Recent progress in Higgs studies at ATLAS and CMS

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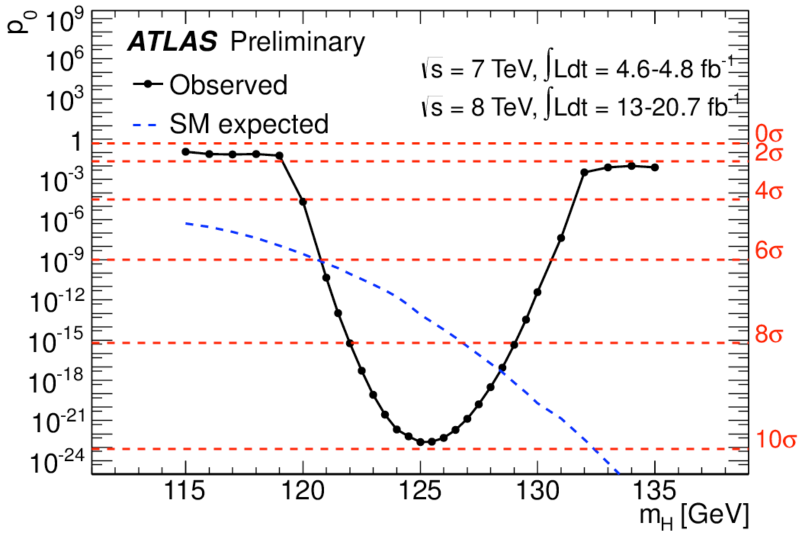
30. April 2013

SLAC Experimental Seminar

Higgs-like resonance @ 125 GeV established

- 2013 Moriond results confirm July 2012 discovery.



ATLAS

Decay mode	Expected (σ)	Observed (σ)
ZZ	4.4	6.6
γγ	4.1	7.4
WW	3.7	3.8
bb	< 1.2 x SM	< 1.9 x SM
ττ	< 1.9 x SM	< 1.8 x SM

To be updated

- Detectors perform very similarly: differences driven mainly by analysis choices.

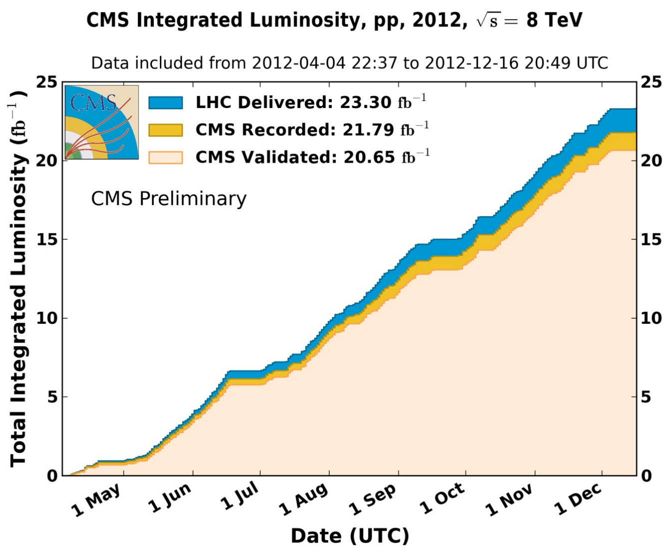
- Consistent with SM Higgs boson? → Detailed studies of properties (mass, couplings, spin) started...

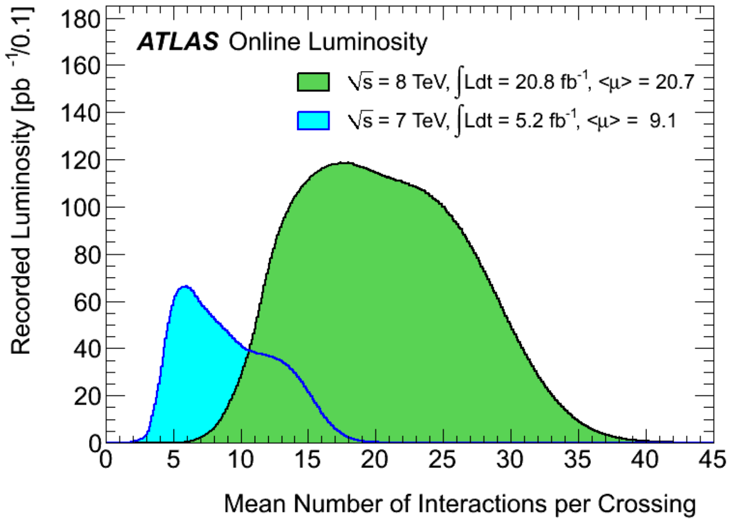
CMS

Decay mode	Expected (σ)	Observed (σ)
ZZ	7.1	6.7
γγ	3.9	3.2
WW	5.3	3.9
bb	2.2	2.0
ττ	2.6	2.8

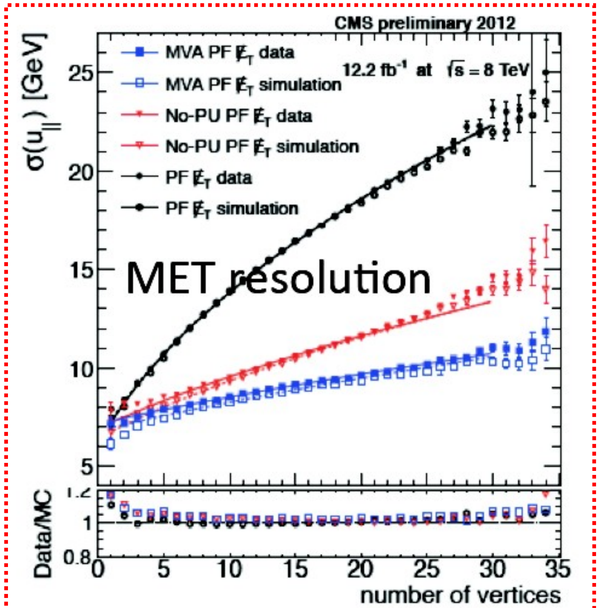
Run-I dataset

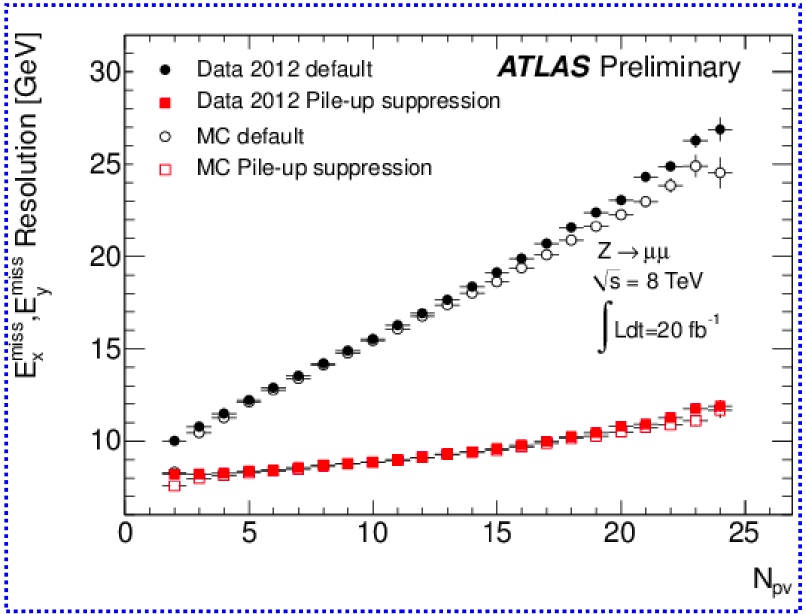
- ATLAS and CMS have by now collected ~5 fb-1 @ 7 TeV and ~20 fb-1 @ 8 TeV.





- The LHC accelerator has beautifully exceeded expectations, but at the cost of much higher pile-up rates than originally foreseen for the first "low-lumi" run.

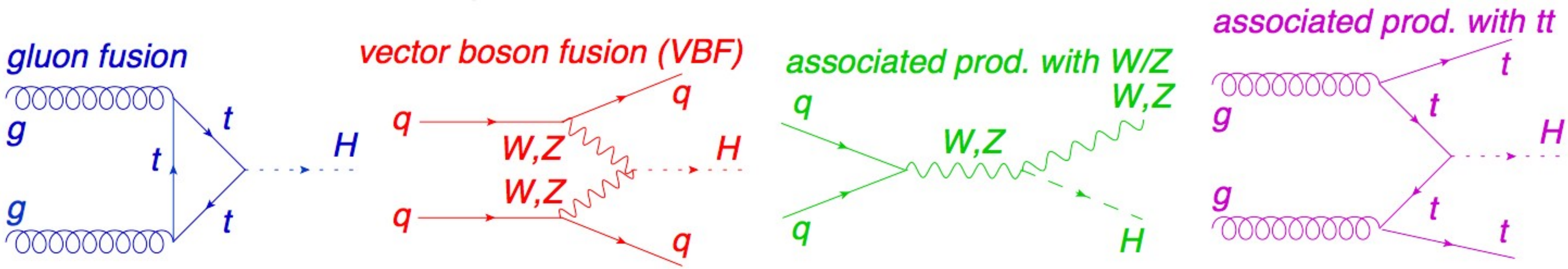


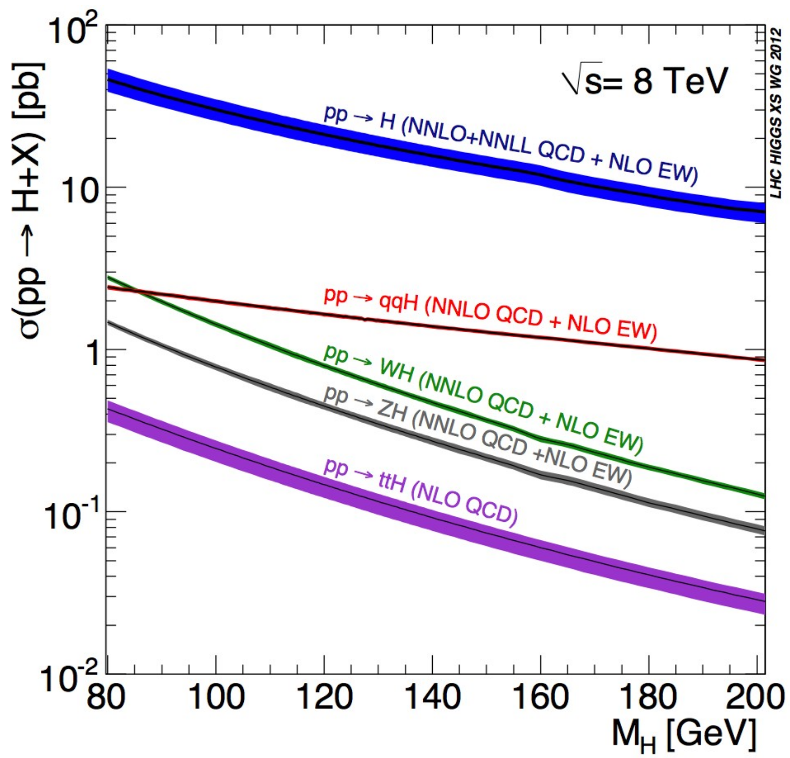


- A huge amount of work to keep up with trigger rate & make algorithms robust against pile-up (e.g. MissingET resol.).
- Particular impact on the most complex channels (bb,ττ)

Higgs production

- Production modes:

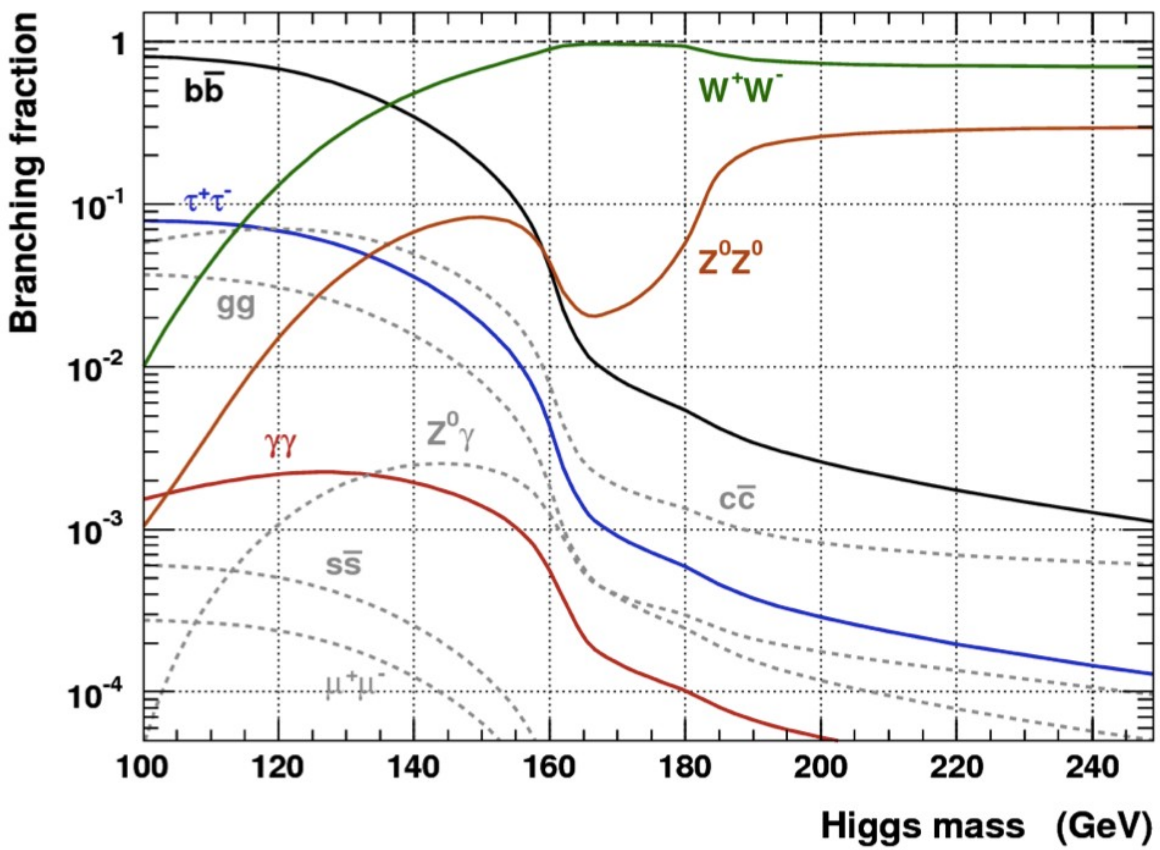




- Main production mode gluon fusion (theory uncertainty ~10%)
- Observation of other production modes important test to establish SM Higgs boson.
  - Vector Boson Fusion
  - Associated production with W and Z boson
  - Associated production with top pair
- Allows to directly explore couplings to fermions and top quarks.

Higgs decays

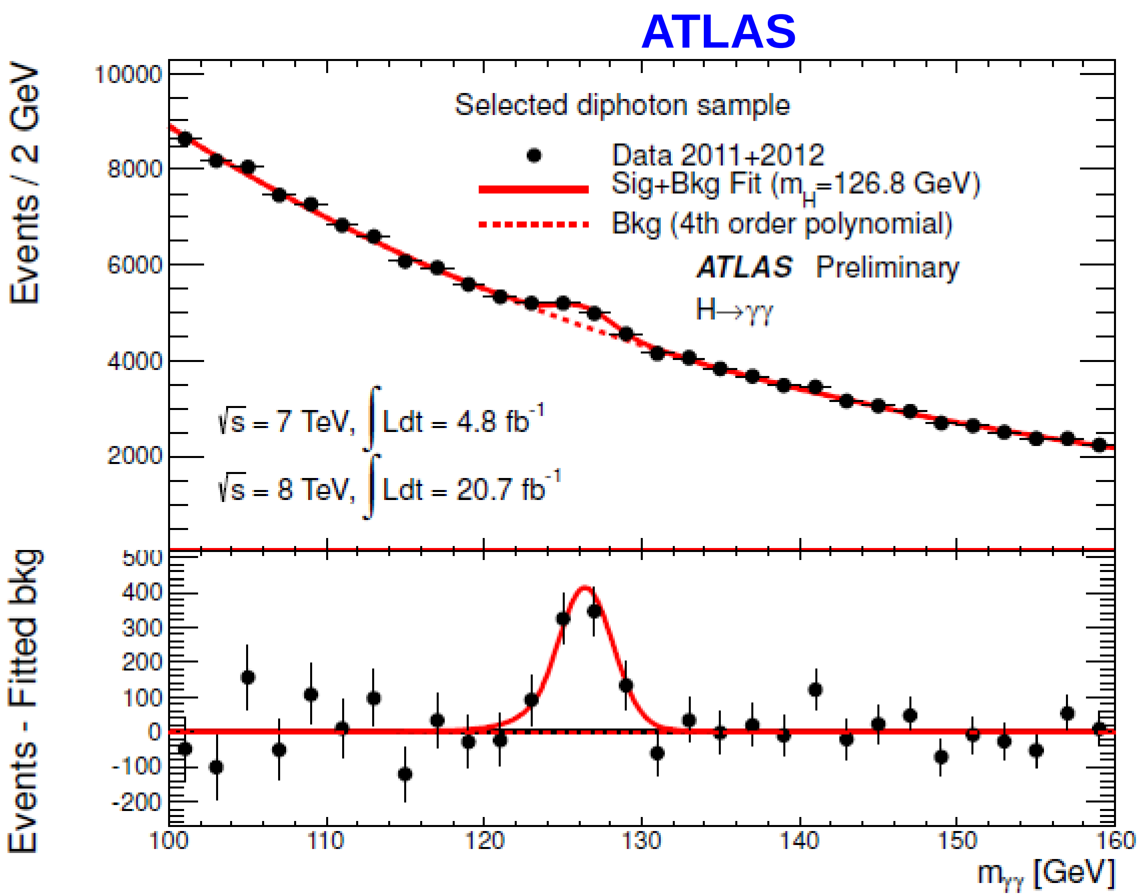
- ATLAS and CMS have by now collected ~5 fb^{-1} @ 7 TeV and ~20 fb^{-1} @ 8 TeV.



- Tree level couplings:
  - WW,ZZ → bosons
  - bb,ττ → fermions
- Loop induced:
  - γγ
- Fermionic channels also give direct access to coupling to fermions.
- Measuring all decays is important to indirectly constrain the Higgs width (Γ_H~4 MeV not directly accessible)

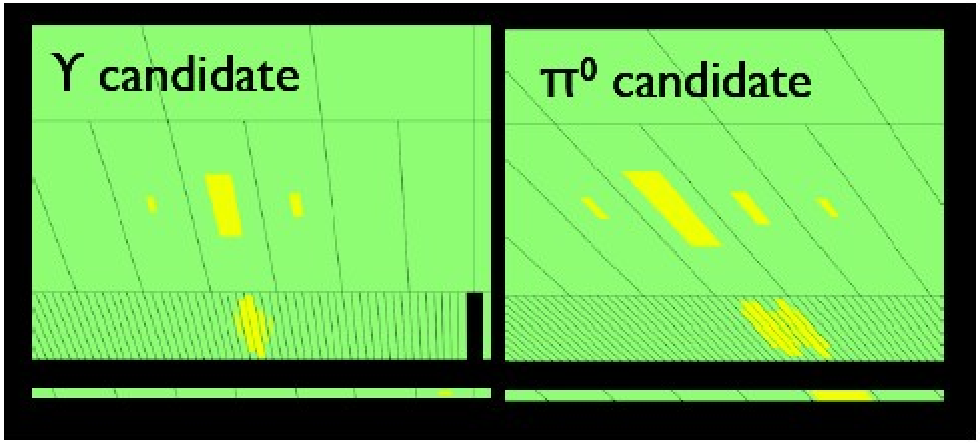
Higgs → γγ

- Simple topology: select two high-ET photons, look for excess in mγγ.
- Sensitivity depends on:
  - 1. Rejection of reducible γj and jj backgrounds
  - 2. Invariant mass resolution
    - Energy resolution
    - Correct identification of primary vertex
- Both detectors made important (and different) choices to try to improve the sensitivity in this channel.
- Comparison not easy because of different object ID & analyses strategies.



Higgs → $\gamma\gamma$: signal ID and background rejection

- **ATLAS** profits from the fine lateral segmentation of the calorimeter ($\Delta\eta$~0.003)
  → improves separation of isolated photons from boosted π^0 to $\gamma\gamma$ decays in jets.



- Photon identification:
  - **CMS** uses a BDT combining shower shape and particle flow based isolation variables. A second BDT is used to improve the energy estimation.
  - **ATLAS** uses a cut based approach, based on shower shape variables and adds separately charged and neutral isolation cuts afterwards.
- ATLAS quotes ID efficiencies between ~85% and ~95% for ET>100 GeV. CMS quotes overall ~92 to ~95% event efficiency of the photon based preselection.
- Similar rejection levels of reducible background.
  - Fraction of irreducible bkg is 75 ± 3 % in **ATLAS**, ~70% from MC in **CMS**.

Higgs → γγ: mass resolution (I)

- **CMS** profits from better intrinsic calorimeter resolution
- **ATLAS** profits again from the fine lateral segmentation, which allows to determine the PV z position through photon pointing within ~1.5 cm (beam spot spread is ~5-6cm)

$$m_{\gamma\gamma}=\sqrt{2E_1E_2(1-\cos(\delta\alpha))}$$

Primary Vertex Finding strategy

CMS

- Use BDT with inputs:
  - Sum, squared sum of track pT
  - Correlation with pT(γγ)
  - Asymmetry between PV tracks and γγ system
  - Conversion info (if available)
- → Resolution: ~80% → <1cm
  ~20% → ~5-6cm

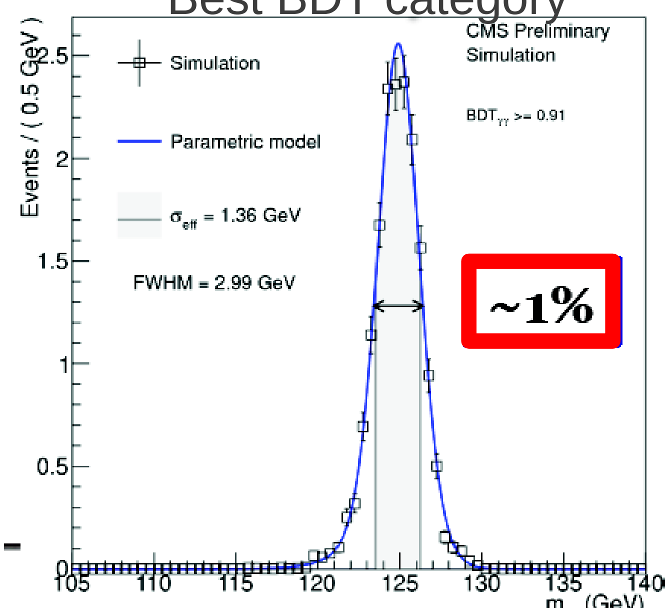
ATLAS

- Use NN with inputs:
  - Photon pointing
  - Sum, squared sum of track pT
  - Correlation with pT(γγ)
  - Conversion info (if available)
- → Resolution: ~75% → < 0.3mm
  ~25% → ~1.5cm

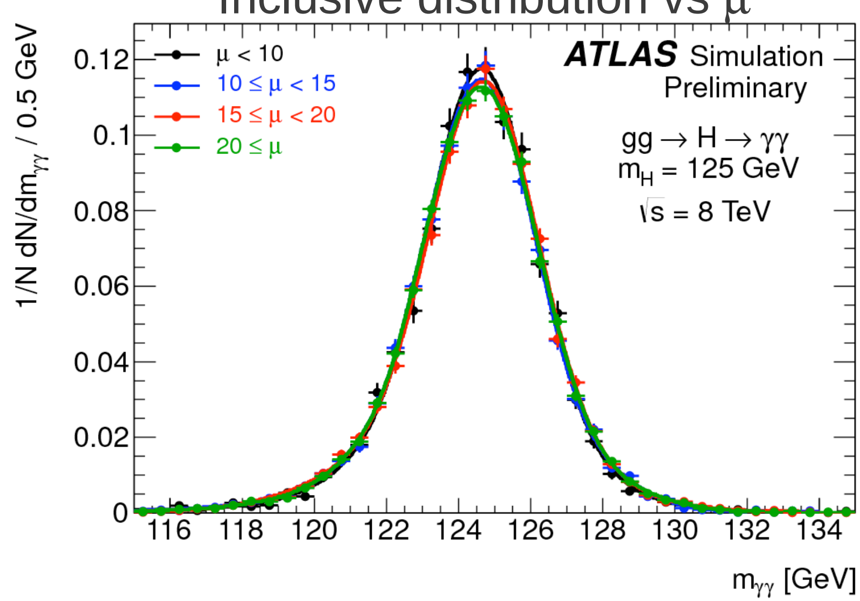
Higgs → γγ: mass resolution (II)

- In the end the better resolution for unconverted photons in **CMS** (but >50% events have ≥1 converted photon!) and the better identification capabilities of the PV in **ATLAS** seem a bit to compensate each other.
- Mass resolution (σ(CB) for ATLAS vs FWHM/2.35 for CMS):
  - **ATLAS**: 1.1 – 2.0% (average 1.3%)
  - **CMS**: 1.0 – 1.7% (average 1.2%)

Best BDT category



Inclusive distribution vs μ



Higgs → γγ: categorization (CMS)

- **CMS** uses a complex series of BDTs to classify the events in different S/B regions.

1. BDT — Estimate event-by-event vertex misidentification probability

reduce signal weight in BDT if vertex is misidentified

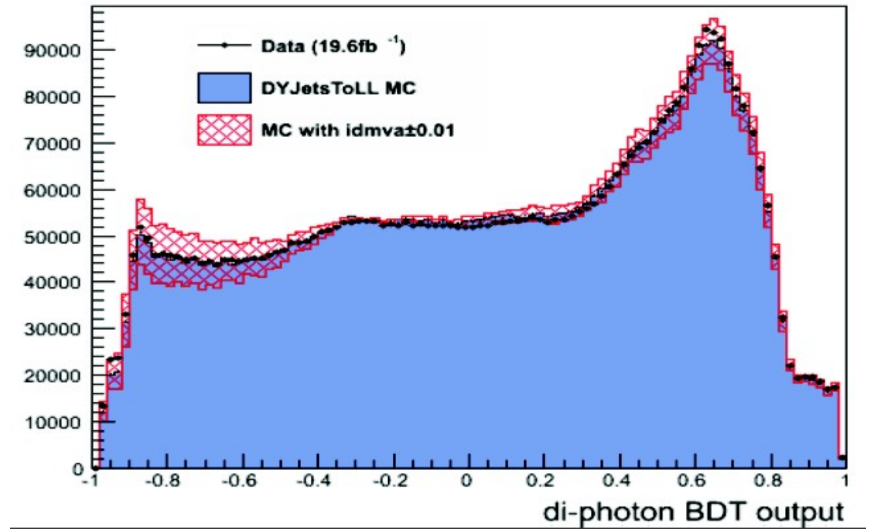
2. BDT — Estimate event-by-event photon energy resolution

3. BDT — Photon identification based on shower shapes

Other inputs:
1. pT(1,2)/mγγ
2. η(1,2)
3. cos(α_γγ)

4. BDT — Train signal against background (with variables uncorrelated with mγγ)

- Validated using Z → ee data
  - An uncertainty of ±0.01 on photon ID BDT and ±10% on photon resolution estimate covers difference observed in data in the final **BDT** distribution.
  - The final BDT is used to separate 4 classes of events with different S/B.
- A cut based analysis is used as cross-check.



Higgs → γγ: categorization (ATLAS)

- **ATLAS** uses a simpler S/B categorization based on:

1. ≥1 converted γ 2. unconverted 3. converted γ in transition region	⊗	1. PTt > 60 GeV 2. PTt < 60 GeV	⊗	1. both γ |h|<0.75 2. rest

- PTt is the momentum of the γγ system transverse to the "thrust axis". This quantity is sensitive to pT(γγ), but is less sensitive to energy mis-measurements.

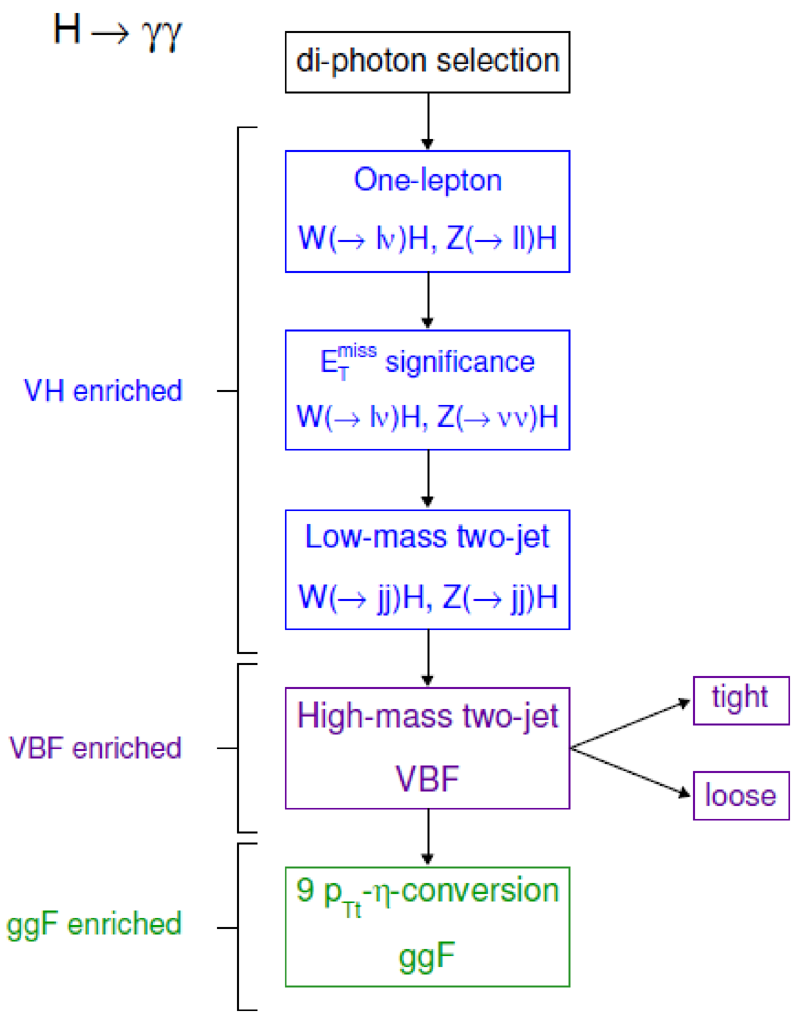
$$\hat{t} = \frac{\vec{p}_T^{\gamma 1} - \vec{p}_T^{\gamma 2}}{|\vec{p}_T^{\gamma 1} - \vec{p}_T^{\gamma 2}|}$$

- For a mass window containing 90% of signal events around m=125 GeV, S/B in these categories range from ~1% to ~15%.

- Both ATLAS and CMS have recently added categories to specifically probe the VH and VBF production modes!

Higgs → γγ: VH/VBF categorization

- **ATLAS** now looks beyond ggF:



- 2 VBF enriched categories, based on BDT with inputs:

$$m_{jj} \quad \Delta\eta_{jj} \quad \eta_{j1} \quad \eta_{j2} \quad p_{Tt}$$
$$\Delta\phi_{\gamma\gamma;jj} \quad \eta^* = \eta_{\gamma\gamma} - \frac{\eta_{j1}+\eta_{j2}}{2} \quad \Delta R^{\gamma j}_{\min}$$

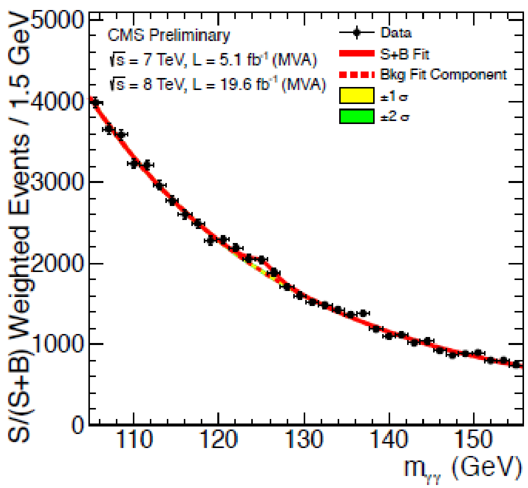
- Tight (loose) categories are defined, with VBF purities of ~80% (~50%)
  - S/B increased to~60% (20%)!
- **CMS** does basically the same, adding:
  - Two categories for VBF, again with a BDT based on:

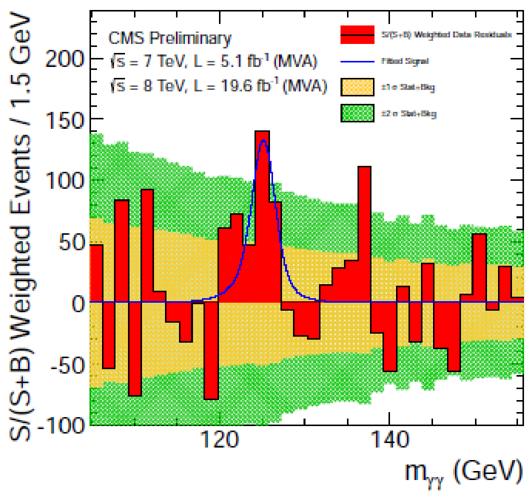
$$p_T^\gamma(1)/m_{\gamma\gamma} \quad p_T^\gamma(2)/m_{\gamma\gamma} \quad p_T^j(1) \quad p_T^j(2)$$
$$m_{jj} \quad \Delta\varphi_{jj,\gamma\gamma} \quad \Delta\eta_{jj,\gamma\gamma}$$

  - 3 categories defined for VH (muon, electron or Etmiss based)

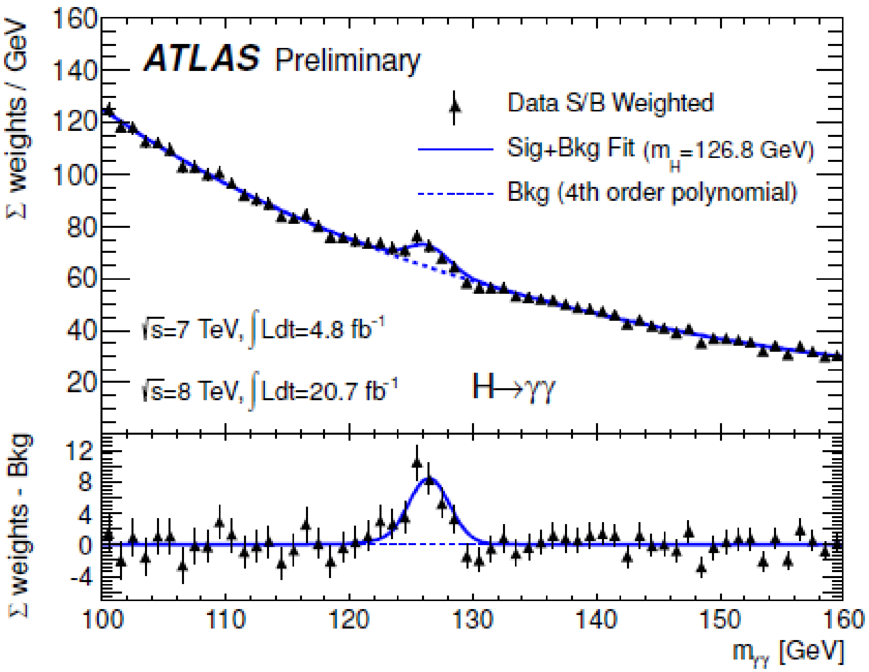
Higgs → γγ: inclusive result

CMS



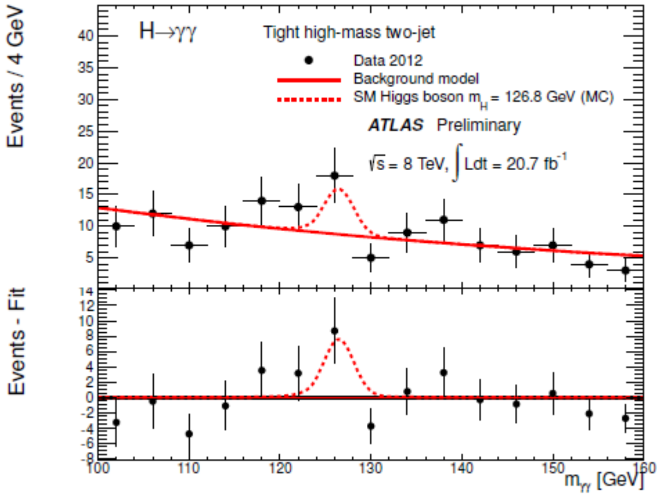


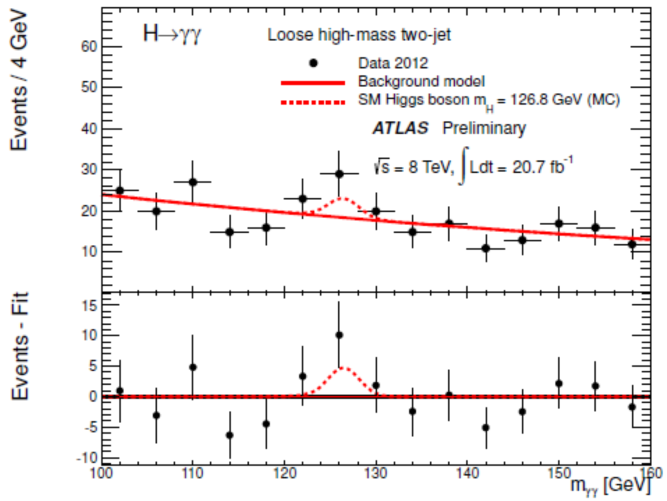
ATLAS



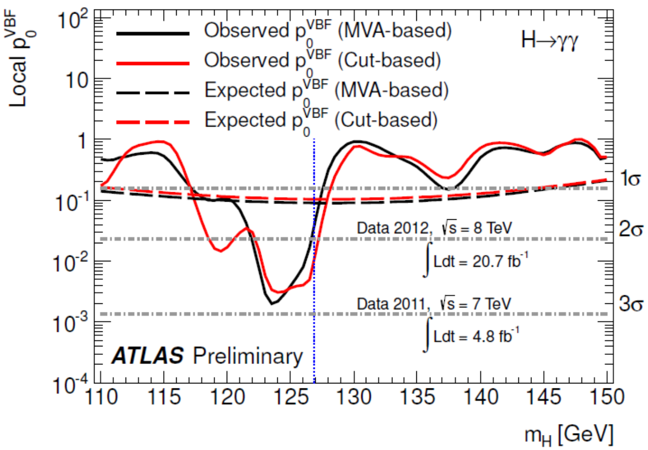
- Measured μ values:
  - ATLAS: 1.65 ± 0.2 (stat) ± 0.7 (syst)
  - CMS: 0.78 ± 0.27
- In CMS both estimated μ value and observed significance (3.2σ) have gone down with the new analysis.
- More robust cut based analysis sees more signal (1.11 ± 0.31).
- Studying statistical correlations, the level of compatibility of the two cut based & MVA 8 TeV (7+8 TeV) analyses have found to be at 1.8σ (1.5σ) level.

Higgs → γγ: VBF production observed?

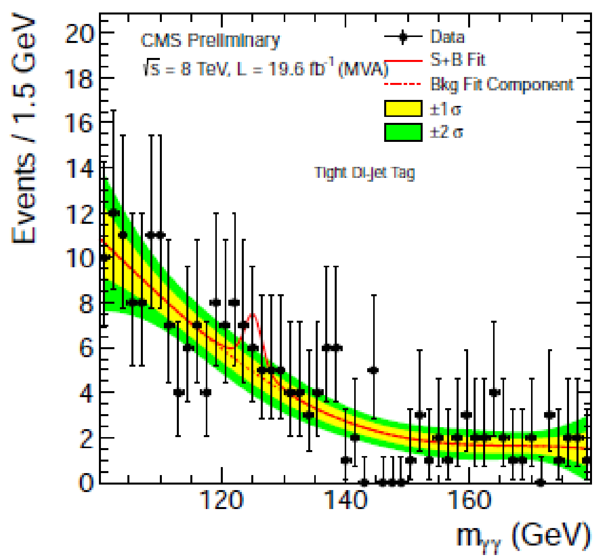


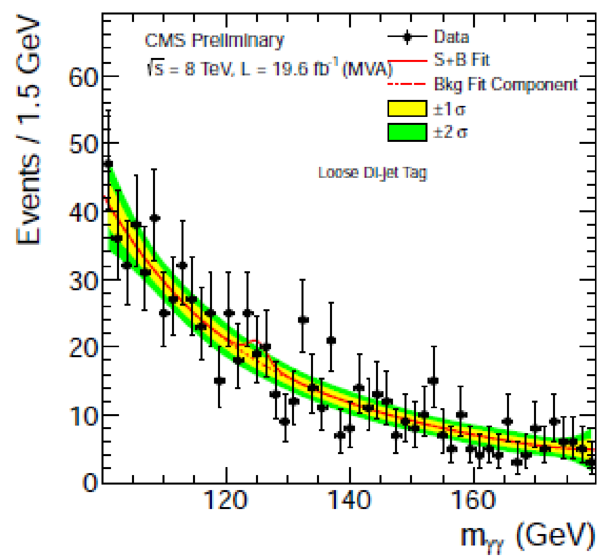


ATLAS



CMS

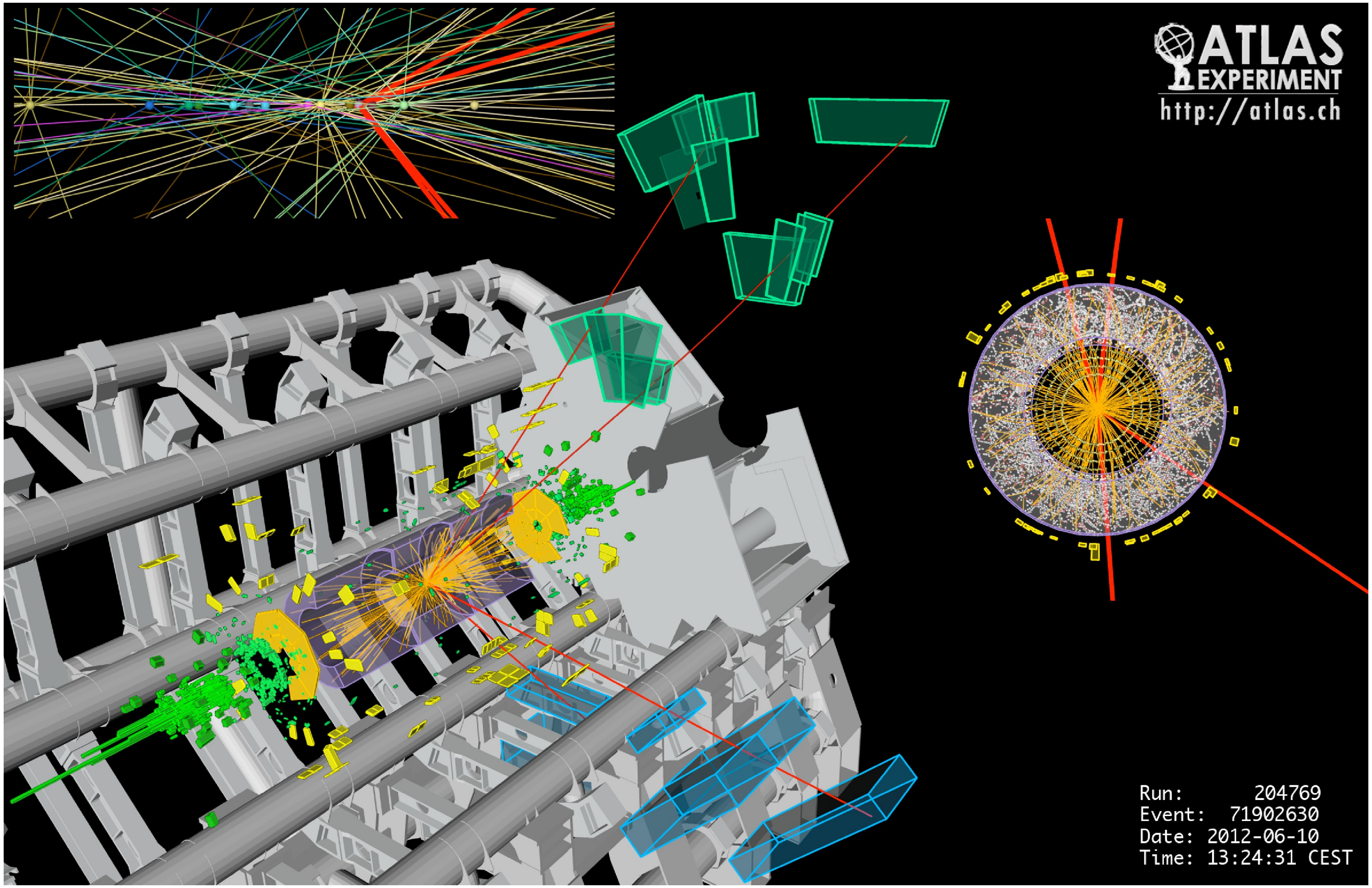




ATLAS sees a ~2.0σ signal for VBF (expected ~1.3σ) @ mH=126.8 GeV.

CMS sees ~1σ (not quoted precisely in the note).

Higgs → 4ℓ

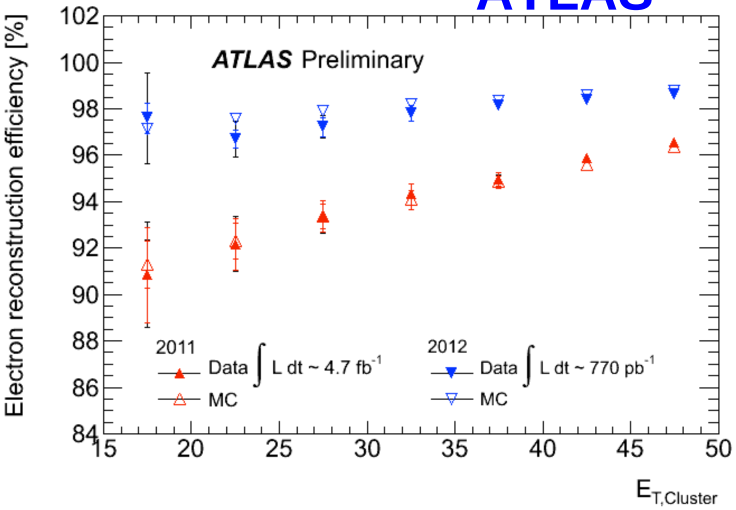


- 2 same flavour, opposite charge lepton pairs, one consistent with the Z mass.
- Good S/B (~1.5), low S (exp. ~16 for full dataset): maximize signal efficiency!

Higgs → 4ℓ: event selection (I)

- Both **ATLAS** and **CMS** now use state-of-the-art theory computations
  - e.g. include full final state interference effects @ NLO for same flavour and same sign leptons).
- Main backgrounds
  - irreducible: ZZ*
  - reducible: Z+jets (e.g. Zbb), top pair production
- Both experiments have worked hard to maximize the signal reconstruction efficiency:
  - However ATLAS and CMS notes do not quote efficiencies which can be directly compared.

ATLAS



- But muon and electron efficiencies should be close. From quotes and ~plots:

Muon efficiency
CMS quotes >98%
ATLAS has ~96-98%

Electron efficiency
CMS quotes 70(60)% at 7<pT<10 GeV, 85(77)% at pT~10 GeV and 95(89)% at pT>20 GeV in barrel (endcap)
ATLAS has ~87% at pT~10 GeV, ~95% at pT>20 GeV

- Both experiments now use a Gaussian Sum Filter to fit electron tracks.

Higgs → 4ℓ: event selection (II)

- Further requirements:
  - To reject leptons from semi-leptonic b-decays:
    - Requirement on lepton impact parameter (IP):
      - **ATLAS**: requirement on transverse IP significance < 3.5 (<6.5) for muons (electrons)
      - **CMS**: requirement on 3d IP significance < 4
    - Lepton isolation requirement
      - **ATLAS** requires the charged tracks (calorimeter deposits) in a cone of size R=0.2 around the lepton to sum up in pT to less than 0.15 (0.2) of the lepton pT
      - **CMS** requires the isolation computed with the particle flow algorithm:

$$R^{\ell}_{\mathrm{Iso}} \equiv \left(\sum p_{\mathrm{T}}^{\mathrm{charged}} + \mathrm{MAX}\left[0, \sum p_{\mathrm{T}}^{\mathrm{neutral}} + \sum p_{\mathrm{T}}{}^{\gamma} - \rho \times A_{\mathrm{eff}},\right]\right) / p_{\mathrm{T}}^{\ell}$$

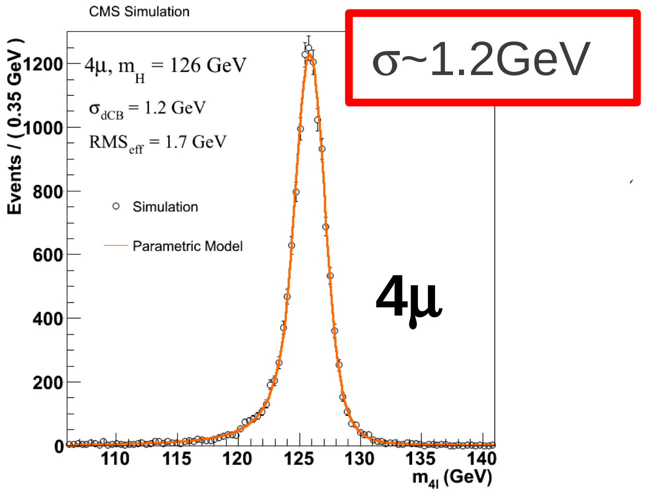
computed in a R=0.4 cone and required to be < 0.4.

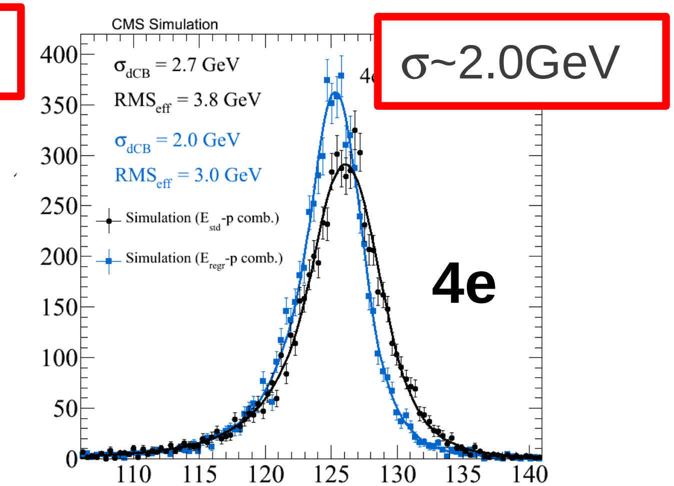
      - Both experiments use the “jet area” technique to remove the average PU contribution.
- Both experiments use a very similar photon FSR recovery algorithm, which leads (according to CMS) to an increase of signal efficiency of ~3%.

Higgs → 4ℓ: inv. mass distribution

- Invariant mass of 4l system used as main discriminant against the background.

CMS





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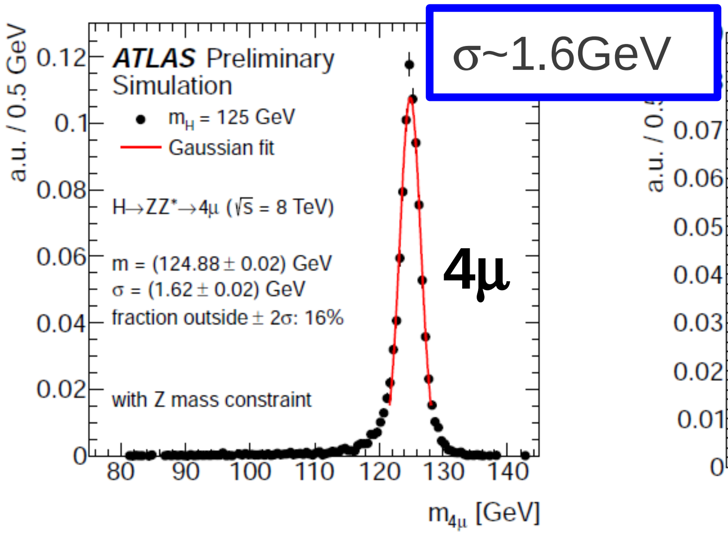
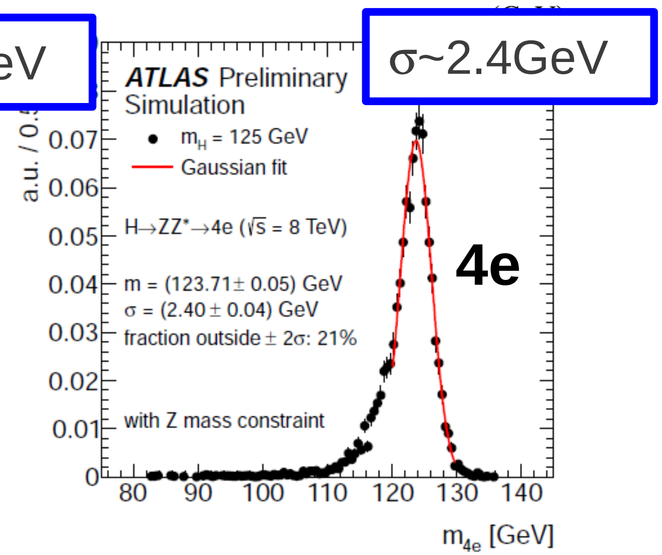
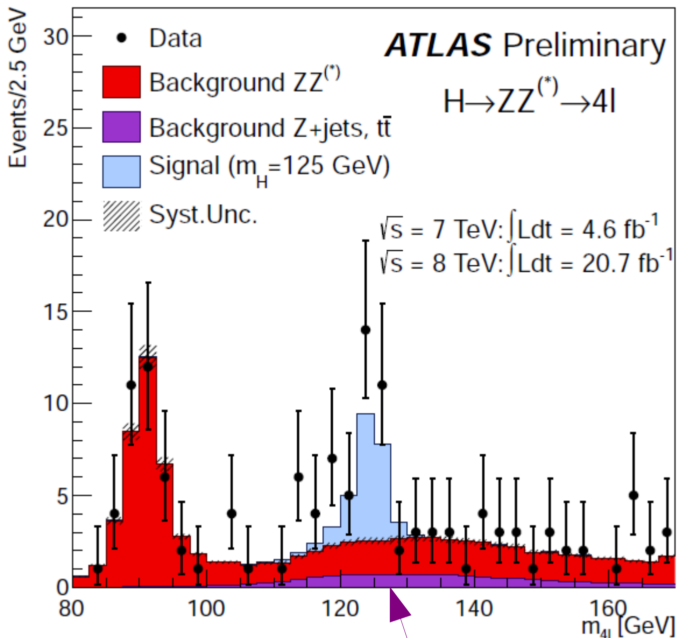


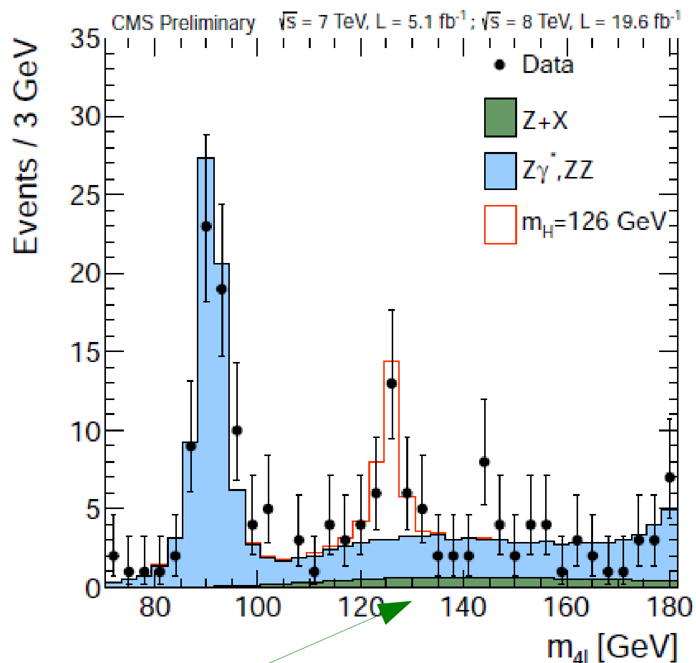


- Invariant mass resolution is crucial to enhance sensitivity.
- Effect of higher B-field in CMS?
  - Likely for muons.
- For electrons, CMS uses a BDT based regression algorithm to improve the electron energy resolution.

Higgs → 4ℓ: background estimation

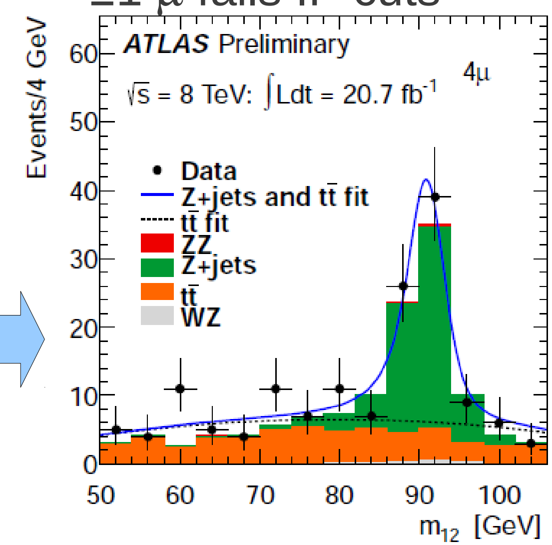
- Invariant mass of 4lep system used as main discriminant against the background.





- Clear signal peak is seen by both experiments.
- Categories defined for VH and VBF but not enough statistics yet to see a signal there.

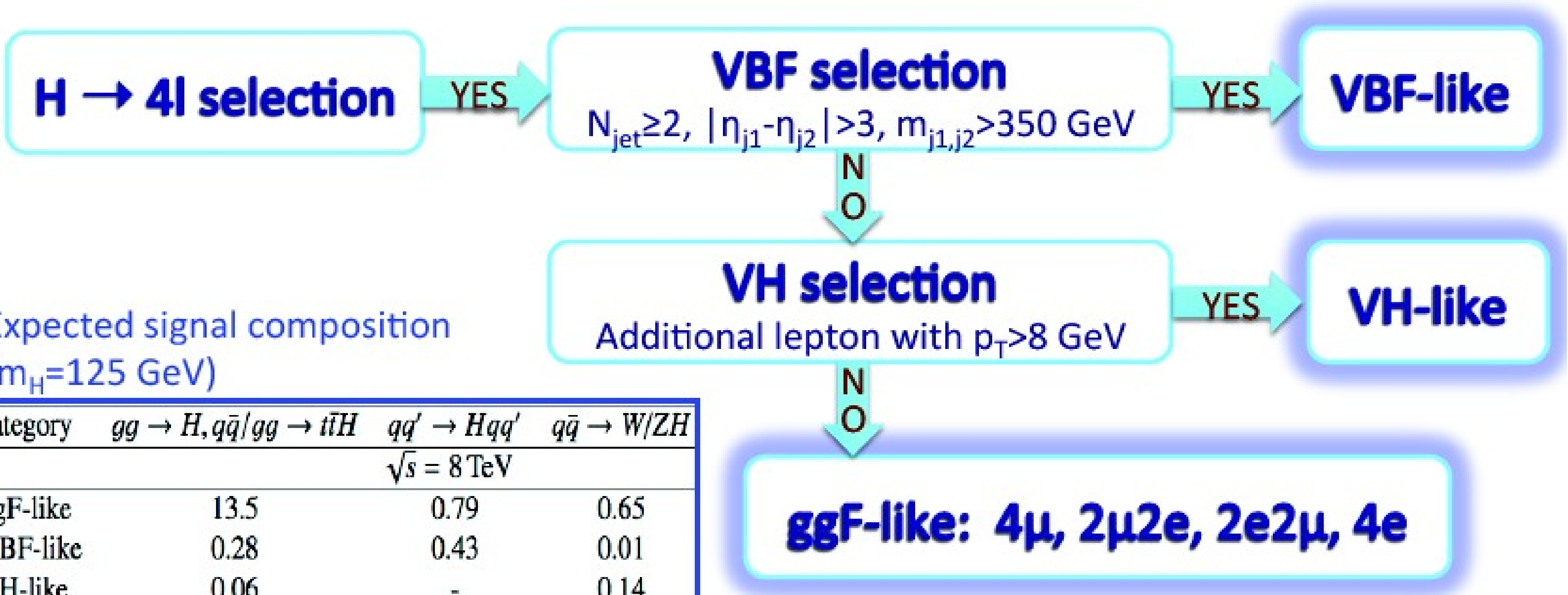
ℓℓμμ: remove isolation + ≥1 μ fails IP cuts



- ZZ* background estimated from MC, considering theory uncertainties on top.
- W+jet and top pair background estimated by either reverting lepton isolation and/or impact parameter cuts and/or requiring the subleading lepton pair to be same rather than opposite sign.
- **CMS** uses Matrix Element method to improve sensitivity.

Higgs → ZZ: VBF/VH categories

- **ATLAS**



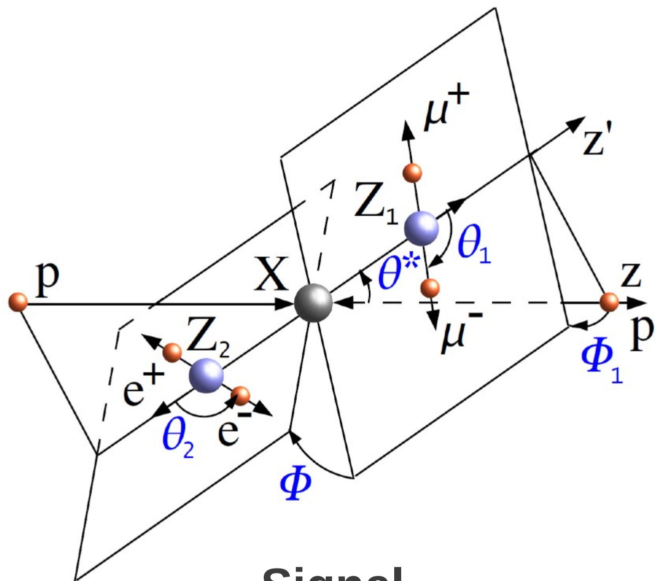
Expected signal composition (m_H=125 GeV)

category	$gg \to H, q\bar{q}/gg \to t\bar{t}H$	$qq' \to Hqq'$	$q\bar{q} \to W/ZH$
		$\sqrt{s} = 8$ TeV	
ggF-like	13.5	0.79	0.65
VBF-like	0.28	0.43	0.01
VH-like	0.06	-	0.14

- **CMS**
  - Variables which separate ggF and VBF/VH are added to the likelihood function.
    - 0 or 1 jet: additional discriminant X = pT(4ℓ) / m(4ℓ)
    - 2 jets: additional BDT discriminator based on VBF sensitive observables

Higgs → ZZ: Matrix Element method

- While **ATLAS** uses the matrix element approach only for the spin analysis, **CMS** uses it in the search as well:

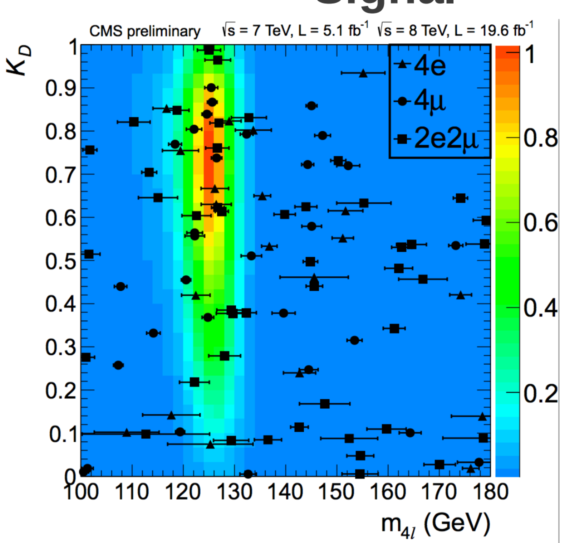


- Matrix Element Likelihood Analysis: uses full kinematic characterization of ZZ decay (m12,m34,θ1,θ2,θ,ϕ,ϕ1) to improve discrimination against background.

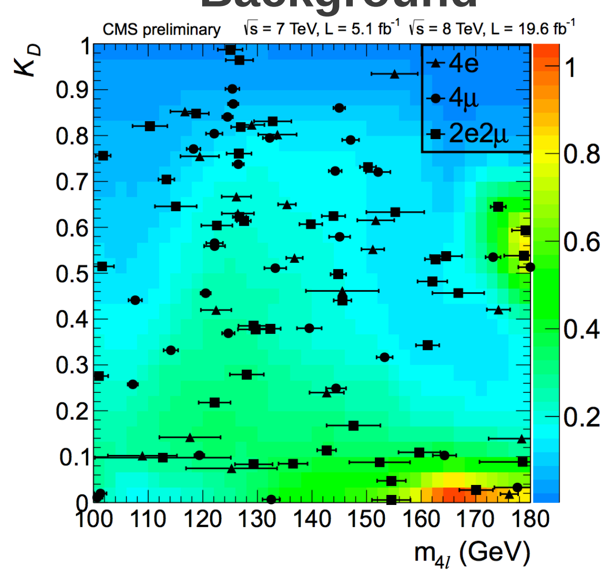
$$\mathrm{MELA} = \left[1 + \frac{\mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \theta_1, \theta_2, \Phi, \theta^*, \Phi_1 | m_{4\ell})}\right]^{-1}$$

- A discriminator K_D is obtained based on LO ME for signal and background (for Z+X same discriminator is used as for ZZ), but PDFs are then determined on the nominal MC.
- A PDF with a third variable X is used which discriminates between ggF and VBF signal.
- LH function = PDF(m4ℓ) PDF(K_D|m4ℓ) PDF(X|m4ℓ)

Signal

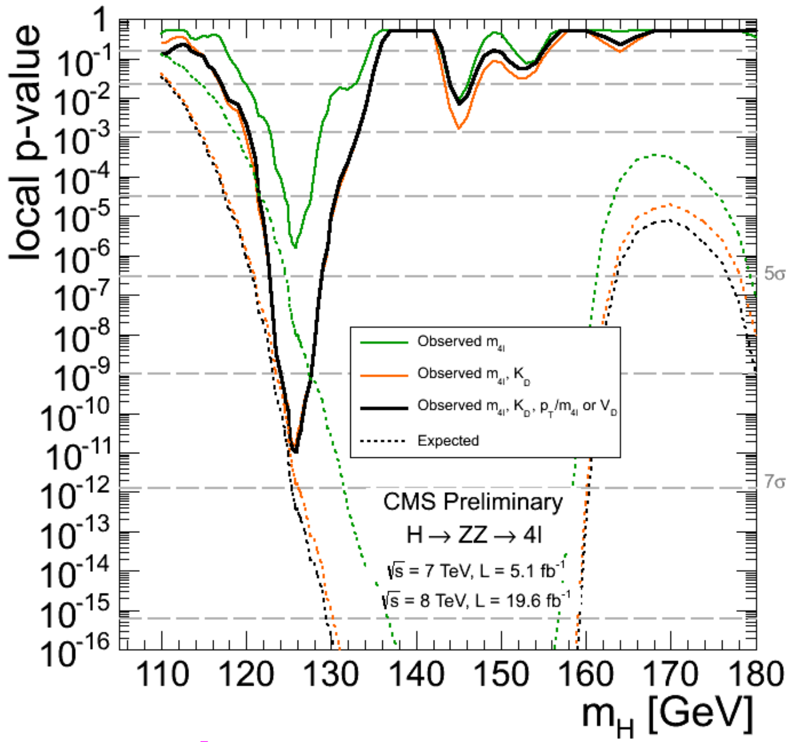


Background

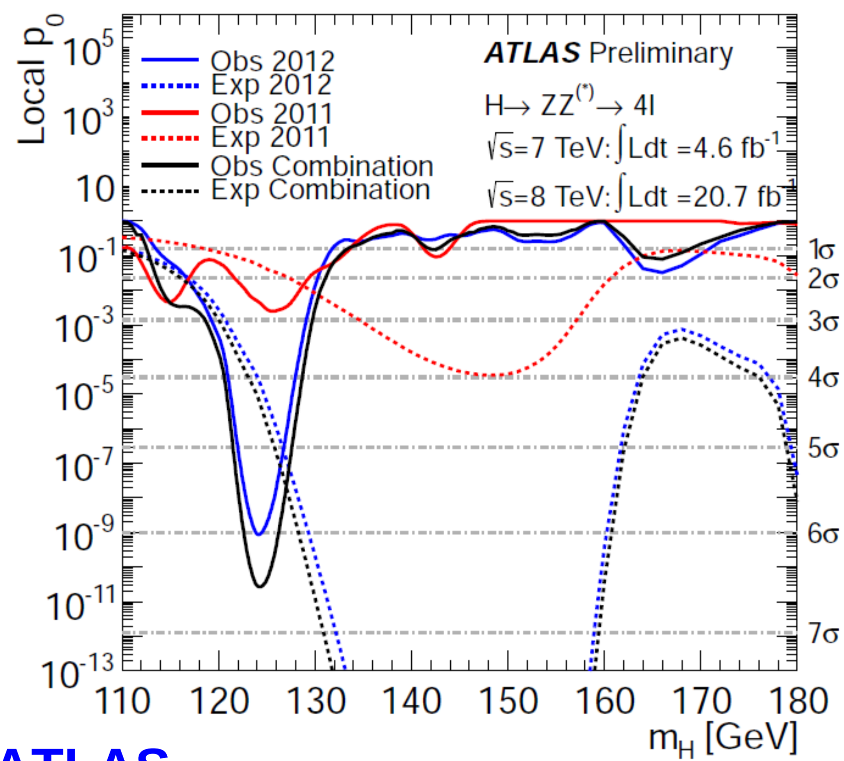


Higgs → ZZ: significance and signal strength

CMS



ATLAS



p0-values **CMS** **ATLAS**

Model	CMS Obs.	CMS Exp.	ATLAS Obs.	ATLAS Exp.
3-dim	6.7σ	7.2σ		
2-dim	6.6σ	6.9σ		
1-dim	4.7σ	5.6σ	6.6σ	4.4σ

signal strength

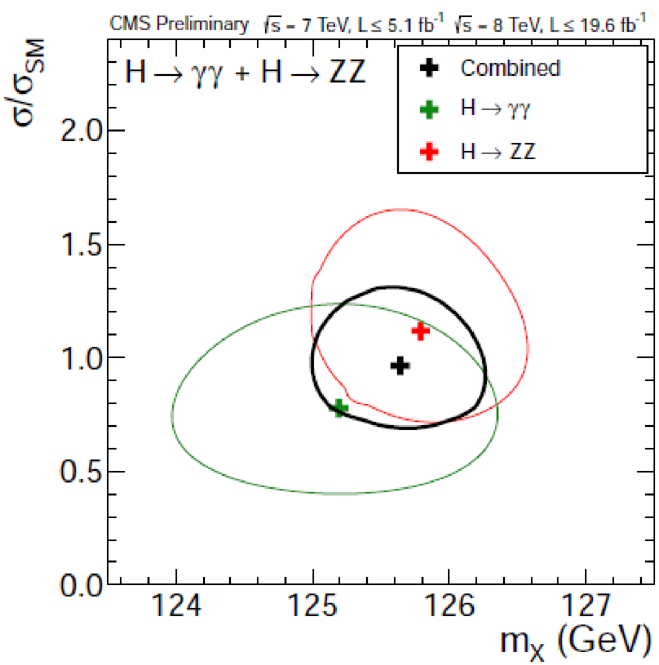
ATLAS μ=1.7 (+0.4,–0.5)

CMS μ=0.91 (+0.30,–0.24)

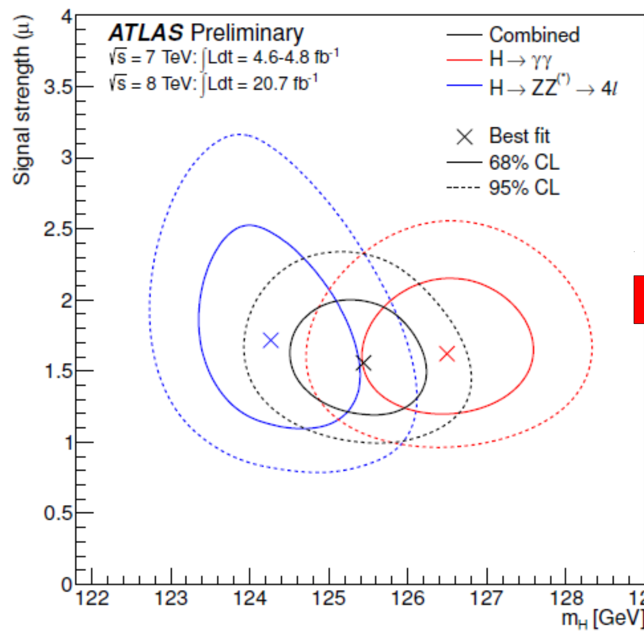
Combined mass measurement ($\gamma\gamma$ + 4ℓ)

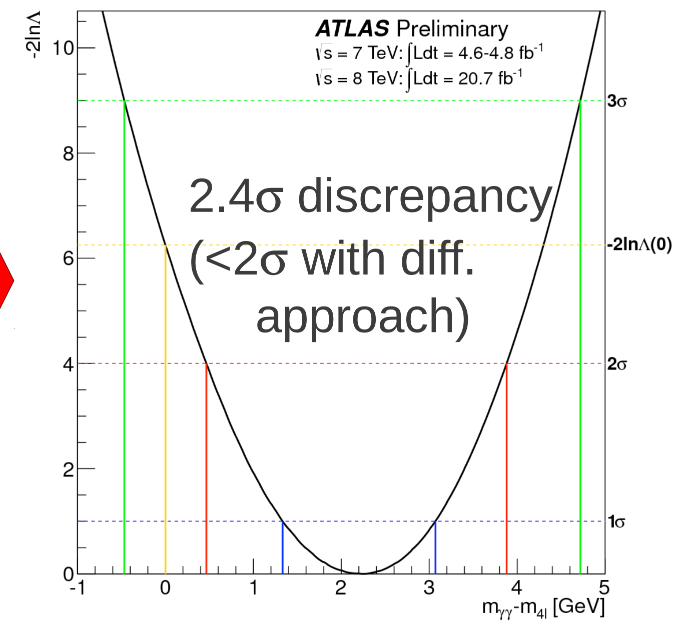
- A single combined likelihood is maximized, as a function of the parameter of interests (m_H and μ).

CMS



ATLAS





- Very good agreement between channels in CMS, some tension in ATLAS.
  - ATLAS: mX = 125.5 ± 0.2 (stat) ± 0.6 (syst) GeV
  - CMS: mX = 125.7 ± 0.3 (stat) ± 0.3 (syst) GeV
- Very good agreement between experiments.

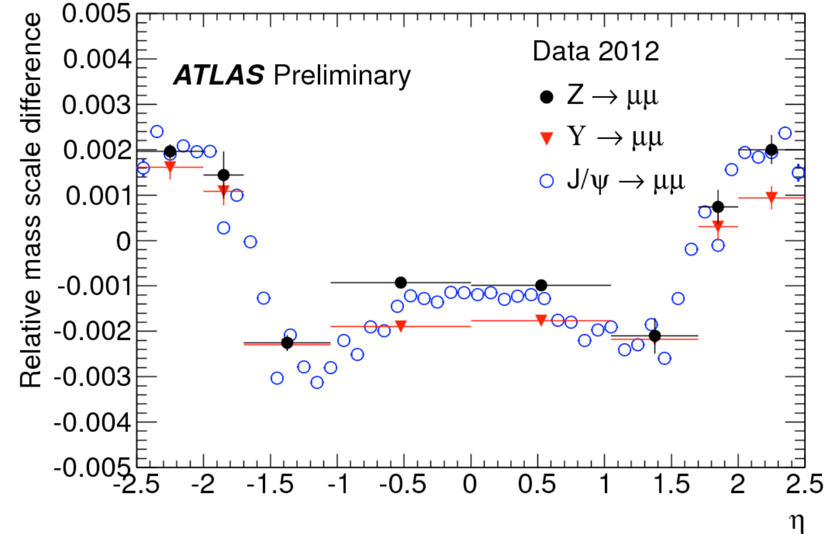
Mass measurement – systematic uncertainties

- Both experiments have by now carefully evaluated their lepton/photon energy scale uncertainties, which determine the mass uncertainty.
- **H → γγ**
  - **ATLAS**
    - Extrapolation of energy scale from Z → ee to photons (±0.3%)
    - Material modelling (±0.3%)
    - Presampler energy scale (±0.1%)
    - Many additional uncertainties (non-linearities of EM calorimeter, mismodelling of shower shape variables, signal resolution uncertainty, mismodelling of fraction of converted photons, …) have been found to be sub-leading.
  - **CMS**
    - Extrapolation from Z → ee
    - Non linearities in the extrapolation from the Z to the Higgs mass

    } ±0.47%

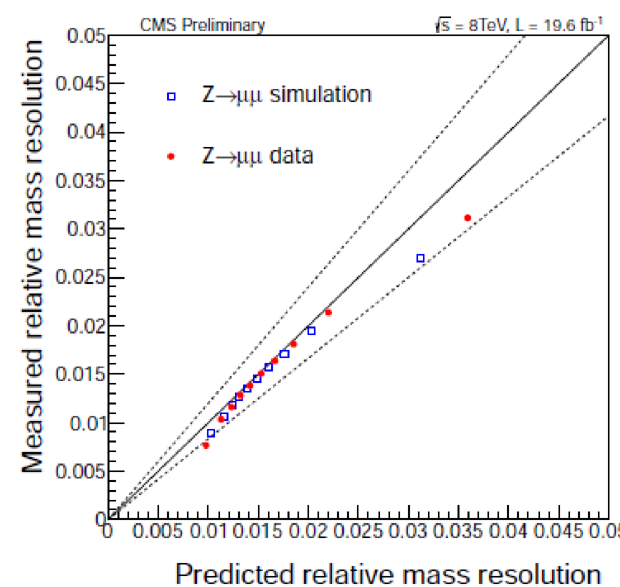
Mass measurement – systematic uncertainties

- **H → 4ℓ**
  - **ATLAS**
    - Electron mom. scale uncertainty: ± 0.4% (±0.2%) on mX in 4e (2e2μ)
    - Muon mom. scale uncertainty: ± 0.2% (±0.1%) on mX in 4μ (2μ2e)

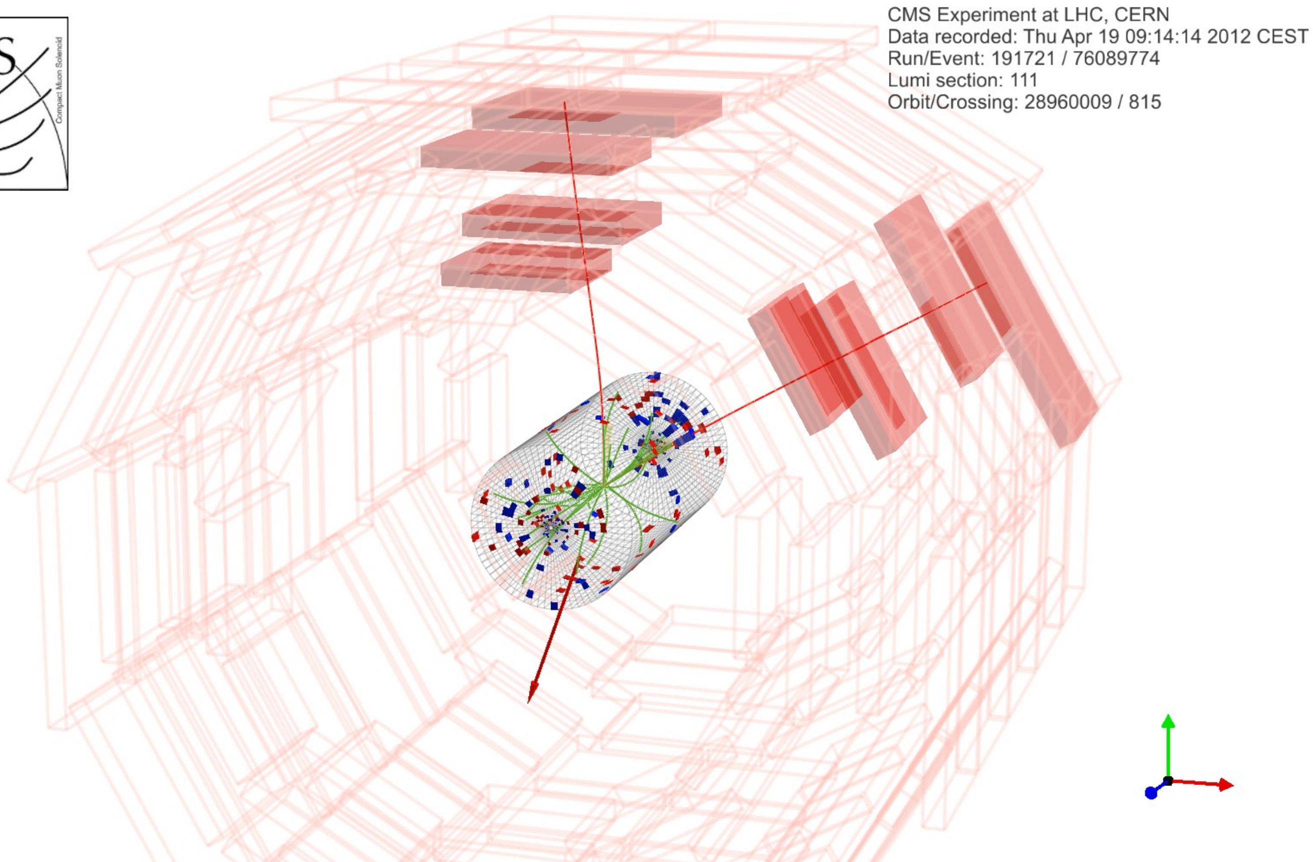


  - **CMS**
    - More complex approach: the mass is estimated with a likelihood function: L = PDF(m4ℓ|σ(m4ℓ)) PDF(K_D|m4ℓ) PDF(X|m4ℓ) which depends conditionally on the event-by-event estimated mass error.
      - Improves mass determination by ~8%.
    - 20% uncertainty on per-event σ(m4ℓ).
    - Electron mom. Scale uncertainty: ± 0.3% on mX for 4e
    - Muon mom. scale uncertainty: ± 0.1% on mX in 4μ

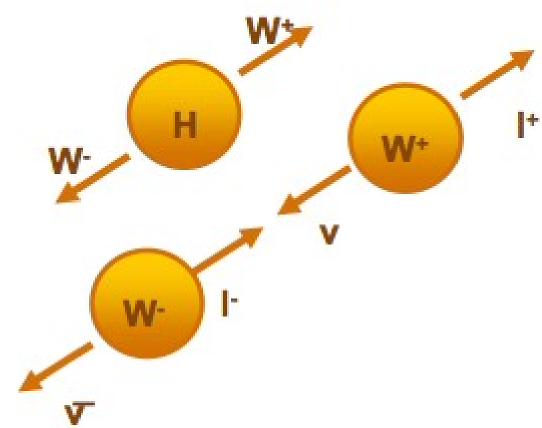
Validation of per event errors:



H → WW* → ℓυℓυ



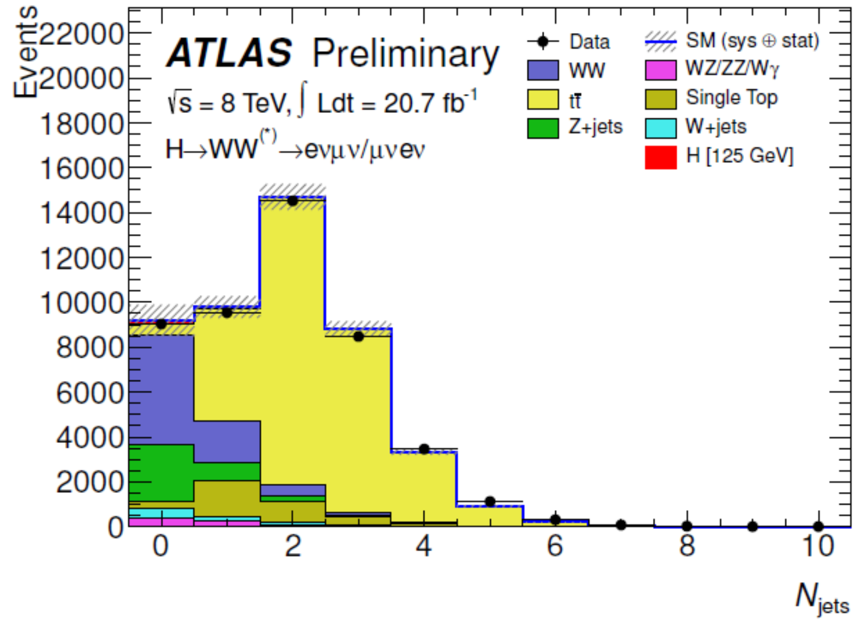
S/B ~ 0.15
S ~ 200

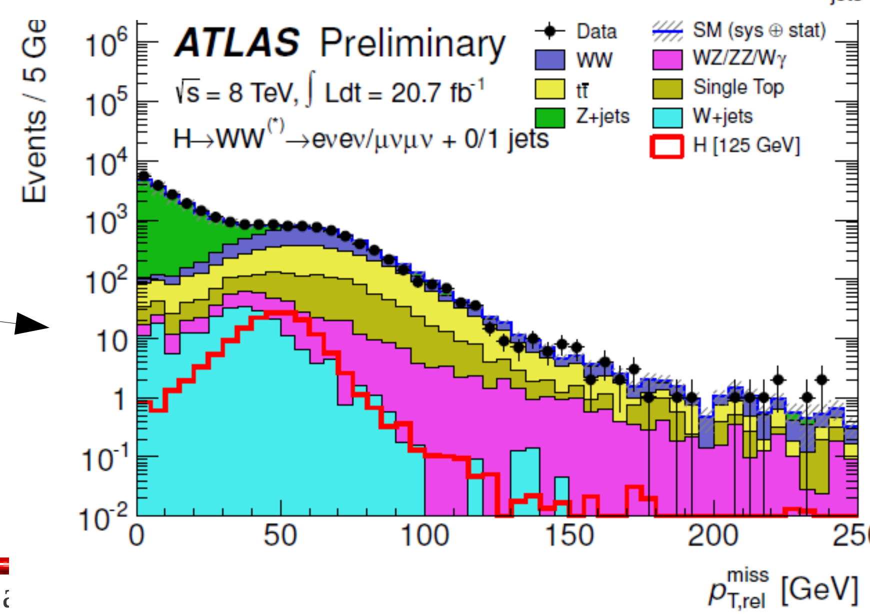


- Topology given by two opposite sign high-pT isolated leptons + missing ET.
  - Spin correlations lead to small Δϕ(ℓℓ) opening angle.

H → WW* → ℓνℓν : main backgrounds

- Analysis divided in two main channels, eμ (cleaner!) and ee+μμ.
- Divide into 0,1 and 2 jets channels. Specific VBF cuts for the 2 jets channel. (VBF analysis presently being updated in CMS)
- Main backgrounds:
  - WW (irreducible)
  - Drell-Yan (mainly Z → ττ in eμ, a lot of Z → ee/μμ/ττ in ee+μμ)
  - Top background (in particular in 1- or 2-jets)
  - W → ℓν + “fake” lepton
- No clear mass peak. Background estimate is crucial!



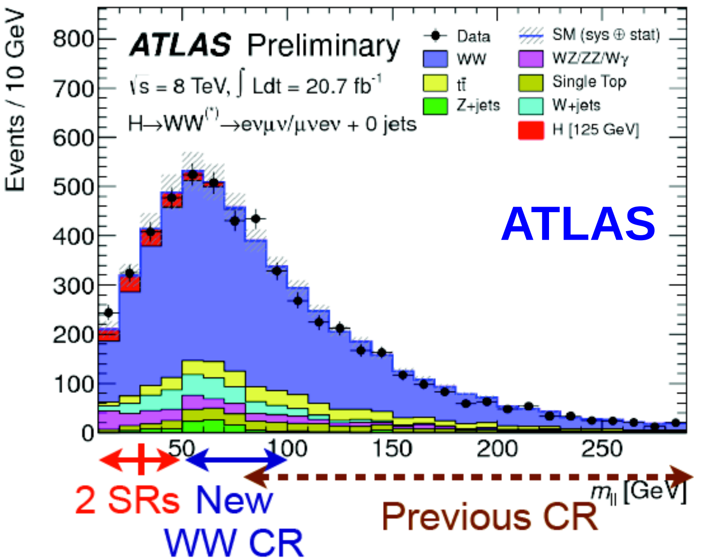


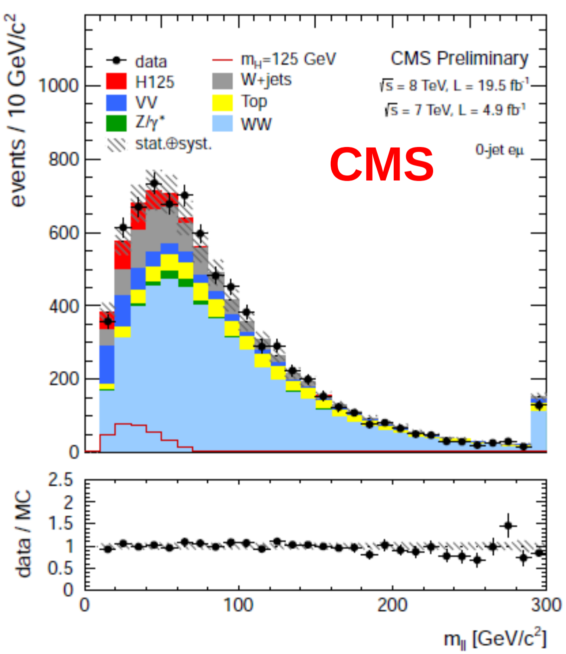
$H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$: analysis strategy

- Basic lepton selection, including isolation, very similar
  - **CMS** goes to slightly lower thresholds.
- Cuts on "relative" Missing Et are applied against **Drell-Yan background** ($E^{rel}_{T,miss} = E_{T,miss}\cos(\Delta\varphi_{closest})$ if there is any object closer than $\pi/2$ to $E_{T,miss}$)
  - A Z--> $\ell\ell$ mass veto and a stricter selection is applied in the ee/$\mu\mu$ channels (**ATLAS** uses the "hadronic recoil", **CMS** a BDT classifier based on Missing ET + kinematic and topological variables)
- Both experiments apply a b-tag veto (ε(top) ~ 80-85% in the Njet=1 channel) to reduce the **top background**.
- Different strategies used to extract the signal:
  - **ATLAS** cuts on basic kinematic quantities including pT($\ell\ell$), $\Delta\phi$($\ell\ell$), m($\ell\ell$) and then uses a 1d LH fit to the transverse mass ($m_T = E_{T,miss}\, p_T^{lep}\cos(\Delta\varphi(lep, MET))$).
  - **CMS** uses, after a basic preselection, a 2-dim. LH fit to (m($\ell\ell$),m_T)

    (cut based analysis used in ee/$\mu\mu$ channel only or as a cross-check)

H → WW* → $\ell\nu\ell\nu$: background estimates

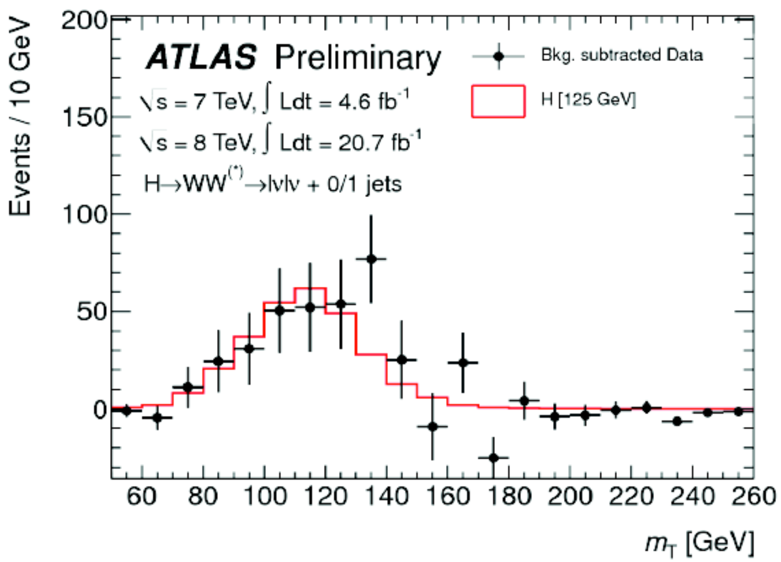




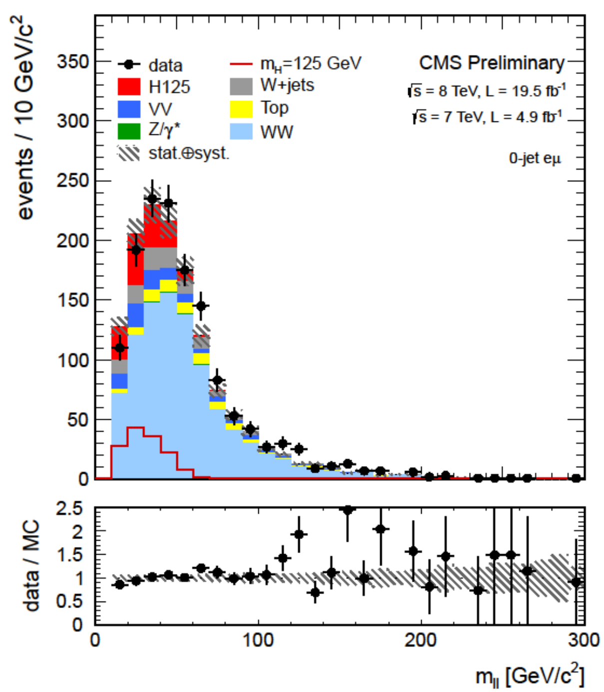
- **WW background**: normalization estimated from data in both experiments
  - ATLAS in the last round made the control region much closer to the signal region, reducing the extrapolation uncertainty to ~5% (CMS quotes ~10%)
- **Top background** (fully from data!): both experiment extrapolate from a b-tagged region to an anti b-tagged region
- **W+jets:** fully estimated from data relaxing the lepton identification + isolation
- **Z → $\ell\ell$**: extrapolation from Z mass peak
- **Z → ττ**: normalization cross-checked in high $\Delta\pi(\ell\ell)$ control region (ATLAS), estimated using Z → μμ data and replacing muons with simulated taus (CMS)

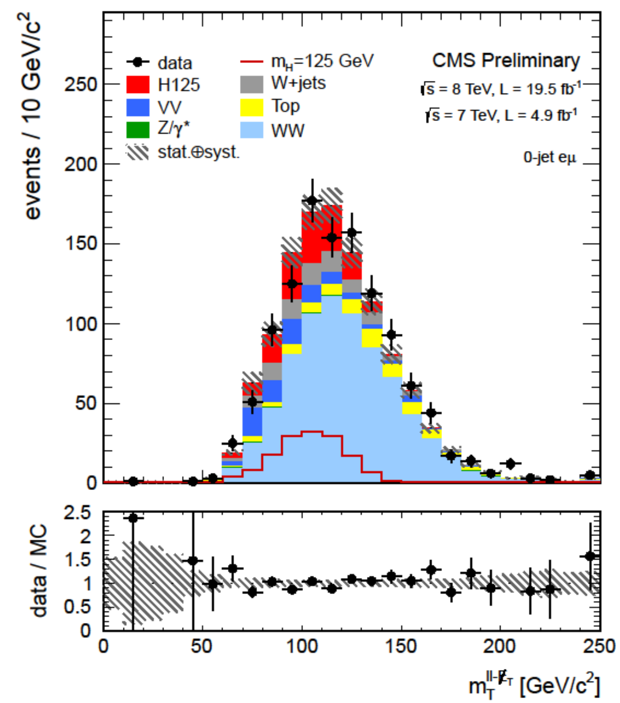
H → WW* → ℓνℓν: results

- **ATLAS**



- **CMS**





- **ATLAS** sees (expects) a 3.7σ (3.8σ) signal
- **CMS** sees (expects) a 4σ (~5σ) signal
- **ATLAS** also sees (expects) 2.5σ (1.6σ) of VBF signal

signal strength

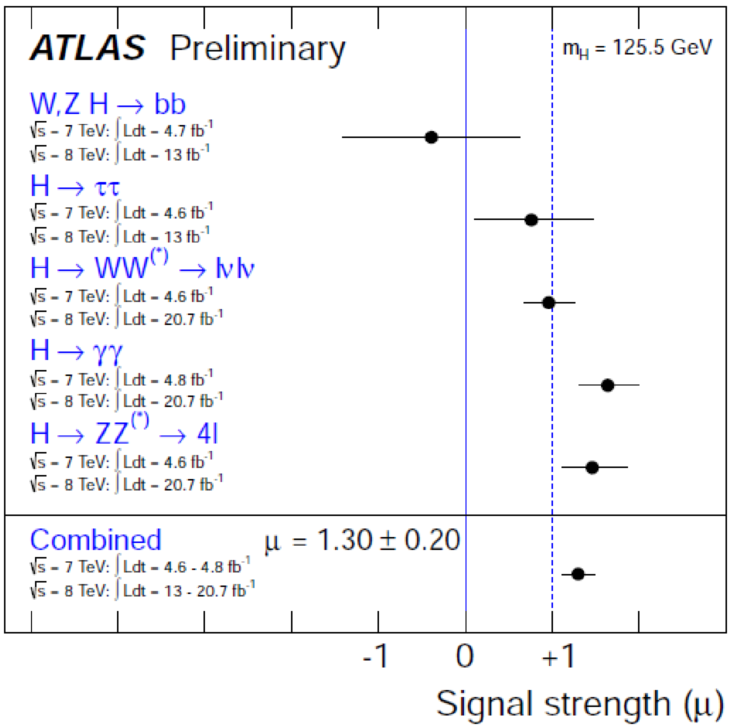
ATLAS $\mu = 1.01 \pm 0.31$

CMS $\mu = 0.76 \pm 0.21$

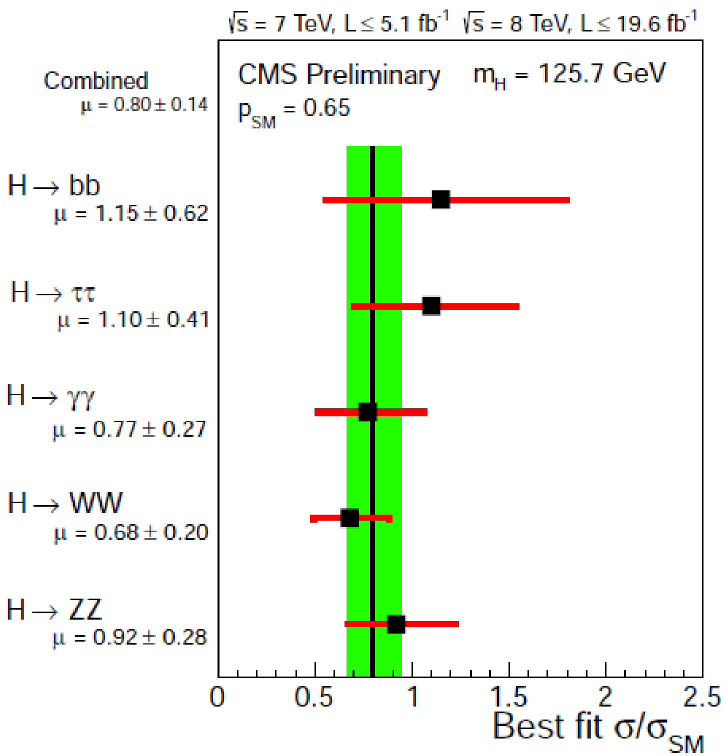
Overall signal strength

- The Higgs-boson like resonance has now been seen already in many channels:

ATLAS



CMS



Overall signal strength

ATLAS $\mu = 1.30 \pm 0.19$

CMS $\mu = 0.80 \pm 0.14$

- The combination would come out pretty much at 1!

First "evidence" of VBF production

- Test different production & decay modes.

$$n^k_{\text{signal}} = \left(\sum_i \mu_i \sigma_{i,\text{SM}} \times A^k_{if} \times \varepsilon^k_{if} \right) \times \mu_f \times B_{f,\text{SM}} \times \mathcal{L}^k$$

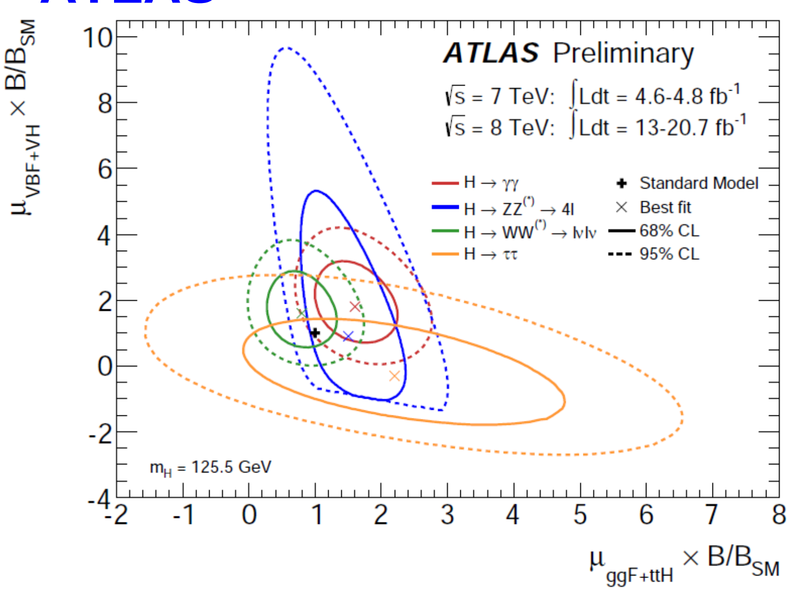
- Test parameter of interests (e.g. µggF and µVBF) by using profile likelihood ratio.

$$\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\theta}}(\mu))}{L(\hat{\mu}, \hat{\theta})}$$

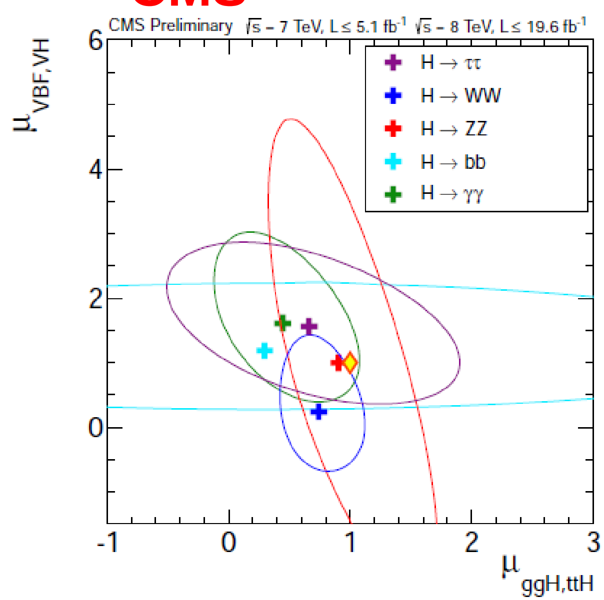
$$\mu_i = \sigma_i / \sigma_{i,\text{SM}}$$

$$\mu_f = B_f / B_{f,\text{SM}}$$

ATLAS



CMS



- ATLAS sees hints of VBF production in H → γγ and H → WW
- CMS sees hints of VBF production mostly in H → γγ and H → ττ

VBF production:

ATLAS 3.1σ evidence: µ(VBF)/µ(ggF) = 1.2 (+0.7,-0.5)

CMS ~2.0σ signal: µ(VBF) = ~1.0 ± ~0.5

Measurement of couplings

- In general: $$\sigma \times BR(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$
- Idea is to modify the SM Higgs couplings by LO motived “k factors” to be determined on data. E.g. for H → γγ:

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

- In general, apart from undetectable modes (e.g. cc,ss,gg,μμ), 7 couplings:

$$\kappa_g\, \kappa_\gamma\, \kappa_Z\, \kappa_W\, \kappa_t\, \kappa_b\, \kappa_\tau$$

- where κγ (Higgs γγ decay) and κg (Higgs ggF production mode) are loop induced and are potentially sensitive to extra-SM particles if treated as effective parameters
- When κ=1, the full SM result (including terms [well] beyond LO) is recovered.
- Any measurement with κ!=1 is a sign of physics beyond the SM.

Vector boson vs fermionic couplings

- Not enough statistics to fully determine all couplings from data yet.
- → Look for deviations from the SM in simplified scenarios.
- E.g. test deviation of fermionic wrt to vector boson couplings, assun

$$\kappa_V = \kappa_W = \kappa_Z$$
$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

$$\kappa_{ZZ} = \kappa_Z \cdot \kappa_Z / \kappa_H$$
$$\lambda_{WZ} = \kappa_W / \kappa_Z$$
$$\lambda_{FZ} = \kappa_F / \kappa_Z \quad .$$

$$\sigma(gg \to H) * BR(H \to \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

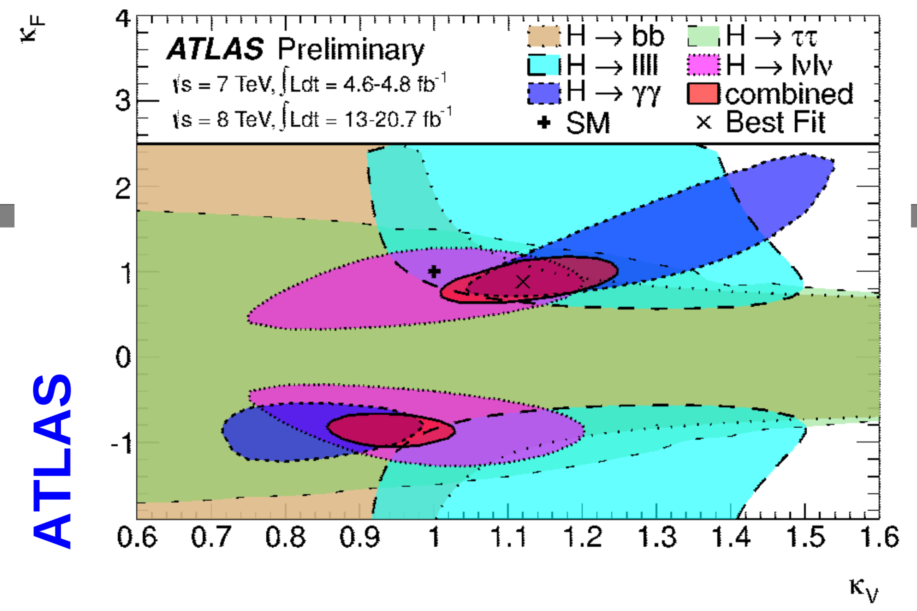
$$\sigma(qq' \to qq'H) * BR(H \to \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

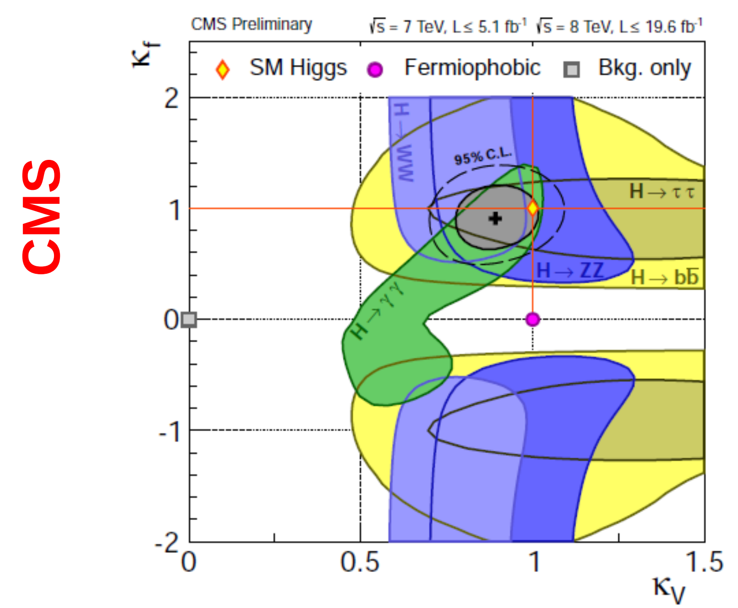
$$\sigma(gg \to H) * BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H) * BR(H \to ZZ^{(*)}, H \to WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \to qq'H, VH) * BR(H \to \tau\tau, H \to b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\kappa_\gamma^2(\kappa_F, \kappa_V) = 1.59 \cdot \kappa_V^2 - 0.66 \cdot \kappa_V \kappa_F + 0.07 \cdot \kappa_F^2$$





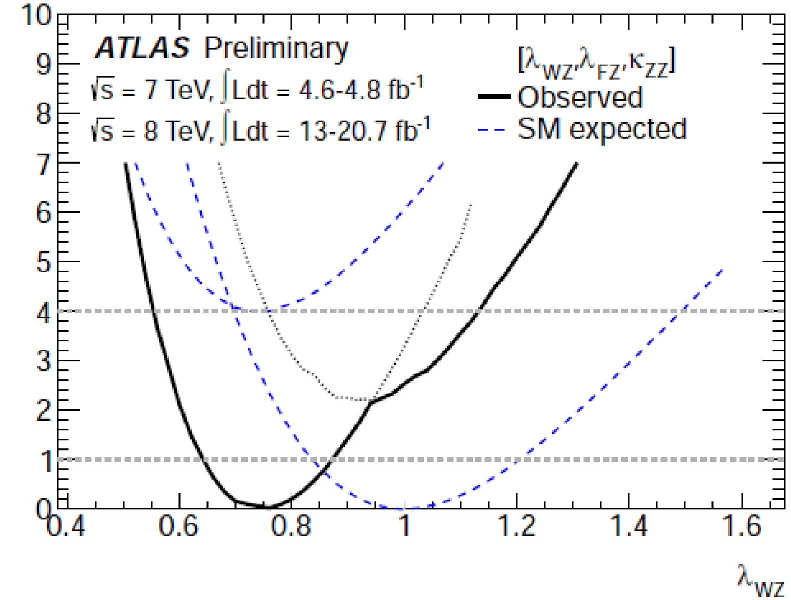
- Compatibility with SM within 1σ (**CMS**), at ~8% (**ATLAS**)
- With no assumption on total Higgs width, looser constraints.

W vs Z couplings (custodial symmetry)

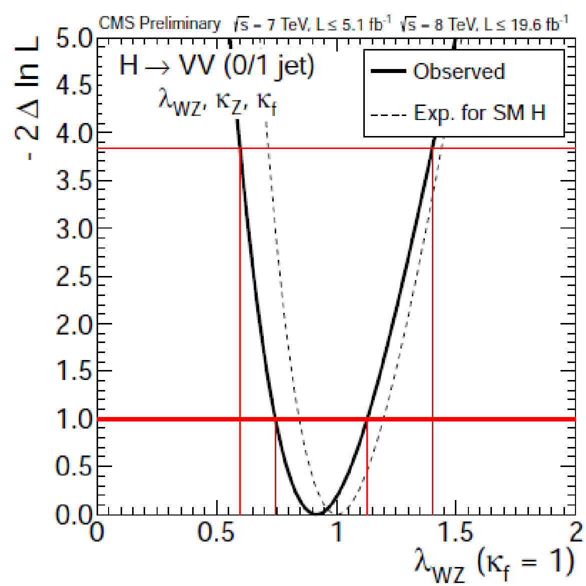
- This time assume:

$$
\begin{aligned}
\kappa_{ZZ} &= \kappa_Z \cdot \kappa_Z / \kappa_H \\
\lambda_{WZ} &= \kappa_W / \kappa_Z \\
\lambda_{FZ} &= \kappa_F / \kappa_Z \quad .
\end{aligned}
$$

ATLAS



CMS

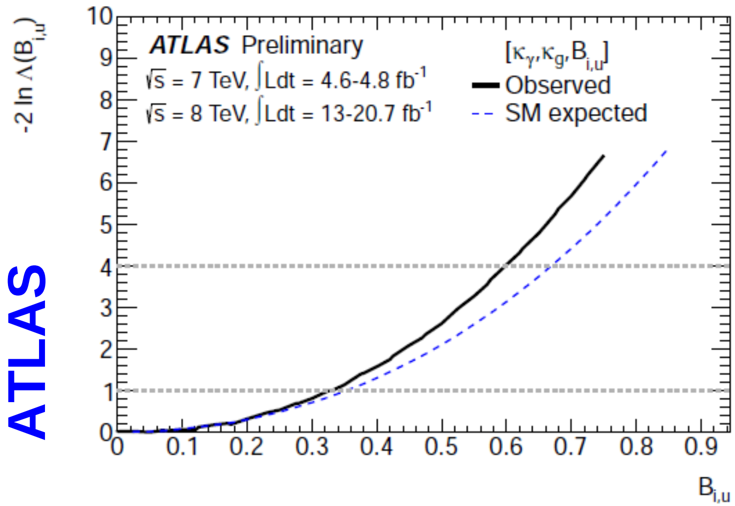


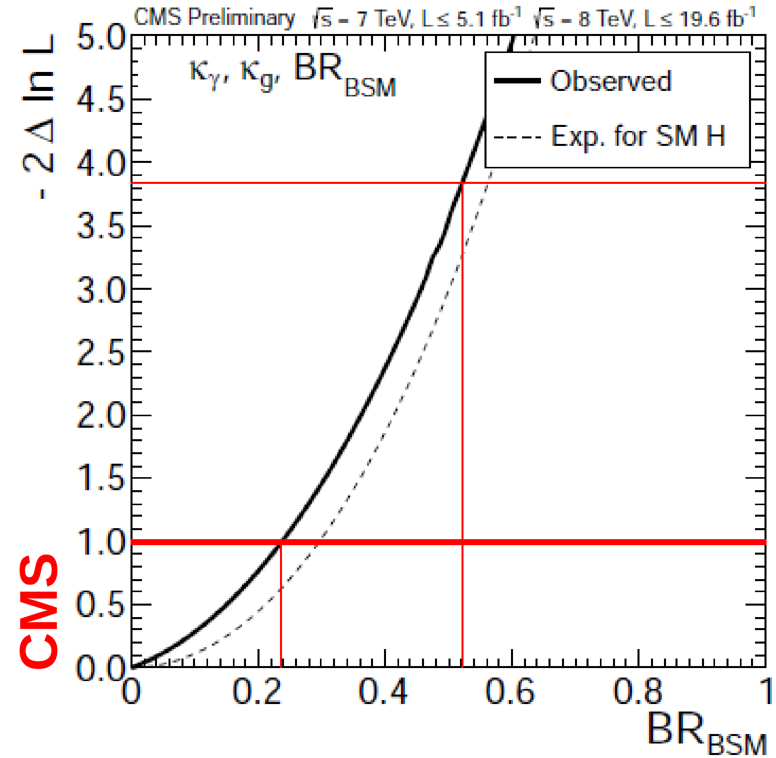
- **CMS**: good compatibility with SM
- **ATLAS**: compatibility at ~5% level.

Probing beyond SM contributions...

- Assume H → gg and ggF loops to be free parameters (κ(γ) , κ(g))
  + no constraint on Higgs decay width (all other couplings assume κ=1):

$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{inv.,undet.})} \Gamma_H^{SM}$$





- **CMS**: BR(inv.und.) within [0,0.52] @ 95% CL
- **ATLAS**: BR(inv.und.) within [0,~0.6] @ 95% CL
- No significant deviations observed for κ(γ) , κ(γ) (but in ATLAS κ(γ) almost 2σ high)

Towards a complete test of couplings...

- **CMS** has presently the best handle on the fermionic channels ($H \rightarrow bb$ and $H \rightarrow \tau\tau$), while improved **ATLAS** results are in preparation.

- This allows to test six independent parameters

$$\kappa_g \; \kappa_\gamma \; \kappa_V \; \kappa_t \; \kappa_b \; \kappa_\tau$$

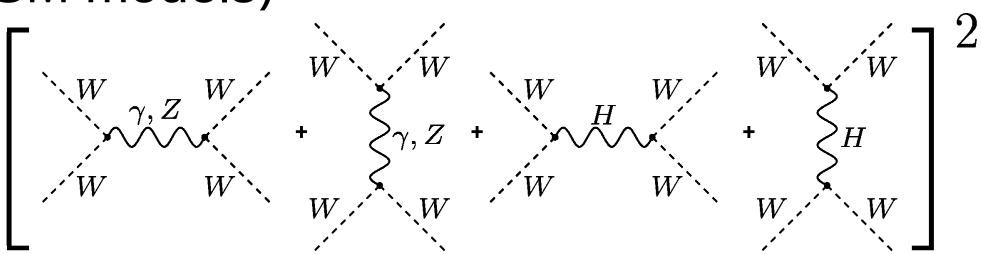
+ an additional contribution to the Higgs width from undetected decays.

- One limitation: presently same κ factor assumed for W and Z couplings.

- Total width is then constrained by:
  - Lower limit from sum of visible decay widths (that's why the fermionic channels, in particular **$H \rightarrow bb$** [BR~60%], are crucial!!)

$$\Gamma_H \geq \Gamma_W + \Gamma_Z + \Gamma_g + \Gamma_\tau + \Gamma_b$$

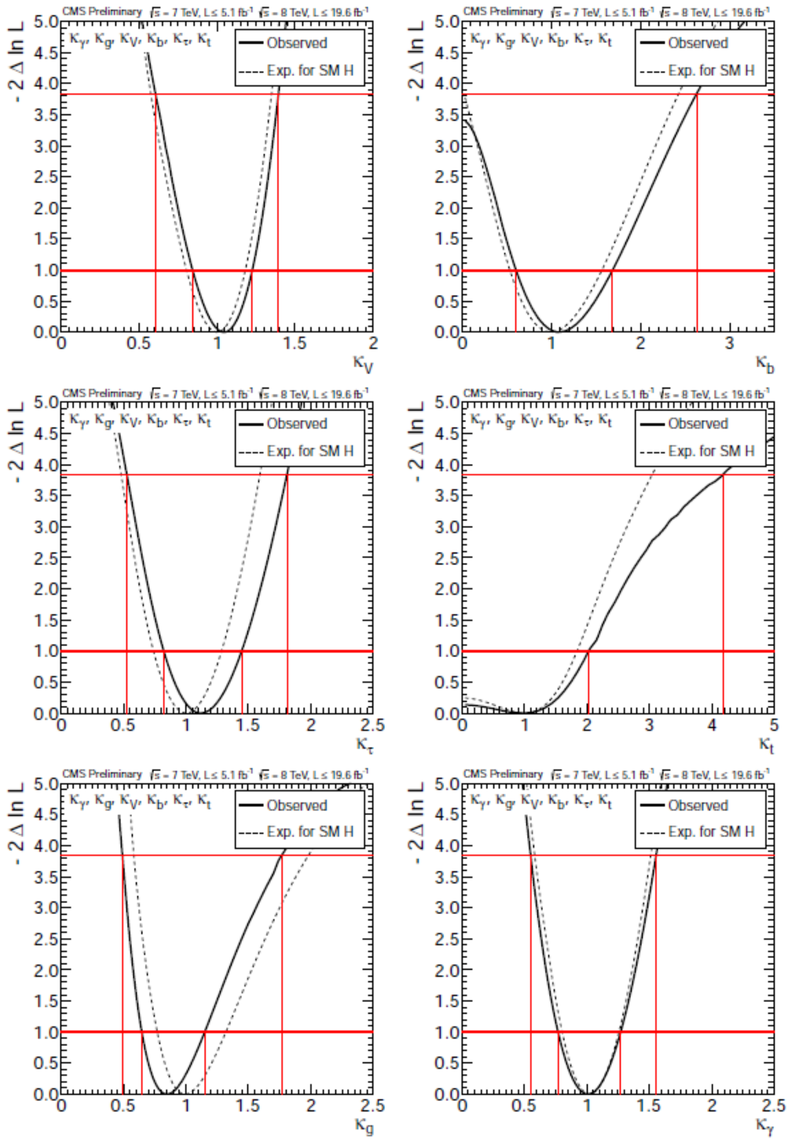
  - Upper limit from fullfilling unitarity in WW scattering (valid for a very large set of BSM models)



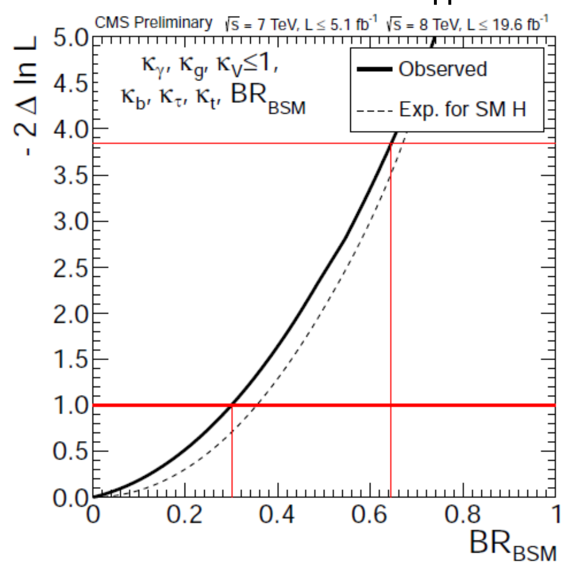
$$< \infty \;\Rightarrow\; \kappa_V \leq 1$$

Towards a complete test of couplings... (II)

- Constraint on couplings assuming no extra-SM contribution:



- Can presently extract couplings with precisions between ~20 and ~60% (but no good constraint on κ_t)
- Good compatibility with SM.
- Constraint assuming possible BSM contributions in Γ_H:

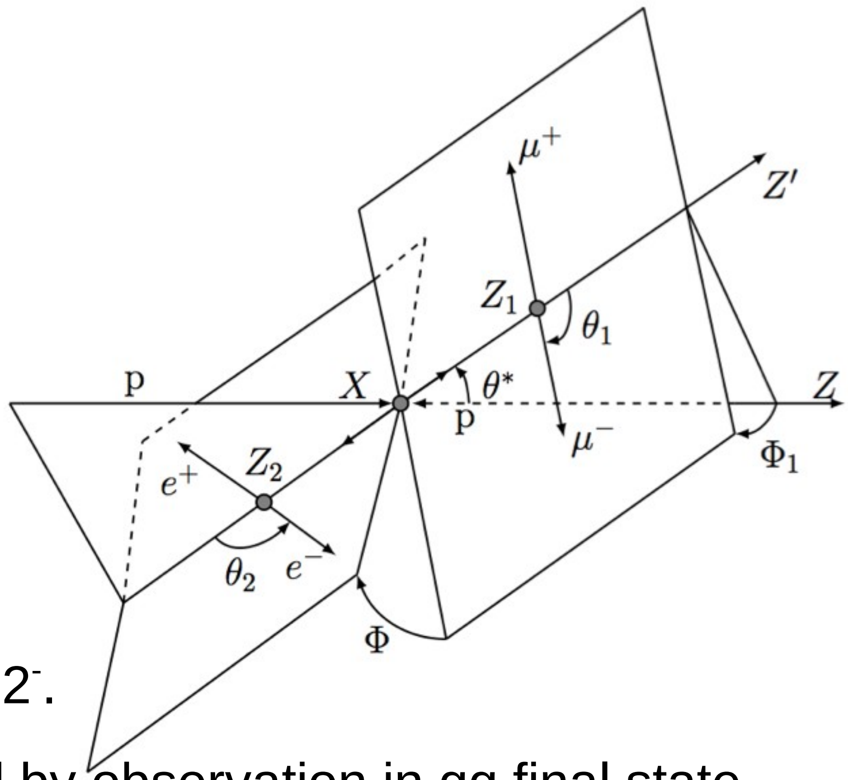


BR(inv.und.) < 0.64 @ 95% CL

- Still quite loose constraint, but really interesting first step!

Spin studies

- Spin studies in three different decay modes:
  - **H → ZZ**: fully recontruct 4-momenta of leptonic final states → Have direct access to angles (θ1,θ2,θ,ϕ,ϕ1).
  - **H → γγ**: fully reconstructed, but only photon decay angle available
  - **H → WW**: direct calculation of decay angles not possible, use other kinematic distributions

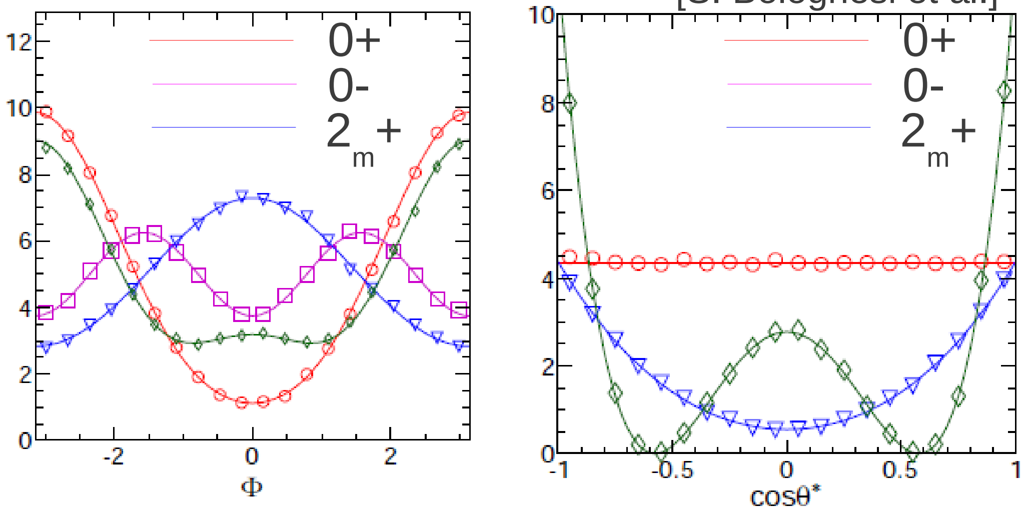


- H → ZZ can test 0^+ hypothesis vs 0^-, 1^+, 1^-, 2^+, 2^-.
- However spin 1 hypothesis strongly disfavored by observation in gg final state (Landau-Yang theorem)
- Spin 2 hypothesis is model dependent: first tests performed using a graviton-like minimal coupling model, and scanning for different mixtures of qq and gg production.

Spin studies: H → ZZ → 4ℓ

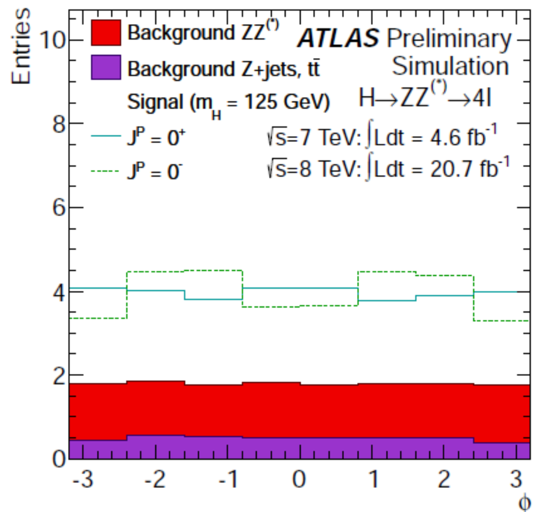
- Spin and parity dependent observables:

[S. Bolognesi et al.]



With detector smearing + background

ATLAS

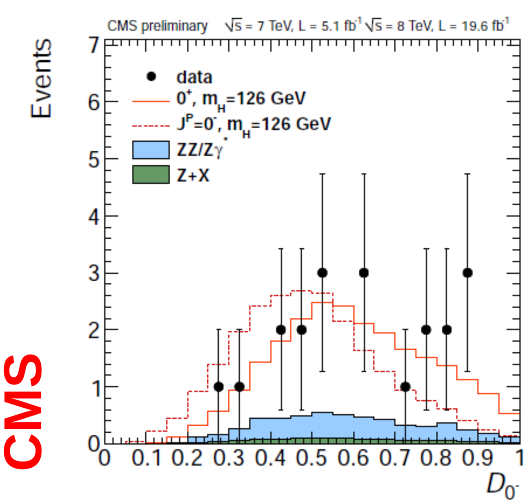


- CMS uses same Matrix Element approach as used in signal extraction, but now adding a second discriminator between two different spin / parity hypothesis:

$$\mathcal{D}_{J^P} = \frac{\mathcal{P}_{\rm SM}}{\mathcal{P}_{\rm SM} + \mathcal{P}_{J^P}} = \left[1 + \frac{\mathcal{P}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\rm SM}(m_{Z_1}, m_{Z_2}, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$

- Correlations the two discriminators (D^{JP},D^{bkg}) are taken into account in building the PDF for the new likelihood function.

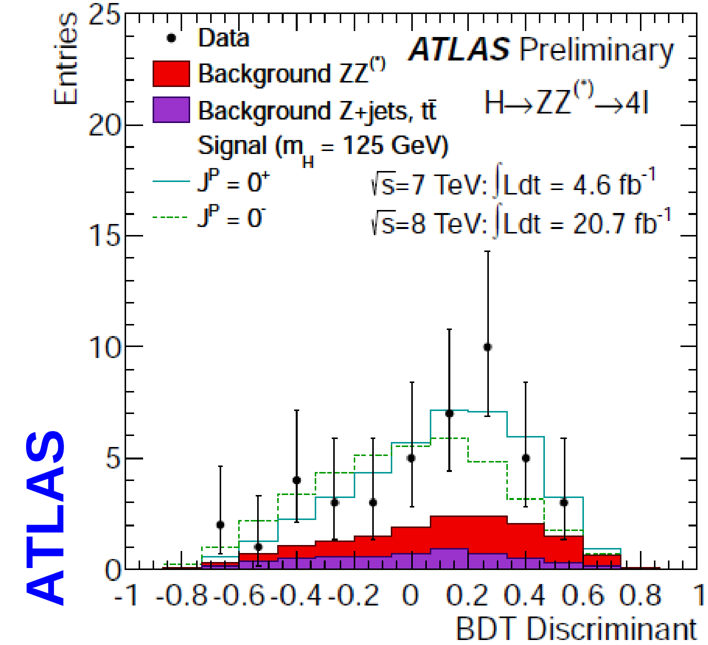
CMS



- Discriminator against 0- hypothesis shown for D^{bkg}>0.5.

Spin studies: H → ZZ → 4ℓ

- **ATLAS** uses a simpler 1-dim ME or a BDT discriminator, while two categories are defined based on m(4ℓ) with different S/B.
- Both experiments start to exclude a variety of hypotheses alternative to the SM.



ATLAS

		BDT analysis			
		tested J^P for an assumed 0^+		tested 0^+ for an assumed J^P	CL_S
		expected	observed	observed*	
0^-	p_0	0.0037	0.015	0.31	0.022
1^+	p_0	0.0016	0.001	0.55	0.002
1^-	p_0	0.0038	0.051	0.15	0.060
2^+_m	p_0	0.092	0.079	0.53	0.168
2^-	p_0	0.0053	0.25	0.034	0.258

CMS

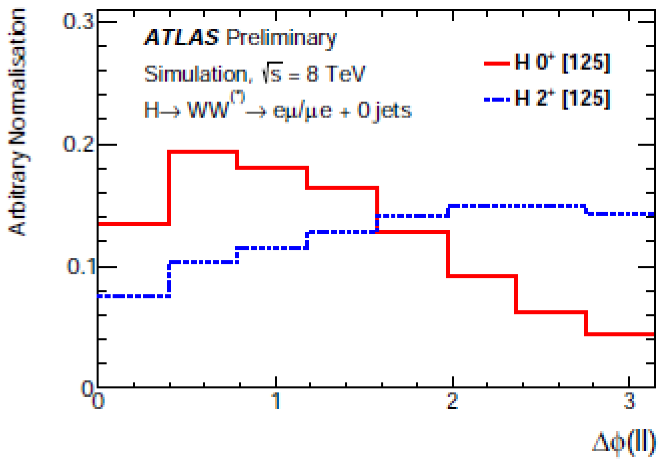
J^P	production	comment	expect (μ=1)	obs. 0^+	obs. J^P	CL_s
0^-	$gg \to X$	pseudoscalar	2.6σ (2.8σ)	0.5σ	3.3σ	0.16%
0^+_h	$gg \to X$	higher dim operators	1.7σ (1.8σ)	0.0σ	1.7σ	8.1%
2^+_{mgg}	$gg \to X$	minimal couplings	1.8σ (1.9σ)	0.8σ	2.7σ	1.5%
$2^+_{mq\bar{q}}$	$q\bar{q} \to X$	minimal couplings	1.7σ (1.9σ)	1.8σ	4.0σ	<0.1%
1^-	$q\bar{q} \to X$	exotic vector	2.8σ (3.1σ)	1.4σ	$>4.0\sigma$	<0.1%
1^+	$q\bar{q} \to X$	exotic pseudovector	2.3σ (2.6σ)	1.7σ	$>4.0\sigma$	<0.1%

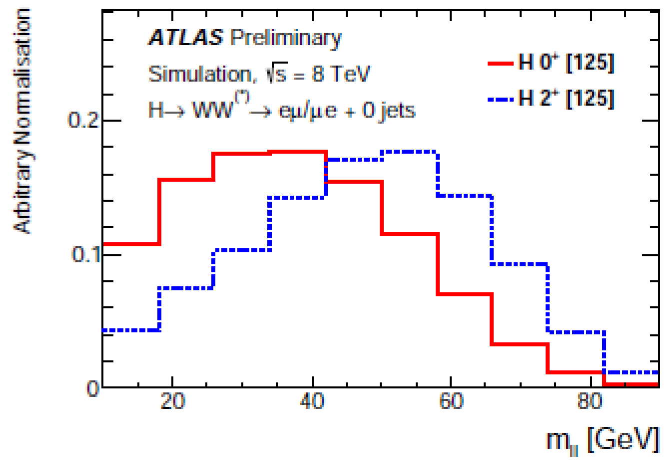
- Can the γγ and WW channels help in making these limits tighter? (e.g. vs spin 2)

Spin studies: H → WW* → ℓυℓυ

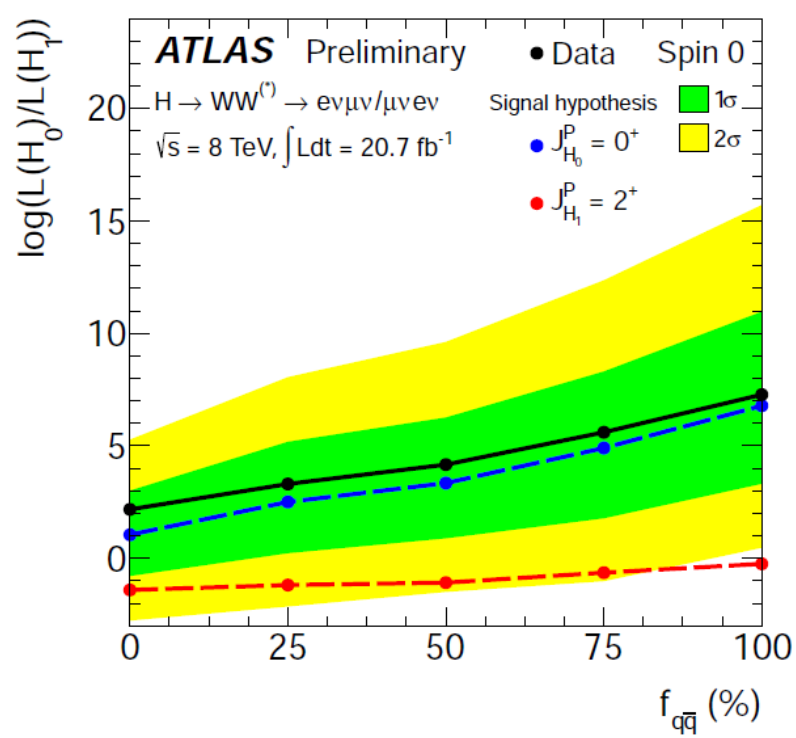
- Spin of resonance changes lepton spin correlations:

ATLAS



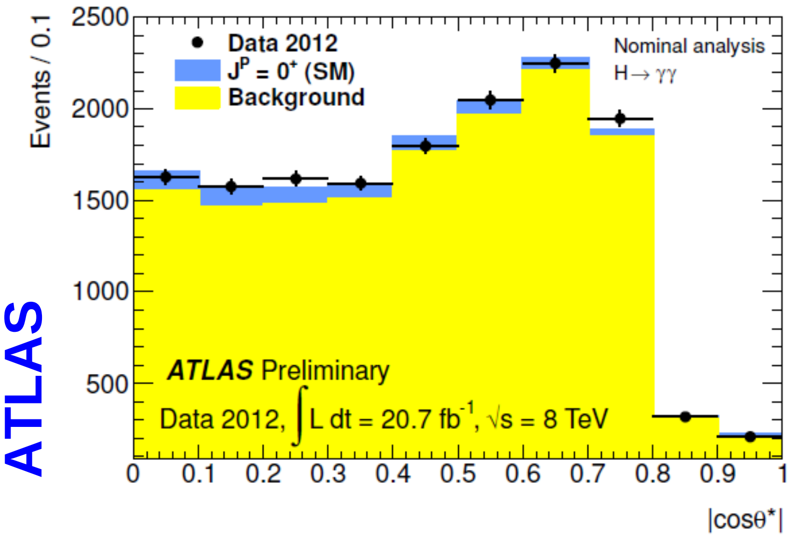


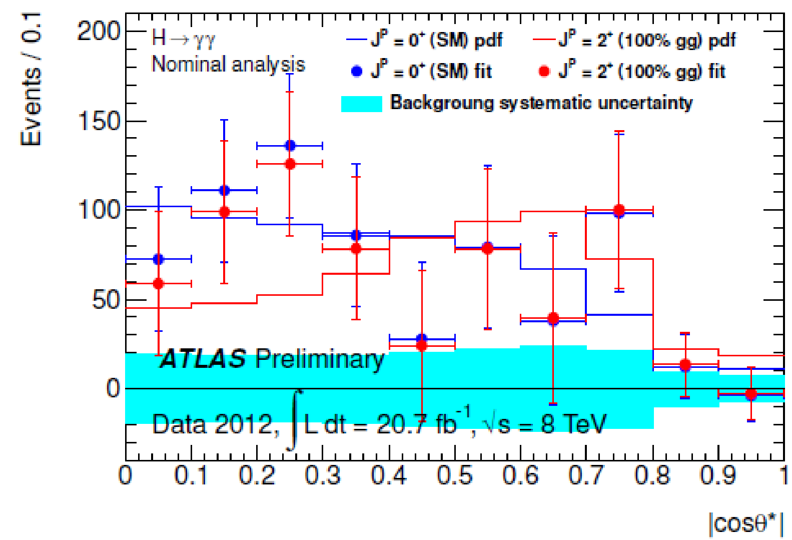
- **ATLAS** exploits H → WW analysis with relaxed cuts and then a BDT is trained to distinguish between different spin hypotheses.
- **CMS** uses fit to 2-dim (m(ℓℓ),m_T) distribution as in the main analysis.
- Both test the 2^+_m model, in ATLAS as a function of the fraction of relative qq/gg production rate.



Spin studies: H → γγ

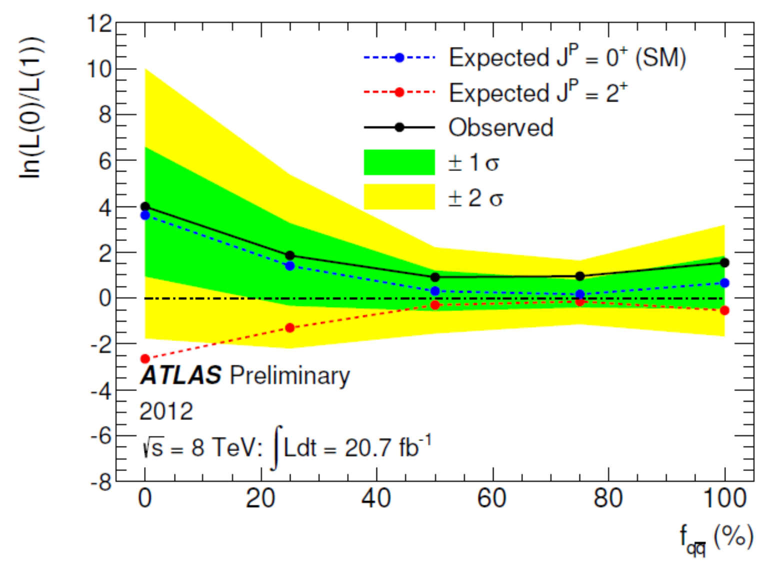
- Only photon decay angle θ* is accessible
  (when θ* is defined in Collins-Soper frame, nearly uncorrelated with mγγ)





- Background subtraction performed
  cos(θ*) distribution from mass sidebands:

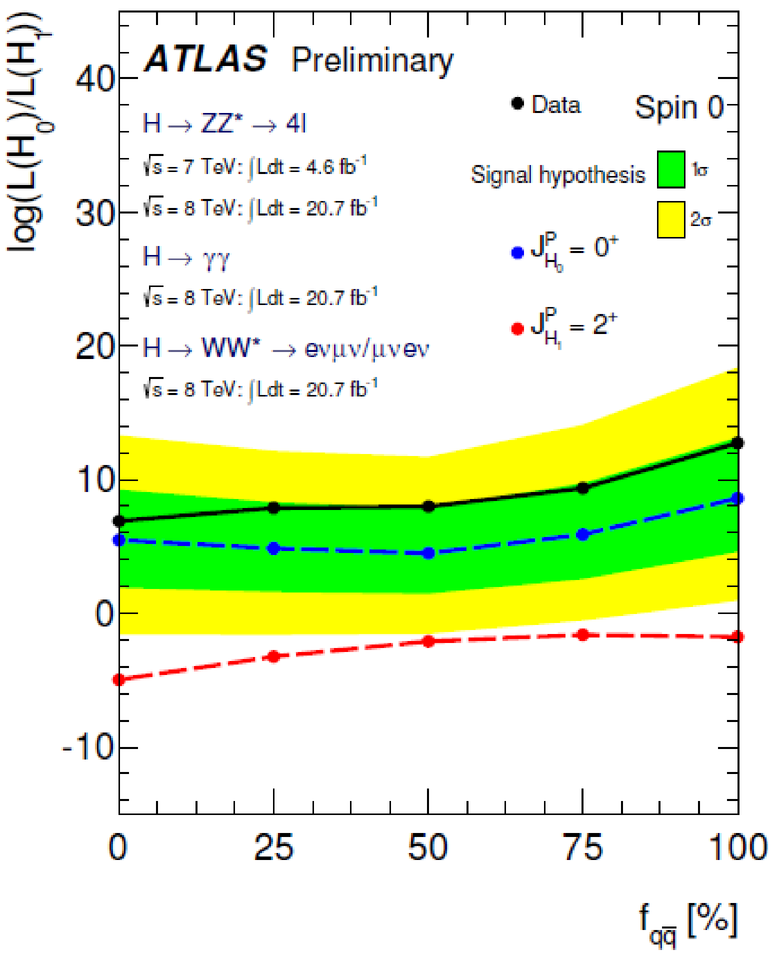
$$-\ln\mathcal{L} = (n_S + n_B) - \sum_{\text{events}} \ln\left[n_S \cdot f_S\left(|\cos\theta^*|\right) \cdot f_S(m_{\gamma\gamma}) + n_B \cdot f_B(|\cos\theta^*|) \cdot f_B(m_{\gamma\gamma})\right]$$

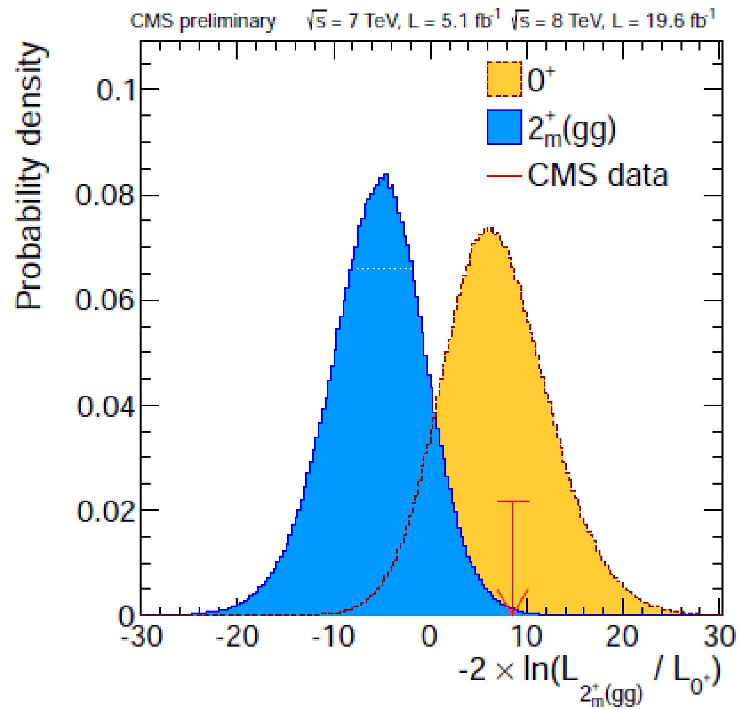


- Best discrimination against 2^+_m model in case of 100% qq production.
- Nicely complementary to WW channel.

Spin studies: combination (0^+ vs 2_m^+)

- Both experiments have published first combined spin studies for comparing 0+ and 2_m^+ with graviton-like minimal couplings.

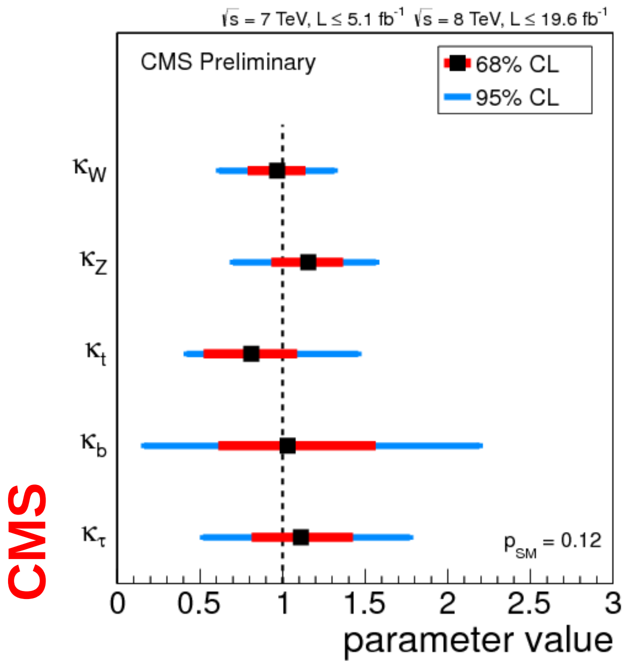




- 2_m^+ model with f_{qq}=0% excluded by **CMS** at >99% CL, for any f_{qq} excluded by **ATLAS** at >99% CL

Conclusions

- Entered the area of precision physics measurement in the Higgs sector
- Mass measured with a precision of ~3.5-5%:
  - ATLAS: m(X) = (125.5 ± 0.6) GeV
  - CMS: m(X) = (125.7 ± 0.4) GeV
- First evidence for VBF production mode at the 3.1 (~2) σ level in ATLAS (CMS)



- First **coupling measurements** performed:
  - no compelling deviation from SM observed.
  - moving towards a complete fit to all couplings, the fermionic channels (**H → ττ** and **H → bb**) play a fundamental role (stay tuned for updates!)
- First **spin studies** allow to exclude a J^P of 0-, 1-, 1+ and 2^+_m state, and are all compatible with a 0^+ SM-like Higgs boson.