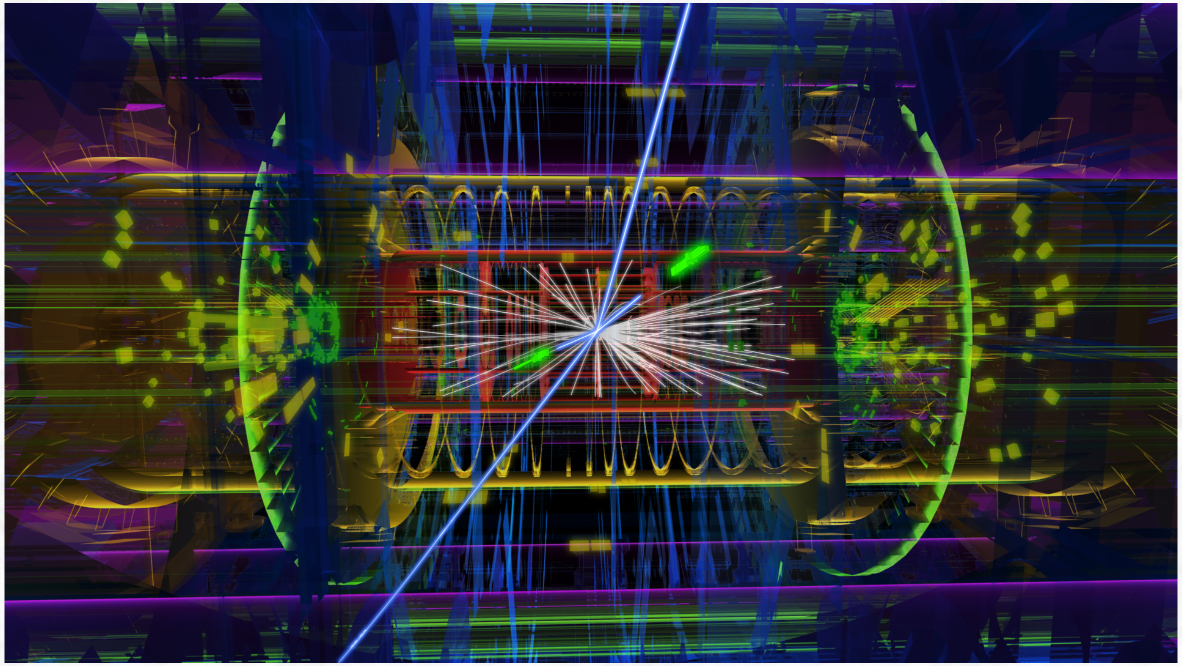
Experimental Status and Recent Progress on Electroweak Symmetry Breaking



Karl Jakobs, University of Freiburg

-Results from the ATLAS and CMS Collaborations-

"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)

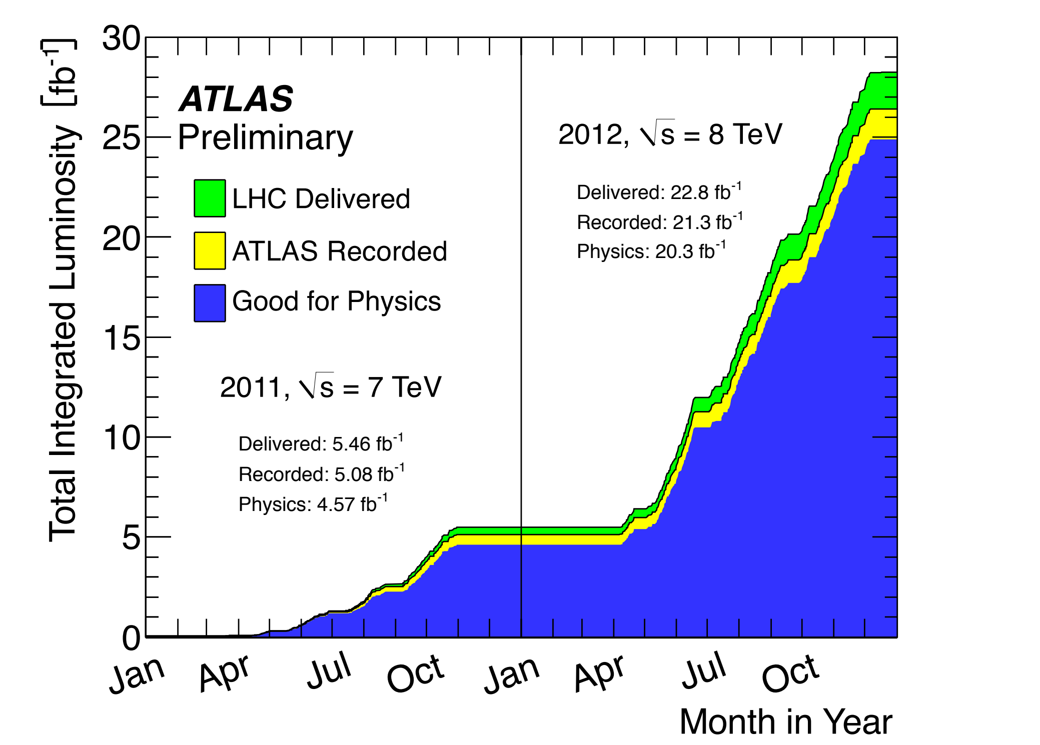
- Additional Higgs bosons?

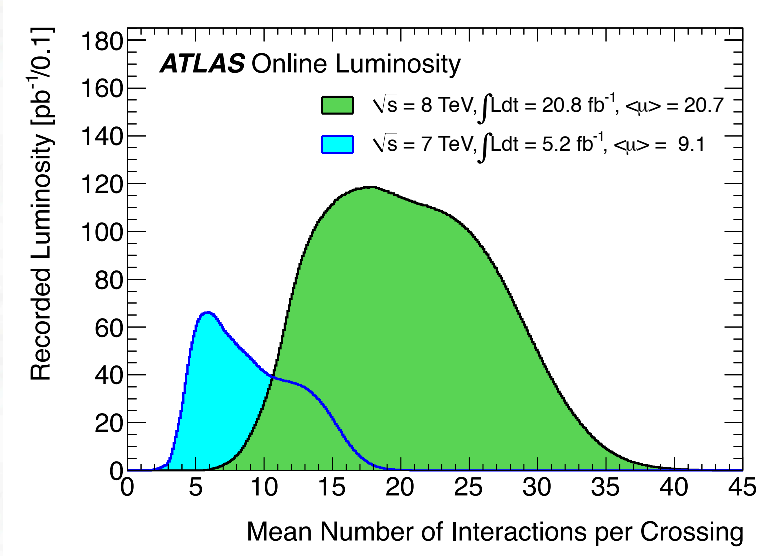
- Prospects for LHC Run 2

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

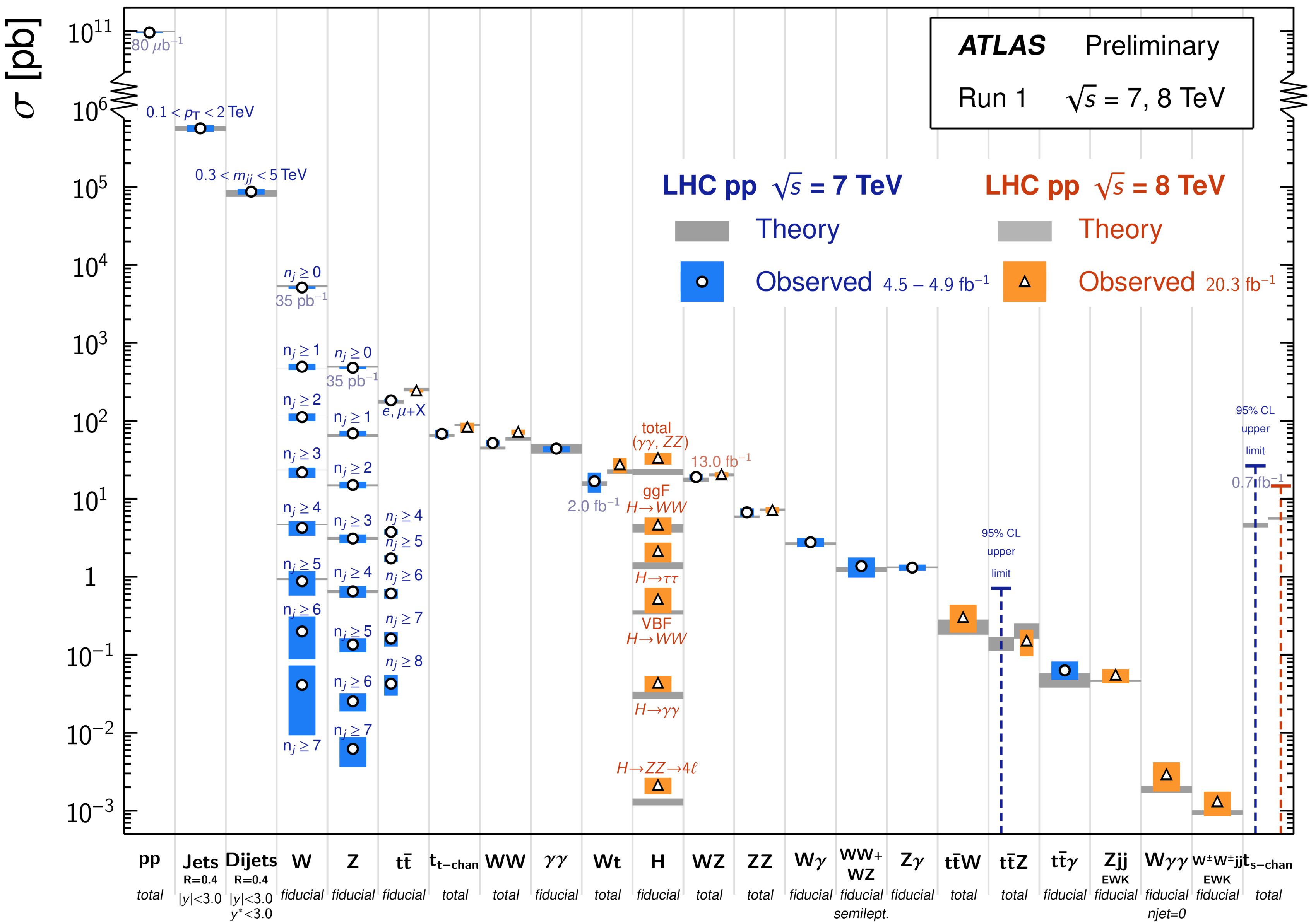


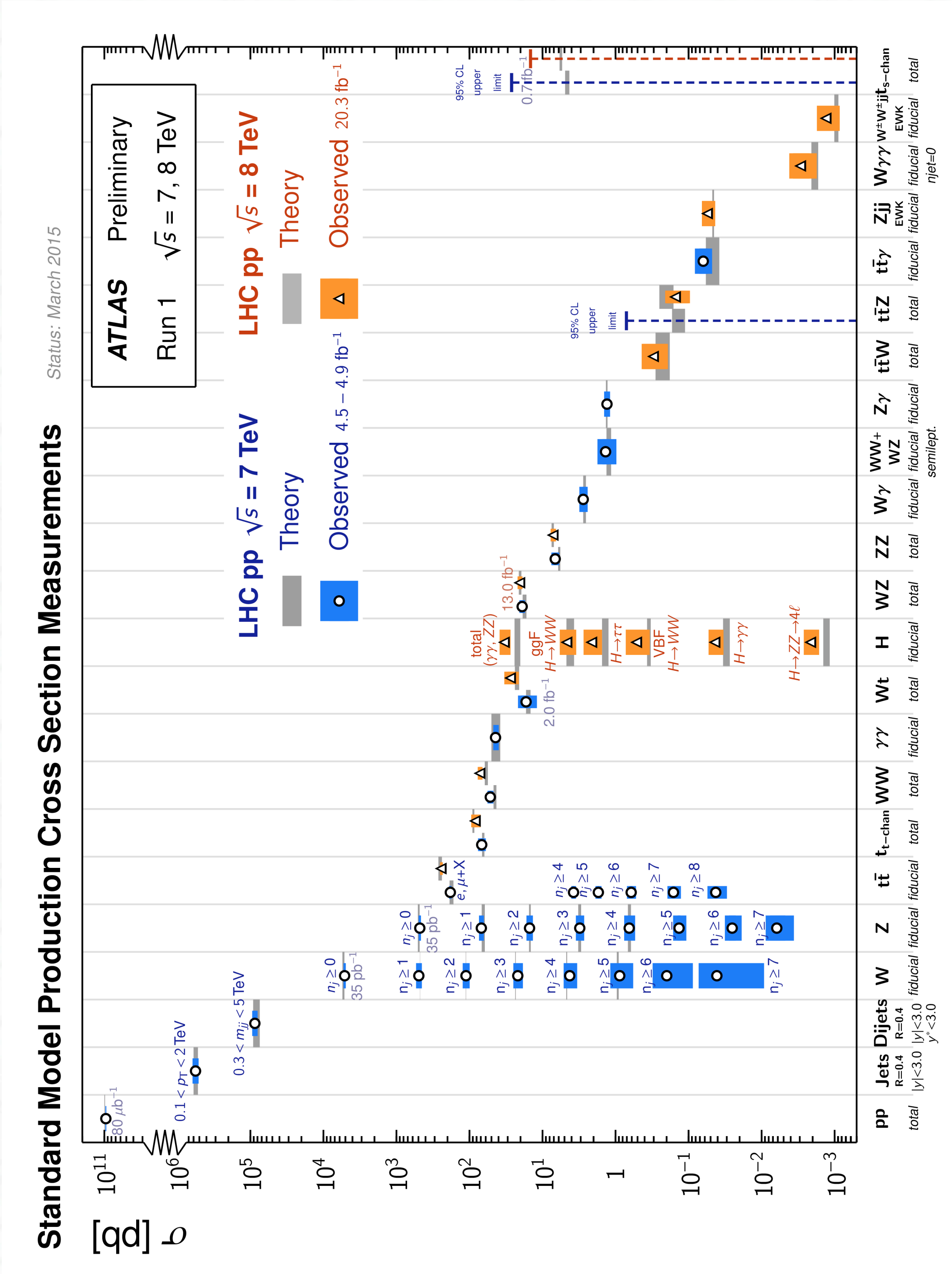


- Excellent LHC performance in 2011 and 2012
- Peak luminosities > 7 10^{33} cm^{-2} s^{-1}
- High level of pileup: mean of ~20 interactions / beam crossing in 2012
- Excellent performance of the ATLAS and CMS experiments:
  (Data recording efficiency: ~93.5%, working detector channels >97 % for most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

Standard Model Production Cross Section Measurements

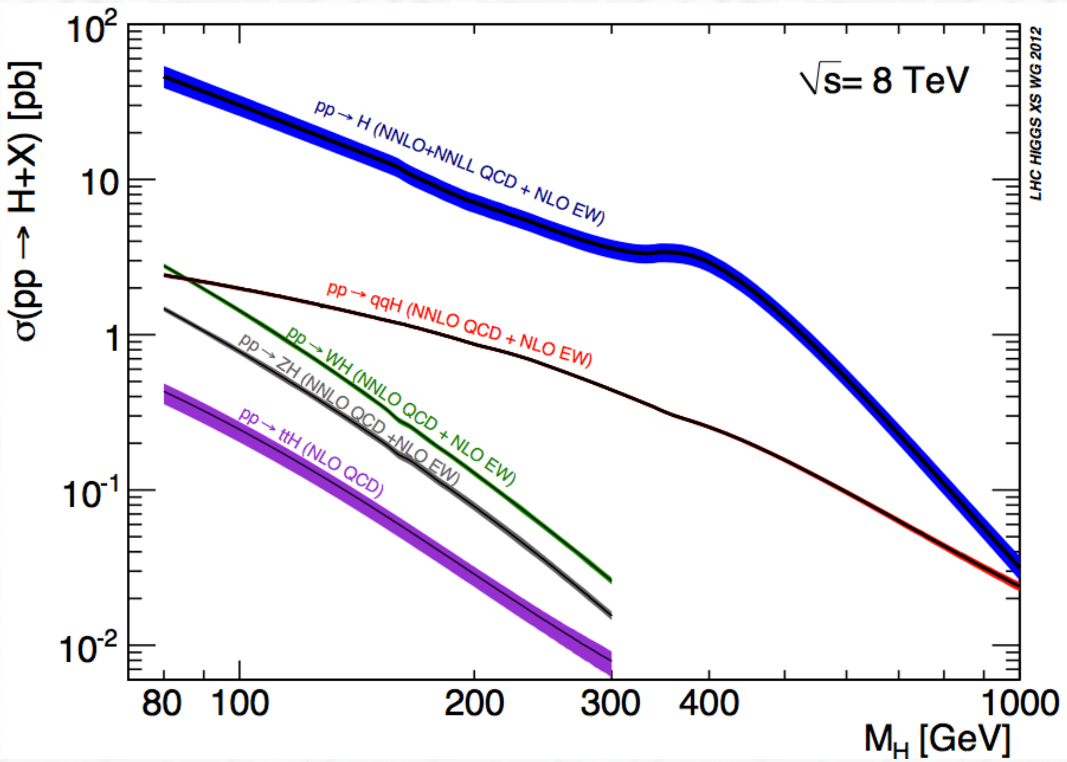
Status: March 2015

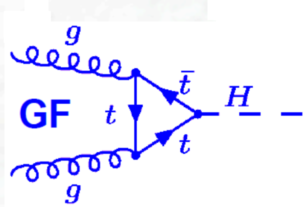




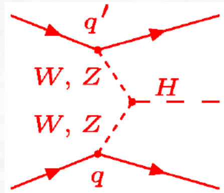
“Stairway to Heaven”

Higgs Boson Production



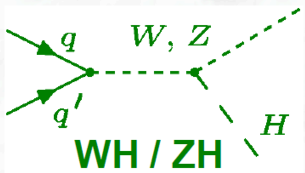


Gluon fusion

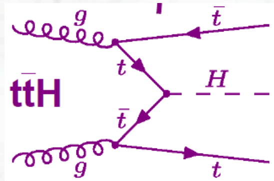


VBF

Vector boson fusion



WH/ZH associated production



tt associated production

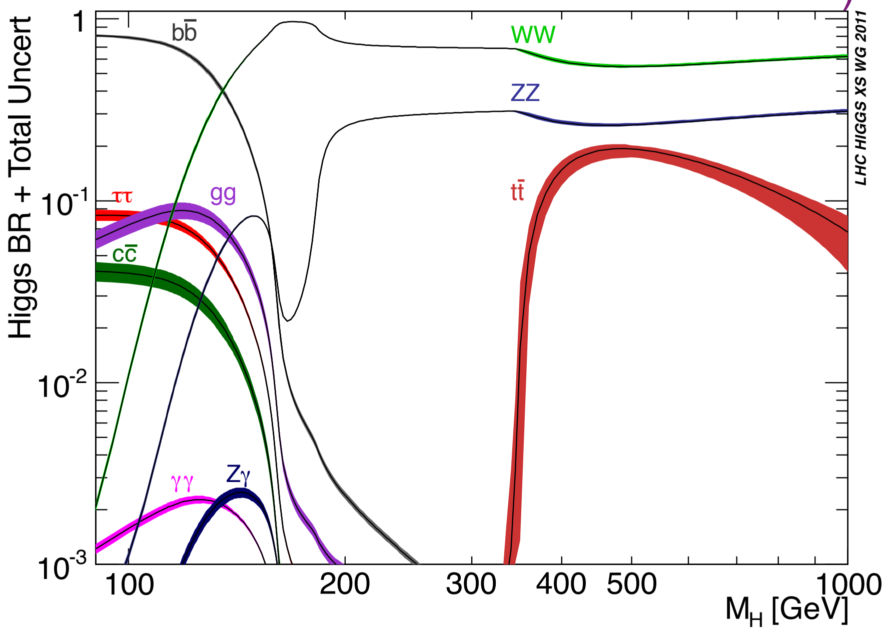
*) LHC Higgs cross-section working group
Large theory effort

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

→ LHC = Long and Hard Calculations

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)

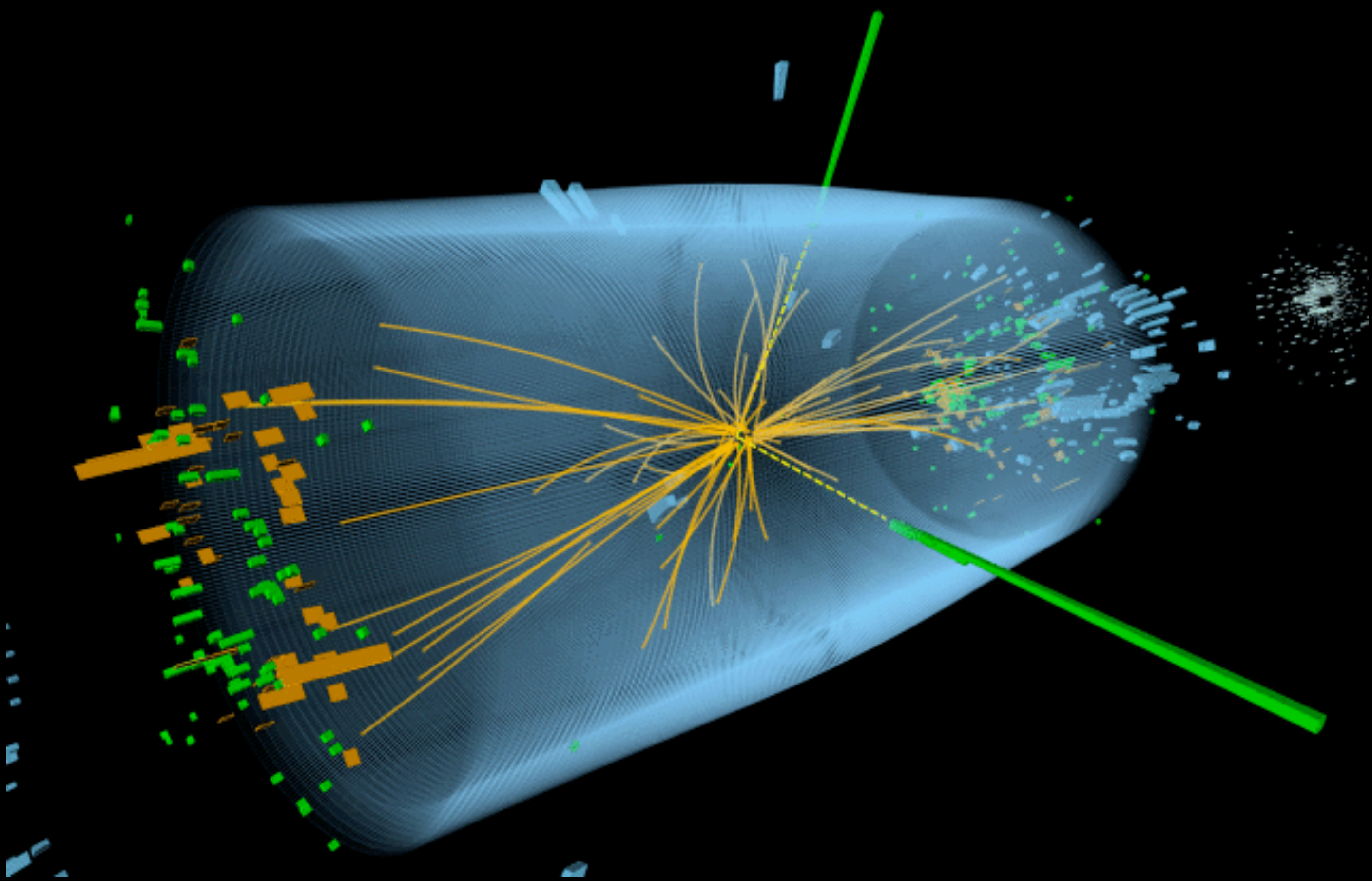
SM predictions (m_H = 125.5 GeV):

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

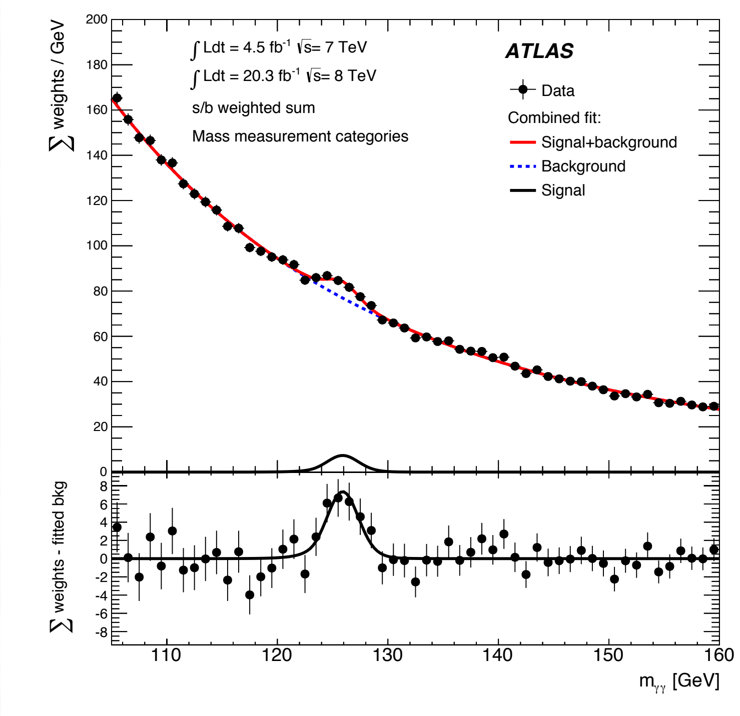


Expected number of decays, before selection cuts, in the data, m_H = 125 GeV:

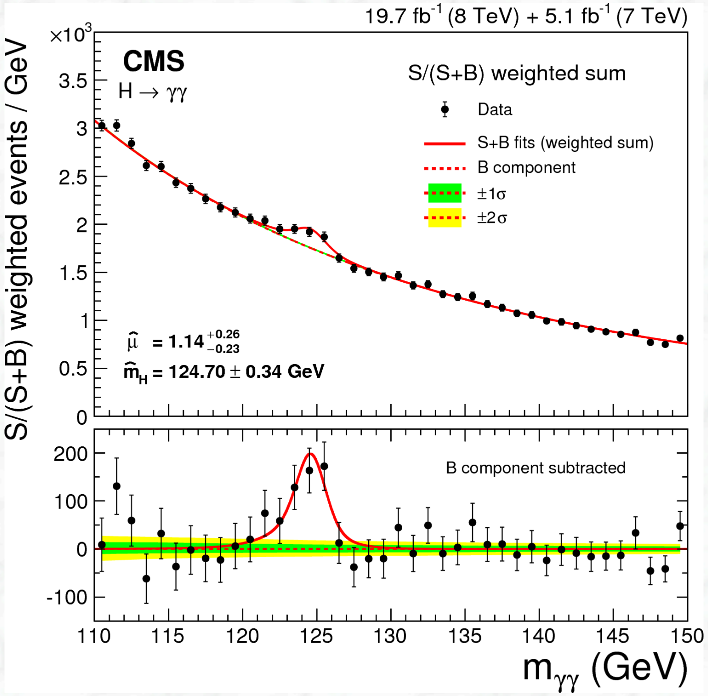
~ 950 $H \rightarrow \gamma\gamma$
~ 60 $H \rightarrow ZZ^* \rightarrow 4\,\ell$
~ 9000 $H \rightarrow WW^* \rightarrow \ell\nu\,\ell\nu$

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



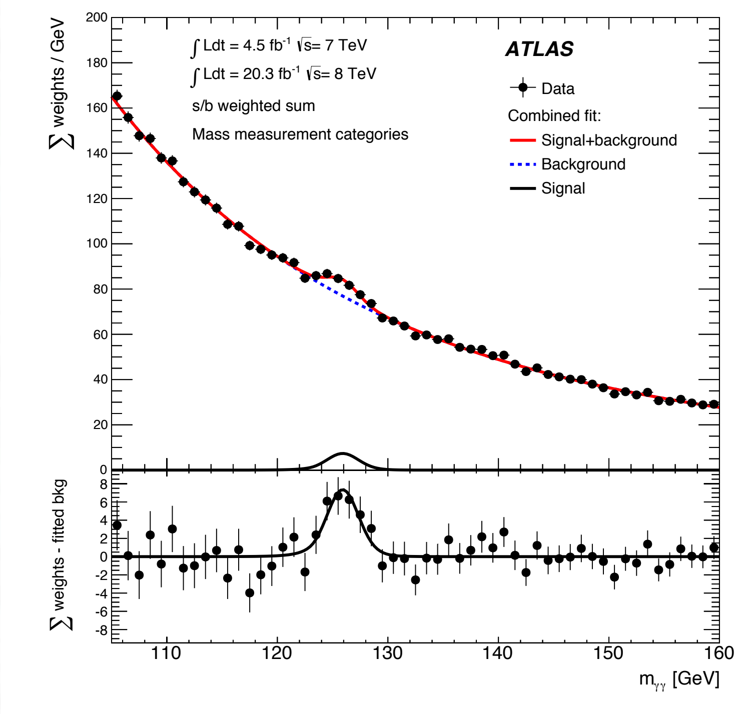
EPJ C74 (2014) 3076



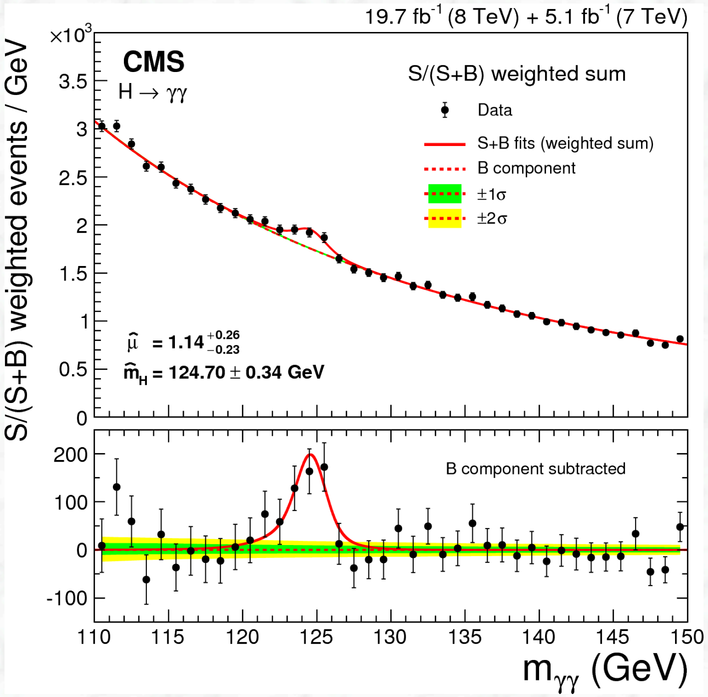
- Background interpolation in the region of the excess (obtained from sidebands)
- Reducible γ-jet and jet-jet background at the level of 25%
- High signal significance in both experiments: ATLAS: 5.2σ (4.6σ expected)
  CMS: 5.7σ (5.2σ expected)
- Establishes the discovery in this channel alone

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



EPJ C74 (2014) 3076

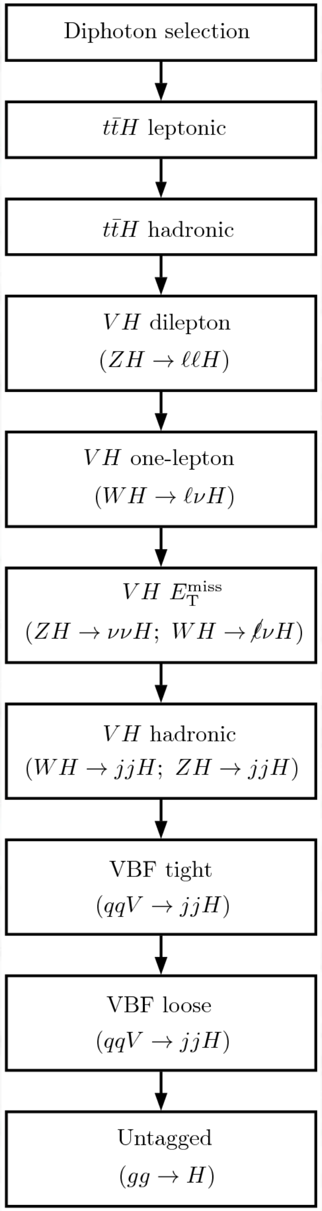


Measured signal strengths: $\mu = \sigma_{obs} / \sigma_{SM}$

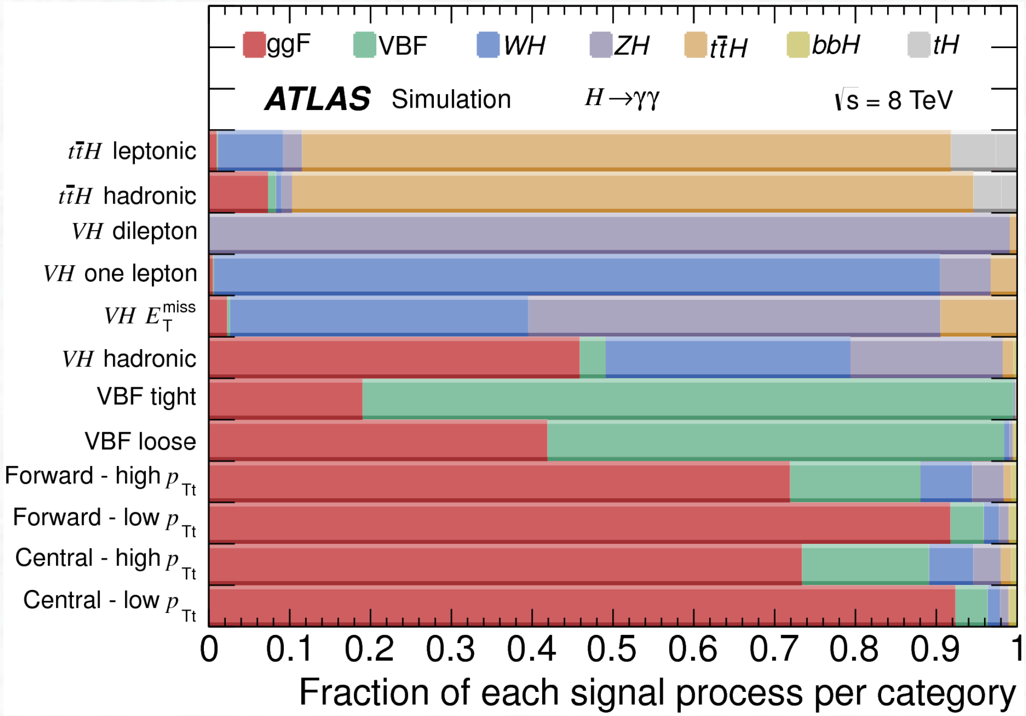
ATLAS: $\mu = 1.17 \pm 0.27$

CMS: $\mu = 1.14 \pm 0.26$

Categorisation of H → γγ candidate events



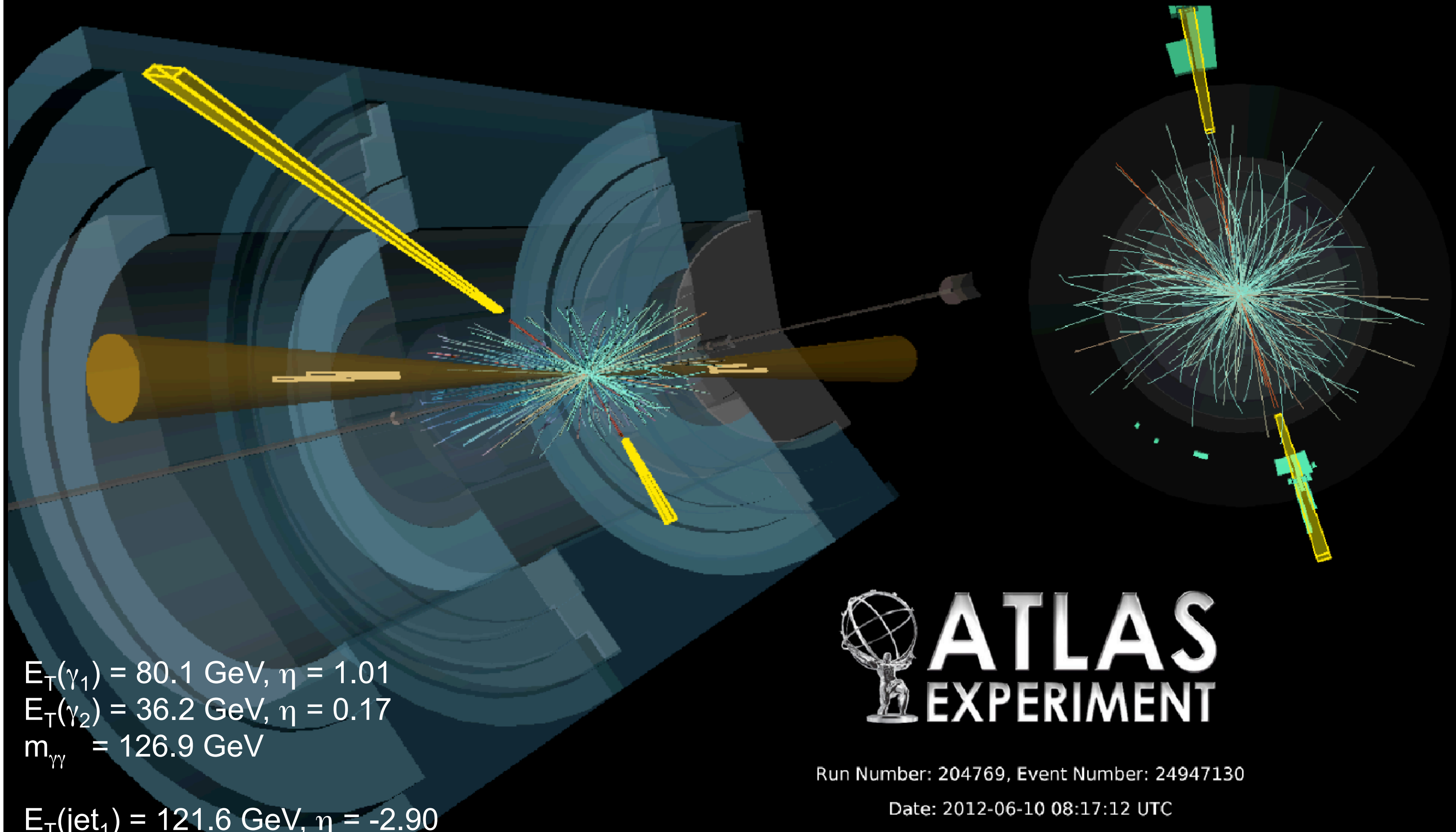
Categorisation: to increase overall sensitivity and sensitivity to different production modes (VBF, VH)



- 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
  for different detector regions,
  γγ conversion status and p_{Tt}

Phys. Rev. D90 (2014) 112015

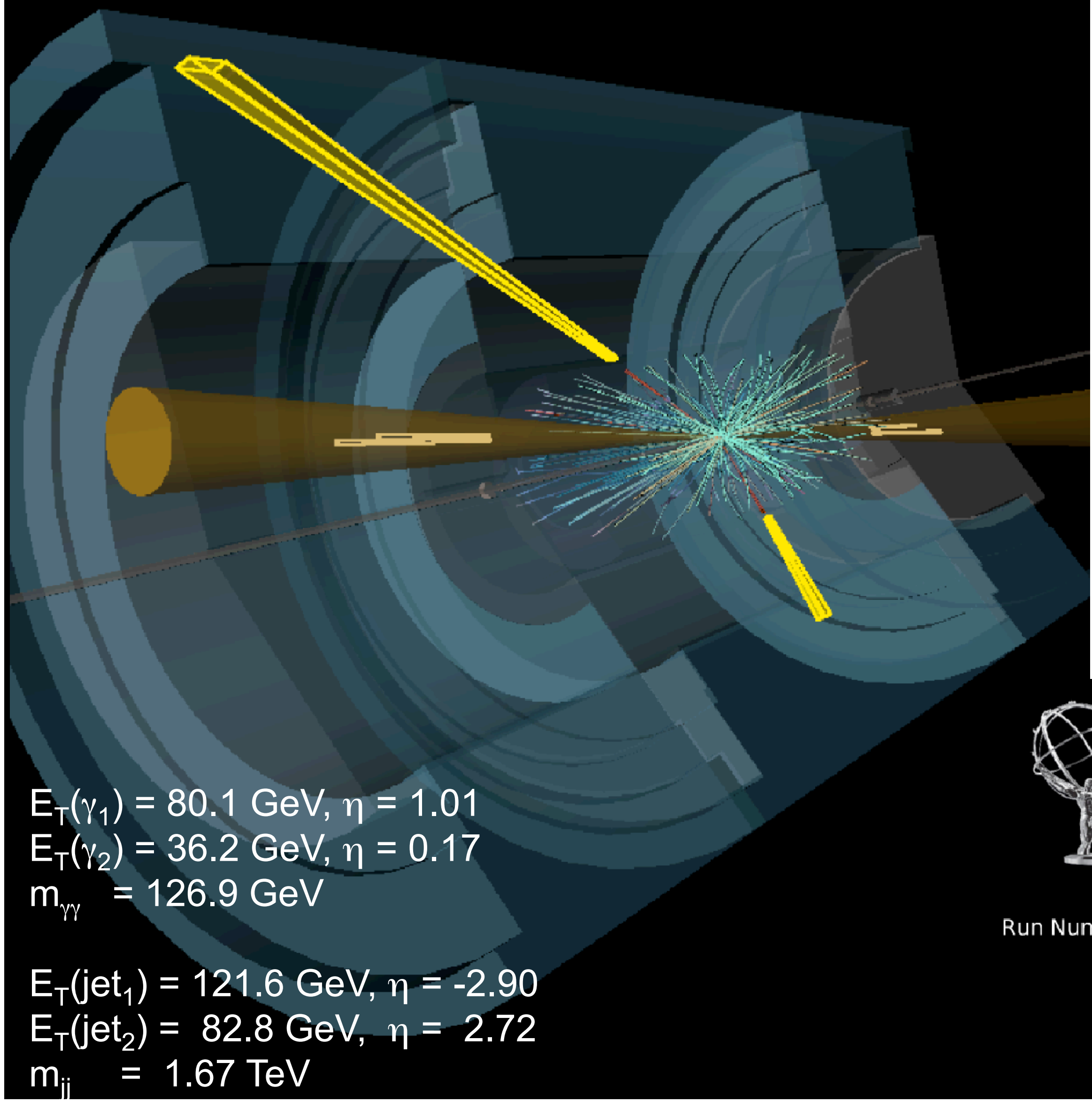
$H \rightarrow \gamma\gamma$ VBF candidate event



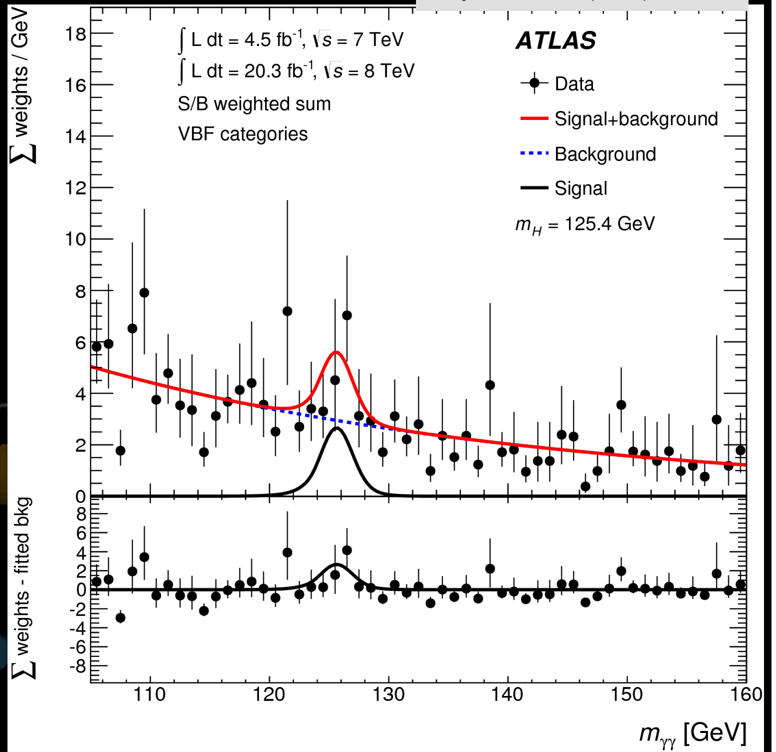
$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

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

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



Phys. Rev. D90 (2014) 112015



ATLAS EXPERIMENT

Run Number: 204769, Event Number: 24947130

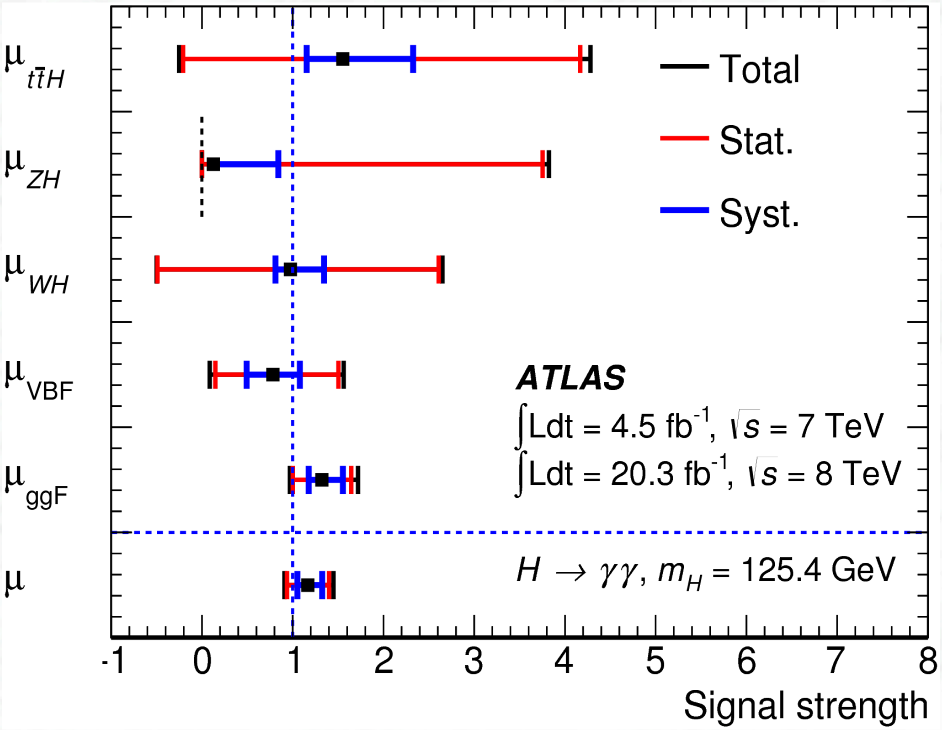
Date: 2012-06-10 08:17:12 UTC

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

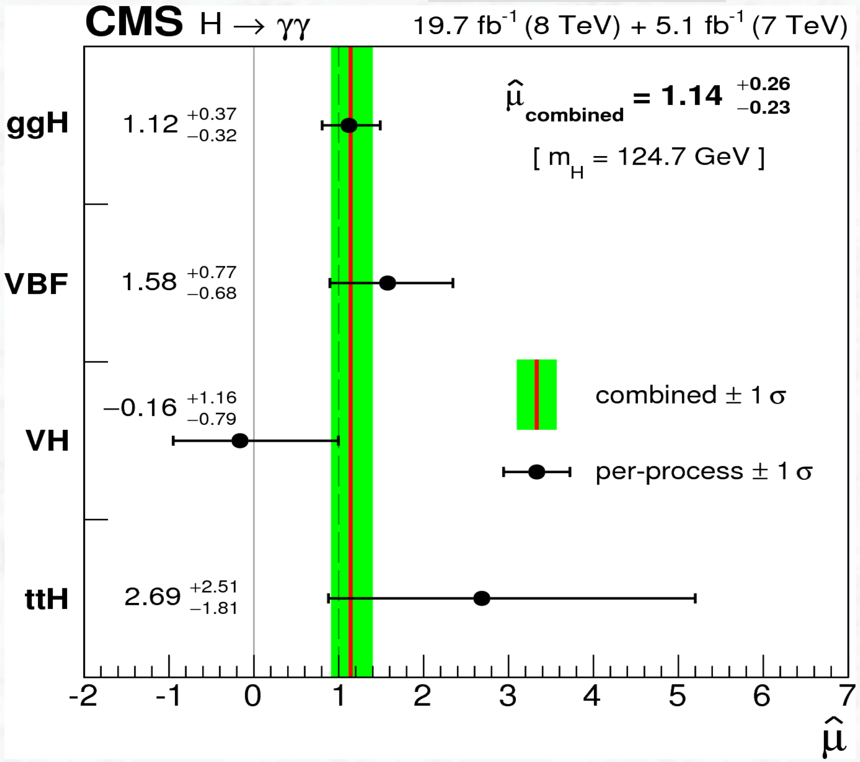
$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

γγ signal strengths for various production modes

Phys. Rev. D90 (2014) 112015

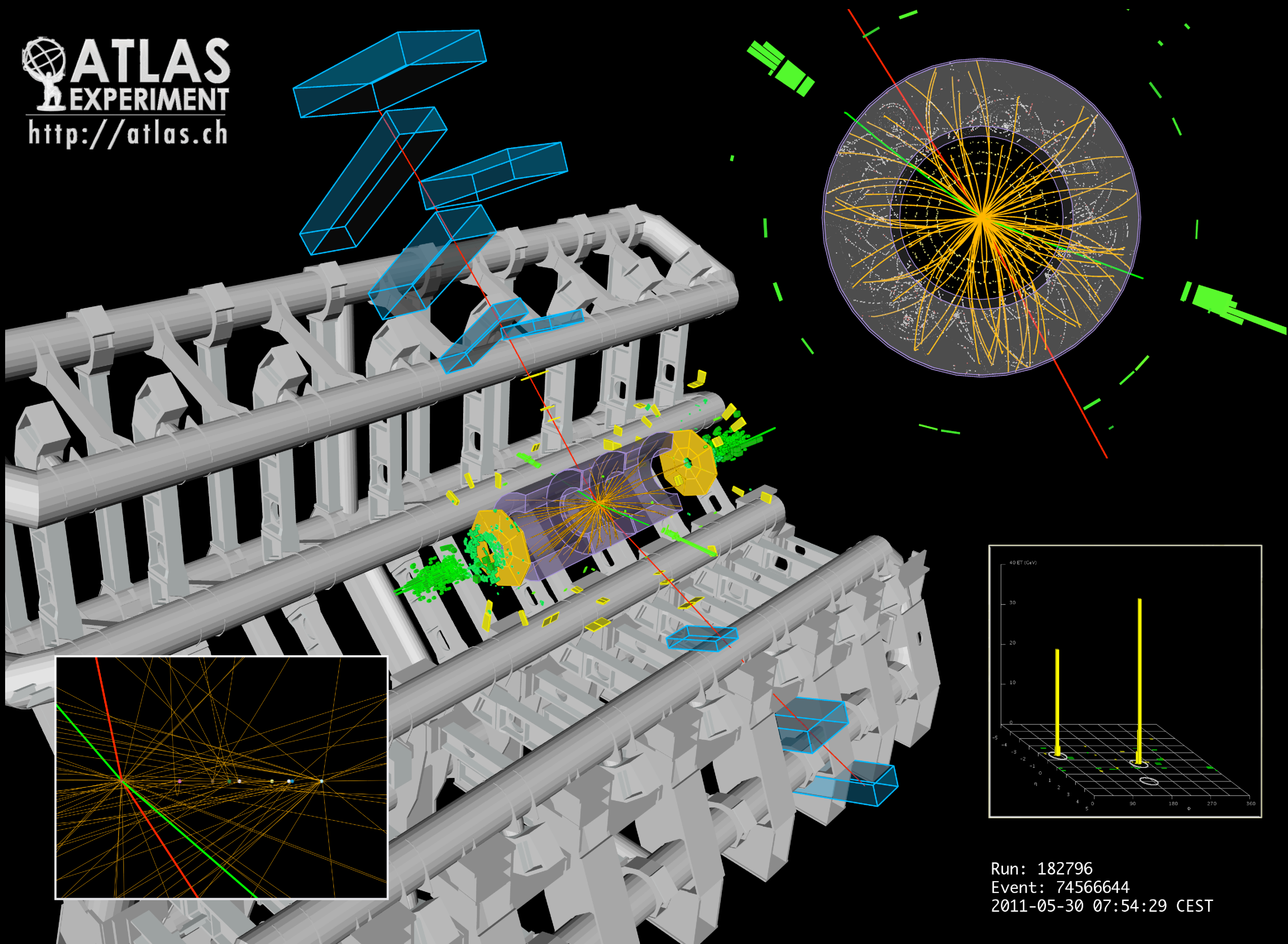


EPJ C74 (2014) 3076



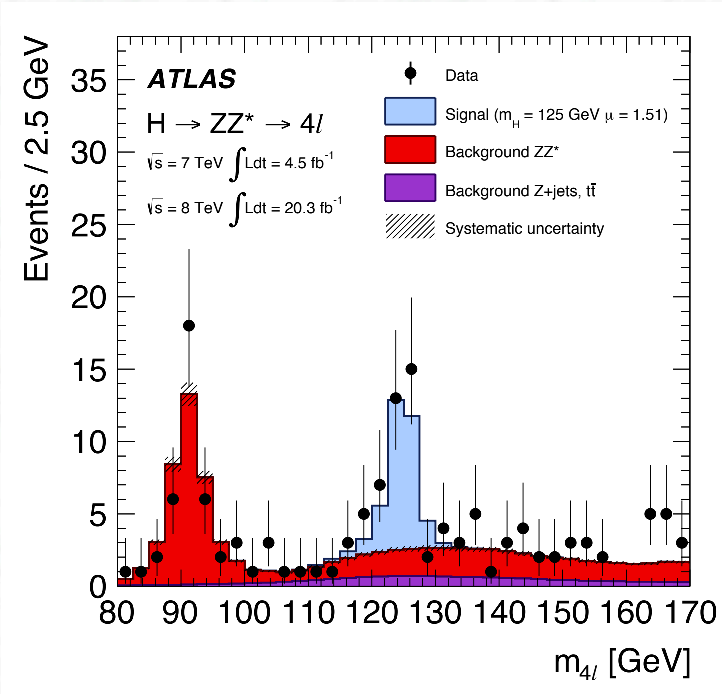
Fit results for individual production processes are consistent with the Standard Model expectations

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

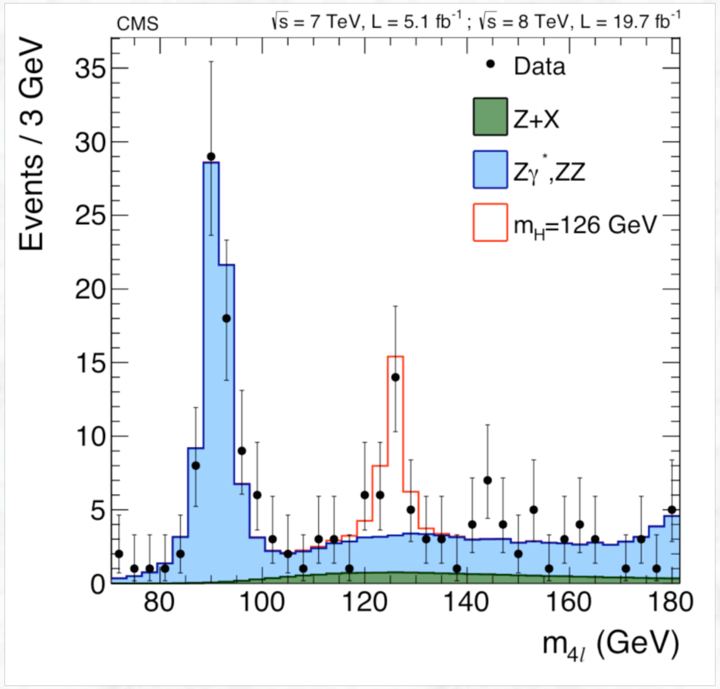


Reconstructed mass spectra from 4ℓ decays

Phys. Rev. D91 (2014) 012006



Phys. Rev. D89 (2014) 092007



Measured signal strengths:

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

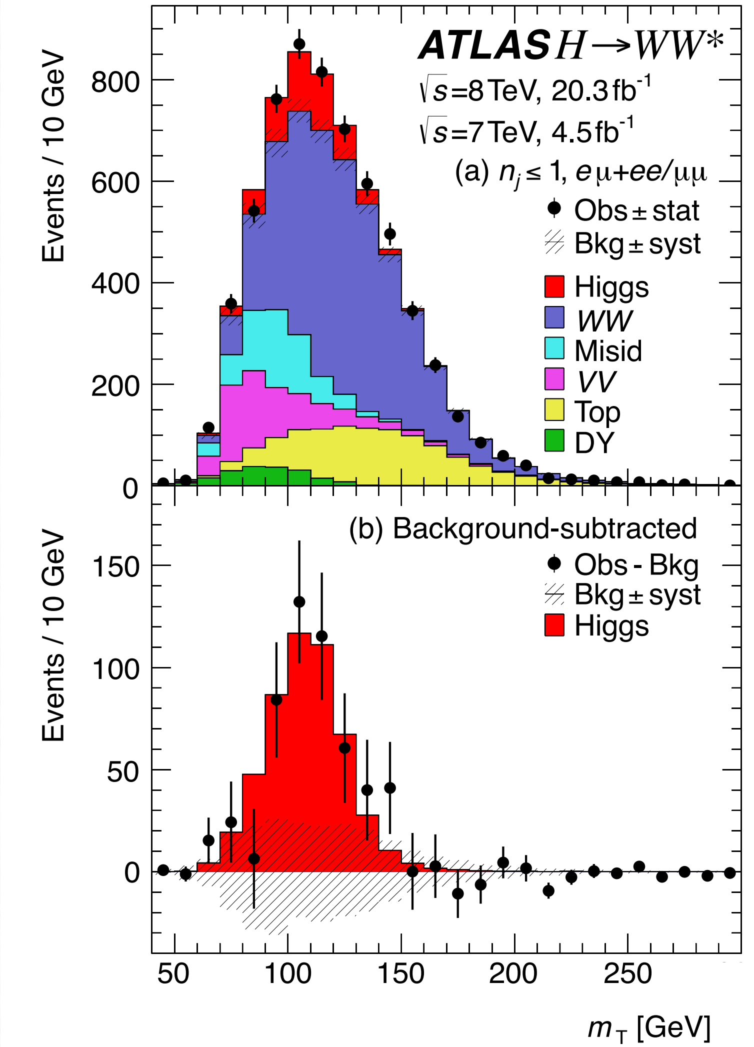
CMS: $\mu = 0.93^{+0.29}_{-0.23}$

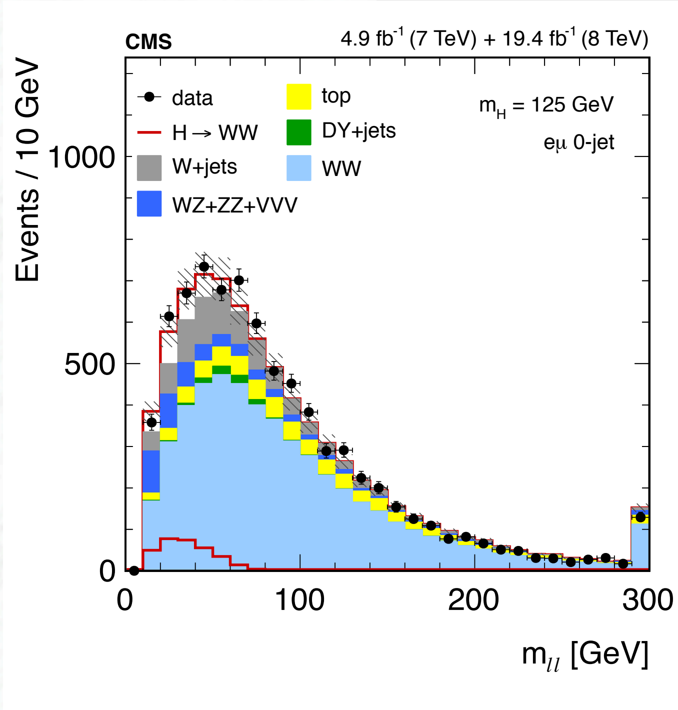
Significance in each experiment > 6σ

H → WW* → ℓν ℓν signal

arXiv:1412.2641

JHEP 01 (2014) 096





Measured signal strengths:

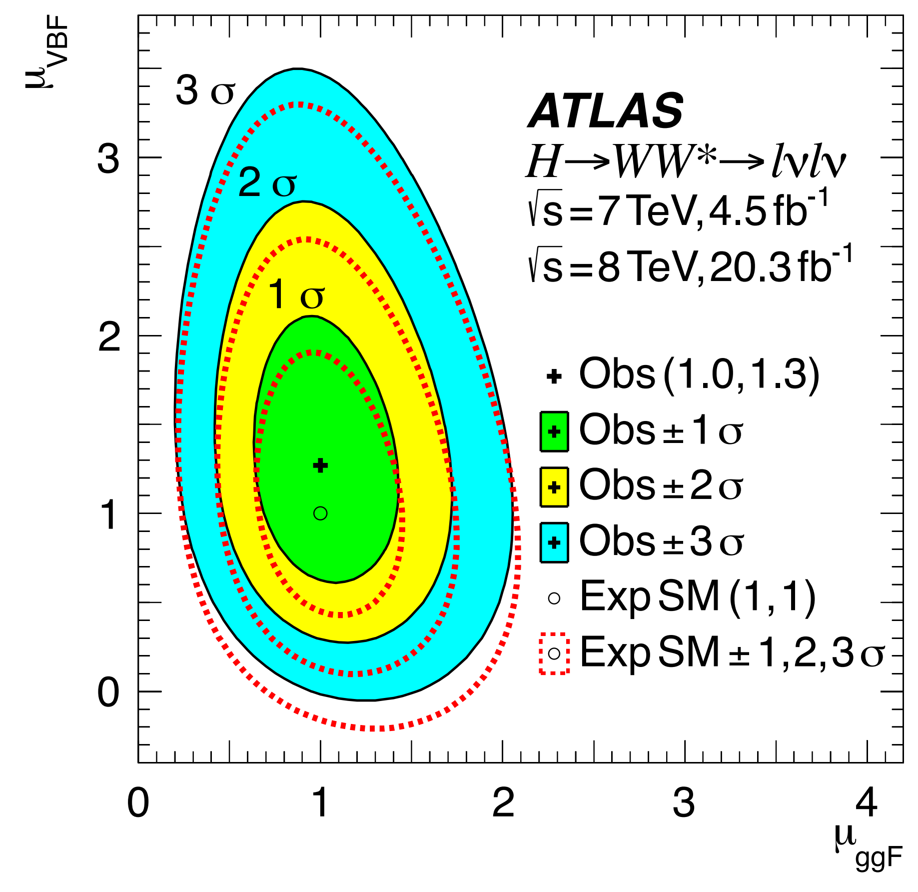
ATLAS: $\mu = 1.09\,^{+0.23}_{-0.21}$

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

arXiv:1412.2641



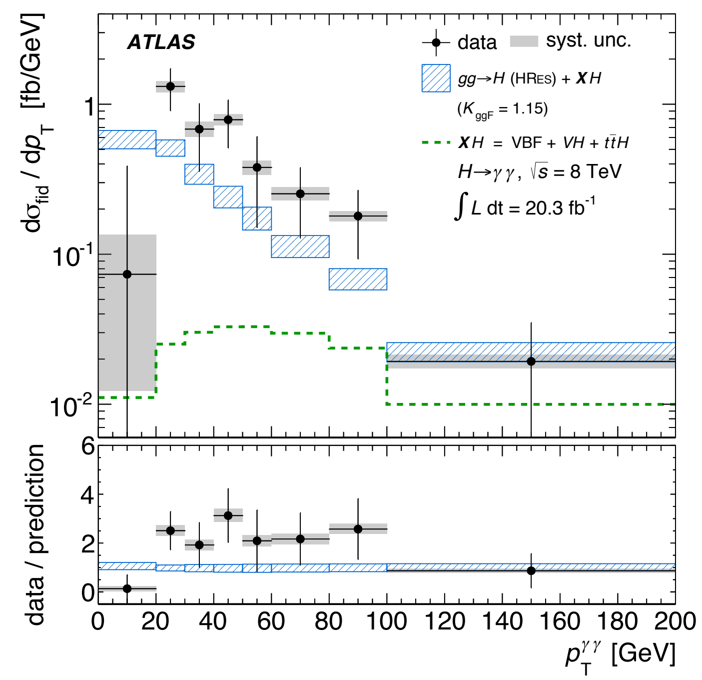
Measured signal strengths: ATLAS

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

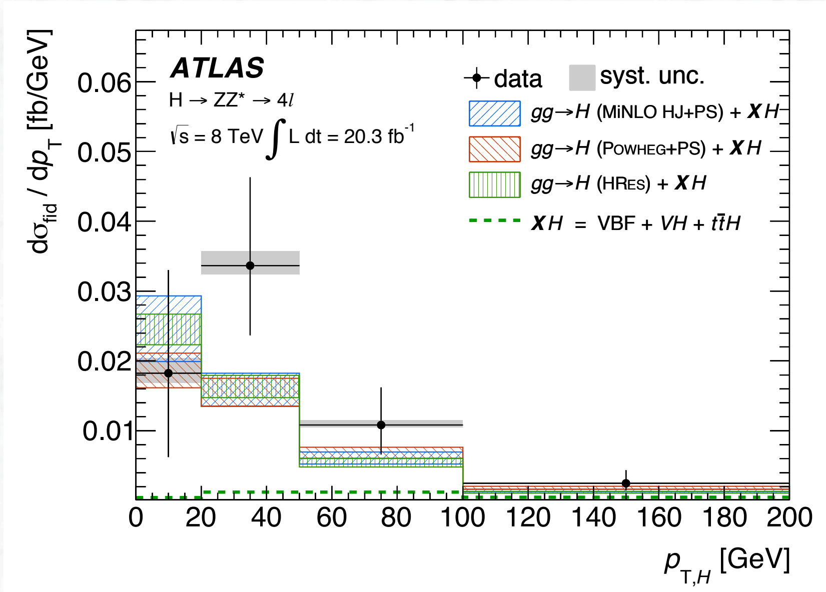
VBF: $\mu = 1.27^{+0.53}_{-0.45}$

Differential cross-section measurements

JHEP 09 (2014) 112

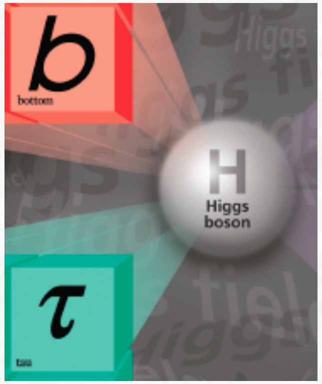


Phys. Lett B738 (2014) 234

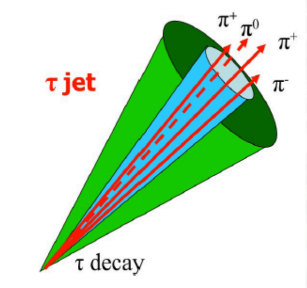


- First fiducial, differential cross-section measurements in bosonic channels
- Good agreement within present experimental and theoretical uncertainties, (… except normalization?)
- Large future potential: probe Higgs boson kinematics, jet activity, VBF contributions, spin-CP nature, …

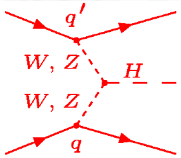
Couplings to quarks and leptons ?



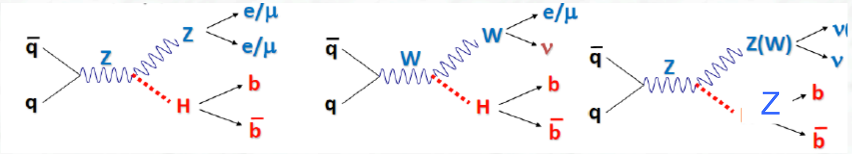
- Search for H → ττ and H → bb decays;
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays

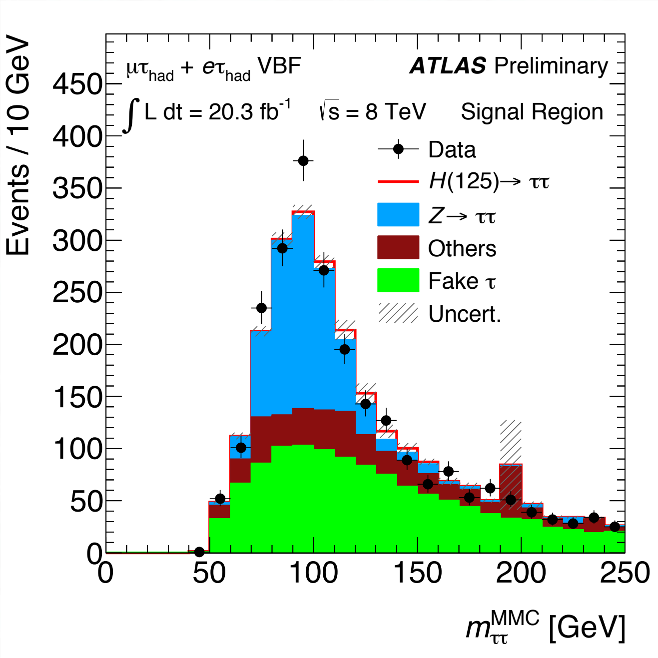


- Vector boson fusion mode essential for H → ττ decays



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



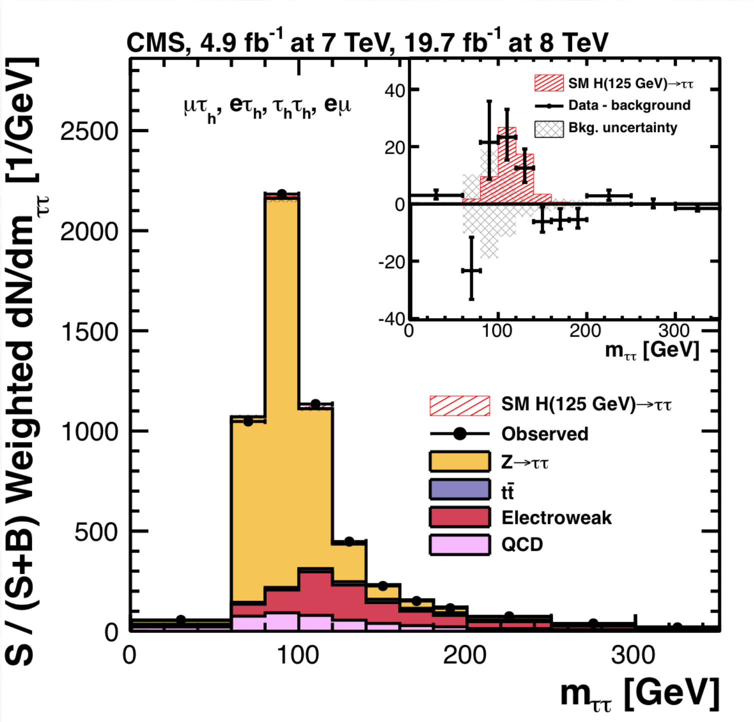


- Exploitation of multivariate analyses

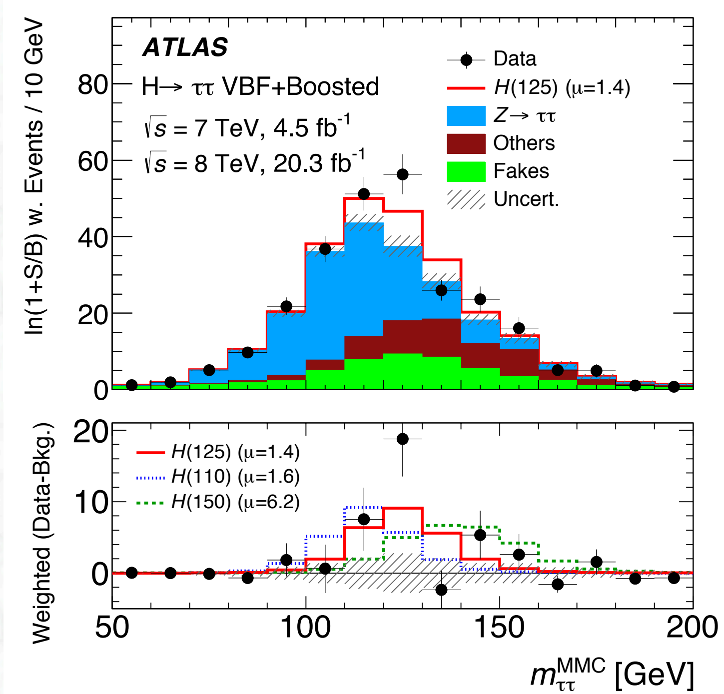
Parallel Session Talks: Silvio Donato, Prolay Mal

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:

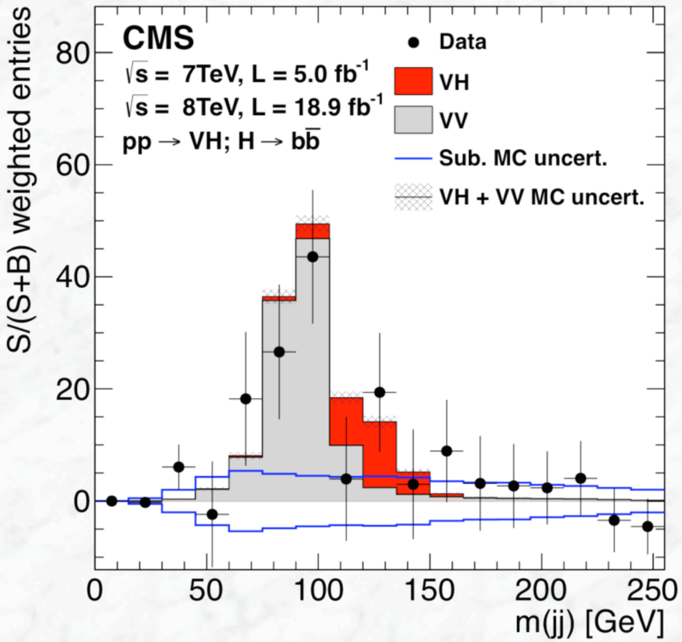
ATLAS: $\mu = 1.43\ ^{+0.43}_{-0.37}$ (4.5σ)

CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

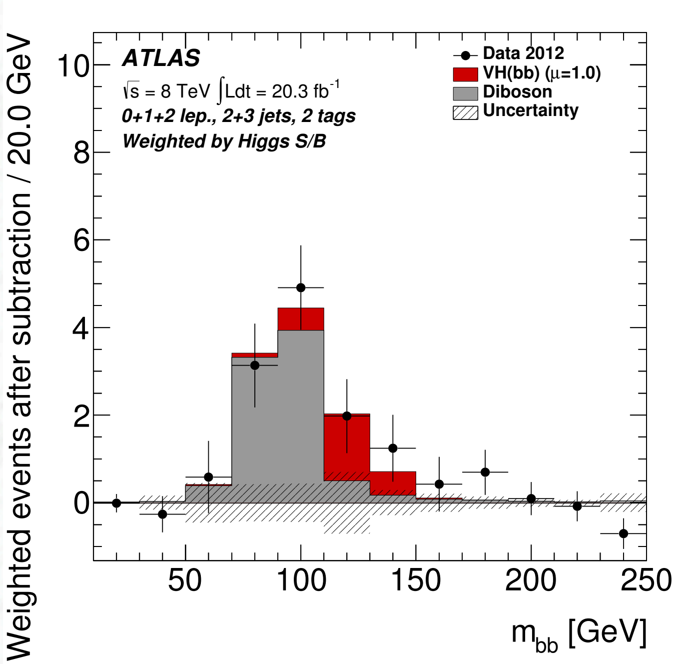
One of the most important LHC results in 2014

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

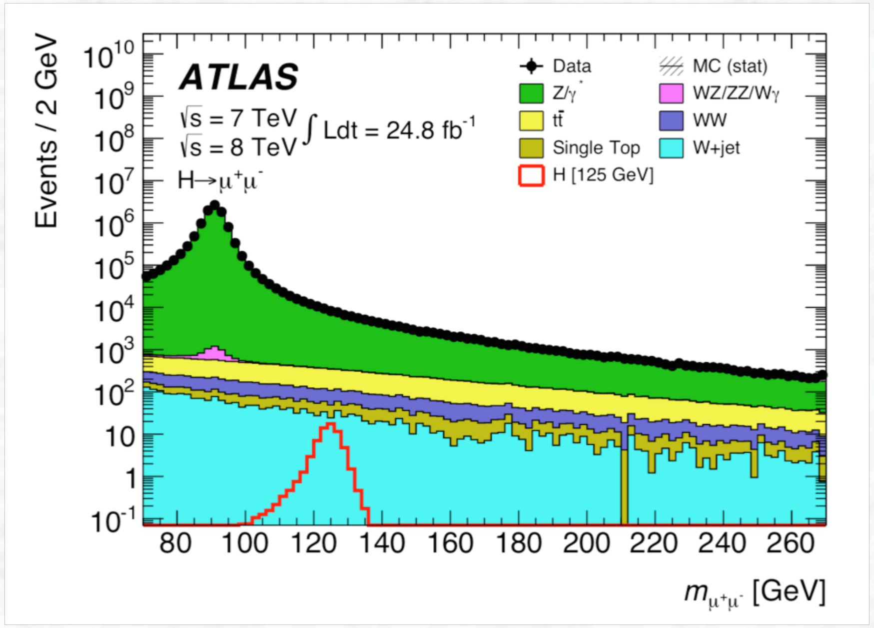
Signal strengths:

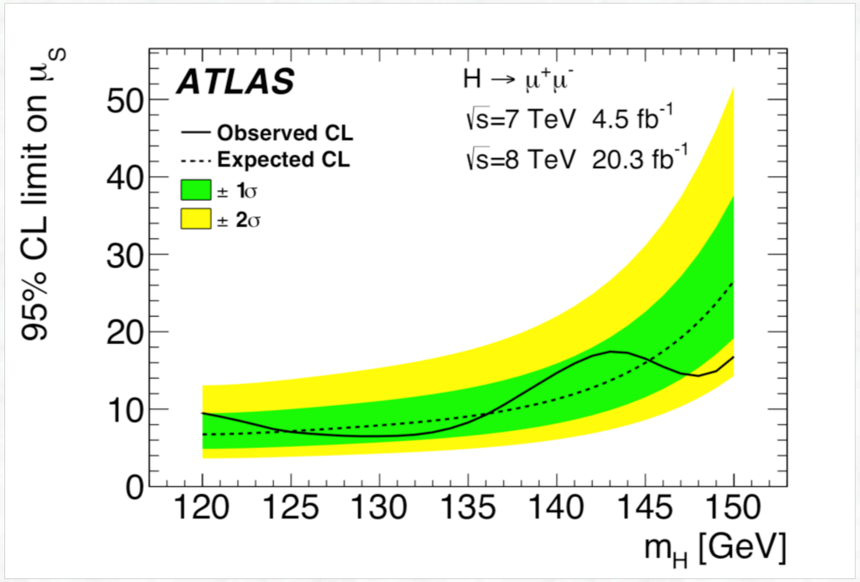
ATLAS: $\mu = 0.50 \pm 0.36$

CMS: $\mu = 1.0 \pm 0.5$

Results on the search for H→ μμ decays

Phys. Lett. B738 (2014) 68





m_H = 125 GeV:

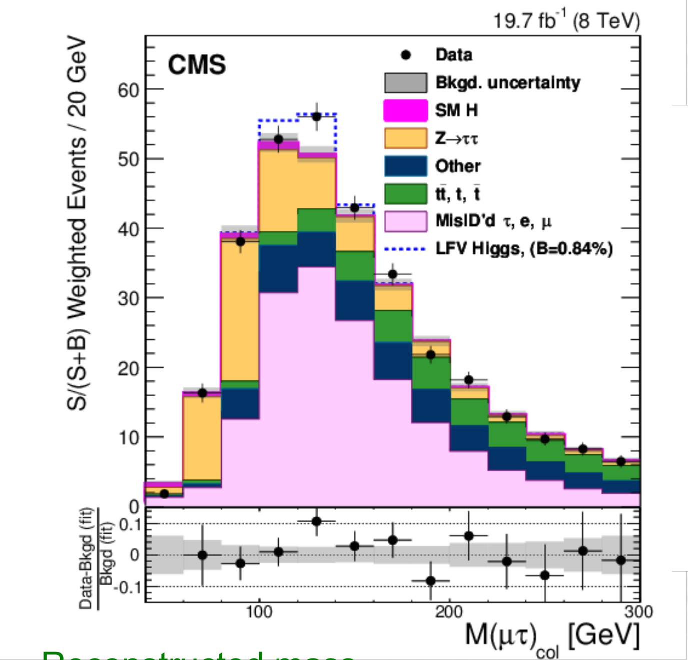
ATLAS 95% CL: 7.0σ_{SM} (7.2 expected, no Higgs) [Phys. Lett. B738 (2014) 68]
CMS 95% CL: 7.4σ_{SM} (6.5 expected, no Higgs) [Phys. Lett. B744 (2015) 184]

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

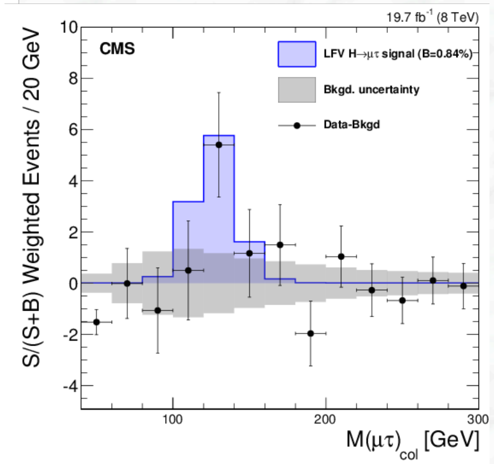
Lepton-flavour violating H→ τμ decays?

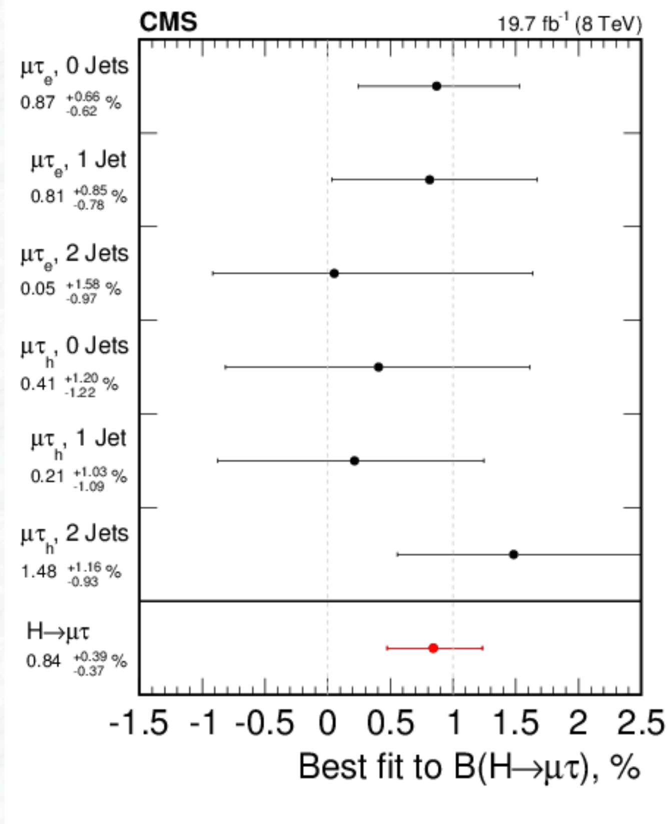
arXiv:1502.07400

Search for τ → had ν or τ → eνν accompanied by 0, 1 or 2 jets



Reconstructed mass, all channels combined

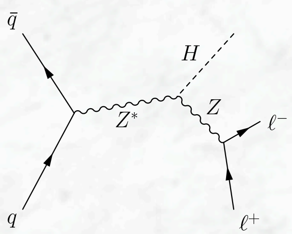


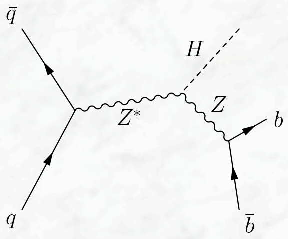


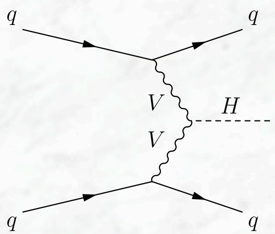
- CMS analysis: a slight excess of events observed (2.4σ)
- Consistent with a signal at 125 GeV with a H → τμ branching ratio of $(0.84^{+0.39}_{-0.37})$%
- ATLAS results on this search are eagerly awaited, expected soon

Search for invisible Higgs boson decays

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

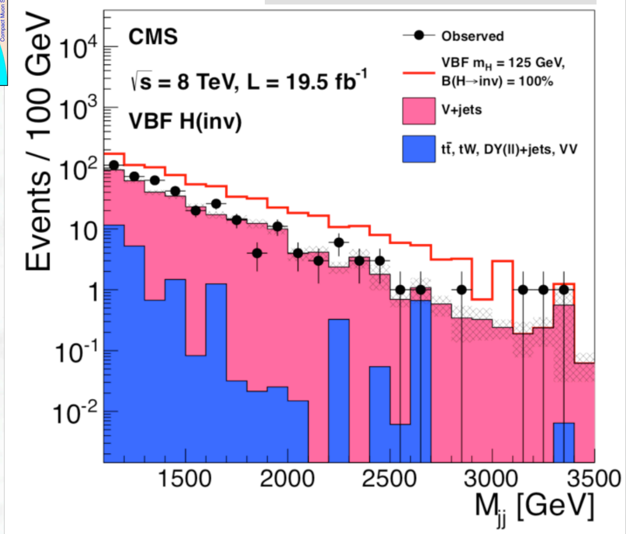






- Search for excess in ZH associated production and VBF production

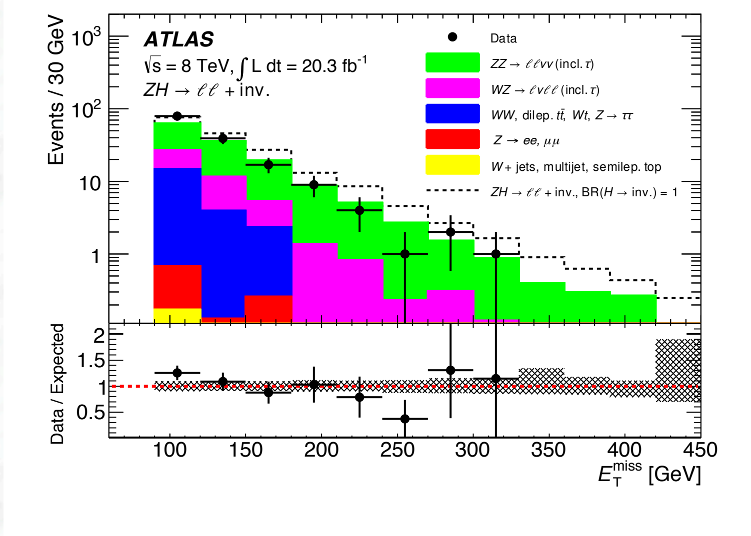
EPJ C74 (2014) 2980



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)

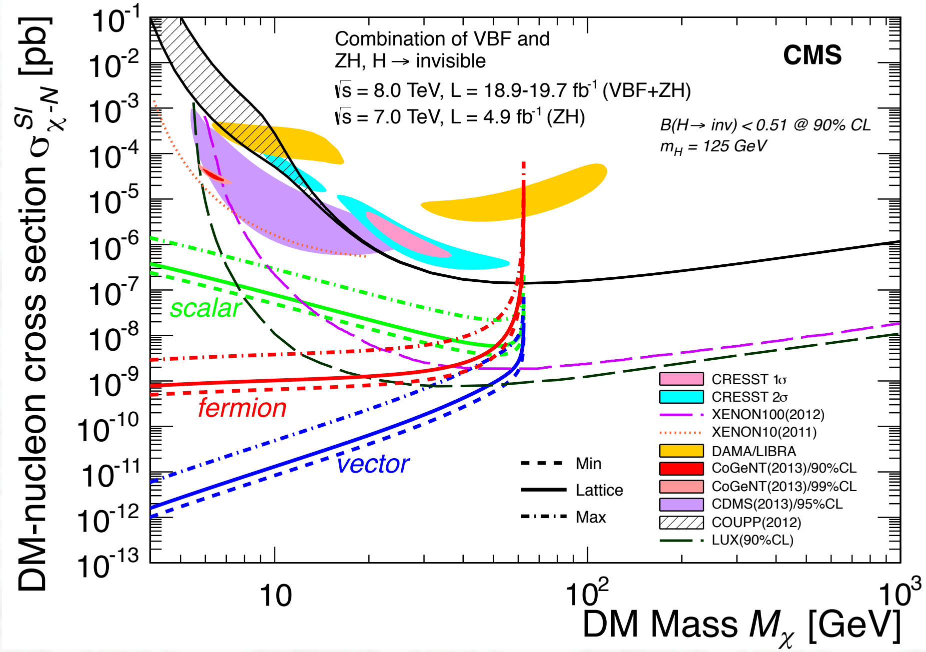
Interpretation in Higgs-portal models

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

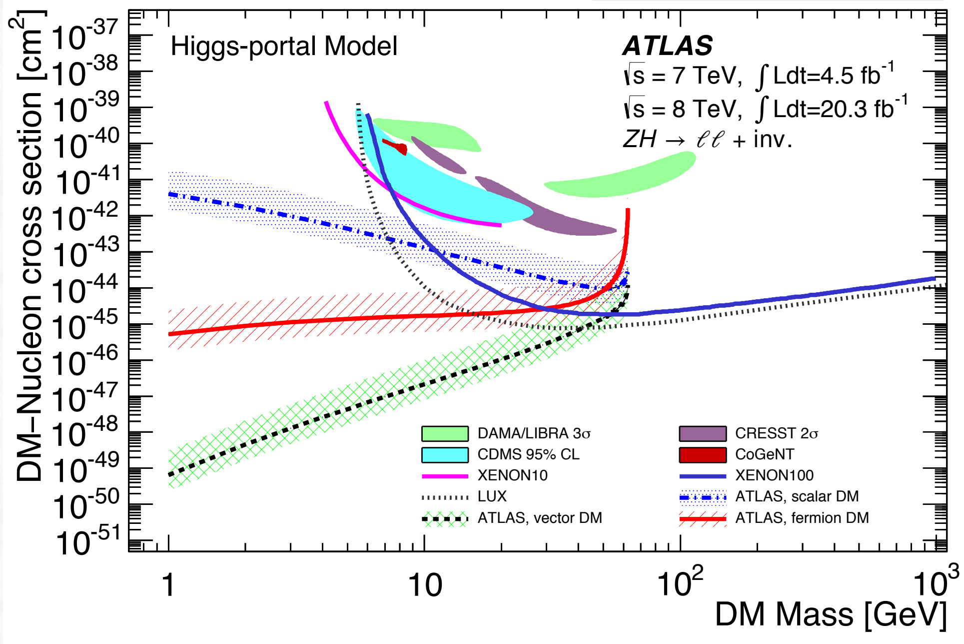
- For $m_\chi < m_H/2$, limits on invisible branching ratios can be translated to the spin-independent DM-nucleon elastic cross section for scalar, vector and fermionic DM particles
- Higgs-nucleon coupling, model dependent: assume $0.33^{+0.30}_{-0.07}$ (lattice calculations)
- Within this model, interesting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

Parallel Session Talks: James Beacham

EPJ C74 (2014) 2980



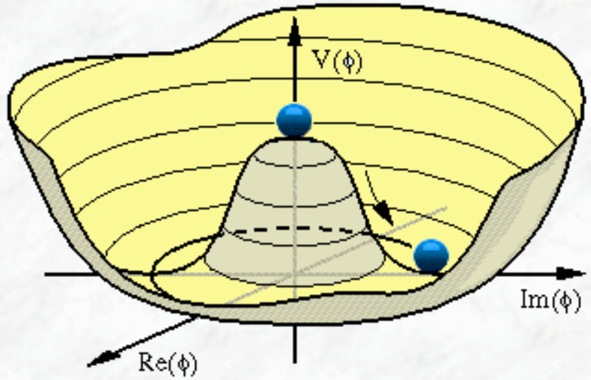
PRL 112 (2014) 201802



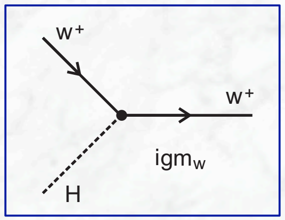
Profile of the New Particle

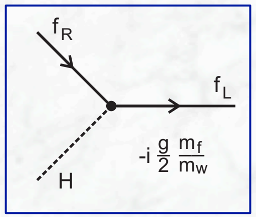
Is it the Standard Model Higgs Boson?

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



Couplings to bosons and fermions





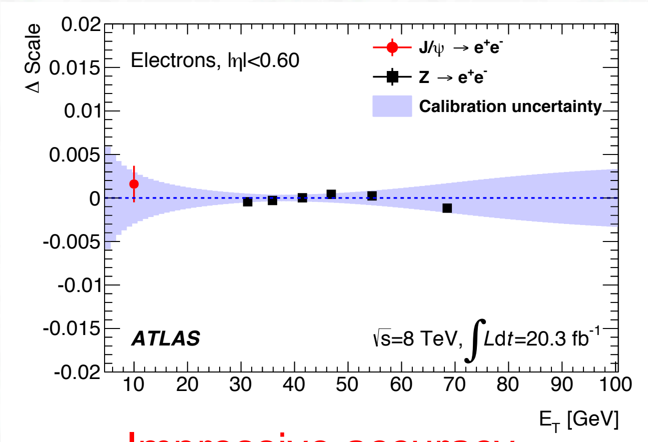
Parallel Session Talks:

- Marcello Fanti (couplings / properties)
- Daniele Zanzi (ttH)

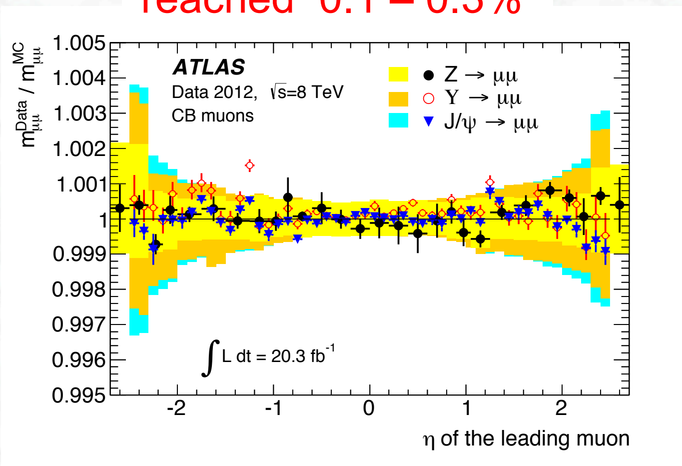
Higgs boson mass

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

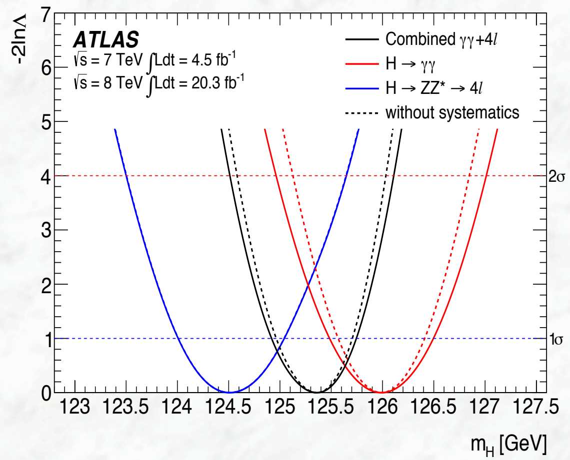
- Good control of the lepton and photon energy scales, calibration via Z → ℓℓ and J/ψ and ϒ signals, improved understanding of lepton and photon reconstruction



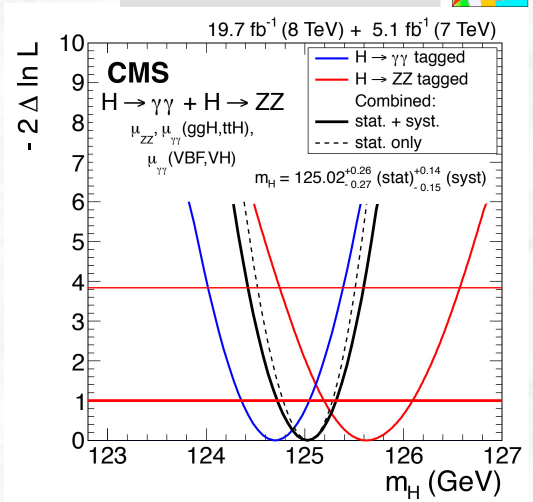
Impressive accuracy reached 0.1 – 0.3%



Phys. Rev. D90 (2014) 052004



EPJ C75 (2015) 5, 212



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

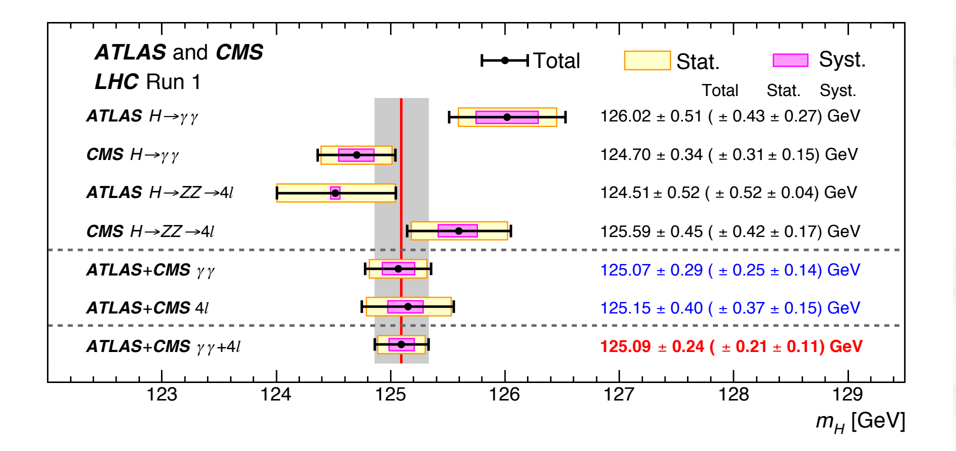
CMS: $m_H = 125.02\ ^{+0.26}_{-0.27}\ (stat)\ ^{+0.14}_{-0.15}\ (syst)$ GeV

Higgs boson mass (cont.)

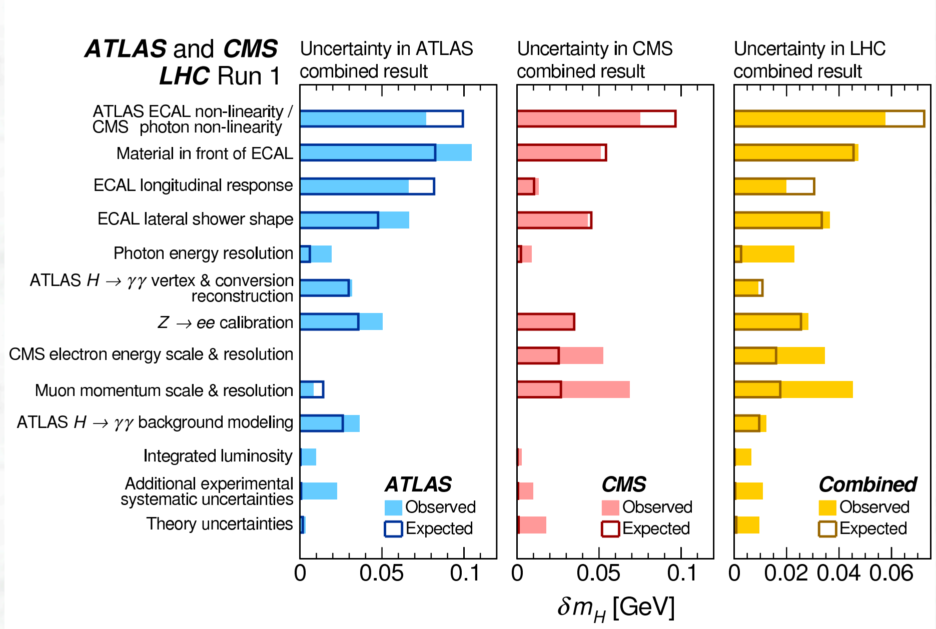
-First ATLAS and CMS combination of Higgs boson results-

PRL 114 (2015) 191803

Individual and combined results:



Uncertainties:



ATLAS + CMS:

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

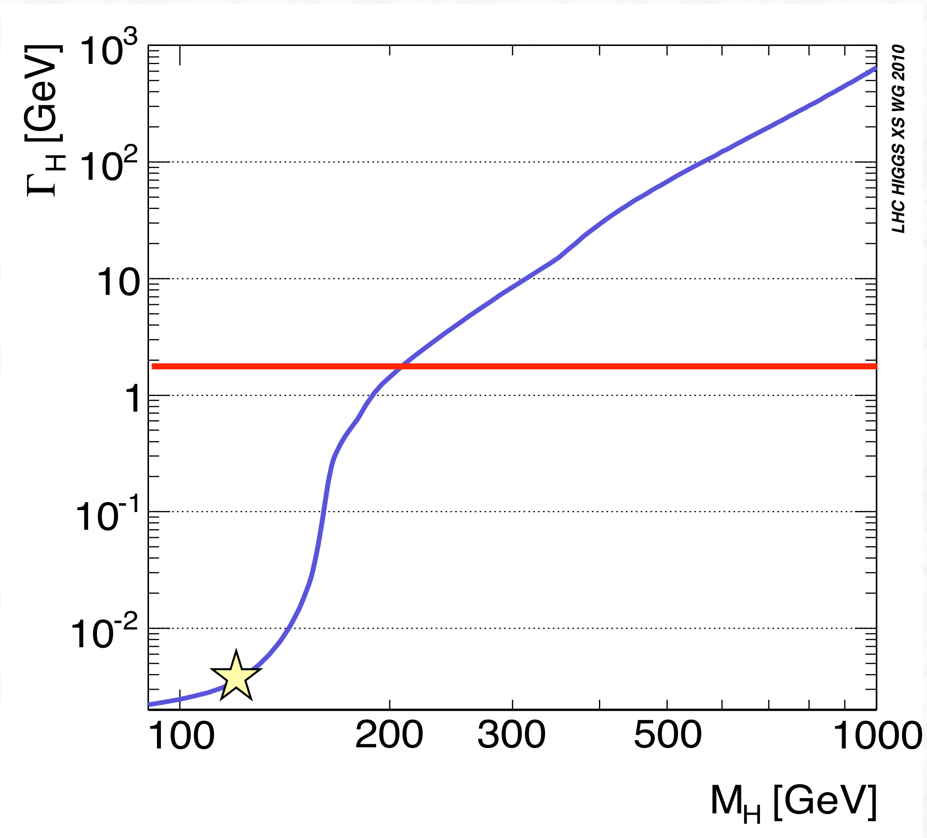
Precision of 0.2%

- Statistical uncertainty still dominant
- Major systematic uncertainties: Lepton and photon energy scales and resolutions
- Theoretical uncertainties small (correlated), 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 $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ 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)

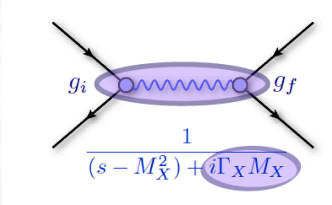
Parallel Session Talk: Roberto Covarelli

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

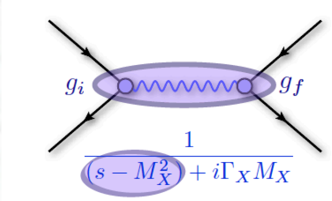
- Different sensitivity of on-shell and off-shell cross sections on the Higgs boson width

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

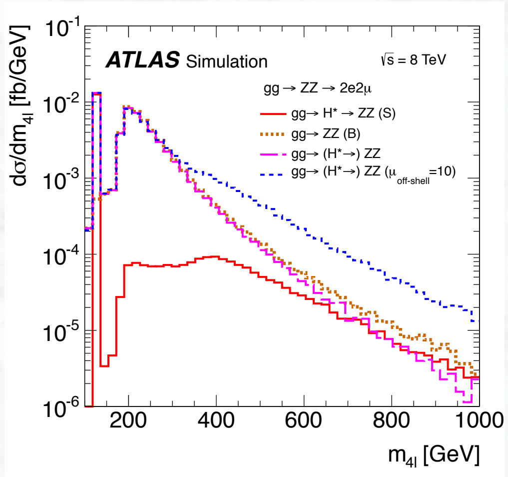
- Dependence on K-factors for signal and backgrounds (gg → VV)



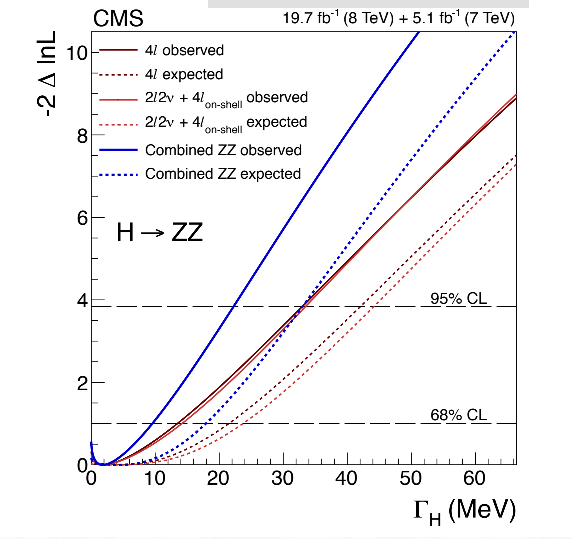
$$\sigma^{on}_{i\to X\to f} \sim \frac{g_i^2 g_f^2}{\Gamma_X}$$



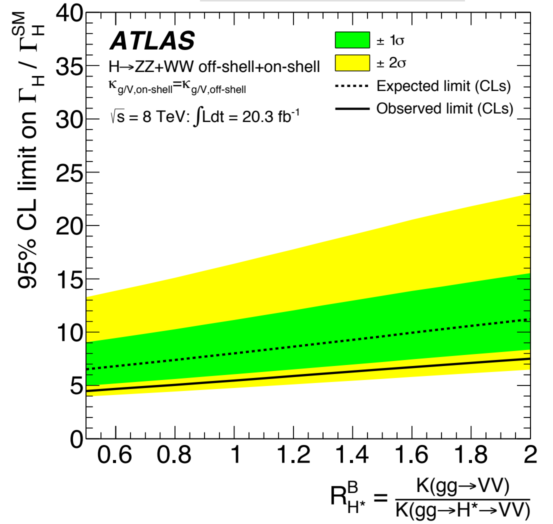
$$\sigma^{off}_{i\to X\to f} \sim g_i^2 g_f^2$$



EPJ C75 (2015) 5, 212

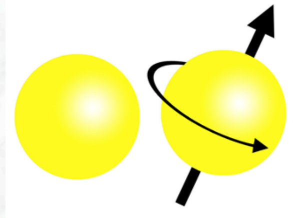


arXiv: 1503.01060



Results:	95% CL limits	
CMS:	Γ_H / Γ_{SM} < 5.4	(= 22 MeV)
ATLAS:	Γ_H / Γ_{SM} < 5.5	($R_B^{H^*}$ = 1)

Spin and CP

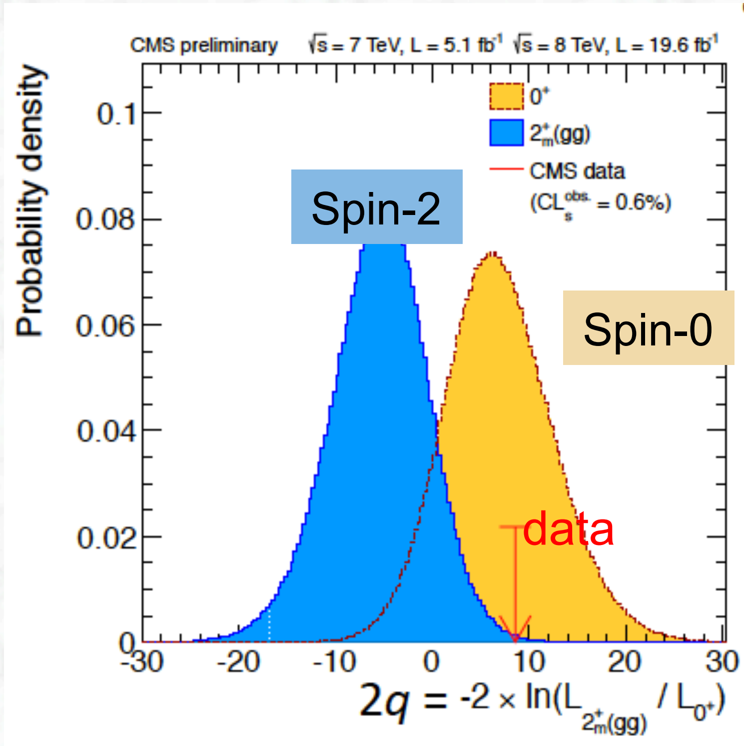


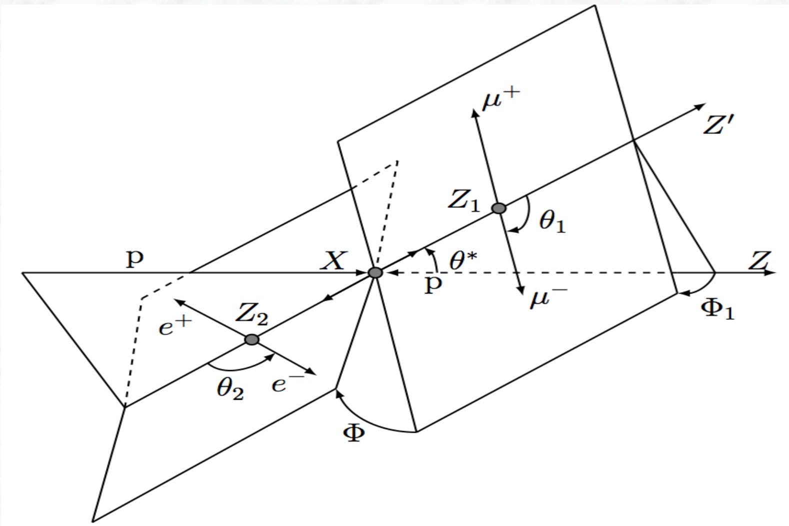
- Standard Model Higgs boson: $J^P = 0^+$

  → 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)

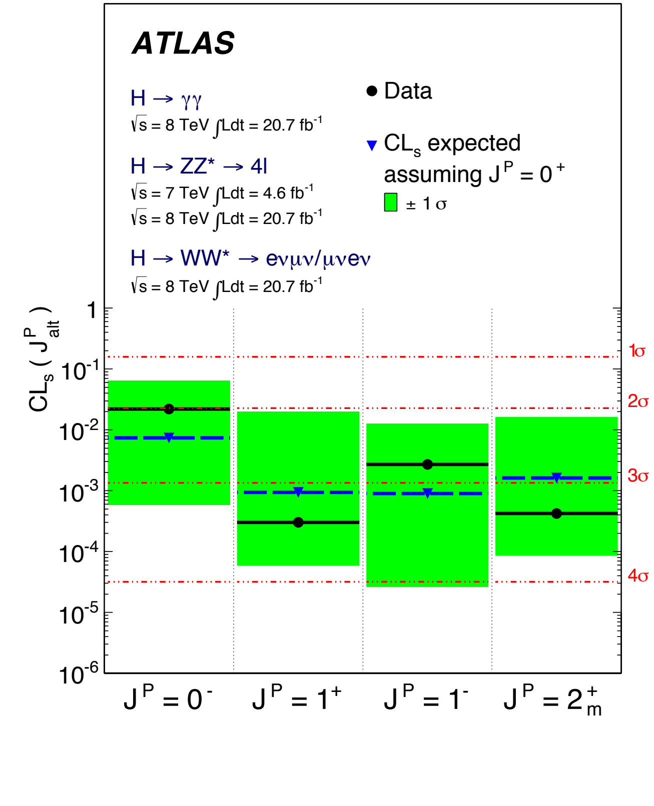




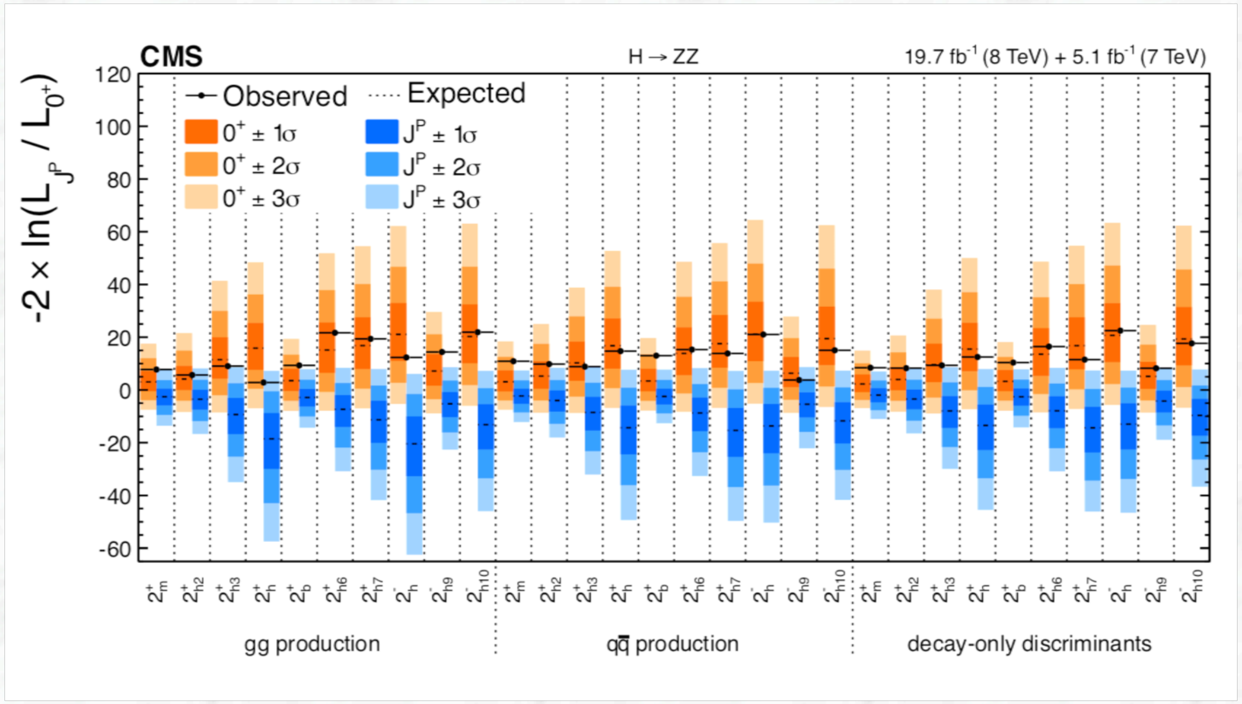
- Data strongly favour the spin-0 hypothesis of the Standard Model
- Many alternatives can be excluded with confidence levels > 99%)

Result on different J^{CP} hypothesis tests

Phys. Lett. B726 (2013) 120



arXiv:1411.3441



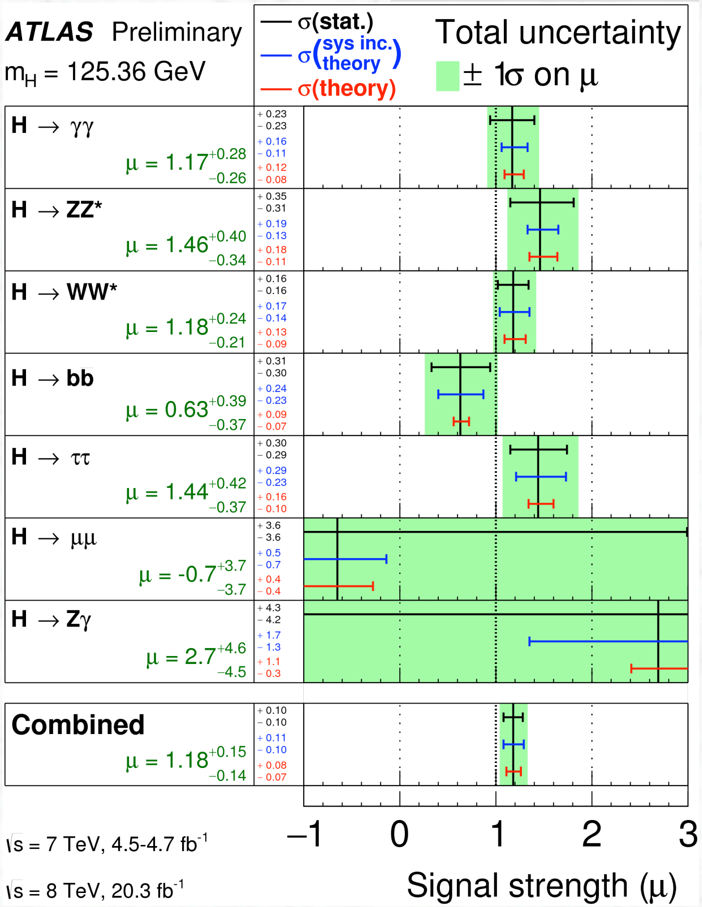
- In both experiments, data are consistent with $J^P = 0^+$ hypothesis, many alternative models are excluded with high significance

Parallel Session Talks: Marcello Fanti

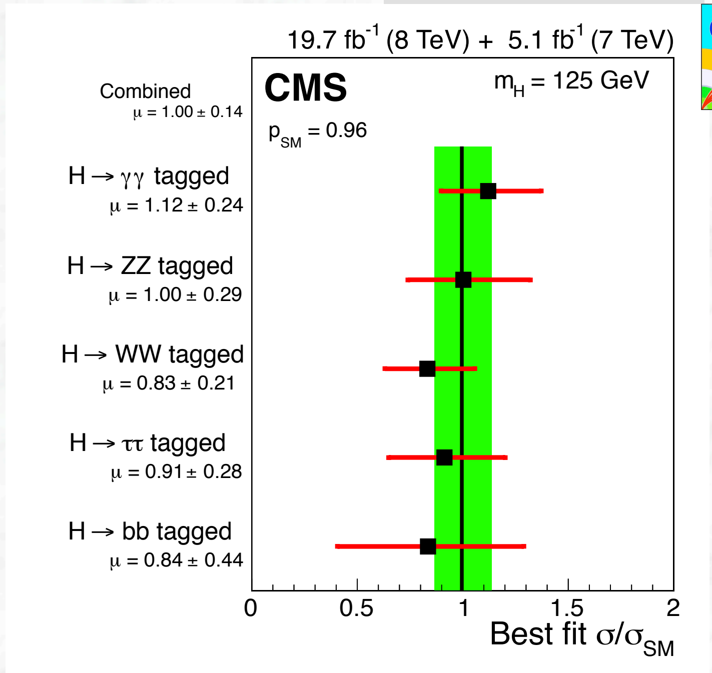
Signal strength in individual decay modes

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

ATLAS-CONF-2015-007



EPJ C75 (2015) 5, 212



Signal strengths:

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

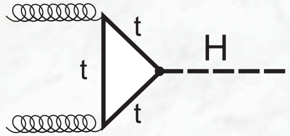
CMS: $\mu = 1.00 \pm 0.14$

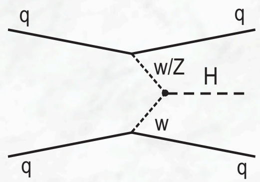
- Data are consistent with the hypothesis of the Standard Model Higgs boson
- If ATLAS and CMS combined: clear evidence for coupling to fermions

Higgs boson couplings

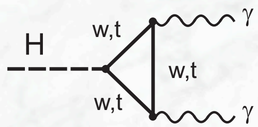
- Production and decay involve several couplings

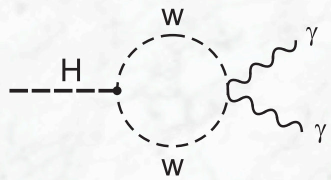
Production:





Decays: e.g H → $\gamma\gamma$ (best example)
(Decay widths depends on W and top-coupling, destructive interference)





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

  - Signals observed originate from a single resonance;
    (mass assumed here is 125.36GeV (ATLAS) and 125.02 GeV (CMS))

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

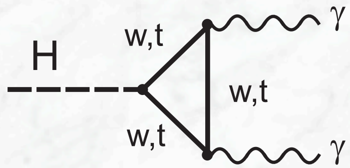
$$\sigma \cdot B\,(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

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

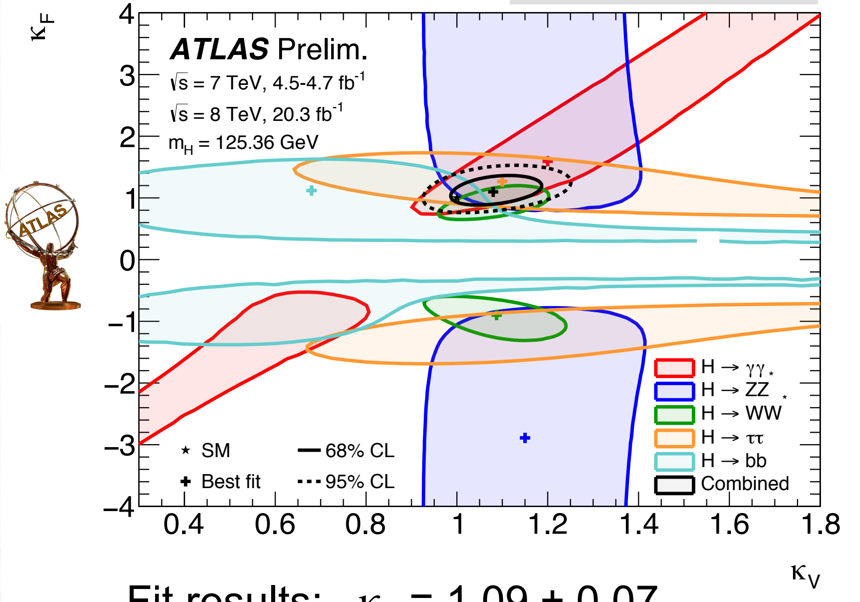
  - Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model

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 $\kappa_V > 0$)

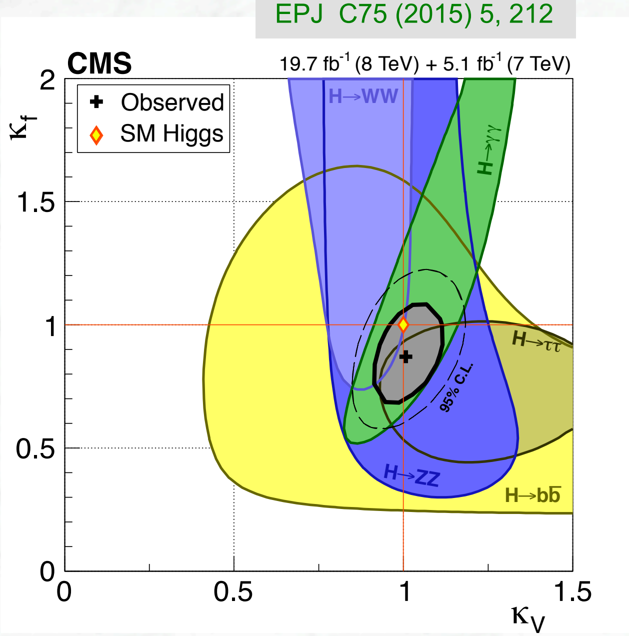


ATLAS-CONF-2015-007



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

EPJ C75 (2015) 5, 212



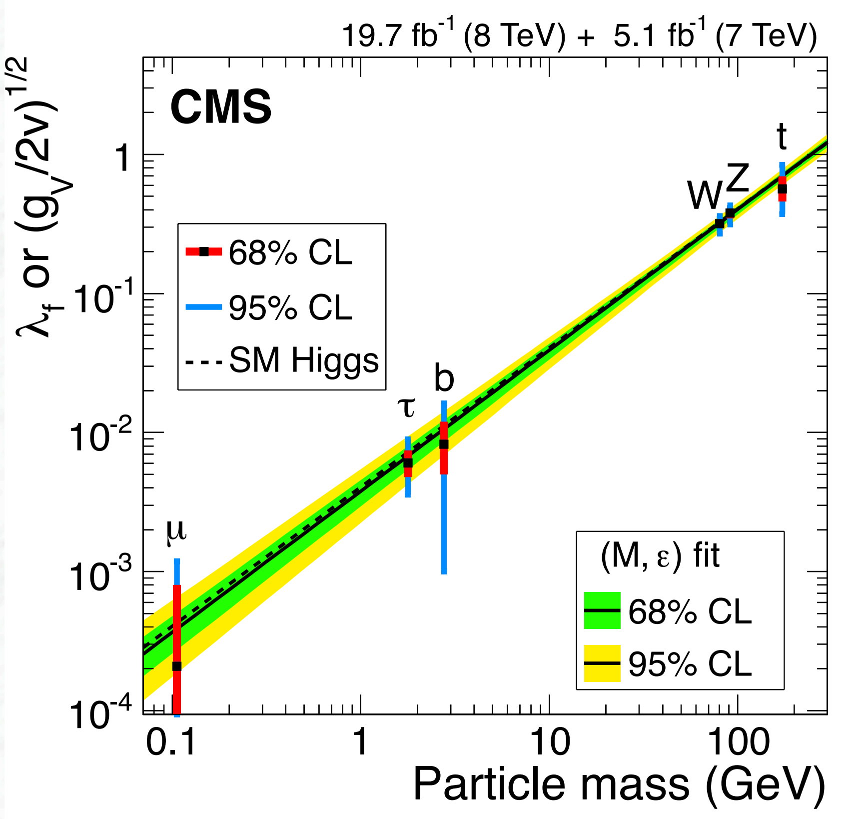
Fit results: $\kappa_V \in [0.87, 1.14]$ (95% CL)
$\kappa_F \in [0.63, 1.15]$ (95% CL)

Higgs boson couplings

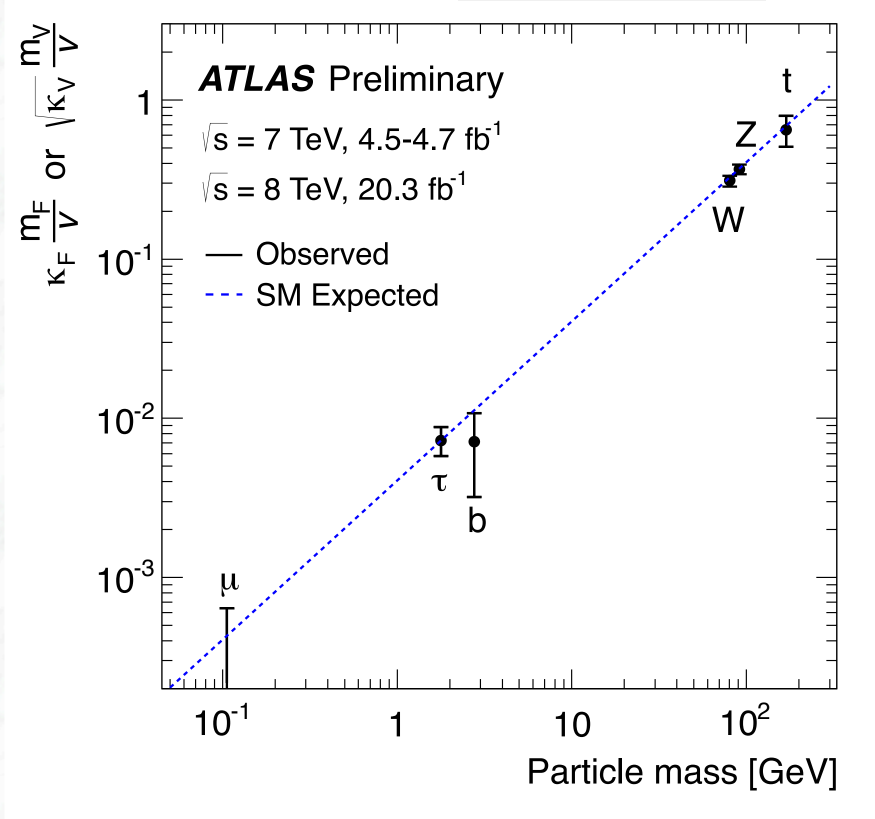
- Fit all coupling scale factors for relevant particles (W, Z, t, b, τ, μ) independently;
- Loop factors expressed in terms of these scale factors, assume SM particle content

λ = Yukawa coupling for fermions
√g/2v = couplings for W/Z bosons

EPJ C75 (2015) 5, 212



ATLAS-CONF-2015-007

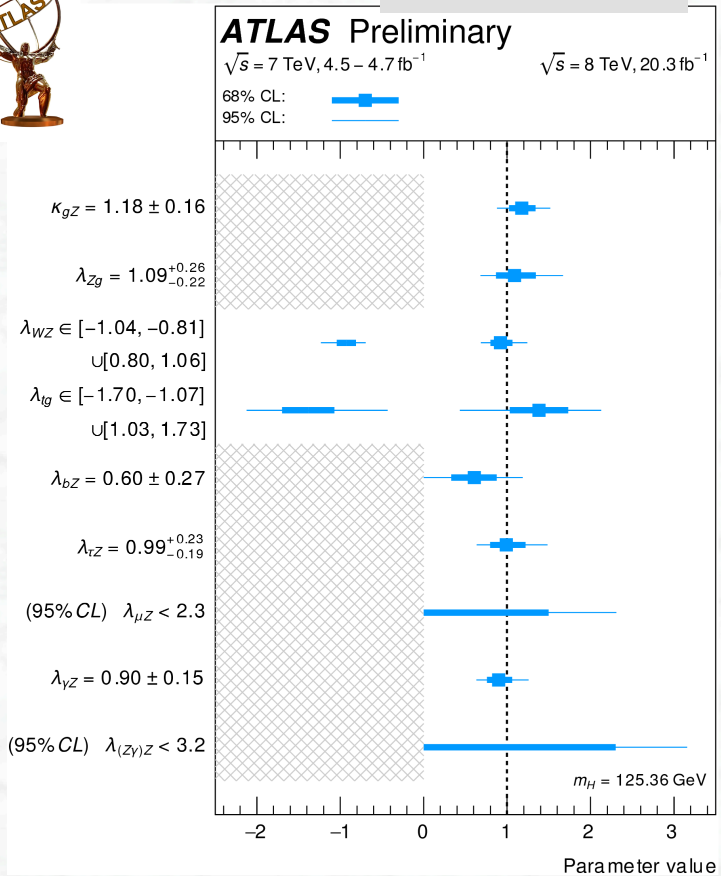


For the first time, non-universal, mass-dependent couplings observed

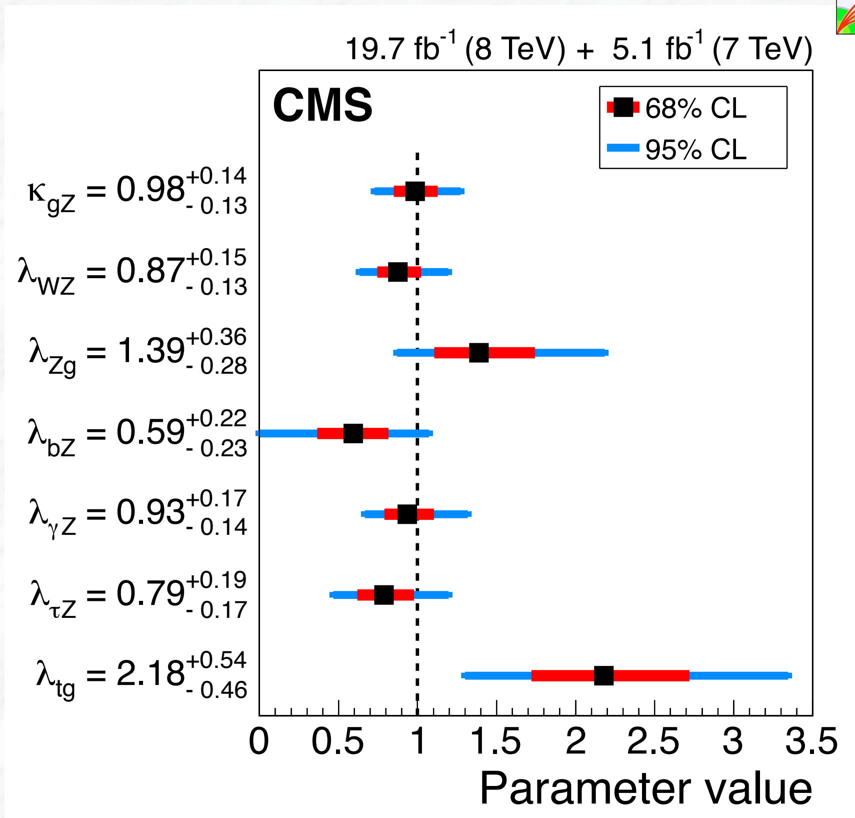
Ratios of Higgs boson couplings (model independent)

- In the most general model, only ratios of couplings can be measured independently on any assumptions on the total width (allowing also deviations in vertex loop coupling strength)

ATLAS-CONF-2015-007



EPJ C75 (2015) 5, 212



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

Good consistency with the Standard Model Higgs boson hypothesis

Additional Higgs bosons?

Composite Higgs bosons

MSSM Higgs bosons

Dark Higgs

More Higgs bosons

SUSY Higgs

Heidi Higgs

No Higgs at the LHC

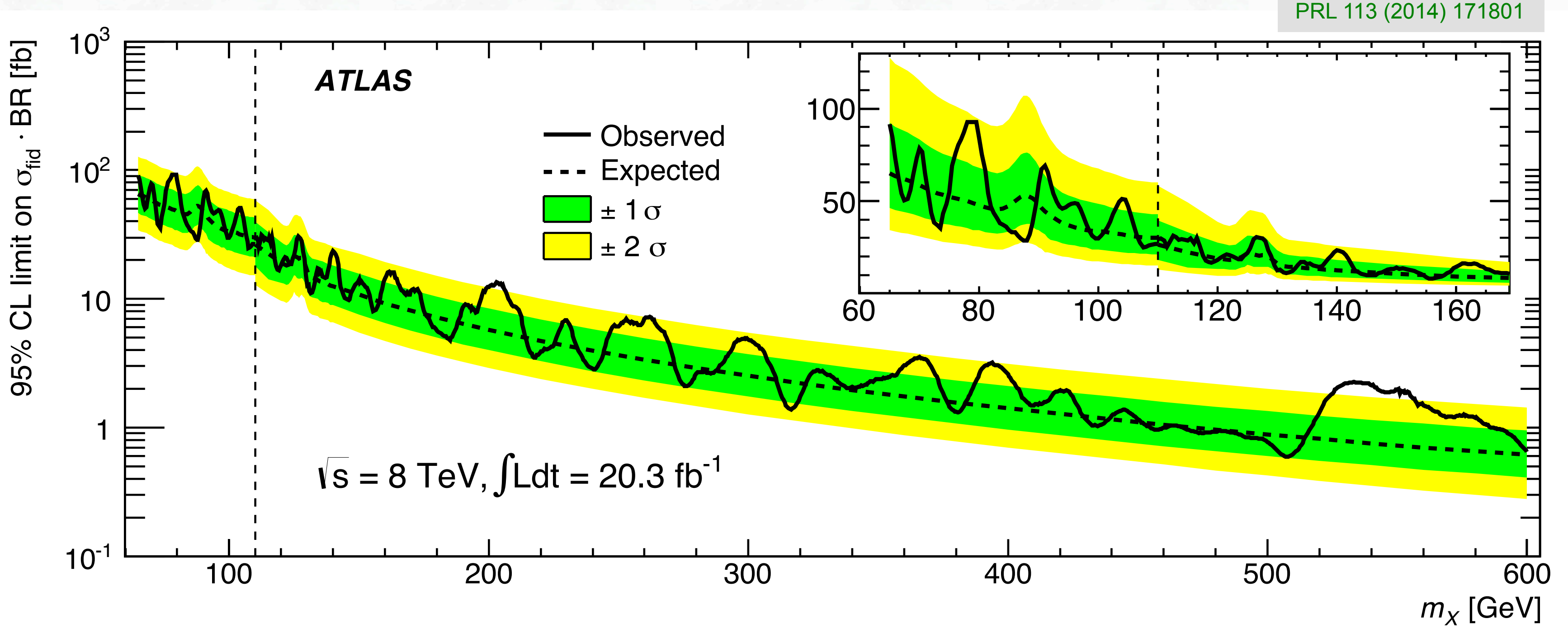
Parallel Session Talks:

- Matthias Mozer
- Nicolaos Rampotis
- Glauber Dorsch

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

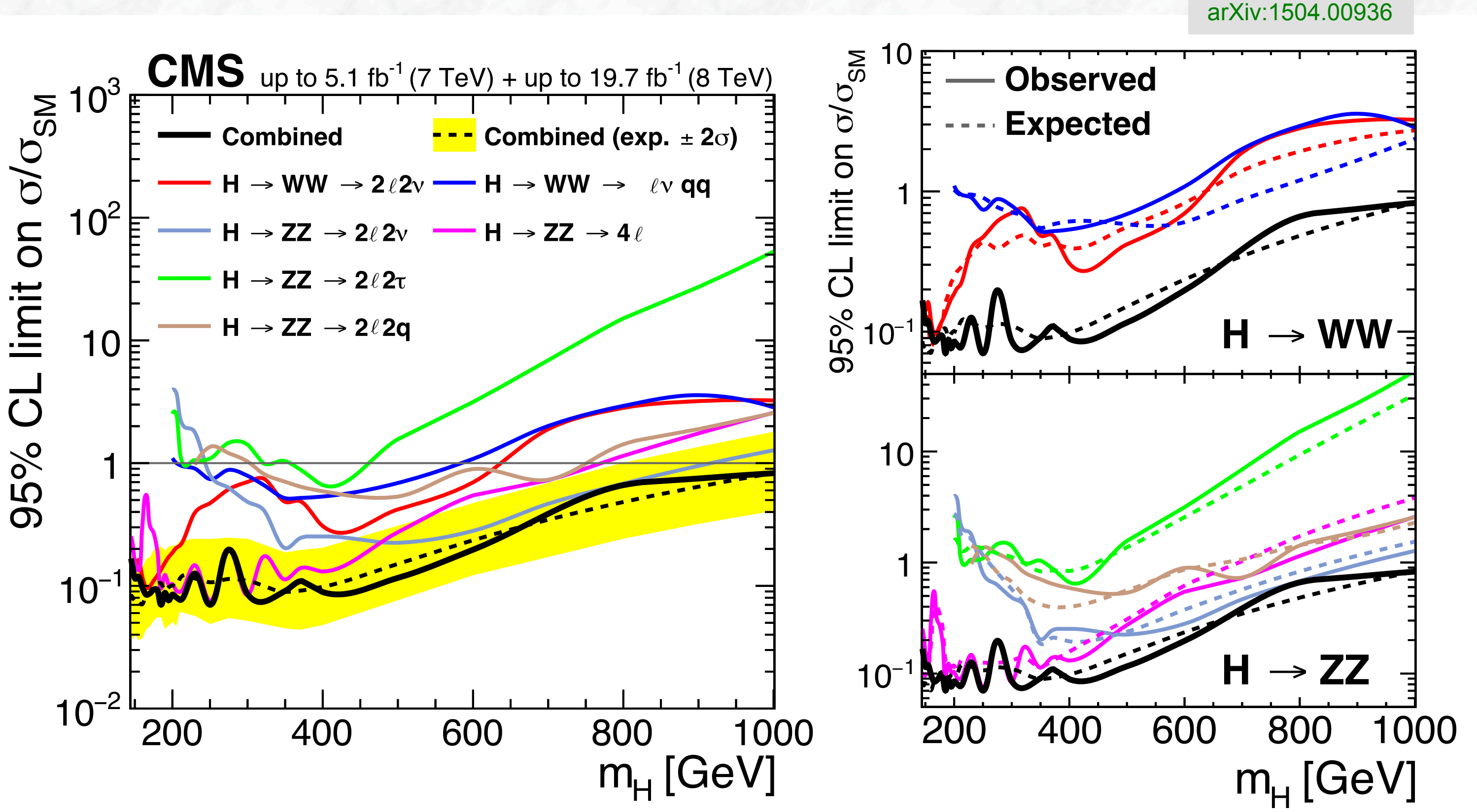


Observed and expected 95% CL limits on the fiducial cross section times branching ration BR(X → $\gamma\gamma$) as a function of mass

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

(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

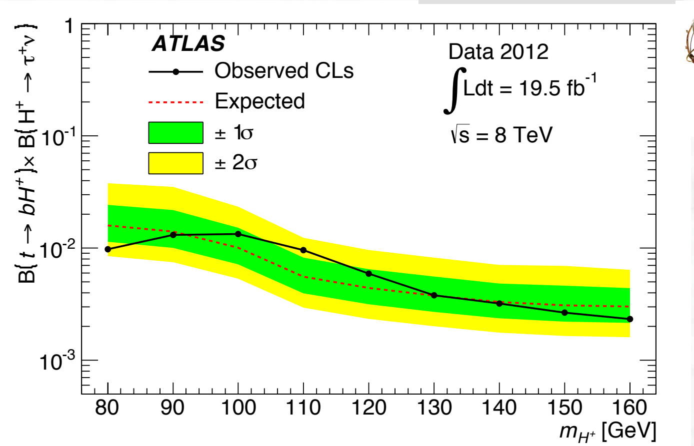
Parallel Session Talks: Matthias Mozer

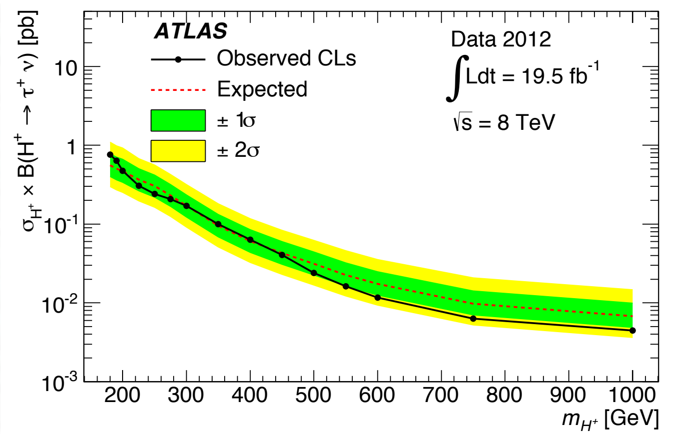
(iii) Search for charged and heavy neutral MSSM Higgs bosons

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

Parallel Session Talks: Nicolaos Rompotis

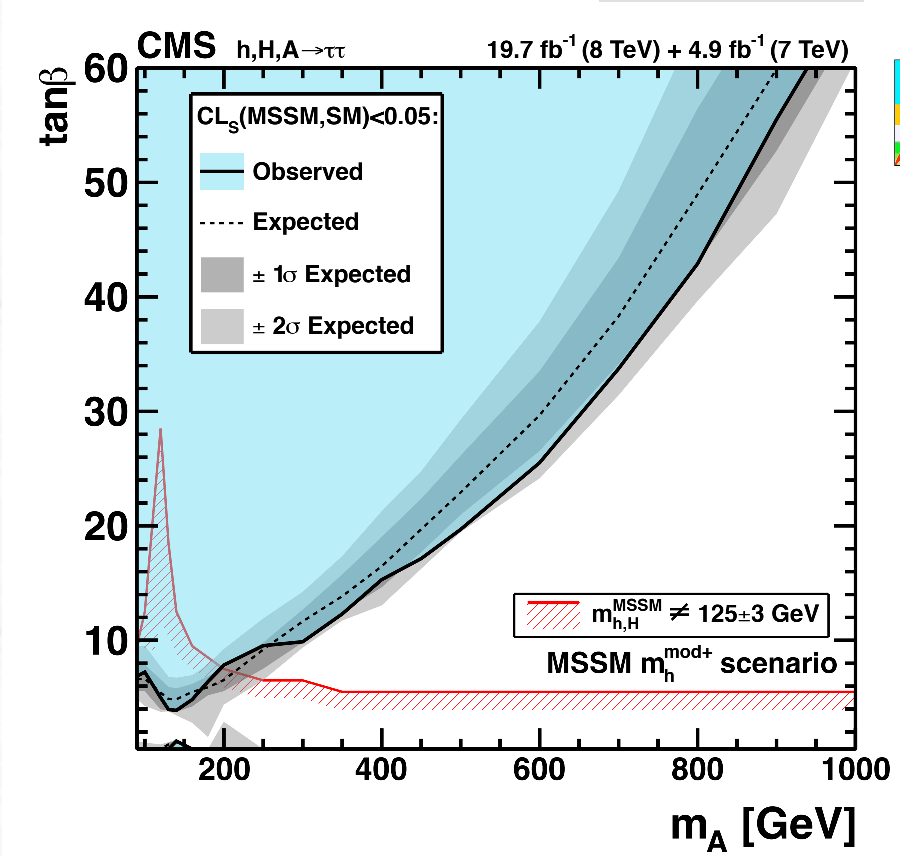
JHEP 03 (2015) 088





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

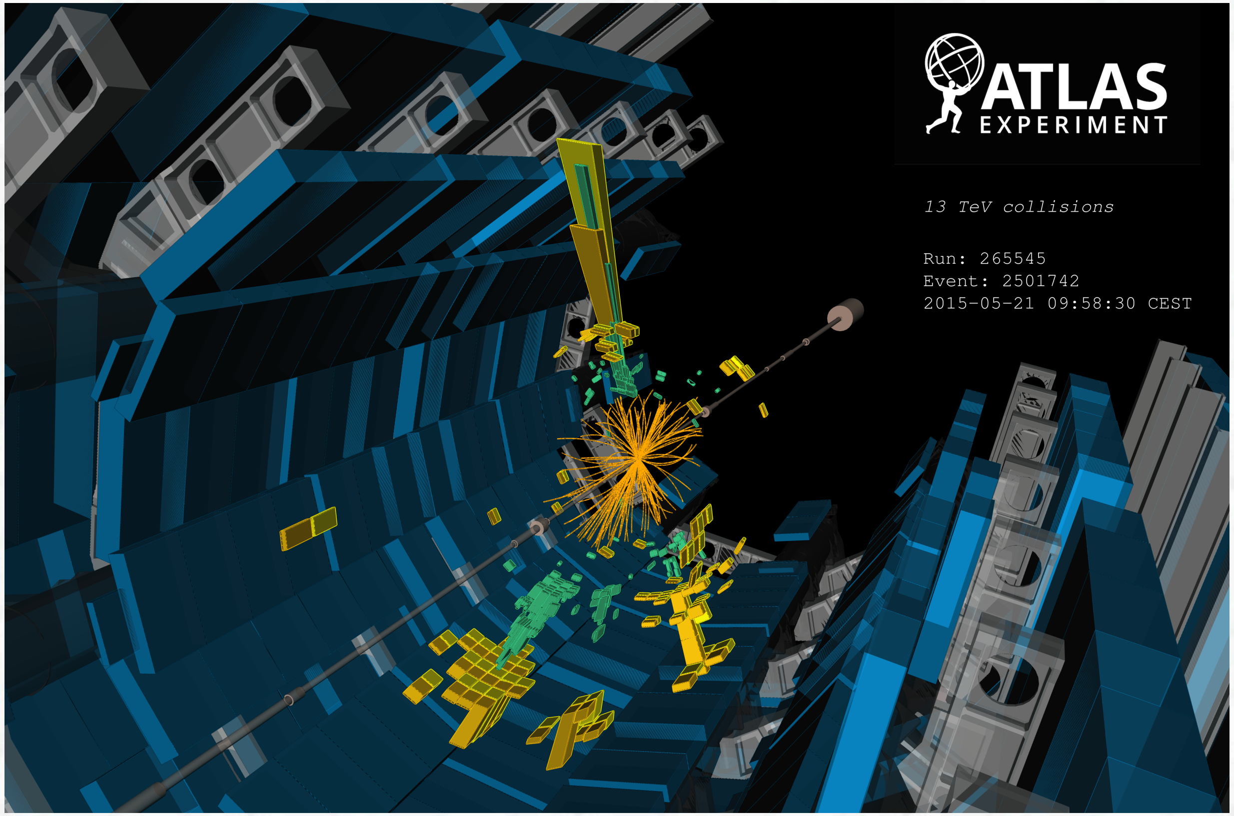
JHEP 10 (2014) 160



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

What next?

The LHC has started operation at $\sqrt{s}$ = 13 TeV



A proton-proton collision at 13 TeV, recorded by the ATLAS experiment on 21. May 2015

A new energy range will be explored !!

Major physics topics:

(i) Extend the searches for New Physics

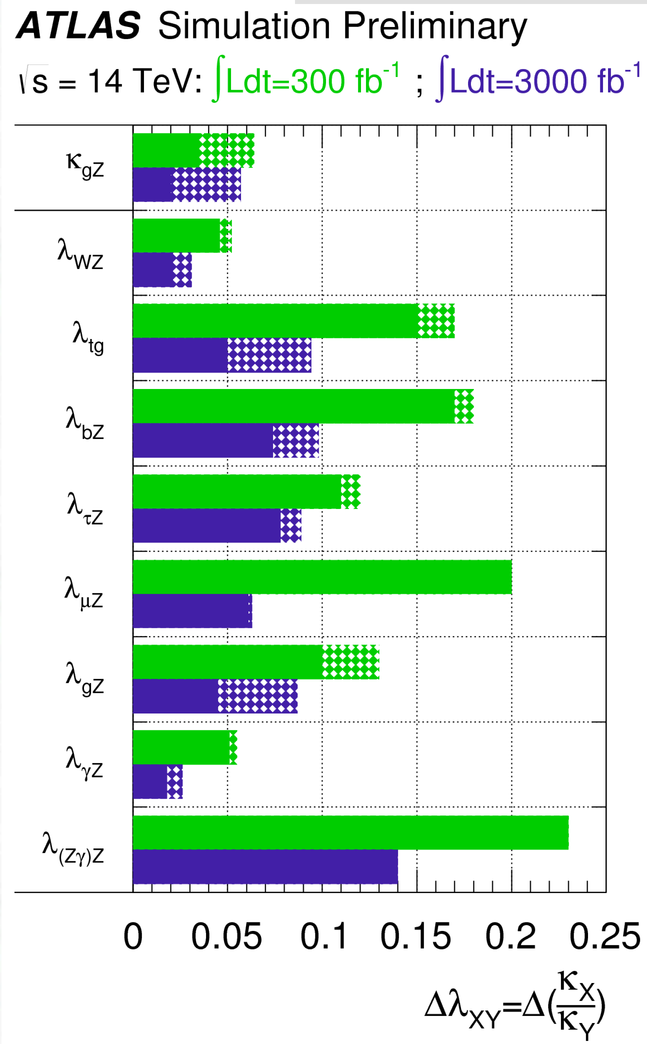
(ii) Precise measurements of the Higgs boson profile

(iii) Additional Higgs bosons?

(iv) Scattering of vector bosons

(v) Precision measurements (m_W, m_{top}, Higgs couplings)

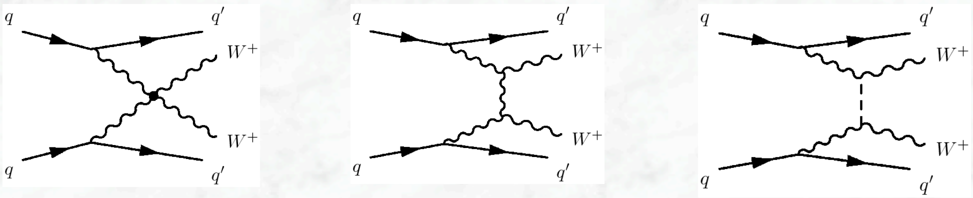
ATL-PHYS-PUB-2013-016



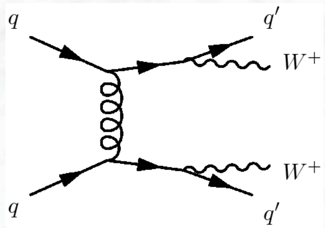
Parallel Session Talk: Monica Trovatelli

First evidence for electroweak $W^{\pm}W^{\pm}jj$ production (Run 1)

- Higgs boson needed in the SM to regularise VV scattering at high energies;
- Key experimental process: $W^{\pm}W^{\pm}$ scattering

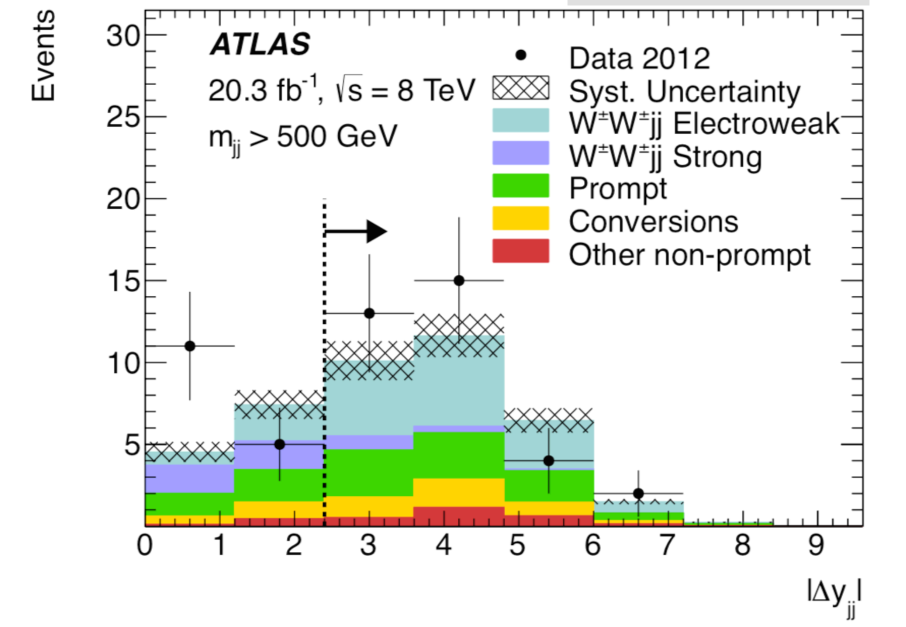


Electroweak production



Strong production

PRL 113 (2014) 141803



VBS enhancement by cutting on mass (m_{jj}) and rapidity separation Δy_{jj}

ATLAS: 3.6σ for electroweak production

CMS: 2.0σ PRL 114 (2015) 051801

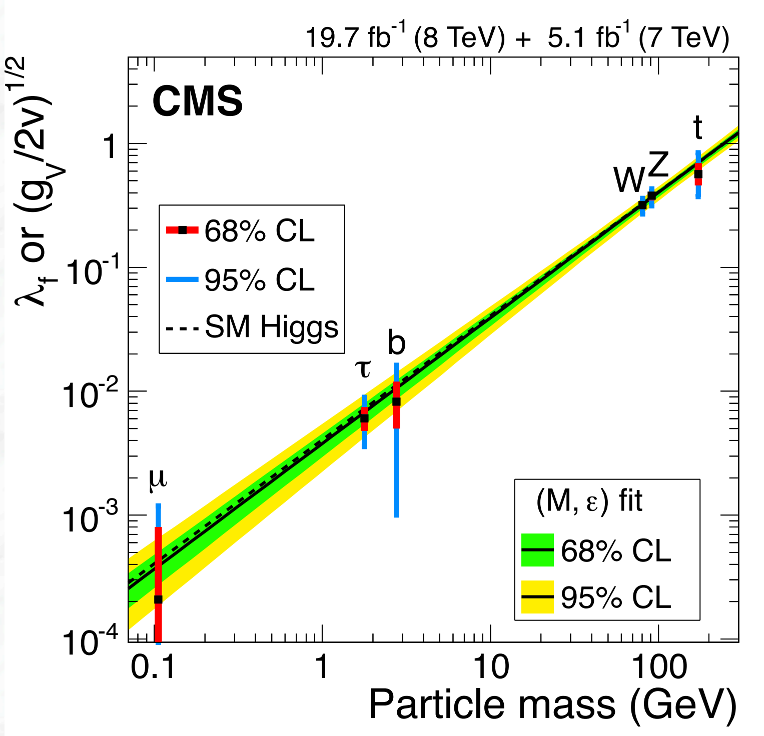
(expected: in both experiments about 3σ)

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