

Higgs and Electroweak Measurements at the LHC

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Michiel Sanders

Ludwig-Maximilians-Universität München

For the ATLAS and CMS Collaborations

Outline

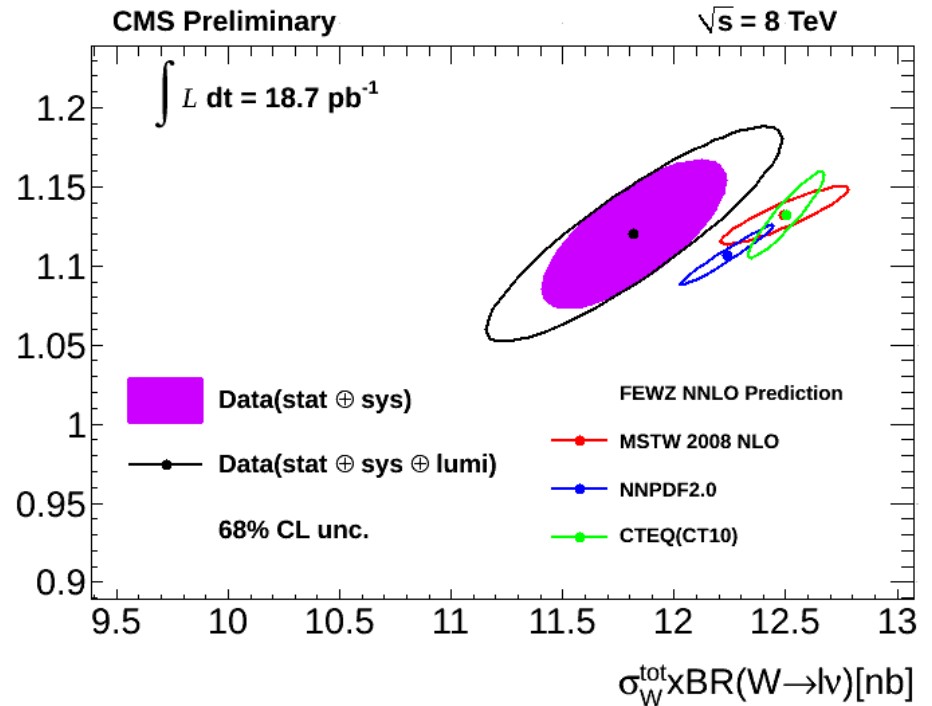
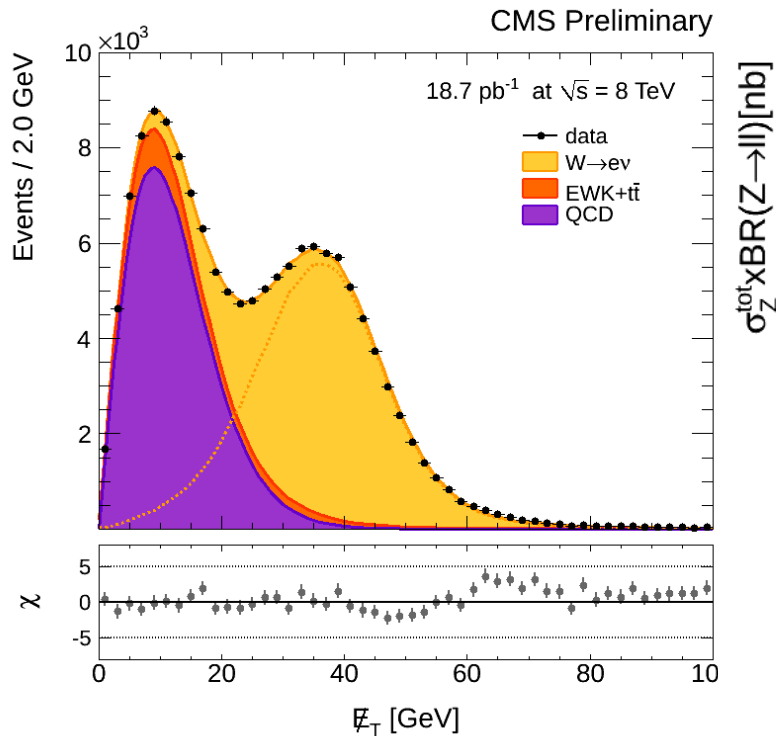
- Electroweak theory
- Electroweak measurements
 - * Di-boson production
 - * Triple-gauge-couplings
 - * Forward-backward asymmetry
- Higgs boson
 - * Observation
 - * Property measurements
- Summary

The Electroweak Theory

- Based on local $SU(2)_L \otimes U(1)_Y$ gauge symmetry
- ⇒ Coupling of W and Z gauge bosons to fermions
 - * Single W/Z production
 - * In hadron-hadron collisions, closely linked with QCD
- ⇒ TGC (γWW , ZWW) and QGC ($\gamma\gamma WW$, γZWW , ...)
 - * Di-boson production ($W\gamma$, $Z\gamma$, WW , WZ , ZZ)
 - * Two-photon production of WW, $pp \rightarrow pWWp$

Inclusive W / Z Production (CMS)

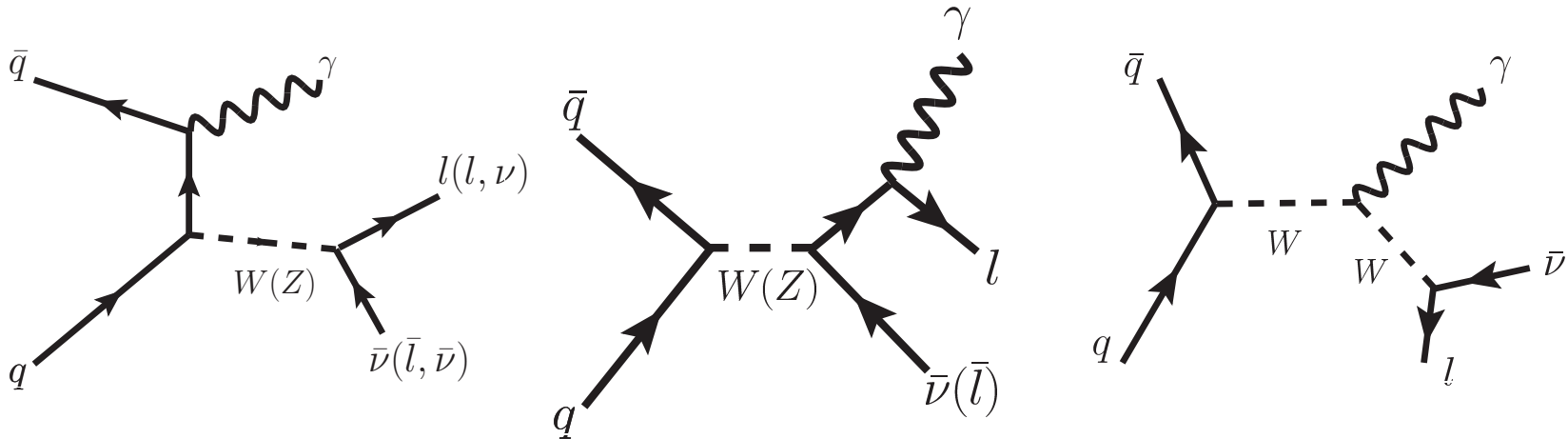
$\int \mathcal{L} dt \simeq 18.7 \text{ pb}^{-1}$ @ 8 TeV, special low \mathcal{L} / pile-up runs



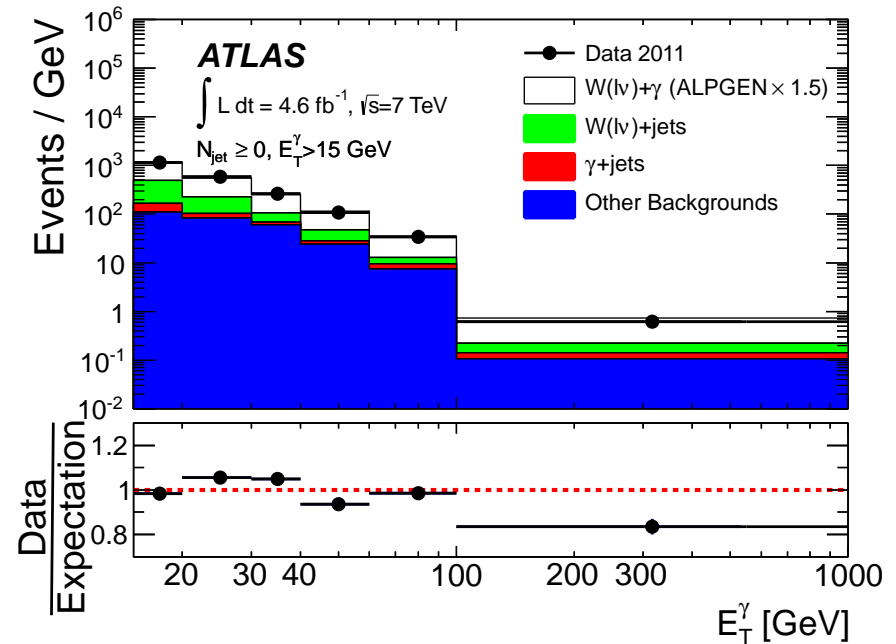
75k W \rightarrow e ν candidates

In agreement with SM@NNLO

$W\gamma$ and $Z\gamma$ Production (ATLAS)



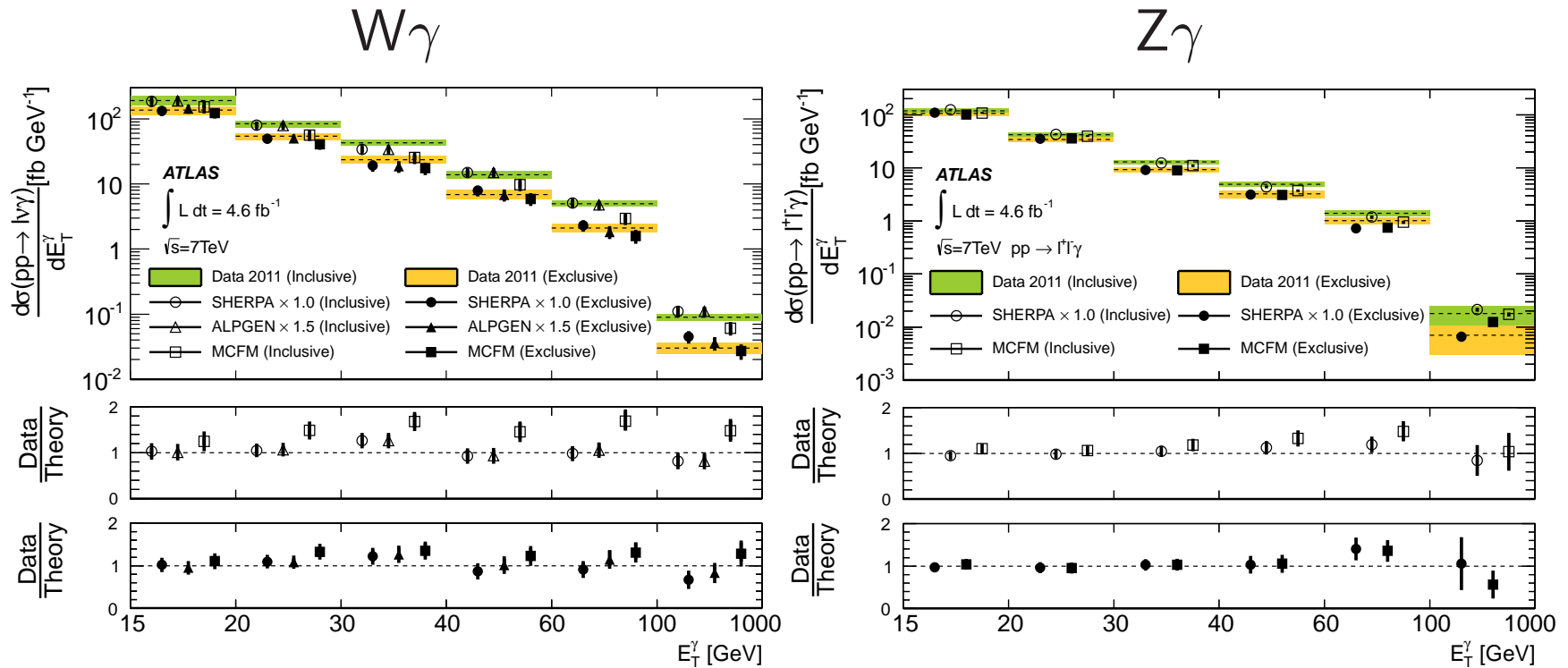
- $\int \mathcal{L} dt = 4.6 \text{ fb}^{-1} @ 7 \text{ TeV}$
- Lepton(s), \cancel{E}_T , γ
- $\Delta R(\ell, \gamma) > 0.7$
- Background: W/Z+jets
- \Rightarrow Differential cross-sections



18.3k $W\gamma$ events,
7.5k background

$W\gamma$ and $Z\gamma$ Production (ATLAS)

Cross-section vs E_γ @ 7 TeV

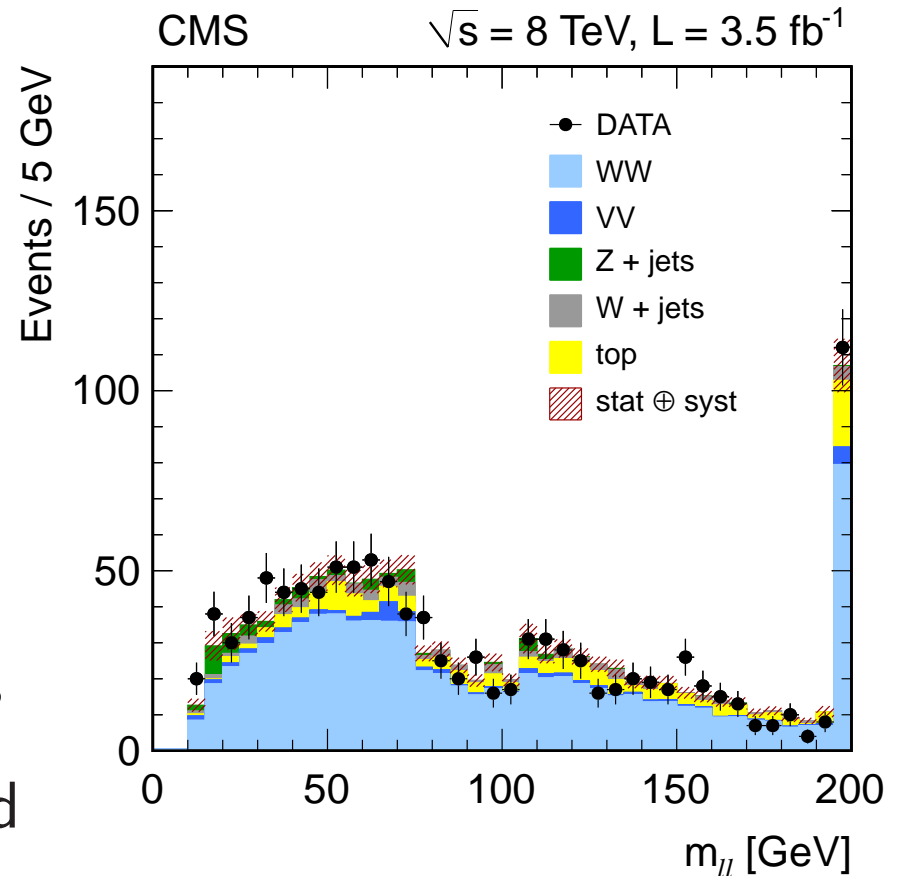


- Shape well described by LO Sherpa/AlpGen
- SM @ NLO (MCFM) breaks down at large E_γ

inclusive: $N_{\text{jet}} \geq 0$; exclusive: $N_{\text{jet}} = 0$

WW Production (CMS)

- $pp \rightarrow WW \rightarrow \ell\nu\ell'\nu'$
 - $\int \mathcal{L}dt = 3.5 \text{ fb}^{-1} @ 8 \text{ TeV}$
 - Two isolated leptons (e, μ)
 - Large \cancel{E}_T to reduce Z
 - No high p_T jets to reduce $t\bar{t}$
 - Background: $t\bar{t}$ and W +jets
- \Rightarrow 1111 events, 275 background



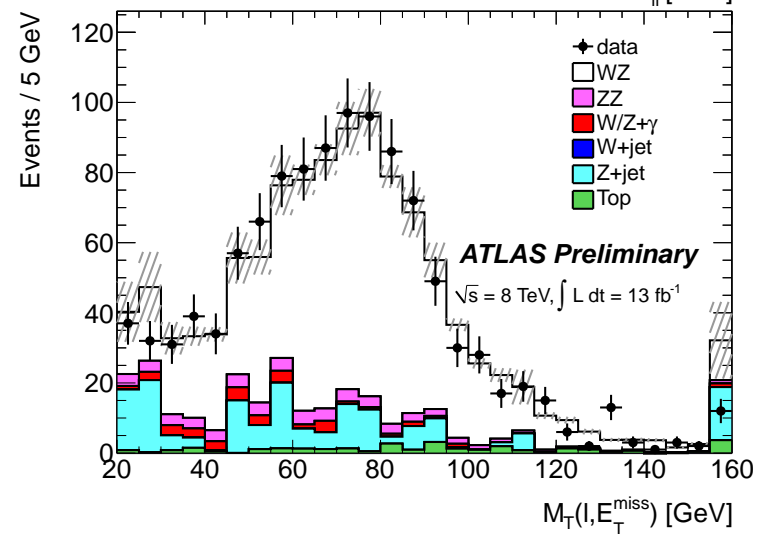
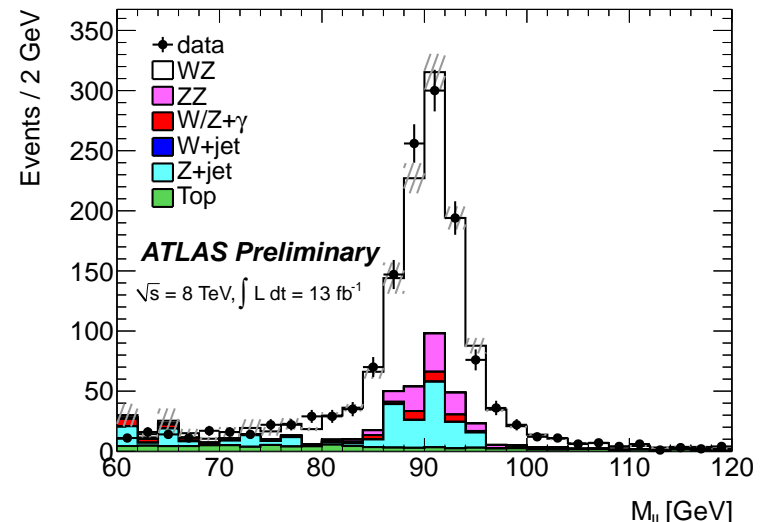
$$\sigma(pp \rightarrow WW) = 69.9 \pm 2.8(\text{stat}) \pm 5.6(\text{sys}) \pm 3.1(\text{lum}) \text{ pb}$$

$$\text{SM: } \sigma = 57.3_{-1.6}^{+2.3} \text{ pb } (+ 5\% \text{ from } H \rightarrow WW, \dots)$$

7 TeV, ATLAS: $51.9 \pm 2.0 \pm 3.9 \pm 2.0 \text{ pb}$ ($44.7_{-1.9}^{+2.1} \text{ pb}$); CMS: $52.4 \pm 2.0 \pm 4.5 \pm 1.2 \text{ pb}$ ($47.0 \pm 2.0 \text{ pb}$)

WZ Production (ATLAS)

- $pp \rightarrow WZ \rightarrow l\nu l' l'$
 - $\int \mathcal{L} dt = 13 \text{ fb}^{-1} @ 8 \text{ TeV}$
 - Three isolated leptons (e, μ)
 - $m_{\ell\ell}$ close to m_Z
 - Large \cancel{E}_T , $m_T > 20 \text{ GeV}$
 - Background from ZZ, Z+jets
- \Rightarrow 1094 events, 277 background

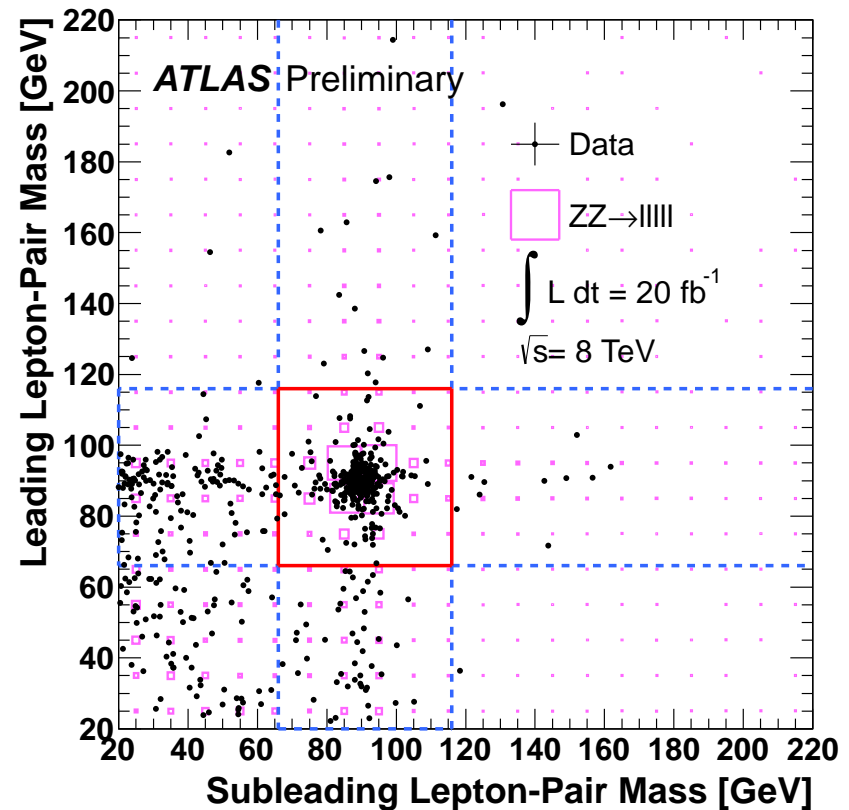


$$\sigma(pp \rightarrow WZ) = 20.3_{-0.7}^{+0.8}(\text{stat})_{-1.1}^{+1.2}(\text{sys})_{-0.6}^{+0.7}(\text{lum}) \text{ pb (=SM)}$$

7 TeV, ATLAS: $19.0_{-1.3}^{+1.4} \pm 0.9 \pm 0.4 \text{ pb}$ ($17.6_{-1.0}^{+1.1} \text{ pb}$); CMS: $17.0 \pm 2.4 \pm 1.1 \pm 1.0 \text{ pb}$ ($19.79 \pm 0.09 \text{ pb}$)

ZZ Production (ATLAS)

- $pp \rightarrow ZZ \rightarrow lll'l'$
 - $\int \mathcal{L} dt = 20.3 \text{ fb}^{-1} @ 8 \text{ TeV}$
 - Four isolated leptons (e, μ)
 - $m_{\ell\ell}, m_{\ell'\ell'}$ close to m_Z
 - Background from $Z+\text{jets}, t\bar{t}$
- \Rightarrow 305 events, 20 background



$$\sigma(pp \rightarrow ZZ) = 7.1_{-0.4}^{+0.5}(\text{stat}) \pm 0.3(\text{sys}) \pm 0.2(\text{lum}) \text{ pb}$$

$$\text{SM: } \sigma = 7.2_{-0.2}^{+0.3} \text{ pb}$$

8 TeV, CMS: $8.4 \pm 1.0 \pm 0.7 \pm 0.4 \text{ pb}$ ($7.7 \pm 0.4 \text{ pb}$)

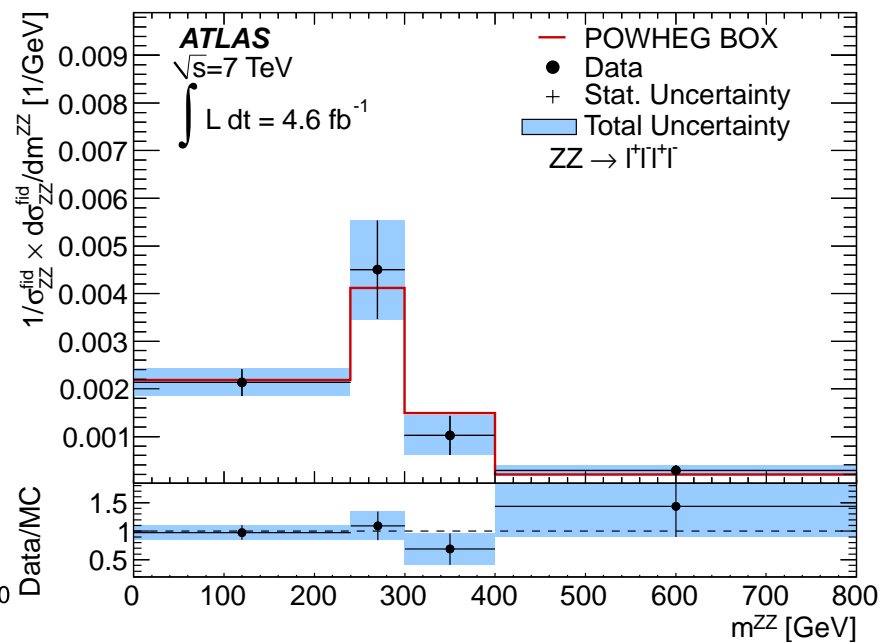
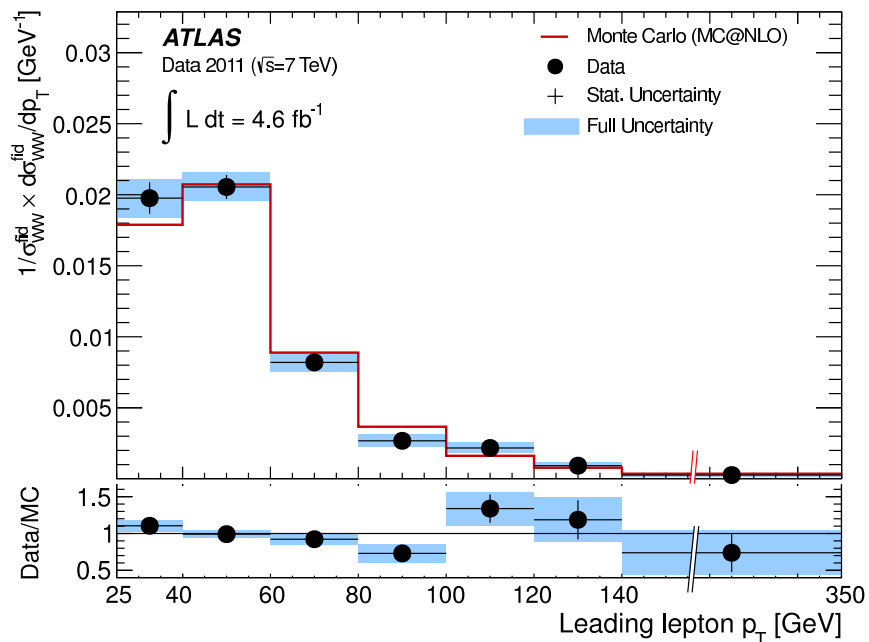
7 TeV, ATLAS: $6.7 \pm 0.7_{-0.3}^{+0.4} \pm 0.3 \text{ pb}$ ($5.89_{-0.18}^{+0.22} \text{ pb}$); CMS: $6.24_{-0.80-0.32}^{+0.86+0.41} \pm 0.14 \text{ pb}$ ($6.3 \pm 0.4 \text{ pb}$)

WW and ZZ Production (ATLAS)

Differential cross-sections @ 7 TeV

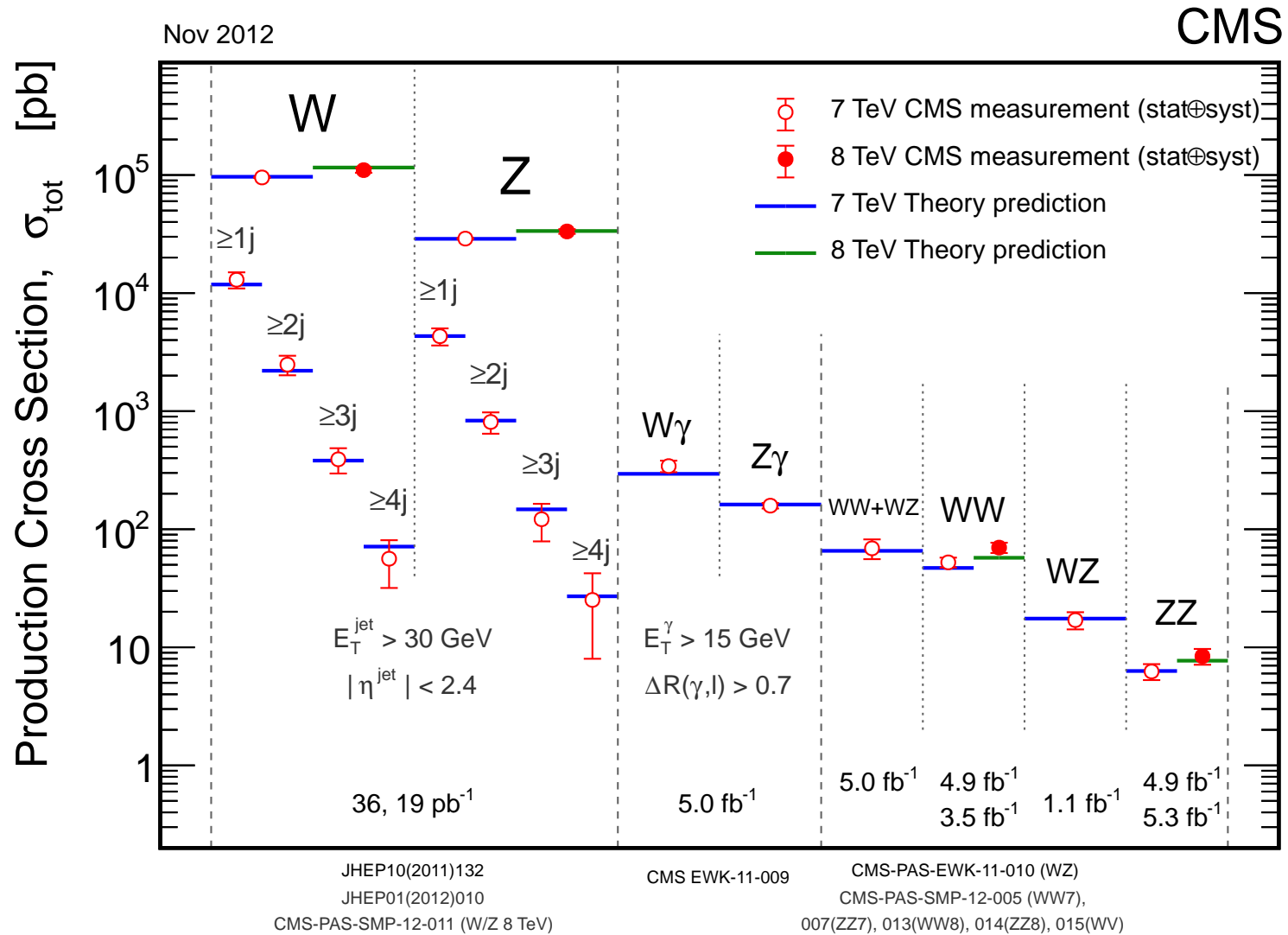
$\sigma(pp \rightarrow WW) \text{ vs } p_T(\ell)$

$\sigma(pp \rightarrow ZZ) \text{ vs } m_{ZZ}$



\Rightarrow Good agreement with SM @ NLO

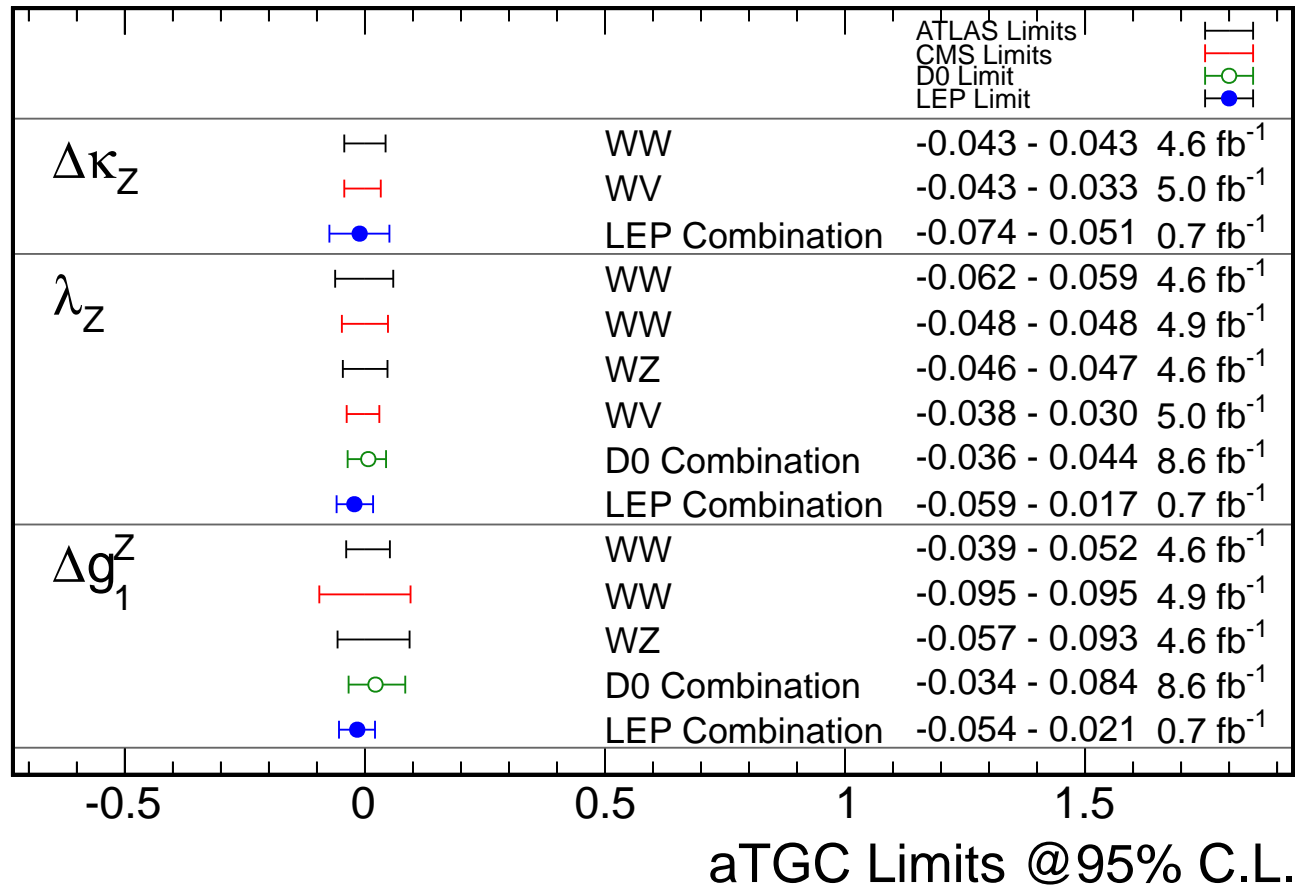
W / Z / Di-Boson Summary (CMS)



No significant deviations from SM \Rightarrow constraints on aTGCs

Triple-Gauge-Couplings

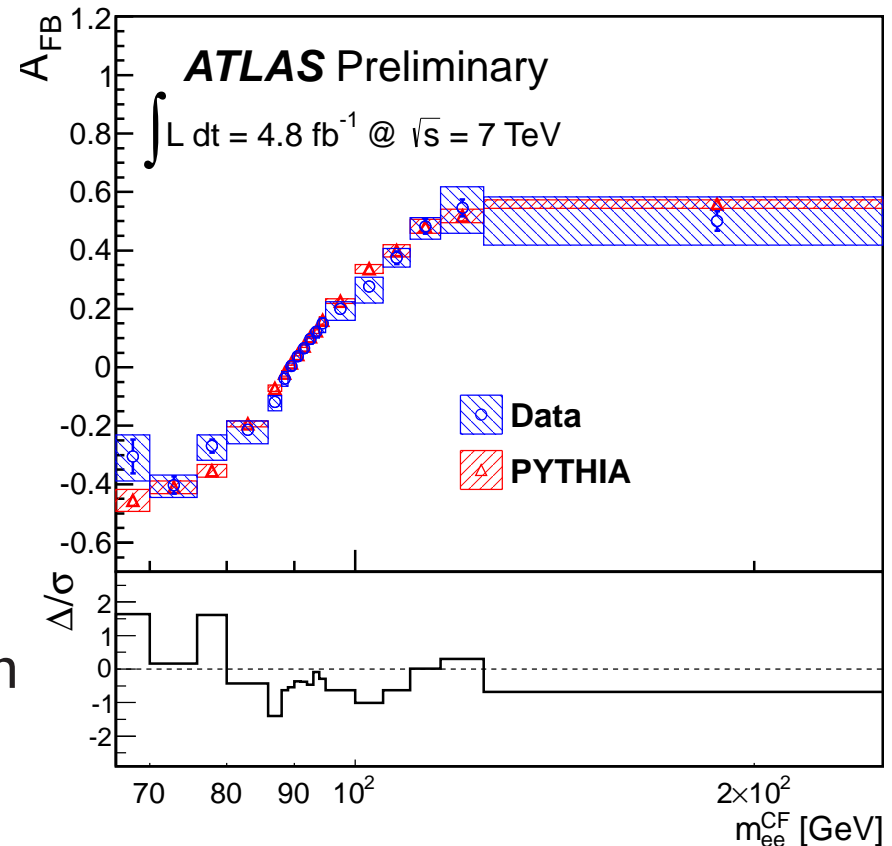
Feb 2013



- No deviation from SM
- WWZ, WW γ : almost world's leading sensitivity
- ZZZ, ZZ γ : world's leading sensitivity

Z Forward-Backward Asymmetry (ATLAS)

- $pp \rightarrow ee/\mu\mu, m_{\ell\ell} < 1 \text{ TeV}$
- $A_{\text{FB}} = \frac{\sigma_{\text{F}} - \sigma_{\text{B}}}{\sigma_{\text{F}} + \sigma_{\text{B}}}$
- Sensitive to $\sin^2\theta_{\text{W}}$
- Dilution from unknown incoming quark direction
- q direction $\simeq p_z(\ell\ell)$ direction
- $|\eta_e|$ up to 4.9



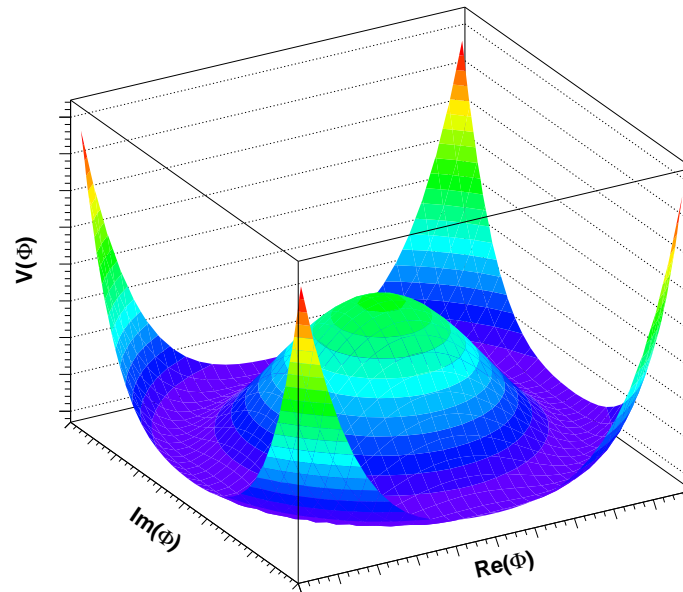
$$\sin^2\theta_{\text{W}}^{\text{eff}} = 0.2297 \pm 0.0004(\text{stat}) \pm 0.0009(\text{sys})$$

as precise as $D\emptyset$ measurement

PDG: $\sin^2\theta_{\text{W}}^{\text{eff}} = 0.23146 \pm 0.00012$

See R.Caputo, Thursday WG3

Spontaneous Symmetry Breaking



- Higgs field breaks electroweak gauge symmetry \Rightarrow
 - * Massive W, Z; massless photon
 - * New particle: massive Higgs boson, $J^P = 0^+$
 - * Couplings WWH , ZZH , $WWHH$, $ZZHH$
 - * Couplings HHH , $HHHH$
- Fermion masses: direct coupling of Higgs and fermion fields

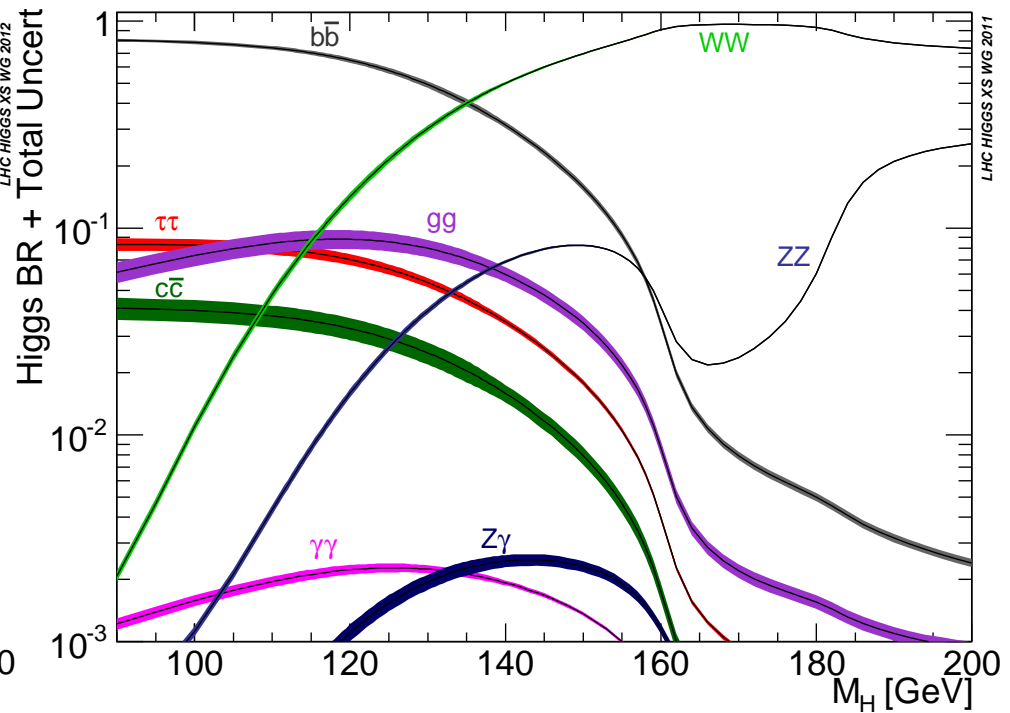
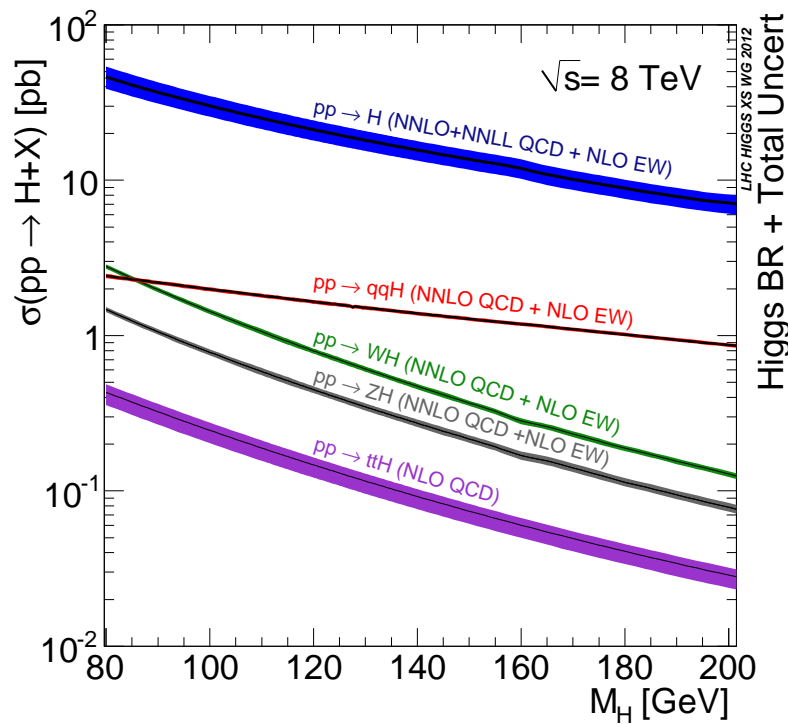
Higgs Boson ?

- Produce it
- Find it . . .
- Measure mass
- Measure spin / parity
- Measure couplings to W , Z , fermions
- Measure coupling to itself

Higgs Production and Decay

$pp \rightarrow H$ @ $\sqrt{s} = 8$ TeV

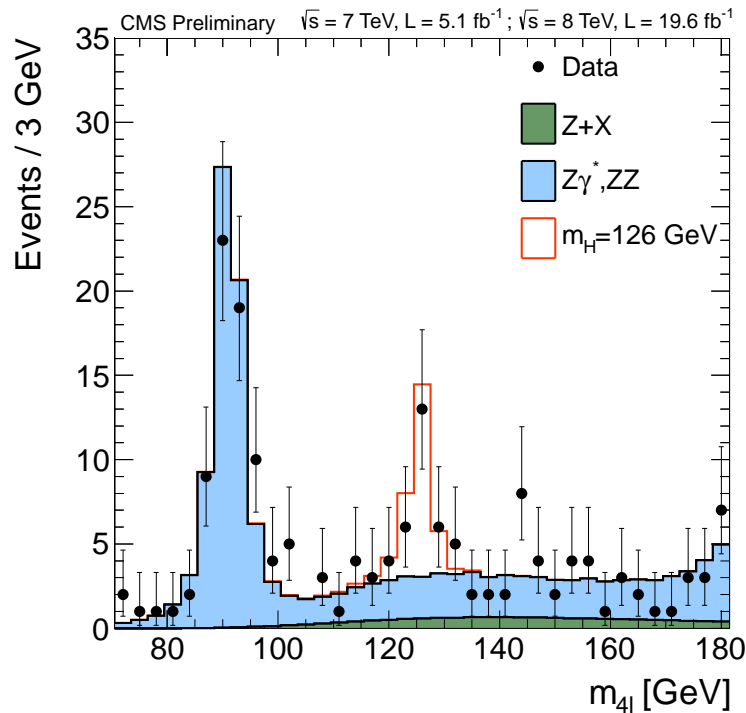
Higgs decay



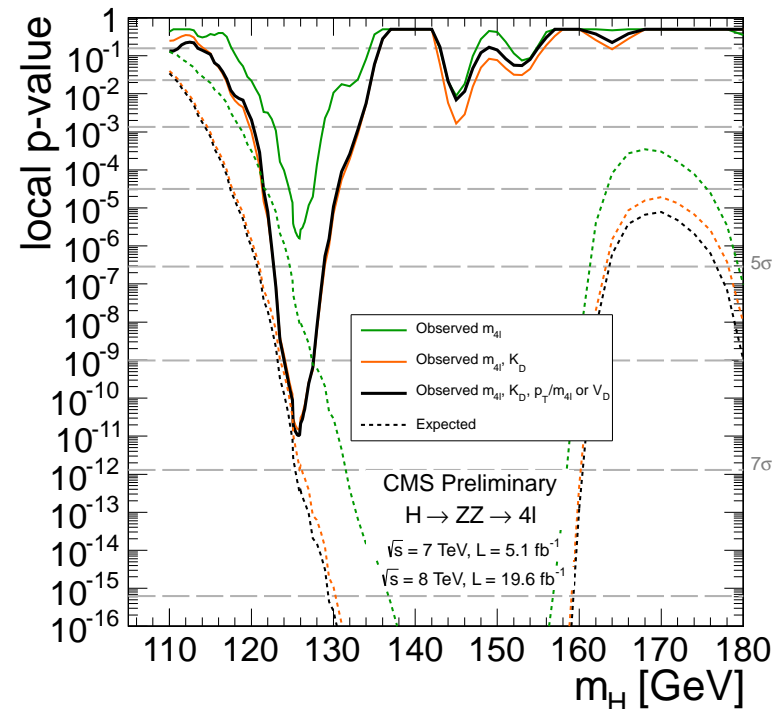
- Gluon fusion through a heavy-quark loop
- Weak boson fusion
- VH associated production

$H \rightarrow ZZ \rightarrow \ell\ell\ell'\ell'$ (CMS)

- Events with four leptons (e, μ, τ), consistent with $ZZ^{(*)}$
- Mass resolution: ~ 2 GeV
- Background from $ZZ, Z+\text{jets}$



$4\mu, 4e, 2e2\mu$



$m_{4\ell}$, kinematic discriminants

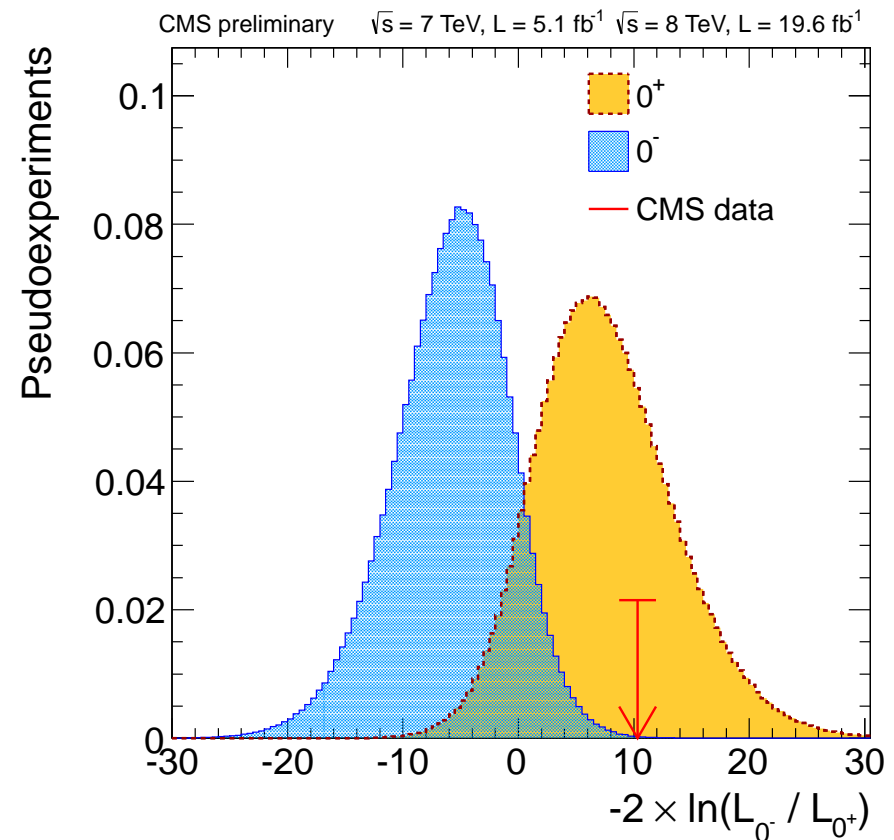
$\Rightarrow 6.7\sigma$ excess over background

$H \rightarrow ZZ \rightarrow lll'l'$ (CMS)

Signal strength: $\mu = \sigma/\sigma_{\text{SM}} = 0.91^{+0.30}_{-0.24}$

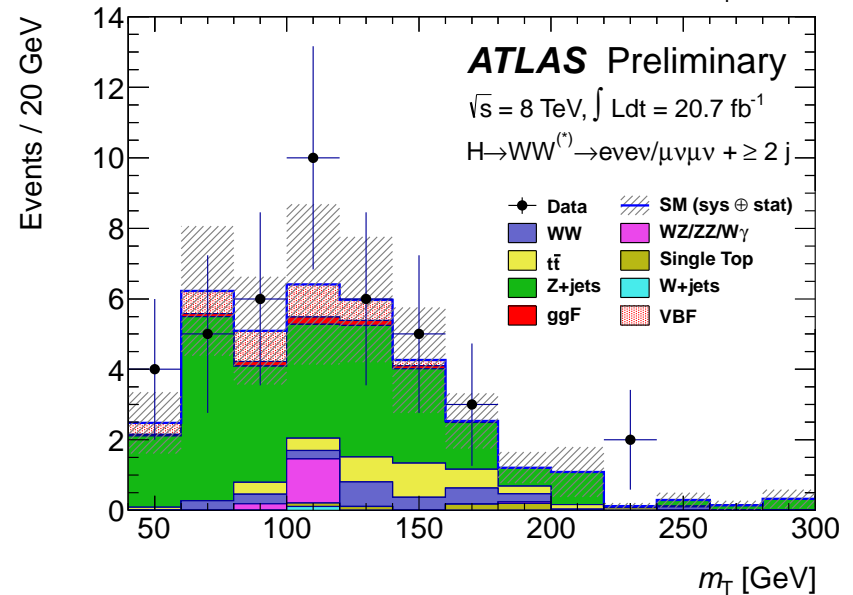
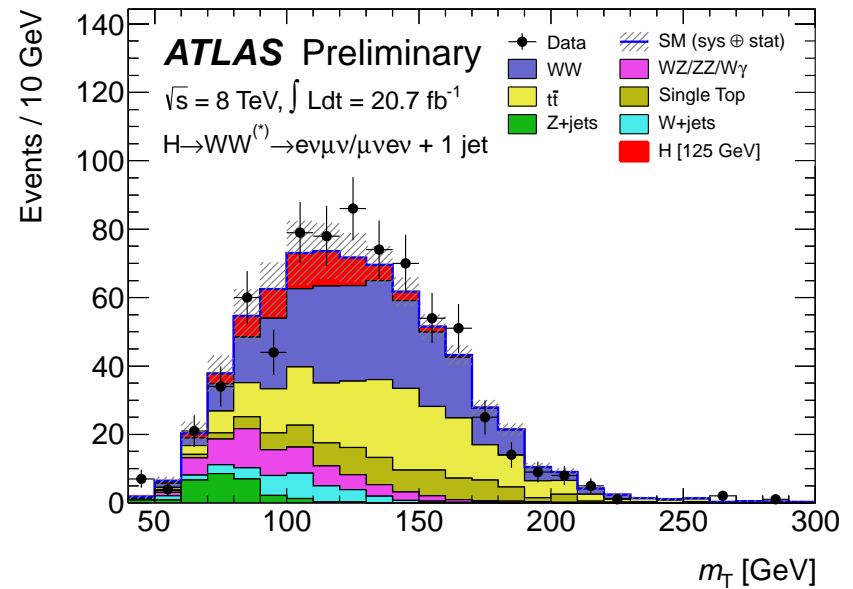
$m_H = 125.8 \pm 0.5(\text{stat}) \pm 0.2(\text{sys}) \text{ GeV}$

- Higgs fully reconstructible
- \Rightarrow Test spin / parity
- Include decay angles
- Construct likelihood ratios
- For several J^P assumptions
 - * 0^- , 2_m^+ , 1^\pm , ...
- $\Rightarrow 0^+$ strongly favoured

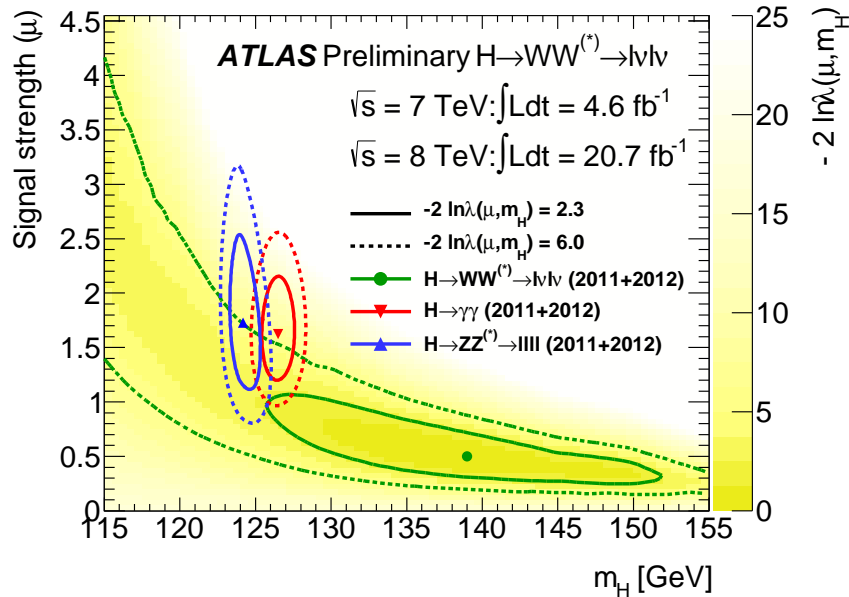


$H \rightarrow WW \rightarrow \ell\nu\ell'\nu'$ (ATLAS)

- $WW \rightarrow (ee/e\mu/\mu\mu) + \cancel{E}_T$
- Large \cancel{E}_T or $\cancel{E}_{T,rel}$
- 0, 1 or ≥ 2 jets, no b-jets
- VBF specific cuts for ≥ 2 jets
- Background: WW , $t\bar{t}$, Z
- Sensitive variable: m_T

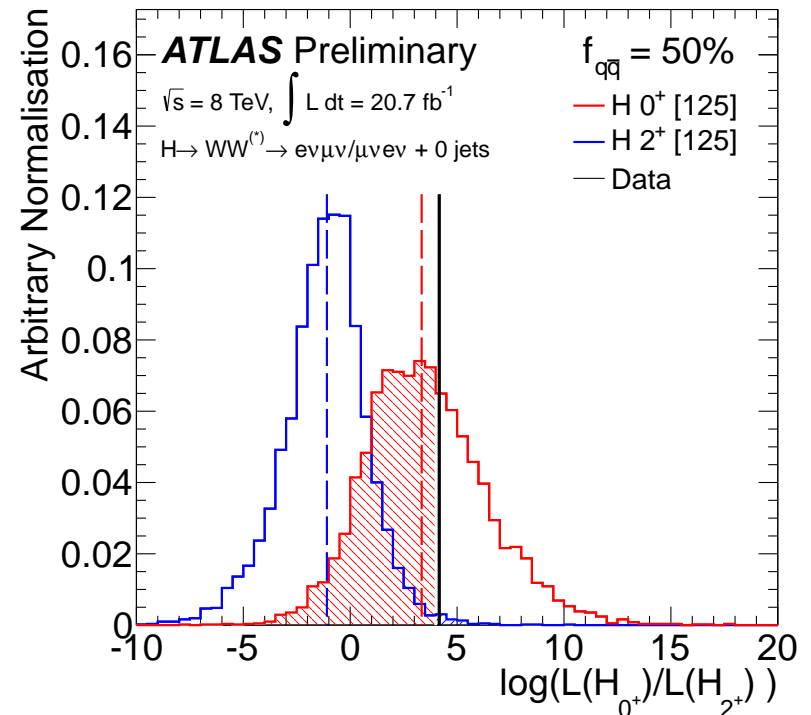


$H \rightarrow WW \rightarrow \ell\nu\ell'\nu'$ (ATLAS)



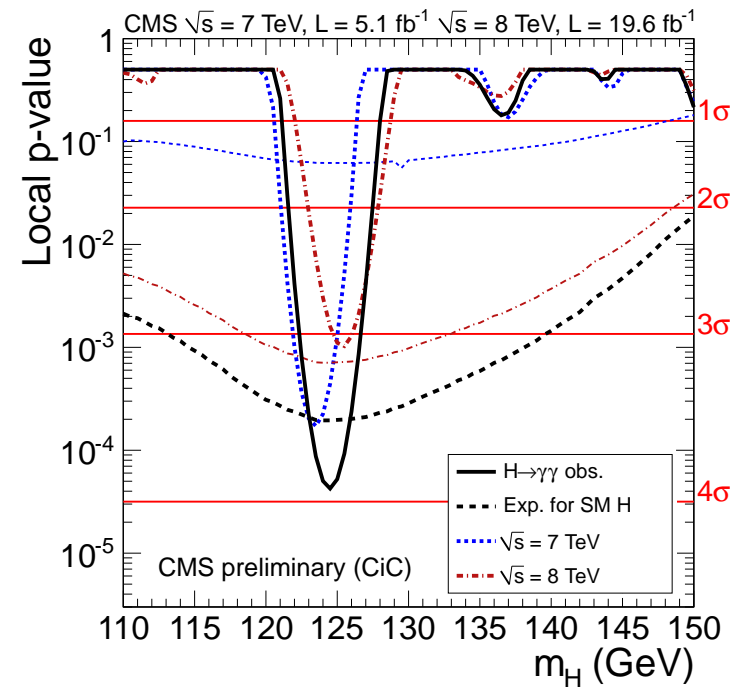
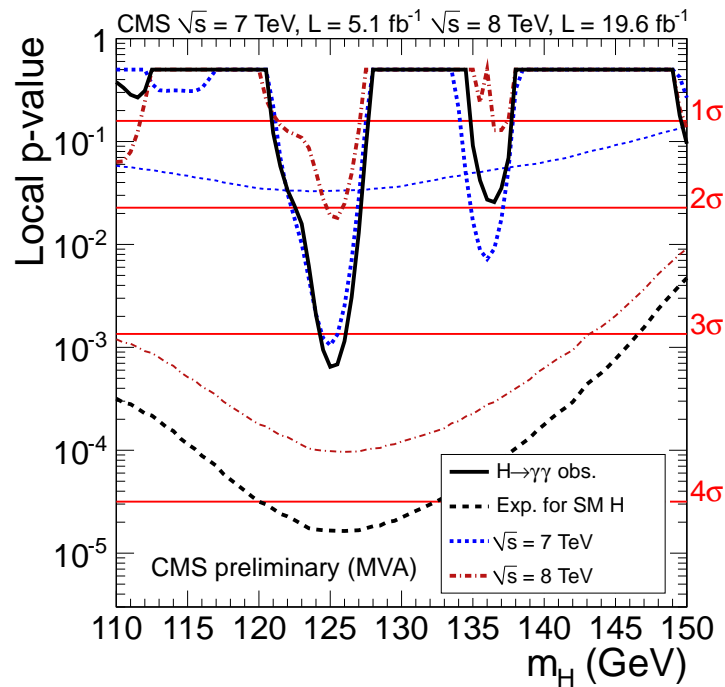
$m_H > 133 \text{ GeV}$ excluded
 $\mu = 1.01 \pm 0.31, 3.8\sigma$ excess
 @ $m_H = 125 \text{ GeV}$

- $J^P: 0^+ \text{ vs } 2_m^+$
 - Only $e\mu, 0\text{-jets}, 8 \text{ TeV}$
 - $m_{\ell\ell}, \Delta\phi_{\ell\ell}, \dots \rightarrow \text{BDTs}$
- $\Rightarrow 2_m^+$ excluded at $> 95\%$ CL



H \rightarrow $\gamma\gamma$ (CMS)

- Narrow $m_{\gamma\gamma}$ peak on a smooth background
- Mass resolution $\lesssim 2$ GeV
- Various photon quality categories, jet multiplicities



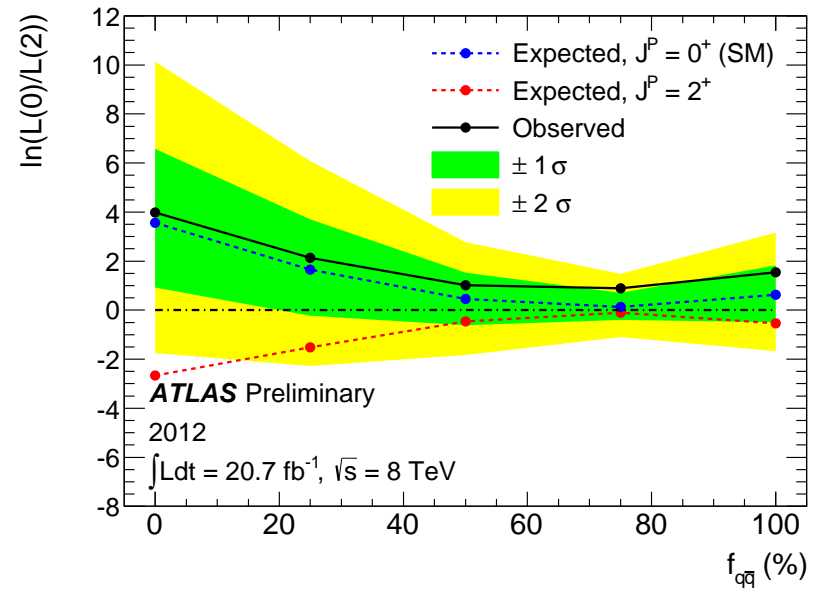
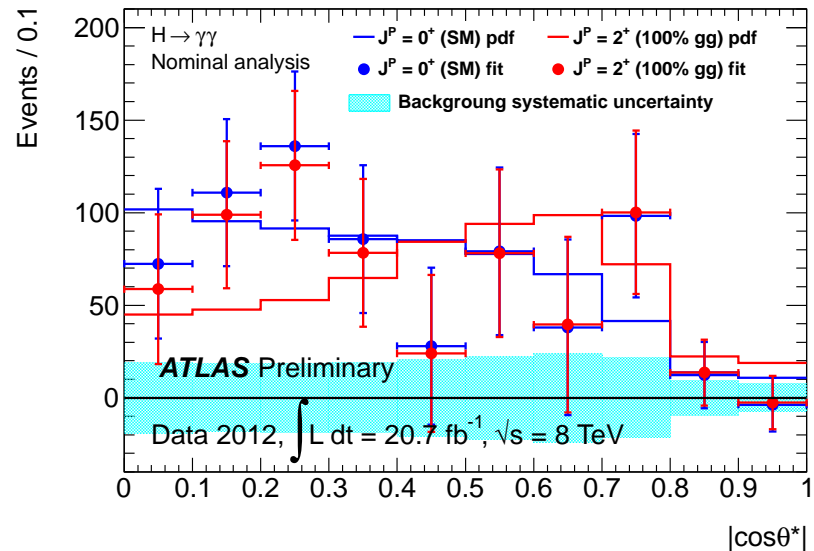
MVA based: $\mu = 0.78^{+0.28}_{-0.26}$

Cut based: $\mu = 1.11^{+0.32}_{-0.30}$

$$m_H = 125.4 \pm 0.5(\text{stat}) \pm 0.6(\text{sys}) \text{ GeV}$$

H \rightarrow $\gamma\gamma$: Spin/Parity (ATLAS)

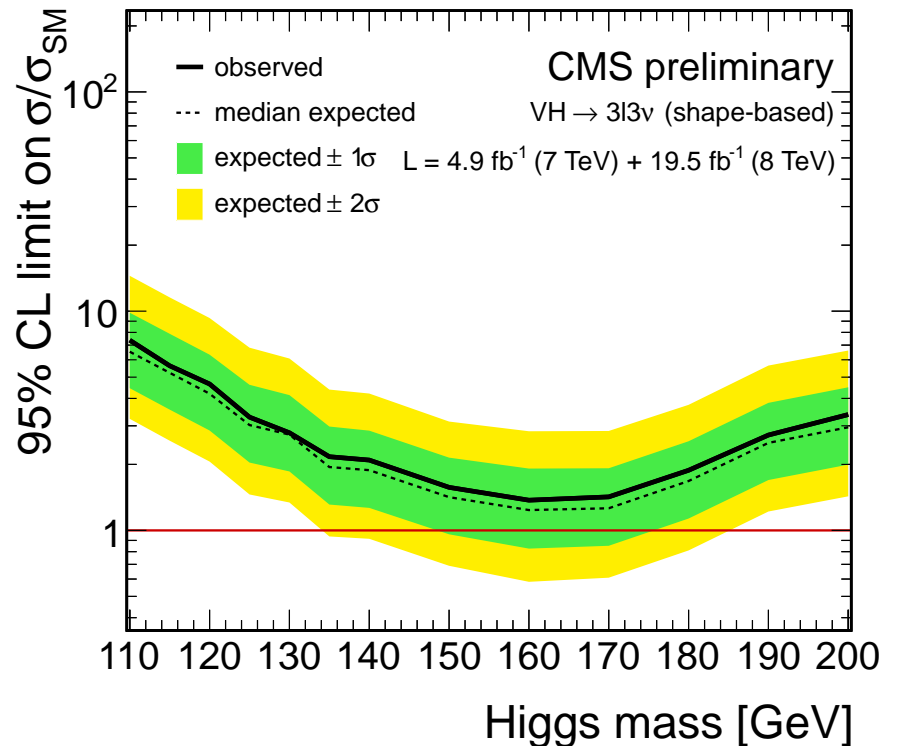
- $\int \mathcal{L} dt = 20 \text{ fb}^{-1} @ 8 \text{ TeV}$
- J^P : 0^+ vs 2_m^+
- Use photon decay angle
 $122 < m_{\gamma\gamma} < 130 \text{ GeV}$
- Background: $m_{\gamma\gamma}$ sideband
- $\Rightarrow J^P = 0^+$ preferred



WH \rightarrow WWW \rightarrow 3 ℓ 3 ν (CMS)

- Probe WWH coupling
- WH, H \rightarrow $\tau\tau$ “Background”
- OS-SF/SS-SF samples, e/ μ
- Require \cancel{E}_T or \cancel{p}_T
- No high p_T jets to reduce $t\bar{t}$
- Background: WZ, Z+jets

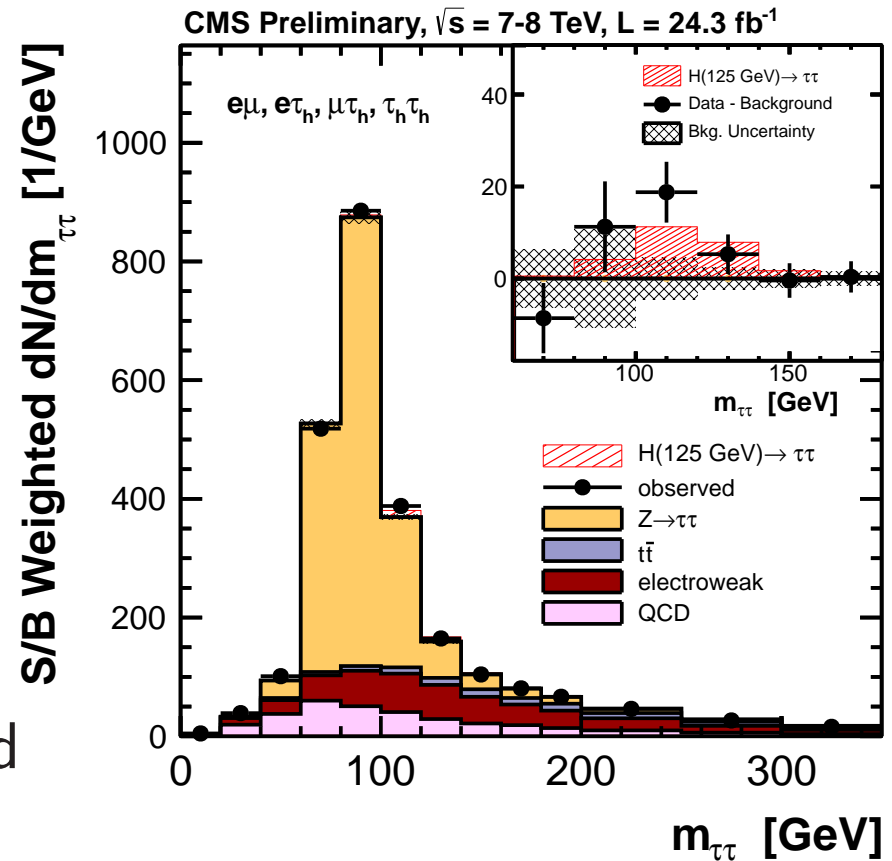
Limits based on $\Delta R(\ell^+\ell^-)$



$3.3 \times \text{SM} @ m_H = 125 \text{ GeV}$

H \rightarrow $\tau\tau$ (CMS)

- $\tau\tau \rightarrow \mu\tau_h/e\tau_h/e\mu/\tau_h\tau_h/\mu\mu$
- Likelihood fit for $m_{\tau\tau}$
- Background from $Z \rightarrow \tau\tau$
 \Rightarrow "embedding"
- VBF in two-jet bin
- Zero-jet bin for background normalization

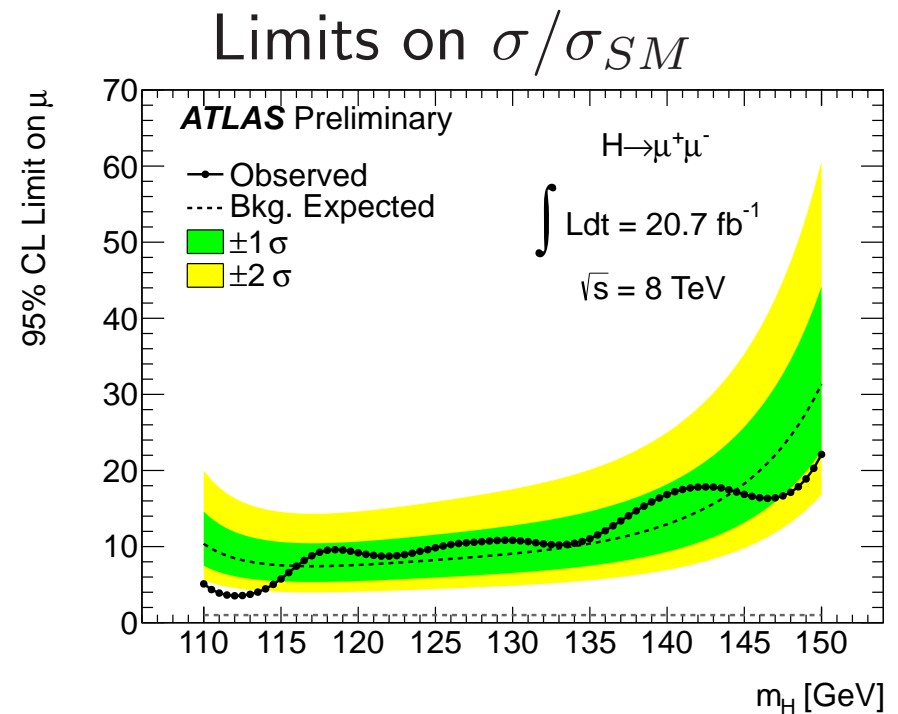
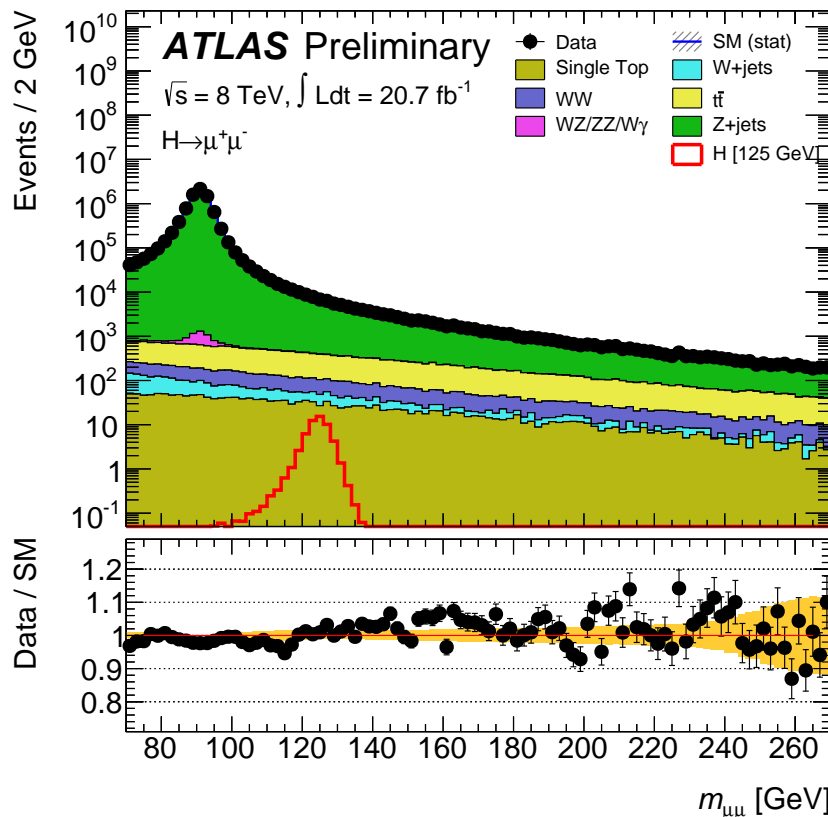


$\mu = 1.1 \pm 0.4, 2.9\sigma$ excess @ $m_H = 125$ GeV

$$m_H = 120_{-7}^{+9} \text{ GeV}$$

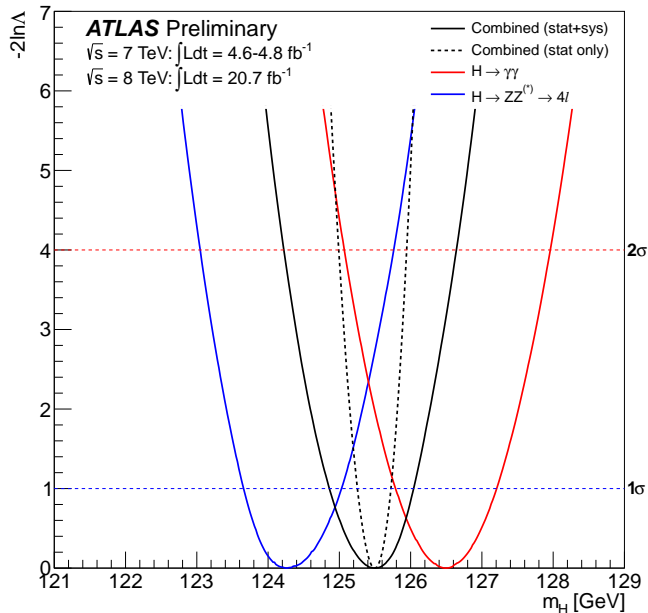
H \rightarrow $\mu\mu$ (ATLAS)

- $\text{Br}(H \rightarrow \mu\mu) = 0.022\% \simeq 2 \times \text{Br}(H \rightarrow ZZ \rightarrow 4e/4\mu/2e2\mu)$
- Narrow $m_{\mu\mu}$ peak on smooth background, $\sigma_m \sim 2.5$ GeV
- Background from $DY \rightarrow p_T(\mu\mu) > 15$ GeV



$9.8 \times \text{SM} @ m_H = 125$ GeV

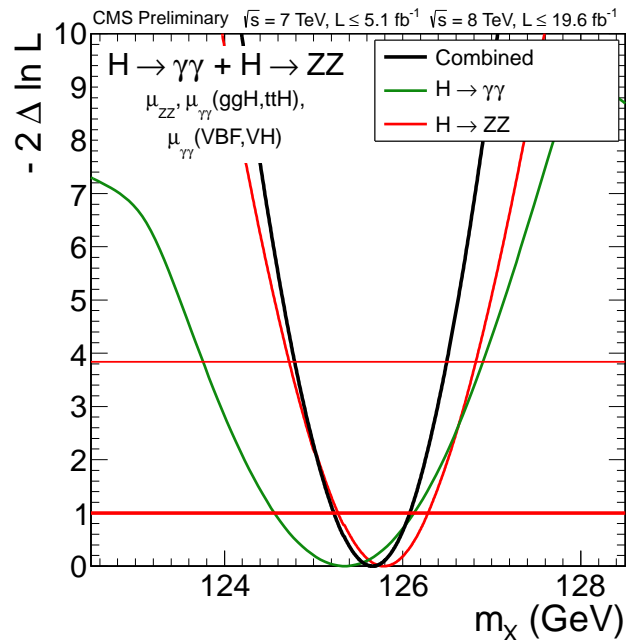
Higgs Boson Mass



ATLAS, $H \rightarrow 4l/\gamma\gamma$ combination

$$m_H = 125.5 \pm 0.2(\text{stat})_{-0.6}^{+0.5}(\text{sys}) \text{ GeV}$$

$$\Delta m_H = 2.3_{-0.7}^{+0.6}(\text{stat}) \pm 0.6(\text{sys}) \text{ GeV } [2.5\sigma]$$

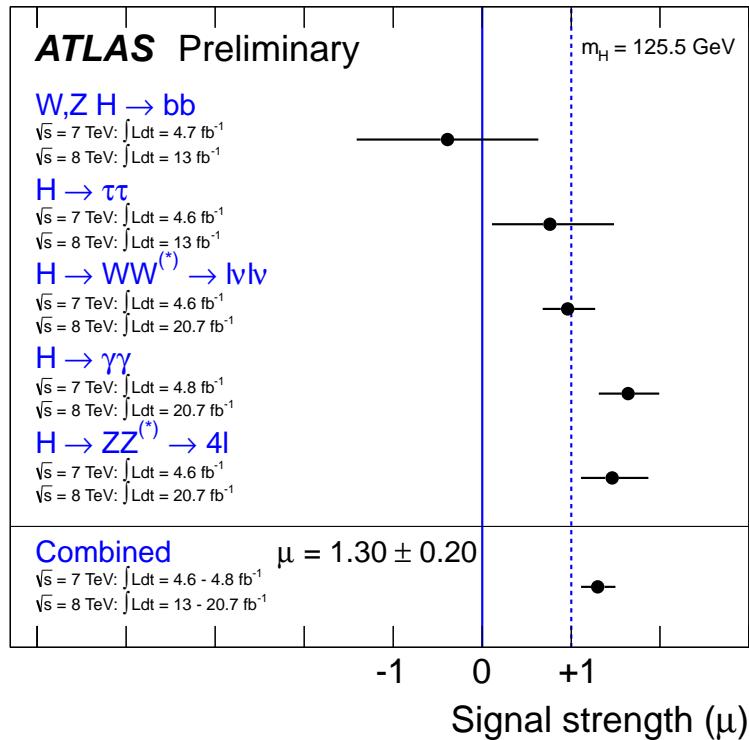


CMS, $H \rightarrow 4l/\gamma\gamma$ combination

$$m_H = 125.7 \pm 0.3(\text{stat}) \pm 0.3(\text{sys}) \text{ GeV}$$

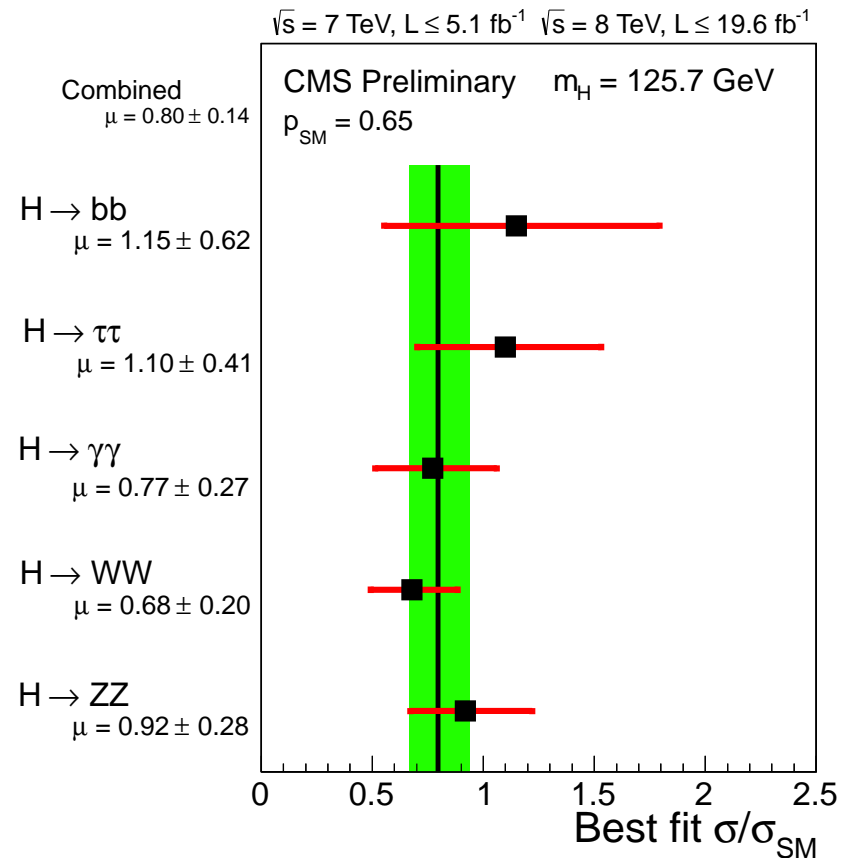
Higgs Signal Strength

ATLAS combination



$$\mu = 1.30 \pm 0.20$$

CMS combination

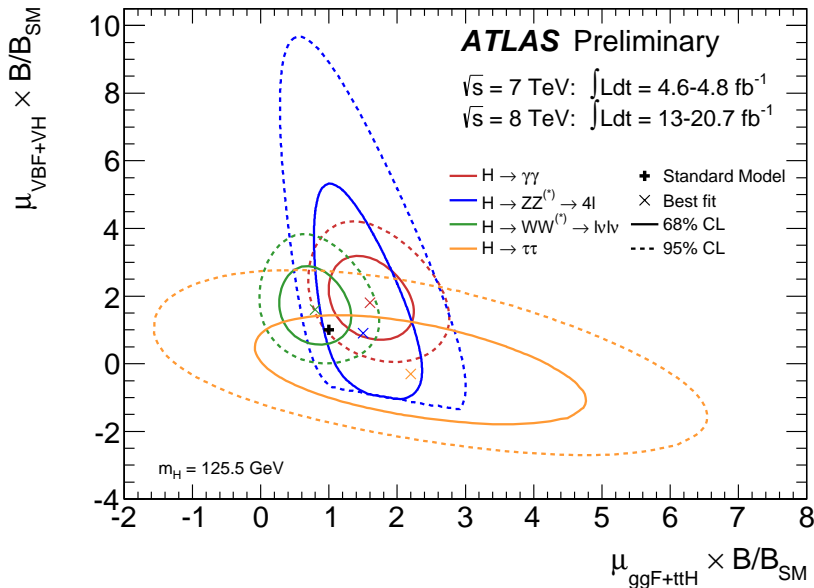


$$\mu = 0.80 \pm 0.14$$

\Rightarrow Consistent with standard model Higgs

Higgs Couplings (ATLAS)

Probe production modes with boson and fermion couplings

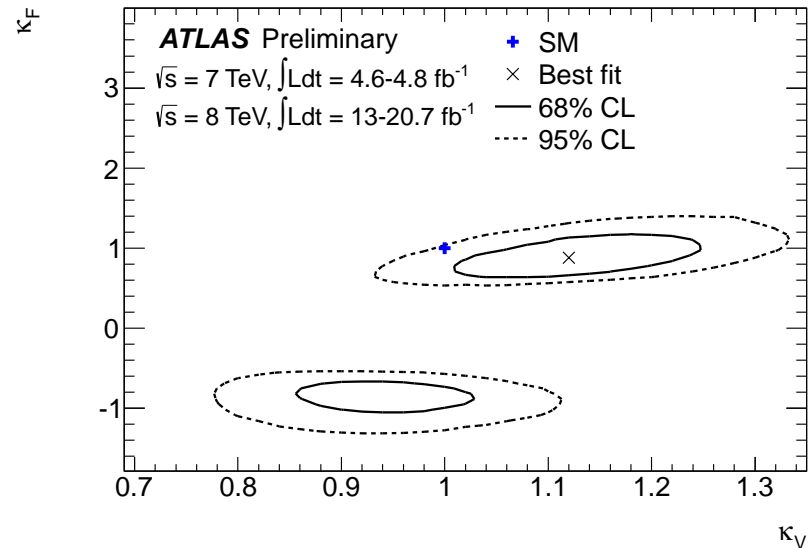


$$\mu_{\text{VBF,VH}} / \mu_{\text{gg}\rightarrow\text{H},\text{ttH}} = 1.2^{+0.7}_{-0.5}$$

> 3σ evidence for VBF

($m_H = 125.5 \text{ GeV}$)

Determine scale factors κ for HVV and Hff couplings

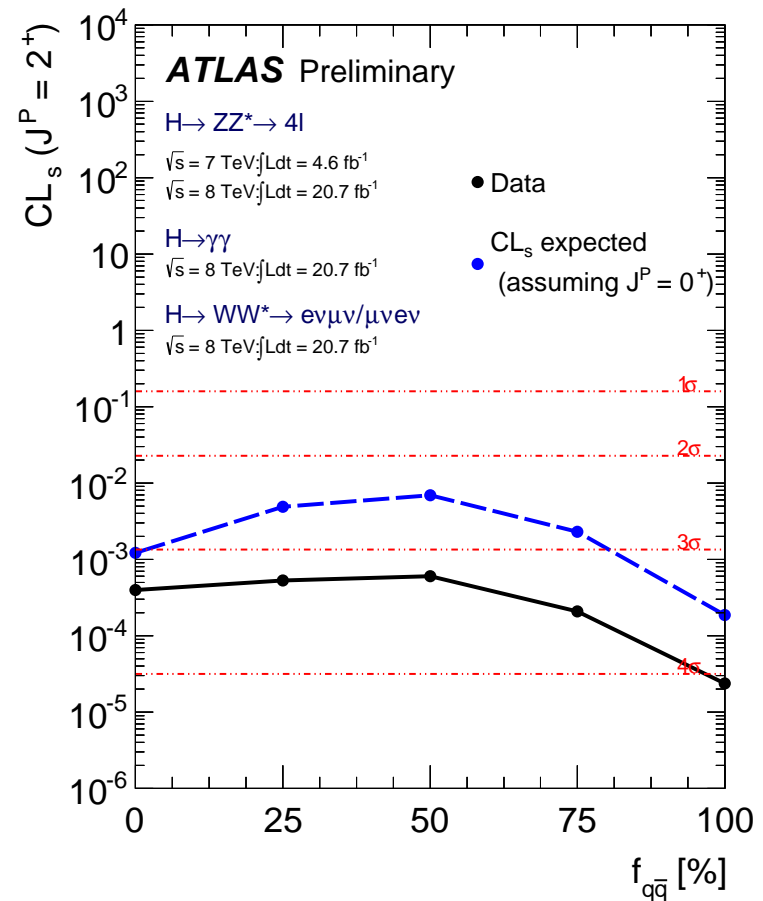
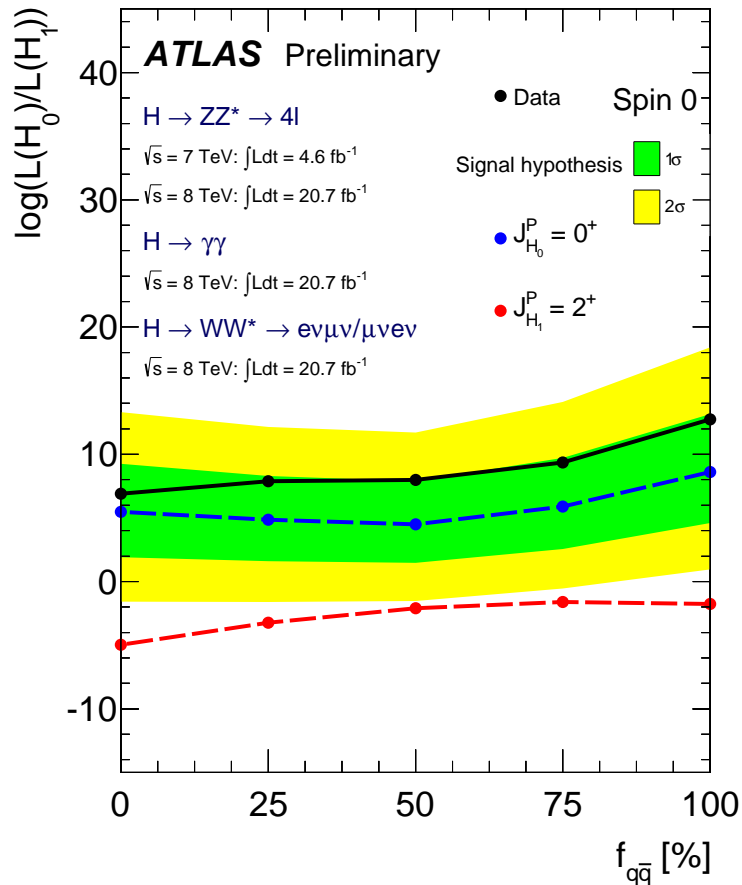


\Rightarrow Consistent with SM Higgs

Similar results from CMS

Spin/Parity Combination (ATLAS)

Test $J^P = 0^+$ vs 2_m^+ with $H \rightarrow \gamma\gamma$, $H \rightarrow \ell\nu\ell'\nu'$, $H \rightarrow 4\ell$



$\Rightarrow J_P = 2_m^+$ excluded at $> 99.9\%$ CL

Summary

- Electroweak measurements
 - * Consistent with theory
 - * Approaching precision coupling measurements (TGC)
- Higgs boson
 - * “Discovery” firmed
 - * Looks like standard model Higgs boson
- Not covered here:
 - * Many W/Z measurements, $t\bar{t}H$, $H \rightarrow b\bar{b}$, $H \rightarrow Z\gamma$
- See also:
 - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic>
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults>