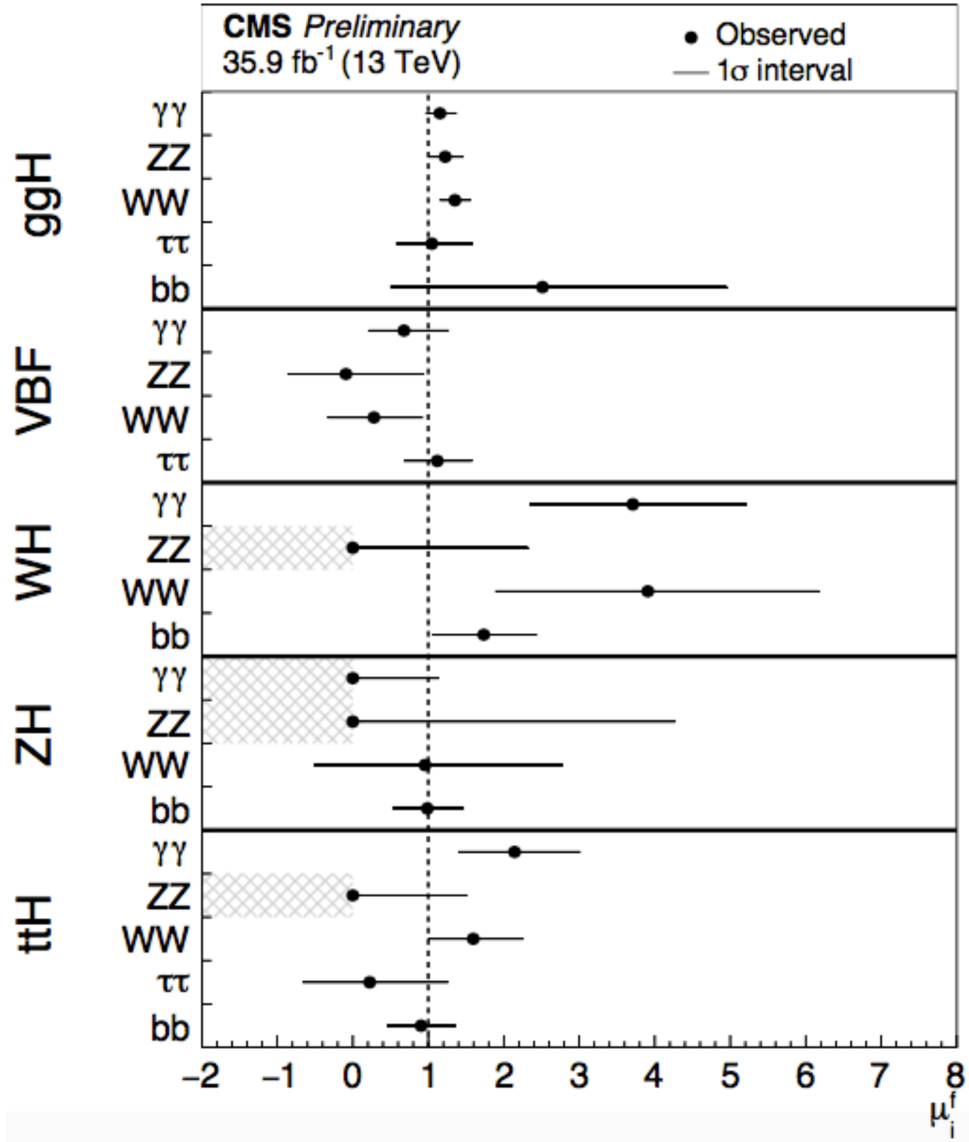
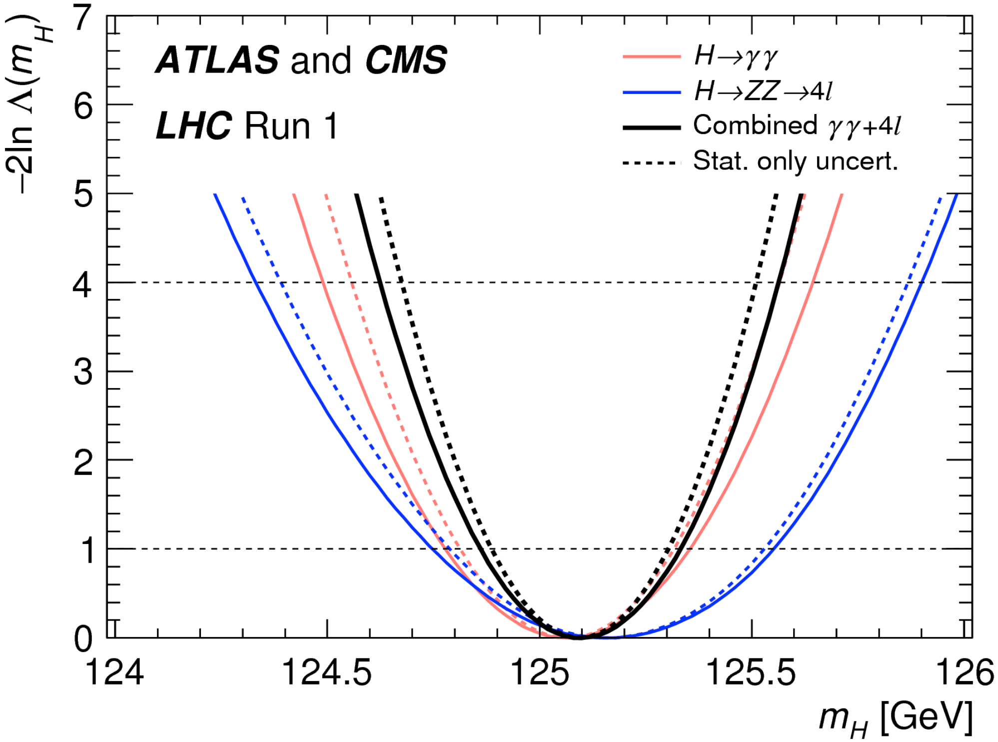


Mass measurement

PRL 114(2015)191803

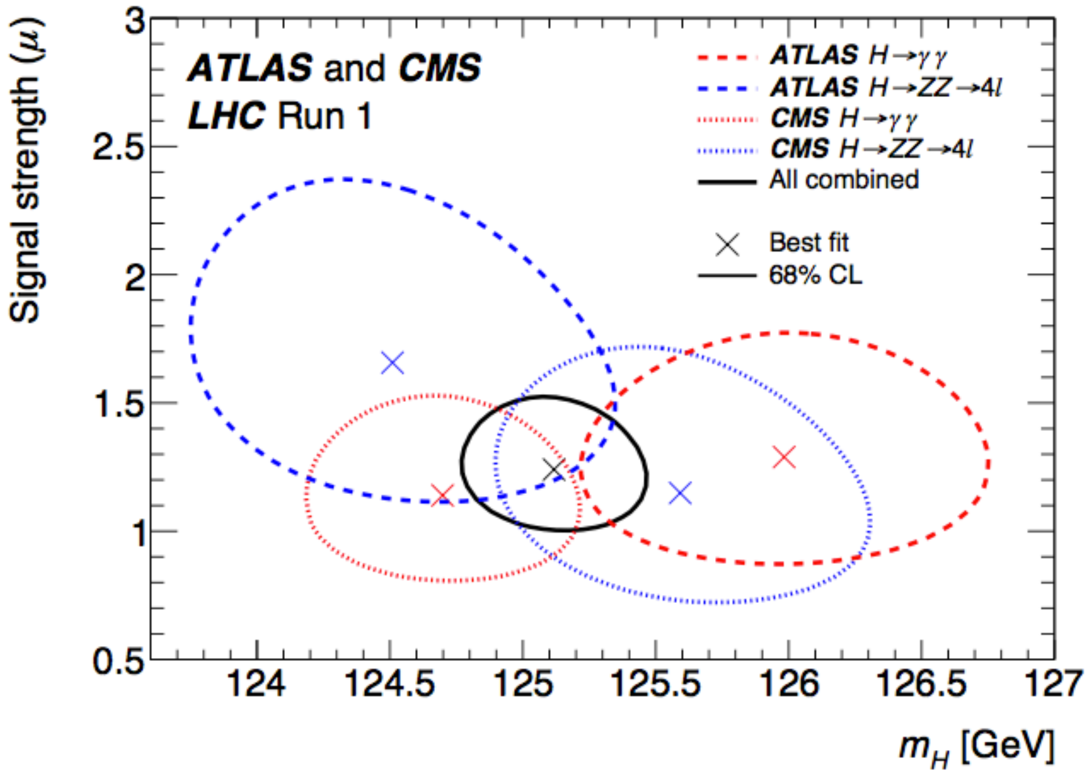
Model-independent mass measurement from high resolution channels (H→ZZ, $\gamma\gamma$)

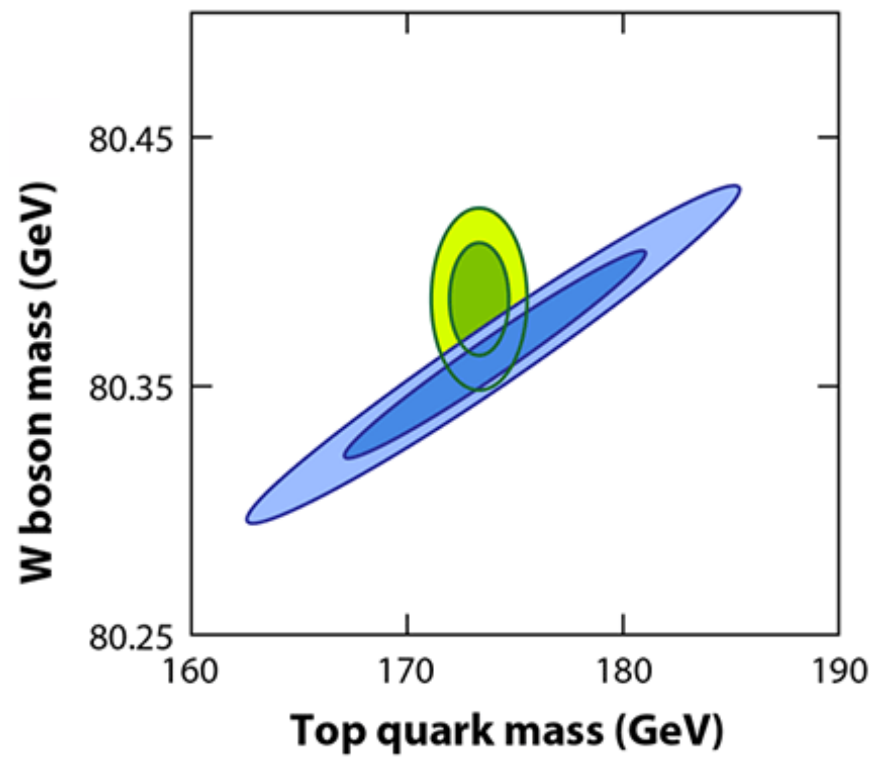


M_H = 125.09 ± 0.24 GeV
= ± 0.21 (stat.) ± 0.11(syst.) GeV

Mass measurement (cont.)

PRL 114(2015)191803

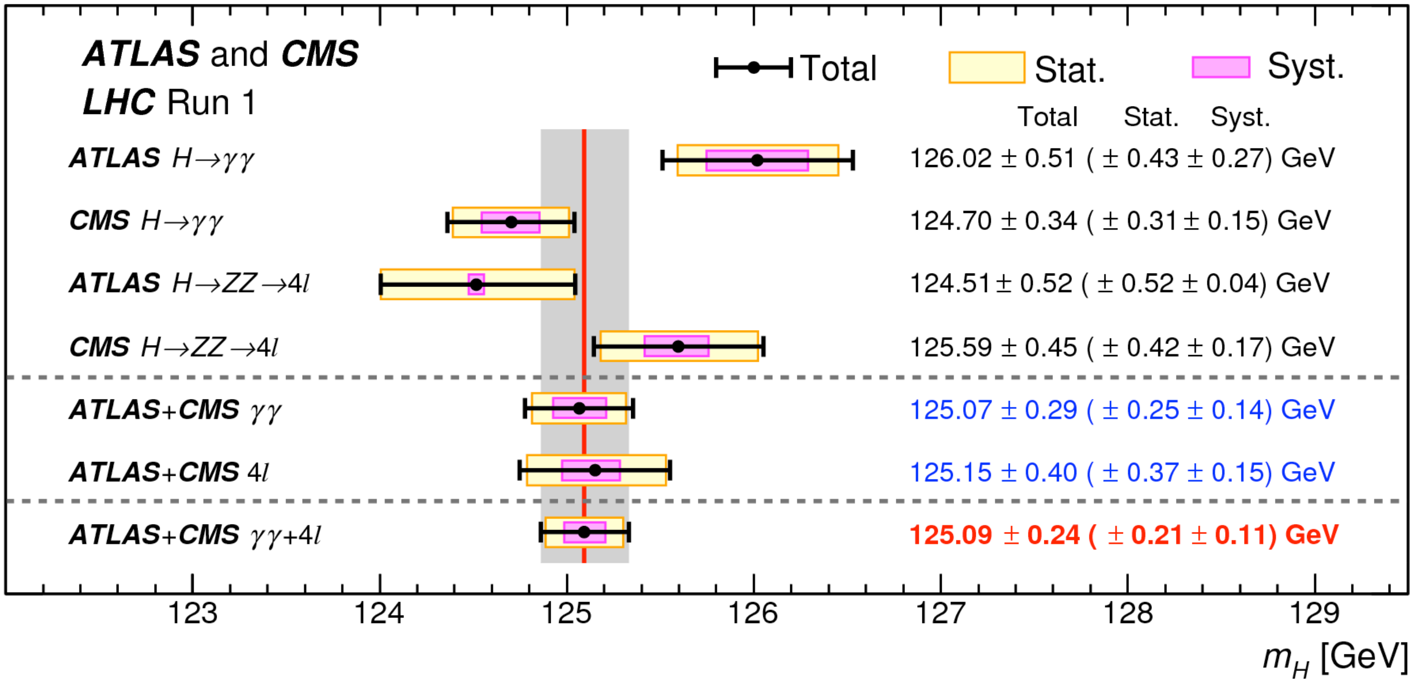




M_H = 125.09 ± 0.24 GeV

= ± 0.21 (stat.) ± 0.11(syst.) GeV

Mass in the individual channels

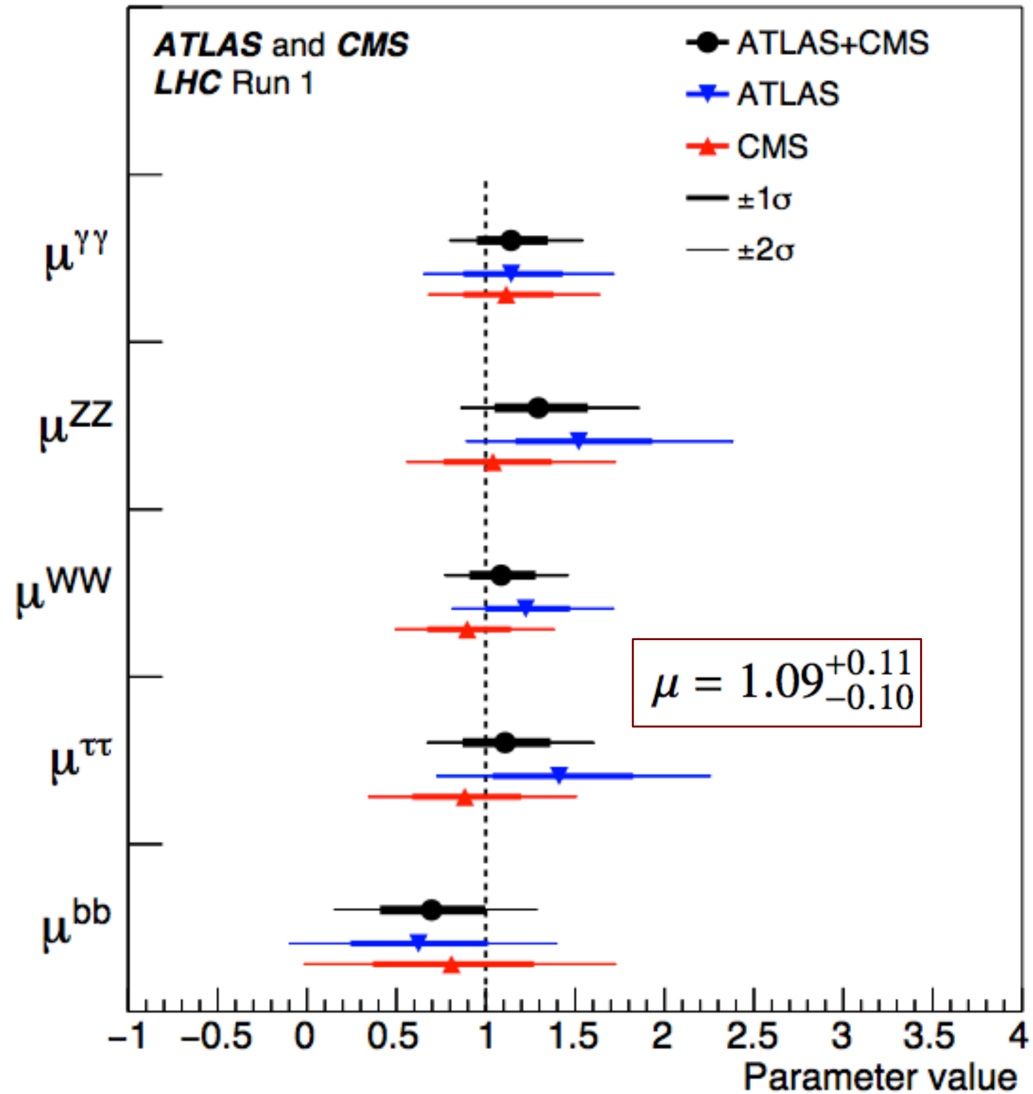


- Most accurate measurement in the γγ and 4l channels
- Some “tension” between the four measurements (p-value ~10%)

Couplings: individual channels

EPJC 75(2015)212, arXiv:1507.04548, arXiv:1606.02266

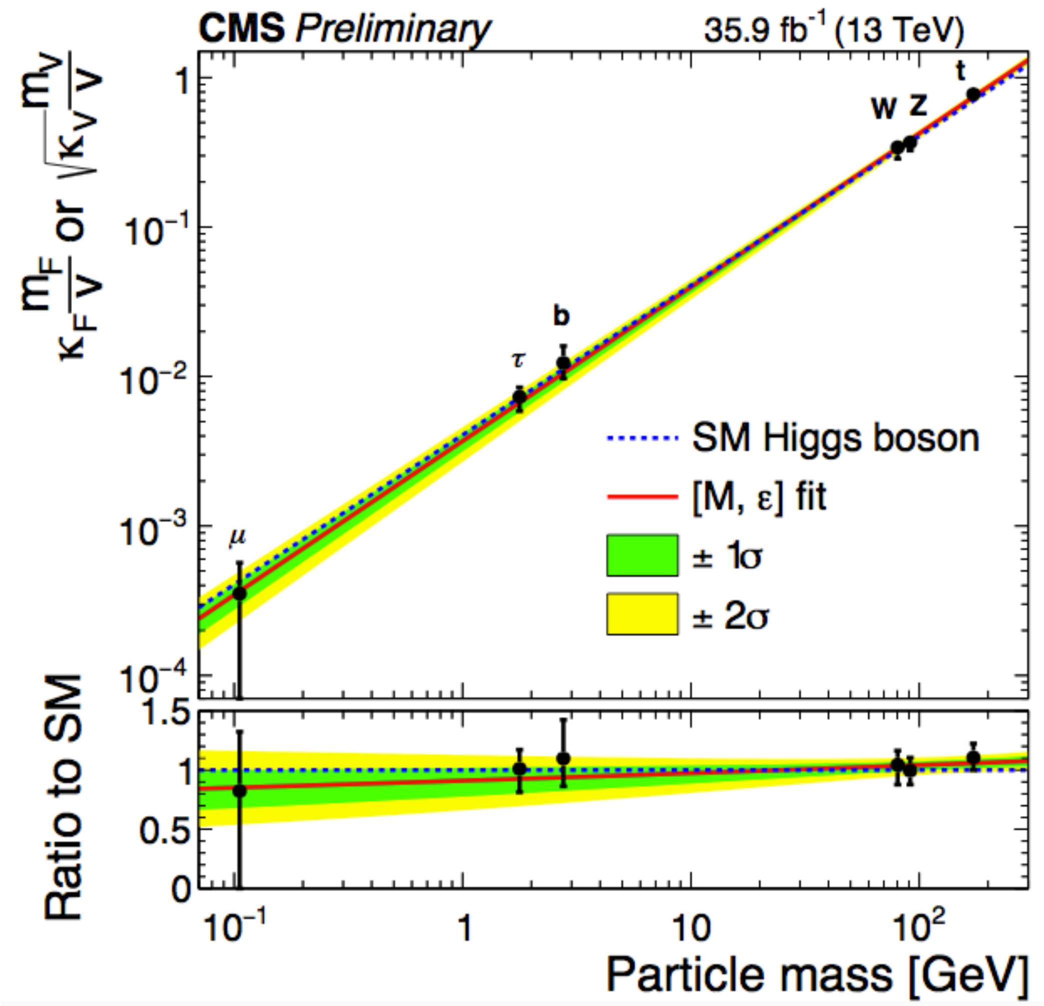
Results based on the full Run 1 data samples



Particle mass coupling dependency

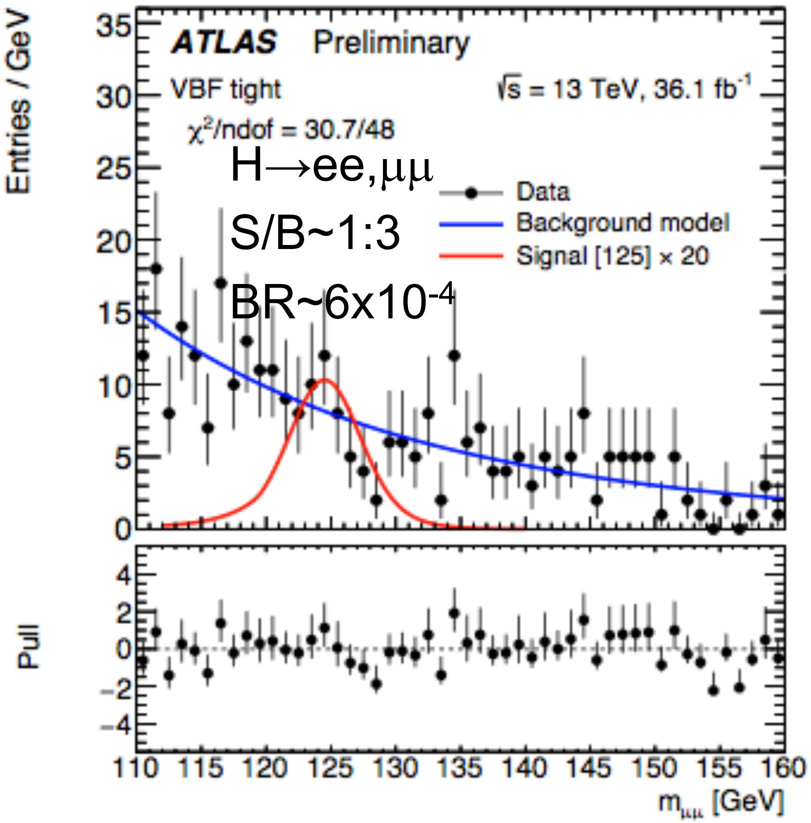
CMS-HIG-17-031

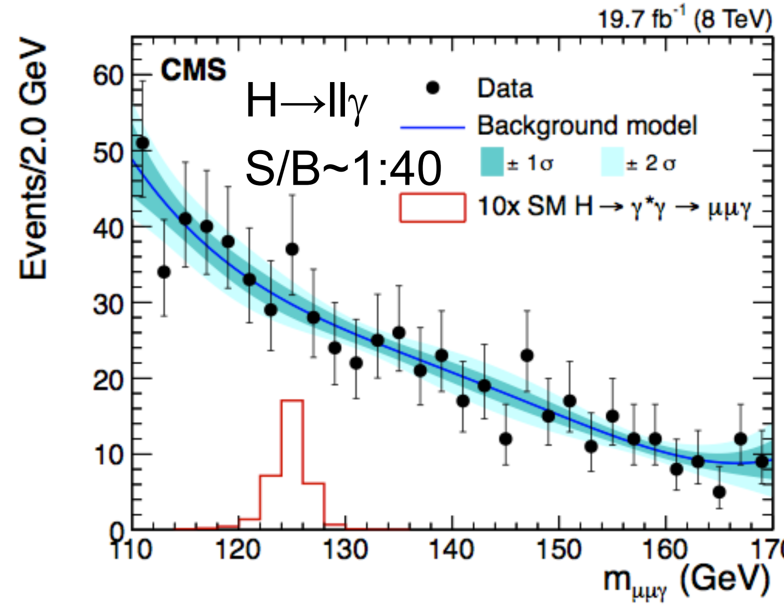
- Fitting the 5 main tree level coupling modifiers and resolving all loops
- Within current precision, couplings scale with particle mass

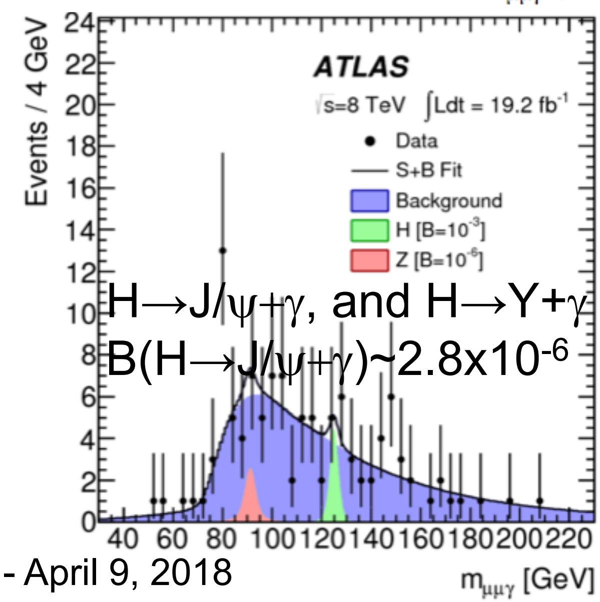


Search for rare decays

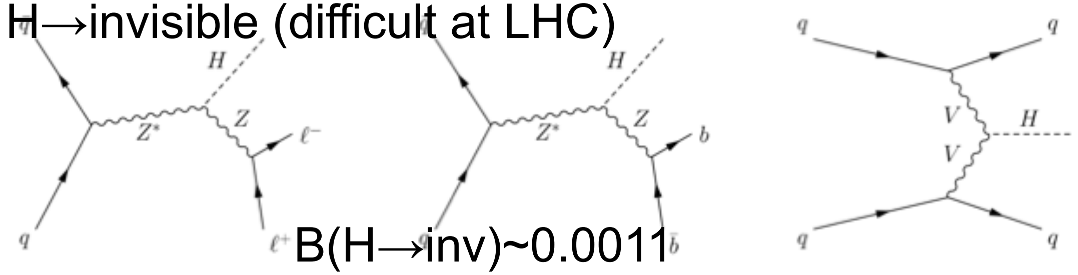
PLB 726(2013)587, arXiv:1507.03031, HIG-15-012, PRL 114(2015)121801, ATLAS-CONF-2016-041 , ATLAS-CONF-2017-014, HIG-17-019







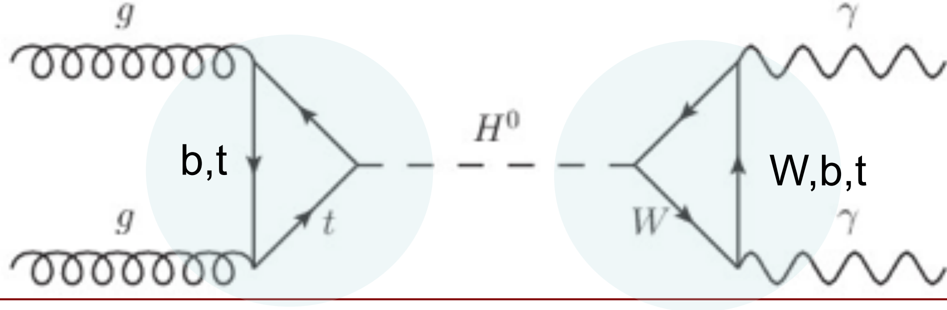
H→invisible (difficult at LHC)



B(H→inv)~0.0011

ATLAS-CONF-2015-044, CMS-HIG-15-002

- Is there BSM physics hidden in the "Higgs sector"?

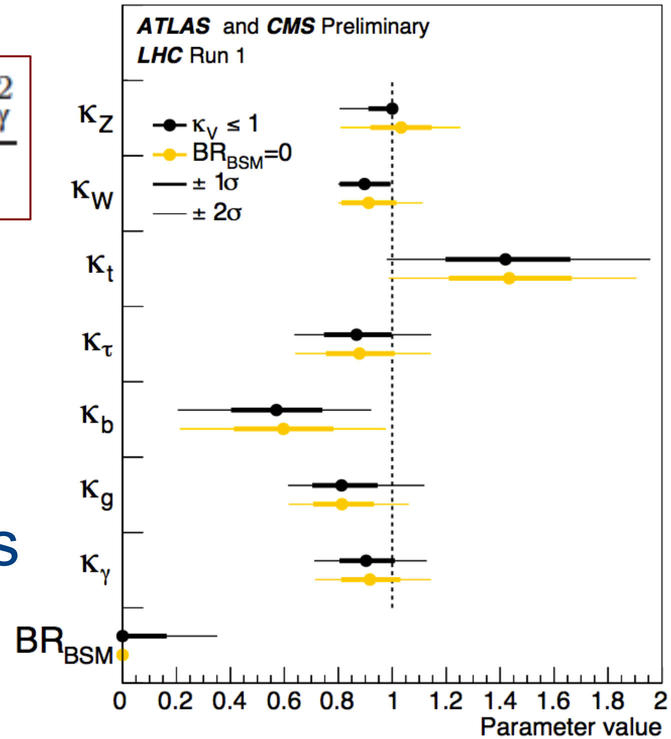


$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \rightarrow \mathrm{H} \rightarrow \gamma\gamma) \;=\; \sigma_{\mathrm{SM}}(\mathrm{gg} \rightarrow \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \rightarrow \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Experimental approach

- Measure H(125) properties
- Search for additional Higgs bosons
- Search for BSM in signatures with Higgs bosons
- Search for BSM Higgs decays

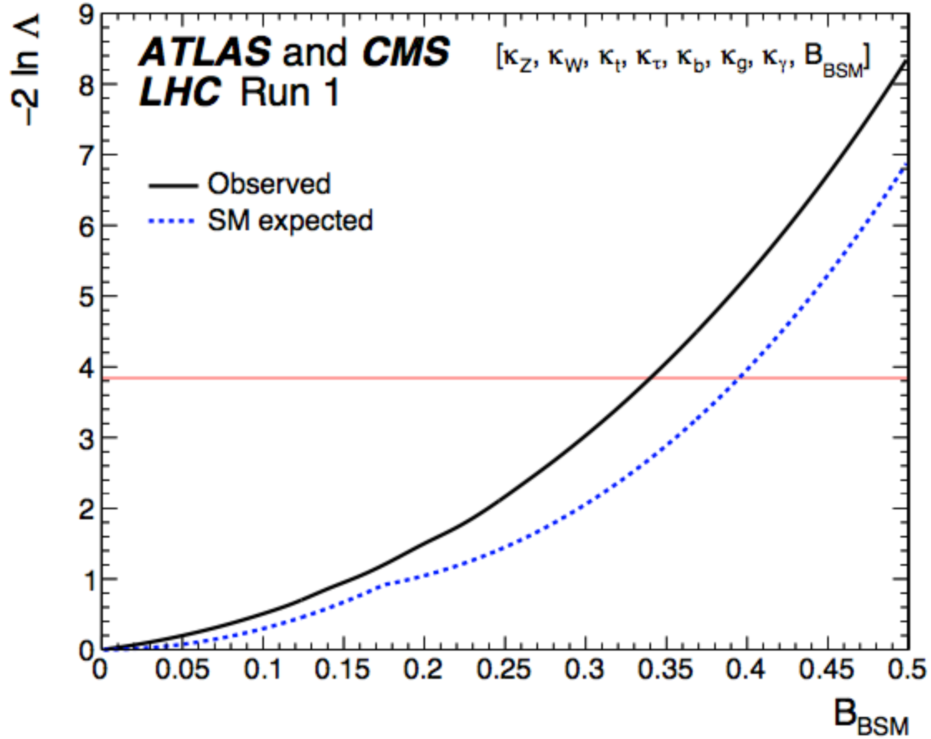
Strategy: parametrize deviations wrt SM in production and decay
$\Rightarrow$ loops are sensitive to BSM physics



Looking for new particles

JHEP08(2016)045

- Constrain BR_{BSM} in a scenario with free parameters
- $\Gamma_{tot}=\Gamma_{WW}+\Gamma_{ZZ}+\Gamma_{bb}+\ldots +\Gamma_{BSM}$
- Likelihood scan vs BR_{BSM}
- Assuming couplings bound by SM expectations (k_v<1)
- $0 \leq BR_{BSM} \leq 0.34$ at 95%CL



Looking for new particles

CMS-HIG-17-031

- Constrain BR_{BSM} in a scenario with free parameters
- $\Gamma_{tot}=\Gamma_{WW}+\Gamma_{ZZ}+\Gamma_{bb}+\ldots+\Gamma_{BSM}$
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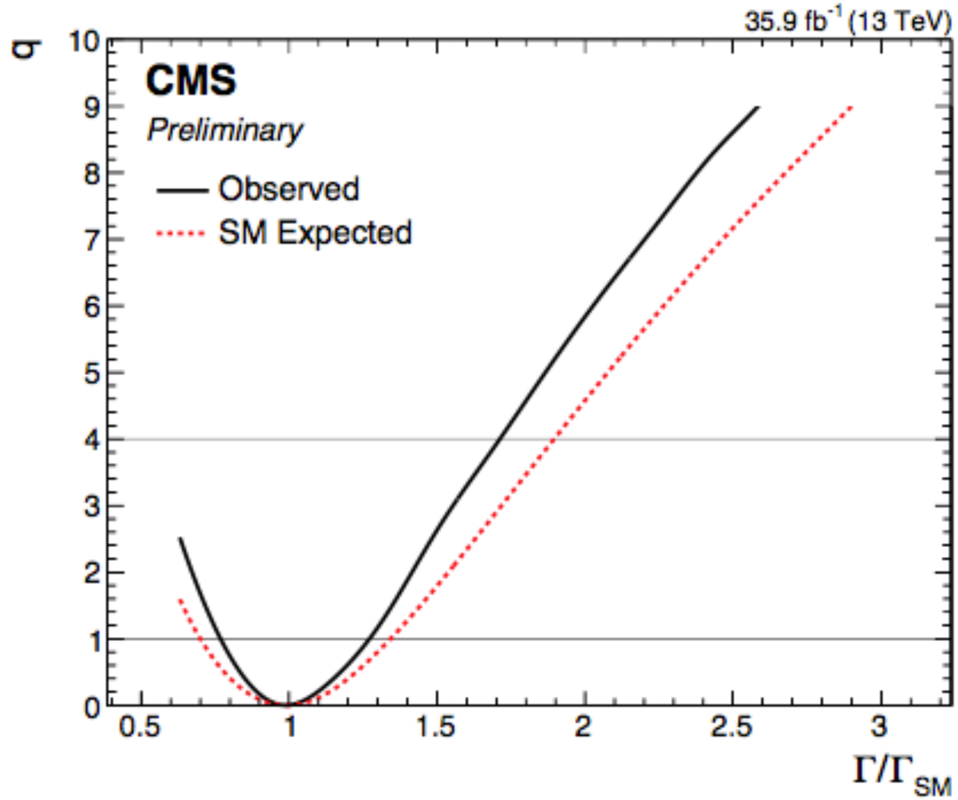
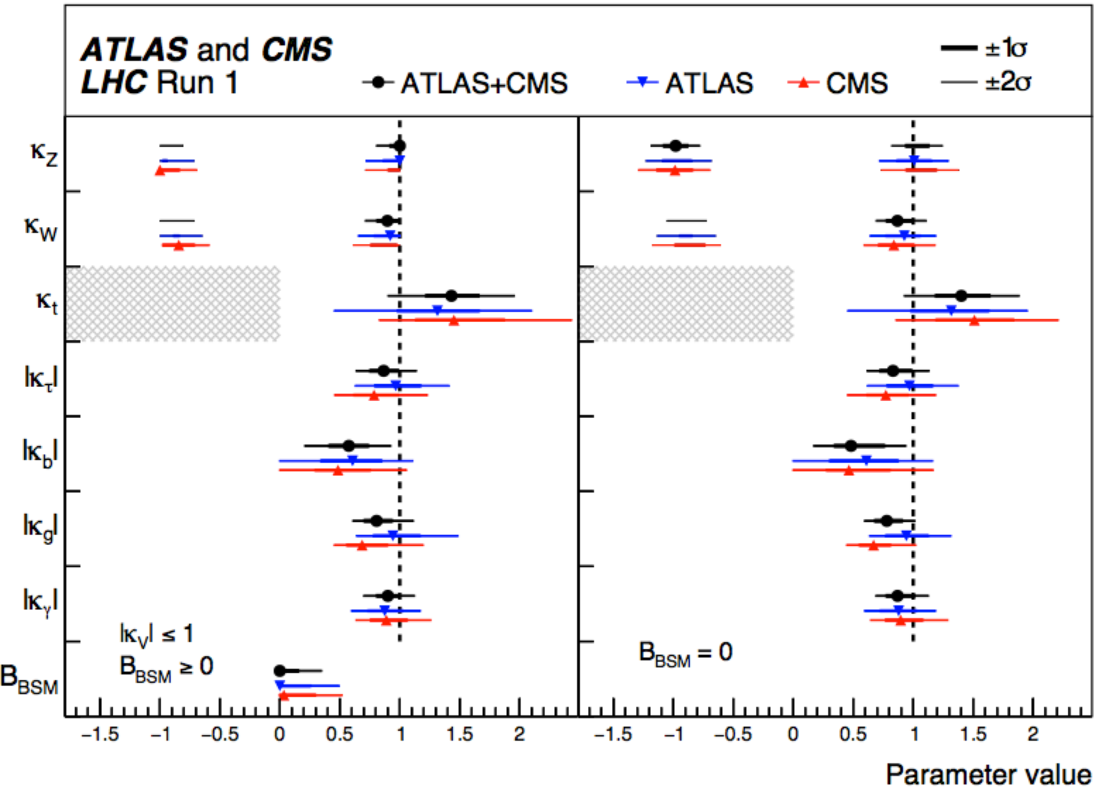


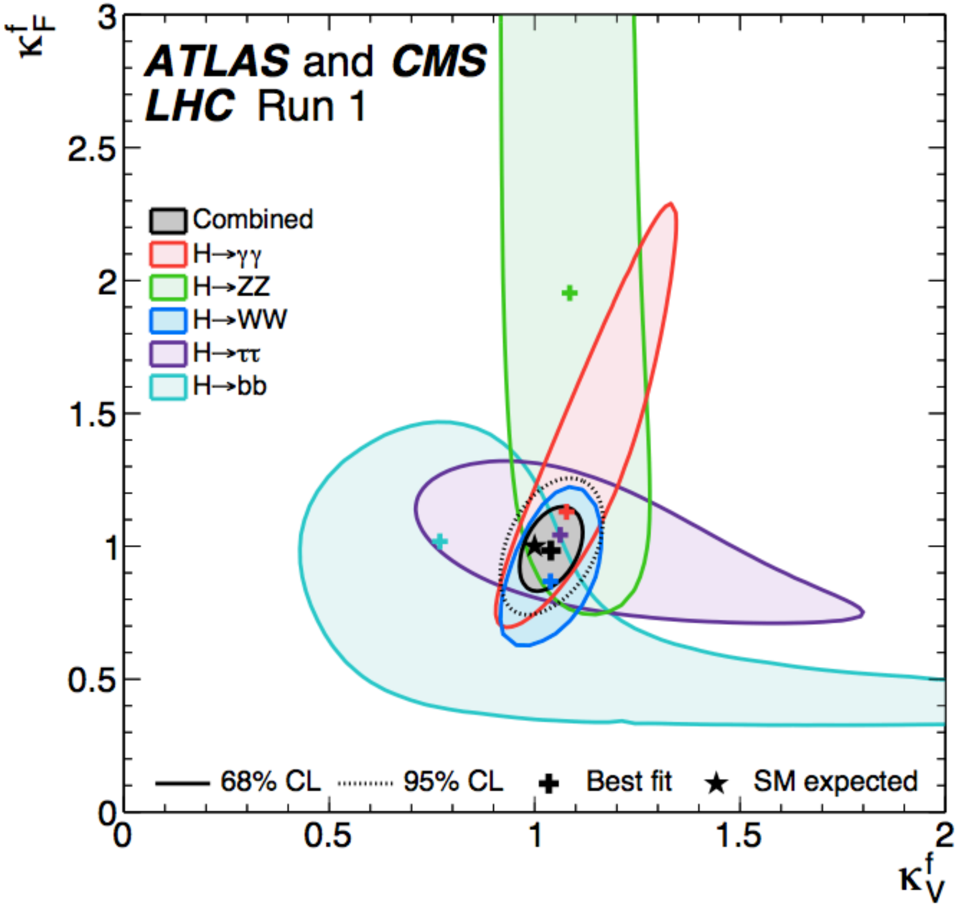
Couplings: decays

ATLAS-CONF-2015-044, CMS-HIG-15-002, JHEP08(2016)045

BSM physics in the loop



Vector and fermion couplings



BR_{BSM} can be measured

BR_{BSM} < 0.34 at 95% C.L. (assuming $\kappa_V \leq 1$)

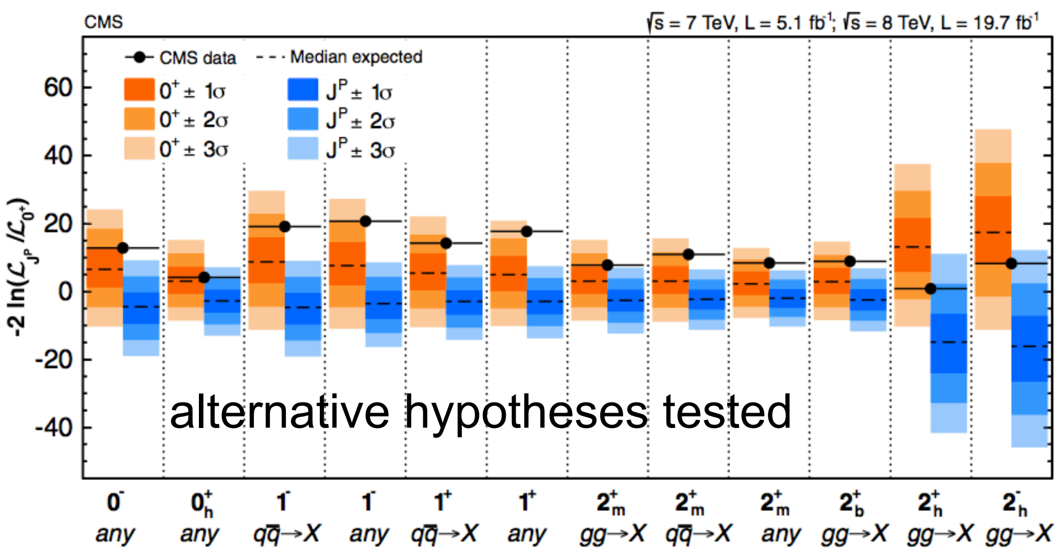
BR_{BSM} includes non standard decays, visible or invisible

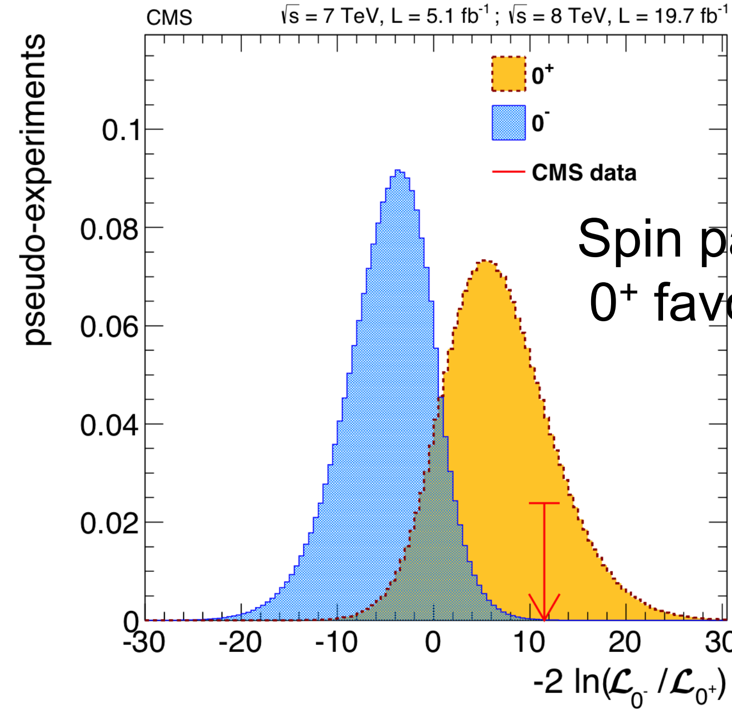
⇒Results in agreement with SM (k_V=k_F=1) within 1σ

Spin

PRD 89(2014)092007

- it may be the first BSM particle produced/observed
- Does it have SM couplings and decays?
- Is it part of an extended scalar sector?
- Does it have exotic properties?



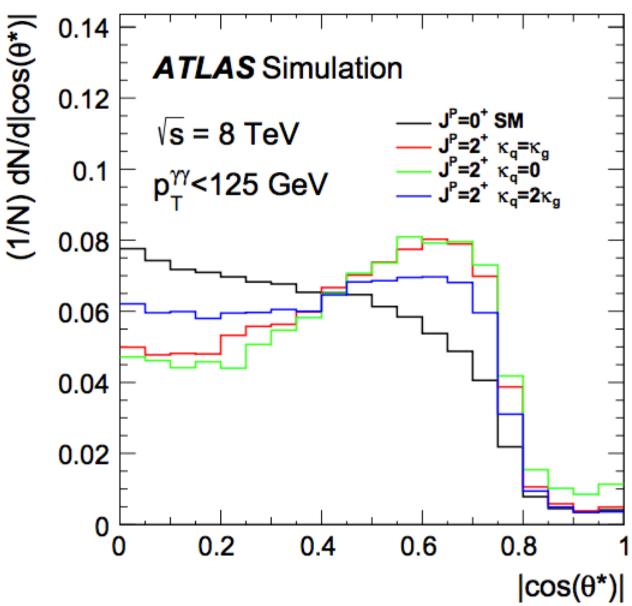


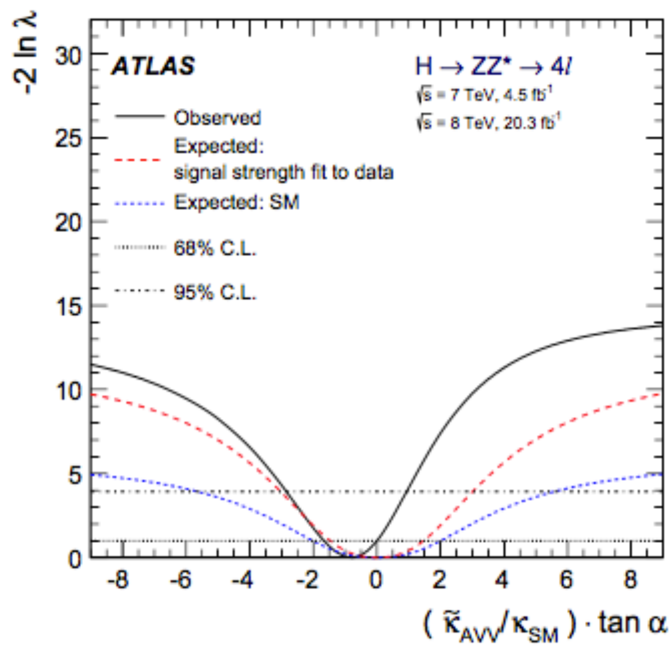
⇒ it is compatible with the SM Higgs boson

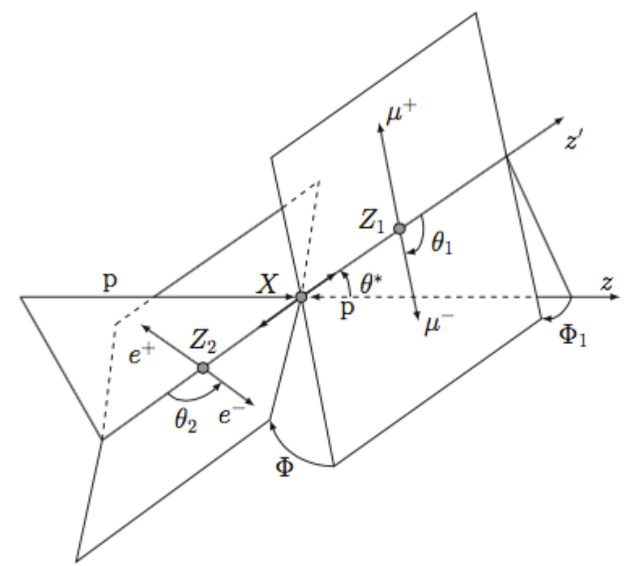
Anomalous Couplings

- Study H→γγ,4l final state with 2 additional jets (VBF, VH)
- Set constraints on anomalous HVV couplings

$$\begin{aligned}\mathcal{L}_0^V = \Big\{ & \cos(\alpha)\kappa_{\rm SM}\Big[\frac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\Big] \\ & -\frac{1}{4}\frac{1}{\Lambda}\Big[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu}+\sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\Big] \\ & -\frac{1}{2}\frac{1}{\Lambda}\Big[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} \\ & +\sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\Big]\Big\}X_0. \qquad (1)\end{aligned}$$







Summary

- Excellent consistency of SM but SM is incomplete
- Extensions foresee existence of additional bosons
- Searches for BSM bosons natural companion to precision SM Higgs boson measurements
- Searches provide no hints for BSM yet