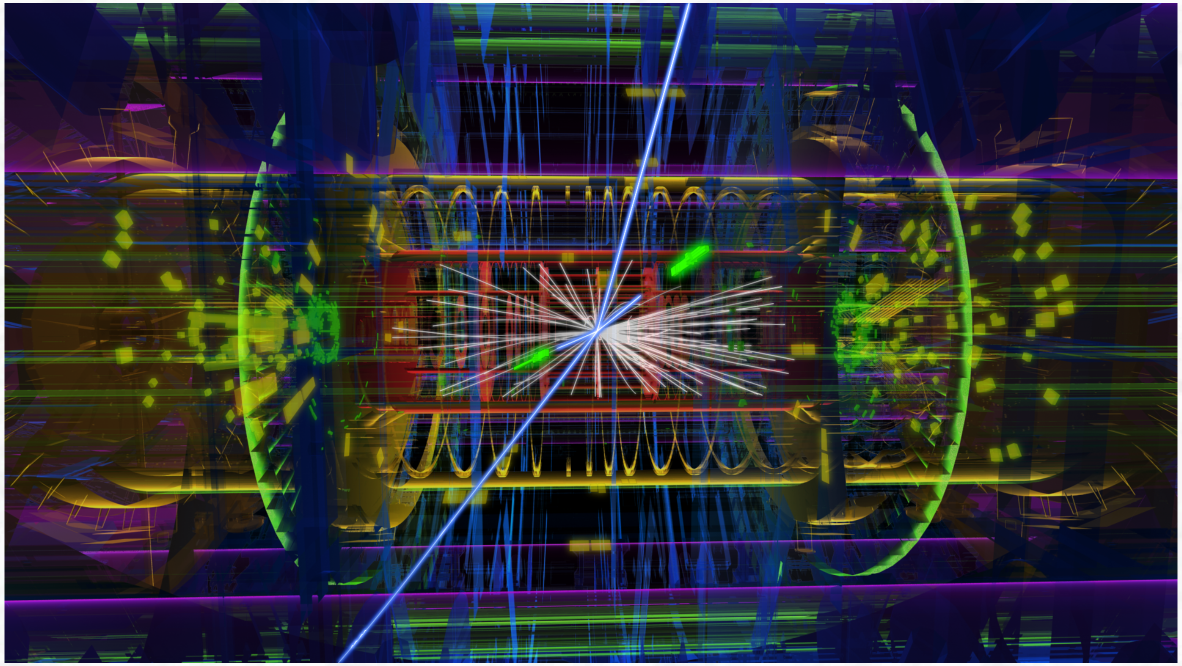
Higgs Boson Physics at the LHC

-The profile of the new particle-



Prof. Karl Jakobs
Physikalisches Institut
Universität Freiburg

Announcement:
4^{th} July 2012

"Summary of Results from LHC Run 1"

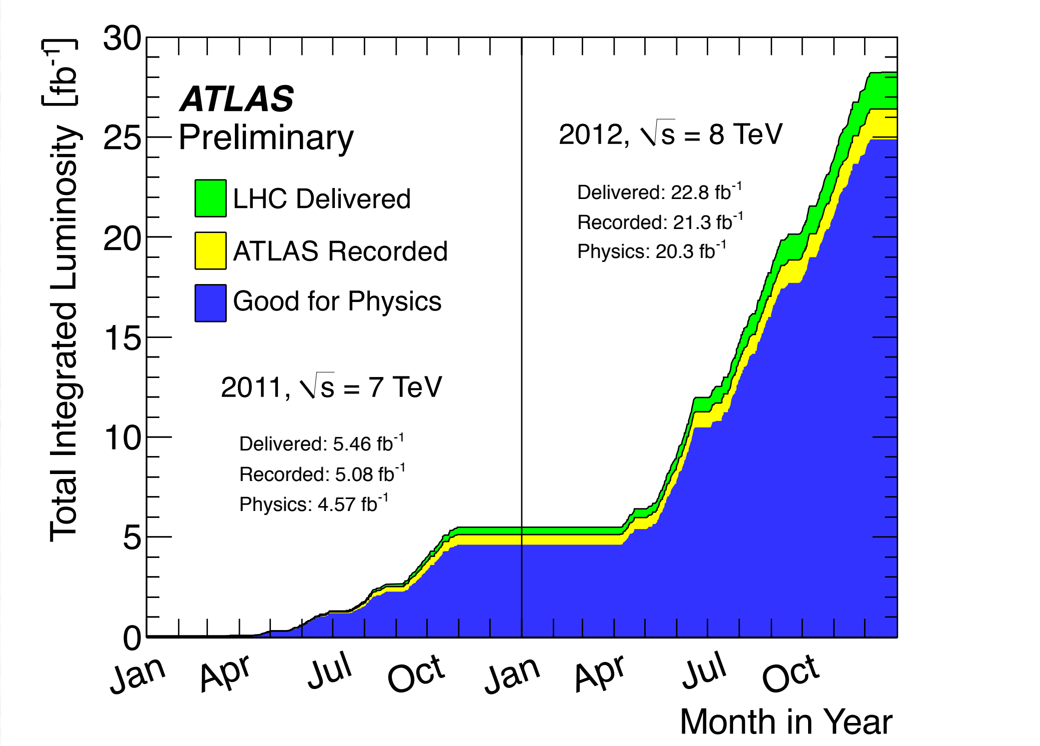
- Present status on:
  - Bosonic decay modes
    $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^*$, $H \rightarrow WW^*$
  - Decays into fermions
  - Search for rare decays
- Profile of the new particle
  (mass, Spin-CP, couplings)
- First results from LHC Run 2

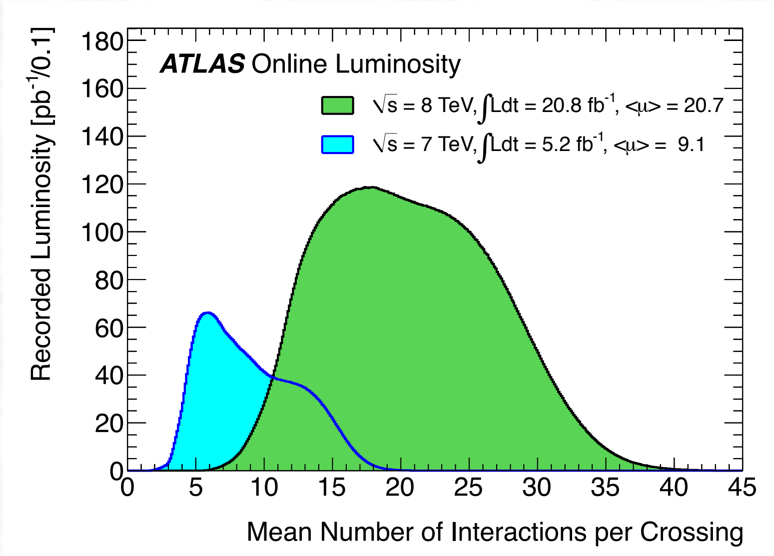
The Large Hadron Collider

Steve Myers PLHC 2012:

"The first two years of LHC operation have produced sensational performance: well beyond our wildest expectations. The combination of the performance of the LHC machine, the detectors and the GRID have proven to be a terrific success story in particle physics."

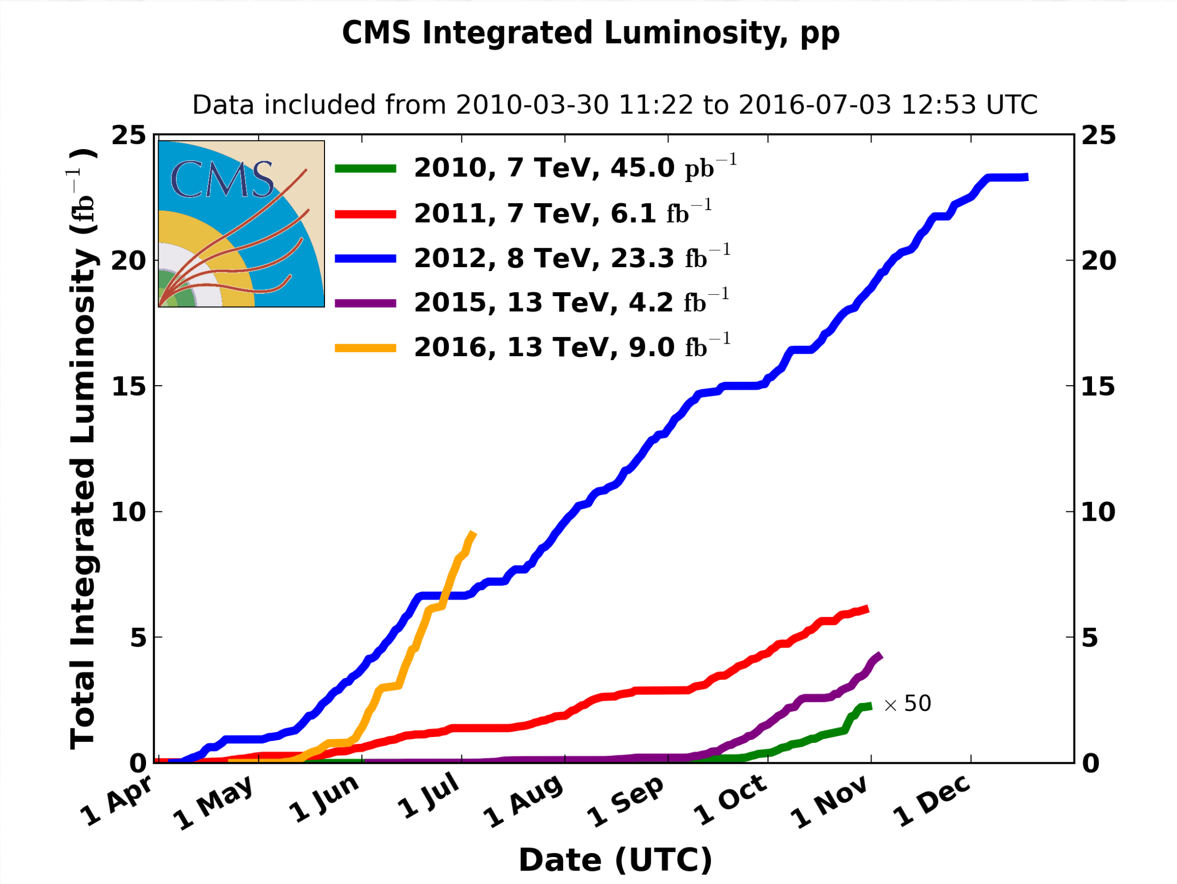
Performance of the LHC and of the experiments





- Excellent LHC performance in 2011 and 2012
- Peak luminosities > 7 10^{33} cm^{-2} s^{-1}
- High level of pileup: mean of ~20 interactions / beam crossing in 2012
- Excellent performance of the ATLAS and CMS experiments:
  (Data recording efficiency: ~93.5%, working detector channels >97 % for most sub-detectors, high data quality, speed of the data analysis)

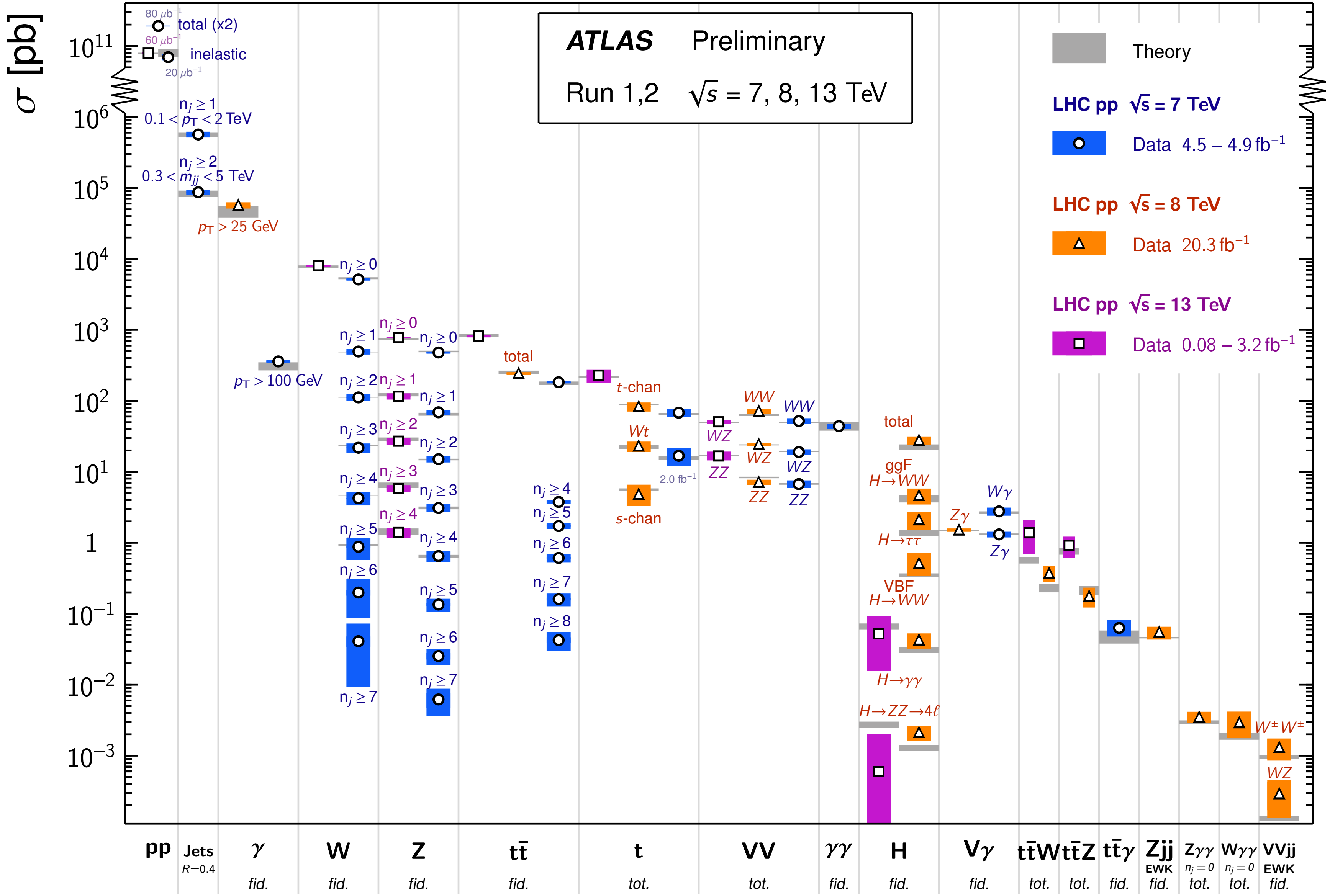
Even better today, the 2016 run at √s = 13 TeV



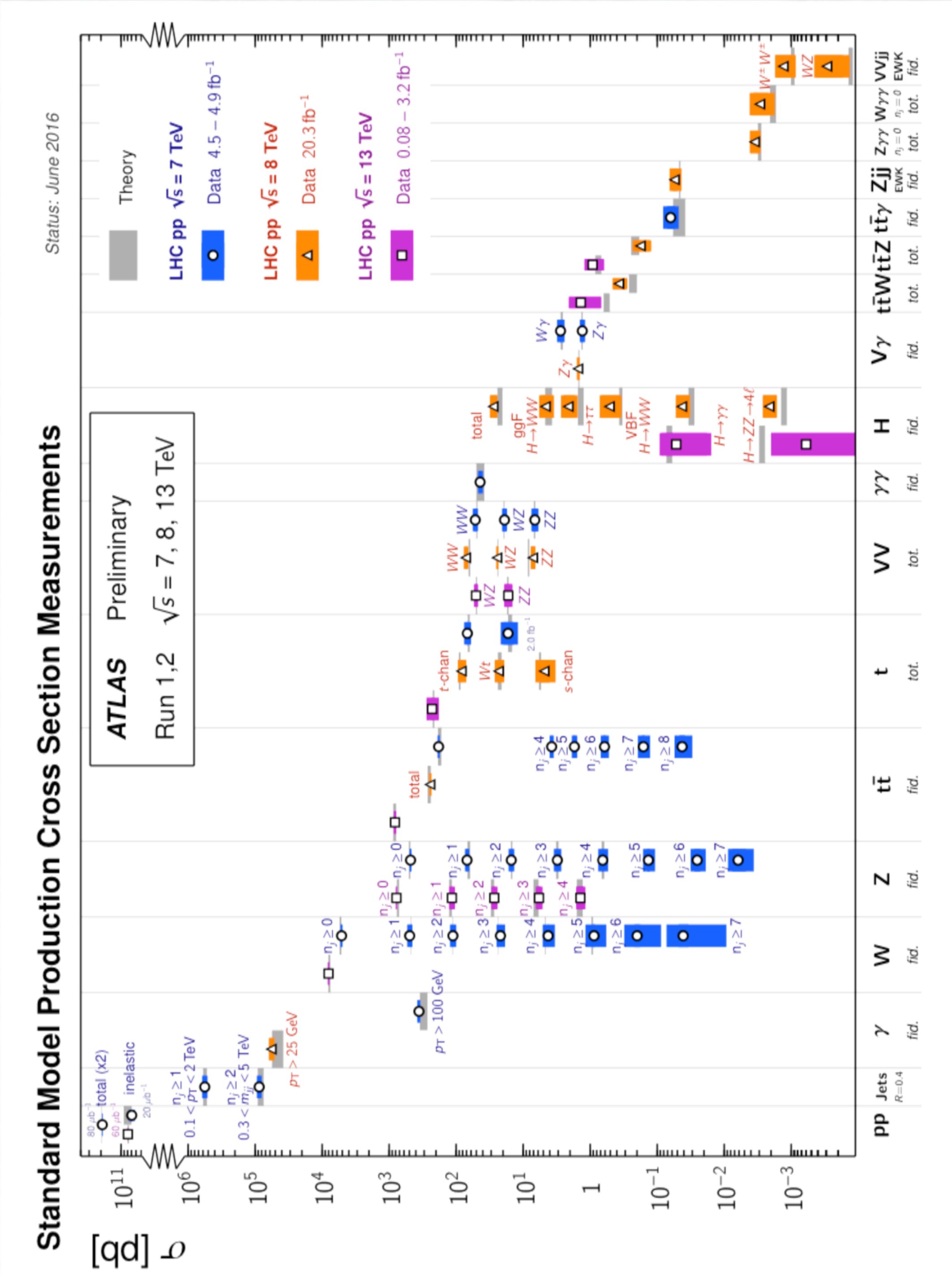
- Peak luminosity > 1 10^{34} cm^{-2} s^{-1}
- High level of pileup, however, running with a bunch separation of 25 ns

Standard Model Production Cross Section Measurements

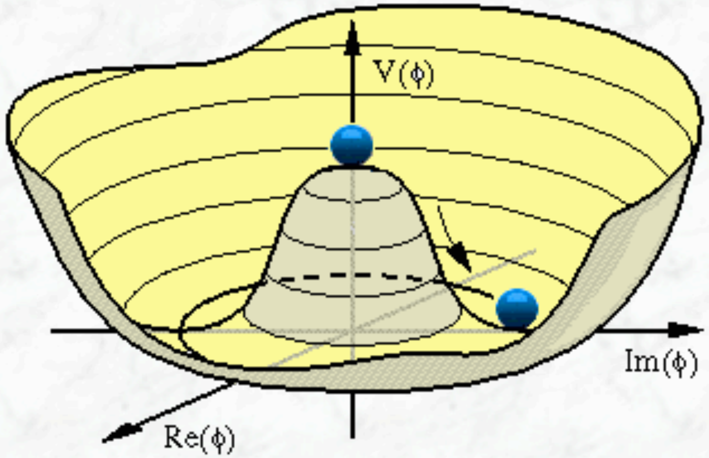
Status: June 2016



“Stairway to Heaven”



The Brout-Englert-Higgs Mechanism



Complex scalar (spin-0) field ϕ with potential:

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

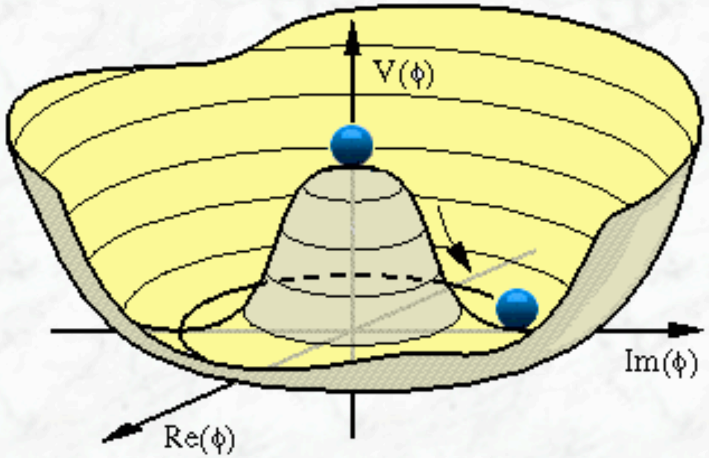
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H <\sim 1000$ GeV)

→ Particles acquire mass through interaction with the Higgs field

The Brout-Englert-Higgs Mechanism



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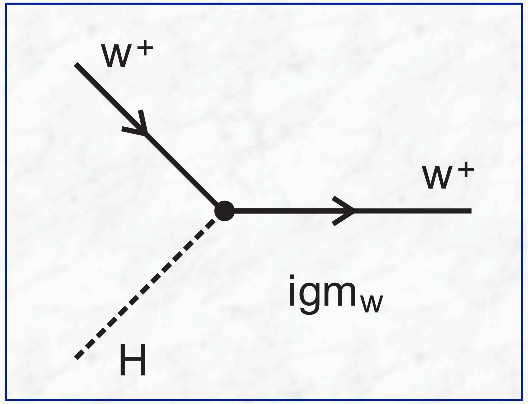
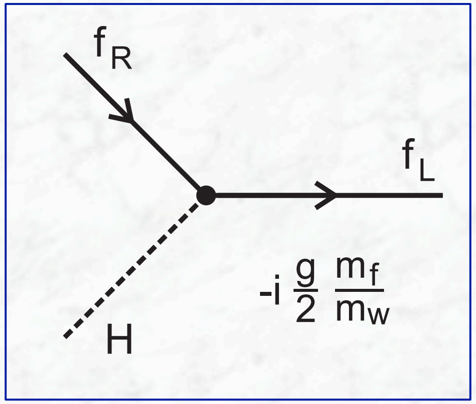


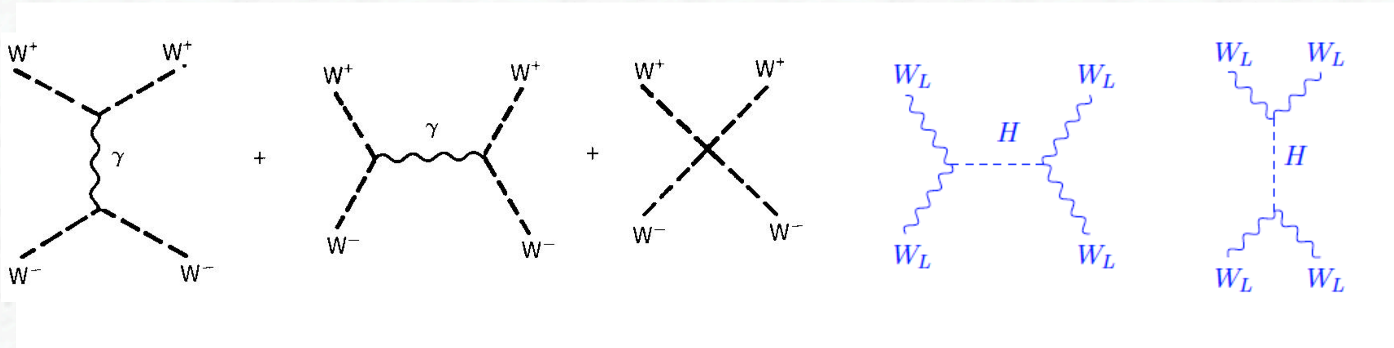


- Couplings proportional to mass

The Higgs field solves two fundamental problems:

(i) Masses of the vector bosons W and Z and fermions

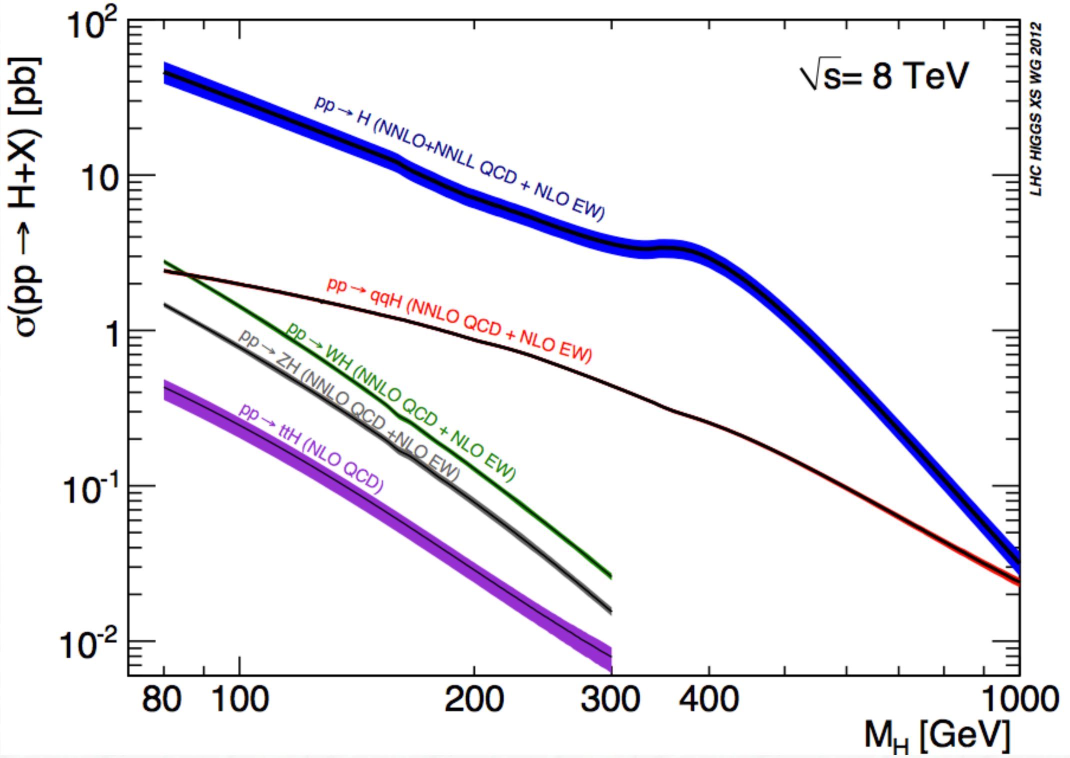
(ii) Divergences in the theory (scattering of W bosons)
("Ultraviolet regulator")

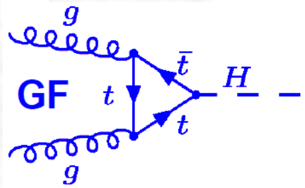


$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$ (no Higgs boson)

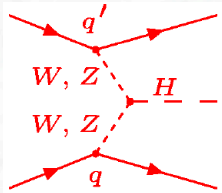
$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$ (with Higgs boson)

Higgs Boson Production



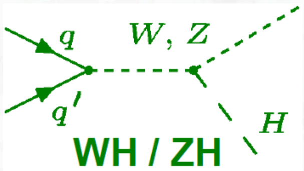


Gluon fusion

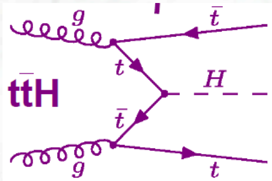


VBF

Vector boson fusion



WH/ZH associated production



tt associated production

*) LHC Higgs cross-section working group
Large theory effort

Meanwhile the NNNLO = N^{3}LO calculation for the gluon-fusion process exists;
B. Anastasiou et al. (2015)

→ LHC = Long and Hard Calculations

Theoretical cross sections and uncertainties

Progress in theoretical calculations — NNLO revolution

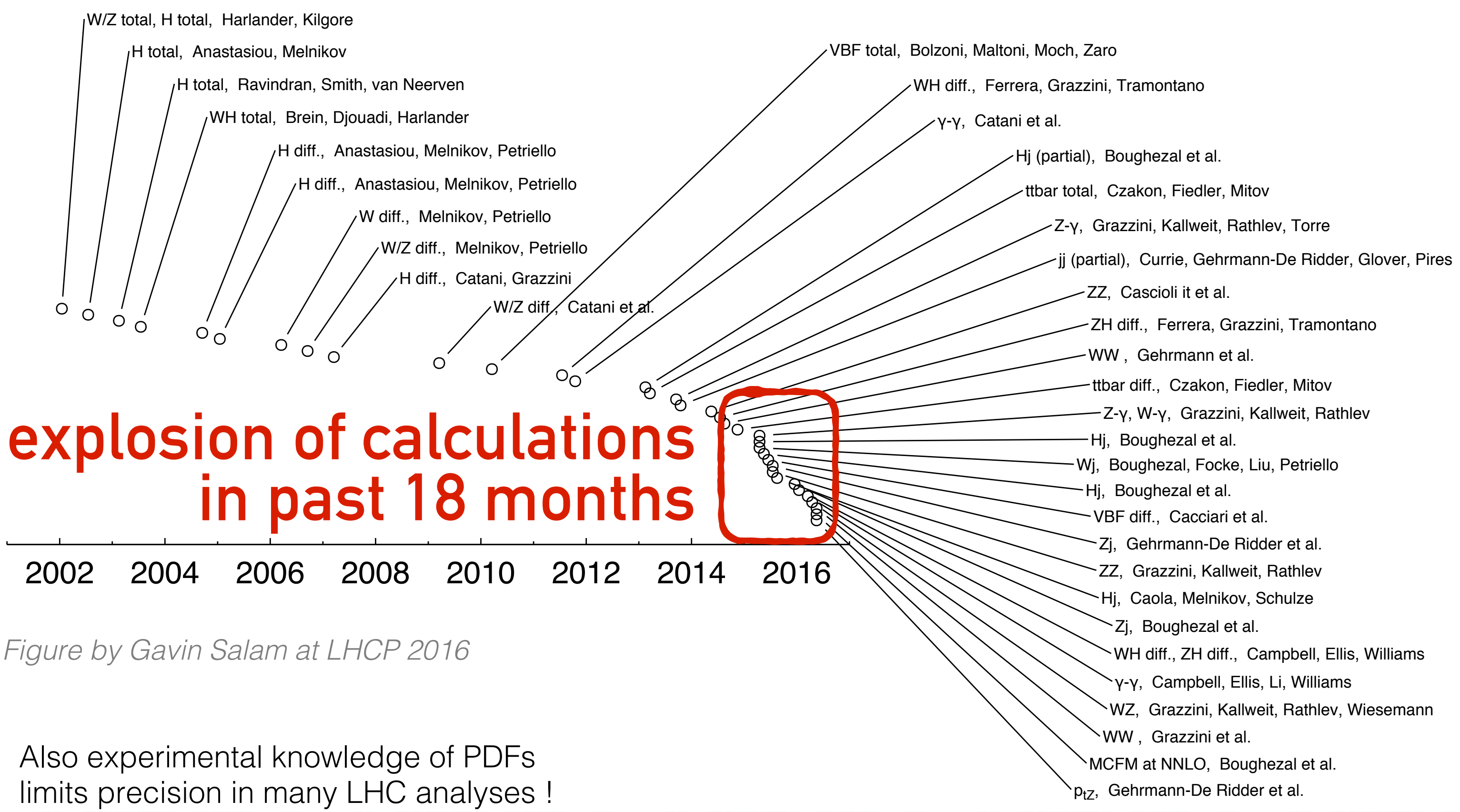


Figure by Gavin Salam at LHCP 2016

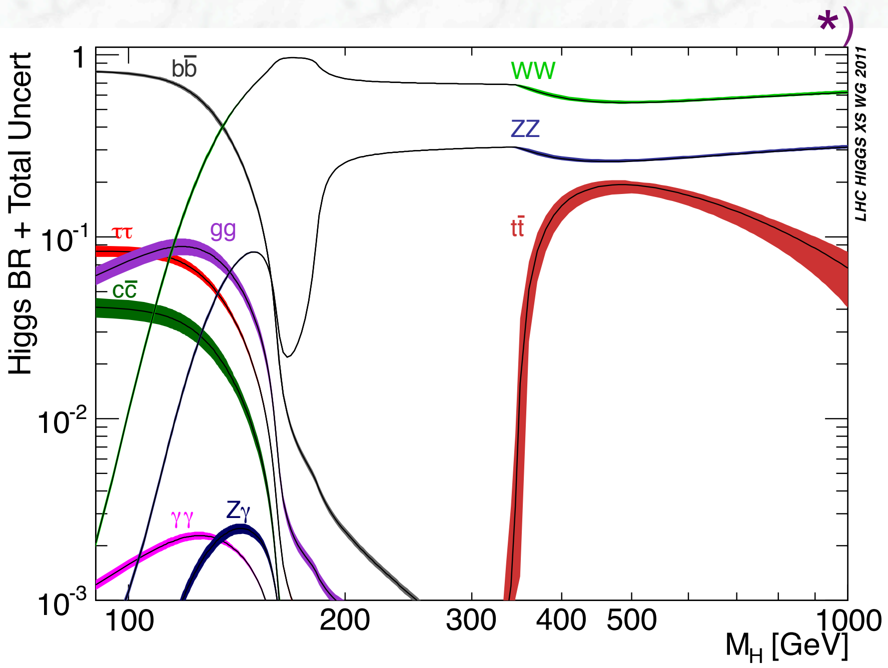
Also experimental knowledge of PDFs limits precision in many LHC analyses !

Higgs Boson Production

Production process	Cross section [pb] $\sqrt{s} = 7$ TeV	Cross section [pb] $\sqrt{s} = 8$ 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) + APPROX. NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD) + NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD) + NLO(EW)
[$ggZH$]	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

	√s=7 TeV	√s=8 TeV	√s=13 TeV	Ratio 13/8 TeV
ggH	15.3 pb	19.4 pb	44.1 pb	**2.27**
VBF	1.25 pb	1.6 pb	3.8 pb	**2.38**
ttH	88.6 fb	133 fb	507 fb	**3.81**
tt	177 pb	253 pb	832 pb	**3.29**

Higgs Boson Decays



Useful decays at a hadron collider:

- Final states with leptons via WW and ZZ decays
- $\gamma\gamma$ final states (despite small branching ratio)
- $\tau\tau$ final states (more difficult)
- In addition: H → bb decays via associated lepton signatures (VBF, VH or ttH production)

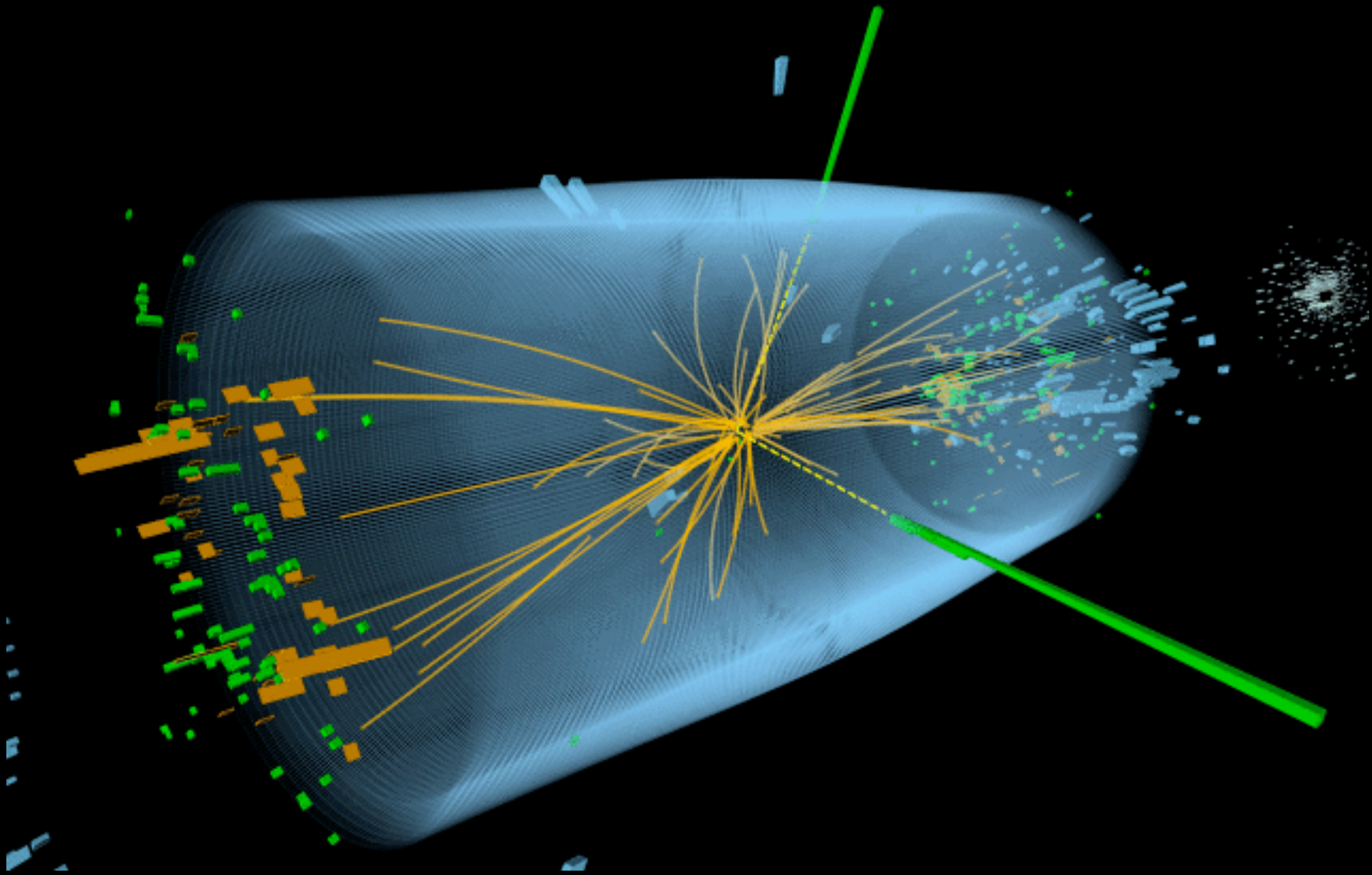
SM predictions (m_H = 125.5 GeV):

BR (H→ WW) = 22.3%	BR (H → bb) = 56.9%
BR (H → ZZ) = 2.8%	BR (H → $\tau\tau$) = 6.2%
BR (H → $\gamma\gamma$) = 0.24%	BR (H →$\mu\mu$) = 0.022%

→ at 125 GeV: only ~11% of decays not observable (gg, cc)

*) LHC Higgs cross-section working group

Status of Higgs boson physics at the LHC

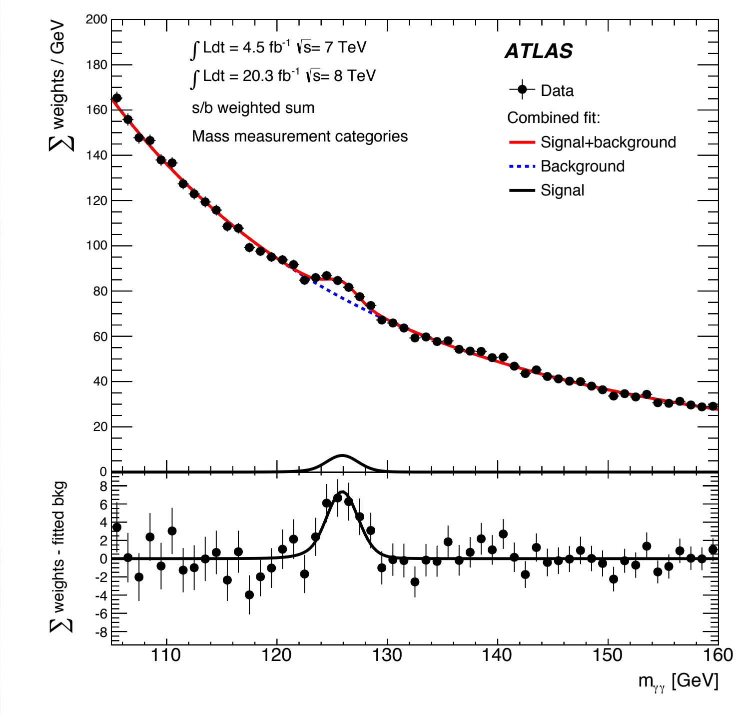


Expected number of decays, before selection cuts, in the Run-1 data, m_H = 125 GeV:

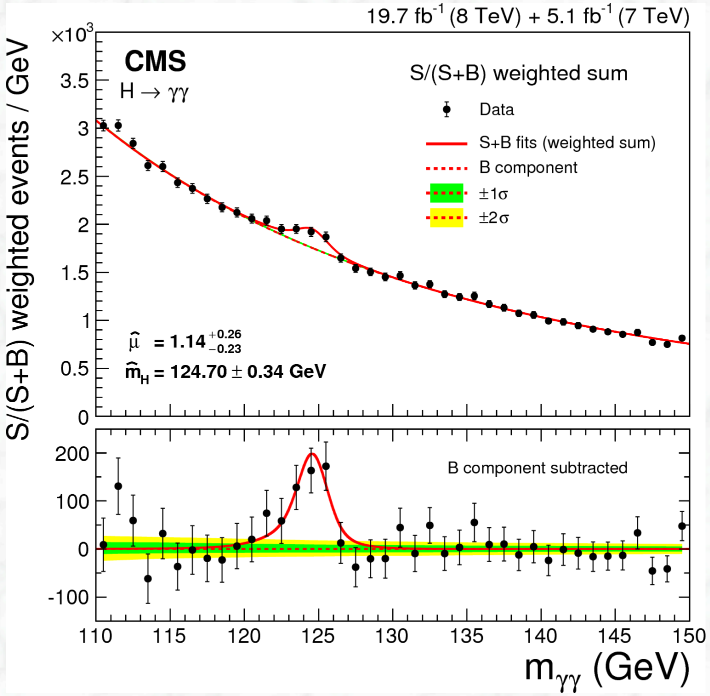
~ 950 H → $\gamma\gamma$
~ 60 H → ZZ* → 4 ℓ
~ 9000 H → WW* → $\ell\nu$ $\ell\nu$

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



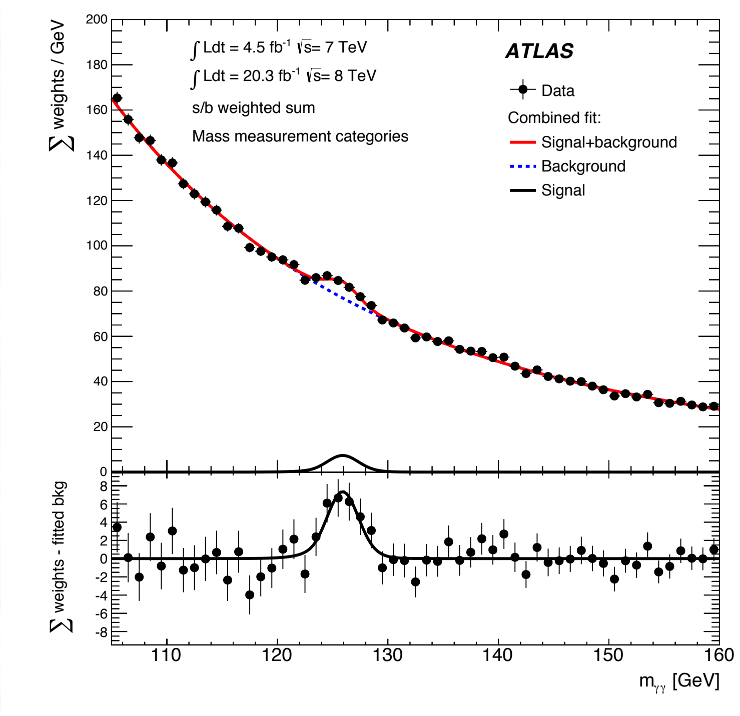
EPJ C74 (2014) 3076



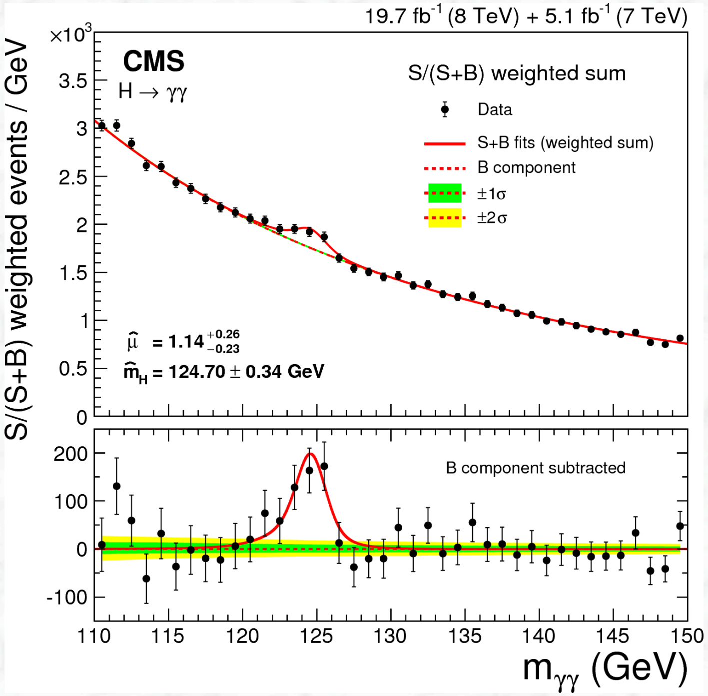
- Background interpolation in the region of the excess (obtained from sidebands)
- Reducible γ-jet and jet-jet background at the level of 25%
- High signal significance in both experiments: ATLAS: 5.2σ (4.6σ expected)
CMS: 5.7σ (5.2σ expected)
- Establishes the discovery in this channel alone

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



EPJ C74 (2014) 3076

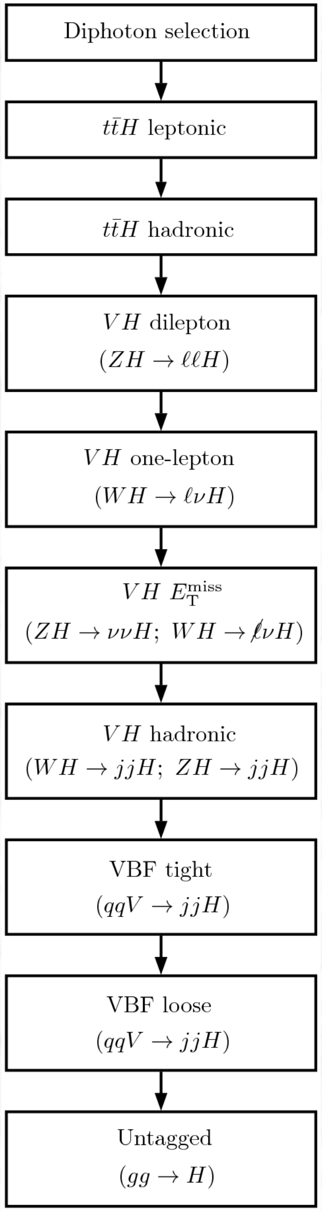


Measured signal strengths: $\mu = \sigma_{obs} / \sigma_{SM}$

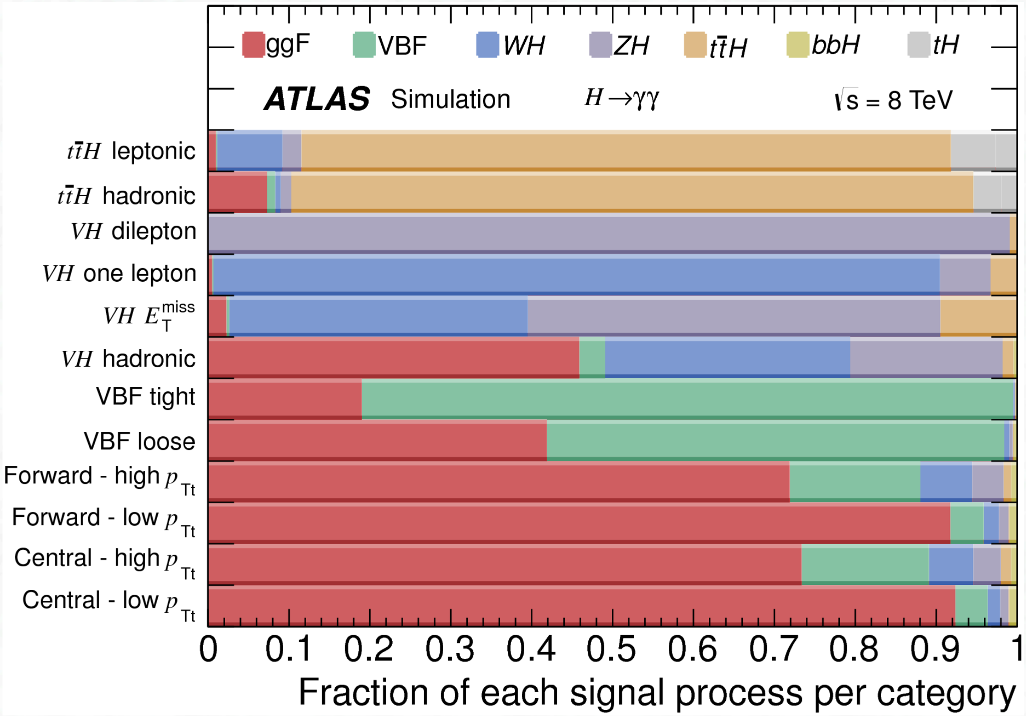
ATLAS: $\mu = 1.17 \pm 0.27$

CMS: $\mu = 1.14 \pm 0.26$

Categorisation of H → γγ candidate events



Categorisation: to increase overall sensitivity and sensitivity to different production modes (VBF, VH)



- VH enriched: one-lepton, E_T^{miss}, low-mass di-jets
- VBF enriched (tag-jet configuration, $\Delta\eta$, m_{jj})
- gluon fusion: exploit different mass resolution for different detector regions, γγ conversion status and p_{Tt}

Phys. Rev. D90 (2014) 112015

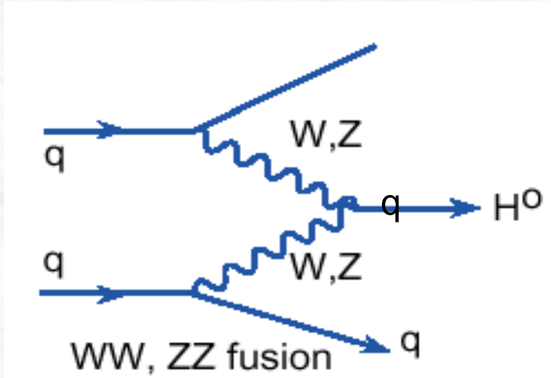
Vector Boson Fusion qqH

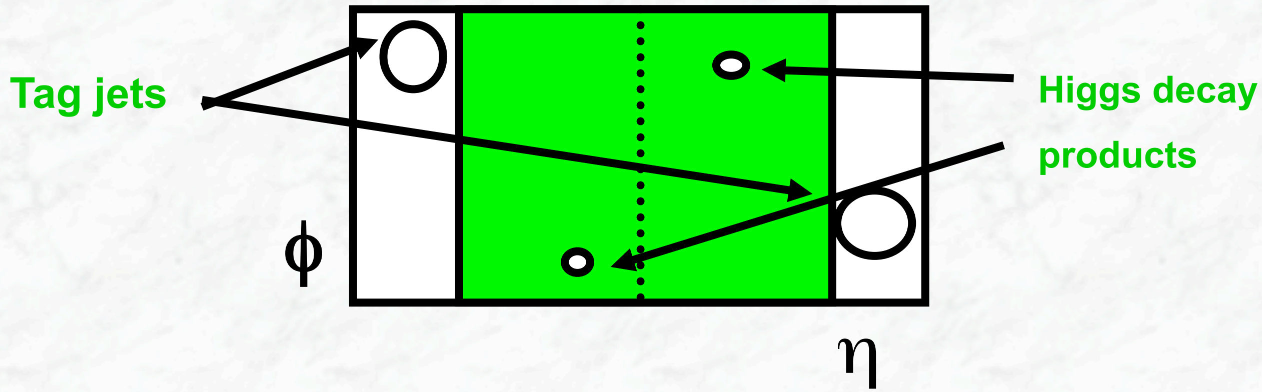
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions, e.g. τ leptons)

Distinctive Signature of:

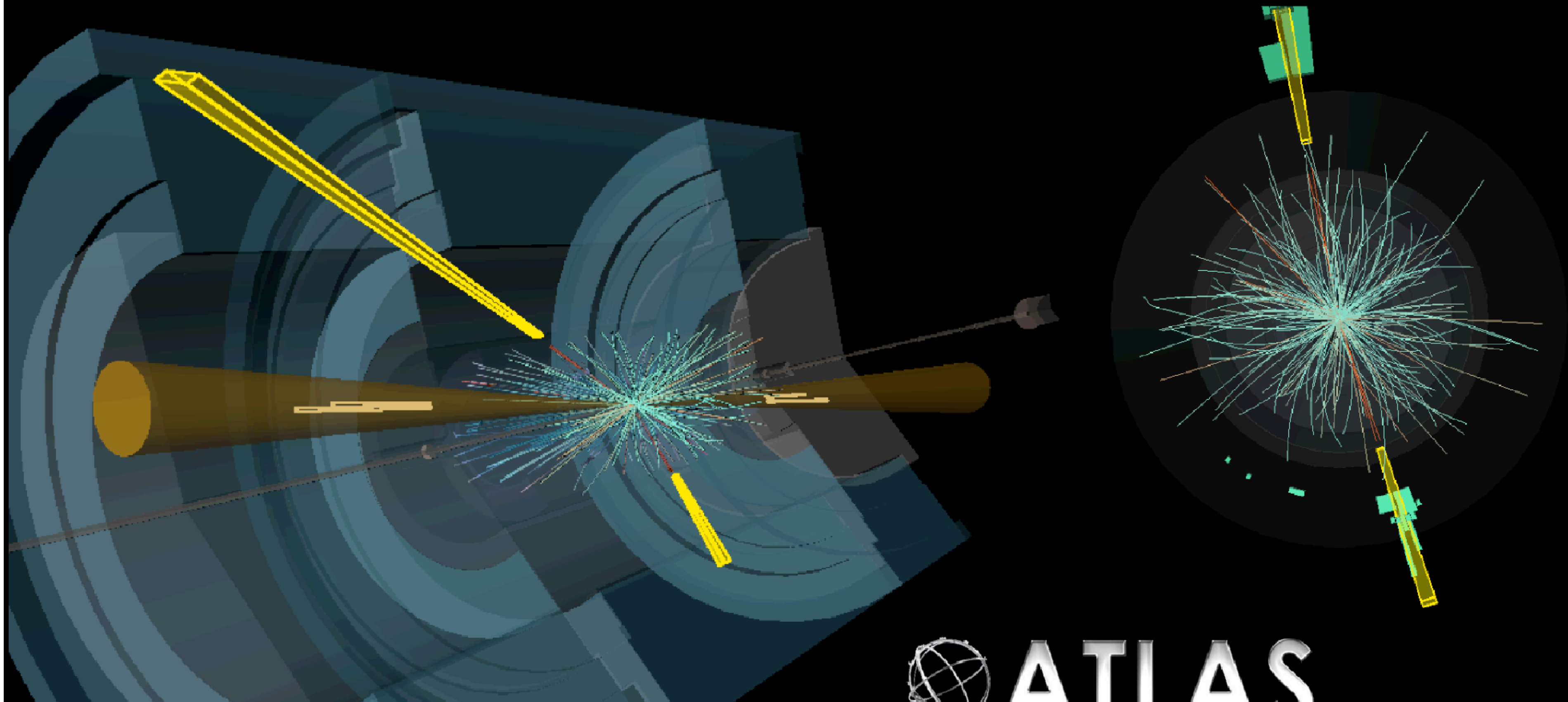
- Two high p_T forward jets (tag jets)
  Large invariant mass, large η separation

- Little jet activity in the central region
  (no colour flow)
  ⇒ central jet Veto





$H \rightarrow \gamma\gamma$ VBF candidate event



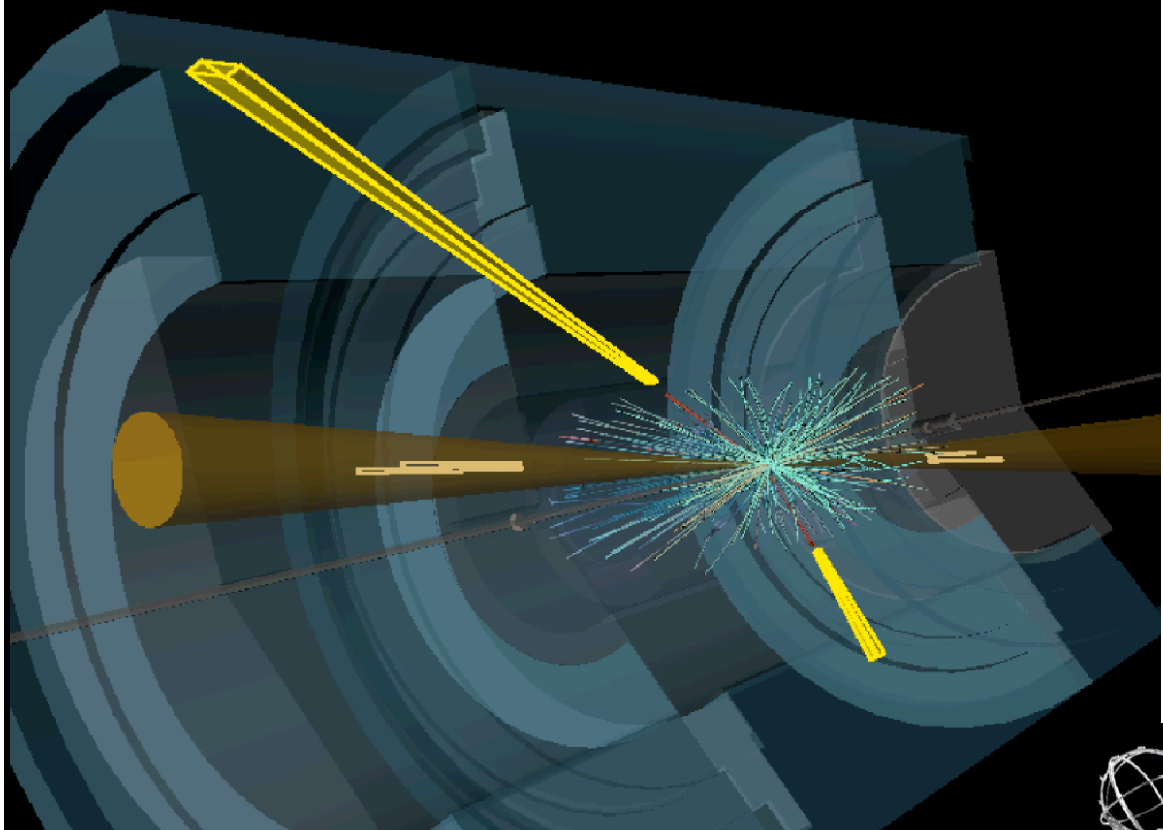
Run Number: 204769, Event Number: 24947130

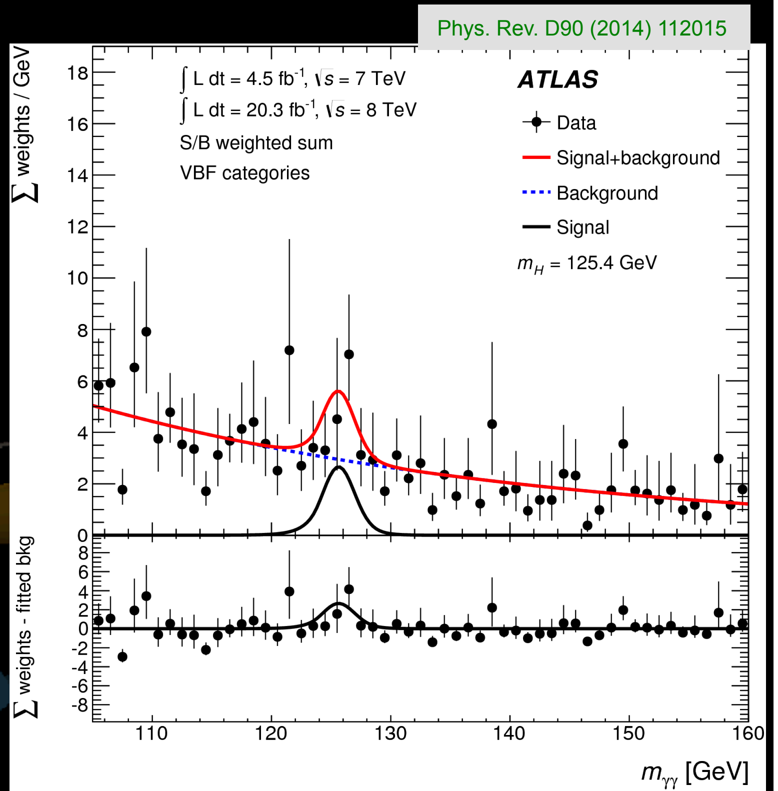
Date: 2012-06-10 08:17:12 UTC

$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

H → γγ VBF candidate event





ATLAS EXPERIMENT

Run Number: 204769, Event Number: 24947130

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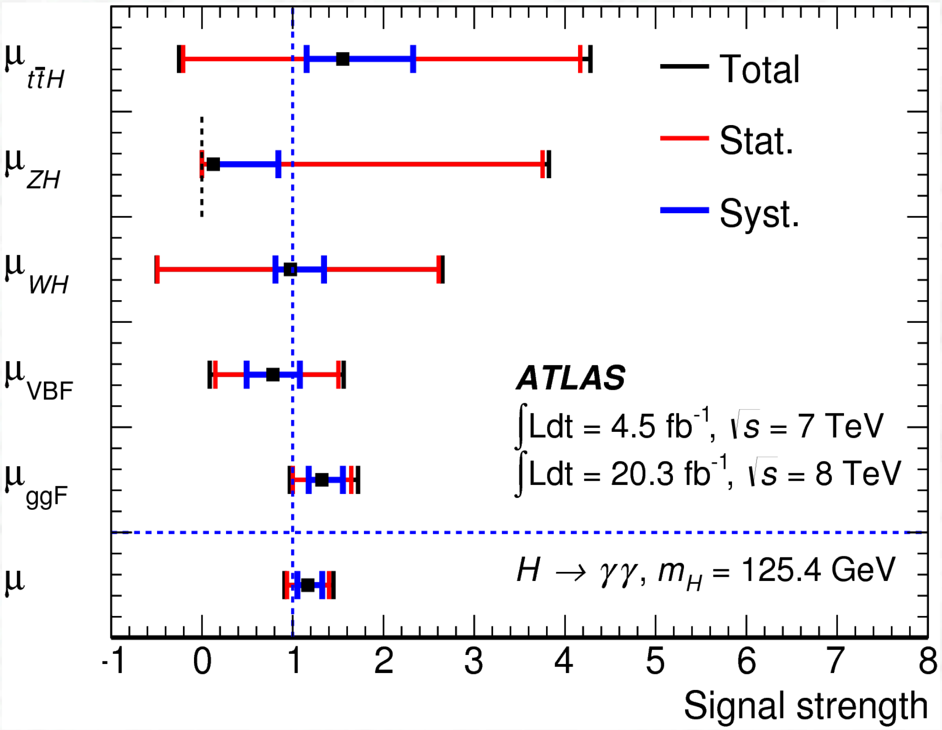
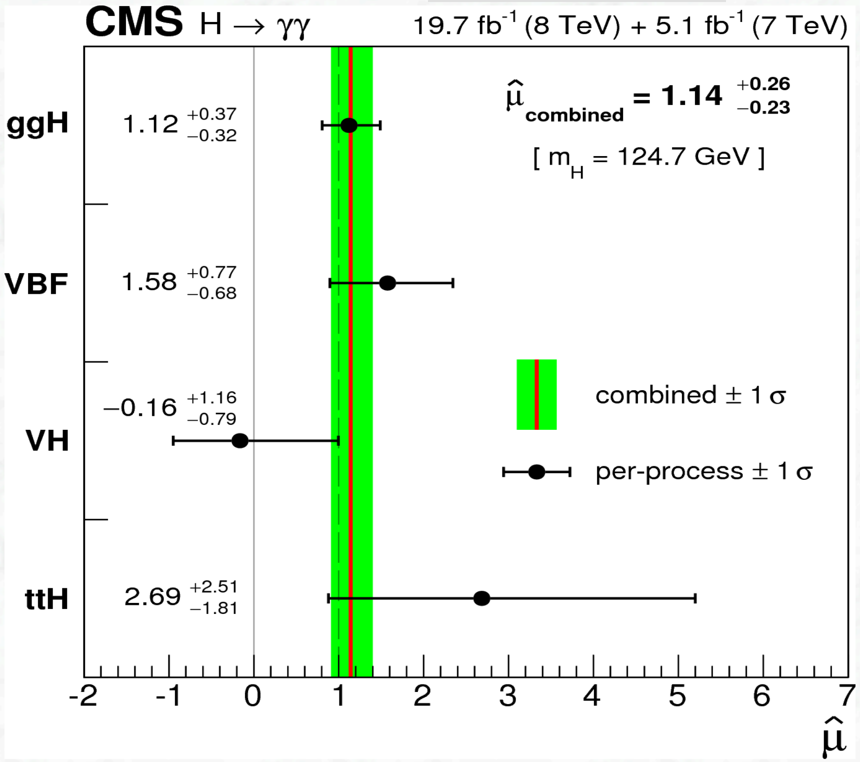
γγ signal strengths for various production modes

Phys. Rev. D90 (2014) 112015

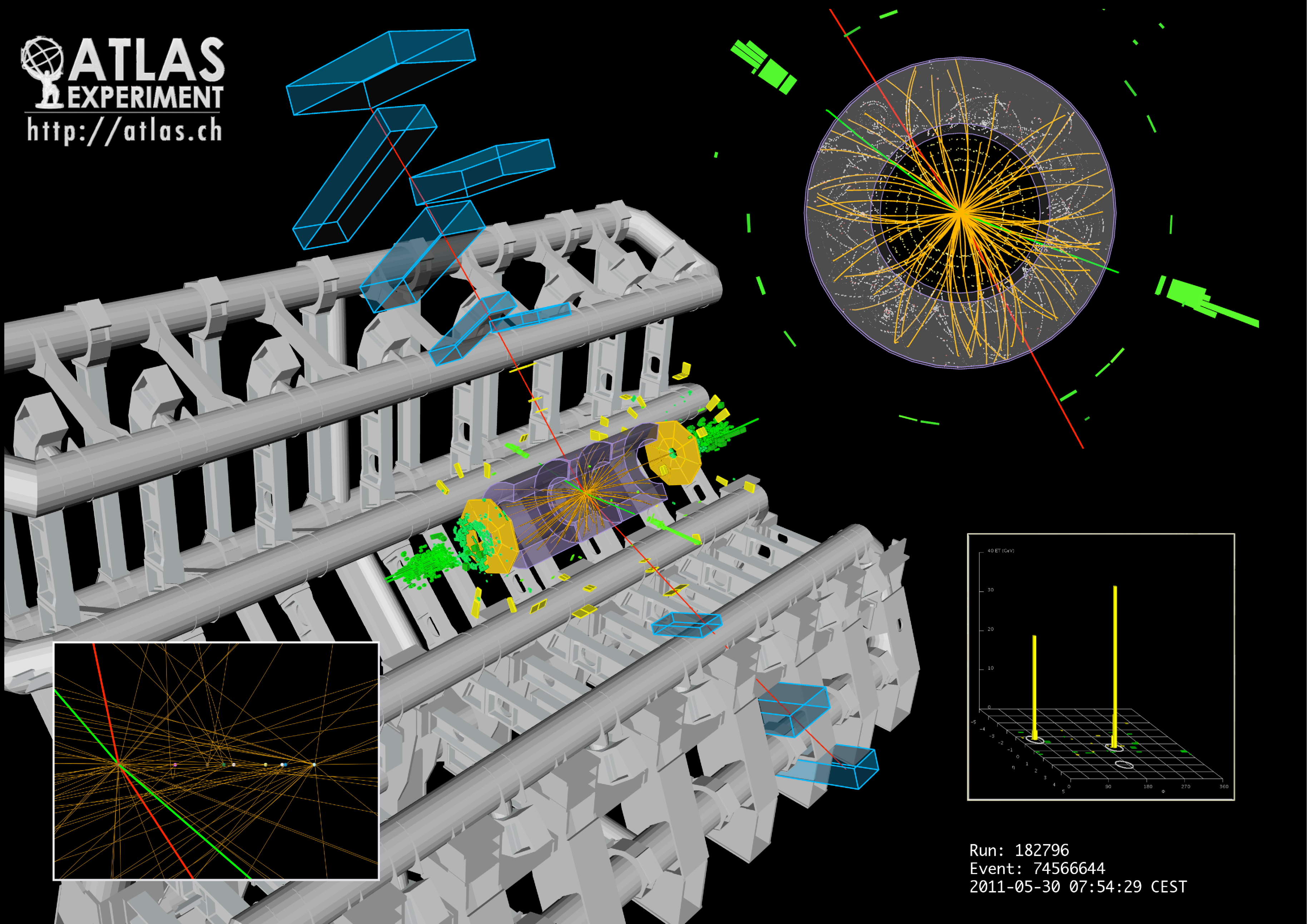


EPJ C74 (2014) 3076



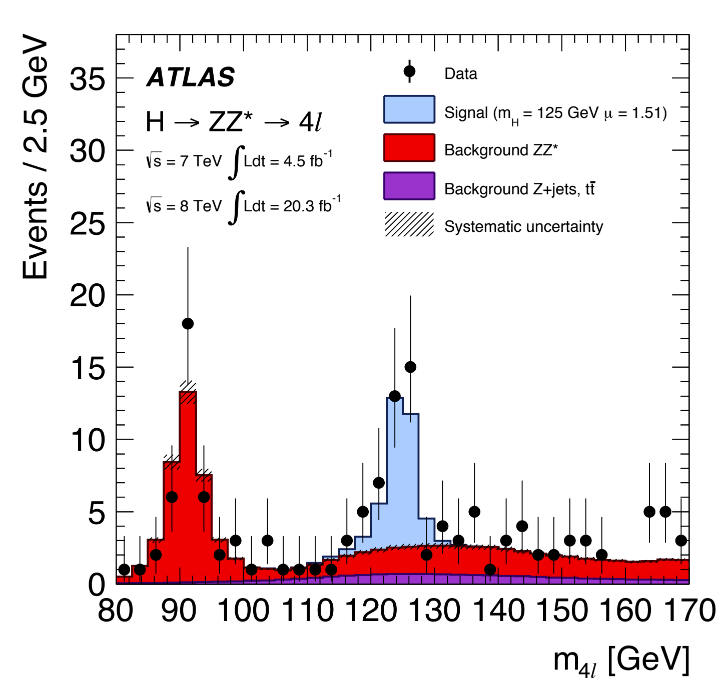
Fit results for individual production processes are consistent with the Standard Model expectations

$H \rightarrow ZZ \rightarrow e^+e^- \mu^+ \mu^-$ candidate event

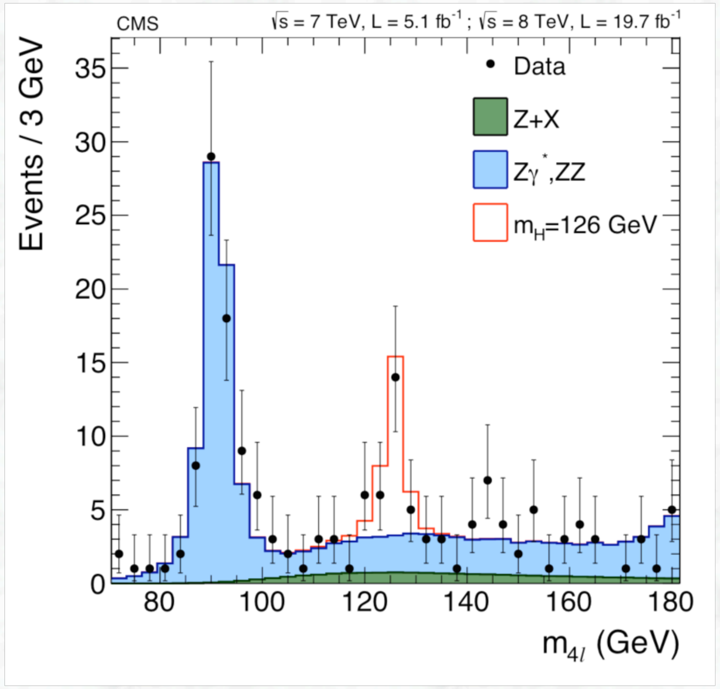


Reconstructed mass spectra from 4ℓ decays

Phys. Rev. D91 (2014) 012006



Phys. Rev. D89 (2014) 092007



Measured signal strengths:

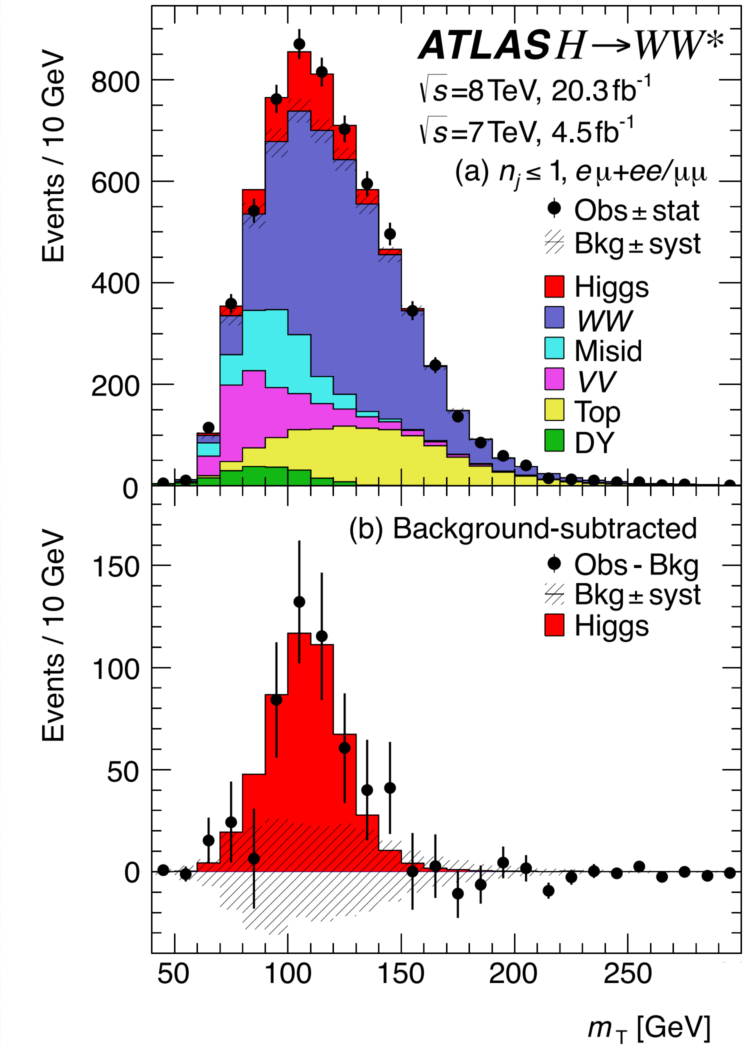
ATLAS: $\mu = 1.44^{+0.40}_{-0.33}$

CMS: $\mu = 0.93^{+0.29}_{-0.23}$

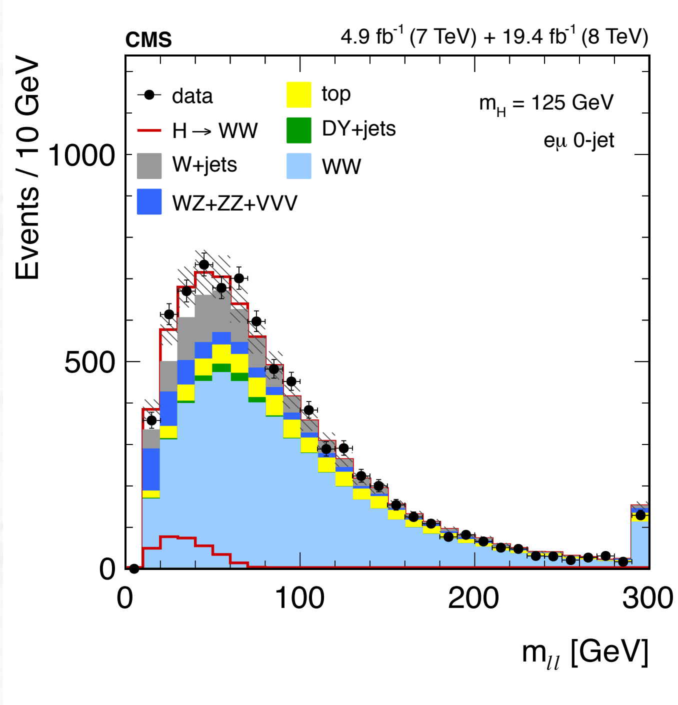
Significance in each experiment > 6σ

H → WW* → ℓν ℓν signal

Phys. Rev. D92 (2015) 012006



JHEP 01 (2014) 096



Measured signal strengths:

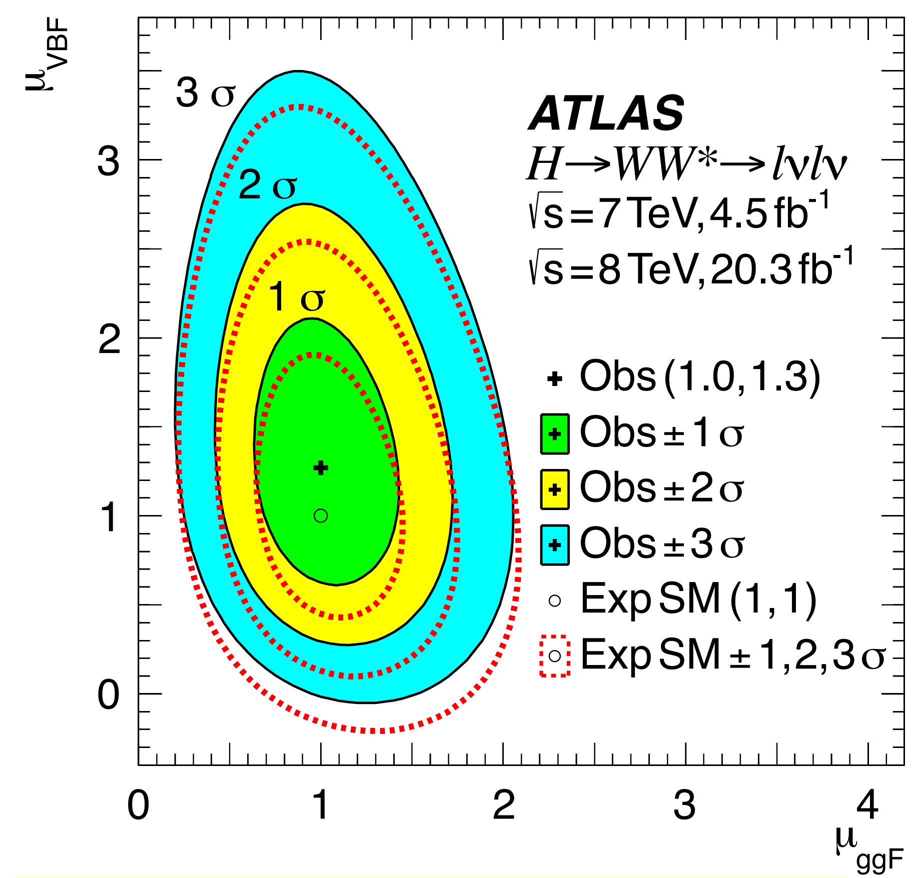
ATLAS: $\mu = 1.09^{+0.23}_{-0.21}$

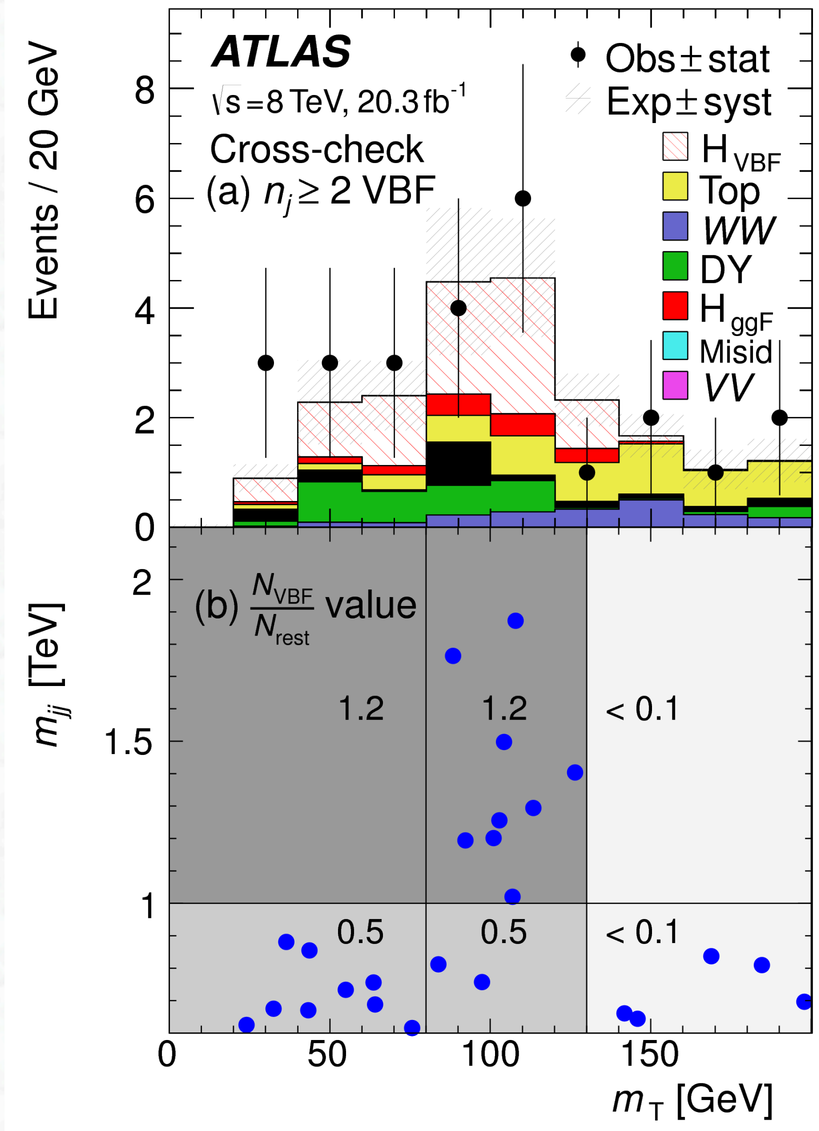
CMS: $\mu = 0.72^{+0.20}_{-0.18}$

- Very significant excesses visible in the “transverse mass” (ATLAS: 6.1σ) and $m_{\ell\ell}$ distributions (CMS: 4.5σ)

H → WW* → ℓν ℓν signal

Phys. Rev. D92 (2015) 012006





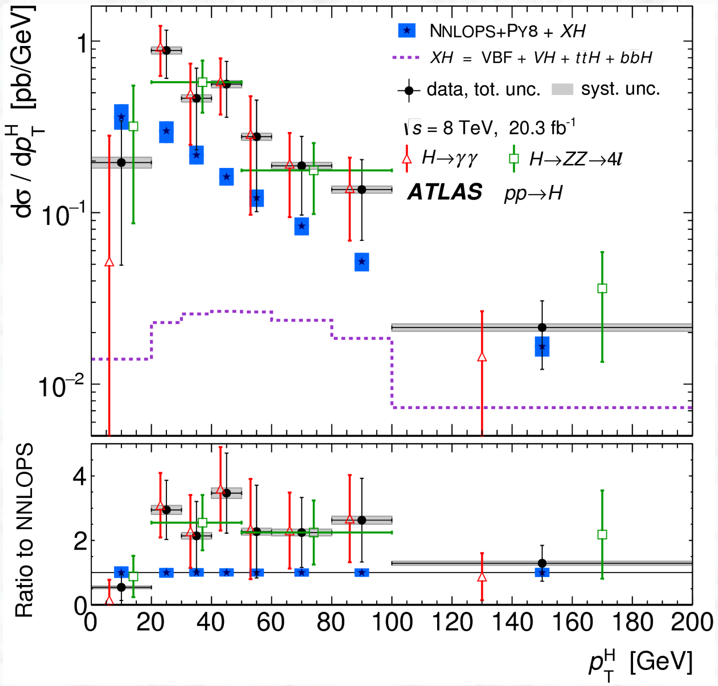
Measured signal strengths: ATLAS

Gluon fusion (ggF): $\mu = 1.02 ^{+0.29}_{-0.26}$

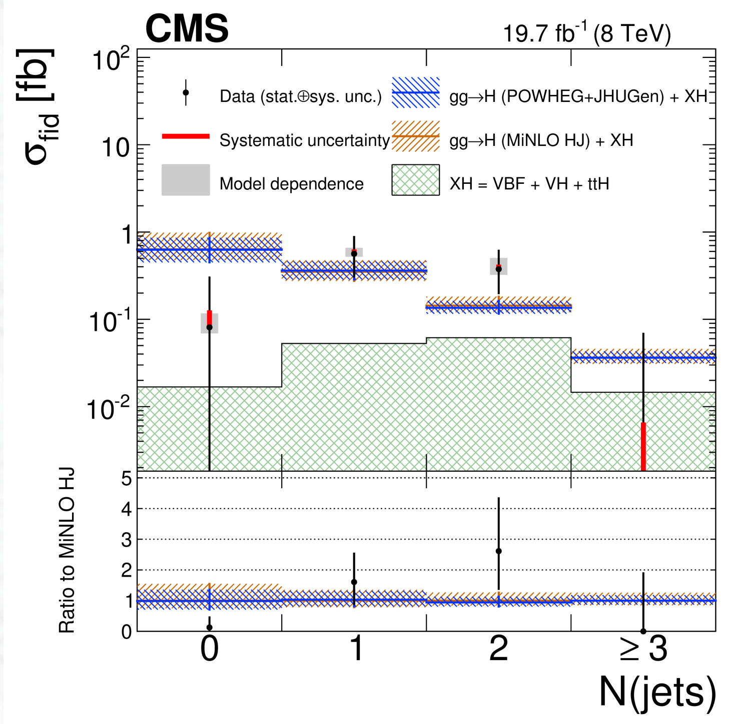
VBF: $\mu = 1.27 ^{+0.53}_{-0.45}$

Differential cross-section measurements

PRL 115 (2015) 091801



JHEP 04 (2016) 005

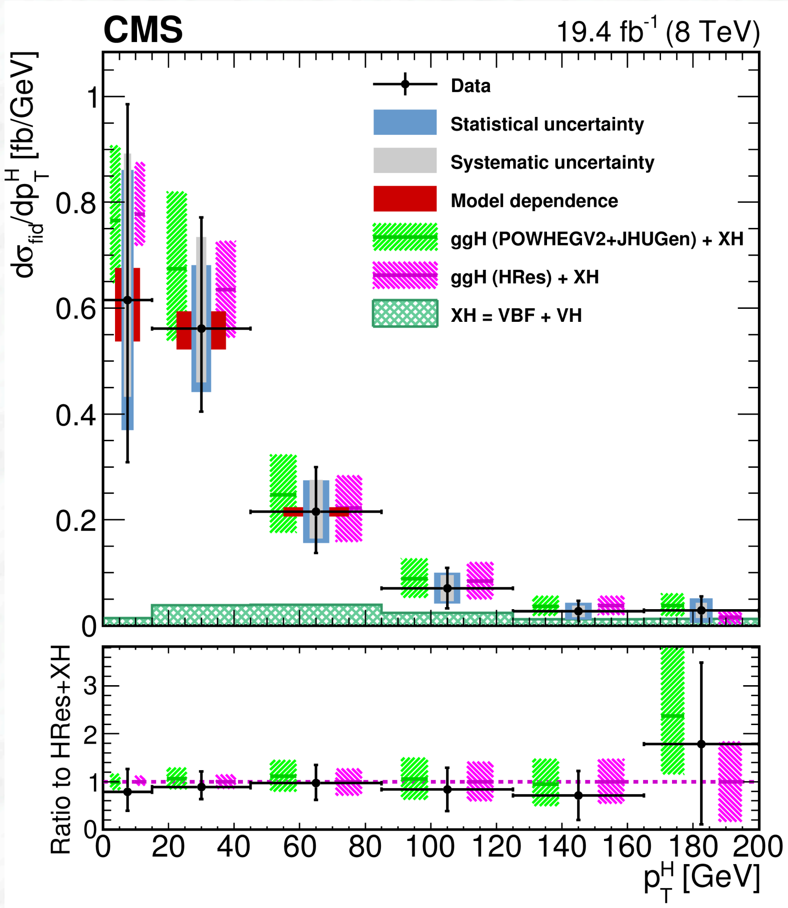


- First fiducial, differential cross-section measurements in bosonic channels
- Present experimental and theoretical uncertainties still large; “reasonable agreement” (statistical uncertainties: 25% - 75%)

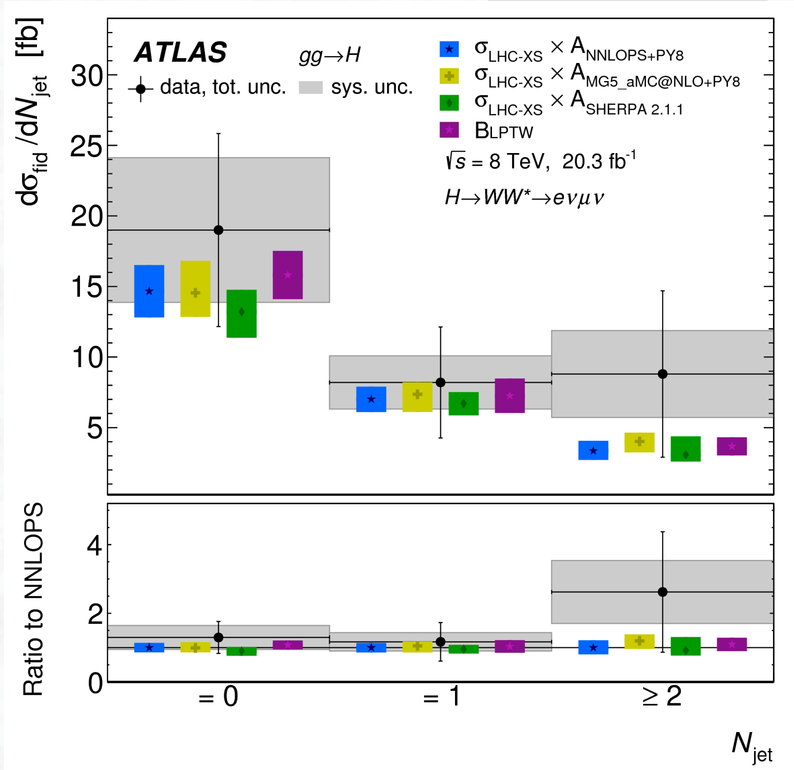
Differential cross-section measurements (cont.)

ATLAS and CMS recently released their first differential measurement for the H → WW channel (larger statistics)

arXiv: 1606.01522

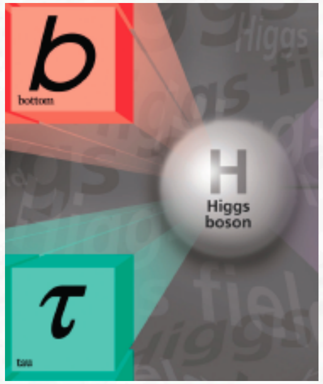


arXiv: 1604.02997

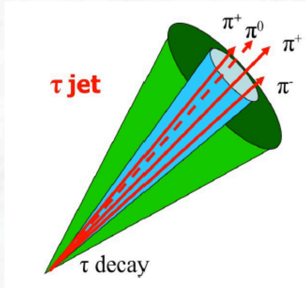


- Large future potential: probe Higgs boson kinematics, jet activity, VBF contributions, spin-CP nature, …

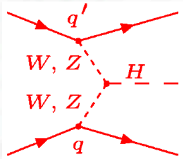
Couplings to quarks and leptons ?



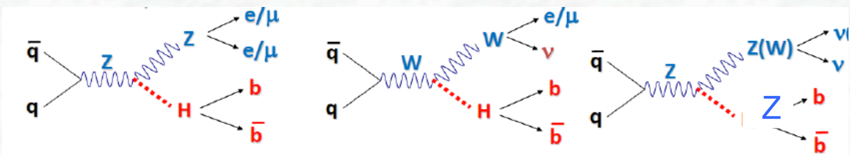
- Search for H → ττ and H → bb decays;
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays



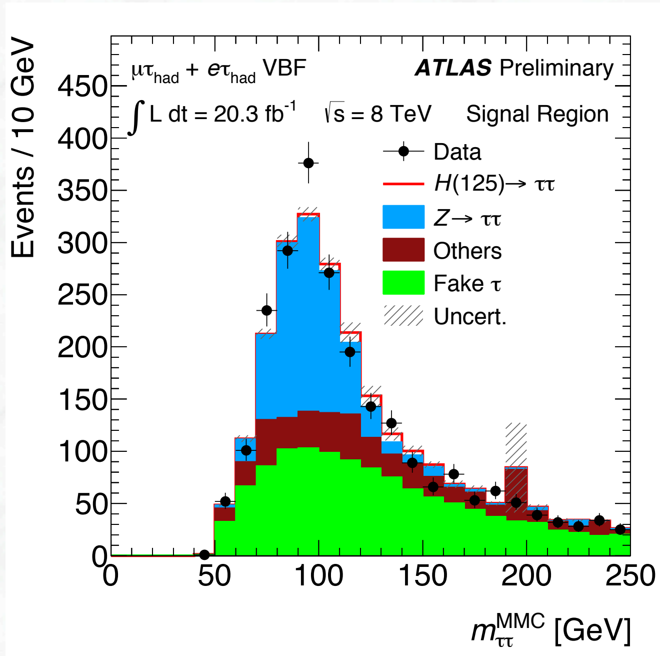
- Vector boson fusion mode essential for H → ττ decays



- Associated production WH, ZH modes have to be used for H → bb decays

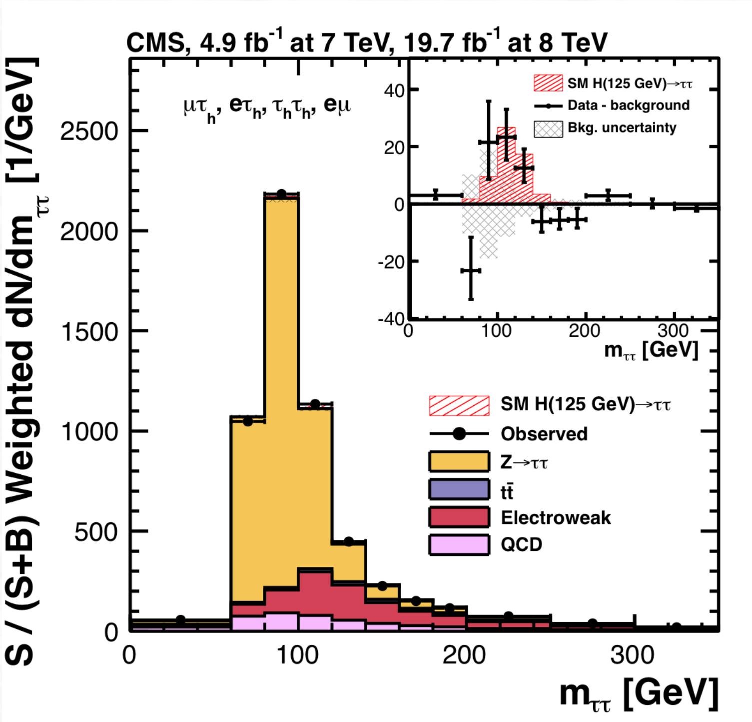


- Exploitation of multivariate analyses

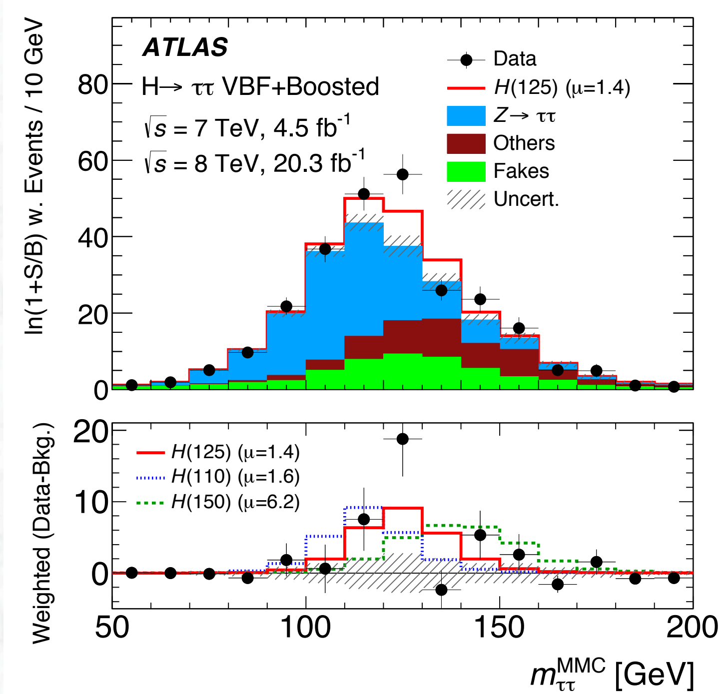


Evidence for H → ττ decays

JHEP 05 (2014) 104



JHEP 04 (2015) 117



$m_{\tau\tau}$ distribution, events weighted by ln (1+S/B)

Measured signal strengths:

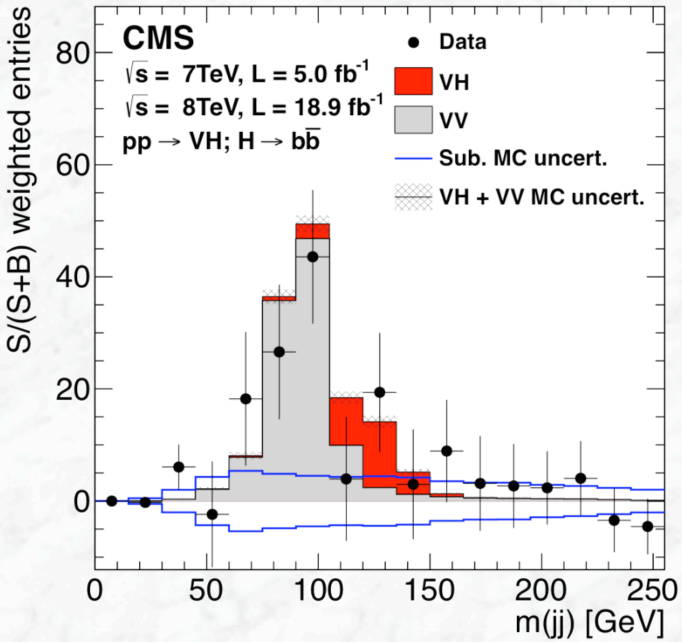
ATLAS: $\mu = 1.43 \,^{+0.43}_{-0.37}$ (4.5σ)

CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

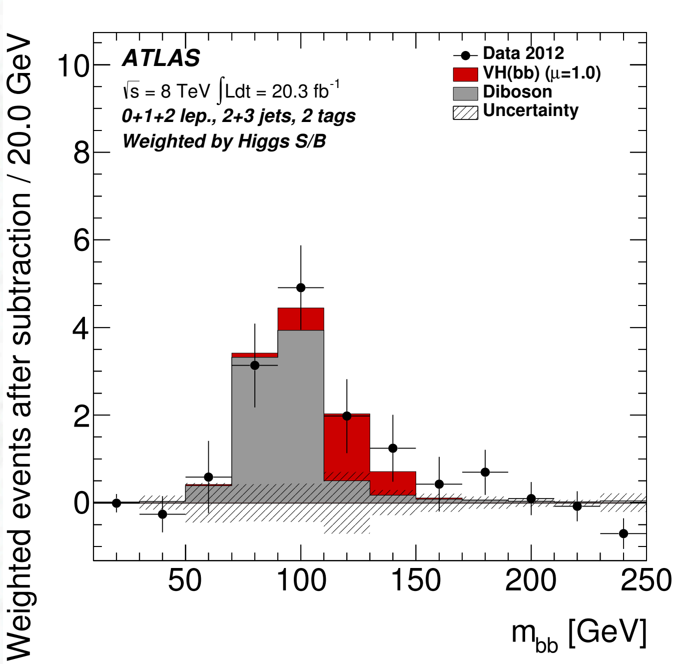
One of the most important LHC results in 2014 / 2015

Results on the search for H → bb decays

Phys. Rev. D89 (2014) 012003



JHEP 1501 (2015) 069



Reconstructed m_{bb} signals (after subtraction of major, non-resonant backgrounds)

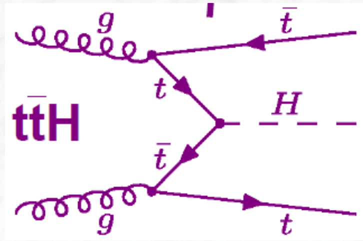
- Reference signal from WZ, and ZZ with Z → bb seen
- Positive, but non-conclusive Higgs boson signal contribution observed

Signal strengths:

ATLAS: $\mu = 0.50 \pm 0.36$

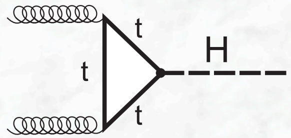
CMS: $\mu = 1.0 \pm 0.5$

Results on the search for ttH production



- The **ttH production** mode is important to directly probe the coupling between the Higgs boson and the top quark

  Crucial for probing for new particles contributing to loops in the Higgs boson production or decay



- Very rich experimental signature, depending on the decay of the top quarks and the Higgs boson

  Search can be performed using several Higgs boson decay modes:

  H → bb, H → γγ, H → WW, ZZ, ττ → leptons + X

  (leptons might also come from top-quark decays)

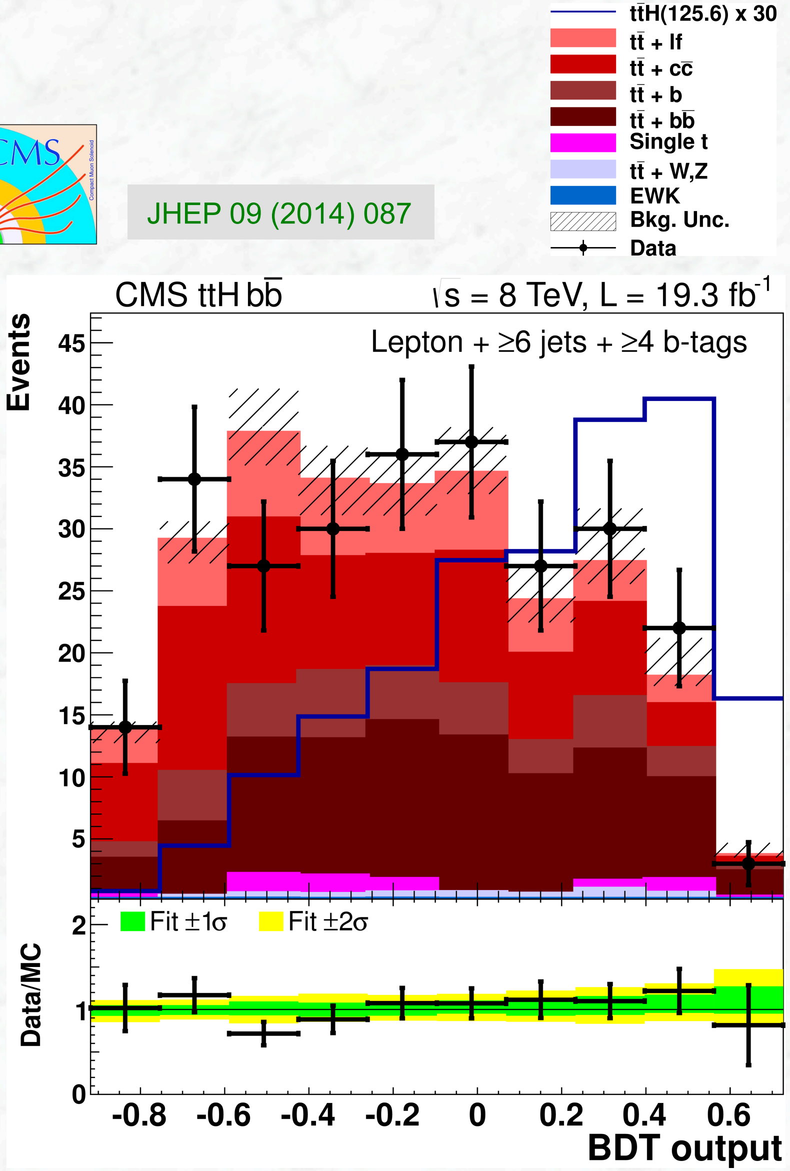
- It is critical to model the tt background in peculiar phase-space regions

  tt production and the associated **ttbb, ttW, ttZ** production are important and for some final states overwhelming backgrounds

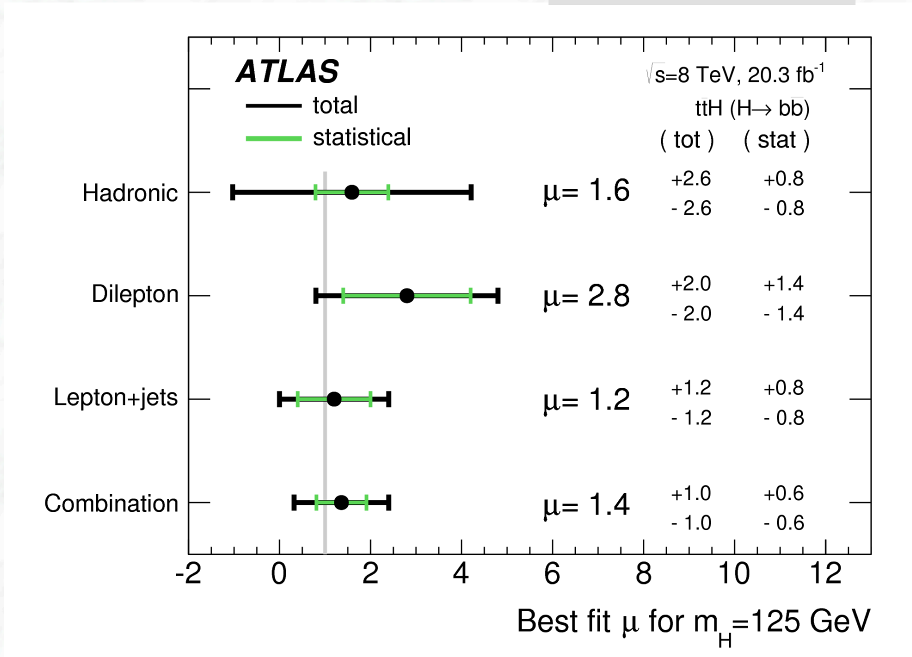
- Complicated analyses, multivariate techniques heavily used

Results on the search for ttH, H → bb decays

JHEP 09 (2014) 087

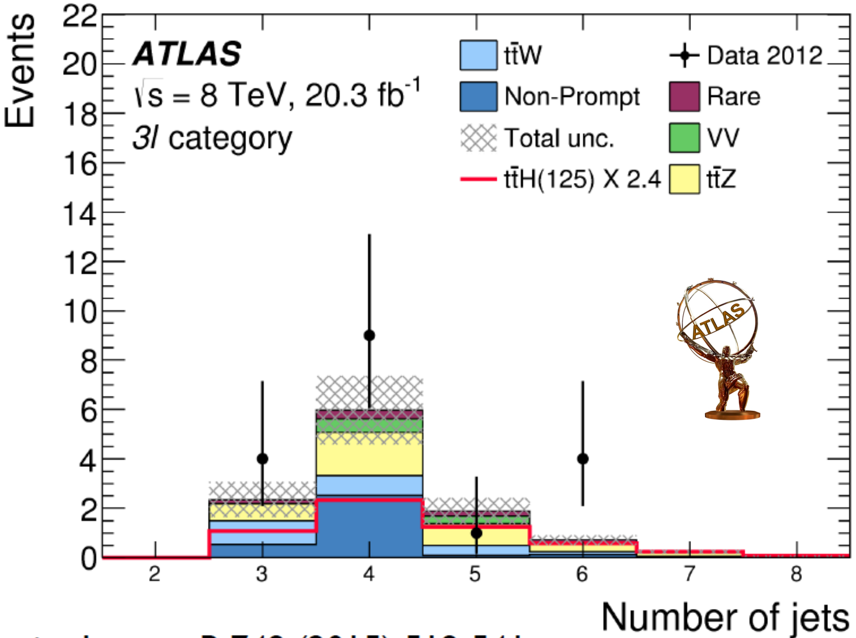


JHEP 05 (2016) 160

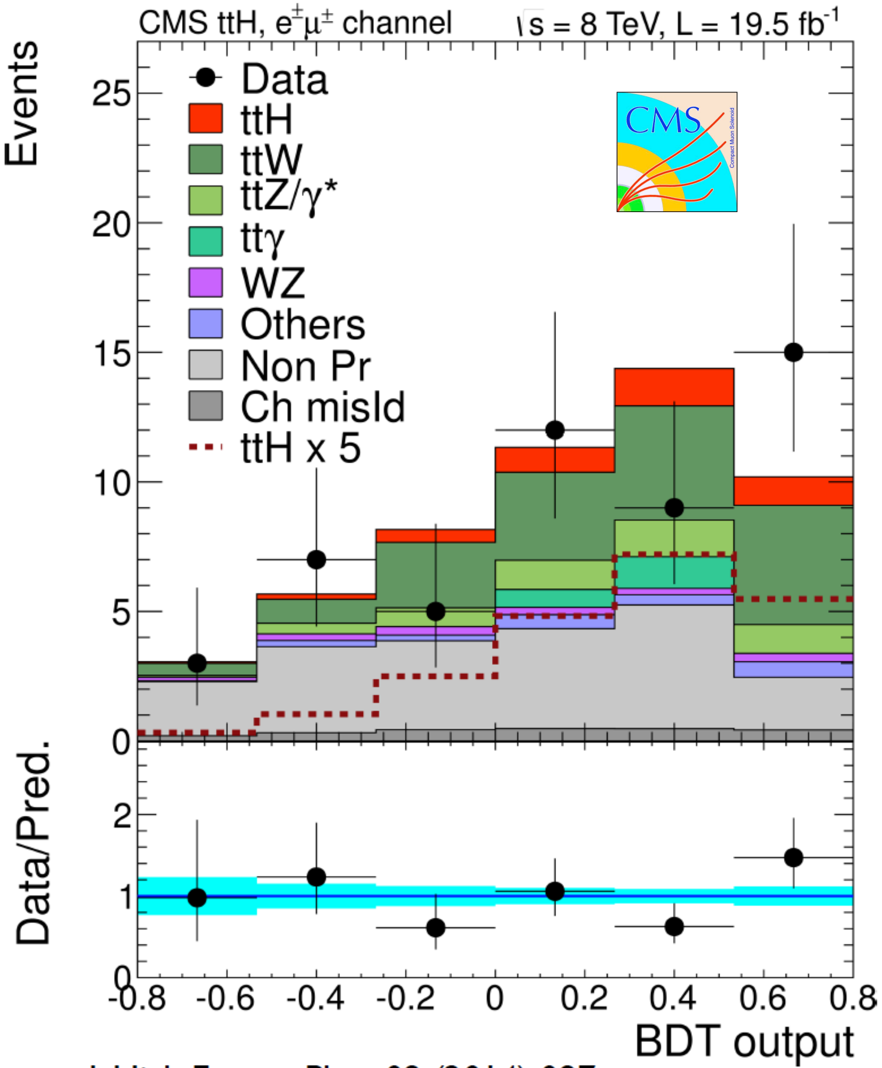


Results on the search for ttH, (→ multileptons)

- Higgs boson decays to WW, ZZ or $\tau\tau$ can be probed in multilepton final states.
  - For example 3 leptons, or requiring a pair of same-charge leptons.
  - Can additionally require b-tagged jets to further increase the signal to background.



Physics Letters B 749 (2015) 519-541



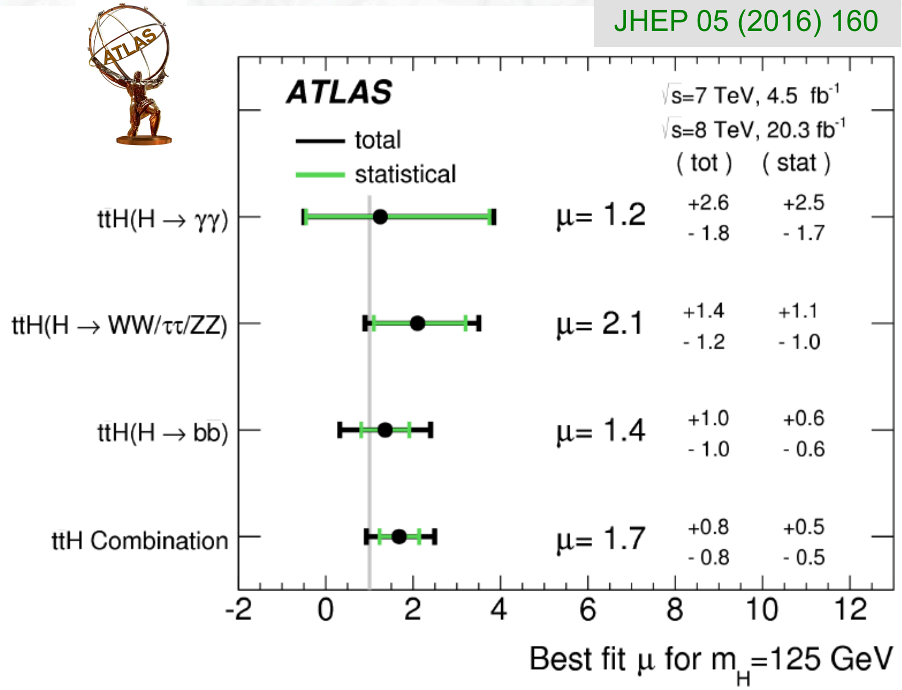
J. High Energy Phys. 09 (2014) 087

Summary of Run-1 Results on ttH production

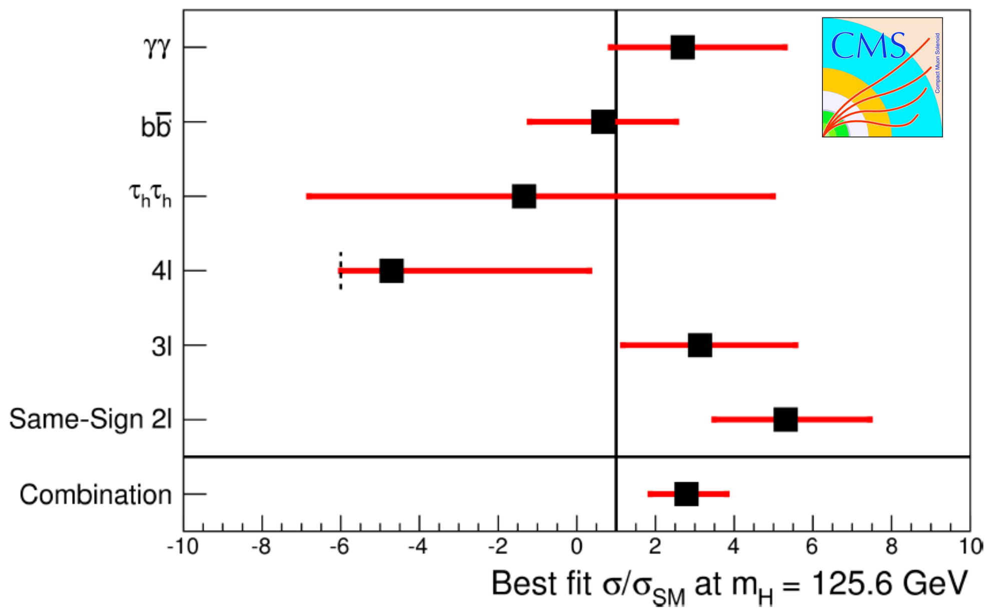
- Even after the combination of the results of all different ttH channels, the observed significance based on Run-1 data is marginal
  However, it adds to the determination of Higgs boson couplings

- Much more data needed → important measurements in Run 2

JHEP 05 (2016) 160



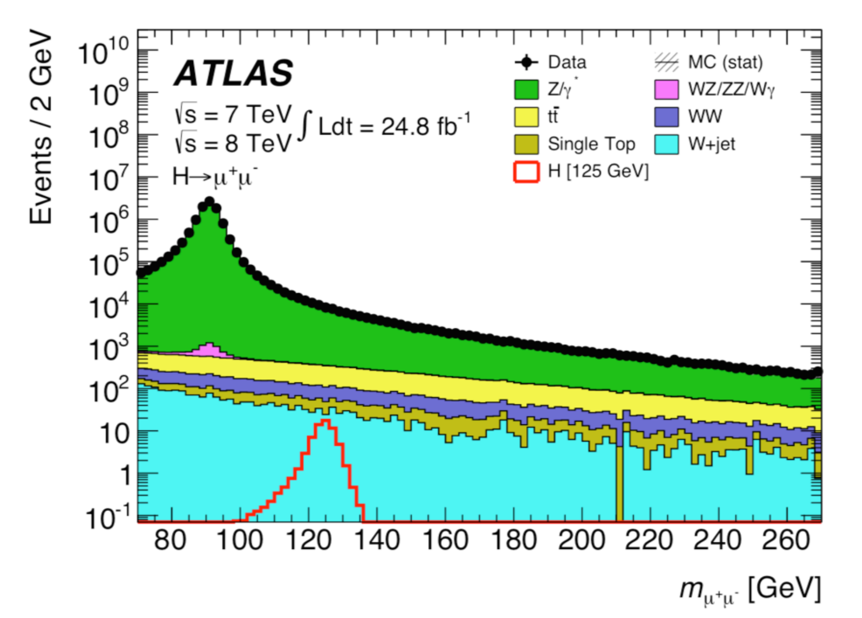
JHEP 09 (2014) 087

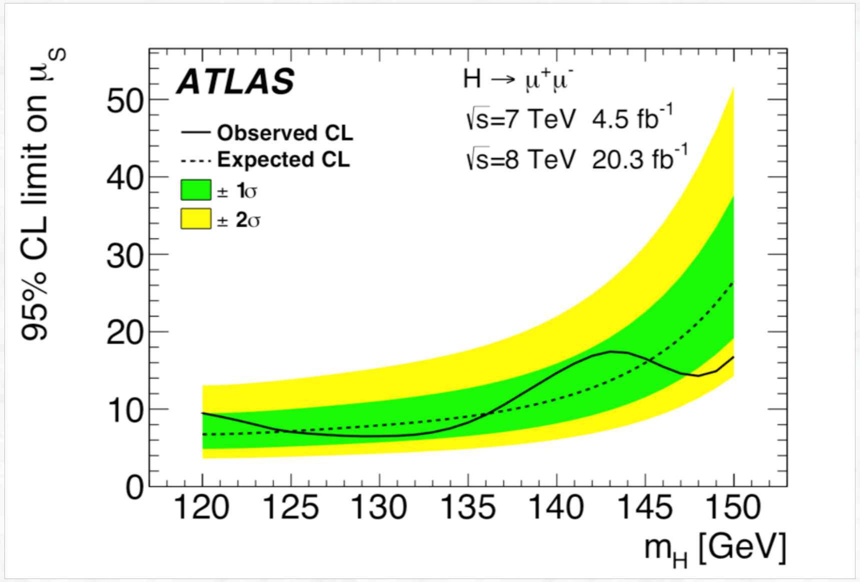


Both experiments measure large m values for this production mode, however, large uncertainties

Results on the search for H→ μμ decays

Phys. Lett. B738 (2014) 68





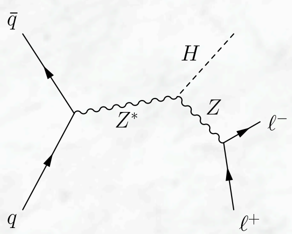
m_H = 125 GeV:

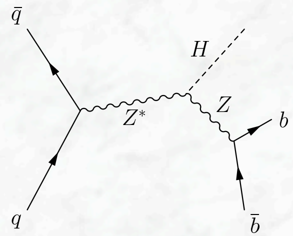
ATLAS 95% CL: $7.0\sigma_{SM}$ (7.2 expected, no Higgs) [Phys. Lett. B738 (2014) 68]
CMS 95% CL: $7.4\sigma_{SM}$ (6.5 expected, no Higgs) [Phys. Lett. B744 (2015) 184]

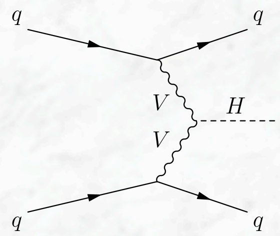
→ BR (H → μμ) < ~1.5 10^{-3}
Significantly smaller than BR(H → ττ) → no evidence for flavour-universal coupling

Search for invisible Higgs boson decays

- Some extensions of the Standard Model allow a Higgs boson to decay to stable or long-lived particles

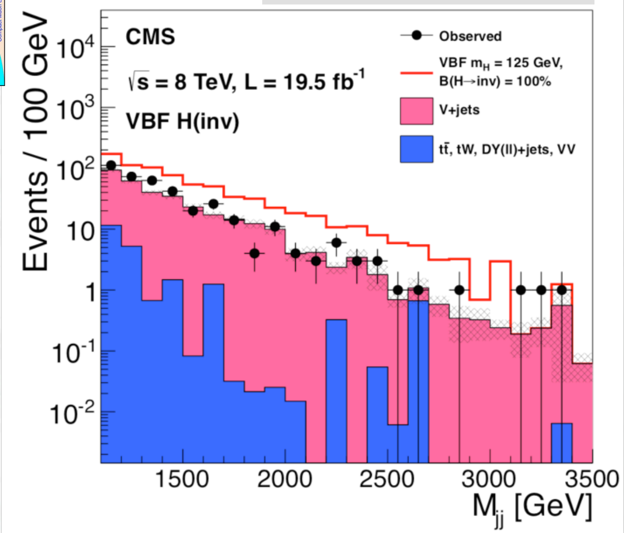






- Search for excess in ZH associated production and VBF production

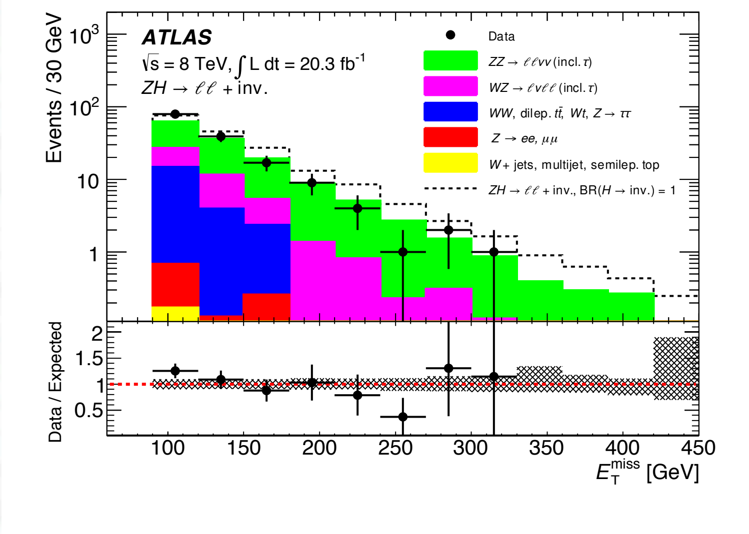
EPJ C74 (2014) 2980



VBF

ZH

PRL 112 (2014) 201802



Assuming the ZH and VBF production rates for m_H = 125 GeV:

ATLAS: 95% CL on BR (H → inv.) < 0.75 (from ZH production)

95% CL on BR (H → inv.) < 0.29 (from VBF production) [ATLAS-CONF-2015-004]

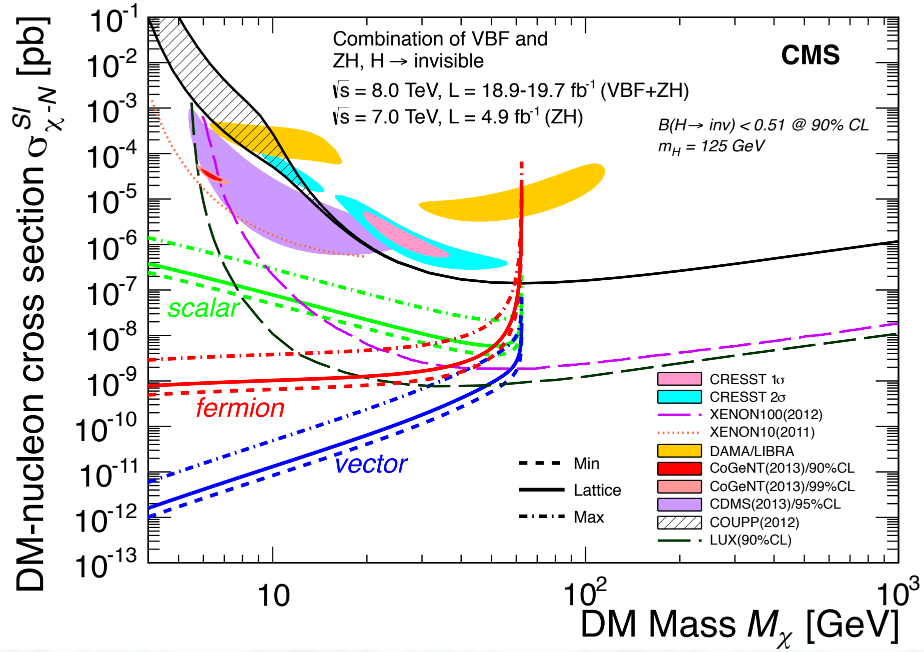
CMS: 95% CL on BR (H → inv.) < 0.58 (from ZH + VBF combination)

Interpretation in Higgs-portal models

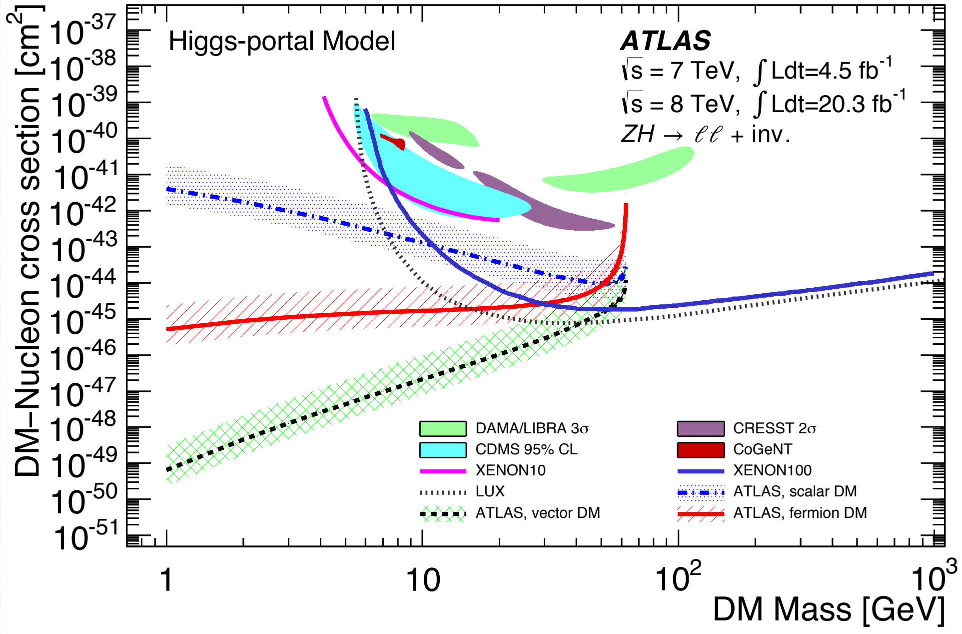
-Stable dark matter particles with couplings to the Higgs boson-

- For $m_\chi < m_H/2$, limits on invisible branching ratios can be translated to the spin-independent DM-nucleon elastic cross section for scalar, vector and fermionic DM particles
- Higgs-nucleon coupling, model dependent: assume $0.33^{+0.30}_{-0.07}$ (lattice calculations)
- Within this model, interesting limits for low m_χ masses

EPJ C74 (2014) 2980

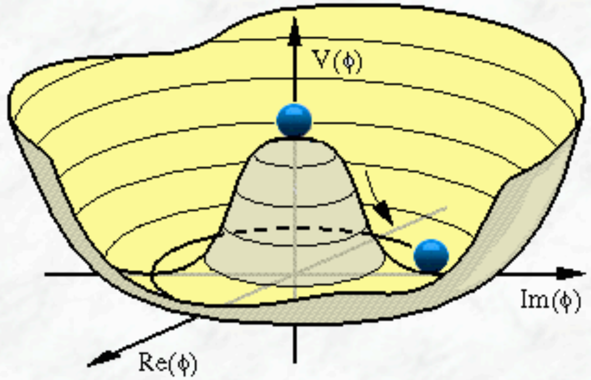


PRL 112 (2014) 201802



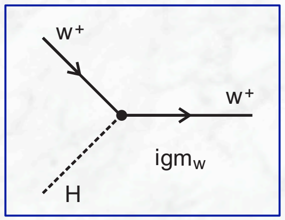
Profile of the New Particle

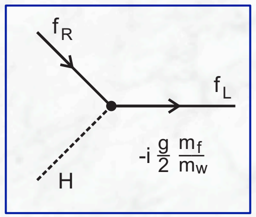
Is it the Standard Model Higgs Boson?



- Mass ("input parameter")
- Width
- Spin, J^{CP} quantum number
- Production rates

Couplings to bosons and fermions

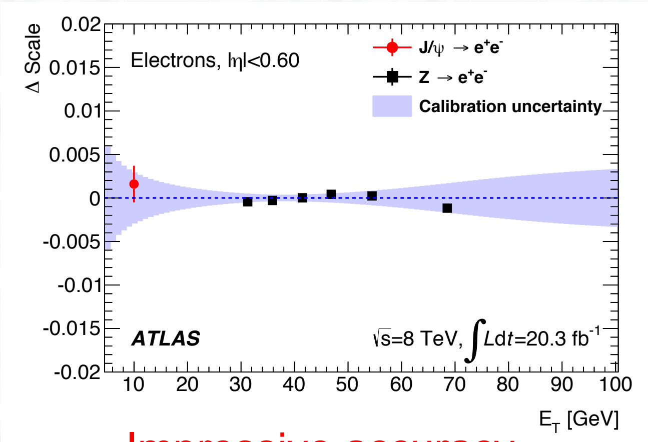




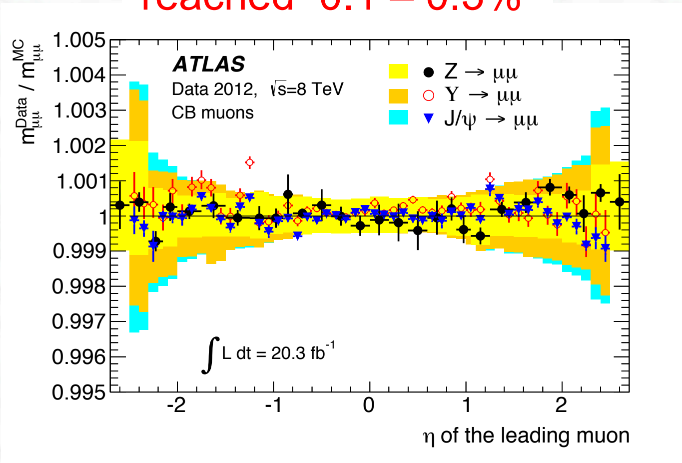
Higgs boson mass

- The two high resolution channels H → ZZ*→ 4ℓ and H → γγ are best suited (reconstructed mass peak, good mass resolution)

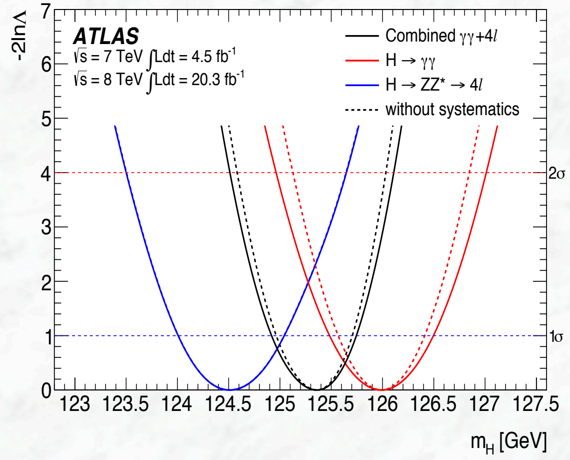
- Good control of the lepton and photon energy scales, calibration via Z → ℓℓ and J/ψ and ϒ signals, improved understanding of lepton and photon reconstruction



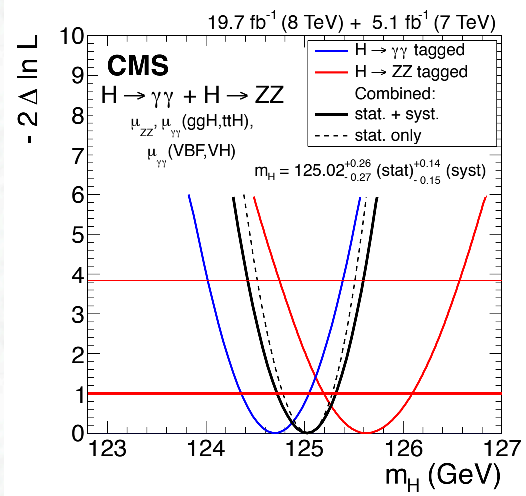
Impressive accuracy reached 0.1 – 0.3%



Phys. Rev. D90 (2014) 052004



EPJ C75 (2015) 5, 212



ATLAS: $m_H = 125.36 \pm 0.37\ (\text{stat}) \pm 0.18\ (\text{syst})$ GeV

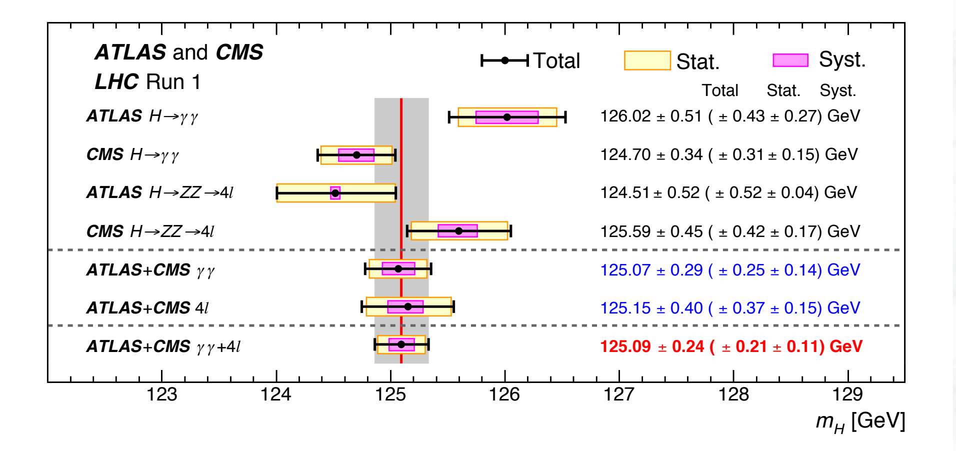
CMS: $m_H = 125.02\ ^{+0.26}_{-0.27}\ (\text{stat})\ ^{+0.14}_{-0.15}\ (\text{syst})$ GeV

Higgs boson mass (cont.)

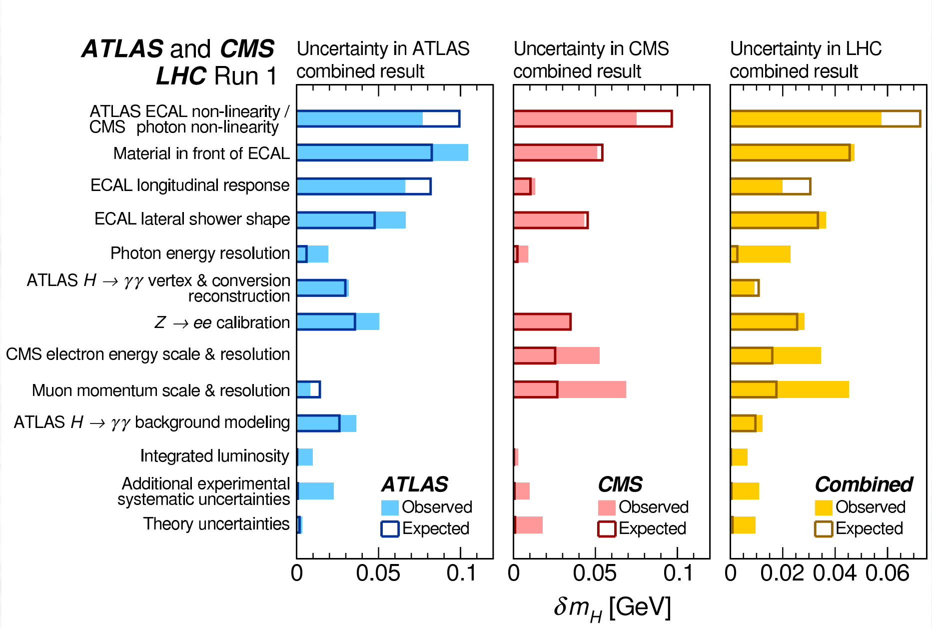
-First ATLAS and CMS combination of Higgs boson results-

PRL 114 (2015) 191803

Individual and combined results:



Uncertainties:



ATLAS + CMS:

m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

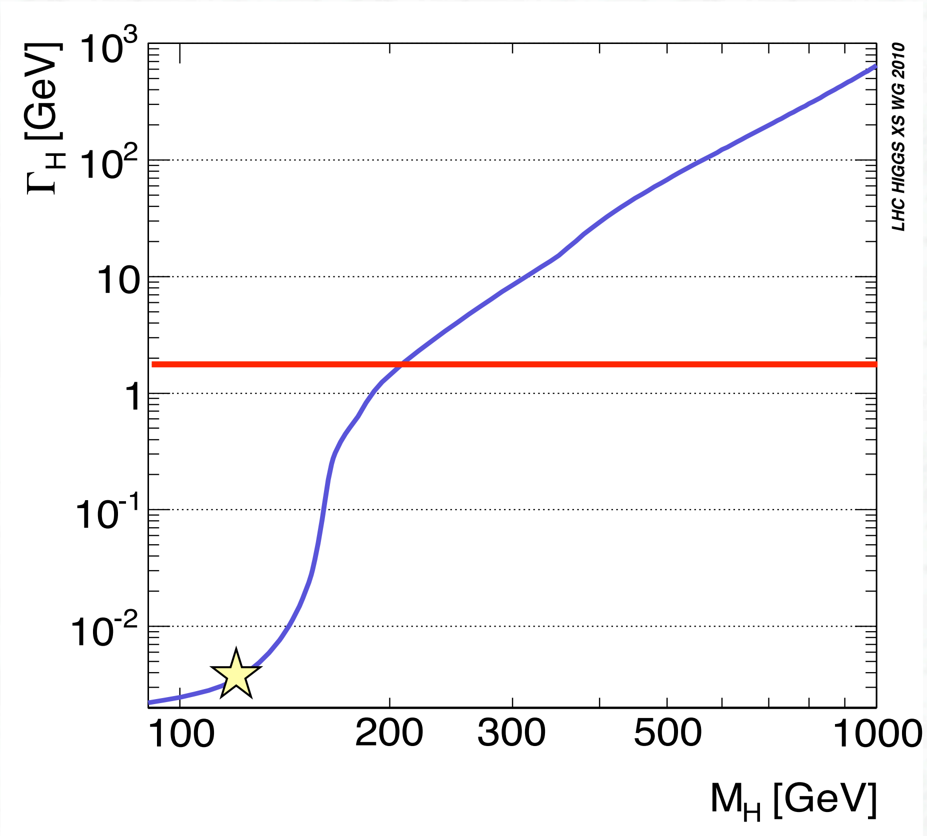
Precision of 0.2%

- Statistical uncertainty still dominant
- Major systematic uncertainties: Lepton and photon energy scales and resolutions
- Theoretical uncertainties small, γγ interference effects neglected

Higgs boson width

- The Standard Model Higgs boson width is expected to be small: $\Gamma_H \sim 4$ MeV
- Experimental mass resolution in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channel ~1 - 2 GeV

→ only upper limits can be extracted from the observed mass peaks



EPJ C75 (2015) 5, 212

Results: 95% CL limits

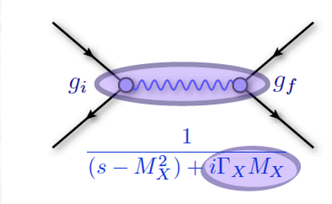
Γ_H < 1.7 GeV (2.3 expected)

Indirect constraint on the Higgs boson width from "off-shell cross sections"

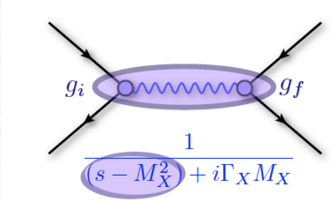
- Different sensitivity of on-shell and off-shell cross sections on the Higgs boson width

- However, model dependent: assumes that on-shell and off-shell couplings are the same

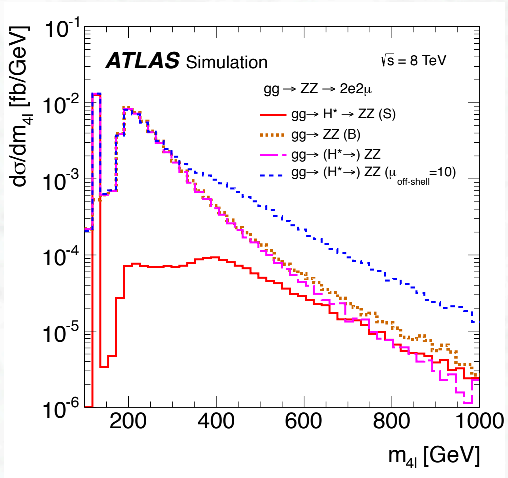
- Dependence on K-factors for signal and backgrounds (gg → VV)



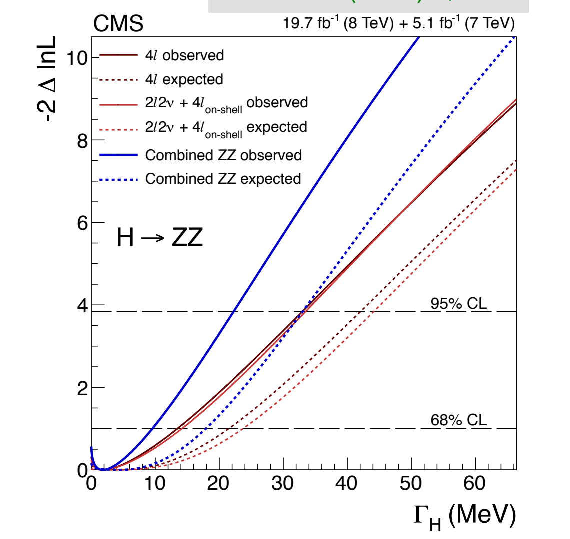
$$\sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$



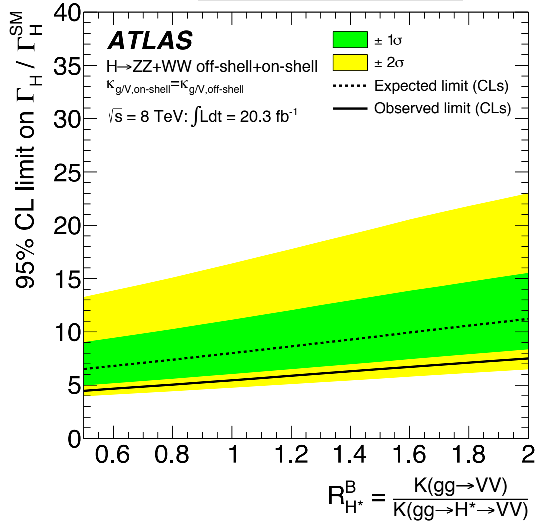
$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$



EPJ C75 (2015) 5, 212



arXiv: 1503.01060

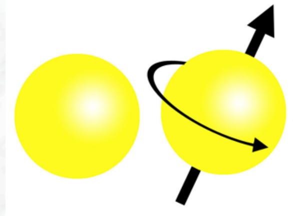


Results: 95% CL limits

CMS: $\Gamma_H / \Gamma_{SM} < 5.4$ (= 22 MeV)

ATLAS: $\Gamma_H / \Gamma_{SM} < 5.5$ ($R_B^{H^*} = 1$)

Spin and CP

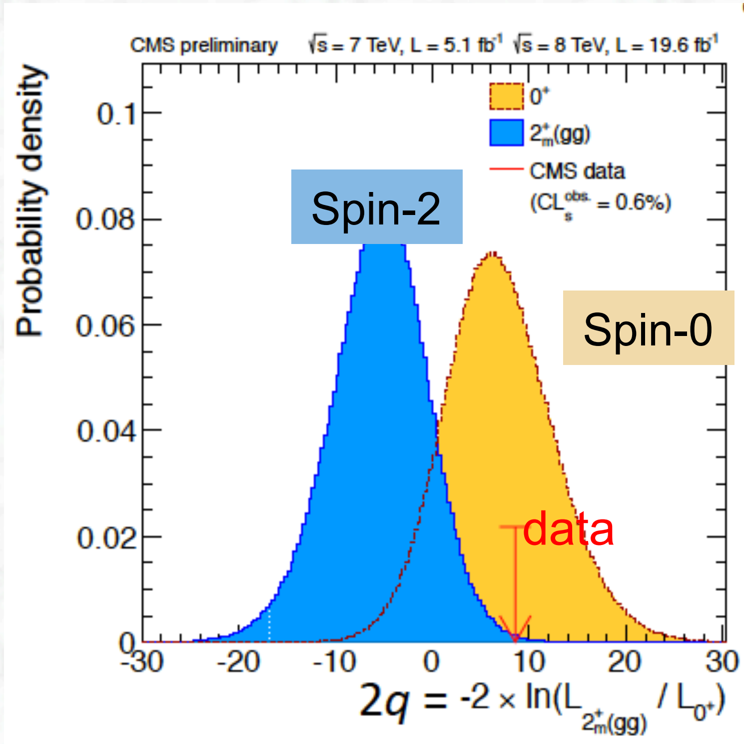


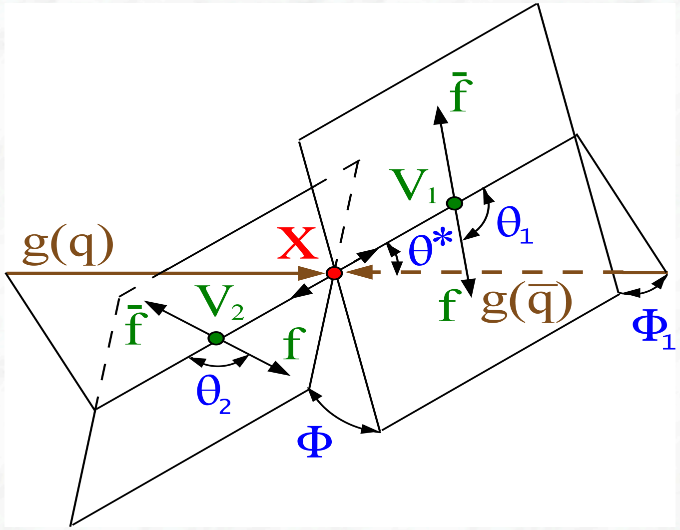
- Standard Model Higgs boson: $J^P = 0^+$

  → strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

- Angular distributions of final state particles show sensitivity to spin

  In particular: H → ZZ* → 4ℓ decays
  (in addition: H → WW* → ℓν ℓν)



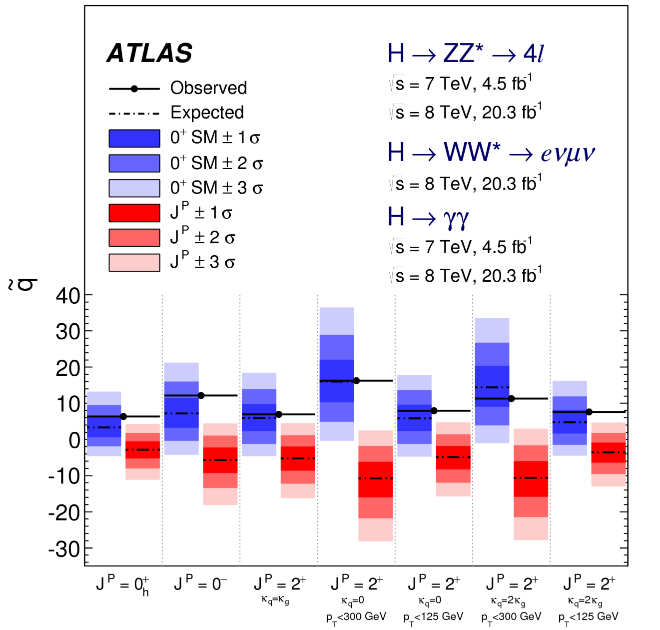


- Data strongly favour the spin-0 hypothesis of the Standard Model

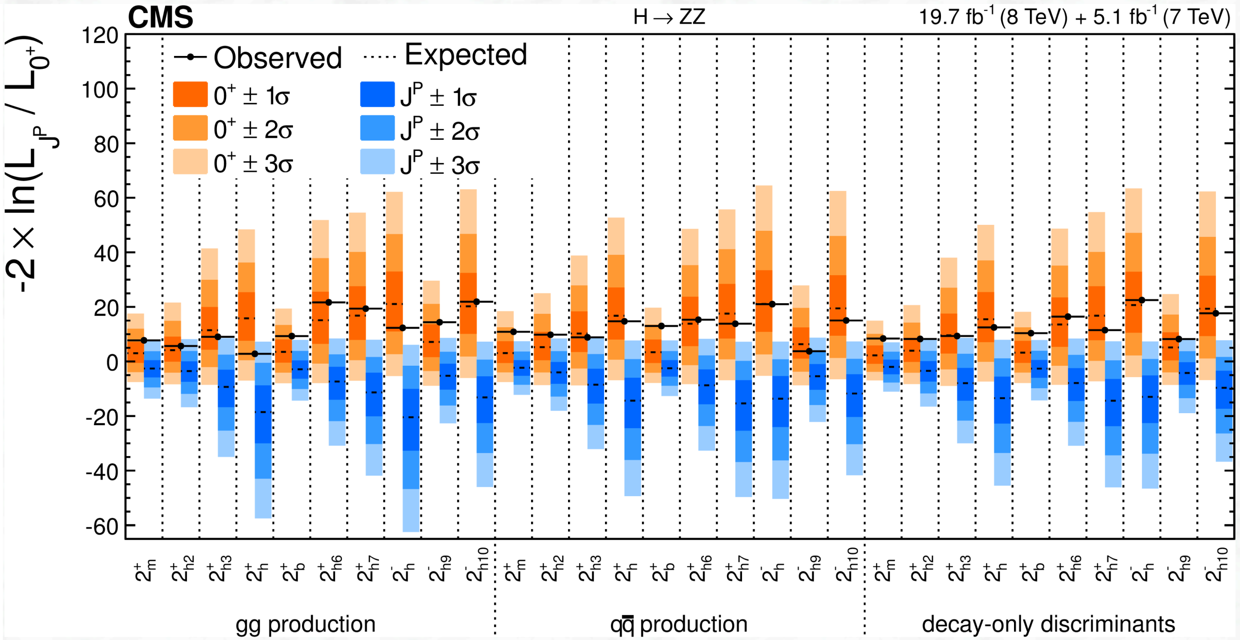
- Many alternatives can be excluded with confidence levels > 99%)

Result on different J^{CP} hypothesis tests

Eur. Phys. J C75 (2015) 476



Phys. Rev. D92 (2015) 012004

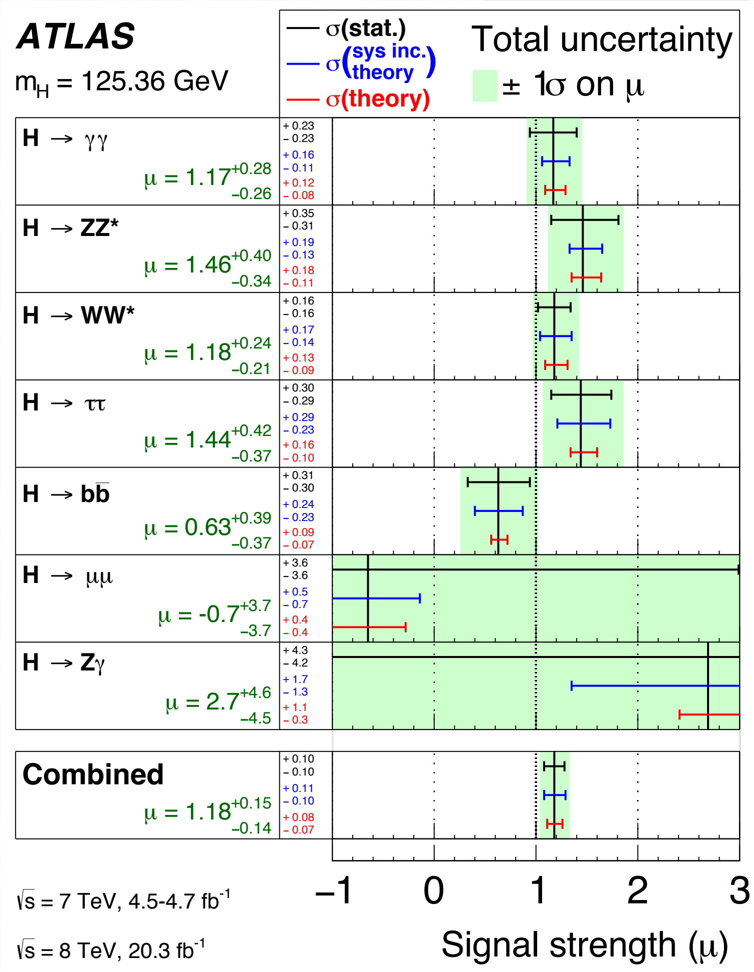


- In both experiments, data are consistent with $J^P = 0^+$ hypothesis, many alternative models are excluded with high significance

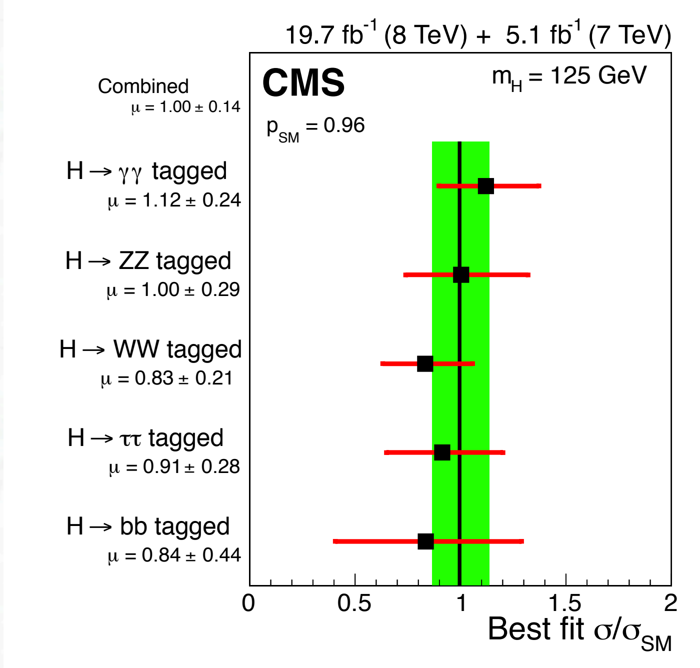
Signal strength in individual decay modes

-normalised to the expectations for the Standard Model Higgs boson-

EPJ C76 (2016) 1, 6



EPJ C75 (2015) 5, 212



Signal strengths:

ATLAS: $\mu = 1.18\,^{+0.15}_{-0.14}$

CMS: $\mu = 1.00 \pm 0.14$

Data are consistent with the hypothesis of the Standard Model Higgs boson

Signal strength Fits

Combined ATLAS + CMS results

arXiv:1606.02266

- Assuming the Standard Model and the calculated Higgs boson production cross sections, the (ATLAS + CMS) combined signal strength is:

$$\mu = 1.09 \,^{+0.11}_{-0.10} = 1.09 \,^{+0.07}_{-0.07}\,(\text{stat}) \,^{+0.04}_{-0.04}\,(\text{exp}) \,^{+0.03}_{-0.03}\,(\text{theo.bgd}) \,^{+0.07}_{-0.06}\,(\text{theo.sig})$$

- The signal strengths have also been measured using:

  - SM cross sections and free BRs
  - Free cross sections and Standard Model BRs

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

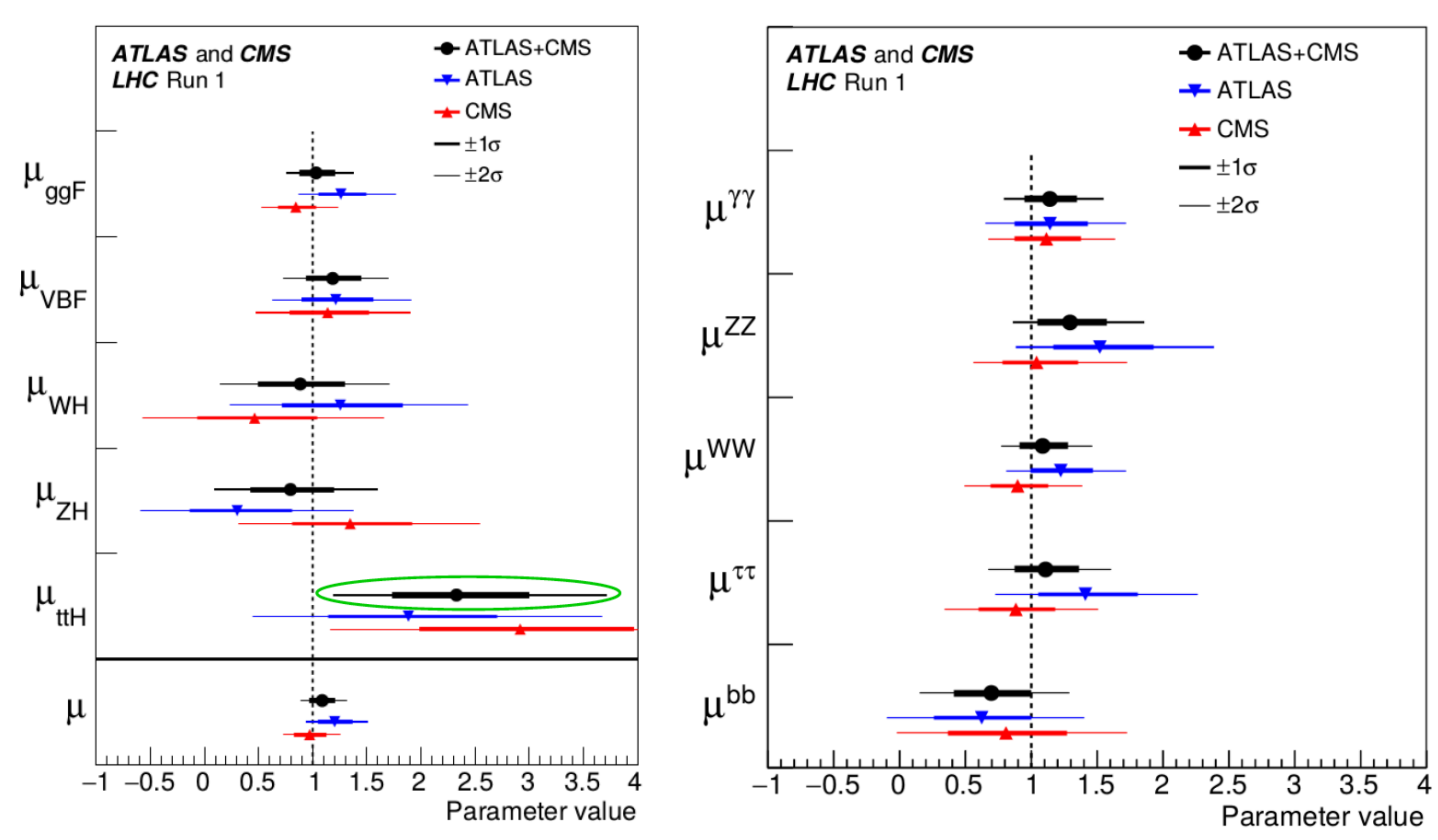
- In both cases, the data are compatible with the Standard Model with p-values of 24% and 75%, respectively

- The only "outlier" (> 2σ from the SM expectation) is: $\mu_{ttH} = 2.3 \,^{+0.7}_{-0.6}$

Signal strength Fits

Combined ATLAS + CMS results

arXiv:1606.02266



Signal strength Fits

Combined ATLAS + CMS results

arXiv:1606.02266

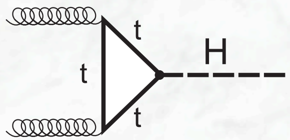
- From the combined ATLAS + CMS results, the vector boson fusion and the $H \rightarrow \tau\tau$ decay mode reach a significance of more than 5σ

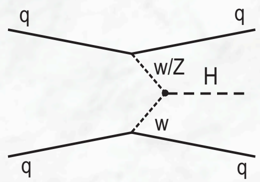
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \rightarrow \tau\tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7

Higgs boson couplings

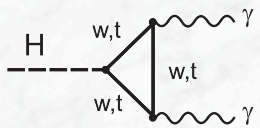
- Production and decay involve several couplings

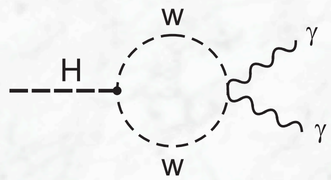
Production:





Decays: e.g H → γγ (best example)
(Decay width depends on W and top coupling,
destructive interference)





- Benchmarks defined by LHC cross section working group
(leading order tree-level framework: κ framework):

- Signals observed originate from a single resonance;
(mass assumed here is 125.09 GeV (ATLAS + CMS average)

- Narrow width approximation: → rates for given channels can be decomposed as:

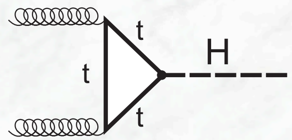
$$\sigma \cdot B\,(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

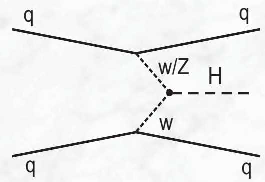
i, f = initial, final state
Γ_f, Γ_H = partial, total width

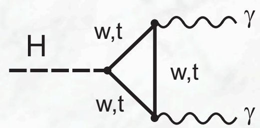
- Modifications to coupling strength are considered (coupling scale factors κ),
tensor structure of Lagrangian assumed as in Standard Model

Higgs boson couplings (in the κ framework)

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t\kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z\kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t\kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t\kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W\kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$



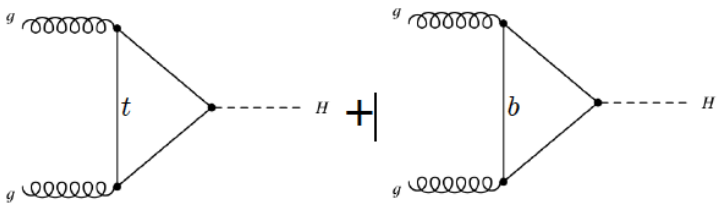




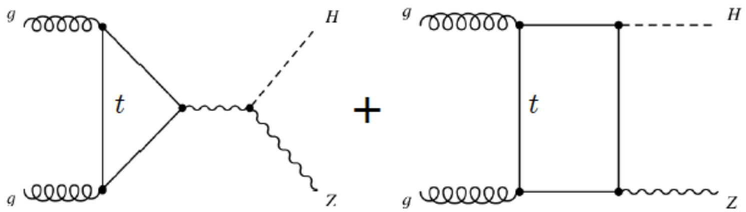
Higgs boson couplings (in the κ framework)

- The interference effects allow to determine the relative sign between two couplings

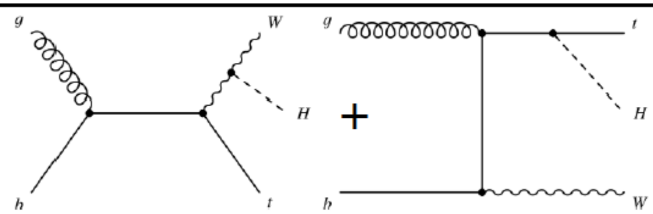
ggF: $1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$



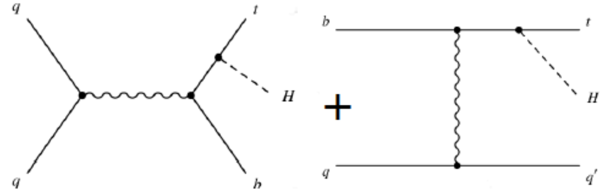
ggZH: $2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$



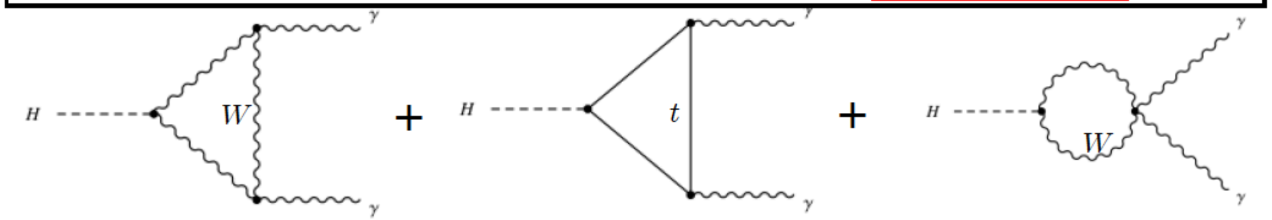
tHW: $1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$



tHq: $3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$

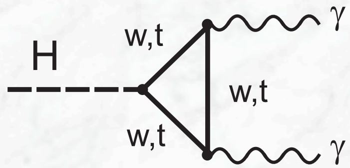


H → γγ: $1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$

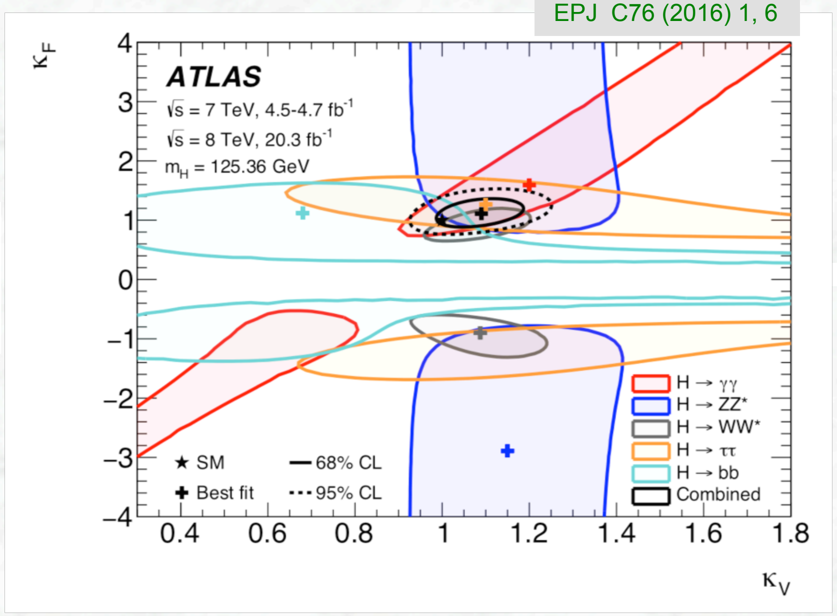


Couplings to fermions and bosons

- Assume only one scale factor for fermion and vector couplings:
  $\kappa_V = \kappa_W = \kappa_Z$ and $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$
- Assume that H → γγ and gg → H loops and the total Higgs boson width depend only on κ_V and κ_F (no contributions from physics beyond the Standard Model)
- Sensitivity to relative sign between κ_F and κ_V only from interference term in H → γγ decays (assume $\kappa_V > 0$)

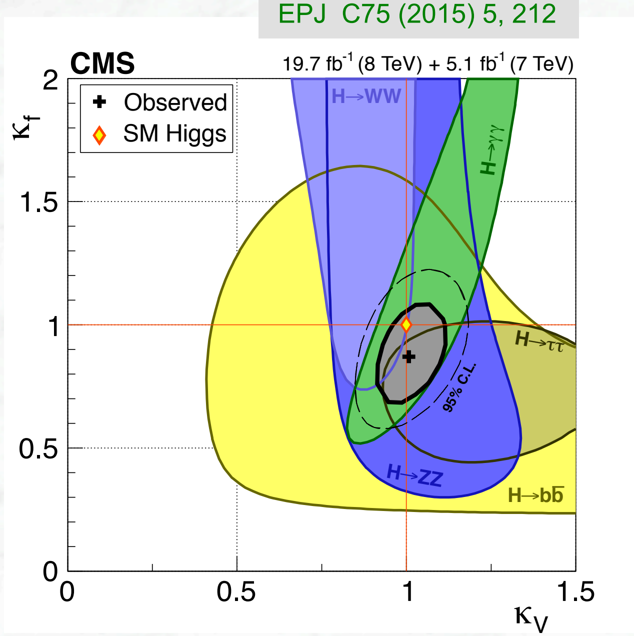


EPJ C76 (2016) 1, 6



Fit results: $\kappa_V = 1.09 \pm 0.07$
$\kappa_F = 1.11 \pm 0.16$

EPJ C75 (2015) 5, 212

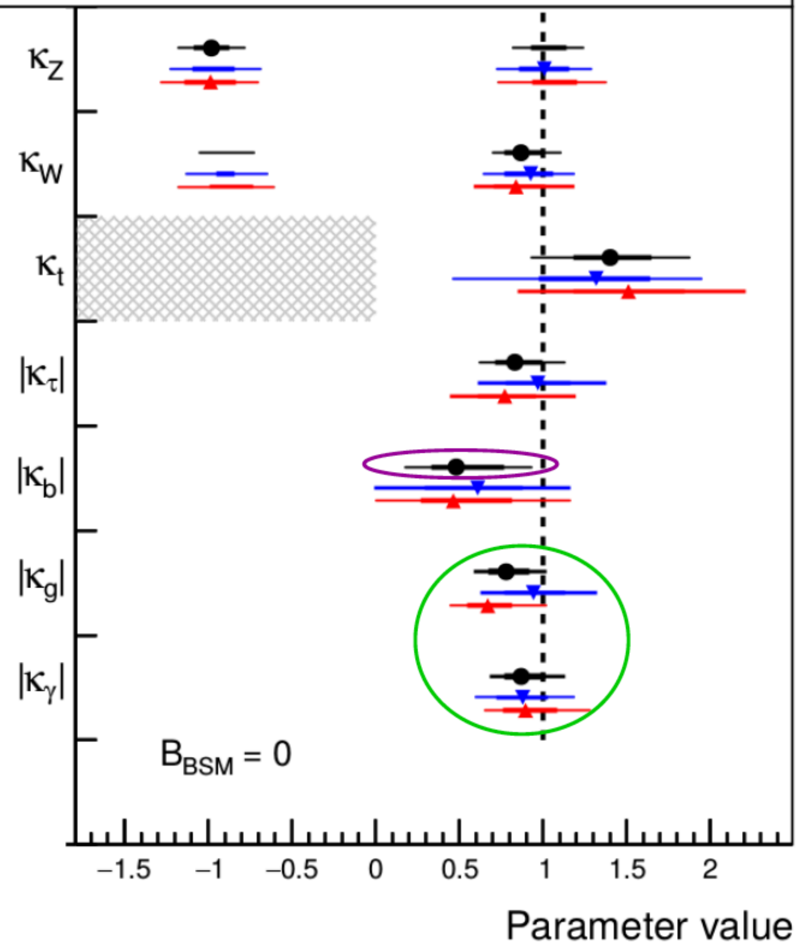


Fit results: $\kappa_V \in [0.87, 1.14]$ (95% CL)
$\kappa_F \in [0.63, 1.15]$ (95% CL)

arXiv:1606.02266

Fits for individual κ values within the SM

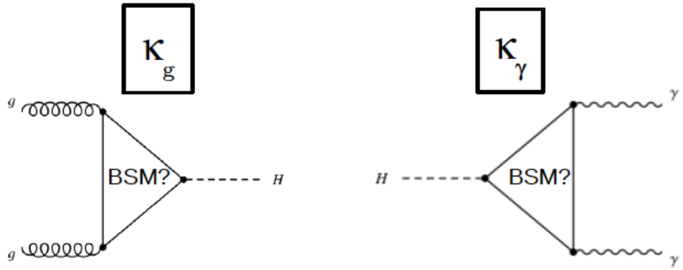
- All κ_i are compatible with the SM within 2σ, but $\kappa_b = 0.49^{+0.27}_{-0.15}$.
- $\kappa_{g/\gamma}$ compatible with SM:
  - $\kappa_g = 0.81^{+0.13}_{-0.10}$
  - $\kappa_\gamma = 0.90^{+0.10}_{-0.09}$
- **Global p-value compatibility with SM is 11%.**



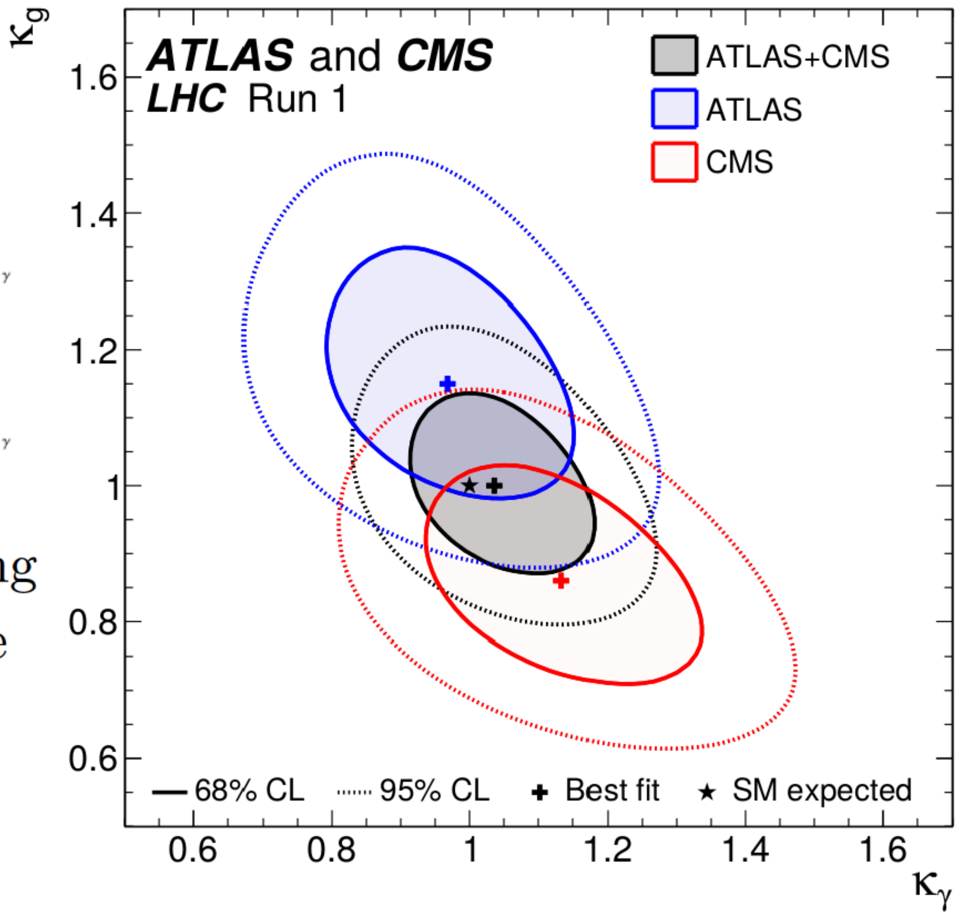
Higgs boson couplings
- Effective loop couplings-

arXiv:1606.02266

- New Physics could modify the effective Higgs-gluon and Higgs-γ couplings.

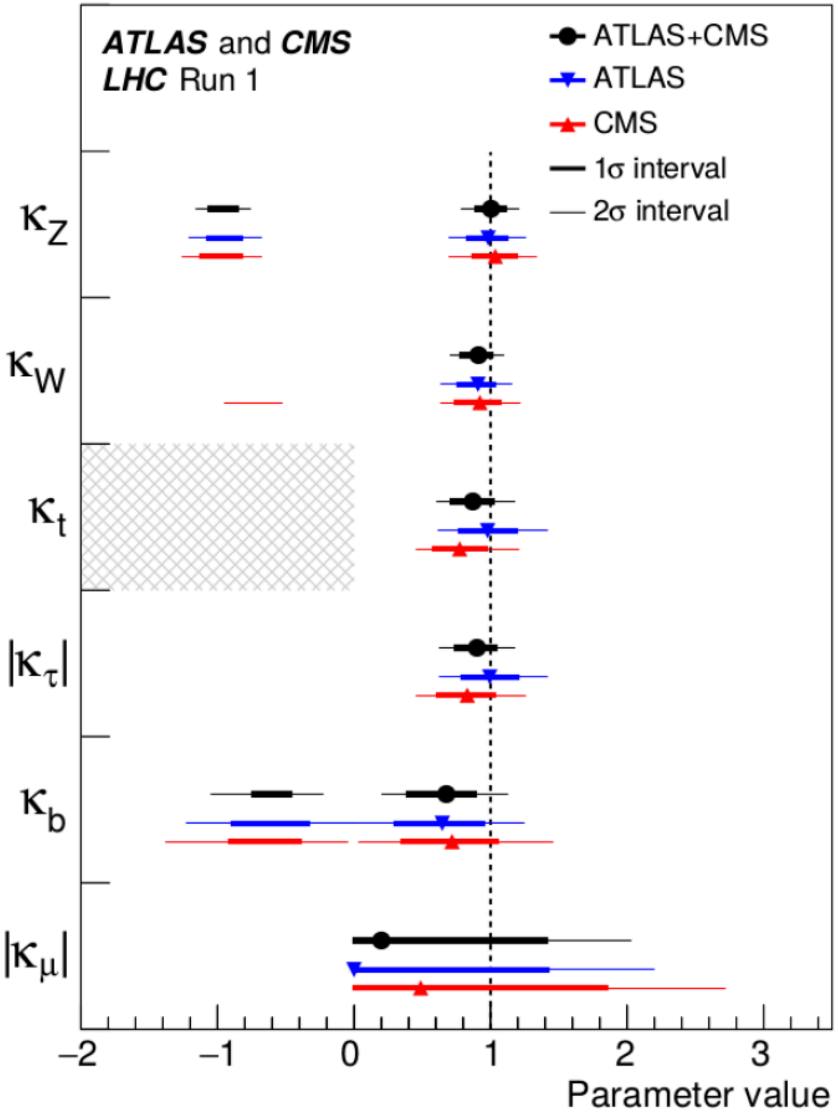


- They have been fitted fixing all other parameters to the SM prediction.
- Both κ_γ and κ_g have been found compatible with SM.



Higgs boson couplings
-The Standard Model fit-

arXiv:1606.02266



- Assuming loops with SM structures and no BSM decays, the fit is still compatible with the SM prediction.
- **The p-value compatibility data/SM is 74%.**

Higgs boson couplings

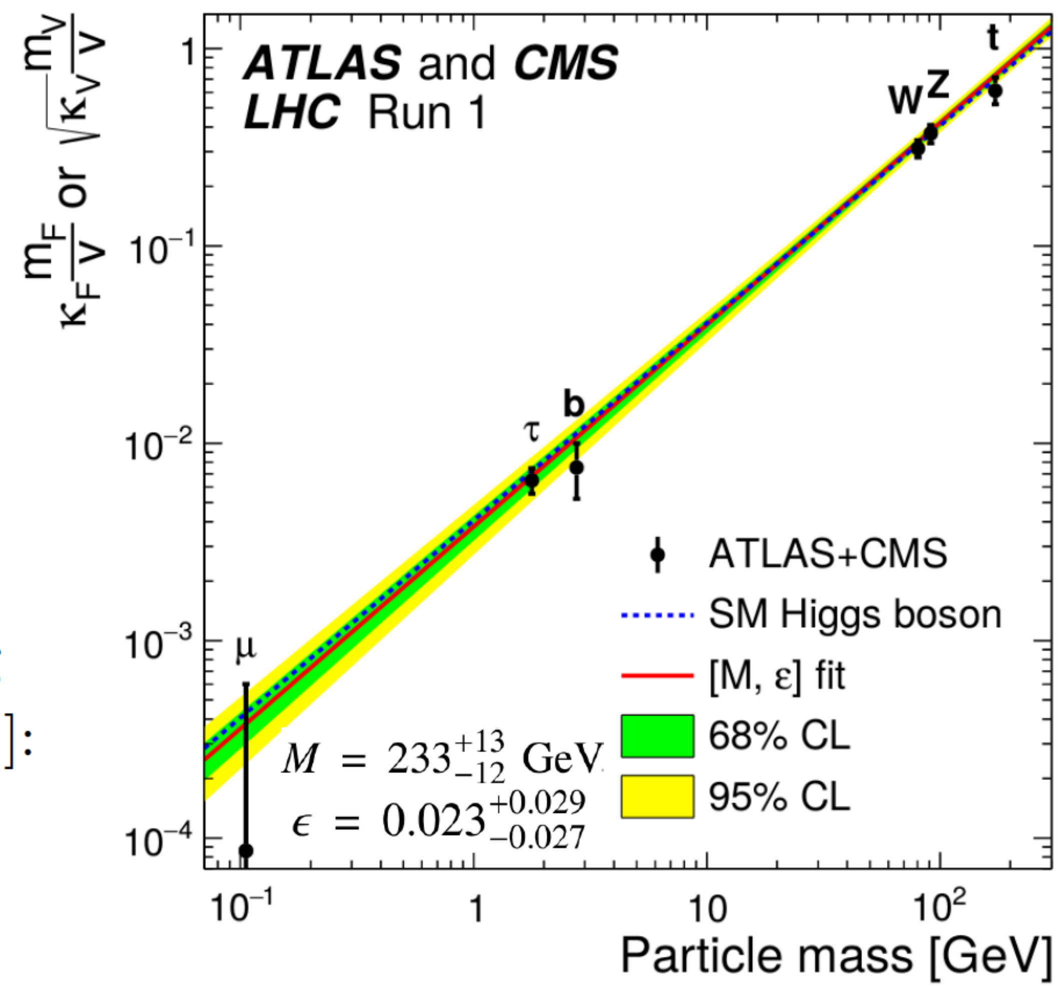
-The Standard Model fit-

arXiv:1606.02266

- The dependence of couplings vs particle mass have been checked using:
  - $y = k_F \frac{m_F}{v}$ (fermions);
  - $y = \sqrt{k_V}\frac{m_V}{v}$ (bosons);

  (v = 246 GeV).
- Data fitted directly using two degrees of freedom [1]:

$$\kappa_{V,i} = v \cdot m_{V,i}^{2\epsilon}/M^{1+2\epsilon}.$$
$$\kappa_{F,i} = v \cdot m_{F,i}^{\epsilon}/M^{1+\epsilon}$$



[1] JHEP **06** (2013) 103

For the first time, non-universal, mass-dependent couplings observed

Higgs boson couplings
-The most general model: ratios of coupling modifiers-

$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

- The coupling modifiers can also be fitted using σ_i and B_f, normalized to a reference process, e.g. gg → H → ZZ

  → it becomes independent from the Higgs boson width (and the corresponding assumptions, as always used so far)

  → Highest model independence at the LHC

- In this case the fit parameters correspond to ratios modifiers λ

Coupling modifier ratio parameterisation
$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\lambda_{tg} = \kappa_t/\kappa_g$
$\lambda_{WZ} = \kappa_W/\kappa_Z$
$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
$\lambda_{bZ} = \kappa_b/\kappa_Z$

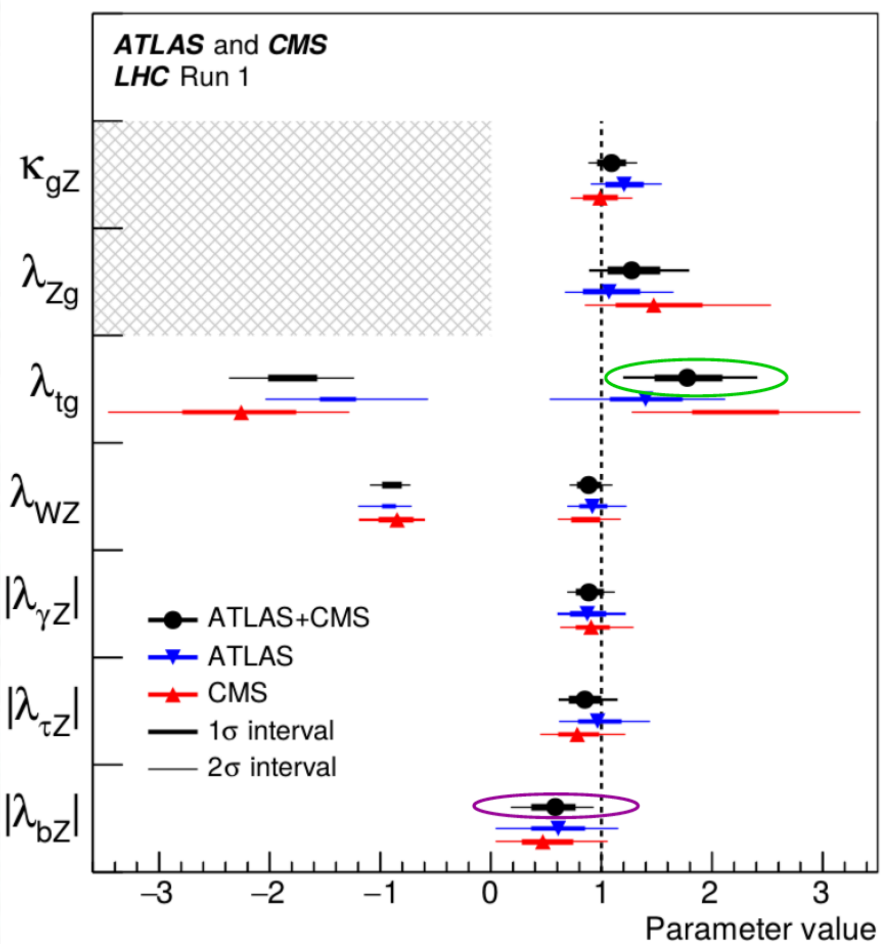
- Example: ttH → bb + X

$$\sigma_{ttH}B^{bb}/\sigma_{ggF}B^{ZZ} = k_t^2 k_b^2/k_g^2 k_Z^2 = \lambda_{tg}^2 \lambda_{bZ}^2$$

Higgs boson couplings

-The most general model: ratios of coupling modifiers-

arXiv:1606.02266



λ_{WZ}: test of custodial symmetry

$\lambda_{\gamma Z}$: sensitive to new charged particles in H → γγ loop w.r.t H→ZZ decays

λ_{tg} : sensitive to new coloured particles contributing to gg → H production w.r.t. ttH production

- In general, good agreement with the Standard model

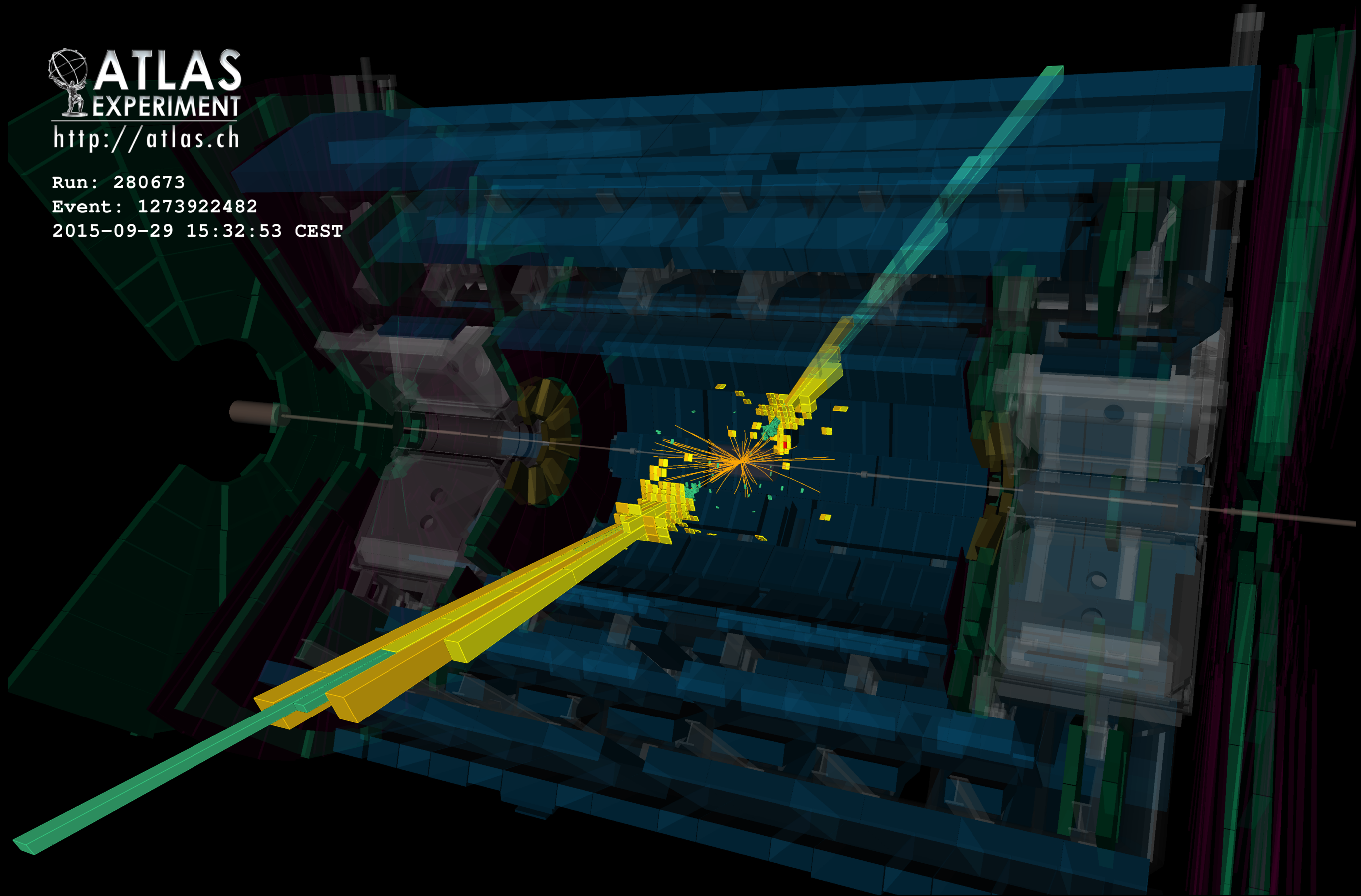
  Compatibility: 13%

- λ_{tg} somewhat high, due to the large ttH rate, but statistically not significant;
  λ_{bZ} somewhat low due to low H → bb rate;

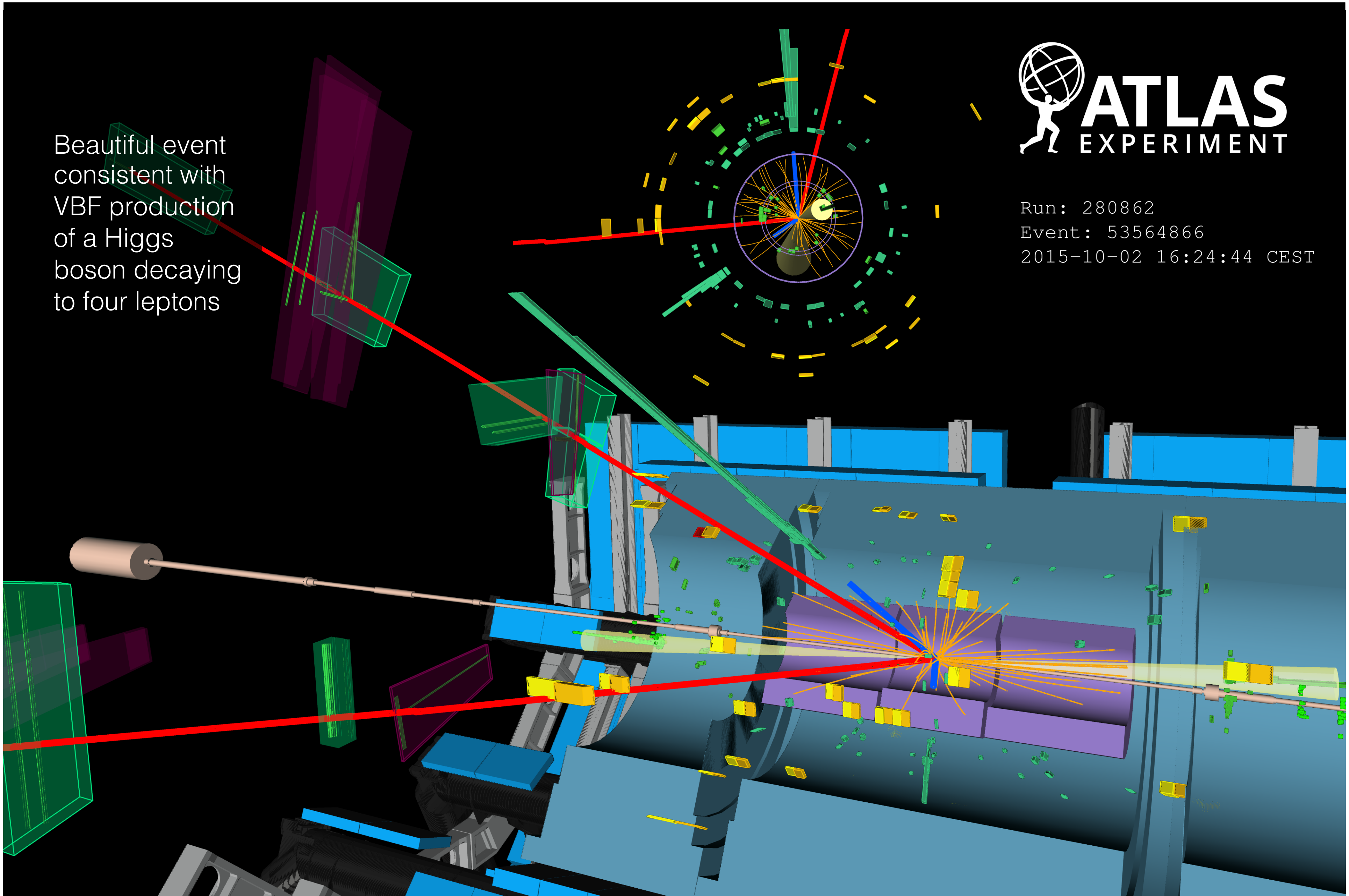
$$\lambda_{tg} = 1.78^{+0.30}_{-0.27}$$
$$|\lambda_{bZ}| = 0.58^{+0.16}_{-0.20}$$

- Large potential for increasing the overall precision in Run 2

First results from LHC Run 2



Highest mass dijet event measured by ATLAS in 2015 ($\sqrt{s}$ = 13 TeV): m_{jj} = 6.9 TeV



Display of H → eeμμ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the dielectron (dimuon) invariant mass is 91 (29) GeV, the pseudorapidity difference between the two jets is 6.4 and the dijet invariant mass is 2 TeV.

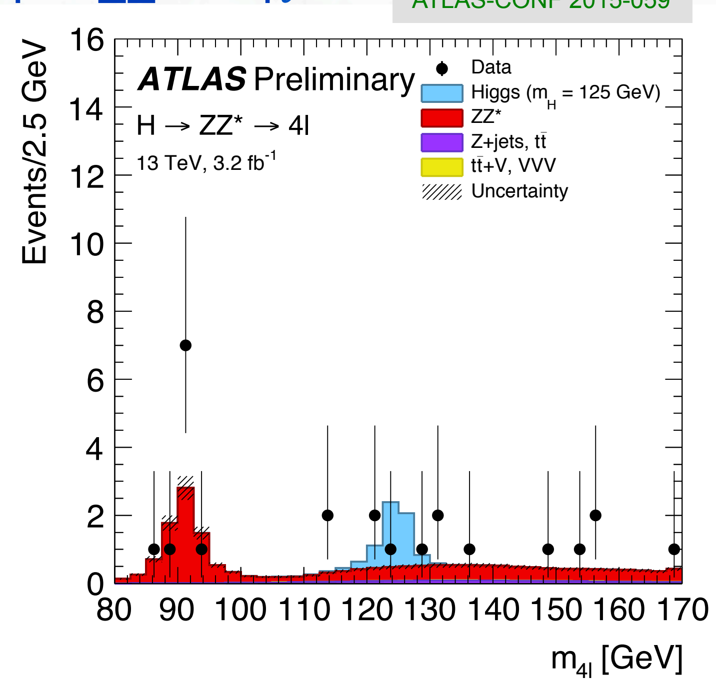
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

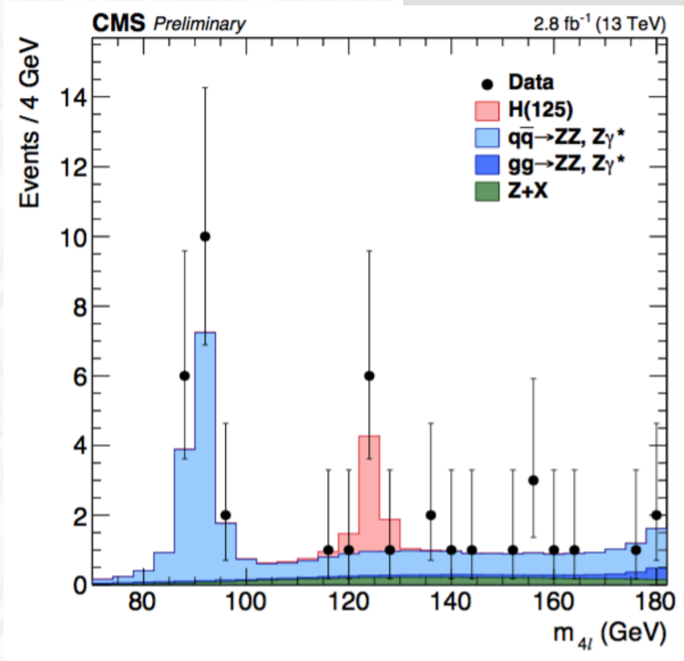
ATLAS & CMS looked for Higgs boson decays to bosonic and fermionic channels

$H \rightarrow ZZ^* \rightarrow 4\ell$

ATLAS-CONF 2015-059



CMS-PAS-HIG-15-004



$\sigma_{tot,data} = 12^{+25}_{-16}$ pb

$\sigma_{tot,SM} = 51 \pm 5$ pb

Expected significance (SM): 2.8σ

$\mu = \sigma_{data} / \sigma_{SM} = 0.82^{+0.57}_{-0.43}$

Expected significance (SM): 3.4σ

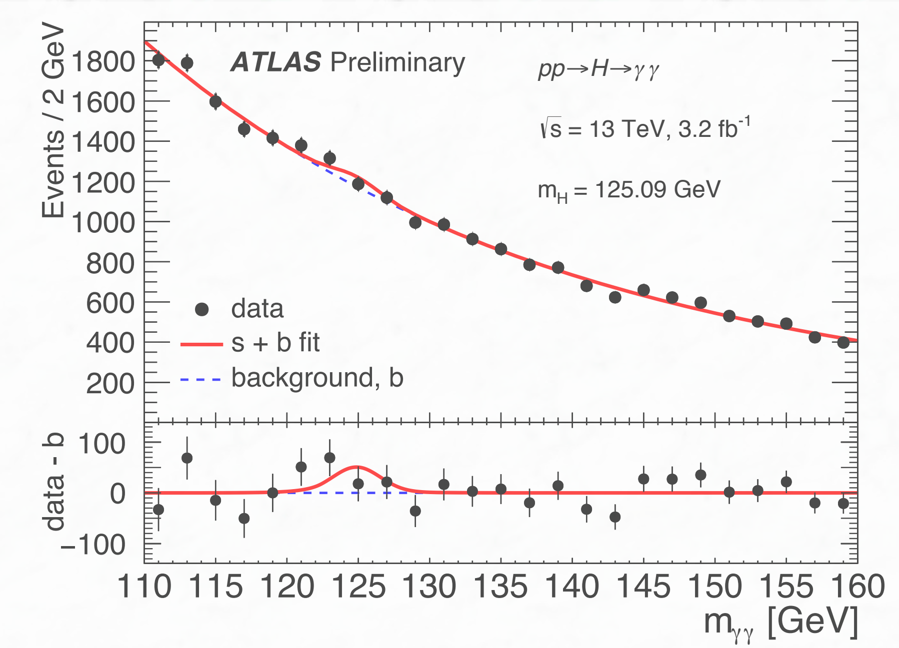
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

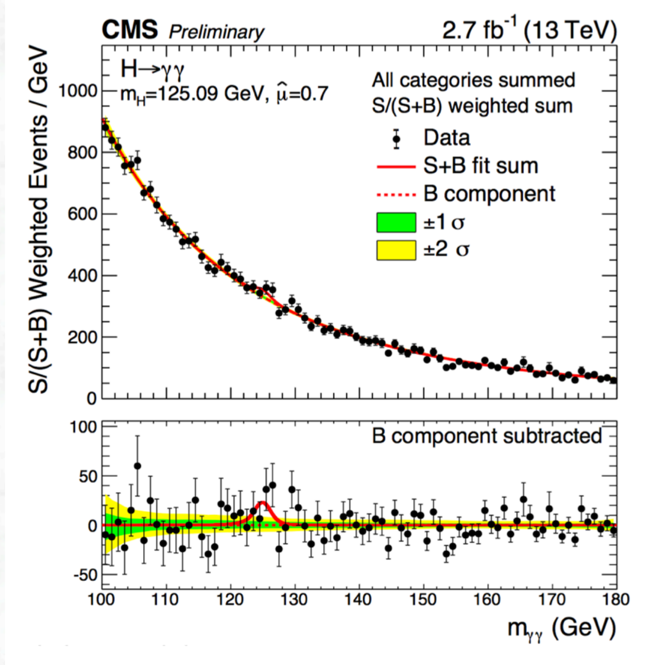
ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

$H \rightarrow \gamma\gamma$

ATLAS-CONF 2015-060



CMS-PAS-HIG-15-005



$$\sigma_{tot,data} = 40 \pm 26\,^{+16}_{-10} \pm 2_{lumi}\ \text{pb}$$

$$\sigma_{tot,SM} = 51 \pm 5\ \text{pb}$$

Expected significance (SM): 1.9σ

$$\mu = 0.69\,^{+0.47}_{-0.42}$$

Expected significance (SM): 2.7σ

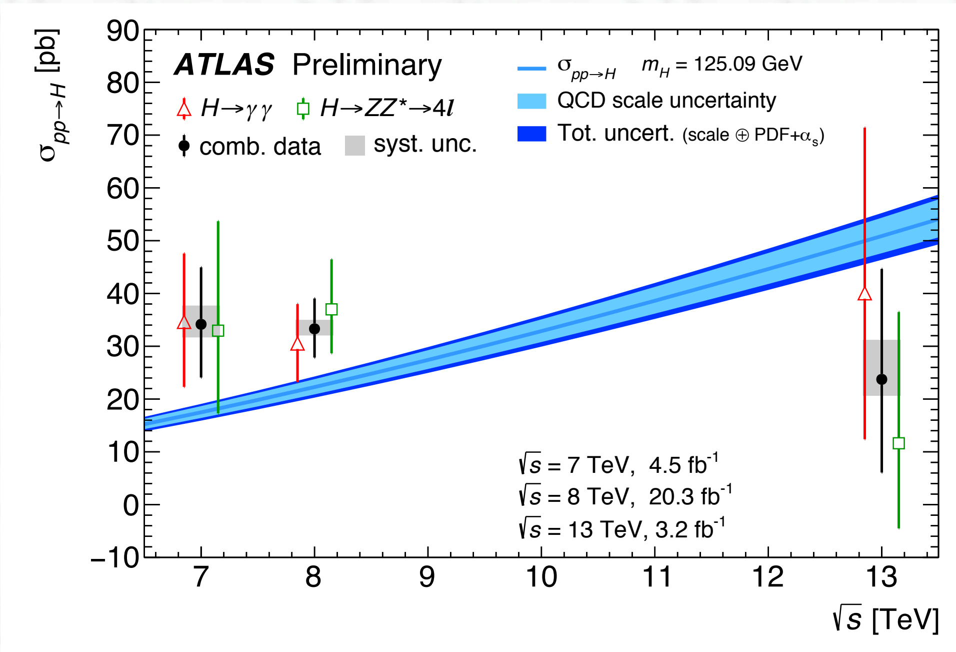
Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

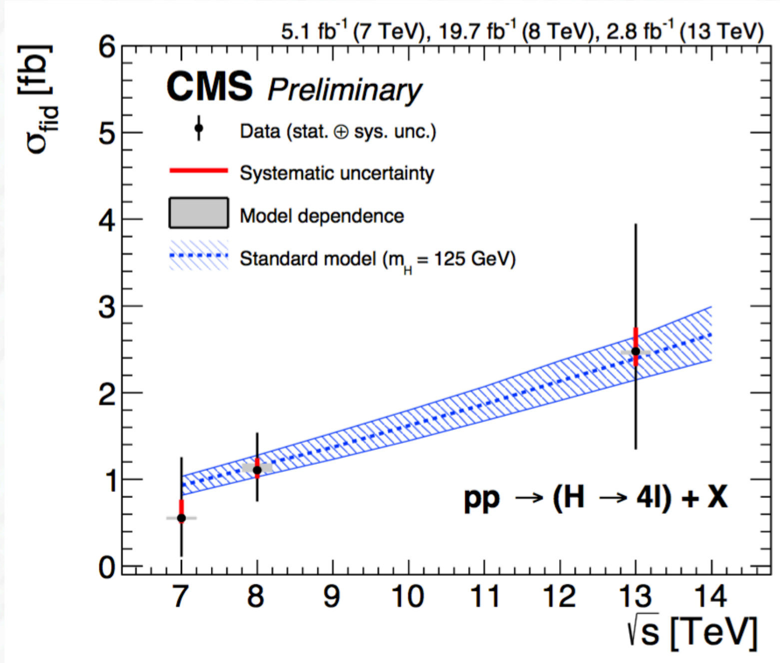
Extracted cross sections vs CM energy

Combined H → 4ℓ, γγ



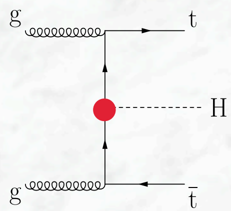
ATLAS-CONF 2015-069

H → 4ℓ, *fiducial* cross section



CMS-PAS-HIG-15-004

Current 13 TeV data sample still marginal for H_{125}



But important to look for the signal in an agnostic way at new CM energy

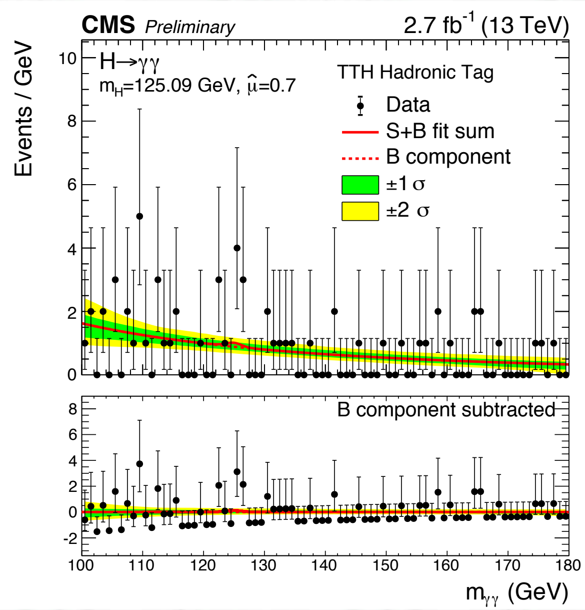
CMS showed preliminary results for ttH in all major Higgs decay channels:
H → γγ, multi-leptons, bb

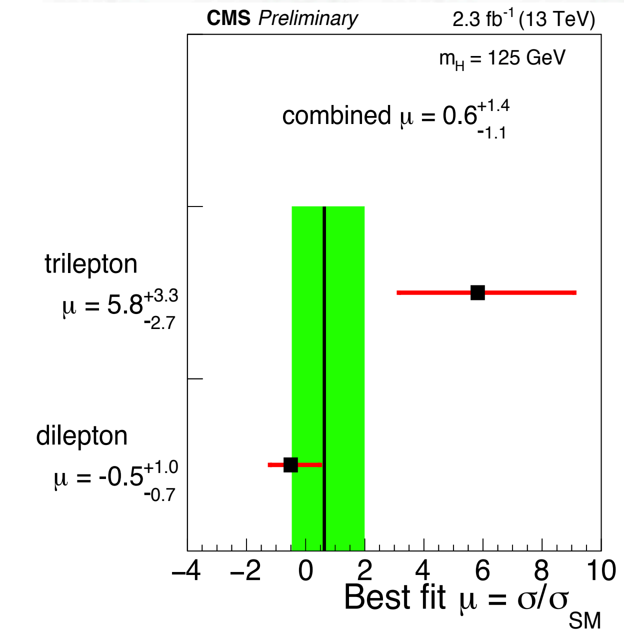
Highly complex analyses, huge effort to get these done so quickly after data taking

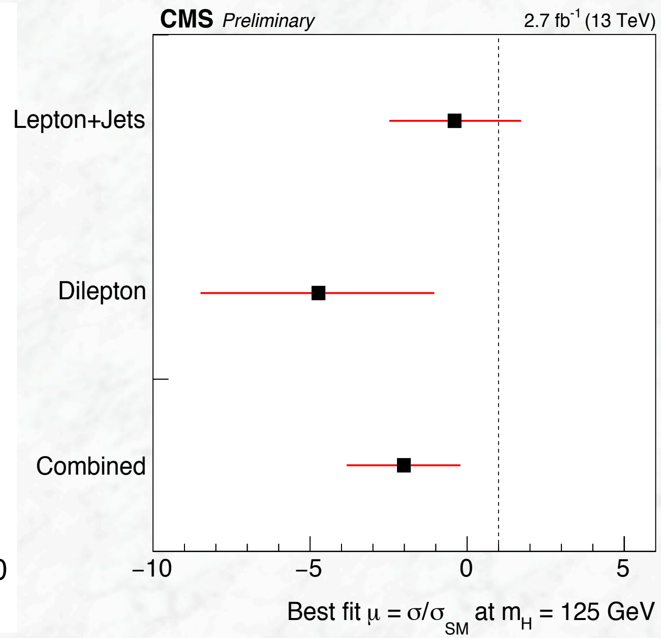
H → γγ,
tt → 0 & 1 leptons

ttH → multi-leptons
2 same charge / 3 leptons

H → bb
tt → 1 & 2 leptons







$\mu = 3.8^{+4.5}_{-3.6}$

CMS-PAS-HIG-15-005

$\mu = 0.6^{+1.4}_{-1.1}$

CMS-PAS-HIG-15-008

$\mu = -2.0 \pm 1.8 < 2.6$ (95% CL)

CMS-PAS-HIG-16-004

Additional Higgs bosons?

Composite Higgs bosons

MSSM Higgs bosons

Dark Higgs

More Higgs bosons

SUSY Higgs

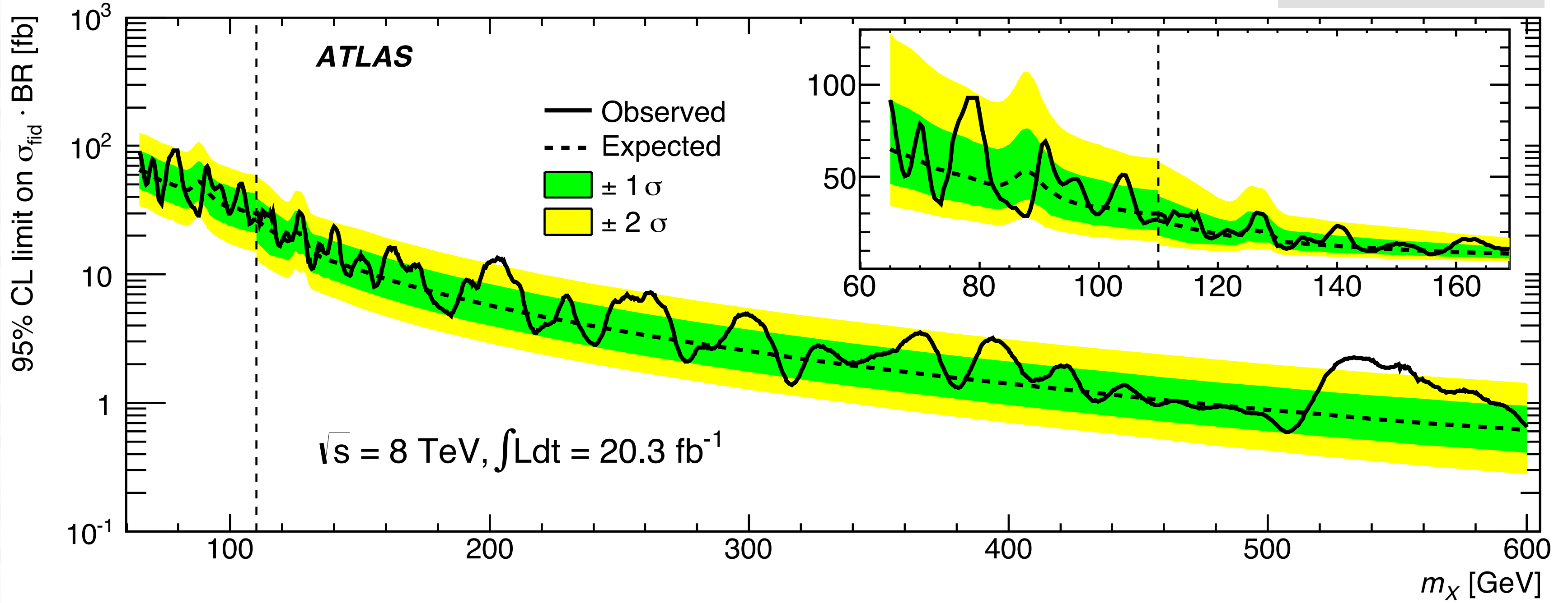
Heidi Higgs

No Higgs at the LHC

Search for Additional Higgs Bosons
-a few examples-

(i) Results of an ATLAS search on additional resonances X decaying into $\gamma\gamma$

PRL 113 (2014) 171801



Observed and expected 95% CL limits on the fiducial cross section times branching ration BR(X → $\gamma\gamma$) as a function of mass

(note: 125 GeV signal was treated as “background” and contribution was subtracted)

Diphoton resonance searches: ATLAS

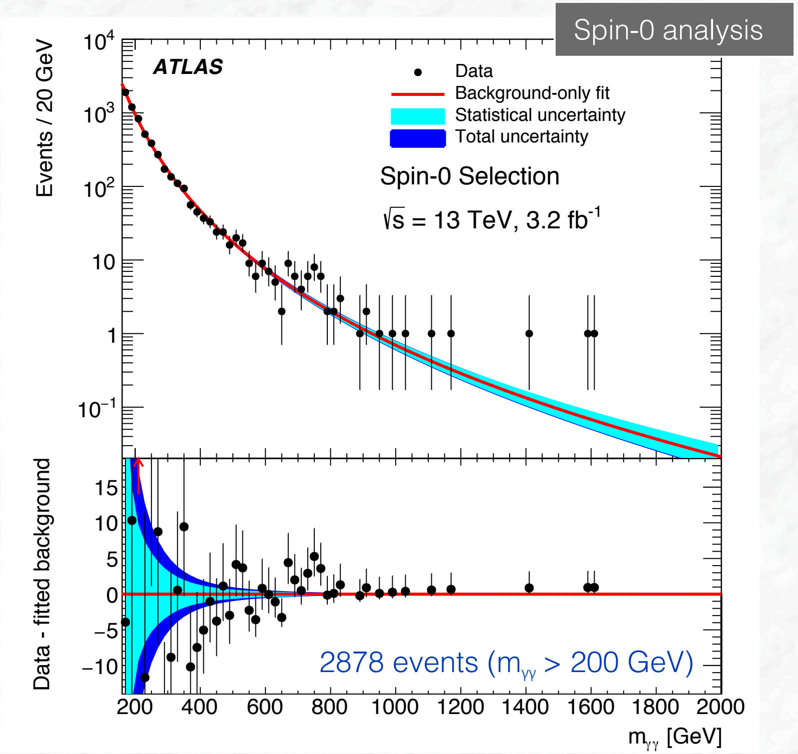
Dedicated searches for a spin-0 and a spin-2 diphoton resonance.

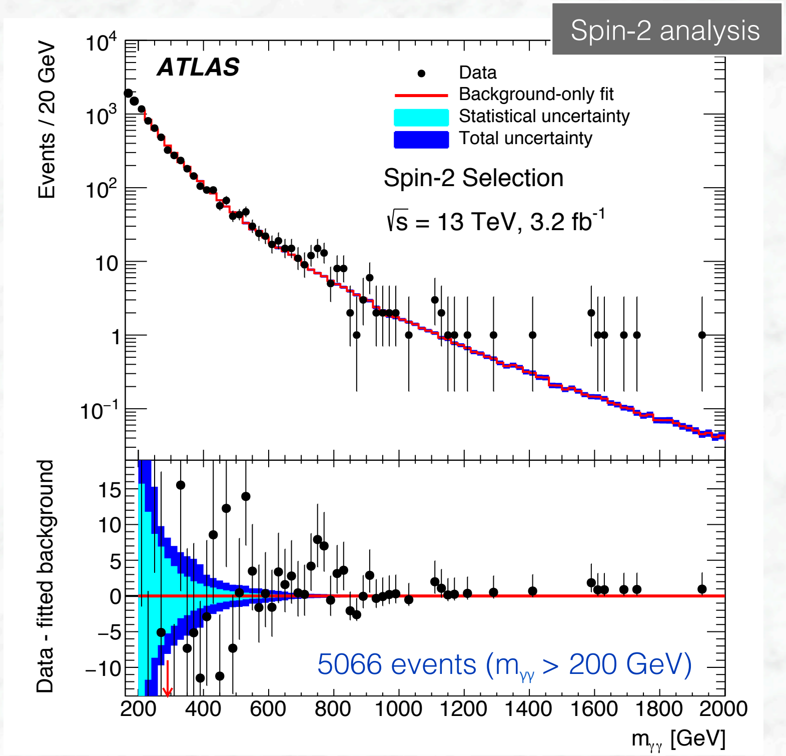
arXiv: 1606.03833

Main difference is acceptance: spin-0: $E_T(\gamma_1) > 0.4 \cdot m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.3 \cdot m_{\gamma\gamma}$, spin-2: $E_T(\gamma_{1/2}) > 55$ GeV

Photons are tightly identified and isolated. Typical purity ~94%

Background modelling empirical in spin-0, and (mainly) theoretical in spin-2 case (for high-mass search)





Lowest p-value at ~750 GeV, Γ ~ 45 GeV (6%)

Local / **global Z** = 3.9 / **2.1σ**

Lowest p-value at ~750 GeV, Γ ~ 7% of mass

Local / **global Z** = 3.8 / **2.1σ**

Diphoton resonance searches: CMS

Agnostic search for spin 0 and 2 bosons

arXiv:1606.04093

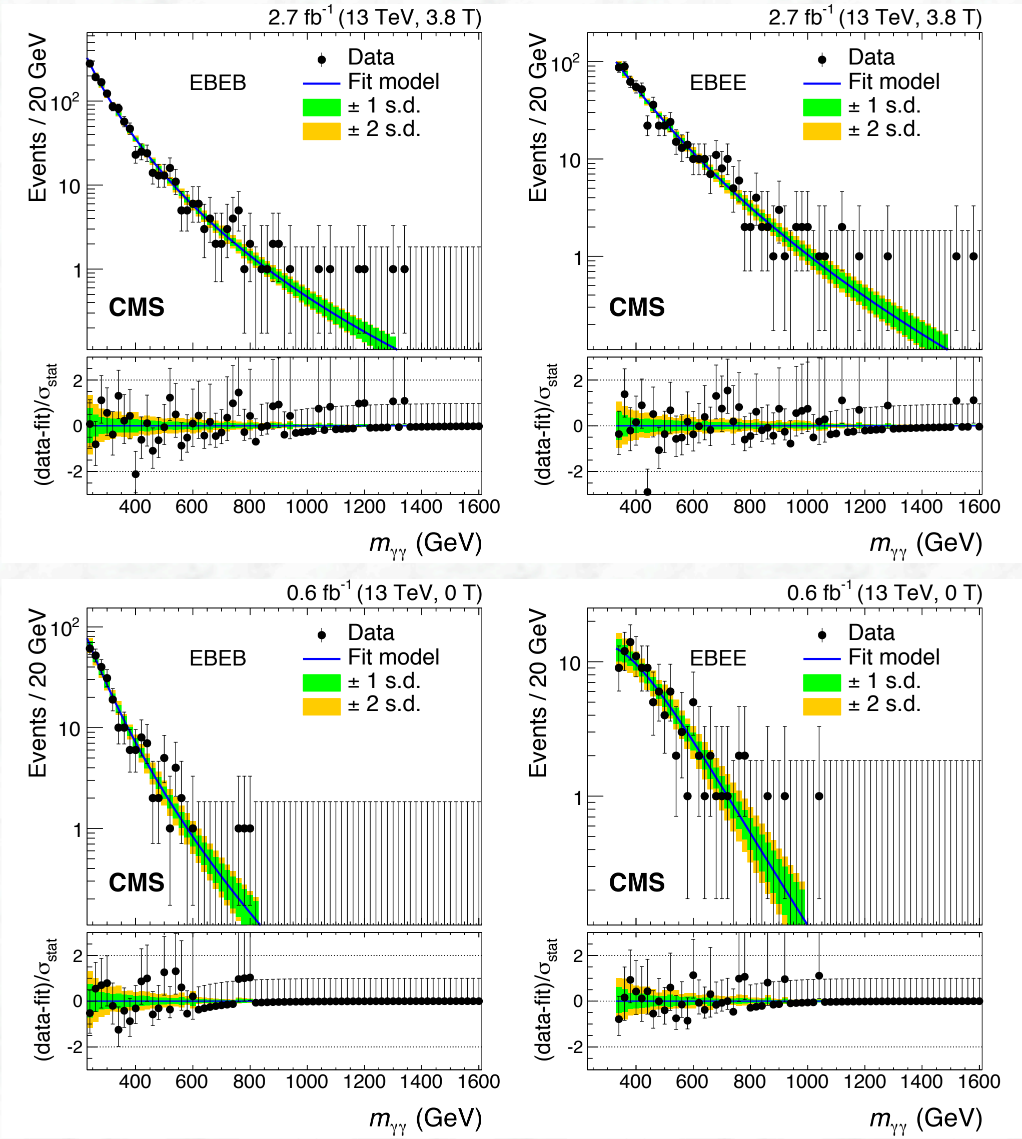
New 13 TeV analysis with improved ECAL calibration (~30% improved resolution above $m_{\gamma\gamma}$ ~ 500 GeV), and including 0.6 fb^{-1} of B-field off data

- Acceptance: $E_T(\gamma_{1/2})$ > 75 GeV, at least one γ with $|\eta|$ < 1.44 (barrel), split EB-EB, EB-EE
- Dedicated calibration of B-field-off data, slightly lower γ-ID efficiency, better resolution, harder PV finding
- Empirical background modelling
- Combination of 13 & 8 TeV data (model-dependent, good compatibility)

Lowest p-value at ~750 GeV
(760 for 13 TeV data only), narrow width

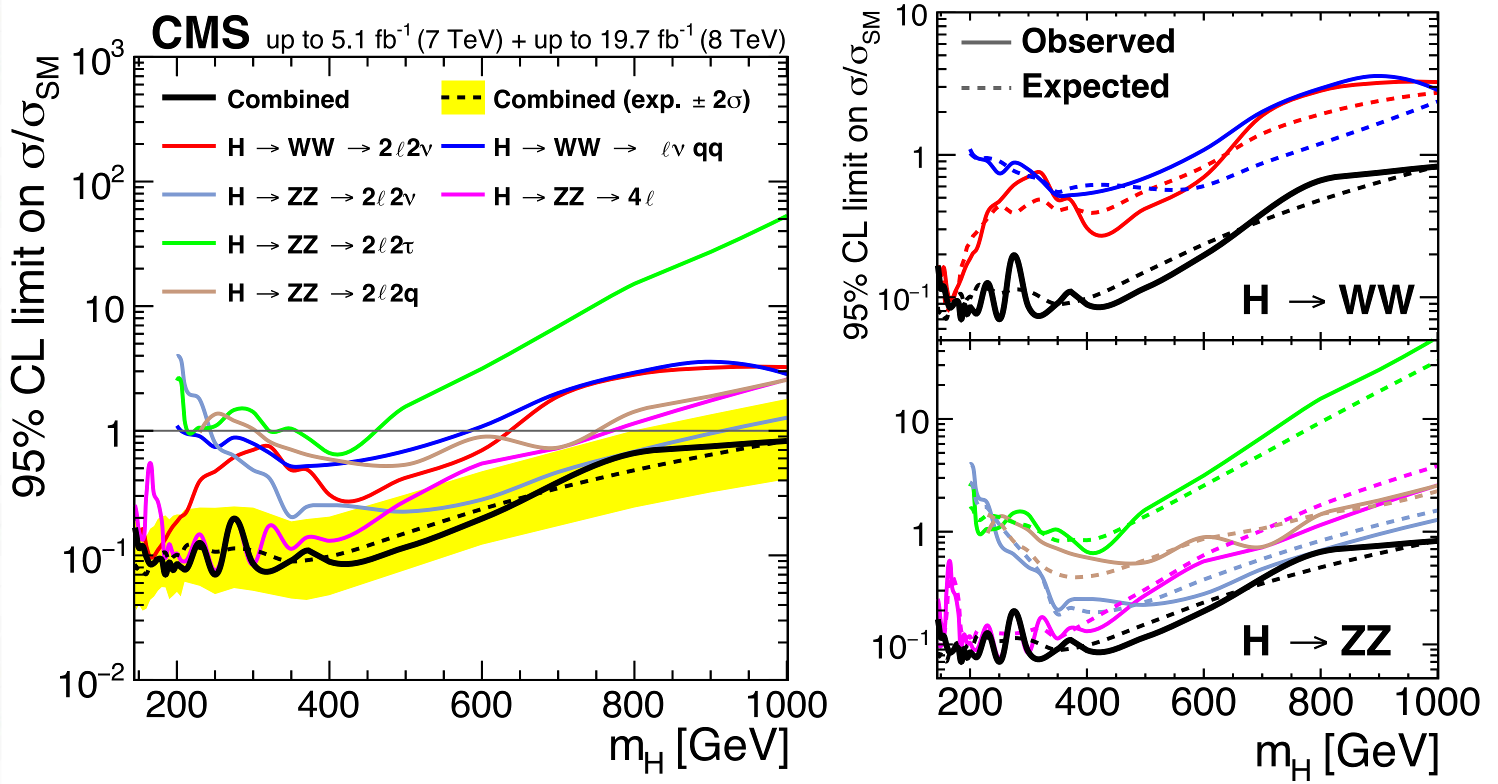
Local / **global Z** = 3.4σ / **1.6σ**
(2.9σ / **< 1** for 13 TeV data only)

No compelling evidence for signal.
More data needed.



(ii) Results of a CMS search on additional SM-like Higgs bosons decaying into ZZ and WW

arXiv:1504.00936

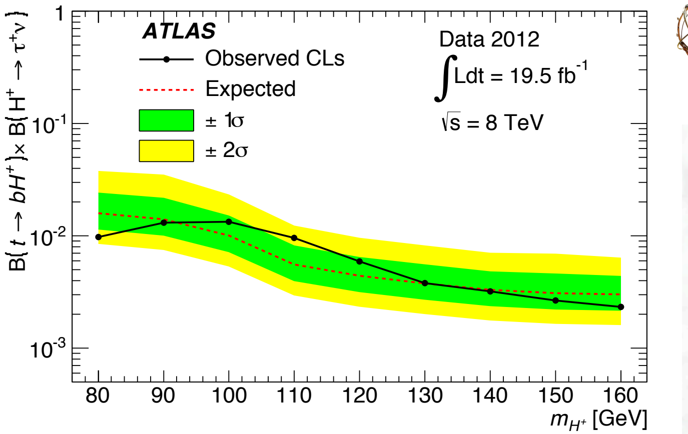


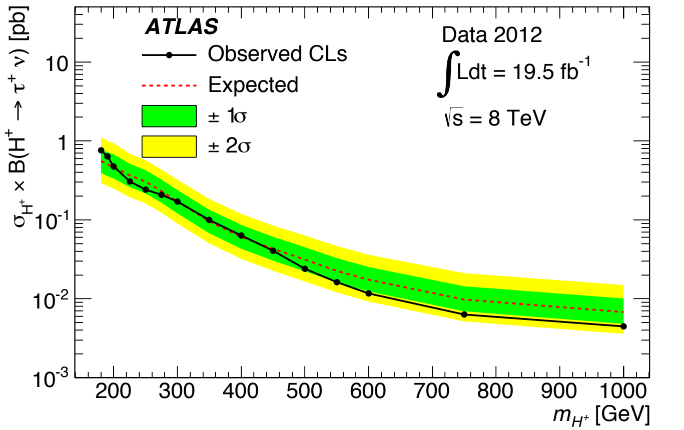
Observed and expected 95% CL limits on the cross section normalised to the SM value for individual channels and their combination

(iii) Search for charged and heavy neutral MSSM Higgs bosons

Search for $H^{\pm} \rightarrow \tau\nu$ decays via
tt production or $tH^{\pm}$ associated production

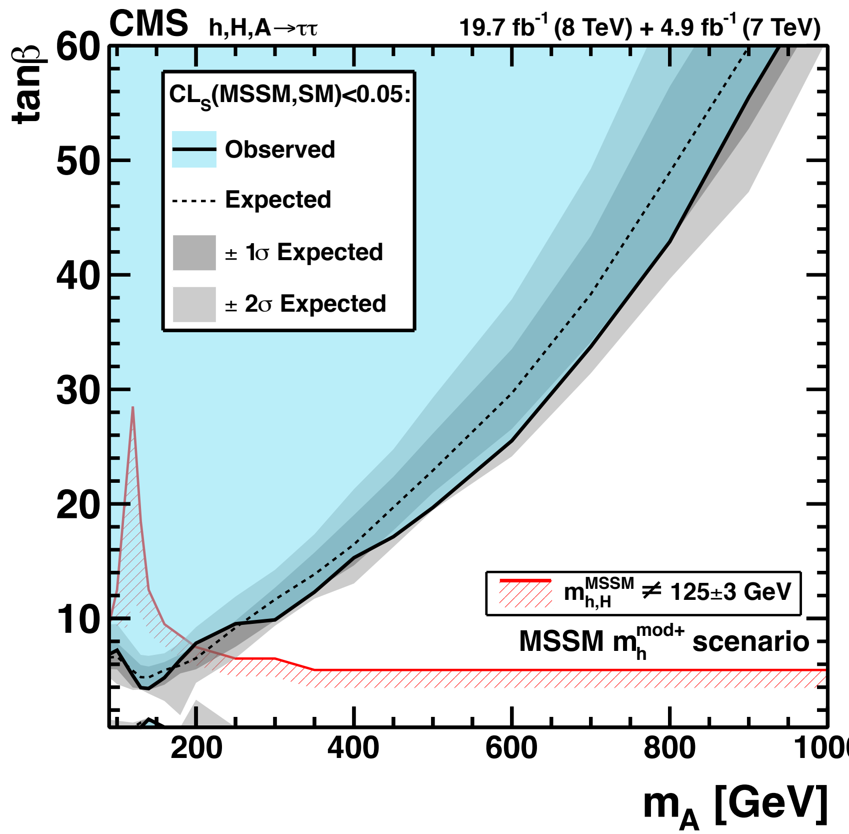
JHEP 03 (2015) 088





95% CL exclusion limits on branching ratios or cross sections times branching ratio

JHEP 10 (2014) 160



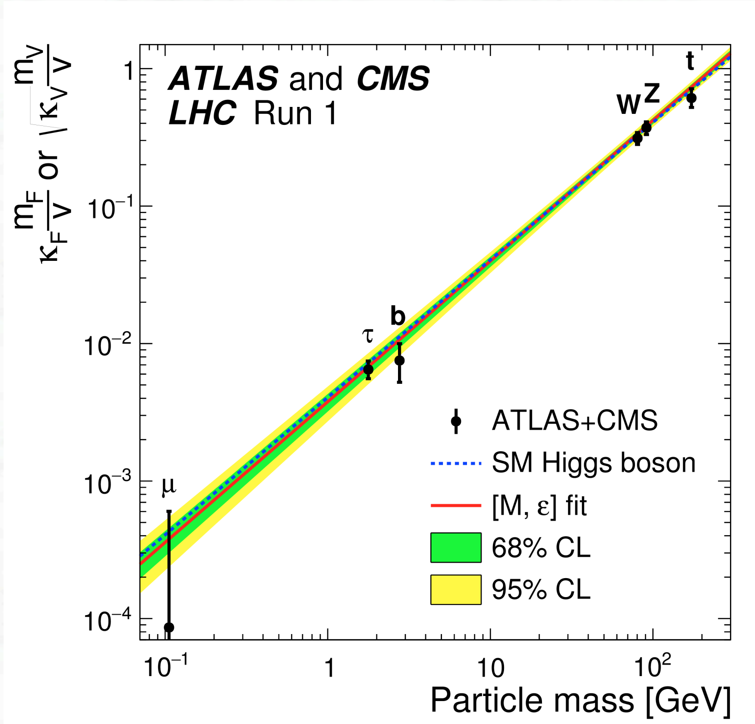
Expected and observed exclusion limits at 95% CL in the (m_A–tan β) parameter plane for the MSSM m_h^{mod+} benchmark scenario

Conclusions

- The analyses of the complete LHC Run 1 dataset by the ATLAS and CMS experiments have consolidated the milestone discovery announced in July 2012

- Properties of the particle (J^{CP}, couplings) are in very good agreement with those expected for the Standard Model Higgs boson

  The experiments have moved from the discovery to the measurement phase;



- Many measurements still statistically limited
  → significant improvements expected in Run 2 and beyond

  → Higgs particle might be the portal to new physics

- Exciting times ahead of us, with new, unexplored energy regime in reach