Measurements of the Higgs Boson Coupling Strength in the ATLAS Experiment

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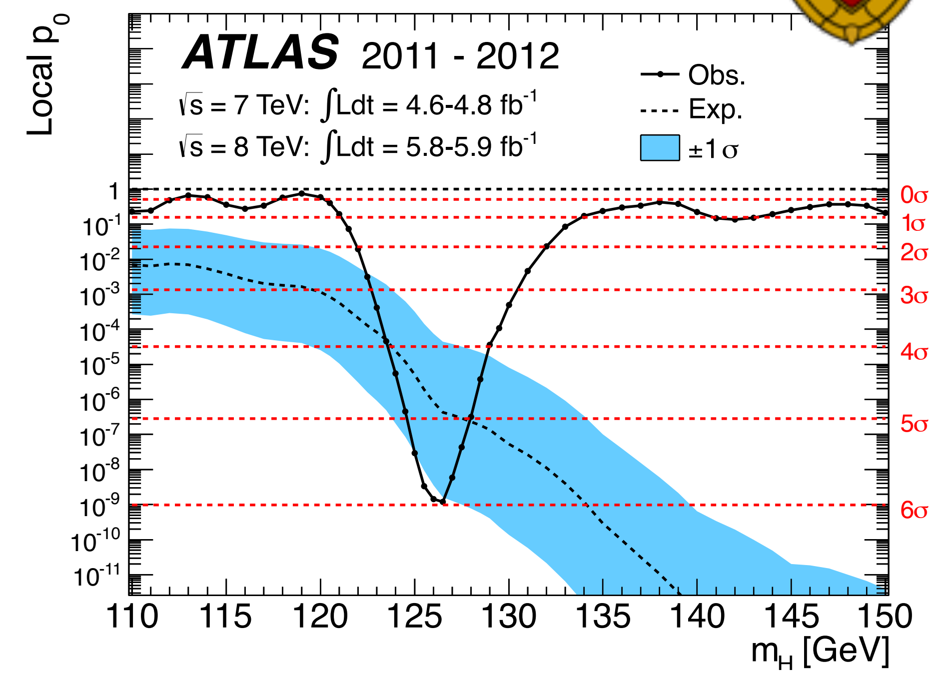
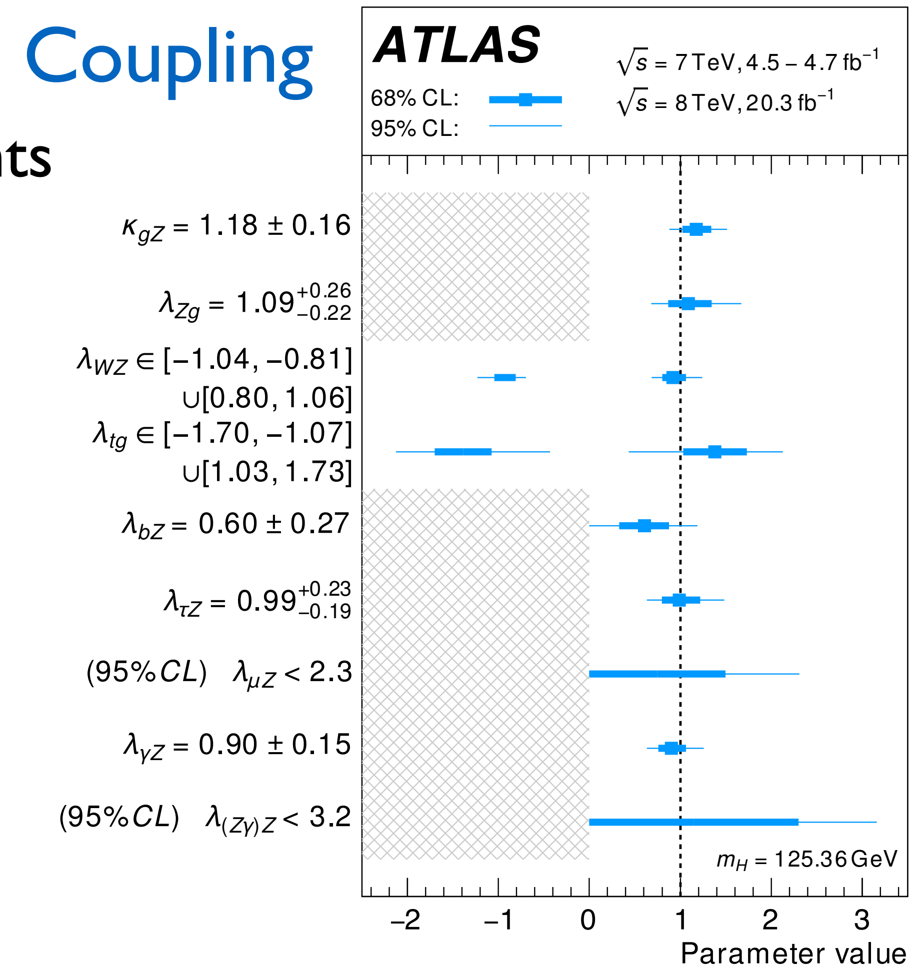
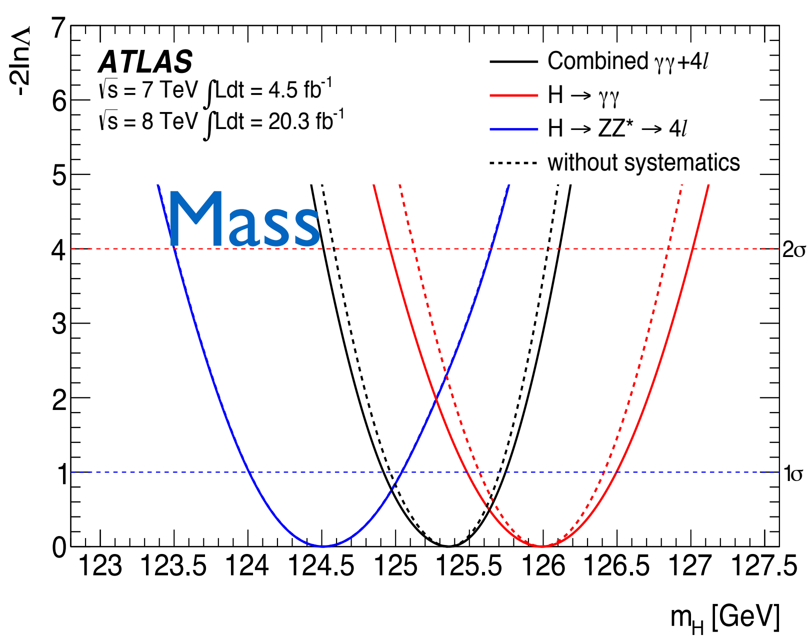
Discovery → Property measurement

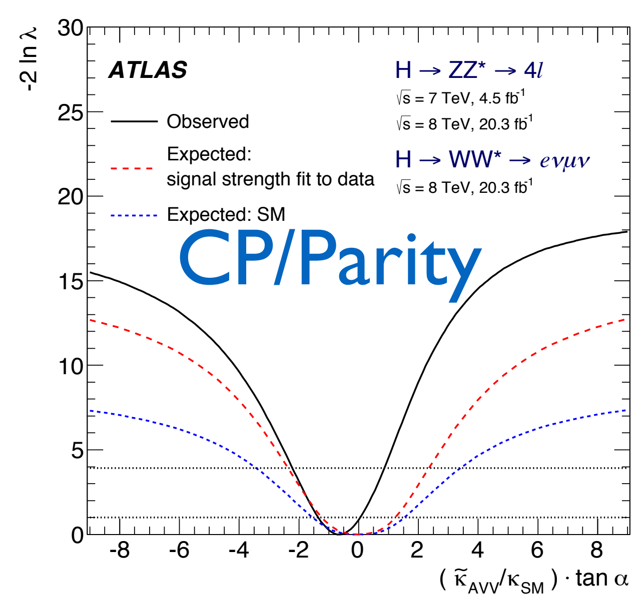
- Higgs discovery in July 2012 *[Phys. Lett. B 716 (2012) 1-29]*
- Now in precision measurement era
  - **June 2014**: 2-channel combined mass measurements *[Phys. Rev. D 90, 052004]*
    H → γγ / ZZ*
  - **June 2015**: boson channel combined spin/parity measurements *[arXiv:1506.05669]*
    H → γγ / ZZ* / WW*
  - **July 2015**: multi-channel combined coupling measurements *[arXiv:1507.04548]*
    H → γγ / ZZ* / WW* / ττ / bb / Zγ / μμ



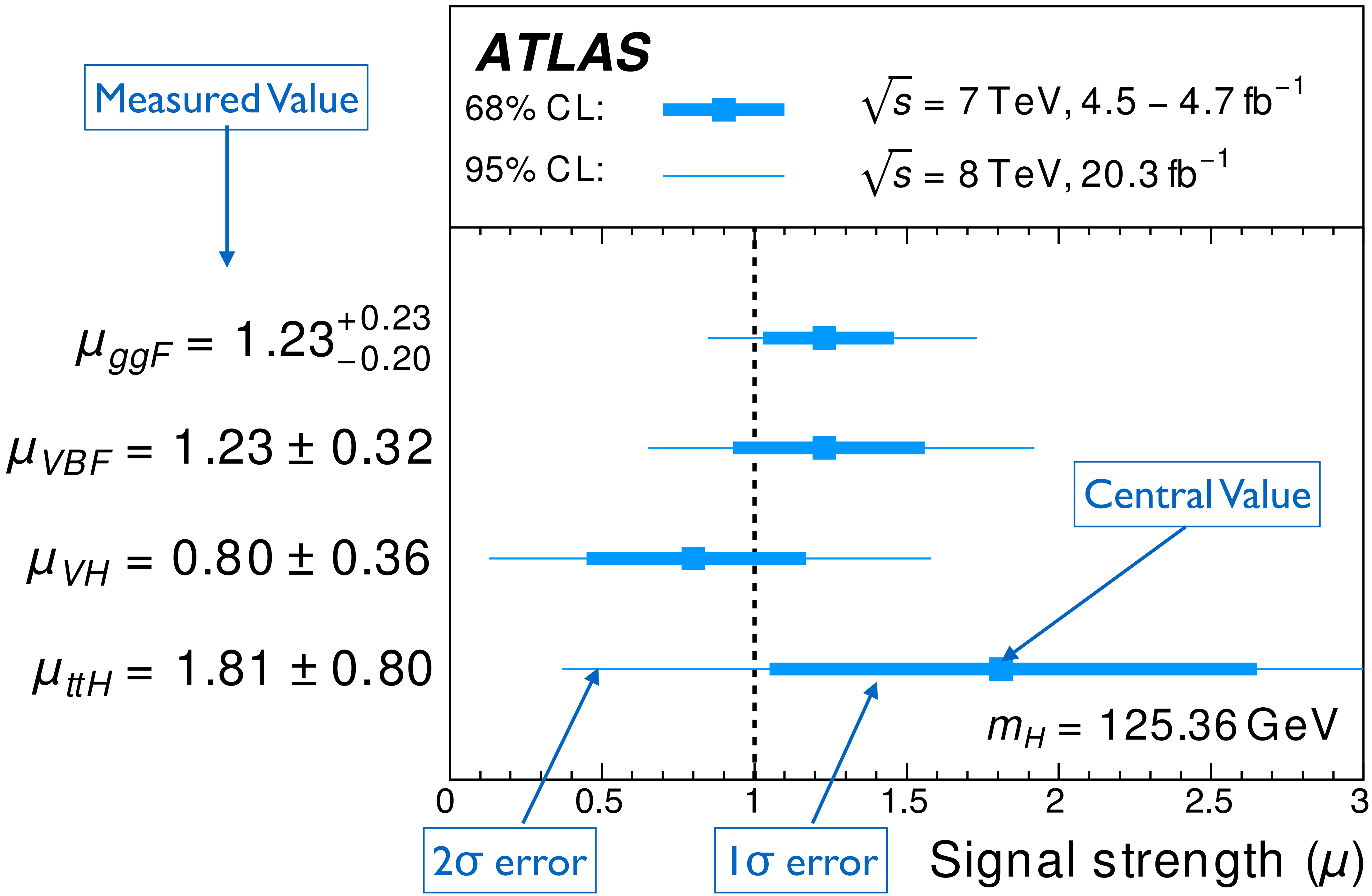
Coupling





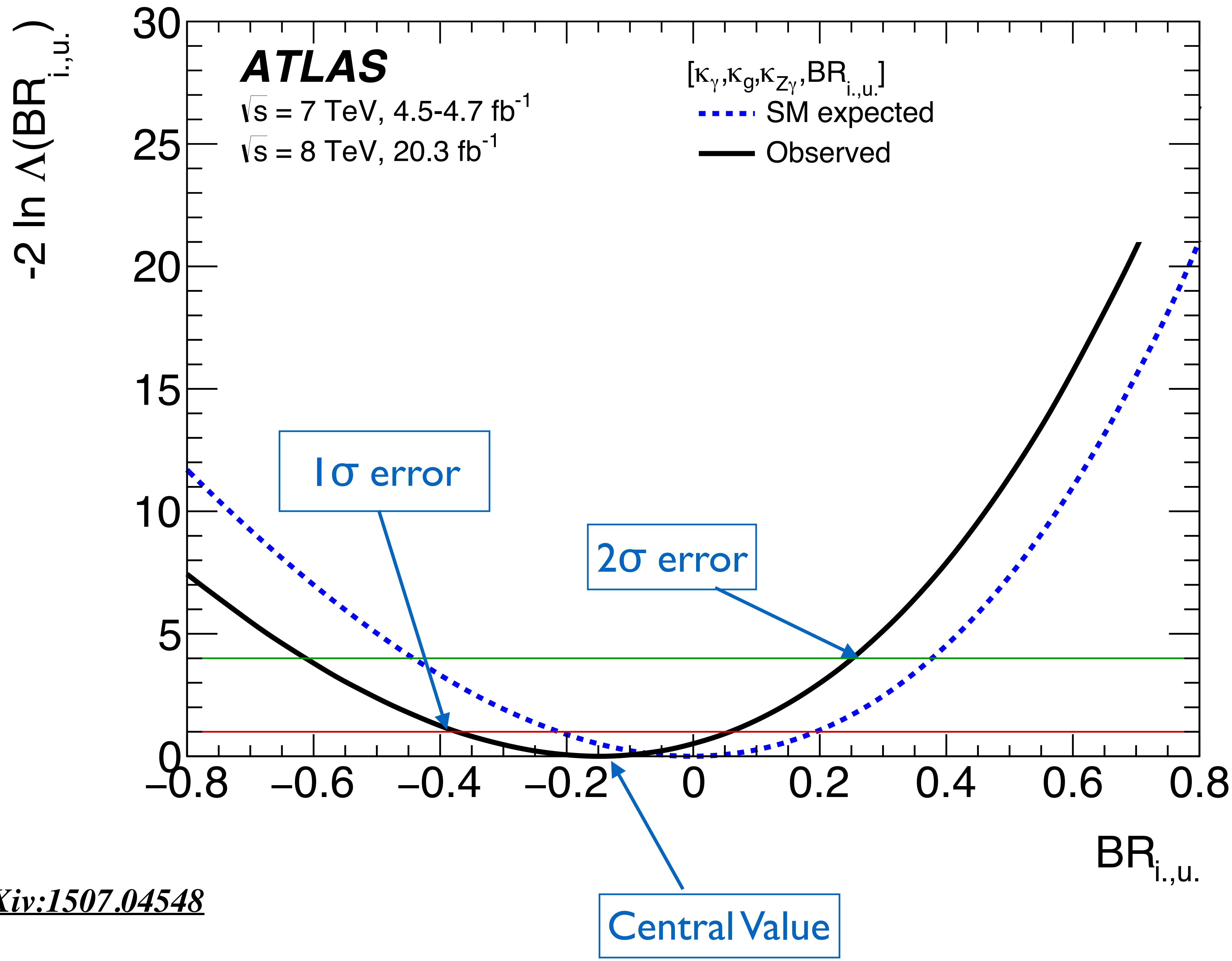


Plot Sample: measurement results



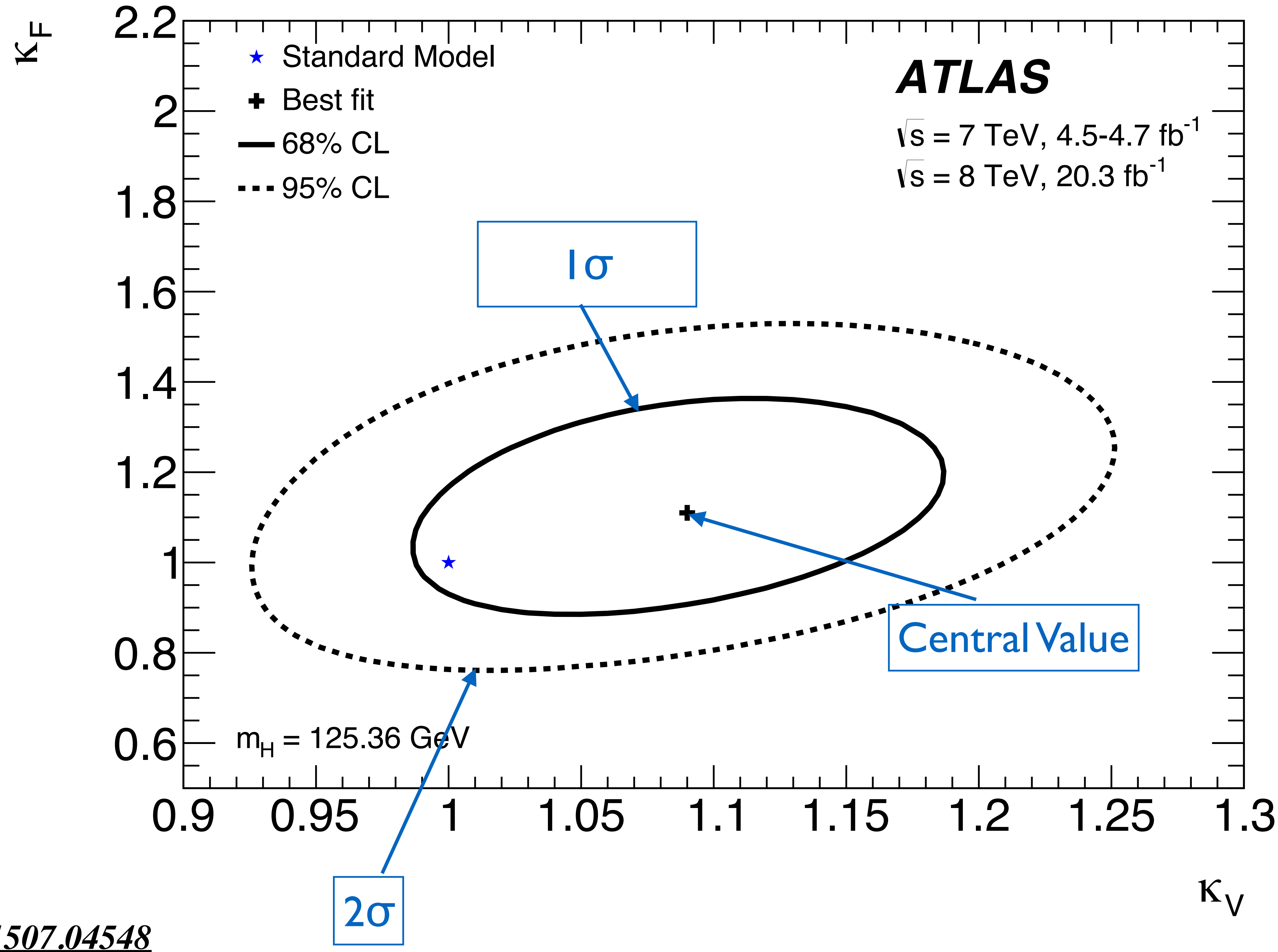
Ref: arXiv:1507.04548

Plot Sample: 1D likelihood scan



Ref: ***arXiv:1507.04548***

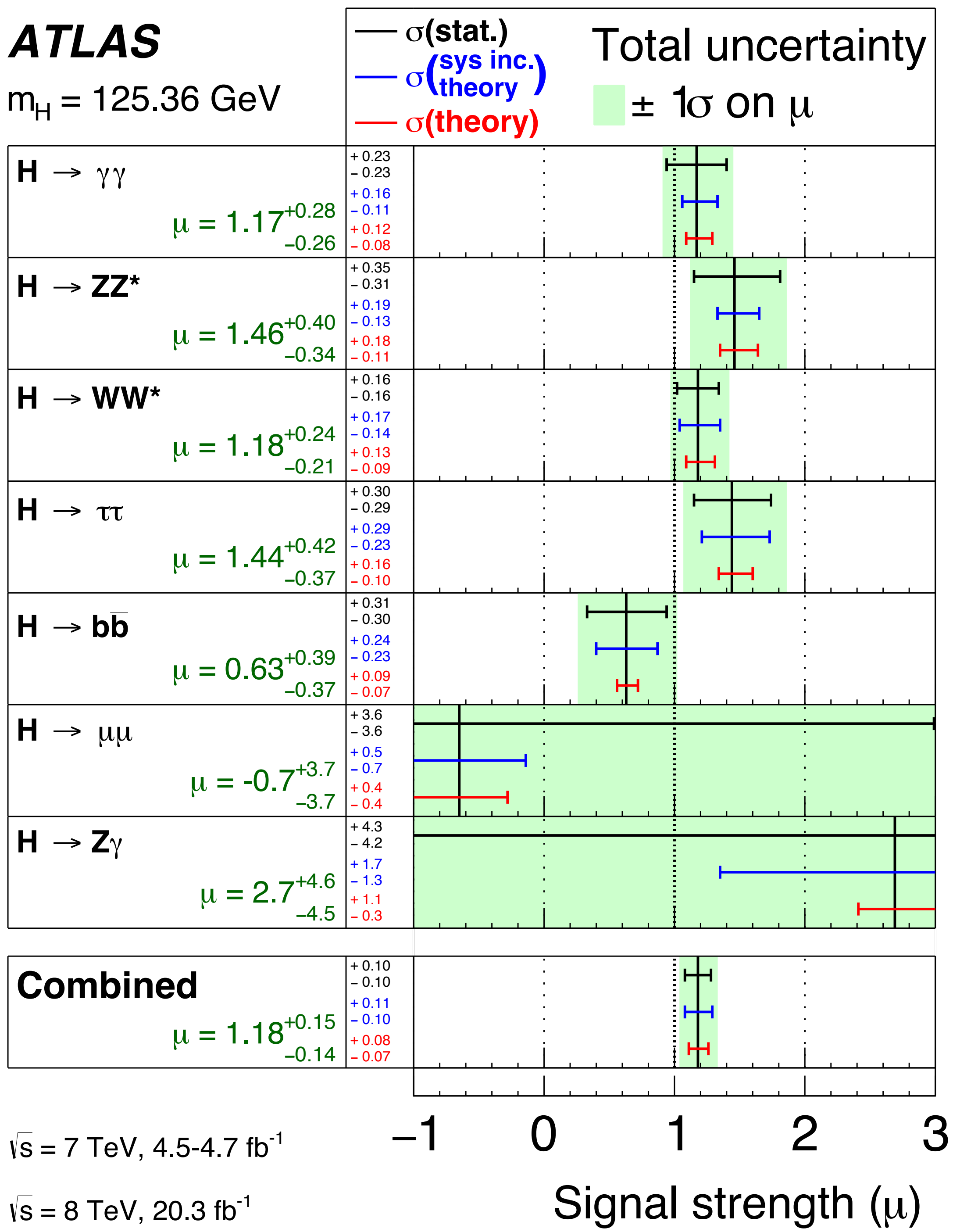
Plot Sample: 2D likelihood contour



Ref: arXiv:1507.04548

Common signal strength (μ)

Contribution from ttH searches assigned to all decay modes except μμ and Zγ



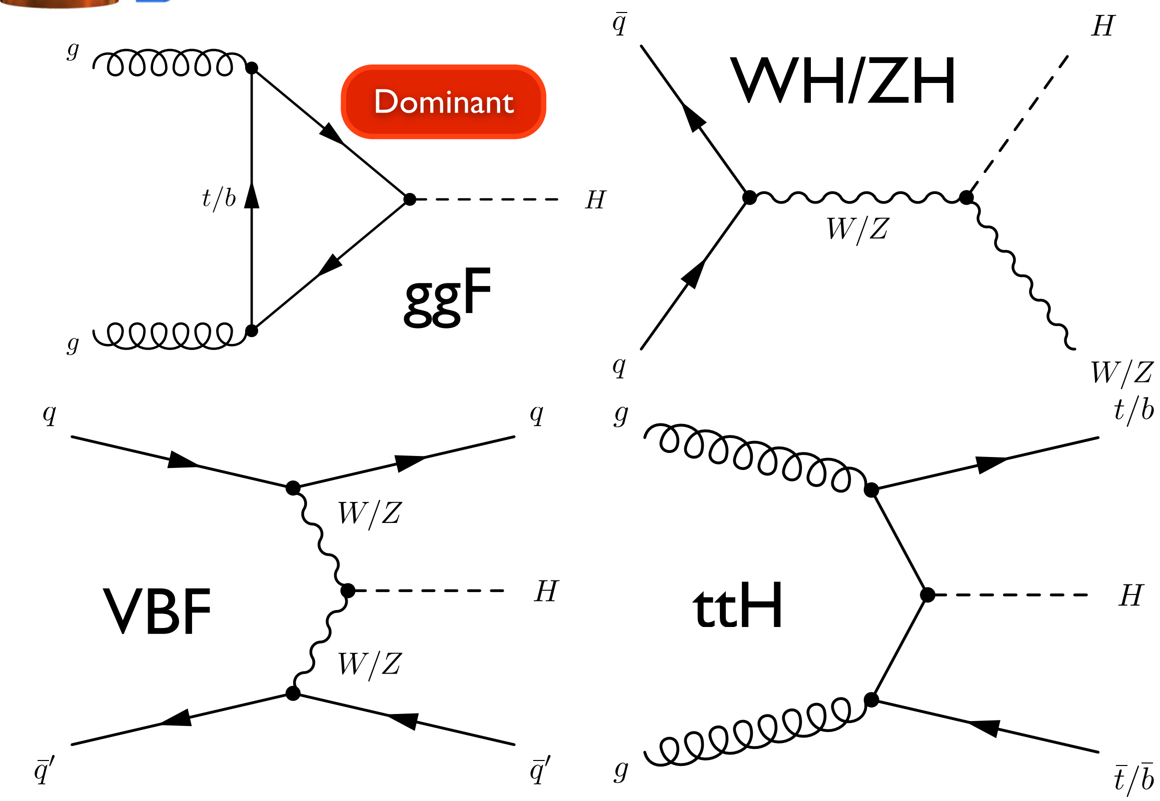
- <u>Common signal strength</u>: ratio of measured signal event yields to SM expectation, accounting for all production and decay modes
  - The most precise measurement
  - No straightforward physics model interpretation, especially for μ > 1
- Combined result includes 7 decay channels:

$$\mu = 1.18 \pm 0.10(\mathrm{stat}) \pm 0.07(\mathrm{exp})^{+0.08}_{-0.07}(\mathrm{theo})$$

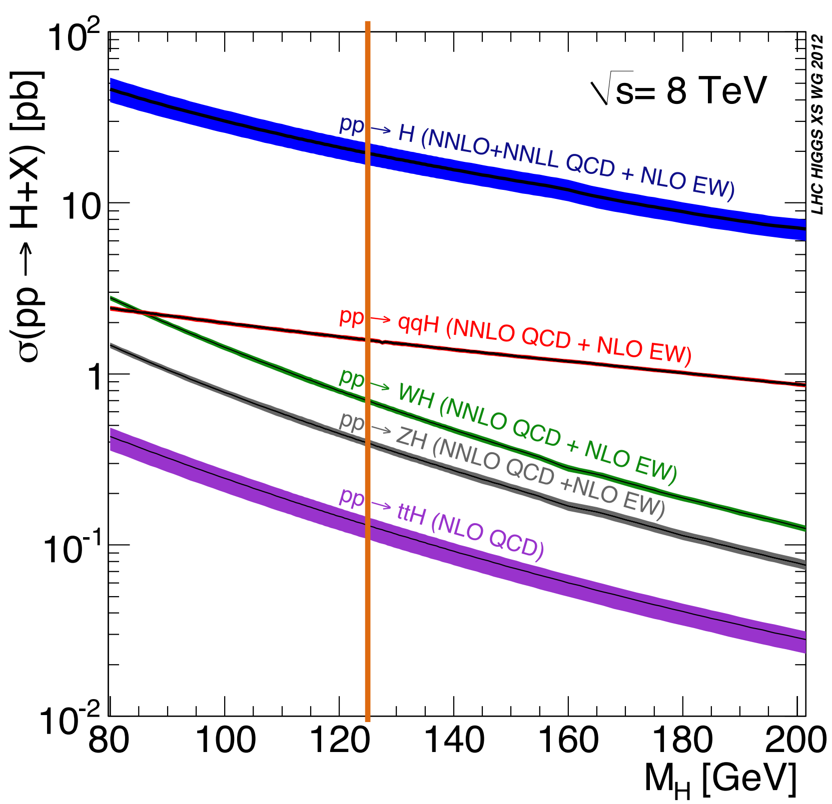
- Compatibility with SM expectation(μ=1) is **18%**

Ref: <u>arXiv:1507.04548</u>

Individual production processes

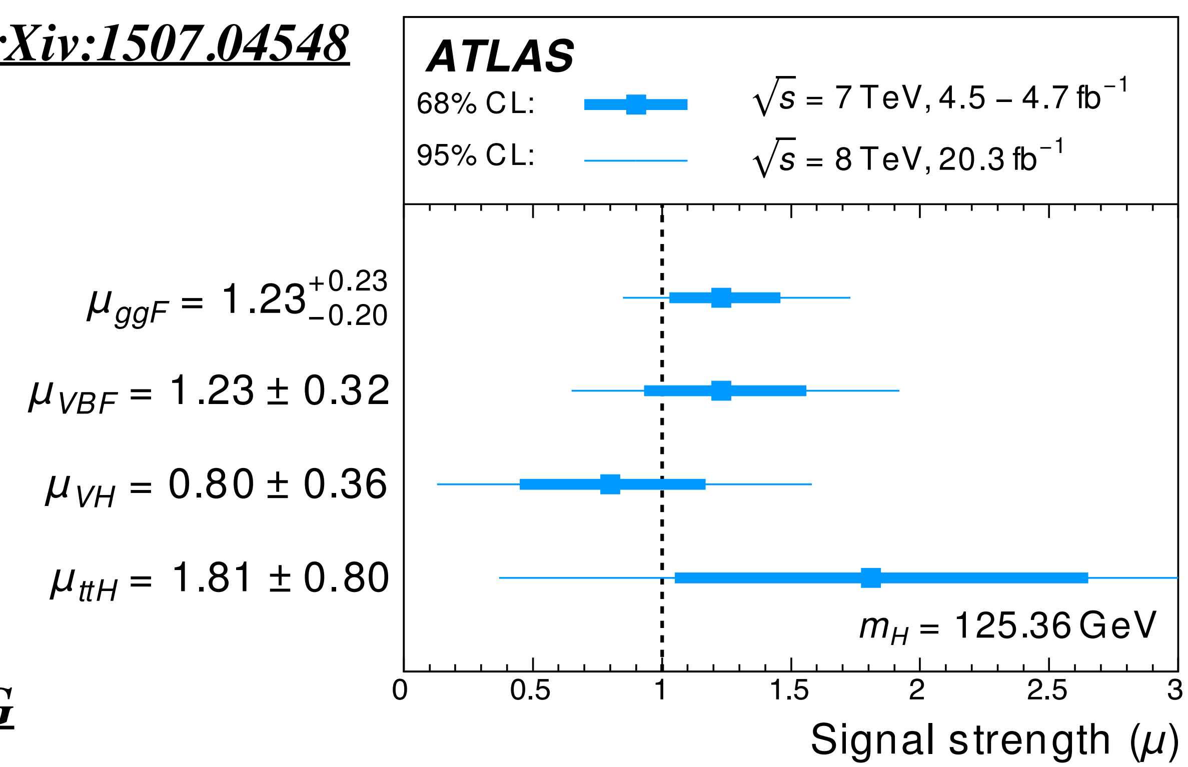


- Decouple signal strengths of different Higgs production modes:
  - Gluon-gluon fusion (ggF, dominant)
  - Vector boson fusion (VBF)
  - Associated production with a vector boson (WH/ZH)
  - Associated production with a top pair (ttH)
- Assuming SM Higgs decay branching ratio
- Results consistent with SM at <2σ

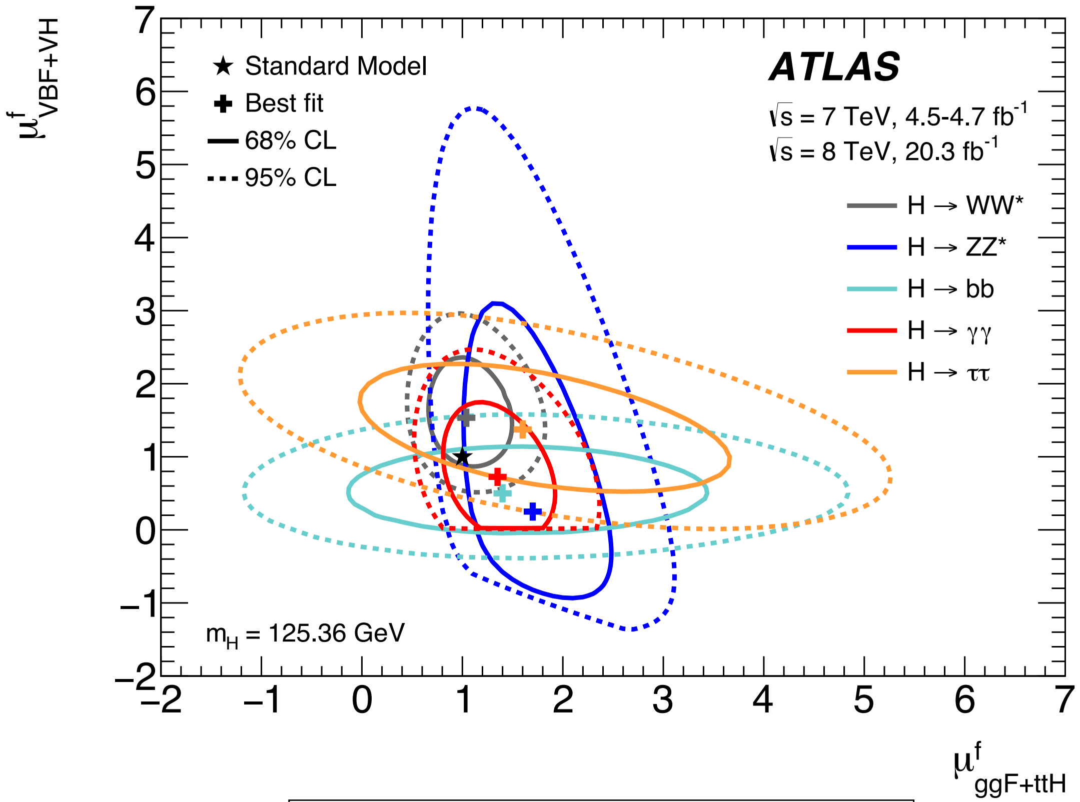


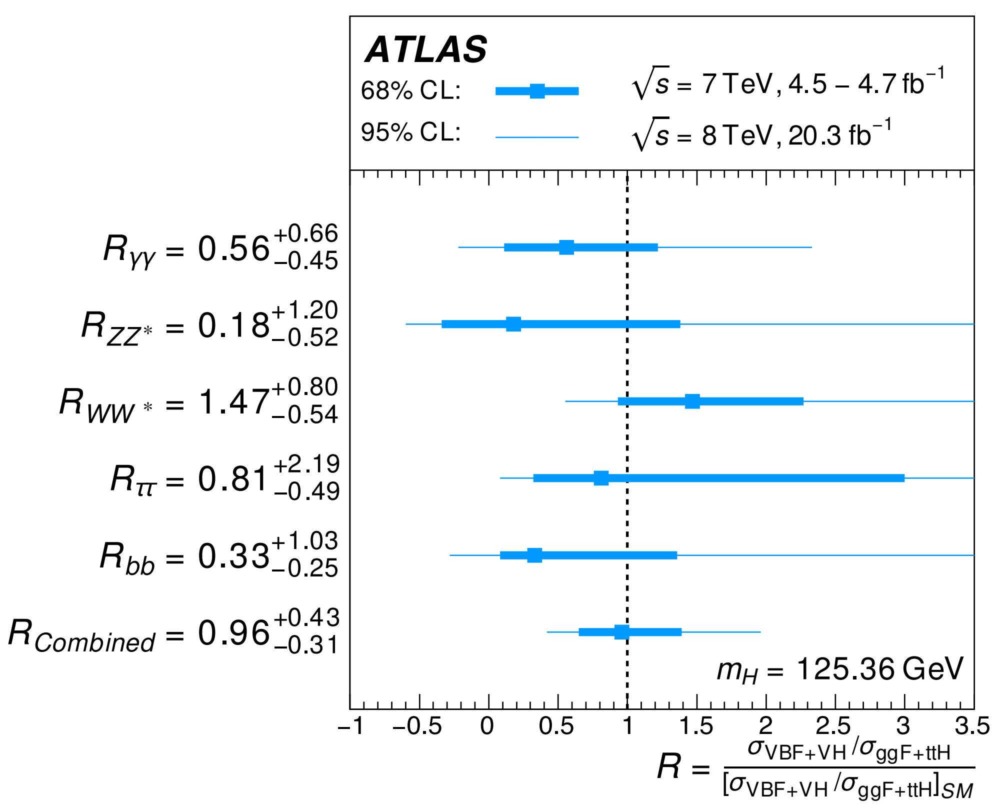
Ref: LHC-XS-WG

Ref: arXiv:1507.04548



Boson and fermion-mediated production





- Categorization of Higgs production processes:
  - Boson mediated (VBF, VH)
  - Fermion mediated (ggF, ttH)
- Assume: $\mu^f_{ggF} = \mu^f_{ttH}$, $\mu^f_{VBF} = \mu^f_{VH}$
- SM expectation within 68% CL contour of most of the measurements

- Relative production cross section $\mu^f_{ggF+ttH} / \mu^f_{VBF+VH}$
- Reduced to production cross section ratios in individual channels (branching ratio canceled)

$$\mu^f_{\mathrm{ggF+ttH}}/\mu^f_{\mathrm{VBF+VH}} = \mu_{\mathrm{ggF+ttH}}/\mu_{\mathrm{VBF+VH}}$$

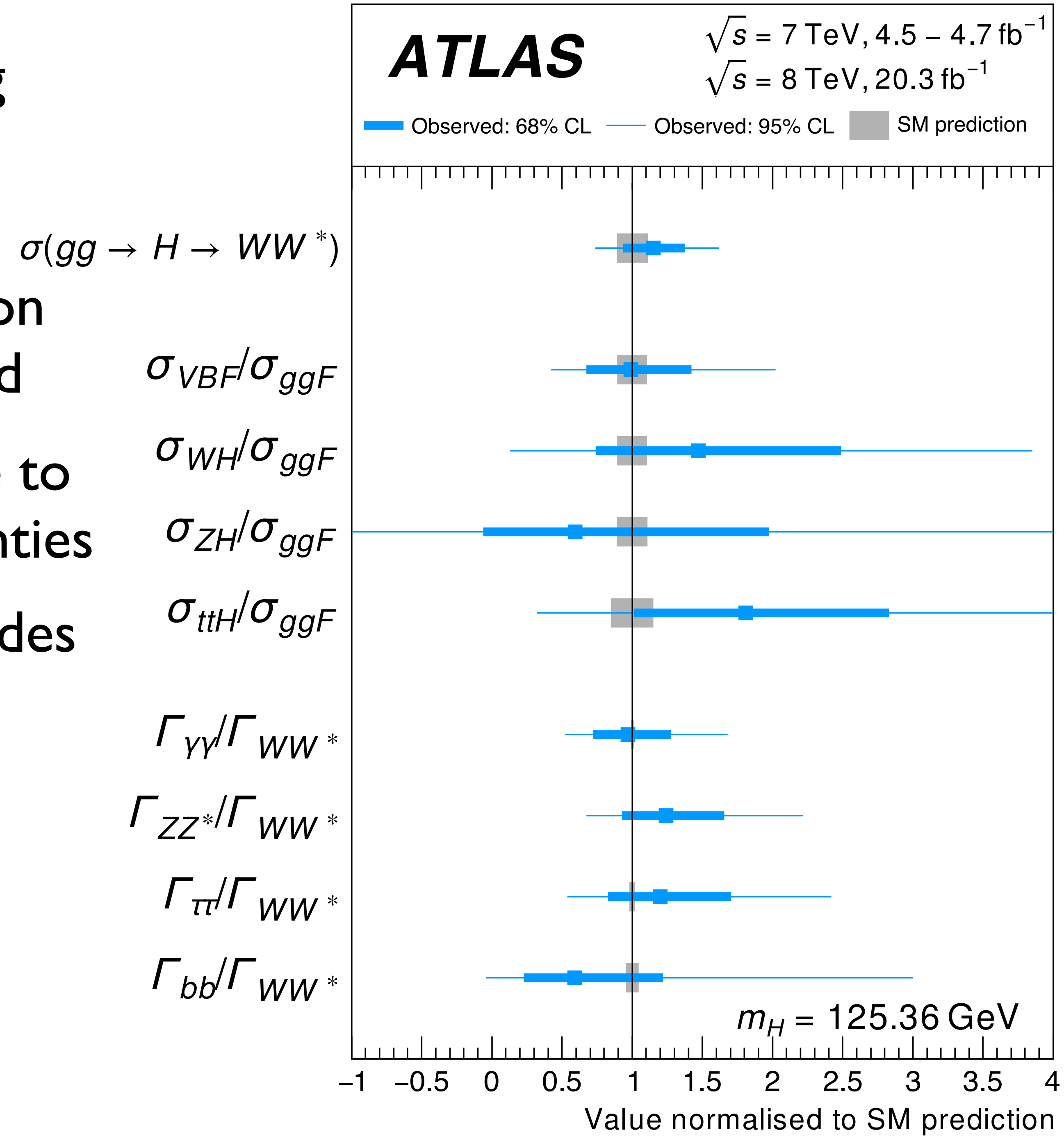
Ref: arXiv:1507.04548

Higgs production and decay modes

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

Ref: arXiv:1507.04548

- The ratios of cross sections and branching ratios can be disentangled without any assumption
  - Only product of production cross section and decay branching ratios are measured
- $gg \to H \to WW^*$ is chosen as reference due to its smallest statistical and overall uncertainties
- Evidence of non-dominant production modes (excluding ratio = 0):
  - VBF: **4.3σ** (exp. **3.8σ**)
  - WH: **2.1σ** (exp. **2.0σ**)
  - ZH: **0.9σ** (exp. **2.1σ**)
  - ttH: **2.5σ** (exp. **1.5σ**)



Models for coupling measurements

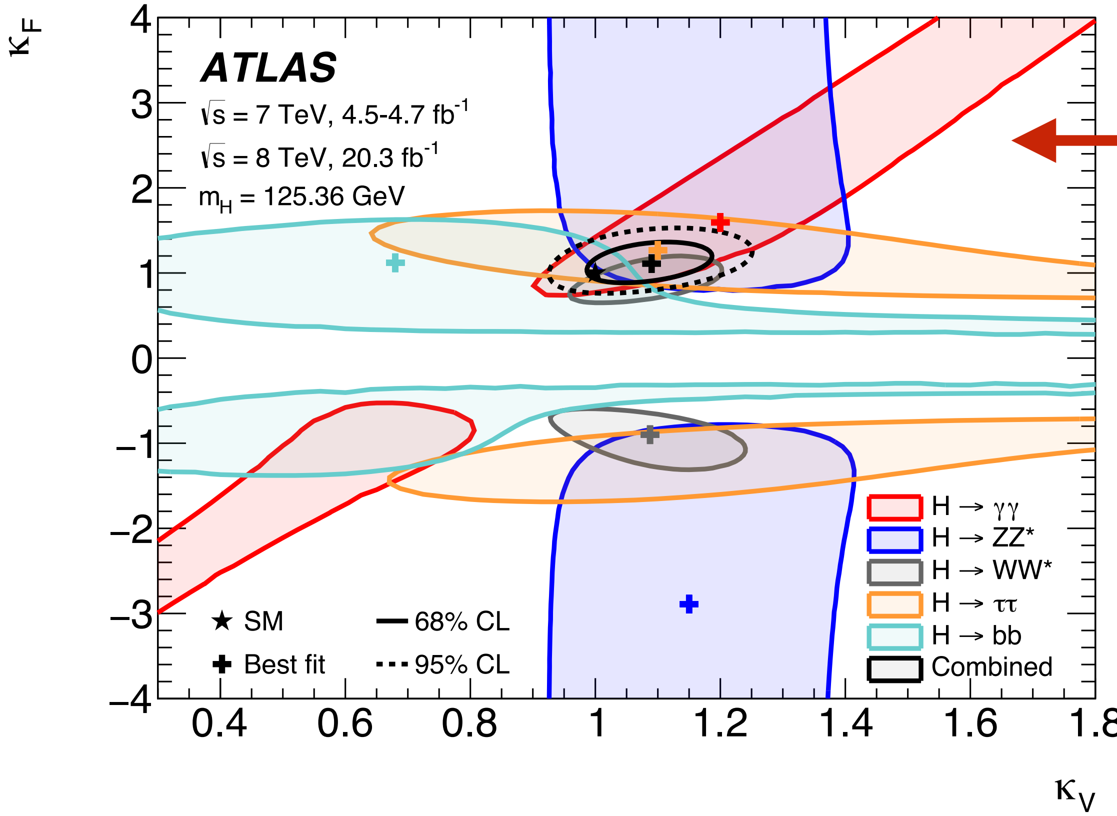
- Higgs coupling to other particles is proportional to $m_{fermion}$ or m_{boson}^2
- Leading order tree-level motivated framework, with assumptions:
  - Signal in different channels originate from single resonance
  - Narrow-width resonance, which justifies zero-width approximation
  - Lagrangian tensor structure is the same as SM Higgs ($J^P=0^+$)
- Coupling strength parametrized via scale factors κ_i w.r.t SM cross section or partial decay width

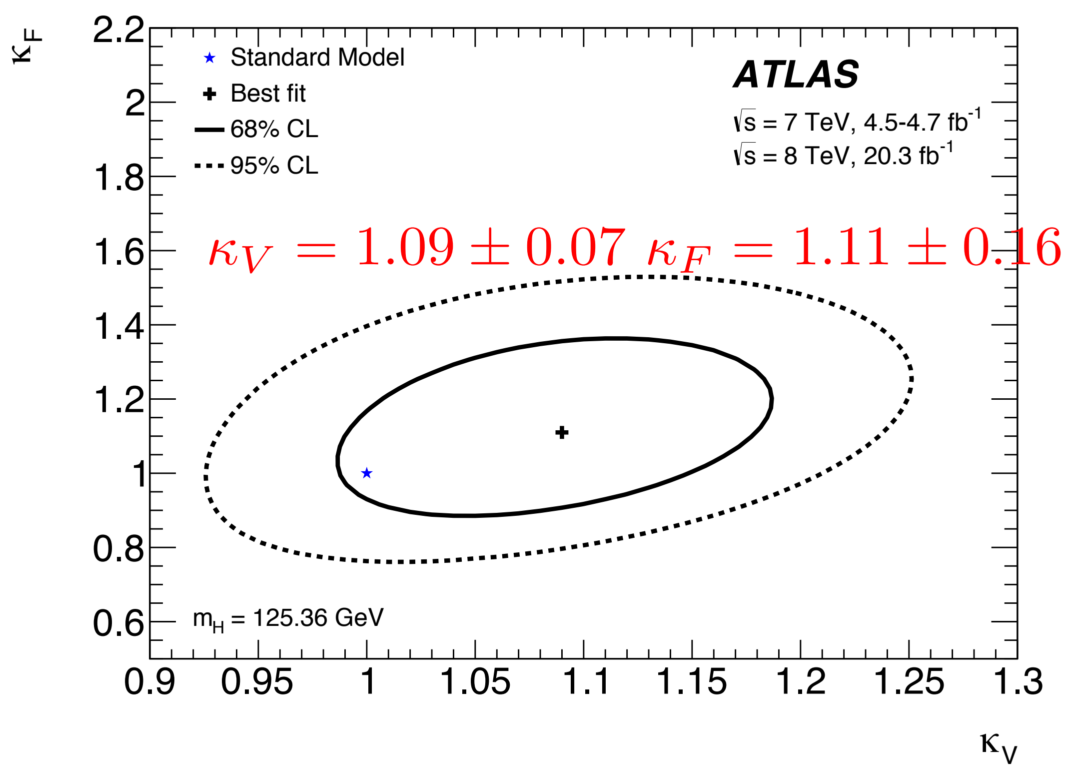
$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \right)$$

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

Production Decay Total width

Fermion vs. boson coupling (1)





- **Higgs couplings to fermions (κ_F) and bosons(κ_V) are essentially different**
- κ_γ and κ_g are expressed in terms of tree-level coupling factors (no BSM contribution)

$$\kappa_\gamma^2 \approx 0.07\kappa_{F(t)}^2 + 1.59\kappa_{V(W)}^2 \boxed{-\,0.66\kappa_F\kappa_V}$$

- κ_F-κ_V relative sign: ambiguity reduced by interference from W- and t-loop in H→γγ, negative disfavored at ~ **4.0σ**
- Assume no BSM contribution to κ_H (total width)

$$\kappa_H^2 \approx 0.25\kappa_V^2 + 0.75\kappa_F^2$$

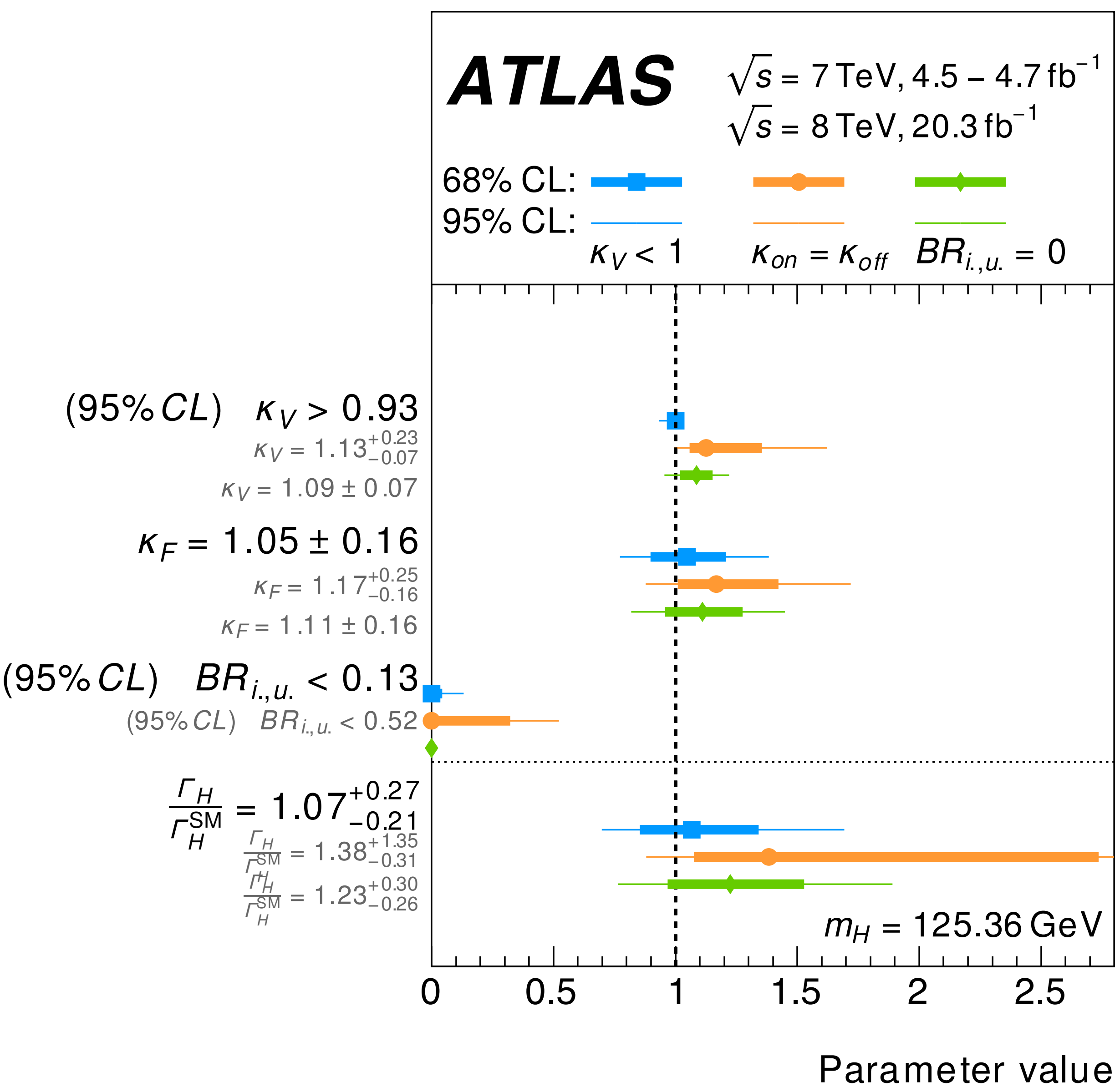
- Compatibility with SM prediction: **41%**

Ref: arXiv:1507.04548

Fermion vs. boson coupling (II)

Compatibility with SM prediction:

- $\kappa_V < 1$: **99%**
- off-shell: 29%



- **Add $BR_{i.,u.}$** as a free parameter to the κ_V-κ_F model: allow variation in SM coupling and the total width, with additional (weaker) constraints:

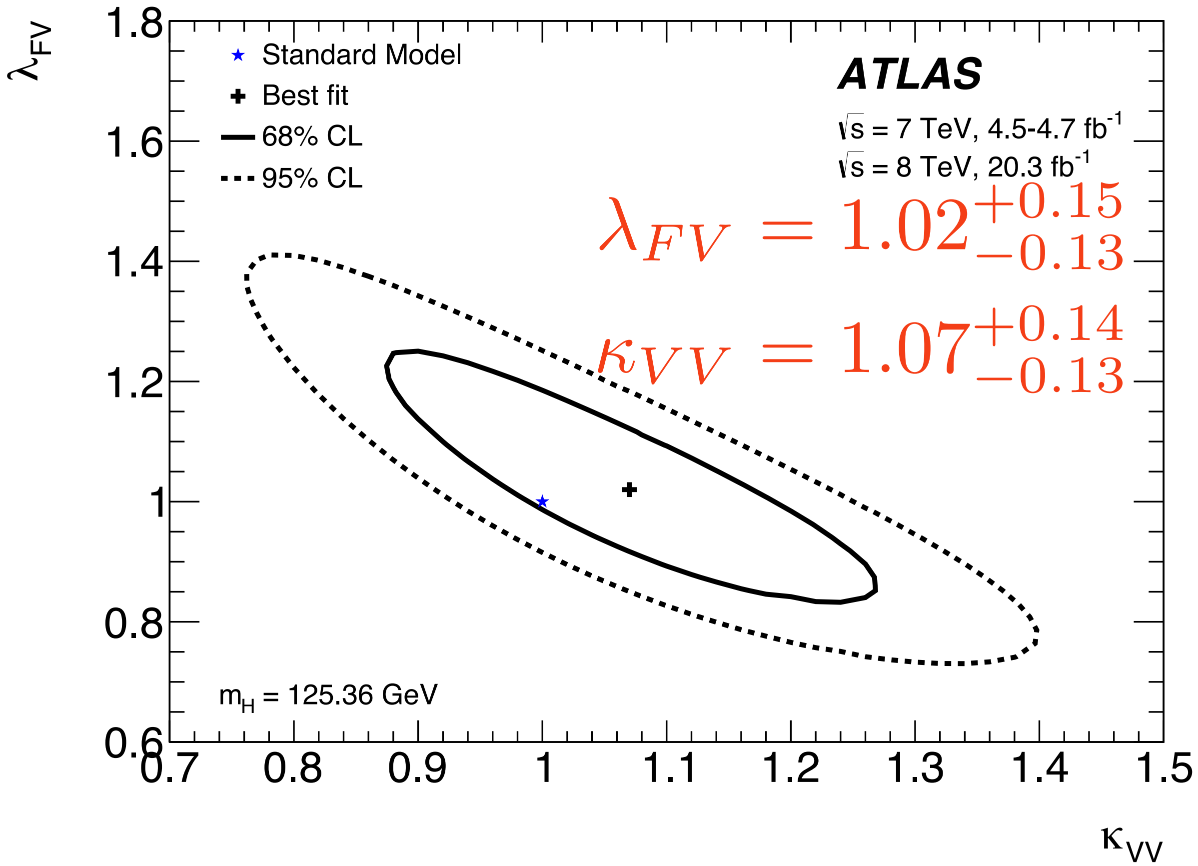
$$\kappa_H^2 = \frac{\kappa^2_{H,SM}(\kappa_V, \kappa_F)}{(1 - BR_{i.,u.})}$$

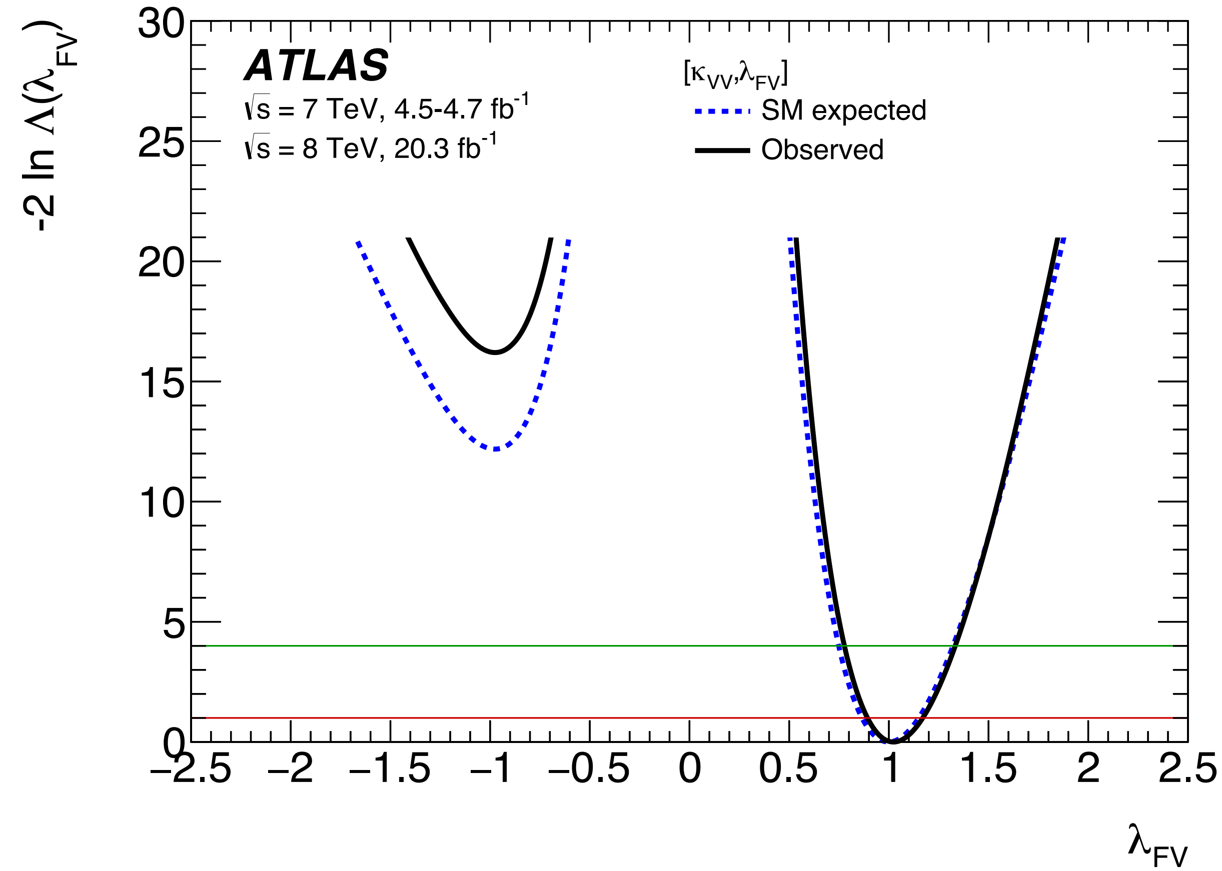
  - $\kappa_V < 1$, OR
  - $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$ (coupling strength of off-shell Higgs from $H \to WW^*/ZZ^*$ above $2m_W/2m_Z$)

- Weaker constraints on Higgs width from off-shell (95% C.L on $BR_{i.,u.}$):
  - $\kappa_V < 1$: $BR_{i.,u.} <$ **0.13**
  - off-shell: $BR_{i.,u.} <$ **0.52**

Ref: arXiv:1507.04548

Fermion vs. boson coupling (III)





$$\kappa_H^2 \approx 0.25\kappa_V^2 \boxed{+ 0.75\kappa_F^2}$$

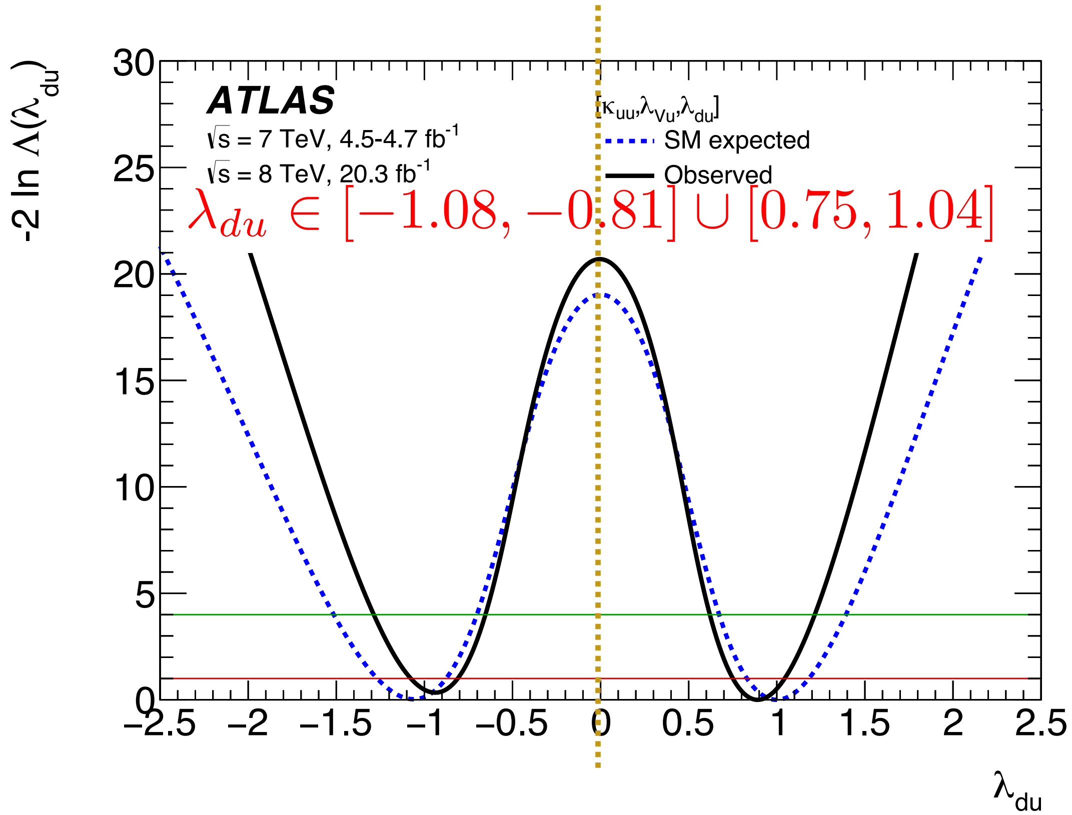
- **Remove the assumption on κ_H**, which provides strong constraint on the fermion coupling

$$\lambda_{FV} = \kappa_F/\kappa_V\,, \kappa_{VV} = \kappa_V^2/\kappa_H$$

- Compatibility with SM prediction: **41%**

Ref: arXiv:1507.04548

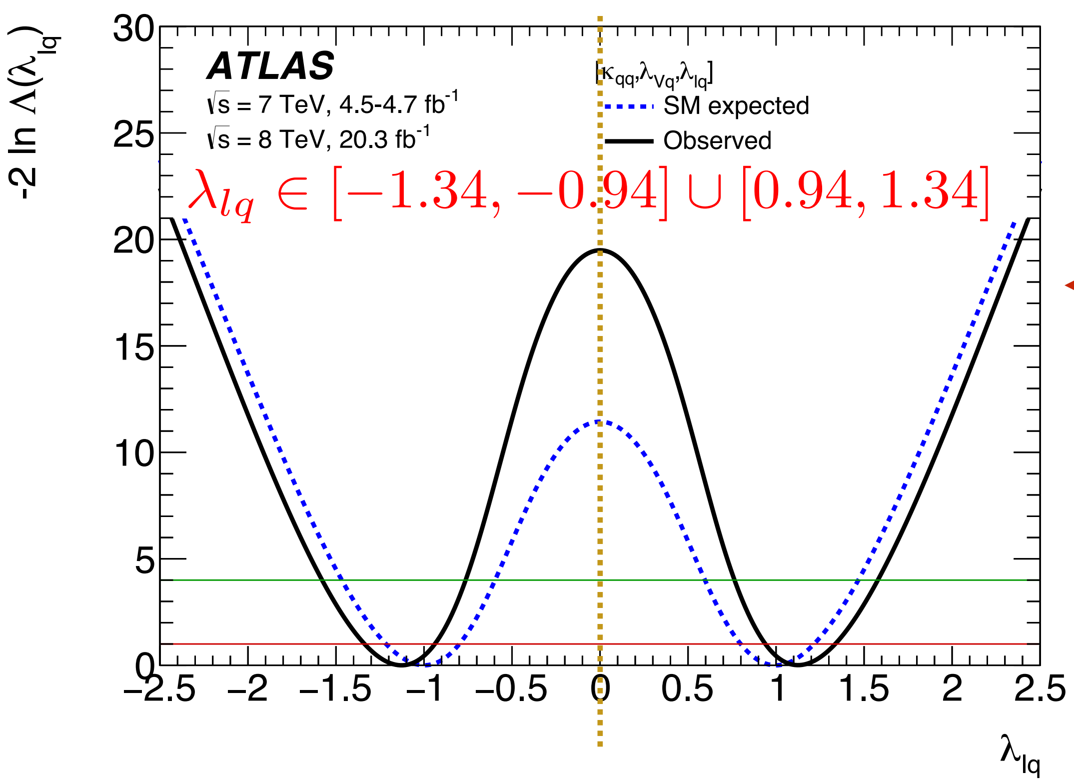
Fermion coupling sector



- **Up-down-type** fermion symmetry: test extension of Standard Model (certain Two-Higgs-Doublet Models)

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

  - Compatibility with SM prediction: **51%**
  - Evidence of Higgs coupling to down-type: **4.5σ**



- **Quark-lepton** symmetry

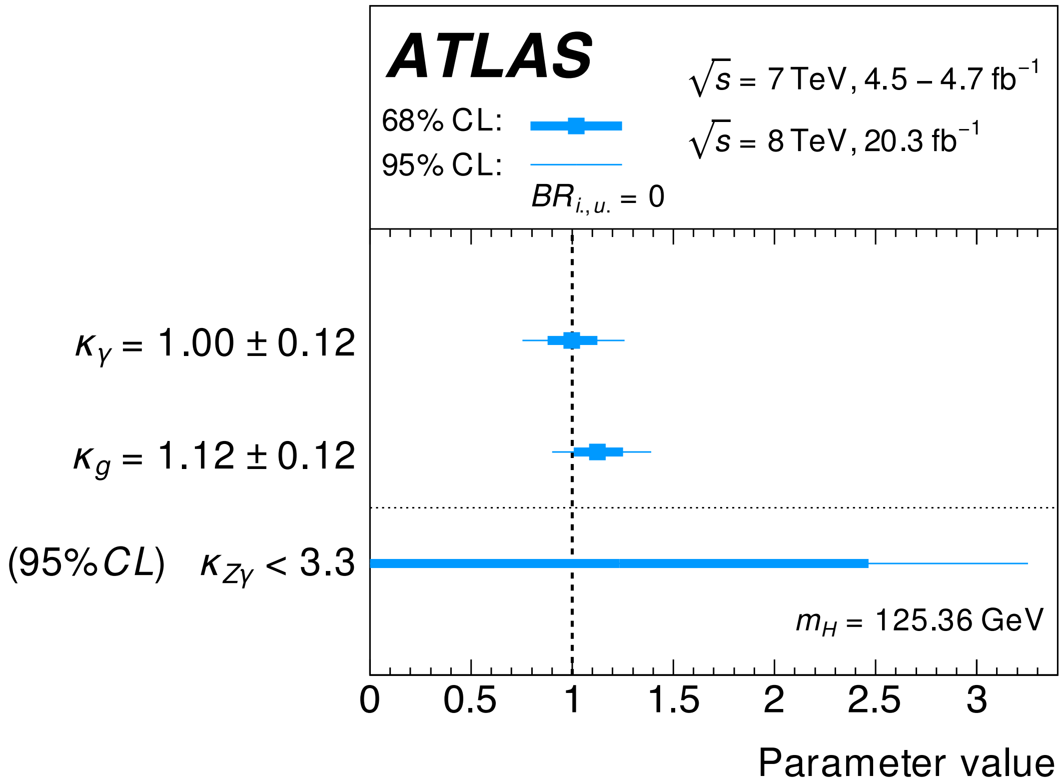
$$\lambda_{lq} = \kappa_l / \kappa_q$$

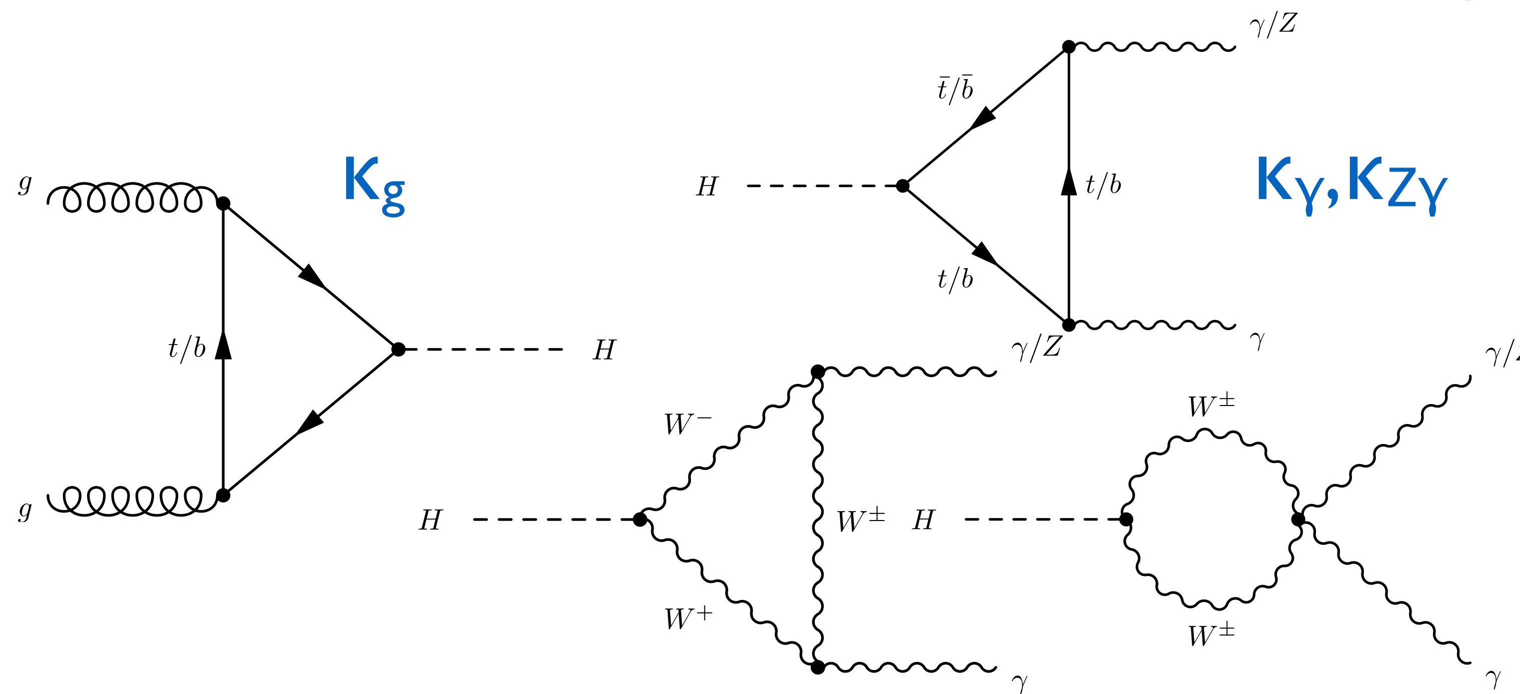
  - Compatibility with SM prediction: **53%**
  - Evidence of Higgs coupling to lepton: **4.4σ**

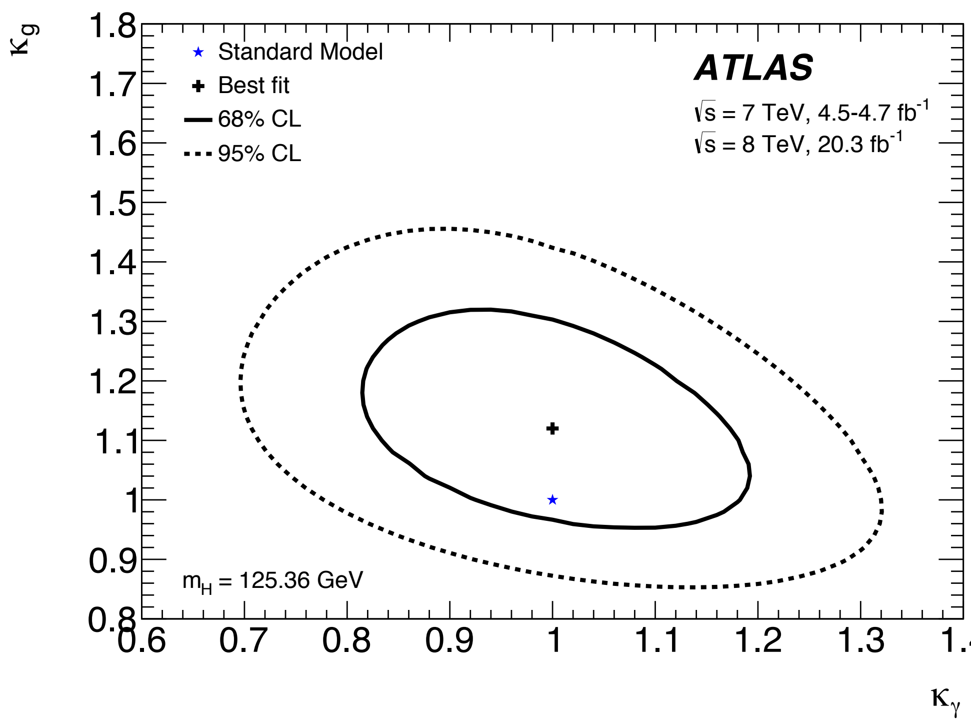
Ref: arXiv:1507.04548

BSM contribution to loop processes

Ref: arXiv:1507.04548

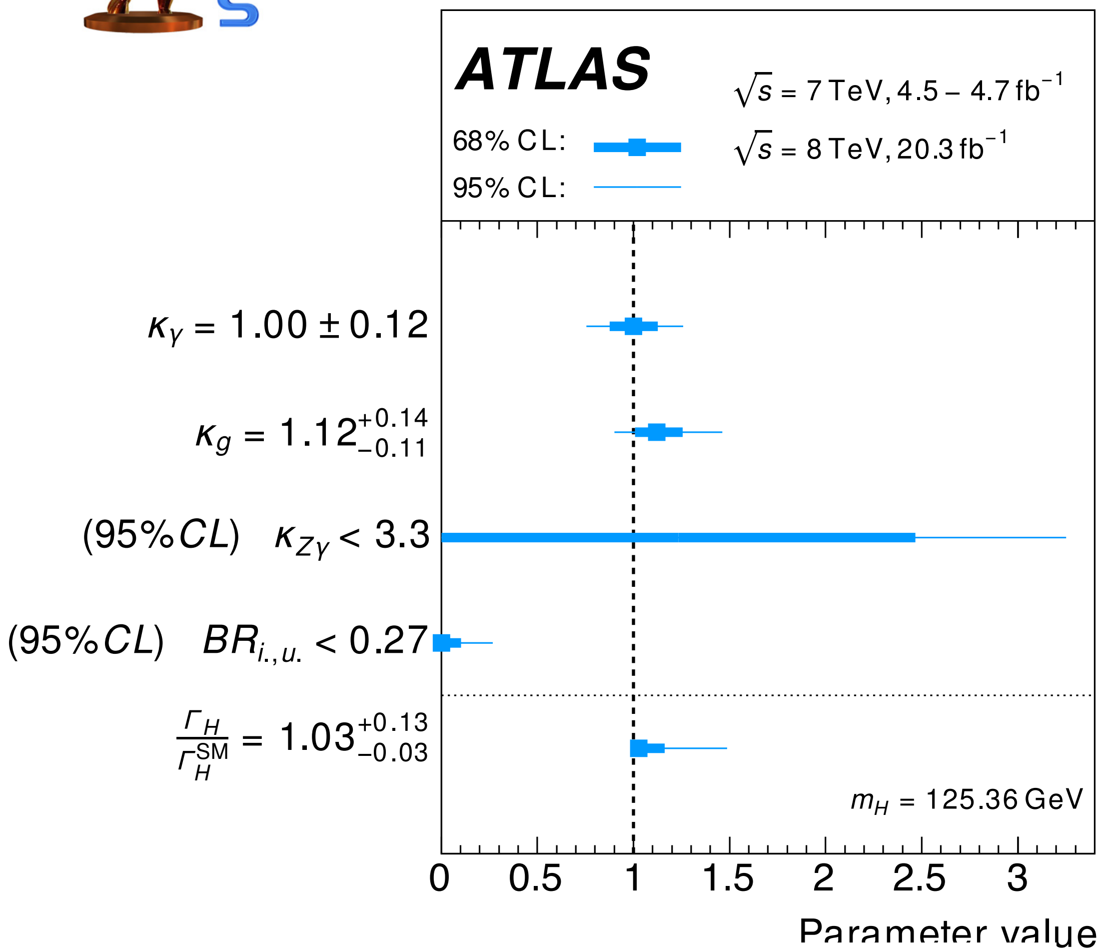


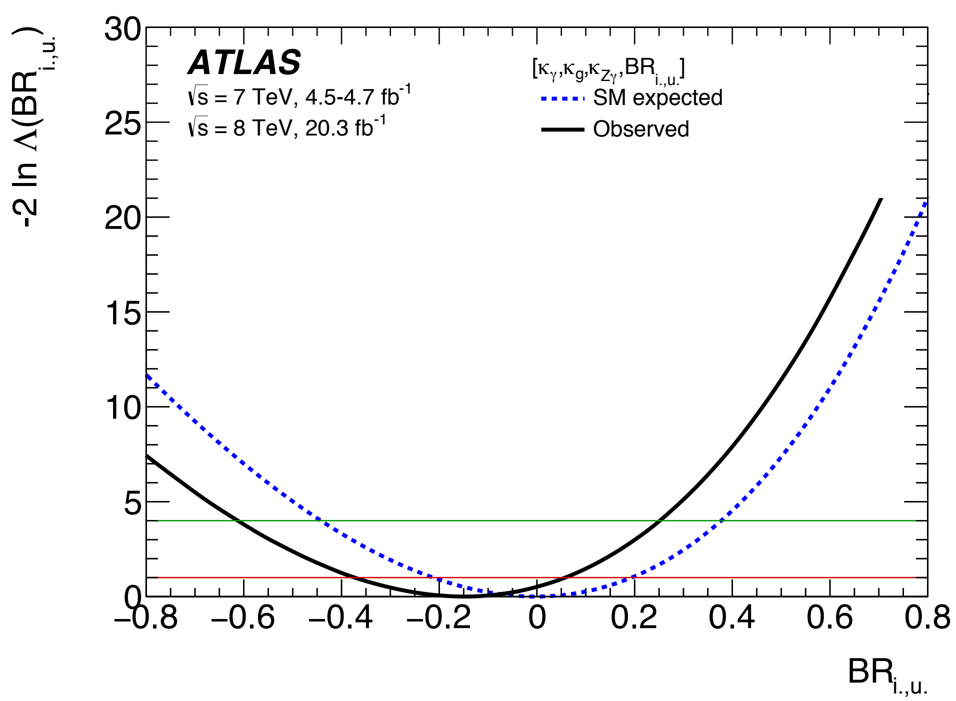




- Higgs loop-induced processes are very sensitive to heavy unknown particles: promising probes for **potential BSM contribution**
  - Effective coupling to gluon(κ_g), γ(κ_γ) and $Z\gamma$($\kappa_{Z\gamma}$)
  - Assume no BSM contribution to all other couplings (scale factors fixed to 1) and decay width
- Compatibility with SM prediction: **69%**

BSM Contribution to total width and loop processes (I)





- Add $BR_{i.,u.}$ as a free parameter to allow variation of total width

$$\kappa_H^2 = \frac{\kappa_{H,SM}^2(1, \kappa_g, \kappa_\gamma, \kappa_{Z\gamma})}{(1 - BR_{i.,u.})}$$

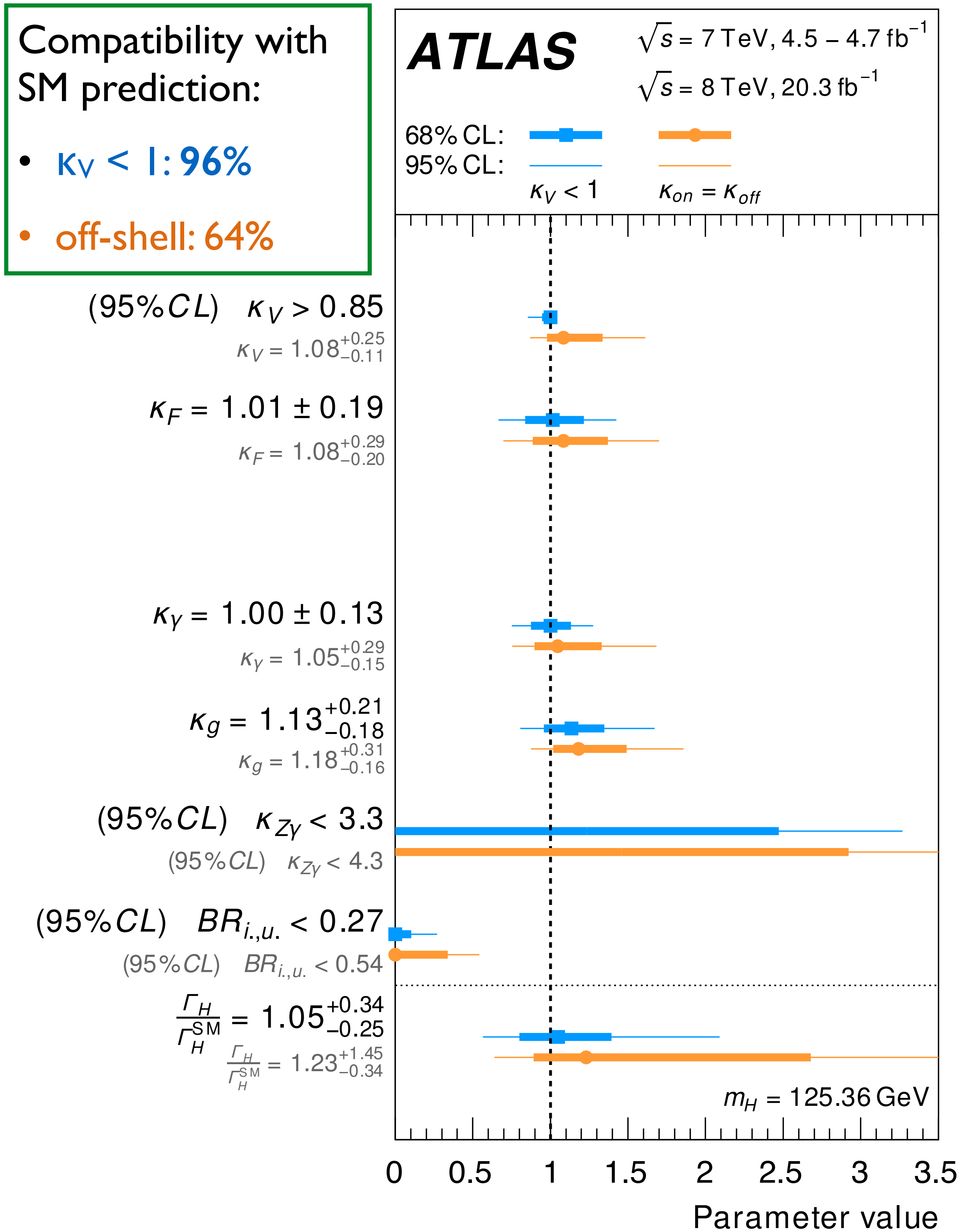
  - Effective coupling to gluon(κ_g), γ(κ_γ) and Zγ($\kappa_{Z\gamma}$)
  - Assume no BSM contribution to all other couplings (scale factors fixed to 1)
- Constraint on Higgs width mostly by VBF and VH production: $BR_{i.,u.}$ **< 0.27 (95% CL)**
- Compatibility with SM prediction: **74%**

Ref: arXiv:1507.04548

BSM Contribution to total width and loop processes (II)

Compatibility with SM prediction:

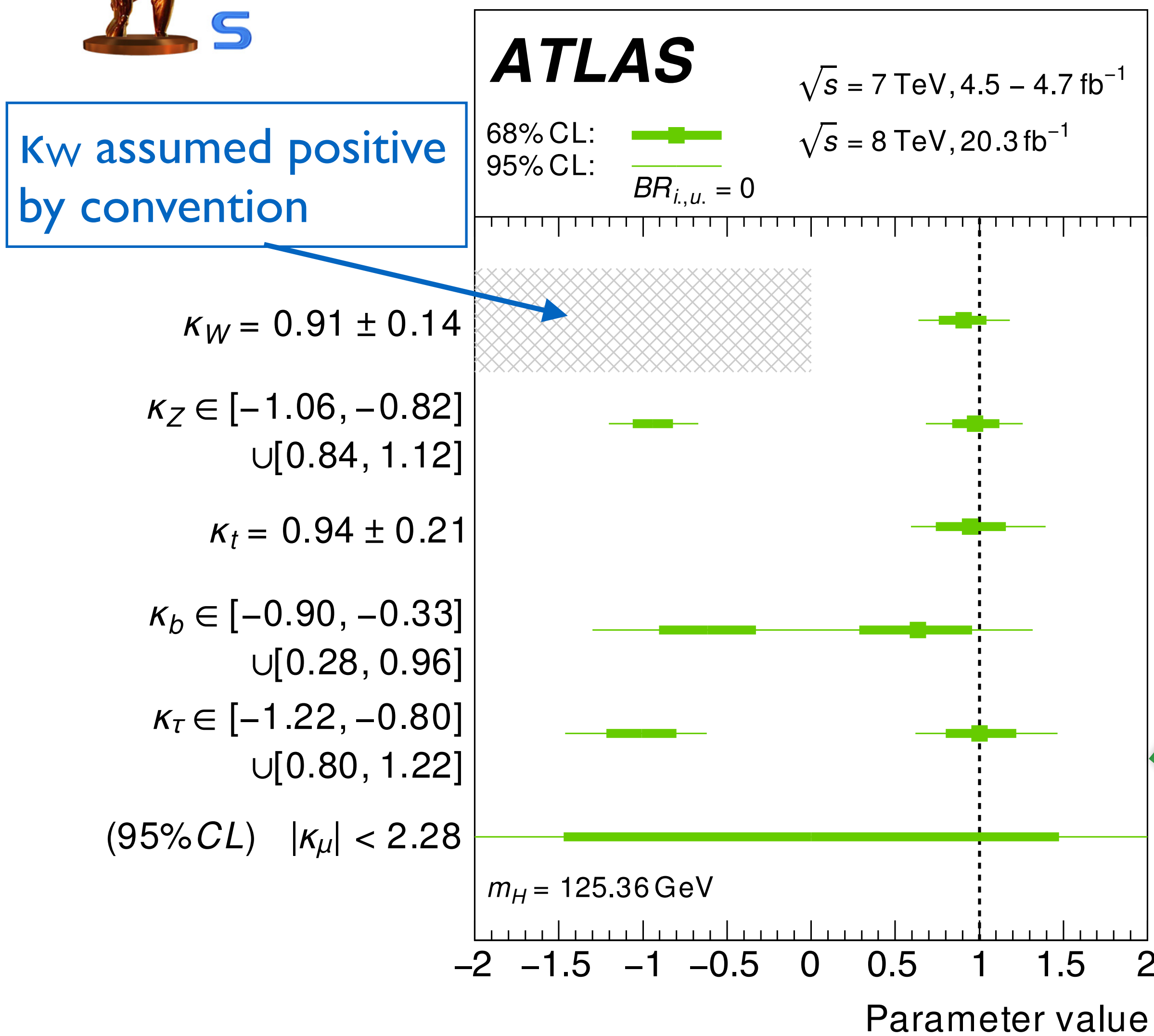
- $\kappa_V < 1$: 96%
- off-shell: 64%



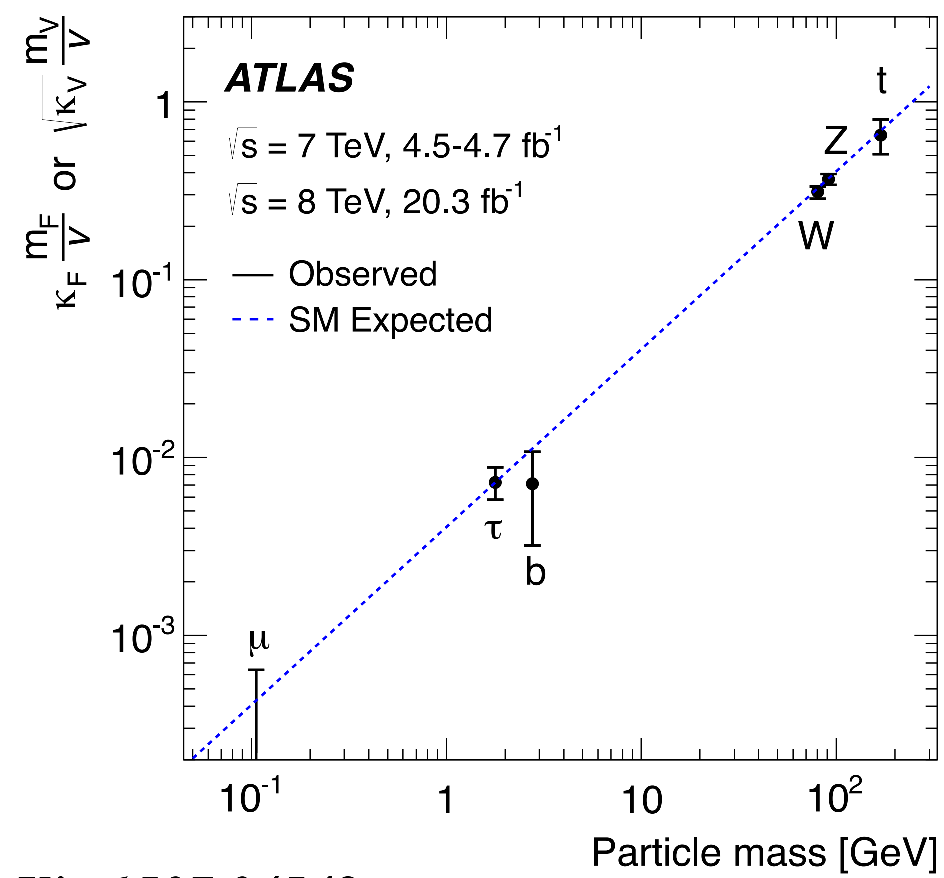
- Add $BR_{i.,u.}$ as a free parameter to the κ_V-κ_F model: allow variation in SM coupling and the total width, with additional constraints:
  - $\kappa_V < 1$, OR
  - $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$
- Simultaneously probe BSM contribution to loop induced processes via effective coupling κ_γ, κ_g and $\kappa_{Z\gamma}$
- Weaker constraints on Higgs width from off-shell (95% C.L on $BR_{i.,u.}$):
  - $\kappa_V < 1$: $BR_{i.,u.} <$ **0.27**
  - off-shell: $BR_{i.,u.} <$ **0.54**

Ref: arXiv:1507.04548

Generic model I: SM loops and total width



- Generic model of tree-level coupling factors, with 2 assumptions:
  - No BSM contribution to loop-induced processes
  - No BSM contribution to total width
- Compatibility with SM prediction: **57%**



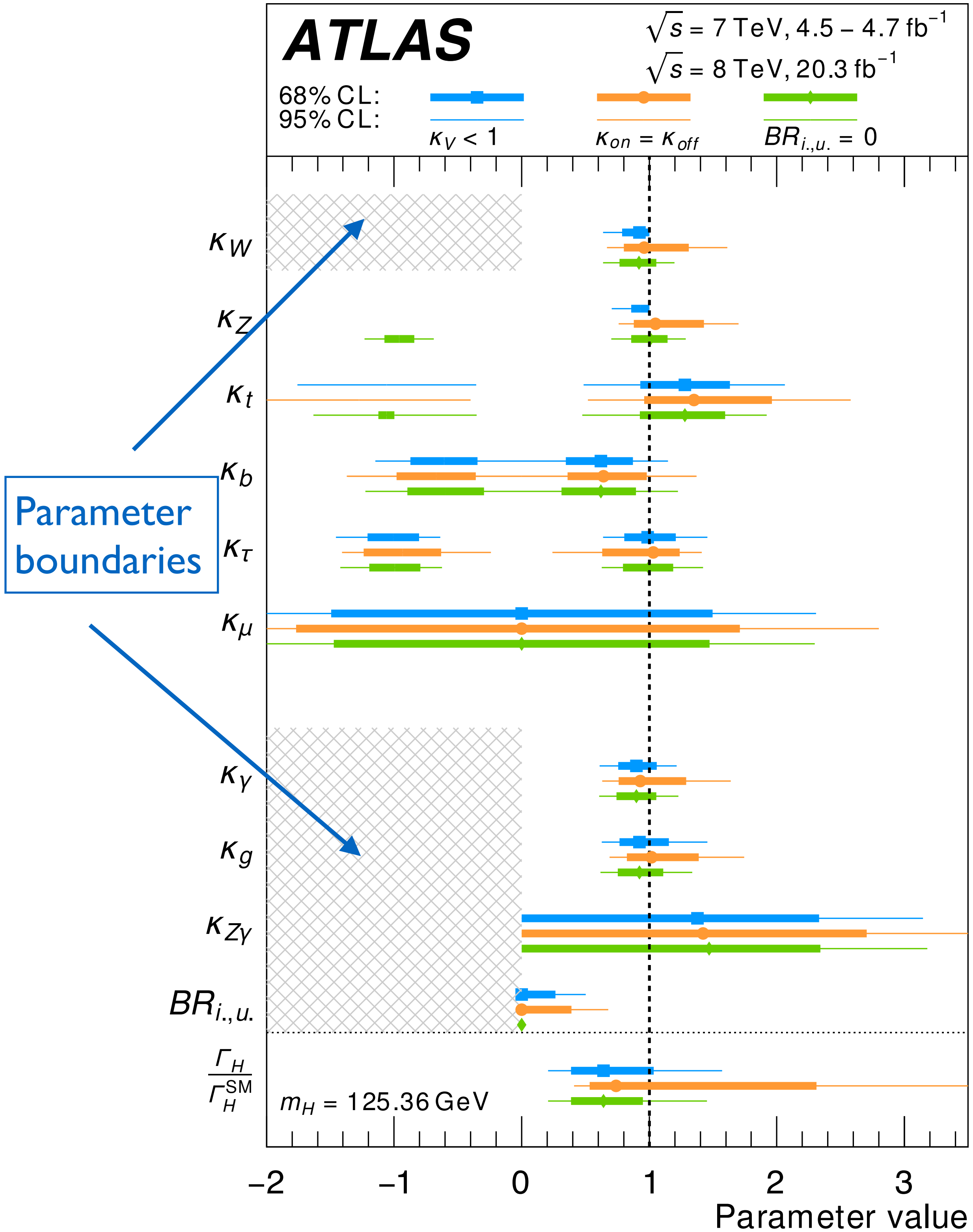
- Reduced coupling strength scale factor: linear ~ m_i

$$y_{F,i} = \kappa_{F,i}\frac{m_{F,i}}{\nu} \quad y_{V,i} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{\nu}$$

- ν: vacuum expectation value of Higgs field

Ref: arXiv:1507.04548

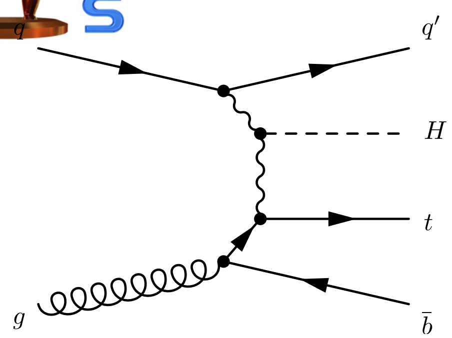
Generic model II: variation in loop and total width

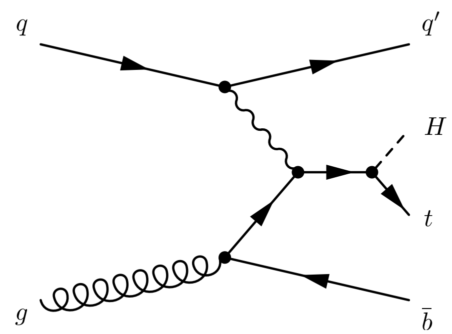


- Generic model of tree-level and effective loop coupling factors, allowing variation in loop processes and total width
- Additional constraints when total width variation is allowed:
  - $\kappa_V < 1$, OR
  - $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$
- Compatibility with SM prediction:
  - BRi.u. = 0: **73%**
  - $\kappa_V < 1$: **80%**
  - $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$: **57%**

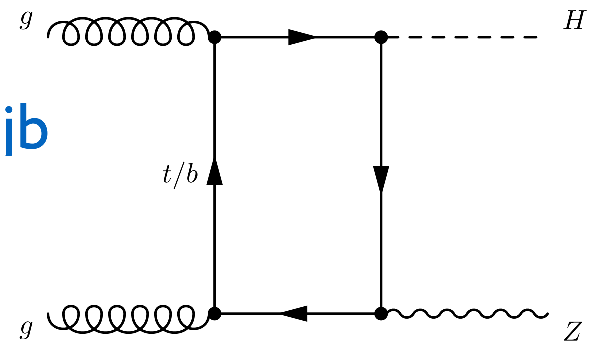
Ref: arXiv:1507.04548

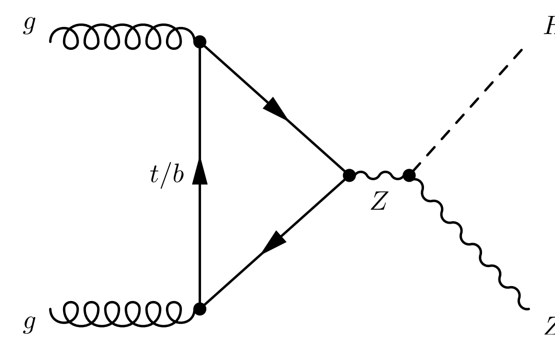
Coupling sign sensitivity: κ_t



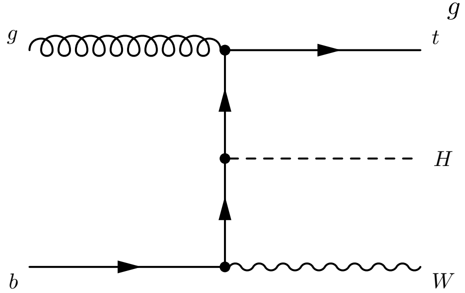


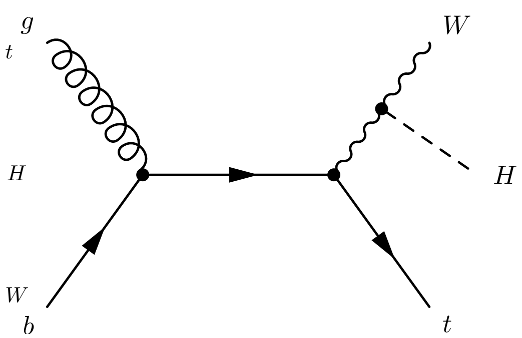
tH: tHjb



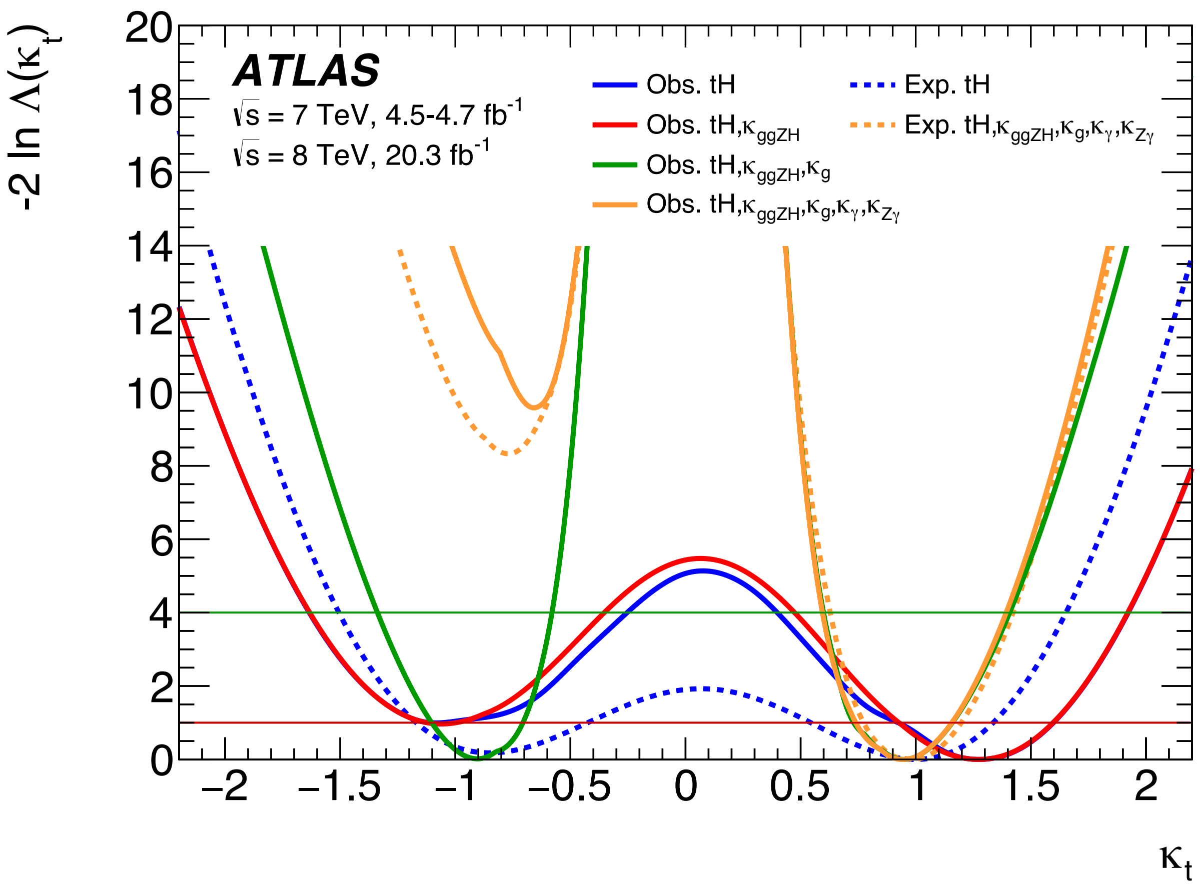


ggZH





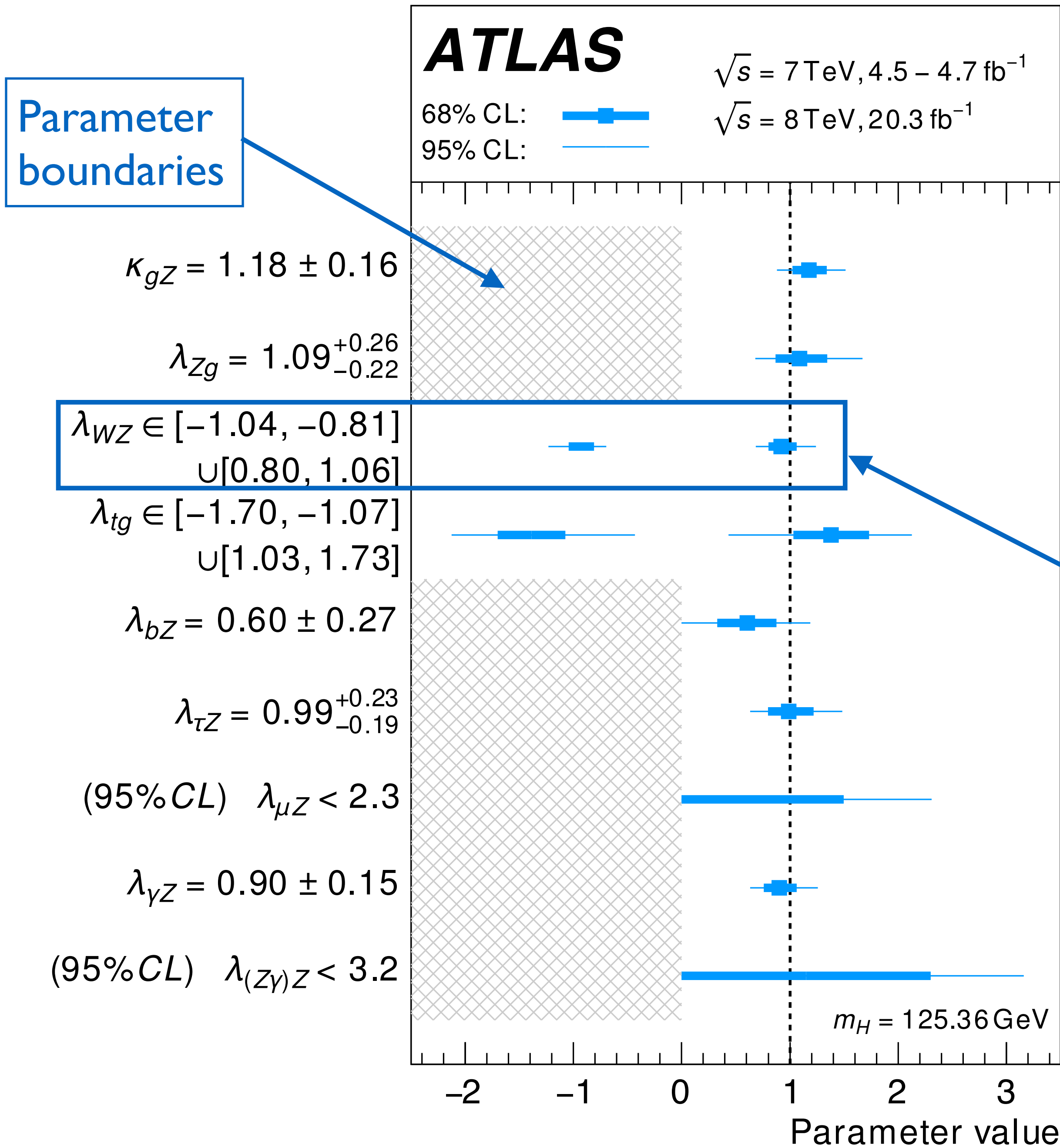
tH:WtH



- **<u>Sign sensitivity of κ_t</u>**: negative solution strongly disfavored at **3.1σ (exp. 2.9σ)**
  - + resolve ggZH: little information on κ_t
  - + resolve ggF: more precise κ_t, but reduce sign sensitivity
  - + resolve γ and Zγ loop: greatly improve sign sensitivity but little contribution to the precision of $|\kappa_t|$

Ref: <u>arXiv:1507.04548</u>

Generic Model III: coupling ratios



- Most generic model (coupling ratios) with no assumption on loop processes or total width

$$\lambda_{ij} = \kappa_i/\kappa_j, \kappa_{ii} = \kappa_i^2/\kappa_H$$

- Probe **custodial symmetry**: W and Z bosons have related couplings to the Higgs boson

$$g_{\mathrm{HVV}} \sim m_{\mathrm{V}}^2/\mathrm{VEV}$$

  - Sign sensitivity from tH and ggZH production modes: negative solution disfavored at **0.5σ (exp. 0.3σ)**

- Compatibility with SM prediction: **73%**

Ref: arXiv:1507.04548

Conclusion

- Higgs physics is in the precise measurement phase
- ATLAS combined mass measurement:

$$m_H^{\gamma\gamma+4l} = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{sys})\ \text{GeV}$$

- Evidence of production processes: VBF(**4.3σ**), WH(**2.1σ**), ZH(**0.9σ**), ttH(**2.5σ**)
- Coupling measurements are consistent with SM expectation at the level of **2σ** or better for all models considered
- The combined coupling measurement of both ATLAS and CMS experiment is ongoing.
- More precise measurement will be achieved with data from the ongoing Run II

Backup

Bibliography

- All results discussed in this presentation can be found at

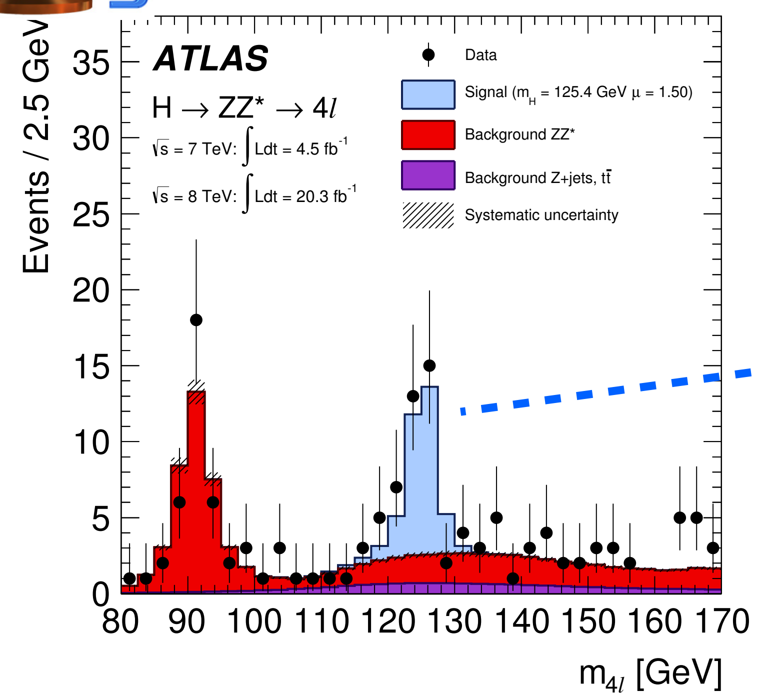
Measurement of the Higgs boson mass from the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels with the ATLAS detector at the LHC
Phys. Rev. D. 90, 052004 (2014)

and

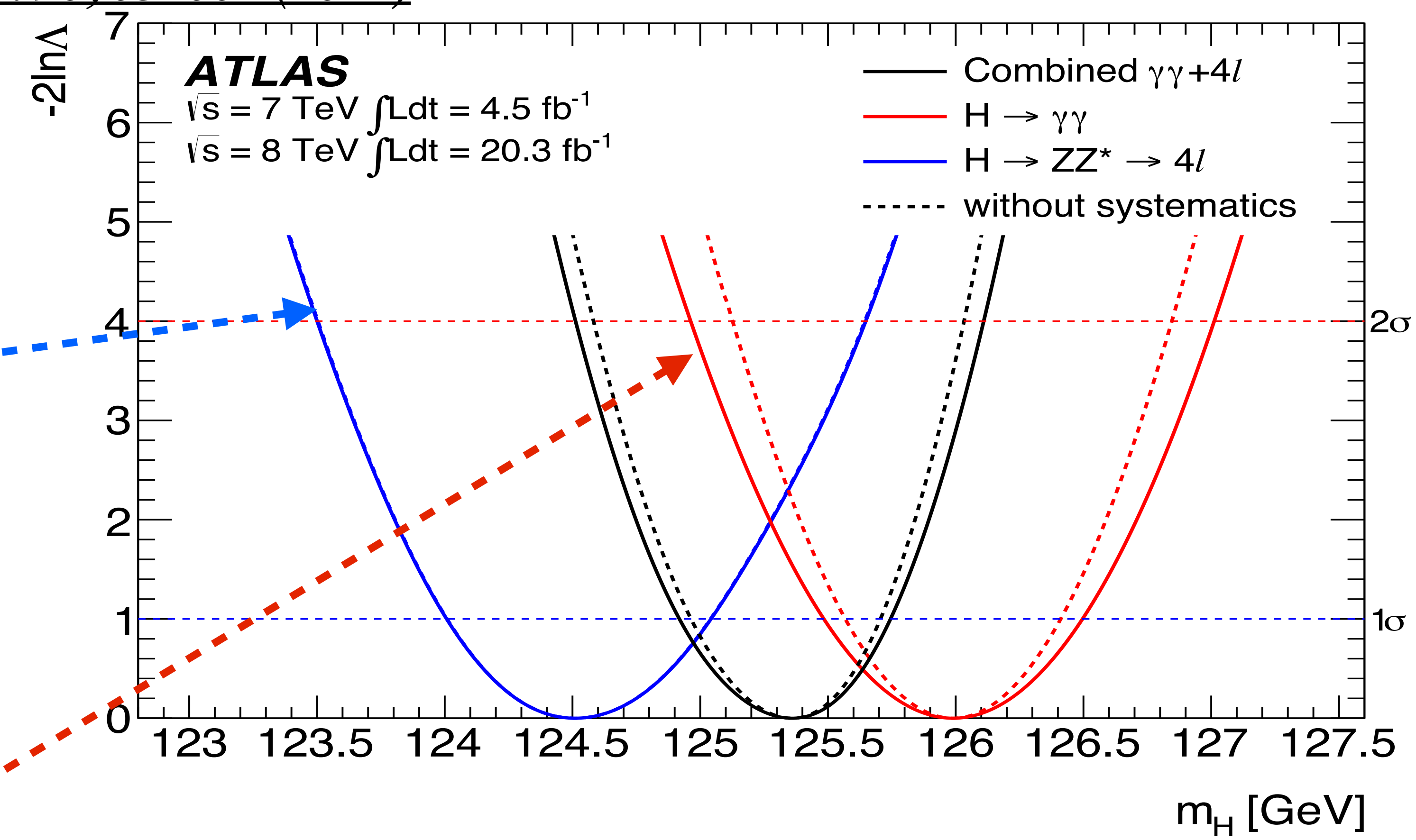
Measurements of the Higgs boson production and decay rates and couplings using pp collision data at sqrt(s) = 7 and 8 TeV in the ATLAS experiment
arXiv:1507.04548 **(submitted to EPJC)**

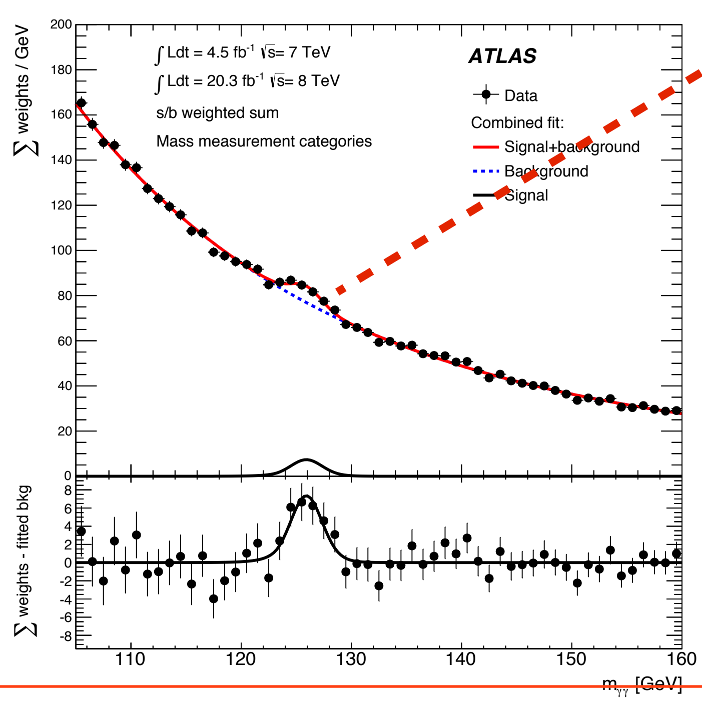
Prerequisite: combined mass measurement

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



$$m_H^{4l} = 124.51 \pm 0.52(\mathrm{stat}) \pm 0.06(\mathrm{sys})\ \mathrm{GeV}$$





$$m_H^{\gamma\gamma} = 125.98 \pm 0.42(\mathrm{stat}) \pm 0.28(\mathrm{sys})\ \mathrm{GeV}$$

- Precise mass measurement: a prerequisite of coupling measurements
- Higgs mass: last unconstrained parameter in Standard Model

$$\boldsymbol{m_H^{\gamma\gamma+4l} = 125.36 \pm 0.37(\mathrm{stat}) \pm 0.18(\mathrm{sys})\ \mathrm{GeV}}$$

- Improvements:
  - Energy calibration → better mass resolution
  - Analyses dedicated to mass measurement

Coupling model parametrization

Production	Loops	Interference	Expression in fundamental coupling-strength scale factors
$\sigma(\text{ggF})$	✓	b–t	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\text{VBF})$	-	-	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	-	-	$\sim \kappa_W^2$
$\sigma(q\bar{q} \to ZH)$	-	-	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	Z–t	$\kappa_{ggZH}^2 \sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(bbH)$	-	-	$\sim \kappa_b^2$
$\sigma(ttH)$	-	-	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	-	W–t	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq')$	-	W–t	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
Partial decay width			
$\Gamma_{b\bar{b}}$	-	-	$\sim \kappa_b^2$
Γ_{WW}	-	-	$\sim \kappa_W^2$
Γ_{ZZ}	-	-	$\sim \kappa_Z^2$
$\Gamma_{\tau\tau}$	-	-	$\sim \kappa_\tau^2$
$\Gamma_{\mu\mu}$	-	-	$\sim \kappa_\mu^2$
$\Gamma_{\gamma\gamma}$	✓	W–t	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma_{Z\gamma}$	✓	W–t	$\kappa_{Z\gamma}^2 \sim 1.12 \cdot \kappa_W^2 + 0.00035 \cdot \kappa_t^2 - 0.12 \cdot \kappa_W \kappa_t$
Total decay width			
Γ_H	✓	$W-t$ $b-t$	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.00022 \cdot \kappa_\mu^2$

Statistical Procedure

- Likelihood function constructed for each individual channel

expected evt #

systematics: nuisance parameter (NP)

constraint on NPs

$$L_c(\mathcal{D}_c|\nu_c,\boldsymbol{\theta}_c) = \mathrm{Pois}(n_c|\nu_c)\prod_{e_c=1}^{n_c} f_c(x_{e_c}|\boldsymbol{\theta}_c)\cdot \boxed{\prod_p g_{p,c}(a_{p,c}|\theta_{p,c})}$$

observed evt #

observable

estimated central value of $\theta_{p,c}$

- Combination by taking product of the likelihood of individual channels and correlating systematics, if necessary

individual likelihood excluding constraint

not simple product of $g_{p,c}$

$$L(\mathcal{D}|\boldsymbol{\nu},\boldsymbol{\theta}) = \boxed{\prod_c \tilde{L}_c(\mathcal{D}_c|\nu_c,\boldsymbol{\theta_c})}\boxed{\prod_p g_p(a_p|\theta_p)}$$

- Hypothesis testing based on the profile likelihood ratio

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

conditional minimum for a given μ

unconditional(global) minimum

μ: parameter of interest, e.g

- signal strength (μ_i)
- mass (m_H) and mass difference (Δm_H)
- coupling scale factors λ_i, κ_i

Formulae for Various Measurements

- Likelihood for combined mass measurement:

$$\Lambda(m_H) = \frac{L(m_H, \hat{\hat{\mu}}_{\gamma\gamma}(m_H), \hat{\hat{\mu}}_{4l}(m_H), \hat{\hat{\theta}}(m_H))}{L(\hat{m}_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4l}, \hat{\theta})}$$

- Likelihood for consistency check of mass measurements:

$$\Lambda(\Delta m_H) = \frac{L(\Delta m_H, \hat{\hat{\mu}}_{\gamma\gamma}(\Delta m_H), \hat{\hat{\mu}}_{4l}(\Delta m_H), \hat{\hat{m}}_H(\Delta m_H), \hat{\hat{\theta}}(\Delta m_H))}{L(\hat{\Delta} m_H, \hat{\mu}_{\gamma\gamma}, \hat{\mu}_{4l}, \hat{m}_H, \hat{\theta})}$$

- SM loop-induced processes:

$$\kappa^2_{\gamma(g)} = \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma^{ij}_{\gamma\gamma(gg)}}{\sum_{i,j} \Gamma^{ij}_{\gamma\gamma(gg)}} \quad i,j \in \begin{cases} \{t,b\} & \text{for } \kappa_g \\ \{t,b,l,W\} & \text{for } \kappa_\gamma \end{cases}$$

- SM total Higgs decay width:

$$\kappa^2_H = \sum_x \kappa^2_x \cdot BR_{SM}(H \to xx)$$

- Expected event yield:

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

$$\to \mu = \mu_i \cdot \mu_f$$