SM Higgs Combination and Higgs Properties Measurements in ATLAS

SUSY2014@Manchester

22th July 2014

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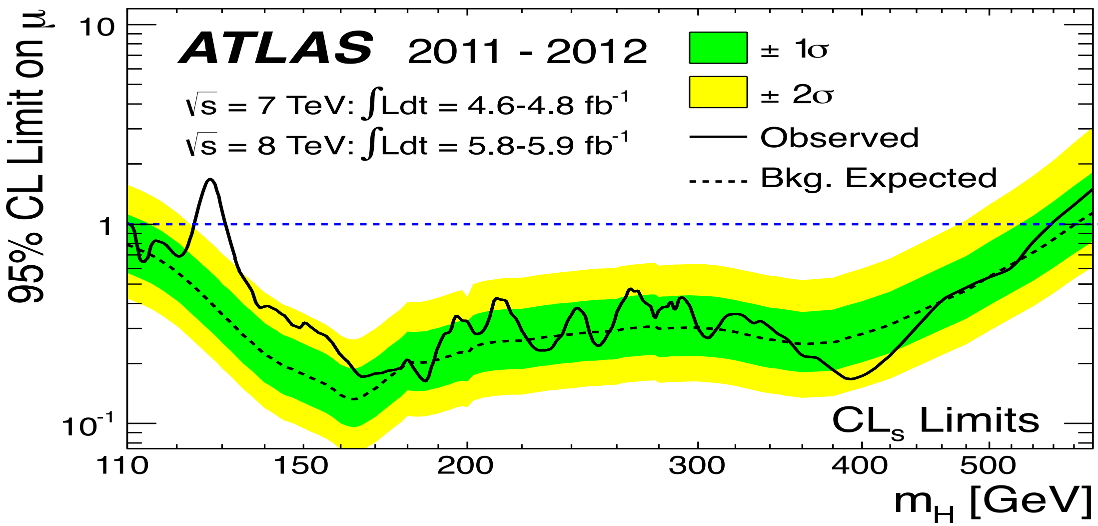
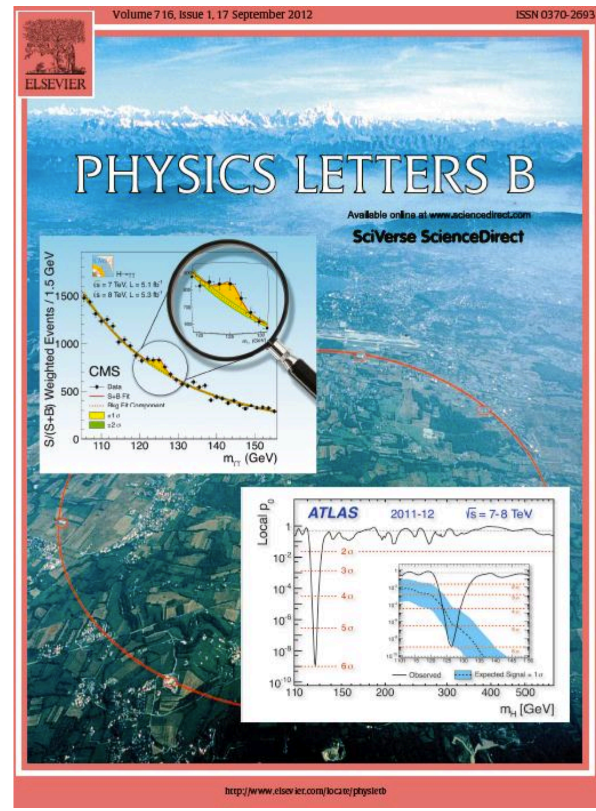
On behalf of the ATLAS Collaboration

Observation of a new boson

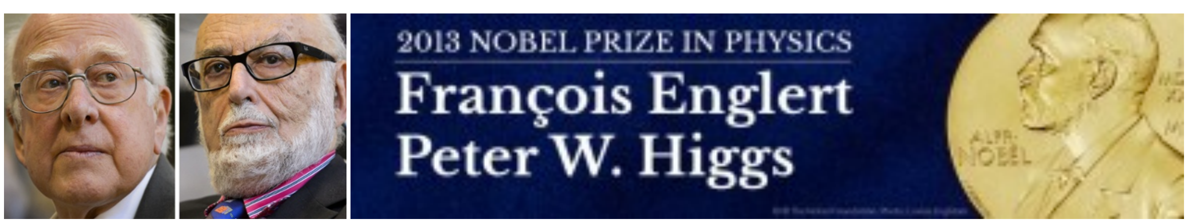
Phys. Lett. B 716 (2012) 1-29

- Observation of a new boson consistent with the SM Higgs boson at the LHC (4th July 2012)





- Nobel Prize 2013 in Physics (8th October 2013)



Property Measurements

- The center of Higgs analysis is property measurements.

Higgs Sector :

$$\mathcal{L}_{SM} = D_\mu H^\dagger D_\mu H + \mu^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \left(y_{ij} H \bar{\psi}_i \psi_j + \text{h.c.}\right)$$

EW gauge bosons Couplings

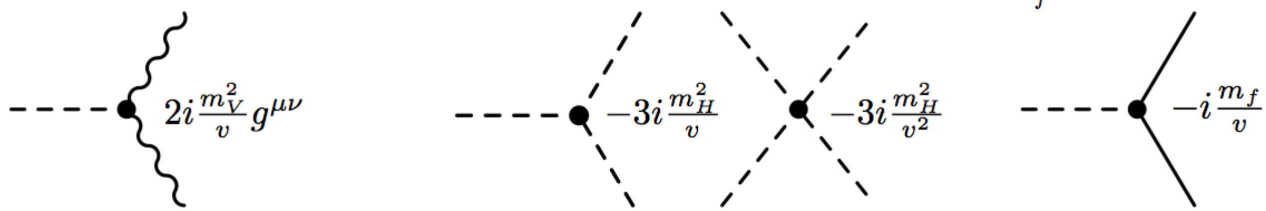
$$\left[m_W^2 W^{\mu +} W_\mu^- + \frac{1}{2} m_Z^2 Z^{\mu 0} Z_\mu^0\right] \cdot \left(1 + \frac{h}{v}\right)^2$$

Self-Couplings

$$-\mu^2 h^2 - \frac{\lambda}{2} v h^3 - \frac{1}{8}\lambda h^4$$

Fermion Couplings

$$-\sum_f m_f \bar{f} f \left(1 + \frac{h}{v}\right)$$

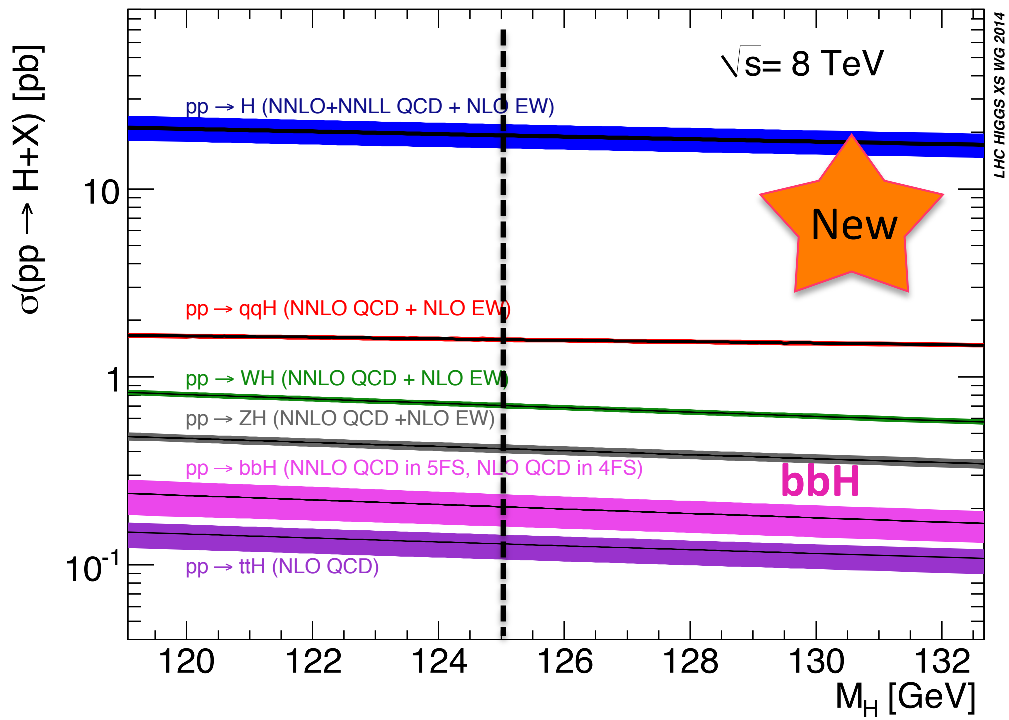


- Mass (m_H) (and width (Γ_H)) -> **Mass Measurement**
- Quantum numbers J^P -> **Spin-Parity Determination**
- Couplings to fermions and bosons -> **Coupling Measurements**
- Self-couplings -> to do in future LHC (Run II -)

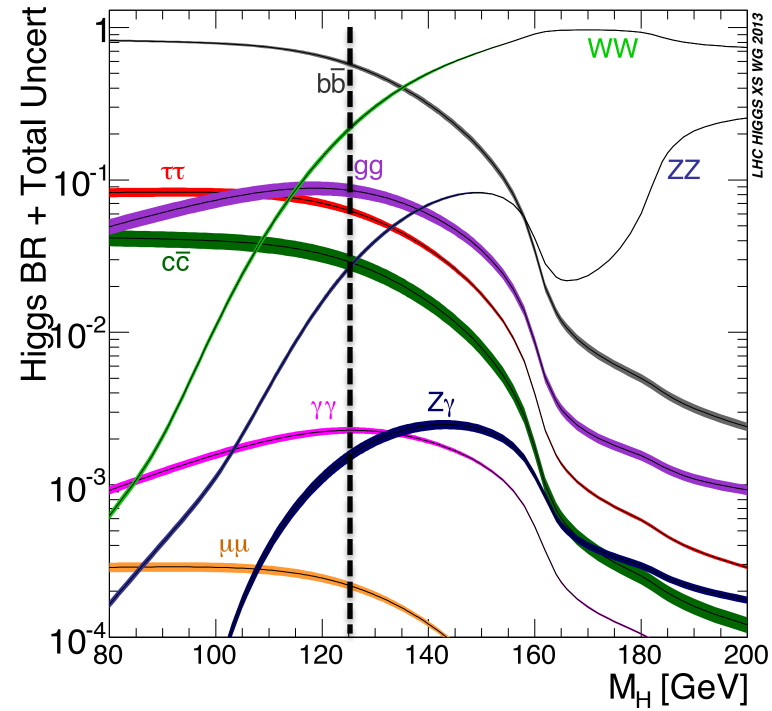
Higgs Phenomenology at the LHC

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSectionsFigures

Production Cross Section



Branching Fraction

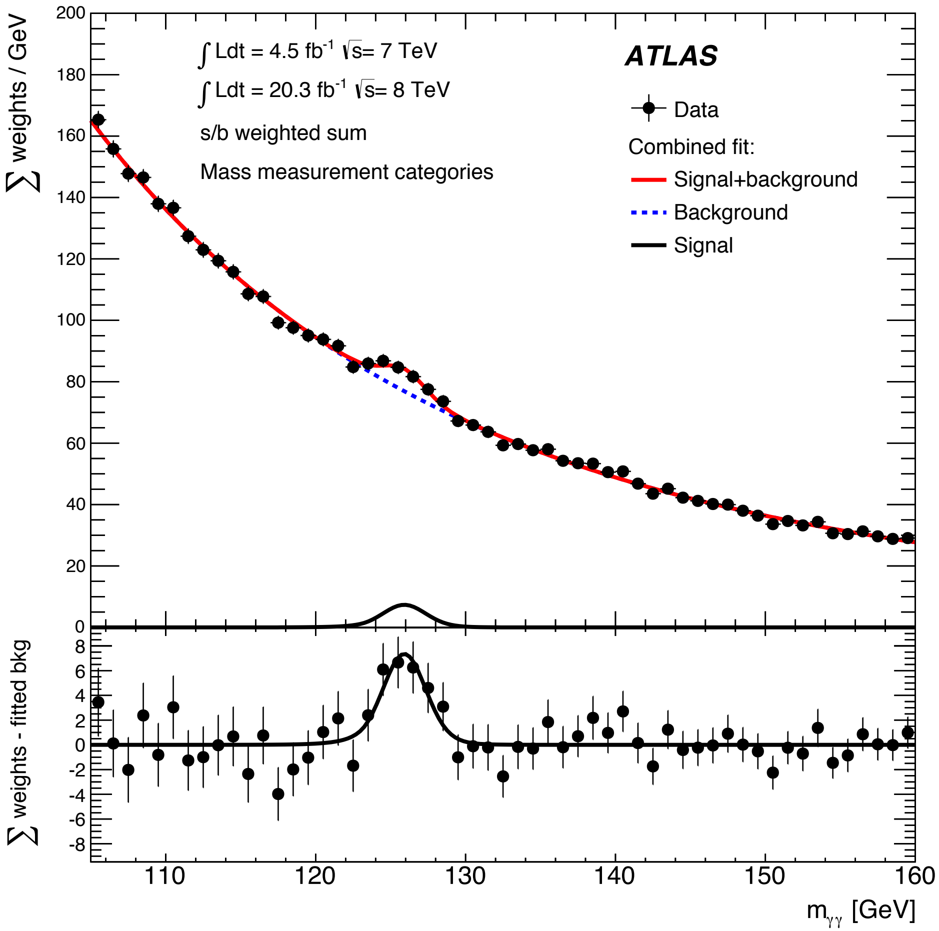


- Dominant production process is the ggF (87%) and VBF(7%).
- Dominant decay process is *H-> bb* (57%) and *H->WW** (22%).

Input for the Higgs Combination

arXiv:1406.3827

H -> γγ channel



γγ channel :

- **Spin/CP measurement**

  0^+ vs 2^+ (spin-1 hypothesis is excluded by Landau-Yang theorem)

- **Mass measurement**

  high energy resolution of photon

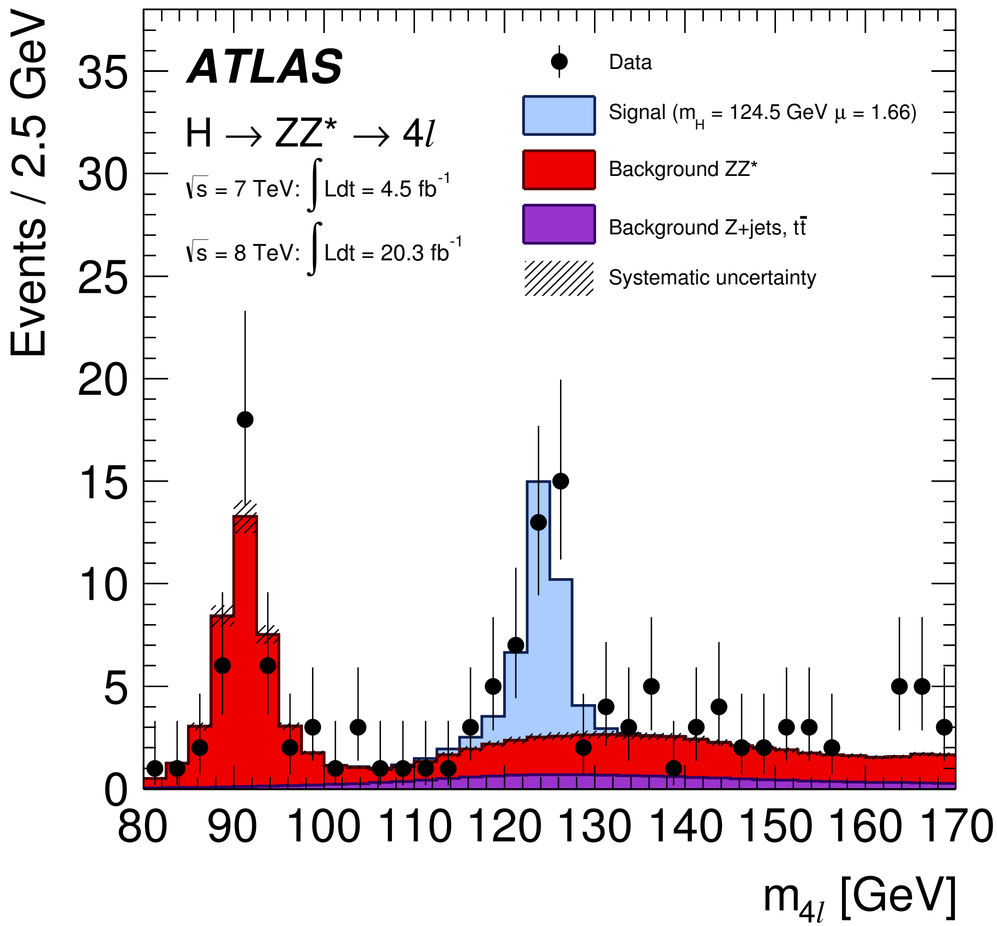
- **Coupling measurement**

  sensitive to loop-induced BSM

Input for the Higgs Combination

arXiv:1406.3827

H -> ZZ-> 4ℓ channel*



ZZ*->4ℓ channel :

- **Spin/CP measurement**

  0^+ vs 0^-, 0^+ vs $1^{+/-}$, 0^+ vs 2^+ test

- **Mass measurement**

  high energy resolution of leptons

- **Coupling measurement**

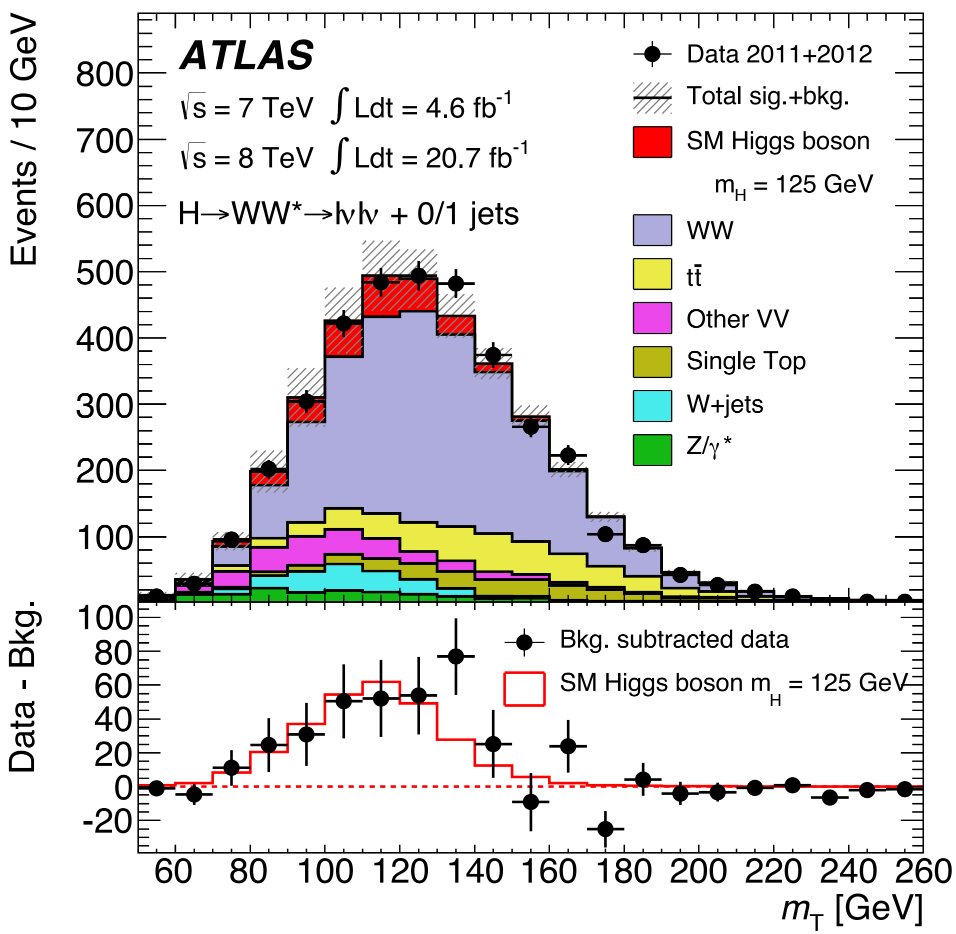
  sensitive to ggF production but

  poor stat for the VBF production

Input for the Higgs Combination

Phys. Lett. B 726 (2013) pp. 88-119

H -> WW*-> ℓνℓν channel



WW* channel :

- **Spin/CP measurement**

  0^+ vs $1^{+/-}$, 0^+ vs 2^+ test

- **Mass measurement**

  -> broad mass peak (two neutrinos)

- **Coupling measurement**

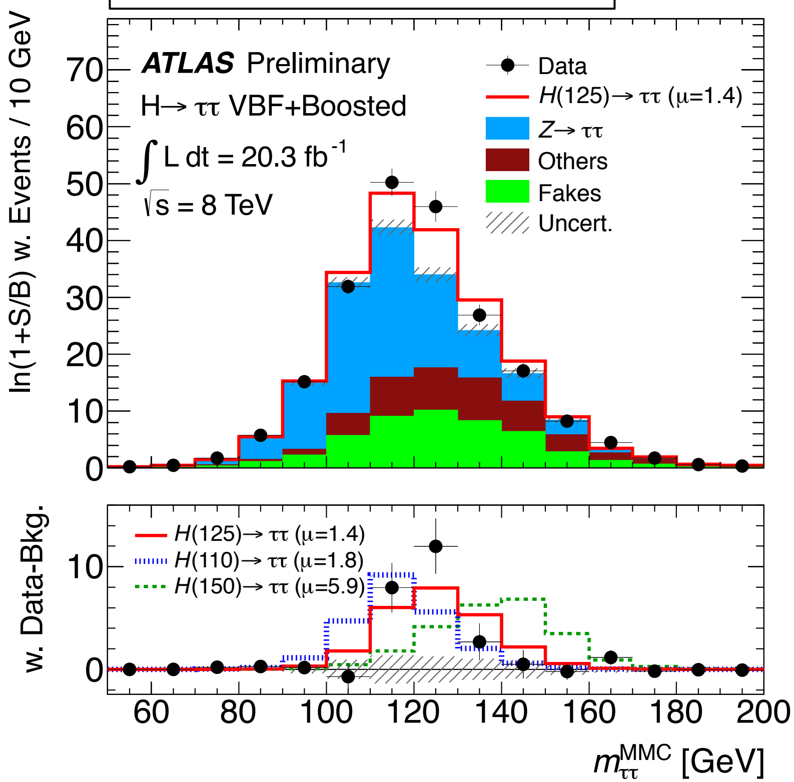
  - large branching fraction, thus

    sensitive to ggF and VBF production

Input for the Higgs Combination

H -> ττ channel

ATLAS-CONF-2013-108



H -> bb channel

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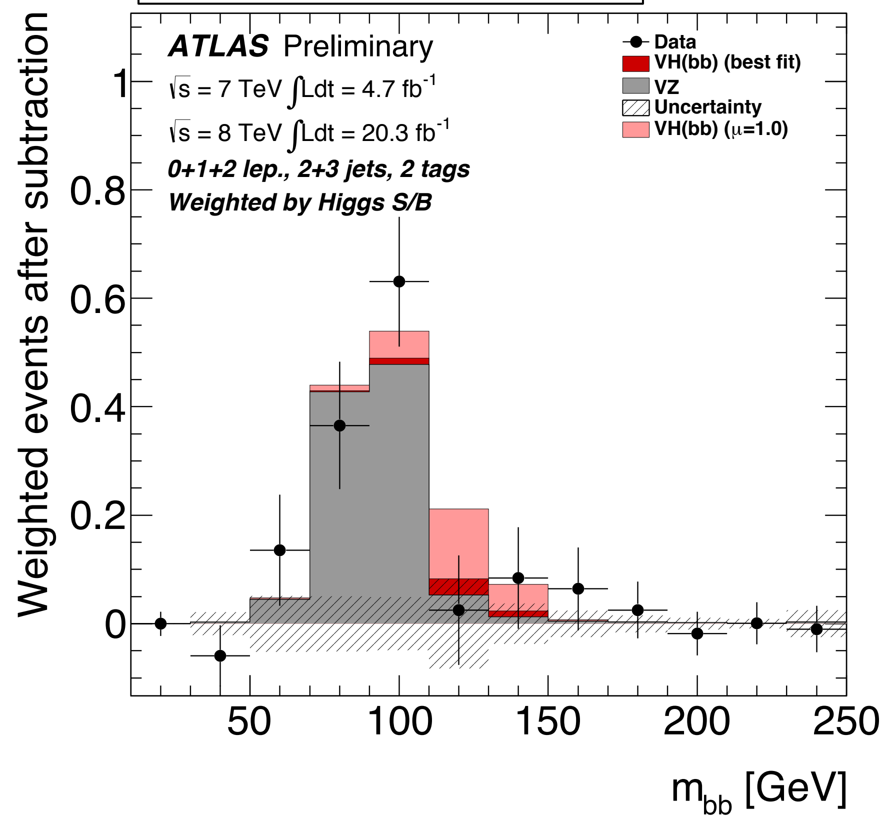


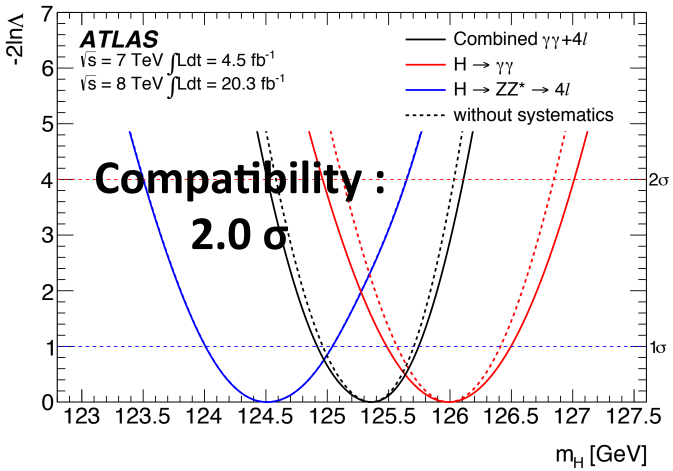
- Final discriminant (mass distribution) for *H->ττ* and *H->bb* channel.
- Fermion channels are mainly used for the coupling measurements.

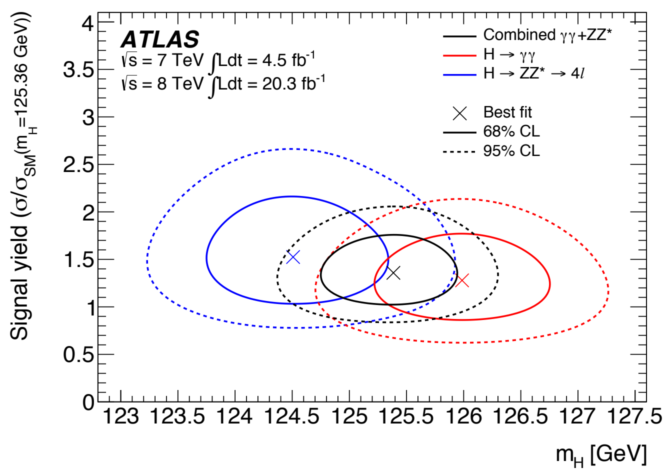
Mass Measurement

arXiv:1406.3827

New

- Measured mass is used as input to other property measurements
- Mass measurements using *γγ* and $ZZ^{*}\text{->}4\ell$ channels.





$$m_H = 125.36 \pm 0.37\,(\text{stat}) \pm 0.18\,(\text{syst})\ \text{GeV}$$
$$= 125.36 \pm 0.41\ \text{GeV}\ \text{(Combined)}$$

*Main syst. uncertainty is on energy scale (e.g. material effect/ non-linearity)

- Improved with respect to the previous result: 125.5 ± 0.2 (stat) $^{+0.5}_{-0.6}$ (syst) GeV, on better modeling of ATLAS detector geometry in simulation.

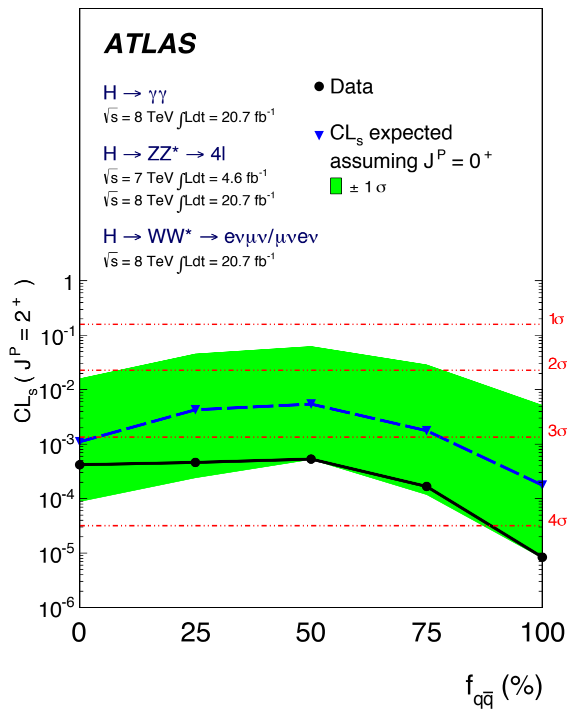
Spin-Parity Determination

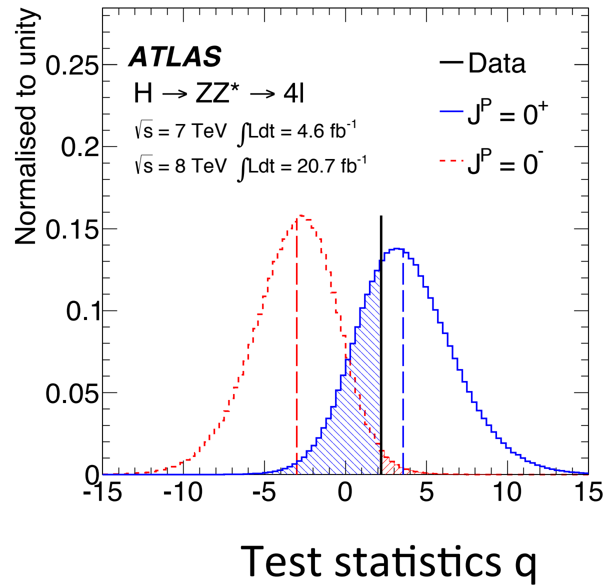
- SM Higgs boson is scalar particle, i.e. $J^P = 0^+$.
- Several alternative specific models, $J^P = 0^-, 1^+, 1^-, 2^+$, are tested against the SM Higgs $J^P = 0^+$ hypothesis, using angular and kinematic distributions in $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$, and $H \to WW^* \to \ell\nu\ell\nu$ channels.
- For spin-2, a model corresponds to a graviton-inspired tensor with minimal couplings to the SM particles is chosen (arXiv:1001.3396), gg-qq fraction has been scanned over entire range.

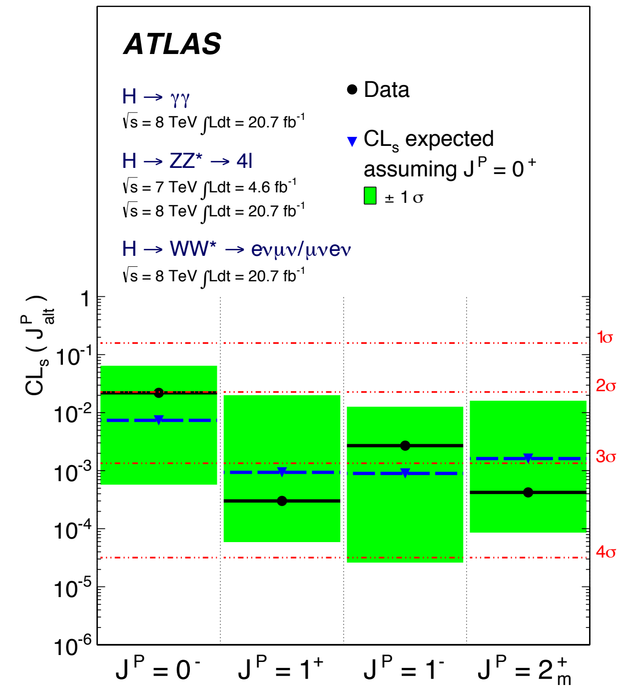
Hypothesis	$\gamma\gamma$	$ZZ^* \to 4\ell$	$WW^* \to \ell\nu\ell\nu$
vs 0^-	-	○	-
vs 1^+	-	○	○
vs 1^-	-	○	○
vs 2^+	○	○	○

Spin-Parity Determination

Phys. Lett. B 726 (2013), pp. 120-144







- Vary unknown qq fraction of production for spin-2.
- Other hypotheses have been excluded at 97.8 % CL.
- **Consistent with SM Higgs $J^P = 0^+$ hypothesis.**

Global Signal Strength

Signal strength μ defined as:

$\mu = \sigma \cdot BR / \sigma \cdot BR_{\text{theory (SM)}}$

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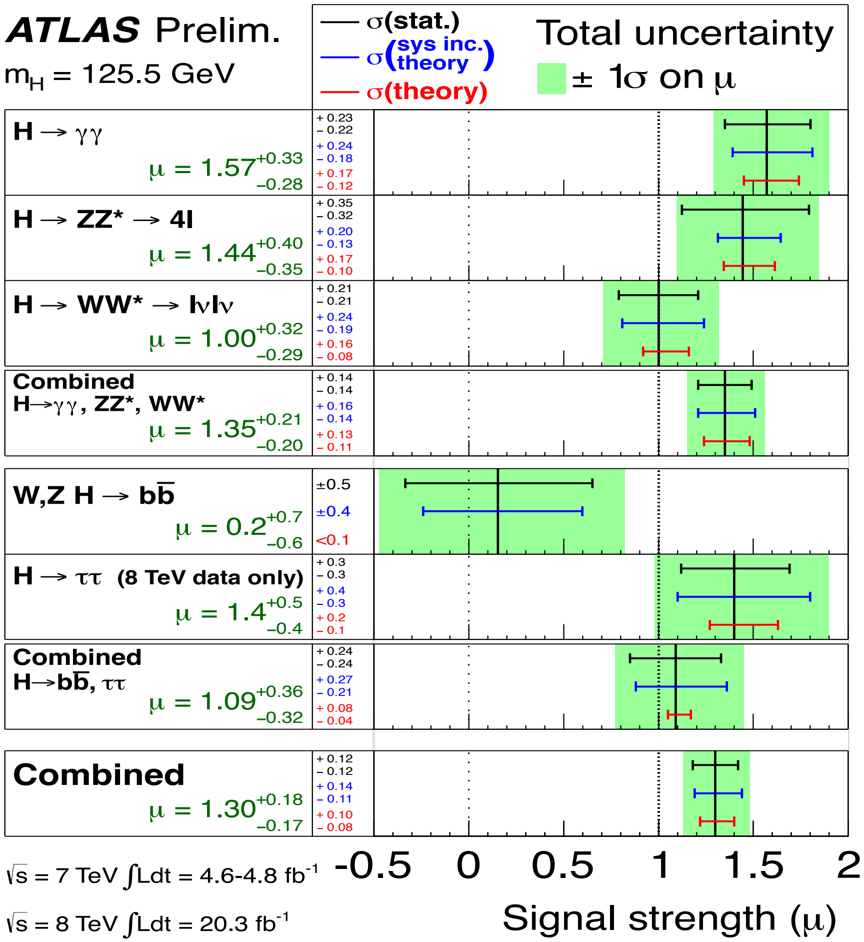
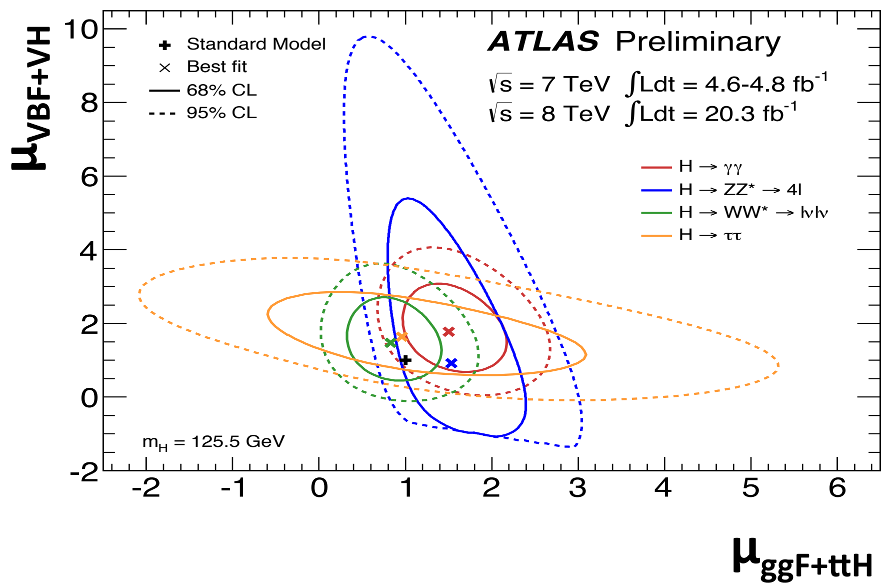


- Measured signal strength μ is :

$\mu_{diboson}$ = 1.35±0.20 , $\mu_{fermion}$ = 1.09±0.35

which corresponds to **3.7 σ** evidence for decay into fermions!

- Decompose into $\mu_{ggF+ttH}$ and μ_{VBF+VH}



- **Compatible with each other and the SM.**

$\mu_{VBF+VH}/\mu_{ggF+ttH}$ Ratio

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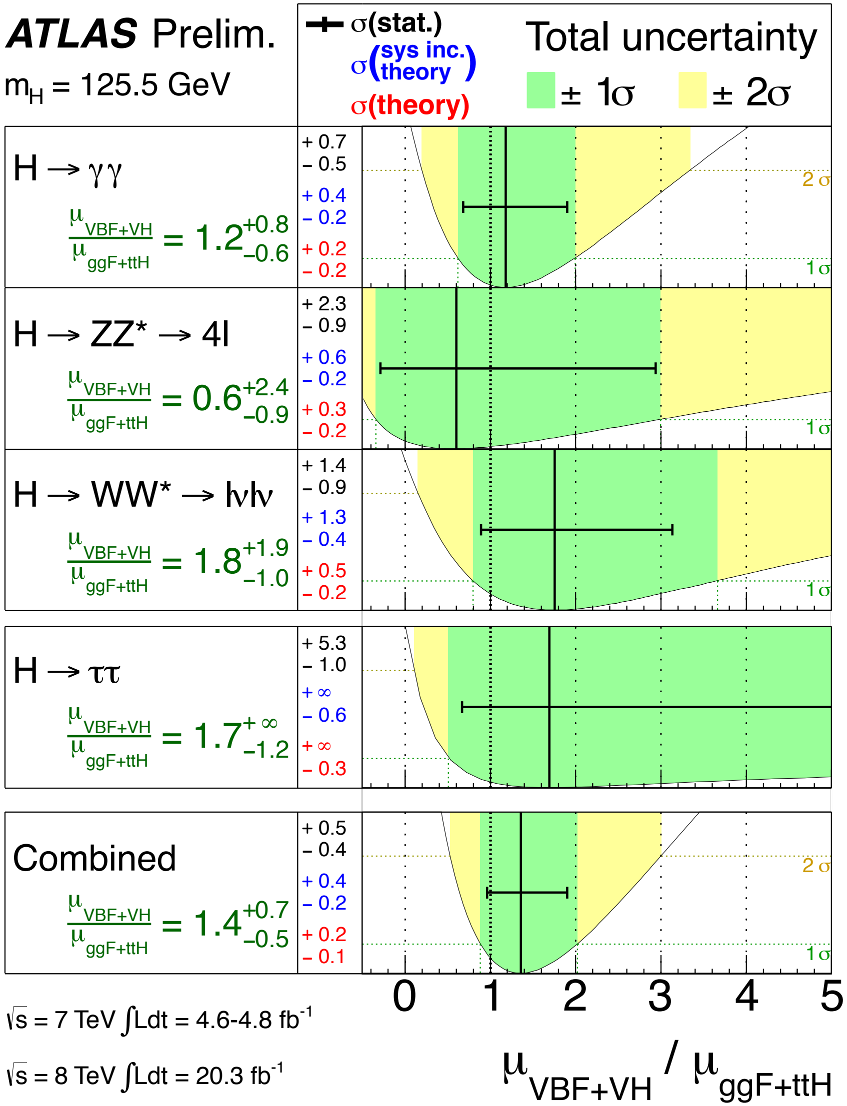


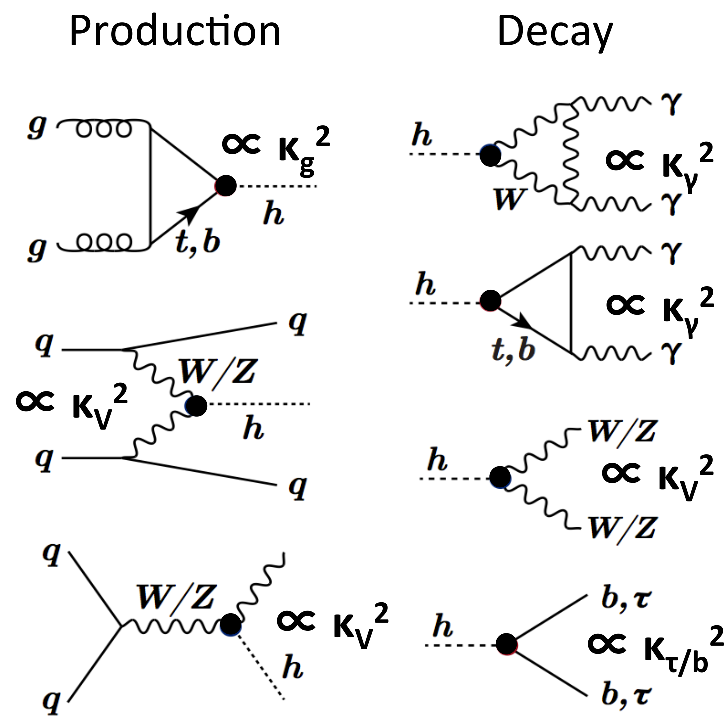
- $\mu_{VBF+VH}/\mu_{ggF+ttH}$ is meaningful observable, since the ratio doesn't depend on the decay.
- Infinite uncertainty on *H->ττ* due to little sensitivity to the ggF process.
- Test the sensitivity to the VBF production process profiling μ_{VH} :

$$\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}\,(\text{stat})\,^{+0.4}_{-0.3}\,(\text{sys})$$

which corresponds to 4.1 σ evidence for the VBF production process.

Coupling Measurement

- Signal strength (μ) -> difficult to treat production and decay independently.
- Try to extract couplings strength assuming LO SM-like diagrams, zero-width, and $J^P = 0^+$.
- Define scale factor κ for each coupling (e.g. κ_g, κ_γ, κ_W, κ_t …), where SM : $\kappa^2 = 1$, BSM : $\kappa^2 \neq 1$.



e.g.) **ggF -> *H* -> *γγ***

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}} \qquad \frac{\sigma \cdot \mathrm{B}(gg \to H \to \gamma\gamma)}{\sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{B}_{\mathrm{SM}}(H \to \gamma\gamma)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

* Allow BSM contribution in κ_H (total decay width) and κ_g and κ_γ loops.

Fermions vs (EW) Gauge bosons

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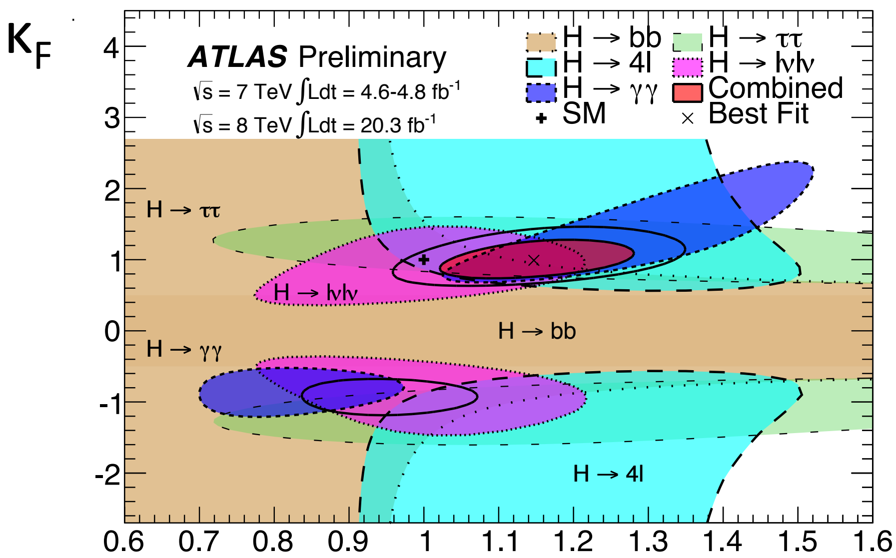
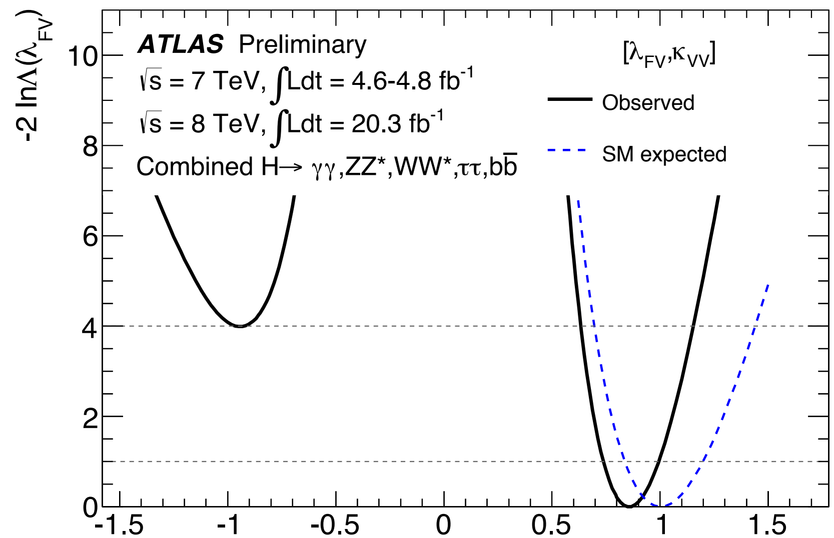
Assume common coupling strength for EW gauge bosons $\kappa_V = \kappa_W = \kappa_Z$,

and for fermions $\kappa_F = \kappa_g = \kappa_b = \kappa_t = \kappa_\tau = \kappa_Z$.





Combined result:

$$\kappa_V = 1.15 \pm 0.08$$
$$\kappa_F = 0.99^{+0.17}_{-0.15}.$$

$$\lambda_{FV} = 0.86^{+0.14}_{-0.12}$$

* No assumption made on total decay width

Symmetry Tests

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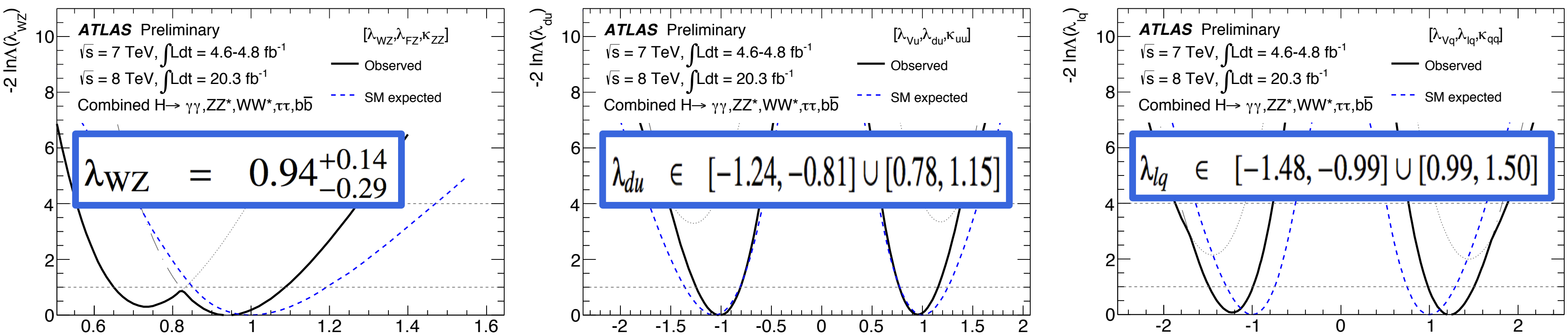
- Introduce three ratios $\lambda_{WZ} = \kappa_W / \kappa_Z$, $\lambda_{ud} = \kappa_u / \kappa_d$, $\lambda_{\ell q} = \kappa_\ell / \kappa_q$
- Test custodial symmetry and ρ parameter ($\rho = m_W^2/m_Z^2\cos\theta_W$) : λ_{WZ}
- Test symmetry of up-type (ggF) and down-type (ττ, bb) fermions (e.g. 2HDM) : λ_{ud}
- Test symmetry of quark and lepton (currently relying on *H->ττ*) : $\lambda_{\ell q}$



$\lambda_{WZ} = \kappa_W / \kappa_Z$ $\lambda_{ud} = \kappa_u / \kappa_d$ $\lambda_{\ell q} = \kappa_\ell / \kappa_q$

- No sensitivity to the sign for fermion test but couplings are in good agreement with the SM expectation.

Probing BSM using ggF->H->γγ

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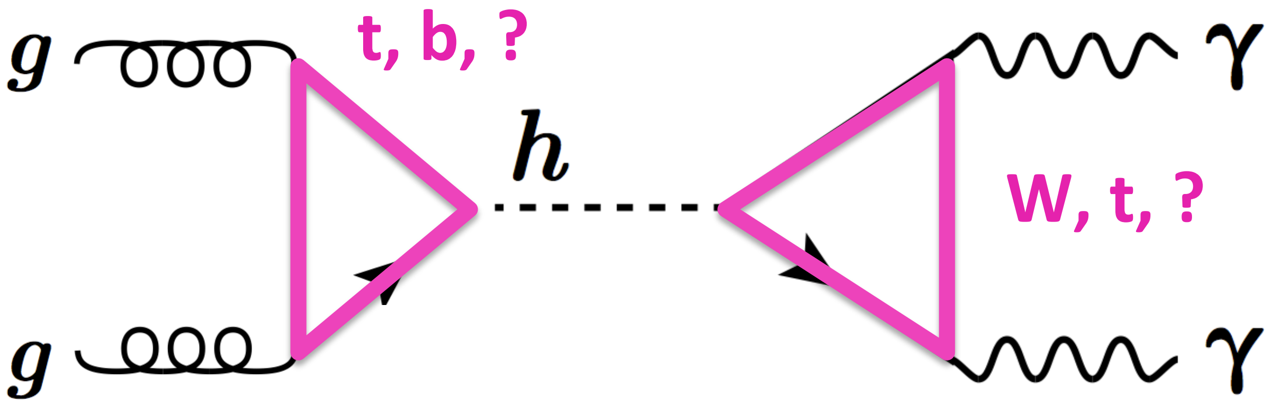
- *H->γγ* is sensitive to the BSM physics (e.g. H->invisibles or undetected particles) via loops.



- Case 1 : Testing the loops (float κ_g and κ_γ , other κ_i s are fixed to be the SM)
- Case 2 : Testing the width $\mathbf{BR_{iu}}$ **(branching fraction for BSM)** defined as :

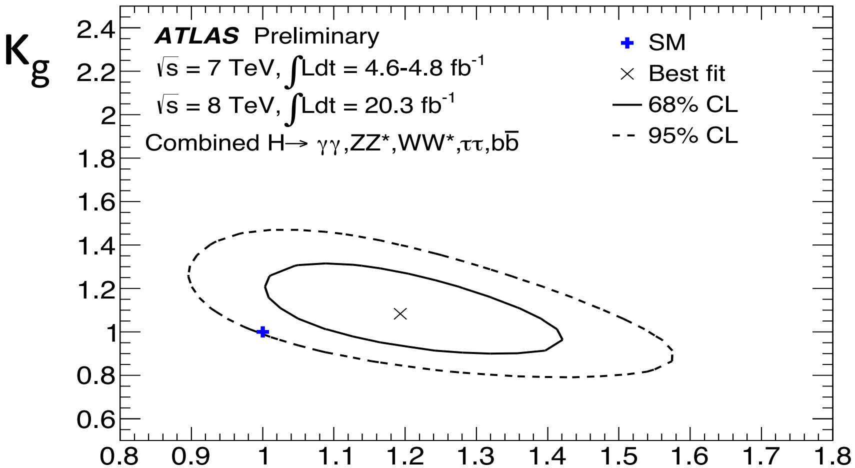
$$\Gamma_H = \frac{\kappa_H^2(\kappa_i)}{(1 - BR_{i.,u.})}\Gamma_H^{SM}$$

Fixing other Other κ_i s to be the SM value (=1) but floating κ_g and κ_γ .

Probing BSM

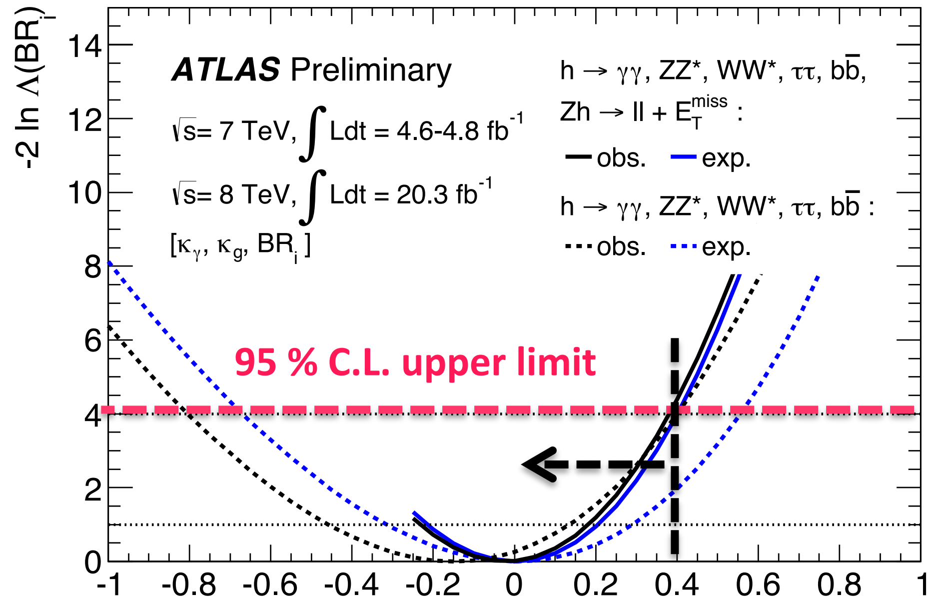
ATLAS-CONF-2014-009
ATLAS-CONF-2014-010

Case 1 (κ_g , κ_γ)



K_γ

Case 2 (κ_g , κ_γ , BR_{iu})

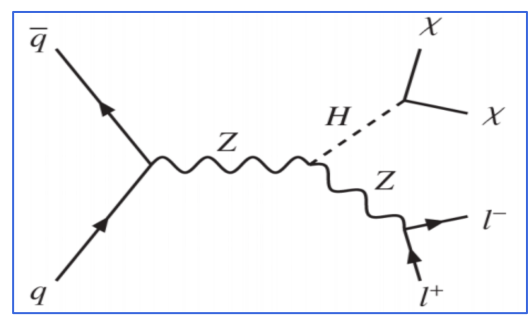


Case 1 :

$$\kappa_g = 1.08^{+0.15}_{-0.13}$$
$$\kappa_\gamma = 1.19^{+0.15}_{-0.12}$$

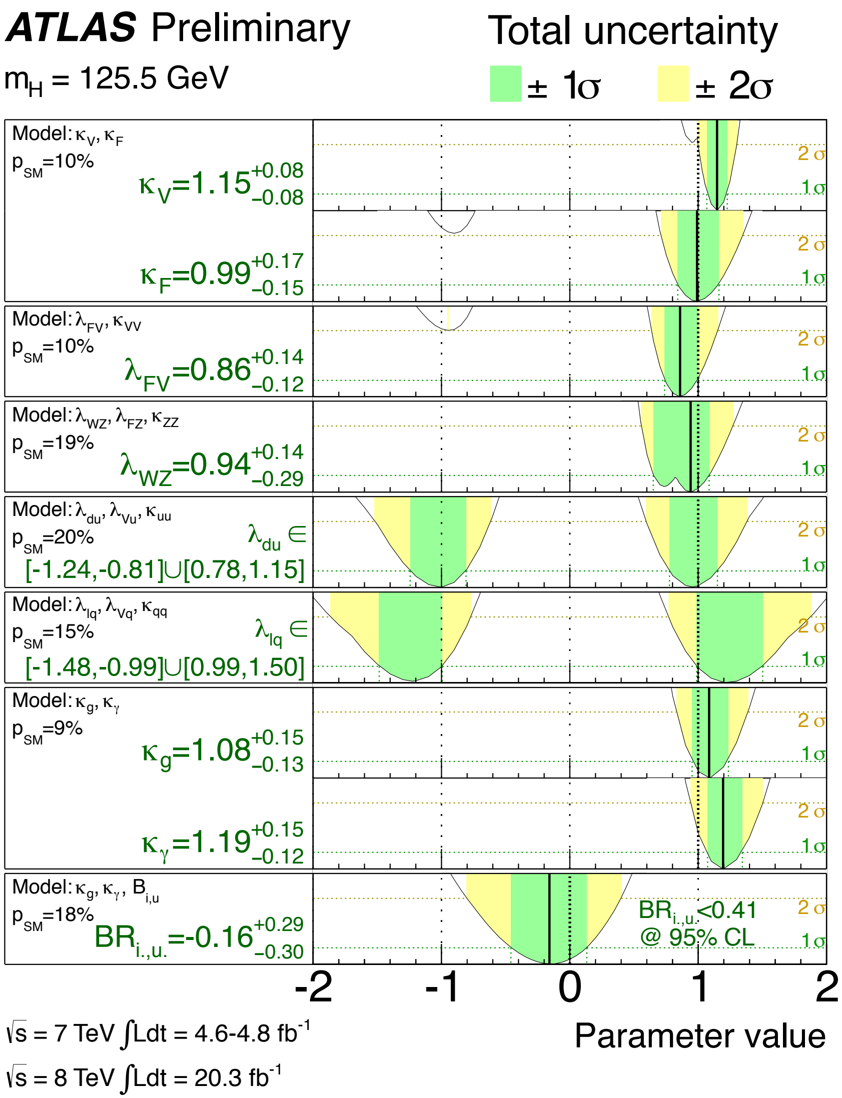
Case 2 : 95% CL upper limit :

BR_{iu} < 0.41 (BR_{iu} < 0.37 in Direct search using ZH->ℓℓ+MET.)



BR_{iu}

Summary



- Updated mass measurement : 125.36 ± 0.41 GeV.
- Spin-parity of the new boson has been tested and found to be consistent with the SM Higgs boson.
- Coupling fit in the context of the LO SM-like framework has been performed.
- **No significant deviation from the SM so far…**
- **More results in Run-1 being finalized : Stay tuned!**
- **More data available in Run-2**


THANKS
FOR
LISTENING

Bonus Slides

Spin-Parity Determination

The SM Higgs boson: JP = 0^+

- The strategy is to falsify the other hypothesis (0^-, 1^+, 1^-, 2^+), and demonstrate the consistency of the SM hypothesis
  - Spin 0: only gluon fusion (gg) production is considered
  - Spin 1: only quark-antiquark (qq) annihilation is considered (Landau-Yan Theorem)
  - Spin 2: a model corresponds to a graviton-inspired tensor with minimal couplings to SM particles is chosen (arXiv:1001.3396). gg- qq fraction has been scanned over entire range
- See distributions of spin & parity sensitive variables which preserve the discrimination against various background

Global Signal Strength

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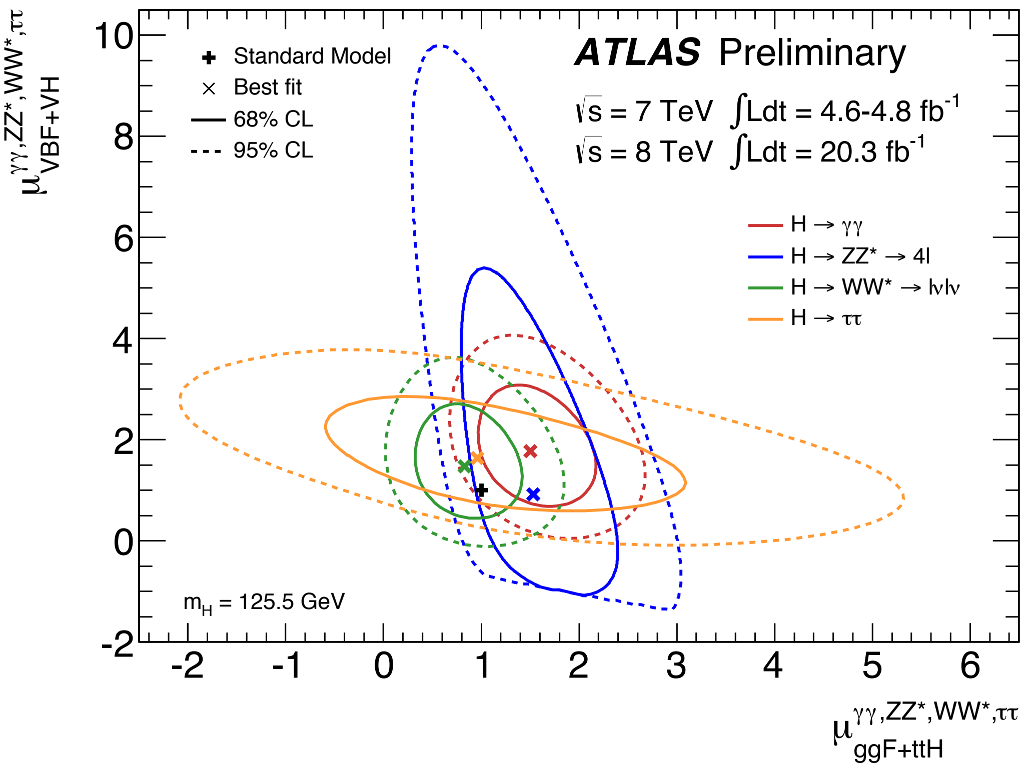

- Signal strength μ is decomposed into two production processes, $\mu_{ggF+ttH}$ and μ_{VBF+VH} , fixing the cross section ratios of ggF/ttH and VBF/VH.
- 4 channels are compatible with each other and the SM expectation.

WIMP Search

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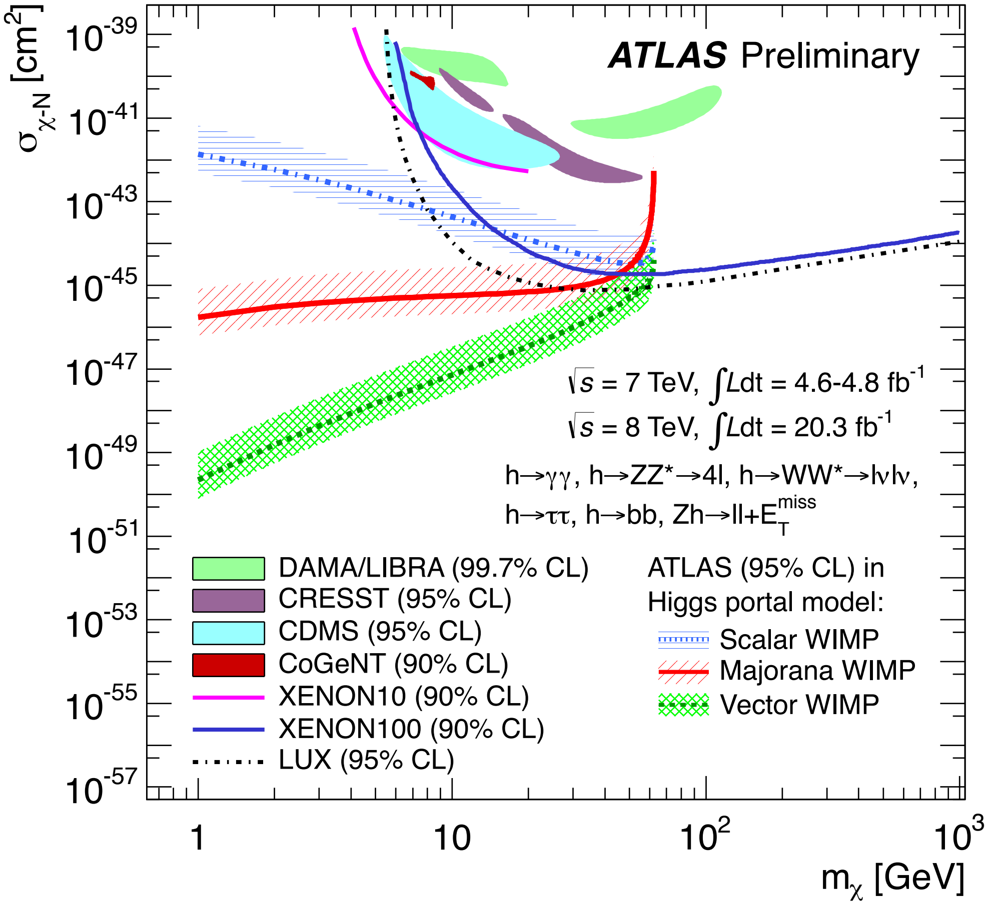


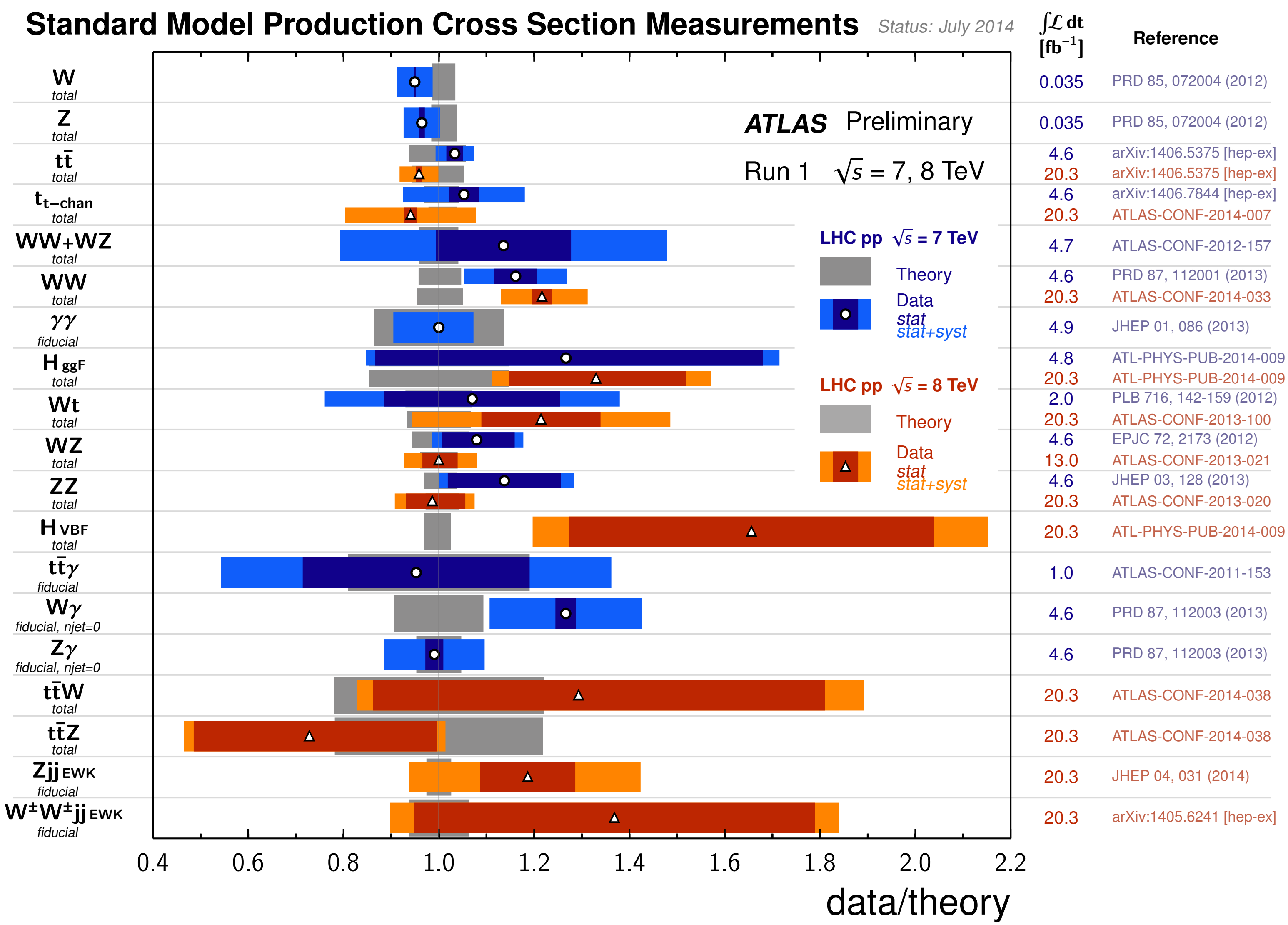
$$\text{scalar } S: \quad \sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$$

$$\text{fermion } f: \quad \sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$$

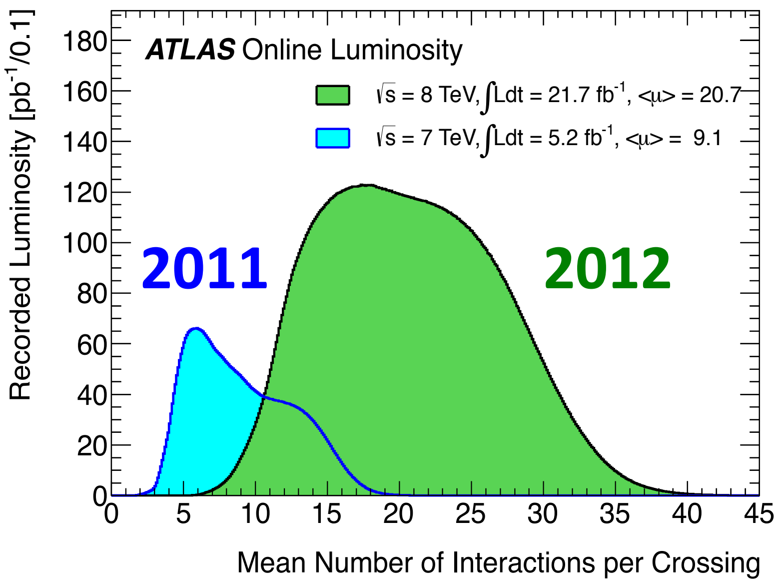
$$\text{vector } V: \quad \sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2},$$

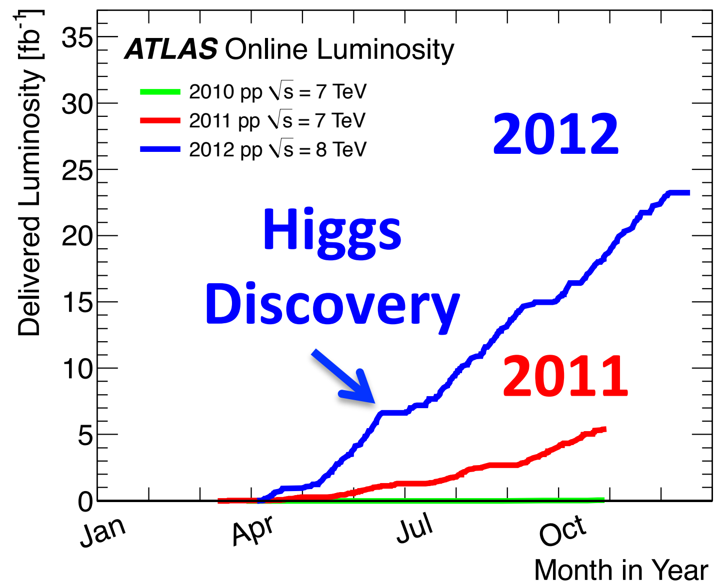
- Made stronger upper limit on cross section at low m_χ region (m_χ<63 GeV)

Summary of SM cross section



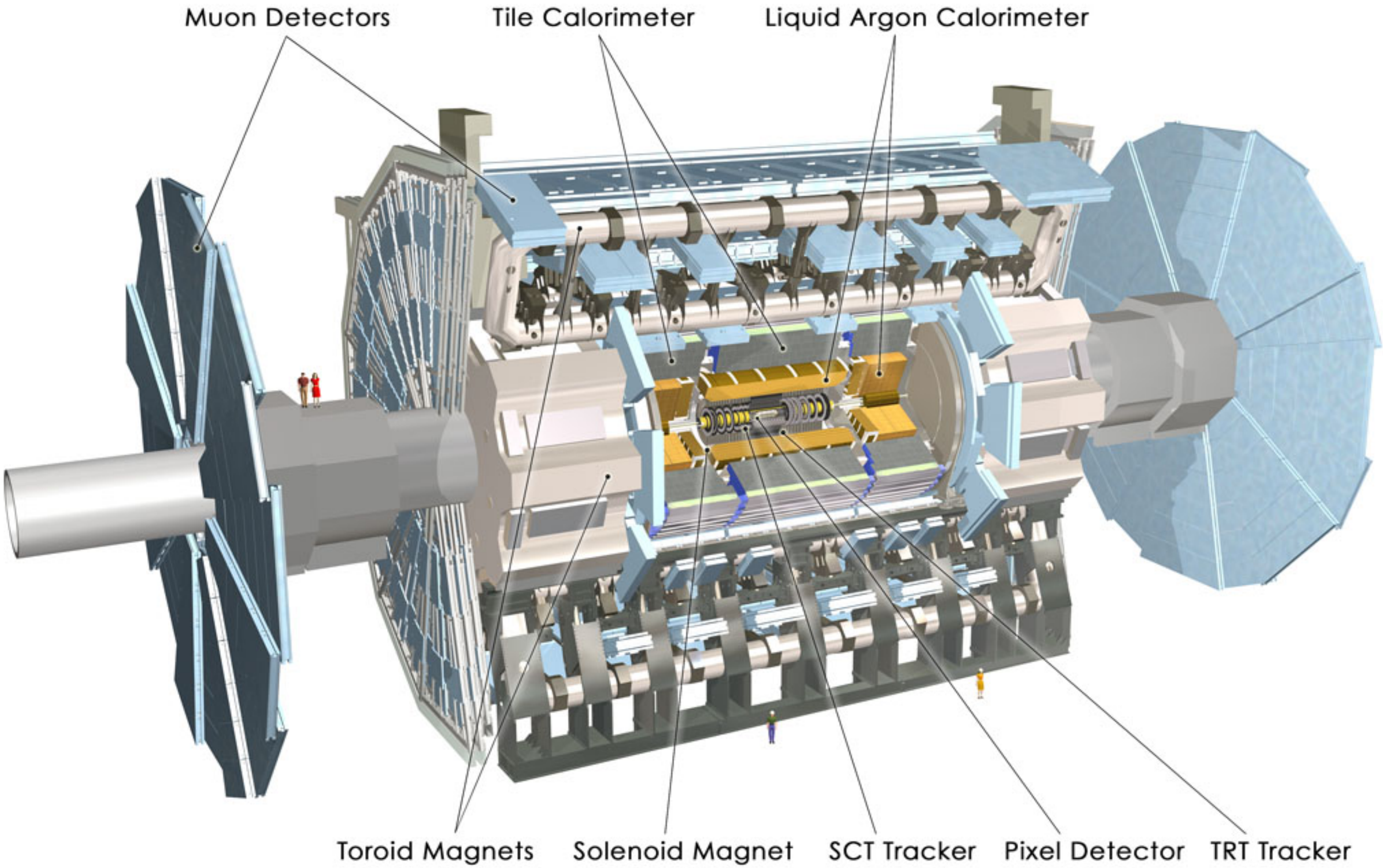
Data-taking during 2011-2012





4.7 fb^{-1} of 7TeV data and 20.7 fb^{-1} of 8TeV data are used for the analyses.

ATLAS Detector



ATLAS Detector

The ATLAS detector was designed with discovery of the Higgs boson in mind.

- Precise measurement of the charged particles by inner detectors.
- Identification of electrons and photons against QCD jets.
- Hermetic calorimeter and good energy resolution.
    - e, γ : 1.5 %, Muon : 2-3 %, and jets : 8 % @ p_T = 100 GeV
- Muon reconstruction and trigger by muon spectrometer.