Precision measurements

Higgs boson mass and width, off-shell production, couplings, CP…

CERN

Petar Bokan on behalf of ATLAS and CMS

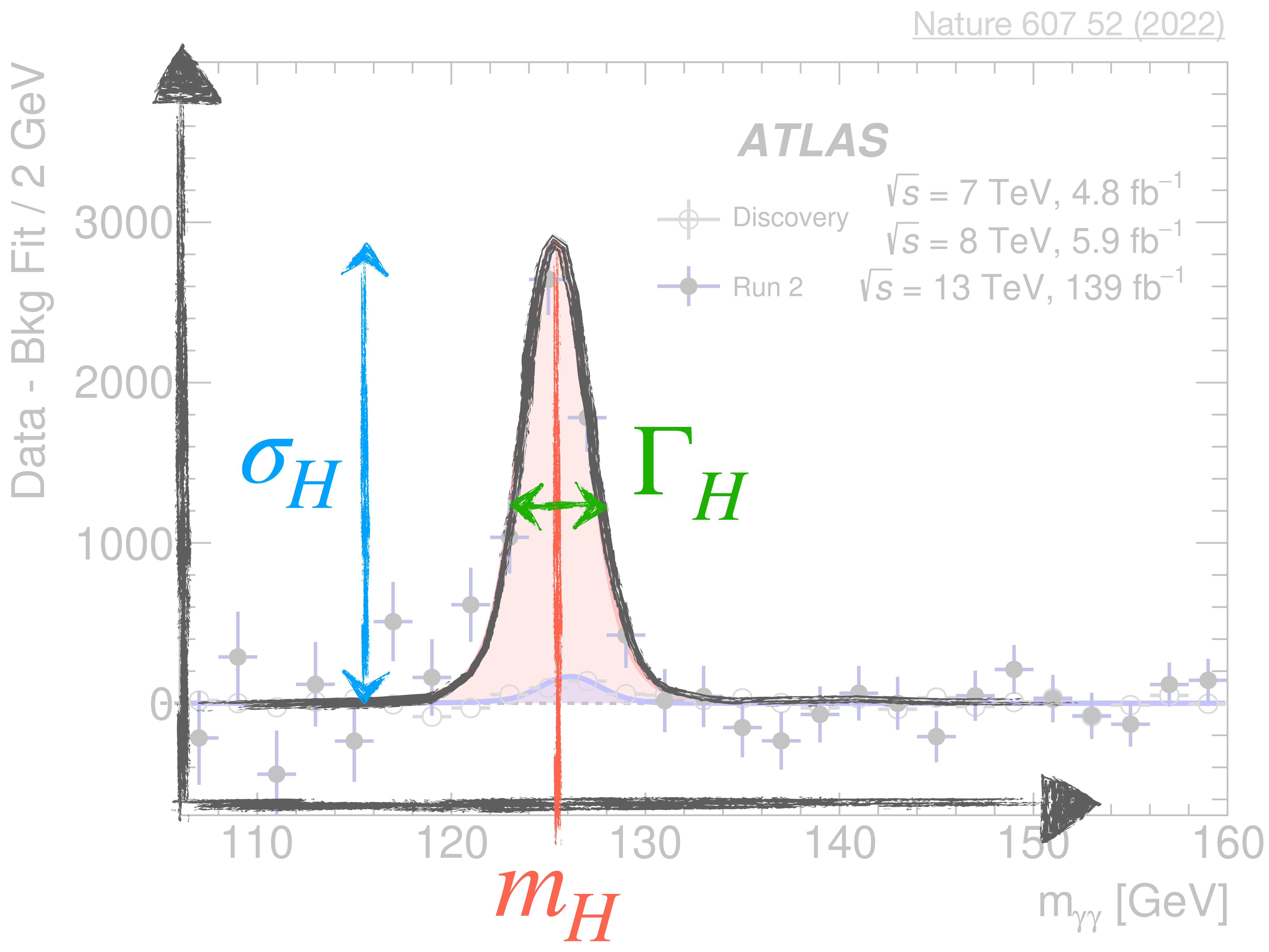
Higgs 2024, Uppsala, Sweden

November 7, 2024

ATLAS EXPERIMENT

CMS Compact Muon Solenoid

The Higgs boson

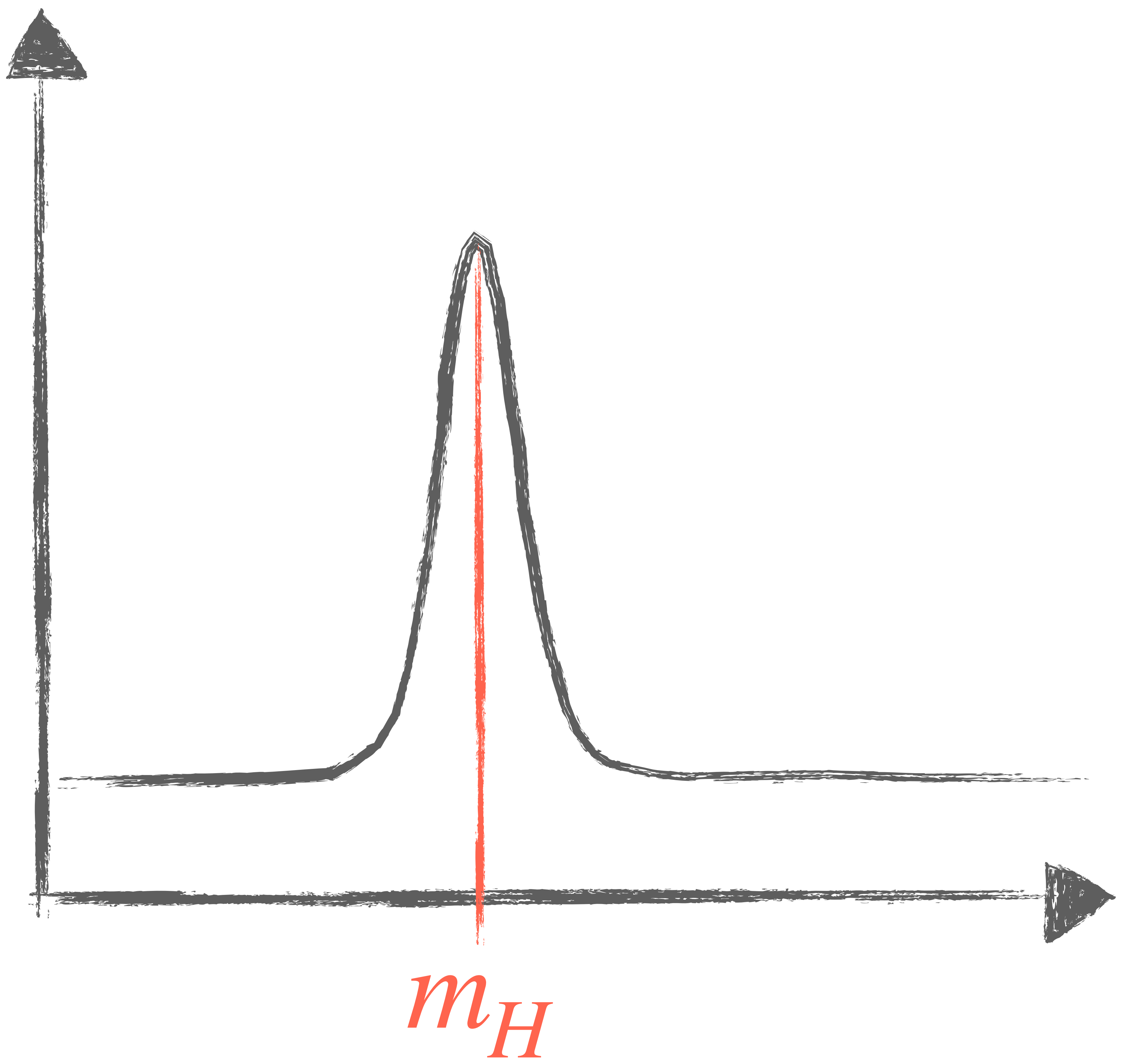


The discovery of the Higgs boson stands as the **LHC's defining achievement**!

Despite discovering it just over a decade ago, ATLAS and CMS have achieved an impressive level of **precision** in measuring its properties.

Precision is important because the Higgs boson lies at the core of the Standard Model, making it a likely **bridge to what exists beyond**.

A selection of results shown due to insufficient time to cover everything



$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

$$V(\Phi) = V_0 + \frac{1}{2}m_H^2H^2 + \lambda\nu H^3 + \frac{1}{4}\lambda H^2$$

$$m_H = \sqrt{2}\mu$$

Mass measurements

The Higgs boson mass is not predicted by the Standard Model → important experimental input!

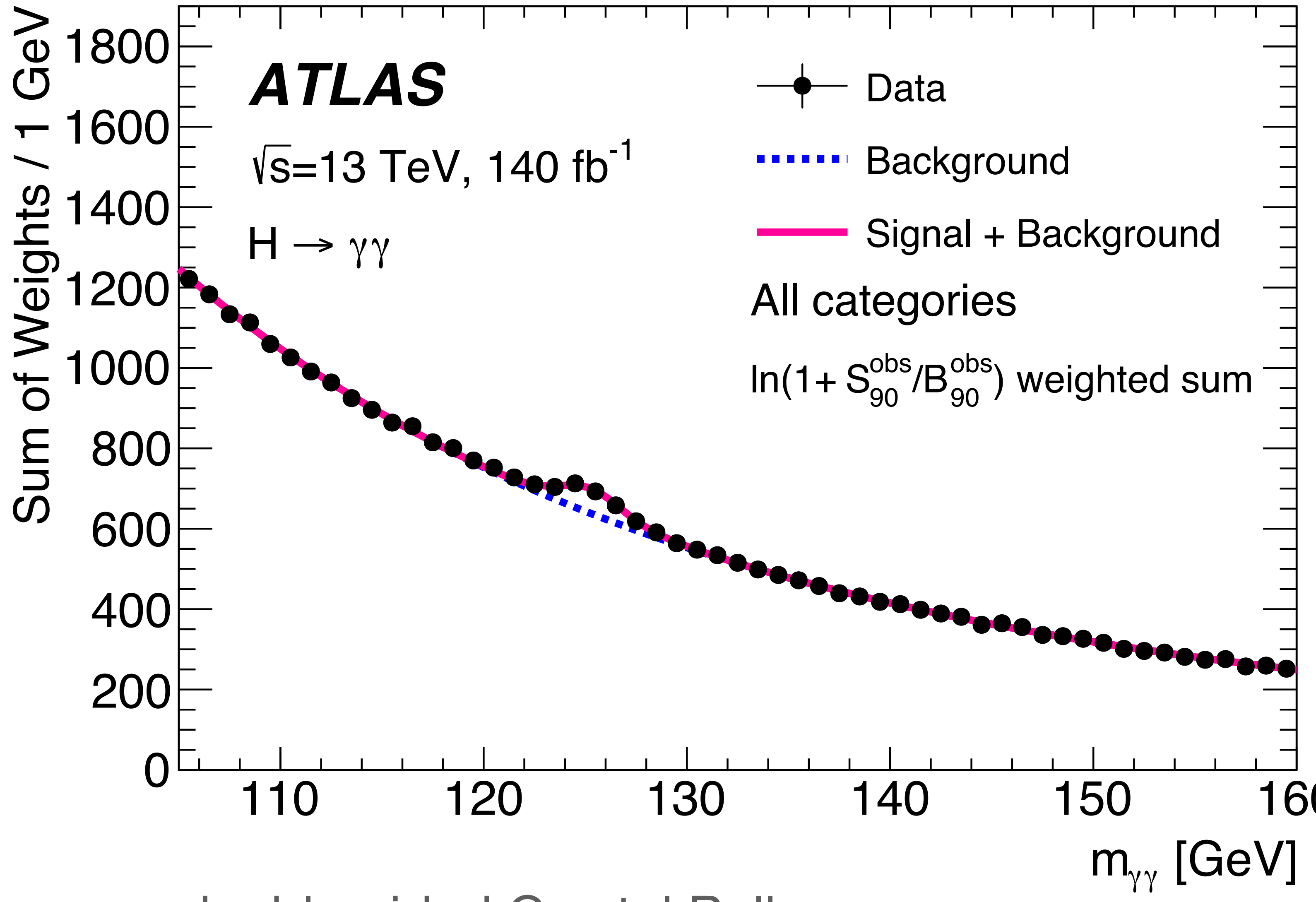
Resolution essential, and thus measured in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channels

Results from ATLAS

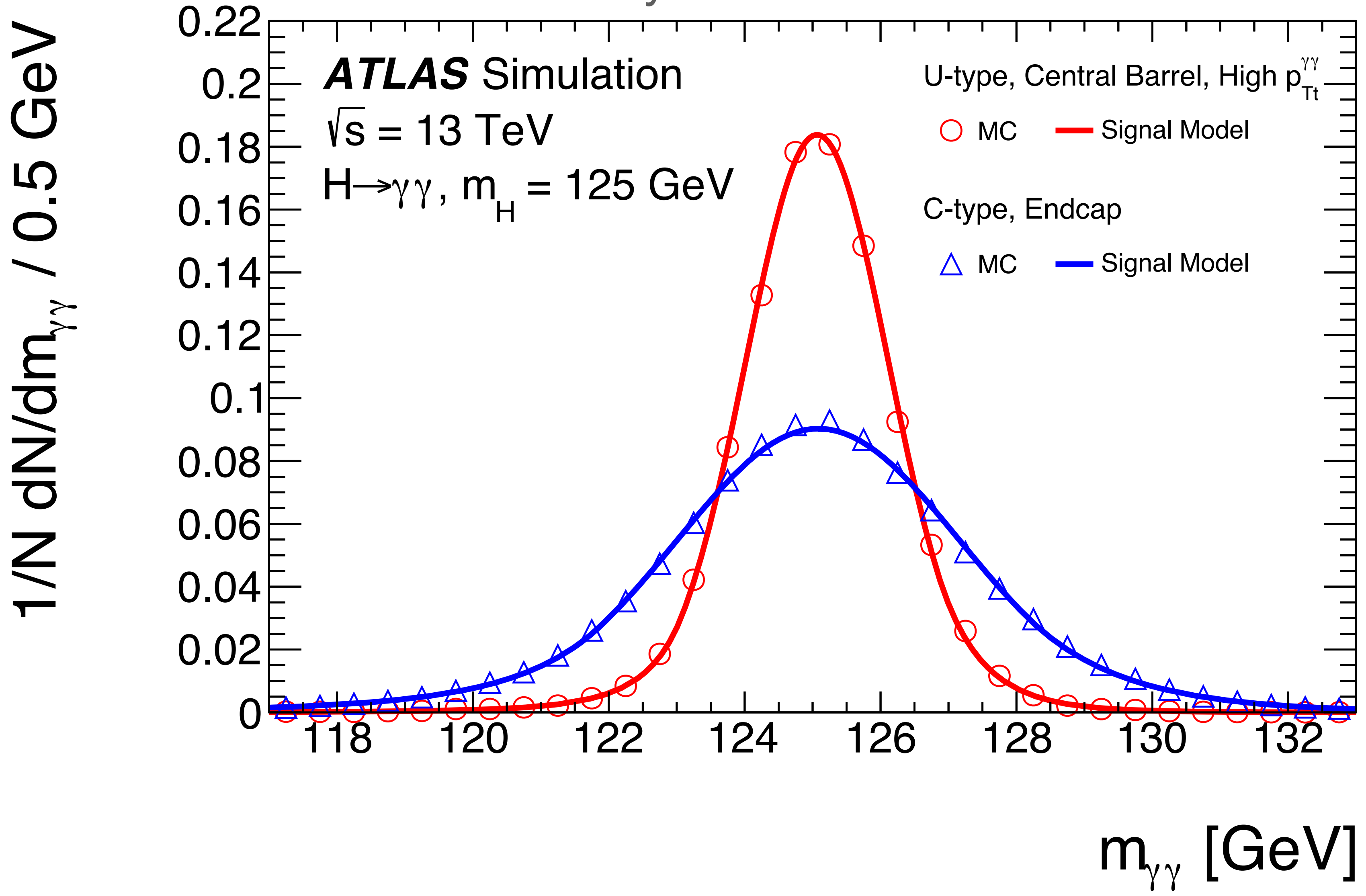
ATLAS + CMS (Run 1)

$m_H = 125.09 \pm 0.24\ (\pm\ 0.21\ \text{stat.})\ \text{GeV}$

PLB 847 (2023) 138315



double-sided Crystal Ball



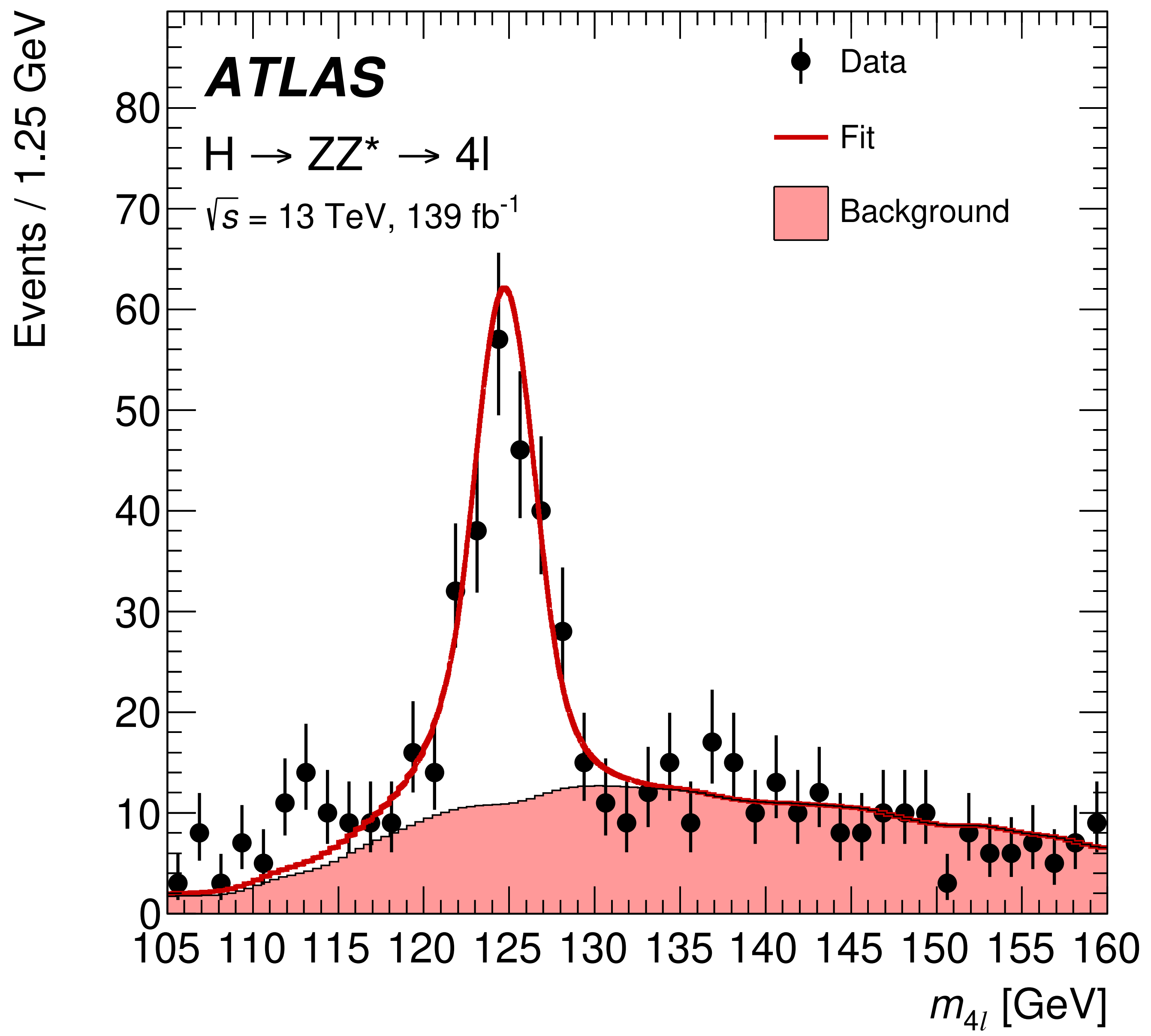
$H \to \gamma\gamma$ (Run 1 + Run 2)

$m_H = 125.22 \pm 0.14\ (\pm\ 0.11\ \text{stat.})\ \text{GeV}$

Event categorisation into 14 regions:
- signal-background ratio
- photon energy scale and resolution
- w/ or w/o photon conversion

Reduction of systematic uncertainty by a factor of 4:
- photon energy scale and resolution,
- E_T dependence of the electron energy scale (e.g. from calorimeter readout non-linearity)

PLB 843 (2023) 137880



$H \to ZZ^* \to 4\ell$ (Run 1 + Run 2)

$m_H = 124.94 \pm 0.18\ (\pm\ 0.17\ \text{stat.})\ \text{GeV}$

ATLAS combination (Run 1 + Run 2)

$m_H = 125.11 \pm 0.11\ (\pm\ 0.09\ \text{stat.})\ \text{GeV}$

Precision of 0.09% PRL 131 (2023) 251802

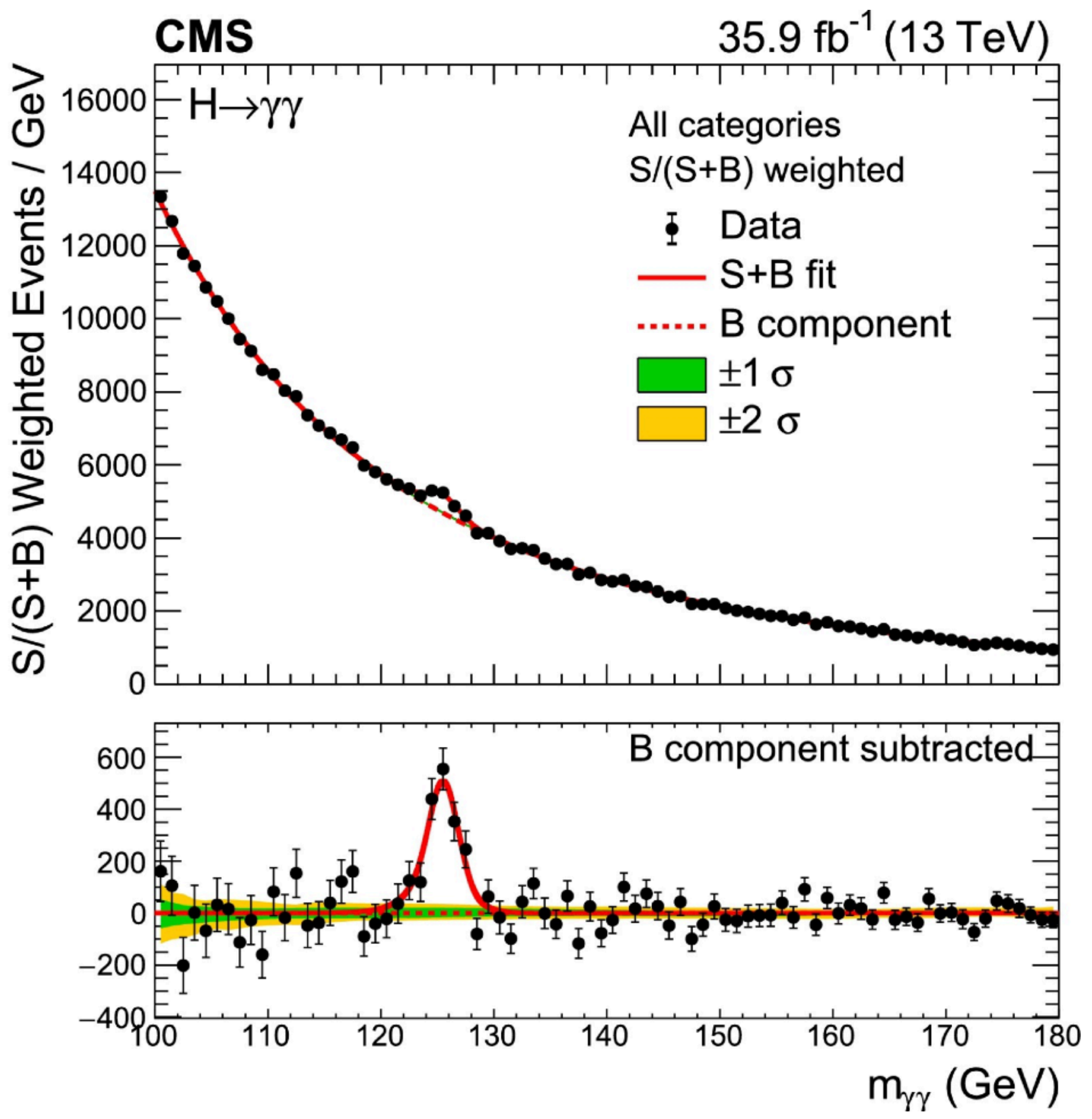
Results from CMS

More details in Ruben's talk (Tuesday)

ATLAS + CMS (Run 1)

$m_H = 125.09 \pm 0.24\ (\pm\ 0.21\ \text{stat.})\ \text{GeV}$

PLB 805 (2020) 135425



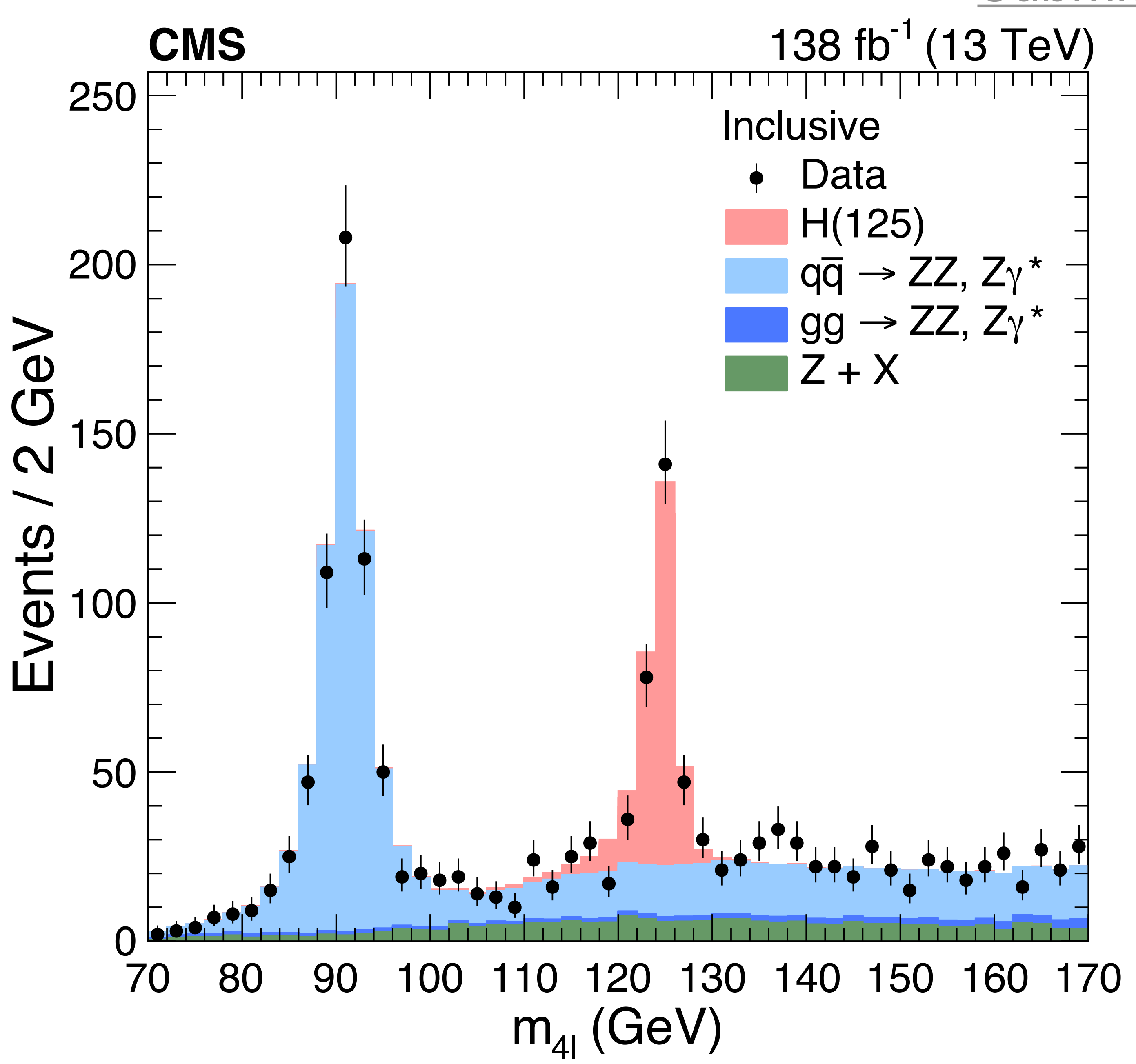
$H \to \gamma\gamma$ (2016, 35.9 fb^{-1})

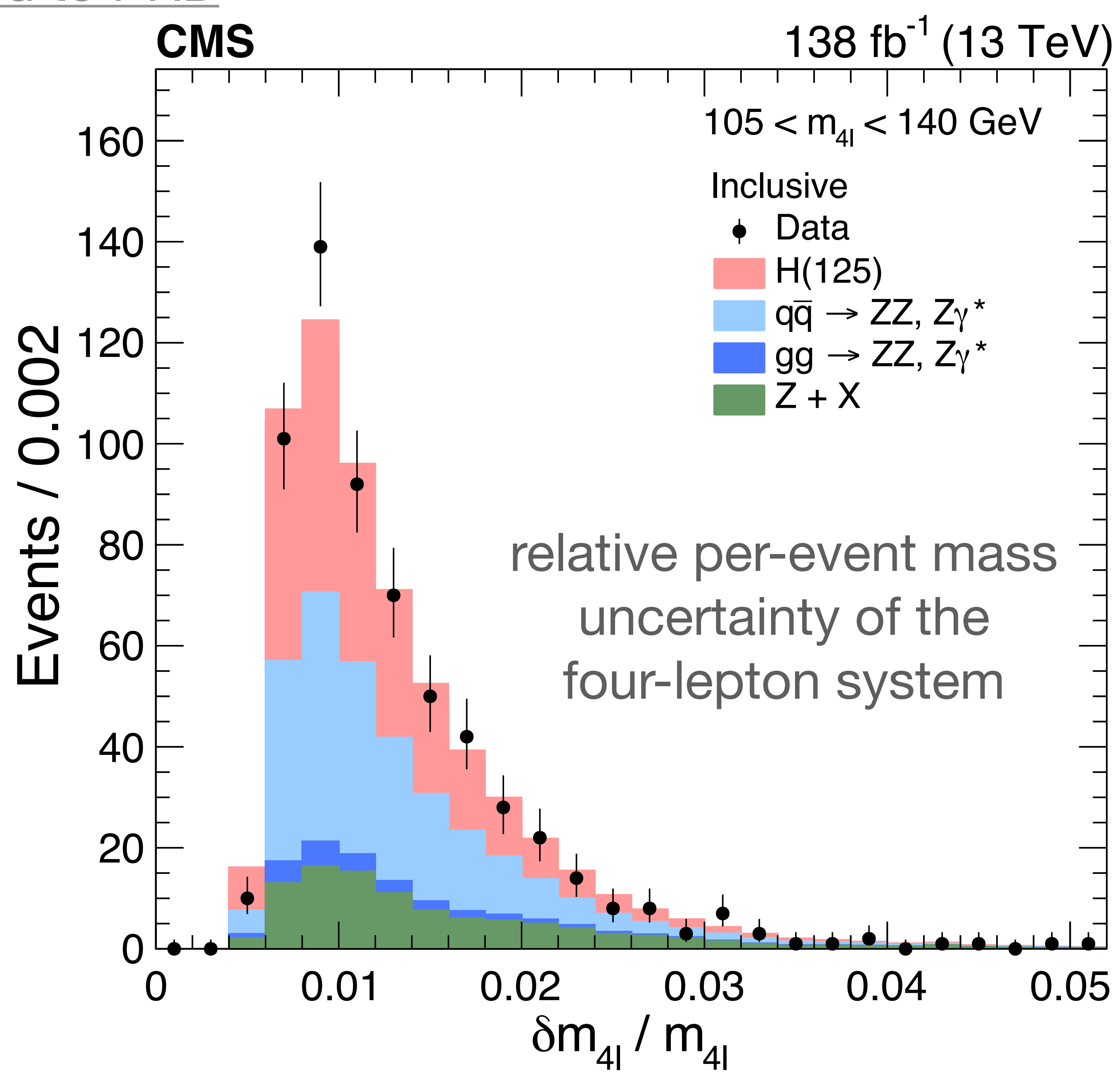
$m_H = 125.78 \pm 0.26\ (\pm\ 0.18\ \text{stat.})\ \text{GeV}$

Improved calibrations.

Dominant uncertainty: non-uniformity of light collections due to radiation damage

Submitted to PRD





$H \to ZZ^* \to 4\ell$ (Run 1 + Run 2)

$m_H = 125.08 \pm 0.12\ (\pm\ 0.10\ \text{stat.})\ \text{GeV}$

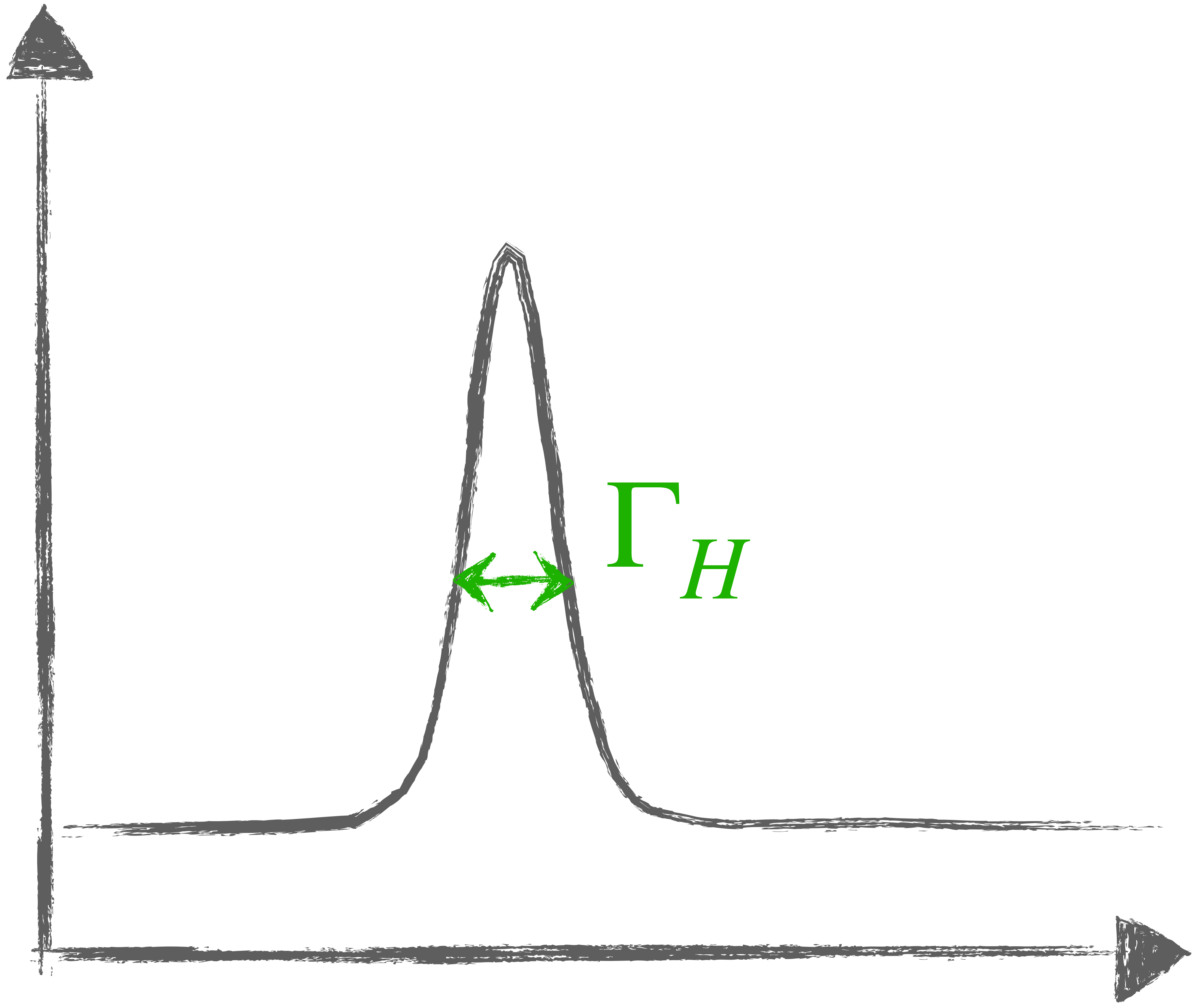
Beam spot included in the refit of muon tracks.

Improved event categorisation based on $\delta m_{4\ell}/m_{4\ell}$

Improved lepton momentum scale and resolution

Most precise single-channel measurement to date!

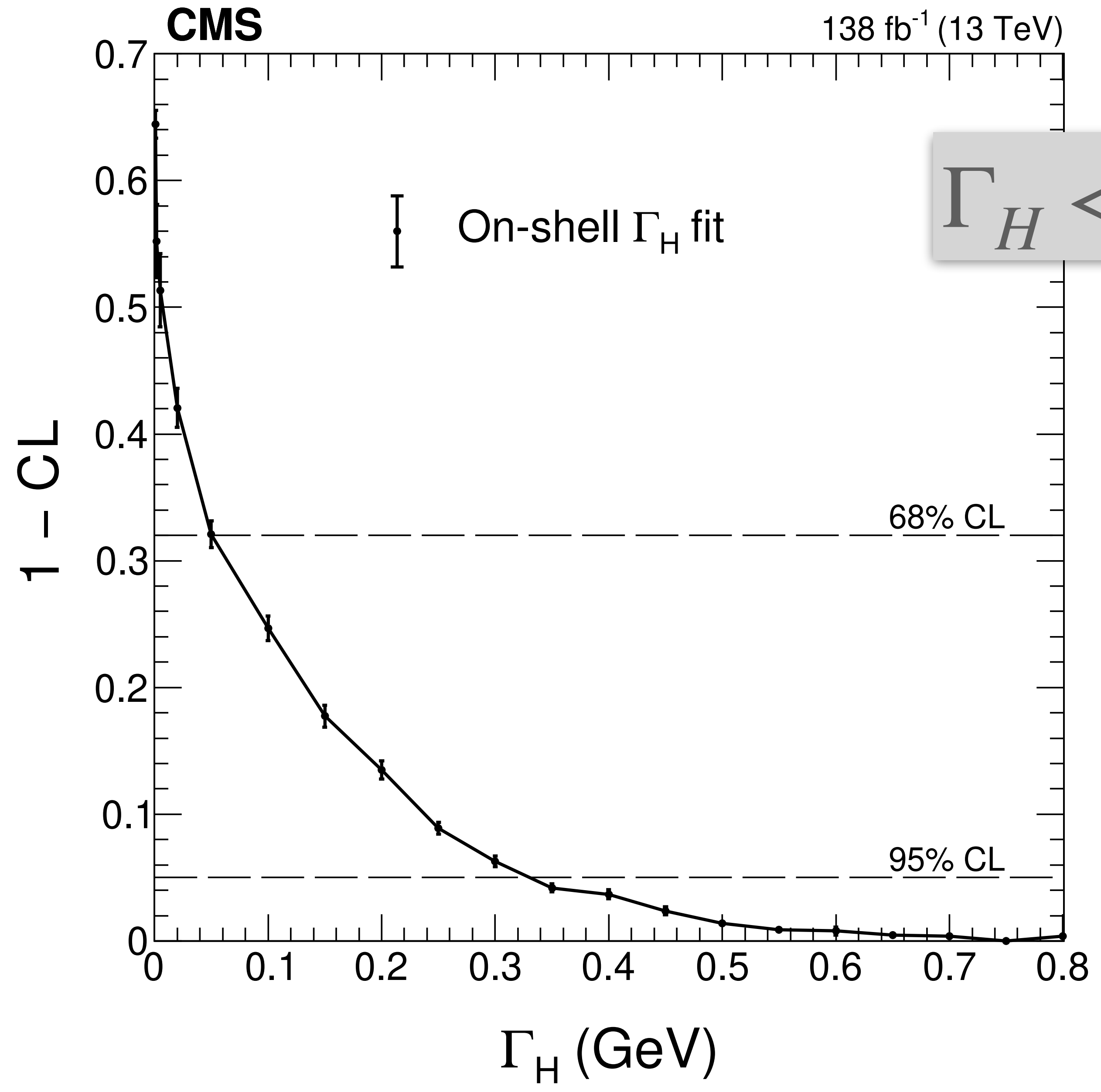
Width measurements



Γ_H dominated by $\Gamma(H \to b\bar{b}) \approx N_c \frac{g_w^2 m_b^2 m_H}{32\pi m_W^2}$

The Standard Model predicts a very small Higgs boson natural width of around 4.1 MeV

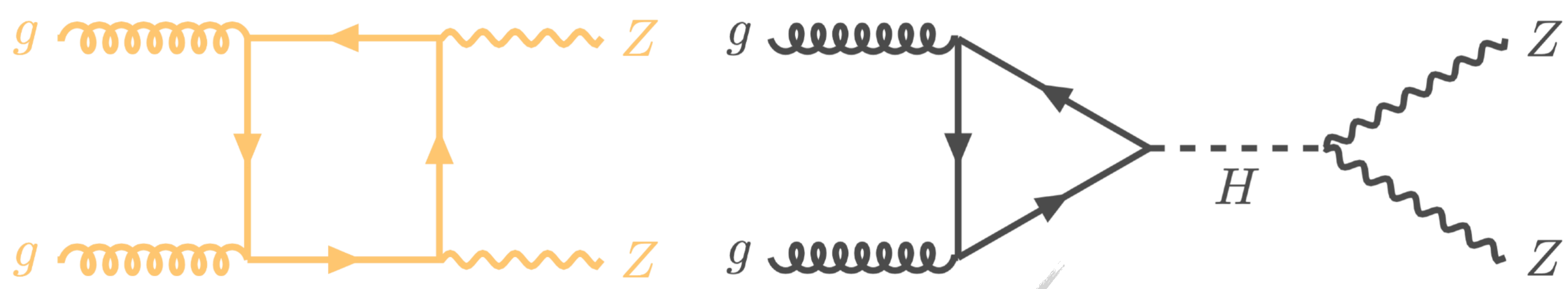
Direct measurements infeasible, can set limits:



Submitted to PRD

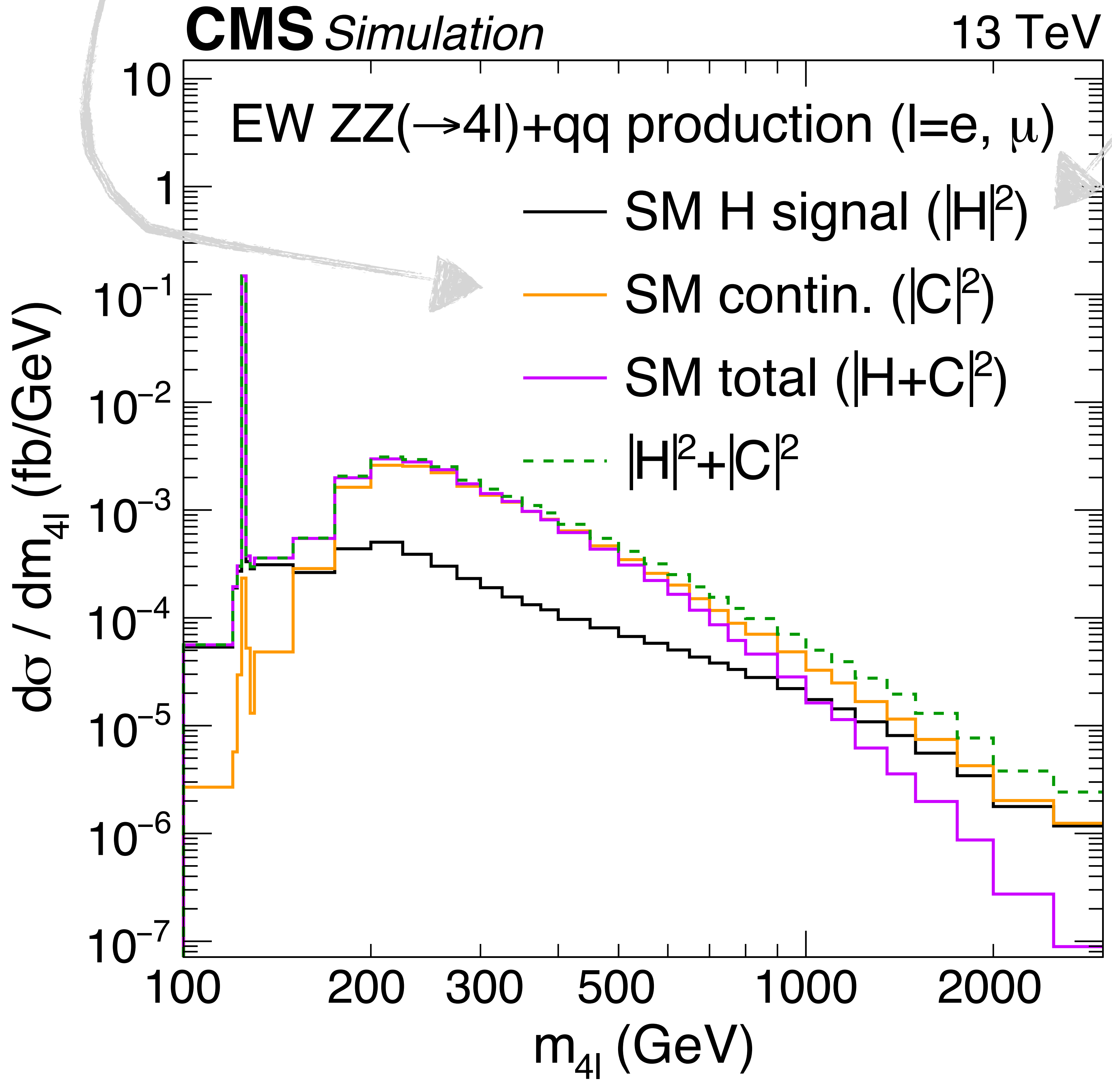
$\Gamma_H < 330$ MeV at 95% CL

Higgs boson width from off-shell production



Destructive interference between the two diagrams for the off-shell Higgs boson production, scales as $\sqrt{\mu^{\text{on-shell}}\Gamma_H}$

Nat. Phys. 18 (2022) 1329

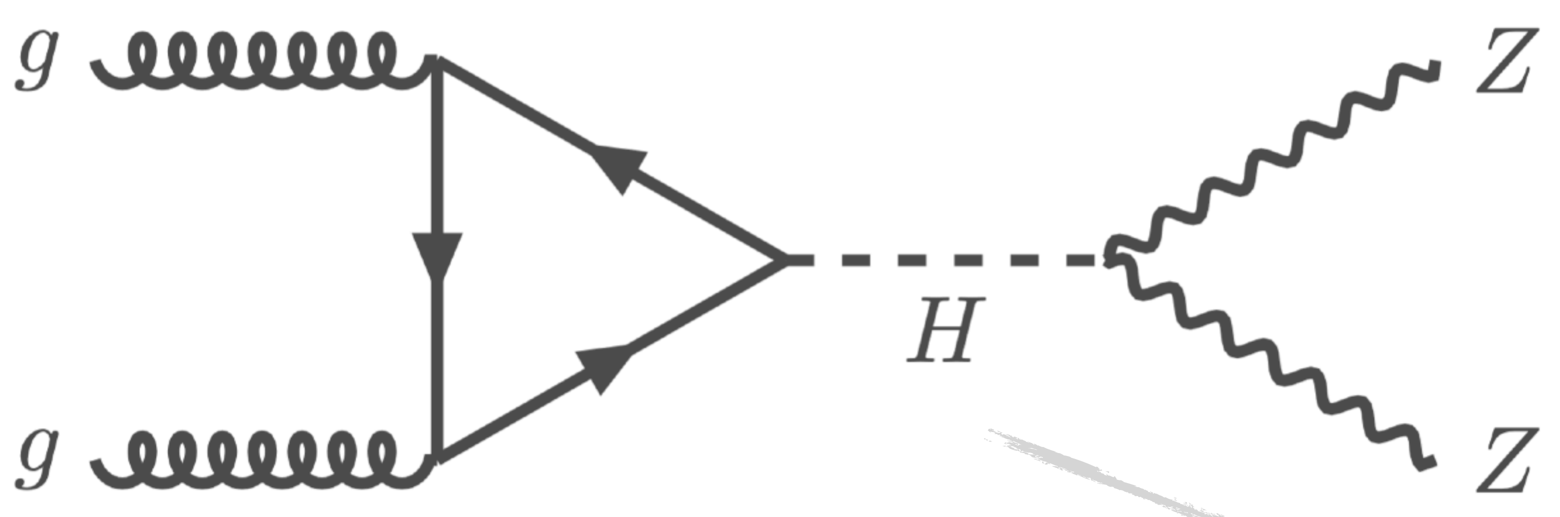


Evidence for off-shell production has been claimed by both ATLAS and CMS:

CMS: 3.8σ (exp. 2.4σ)
Submitted to PRD

ATLAS: 3.7σ (exp. 2.4σ)
ATLAS-CONF-2024-016

Higgs boson width from off-shell production



Destructive interference between the two diagrams for the off-shell Higgs boson production, scales as $\sqrt{\mu^{\text{on-shell}}\Gamma_H}$

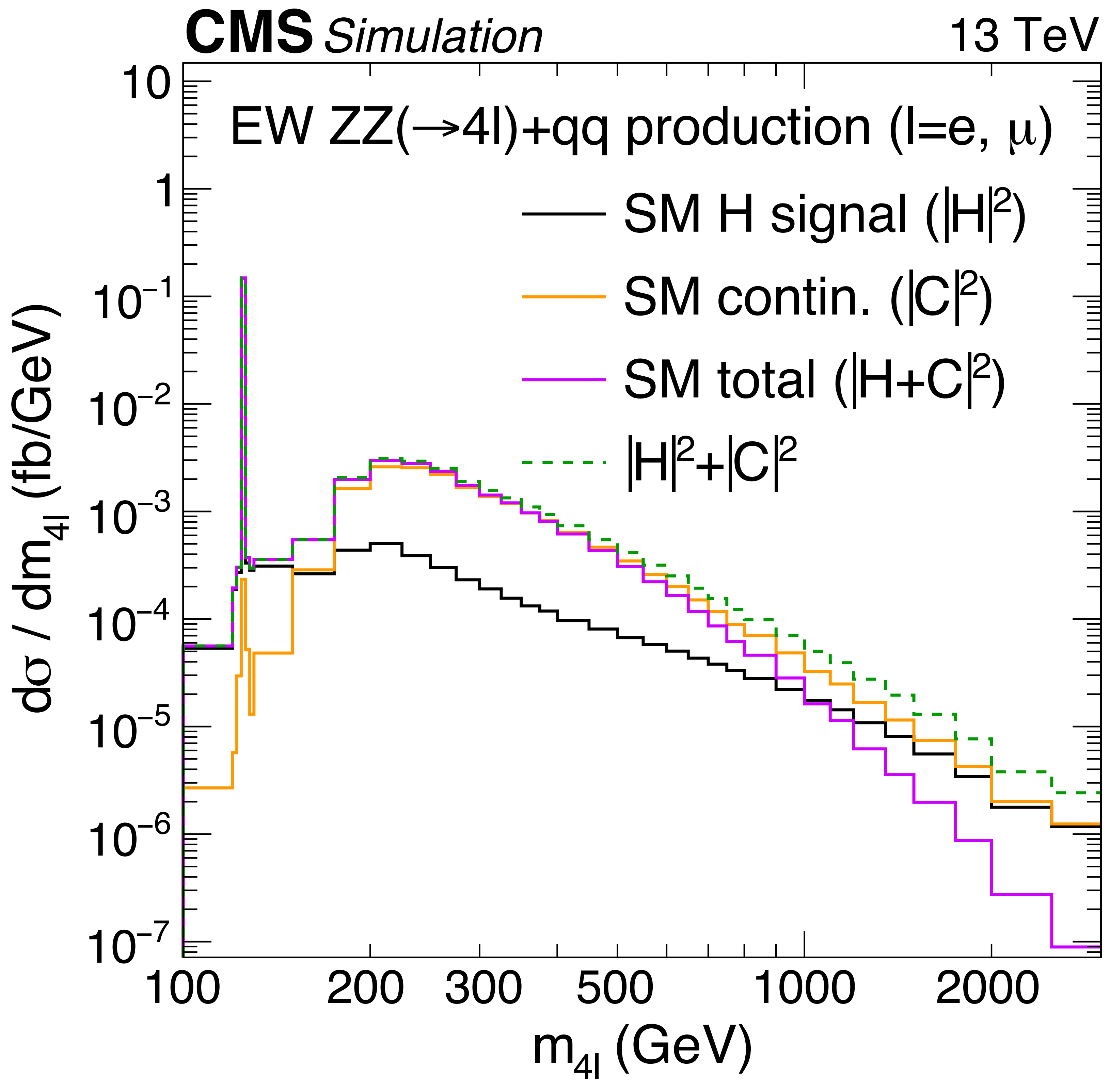
$|\text{Propagator}|^2$: $\dfrac{1}{(q^2 - m_H^2)^2 + \Gamma_H^2 m_H^2}$

Assuming the same coupling modifiers between the on-shell and off-shell Higgs boson production:

$$\sigma_{i\to H\to f}^{\text{on-shell}} \sim \frac{g_i^2 g_f^2}{\Gamma_H} \text{ and } \sigma_{i\to H\to f}^{\text{off-shell}} \sim g_i^2 g_f^2$$

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\mu^{\text{off-shell}}}{\mu^{\text{on-shell}}}$$

Nat. Phys. 18 (2022) 1329



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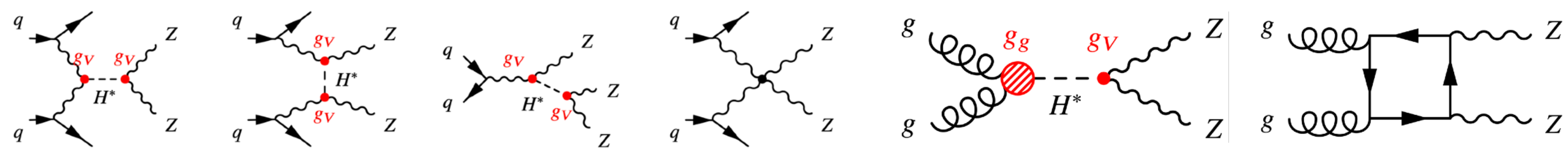
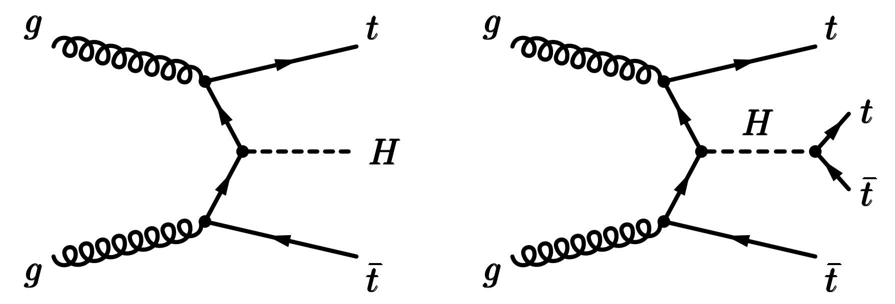
ATLAS-CONF-2024-016

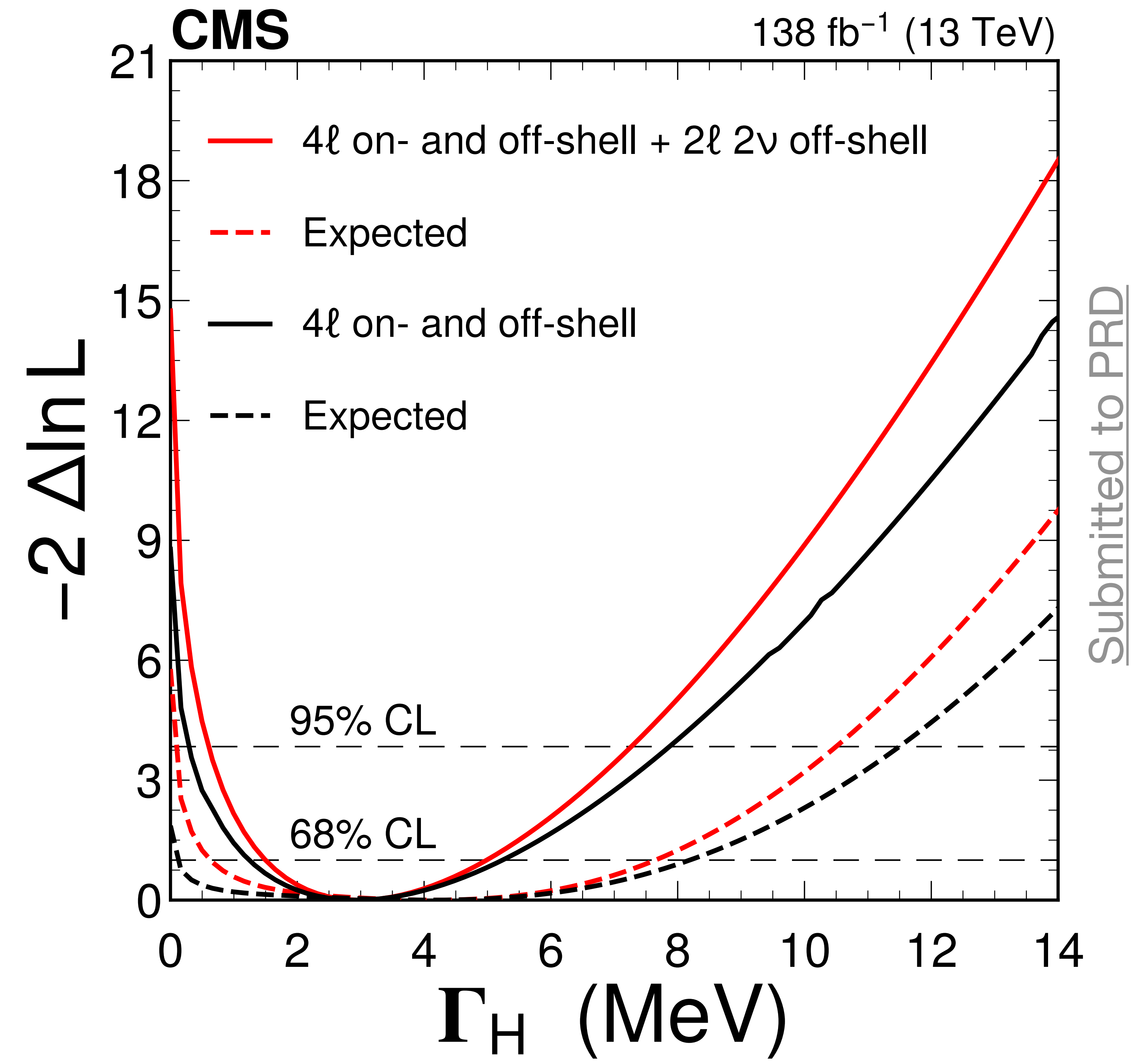
Higgs boson width from off-shell production

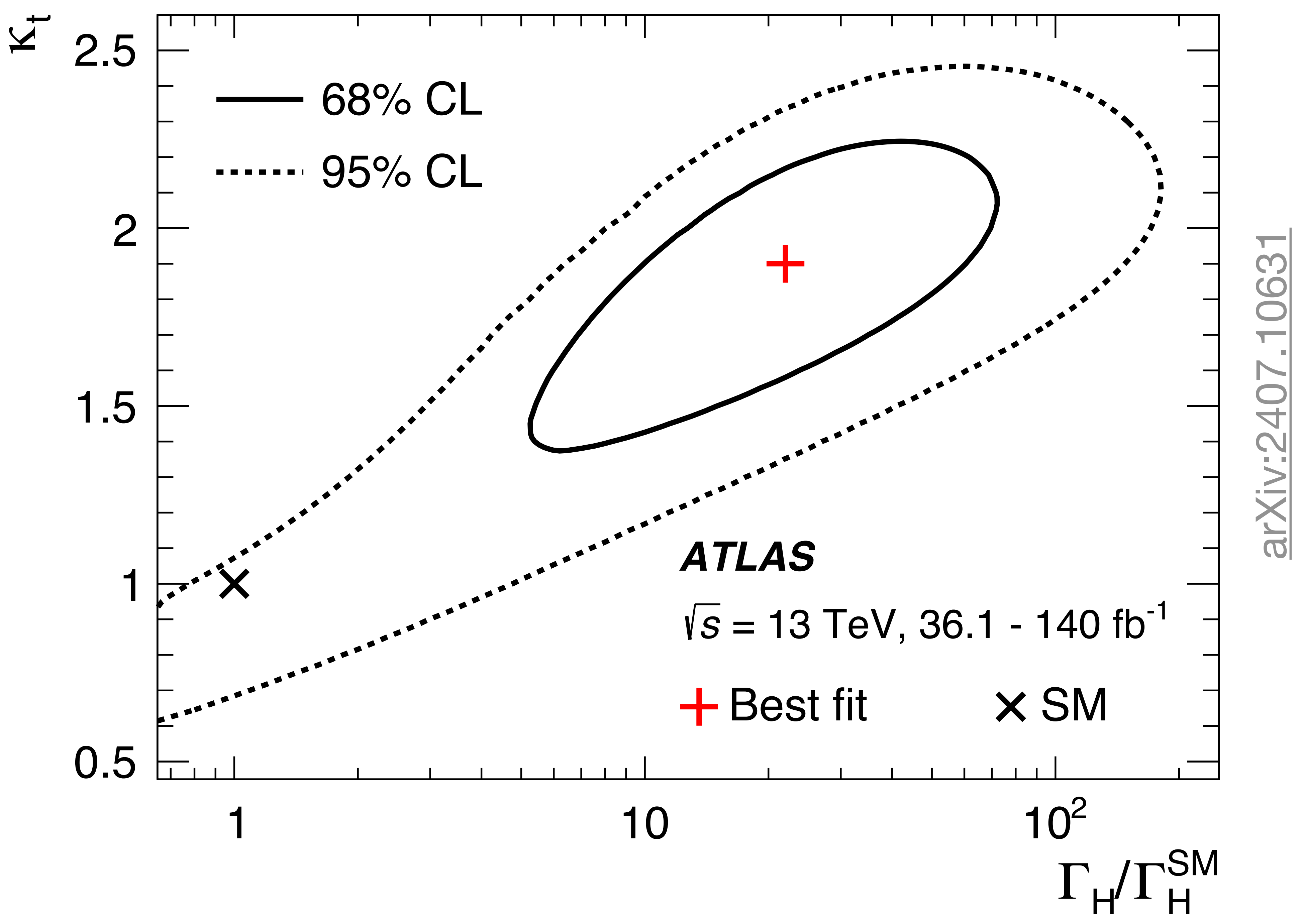
More details in Ruben's and Will's talks (Tuesday)





On-shell result based on: Nature 607 52 (2022)





$gg \to ZZ^* \to 4\ell$ or $2\ell 2\nu$: $\Gamma_H = 3.0^{+2.0}_{-1.5}$ MeV

$\Gamma_H = 2.7^{+2.7}_{-1.8}$ MeV (when allowing contributions from an additional heavy quark in the ggF loop)

$gg \to t\bar{t}t\bar{t}$: $\Gamma_H < 450$ (exp. 75) MeV at 95% CL

$\Gamma_H = 86^{+110}_{-49}$ MeV (2σ deviation from SM)

$\Gamma_H < 160$ (exp. 55) MeV at 95% CL, loops resolved

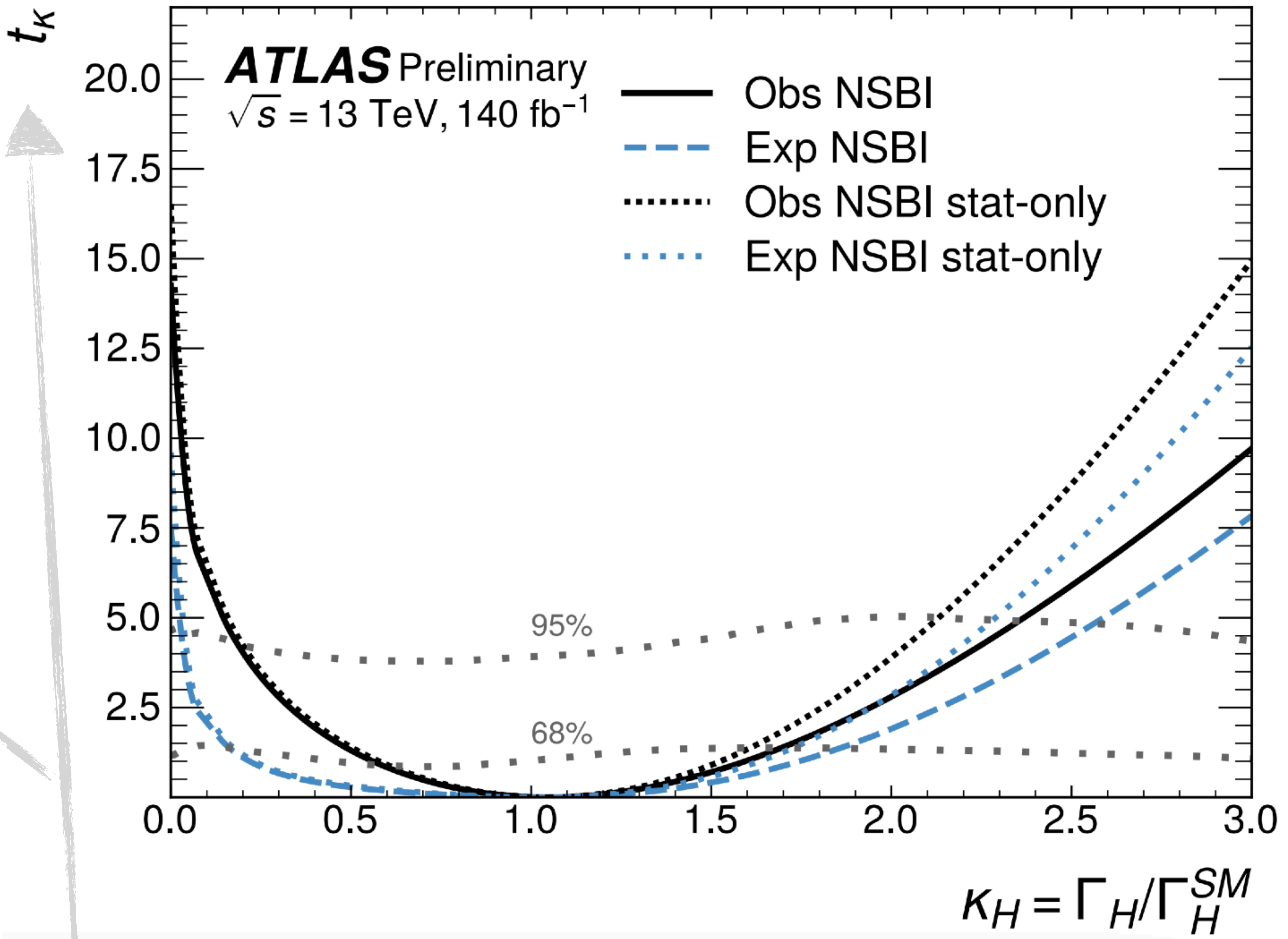
Higgs boson width from off-shell production

ATLAS-CONF-2024-016

More details in Jay's talk (Monday)

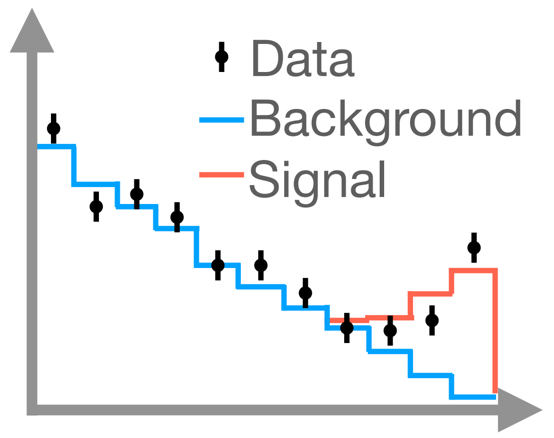
ATLAS $H \to ZZ^* \to 4\ell$ measurement PLB 846 (2023) 138223
reanalysed based on neural simulation-based statistical inference (NSBI)

$gg \to ZZ^* \to 4\ell$ plus $2\ell 2\nu$: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV $\to \Gamma_H = 4.3^{+2.7}_{-1.9}$ MeV



High-dimensional data

Dimension reduction



Histogram

Binned Poisson likelihood

$\mathscr{L}(\mu, \theta \mid \text{Data})$

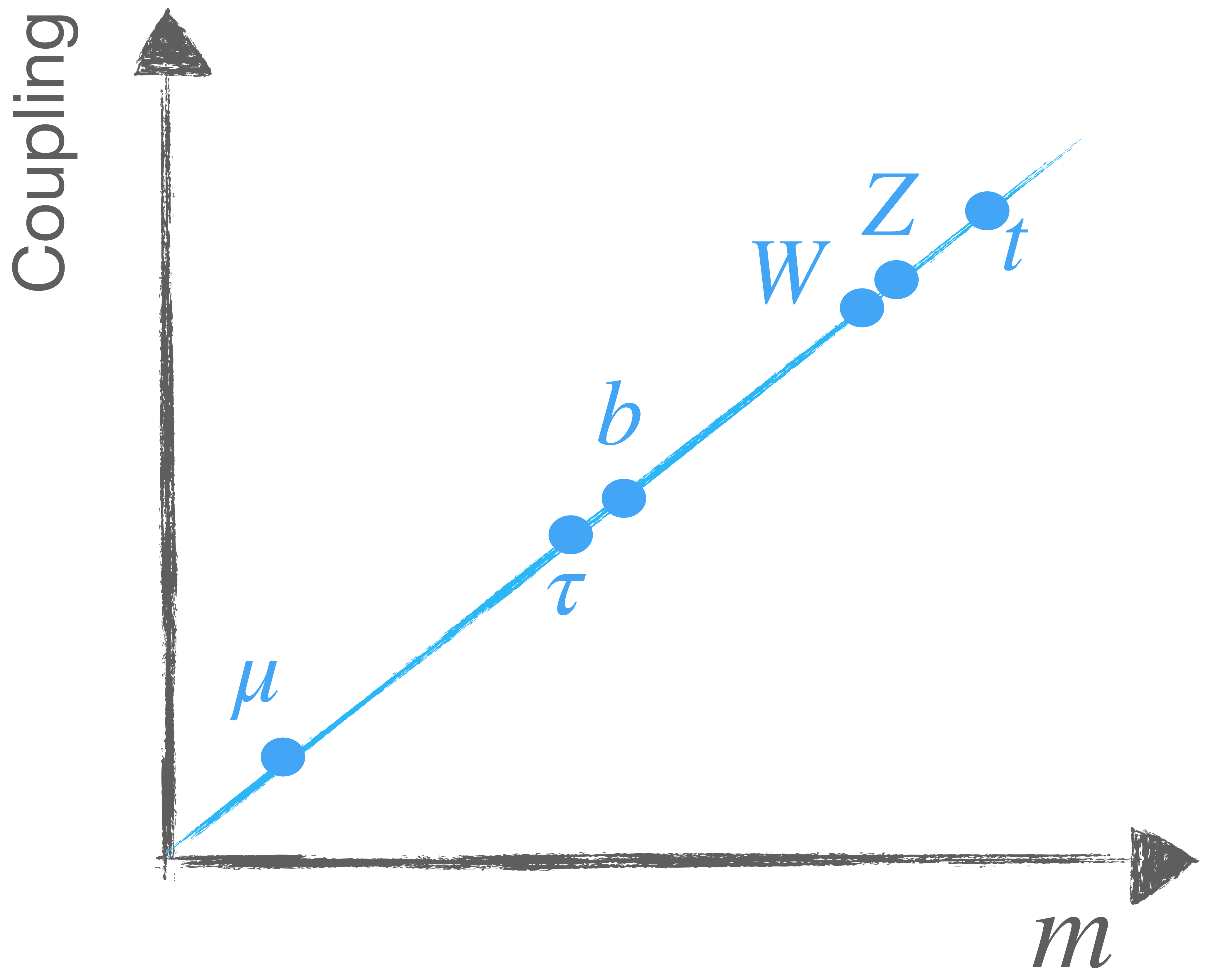
Optimal when signal scales linearly with the parameter of interest

NSBI

$$\frac{p_X(x \mid \mu)}{p_{\text{ref}}(x)} \to \frac{p(x \mid \mu)}{p_{\text{ref}}(x)} = \mu \frac{p_S(x \mid \mu)}{p_{\text{ref}}(x)} + \sqrt{\mu} \frac{p_I(x \mid \mu)}{p_{\text{ref}}(x)} + \frac{p_B(x \mid \mu)}{p_{\text{ref}}(x)} + \frac{p_{NI}(x \mid \mu)}{p_{\text{ref}}(x)}$$

Use neural networks to learn for each process P

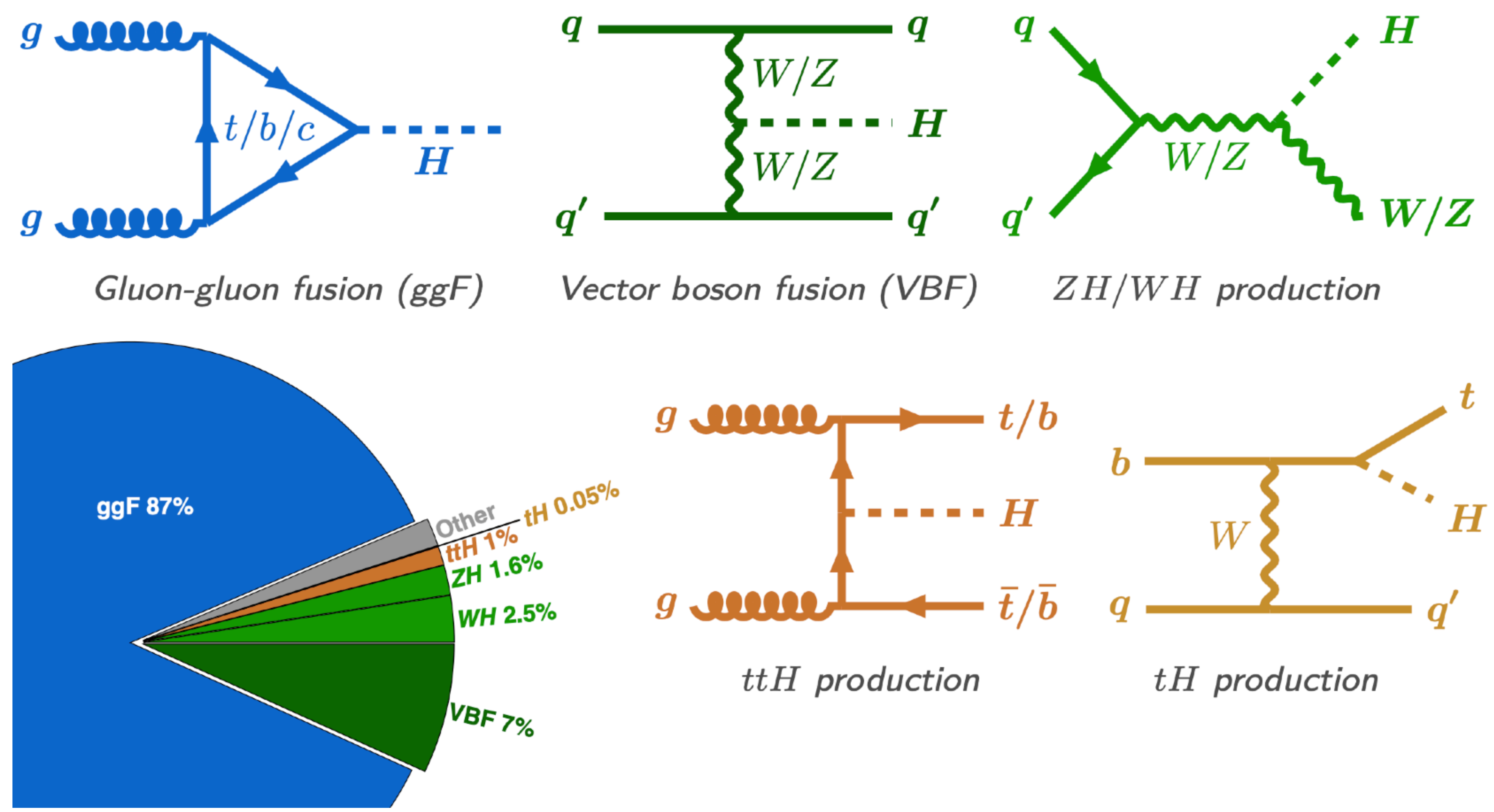
Per-event generalised probability density ratio is used to build the test statistic

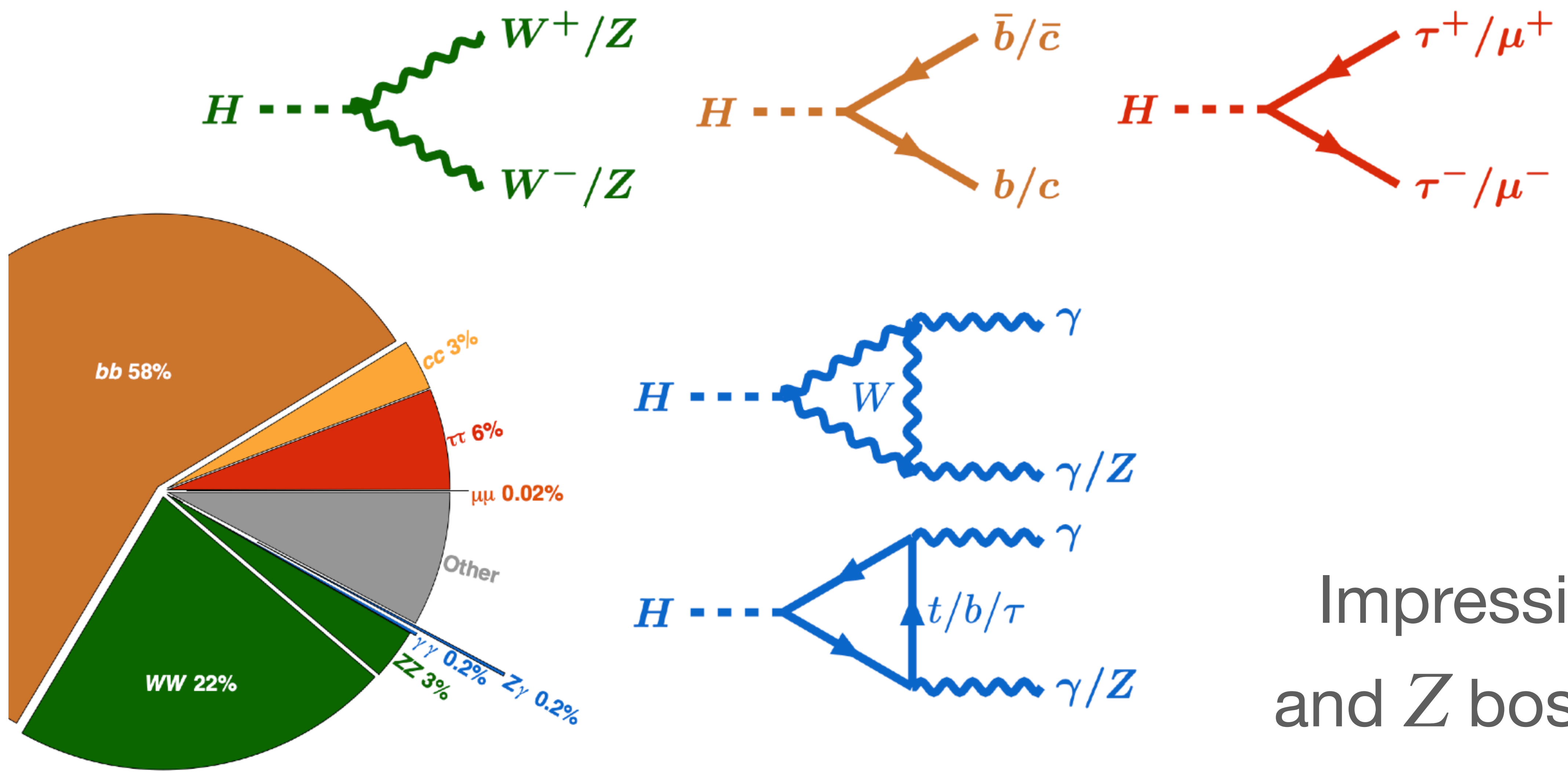


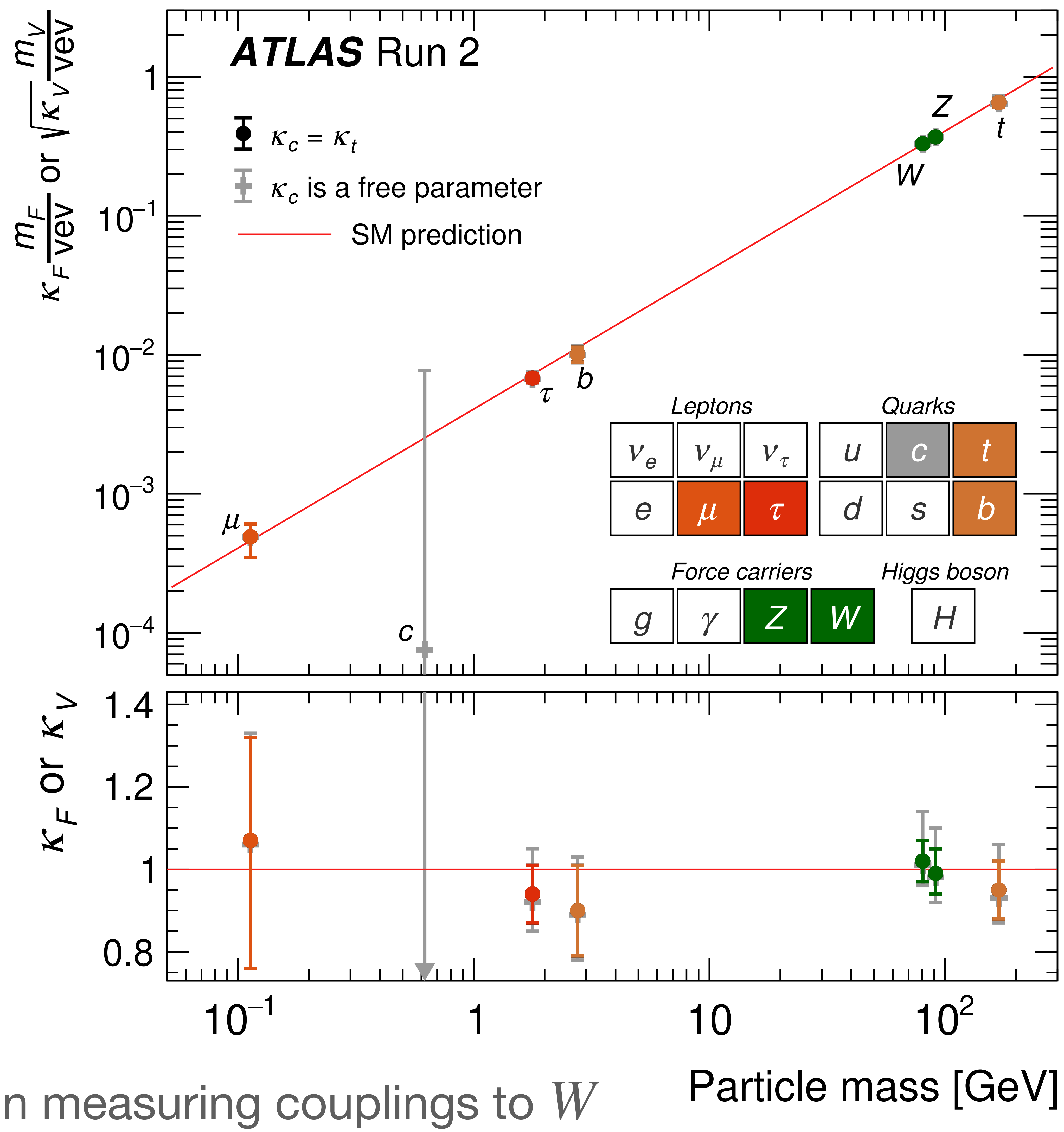
Coupling measurements

Higgs boson couplings

Nature 607 52 (2022)



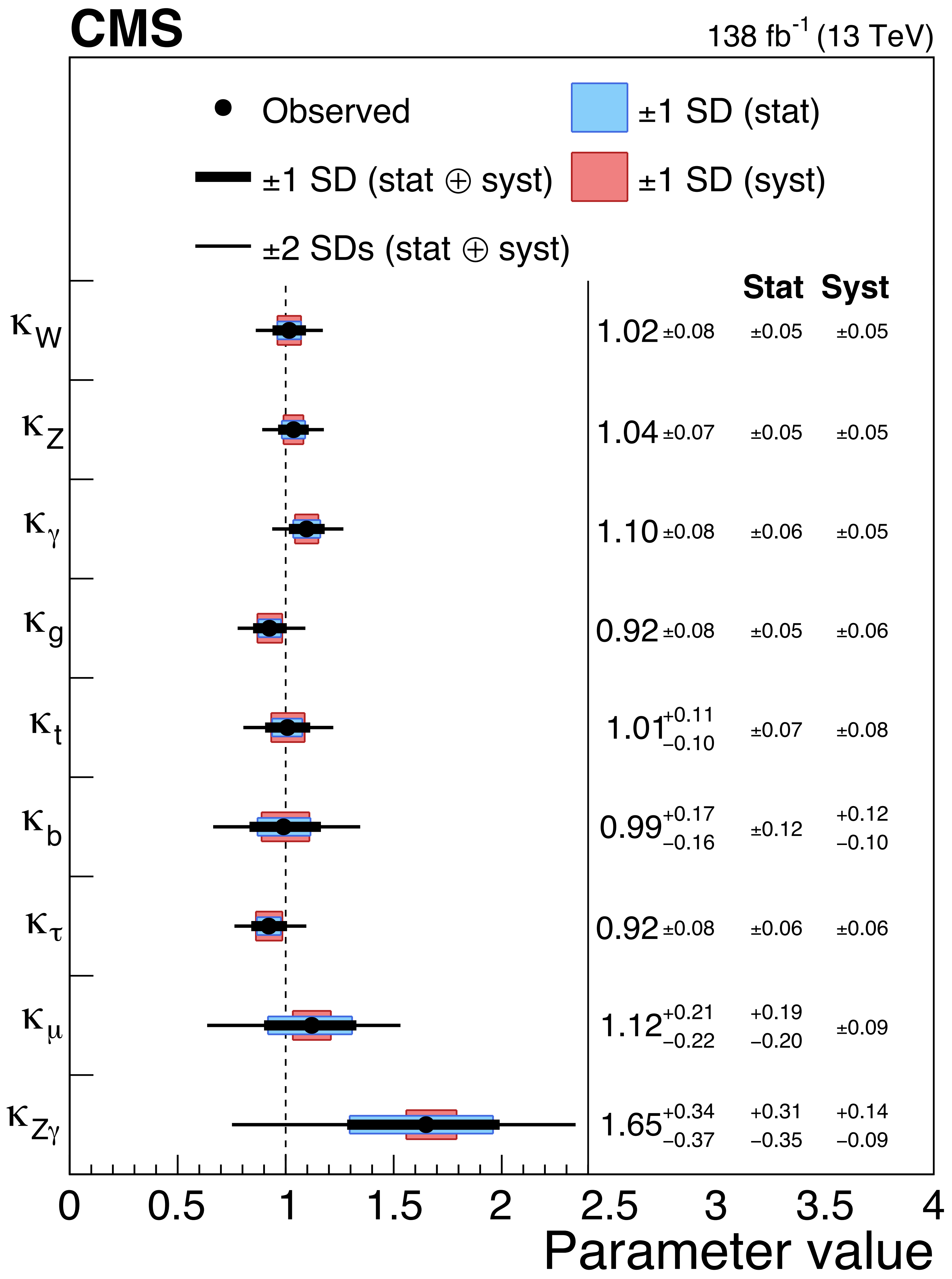




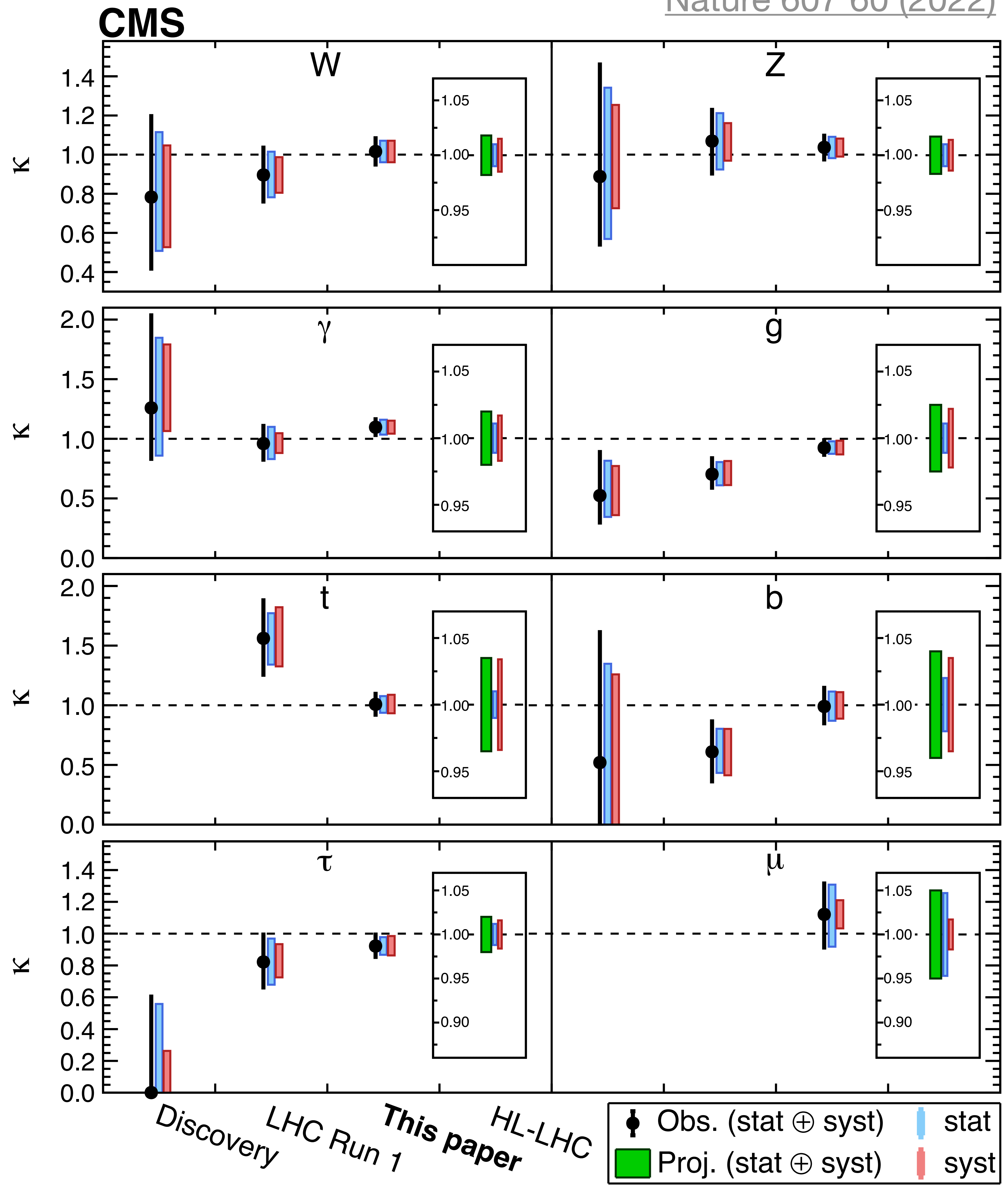
Impressive precision in measuring couplings to W and Z bosons and third generation charged fermions

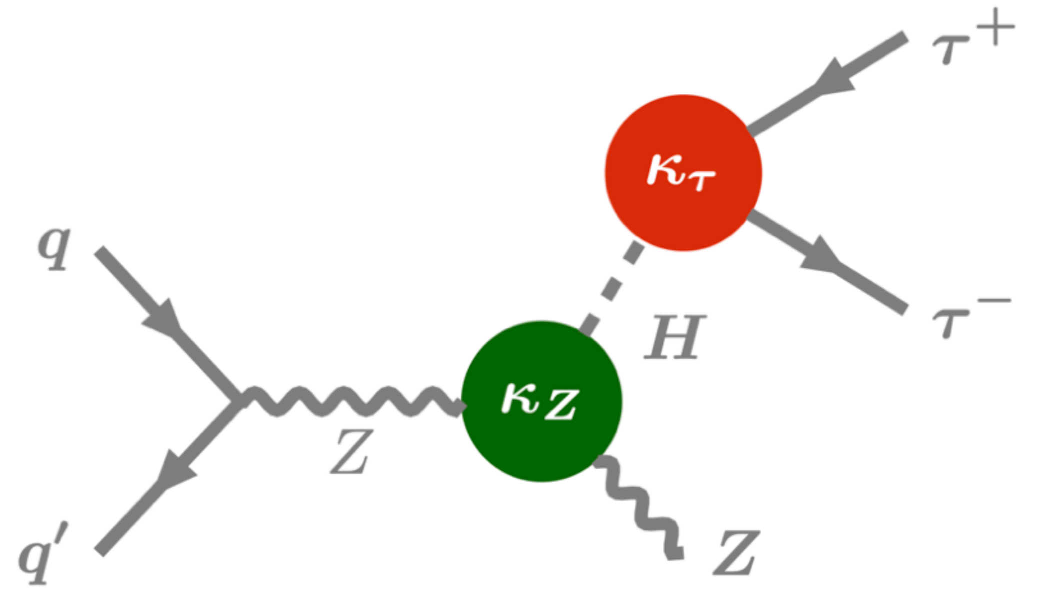
Interpretation: κ framework

More details in Oliver's and Massimiliano's talks (Tuesday)



Nature 607 60 (2022)



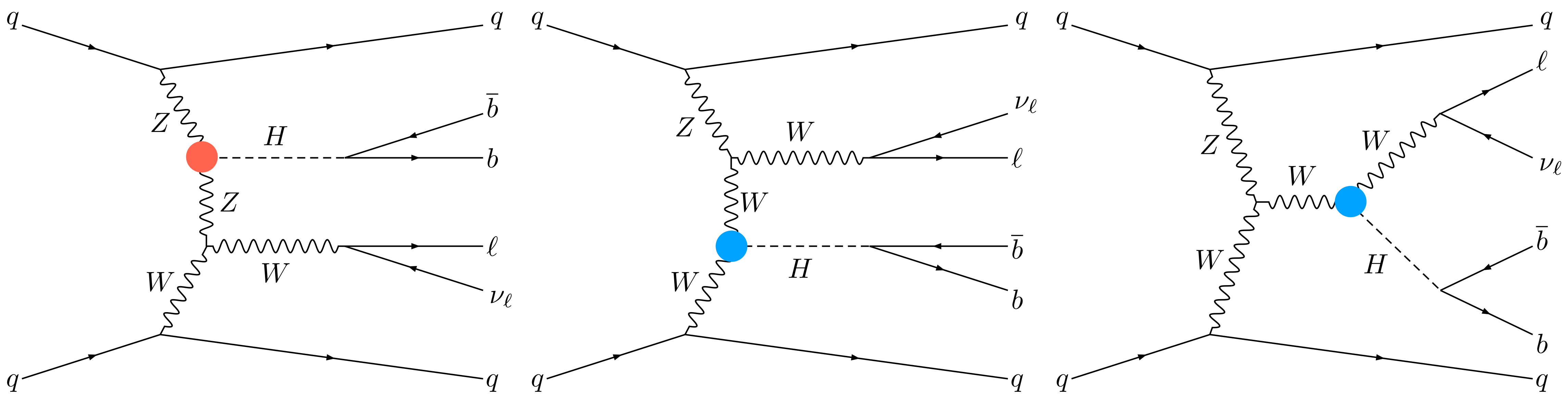


Production and decay parametrised in terms of coupling modifiers (κ)

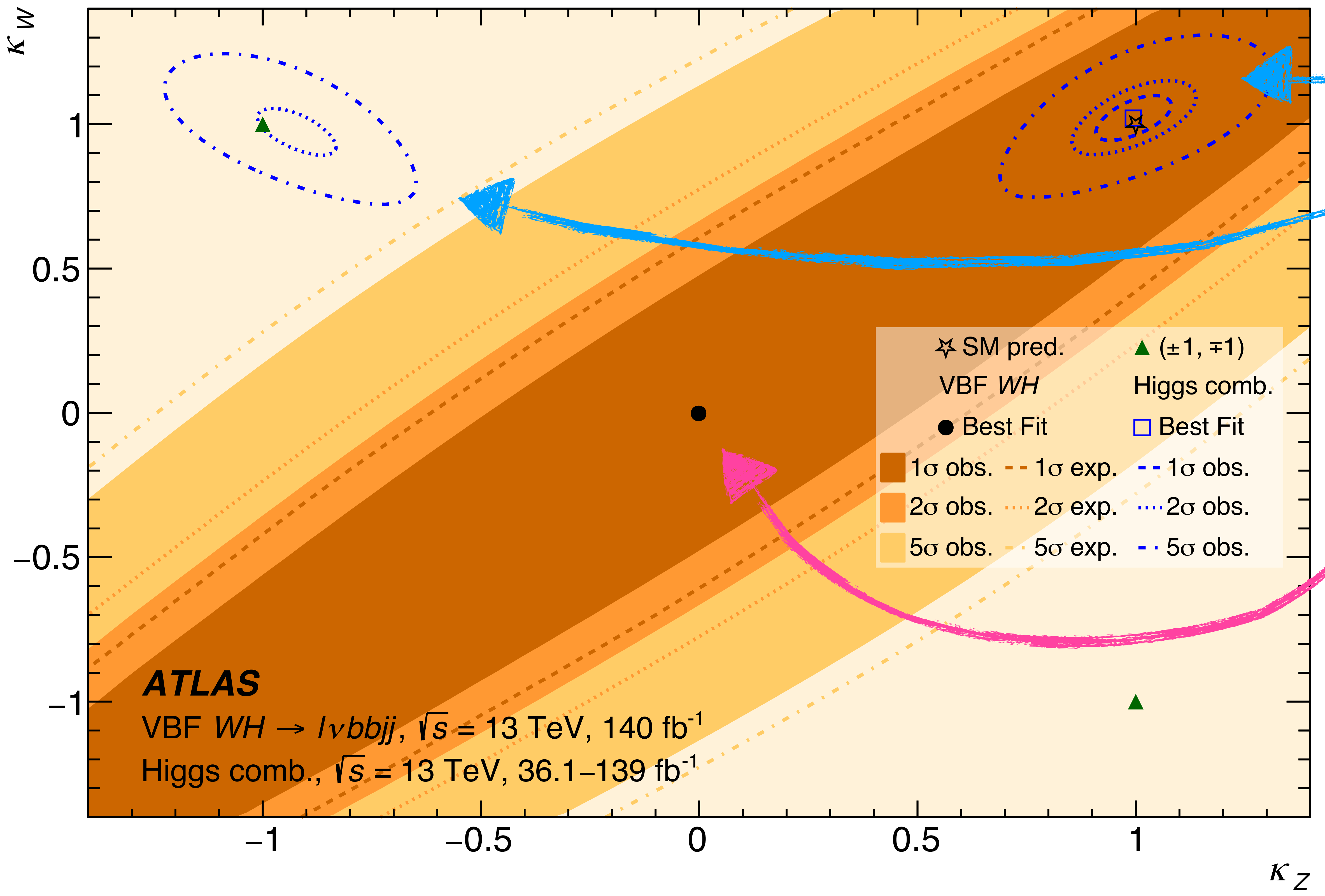
Similar sensitivity between the two experiments, consistent with the SM

At HL-LHC, expected to measure these κ's with a precision of 2-5%

Relative sign of W and Z couplings



PRL 133 (2024) 141801 CMS: Submitted to PLB



More details in Marion's talk (Wednesday)

In VBF WH production, the Higgs boson interacts either with W or Z boson (parameterised by κ_Z and κ_W)

Probing κ_W/κ_Z sign (previously unconstrained)

Higgs combination: constraints well $|\kappa_Z|$ and $|\kappa_W|$, but not the relative sign between the two couplings

VBF WH analysis: constraints less $|\kappa_Z|$ and $|\kappa_W|$, but excludes regions around (1, -1) and (-1, 1)

Opposite-sign hypothesis excluded with significance much greater than 5σ by both experiments

Interpretation: SM Effective Field Theory (EFT)

More details in Oliver's talk (Tuesday)

To estimate potential impact of high-mass-scale BSM contributions:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

Λ - Assumed energy scale (1 TeV)

c_i - Wilson coefficients

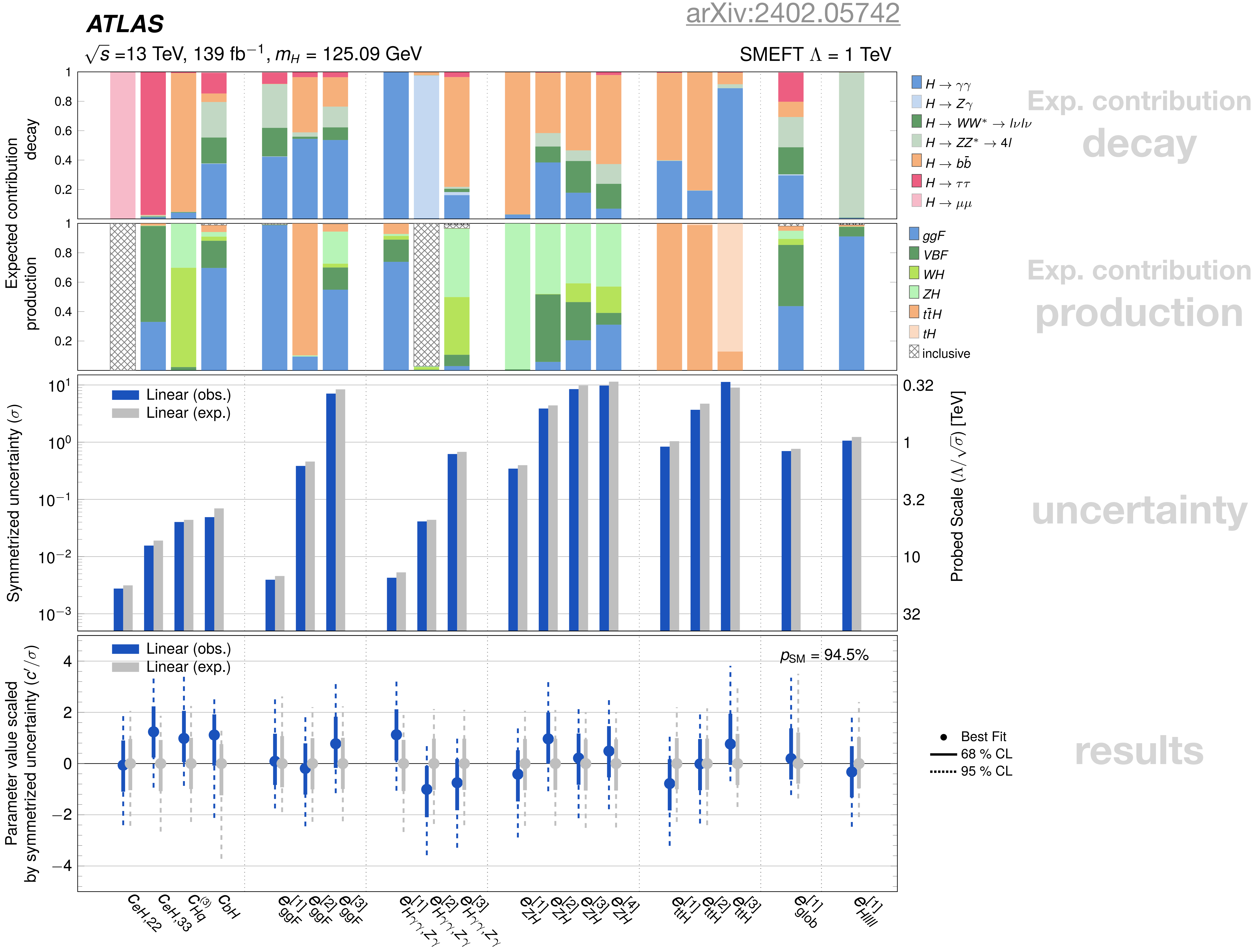
$\mathcal{O}_i$ - SMEFT Operators

(Warsaw basis used, CP-even $\mathcal{O}$ probed)

From combination: Cross-sections (STXS) and branching ratios parameterised in terms of the impact of SMEFT operators

The fit is performed in a rotated basis, defined by balancing fit stability and fit-parameter interpretability. Directions for which there is no constraining power are fixed to SM (zero)

arXiv:2402.05742



*18 linear combinations of Wilson coefficients constrained - **consistent with the SM!***

Interpretation: SM Effective Field Theory (EFT)

More details in Vasilije's talk (Wednesday)

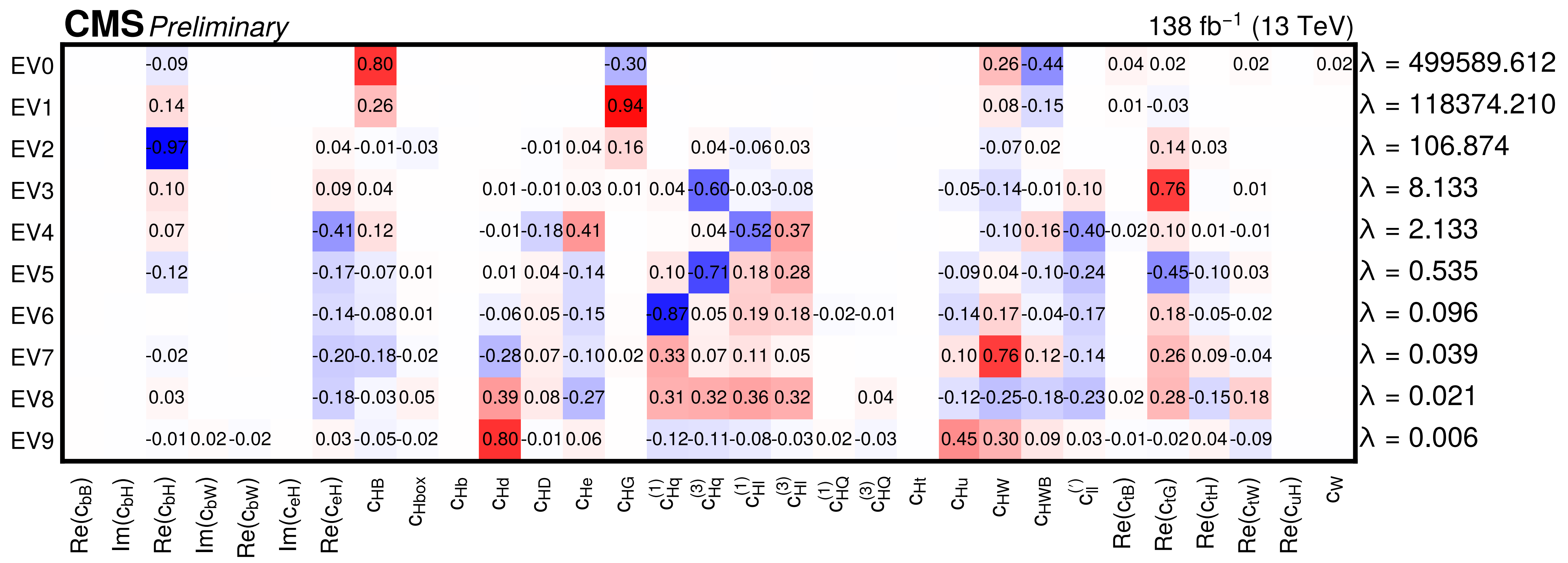
Potential impact of high-mass-scale BSM contributions:

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{i}^{N_{d=6}} \frac{c_i}{\Lambda^2} \mathscr{O}_i^{(6)} + \dots$$

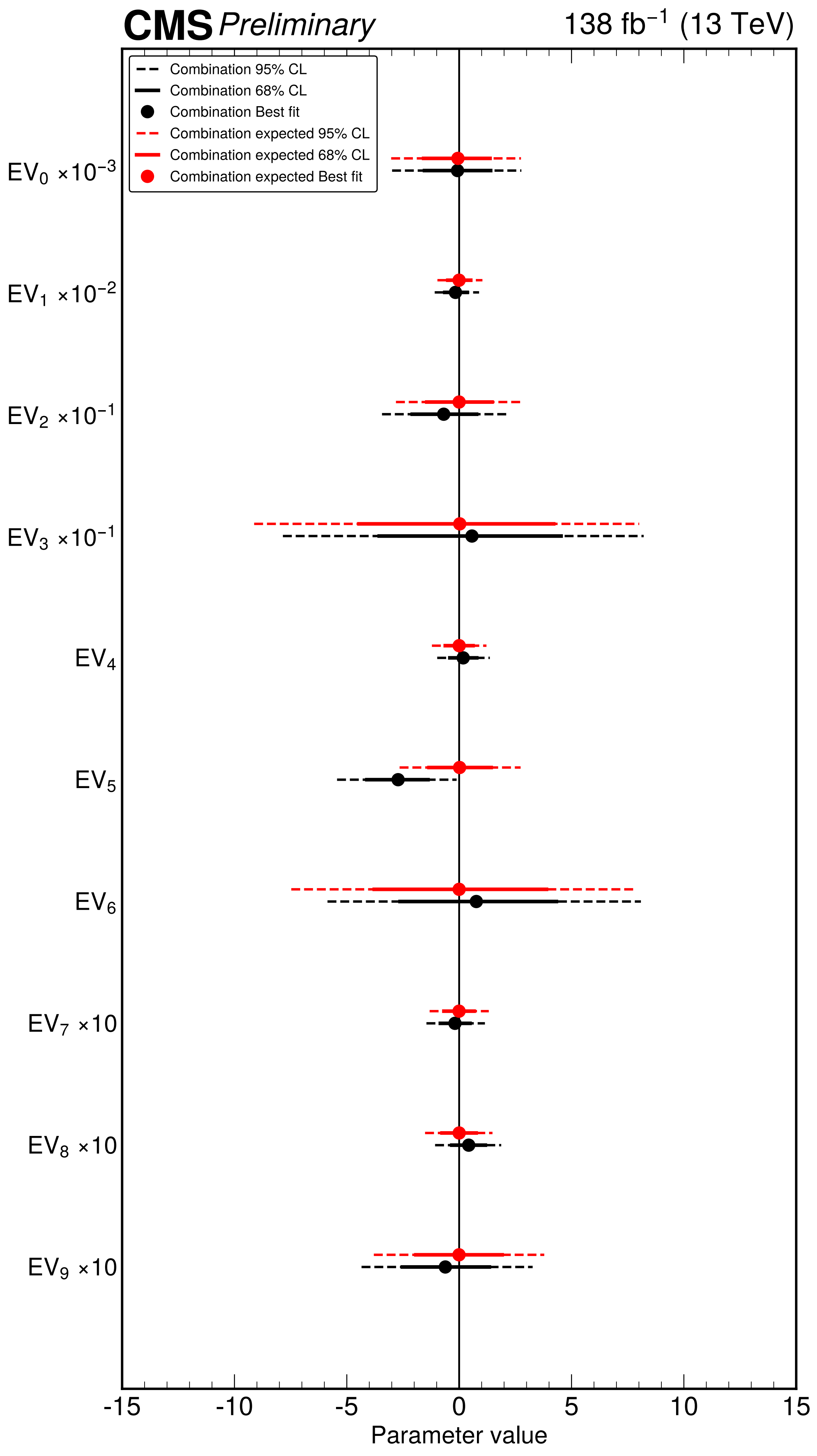
Input analyses

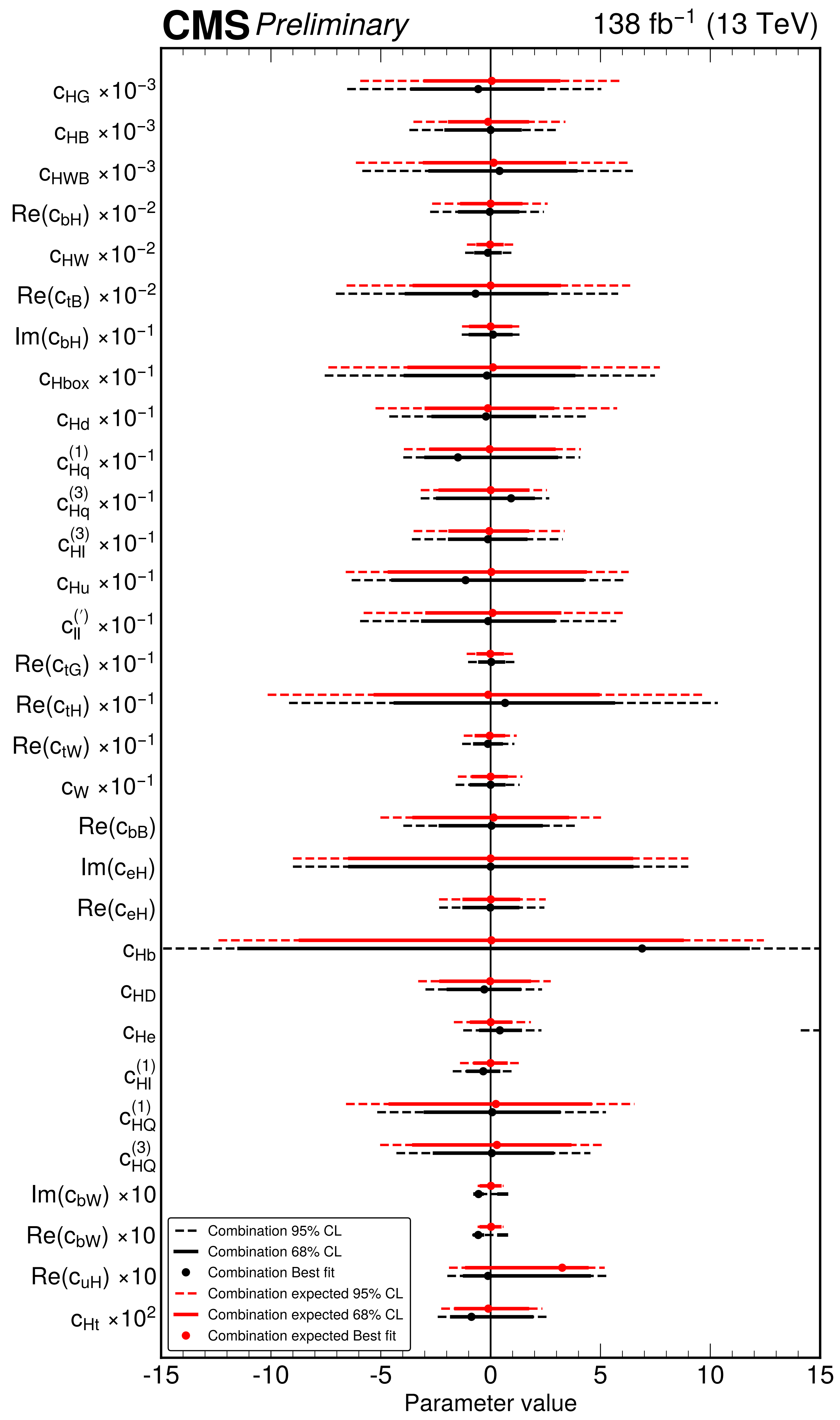
$$H \to \gamma\gamma, H \to ZZ^* \to 4\ell, H \to W^+W^- \to e^\pm\mu^\mp\nu\bar{\nu}, H \to \tau^+\tau^-$$

*Rotation matrix: Warsaw basis → **Fit basis***



CMS-PAS-HIG-23-013





SMEFT interpretation of $H \to \gamma\gamma$, electroweak vector boson, top quark and multi-jet measurements also performed: CMS-PAS-SMP-24-003

*10 linear combinations of Wilson coefficients constrained, **consistent with the SM!***

CP violation

CP violation: $t\bar{t}H$ interaction

$t\bar{t}H$ and tH production: Adding CP-odd admixture to the top-Yukawa coupling

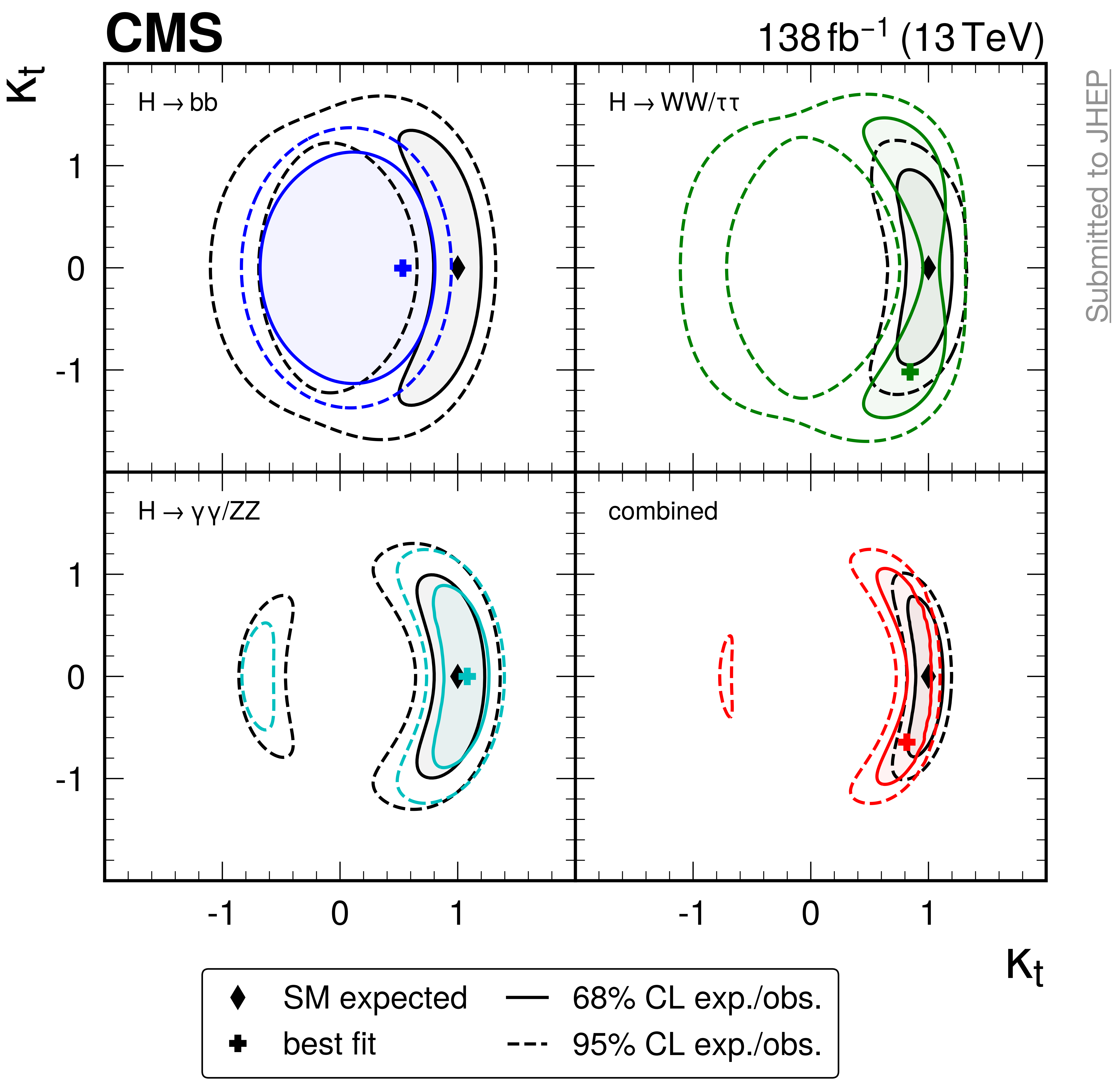
$$\mathscr{L}_{t\bar{t}H} = -\, y_t H \bar{\psi}_t \, (\kappa_t + i\gamma_5 \tilde{\kappa}_t) \; \psi_t$$

SM: $\kappa_t = 1,\ \tilde{\kappa}_t = 0$

$$\cos\alpha = \frac{\kappa_t}{\sqrt{\kappa_t^2 + \tilde{\kappa}_t^2}} > 0.39 \text{ at 95\% CL}$$

Results consistent with the SM (no evidence of CP-odd admixture to the top-Yukawa coupling)

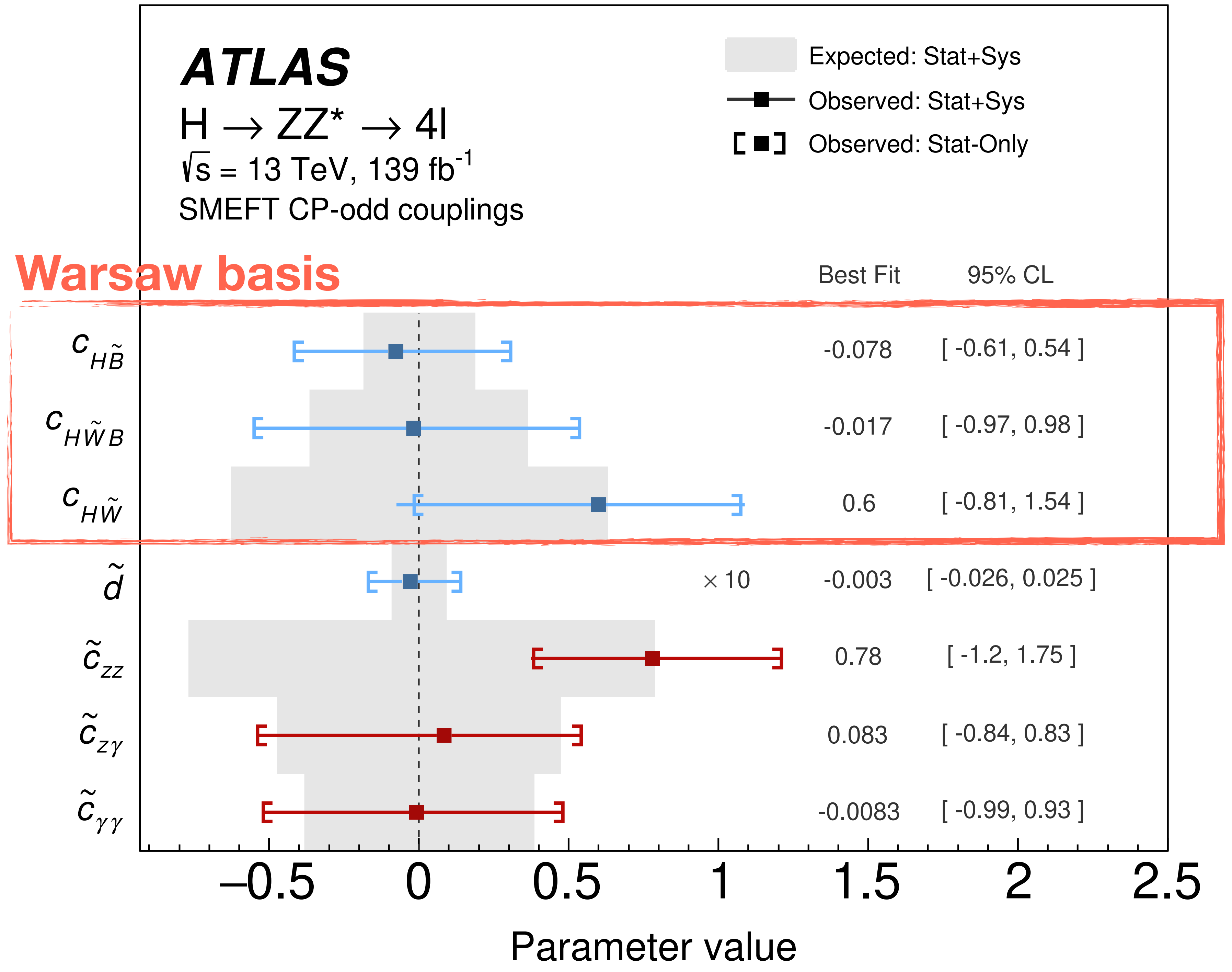
Similar results by ATLAS



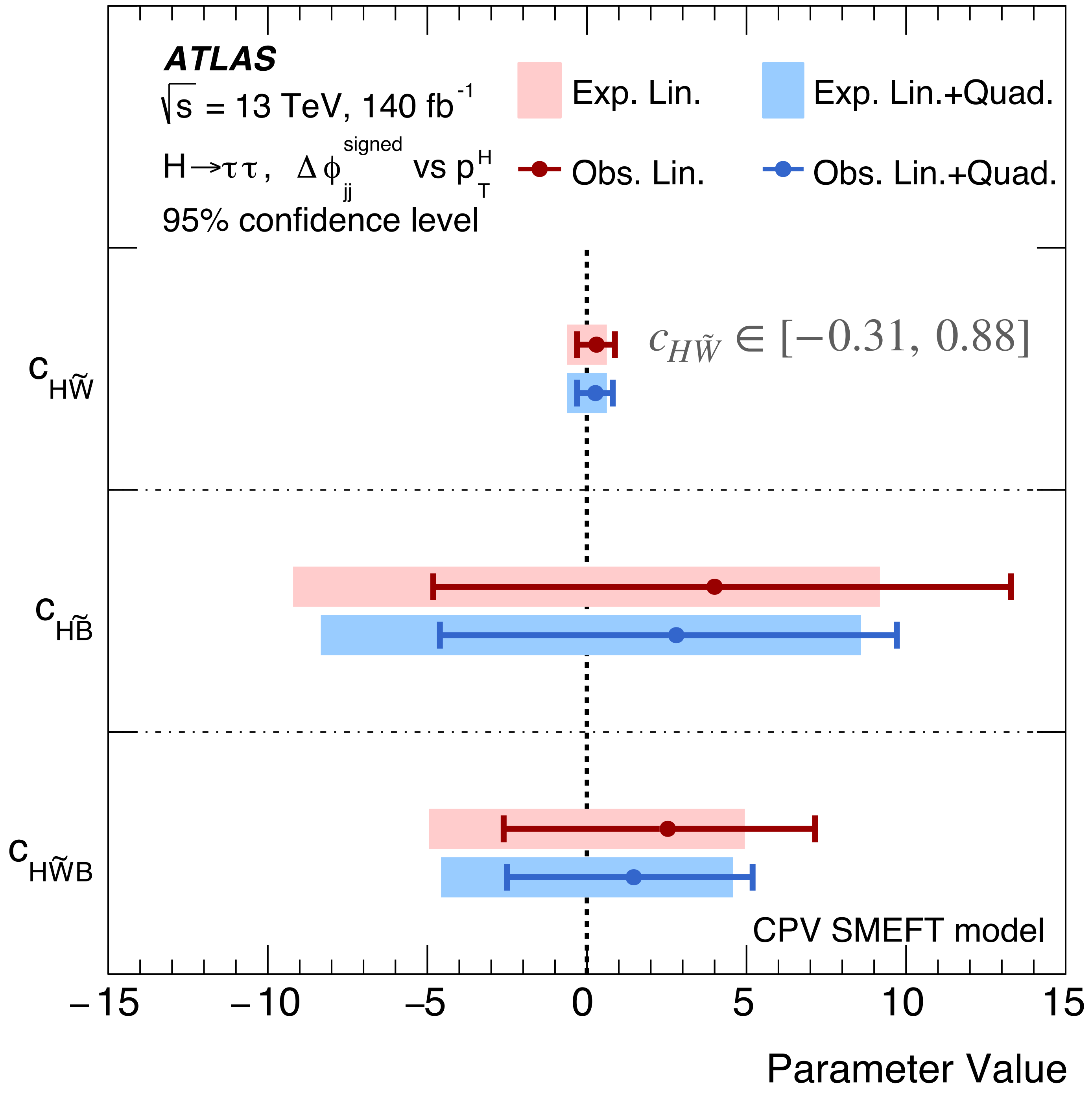
CP violation: VVH interaction

SMEFT to probe the CP nature of the VVH coupling, VBF production: 3 CP-odd operators

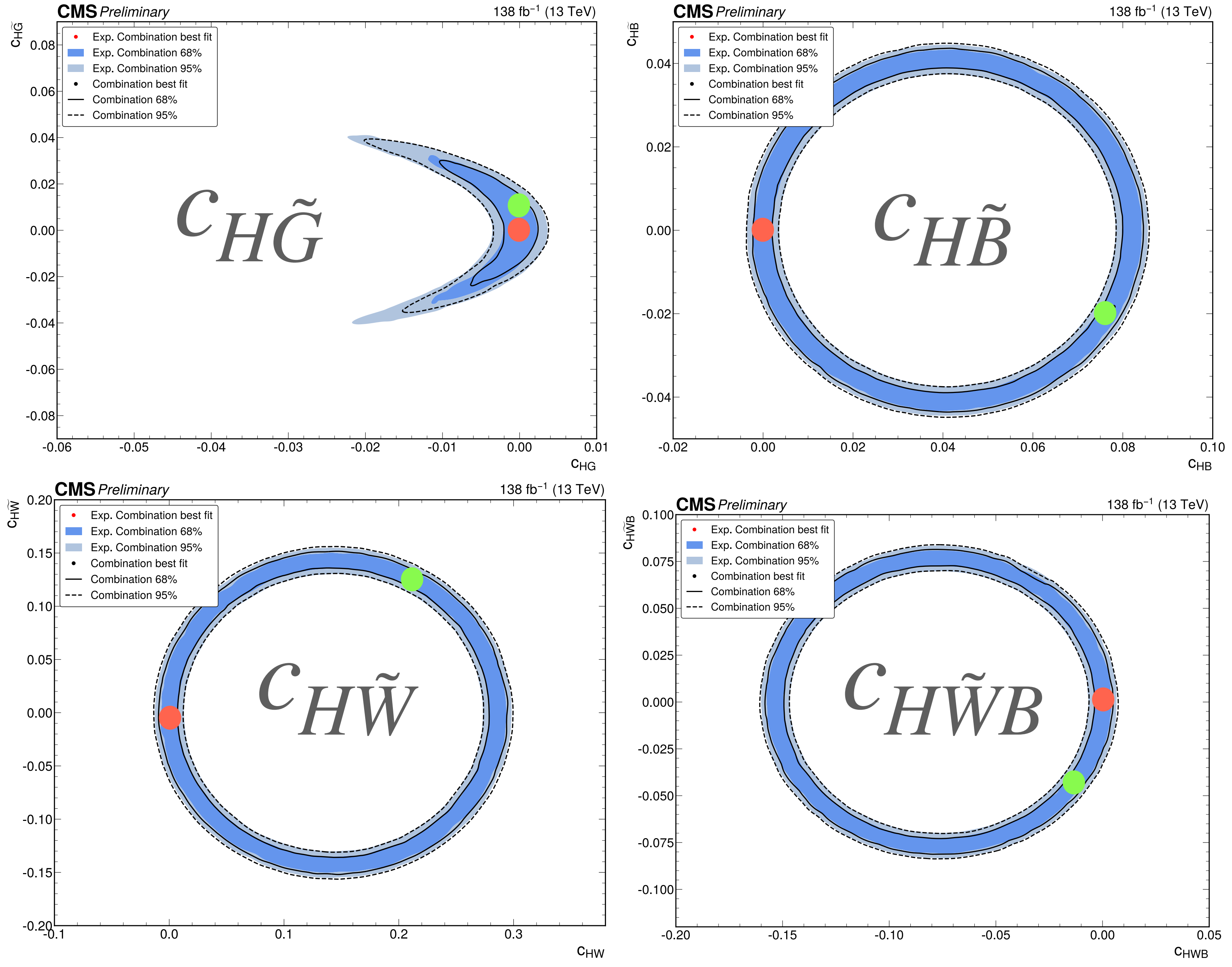
JHEP 05 (2024) 105, VBF $H \to ZZ^* \to 4\ell$



arXiv:2407.16320, VBF $H \to \tau\tau$



CMS-PAS-HIG-23-013



$H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^*$, $H \to \tau\tau$

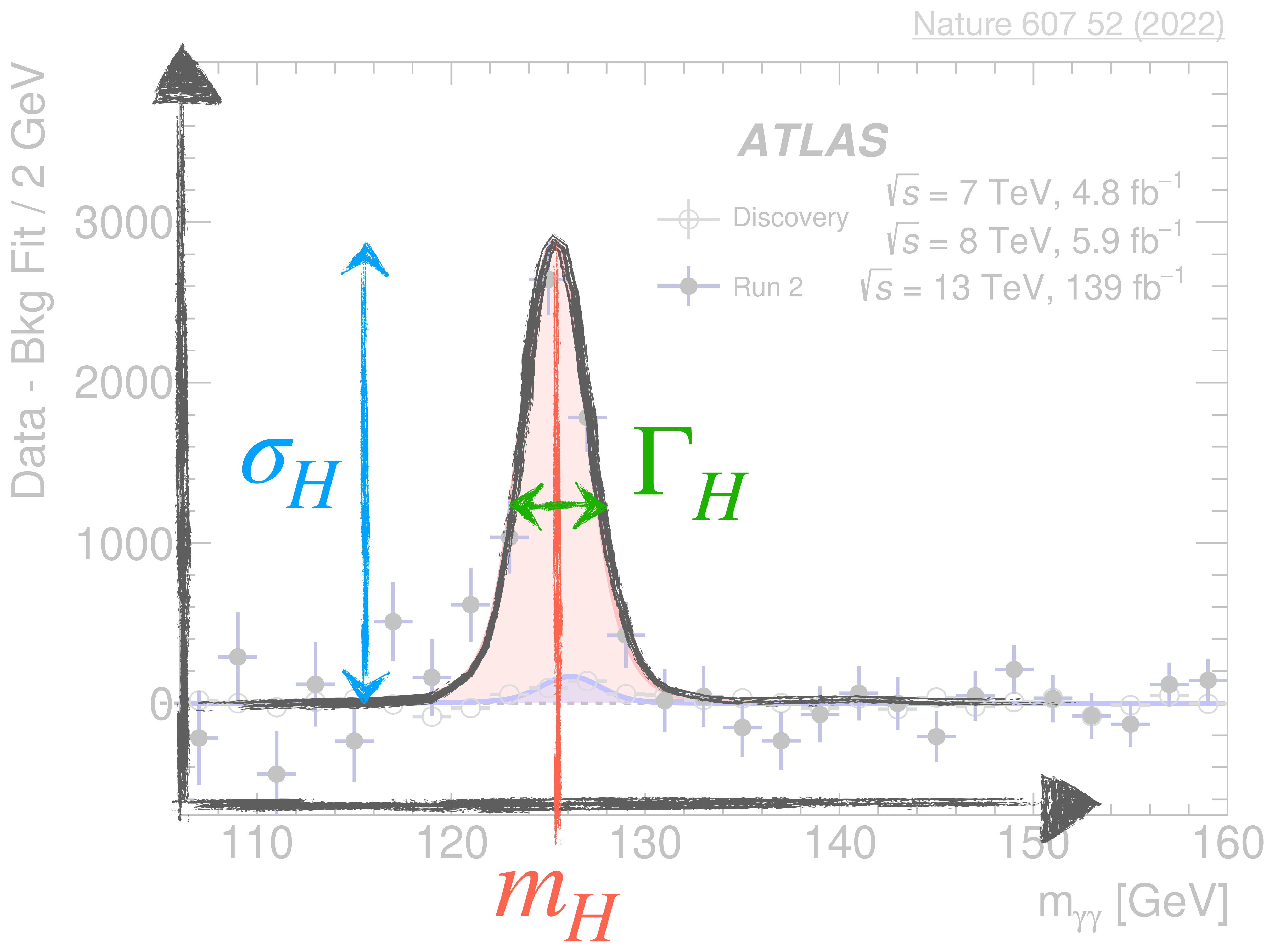
PRL 131 (2023) 061802, VBF $H \to \gamma\gamma$ (ATLAS)

$c_{H\tilde{W}} \in [-0.53,\ 1.02]$ at 95% CL

Other two Wilson coefficients fixed to zero

No significant CP-odd component observed in any of the measurements

Conclusion



Great precision in measuring **Higgs boson mass**
Combined ATLAS and CMS result expected?

Higgs boson width determination relies on off-shell to on-shell signal strength ratio. Observation of the off-shell production around the corner?

Excellent precision in measuring **couplings** to *W* and *Z* bosons, as well as third generation fermions.

No evidence of **CP violation** in Higgs boson interactions.

All results consistent with the Standard Model!

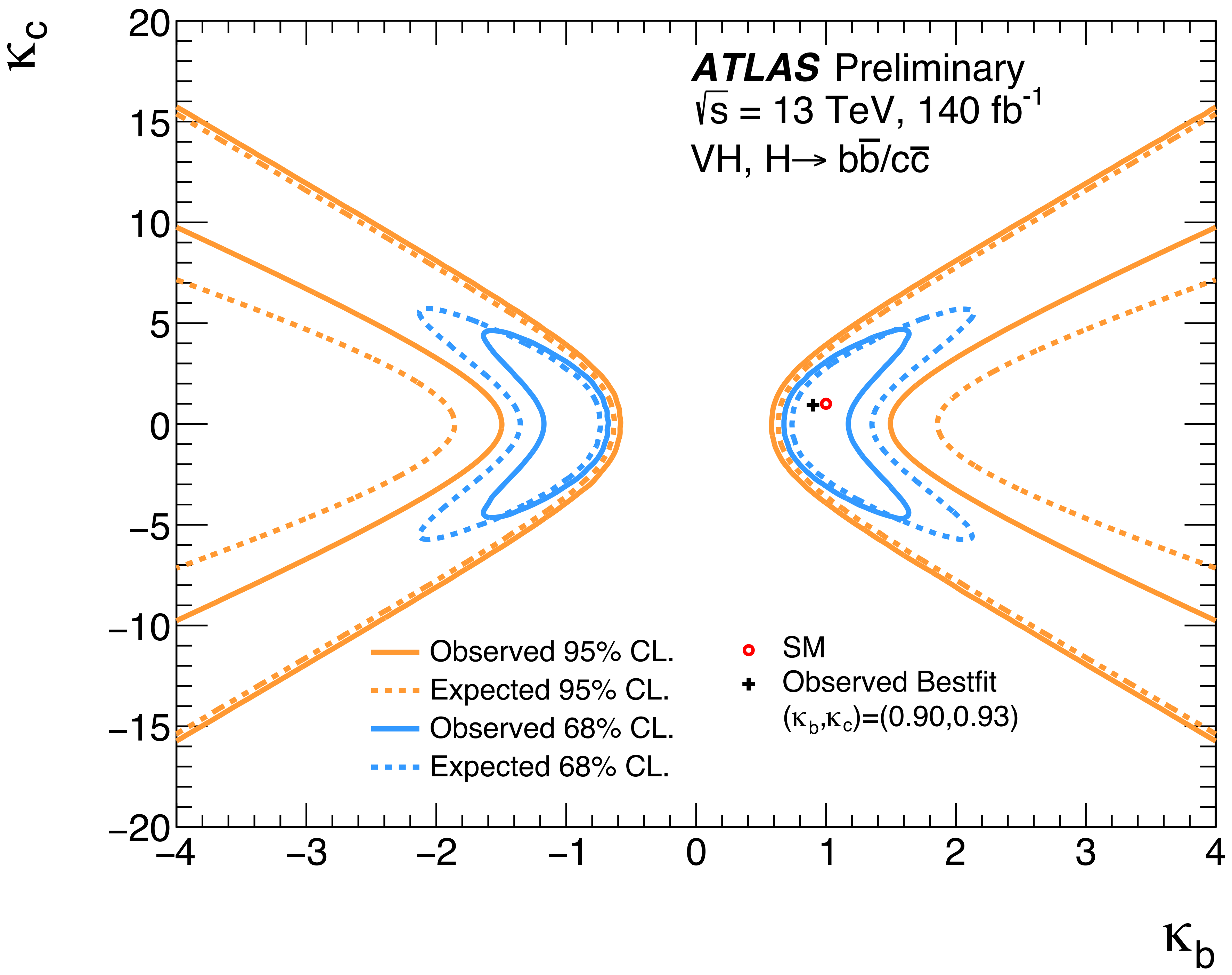
Thanks for your attention!

Charm-Yukawa coupling

Not quite on the topic of precision,
but impressive results from ATLAS and CMS:

More details in Marion's talk (Wednesday)

ATLAS-CONF-2024-010



ATLAS

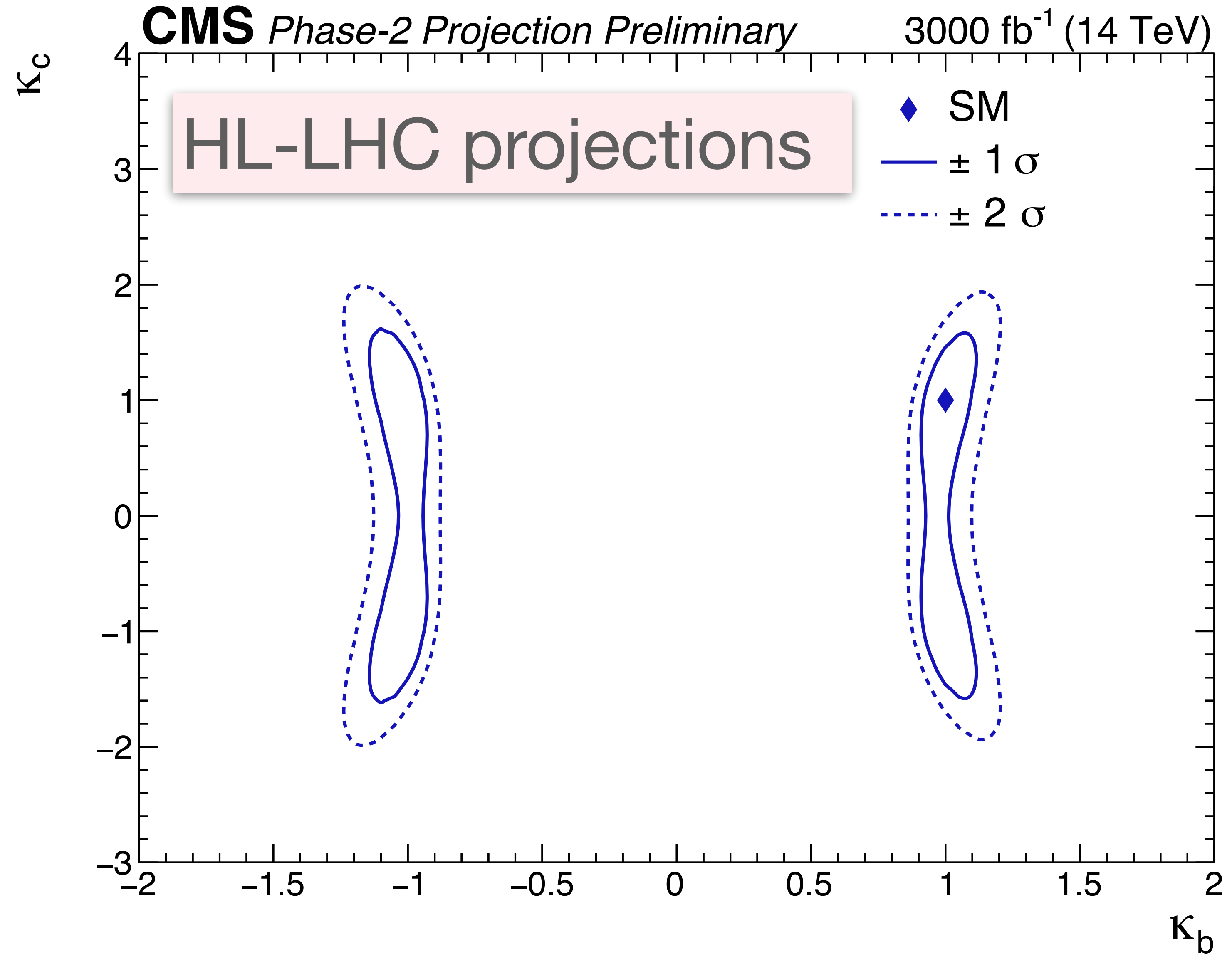
$|\kappa_c| < 4.2$ (exp. 4.1) at 95% CL

$|\kappa_c/\kappa_b| < 3.6$ (exp. 3.5)

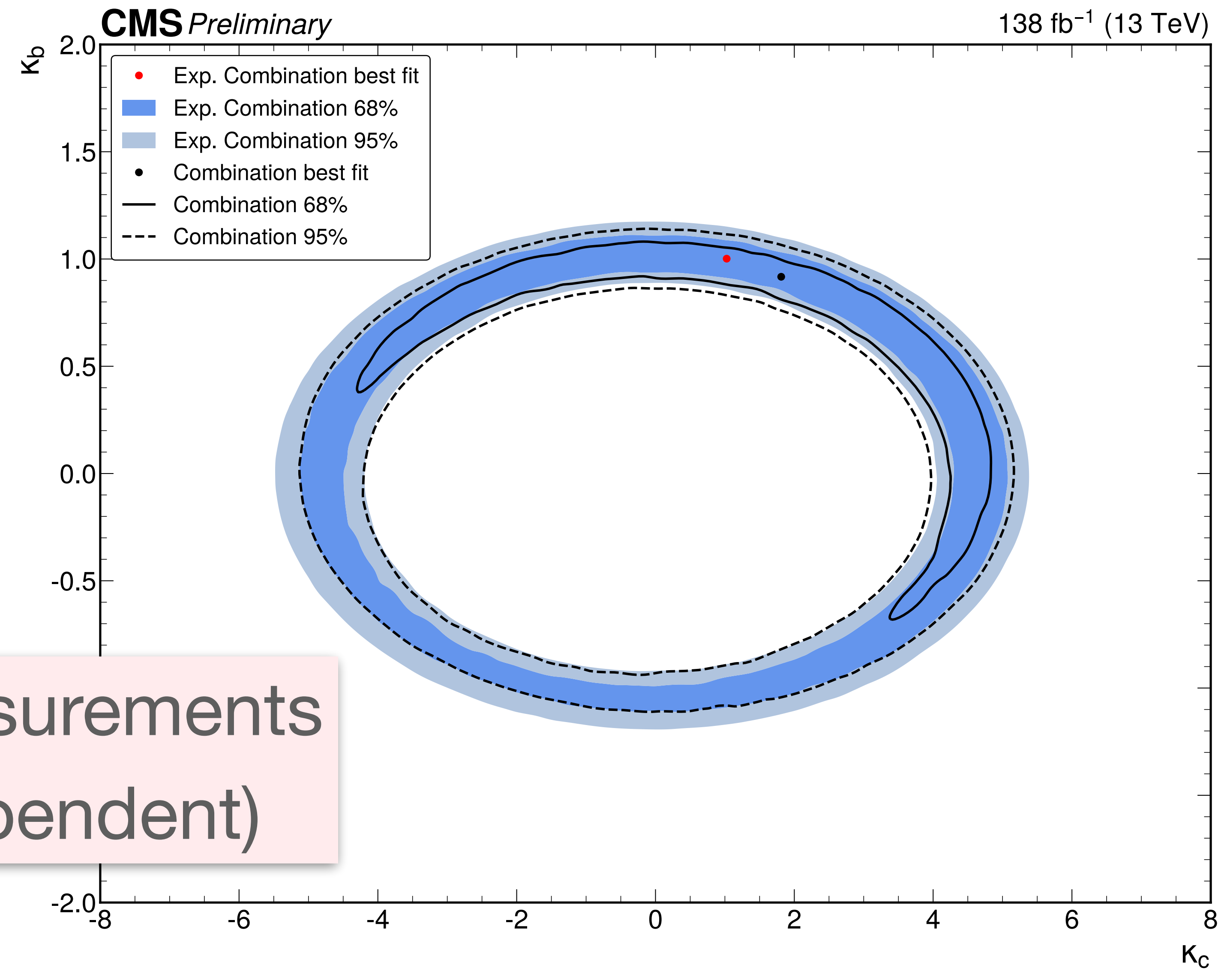
Uncertainty in the $H \to c\bar{c}$ improved by a factor of 3 with respect to the previous analysis based on the same dataset

CMS

$1.1 < |\kappa_c| < 5.5$ (exp. $|\kappa_c| < 3.4$) at 95% CL



PRL 131 (2023) 061801



Indirect measurements (model-dependent)

CMS-PAS-HIG-23-013