Higgs Combination

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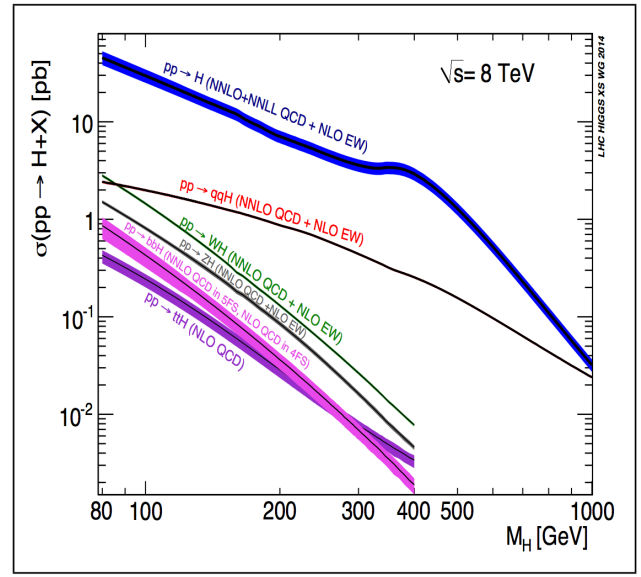
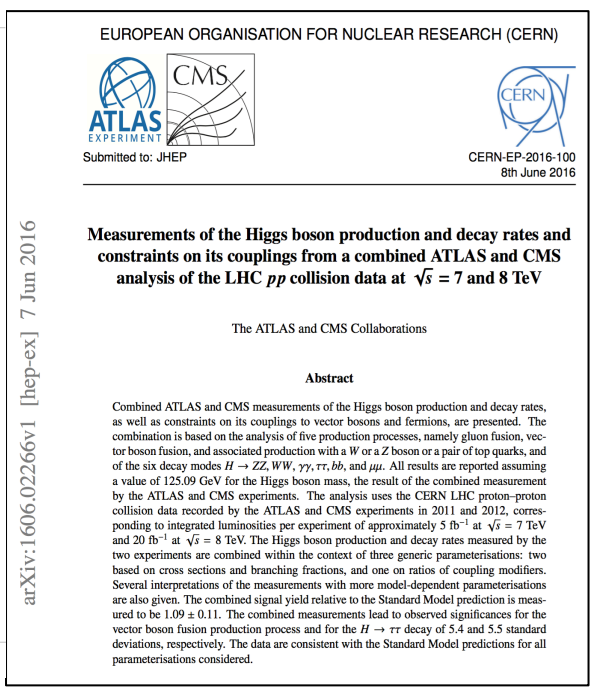
Introduction

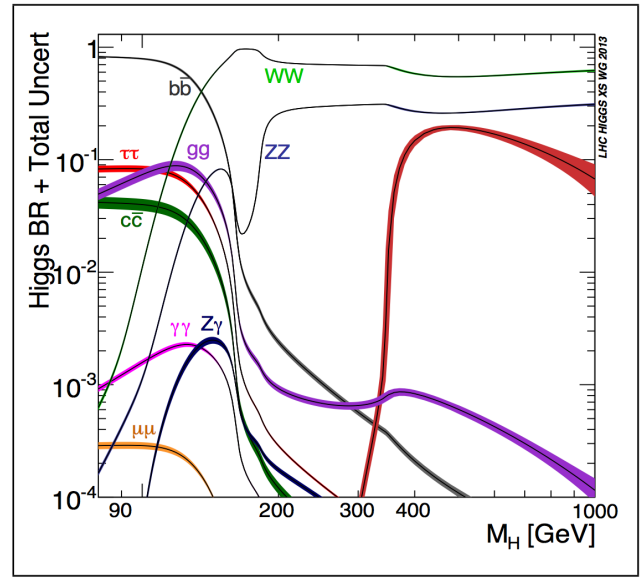
- After the discovery, emphasis at LHC shifted towards measurement of properties of the new particle
- Statistical uncertainty reduced by combining two experiments



Higgs mass paper
PRL 114 (2015) 191803

Higgs coupling paper
arXiv:1606.02266





Combination Input

Based on the inputs to the separate CMS and ATLAS combinations: the main **five decay channels + ttH analyses**

	Untagged	VBF	VH	ttH
$H\to\gamma\gamma$	✓	✓	✓	✓
$H\to ZZ\to 4l$	✓	✓	✓	✓
$H\to WW\to 2l2\nu$	✓	✓	✓	✓
$H\to\tau\tau$	✓	✓	✓	✓
$H\to bb$			✓	✓
$H\to\mu\mu$	✓	✓		

- $H\to\mu\mu$ only included for one particular result
- Each analysis targeting a particular production/decay mode may also consider contributions from other processes that are not specifically targeted, e.g. **$H\to WW$ entering $H\to\tau\tau$ analysis, single-top + Higgs production in ttH**

Statistics

- Workhorse of the combination is the **profile likelihood ratio, Λ**

$\vec{\alpha}$ = **Set of POIs at some fixed values to be tested**

$\vec{\theta}$ = **Nuisance parameters**

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

Values of $\vec{\theta}$ that maximise the likelihood given the fixed values of $\vec{\alpha}$ being tested (conditional estimate)

Values of $\vec{\alpha}$ and $\vec{\theta}$ that globally maximise the likelihood (unconditional estimate)

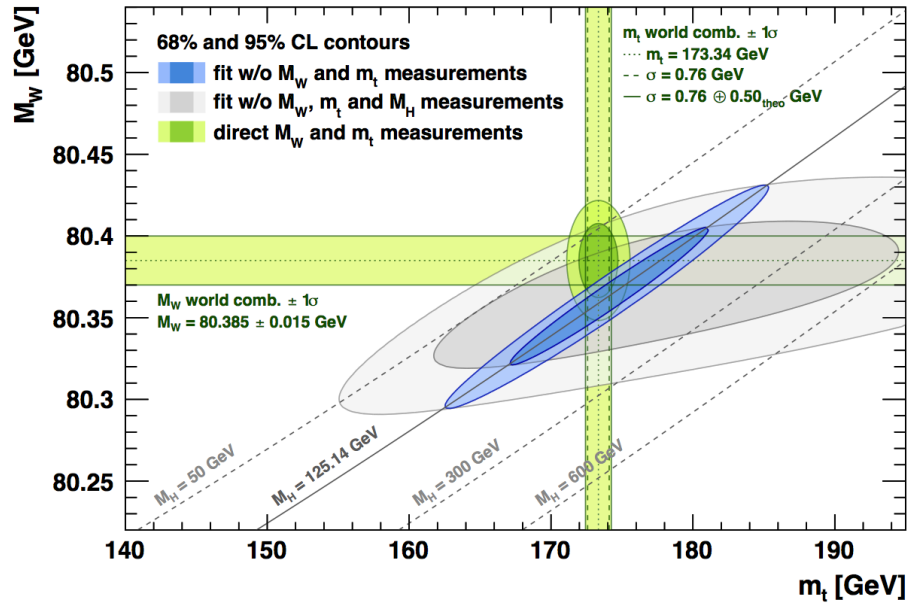
- Exploit the **asymptotic limit**:
  - Test statistics $q(\vec{\alpha}) = -2 \ln(\Lambda(\vec{\alpha}))$ is assumed to follow a χ^2 distribution with $\vec{\alpha}$ degrees of freedom
  - To determine a confidence-level (CL) interval for a single parameter α, we only need to find the values of α where $q(\alpha)$ = the χ^2 critical value for that CL, e.g. 1D 68% CL at $q(\alpha) = 1.00$

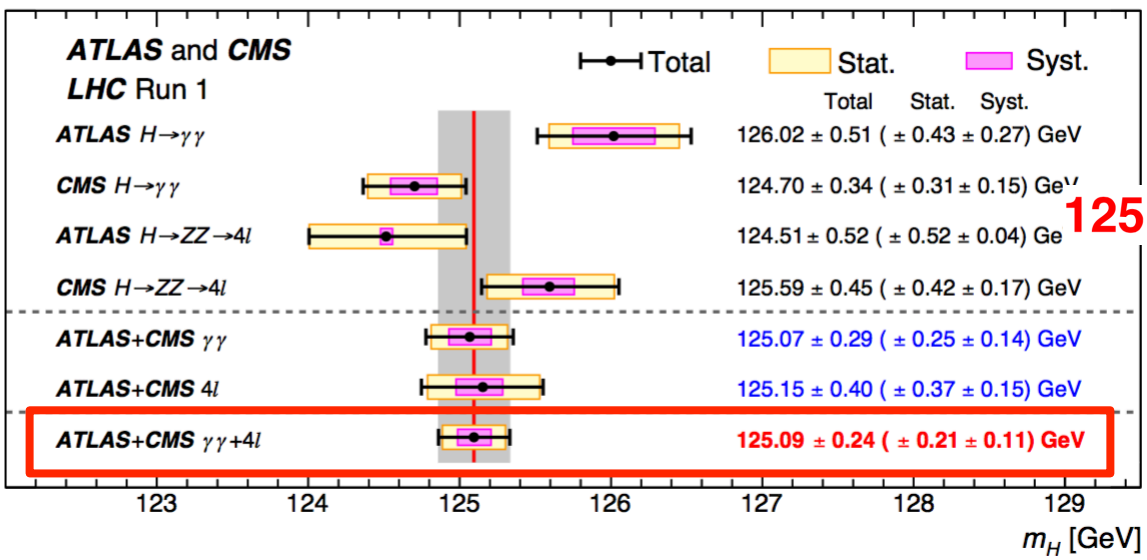
Technical Challenges

- **Fit convergence:** ~4300 nuisance parameters
  - Minuit handles such fits surprisingly well, few tricks used to reduce the time needed for convergence
- **Memory usage:** ~4-5GB needed for combination
- **Fitting time:**
  - **0.5-1 hours per combined fit** thanks to significant low-level optimizations in the likelihood evaluation
  - Each best-fit value + uncertainties from **scan of ~ 40 points**
  - Total number of fits = 150 (POIs) * 40 (points) * 2 (observed, asimov)
  - + **~10 2D scans** requiring 1600 fits each
  - Total CPU time ~ 12000 hours

Higgs mass

- ATLAS+CMS combination on mass measurement with high-resolution channels: **H→γγ and H→ZZ→4l**
  - **Self-consistency test of SM parameters**
  - **Precise calculation XS•BR**





m_H=

125.09 ± 0.24 (± 0.21 ± 0.11) GeV

Statistical uncertainty still dominates and can be further reduced in future

Higgs rates & couplings

- Signal parameterization

Signal strengths, μ

Parameters scale cross sections and BRs relative to SM

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\rm SM}} \qquad \mu^f = \frac{{\rm BR}^f}{{\rm BR}^f_{\rm SM}}.$$

Scaling of generic i → H → f process

$$\mu_i^f \equiv \frac{\sigma_i \cdot {\rm BR}^f}{(\sigma_i \cdot {\rm BR}^f)_{\rm SM}} = \mu_i \times \mu^f$$

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

$$\kappa_j^2 = \sigma_j/\sigma_j^{\rm SM} \qquad \kappa_j^2 = \Gamma_j/\Gamma_j^{\rm SM}$$

$$\sigma_i \cdot {\rm BR}^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\rm H}},$$

Total width determined as

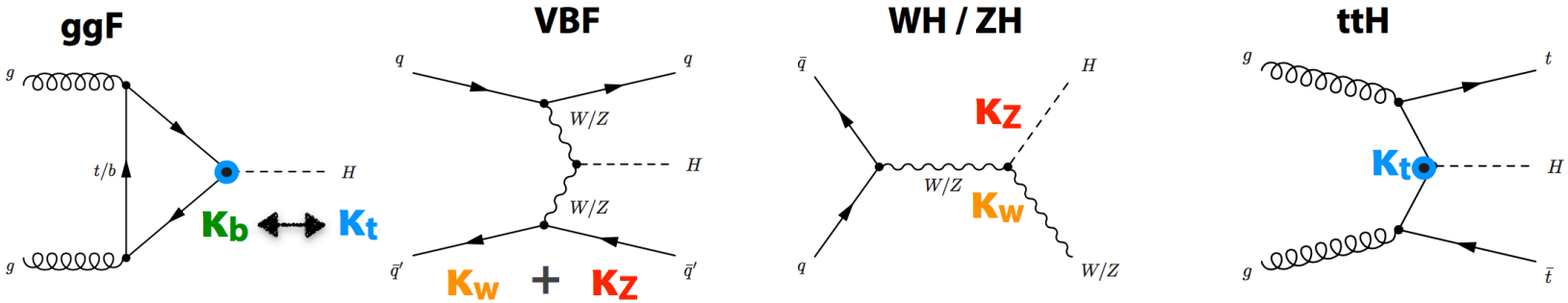
$$\Gamma_{\rm H} = \frac{\kappa_H^2 \cdot \Gamma_H^{\rm SM}}{1 - {\rm BR}_{\rm BSM}}$$

Where

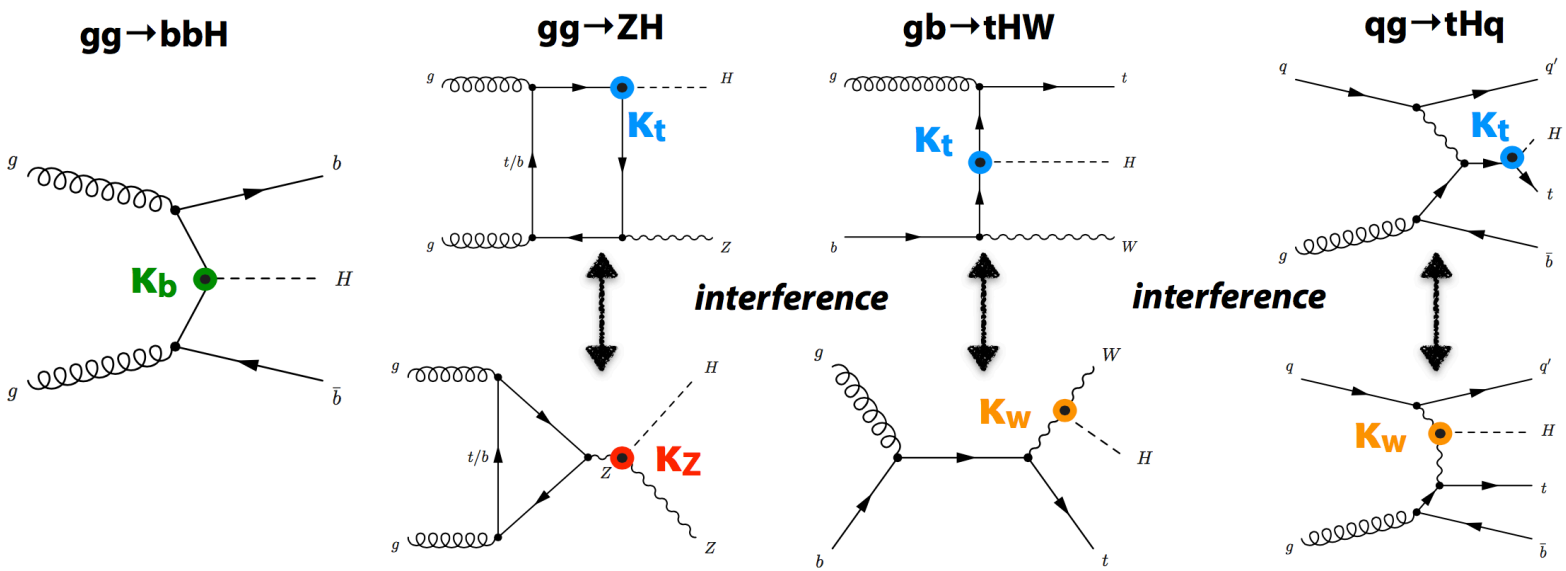
$$\kappa_H^2 = \sum_j {\rm BR}^j_{\rm SM} \kappa_j^2$$

Higgs production processes

- **Usual suspects:**



- **Rare processes:**

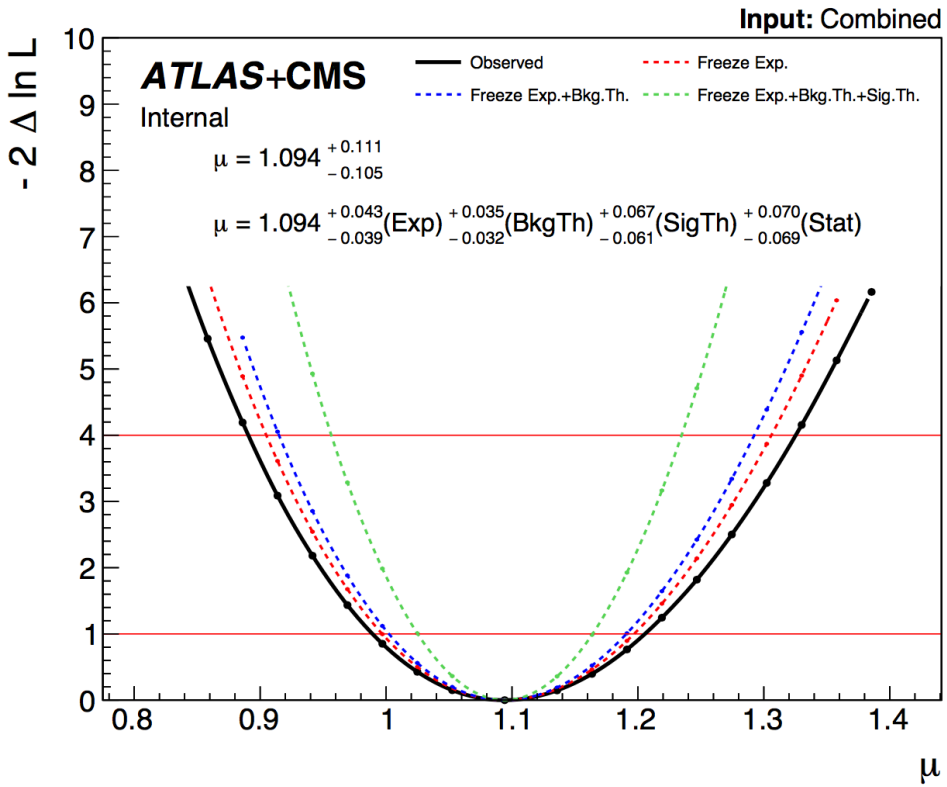


Overall signal strength

- **Assumptions**
  - SM ratios of all cross sections and BRs
  - 7/8 TeV ratios as in SM

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\ (\text{stat})\ ^{+0.04}_{-0.04}\ (\text{expt})\ ^{+0.03}_{-0.03}\ (\text{thbgd})^{+0.07}_{-0.06}\ (\text{thsig})$$

- For this, and other key measurements, break uncertainty down into 4 components:
  - statistical, experimental, background theory, signal theory
- All ~4300 NPs assigned to one of these groups
- Each component determined by fixing successive group of NPs to best-fit values $\hat{\theta}$ and repeating NLL scan



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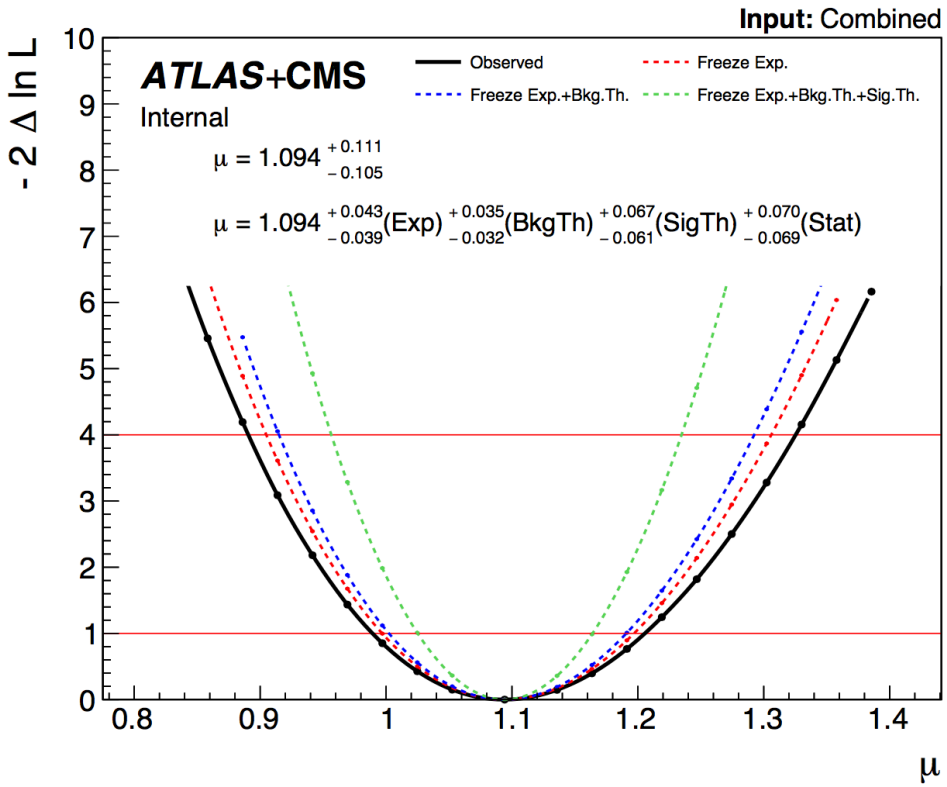
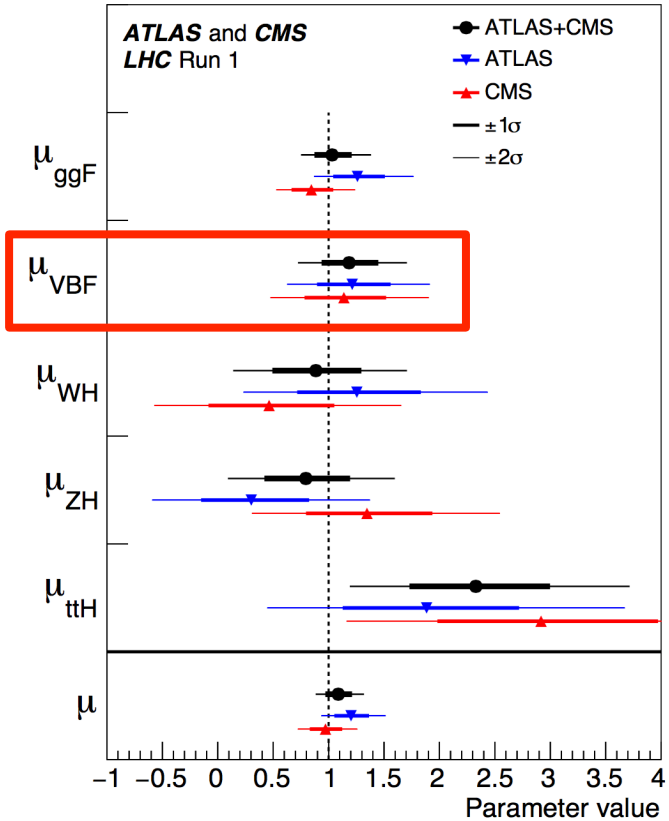
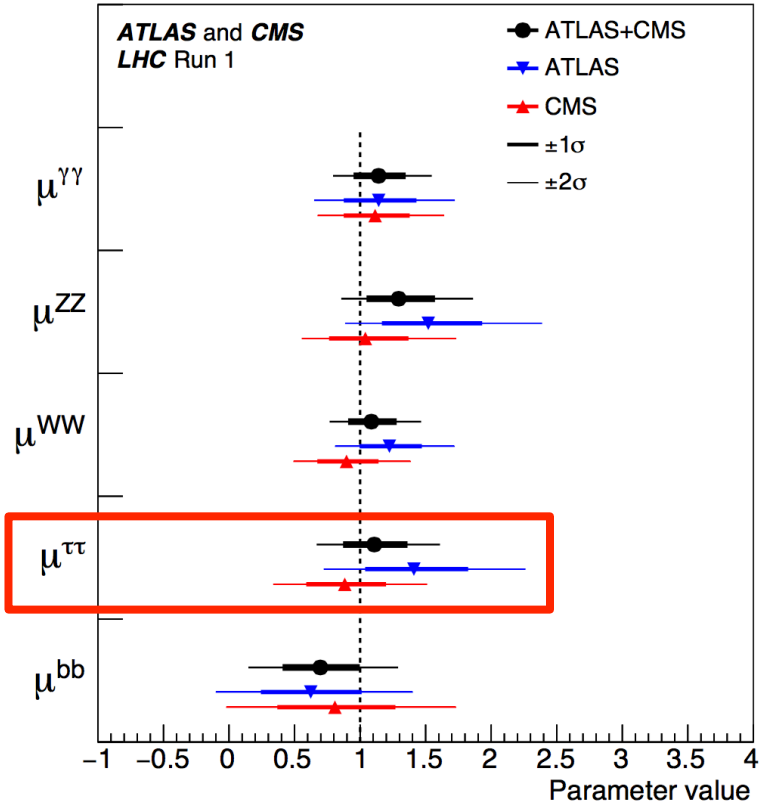
- Useful for extrapolating results to higher luminosity and understanding what sources may limit future precision
- Signal theory uncertainty as large as statistical uncertainty
- However dominant parts will be reduced for Run 2:
  - **N3LO ggH scale:** 8% → 2-3%
  - **New PDF4LHC**: 7% → 2%



Signal strengths in each prod./decay





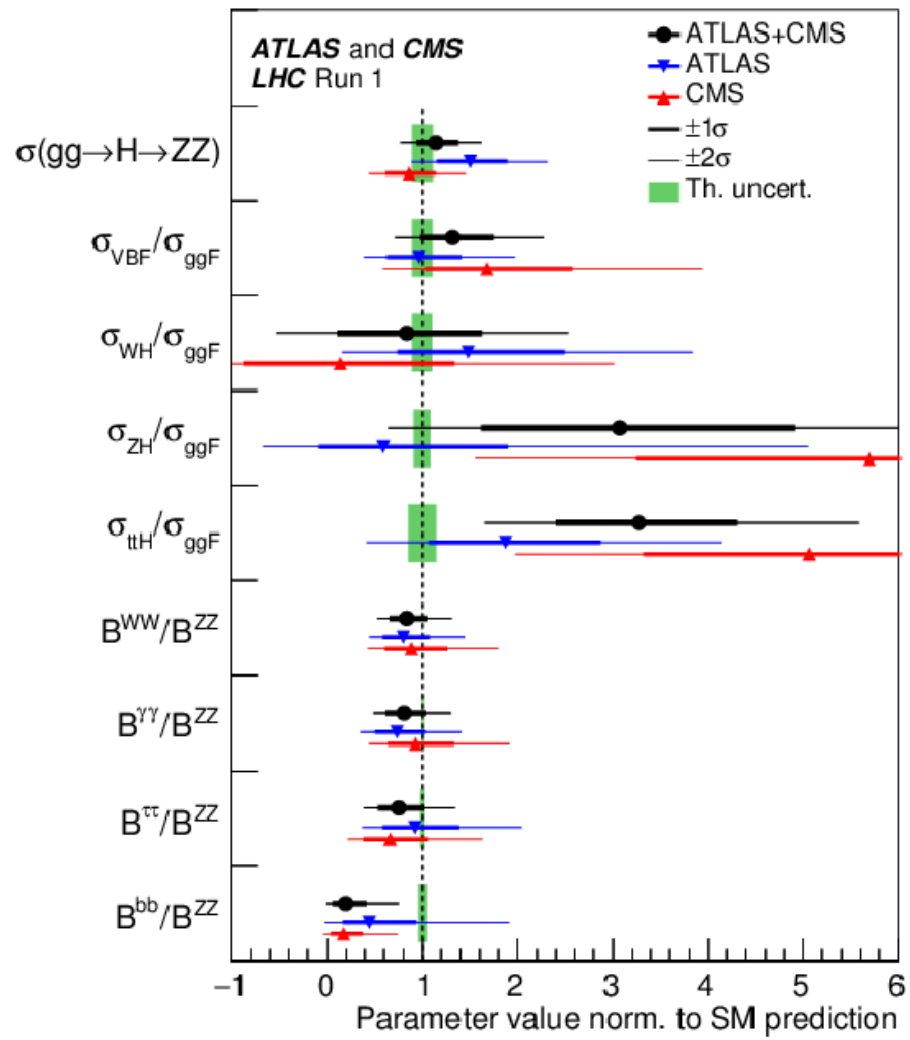
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

H→ττ decay mode and VBF process established through combination

Signal strength ratios

- Assumptions: **only the 7/8 ratios as in SM**
- Normalize the rate for any particular channel to a reference process using ratios of cross sections and branching ratios
- Motivation:
  - No assumptions on relative cross sections or BRs
  - Measured values independent of SM prediction and inclusive theory uncertainties
  - Cancellation of common systematic uncertainties in ratios
- Choose reference process as one measured with the **smallest systematic uncertainty: gg→H→ZZ**

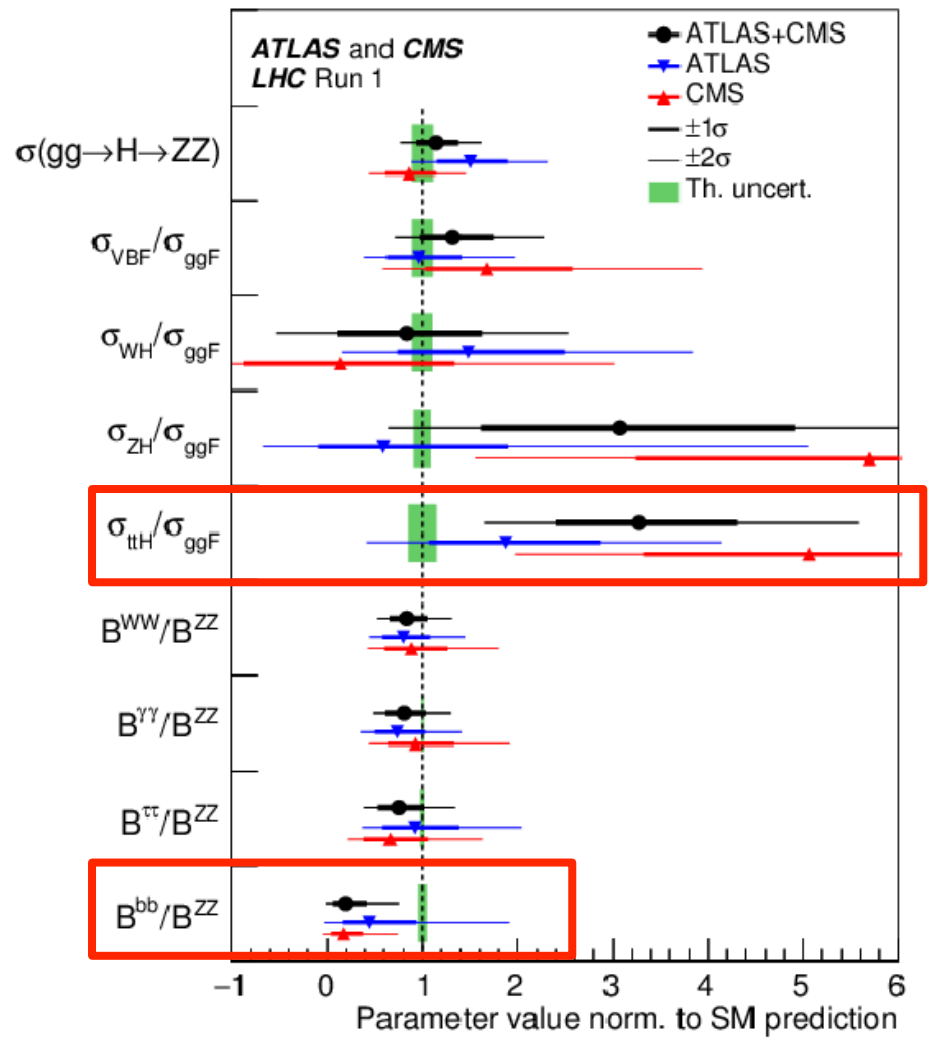
$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \to H \to ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$



Signal strength ratios

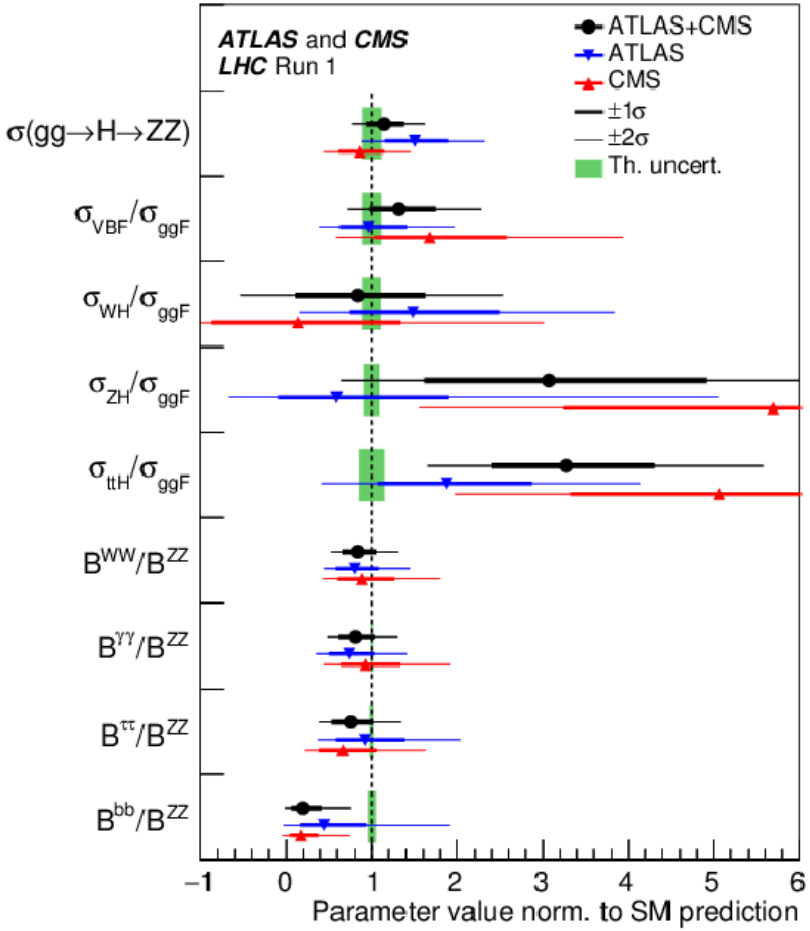
- Largest disagreement in $\sigma_{ttH}/\sigma_{ggF}$ (~3σ)
  - mainly due to the multi-lepton categories
- In this parameterization, the high values found for the production cross section ratios for the *ZH* and *ttH* processes induce a low value for the $H \rightarrow bb$ decay branching fraction because the $H \rightarrow bb$ decay mode does not contribute to the observed excesses.
- BR_{bb}/BR_{ZZ} (2.5σ)
  - Anti-correlated with above excess

$$\sigma_i \cdot \mathrm{BR}^f = \sigma(gg \rightarrow H \rightarrow ZZ) \times \left(\frac{\sigma_i}{\sigma_{ggF}}\right) \times \left(\frac{\mathrm{BR}^f}{\mathrm{BR}^{ZZ}}\right)$$

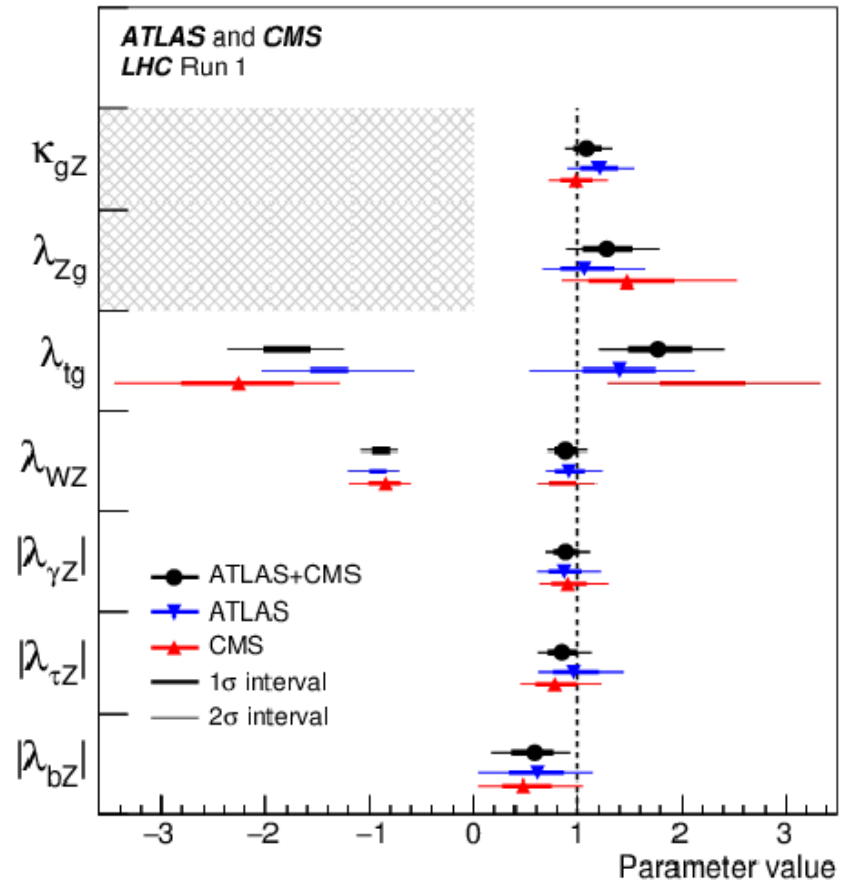


Ratio of rates → Ratio of couplings

Re-fit fewer couplings to actual particles as ratios to Z and gluon, $\lambda_{ij} = \kappa_i/\kappa_j$

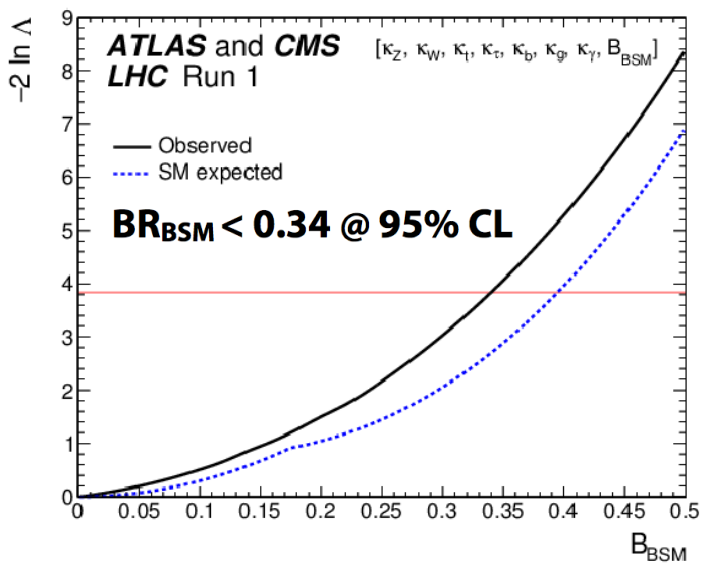


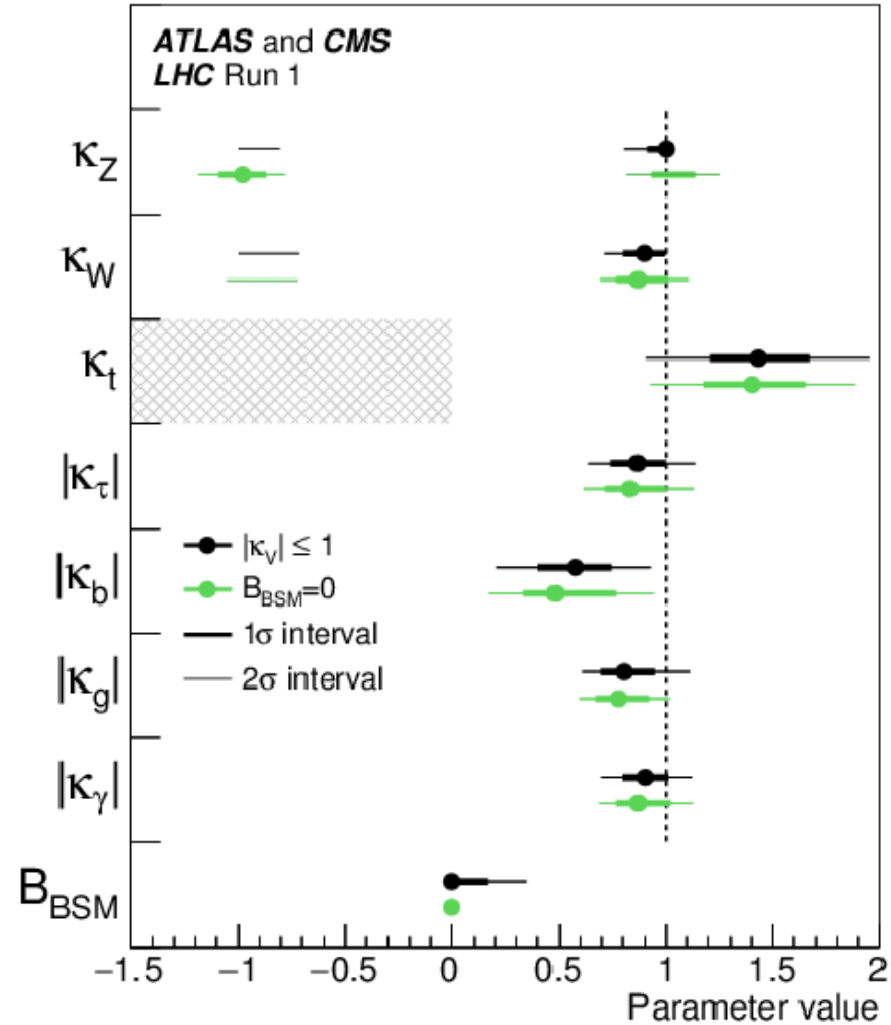
Refit →



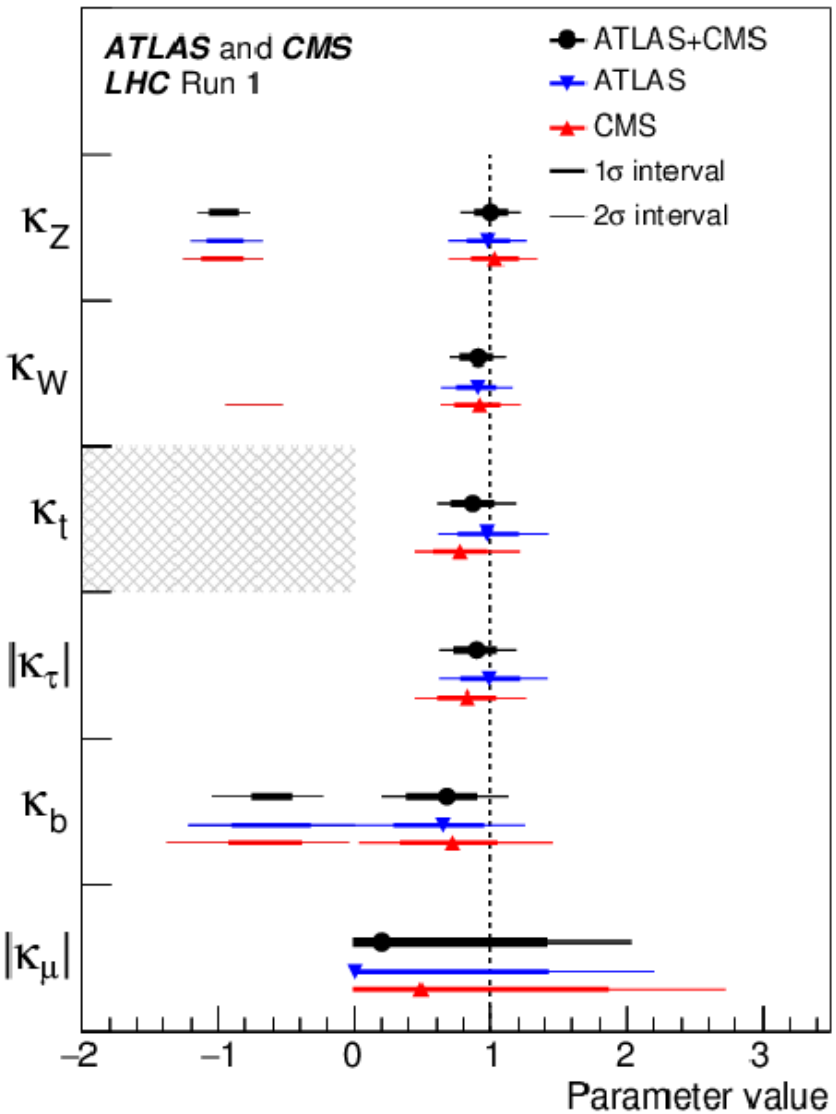
Allowing for BSM loop/decay contributions

- Use effective couplings for ggH (κ_g) and H→γγ (κ_γ)
- Consider two scenarios:
  - **BR_{BSM} = 0**
  - **BR_{BSM} floating, but $\kappa_W, \kappa_Z < 1$**
- Care needed with BR_{BSM}: not just Higgs decays to new particles but also non-SM BRs to unmeasured final states, e.g. gg and cc

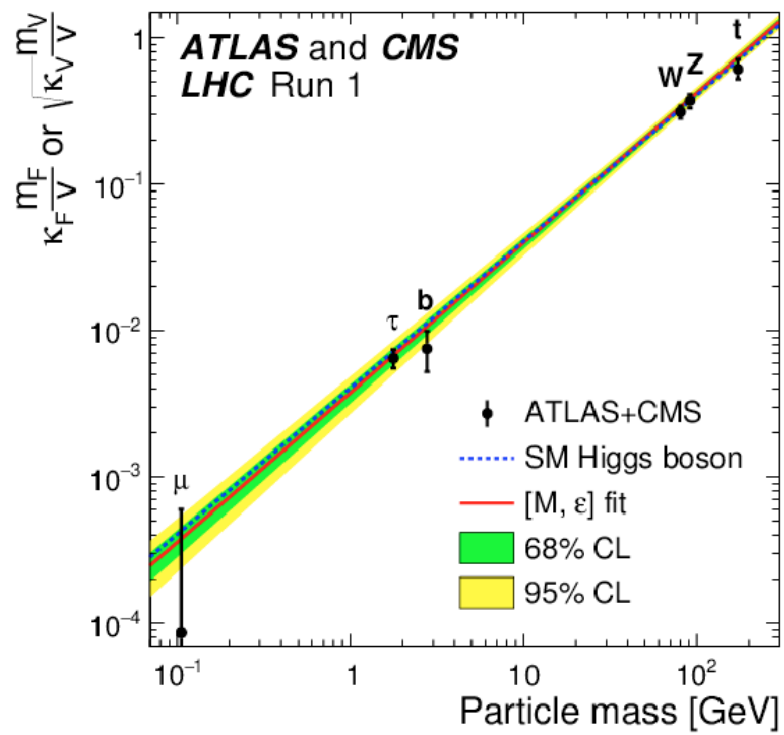




No BSM loop/decay contributions

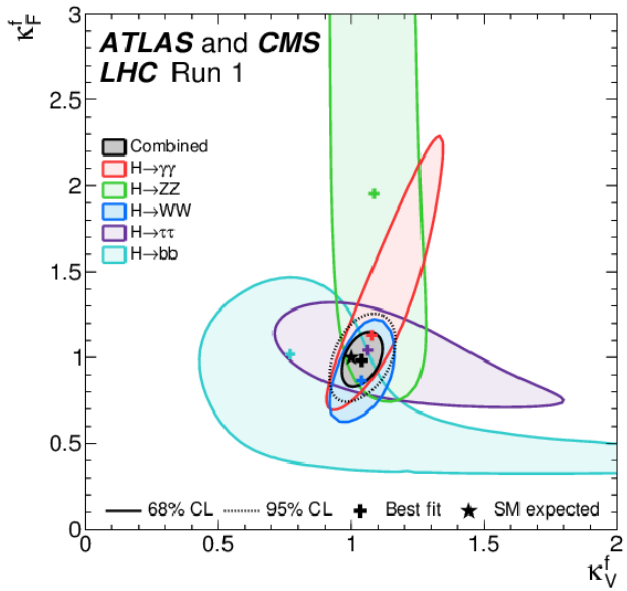


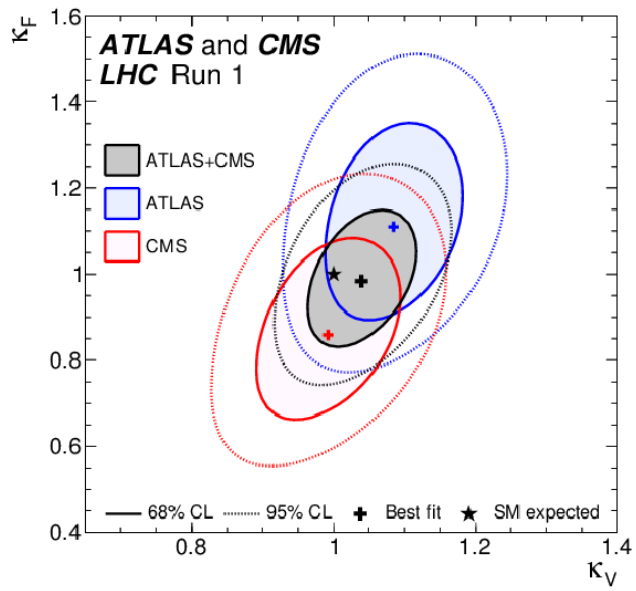
- **Resolve ggH (κ_g) and H→γγ (κ_γ) loops**
- Includes H→μμ analyses for reduced coupling vs. particle mass



2D scans of κ_V, κ_F

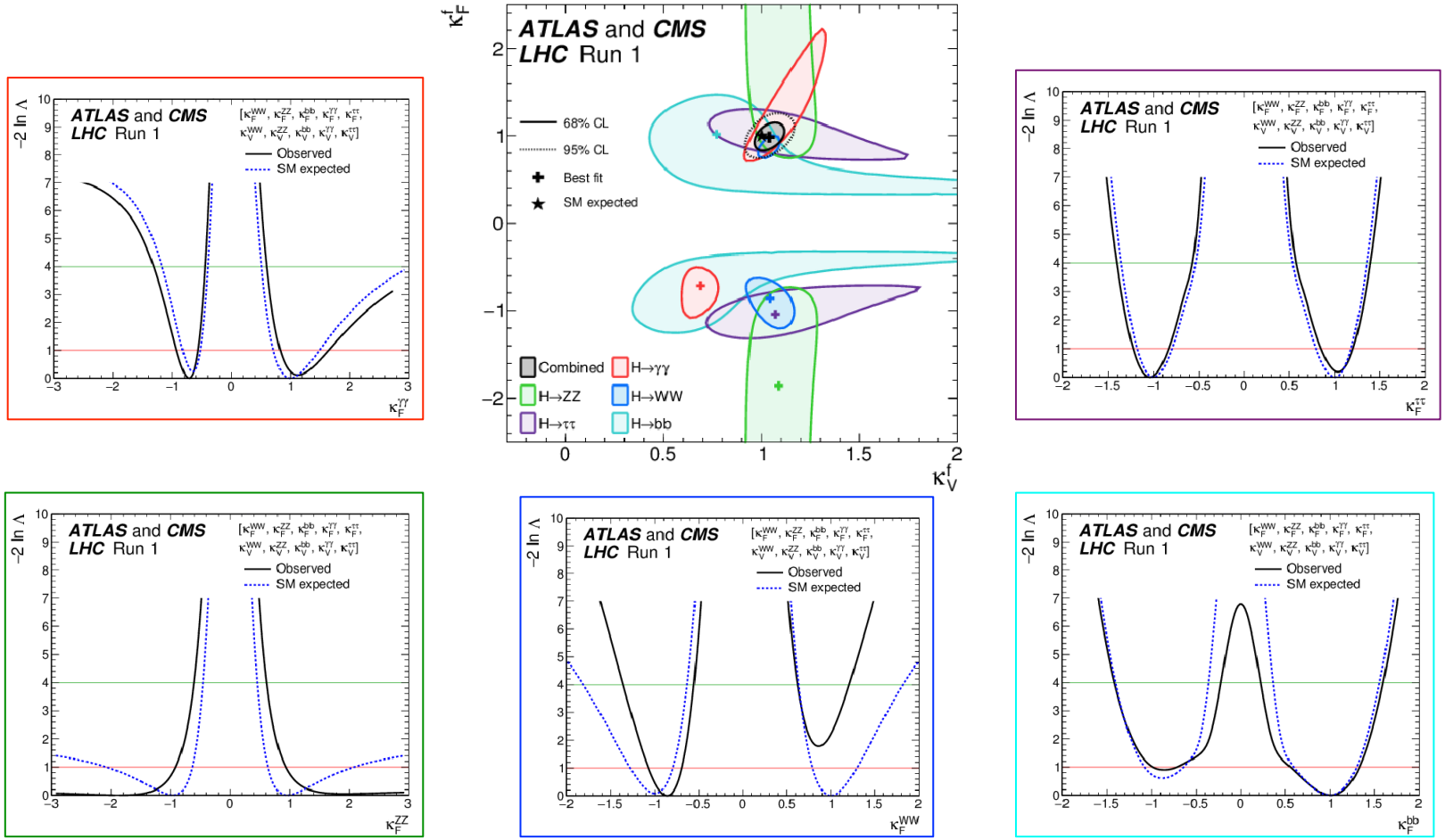
- Commonly-presented model in which
  - $\kappa_V=\kappa_W=\kappa_Z$
  - $\kappa_F=\kappa_t=\kappa_b=k_\tau$
- Perform additional scans in a model with separate κ_V^f, κ_F^f per decay-mode
  - 10 parameter fit for 5 channels
- Here the best-fit is restricted to quadrant where $\kappa_V>0$, $\kappa_F>0$
- All channels compatible with $\kappa_V=\kappa_F=1$





2D scans of κ_V, κ_F

- Most channels nearly degenerate in relative sign of κ_V and κ_F



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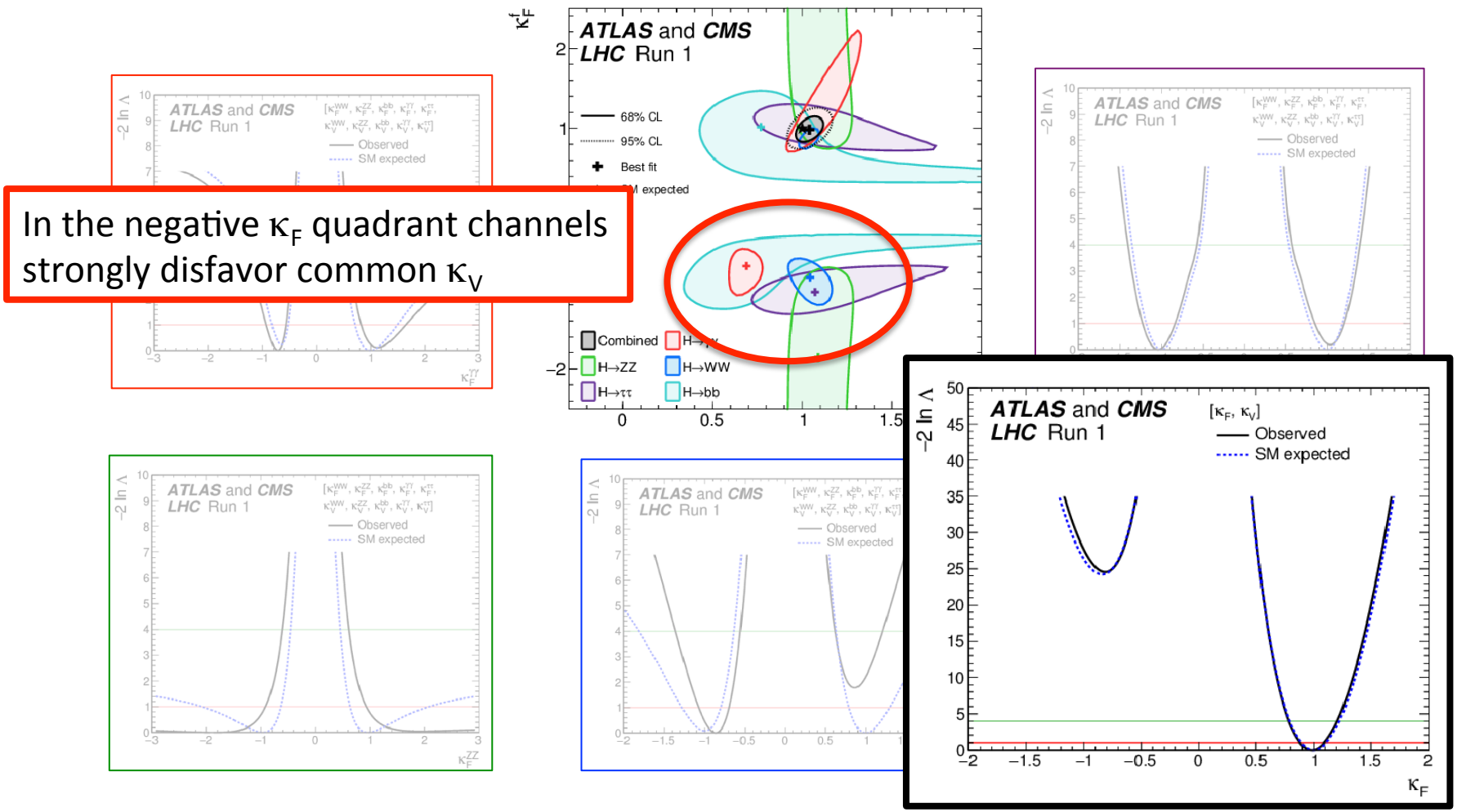
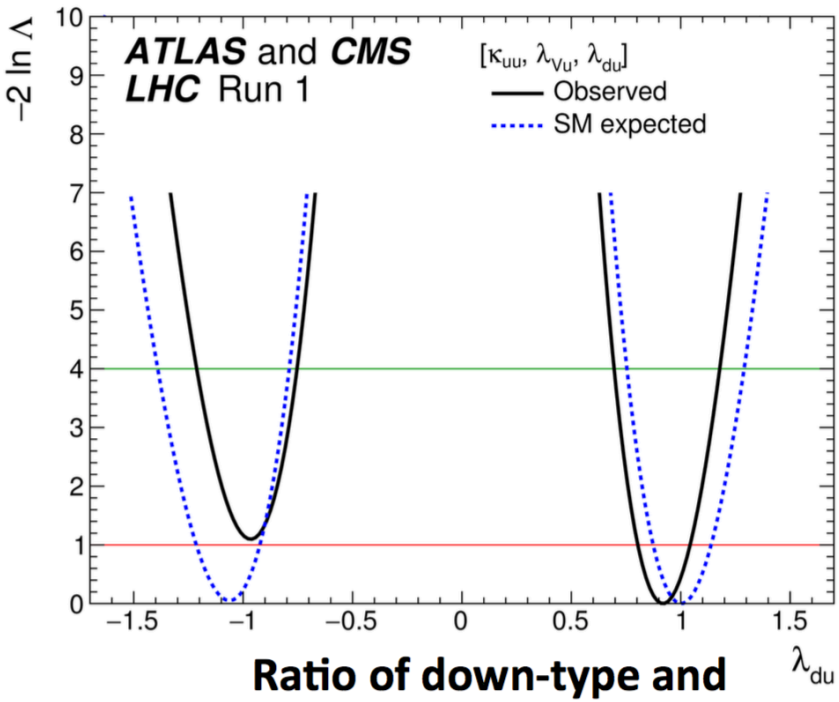


In the negative κ_F quadrant channels strongly disfavor common κ_V

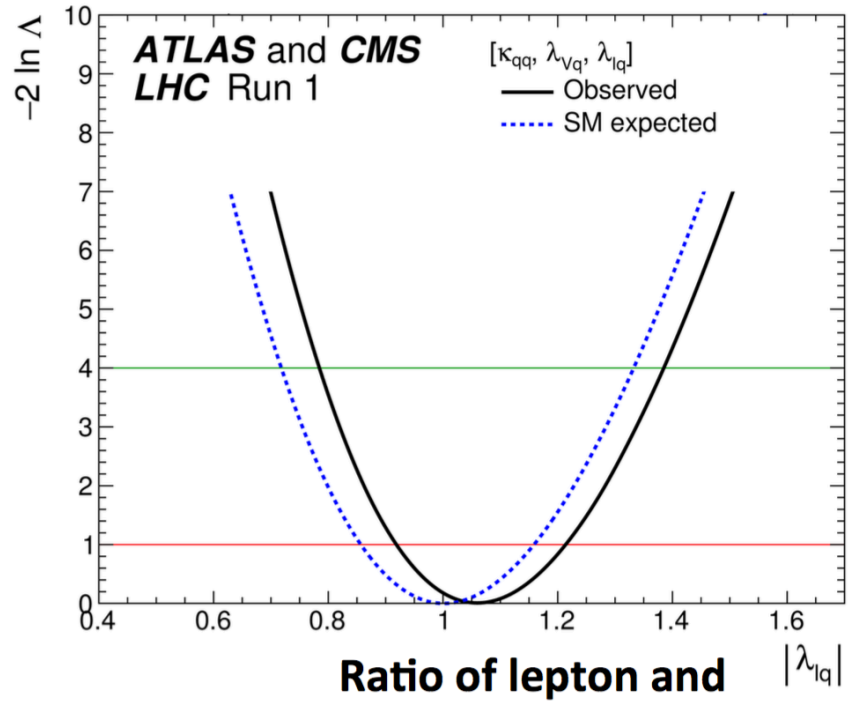
Fermion Couplings

- In MSSM / 2HDM Type II [κ_V, κ_d, κ_u], ratio of down-type (b, τ, μ) and up-type (t) fermion couplings is tested with ~10% precision
- No enhancement observed wrt SM, i.e. consistent with alignment limit

- In 2HDM Lepton-Specific [κ_V, κ_l, κ_q], ratio of lepton (τ, μ) and quark couplings (t, b) would be enhanced at large tan β
- Also good agreement with SM



Ratio of down-type and up-type fermion couplings



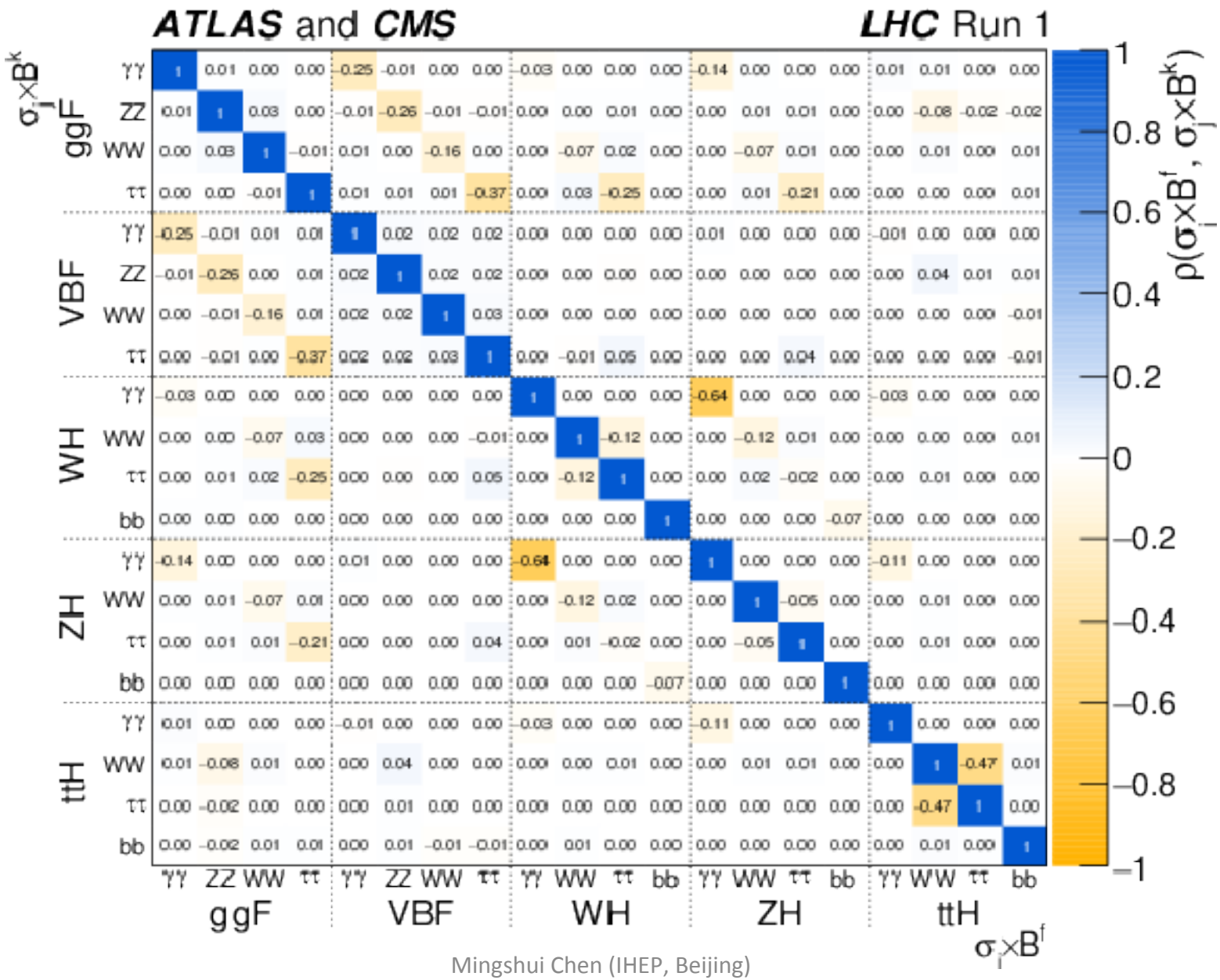
Ratio of lepton and quark couplings

Summary

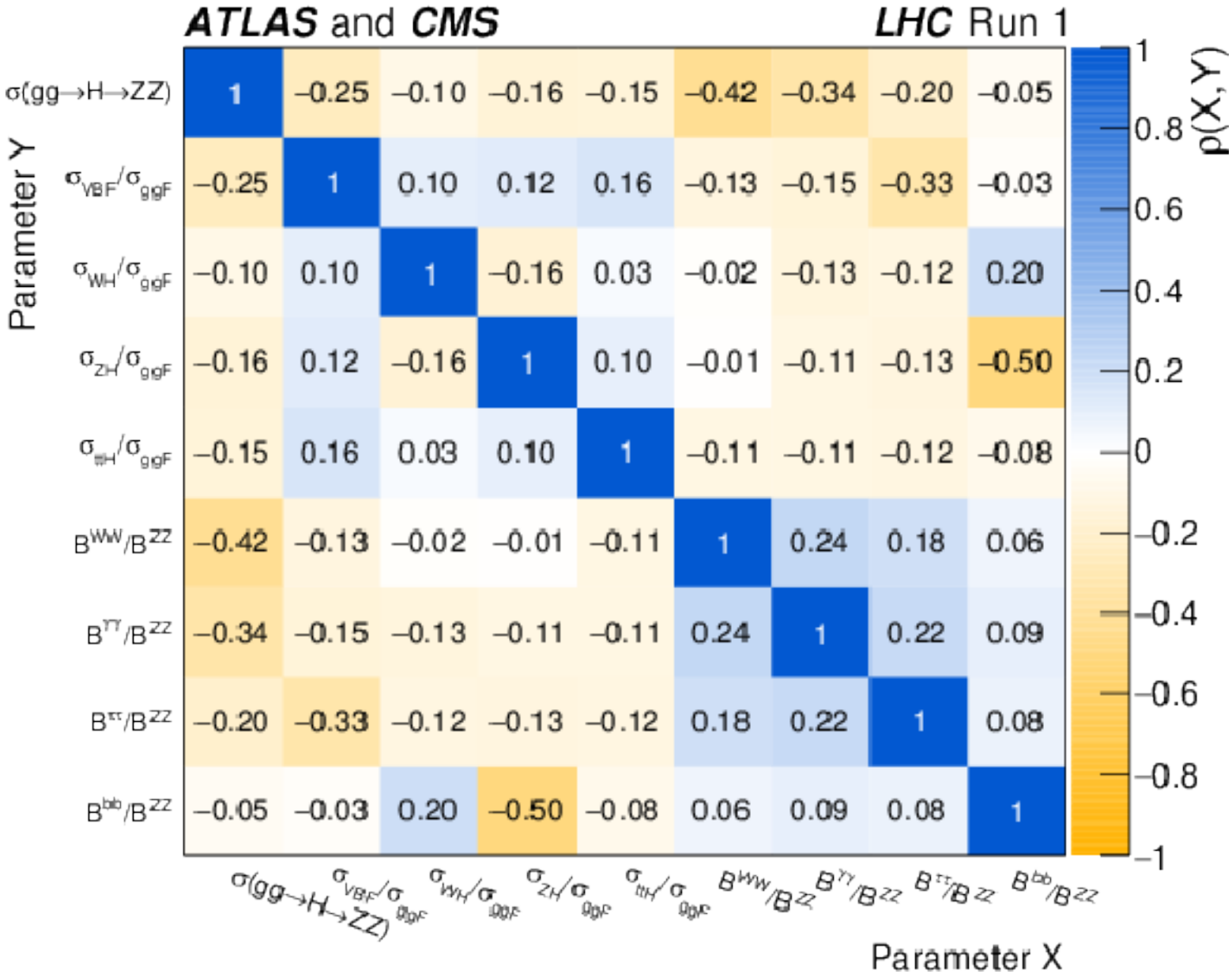
- **Run 1 Higgs mass precision < 0.2%**
- A comprehensive combined measurement of ATLAS and CMS Higgs boson couplings has been performed
  - Precision usually better by ~$1/\sqrt{2}$ wrt single experiment
- **Strong picture of overall consistency with SM** expectations
  - Results given in a range of models based on either signal strength or coupling modifiers
- **$H \rightarrow \tau\tau$ decay mode and VBF process established through combination**

Backup

Correlation Matrix



Correlation Matrix



Coupling Parameterization

Production	Loops	Interference	Effective scaling factor	Resolved scaling factor
$\sigma(ggF)$	✓	t–b	κ_g^2	$1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(\mathrm{VBF})$	–	–		$0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–		κ_W^2
$\sigma(qq/qg \to ZH)$	–	–		κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z		$2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–		κ_t^2
$\sigma(gb \to tHW)$	–	t–W		$1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qq/qb \to tHq)$	–	t–W		$3.40 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–		κ_b^2
Partial decay width				
Γ^{ZZ}	–	–		κ_Z^2
Γ^{WW}	–	–		κ_W^2
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–		κ_τ^2
Γ^{bb}	–	–		κ_b^2
$\Gamma^{\mu\mu}$	–	–		κ_μ^2
Total width ($B_{BSM} = 0$)				
Γ_H	✓	–	κ_H^2	$0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 +$ $0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 +$ $0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{(Z\gamma)}^2 +$ $0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Ratio of couplings