Combination of couplings of the Higgs boson by the ATLAS experiment with Run 1 data

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On behalf of the ATLAS collaboration

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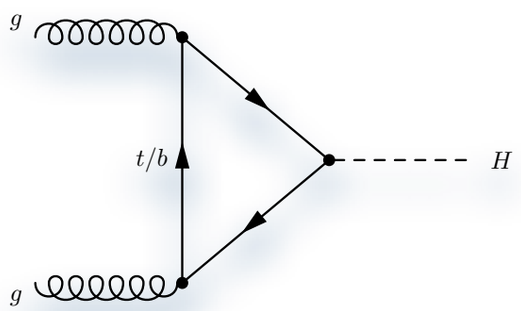
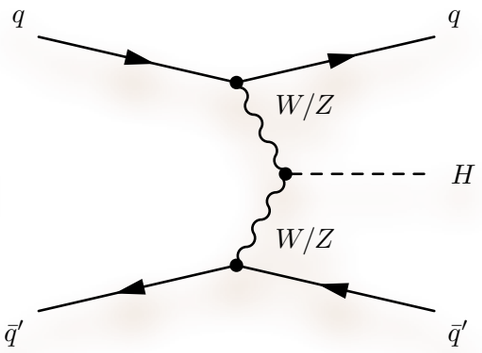
SM Higgs production and decay at LHC

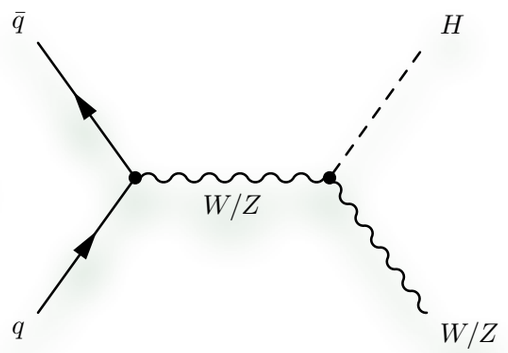
ggH



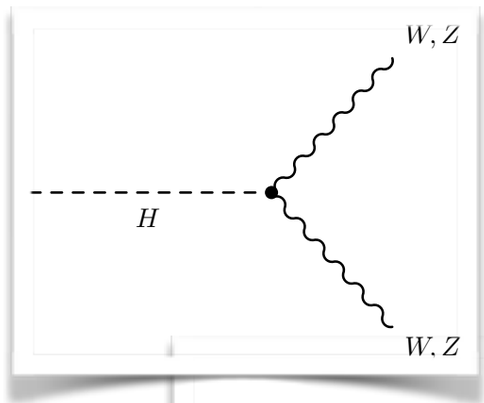
VBF



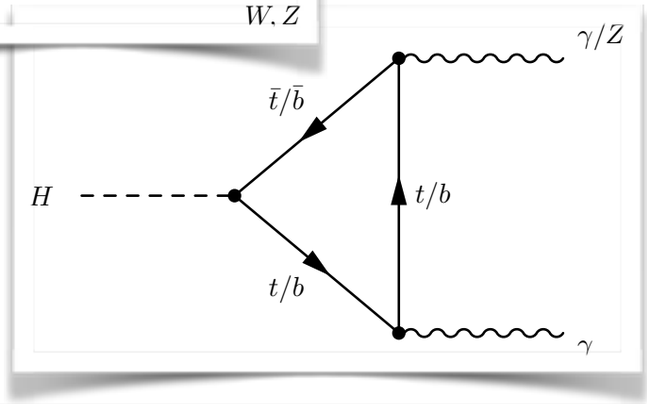
VH

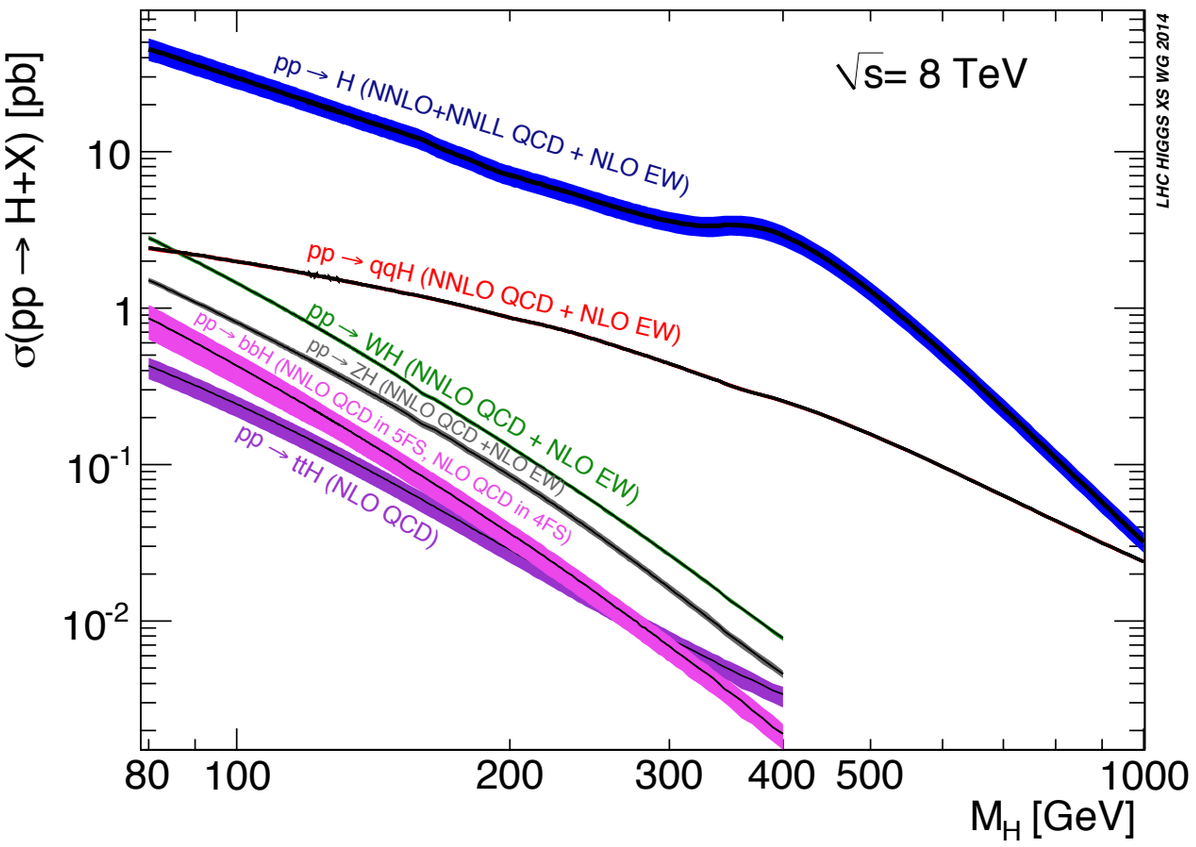


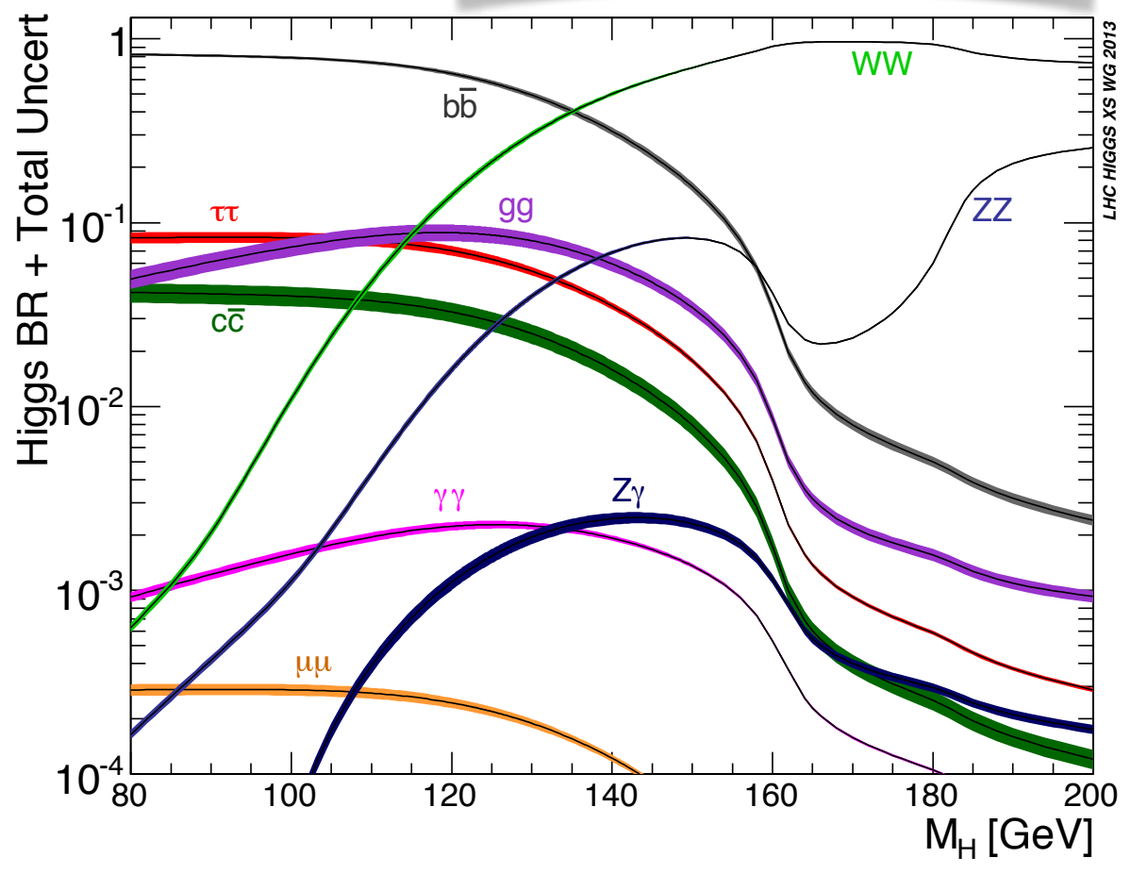
HZZ, HWW



Hγγ, HZγ







- m_H:fundamental parameter of the SM with no expected value
- Expected limit: somewhere below ~1 TeV

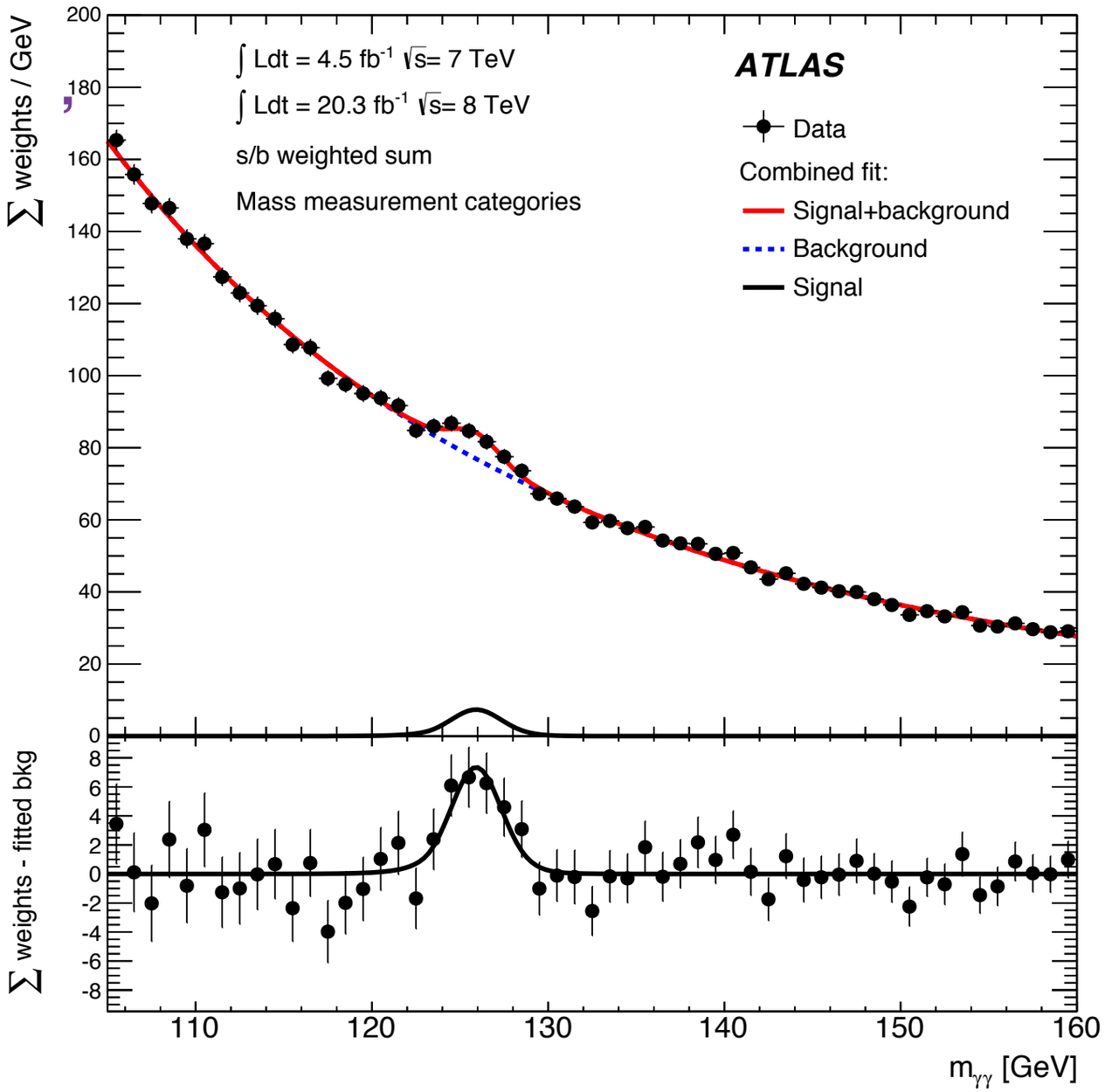
Higgs boson mass measurement

- Input for testing SM Higgs coupling structure

H → γγ channel

Phys. Rev. D. 90, 052004 (2014)

ATLAS m_H measurement using
H → γγ and *H →ZZ*→ 4l decay channels.*



Mass measurement method

Simultaneously fit of mass spectra for ten categories and at 7 and 8TeV.

Signal modeling

Crystal Ball + Gaussian

Background modeling and estimation

- Fit to diphoton mass distribution in the data.
- Exponential functional of first/ second-order polynomial

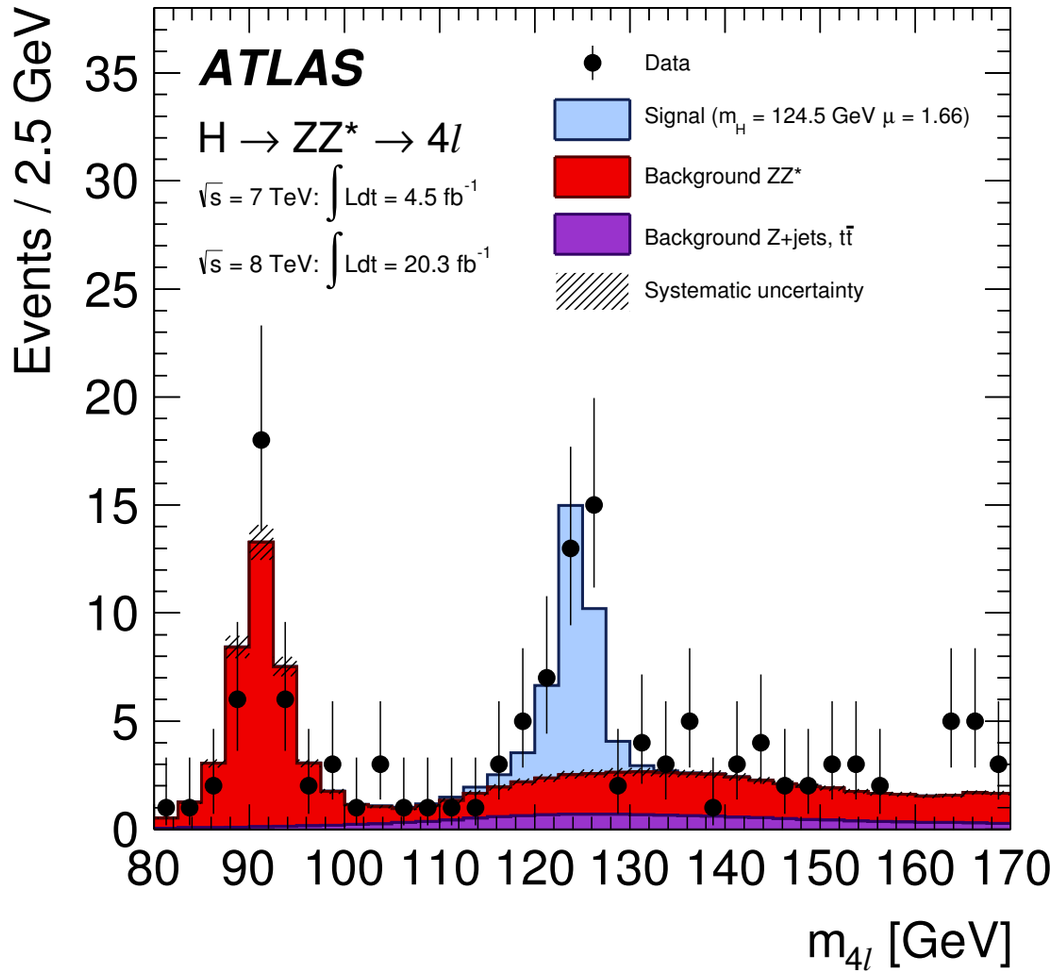
Main systematics:

Photon energy scale uncertainties

Result from H → γγ
m_H=125.98±0.50 GeV
=125.98±0.42(stat.)±0.28(syst.)GeV

Higgs boson mass measurement $H \to ZZ^* \to 4l$ channel

- Input for testing SM Higgs coupling structure



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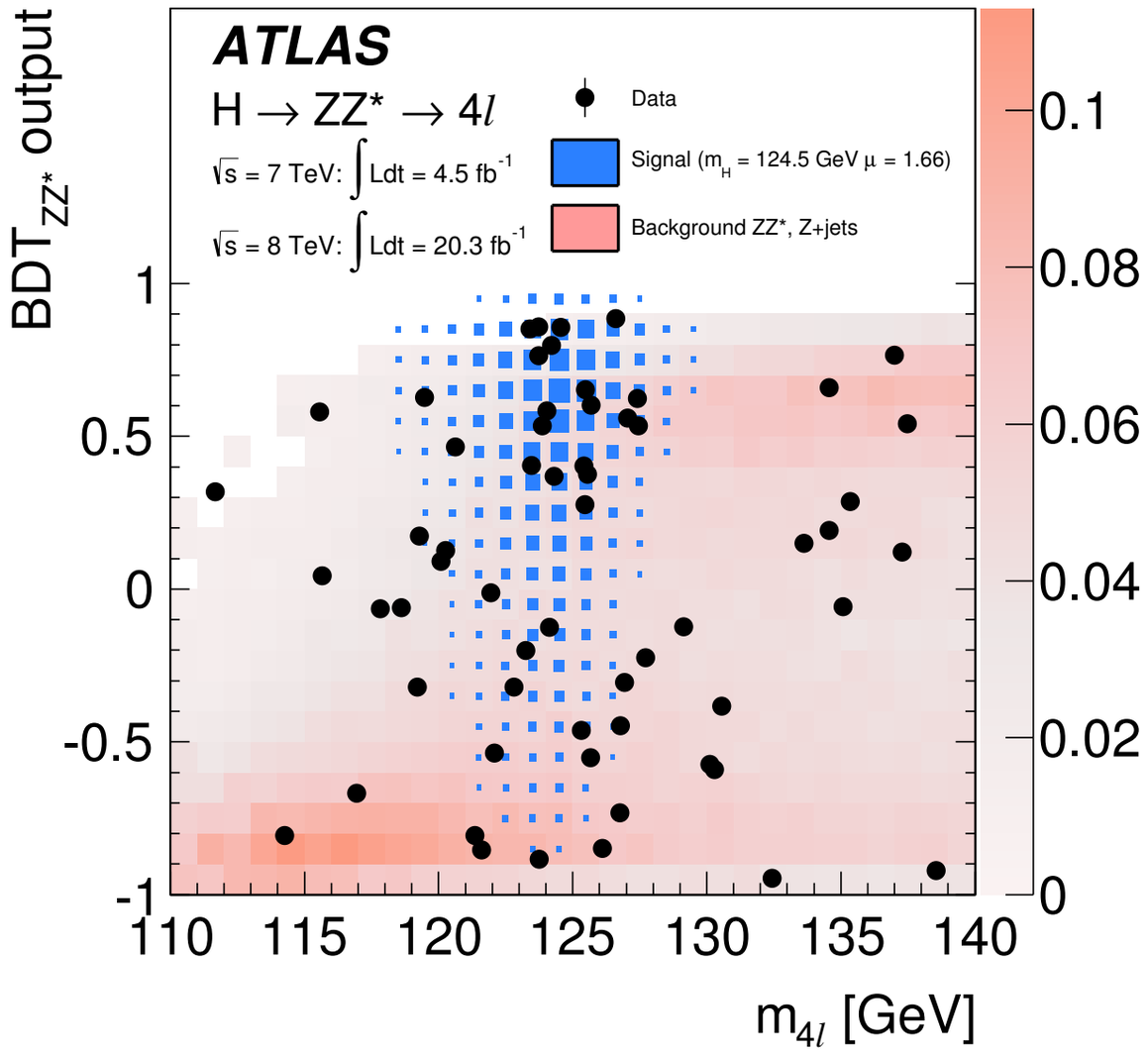


Mass measurement method

2D fit to **m_{4l}** and **BDT_{ZZ^*} output**

- **Multivariate discriminant BDT_{ZZ^*}** : reduce impact from main background ZZ*

Variables used in training

$$p_{T,4\ell},\ \eta_{4\ell},\ D_{ZZ^*} = \ln\left(\frac{|\mathcal{M}_{sig}|^2}{|\mathcal{M}_{ZZ}|^2}\right)$$

Result from $H \to ZZ^* \to 4l$

m_H=124.51±0.52 GeV

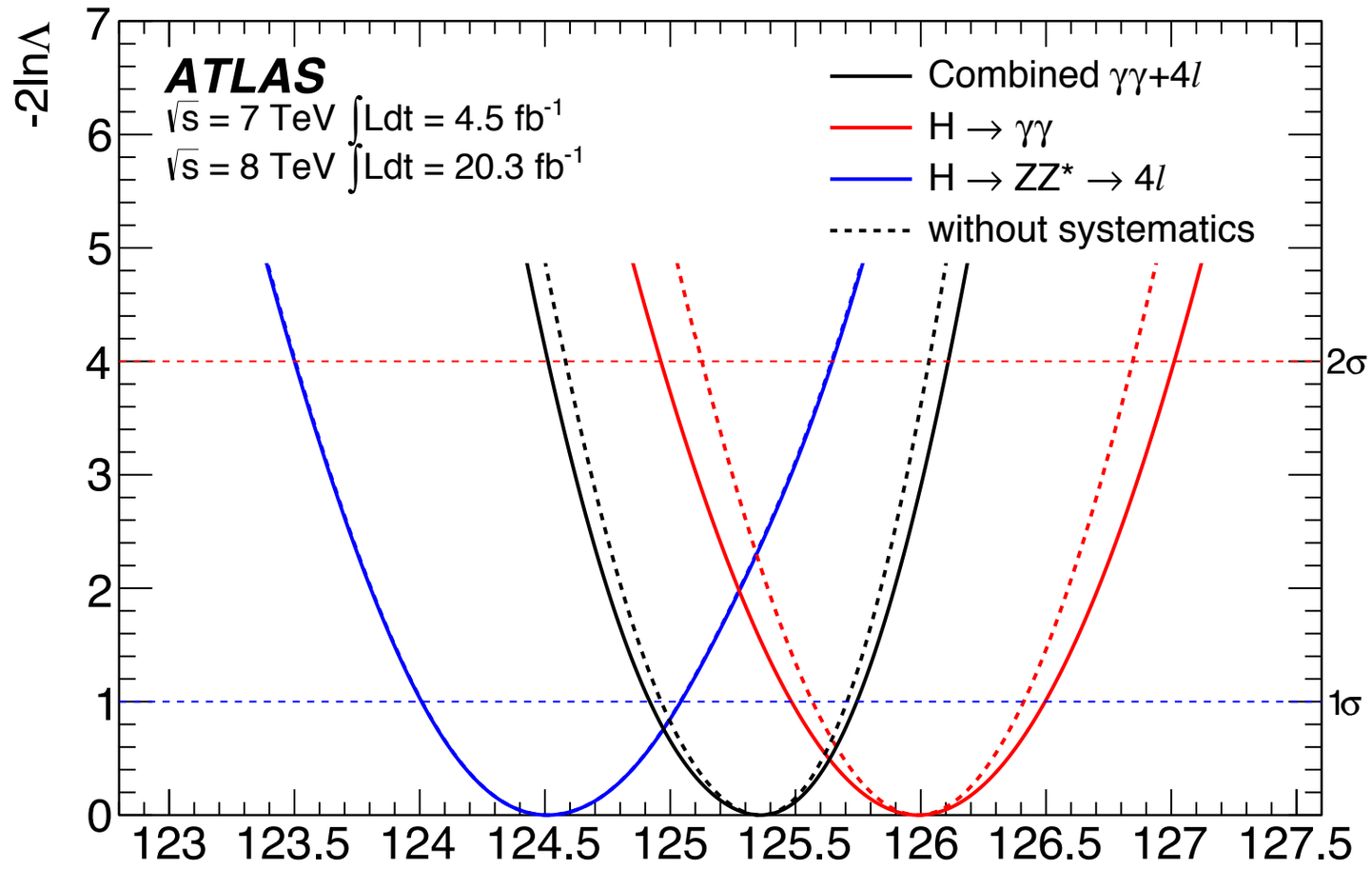
=124.51±0.52(stat.)±0.06(syst.)GeV

Combined mass measurement result

- **Model independent measurement**: Signal strength for γγ and 4l, $\mu_{\gamma\gamma}$ and μ_{4l} , allowed to vary independently.
- Compatibility of the measurements in H →γγ and H →ZZ→4l channels at 2**σ** level

Signal strength definition
$\mu=(\sigma\times BR)/(\sigma_{SM}\times BR_{SM})$

Phys. Rev. D. 90, 052004 (2014)
PRL114,191803(2015)

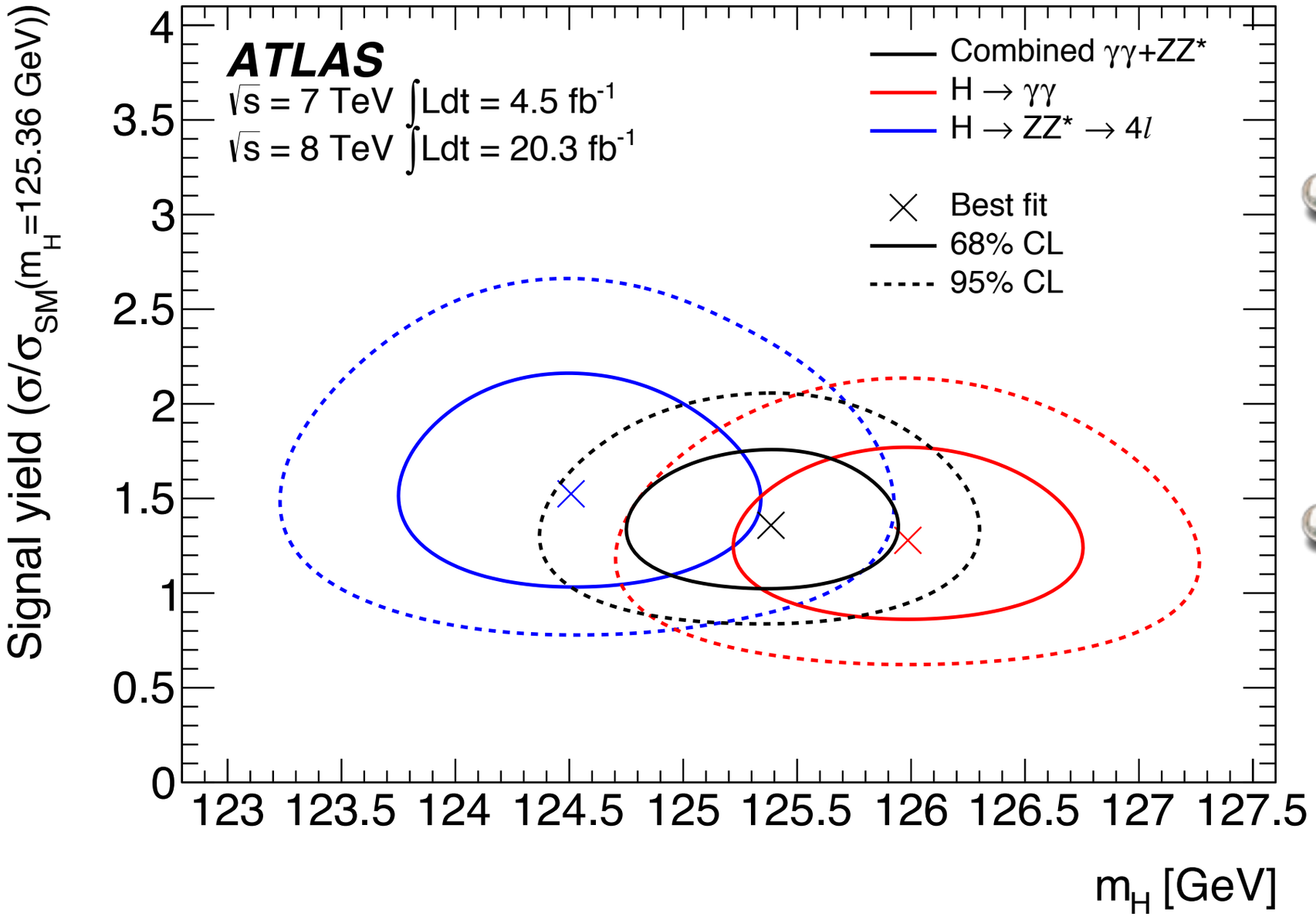


ATLAS *Combined measurement*
m_H = 125.36 ± 0.41 GeV
= 125.36 ± 0.37(stat.) ± 0.18(syst.)GeV

Talk by Prof Pascal VANLAER link

ATLAS+CMS combined *measurement*
m_H = 125.09 ± 0.24 GeV
= 125.09 ± 0.21(stat.) ± 0.11(syst.)GeV

Combined mass measurement result



- No significant correlation between the two fitted variables observed
- confirming the model-independence of the mass measurement

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Direct limit on the total width

Method: limit set from the observed width of the invariant mass peak

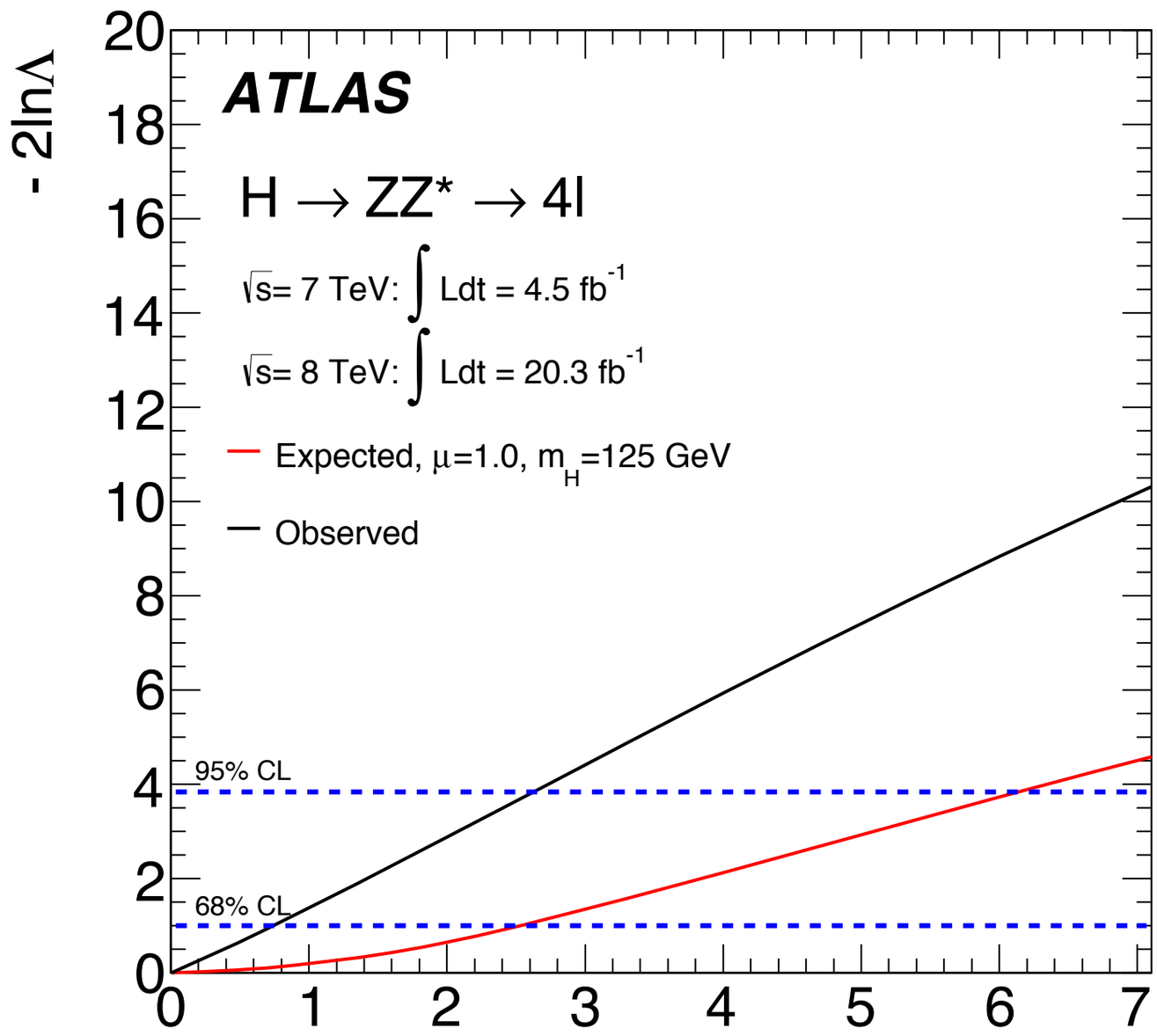
Signal model:

- **H →γγ: Convolution of detector resolution with a non relative Breit-Wigner distribution**
- **H →ZZ→4l:per-event resolution model**

Observed 95% CL upper limit on the width:

H →γγ: 5.0 GeV

H →ZZ→4l: 2.6 GeV



Talk by Prof Pascal VANLAER link

Indirect limit on the total width from off-shell Higgs boson measurement

Phys. Rev. D. 90, 052004 (2014)

Measurement of the Higgs boson production and decay rates and coupling strength

- **Measured at ALTAS combined mass of 125.36 GeV**

- **The study combines the following specific analysis:**
  - **H →γγ, ZZ*, WW*, Zγ, $b\bar{b}$, $\tau\tau$ and μμ decay channels.**
  - **Searches for ttH production (*talk by Yang Qin Link*)**
  - **Measurements of off-shell Higgs boson production**

(Talk by Prof Pascal VANLAER link)

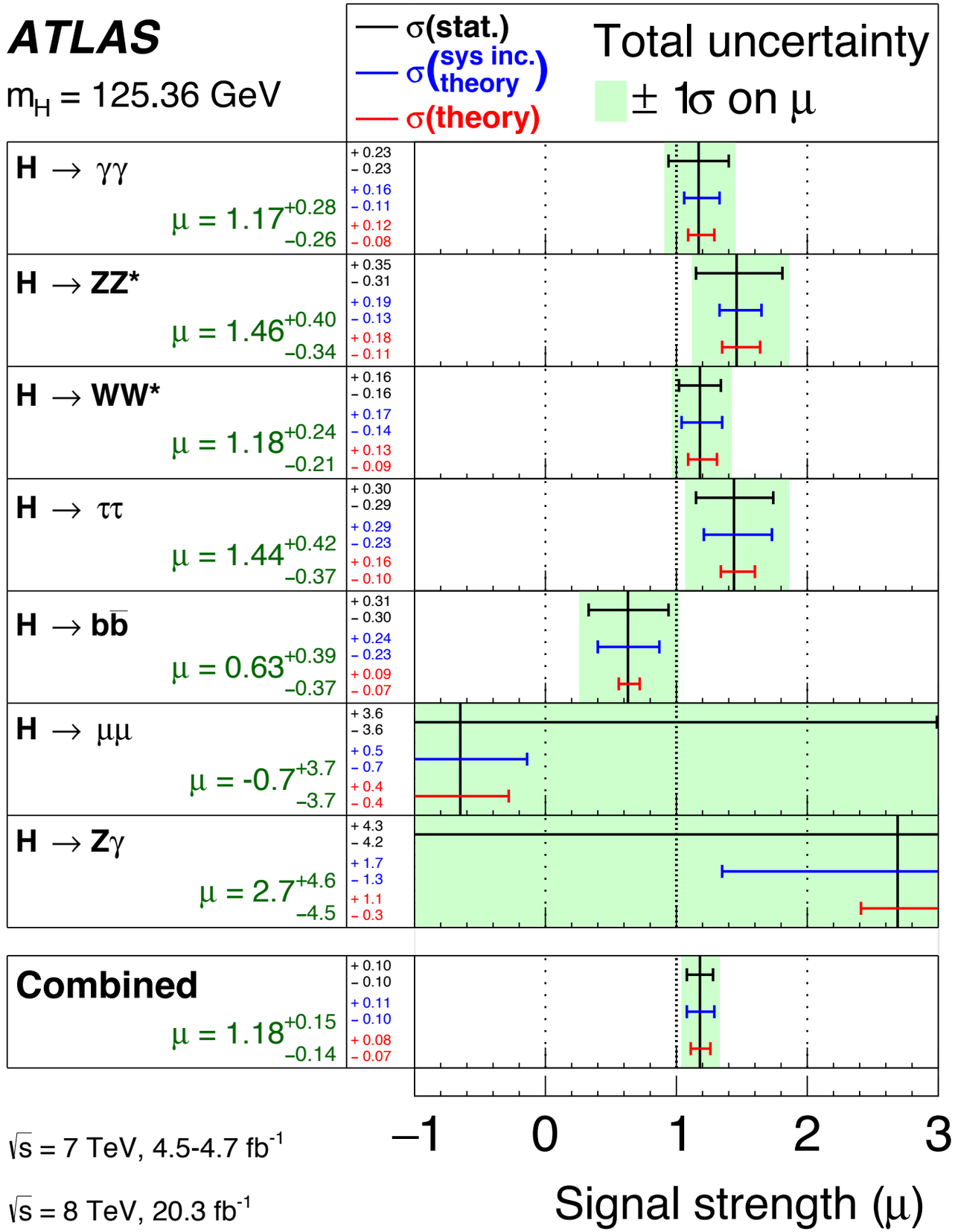
Rate measurements

- Assuming a multiplier common to all decay modes
- combined measurement of signal strengths compatible with SM expectation
  p-value =18%
- Combined result:

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

$$= 1.18 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})\ ^{+0.08}_{-0.07}\,(\text{theo.})$$

arXiv:1507.04548



Decouple different Higgs production modes

arXiv:1507.04548

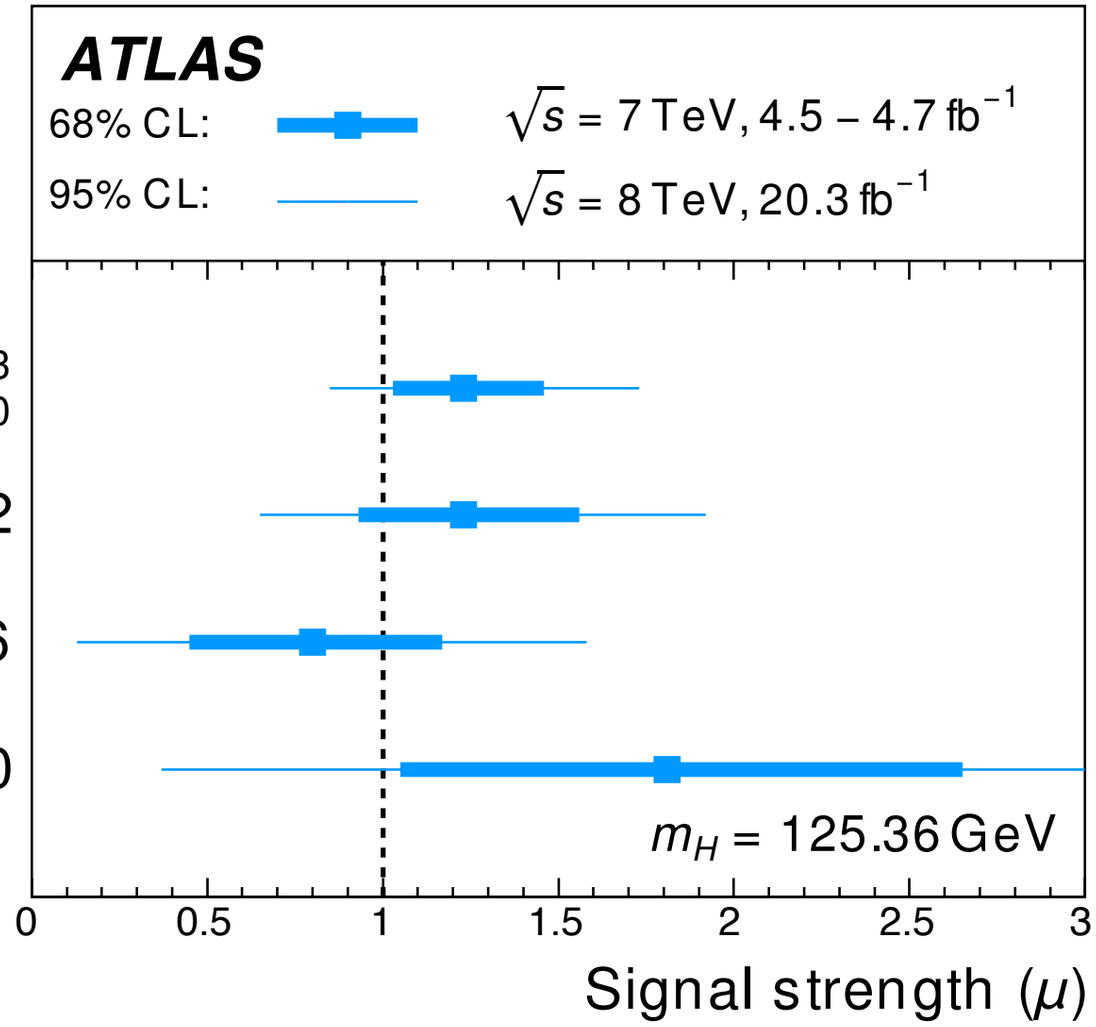
- Assuming SM Higgs decay branching ratio
- Compatibility of the SM hypothesis at 1**σ** level

$\mu_{ggF} = 1.23^{+0.23}_{-0.20}$

$\mu_{VBF} = 1.23 \pm 0.32$

$\mu_{VH} = 0.80 \pm 0.36$

$\mu_{ttH} = 1.81 \pm 0.80$



- Total measured Higgs production cross sections

$\sigma_H(7\,\text{TeV}) = 22.1\,^{+7.4}_{-6.0}\,\text{pb} = 22.1\,^{+6.7}_{-5.3}\,(\text{stat.})\,^{+2.7}_{-2.3}\,(\text{syst.})\,^{+1.9}_{-1.4}\,(\text{theo.})\,\text{pb}$

$\sigma_H(8\,\text{TeV}) = 27.7 \pm 3.7\,\text{pb} = 27.7 \pm 3.0\,(\text{stat.})\,^{+2.0}_{-1.7}\,(\text{syst.})\,^{+1.2}_{-0.9}\,(\text{theo.})\,\text{pb}$

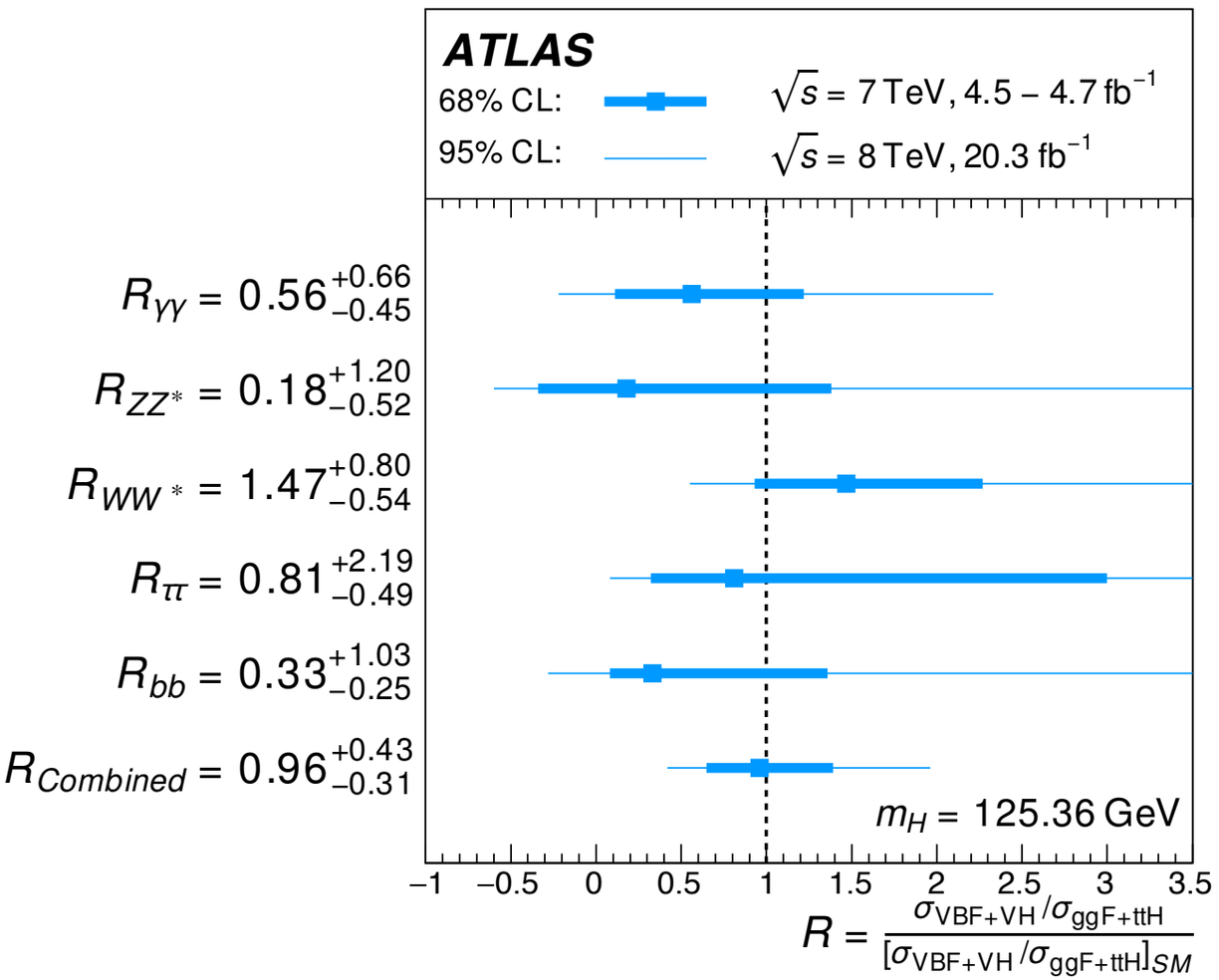
Theoretical predictions

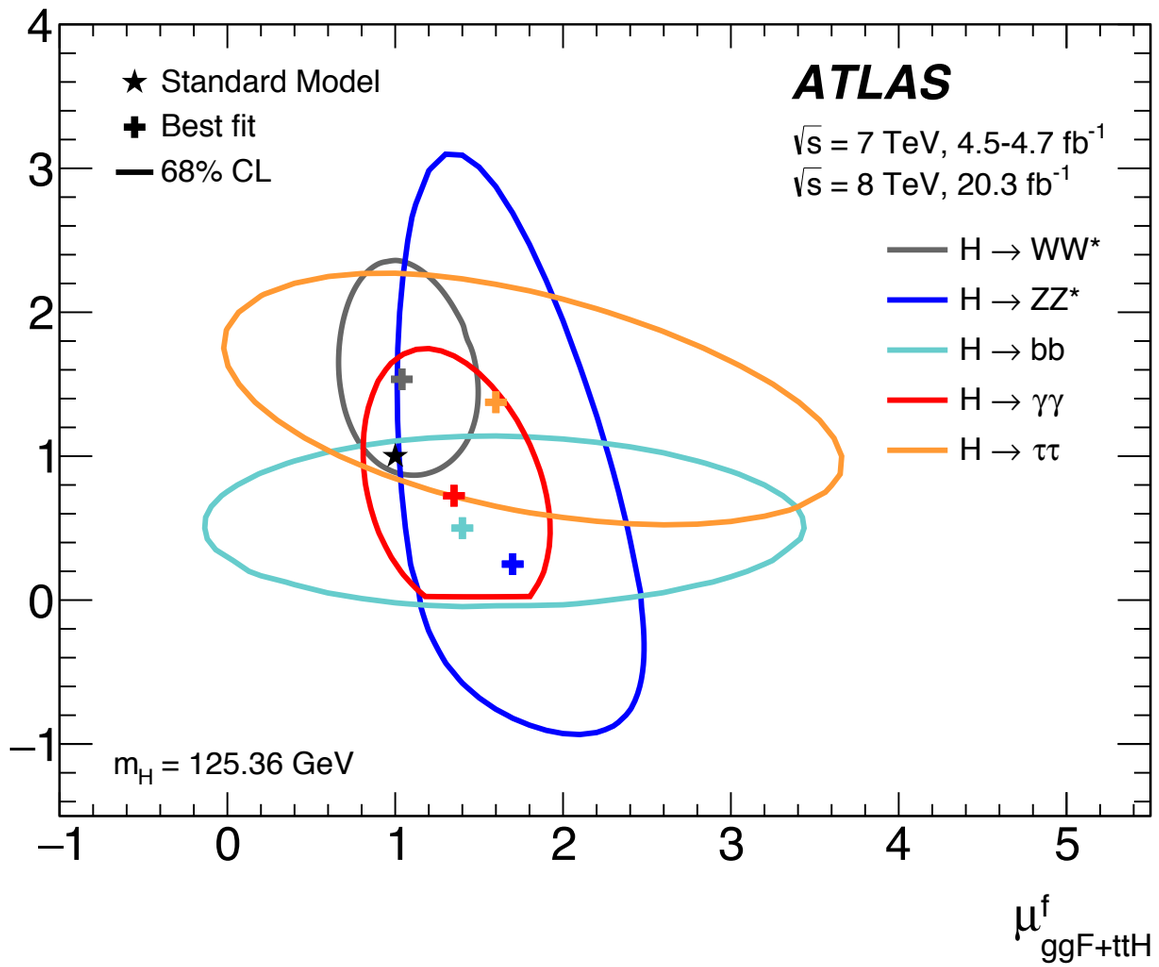
7TeV: 17.4 ± 1.6 pb

8TeV: 22.3 ± 2.0 pb

Boson and fermion-mediated production processes

- Higgs production processes:
  - Fermion mediated $\mu^f_{\mathrm{ggF}+ttH} \equiv (\mu^f_{\mathrm{ggF}} = \mu^f_{ttH})$
  - Boson mediated $\mu^f_{\mathrm{VBF}+VH} \equiv (\mu^f_{\mathrm{VBF}} = \mu^f_{VH})$
- Result consistent with the SM expectation





Relative production cross section R
Higgs decay branching ratios cancel

$$\frac{\mu^f_{\mathrm{VBF}+VH}}{\mu^f_{\mathrm{ggF}+ttH}} = \frac{\sigma_{\mathrm{VBF}+VH}/\sigma_{\mathrm{ggF}+ttH}}{\left[\sigma_{\mathrm{VBF}+VH}/\sigma_{\mathrm{ggF}+ttH}\right]_{\mathrm{SM}}} = \frac{\mu_{\mathrm{VBF}+VH}}{\mu_{\mathrm{ggF}+ttH}} \equiv R_{ff}$$

arXiv:1507.04548

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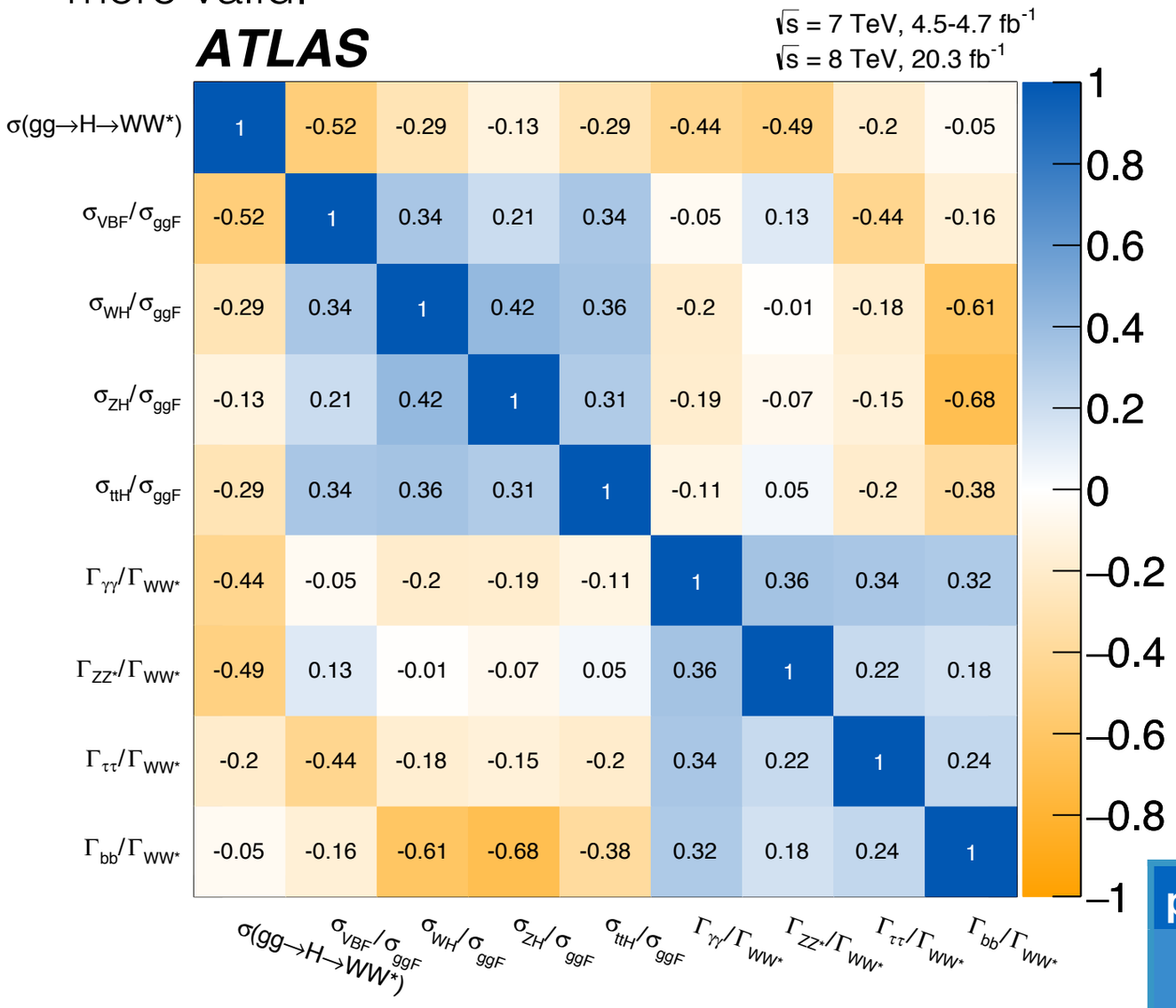
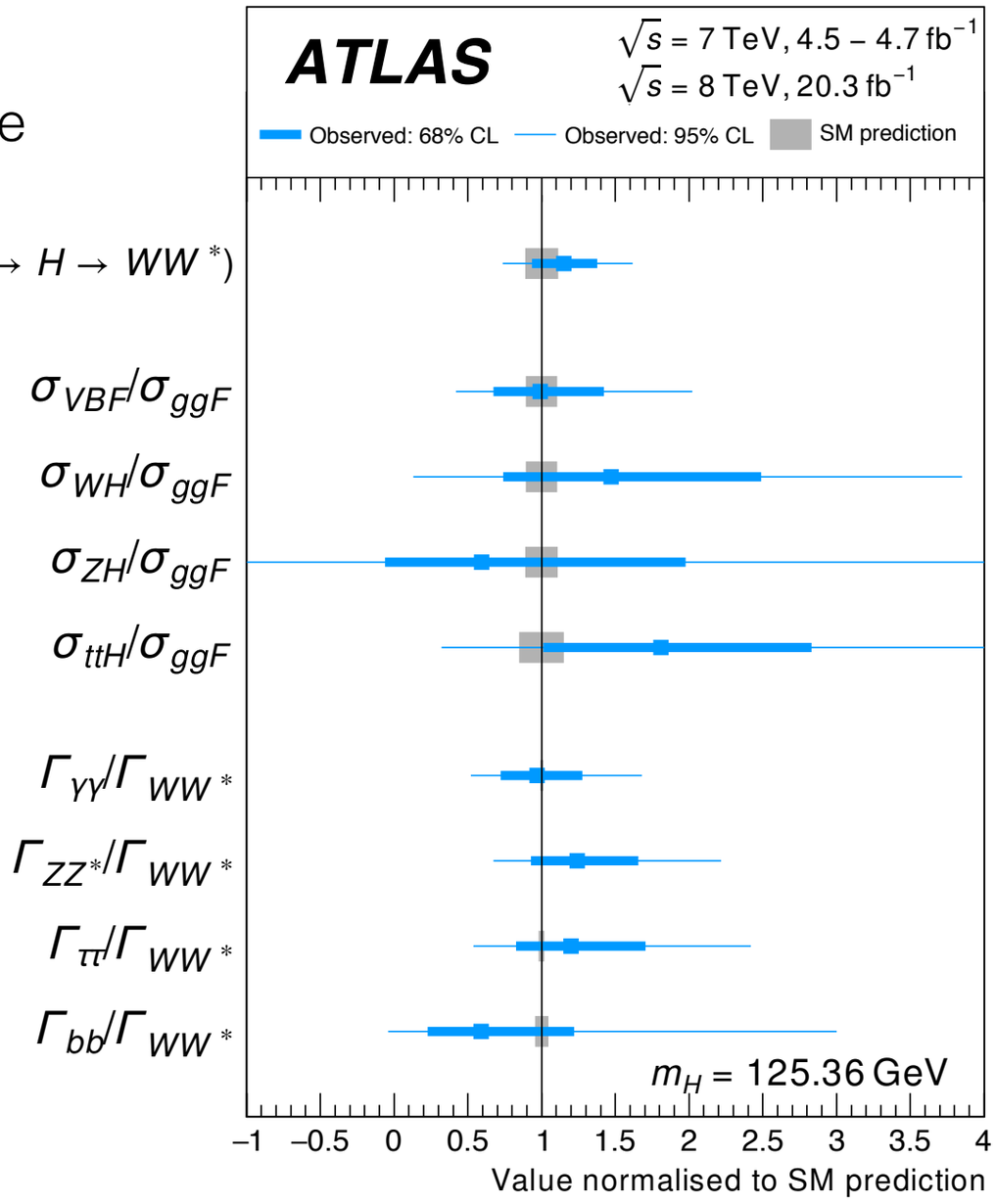
Generic measurement of cross sections and partial decay width

$$\sigma_i \cdot \mathrm{BR}_f = \left(\sigma_{\mathrm{ggF}} \cdot \mathrm{BR}_{WW^*}\right) \times \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \times \left(\frac{\mathrm{BR}_f}{\mathrm{BR}_{WW^*}}\right) = \sigma(gg \to H \to WW^*) \times \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \times \left(\frac{\Gamma_f}{\Gamma_{WW^*}}\right)$$

- Unlike most other measurements **the inclusive theory uncertainties are not part of this measurement**. Hence if theory prediction changes, this measurement will stay more valid.





production process	ggF	VBF	ttH	WH	ZH	VH
observed significance / σ	well above 5	4.3	2.5	2.1	0.9	2.6

Framework for coupling-strength measurements

arXiv:1507.04548

- Leading order tree-level motivated framework with assumptions:
  - Signal observed in different channels originate from a single resonance m_H ~125.36 GeV
  - Narrow width approximation.
  - Lagrangian tensor structure: SM hypothesis $J^{CP} = 0^{++}$

Yield for the production and decay $i \to H \to f$ parametrized in terms of coupling scale factors scaling the SM cross sections and widths

$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \right)$$

Coupling scale factors:

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}} \qquad \kappa_H^2 = \frac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$$

Production **Decay** **Total width**

- Higgs boson width Γ_H not experimentally constrained to a meaningful precision at the LHC:
  - No assumptions on Γ_H: Ratios of coupling strength can be measured
  - Make assumption on Γ_H: absolute coupling strengths can be measured.

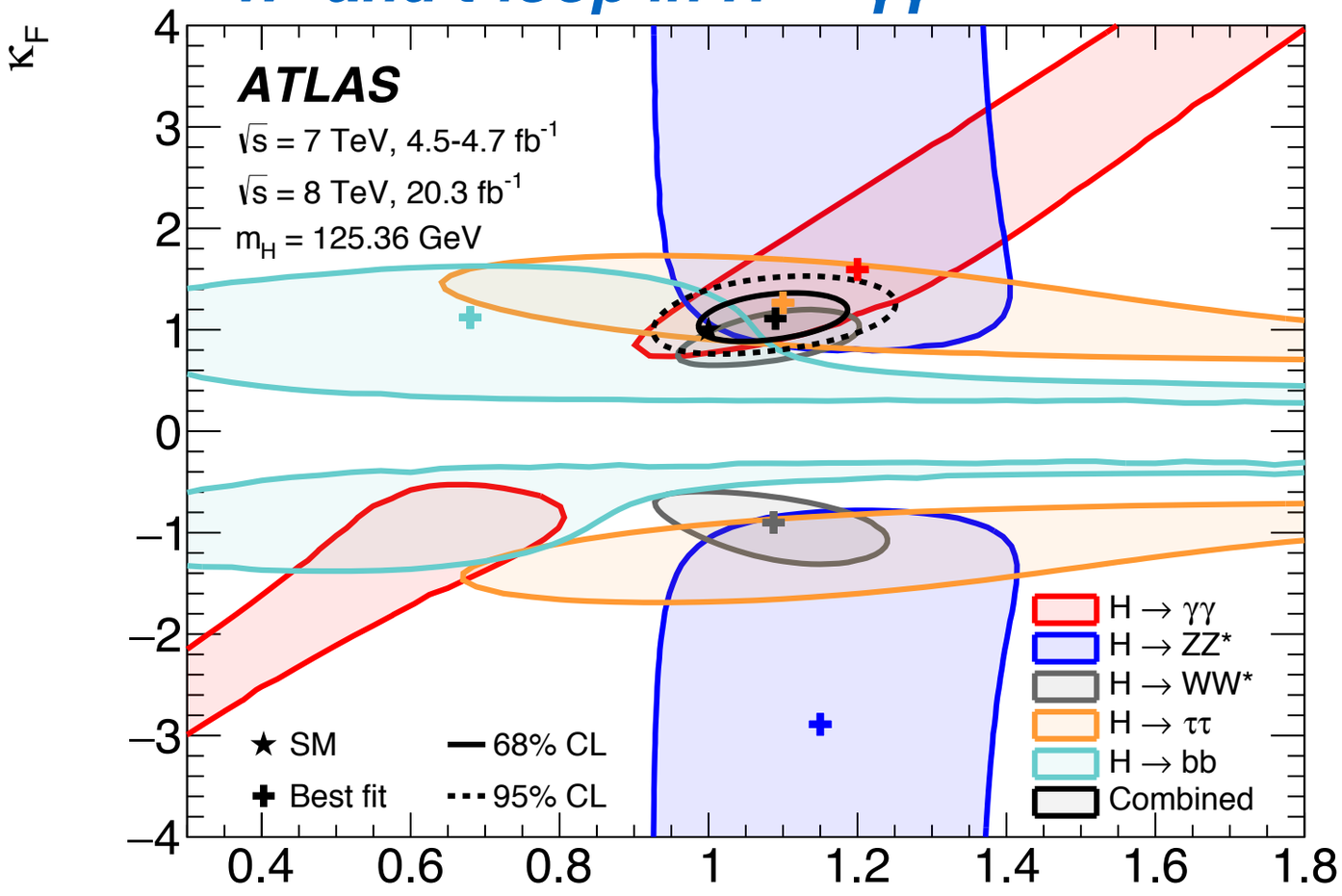
Fermion versus boson coupling

arXiv:1507.04548

Assuming only SM contributions to the total width

$$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$$

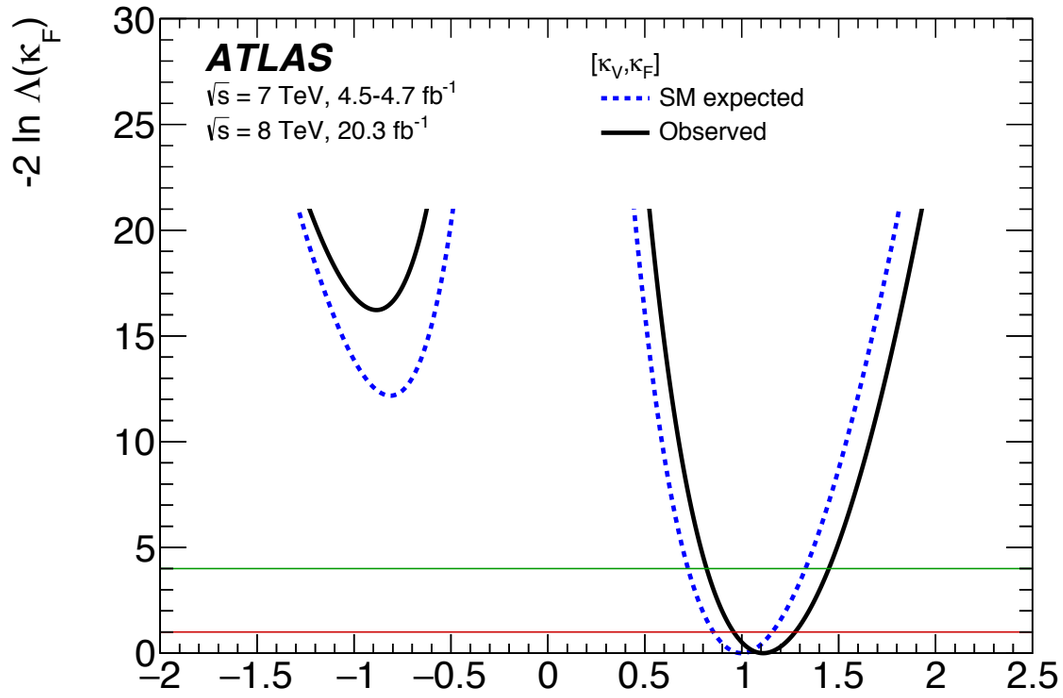
κ_F - κ_V relative sign sensitivity from W- and t-loop in H → γγ



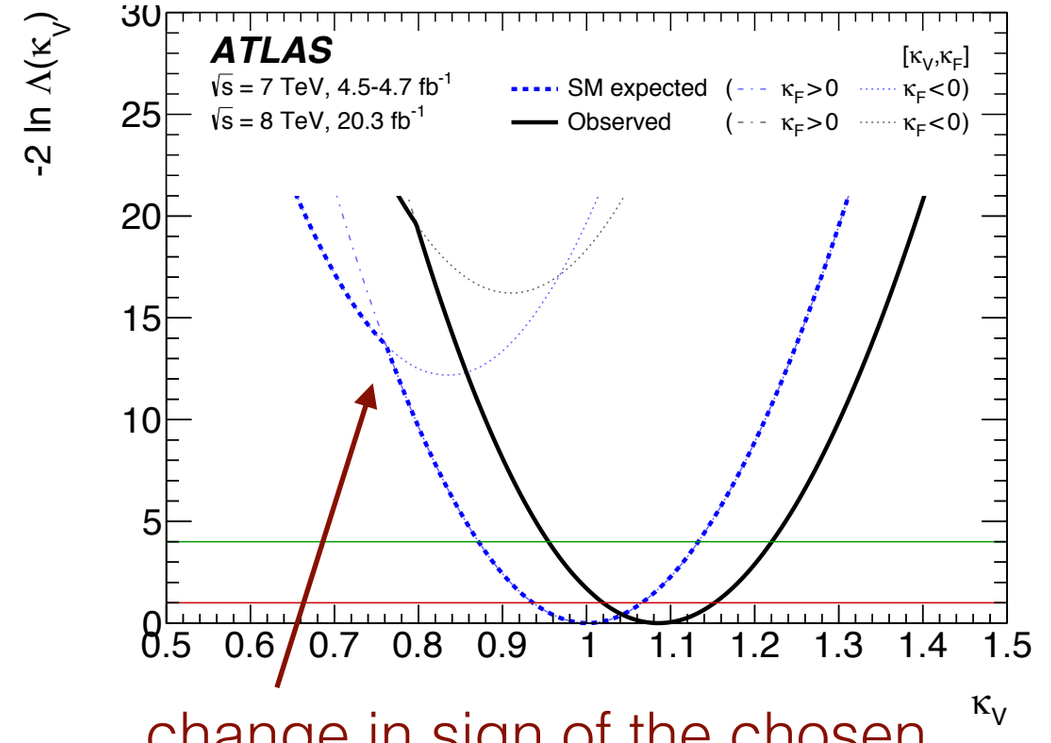
$\kappa V = \kappa W = \kappa Z$ $\quad$ $\kappa F = \kappa t = \kappa b = \kappa \tau = \kappa g = \kappa \mu$

$$\kappa_V = 1.09 \pm 0.07 \left[{}^{+0.05}_{-0.05}(\text{stat.}) \, {}^{+0.03}_{-0.03}(\text{syst.}) \, {}^{+0.04}_{-0.03}(\text{theo.}) \right]$$

$$\kappa_F = 1.11 \pm 0.16 \left[{}^{+0.12}_{-0.11}(\text{stat.}) \, {}^{+0.10}_{-0.09}(\text{syst.}) \, {}^{+0.06}_{-0.05}(\text{theo.}) \right]$$



Negative solution strongly disfavored at ~4σ



change in sign of the chosen profiled solution of κ_F

BSM contributions in loop vertices and to the total width allowing modified couplings to SM particles

$$\Gamma_H(\kappa_j, \mathrm{BR}_{\mathrm{i.,u.}}) = \frac{\kappa_H^2(\kappa_j)}{(1 - \mathrm{BR}_{\mathrm{i.,u.}})}\Gamma_H^{\mathrm{SM}}$$

Constraints on the total width:

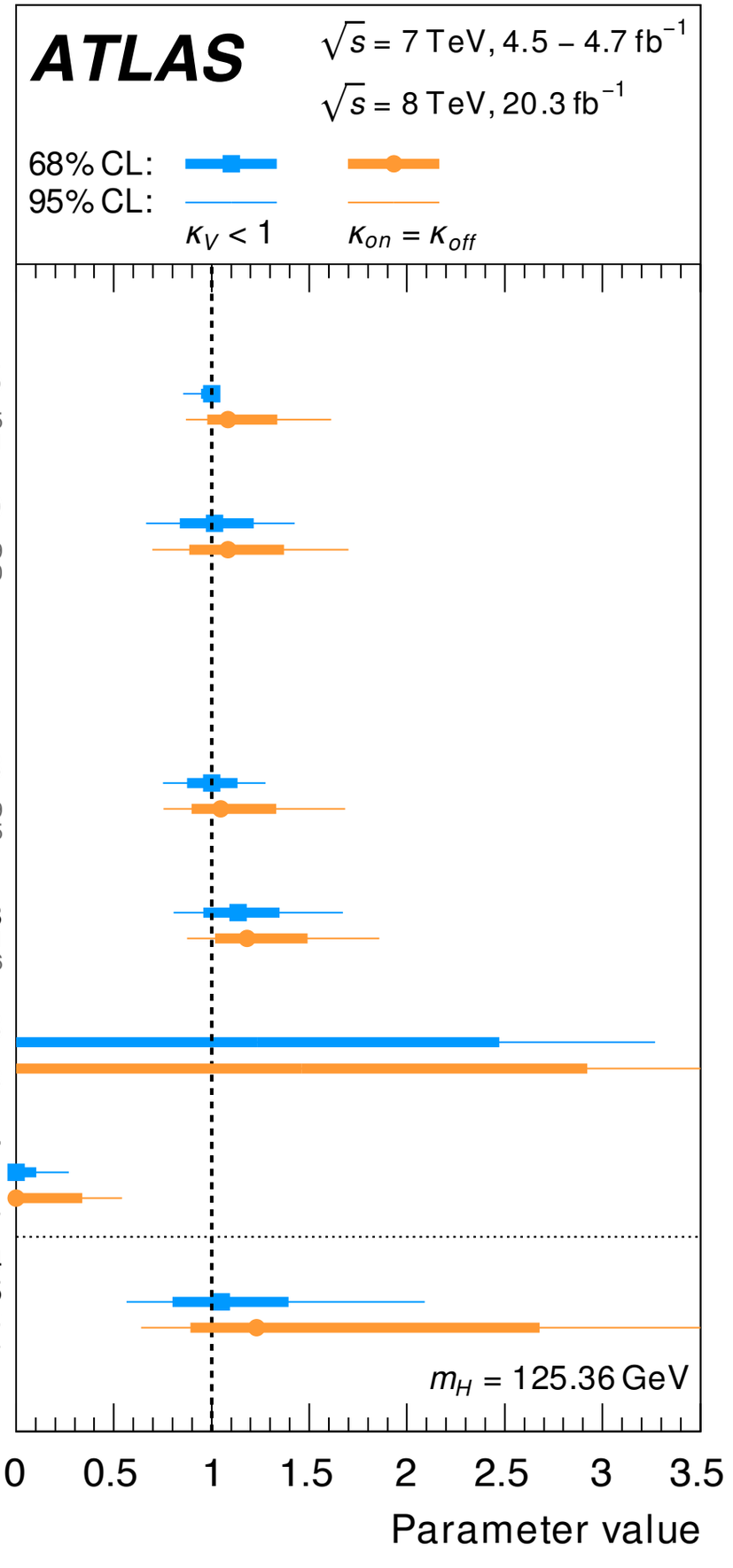
κ_V <1: Higgs boson should solve the unitarity problem in vector boson scattering, valid in a wide class of BSM models.

$\kappa_{on} = \kappa_{off}$: coupling strength in off-shell Higgs boson production identical to those for on-shell Higgs boson production

Compatibility with SM hypothesis

κ_V <1: 96%

$\kappa_{on} = \kappa_{off}$: 64%

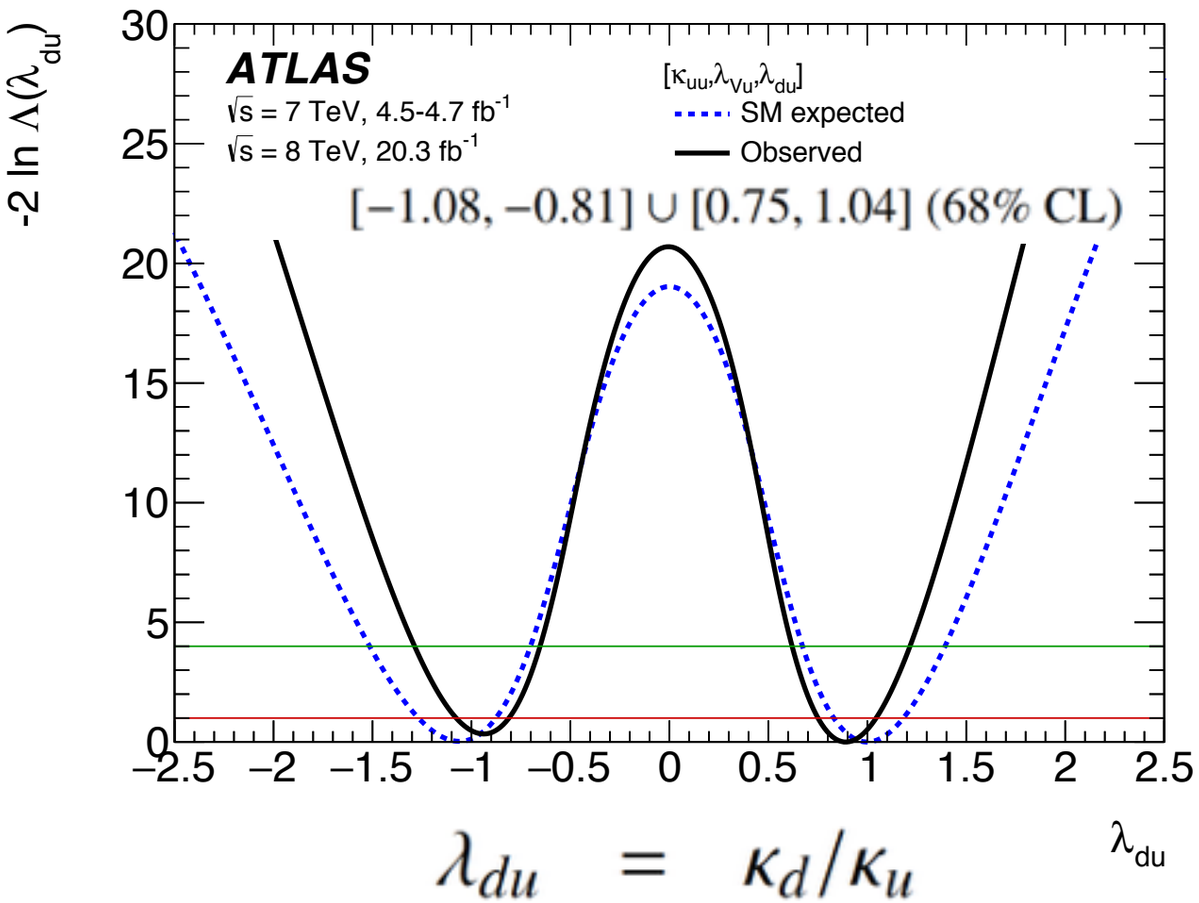


arXiv:1507.04548

Probing relations within the fermion coupling sector

- Motivation: Many extensions of the SM contain: (e.g. certain Two-Higgs-Doublet Models)
  - **different coupling strengths of the Higgs boson to up-type and down-type fermions**.
  - **different coupling strengths of the Higgs boson to leptons and quarks**

Probe up- and down type fermion symmetry



$$\lambda_{du} = \kappa_d / \kappa_u$$

- Compatibility with the SM hypothesis: 51%
- Evidence of Higgs coupling to down-type fermions: 4.5σ

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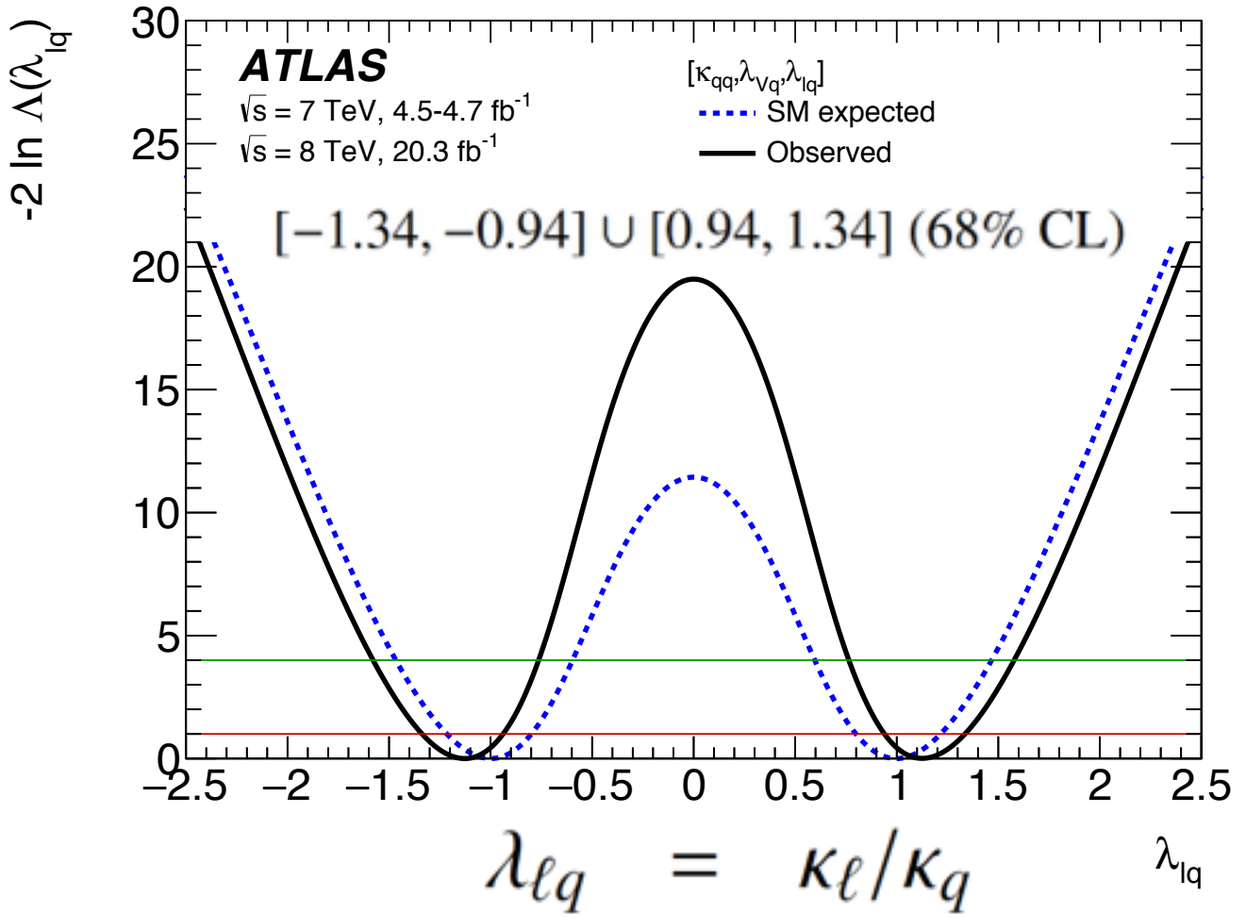
Probe quark and lepton symmetry



$$\lambda_{\ell q} = \kappa_\ell / \kappa_q$$

- Compatibility with the SM hypothesis: 53%
- Evidence of Higgs coupling to lepton: 4.4σ

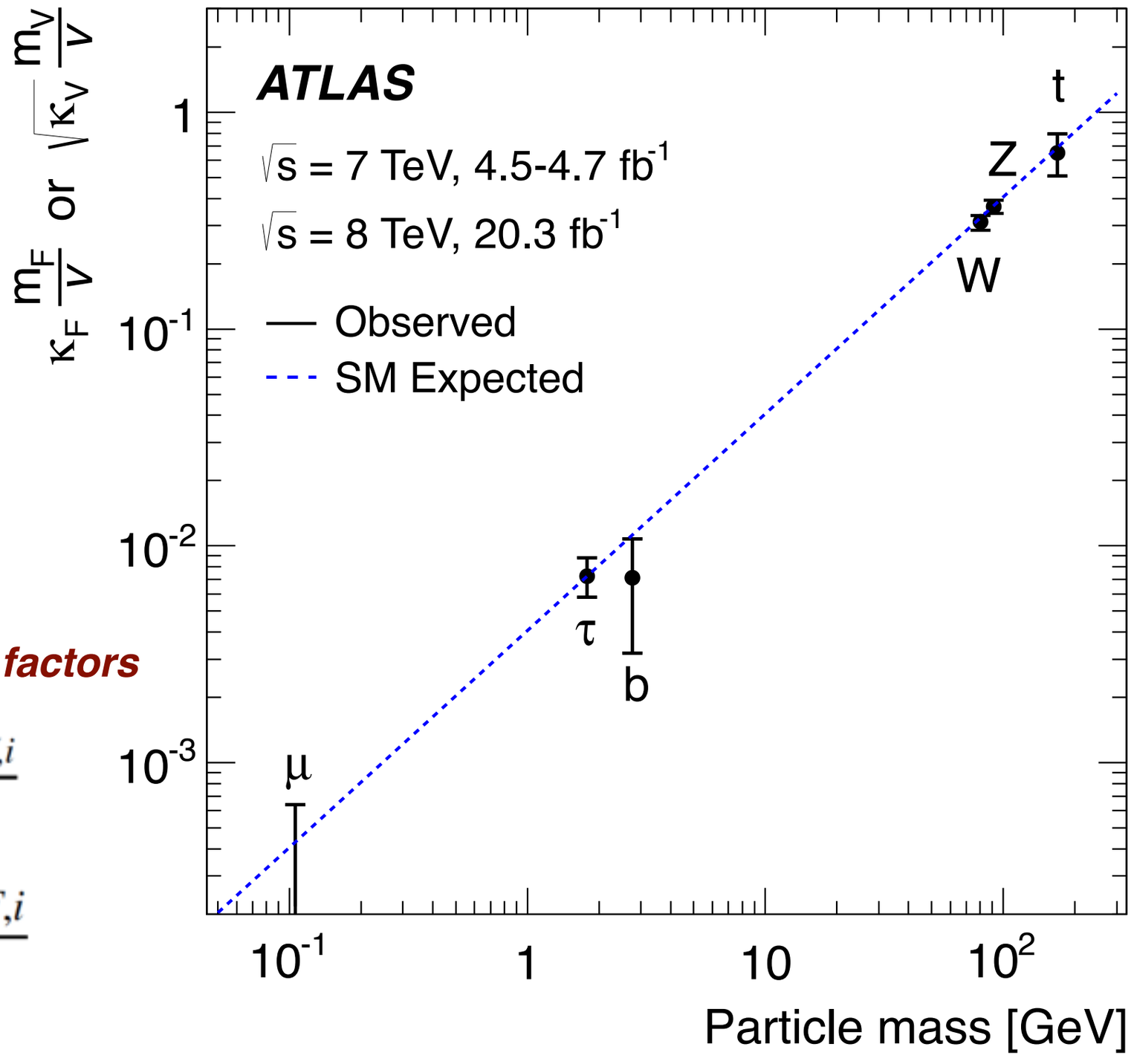
Mass dependence

- Generic model of tree-level coupling factors, with assumptions that no BSM contributions to loop-induced process and to total width.
- Compatibility with the SM hypothesis: 57%

Reduced coupling-strength scale factors

$$y_{V,i} = \sqrt{\kappa_{V,i}}\frac{g_{V,i}}{2v} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

$$y_{F,i} = \kappa_{F,i}\frac{g_{F,i}}{\sqrt{2}} = \kappa_{F,i}\frac{m_{F,i}}{v}$$



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Generic model: allow new particles in loops no assumption on the total width

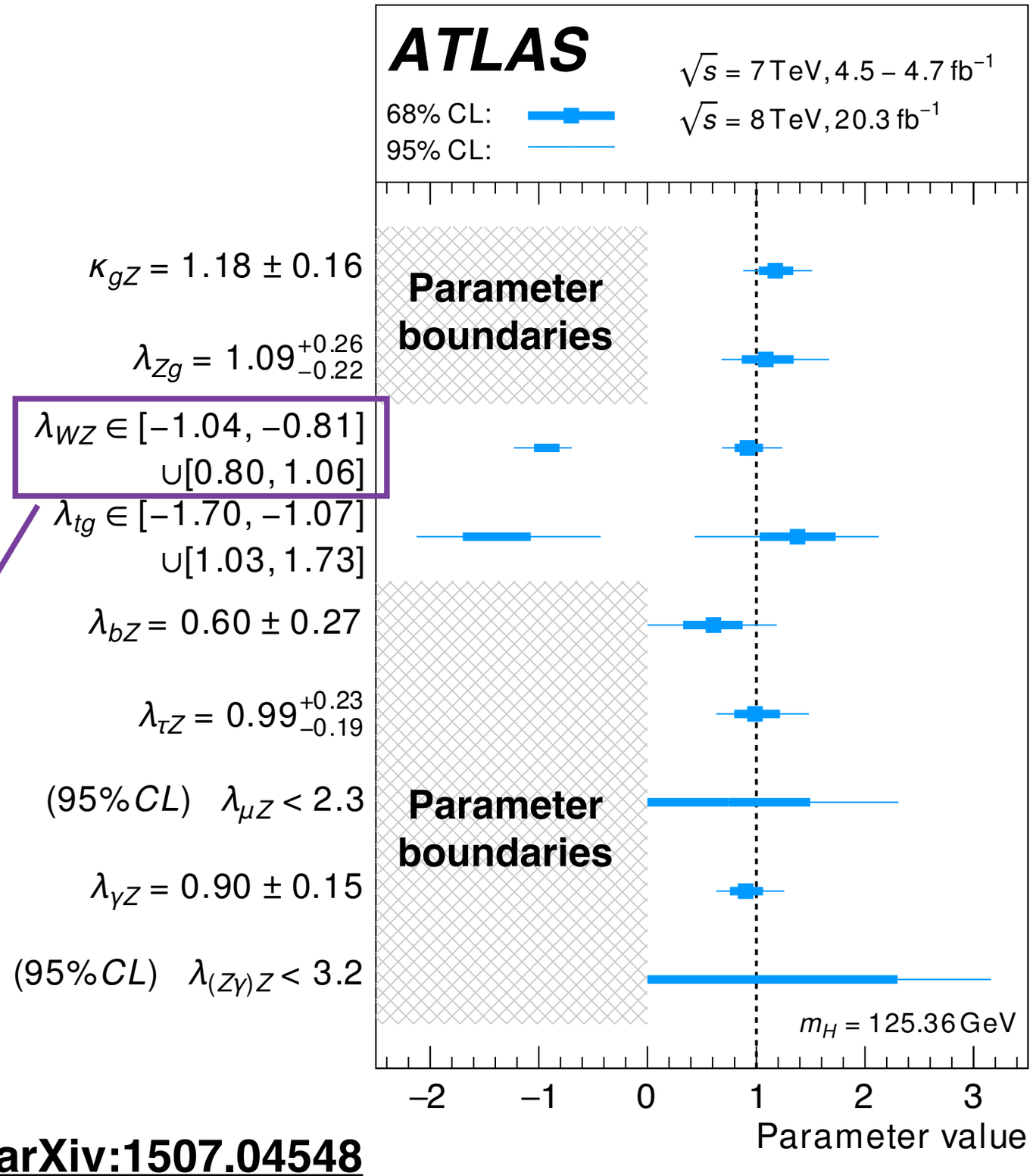
- **Most model-independent determination of coupling-strength scale factors that is currently possible.**

  Ratios of scale factors:

  $$\lambda_{ij} = \kappa_i / \kappa_j \,,\ \kappa_{ij} = \kappa_i \cdot \kappa_j / \kappa_H$$

- Compatibility with the SM hypothesis: 73%

- λ_{WZ} measurement in excellent agreement with the prediction of **SU(2) custodial symmetry**.



arXiv:1507.04548

Conclusion

Using LHC run-1 pp collision dataset collected by ATLAS detector:

- Combined measurement of Higgs boson mass
$m_H = 125.36 \pm 0.41$ GeV = 125.36 ± 0.37(stat.) ± 0.18(syst.)GeV

- Combined measured signal yield normalized to SM expectation

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

- The observed Higgs boson production and decay rates interpreted in a leading-order coupling framework. **The observed data found to be compatible with the SM expectations for all models considered.**

Expect more precise measurements in Run 2.

Effective field theory approach with consistent calculations of higher order corrections and including CP-odd coupling, promising for future precision measurements.

Thank you!

References

Phys. Rev. D. 90, 052004 (2014) Measurement of the Higgs boson mass from the H → γγ and H → ZZ* → 4l channels with the ATLAS detector using 25 fb−1 of pp collision data

arXiv:1507.04548, Submitted to EPJC: Measurements of the Higgs boson production and decay rates and coupling strengths using pp collision data at sqrt(s) = 7 and 8 TeV in the ATLAS experiment

arXiv:1307.1347: Handbook of LHC Higgs Cross Sections: 3. Higgs Properties