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Run 1 LHC Higgs Coupling Combination

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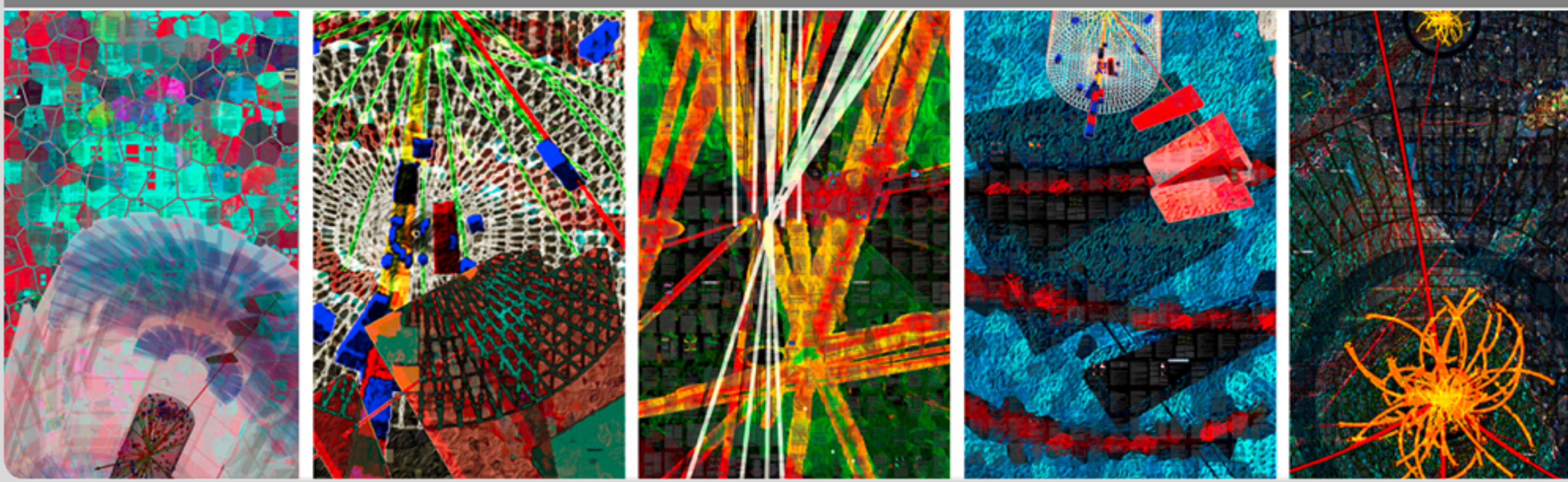
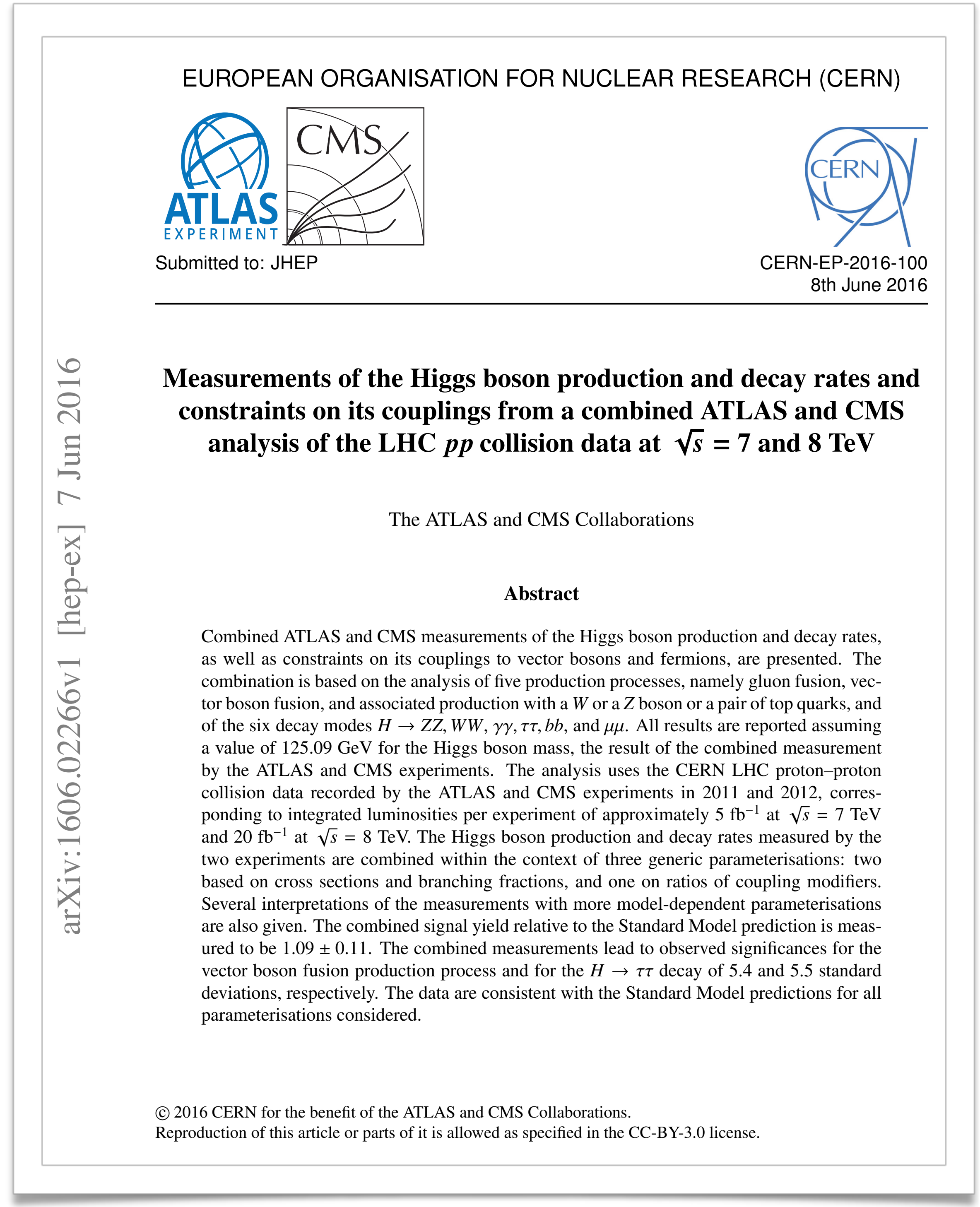


Introduction

- Yesterday we reviewed how the analyses of each Higgs decay channels progressed in CMS during Run 1 of the LHC
- Same set of channels also studied in ATLAS
- Both experiments also published **combination** results
- Not a combination of results, a new combined result ⇒ **perform fits to the data of all channels simultaneously**
- At the beginning of 2015 CMS and ATLAS embarked on an effort to make a combined analysis of the Higgs couplings
- 1.5 years later… resulting paper submitted for publication



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

ATLAS EXPERIMENT CMS CERN

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Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV

The ATLAS and CMS Collaborations

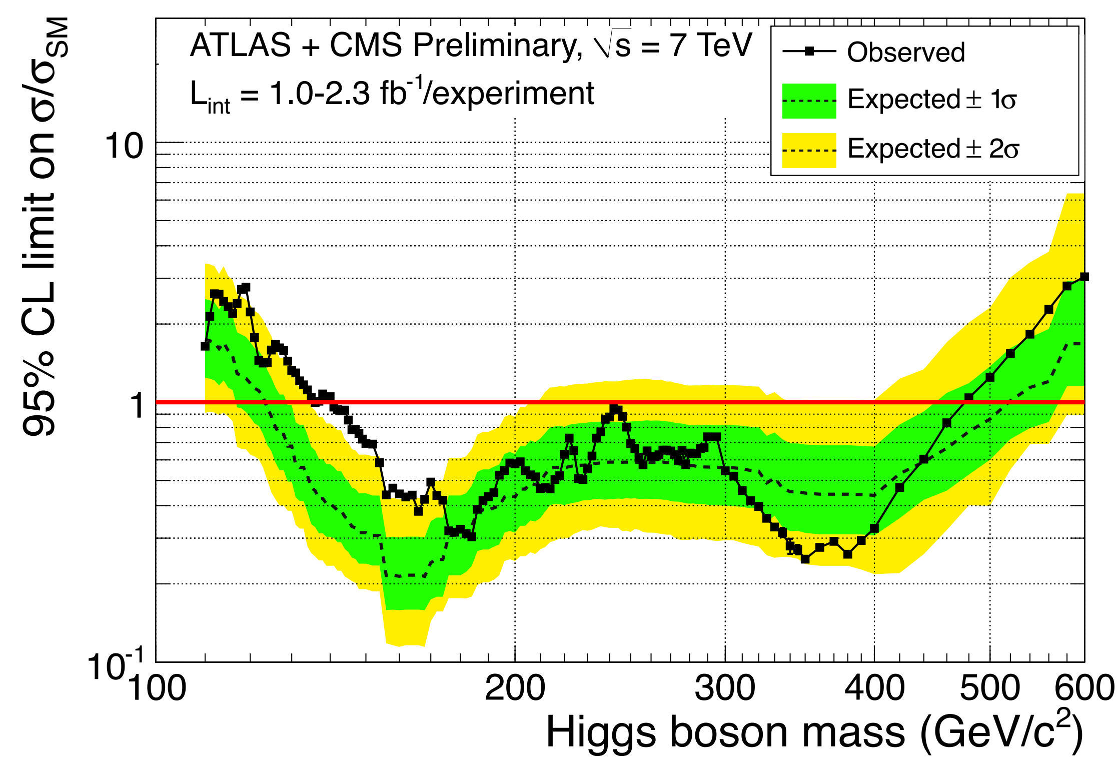
Abstract

Combined ATLAS and CMS measurements of the Higgs boson production and decay rates, as well as constraints on its couplings to vector bosons and fermions, are presented. The combination is based on the analysis of five production processes, namely gluon fusion, vector boson fusion, and associated production with a W or a Z boson or a pair of top quarks, and of the six decay modes $H \to ZZ, WW, \gamma\gamma, \tau\tau, bb$, and $\mu\mu$. All results are reported assuming a value of 125.09 GeV for the Higgs boson mass, the result of the combined measurement by the ATLAS and CMS experiments. The analysis uses the CERN LHC proton–proton collision data recorded by the ATLAS and CMS experiments in 2011 and 2012, corresponding to integrated luminosities per experiment of approximately 5 fb^{-1} at $\sqrt{s}$ = 7 TeV and 20 fb^{-1} at $\sqrt{s}$ = 8 TeV. The Higgs boson production and decay rates measured by the two experiments are combined within the context of three generic parameterisations: two based on cross sections and branching fractions, and one on ratios of coupling modifiers. Several interpretations of the measurements with more model-dependent parameterisations are also given. The combined signal yield relative to the Standard Model prediction is measured to be 1.09 ± 0.11. The combined measurements lead to observed significances for the vector boson fusion production process and for the $H \to \tau\tau$ decay of 5.4 and 5.5 standard deviations, respectively. The data are consistent with the Standard Model predictions for all parameterisations considered.

LHC Higgs Combination Group

- Launched at the end of 2010
- **Initial work:** *(ATL-PHYS-PUB-2011-11/CMS NOTE-2011/005):*
  - Defining statistical procedures for setting exclusion limits on signals or quantifying an excess
  - Identifying common systematic uncertainties and how uncertainties will be modelled (in particular on the signal processes)
  - Toy combinations as a technical exercise / validation
- **Results:**
  - Established RooFit workspaces and fitting framework as common tools
  - Definition of test statistic and CLs criteria that would be used for virtually all ATLAS and CMS Higgs results

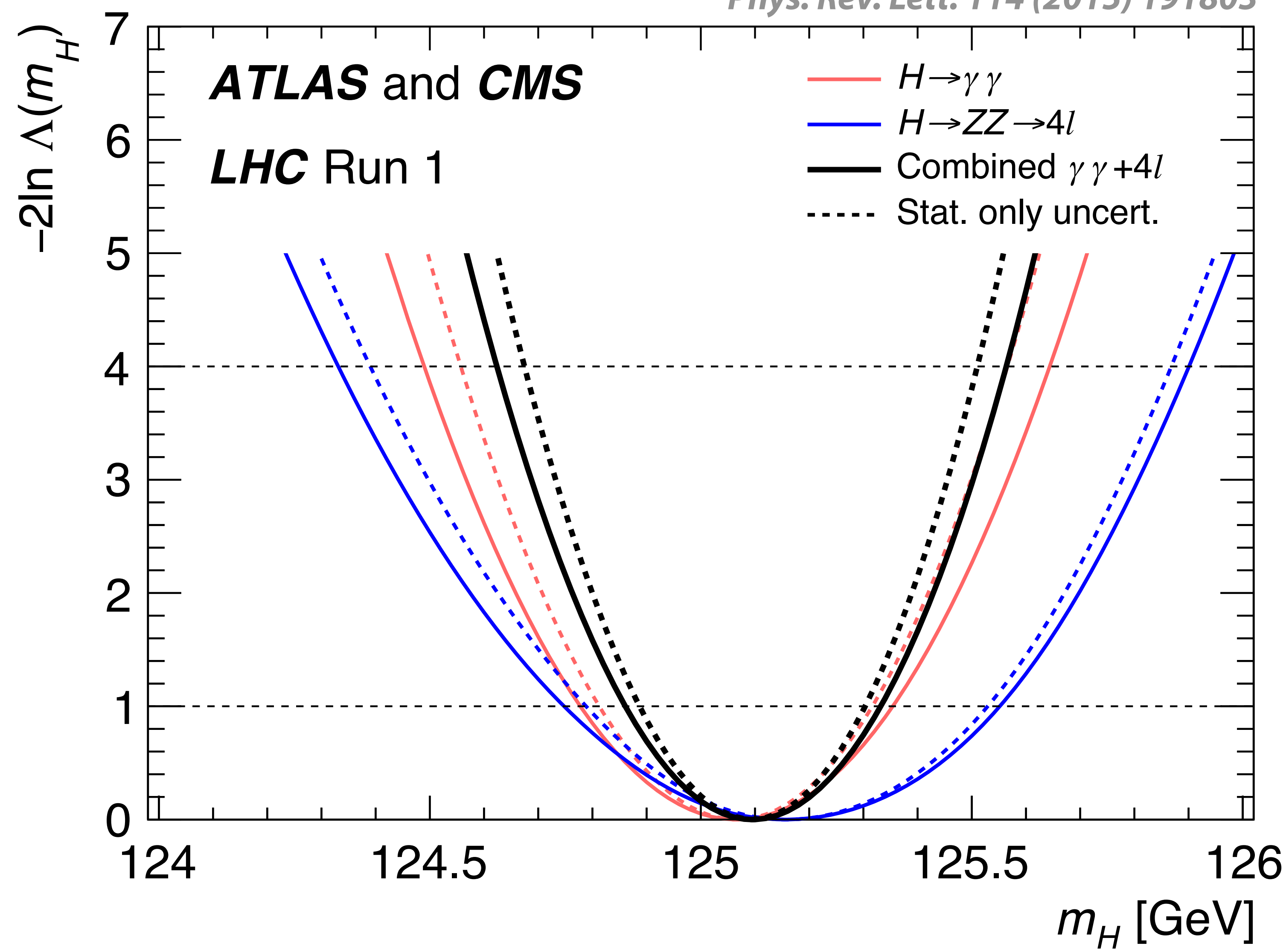
- CMS+ATLAS combination with 7 TeV data
  - *ATLAS-CONF-2011-157 / CMS PAS HIG-11-023*
  - ZZ, WW, γγ, ττ, bb final states
  - 268 nuisance parameters
  - CLs values determined by fitting toy datasets for test stat. distributions
  - Asymptotic formulae used as a cross check



Run 1 Legacy Mass Combination

- Important to establish the best measurement of m_H before attempting couplings
- Using high resolution $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ channels

Phys. Rev. Lett. 114 (2015) 191803

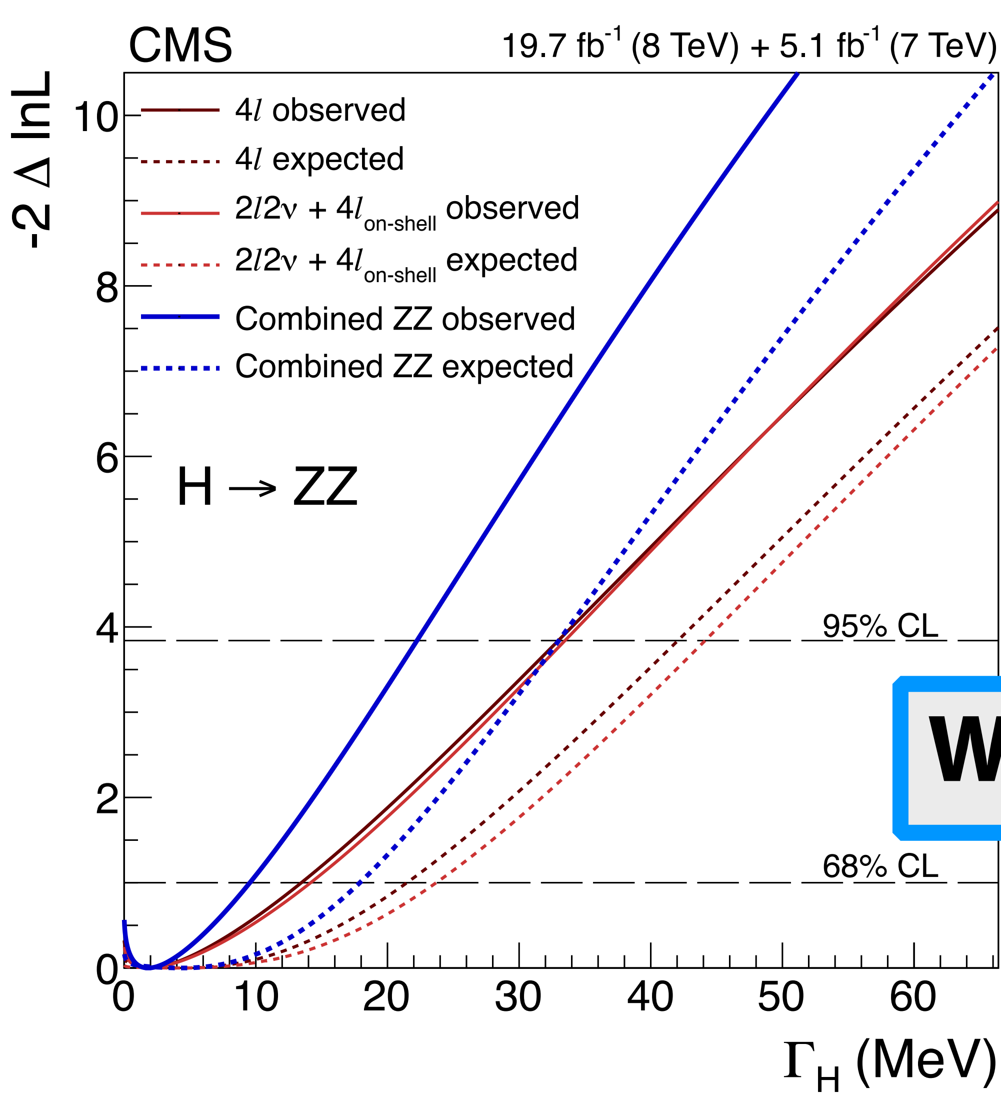


$m_H = 125.09 \pm 0.24$ GeV $= \pm 0.21$ (stat.) ± 0.11 (syst) GeV

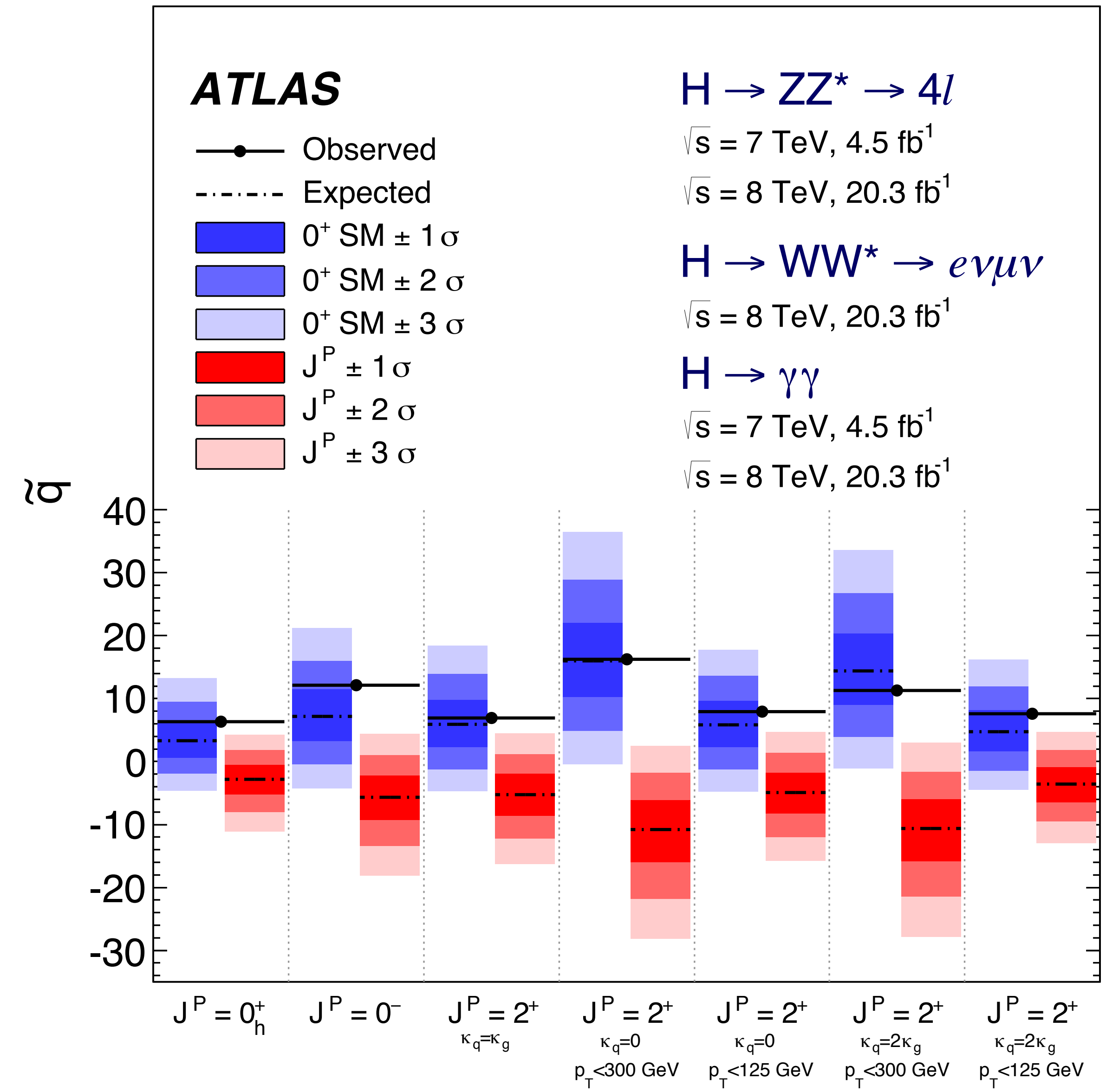
Properties

Spin/Parity

- Indirect constraint on the width using ratio of off-shell to on-shell production in H→ZZ
- SM predicts Γ ~ 4 MeV
- ATLAS and CMS find limits on Γ/Γ_{SM} ~ 4-8



Width



- Test many alternative hypotheses against SM CP-even scalar, $J^P = 0^+$, e.g. pseudoscalar, spin-2
- All rejected at 99.9% CL

Input Preparation

Combination Inputs

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

	Untagged	VBF	VH	ttH
H→γγ	✓	✓	✓	✓
H→ZZ→4l	✓	✓	✓	✓
H→WW→2l2ν	✓	✓	✓	✓
H→ττ	✓	✓	✓	✓
H→bb			✓	✓
H→μμ	✓	✓		

- **Not included as not in both CMS and ATLAS combination results:**
  - H→Zγ search
  - Off-shell measurements
  - H→invisible searches
  - VBF H→bb

- H→μμ 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→WW entering H→ττ analysis**, **single-top + Higgs production in ttH**

Nuisance Parameter Correlations

- Luminosity uncertainties partially correlated as for mass combination

- The conclusion of the review was that the majority of **background-related uncertainties are uncorrelated** between experiments, as:
  - many are fully or partially data-driven,
  - different MC generators, correction factors, analysis selections are used.
  - Exceptions include inclusive cross section uncertainties on $qq \rightarrow ZZ$ and $t\bar{t} + V$ processes

- **Signal theory uncertainties** are main source of correlation between experiments
  - **QCD scale:**
    - Simple to correlate inclusive uncertainty, jet bins more difficult
  - **PDFs:**
    - Correlate inclusive PDF uncertainties between experiments
  - **Underlying event, parton shower and branching ratio uncertainties:**
    - Generally a smaller effect but also correlated between experiments

Technical Implementation

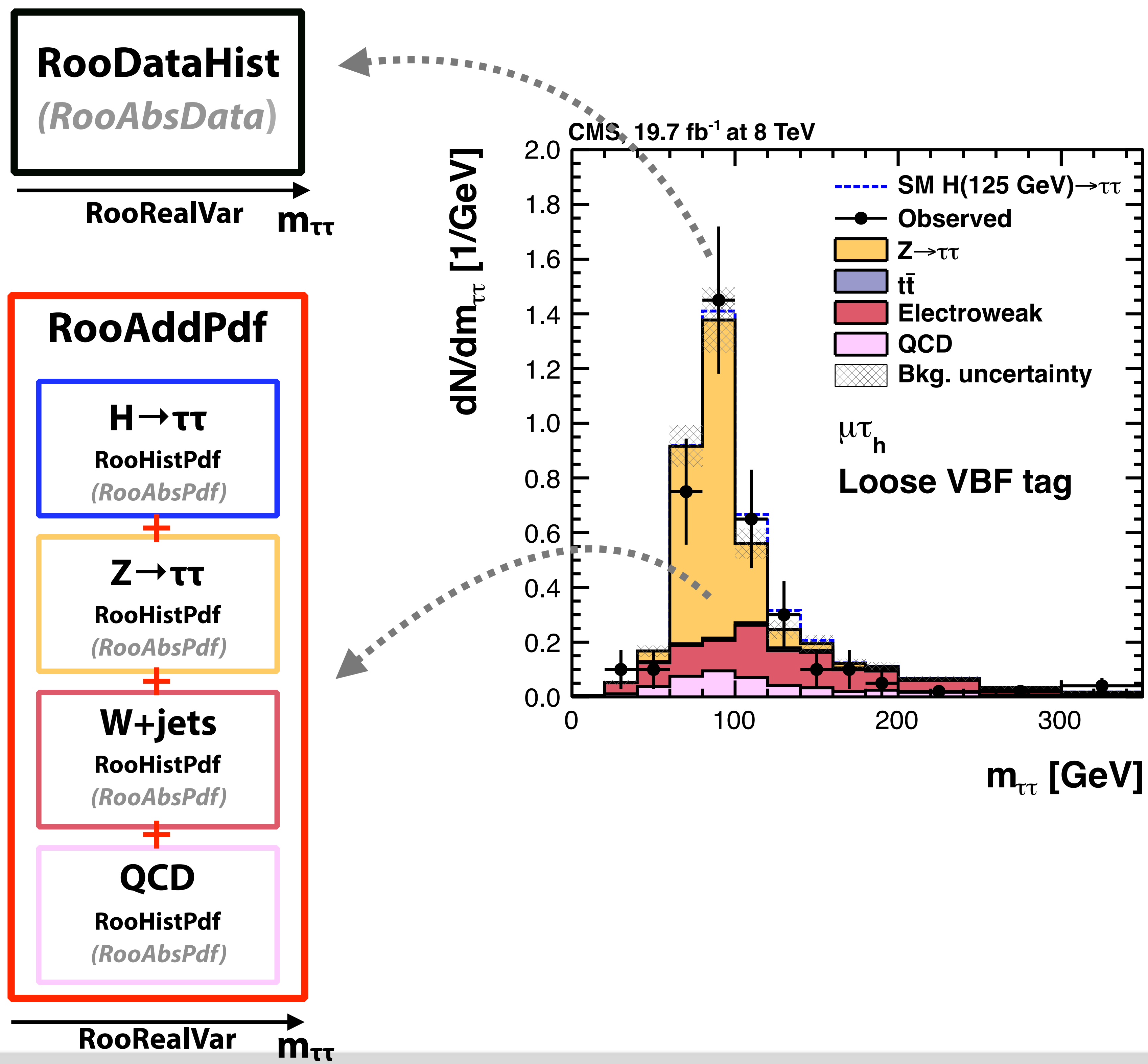
- RooFit & RooStats packages (built on top of ROOT) are the frameworks of choice
- Big advantage of RooFit is its OOP design and abstraction of virtually every aspect of model-building. Everything is an object:

Mathematical concept			RooFit class
variable	x	→	`RooRealVar`
function	$f(x)$	→	`RooAbsReal`
PDF	$f(x)$	→	`RooAbsPdf`
space point	$\vec{x}$	→	`RooArgSet`
integral	$\int_{x_{\min}}^{x_{\max}} f(x)dx$	→	`RooRealIntegral`
list of space points		→	`RooAbsData`

W. Verkerke

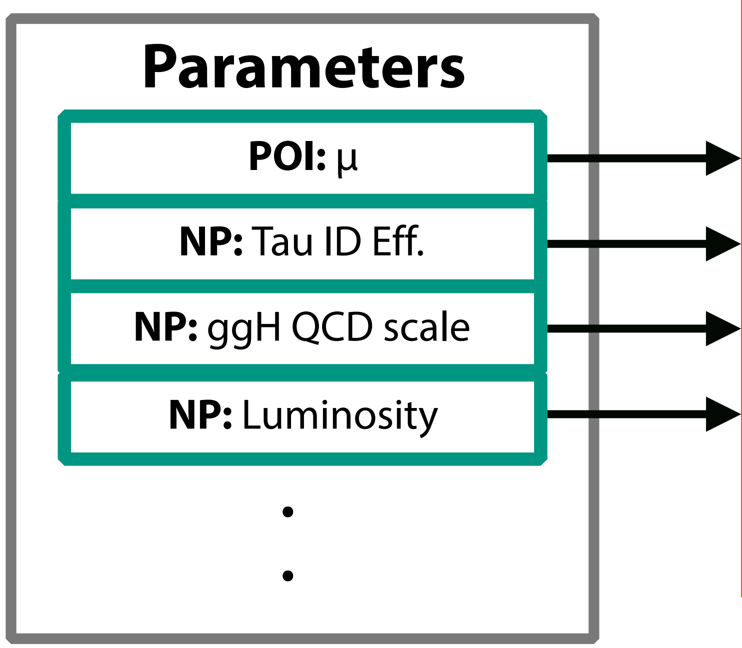
Technical Implementation - An Example

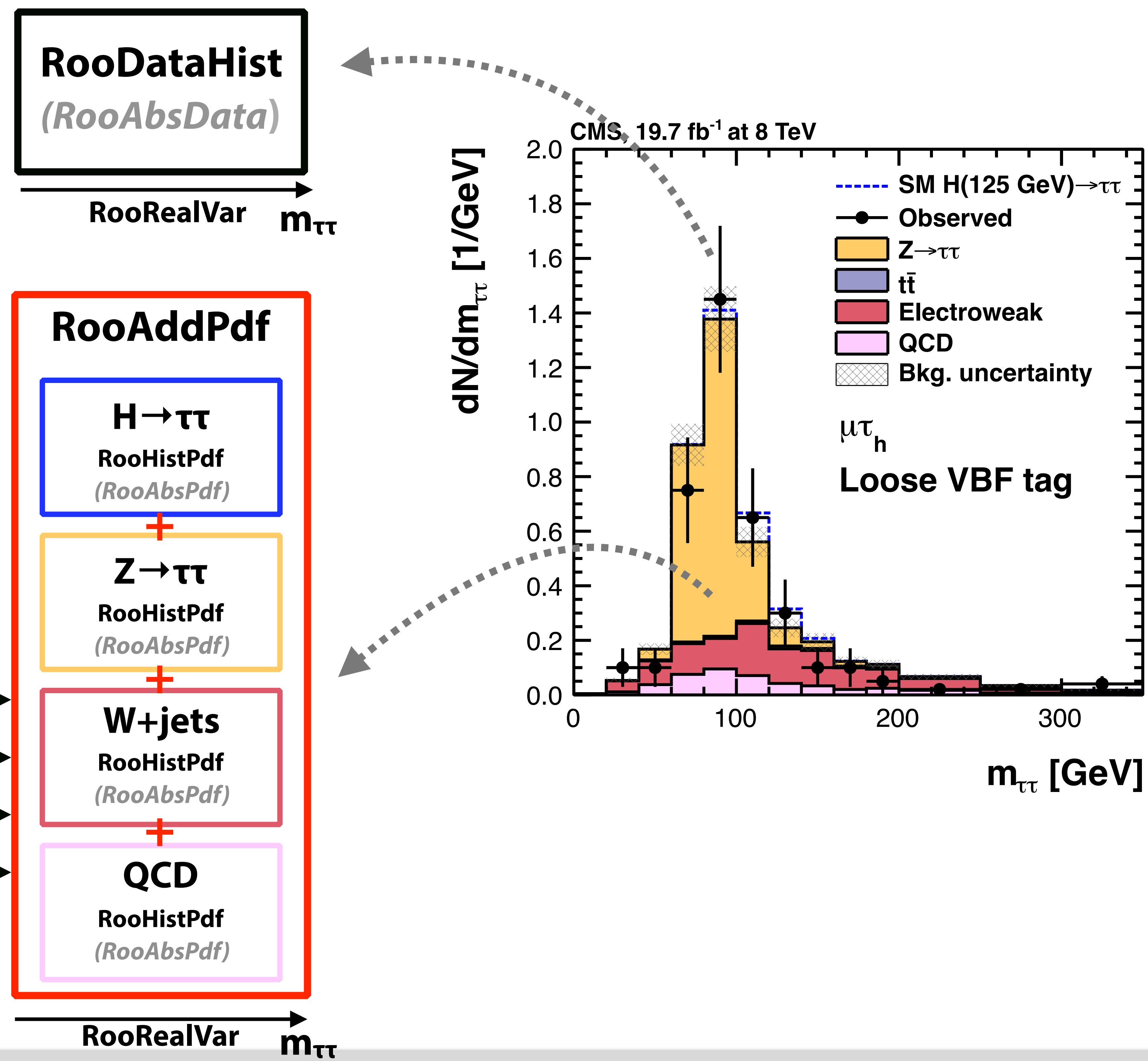
- Every analysis category represented as a dataset (binned or un-binned)
- The signal + background described by a PDF, typically the sum of several signal and background PDFs
- Both data and PDF defined in terms of observables, e.g. di-tau mass here, but in principle any N-dimensional space



Technical Implementation - An Example

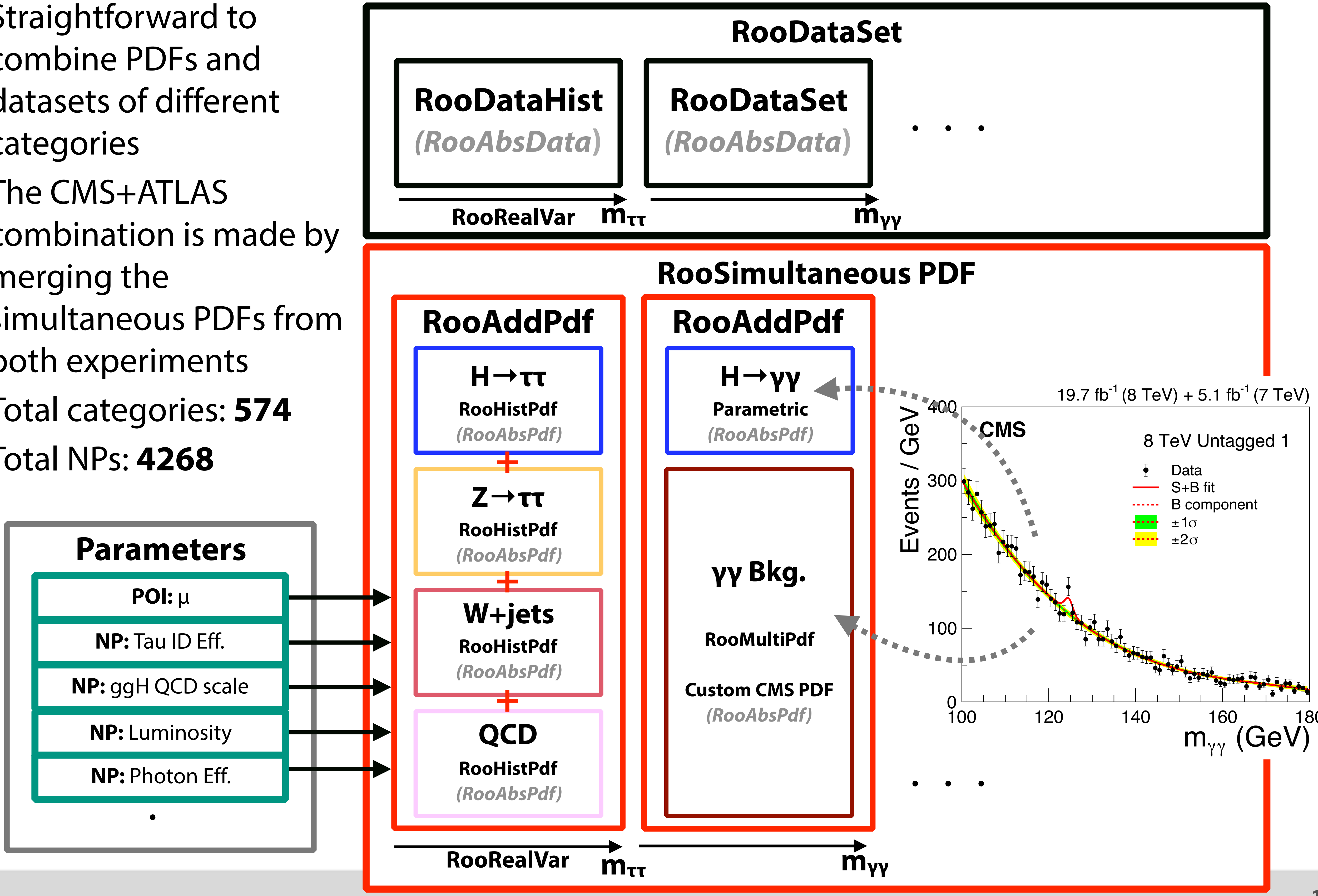
- PDF normalisations and shapes typically depend on a number of parameters:
  - Parameters of interest **(POIs)**
  - Nuisance parameters (**NPs**) e.g. to represent systematic uncertainties



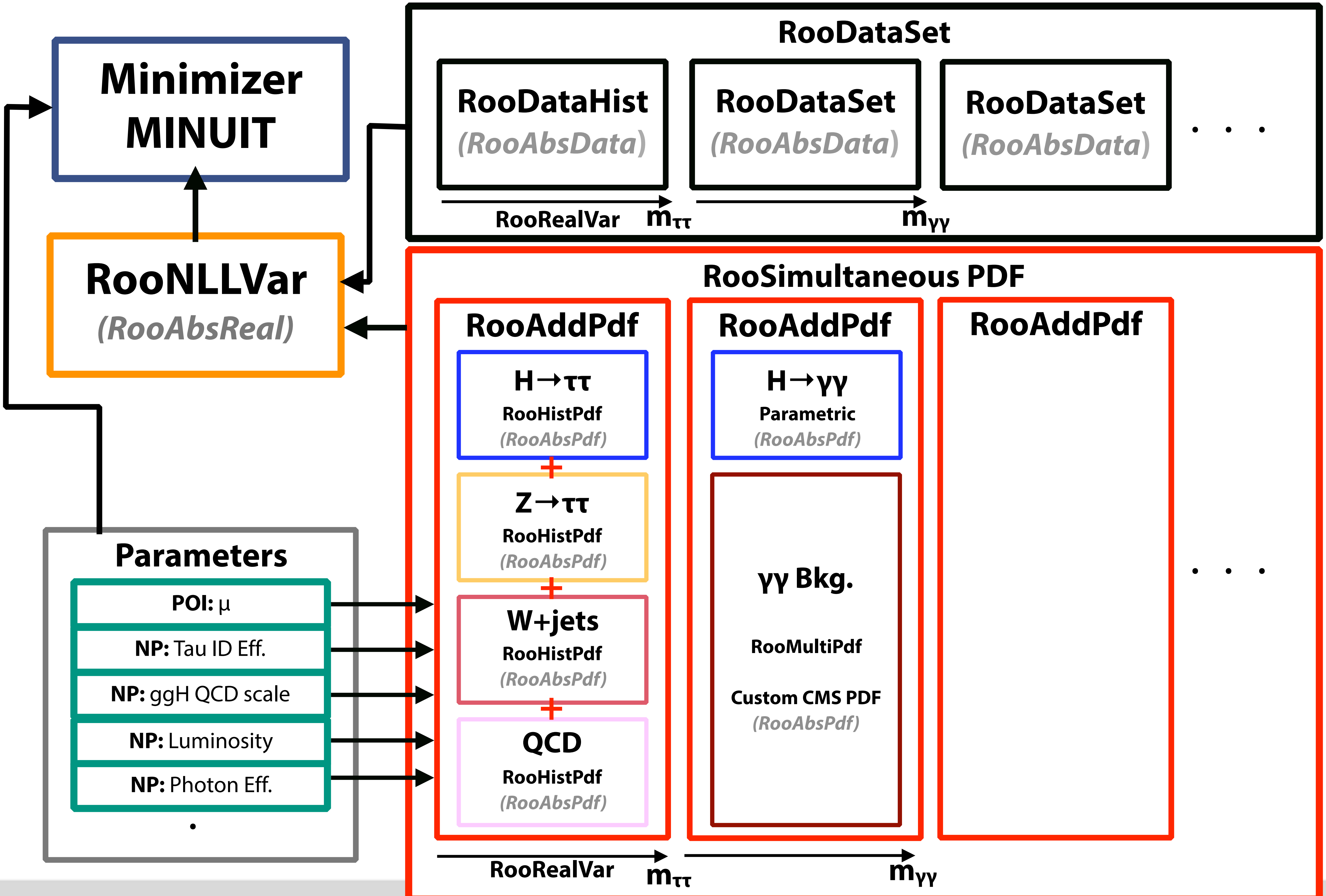


Technical Implementation - An Example

- Straightforward to combine PDFs and datasets of different categories
- The CMS+ATLAS combination is made by merging the simultaneous PDFs from both experiments
- Total categories: **574**
- Total NPs: **4268**



Technical Implementation - An Example



Technical Challenges

- **Fit convergence:** Minuit handles a 4300 parameter fit 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 optimisations by previous combine developers
    - 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 (fairly modest by HEP standards)

Methodology & Signal Parameterisation

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 statistic $q(\vec{\alpha}) = -2 \ln (\Lambda(\vec{\alpha}))$ 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 $q(\vec{\alpha})$ = the χ^2 critical value for that CL, e.g.
    - 1D 68% CL at $q(\alpha) = 1.00$

Signal Parameterisation

Signal strengths, μ

Parameters scale cross sections and BRs relative to SM

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

Scaling of generic i → H → f process

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

Couplings, κ

Parameters scale cross sections and partial widths relative to SM

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

$$\sigma_i \cdot BR^f = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H},$$

Total width determined as

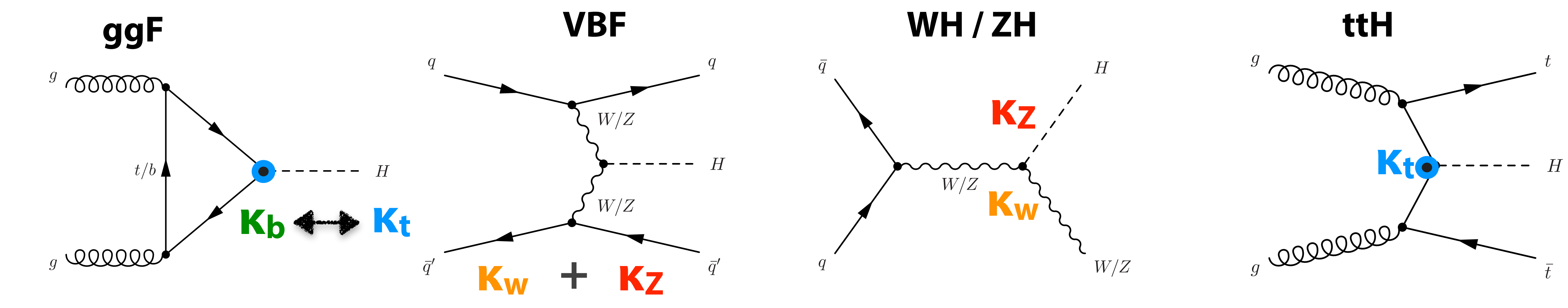
$$\Gamma_H = \frac{\kappa_H^2 \cdot \Gamma_H^{SM}}{1 - BR_{BSM}}$$

Where

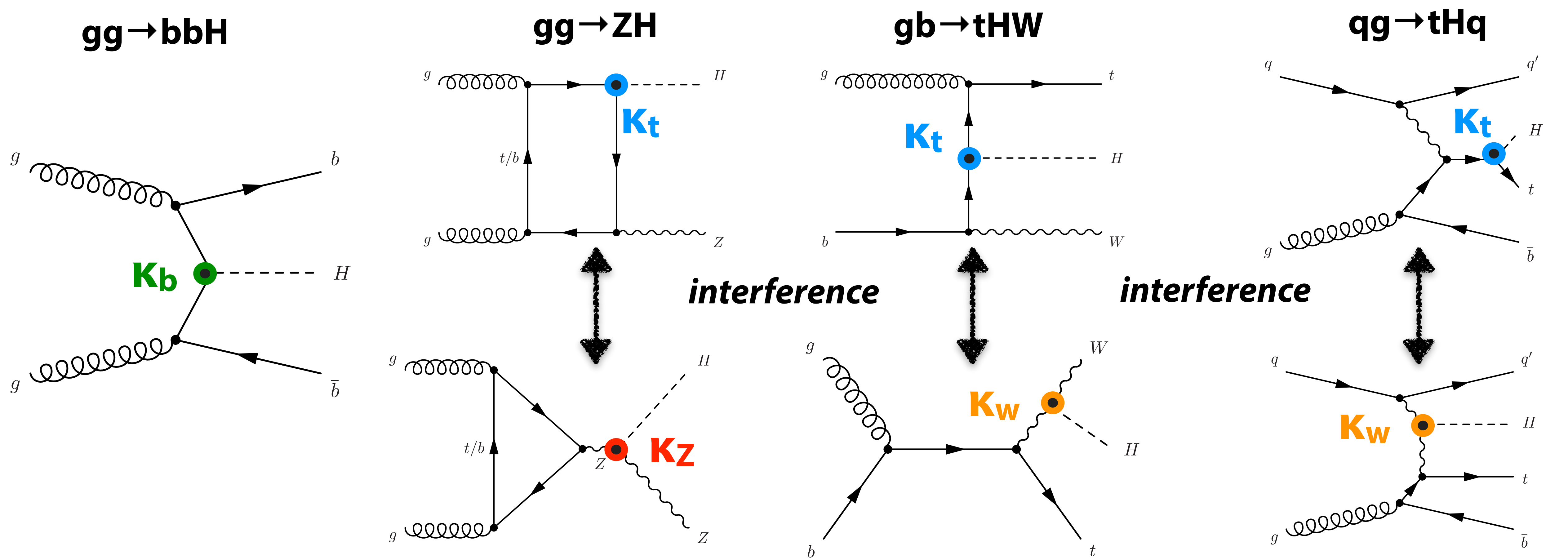
$$\kappa_H^2 = \sum_j BR^j_{SM} \kappa_j^2$$

Signal Processes - Production

- **Usual suspects:**



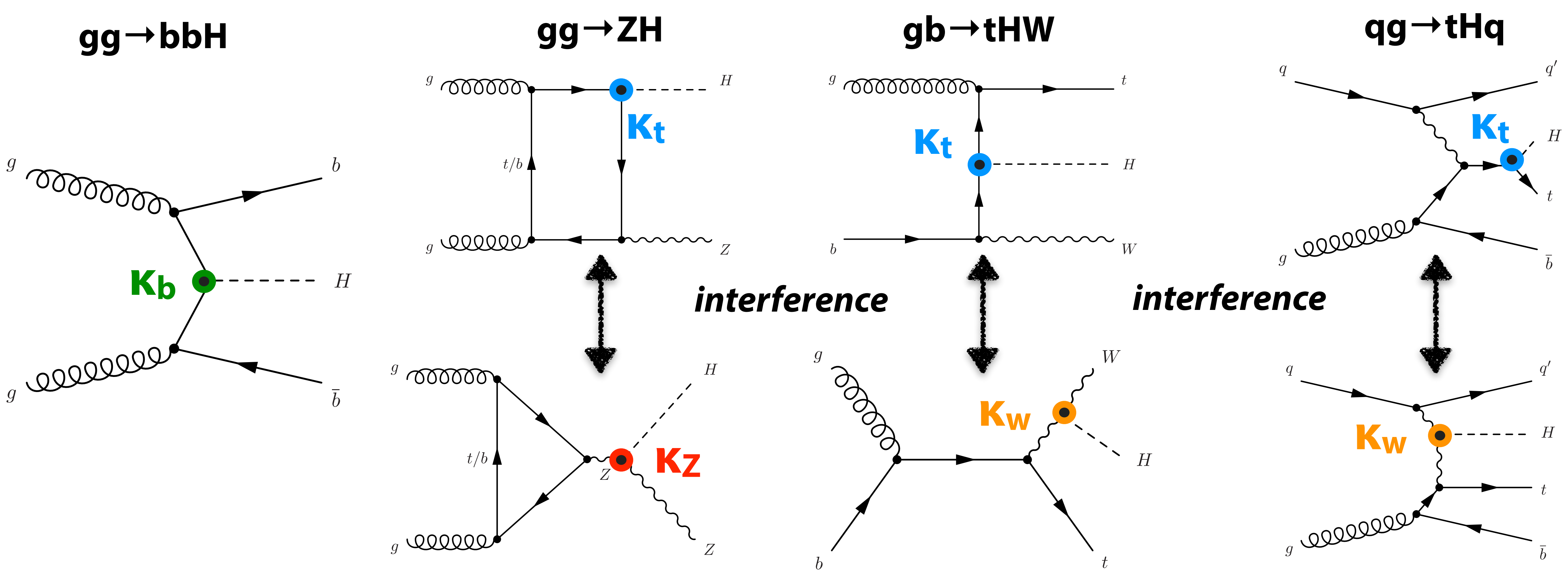
- **Rare processes:**



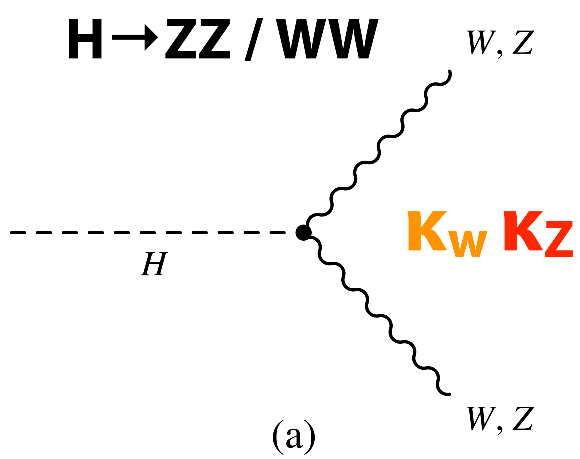
Signal Processes - Production

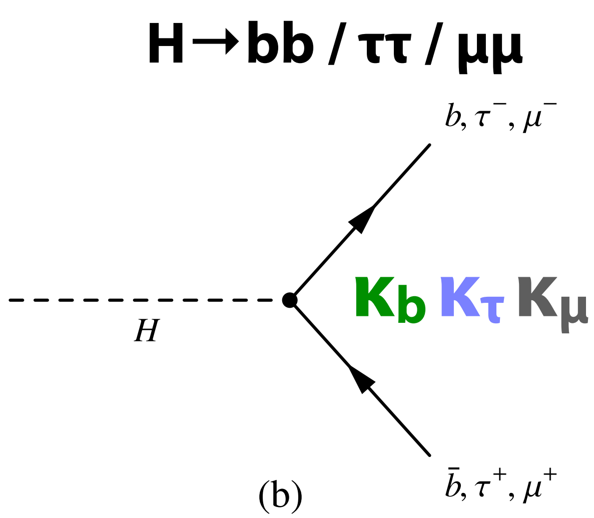
Production process	Cross section [pb] $\sqrt{s}$ = 7 TeV	Cross section [pb] $\sqrt{s}$ = 8 TeV	Order of calculation
ggF	15.0 ± 1.6	19.2 ± 2.0	NNLO(QCD)+NLO(EW)
VBF	1.22 ± 0.03	1.58 ± 0.04	NLO(QCD+EW)+~NNLO(QCD)
WH	0.577 ± 0.016	0.703 ± 0.018	NNLO(QCD)+NLO(EW)
ZH	0.334 ± 0.013	0.414 ± 0.016	NNLO(QCD)+NLO(EW)
$[ggZH]$	0.023 ± 0.007	0.032 ± 0.010	NLO(QCD)
bbH	0.156 ± 0.021	0.203 ± 0.028	5FS NNLO(QCD) + 4FS NLO(QCD)
ttH	0.086 ± 0.009	0.129 ± 0.014	NLO(QCD)
tH	0.012 ± 0.001	0.018 ± 0.001	NLO(QCD)
Total	17.4 ± 1.6	22.3 ± 2.0	

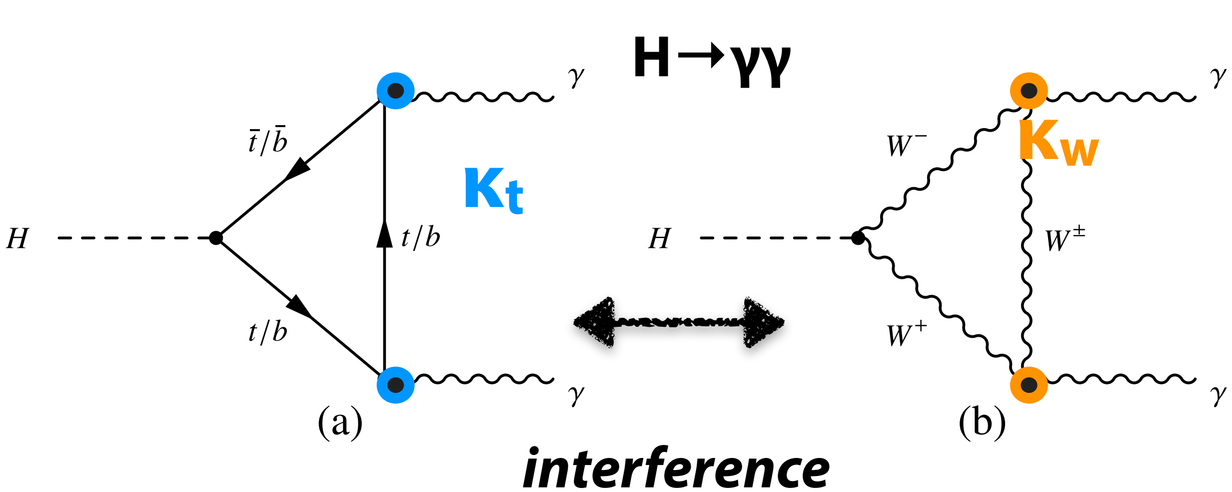
- **Rare processes:**



Signal Processes - Decay







Decay channel	Branching ratio [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

- H→cc, H→gg, H→Zγ not targeted by the input analyses but contribute to the total width

Signal Processes - Summary

CMS

Production	Loops	Interference	Multiplicative factor
$\sigma(ggF)$	✓	$b-t$	$\kappa_g^2 \sim 1.06 \cdot \kappa_t^2 + 0.01 \cdot \kappa_b^2 - 0.07 \cdot \kappa_t \kappa_b$
$\sigma(VBF)$	–	–	$\sim 0.74 \cdot \kappa_W^2 + 0.26 \cdot \kappa_Z^2$
$\sigma(WH)$	–	–	$\sim \kappa_W^2$
$\sigma(qq/qg \to ZH)$	–	–	$\sim \kappa_Z^2$
$\sigma(gg \to ZH)$	✓	$Z-t$	$\sim 2.27 \cdot \kappa_Z^2 + 0.37 \cdot \kappa_t^2 - 1.64 \cdot \kappa_Z \kappa_t$
$\sigma(ttH)$	–	–	$\sim \kappa_t^2$
$\sigma(gb \to WtH)$	–	$W-t$	$\sim 1.84 \cdot \kappa_t^2 + 1.57 \cdot \kappa_W^2 - 2.41 \cdot \kappa_t \kappa_W$
$\sigma(qb \to tHq)$	–	$W-t$	$\sim 3.4 \cdot \kappa_t^2 + 3.56 \cdot \kappa_W^2 - 5.96 \cdot \kappa_t \kappa_W$
$\sigma(bbH)$	–	–	$\sim \kappa_b^2$
Partial decay width			
Γ^{ZZ}	–	–	$\sim \kappa_Z^2$
Γ^{WW}	–	–	$\sim \kappa_W^2$
$\Gamma^{\gamma\gamma}$	✓	$W-t$	$\kappa_\gamma^2 \sim 1.59 \cdot \kappa_W^2 + 0.07 \cdot \kappa_t^2 - 0.66 \cdot \kappa_W \kappa_t$
$\Gamma^{\tau\tau}$	–	–	$\sim \kappa_\tau^2$
Γ^{bb}	–	–	$\sim \kappa_b^2$
$\Gamma^{\mu\mu}$	–	–	$\sim \kappa_\mu^2$
Total width for $BR_{BSM} = 0$			
Γ_H	✓	–	$\kappa_H^2 \sim 0.57 \cdot \kappa_b^2 + 0.22 \cdot \kappa_W^2 + 0.09 \cdot \kappa_g^2 + 0.06 \cdot \kappa_\tau^2 + 0.03 \cdot \kappa_Z^2 + 0.03 \cdot \kappa_c^2 + 0.0023 \cdot \kappa_\gamma^2 + 0.0016 \cdot \kappa_{Z\gamma}^2 + 0.0001 \cdot \kappa_s^2 + 0.00022 \cdot \kappa_\mu^2$

Results

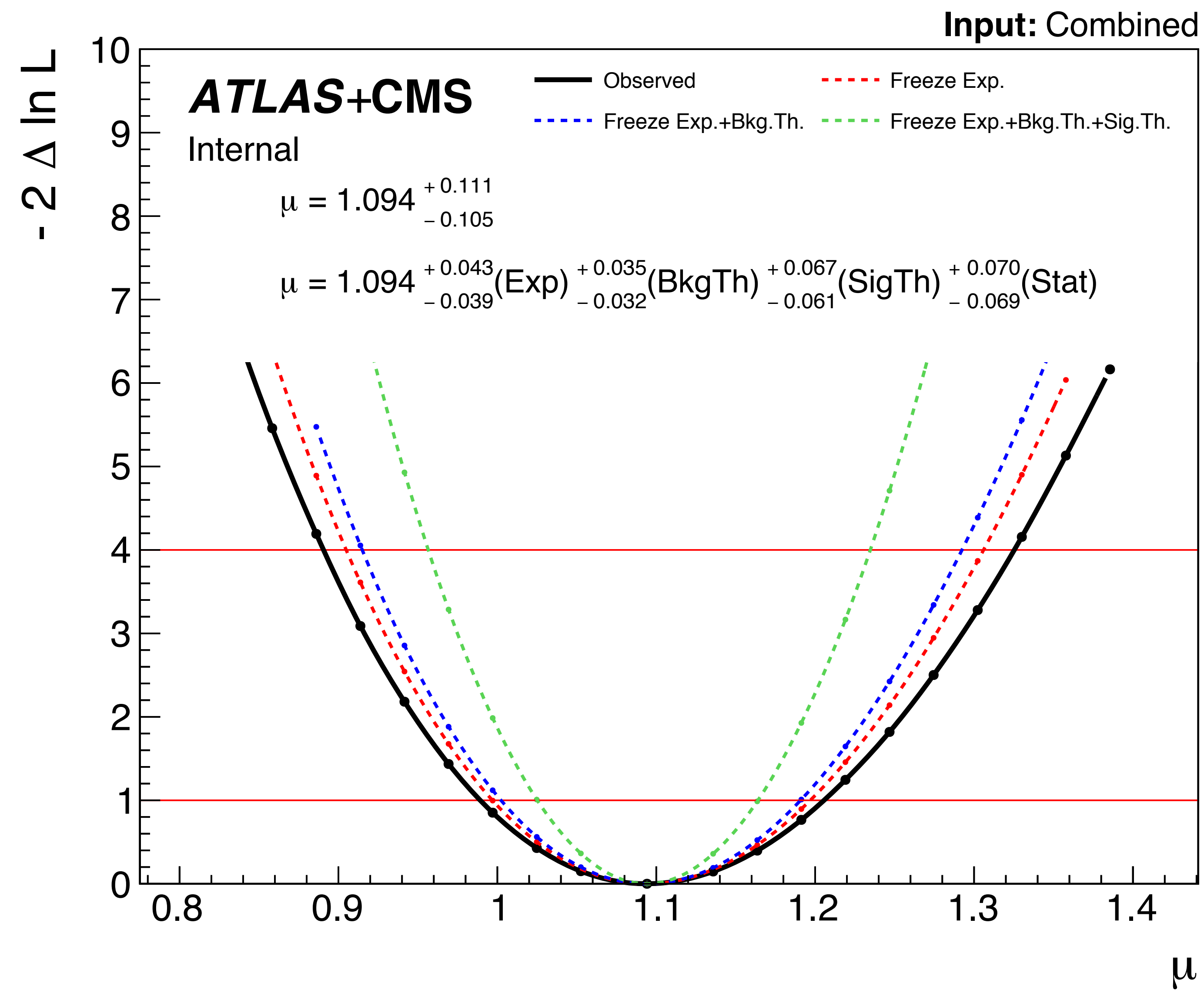
Signal strengths

Overall signal strength

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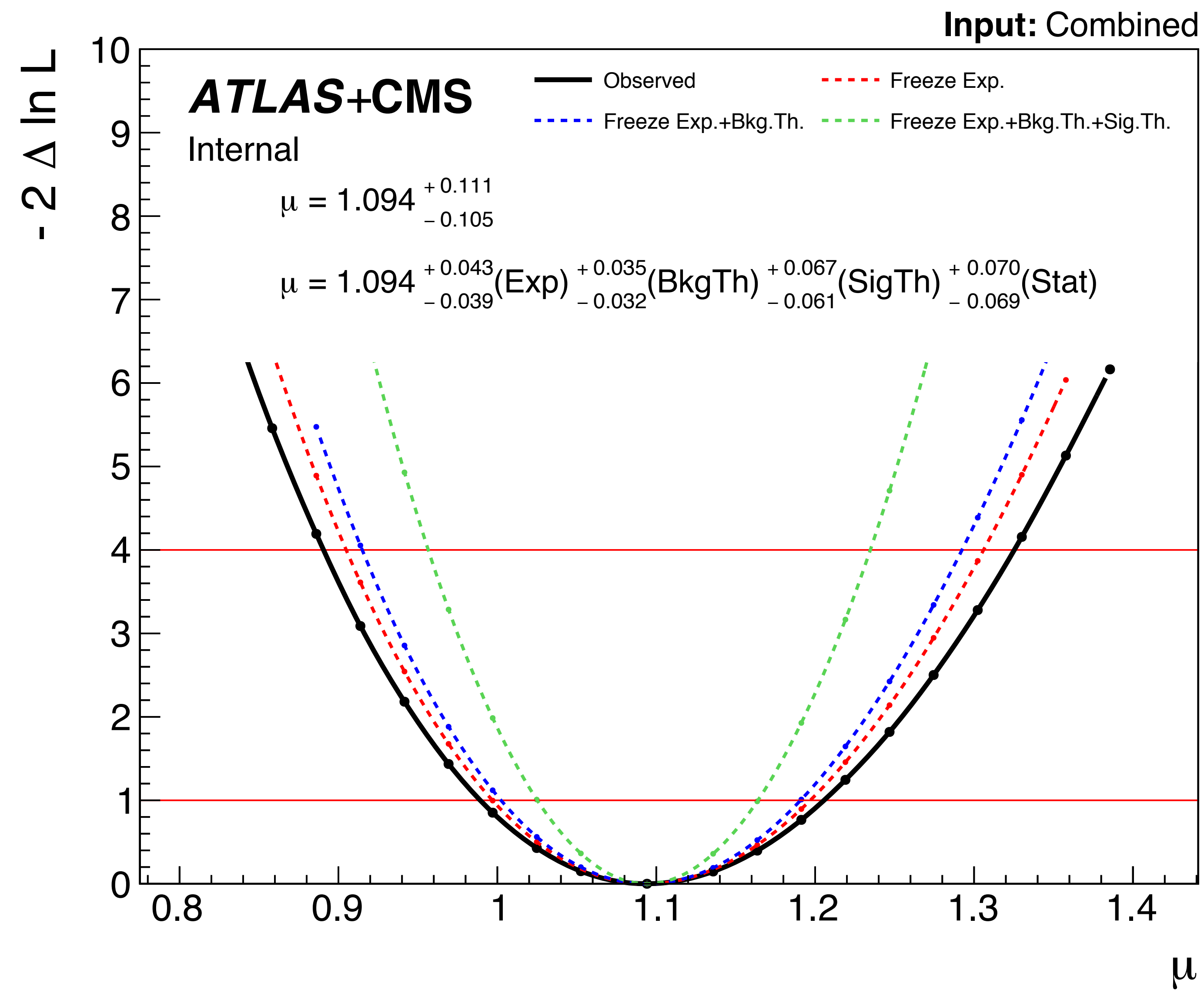
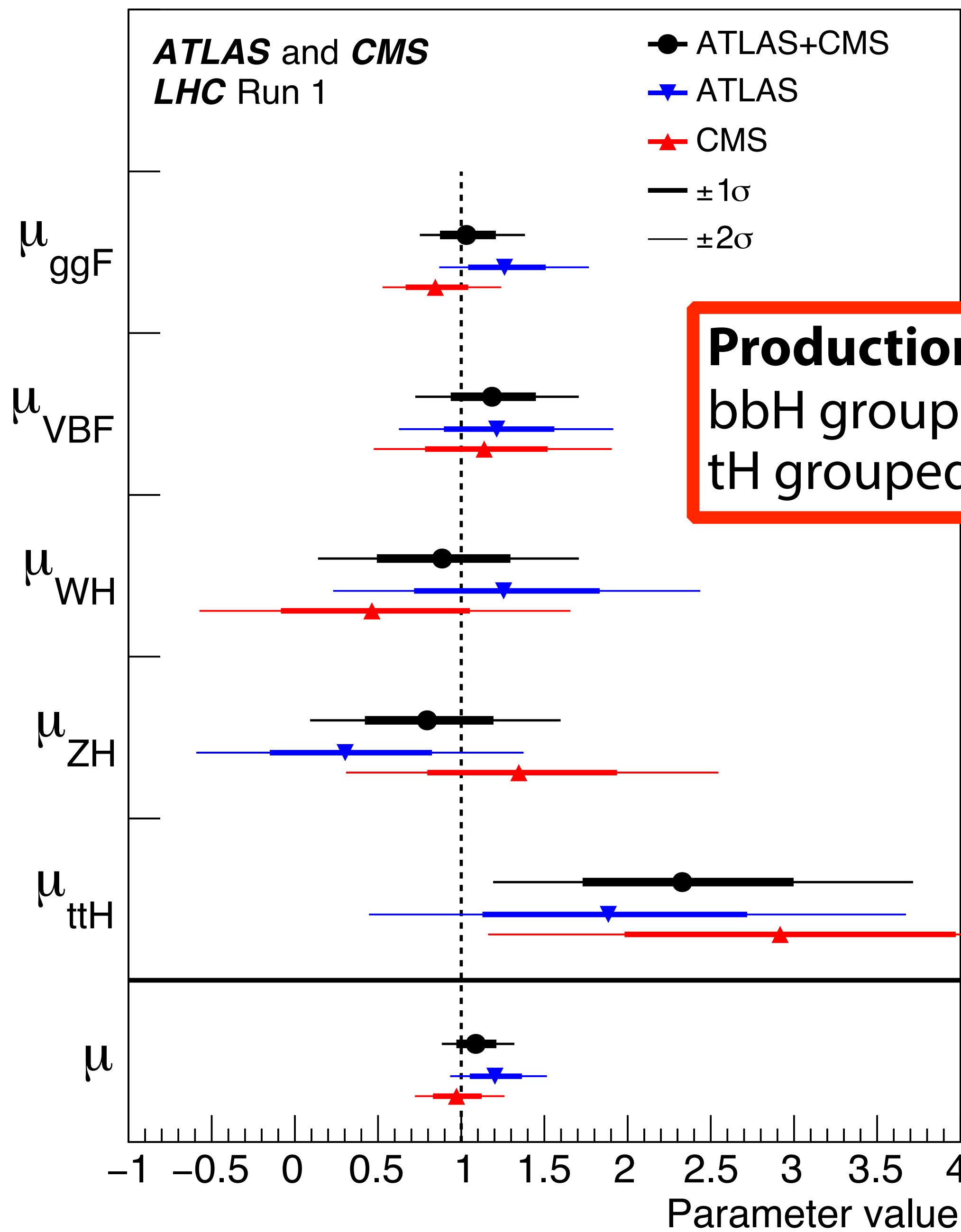
- Useful for extrapolating results to higher luminosity and understanding what sources may limit future precision
- Signal theory uncertainty as large as statistical uncertainty
- However dominant parts will be reduced for Run 2:
  - **N3LO ggH scale:** 8% → 2-3%
  - **New PDF4LHC**: 7% → 2%

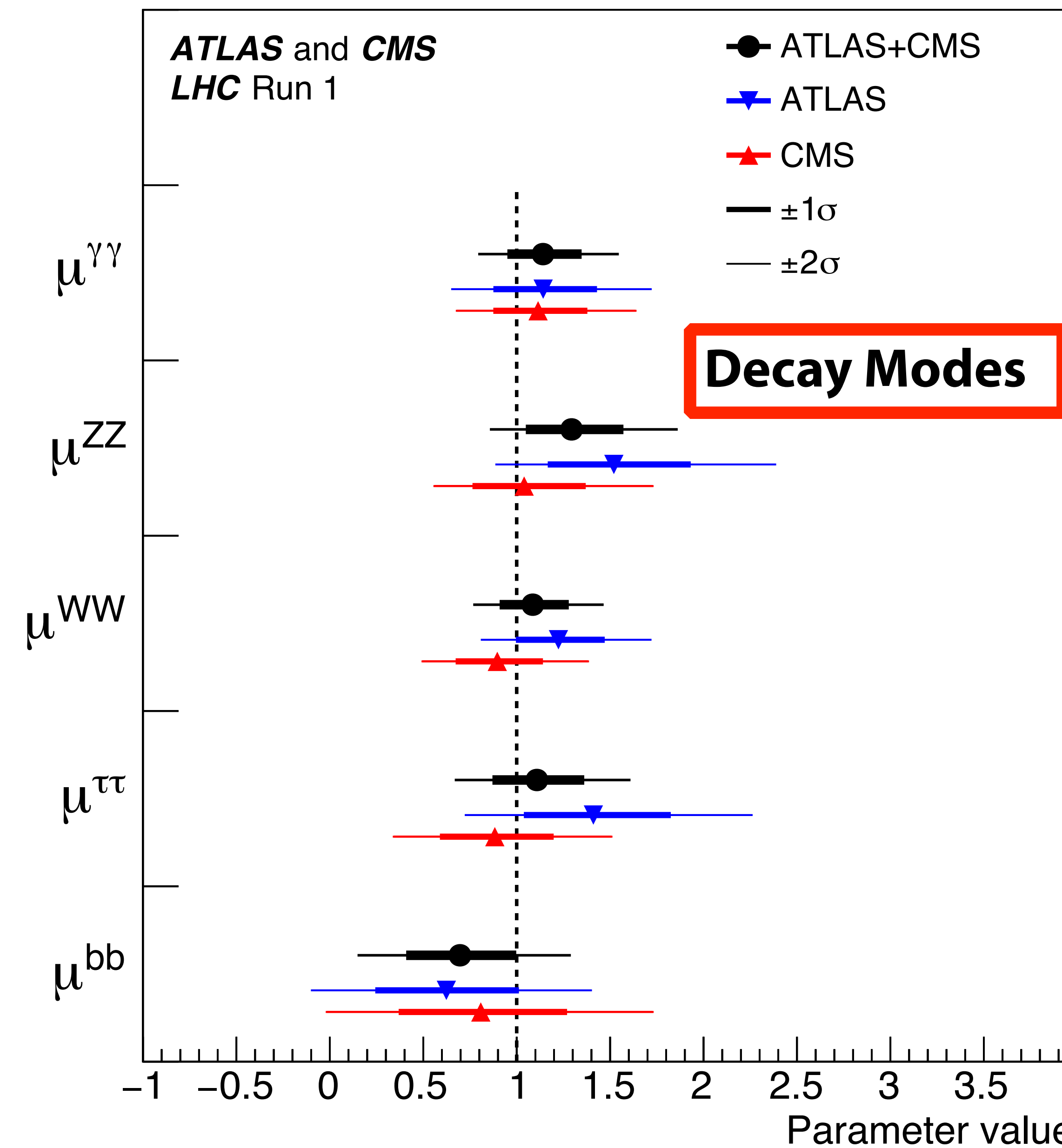


Production & Decay

Assumptions
- SM ratios of BRs **or** cross sections



Production Modes
bbH grouped with ggF
tH grouped with ttH



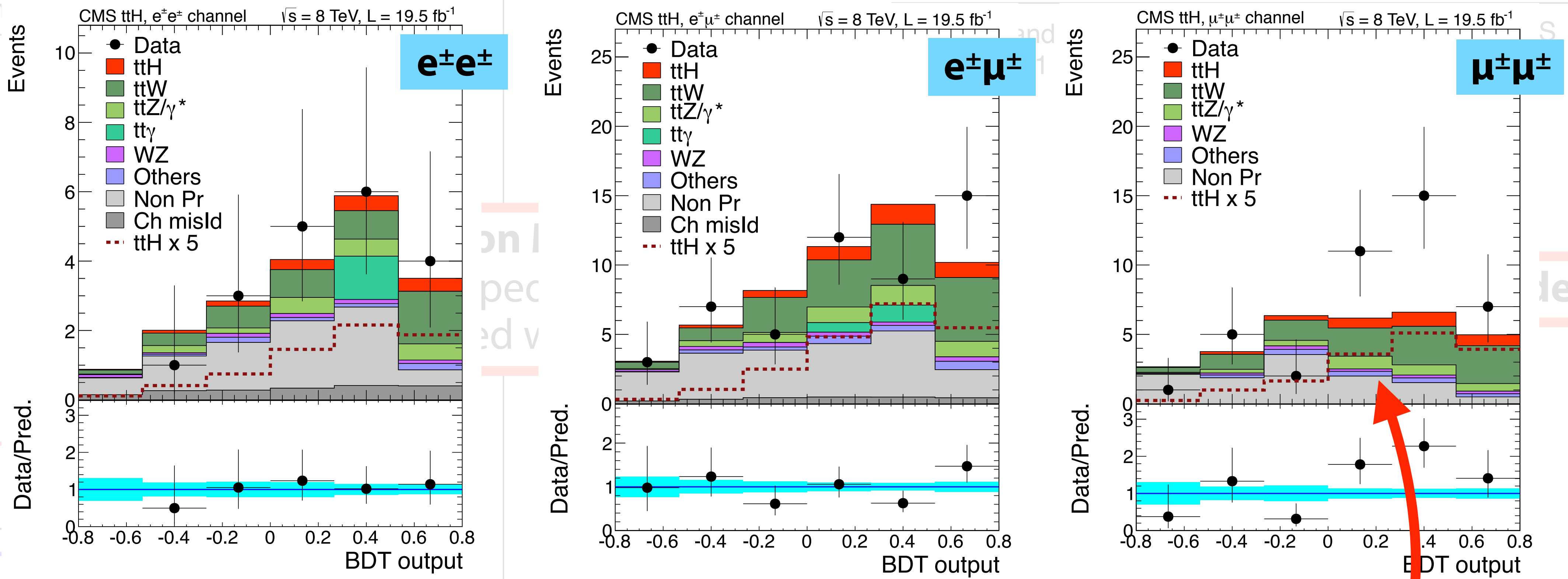
Decay Modes

- Most significant deviation from μ=1 is ttH (2.3σ)

Production & Decay

Assumptions

- SM ratios of BRs **or** cross sections



Visible excess of events in $\mu^\pm\mu^\pm$ final state

- Largely driven by CMS ttH→leptons (WW) analysis
- Can have subtle effects in other models

Significances

- Calculated with respect to μ=0 using asymptotic formulae
- Now ≥ 5σ for: VBF production, H→ττ decay

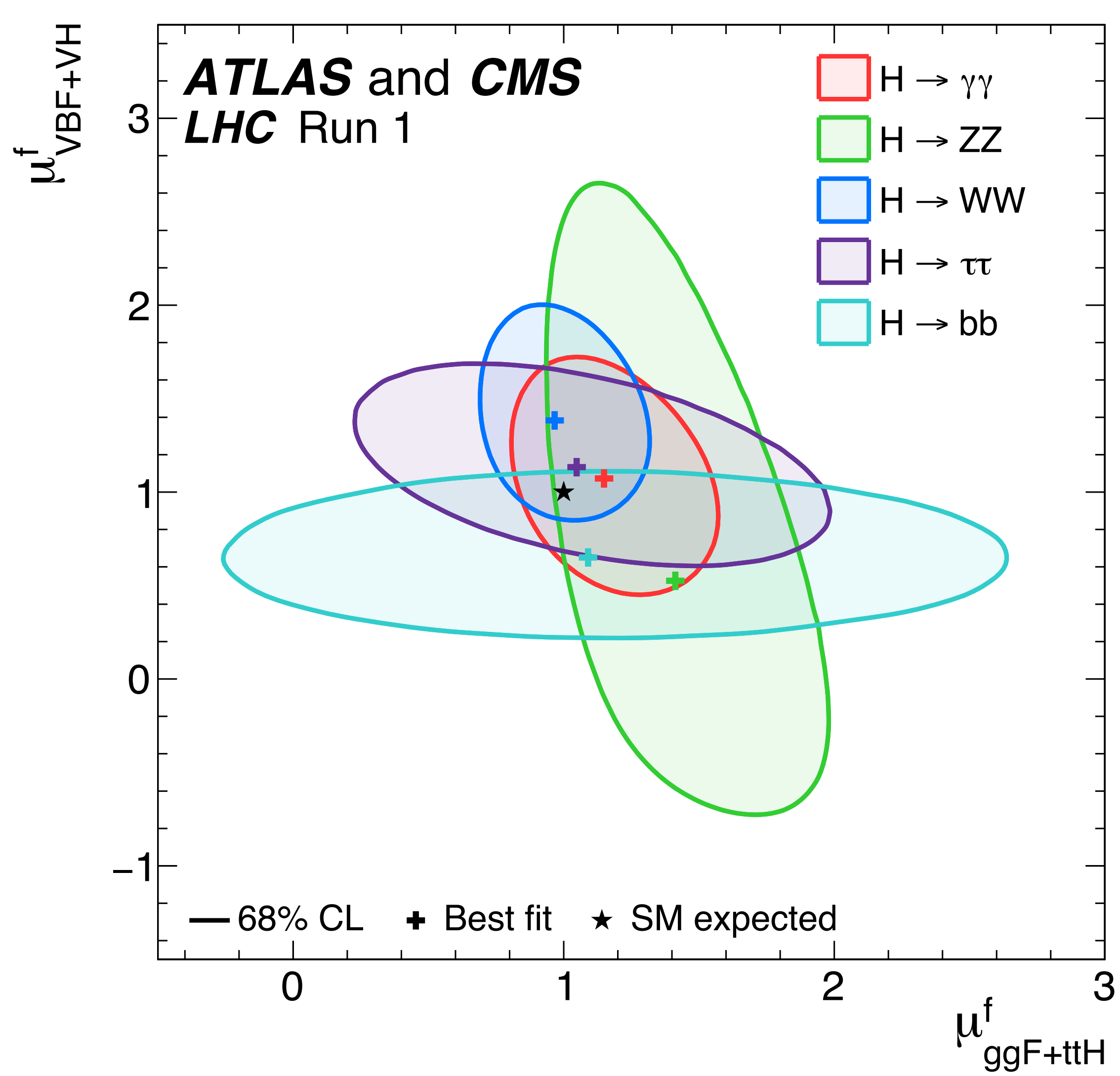
- **Personal take:** 5σ was chosen as the threshold for claiming discovery, in part to due to the look-elsewhere effect - less relevant for specific production/decay modes once Higgs boson is discovered

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		
$H \rightarrow \tau\tau$	5.5	5.0
$H \rightarrow bb$	2.6	3.7

Signal Strengths
2D scans

Assumptions
- VH/VBF and ttH/ggF rates as in SM

- Perform scans of μ_F^i, μ_V^i for each decay mode i (10 parameter fit)
- Purpose is to measure vector boson and fermion-mediated production
- Also a 6 parameter fit with one common μ_V/μ_F and five μ_F^i
  - Ratio $\mu_V/\mu_F = 1.06\,^{+0.35}_{-0.27}$ is independent of assumptions on BRs



Parameter	ATLAS+CMS Measured	ATLAS+CMS Expected uncertainty	ATLAS Measured	CMS Measured
10-parameter fit of μ_F^f and μ_V^f				
$\mu_V^{\gamma\gamma}$	$1.05^{+0.44}_{-0.41}$	$^{+0.42}_{-0.38}$	$0.69^{+0.64}_{-0.58}$	$1.37^{+0.62}_{-0.56}$
μ_V^{ZZ}	$0.48^{+1.37}_{-0.91}$	$^{+1.16}_{-0.84}$	$0.26^{+1.60}_{-0.91}$	$1.44^{+2.32}_{-2.30}$
μ_V^{WW}	$1.38^{+0.41}_{-0.37}$	$^{+0.38}_{-0.35}$	$1.56^{+0.52}_{-0.46}$	$1.08^{+0.65}_{-0.58}$
$\mu_V^{\tau\tau}$	$1.12^{+0.37}_{-0.35}$	$^{+0.38}_{-0.36}$	$1.29^{+0.58}_{-0.53}$	$0.87^{+0.49}_{-0.45}$
μ_V^{bb}	$0.65^{+0.30}_{-0.29}$	$^{+0.32}_{-0.30}$	$0.50^{+0.39}_{-0.37}$	$0.85^{+0.47}_{-0.44}$
$\mu_F^{\gamma\gamma}$	$1.19^{+0.28}_{-0.25}$	$^{+0.25}_{-0.23}$	$1.31^{+0.37}_{-0.34}$	$1.01^{+0.34}_{-0.31}$
μ_F^{ZZ}	$1.44^{+0.38}_{-0.34}$	$^{+0.29}_{-0.25}$	$1.73^{+0.51}_{-0.45}$	$0.97^{+0.54}_{-0.42}$
μ_F^{WW}	$1.00^{+0.23}_{-0.20}$	$^{+0.21}_{-0.19}$	$1.10^{+0.29}_{-0.26}$	$0.85^{+0.28}_{-0.25}$
$\mu_F^{\tau\tau}$	$1.10^{+0.61}_{-0.58}$	$^{+0.56}_{-0.53}$	$1.72^{+1.24}_{-1.13}$	$0.91^{+0.69}_{-0.64}$
μ_F^{bb}	$1.09^{+0.93}_{-0.89}$	$^{+0.91}_{-0.86}$	$1.51^{+1.15}_{-1.08}$	$0.10^{+1.83}_{-1.86}$
6-parameter fit of global μ_V/μ_F and to μ_F^f				
μ_V/μ_F	$1.06^{+0.35}_{-0.27}$	$^{+0.34}_{-0.26}$	$0.91^{+0.41}_{-0.30}$	$1.29^{+0.67}_{-0.46}$
$\mu_F^{\gamma\gamma}$	$1.13^{+0.24}_{-0.21}$	$^{+0.21}_{-0.19}$	$1.18^{+0.33}_{-0.29}$	$1.03^{+0.30}_{-0.26}$
μ_F^{ZZ}	$1.29^{+0.29}_{-0.25}$	$^{+0.24}_{-0.20}$	$1.54^{+0.44}_{-0.36}$	$1.00^{+0.33}_{-0.27}$
μ_F^{WW}	$1.08^{+0.22}_{-0.19}$	$^{+0.19}_{-0.17}$	$1.26^{+0.29}_{-0.25}$	$0.85^{+0.25}_{-0.22}$
$\mu_F^{\tau\tau}$	$1.07^{+0.35}_{-0.28}$	$^{+0.32}_{-0.27}$	$1.50^{+0.66}_{-0.49}$	$0.75^{+0.39}_{-0.29}$
μ_F^{bb}	$0.65^{+0.37}_{-0.28}$	$^{+0.45}_{-0.34}$	$0.67^{+0.58}_{-0.42}$	$0.64^{+0.54}_{-0.36}$

Signal strength ratios

Assumptions
- Only the 7/8 TeV ratios

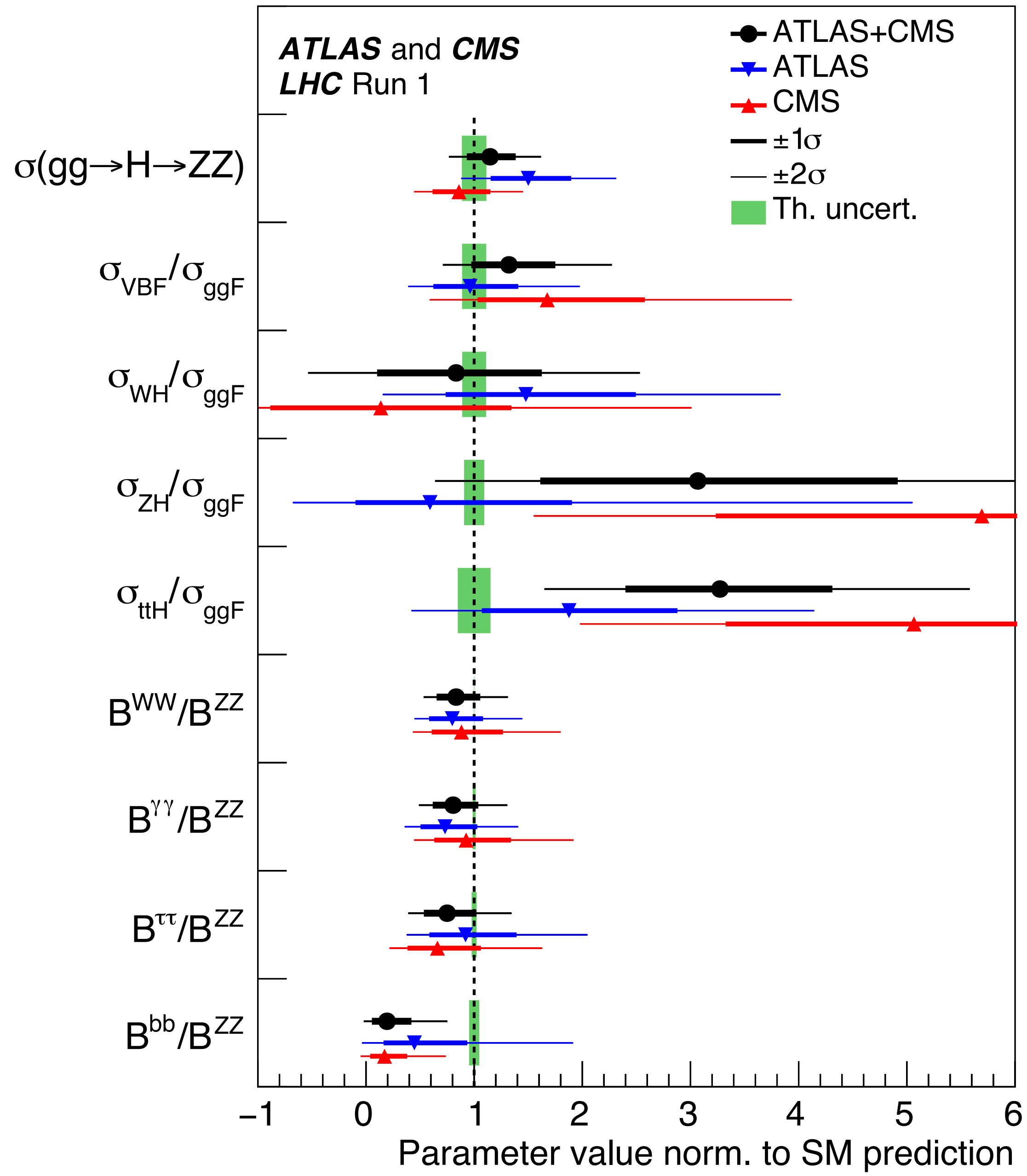
CMS

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

- Introduced by ATLAS - **new model for CMS**
- Normalise the rate for any particular channel to a reference process using ratios of cross sections and branching ratios

- **Motivation**:
  - Explicitly no assumptions on relative cross sections or BRs (unlike other results)
  - Measured values independent of SM prediction and inclusive theory uncertainties
  - Cancellation of common systematic uncertainties in ratios

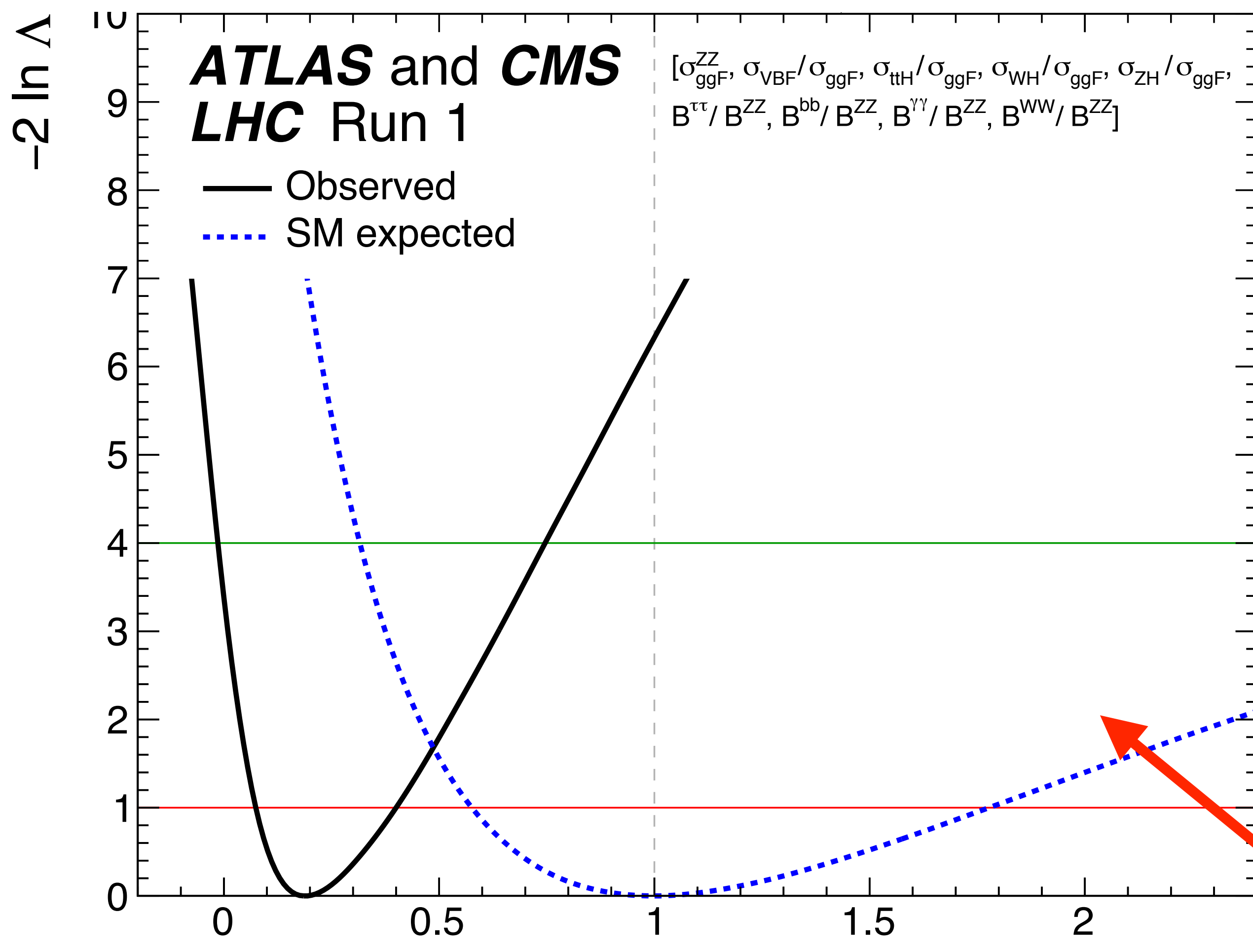
- Choose reference process as one measured with the smallest uncertainty: gg→H→ZZ

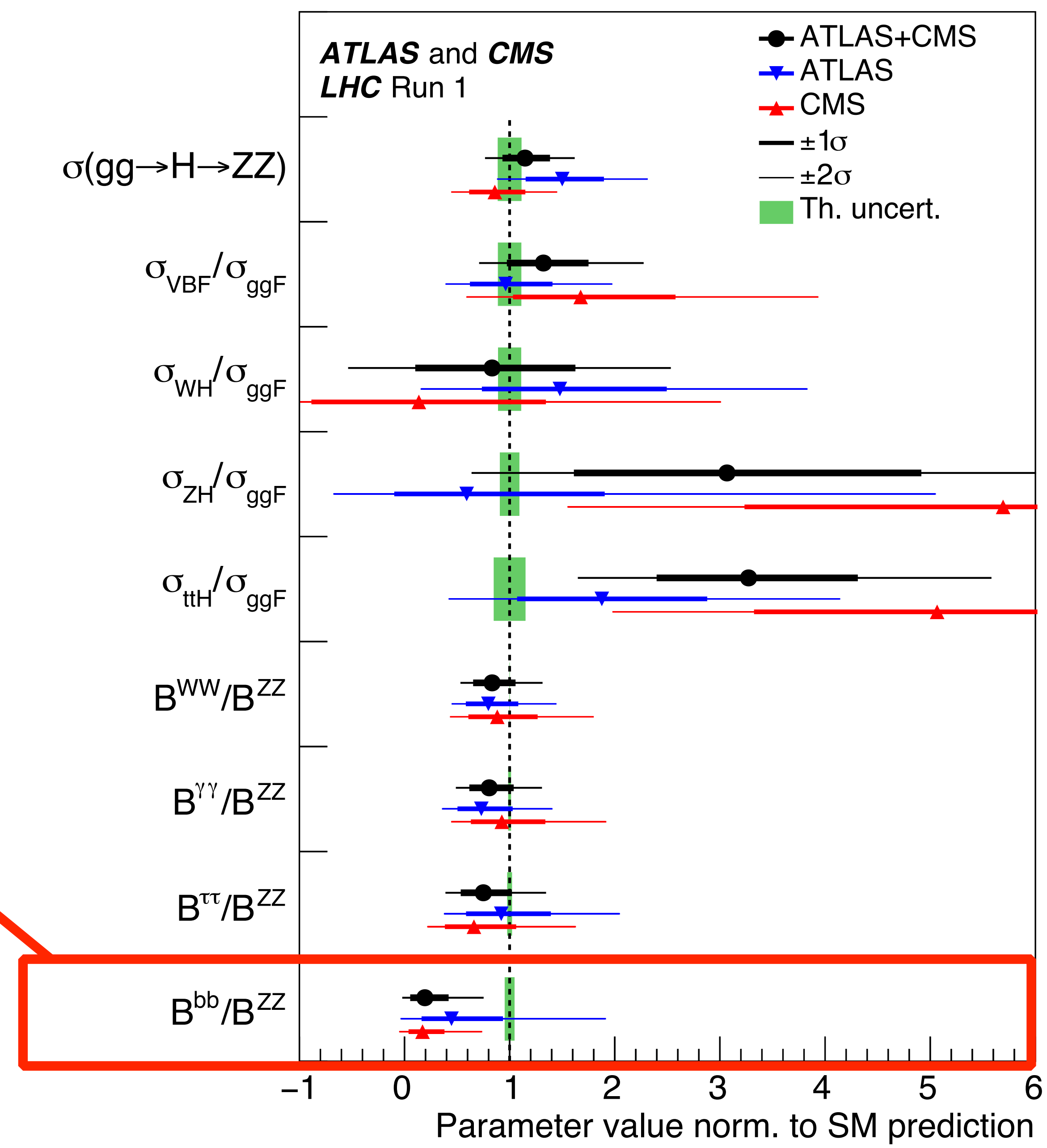


Signal strength ratios

- Largest disagreement in BR^{bb}/BR^{ZZ} (2.4σ)
- Though some care needed with the uncertainties on ratios ⇒ non-Gaussian behaviour

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



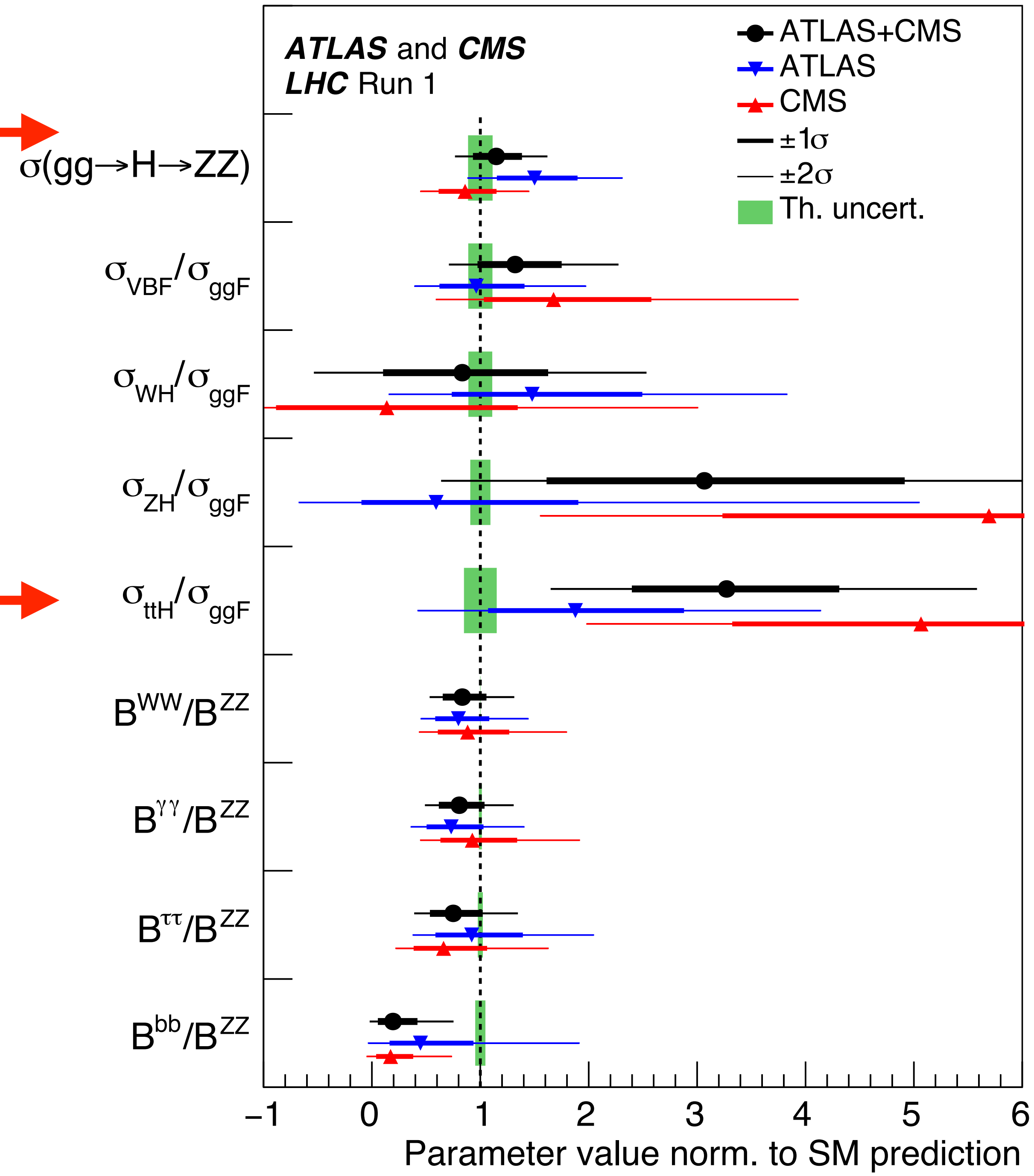


- Does this, and the other features of these results, make sense?

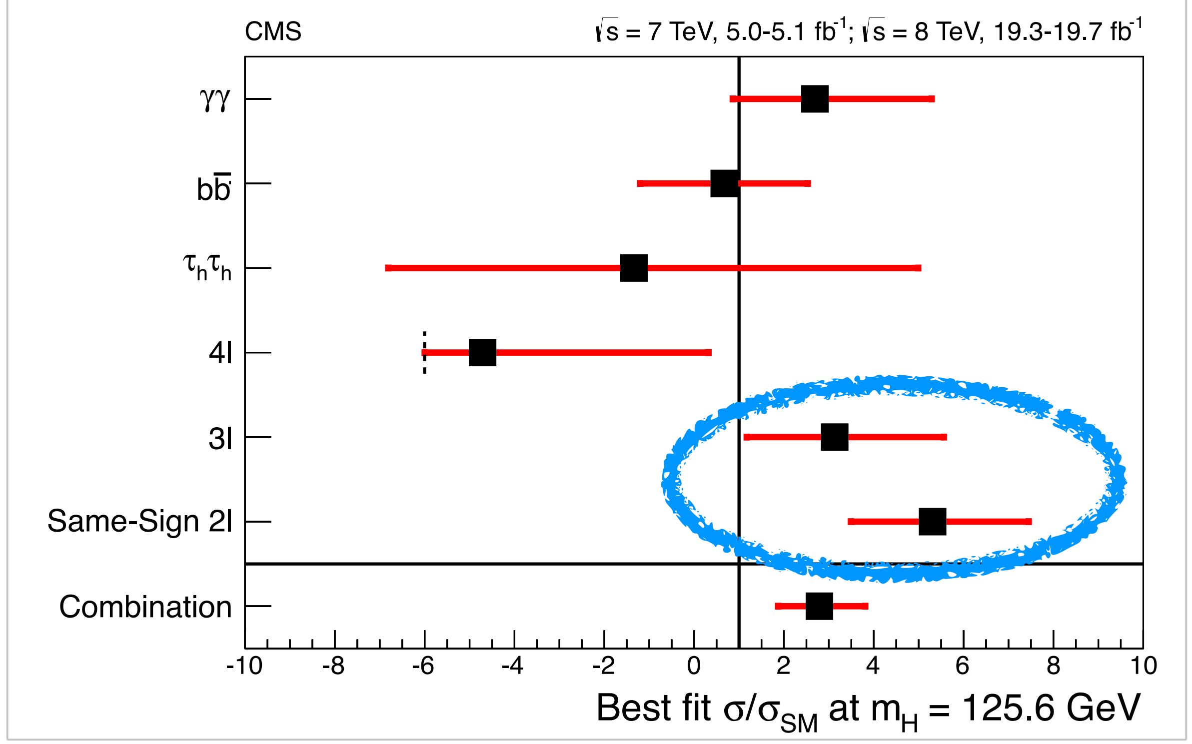
Signal strength ratios

1) Well measured ggF→ZZ: **0.85** $^{+0.27}_{-0.22}$

2) Known excess in ttH→WW ⇒ larger value ttH/ ggF preferred in fit (5.1): **0.85 * 5.1 * 0.9 = 3.9**, in good agreement with ttH result



CMS ttH Results



Signal strength ratios

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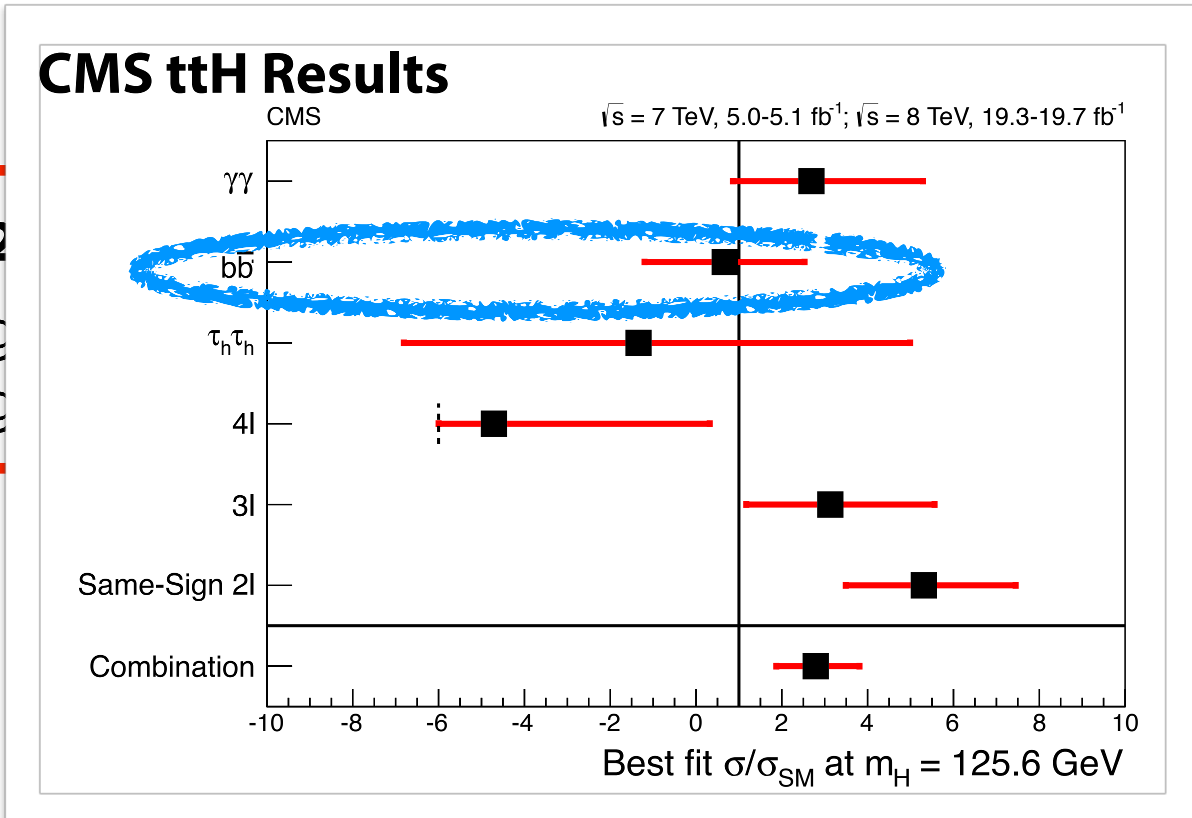
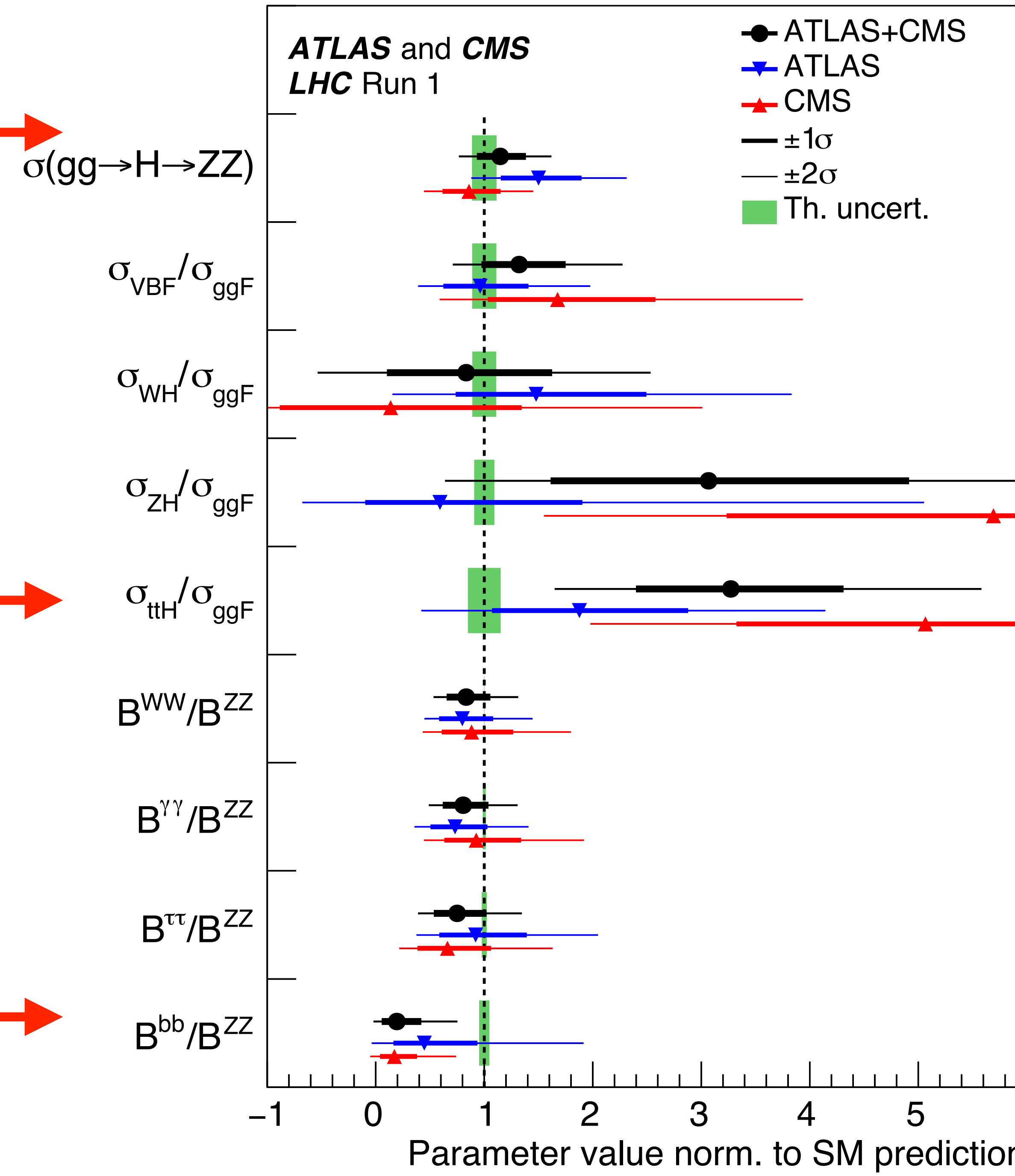
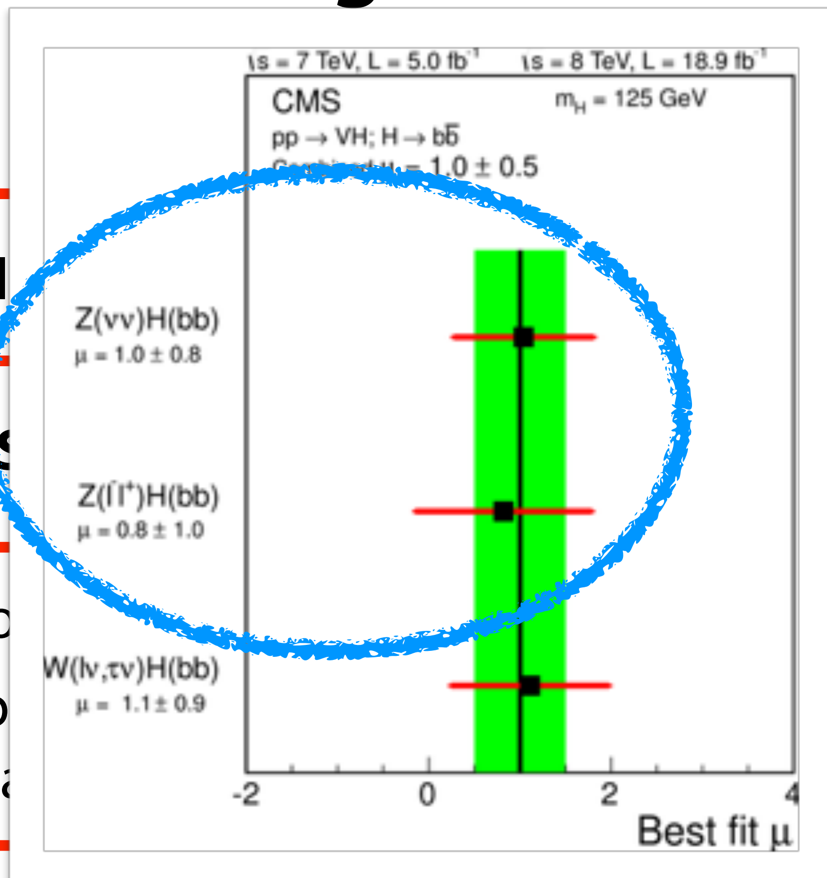




3) Prefer bb/WW low (0.20) for ttH→bb at the observed rate: **0.85 * 5.1 * 0.17 = 0.74**

Signal strength ratios

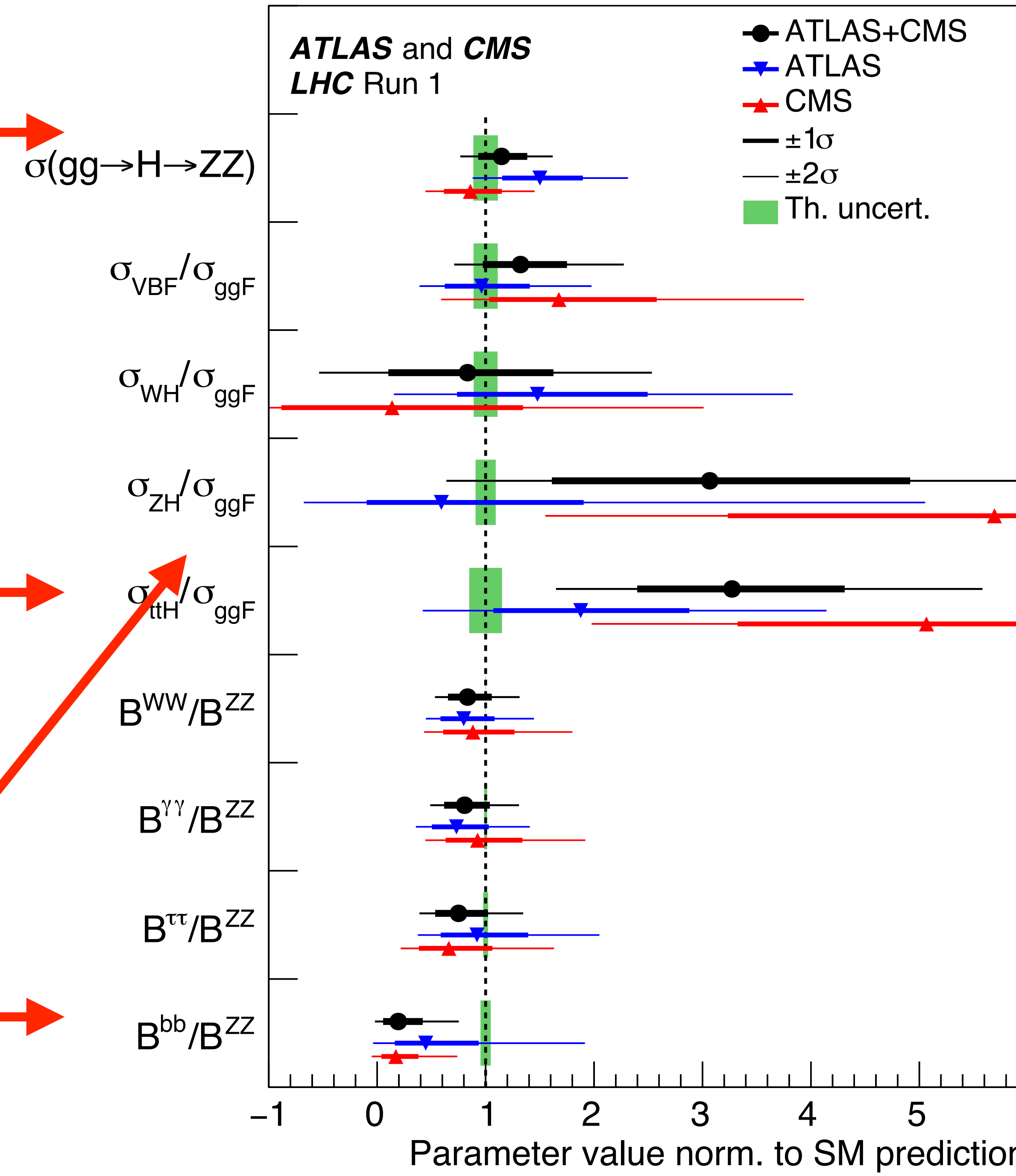


CMS VH Results

1) Wel ... 2

CMS

2) Kno ... alue ttH/ggF p ... = 3.9, in good a ...



4) The ZH production is not strongly constrained.

Becomes large to get observed ZH→bb rate: **0.85 * 0.17 * 5.70(ZH/ggF) = 0.87**

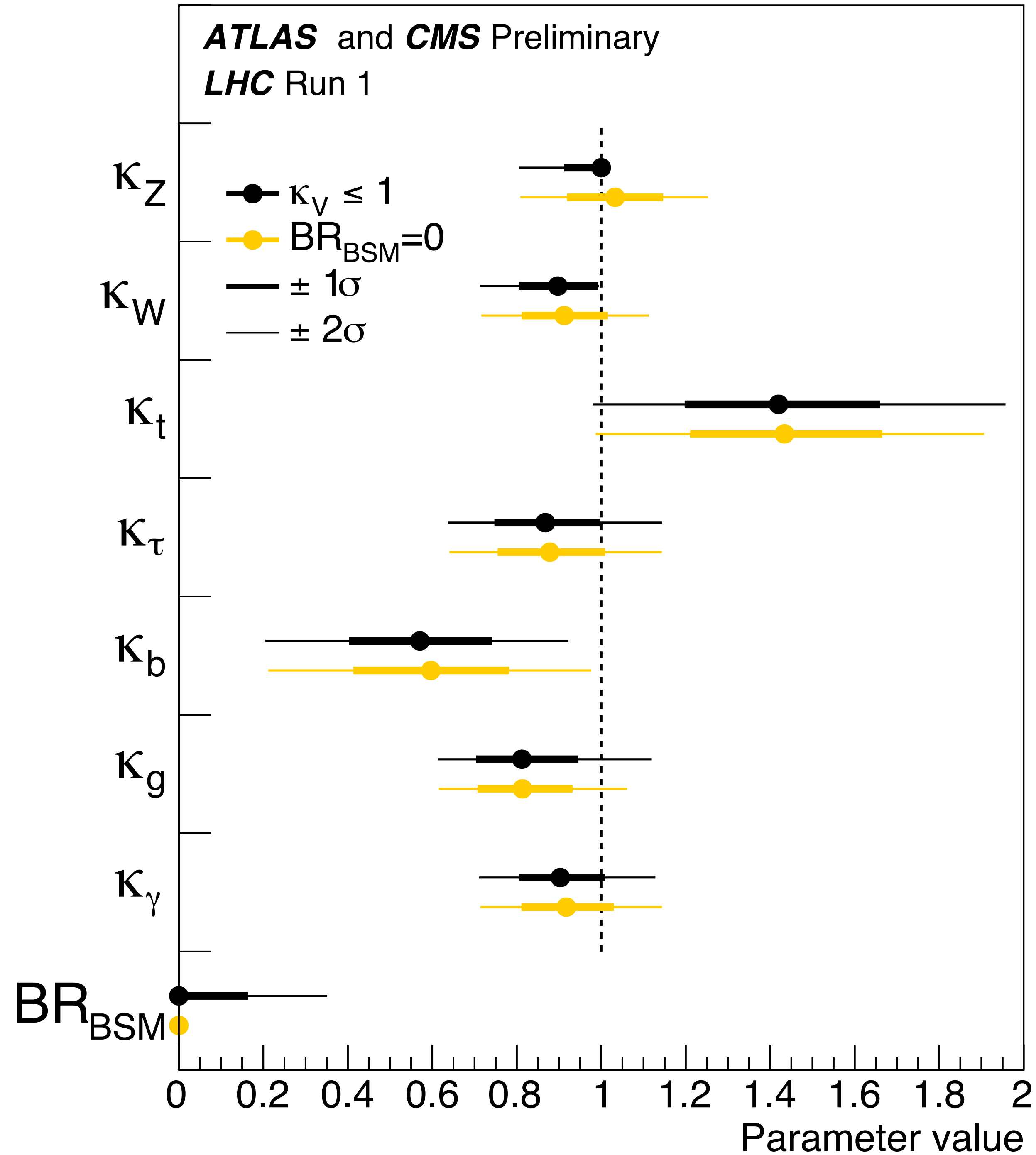
3) Prefer bb/WW low (0.20) for ttH→bb at the observed rate: **0.85 * 5.1 * 0.17 = 0.83**

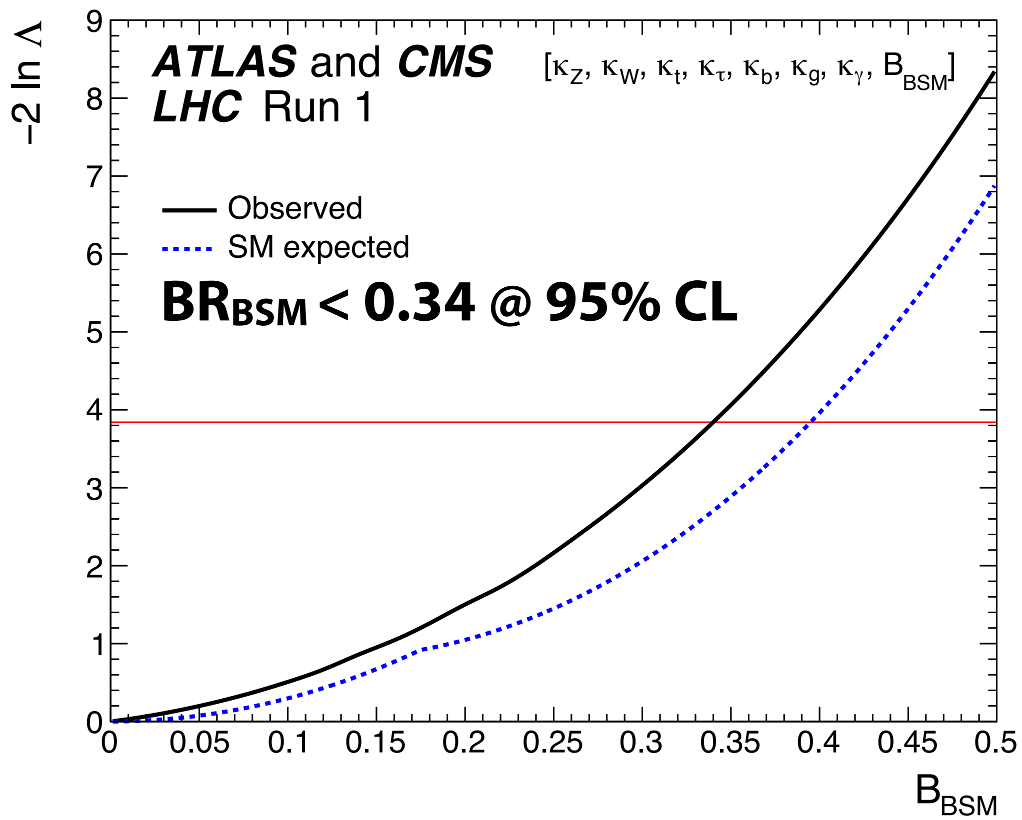
Results

Couplings

Couplings - allowing for BSM loop/decay contributions

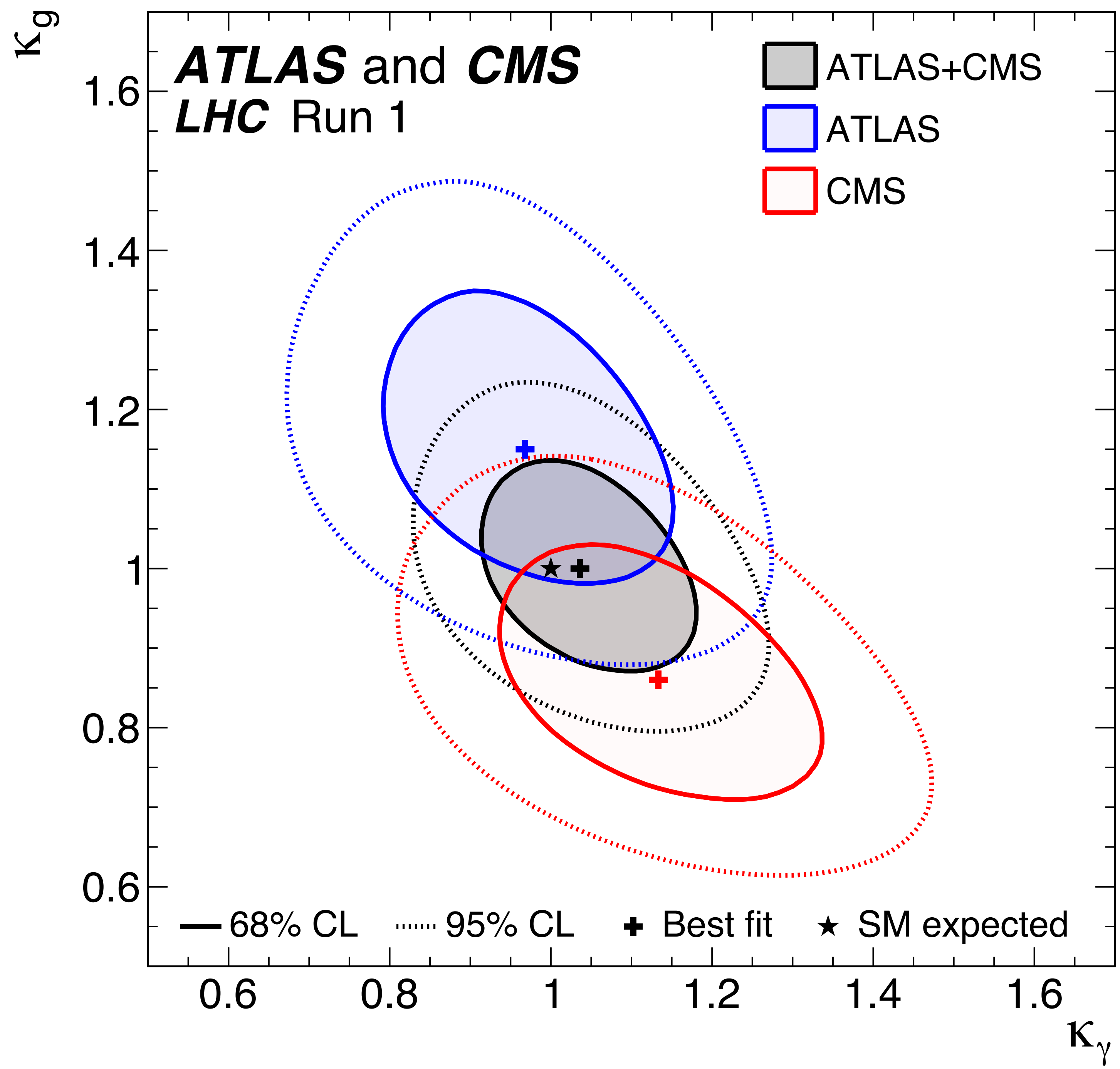
- Use effective couplings for ggH (κ_g) and $H \rightarrow \gamma\gamma$ (κ_γ)
- Consider two scenarios:
  - **$BR_{BSM} = 0$**
  - **BR_{BSM} floating, but κ_W, $\kappa_Z < 1$**
- Care needed with BR_{BSM}: not just Higgs decays to new particles but also non-SM BRs to unmeasured final states, e.g. gg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



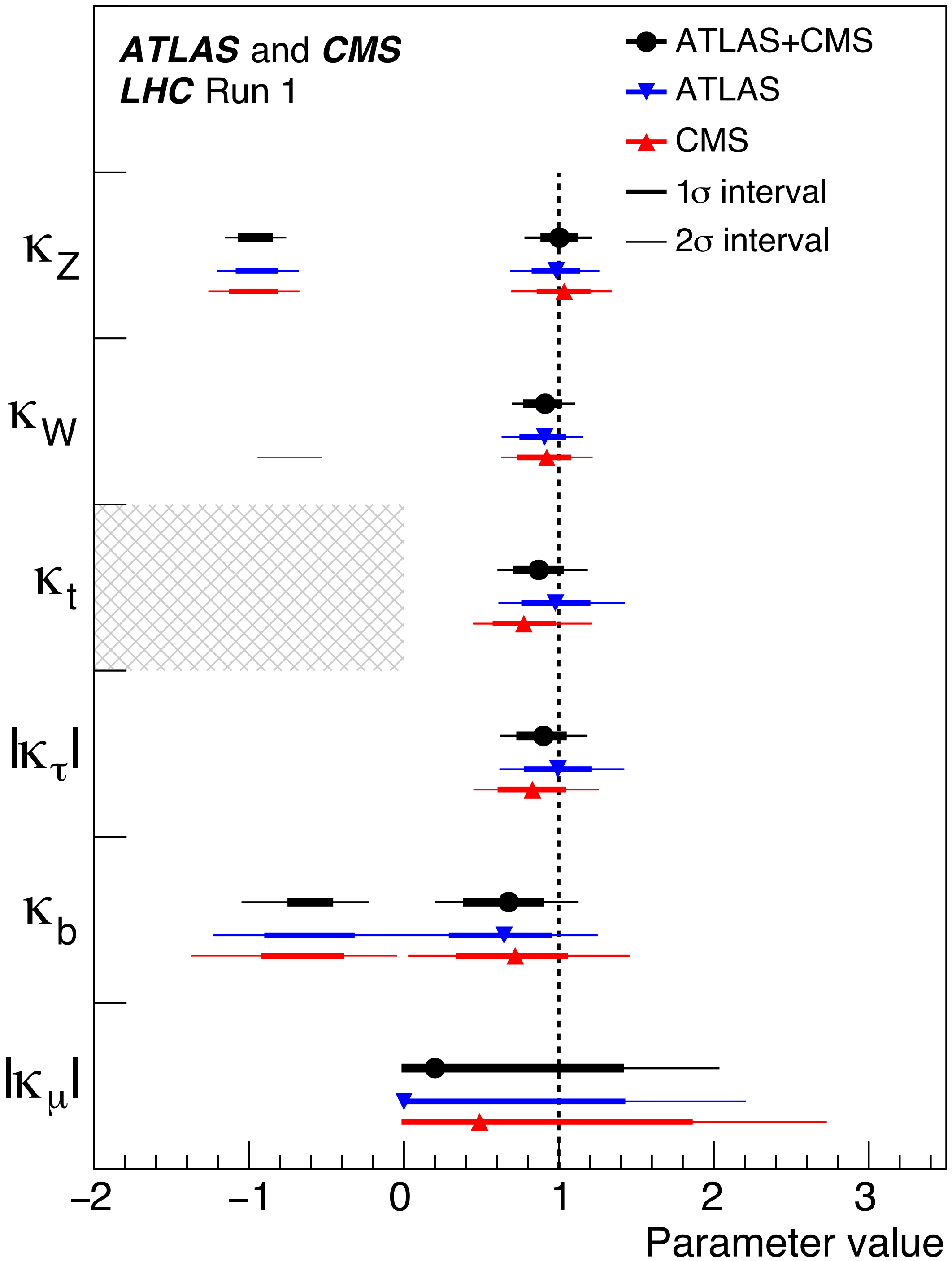


Couplings - allowing for BSM loop/decay contributions

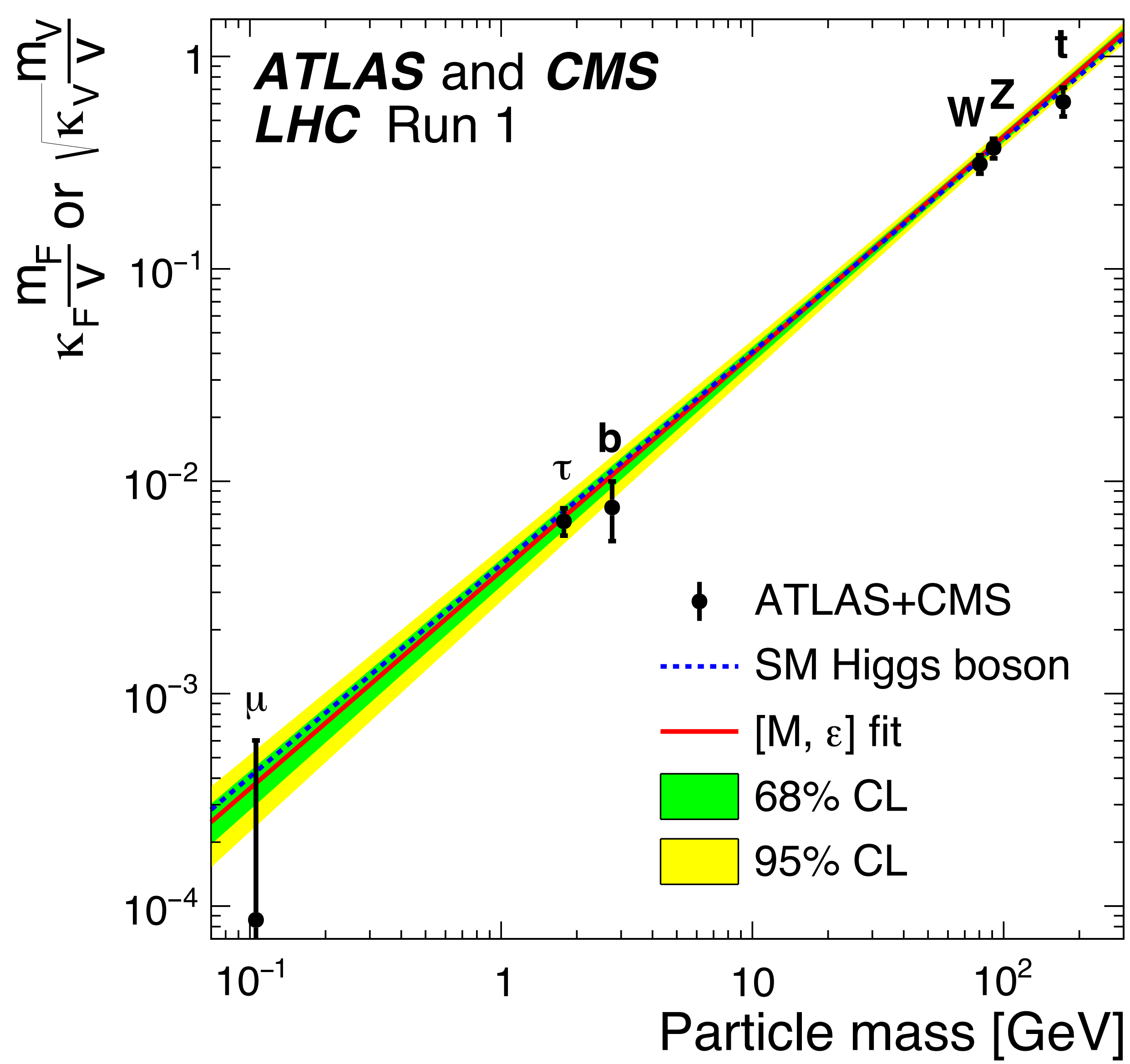
- Alternatively assume BSM modification is **only** in the loops
- E.g. new heavy fermions with mass > $m_H/2$
- Fix $\kappa_t=\kappa_b=\kappa_\tau=\kappa_Z=\kappa_W=1$, $BR_{BSM}=0$ and scan (κ_g, κ_γ)
- Result very compatible with $\kappa_g=\kappa_\gamma=1$



Couplings - no BSM loop/decay contributions



- Resolve ggH (κ_g) and H→γγ (κ_γ) loops
- Include H→μμ analyses here to make "publicity plot"



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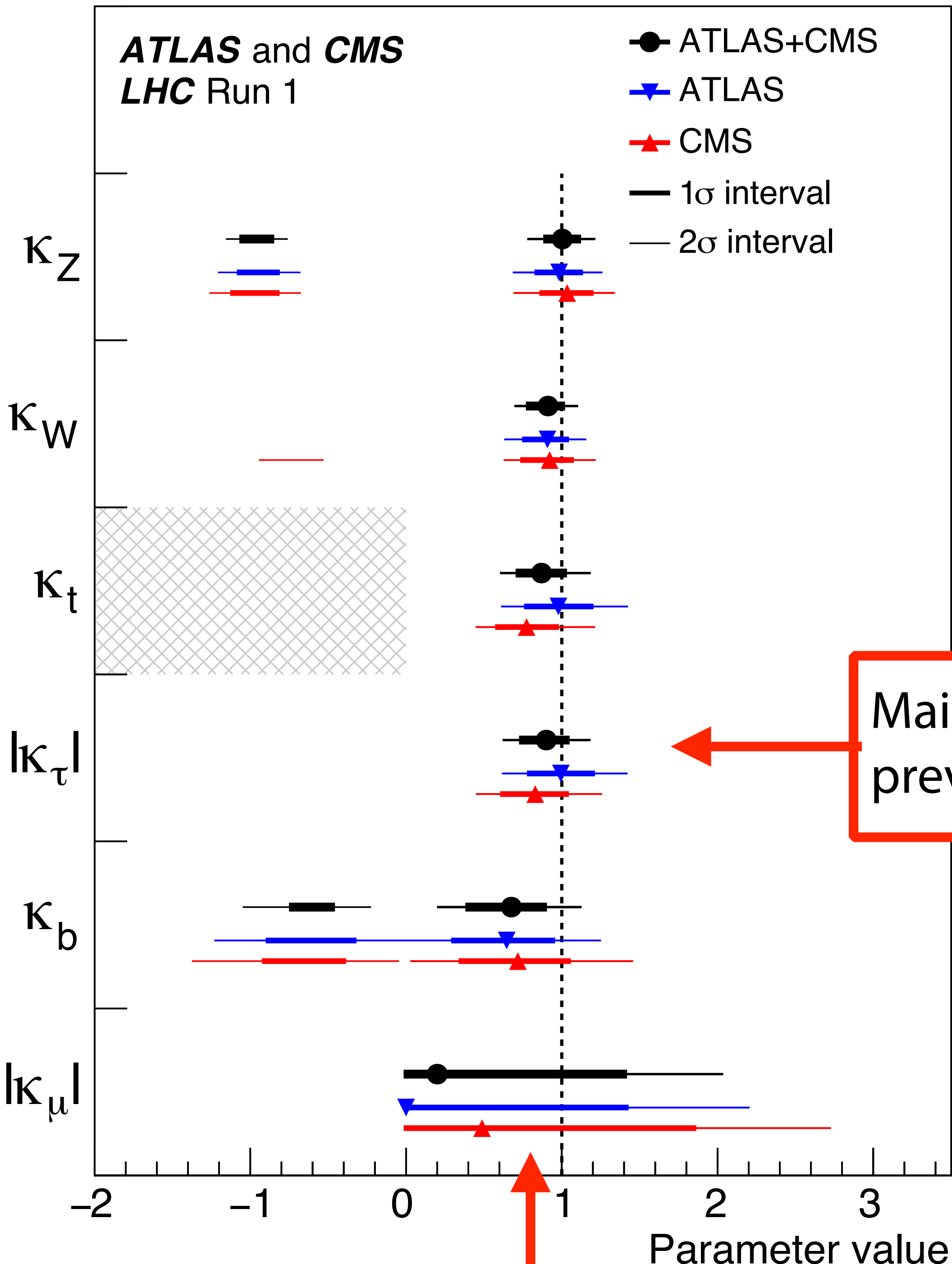
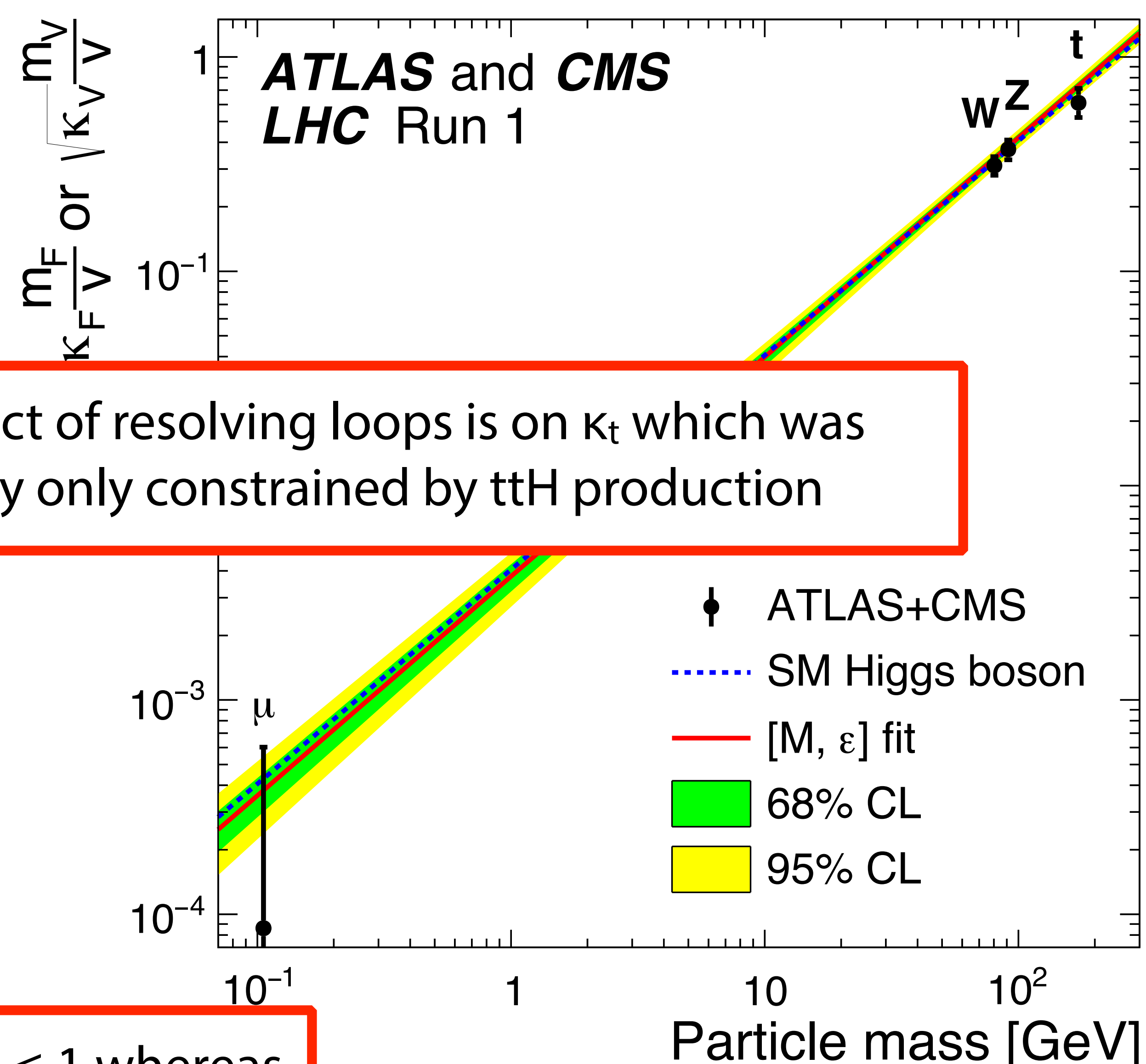
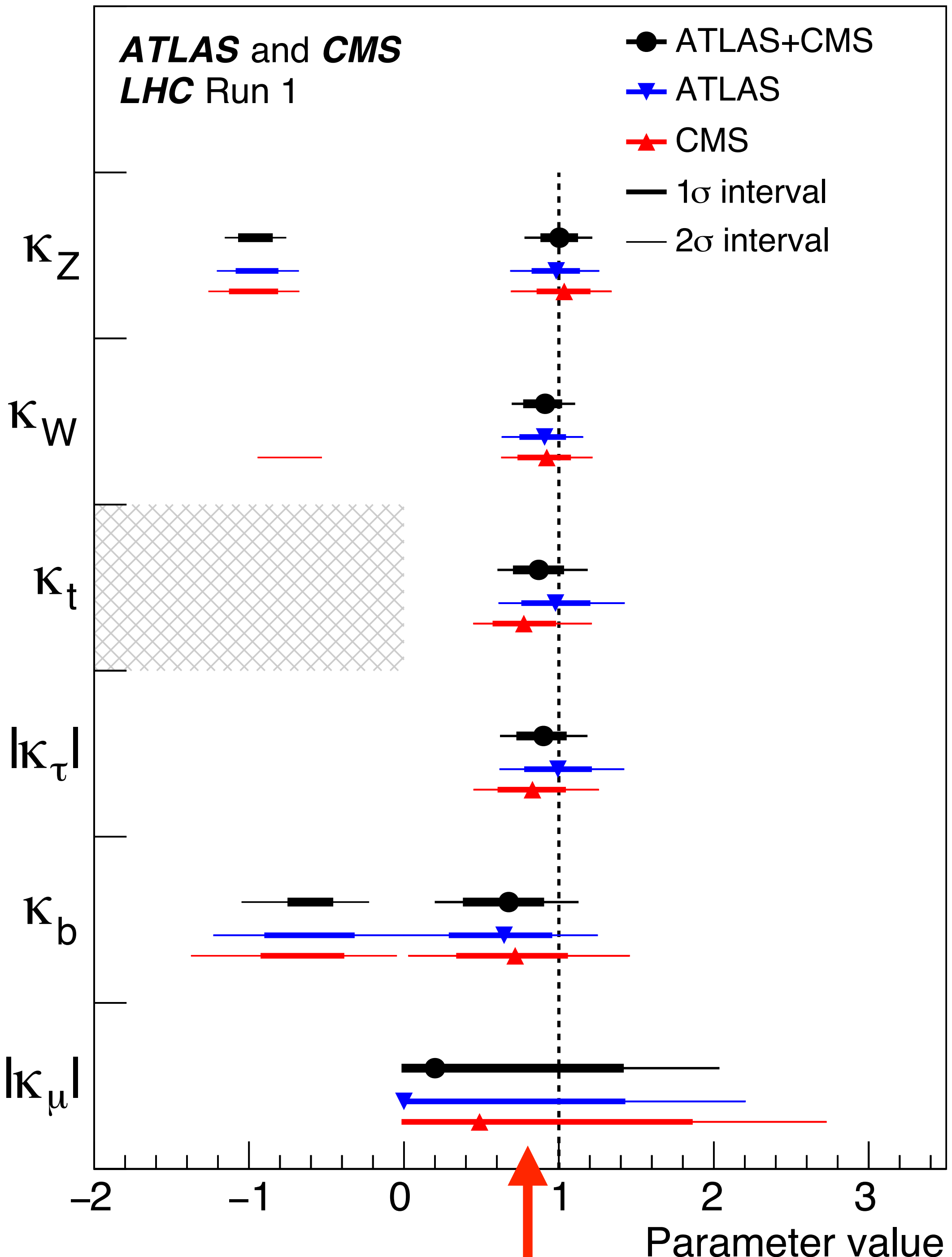




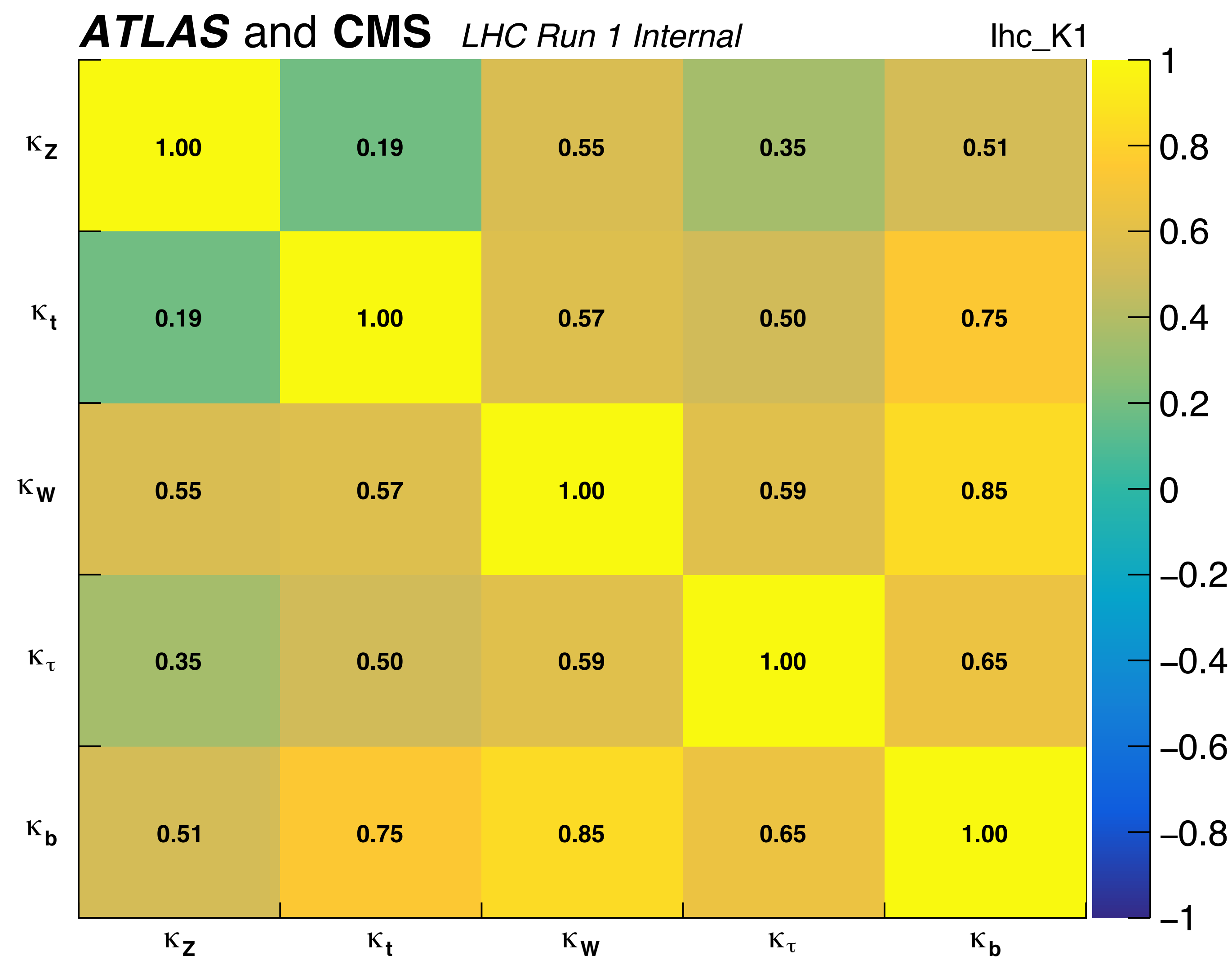
Main effect of resolving loops is on κ_t which was previously only constrained by ttH production

Interesting feature alert! All κ values ≤ 1 whereas overall signal strength is 1.09

Couplings - no BSM loop/decay contributions



- **Couplings are not really independent**
  - Correlation between κ_b, which is low, and the others due to large Γ_{bb}

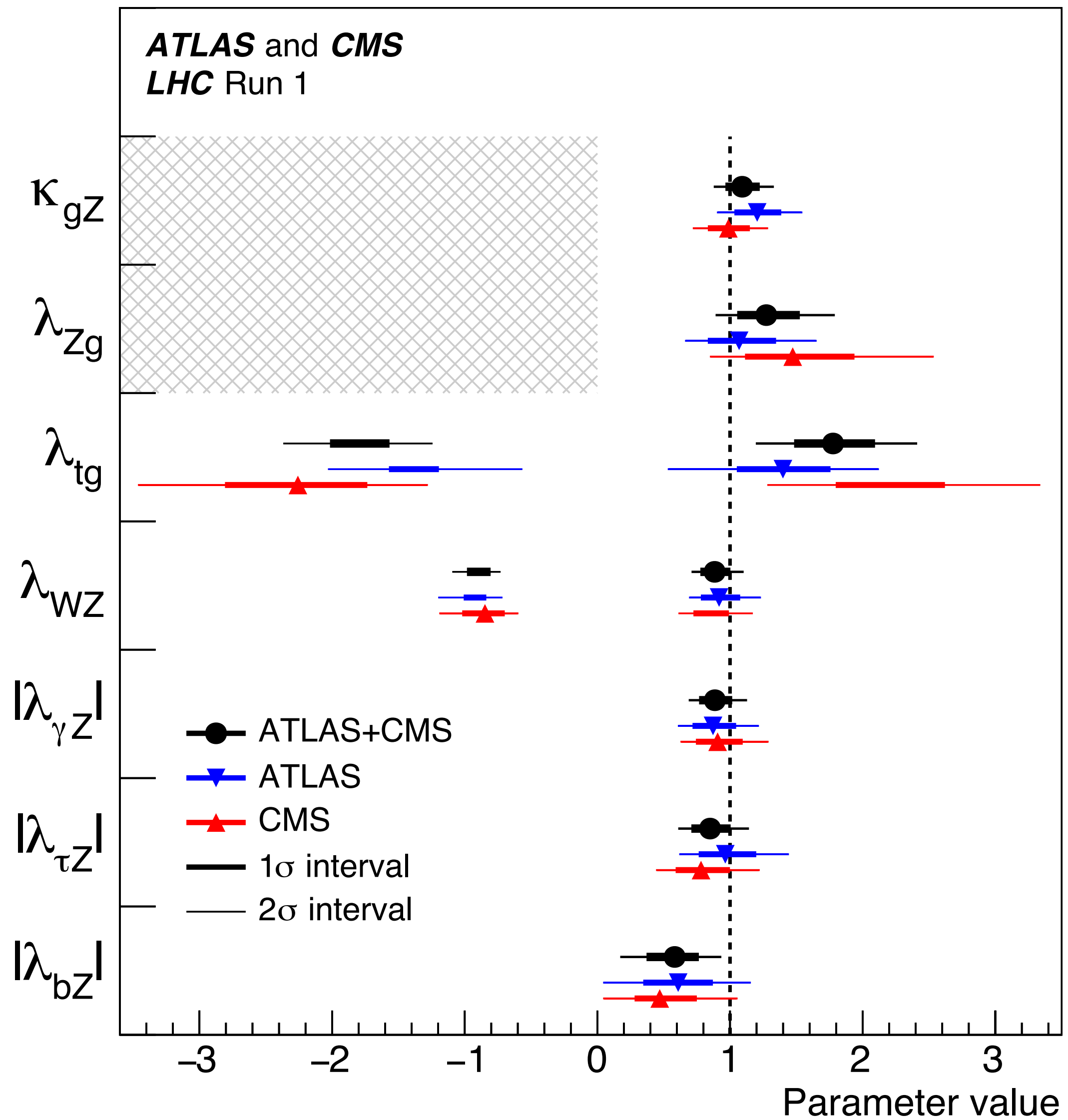


Interesting feature alert! All κ values ≤ 1 whereas overall signal strength is 1.09

Coupling Ratios

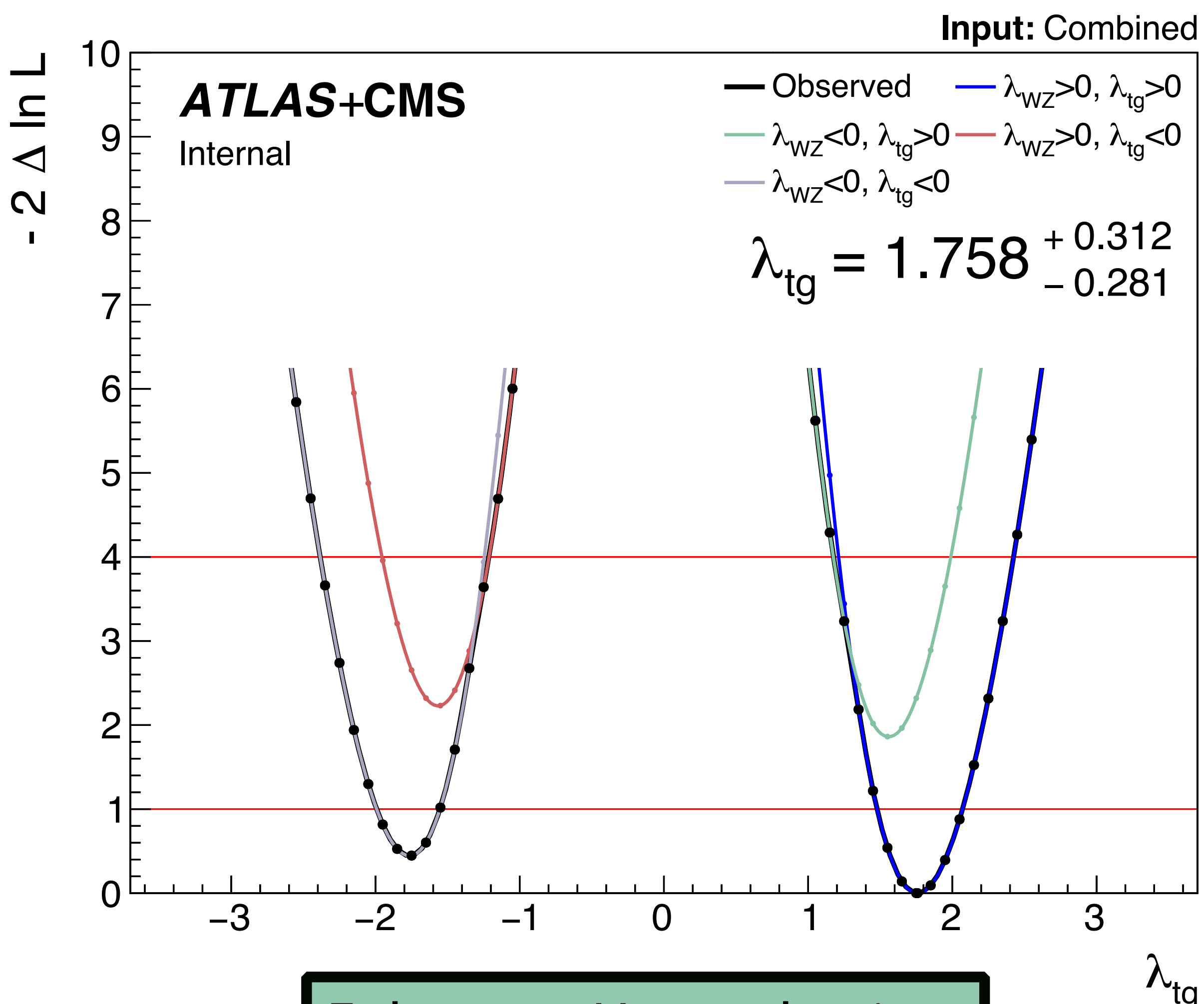
- Similar concept to cross section ratios
- Generic model in which the total width is a free parameter embedded in: $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$
- All other parameters are ratios: $\lambda_{ij} = \kappa_i/\kappa_j$
- Relative signs become important…

σ and BR ratio model	Coupling-strength ratio model
$\sigma(gg \to H \to ZZ)$	$\kappa_{gZ} = \kappa_g \cdot \kappa_Z/\kappa_H$
$\sigma_{VBF}/\sigma_{ggF}$	
σ_{WH}/σ_{ggF}	
σ_{ZH}/σ_{ggF}	$\lambda_{Zg} = \kappa_Z/\kappa_g$
$\sigma_{ttH}/\sigma_{ggF}$	$\lambda_{tg} = \kappa_t/\kappa_g$
BR^{WW}/BR^{ZZ}	$\lambda_{WZ} = \kappa_W/\kappa_Z$
$BR^{\gamma\gamma}/BR^{ZZ}$	$\lambda_{\gamma Z} = \kappa_\gamma/\kappa_Z$
$BR^{\tau\tau}/BR^{ZZ}$	$\lambda_{\tau Z} = \kappa_\tau/\kappa_Z$
BR^{bb}/BR^{ZZ}	$\lambda_{bZ} = \kappa_b/\kappa_Z$

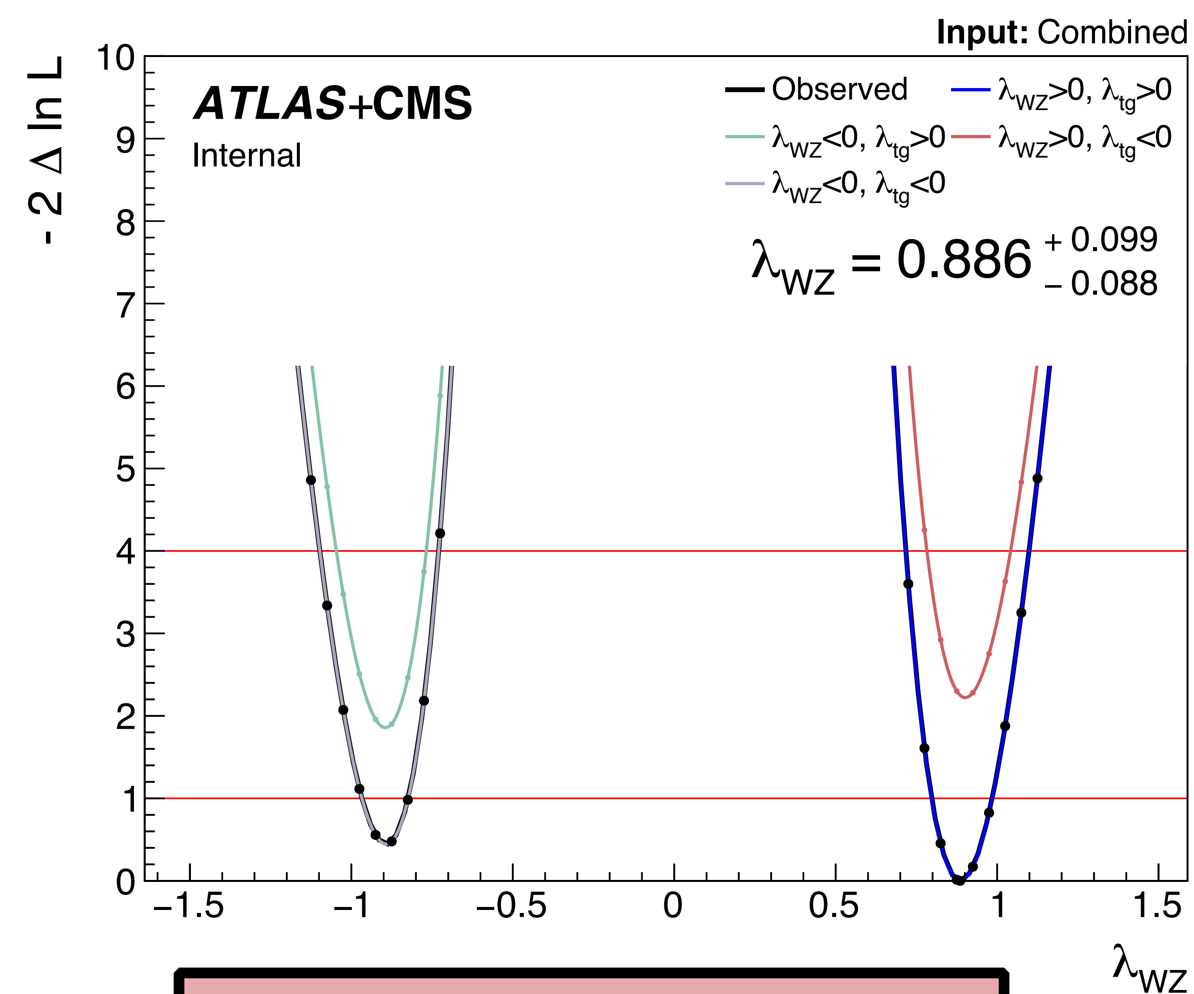


Coupling Ratios - Negative signs

- The signal processes scale as the square of the κ parameters, meaning there is a sign ambiguity that for most processes we cannot resolve
- However for processes with interference between two effective couplings we are sensitive to relative signs
- In this model: $\boldsymbol{\lambda_{WZ}}$ (via interference in VBF) and $\boldsymbol{\lambda_{tg}}$ (via interference in ggZH, tHW, tHq)
- Can obtain up to four distinct likelihood curves for choices of $\boldsymbol{\lambda_{WZ}, \lambda_{tg}}$ = (+, -), (-, +), (+, +), (-, -)



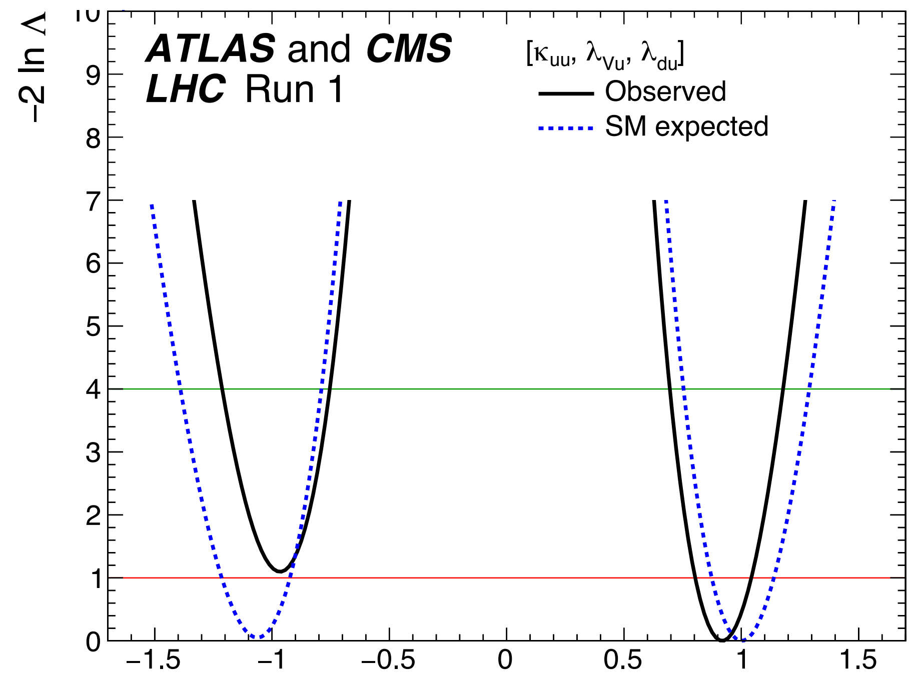
Enhances tHq production by a factor ~13

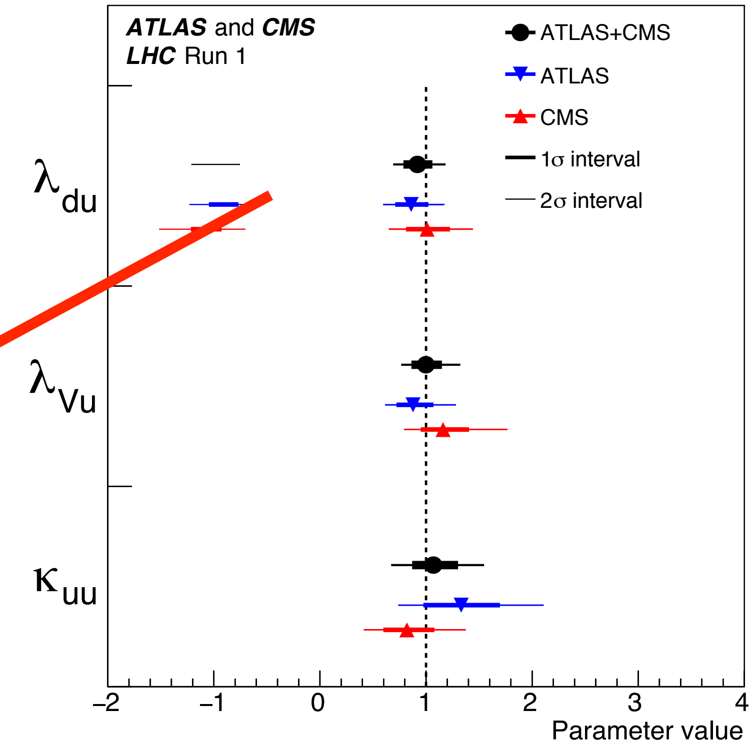


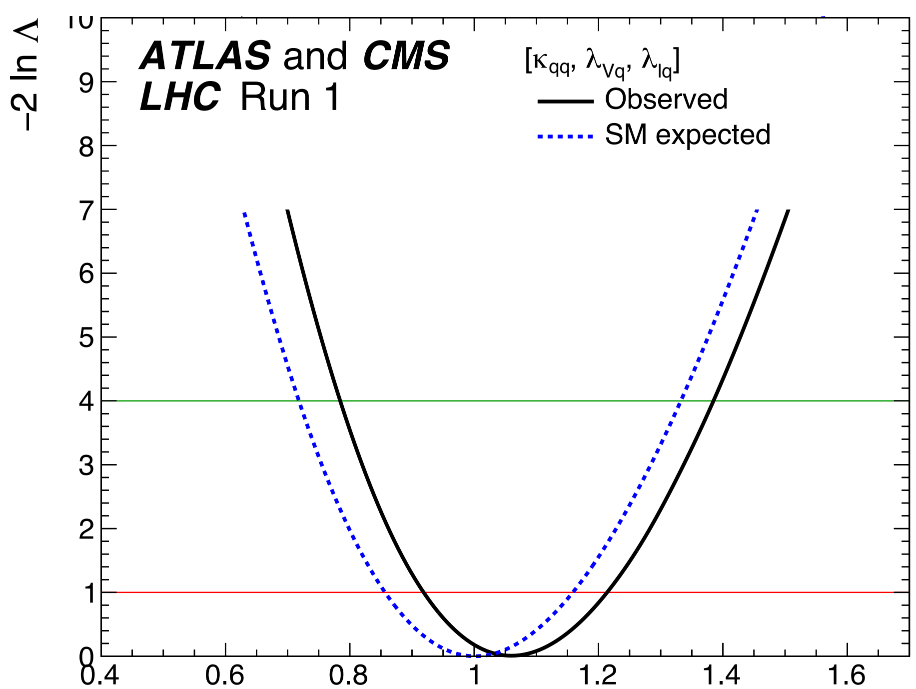
Enhances ggZH production by a factor ~4

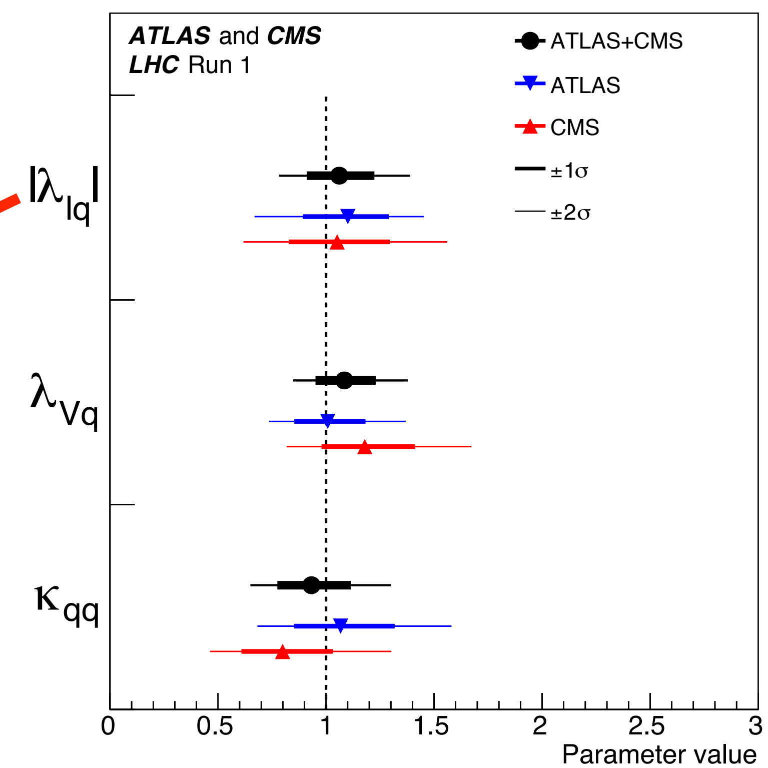
Couplings - Benchmark ratios

- Tests of up-down fermion symmetry and quark-lepton symmetry (relevant for 2HDM, MSSM etc)



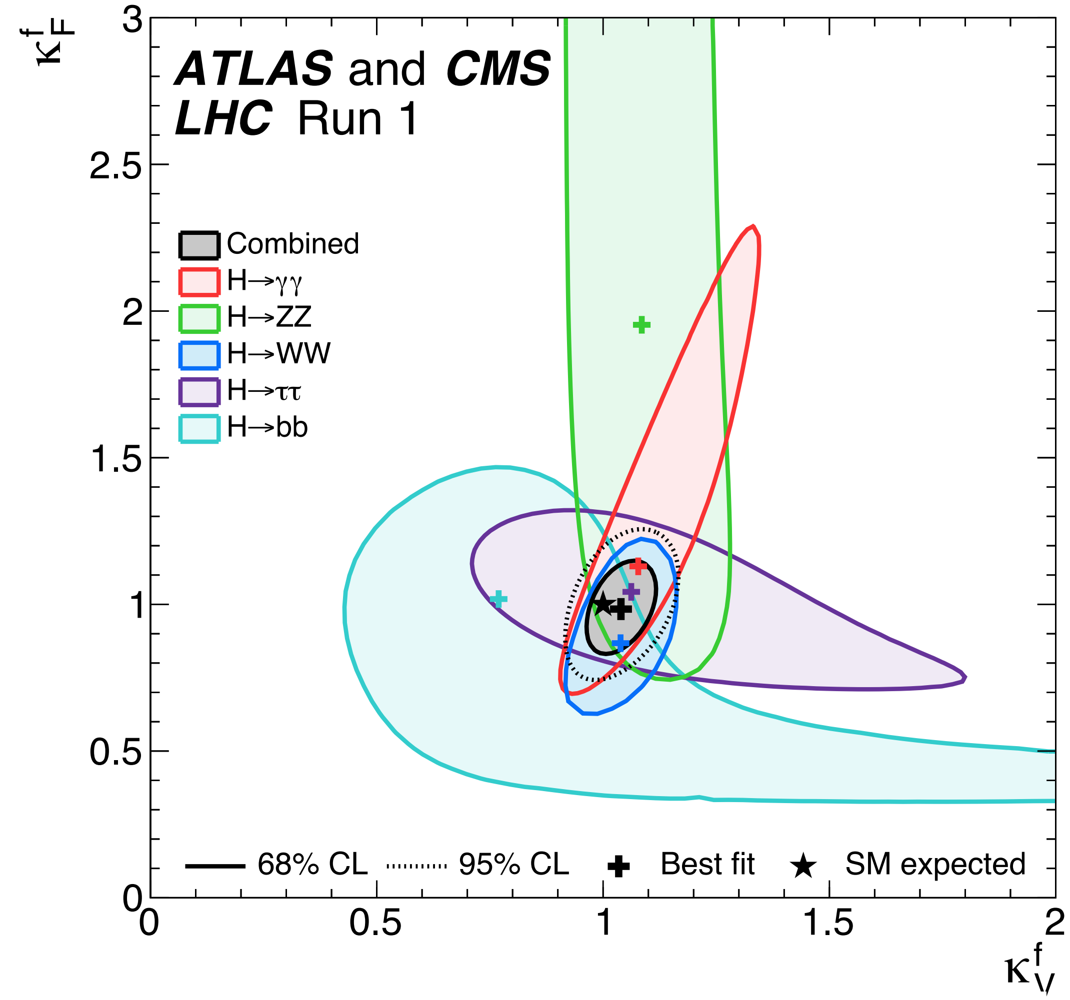


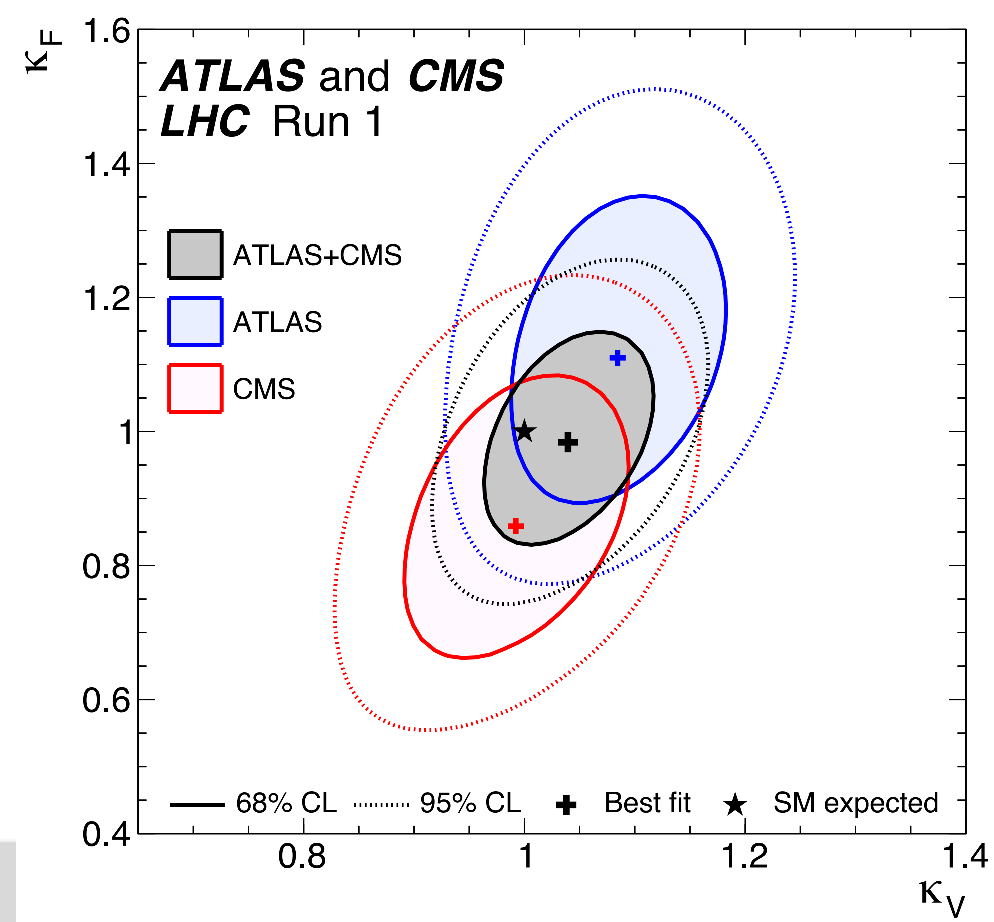




2D scans of κ_V, κ_F

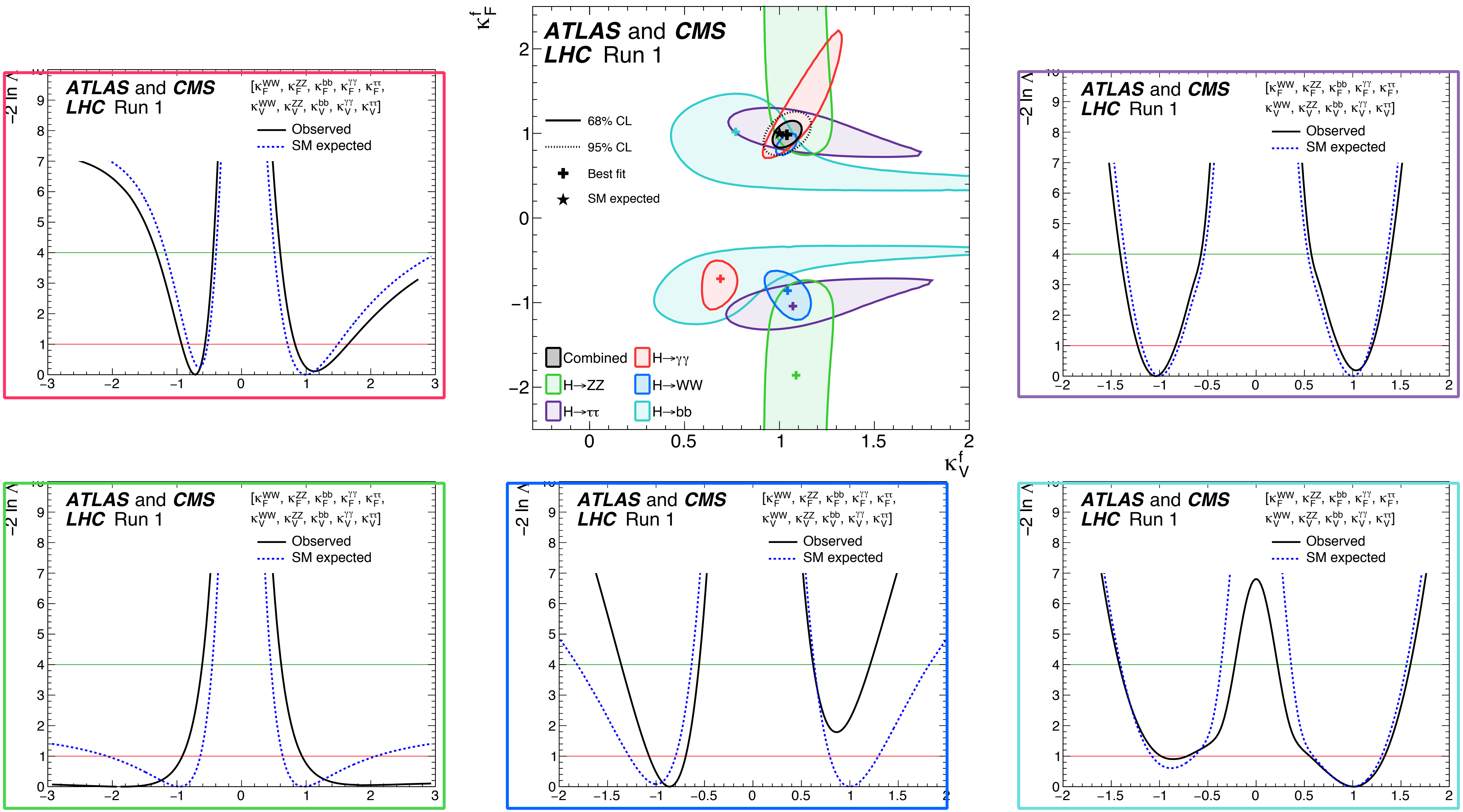
- Commonly-presented model in which
  - $\boldsymbol{\kappa_V} = \kappa_W = \kappa_Z$
  - $\boldsymbol{\kappa_F} = \kappa_t = \kappa_b = \kappa_\tau$
- Perform additional scans in a model with separate κ_V^f, κ_F^f per decay-mode
  - But not that this is a 10 parameter fit instead of 5 x 2 parameter fits
- 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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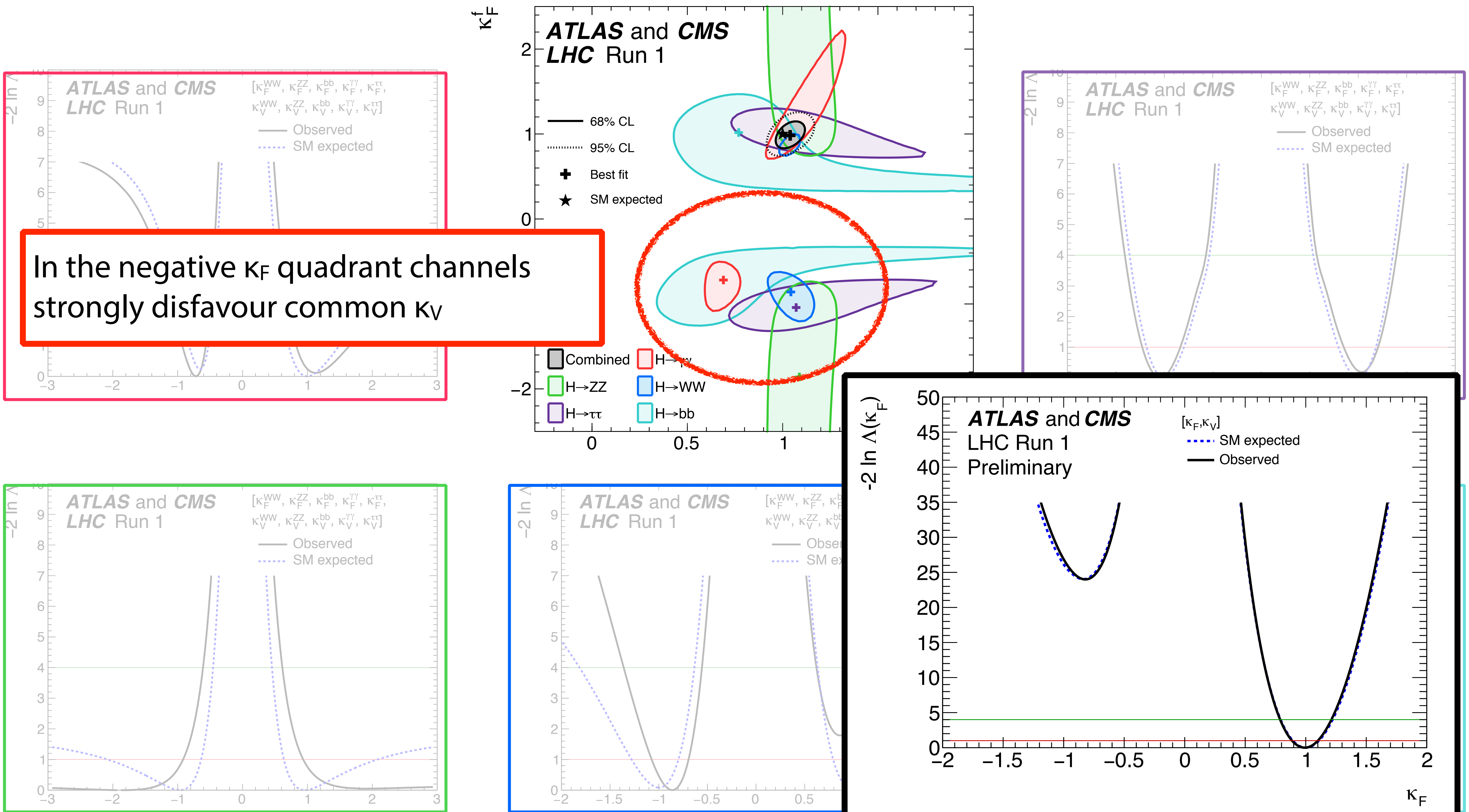

Summary

- **A comprehensive combined measurement of ATLAS and CMS Higgs boson couplings has been performed**
  - Strong picture of overall consistency with SM expectations, but still room for deviations!
  - Also a significant technical achievement

- By combining their datasets the two experiments are able to provide the best overall measurement of the Higgs boson couplings

- Results are given for more constrained (one μ value) and less constrained models (ratio models) in both the signal strength and coupling modifier models

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

Backup