ATLAS Higgs coupling measurements

BSM Higgs workshop @ LPC, 3-5 November 2014

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on behalf of the ATLAS collaboration

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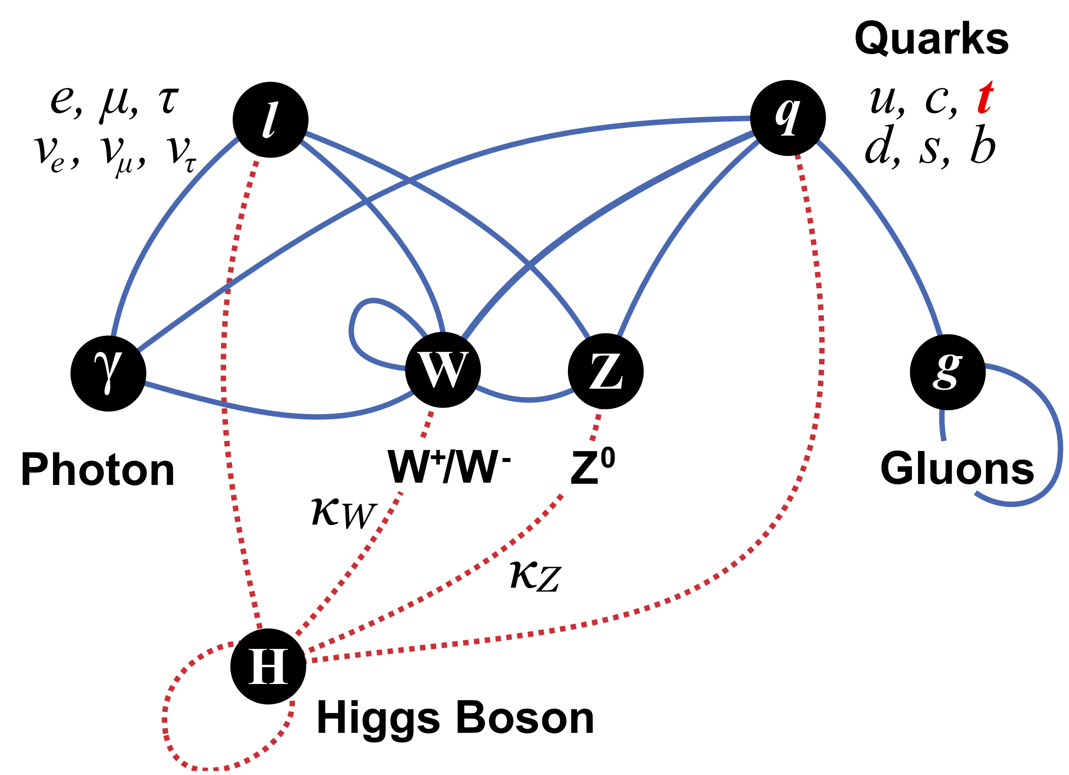
- Inputs to the coupling fits
- Results
  - Signal strength
  - Coupling scale factors
  - Sensitivity to new physics / coupling ratios
- Interpretation in terms of few selected BSM models

Introduction

- Search for deviation of SM Higgs couplings
  - Possibly due to coupling to new particles
- Introducing **multipliers** κ to a **tree level motivated** benchmark model
  - In SM all multipliers = 1

$$
\begin{aligned}
\mathcal{L} = {} & \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H \\
& + \kappa_g \frac{\alpha_s}{12\pi v} G_{\mu\nu}^a G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H \\
& + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W_{\mu\nu}^+ W^{-\mu\nu} \right) H \\
& - \left(\kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\overline{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\overline{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\overline{f} \right) H.
\end{aligned}
$$

Standard Model couplings



Testing the SM couplings

- Following the LHC Higgs XS WG recommendations: http://arxiv.org/abs/1209.0040

- Assumptions
  - Single, narrow, CP−even scalar resonance
    (tensor structure of couplings assumed to be SM one)

Narrow width approximation:

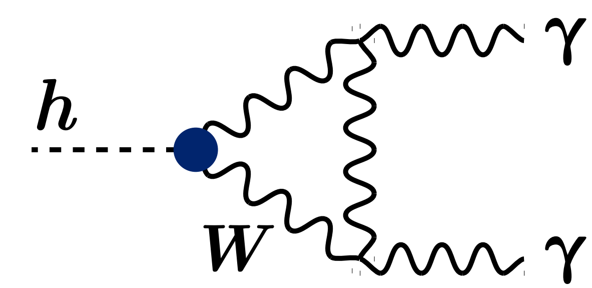
$$\sigma\mathcal{B}\,(i \to H \to f) = \frac{\sigma_i \Gamma_f}{\Gamma_H}$$

- Deviations from SM Higgs parametrized using scaling factors κ :

production: $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{\text{SM}}}$ decay: $\kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\text{SM}}}$ width: $\kappa_H^2 = \frac{\sum \kappa_j^2 \Gamma_j^{\text{SM}}}{\Gamma_H^{\text{SM}}}$

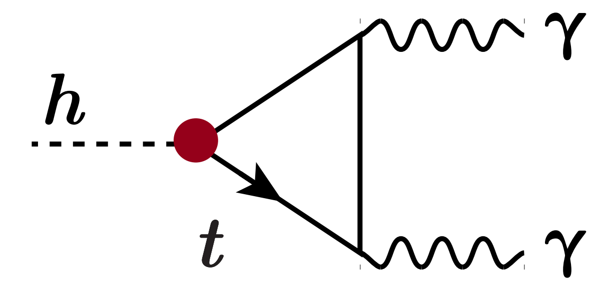
- Example:

$$\sigma\mathcal{B}\,(gg \to H \to \gamma\gamma) = (\sigma_{\text{ggF}}\mathcal{B})_{\text{SM}}\,(gg \to H \to \gamma\gamma) \times \frac{\kappa_g^2 \kappa_\gamma^2}{\kappa_H^2}$$



- κ_g and κ_γ are effective multipliers as Higgs couples only via loops to these particles, containing interference term:

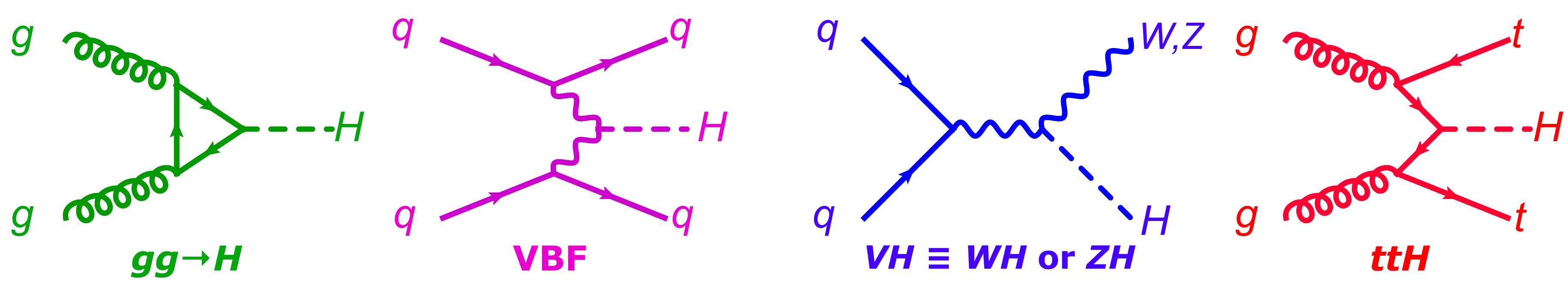
$$\kappa_\gamma^2 = 1.59\kappa_W^2 - 0.66\kappa_W\kappa_t + 0.07\kappa_t^2$$



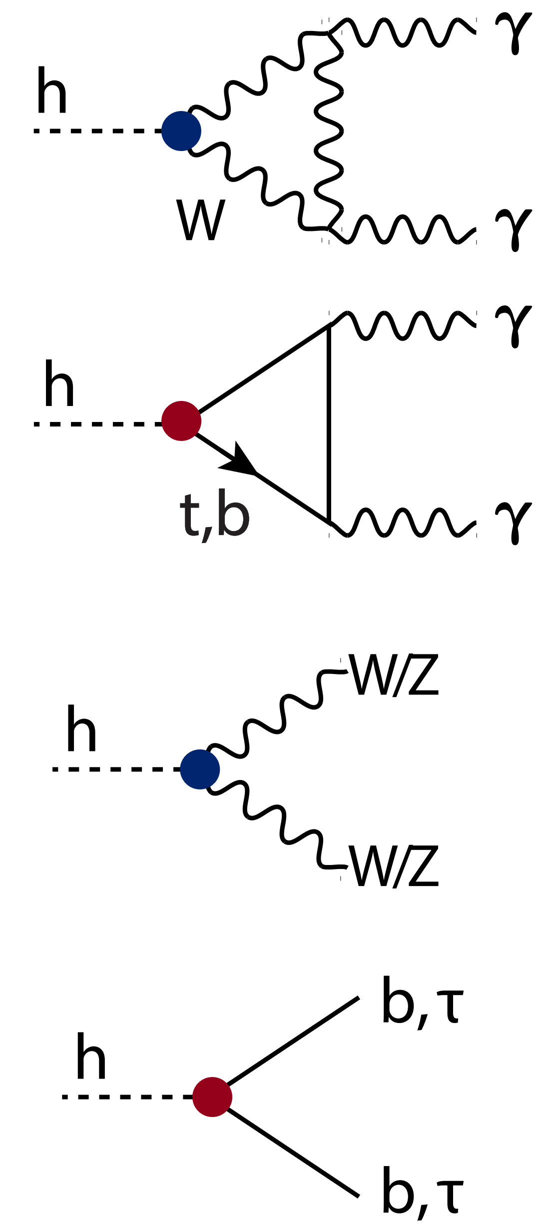
- These relations are modified if non-standard model particles enter

Higgs production and decay

Production modes:



Decays:



Parameter of interest:

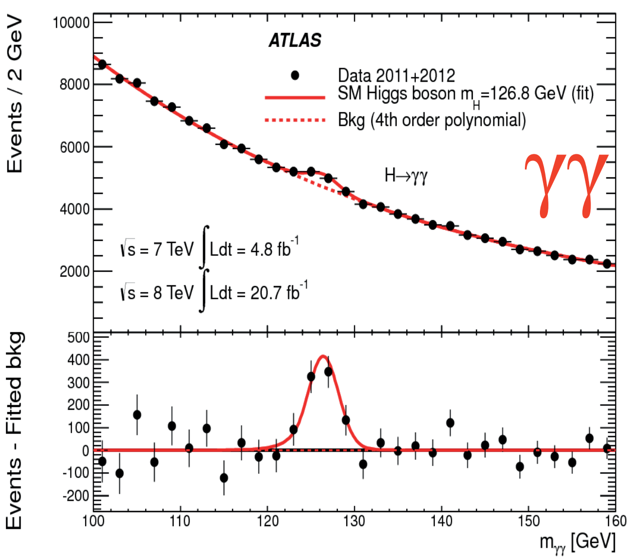
- **Multiplier κ for a given coupling**
  - E.g. κ_t for the Higgs-top quark coupling
  - Also effective couplings, e.g. κ_γ, are considered
  - Different types of models tested by imposing relations between certain scale factors
- **Signal strength $\mu = \sigma_{measured} / \sigma_{SM}$**
  - Multiplier for total yield
  - Can also be defined for each production mode, e.g:
    - $\mu_{VBF} = \sigma_{VBF,measured} / \sigma_{VBF,SM}$
- In both cases, **SM has $\mu = 1$ and $\kappa = 1$**
  - Deviations from unity indicate non-SM Higgs couplings

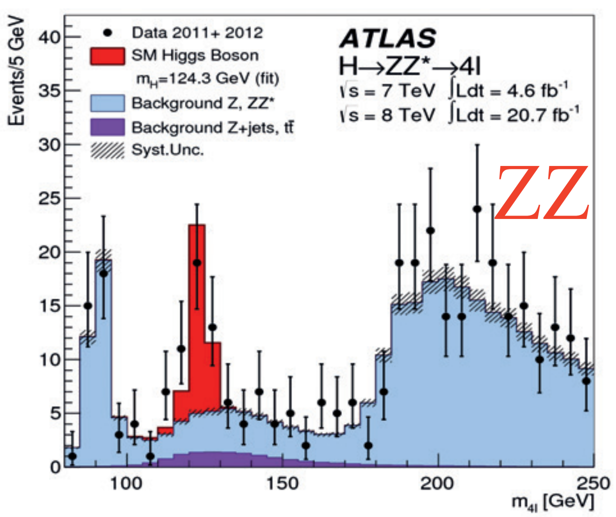
Note: κ allow for more direct access to couplings as μ, contain complex interplay between production and decay

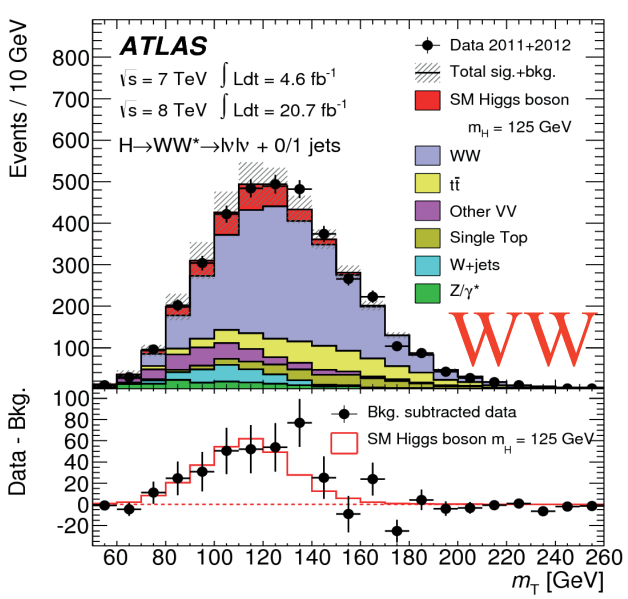
Input to coupling fits

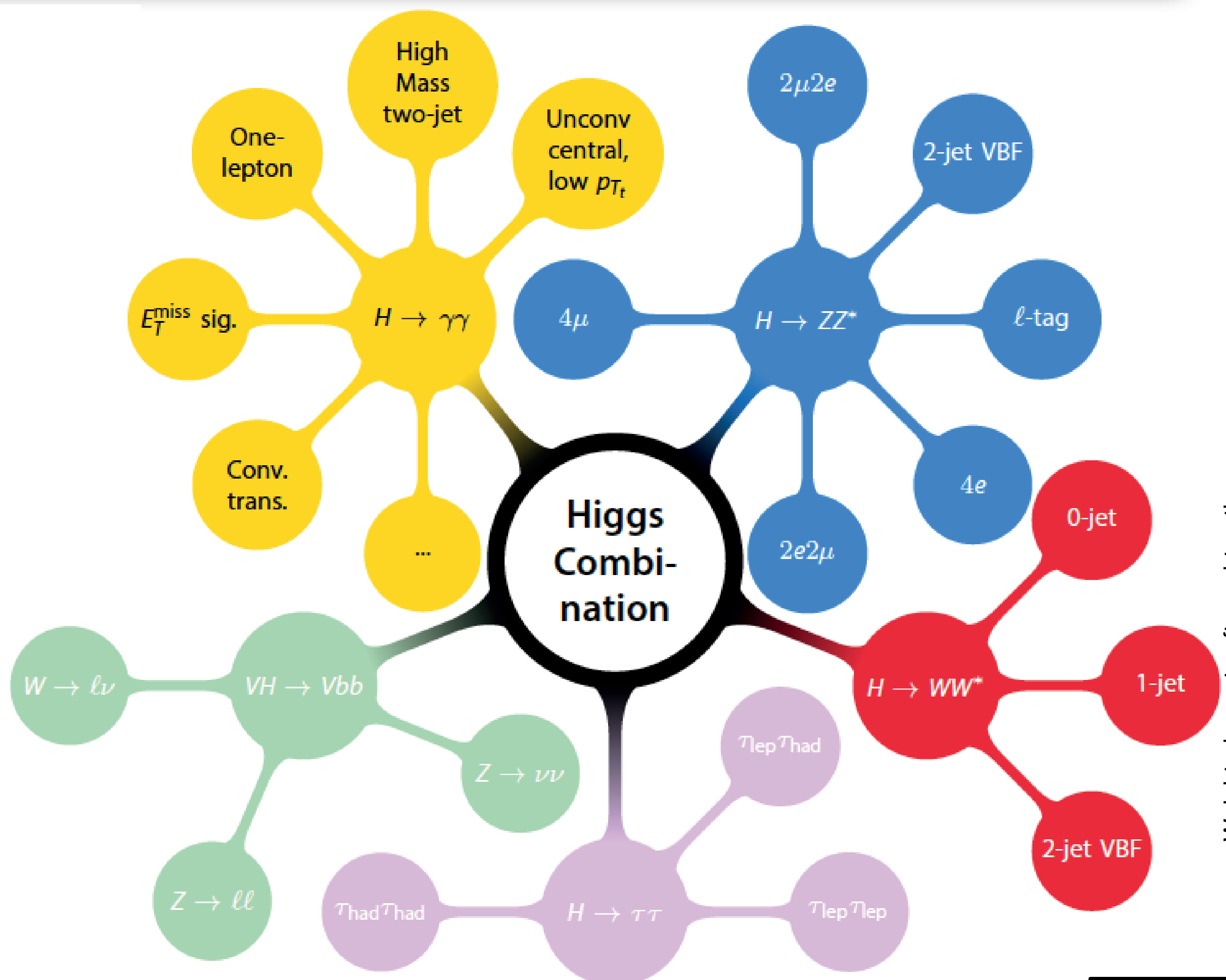
$4.8\,\mathrm{fb}^{-1}$ @ 7 TeV and $20.3\,\mathrm{fb}^{-1}$ @ 8 TeV

Phys. Lett. B726 (2013) 88









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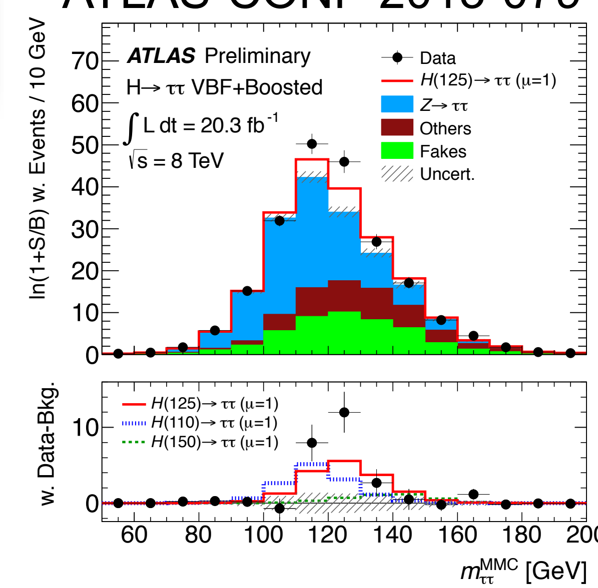

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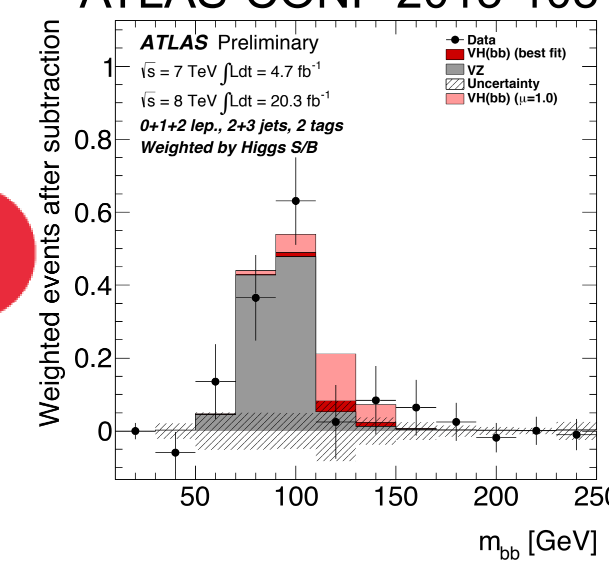
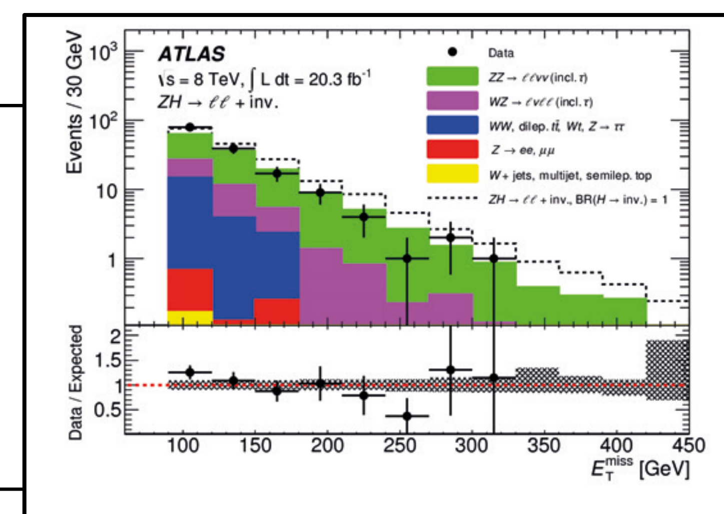


Constrain invisible width of Higgs using Missing Transverse Energy spectrum from Zh → ll + E_T^{miss} channel:

Phys. Rev. Lett. 112 (2014) 201802



Results

Combined signal strength

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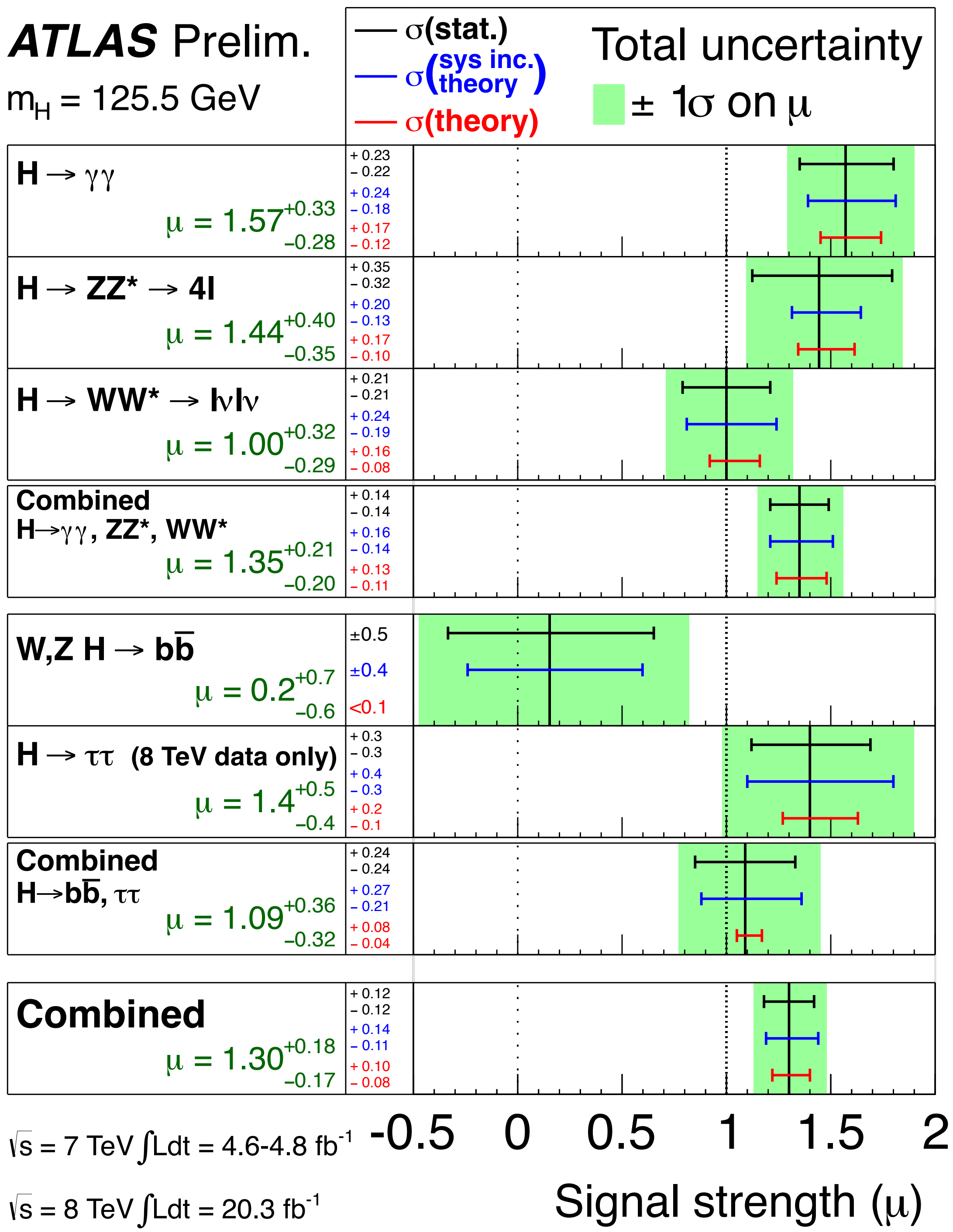
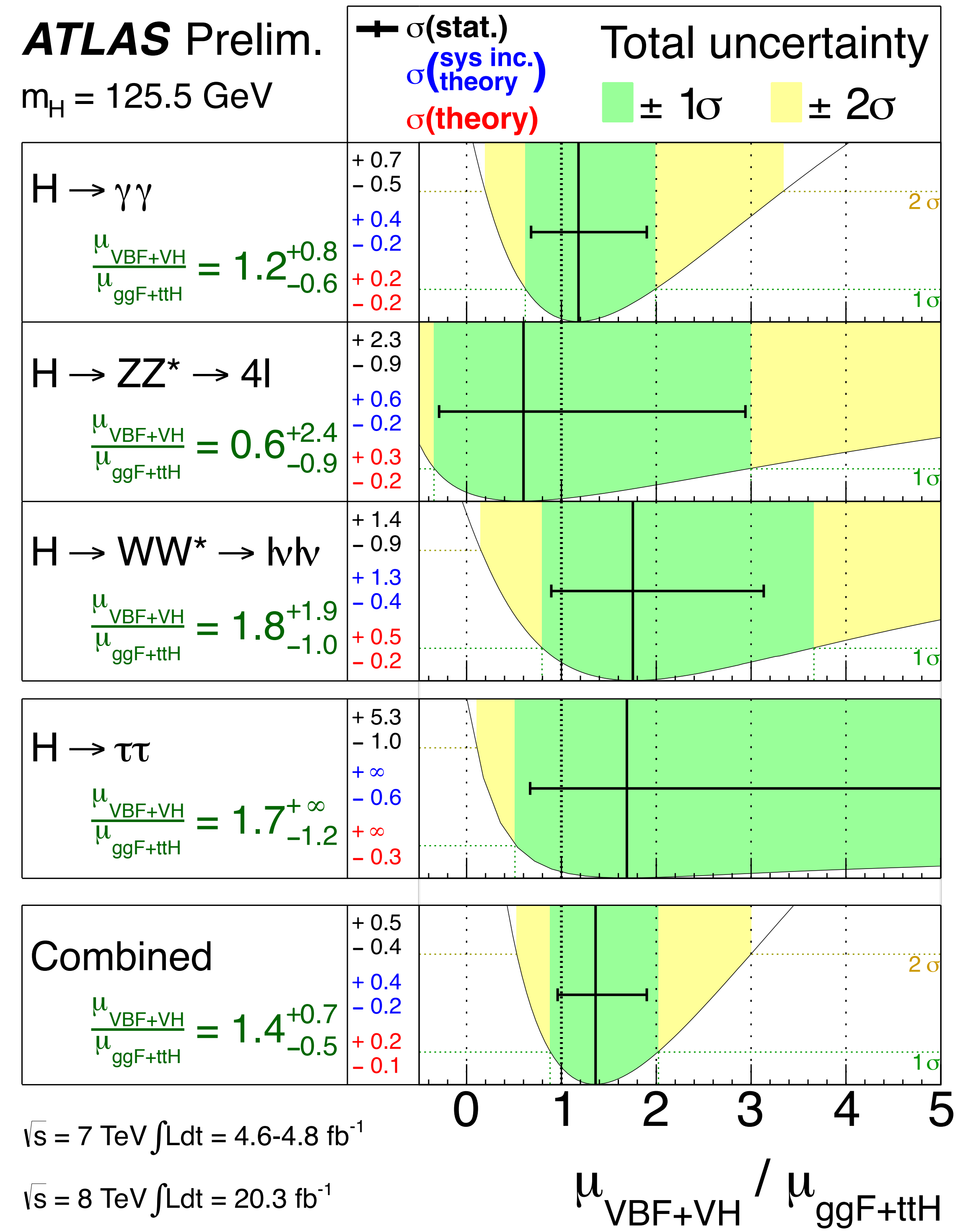
signal strength by decay mode:



signal strength by production modes:



combined $\mu = 1.30^{+0.18}_{-0.17}$

$\mu_{\mathrm{VBF+VH}}/\mu_{\mathrm{ttH+ggF}} = 1.4^{0.7}_{-0.5}$

Probing custodial symmetry

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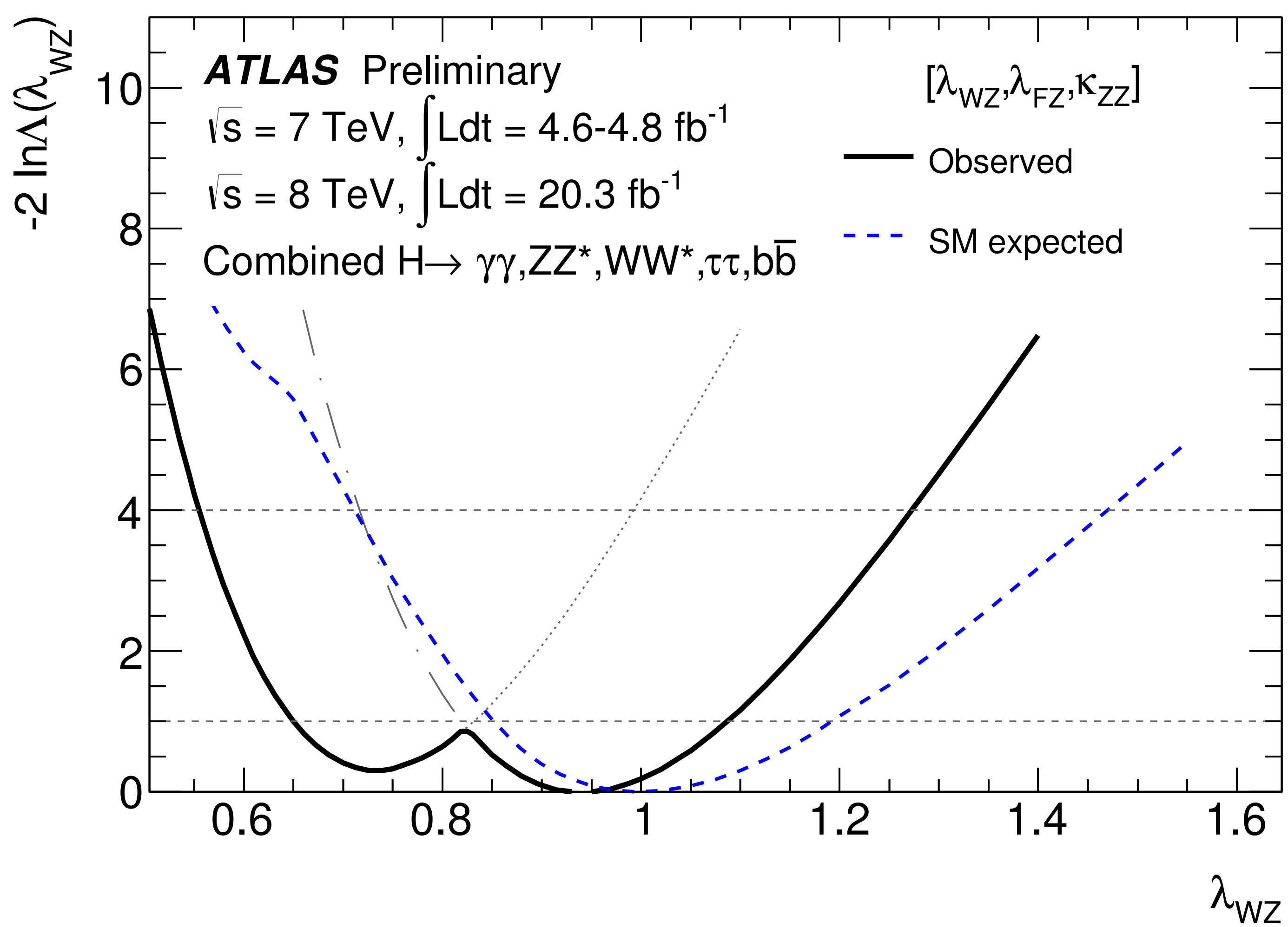
- Parameter of interest: $\lambda_{WZ} = \kappa_W / \kappa_Z$
- Constraint by direct inputs from H→WW and H→ZZ and from VBF measurements
  - Universal coupling to all fermions is assumed
- Measured to be consistent with 1 to high precision at LEP and Tevatron
  - ATLAS measurement also consistent with unity:
  - W & Z bosons treated as identical in the following and denoted V

$$\lambda_{WZ} = 0.94^{+0.14}_{-0.29}$$



Fermion vs. Gauge couplings

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- Scale factors of interest:
- Assume only SM particles contributing to loops

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

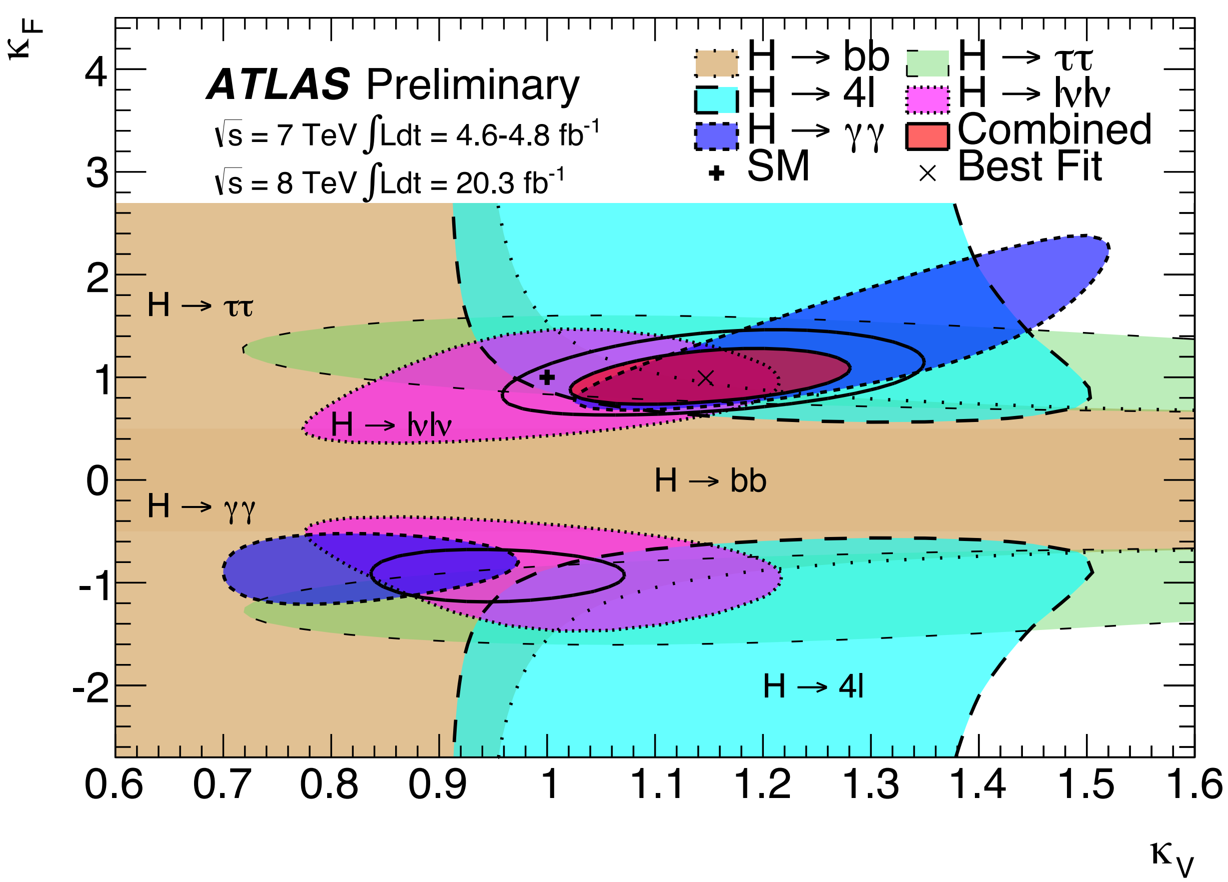
Results:

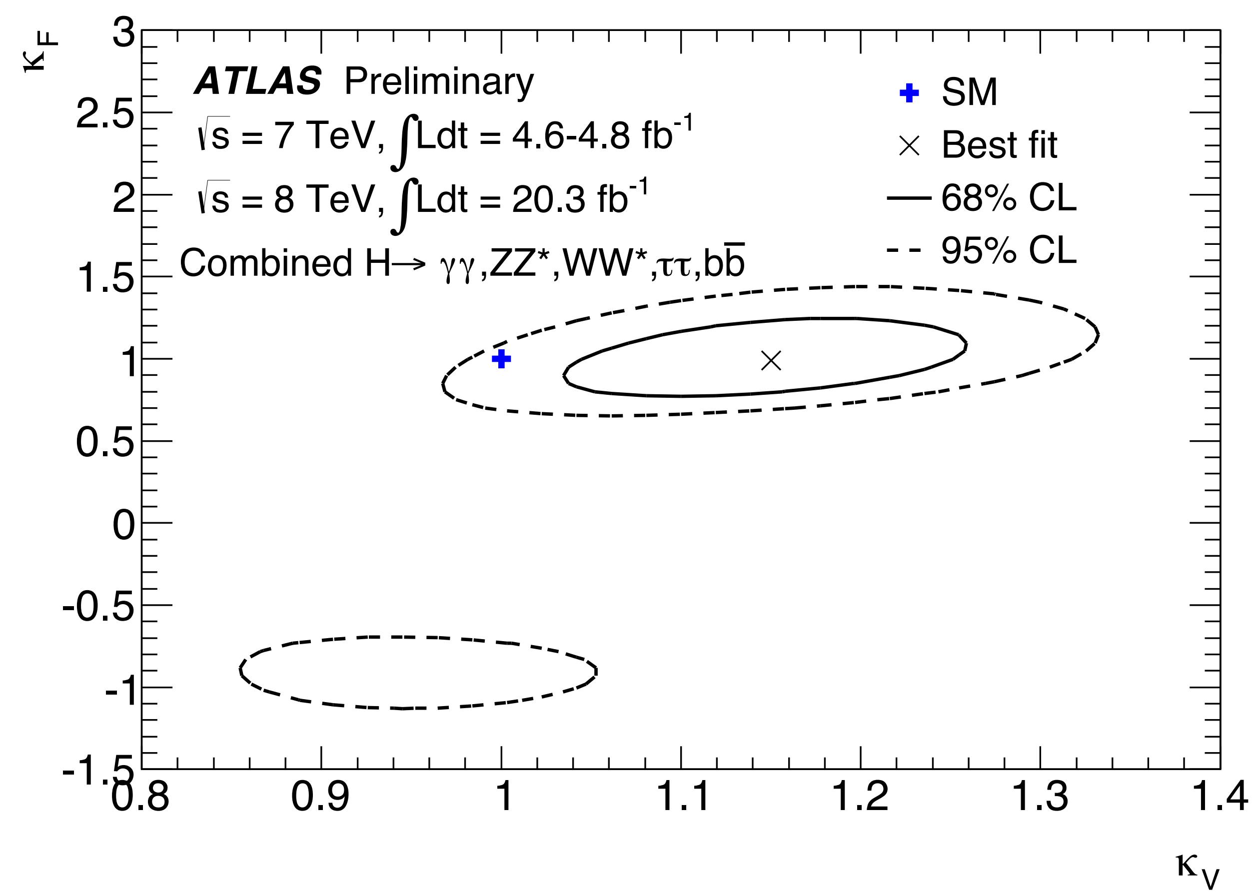
$$\kappa_V = 1.15 \pm 0.08$$
$$\kappa_F = 0.99^{+0.17}_{-0.15}.$$

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

- no deviation from SM
- compatibility: 10%

constraint on total width dropped





Fermion vs. Gauge couplings - Compositeness

- Minimal Composite Higgs Models (MCHM):
  - Higgs is composite pseudo Nambu-Goldstone Boson
  - possible explanation for scalar naturalness problem

$$\xi = v^2/f^2$$

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- Couplings to V and F as function of *compositeness scale f* parametrized by ξ
  - Coupling scale factors expressed in terms of ξ
  - Physical constraint: $\xi \geq 0$
  - SM recovered for $\xi = 0$

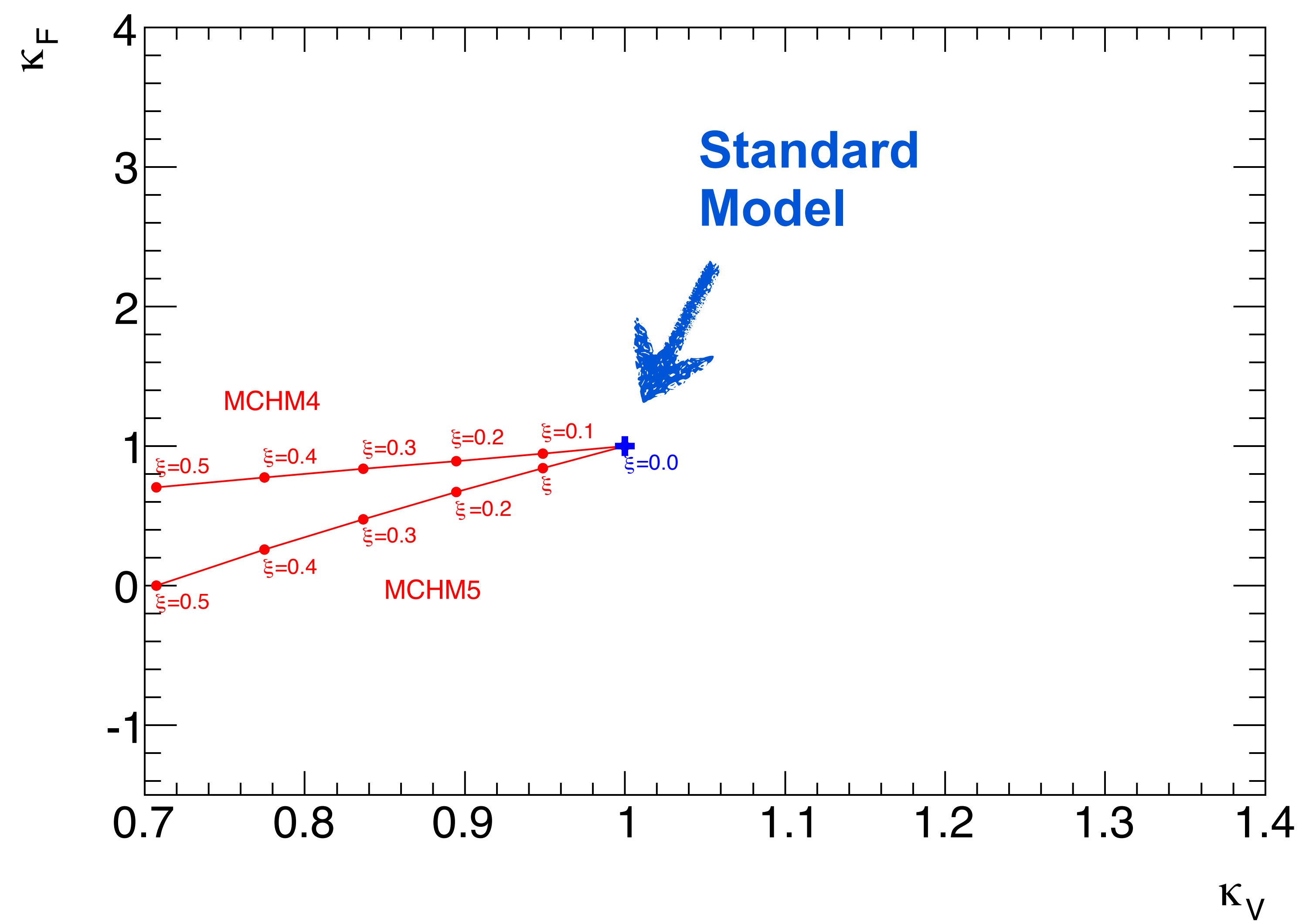
- Two models studied:

- MCHM4:

$$\kappa = \kappa_V = \kappa_F = \sqrt{1-\xi}$$

- MCHM5:

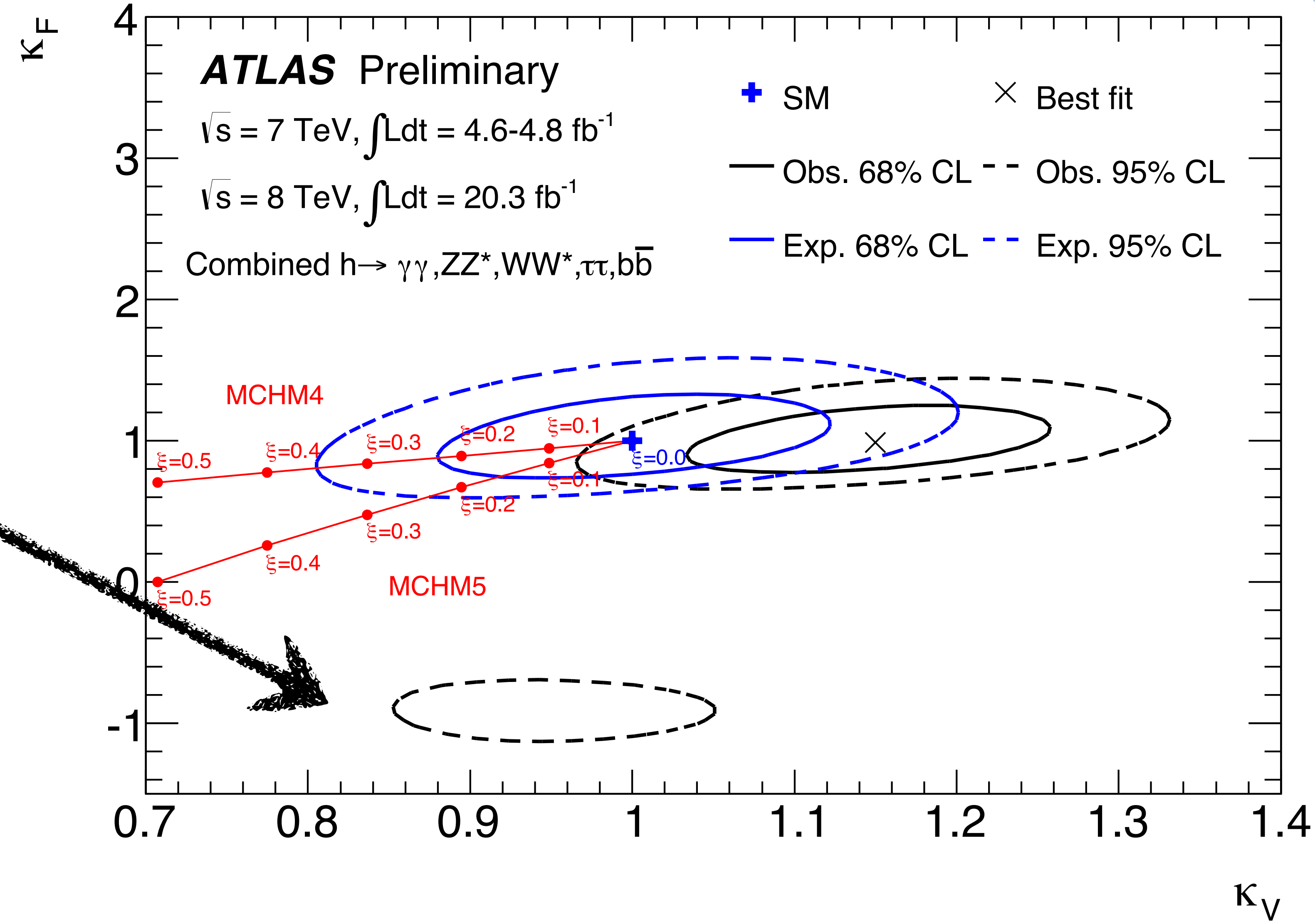
$$\kappa_V = \sqrt{1-\xi} \qquad \kappa_F = \frac{1-2\xi}{\sqrt{1-\xi}}$$



Fermion vs. Gauge couplings - Compositeness

$$\xi = v^2/f^2$$

Due to large measured
$H \rightarrow \gamma\gamma$ rate



Measured limits are stronger than expected ones as
$\mu > 1 \Leftrightarrow \xi < 0$

	95% CL measured (expected)	
Model	$\xi <$	$f >$
MCHM4	0.12 (0.29)	**710 GeV** (460 GeV)
MCHM5	0.15 (0.20)	**640 GeV** (550 GeV)

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Up vs. Down - type couplings

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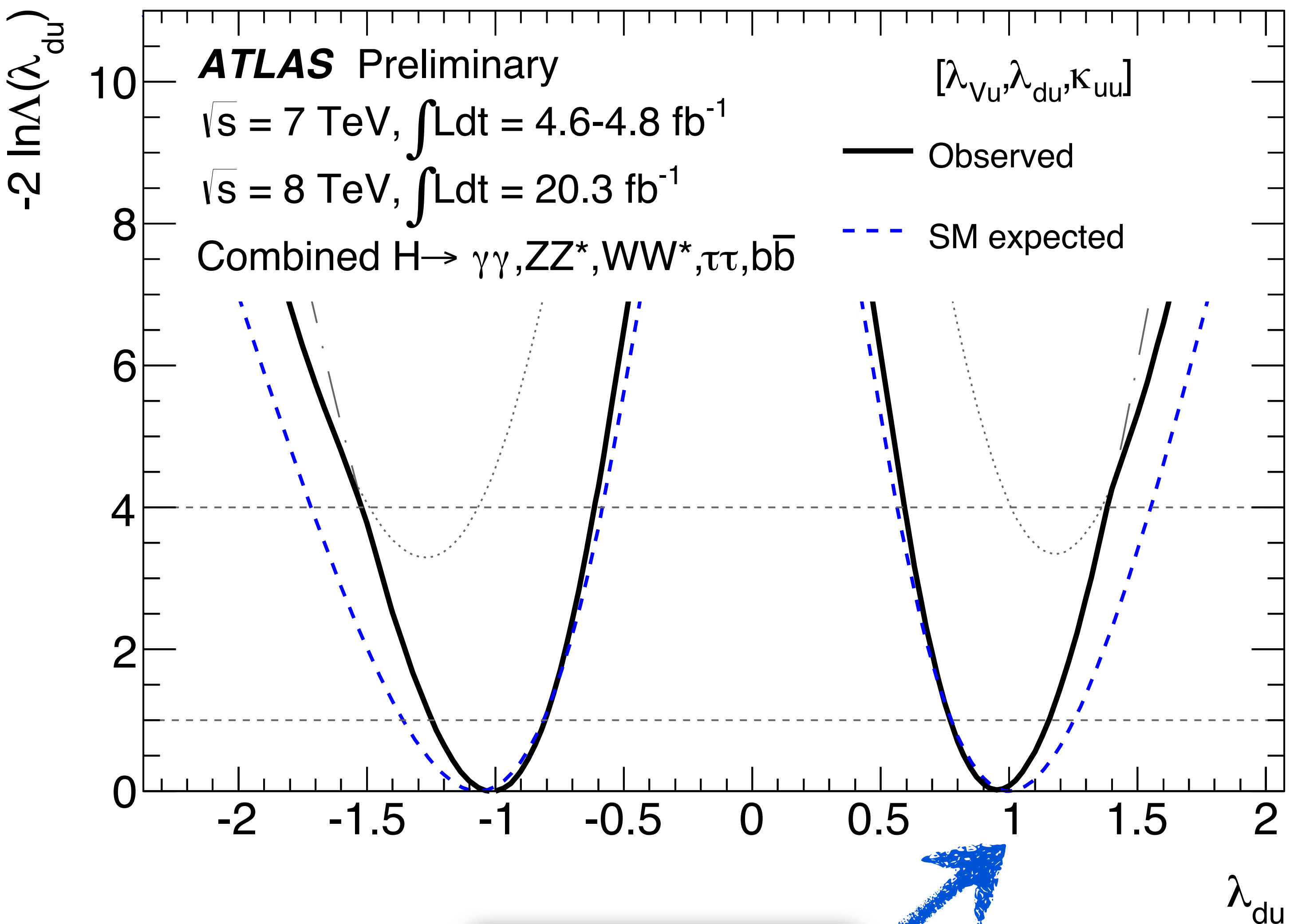
- Common scale factors: up / down - type fermions:
  - Several Two-Higgs-Doublet models predict $\kappa_u \neq \kappa_d$ e.g. MSSM

$$\kappa_u = \kappa_t$$
$$\kappa_d = \kappa_b = \kappa_\tau$$

- Parameter of interest: $\lambda_{ud} = \kappa_u / \kappa_d$



$$\lambda_{du} = 0.95^{+0.20}_{-0.18}$$

Results:

$$\lambda_{du} \in [-1.24, -0.81] \cup [0.78, 1.15]$$
$$\lambda_{Vu} = 1.21^{+0.24}_{-0.26}$$

- 3.6σ evidence for coupling of H to d-type fermions (mostly from H→ττ)
- No deviation from SM
  - Compatibility: 20%

2 Higgs Doublet Model - Type 2

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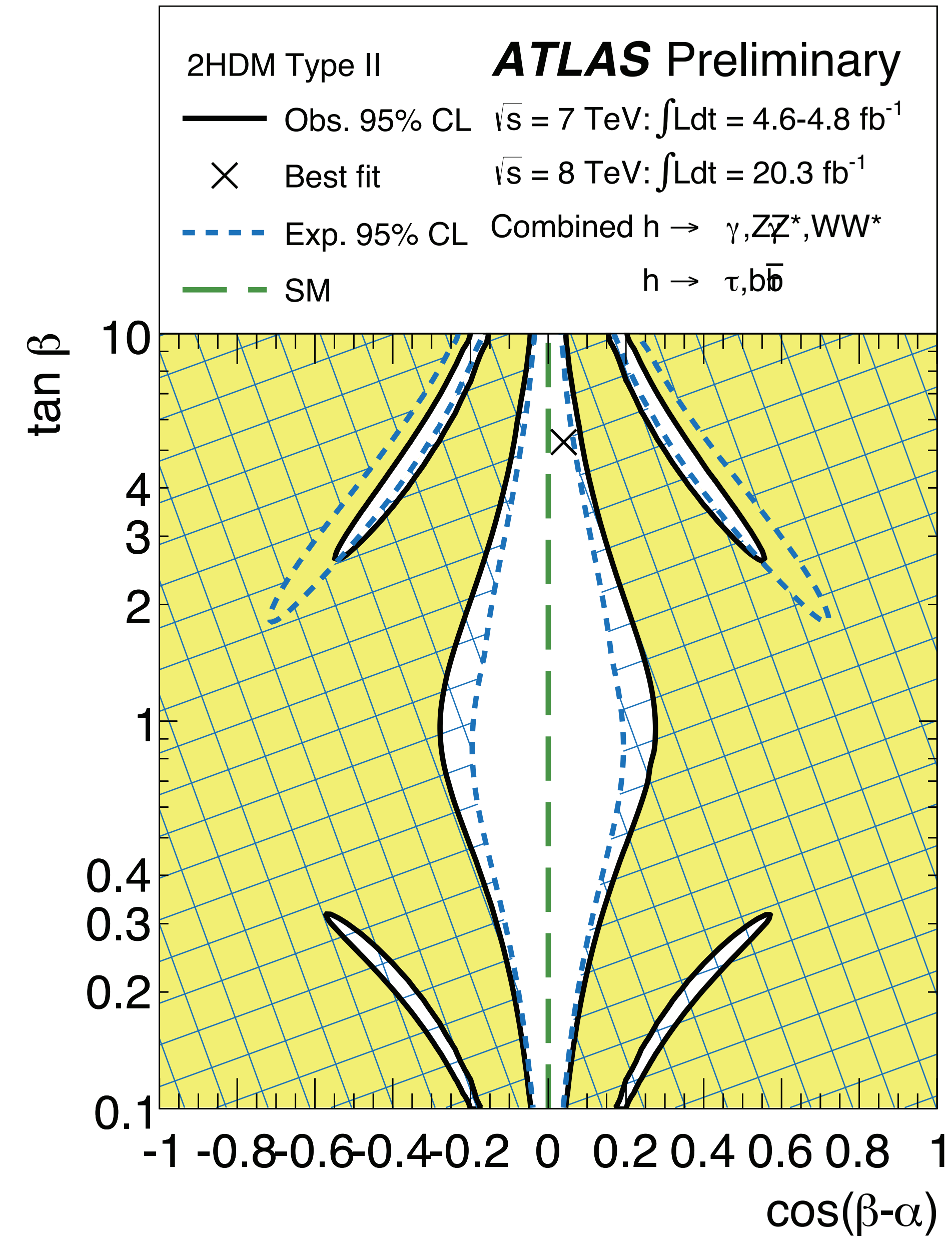
- Type2:
  - one doublet couples to up-type, other to down-type fermions (MSSM like)

Coupling scale factor	Type I	Type II
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$



Limits on simplified MSSM

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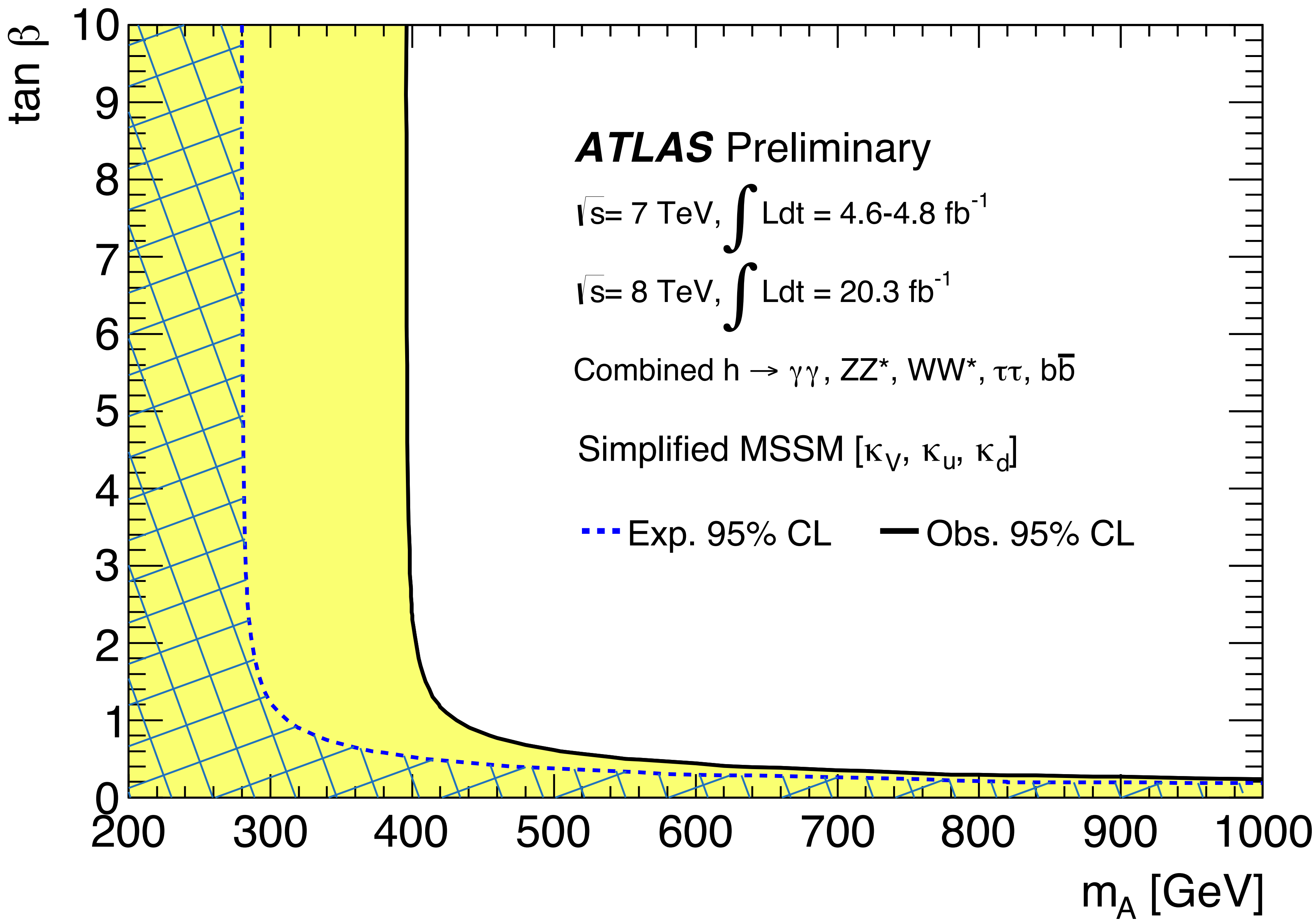
- Probed via couplings to
  - Vector bosons
  - Up-type quarks
  - Down-type quarks and leptons

- For tan(β) > 2:
  - limit on CP-odd Higgs mass is:
  - m_A > 400GeV obs. (m_A > 290GeV exp.)

- Still large unexplored region for tan(β) < 1



Lepton vs. Quark couplings

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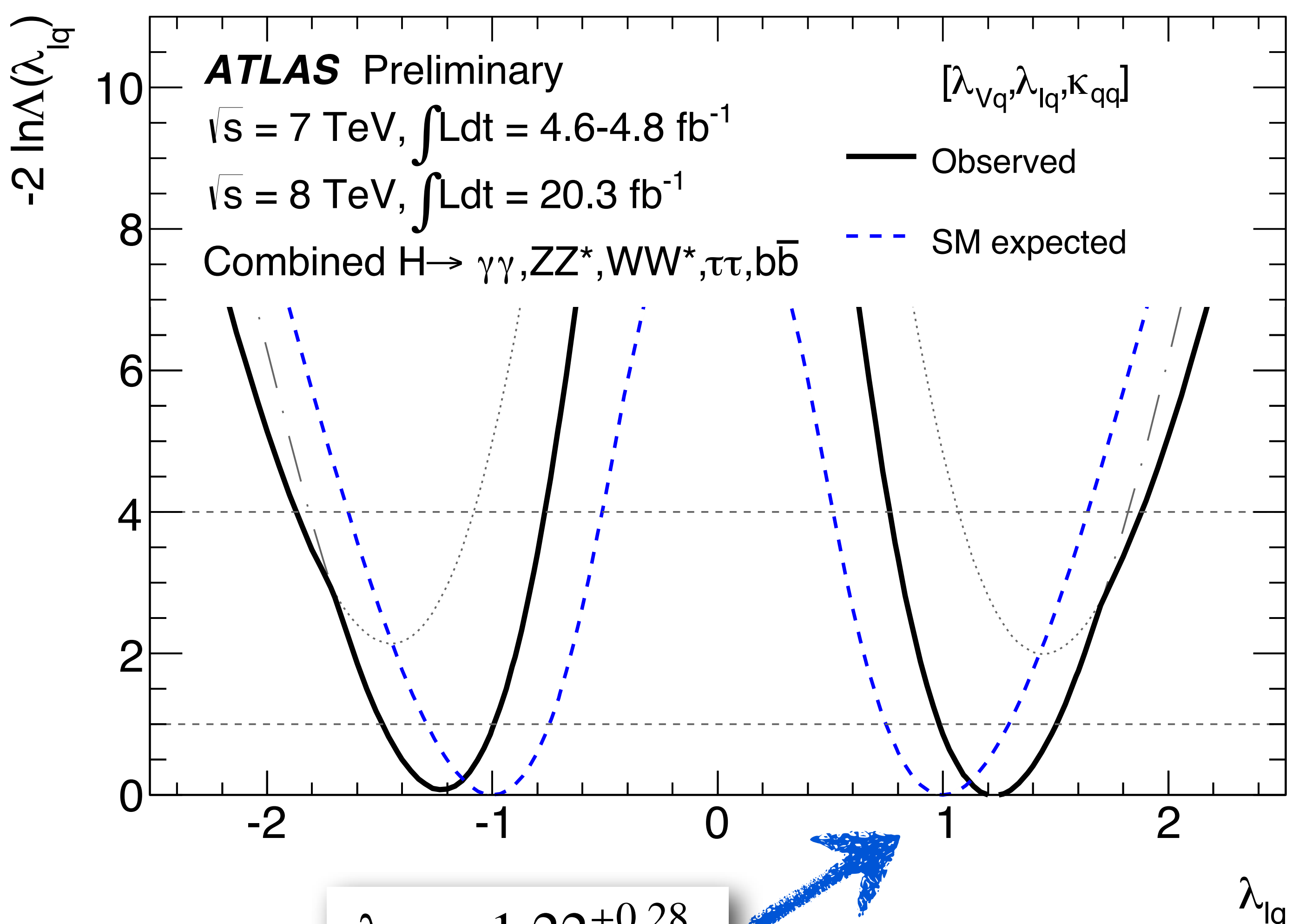
- Parameter of interest:

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

- Assuming unified vector boson couplings

- Lepton coupling strength currently only constraint through $H \to \tau\tau$



$$\lambda_{lq} = 1.22^{+0.28}_{-0.24}$$

Result:

$$\lambda_{lq} \in [-1.48, -0.99] \cup [0.99, 1.50]$$

- Vanishing coupling to leptons excluded at ~4σ level

- No deviation from SM
  - Compatibility: 15%

Mass scaling of coupling

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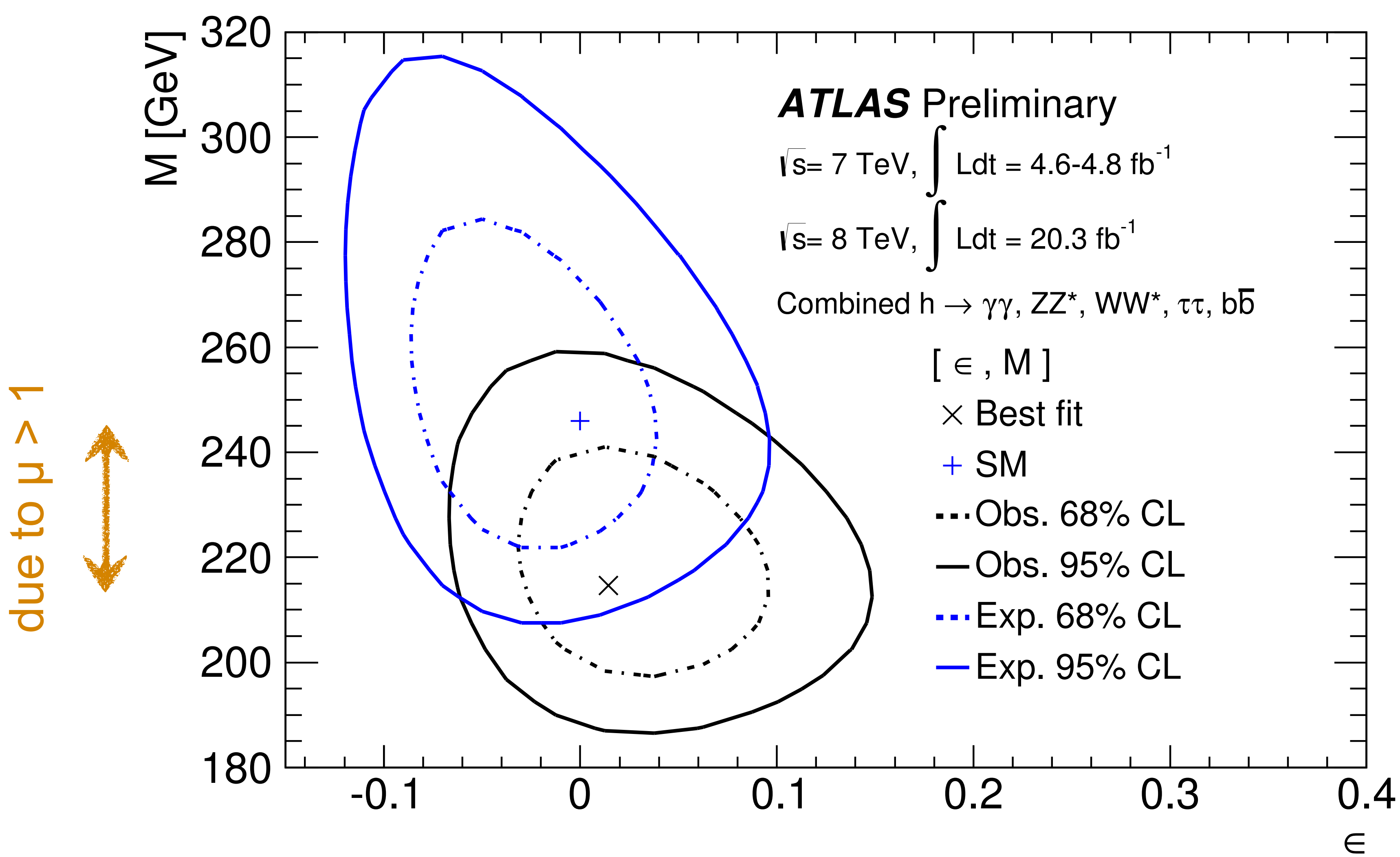
- Coupling scale factor parametrized by mass scaling parameter ε and *vacuum expectation value* M, where v ~ 246 GeV

- SM couplings are recovered for ε = 0 and M = v

$$\kappa_{f,i} = v\frac{m_{f,i}^{\epsilon}}{M^{1+\epsilon}}$$

$$\kappa_{V,i} = v\frac{m_{V,i}^{2\epsilon}}{M^{1+2\epsilon}}$$



- No deviation from SM
  - Compatible: 1.5 σ

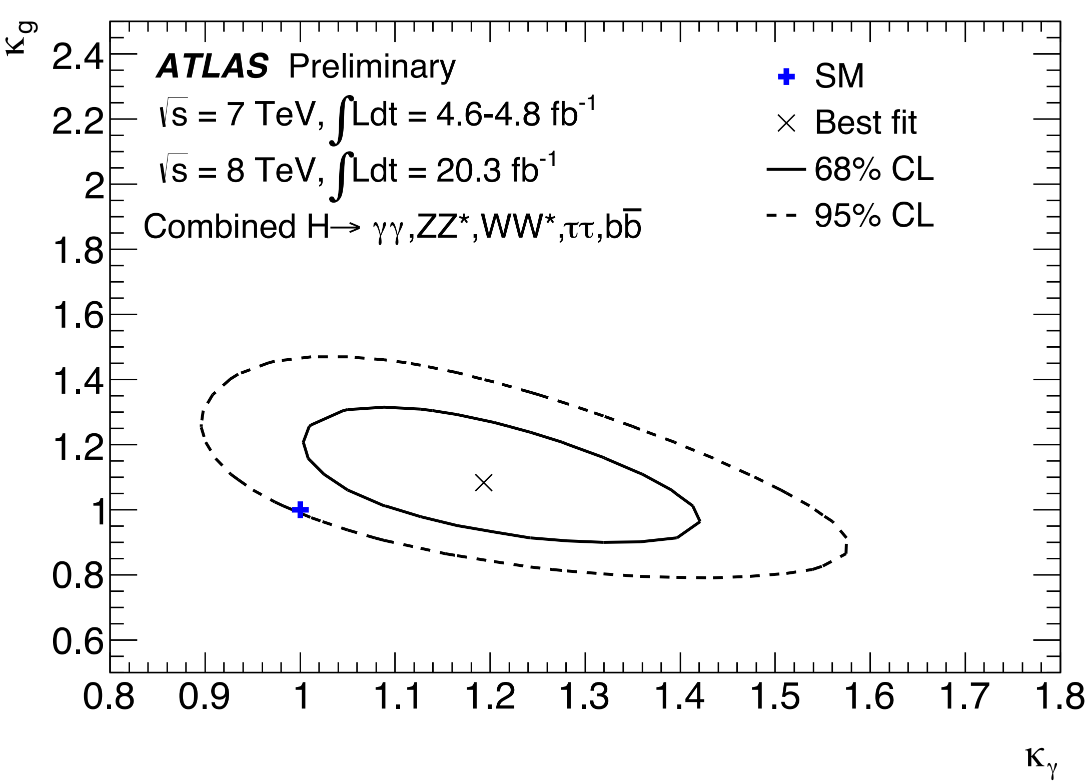
BSM: invisible / undetected decays

- SM couplings assumed: $\kappa_i = 1$ ATLAS-CONF-2014-009

- Effective scale factors for $gg \to H$ and $H \to \gamma\gamma$: $\kappa_g, \ \kappa_\gamma$

- New particles contributing to loops may or may not contribute to the total width, depending on fit model.

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



Results:

Total width fixed:

$\kappa_g = 1.08^{+0.15}_{-0.13}$

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

- No deviation from SM
  - Compatibility: 18%

Total width free:

$\kappa_g = 1.00^{+0.23}_{-0.16}$

$\kappa_\gamma = 1.17^{+0.16}_{-0.13}$

limits @ 95% CL:

$BR_{i.,u.} < 0.41$

$BR_{i.,u.} < 0.37$

with constraint from $Zh \to \ell\ell + E_T^{miss}$

Higgs portal to Dark Matter

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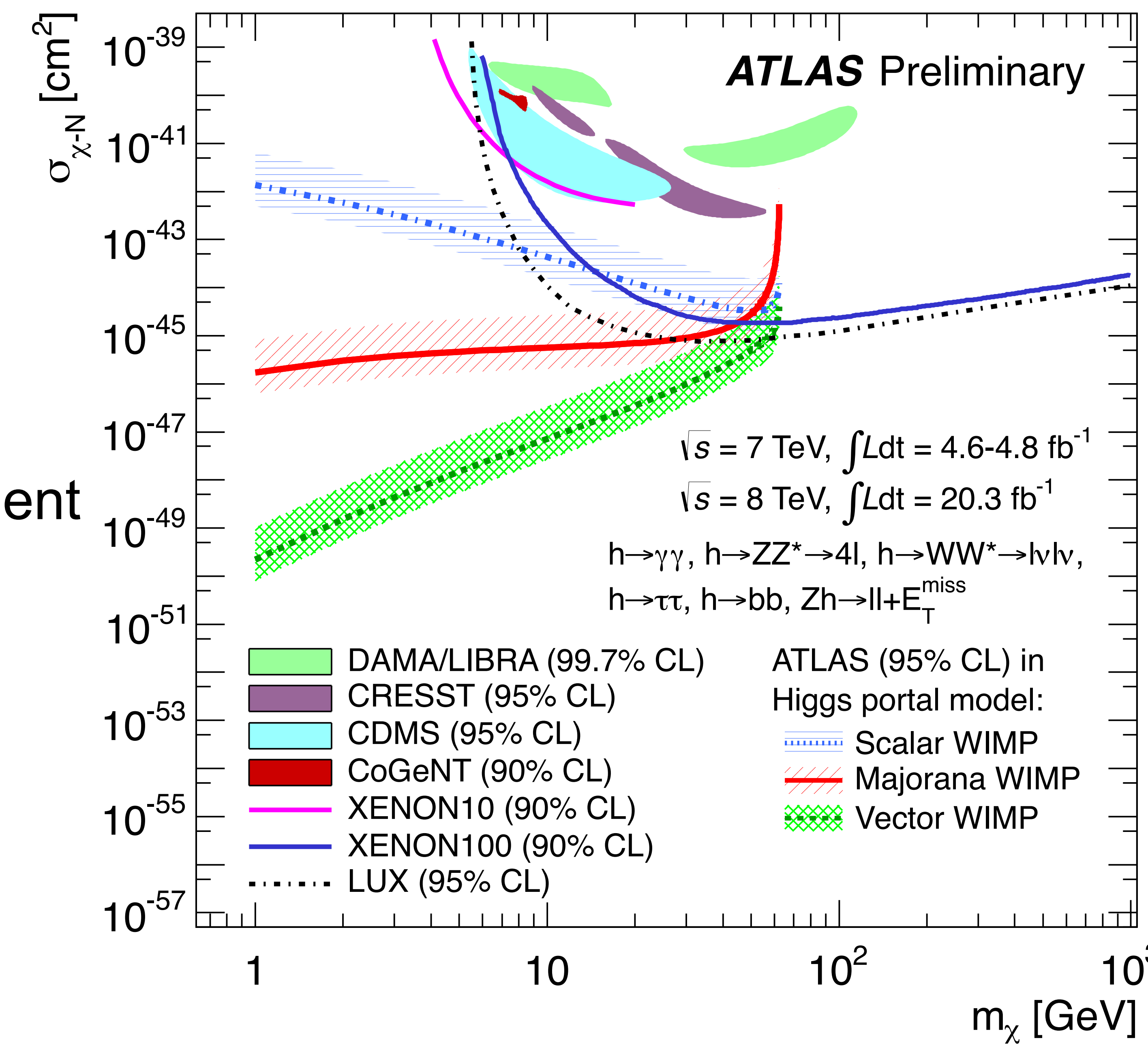
- Decay into invisible particles may be signature for DM

- upper limit on invisible branching ratio (95% CL):
  - $BR_{inv.} < \mathbf{0.37}$ (expected: < 0.39)

- translating into limit on WIMP nucleon scattering x-section
  - H,WIMP coupling deduced dependent on spin
  - re-parametrized as WIMP-nucleon scattering x-section via H exchange

- ATLAS dominates low mass region

- Majorana WIMP:
  - motivated by neutralinos



Generic models

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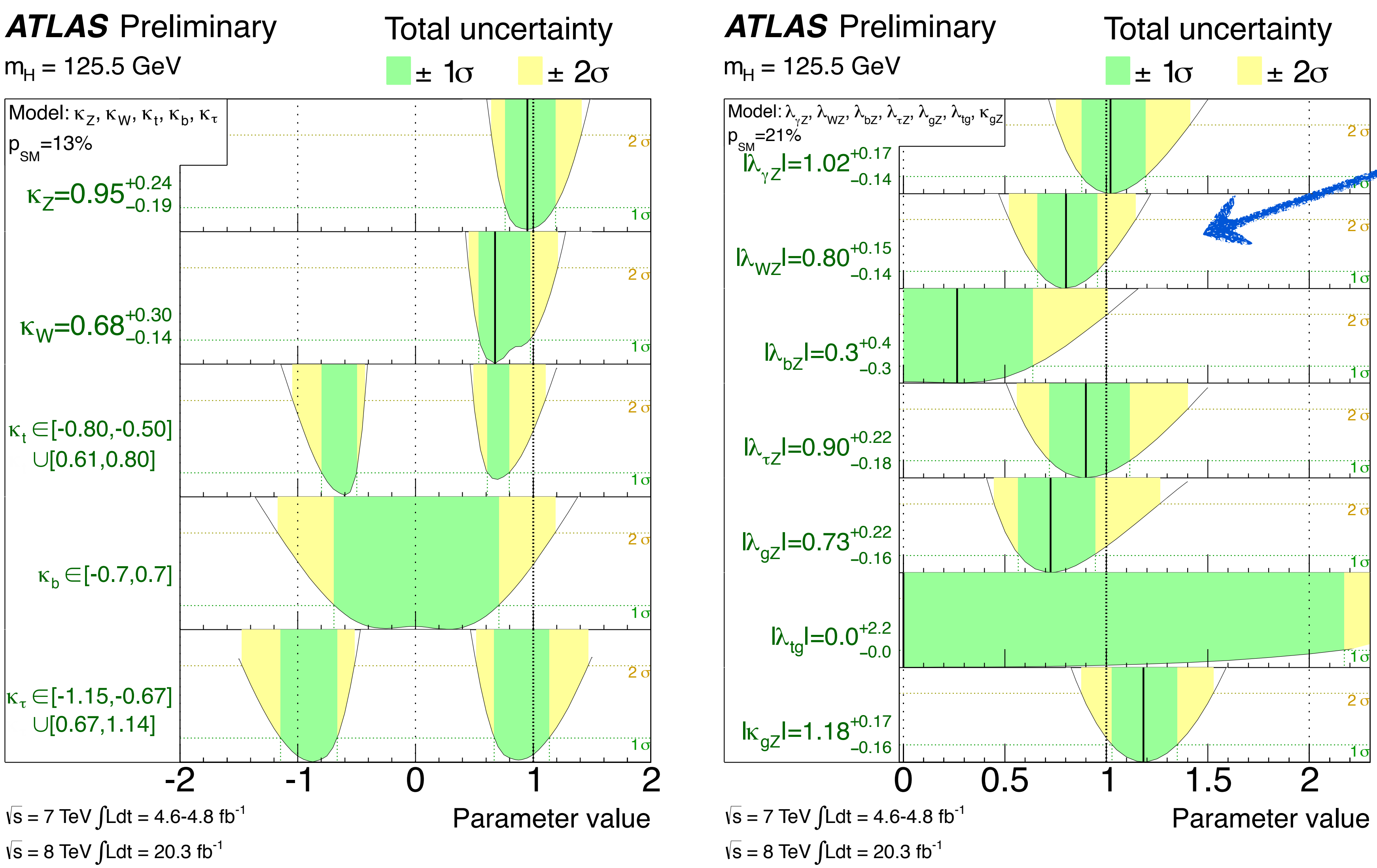
- Previously: minimum number of free parameters to test specific aspects
- Now couplings to W, Z, t, b, τ **treated independently**

- For contributions to loops and the total width 2 models are studied:
  - SM particles are assumed
  - No constraints → only ratios of coupling scale factors can be measured



probing custodial symmetry with less assumptions from SM than before

- No deviation from SM
  - Compatibility: 13% (assuming SM width / loops)
  - Compatibility: 21% (without constraints)

Measured couplings - overview

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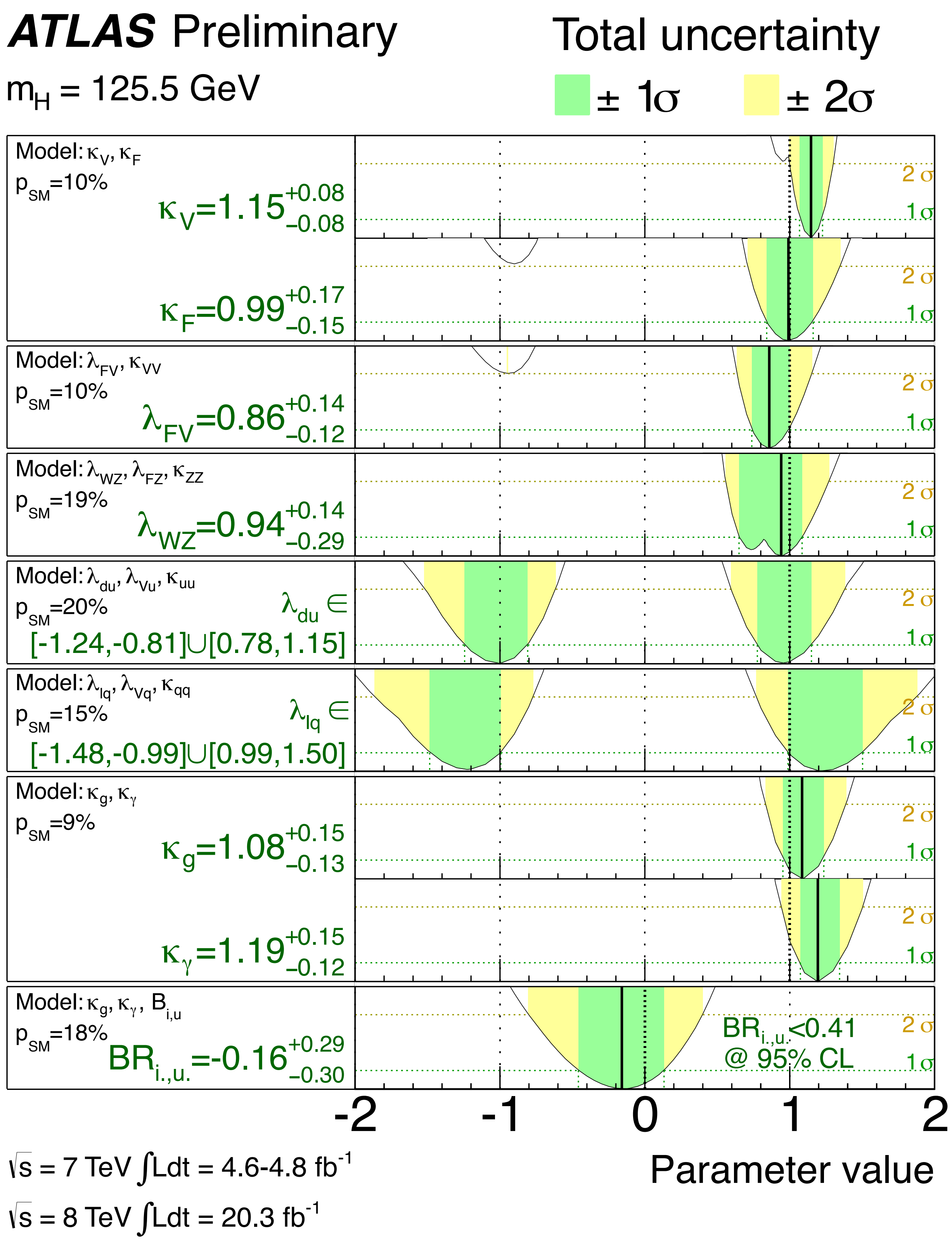

κ_Z	Z boson coupling	$0.95^{+0.24}_{-0.19}$
κ_W	W boson coupling	$0.68^{+0.30}_{-0.14}$
κ_t	t quark coupling	$[-0.80, -0.50] \cup [0.61, 0.80]$
κ_b	b quark coupling	$[-0.7, 0.7]$
κ_τ	τ lepton coupling	$[-1.15, -0.67] \cup [0.67, 1.14]$

All measurements consistent with SM

Compatibility of best fit between 9 and 21 %

Summary

- Higgs boson couplings measured from 5 input channels
- Several coupling scenarios tested:
  - **No significant deviation from SM observed**
  - Compatibility with SM 9% - 21% (within 2σ)
- Overall signal strength: $\mu = 1.3^{+0.18}_{-0.17}$
- Coupling measurements used to set constraints on various BSM models
  - Composite Higgs, simplified MSSM, mass scale deviation, DM
- Most measurements statistically limited
  - Run II will be exciting :-)

BACKUP

Additional EW singlet

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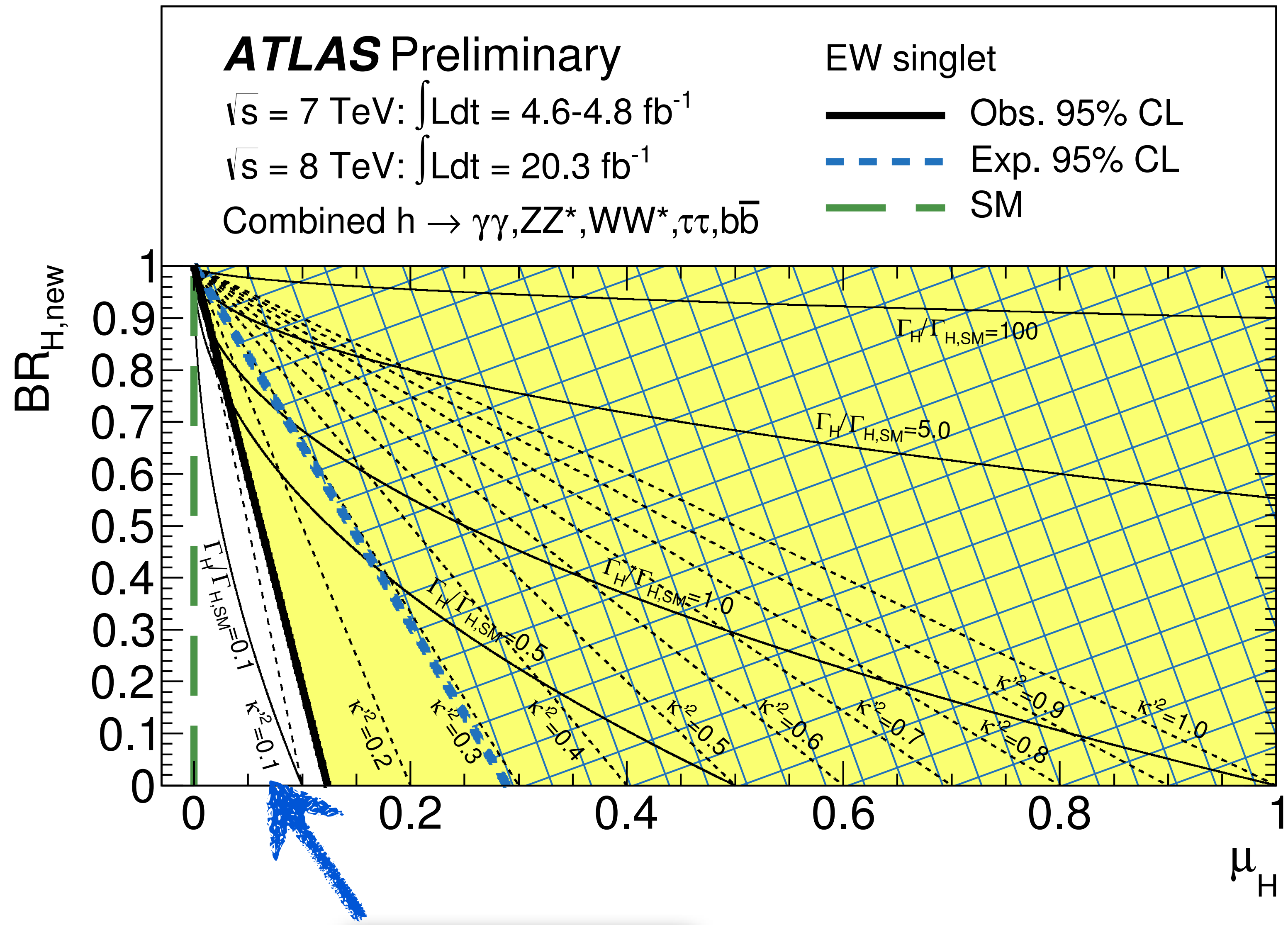
- Adding EW singlet field to SM Higgs doublet
  - 2 CP-even Bosons: h (light) & H (heavy) (non-degenerate)
  - Couplings to SM particles modified by common scale factors κ & κ', respectively
  - unitarity contraint: $\kappa^2 + \kappa'^2 = 1$, where $\kappa'^2 = 1 - \mu_h$

Upper limit @ 95% CL
(assuming physical boundary $\kappa^2 \geq 0$):

$\kappa'^2 < 0.12$ (0.29 exp.)



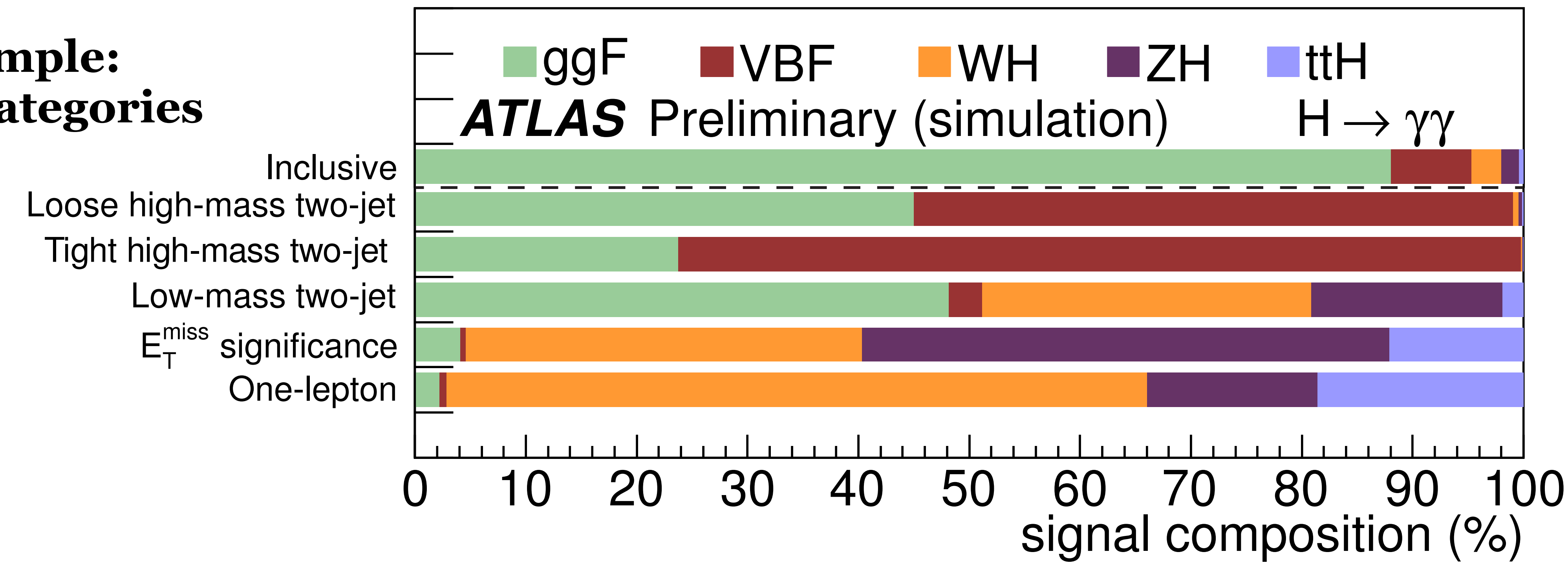
Analysis strategy

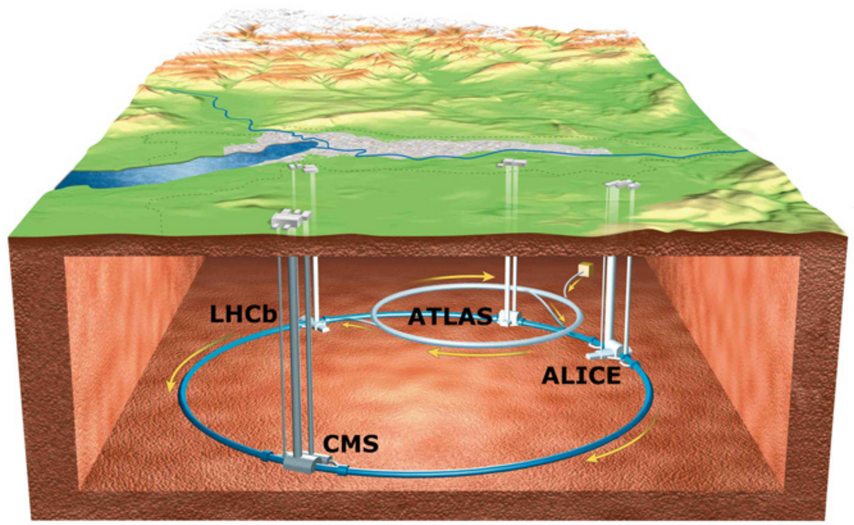
- Each analysis is **further divided into categories** that increases sensitivity:
    - Different *s/b* for certain production-mode / decay compositions
    - Allows to extract Higgs couplings to different particles
    - Assumes standard model acceptances for categories
- Parameter(s) of interest extracted by simultaneous maximal likelihood fit

Example:
***H→γγ* categories**

VBF categories:
large fraction of VBF

low-m_{jj}, E_T^{miss} and lepton categories:
large fraction of *WH*





The Large Hadron Collider

- collides protons (and / or Pb ions)
- 27km long, 40MHz collision rate

- Run Period I (2010 - 2012):
  - 50 ns bunch spacing
  - $\sqrt{s} = 7 - 8\,\mathrm{TeV}\ (pp)$
  - $\mathcal{L} \leq 7 \cdot 10^{33} cm^{-2} s^{-1}$

- Run Period II (starting 2015):
  - 25 ns bunch spacing
  - $\sqrt{s} \simeq 13\,\mathrm{TeV}\ (\mathrm{pp})$
  - $\mathcal{L} \simeq 1.6 \cdot 10^{34} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

The ATLAS experiment

- 100M readout channels
- general purpose detector:
  SM precision measurements to searches for new particles
- mostly rare processes interesting
  - need very selective & efficient realtime event selection
  - ‣ trigger system