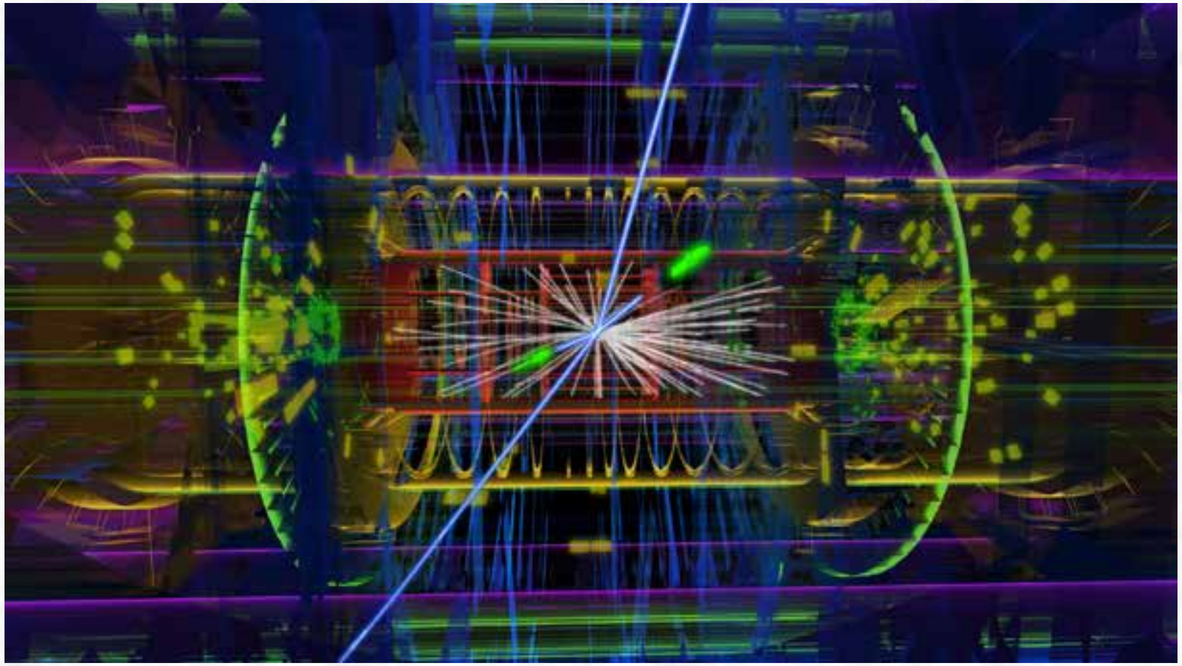
Higgs Boson Physics at the LHC

-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)

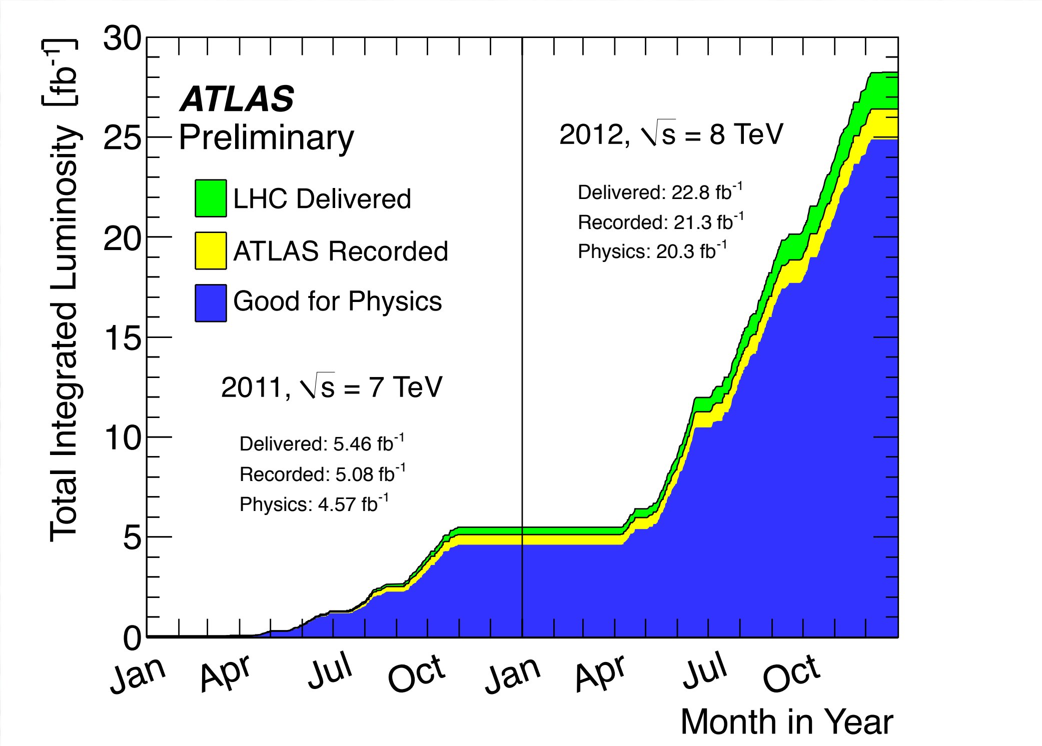
- First results from LHC Run 2

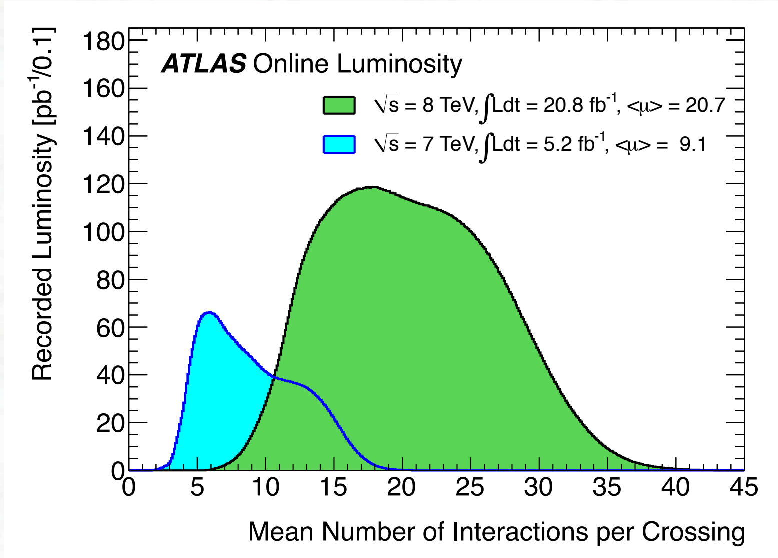
The Large Hadron Collider

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."

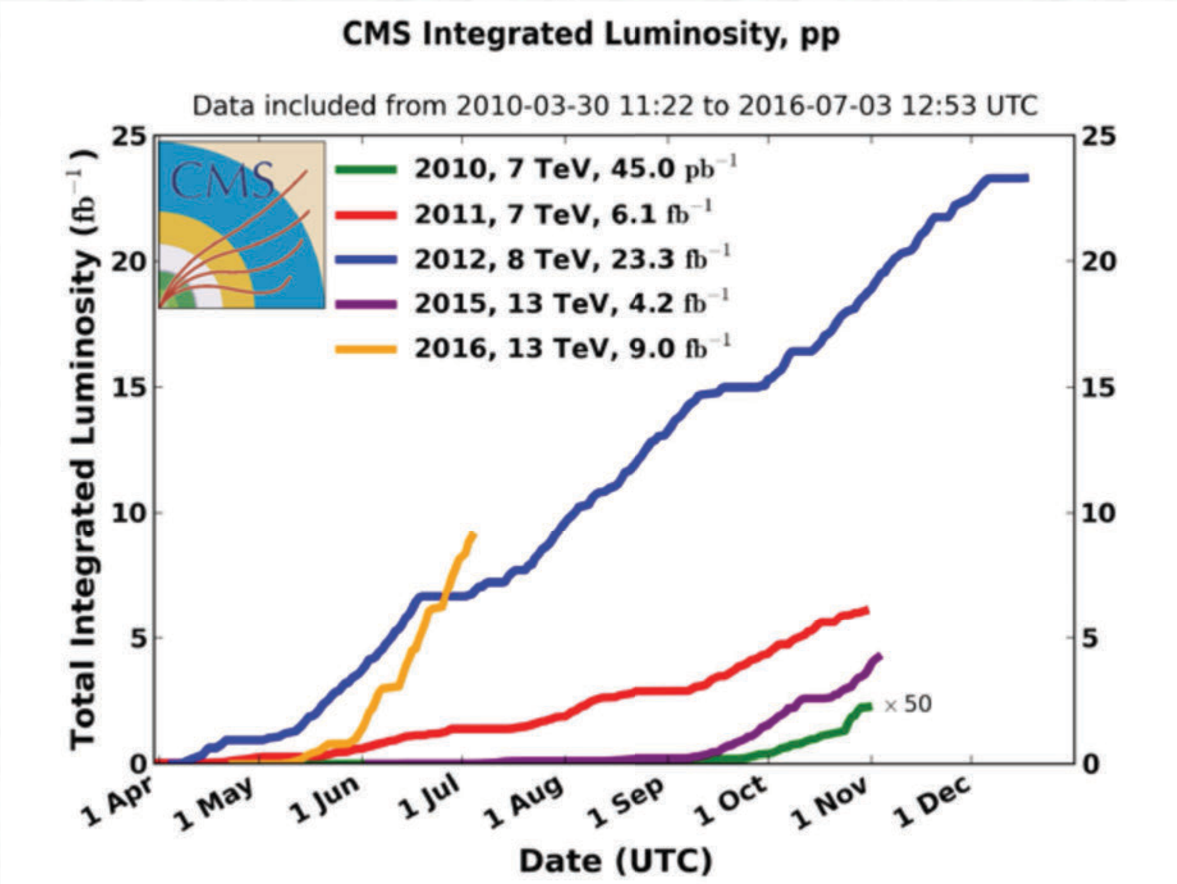
Performance of the LHC and of the experiments





- 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)

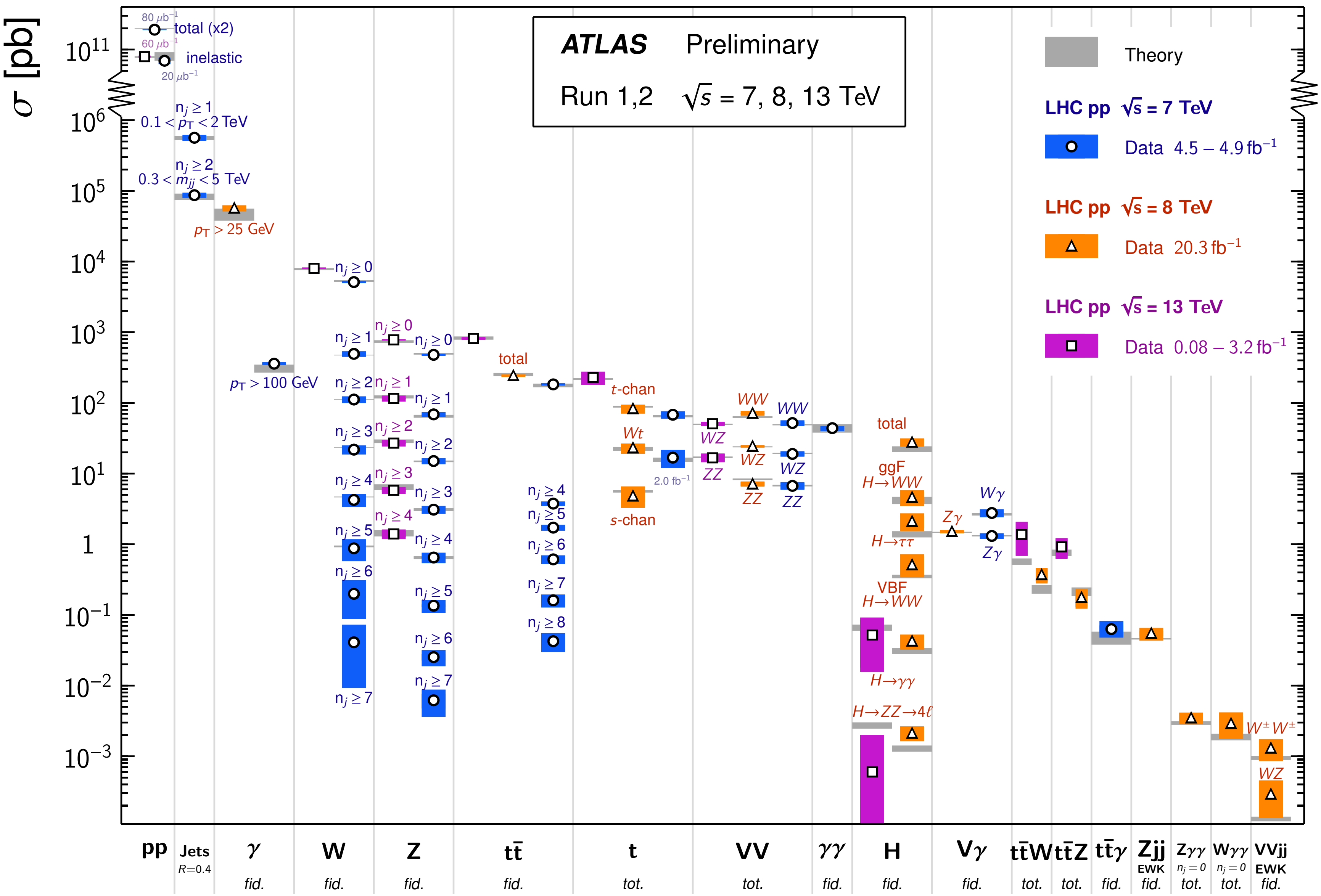
Even better today, the 2016 run at √s = 13 TeV

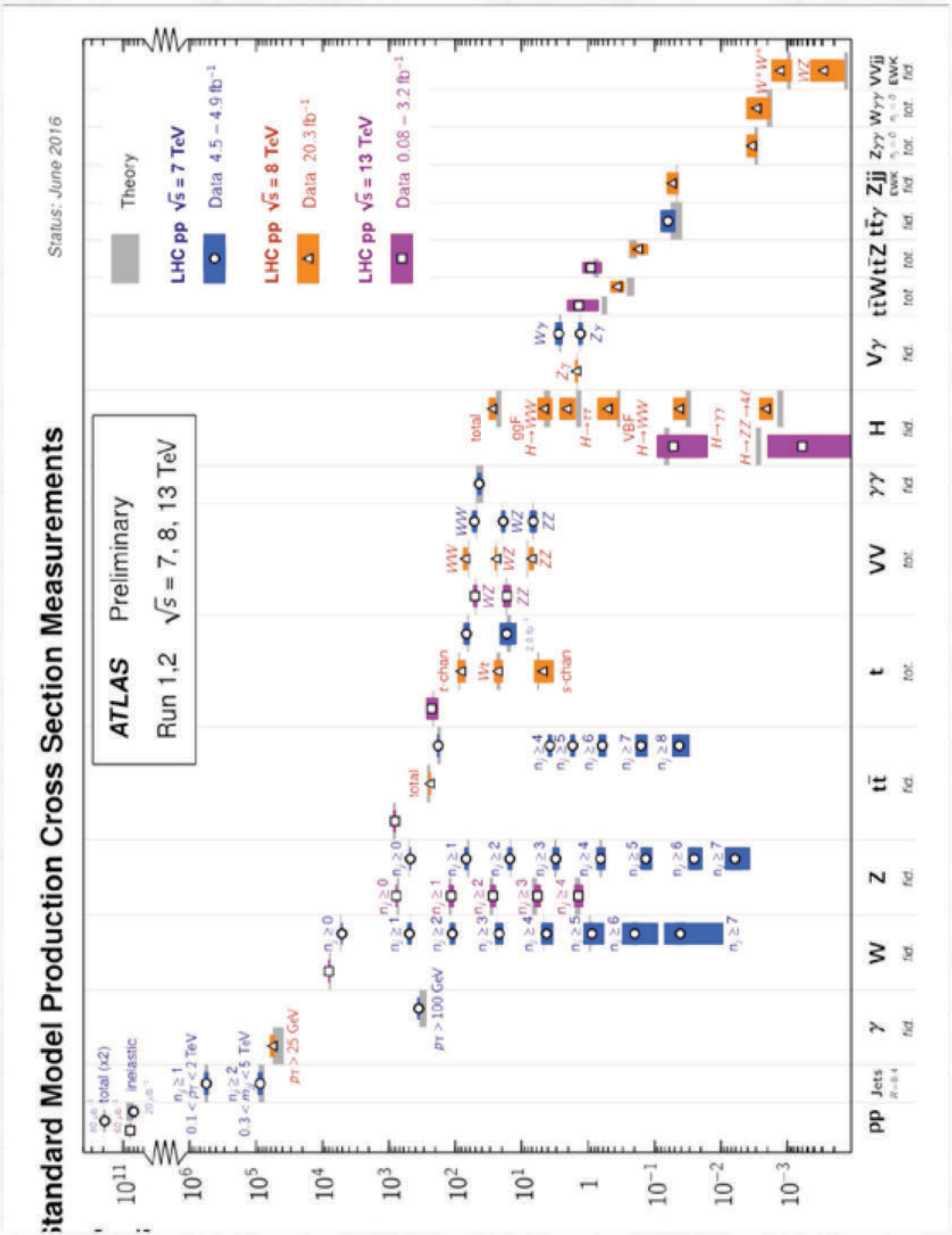


- Peak luminosity > 1 10^{34} cm^{-2} s^{-1}
- High level of pileup, however, running with a bunch separation of 25 ns

Standard Model Production Cross Section Measurements

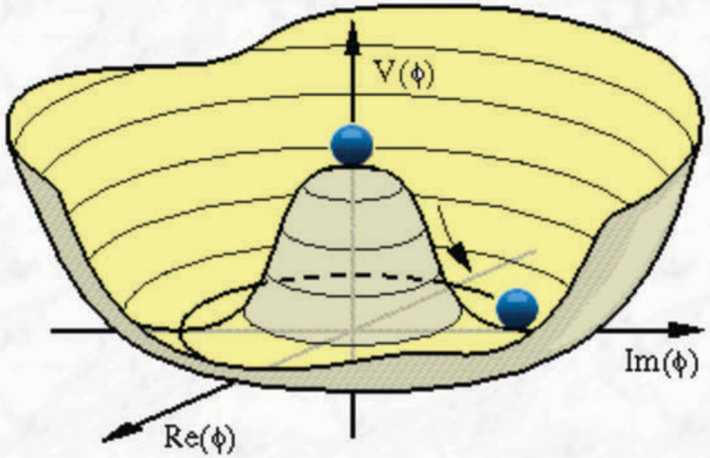
Status: June 2016





"Stairway to Heaven"

The Brout-Englert-Higgs Mechanism



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

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

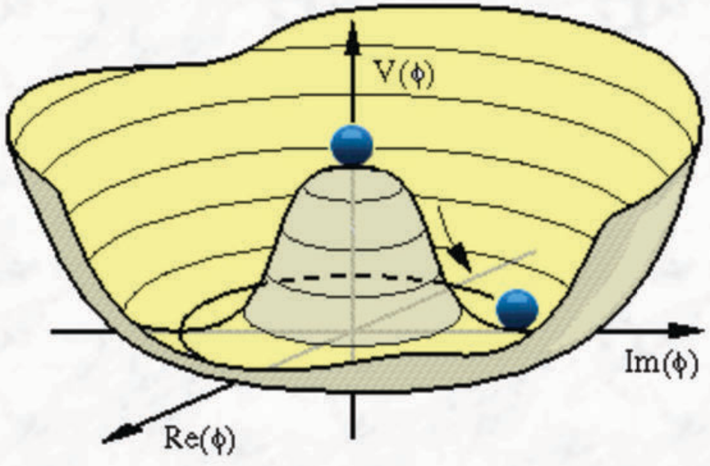
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

→ 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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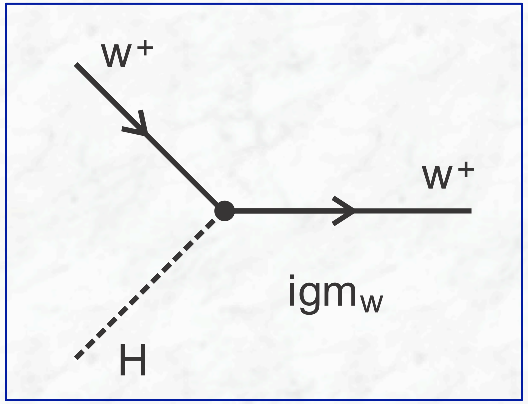
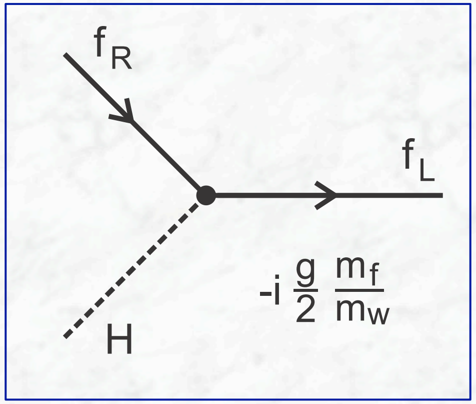
"Spontaneous Symmetry Breaking"



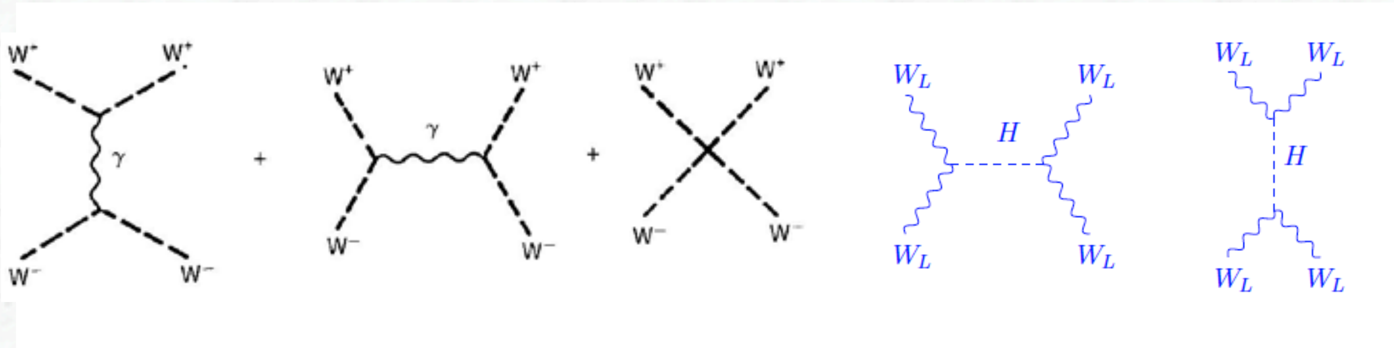


- Couplings proportional to mass

The Higgs field solves two fundamental problems:

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

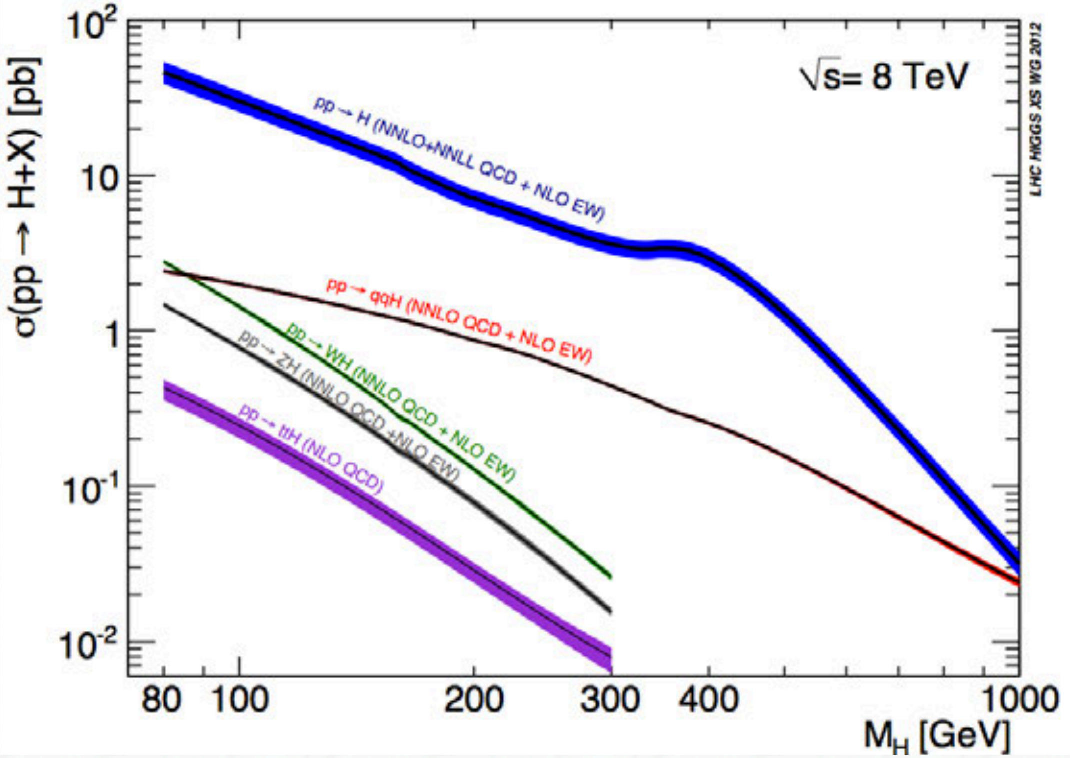
(ii) Divergences in the theory (scattering of W bosons)
("Ultraviolet regulator")

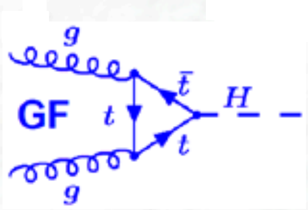


$$-iM(W^+W^- \to W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \to \infty$$ (no Higgs boson)

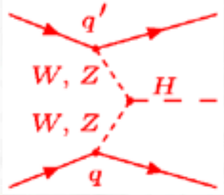
$$-iM(W^+W^- \to W^+W^-) \sim m_H^2 \quad \text{for} \quad s \to \infty$$ (with Higgs boson)

Higgs Boson Production



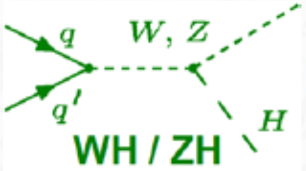


Gluon fusion

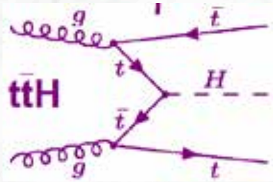


VBF

Vector boson fusion



WH/ZH associated production



tt associated production

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

Meanwhile the NNNLO = N^3LO 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

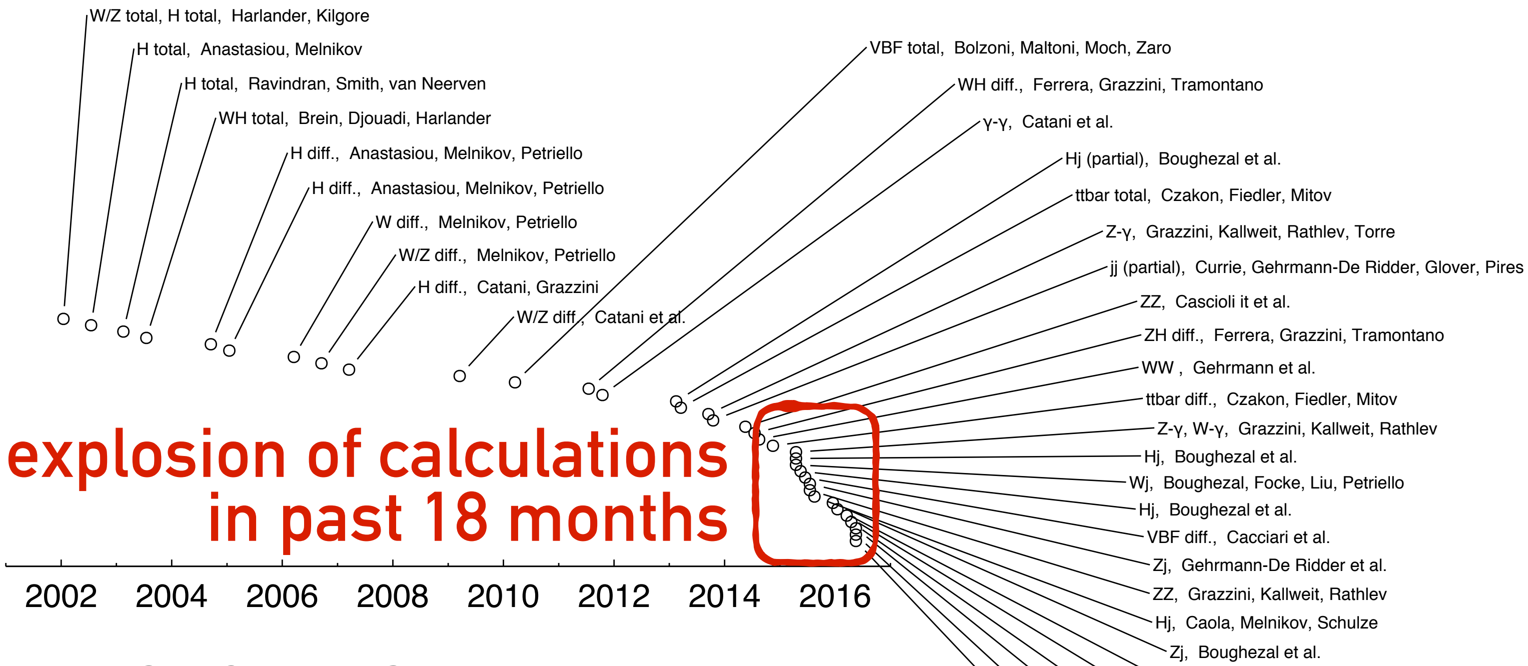


Figure by Gavin Salam at LHCP 2016

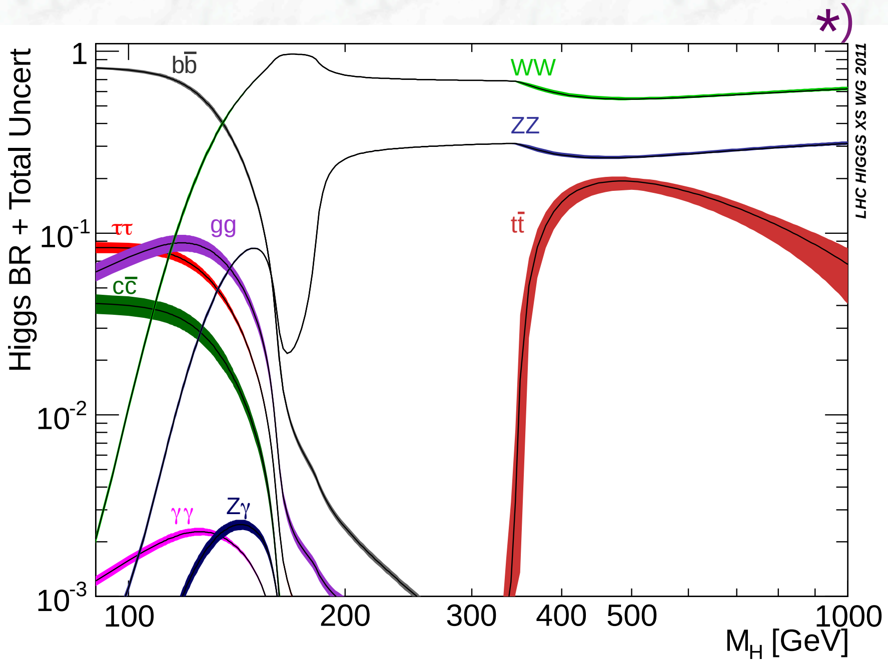
Also experimental knowledge of PDFs limits precision in many LHC analyses !

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
- γγ final states (despite small branching ratio)
- ττ final states (more difficult)
- In addition: H → bb decays via associated lepton signatures (VBF, VH or ttH production)

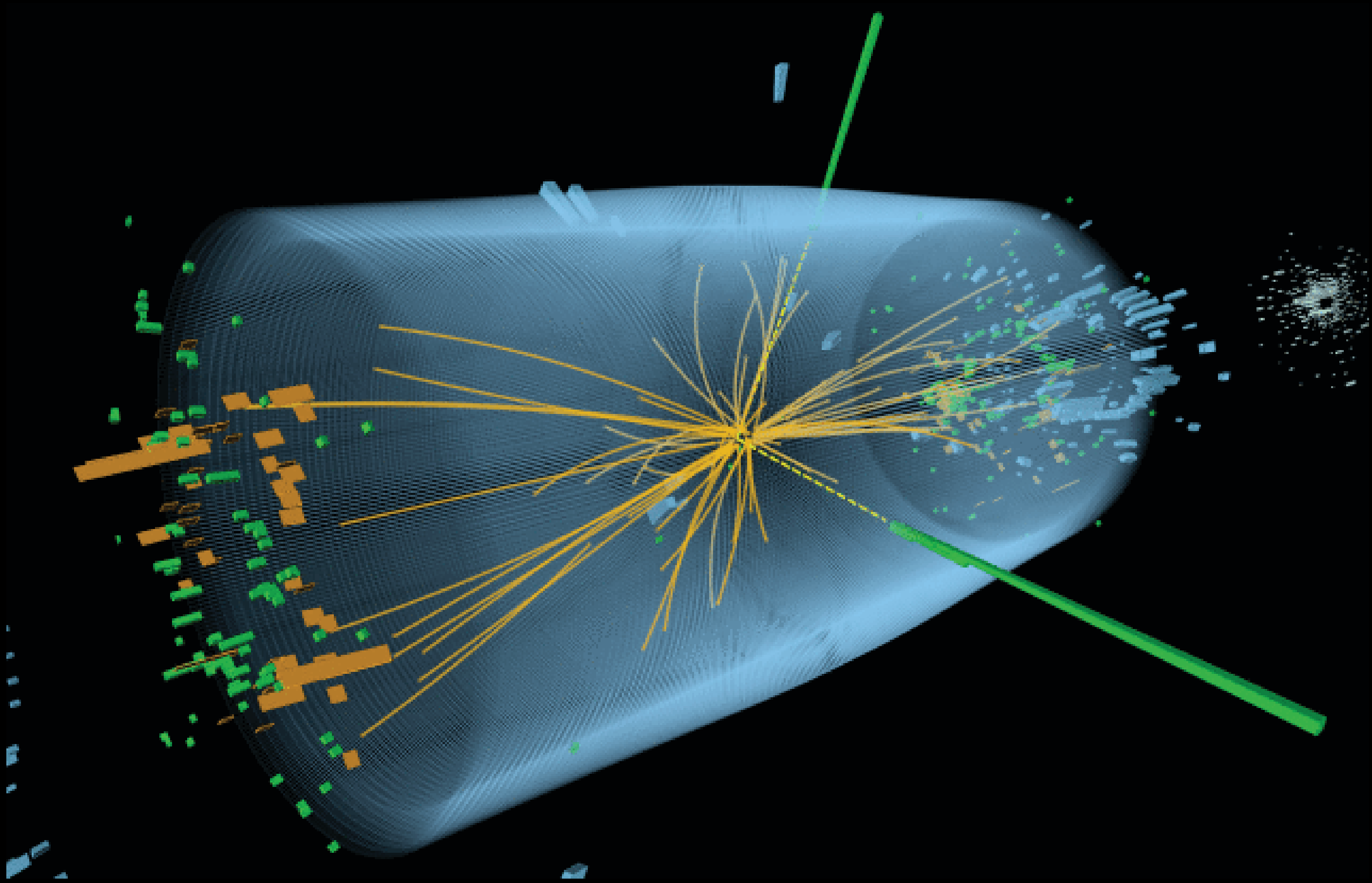
SM predictions (m_H = 125.5 GeV):

BR (H→ WW) = 22.3%	BR (H → bb) = 56.9%
BR (H → ZZ) = 2.8%	BR (H → ττ) = 6.2%
BR (H → γγ) = 0.24%	BR (H →μμ) = 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:

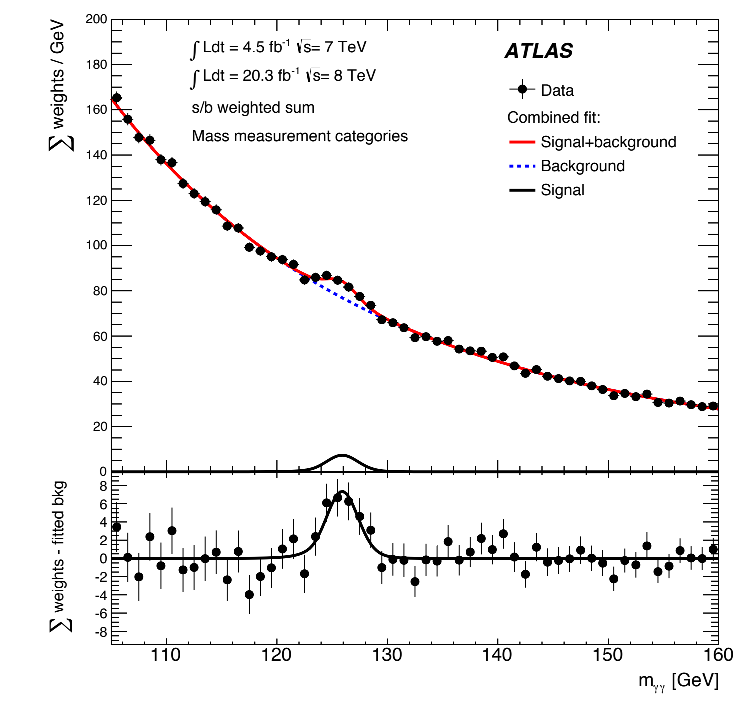
~ 950 $H \rightarrow \gamma\gamma$

~ 60 $H \rightarrow ZZ^* \rightarrow 4\ \ell$

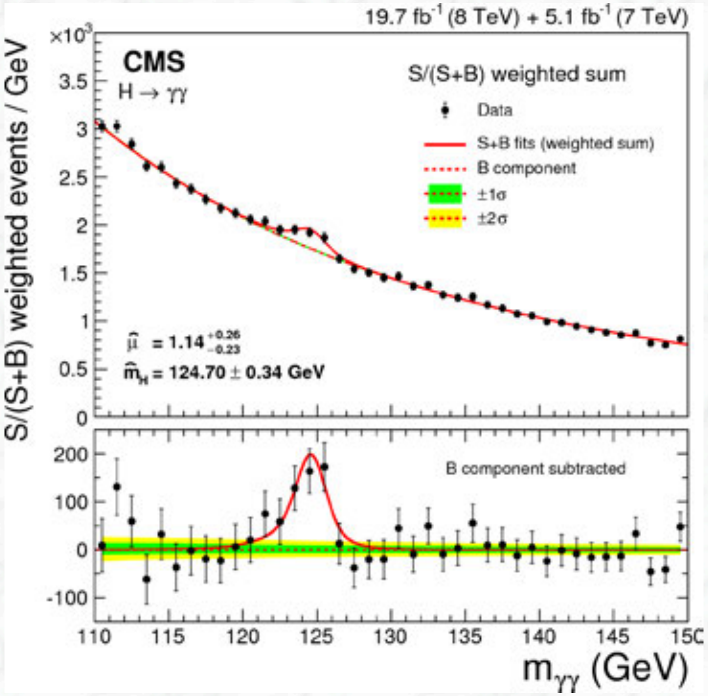
~ 9000 $H \rightarrow WW^* \rightarrow \ell\nu\ \ell\nu$

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



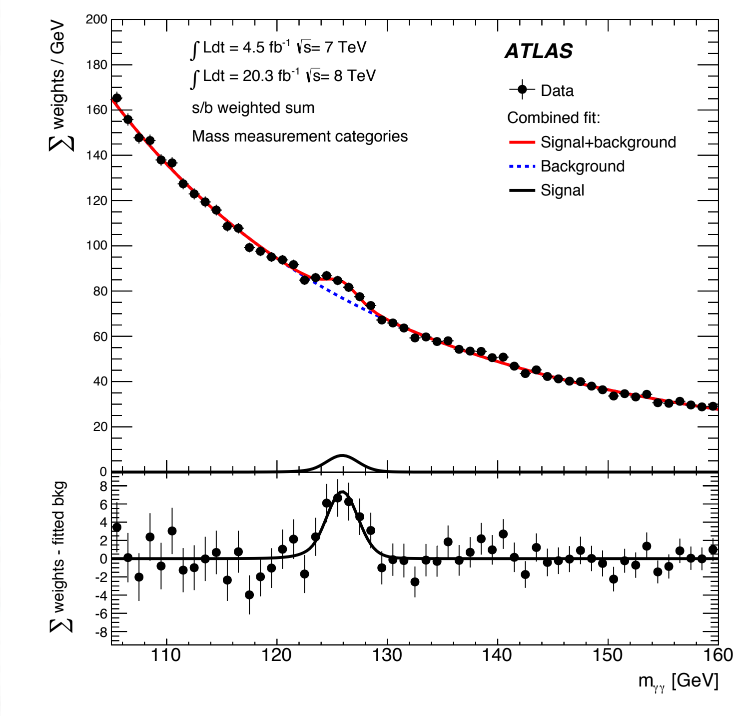
EPJ C74 (2014) 3076



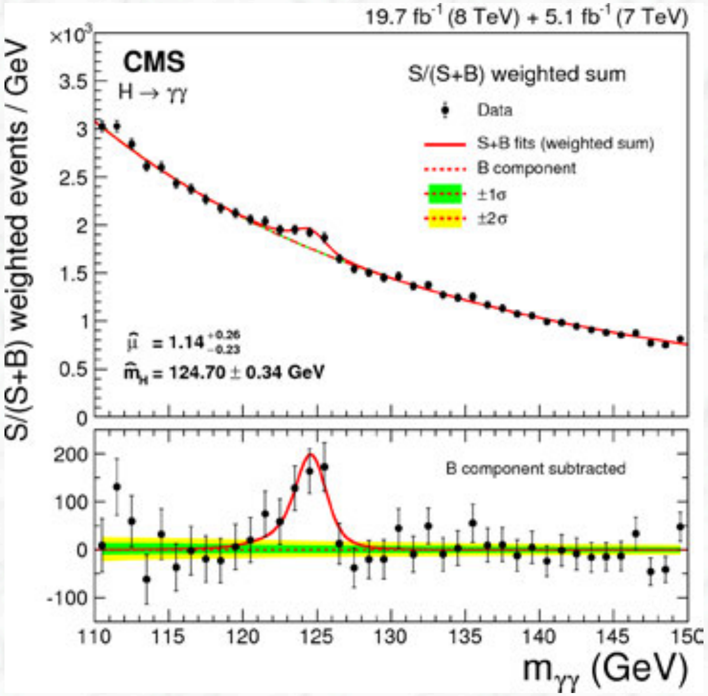
- Background interpolation in the region of the excess (obtained from sidebands)
- Reducible γ-jet and jet-jet background at the level of 25%
- High signal significance in both experiments: ATLAS: 5.2σ (4.6σ expected)
  CMS: 5.7σ (5.2σ expected)
- Establishes the discovery in this channel alone

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



EPJ C74 (2014) 3076

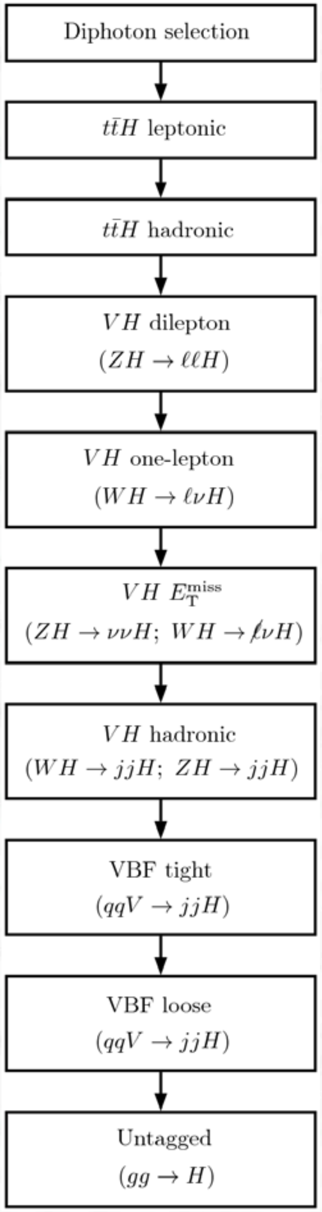


Measured signal strengths: $\mu = \sigma_{obs} / \sigma_{SM}$

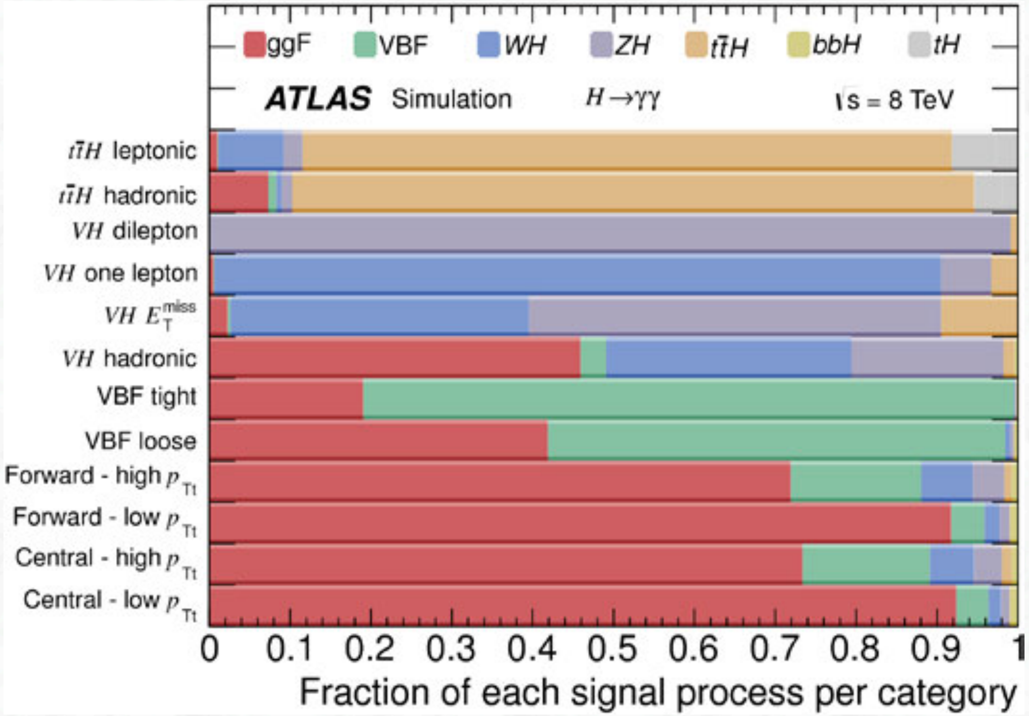
ATLAS: $\mu = 1.17 \pm 0.27$

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

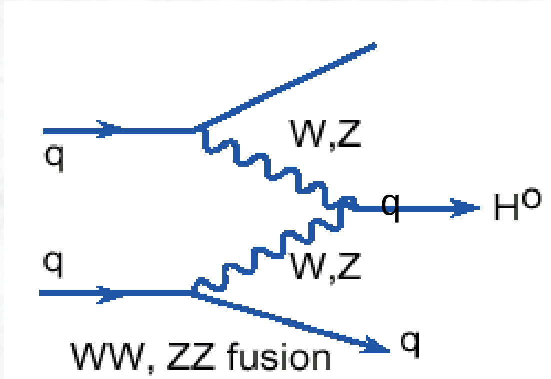
Vector Boson Fusion qqH

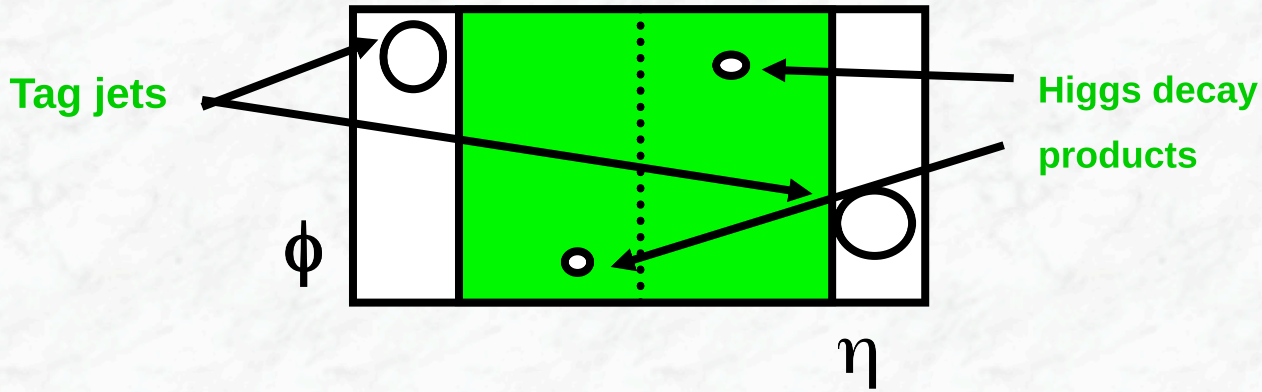
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to bosons, fermions, e.g. τ leptons)

Distinctive Signature of:

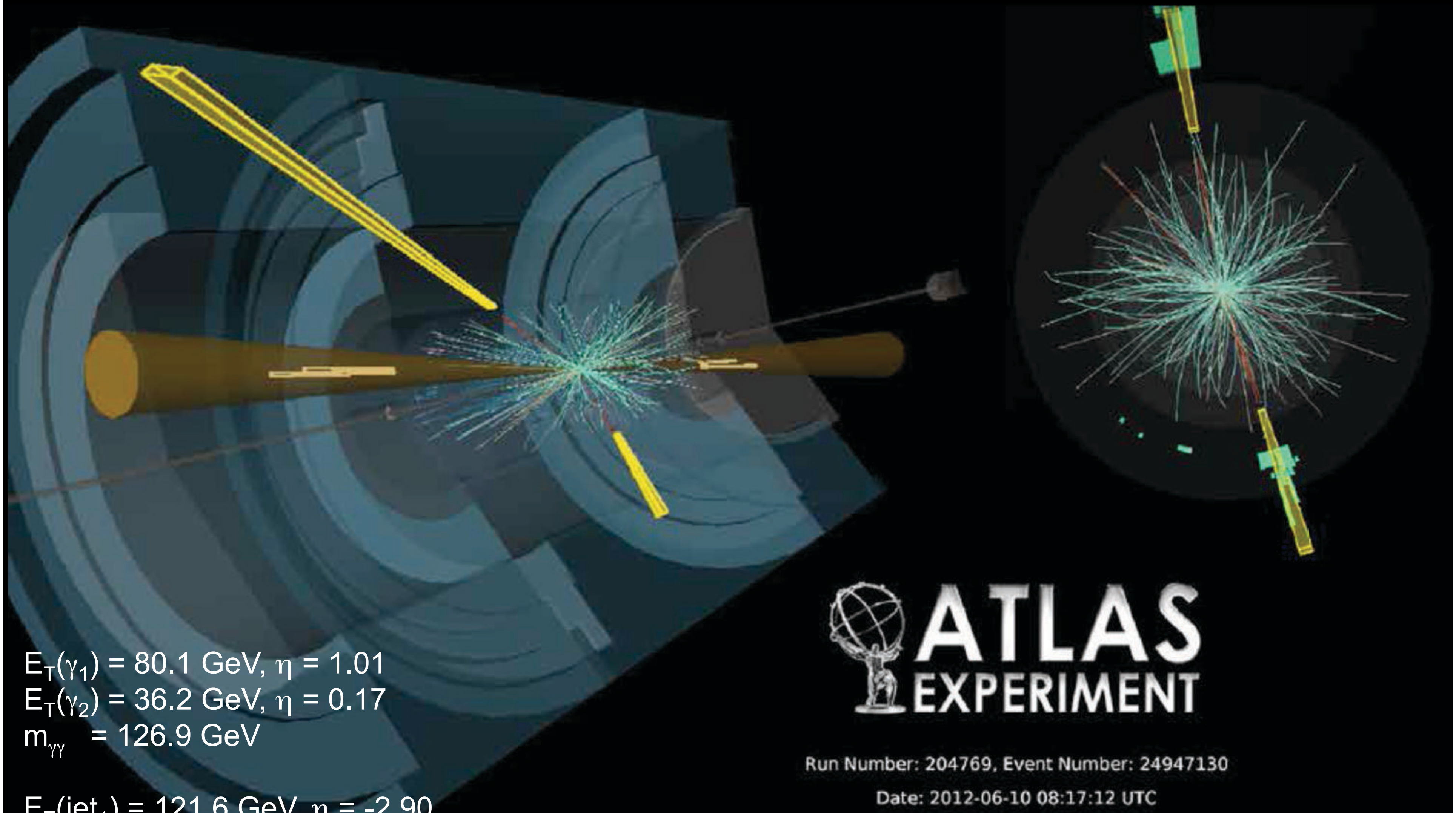
- Two high p_T forward jets (tag jets)
  Large invariant mass, large η separation

- Little jet activity in the central region
  (no colour flow)
  $\Rightarrow$ central jet Veto





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

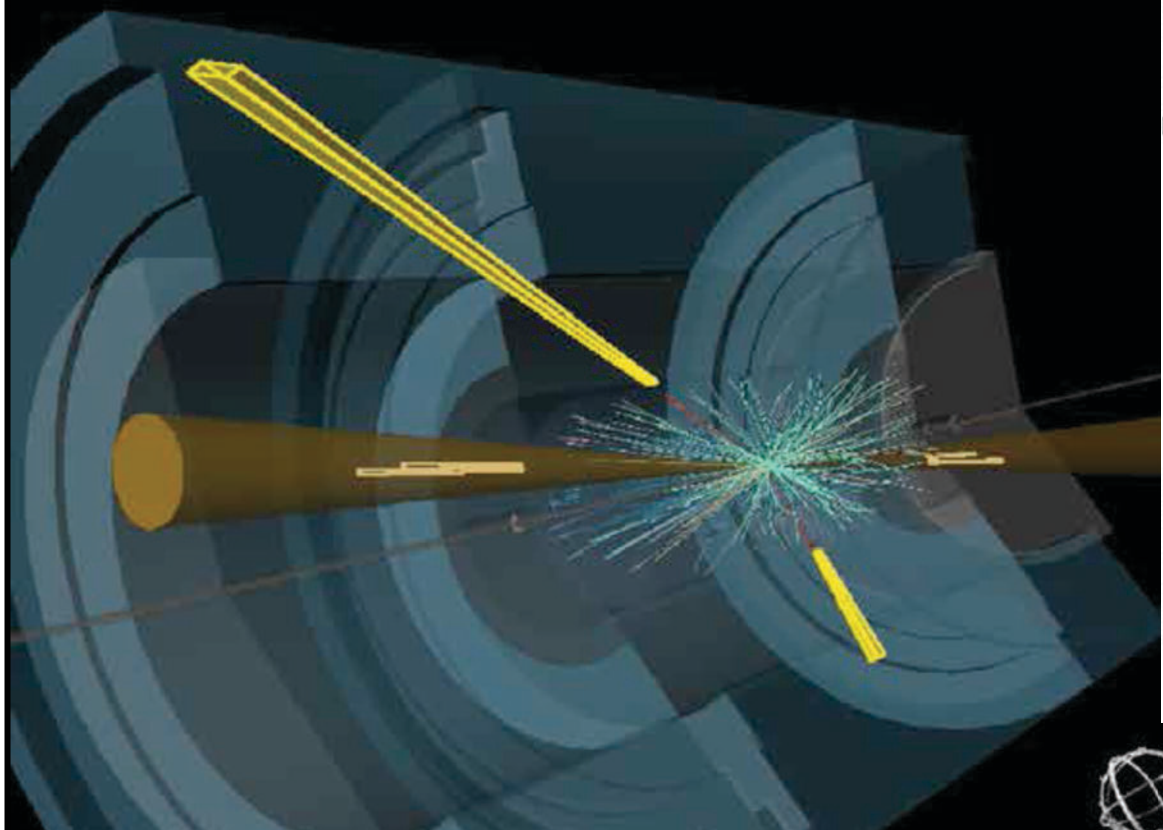


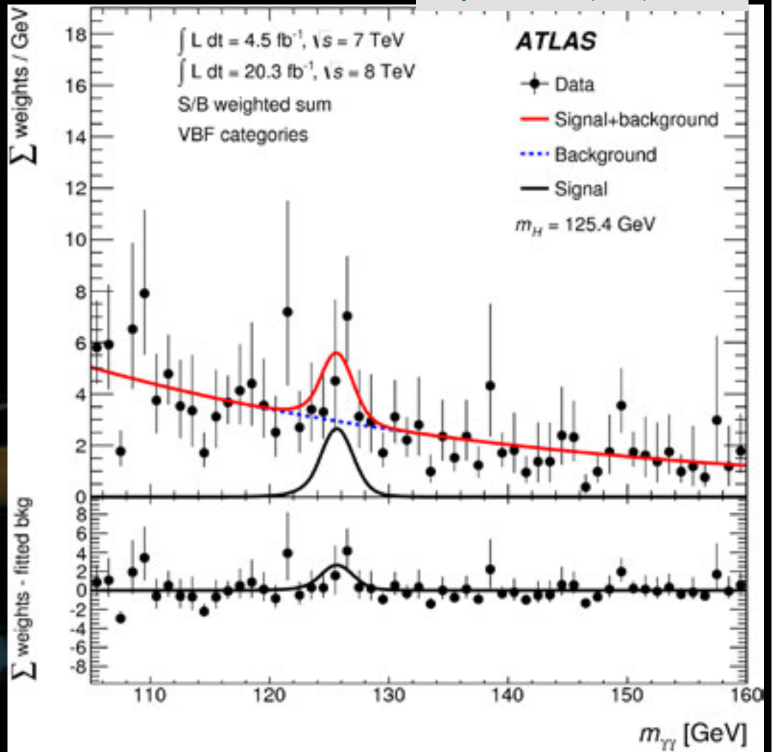
$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

$E_T(jet_1)$ = 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

Phys. Rev. D90 (2014) 112015





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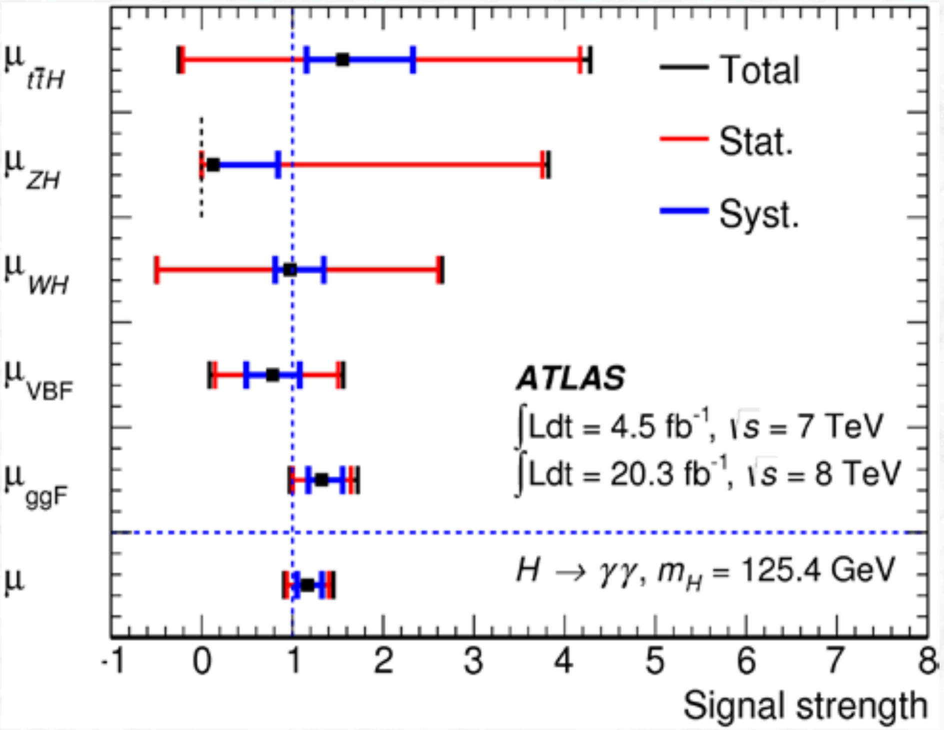
ATLAS EXPERIMENT

Run Number: 204769, Event Number: 24947130

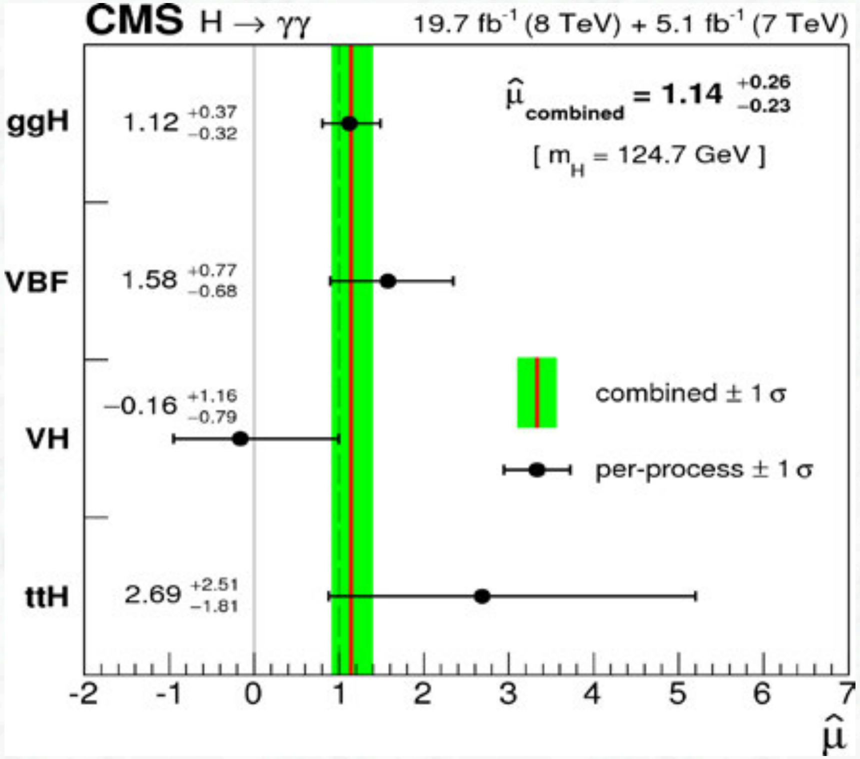
Date: 2012-06-10 08:17:12 UTC

γγ signal strengths for various production modes

Phys. Rev. D90 (2014) 112015

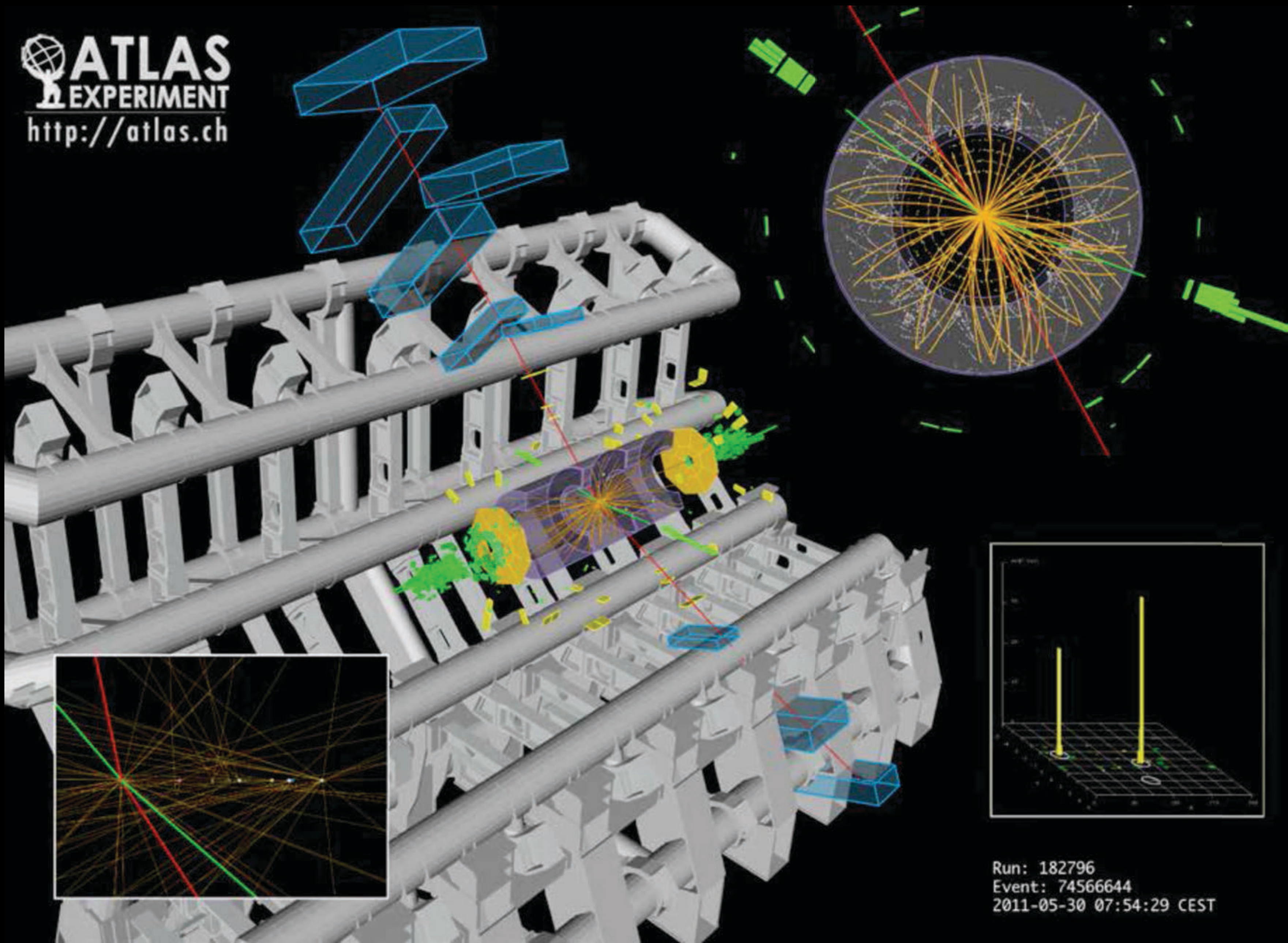


EPJ C74 (2014) 3076



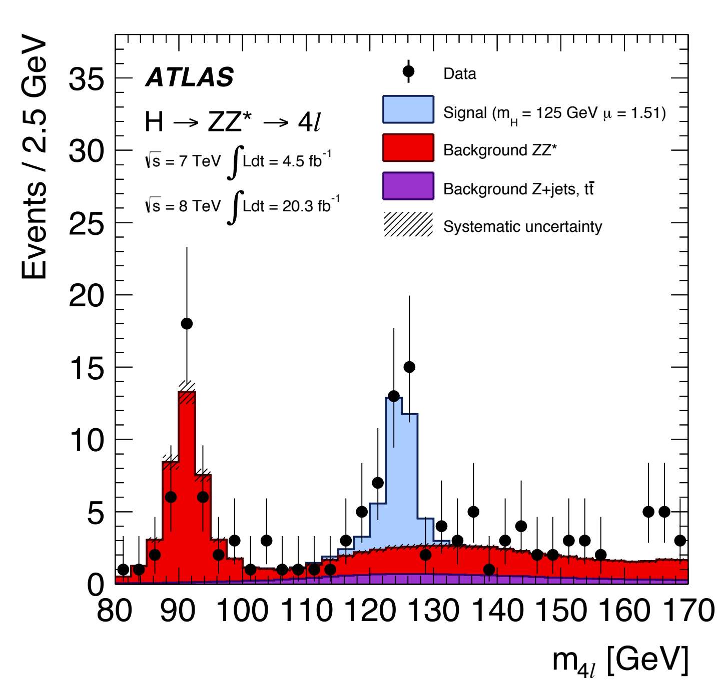
Fit results for individual production processes are consistent with the Standard Model expectations

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

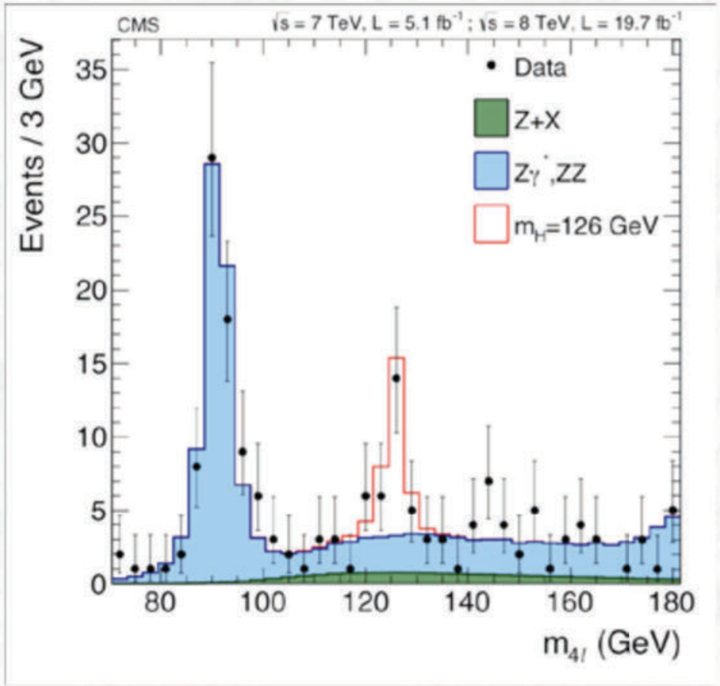


Reconstructed mass spectra from 4ℓ decays

Phys. Rev. D91 (2014) 012006



Phys. Rev. D89 (2014) 092007



Measured signal strengths:

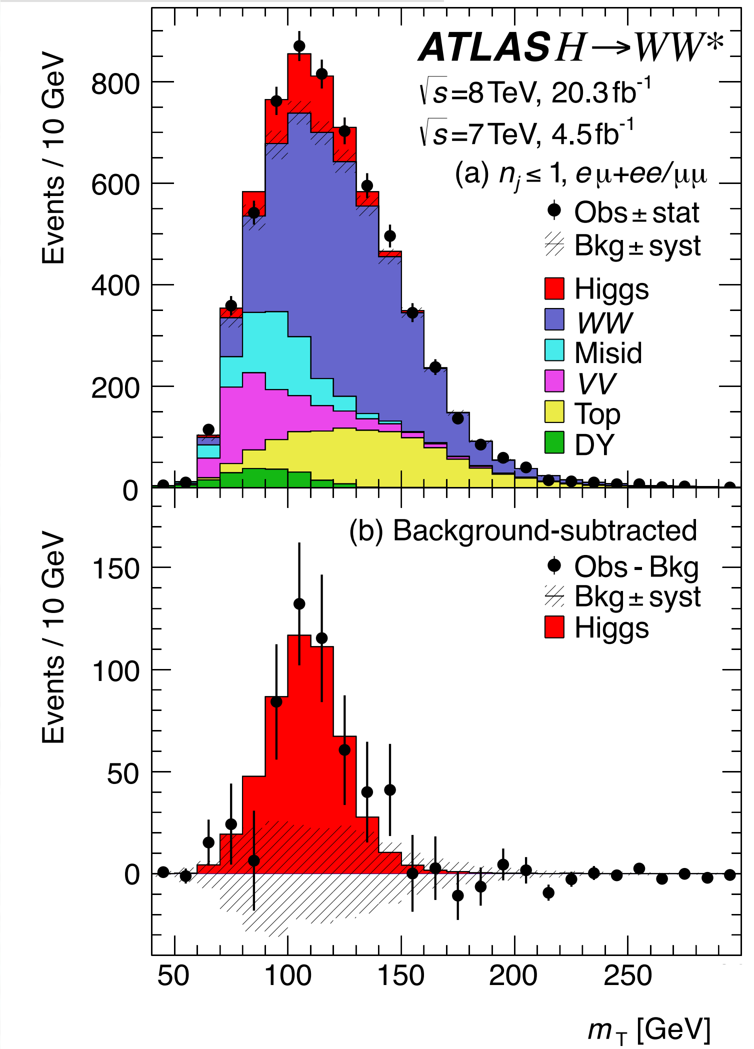
ATLAS: $\mu = 1.44^{+0.40}_{-0.33}$

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

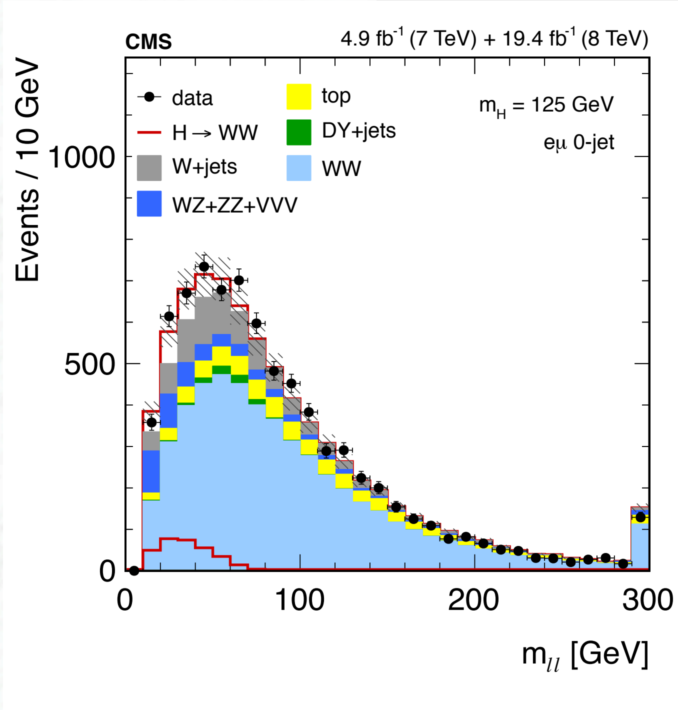
Significance in each experiment $> 6\sigma$

H → WW* → ℓν ℓν signal

Phys. Rev. D92 (2015) 012006



JHEP 01 (2014) 096



Measured signal strengths:

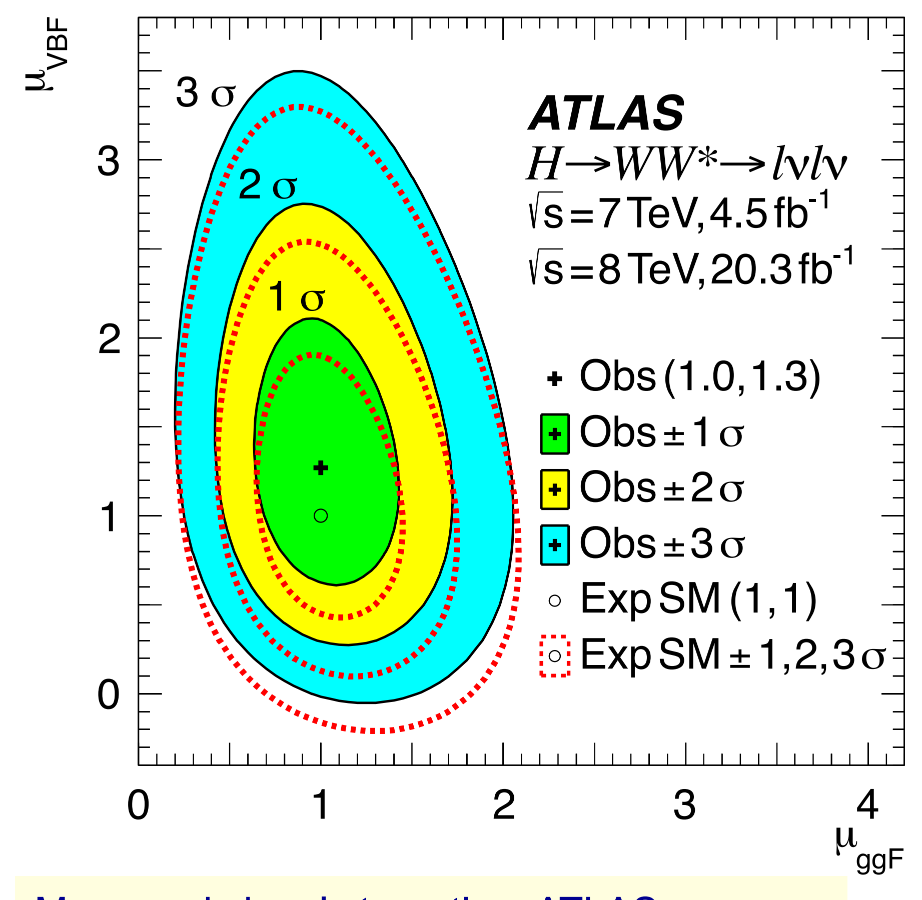
ATLAS: $\mu = 1.09\,^{+0.23}_{-0.21}$

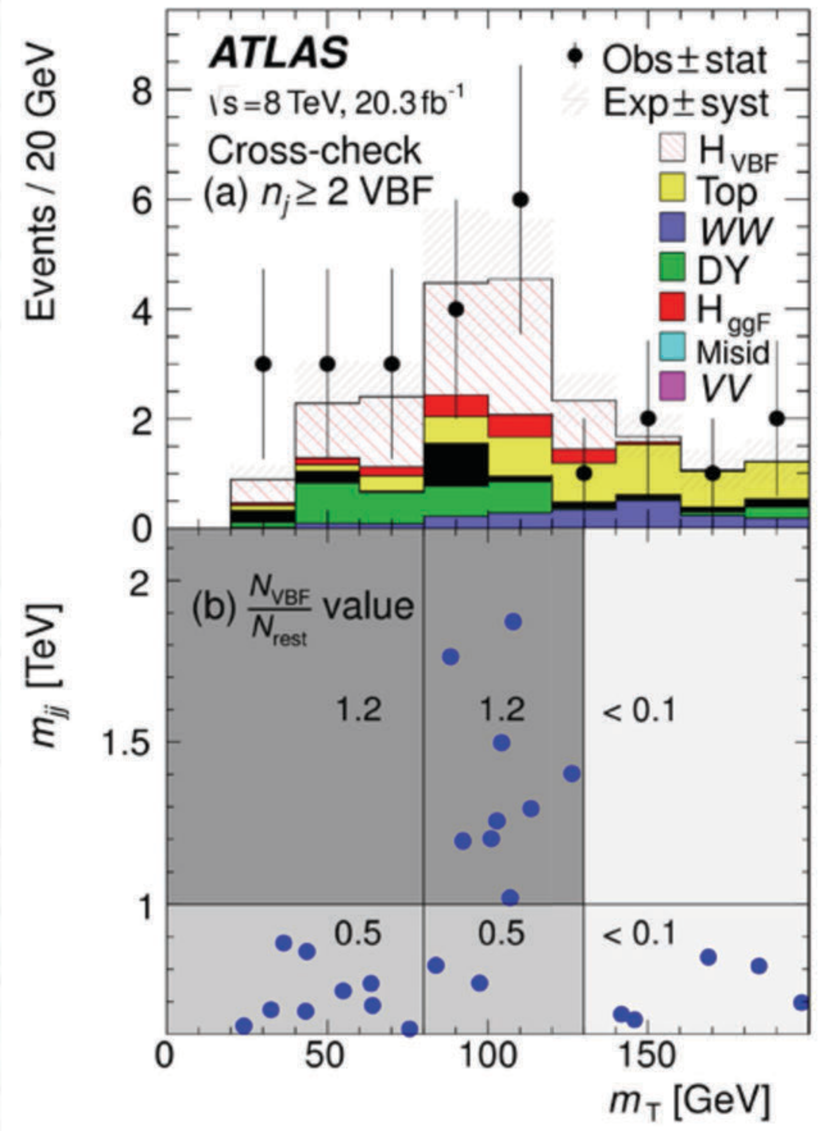
CMS: $\mu = 0.72\,^{+0.20}_{-0.18}$

- 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





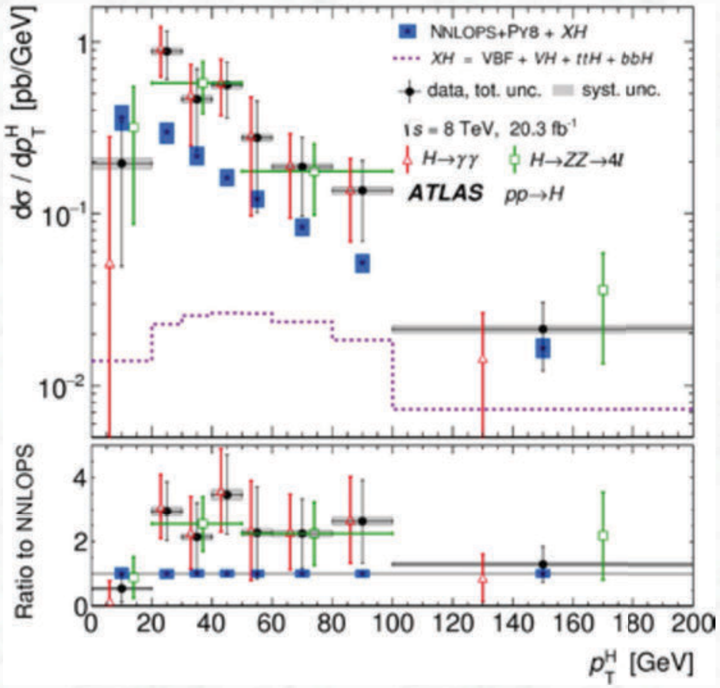
Measured signal strengths: ATLAS

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

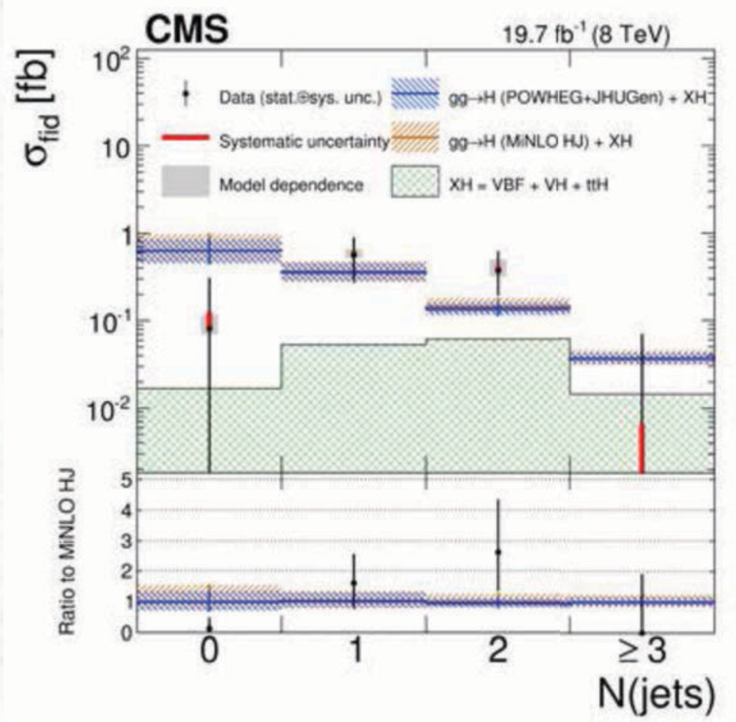
VBF: $\mu = 1.27^{+0.53}_{-0.45}$

Differential cross-section measurements

PRL 115 (2015) 091801



JHEP 04 (2016) 005

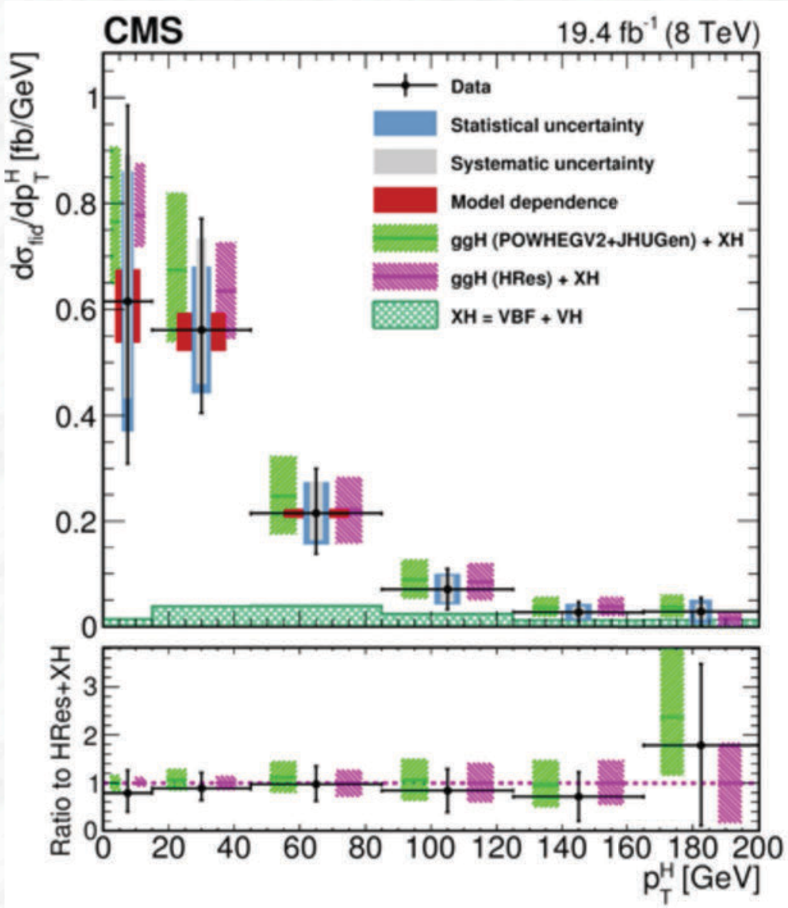


- First fiducial, differential cross-section measurements in bosonic channels
- Present experimental and theoretical uncertainties still large; “reasonable agreement” (statistical uncertainties: 25% - 75%)

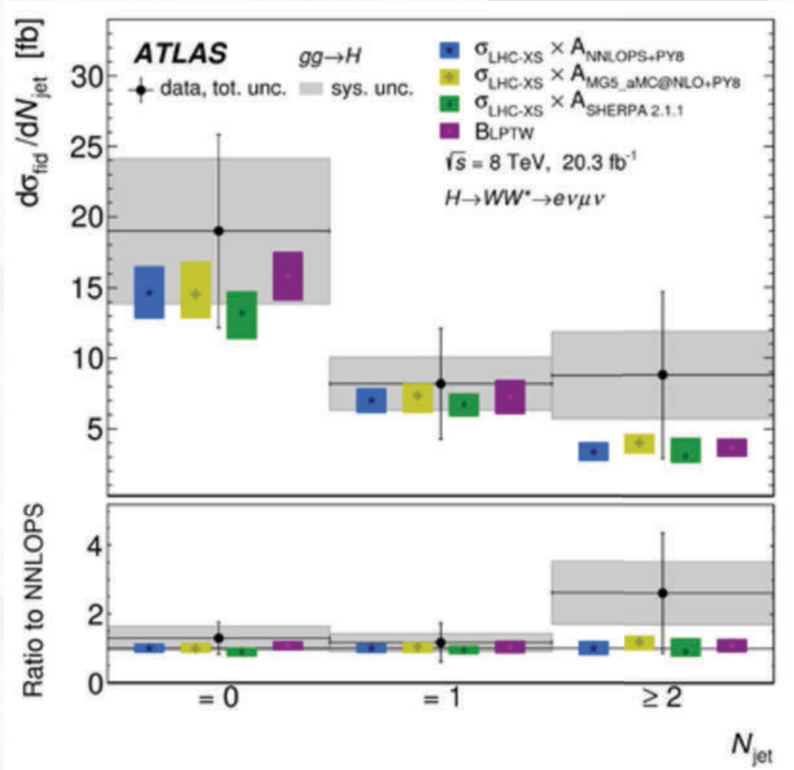
Differential cross-section measurements (cont.)

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

arXiv: 1606.01522

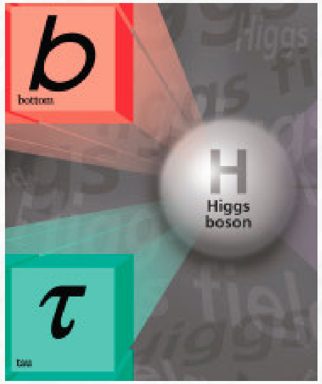


arXiv: 1604.02997

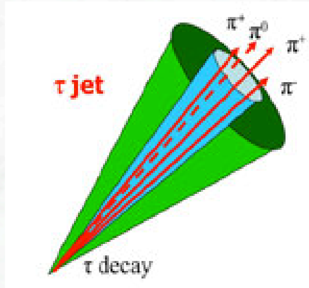


- Large future potential: probe Higgs boson kinematics, jet activity, VBF contributions, spin-CP nature, …

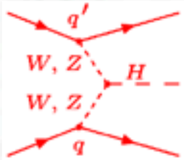
Couplings to quarks and leptons ?



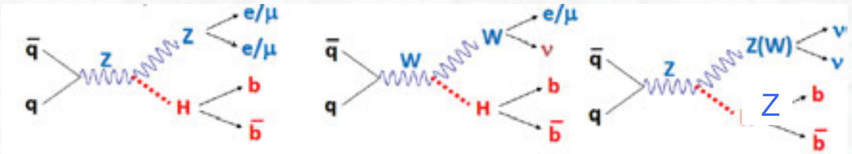
- Search for H → ττ and H → bb decays;
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays



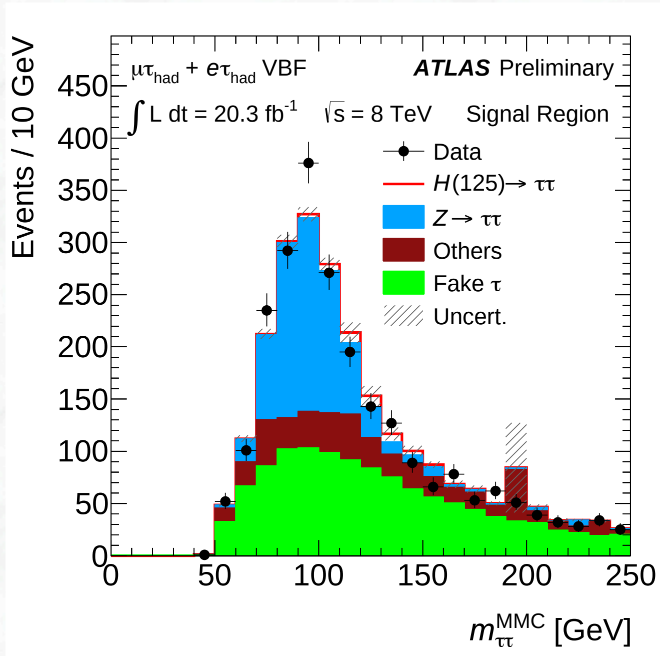
- Vector boson fusion mode essential for H → ττ decays



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

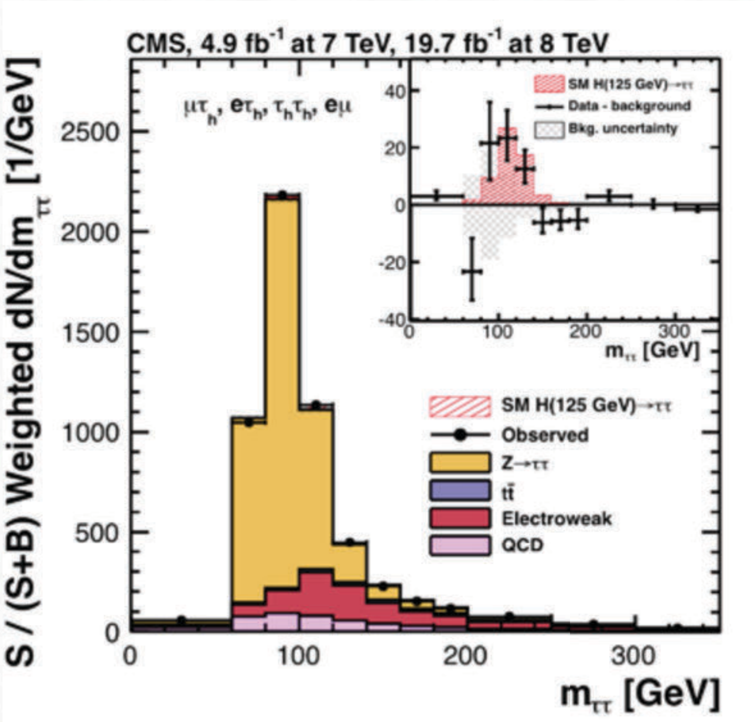


- Exploitation of multivariate analyses

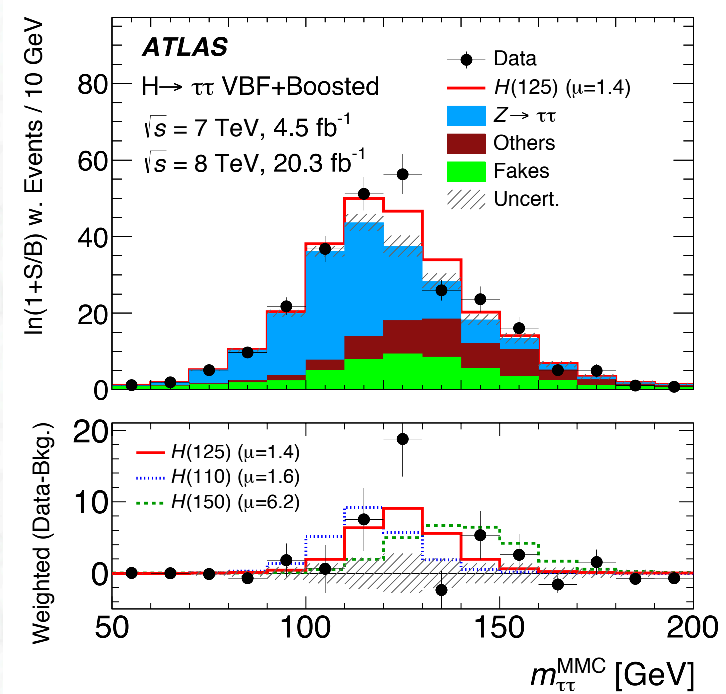


Evidence for H → ττ decays

JHEP 05 (2014) 104



JHEP 04 (2015) 117



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

Measured signal strengths:

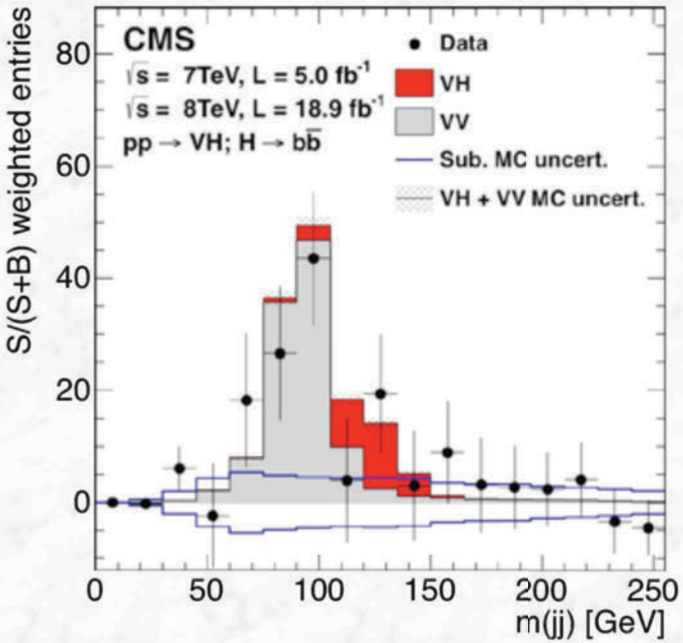
ATLAS: $\mu = 1.43\ ^{+0.43}_{-0.37}$ (4.5σ)

CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

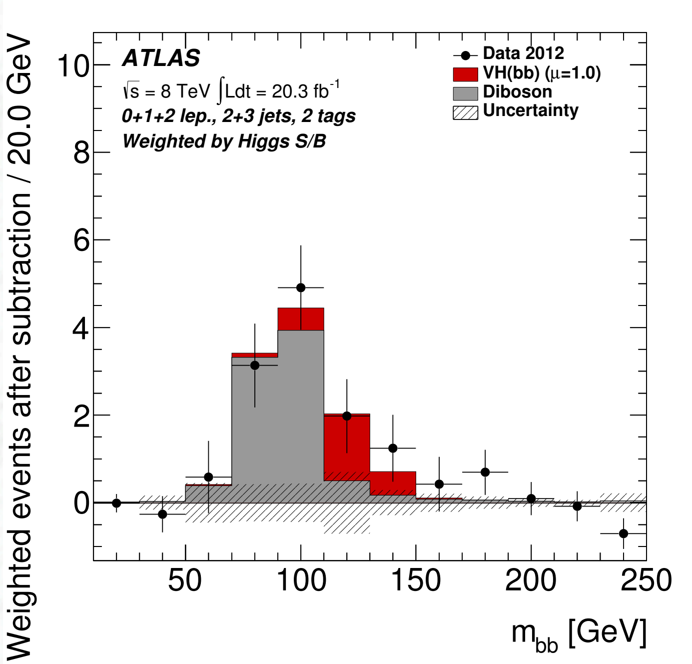
One of the most important LHC results in 2014 / 2015

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

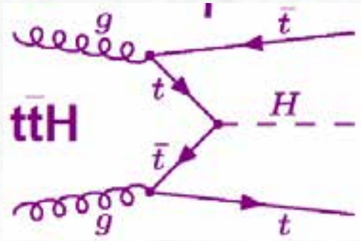
Signal strengths:

ATLAS: $\mu = 0.50 \pm 0.36$

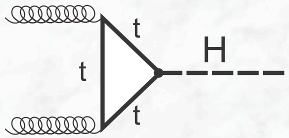
CMS: $\mu = 1.0 \pm 0.5$

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)

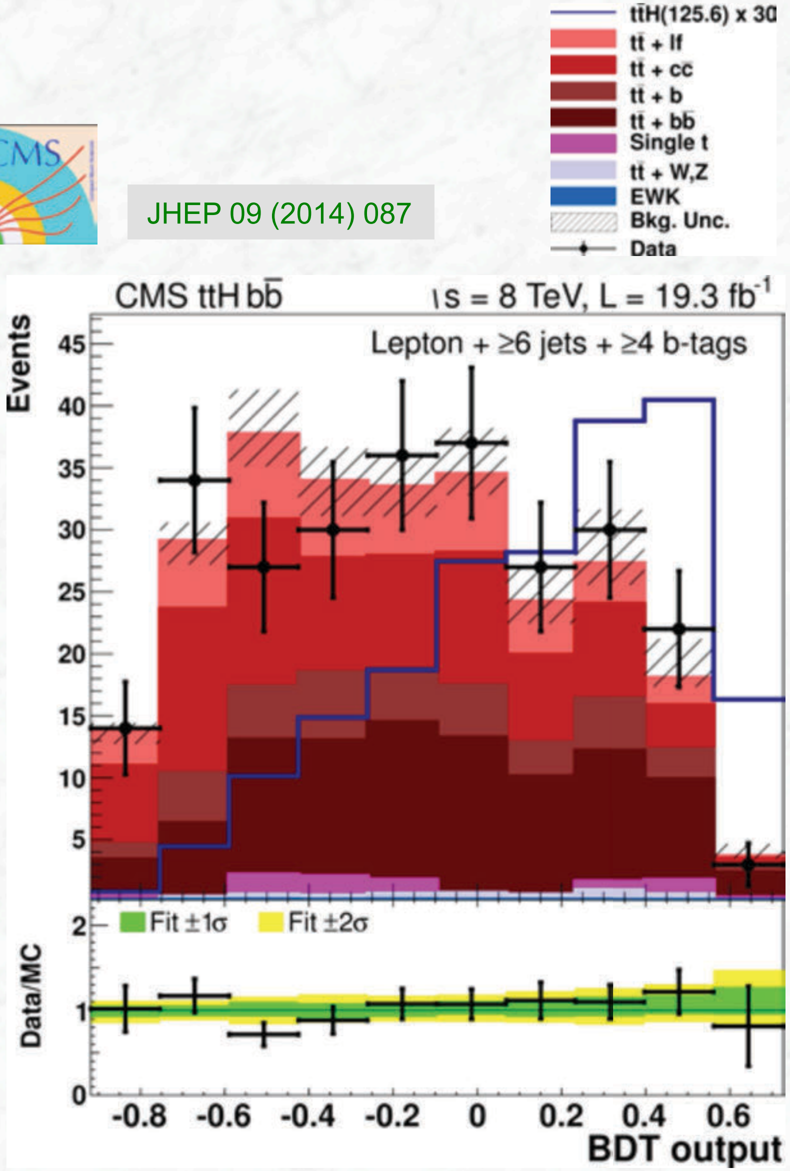
- It is critical to model the tt background in peculiar phase-space regions

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

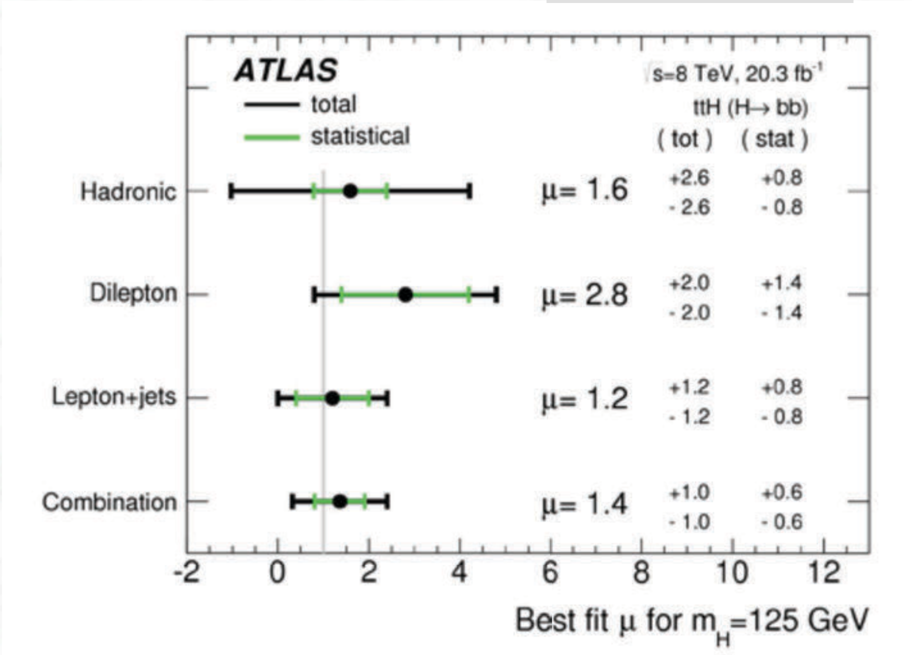
- Complicated analyses, multivariate techniques heavily used

Results on the search for ttH, H → bb decays

JHEP 09 (2014) 087

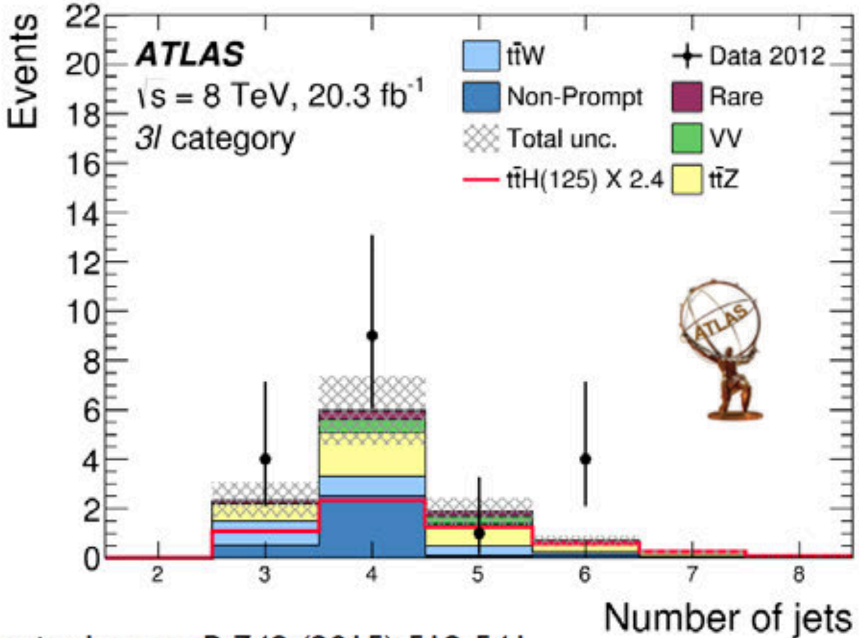


JHEP 05 (2016) 160

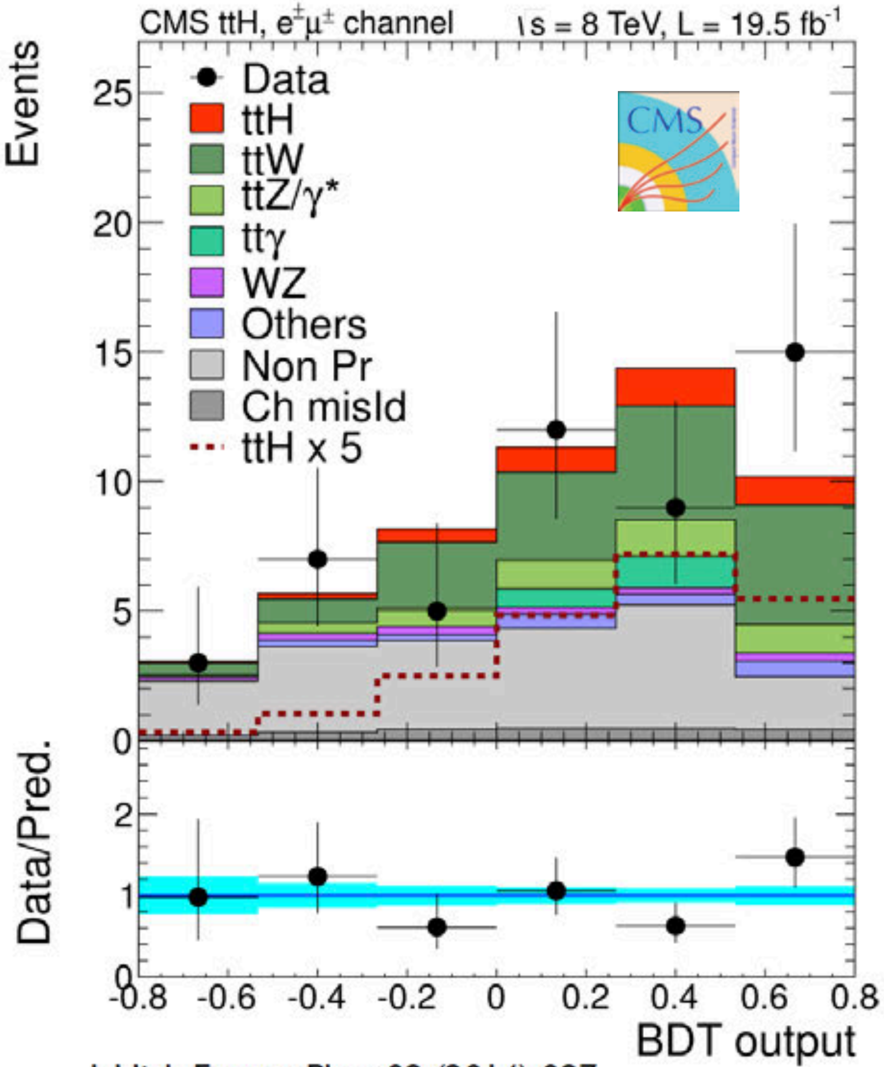


Results on the search for ttH, (→ multileptons)

- 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



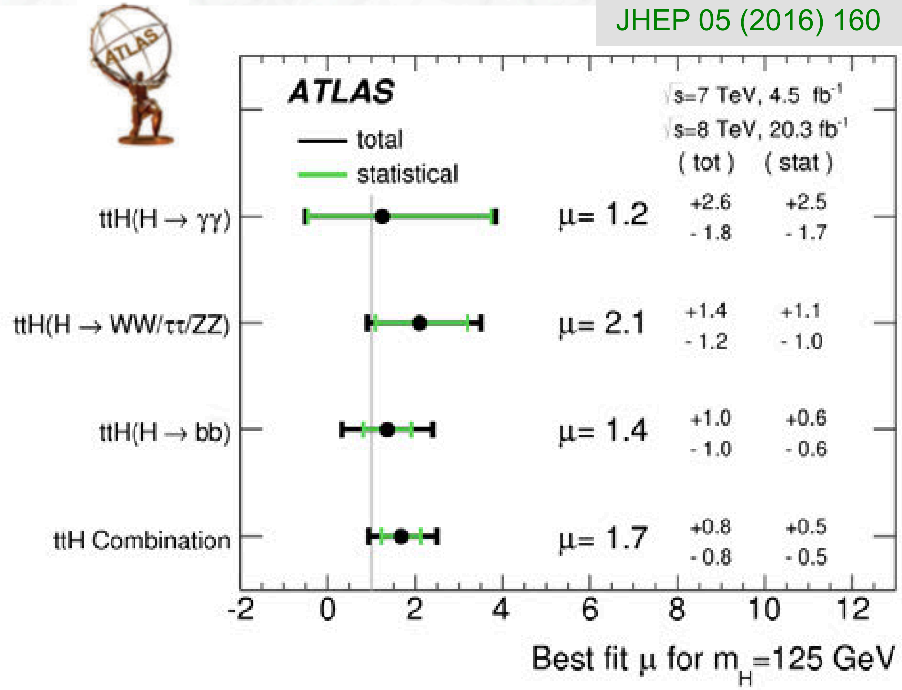
J. High Energy Phys. 09 (2014) 087

Summary of Run-1 Results on ttH production

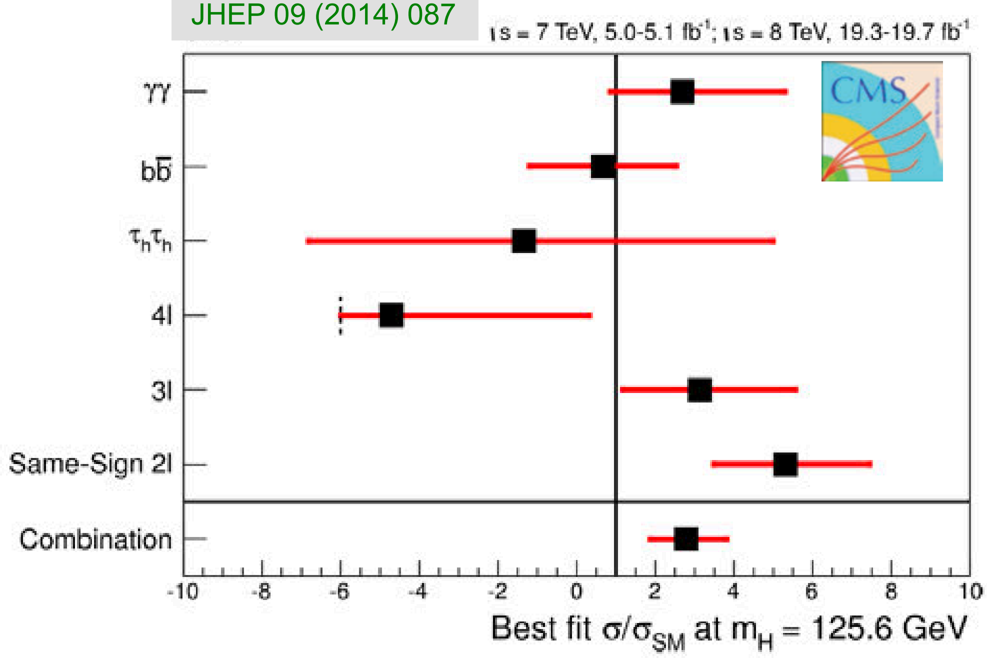
- Even after the combination of the results of all different ttH channels, the observed significance based on Run-1 data is marginal
  However, it adds to the determination of Higgs boson couplings

- Much more data needed → important measurements in Run 2

JHEP 05 (2016) 160



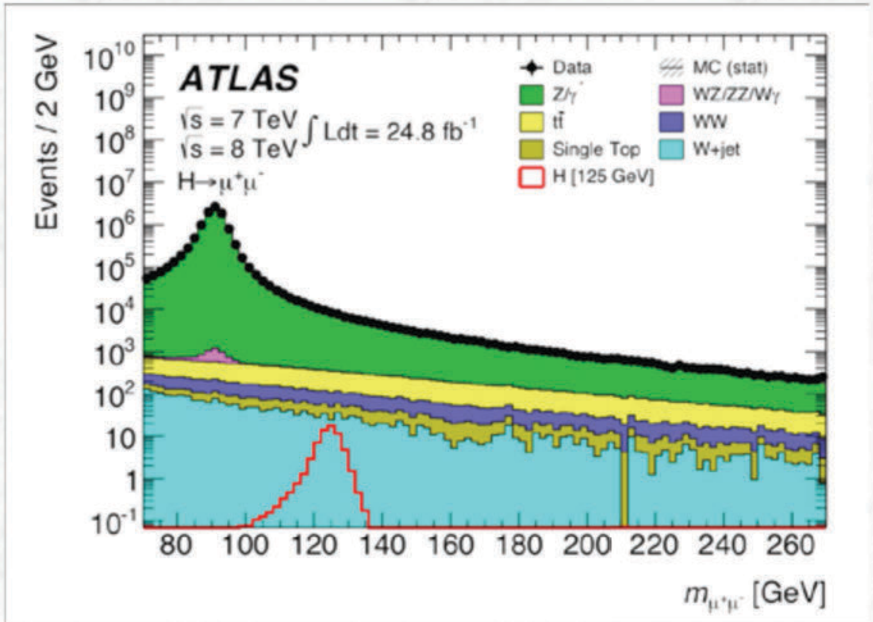
JHEP 09 (2014) 087

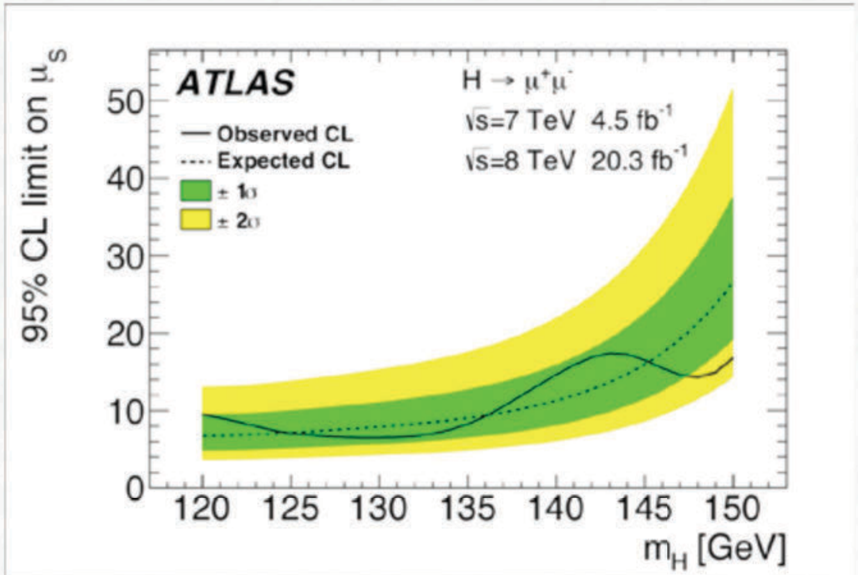


Both experiments measure large m values for this production mode, however, large uncertainties

Results on the search for H→ μμ decays

Phys. Lett. B738 (2014) 68





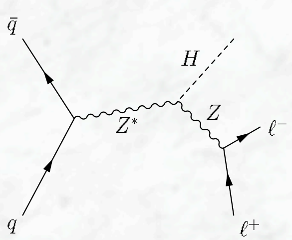
m_H = 125 GeV:

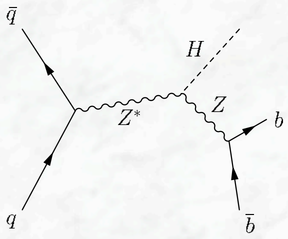
ATLAS 95% CL: 7.0σ_{SM} (7.2 expected, no Higgs) [Phys. Lett. B738 (2014) 68]
CMS 95% CL: 7.4σ_{SM} (6.5 expected, no Higgs) [Phys. Lett. B744 (2015) 184]

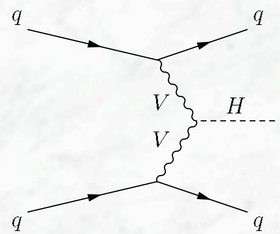
→ BR (H → μμ) < ~1.5 10^{-3}
Significantly smaller than BR(H → ττ) → no evidence for flavour-universal coupling

Search for invisible Higgs boson decays

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

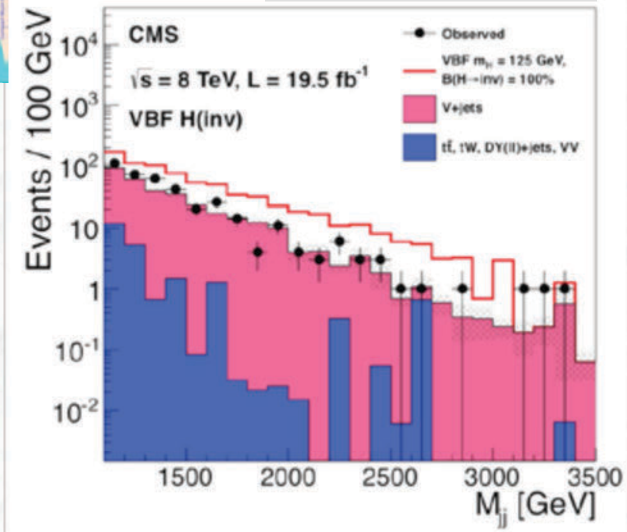






- Search for excess in ZH associated production and VBF production

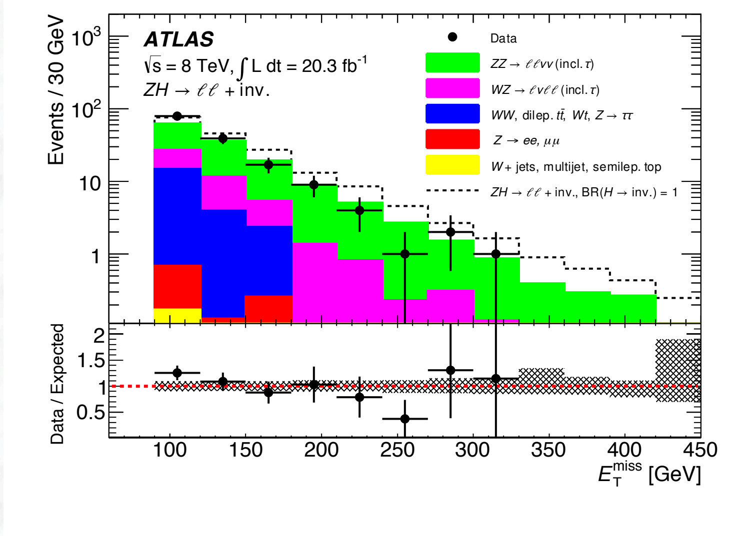
EPJ C74 (2014) 2980



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]

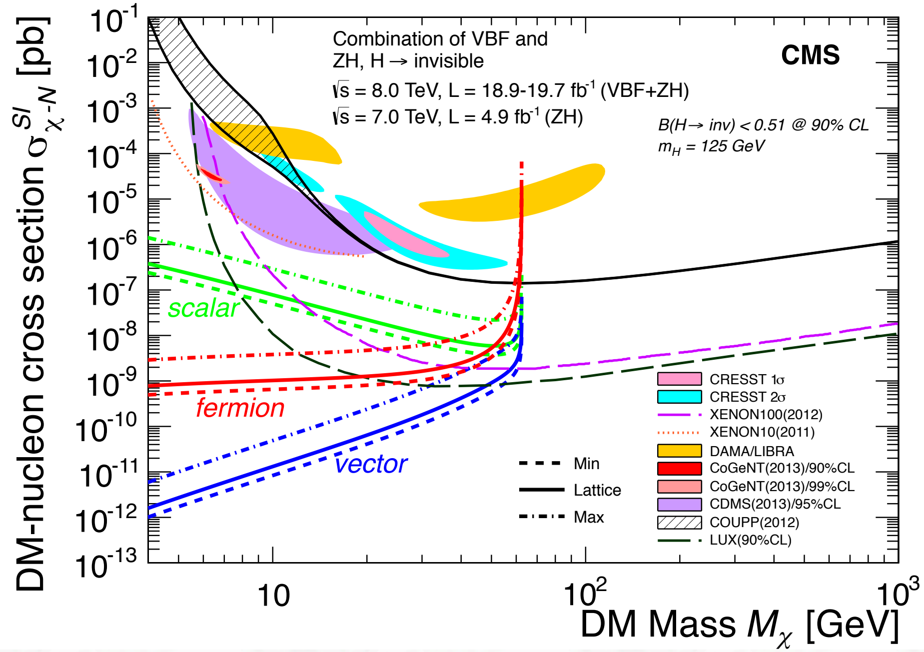
CMS: 95% CL on BR (H → inv.) < 0.58 (from ZH + VBF combination)

Interpretation in Higgs-portal models

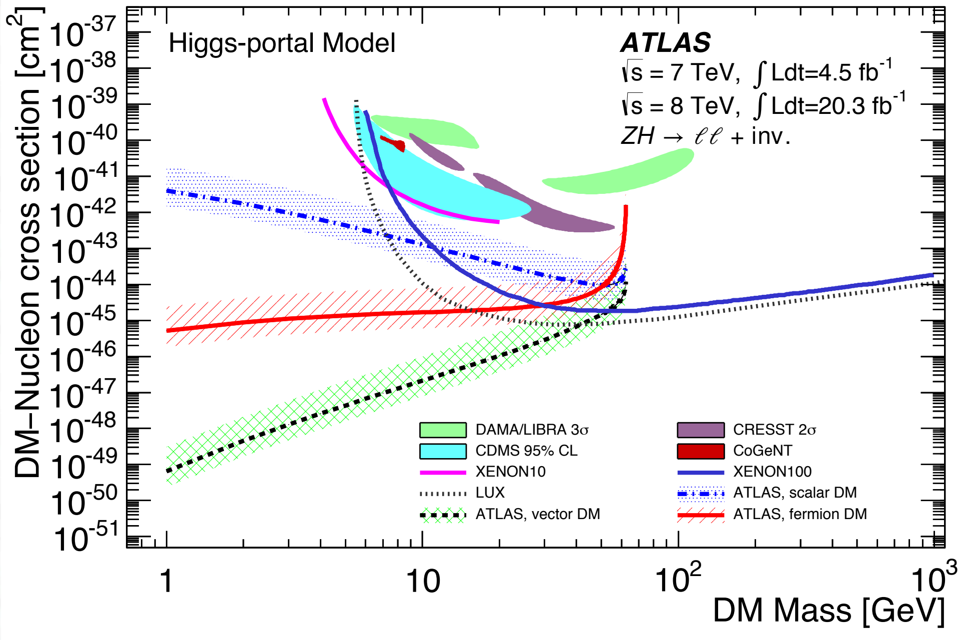
-Stable dark matter particles with couplings to the Higgs boson-

- 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

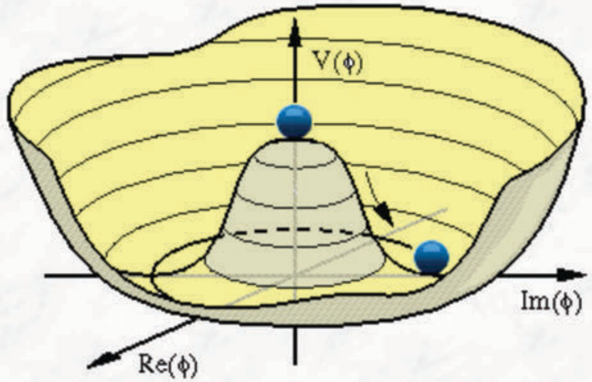


PRL 112 (2014) 201802



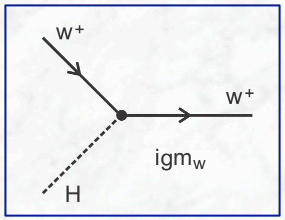
Profile of the New Particle

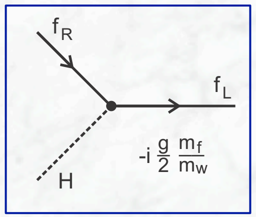
Is it the Standard Model Higgs Boson?



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

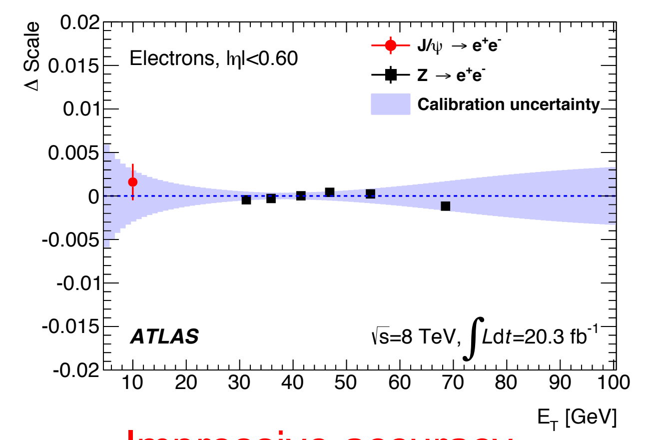
Couplings to bosons and fermions



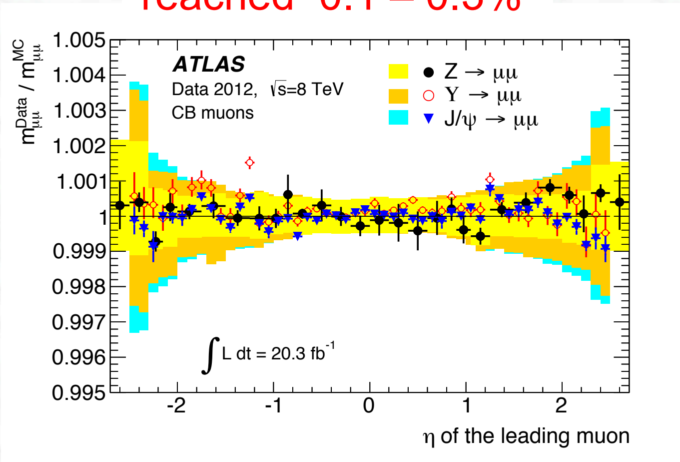


Higgs boson mass

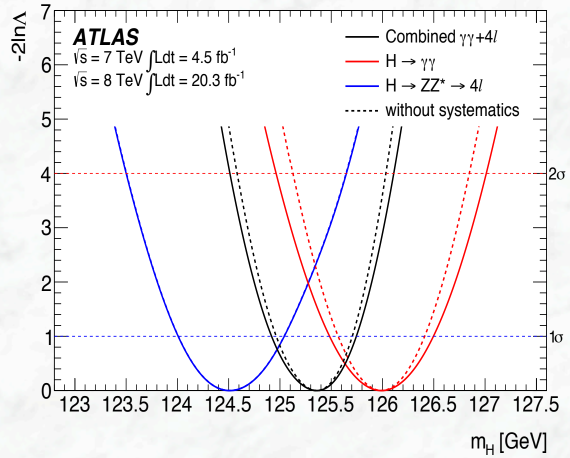
- The two high resolution channels H → ZZ*→ 4ℓ and H → γγ are best suited (reconstructed mass peak, good mass resolution)
- Good control of the lepton and photon energy scales, calibration via Z → ℓℓ and J/ψ and ϒ signals, improved understanding of lepton and photon reconstruction



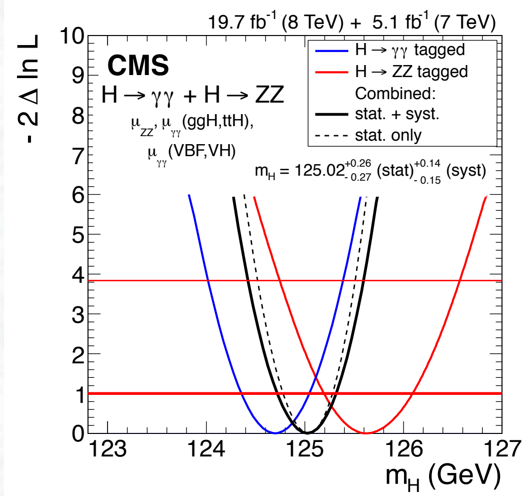
Impressive accuracy reached 0.1 – 0.3%



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