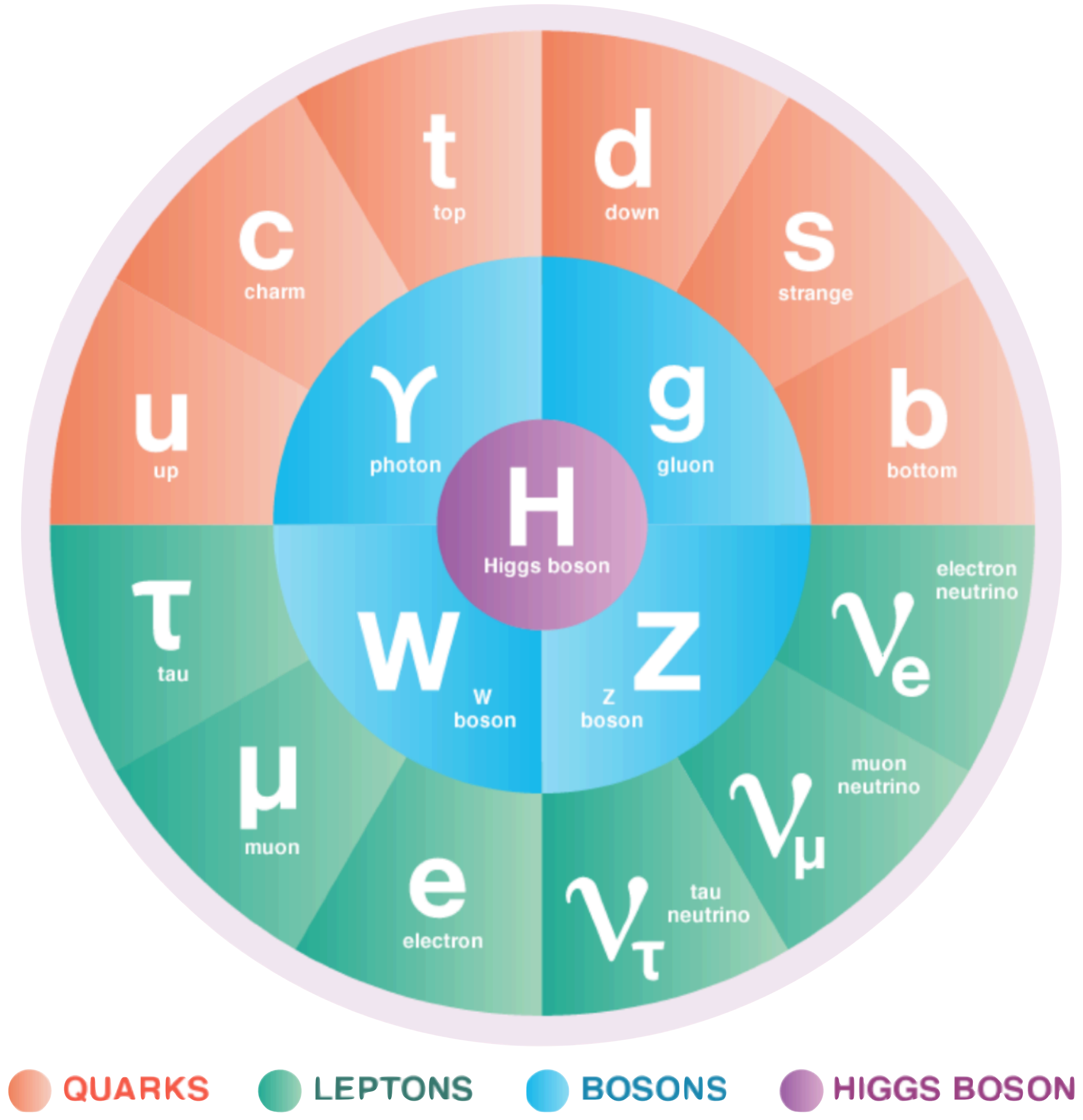
Higgs boson property measurements at the ATLAS experiment

George Iakovidis

on behalf of the ATLAS Collaboration



Symmetry Magazine

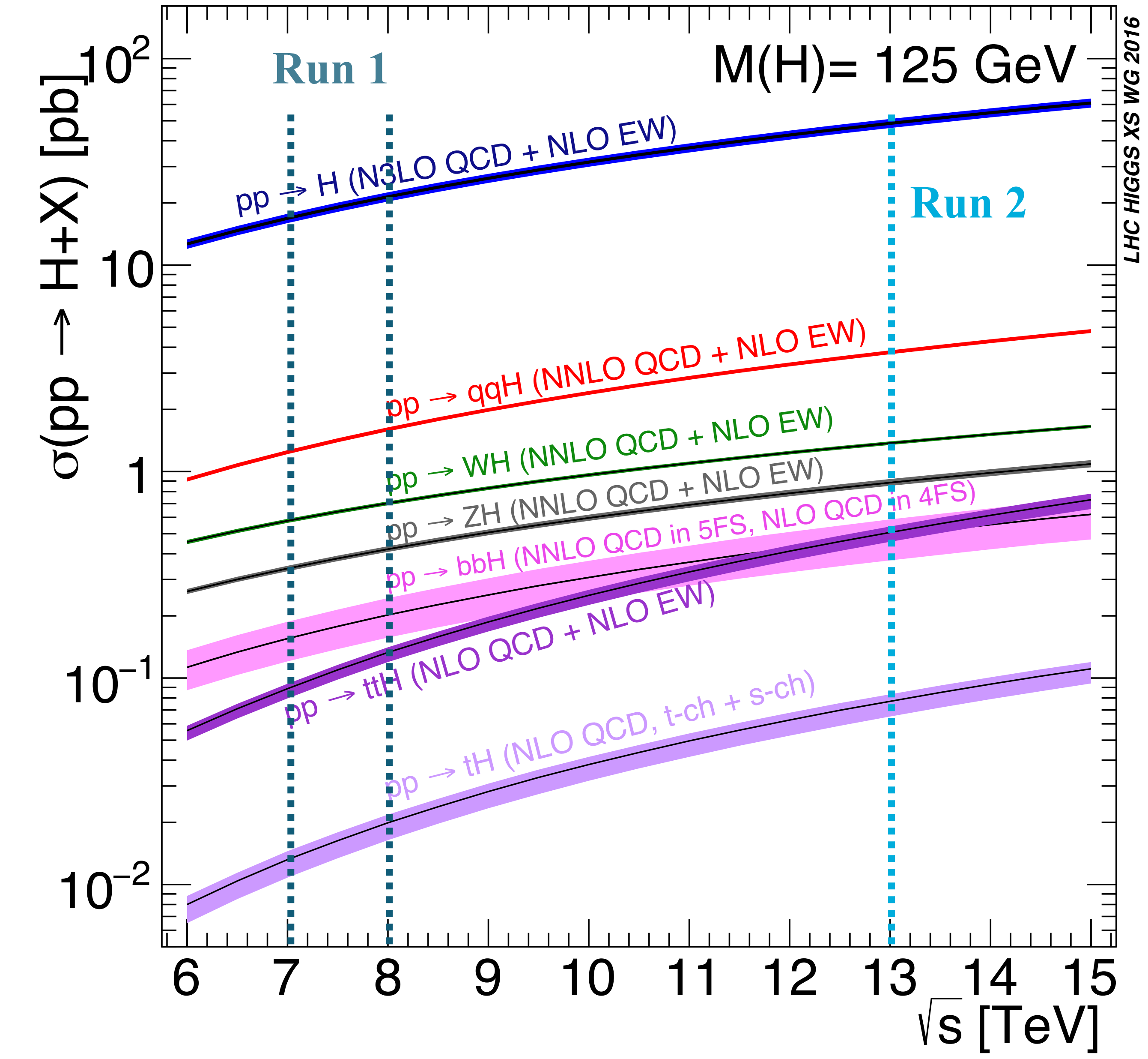
Discovery Physics at the LHC - KRUGER 2022

Dec. 2022

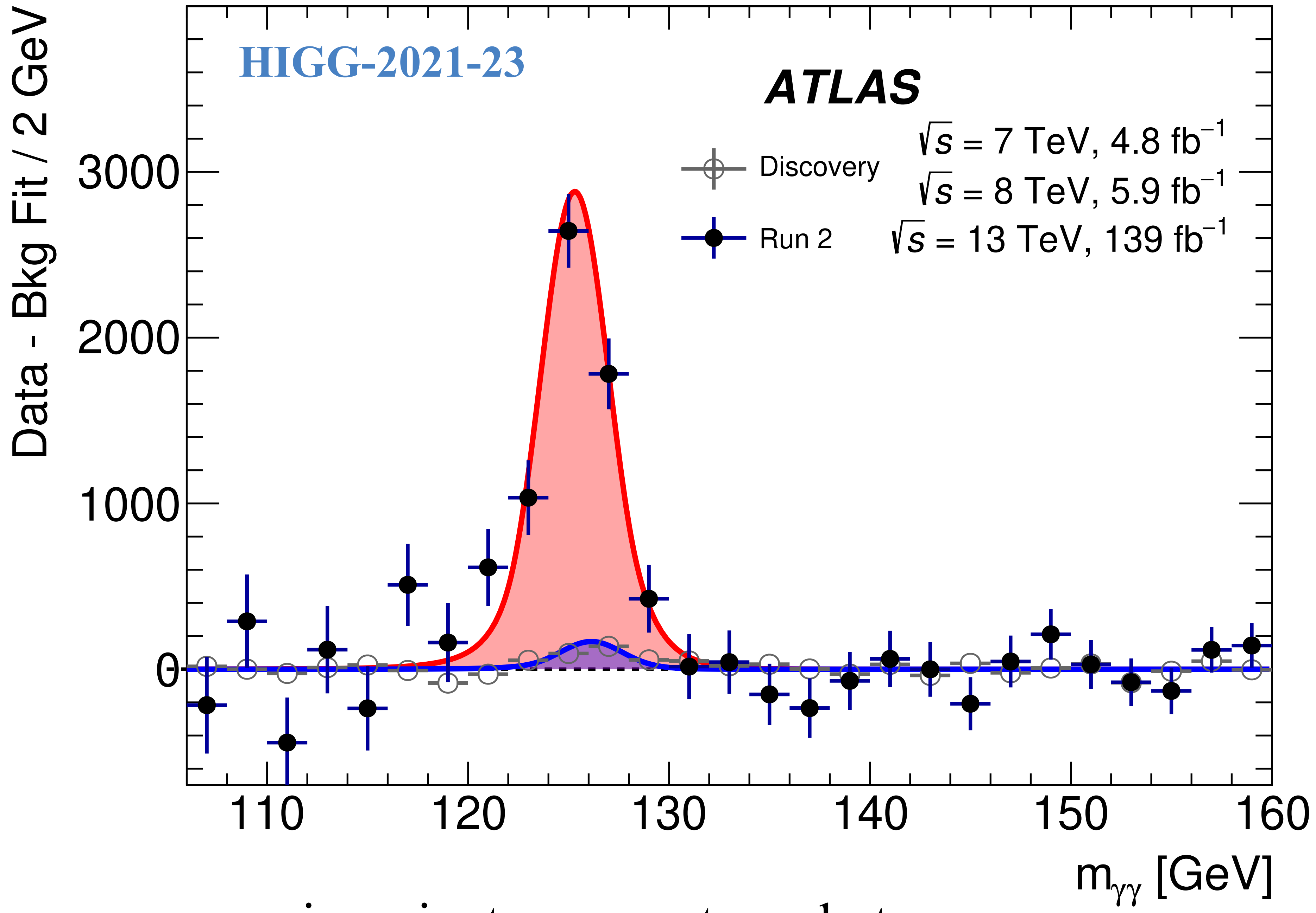
Introduction

- Higgs is essential in the Standard Model.
  - ➡ Discovery during Run 1 by ATLAS and CMS (PLB, Sept. 2012)
  - ➡ 2022 marks the 10th anniversary of the discovery (Nature 607, 52–59 (2022))
- LHC "Run-2" provided significantly more statistics to the ATLAS detector allowing for precise measurements of:
  - ➡ Properties (CP, mass)
  - ➡ Cross-sections,
  - ➡ Couplings to individual particles and self coupling,
- Higgs *serves as an important portal* to either probe new physics beyond the Standard Model or constrain it !
  - This talk: Measurements of Higgs boson properties using the full Run-2 dataset of 139 fb^{-1}

Handbook of LHC Higgs cross sections arXiv:1610.07922



LHC SM Higgs boson production cross sections

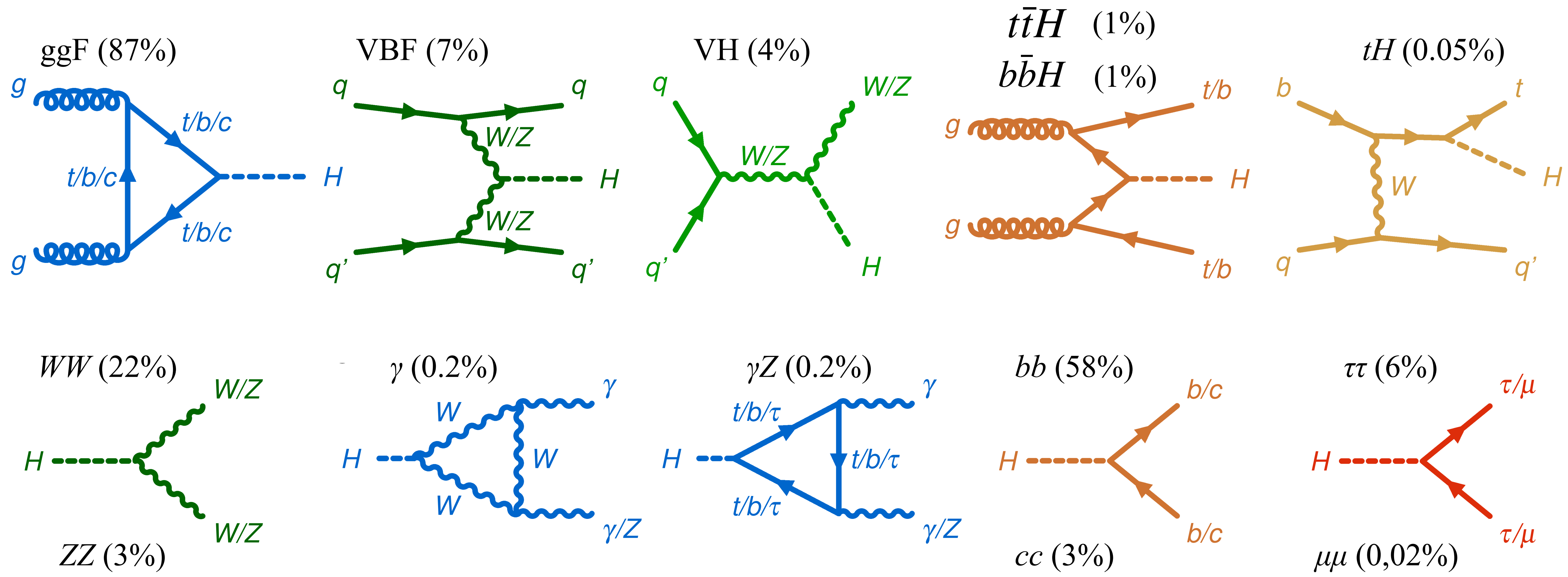


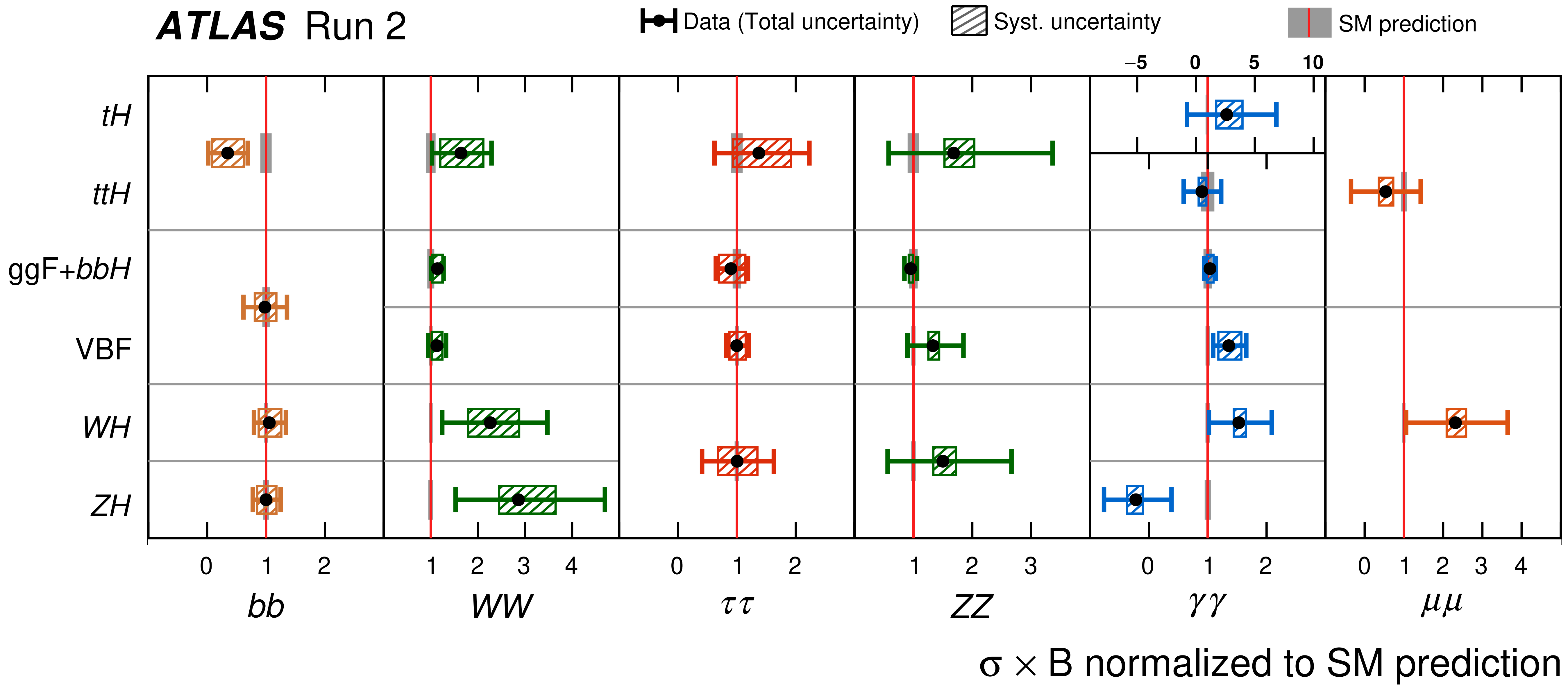
invariant $m_{\gamma\gamma}$ spectrum between discovery and full Run-2 datasets

Higgs Production and Decays - complete picture

- Production **processes** at the LHC
  - **All major observed !**
- Rare/difficult production modes are **important** for beyond the SM (BSM) scenarios
- Higgs boson **decays** ~90% via eight decay modes

Nature 607, 52–59 (2022)





- **Ratio** of observed rate to predicted SM event rate for different combinations of Higgs boson production and decay processes
- SM **compatibility** (*p*-value): 72%
- Already **less than 10%** precision in a few individual ggF channels
- Still several channels **dominated** by the statistical **uncertainty**

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Global *H* Signal strength

- The Higgs boson production rates are probed by the likelihood fit to observed signal yields
- Global signal strength measured for all production processes and decays together
- Expressed in terms of a single **signal-strength modifier** μ:

$$\mu = \frac{\sigma \times B}{(\sigma \times B)_{SM}} = 1.05 \pm 0.06$$

- Systematic uncertainty **reduced** by factor of 2 since the discovery
- Total measurement **uncertainty decreased** by ~30%
- SM **compatibility** (*p*-value): 39%

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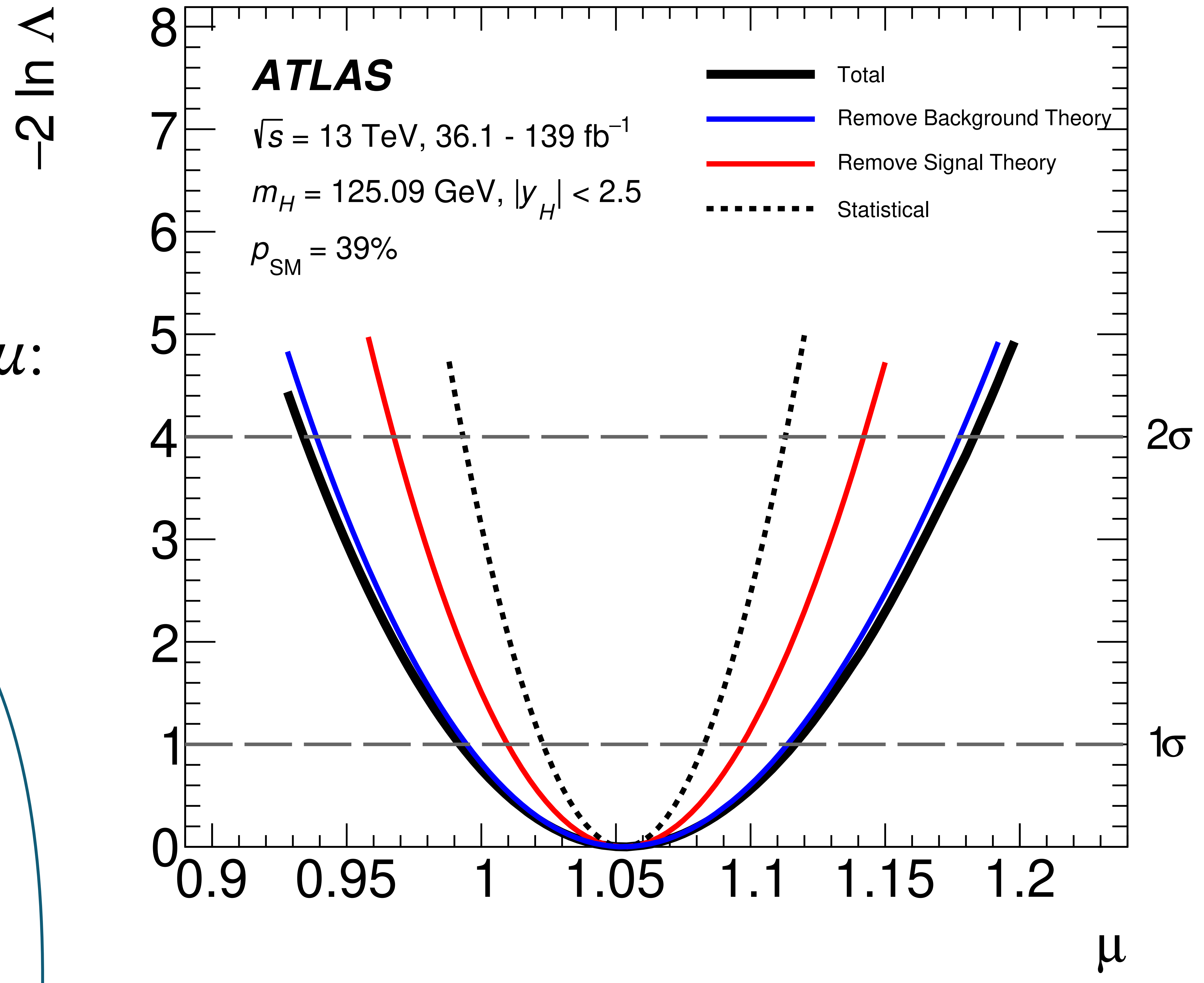


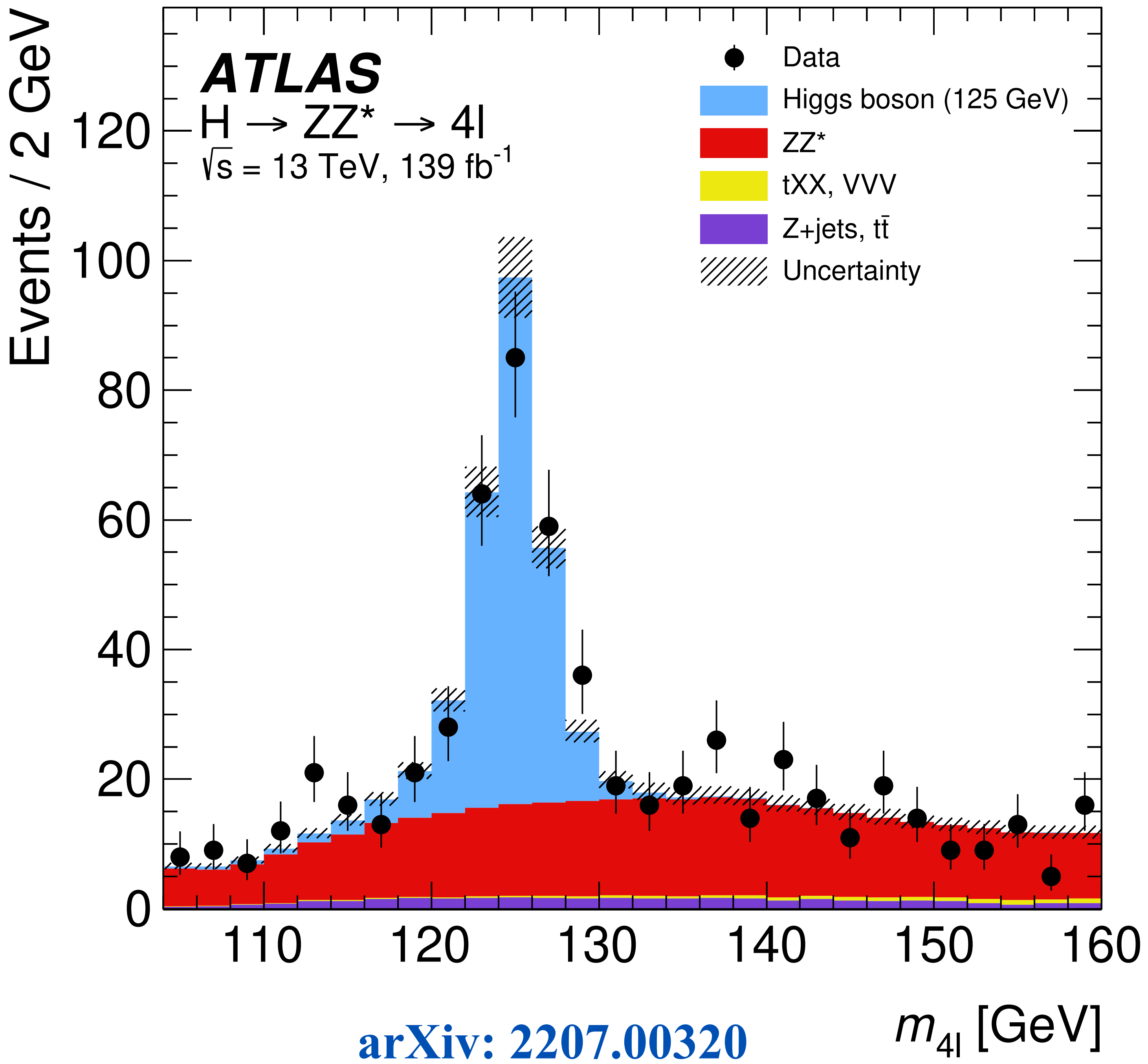
$$\mu = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig . th.}) \pm 0.02(\text{bkg . th.})$$

Mass Measurement $H \to ZZ^* \to 4\ell$

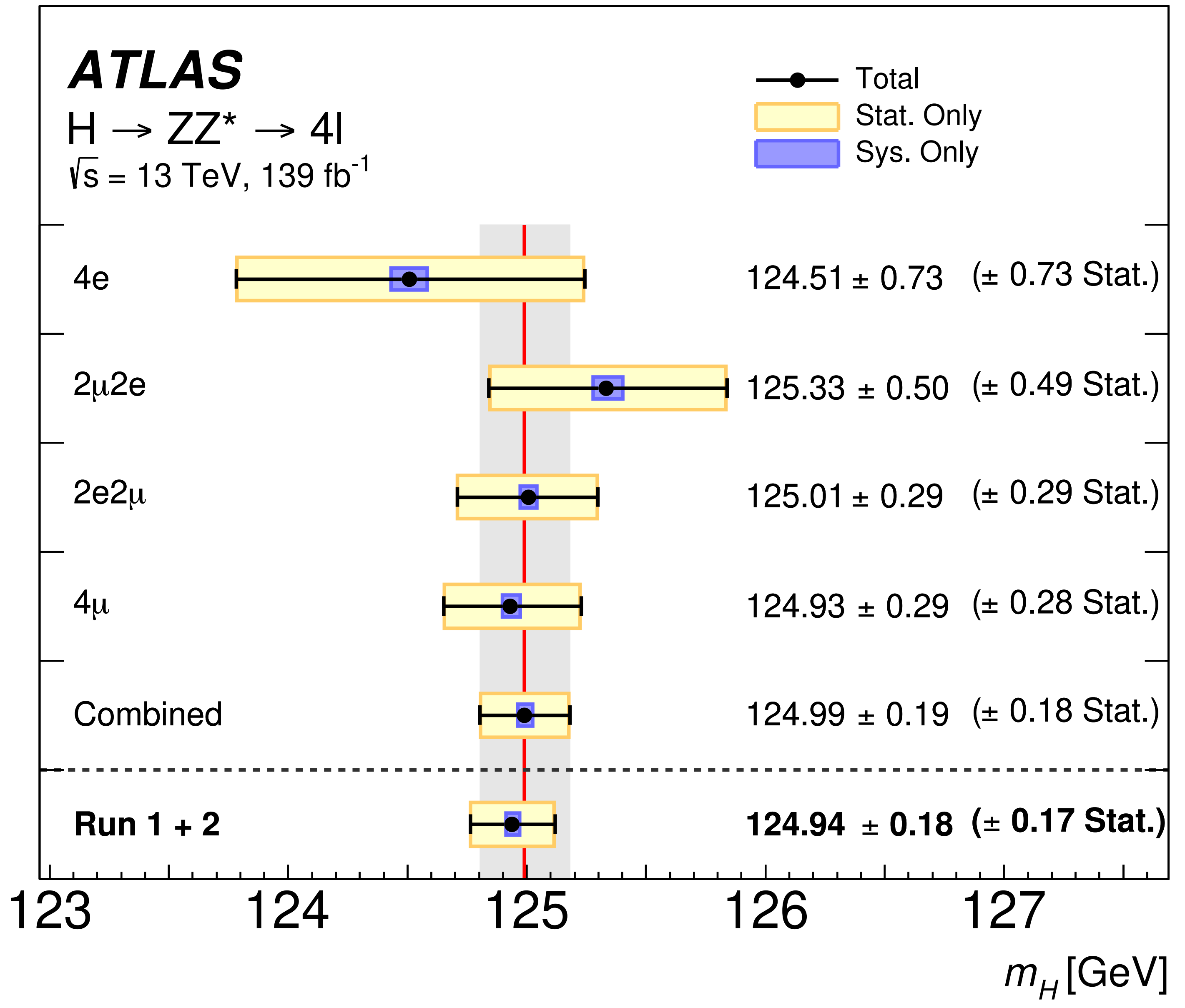
- The $H \to ZZ^* \to 4\ell$ ($\ell = e$ or μ) provides **good discrimination** of signal over background with **fully reconstructed final states**
- **New** analysis is based on **improved** momentum scale **calibration** (statistical uncertainty reduced 50%, systematics by 20%) - MUON-2022-01
  - Employ analytical **per event** model with deep neural network to discriminate signal over background

Final state	Higgs	ZZ, tXX, VVV	Reducible backgrounds	Expected total yield	Observed yield	S/B
4μ	78 ± 5	38.7 ± 2.2	2.84 ± 0.17	120 ± 5	115	1.89
$2e2\mu$	53.4 ± 3.2	26.7 ± 1.4	3.02 ± 0.19	83.1 ± 3.5	94	1.80
$2\mu2e$	41.2 ± 3.0	17.9 ± 1.3	3.4 ± 0.5	62.5 ± 3.3	59	1.93
$4e$	36.2 ± 2.7	15.7 ± 1.6	2.83 ± 0.35	54.8 ± 3.2	45	1.95
Total	209 ± 13	99 ± 6	12.2 ± 0.9	321 ± 14	313	1.88

- The m_H measurements of individual channels are **compatible** with the combined measurement with a ***p*-value of 82%**
- Run 2 (all chan. combined): $m_{4\ell} = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})$ GeV
- Run 1 + 2 combined : $m_{4\ell} = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})$ GeV



arXiv: 2207.00320



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κ-Framework

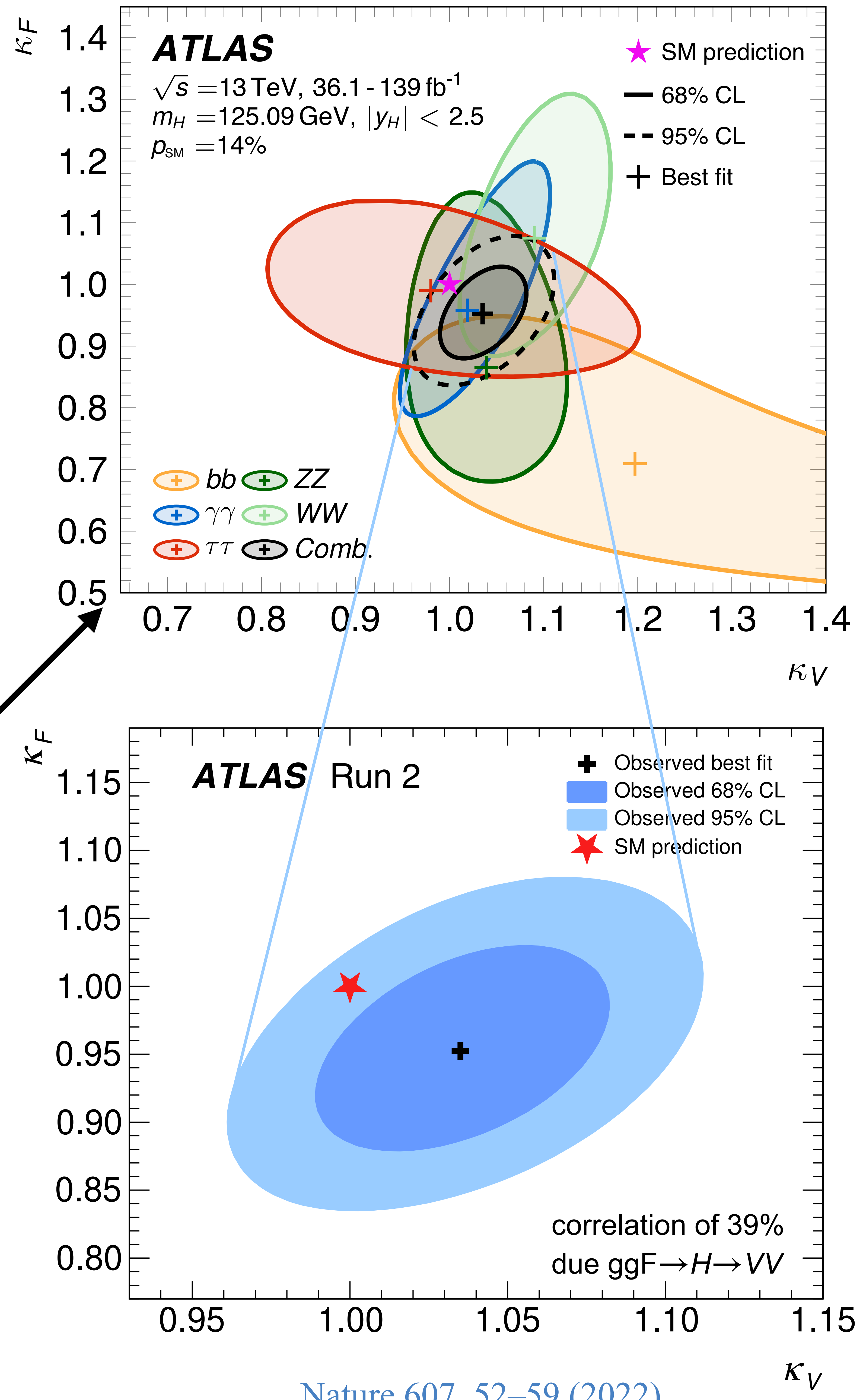
- **Event rates** for Higgs **production** and **decay** processes can be expressed in terms of **coupling modifiers (κ)** multiplying the SM Higgs coupling **strengths** to other particles.

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

- **Three** classes of models with **progressively fewer assumptions**:
  1. **Single** modifier for vector **bosons** $\kappa_V (= \kappa_W = \kappa_Z)$ and single modifier for **fermion** couplings κ_F :

     best-fit values: $\kappa_V = 1.035 \pm 0.031$, $\kappa_F = 0.95 \pm 0.05$, p-value: 14%

     ➡ **Compatible** with **SM** predictions ($\kappa_V = \kappa_F = 1$)
  2. Coupling strength **modifiers** for W, Z, t, b, c, τ and μ are **treated independently** (**only SM** particles assumed, loop processes resolved)
  3. **Same** as 2) but **allows** for the presence of **non-SM particles** in the loop-induced processes with coupling modifiers κ_g, κ_γ, $\kappa_{Z\gamma}$



Nature 607, 52–59 (2022)

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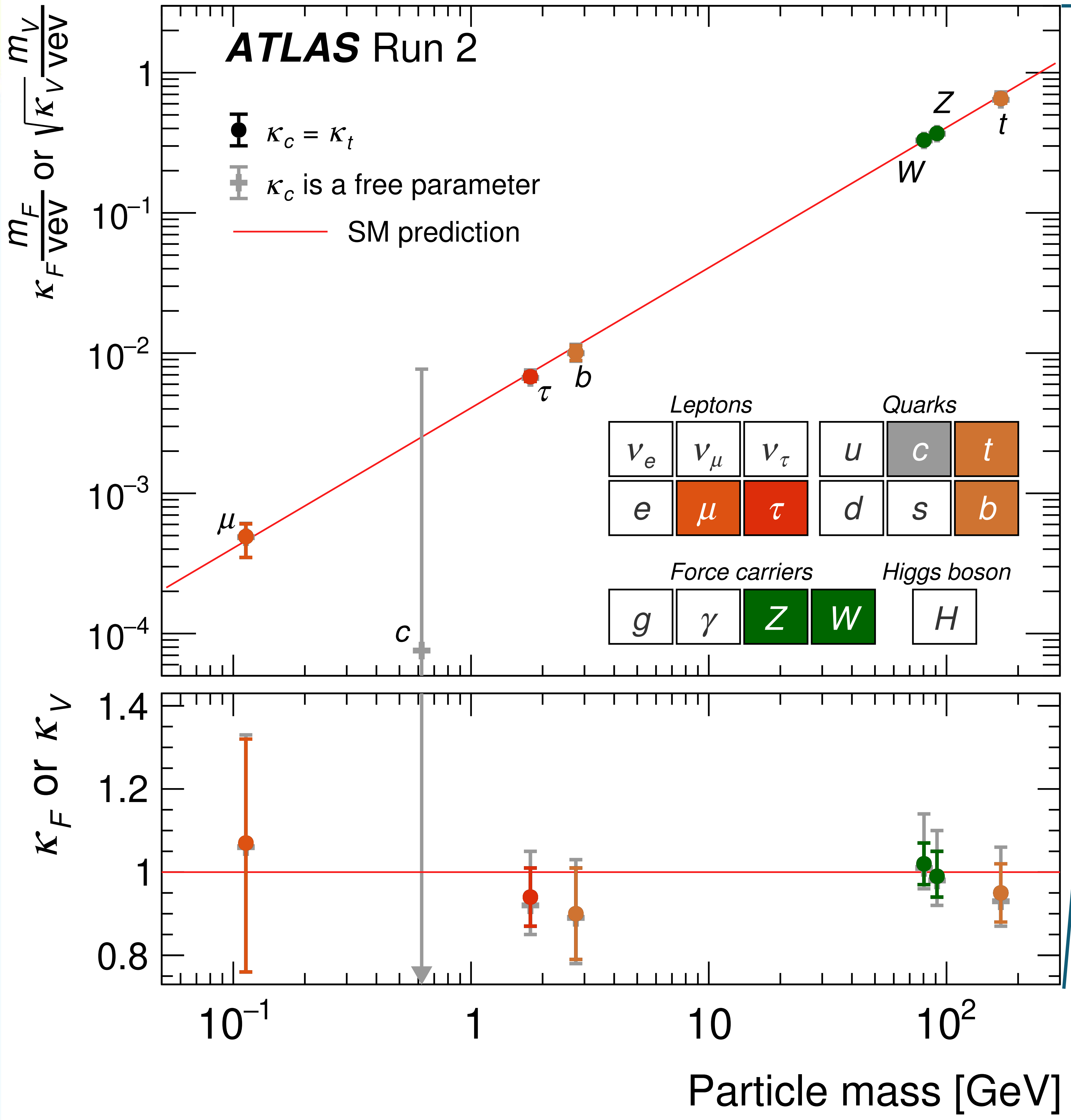
Couplings to individual particle

Nature 607, 52–59 (2022)

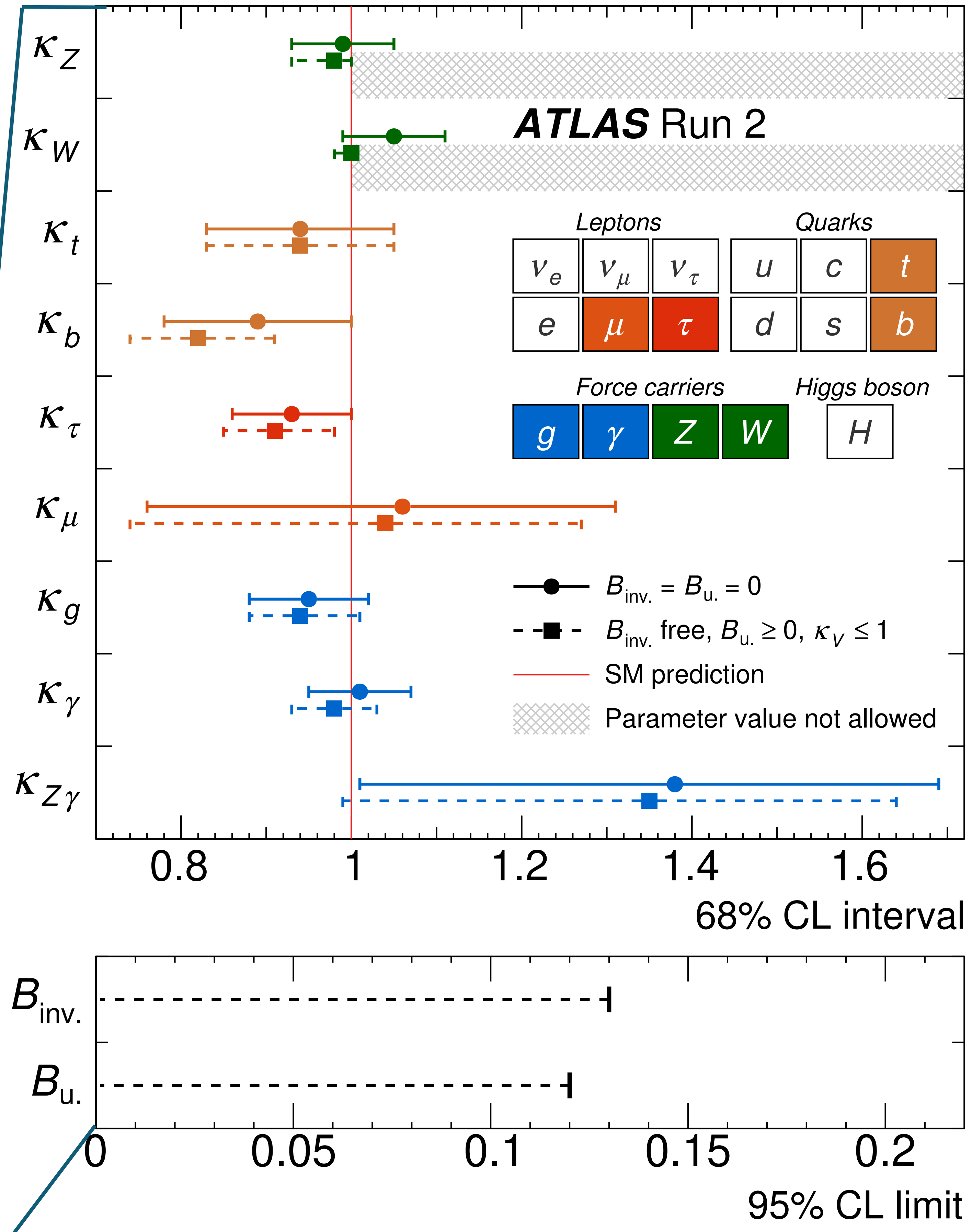


2nd Model

- *VH(cc)* data in the combination **allows** to have κ_c for the first time in this model (free param.)
- **Upper limit** (when left unconstrained) on κ_c is 5.7 (6.7) × SM obs. (exp.) at 95% CL (improve from Eur. Phys. J. C 82 (2022) 717)

3rd Model

- **Effective** photon, $\boldsymbol{Z\gamma}$ and gluon couplings
- **Improves** the current best limit of $B_{\text{inv.}} < 0.145 \rightarrow B_{\text{inv.}} < 0.13$ limit from earlier search: arXiv:2202.07953
- Statistical and the systematic uncertainty contribute almost equally
  - exceptions are the κ_μ, $\kappa_{Z\gamma}$, κ_c and B_u where **statistical** uncertainty **dominates**



SM *p*-value (61%)

All measured coupling strength **modifiers are compatible** with their SM **predictions**

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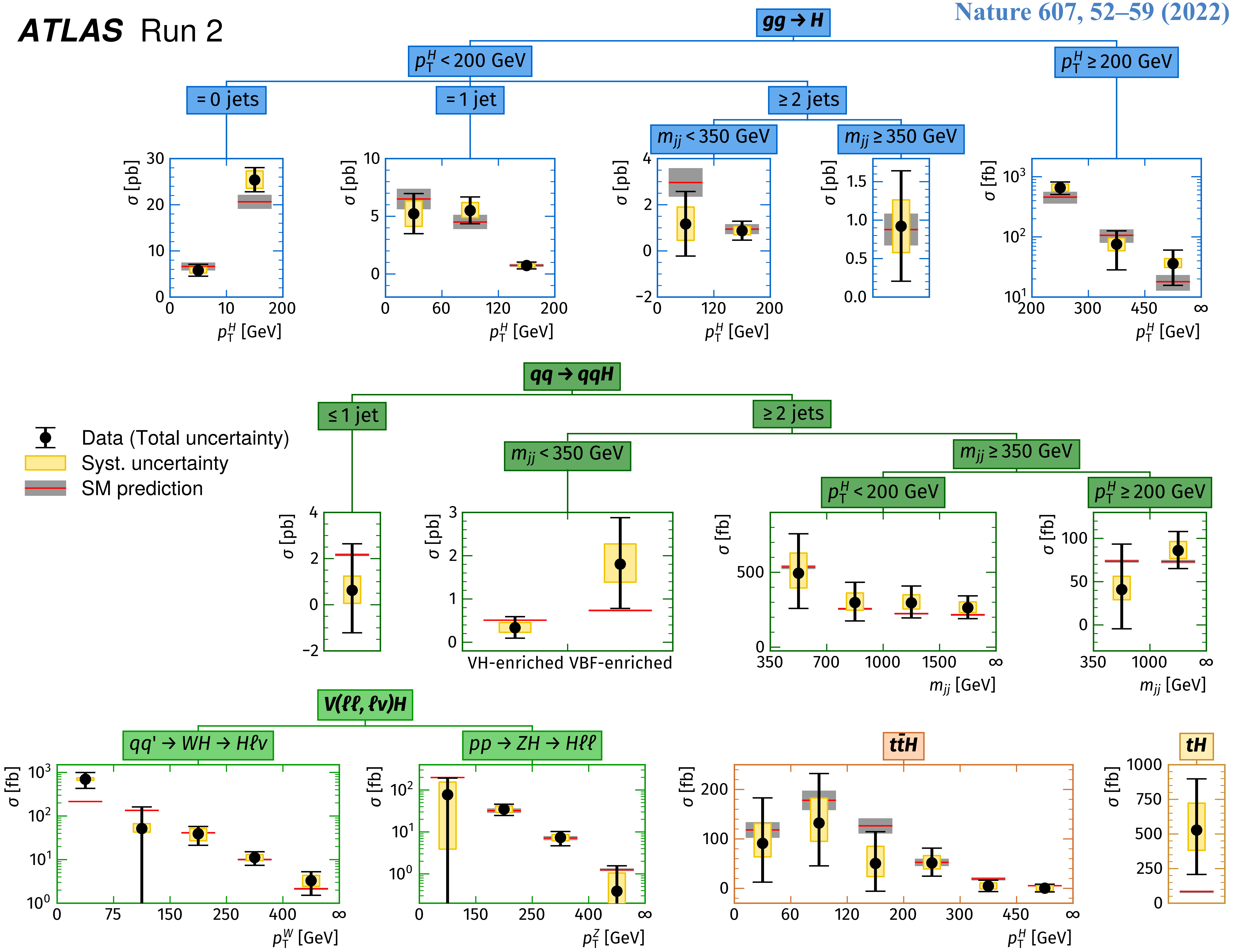
Simplified template cross section (STXS)

- **STXS framework** partitions the Higgs **cross section** measurements **separately** in several bins of **kinematic** regions in an optimized way
  - Split phase space of Higgs production processes into **36 kinematic regions**
  - **Optimise** signal and BSM sensitivity
  - **Reduce** theoretical uncertainties that are directly folded into the measurements.
  - **Allowing** the combination of measurements in different decay channels and eventually between experiments.
  - The ***p*-value** for compatibility of the combined measurement and the **SM** prediction is **94%**

Nature 607, 52–59 (2022)



All measurements are consistent with the SM predictions

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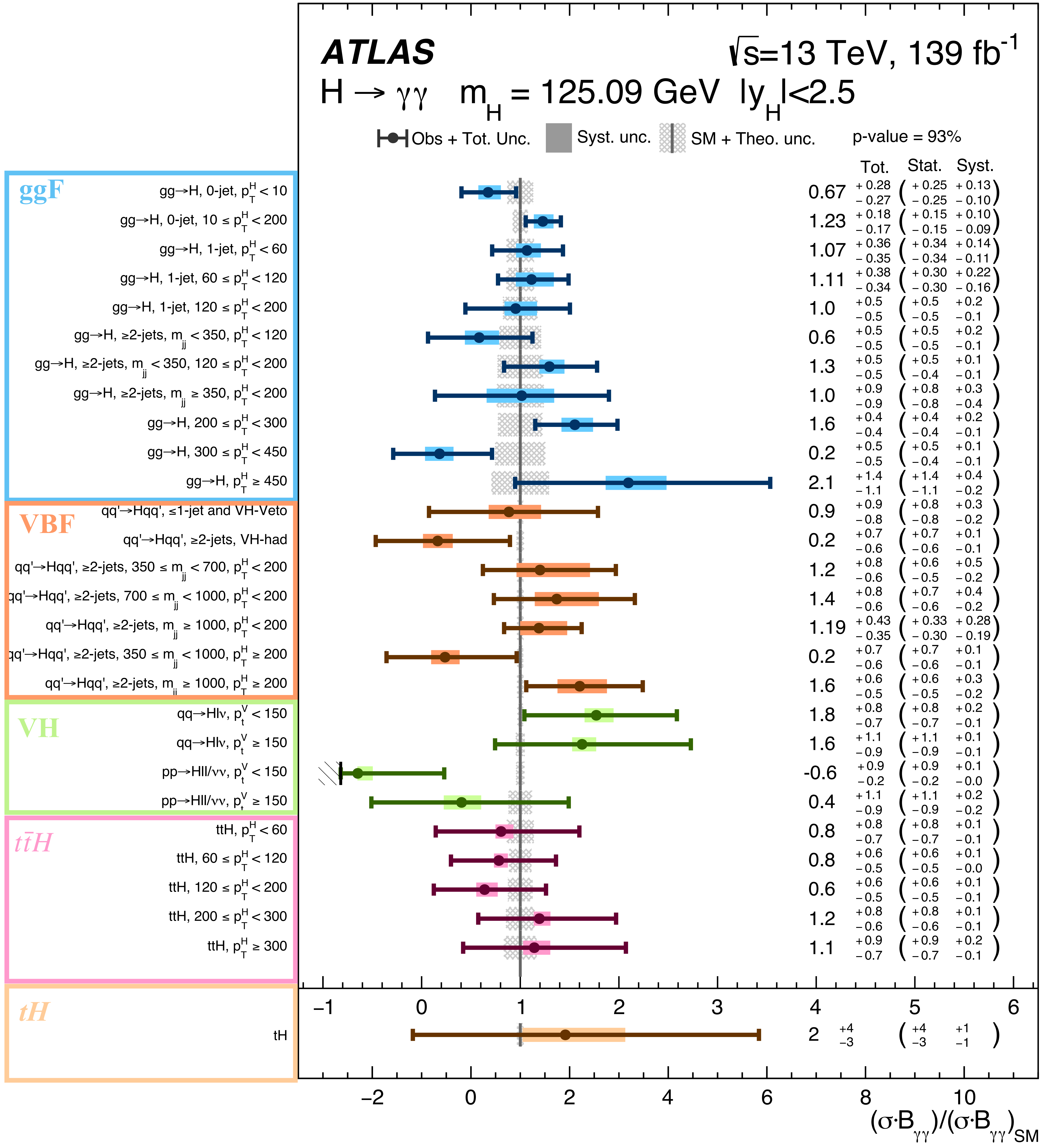
$H \to \gamma\gamma$ channel (STXS)

- **Best-fit values** STXS parameters in each of the **28 regions** normalized to their SM predictions:
  - splitting bins based on **kinematics**
  - **non-overlapping** fiducial regions
- **Uncertainties of 10% for ggF + $b\bar{b}H$, 22% for VBF**, and **35% for WH and $t\bar{t}H$.**
- **Upper limit** of ten times the SM prediction is set for the tH process
- Compatible with their **SM predictions, with a p-value of 93%**

Process ($\|y_H\| < 2.5$)	Value [fb]	Uncertainty [fb] Total	Stat.	Syst.	SM pred. [fb]
ggF+$b\bar{b}H$	106	$^{+10}_{-10}$	$^{+8}_{-8}$	$^{+6}_{-6}$	102^{+6}_{-6}
VBF	9.5	$^{+2.2}_{-1.9}$	$^{+1.5}_{-1.4}$	$^{+1.7}_{-1.4}$	$7.9^{+0.2}_{-0.2}$
WH	4.2	$^{+1.5}_{-1.4}$	$^{+1.5}_{-1.4}$	$^{+0.4}_{-0.2}$	$2.8^{+0.1}_{-0.1}$
ZH	−0.4	$^{+1.1}_{-1.0}$	$^{+1.1}_{-1.0}$	$^{+0.2}_{-0.3}$	$1.8^{+0.1}_{-0.1}$
$t\bar{t}H$	1.0	$^{+0.4}_{-0.3}$	$^{+0.3}_{-0.3}$	$^{+0.1}_{-0.1}$	$1.1^{+0.1}_{-0.1}$
tH	0.5	$^{+0.8}_{-0.6}$	$^{+0.7}_{-0.6}$	$^{+0.3}_{-0.2}$	$0.19^{+0.01}_{-0.02}$



arXiv:2207.00348

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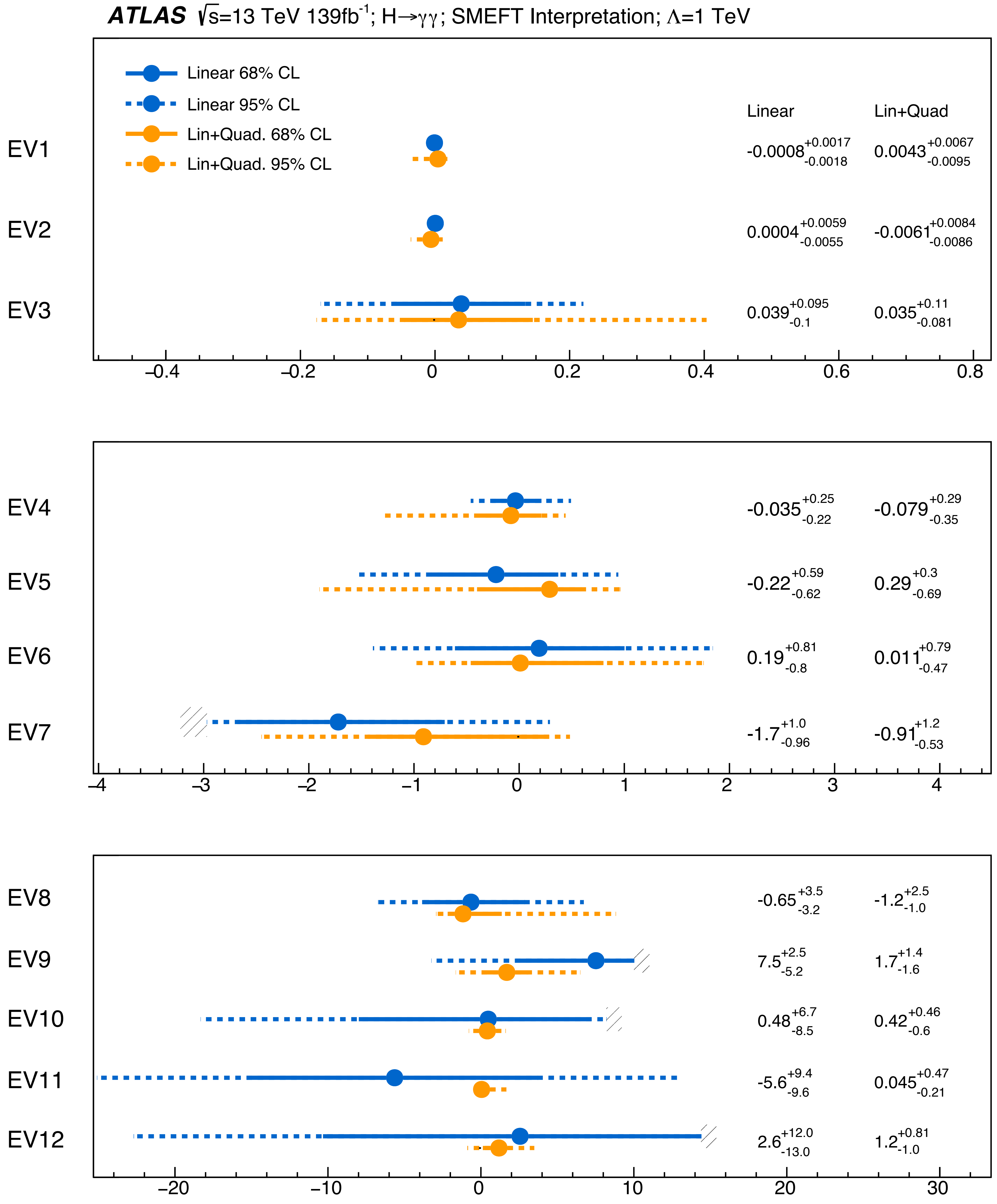
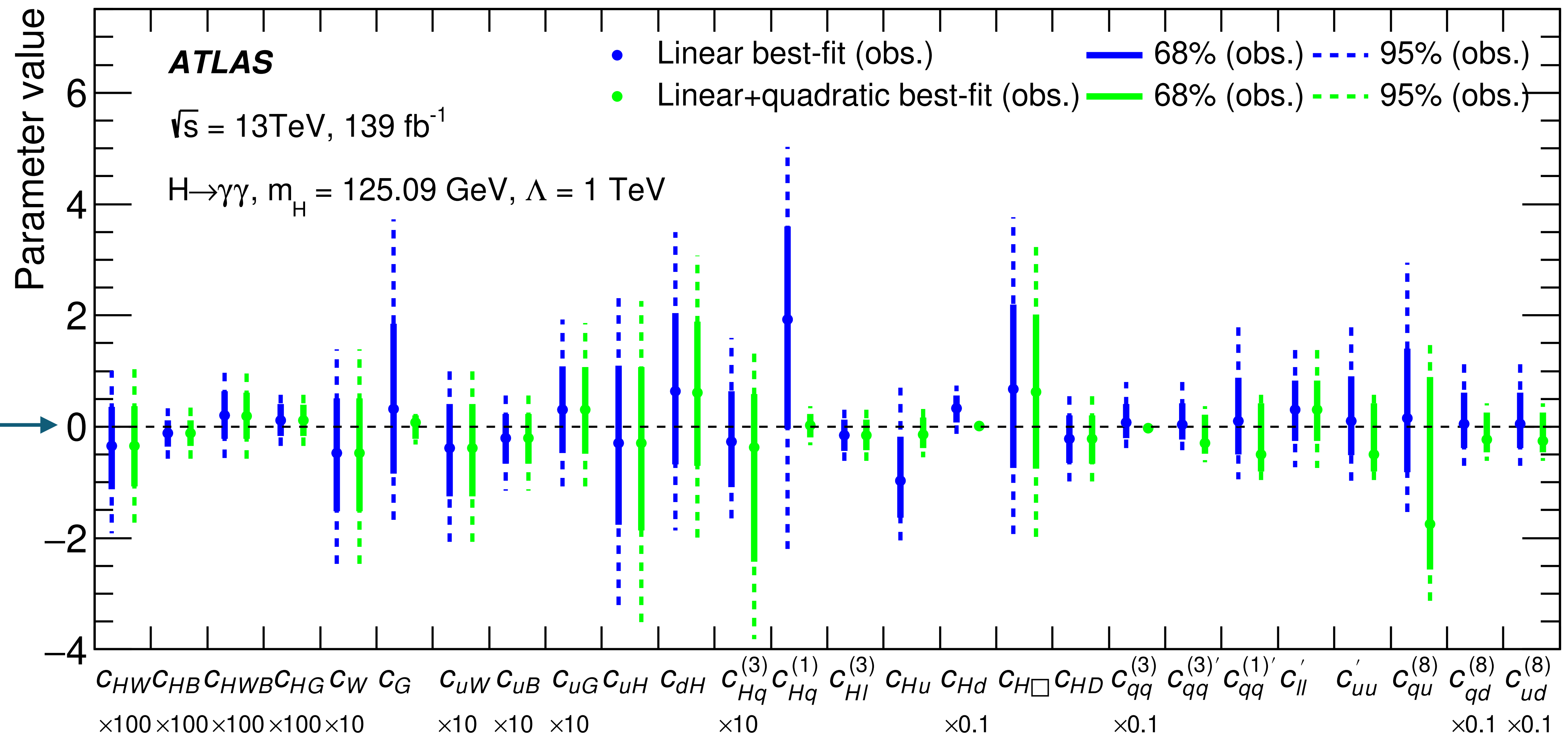
$H \to \gamma\gamma$ channel (SM EFT)

- Standard Model Effective Field Theory (**SMEFT**) provides a **model-independent** setting to **describe deviations from SM** (**33 STXS** regions - better granularity especially at high m_{jj})
- **Lagrangian** up to dimension 6 is written as $\mathscr{L} = \mathscr{L}_{\text{SM}} + \sum_k \frac{c_k}{\Lambda^2} O_k$
- c_k- **Wilson** coefficients operators are expressed in the **Warsaw** basis
  - **Individually measured** c_k with others set to zero
- **Simultaneous** measurement of SMEFT parameters by computing eigenvectors **EVn** with PDF approx. **Gaussian**: $C^{-1}_{\text{SMEFT}} = P^T C^{-1}_{\text{STXS}} P$



The SM - c_k set to 0



SMEFT parameters other than the one measured are fixed to 0

no significant deviation from SM

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Differential x-section

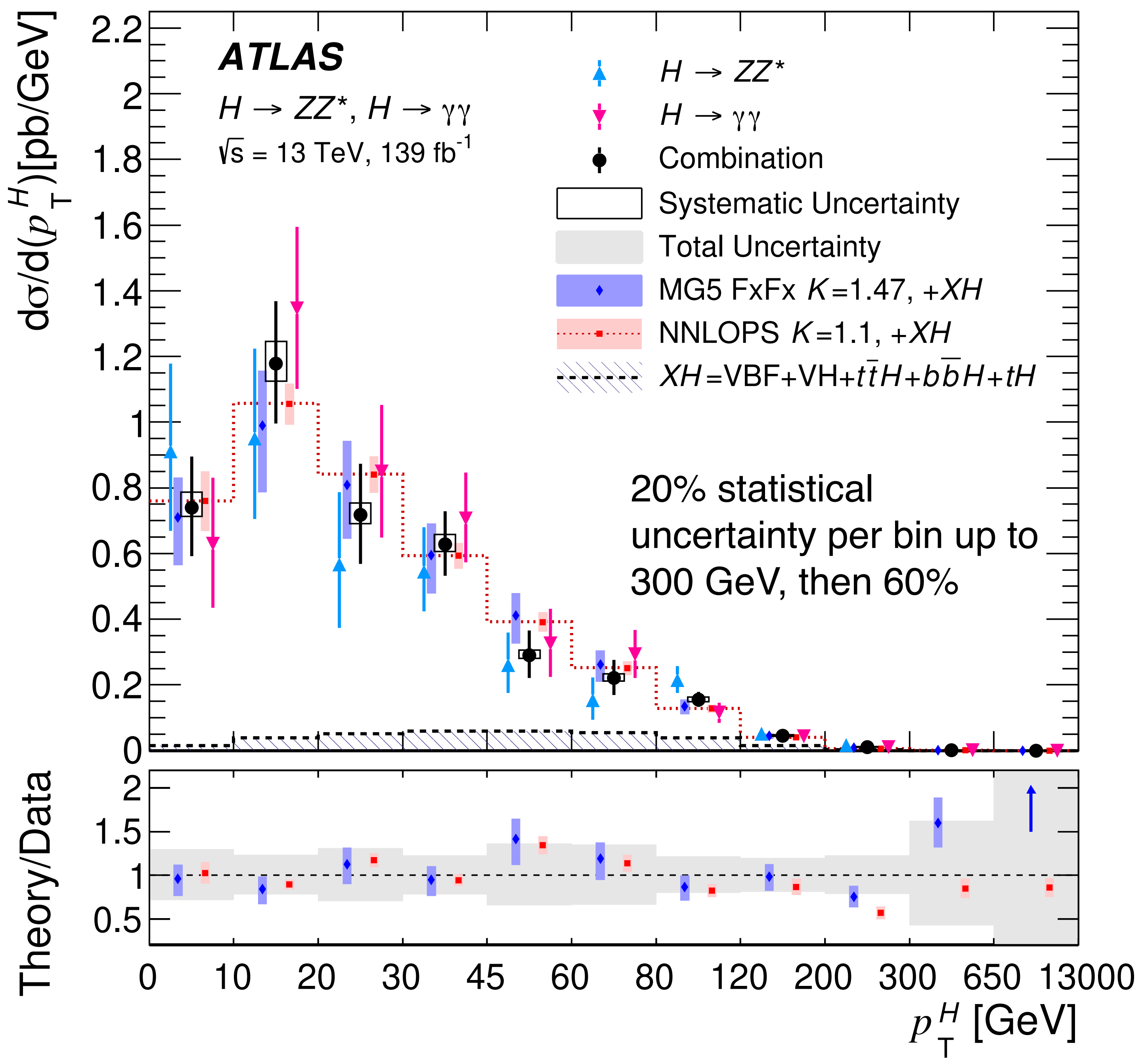
arXiv:2207.08615

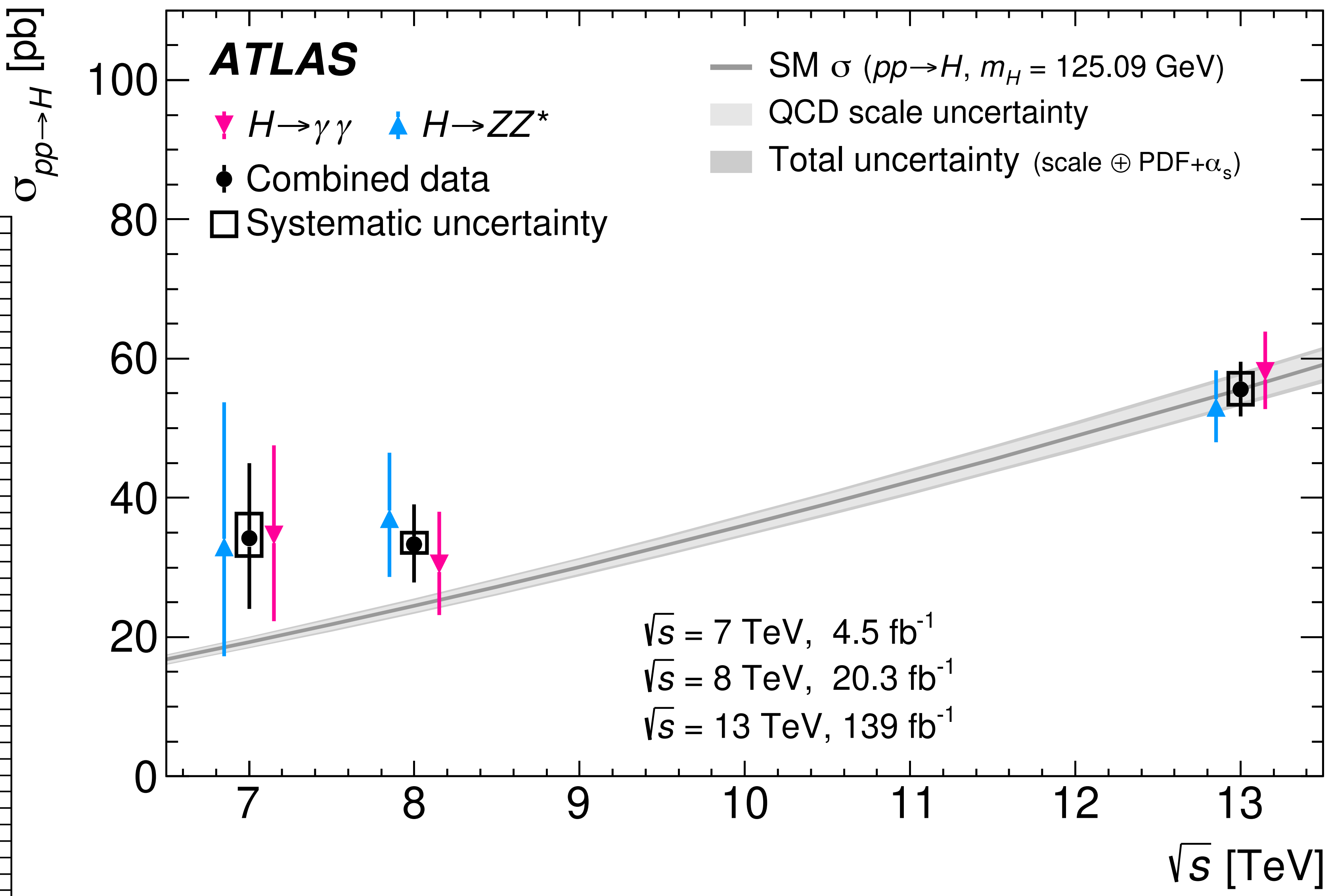
- **Joint** analysis $H \to ZZ^* \to 4\ell$ ($\ell = e$ or μ) and $H \to \gamma\gamma$ channels
- Measure **differential cross-sections** as a function of the following **variables**: p_T^H, $|y_H|$, N_{jets}, $p_T^{lead.jet}$

$$H \to ZZ^* \to 4\ell\text{: } 53.0^{+5.3}_{-5.1}\text{ pb}$$

$$H \to \gamma\gamma\text{: } 58.1^{+5.7}_{-5.4}\text{ pb}$$

- **Total**: $55.5^{+4.0}_{-3.8}$ pb (SM: 55.6 ± 2.8 pb)





- Two decay **channels** are **compatible** with each other with p-value of 49%
- Their **combination agrees** with the SM predictions (p-value of 98%)

- Analysis ggF $H \to WW^* \to e\nu\mu\nu$ to measure **differential cross-sections** (0 and 1 jets)
- Measurements in a **fiducial phase space** - minimizes extrapolations and therefore the model dependence of the results
- Transverse mass m_T as a function : p_T^H, $|y_{j0}|$, p_T^{l0},p_T^{ll}, m_{ll}, y_{ll}, $\Delta\phi_{ll}$, $\cos\theta^*$
- **Compatibility** with SM (p-value) **93-97%**

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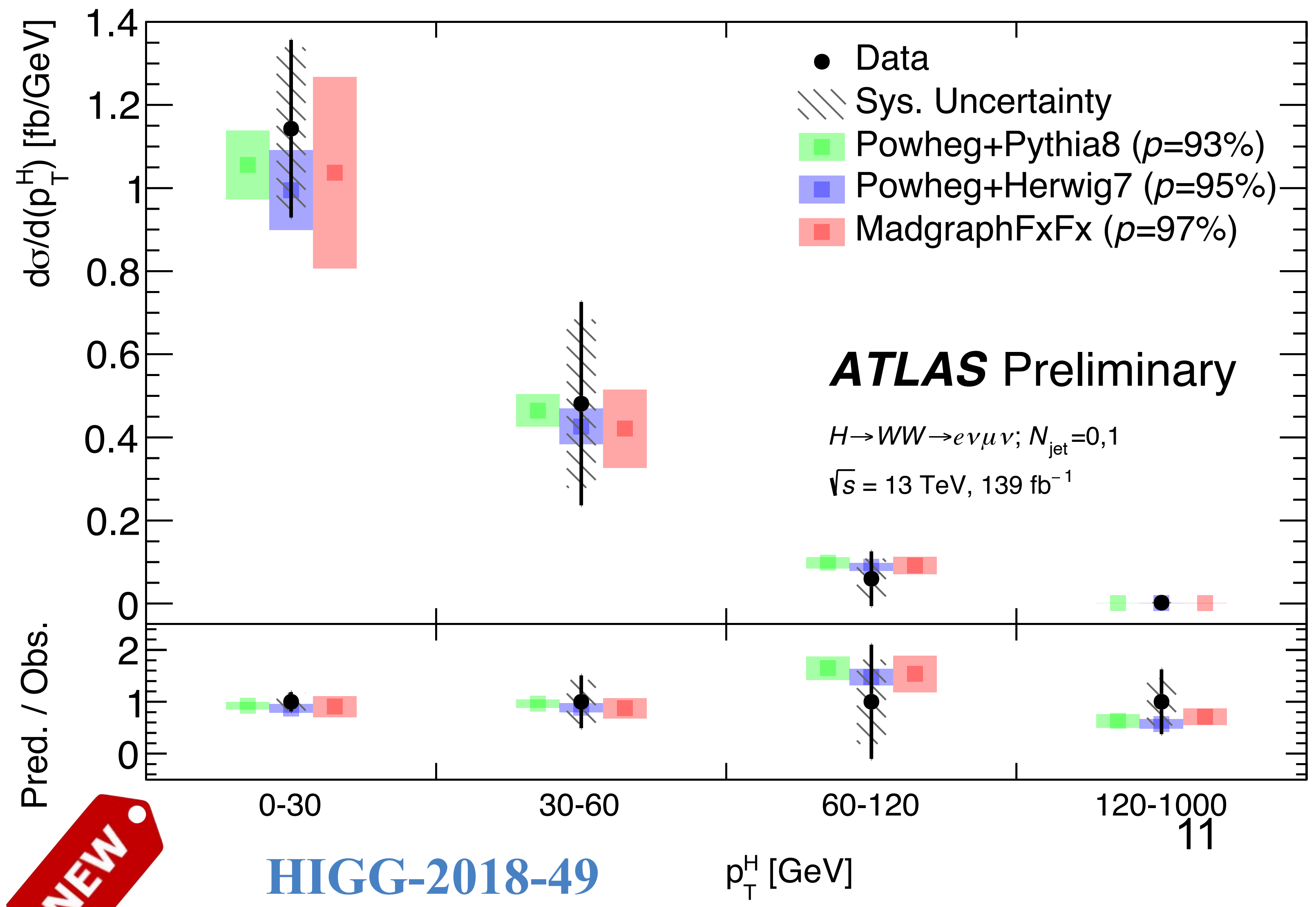


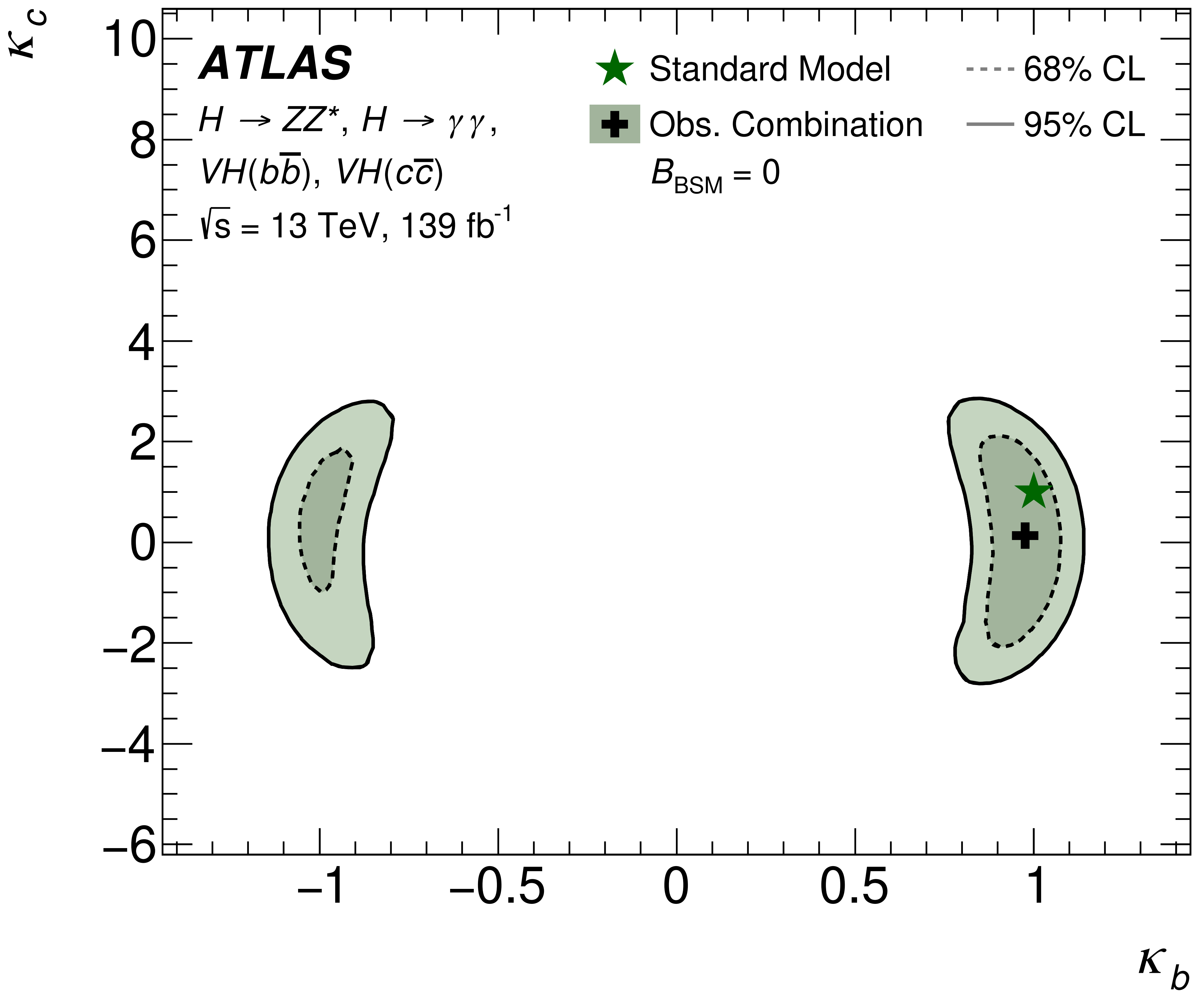
NEW

HIGG-2018-49

Back to κ - Adding $VH(c\bar{c})$, $VH(b\bar{b})$ dataset

- **Combined fit** with the measurement of Higgs bosons produced in **association** with a *W* **or** *Z* boson **decaying to** *b***- or** *c***-quark pairs**
  - Allows for a **more stringent constraints** of the **coupling modifiers** κ_c and κ_b without any assumption on the bottom quark coupling
- Total Higgs width is resolved with κ_c, κ_b and $B_{\mathrm{BSM}} = B_{\mathrm{invis.}} + B_{\mathrm{und.}}$
  - other couplings set to SM
- **Two** scenarios $B_{\mathrm{BSM}} = 0$ or B_{BSM} is a free parameters
- Ultimate sensitivity to κ_c and κ_b at the price of a larger model dependency.
- **Upper limit on κ_c of 4.8×SM at 95% CL**

arXiv:2207.08615



Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{\mathrm{BSM}} = 0$	[−1.61, 1.70]	[−2.47, 2.53]
No assumption on B_{BSM}	[−2.63, 3.01]	[−4.46, 4.81]

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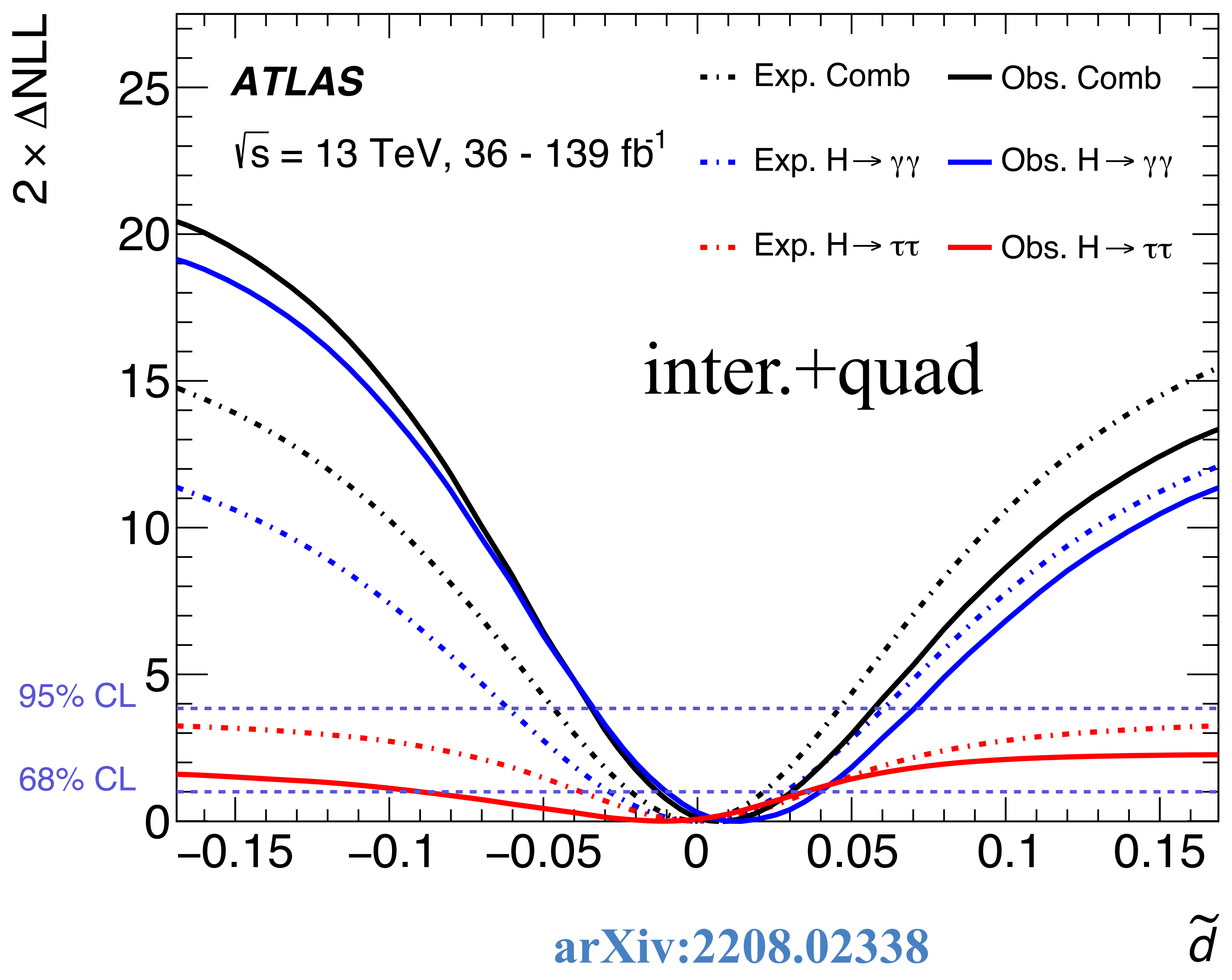
CP property: VBF $H \to \gamma\gamma$

- SM Higgs Spin 0 and positive parity ($J^{CP} = 0^{++}$) **established** with Run 1 data (spin 1 and 2 **excluded** >99.9% CL)
- Test of CP invariance using two effective field theory bases (dim-6) :
  - $\tilde{d}$ in the **HISZ** basis (further **tightened** through **combination** with results from the $H \to \tau\tau$ channel) Phys. Lett. B 805 (2020) 135426
  - $c_{H\tilde{W}}$ in the **Warsaw** basis (for **future** combinations)



arXiv:2208.02338

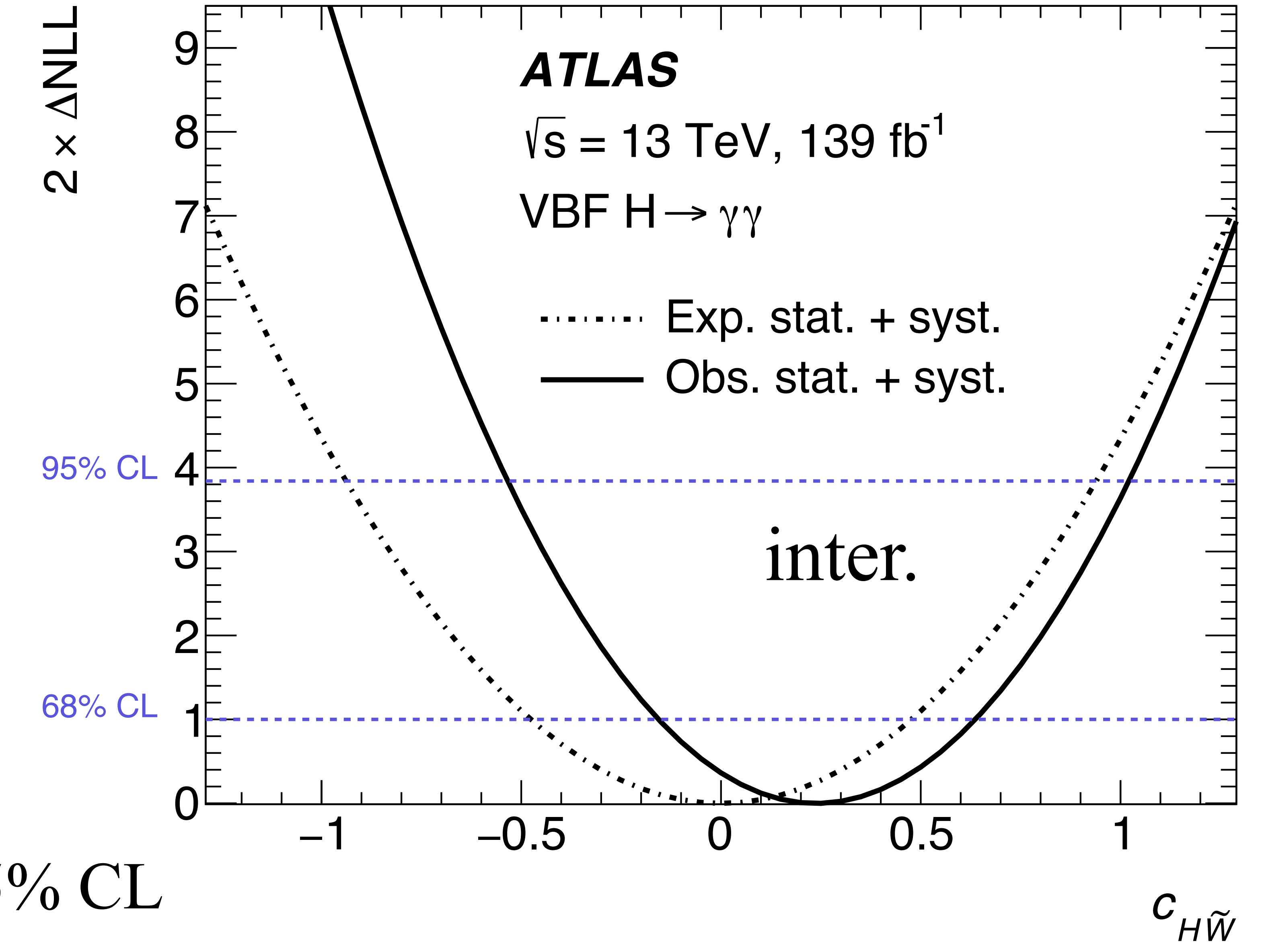
Total Matrix: $|\mathcal{M}|^2 = |\mathcal{M}_{SM}|^2 + 2 \cdot c_i \cdot \mathrm{Re}(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd}) + c_i^2 \cdot |\mathcal{M}_{CP-odd}|^2$

SM Contribution term — CP-odd (c_i Wilson coefficient) — CP-even BSM

Optimal Observable: $OO = 2 \cdot \mathrm{Re}(\mathcal{M}^*_{SM} \cdot \mathcal{M}_{CP-odd})/|\mathcal{M}_{SM}|^2$ Phys. Lett. B 805 (2020) 135426

	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

$\tilde{d}$: 20% **improve** at 68% CL
3x better for 95% CL
$c_{H\tilde{W}}$: **5x more restrictive** at 95% CL



Result compatible with SM and no sign of CP violation is observed in data

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CP mixing angle

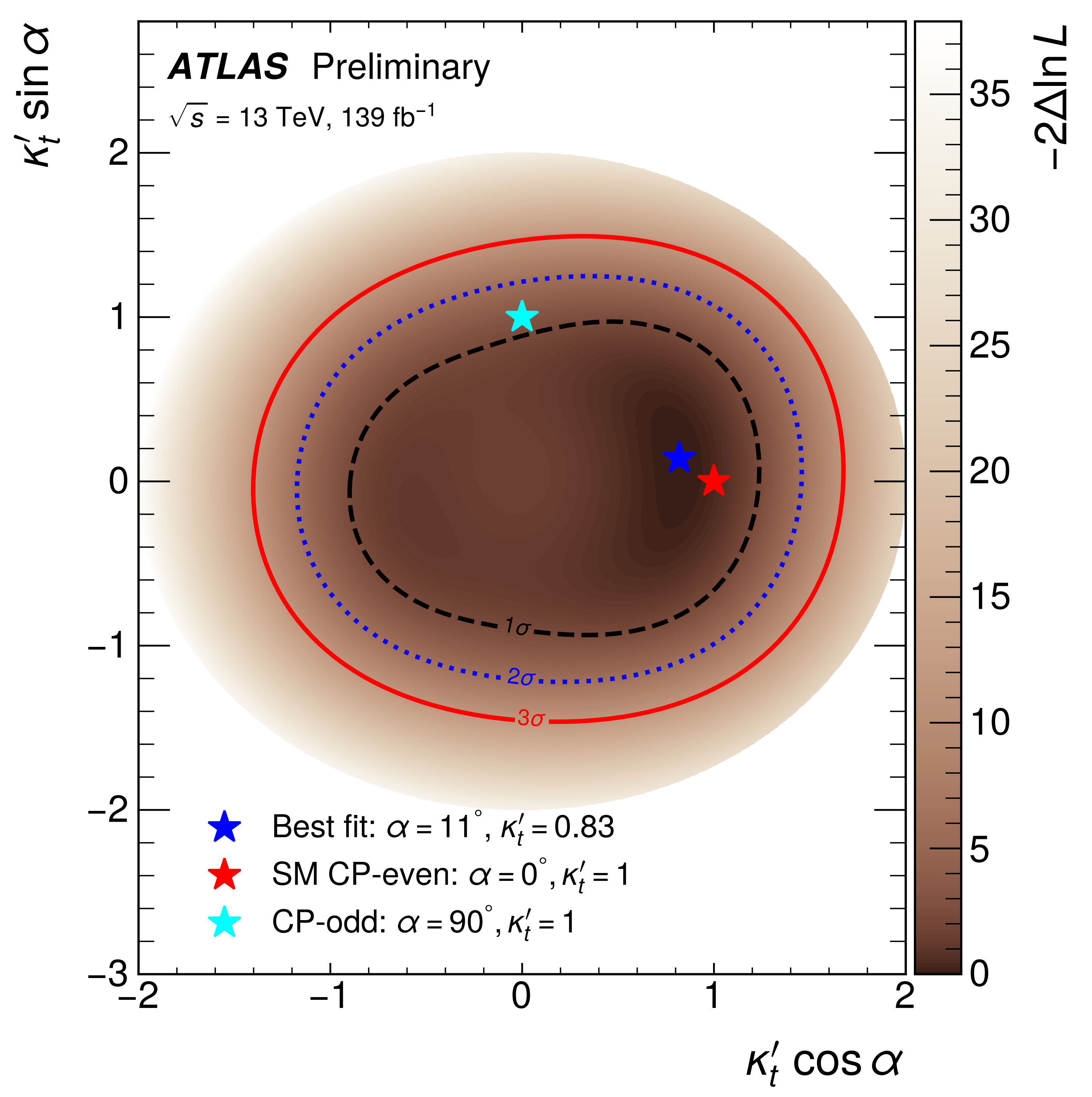
- Probing the ***CP*** nature of the **top-Higgs Yukawa coupling** in $t\bar{t}H$ and tH events with a **Higgs** boson **decaying** to a **pair of** b quarks: $H \to b\bar{b}$

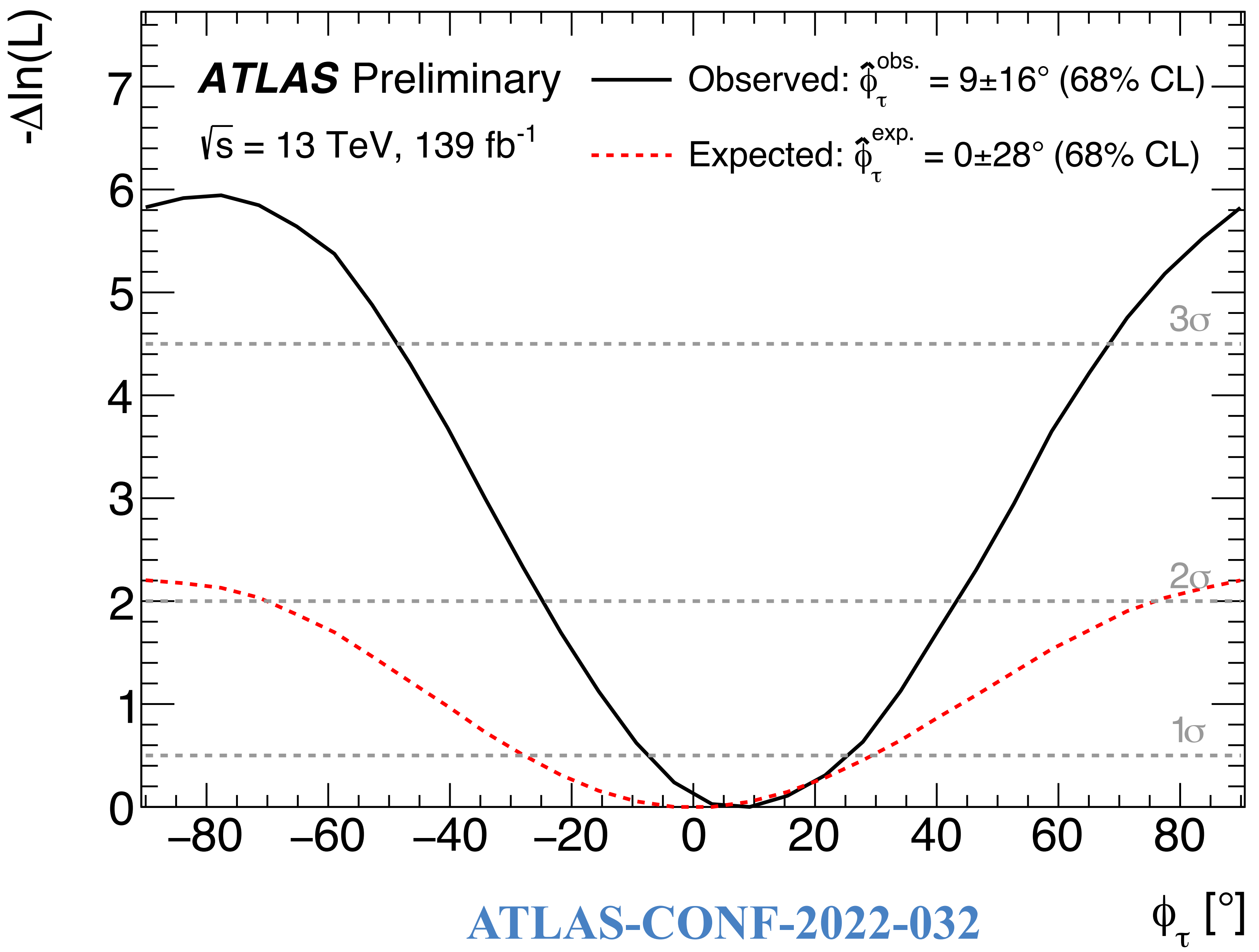
$$\mathscr{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

$$\text{best fit value}: \alpha = 11^\circ\,{}^{+55^\circ}_{-77^\circ},\ \kappa_t' = 0.83\,{}^{+0.30}_{-0.46}$$

➡ Pure *CP*-**odd** coupling is **disfavoured** by the data at $1.2\,\sigma$ CL

ATLAS-CONF-2022-016





ATLAS-CONF-2022-032

- Measuring ***CP*** **properties** of Higgs boson **through** interactions with **τ leptons** using $H \to \tau\tau$

$$\mathscr{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau)H$$

$$\text{Obs.}: \phi_\tau = 9 \pm 16^\circ \text{ at the } 68\,\%\,\text{CL}, \phi_\tau = 0^\circ (CP - \text{even hypothesis})$$

➡ **Pure** *CP*-**odd** hypothesis is **disfavoured** by the data at $3.4\,\sigma$ CL

Results are compatible with the SM expectation within the measured uncertainties

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Off-shell production of the *H*

- Search of **off-shell** production of the Higgs boson has been performed with the full Run-2 dataset
- Two decay states: $ZZ \to 4\ell$ ($\ell = e$ or μ), and $ZZ \to 2\ell 2v$

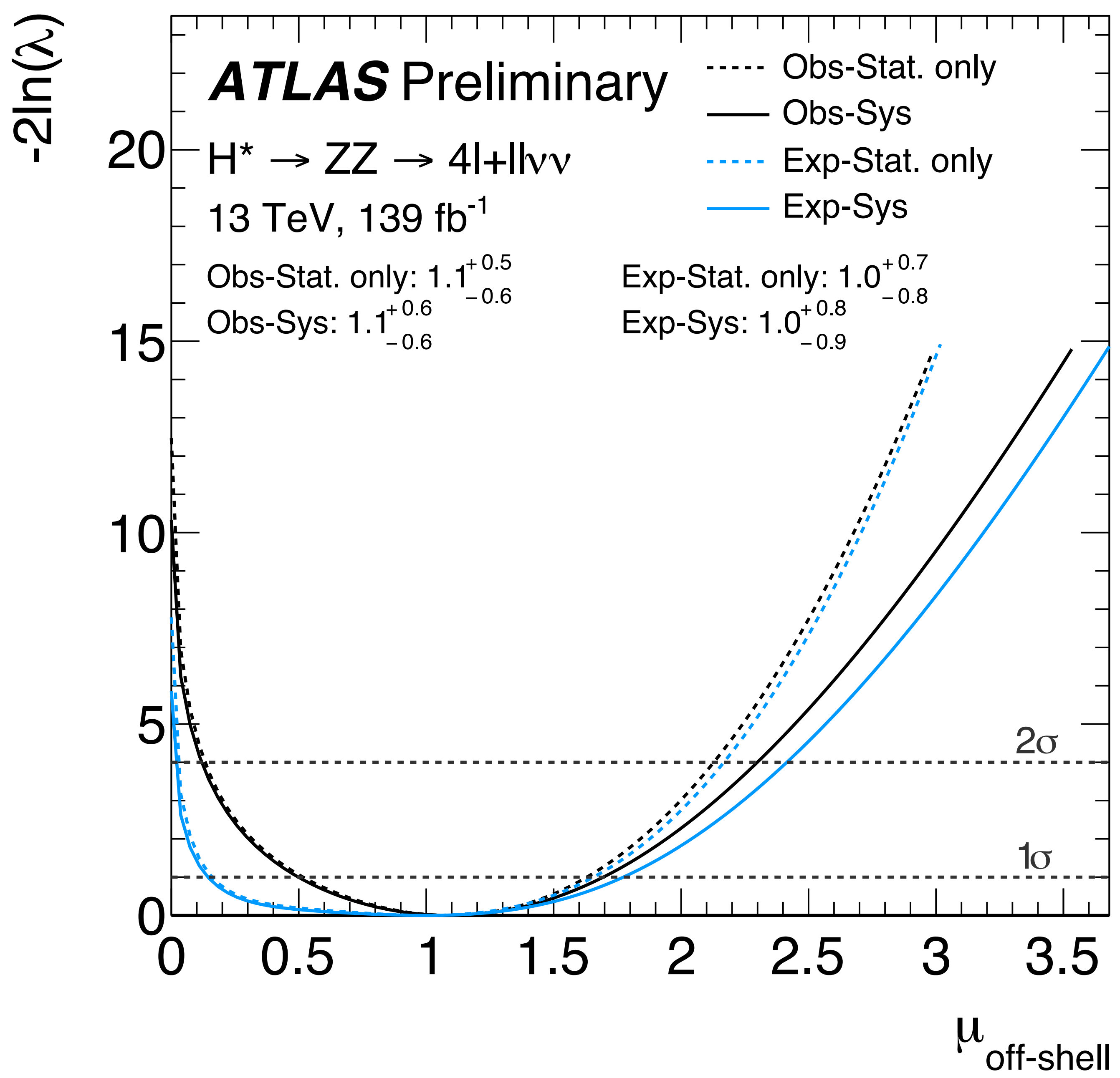
$$\sigma^{\mathrm{on-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}}{m_H \Gamma_H} \qquad \sigma^{\mathrm{off-shell}}_{gg\to H\to VV} \sim \frac{g^2_{\mathrm{ggH}} g^2_{\mathrm{HZZ}}}{m^2_{ZZ}}$$

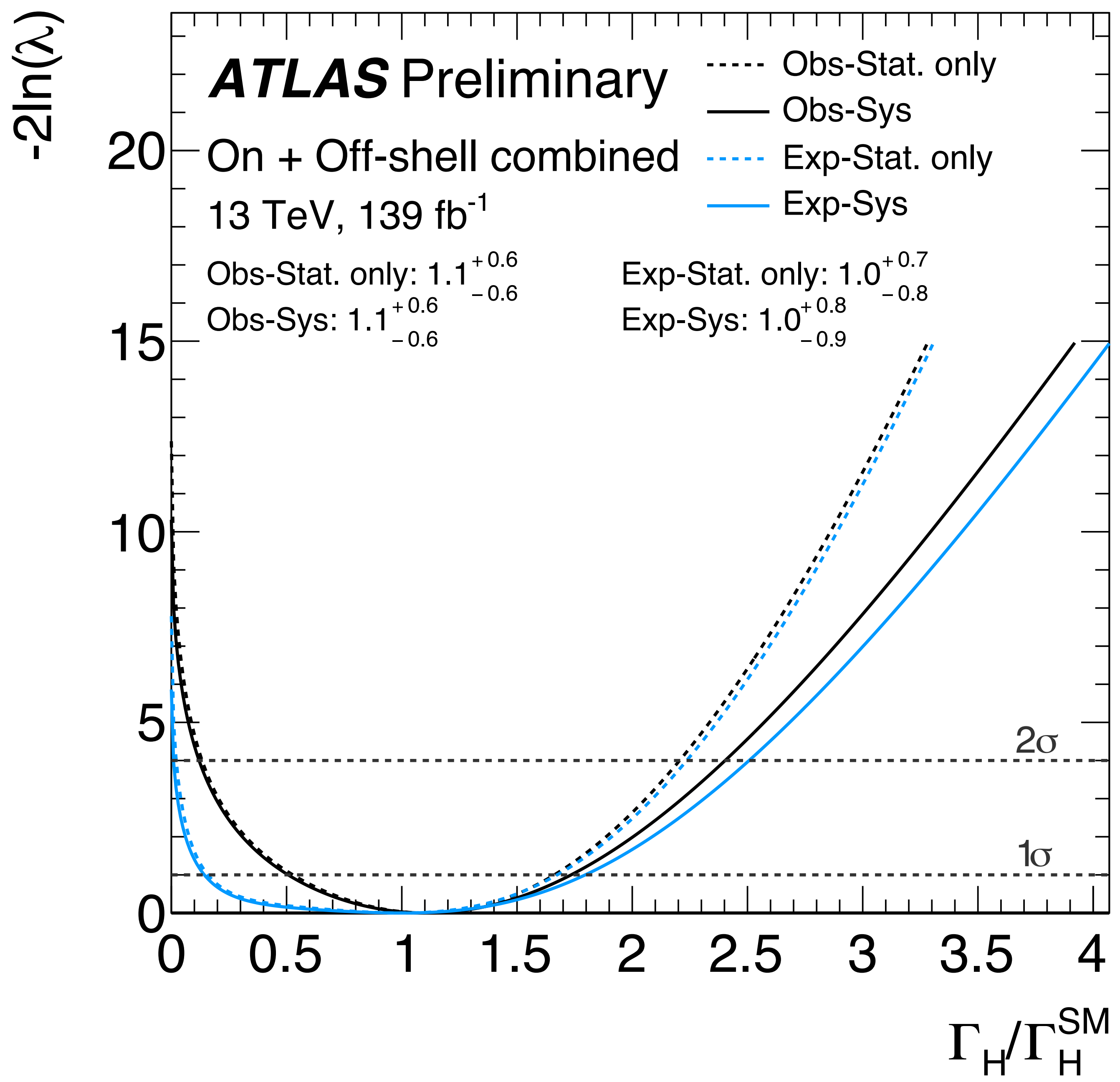
- $\mu_{\mathrm{off-shell}} = 1.1 \pm 0.6$, upper limit 2.3 at 95% CL
- The **background-only** hypothesis is **rejected** with an obs. (exp.) significance of **3.2 σ obs. (2.4 σ exp.)**
  - **Marks** the experimental **evidence** of off-shell Higgs production.
- The **measured total width** (combination with on-shell $H \to ZZ^* \to 4\ell$) of the Higgs is: $4.6^{+2.6}_{-2.5}$ MeV (Exp. SM(Γ_H^{SM}) is 4.1 MeV)
- **Upper limit** on the total **width** is found to be 9.7 MeV obs. (10.2 MeV exp.) at 95% CL

ATLAS-CONF-2022-068

Similar results from CMS: arXiv:2202.06923

NEW





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No deviations from the SM prediction are observed

H self coupling - theory

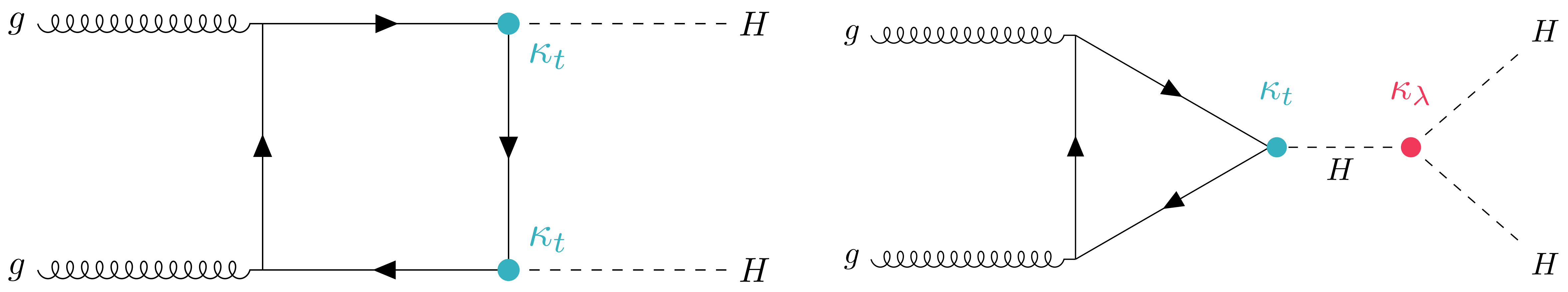
arXiv:2211.01216

- Search is the **double Higgs** production and **self Higgs coupling**
- The Higgs boson self-interactions are characterised by the **trilinear self-coupling** λ_{HHH}
- Results are reported in terms of the **coupling modifier** κ_λ defined as the **ratio** of the Higgs boson self-coupling to its **SM value**

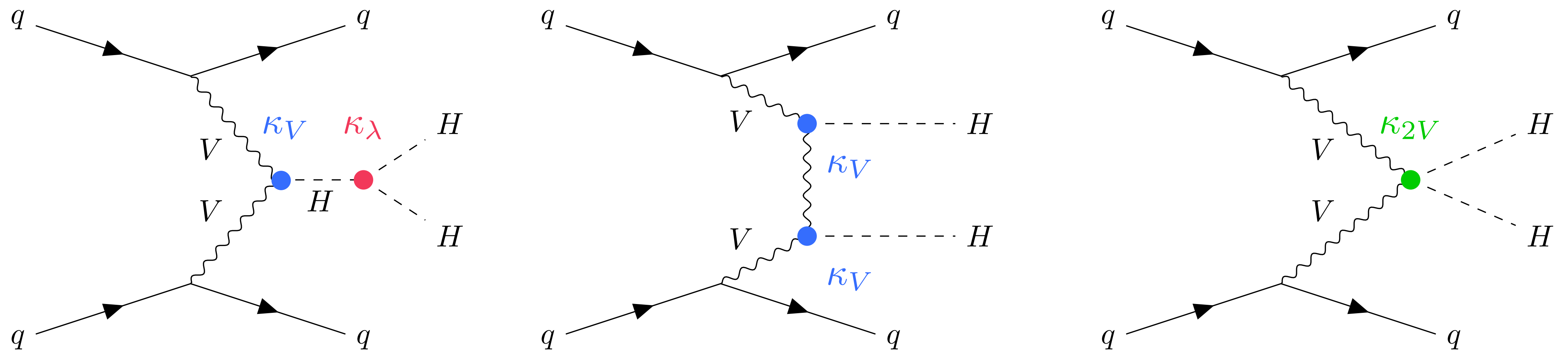
$$\kappa_\lambda = \lambda_{HHH} / \lambda_{HHH}^{\mathrm{SM}}$$

Direct measurements: production of two Higgs bosons

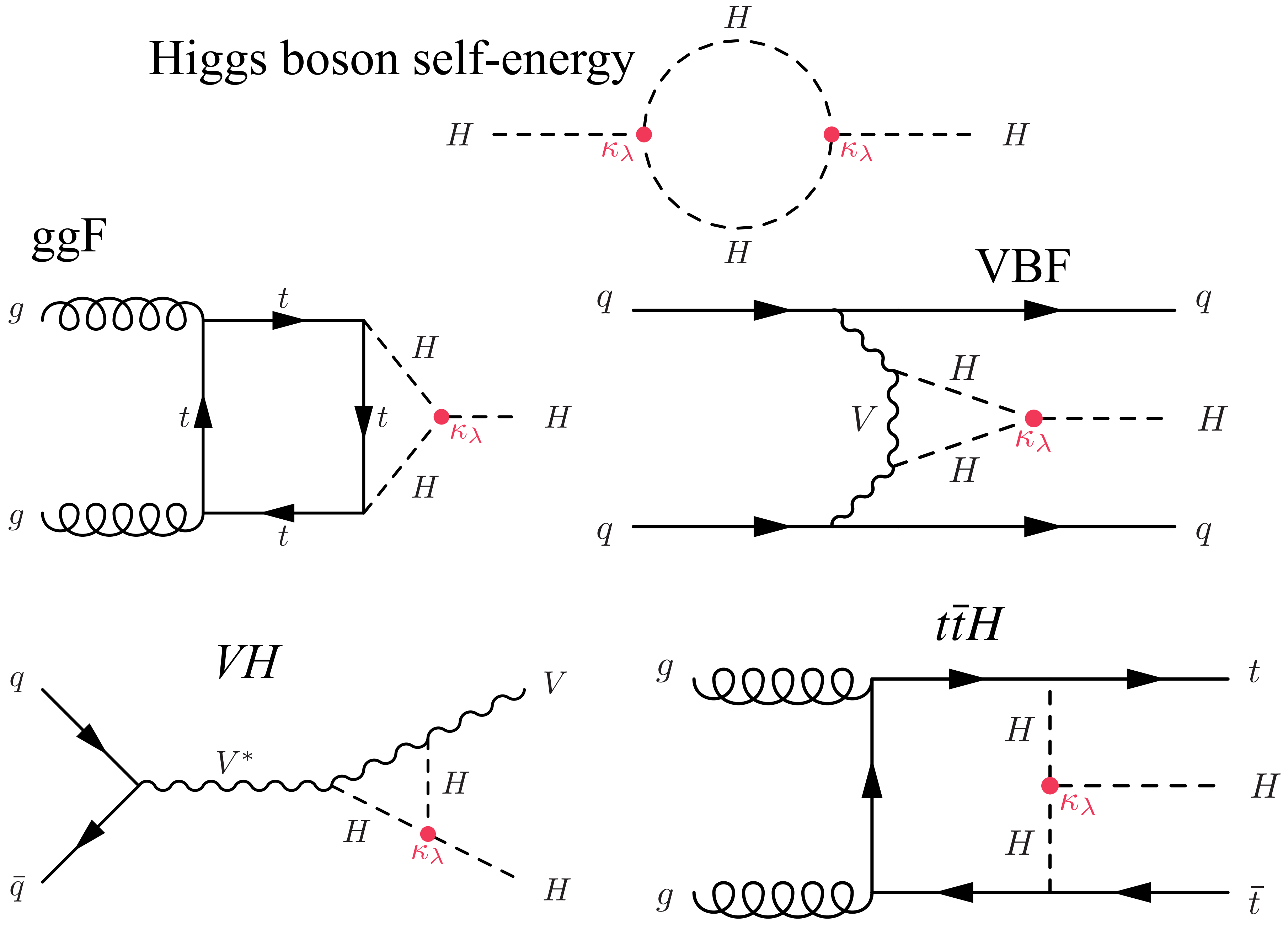
$$\sigma_{\mathrm{ggF}}^{\mathrm{SM}}(pp \to HH) = 31.0^{+2.1}_{-7.2}\ \mathrm{fb\ at}\ \sqrt{s} = 13\ \mathrm{TeV}$$



$$\sigma_{\mathrm{VBF}}^{\mathrm{SM}}(pp \to HH) = 1.72 \pm 0.04\ \mathrm{fb\ at}\ \sqrt{s} = 13\ \mathrm{TeV}$$



Indirect measurements: single-Higgs production



H self coupling - results

- **Single- and double-Higgs** boson analyses based on the complete Run 2
- **Investigate** the Higgs boson self-interaction and **shed more light** on the Higgs boson potential, the source of **EW symmetry breaking** in the SM.

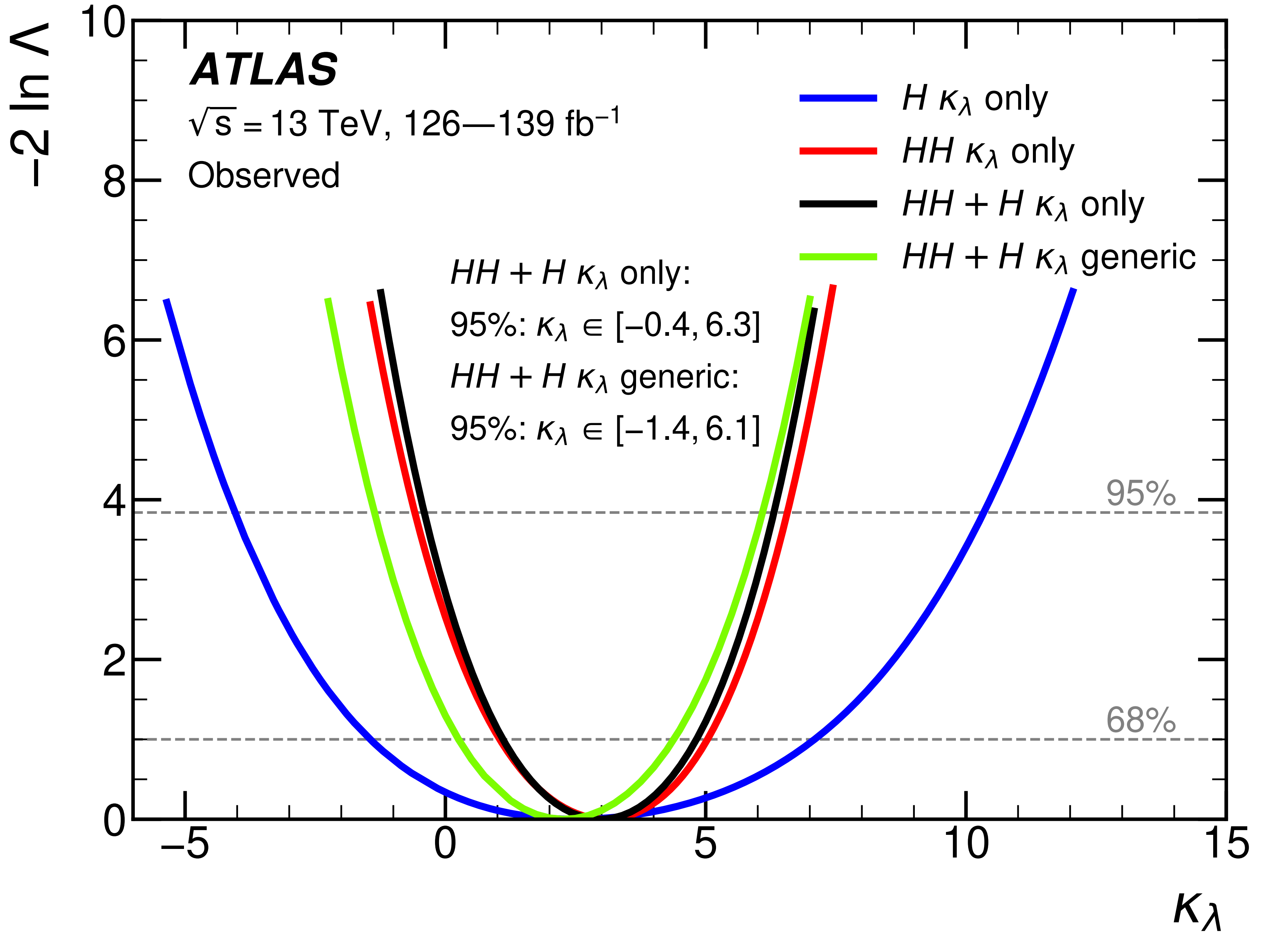
ggF *HH* and VBF *HH* directly sensitive to the Higgs boson self-coupling constraint

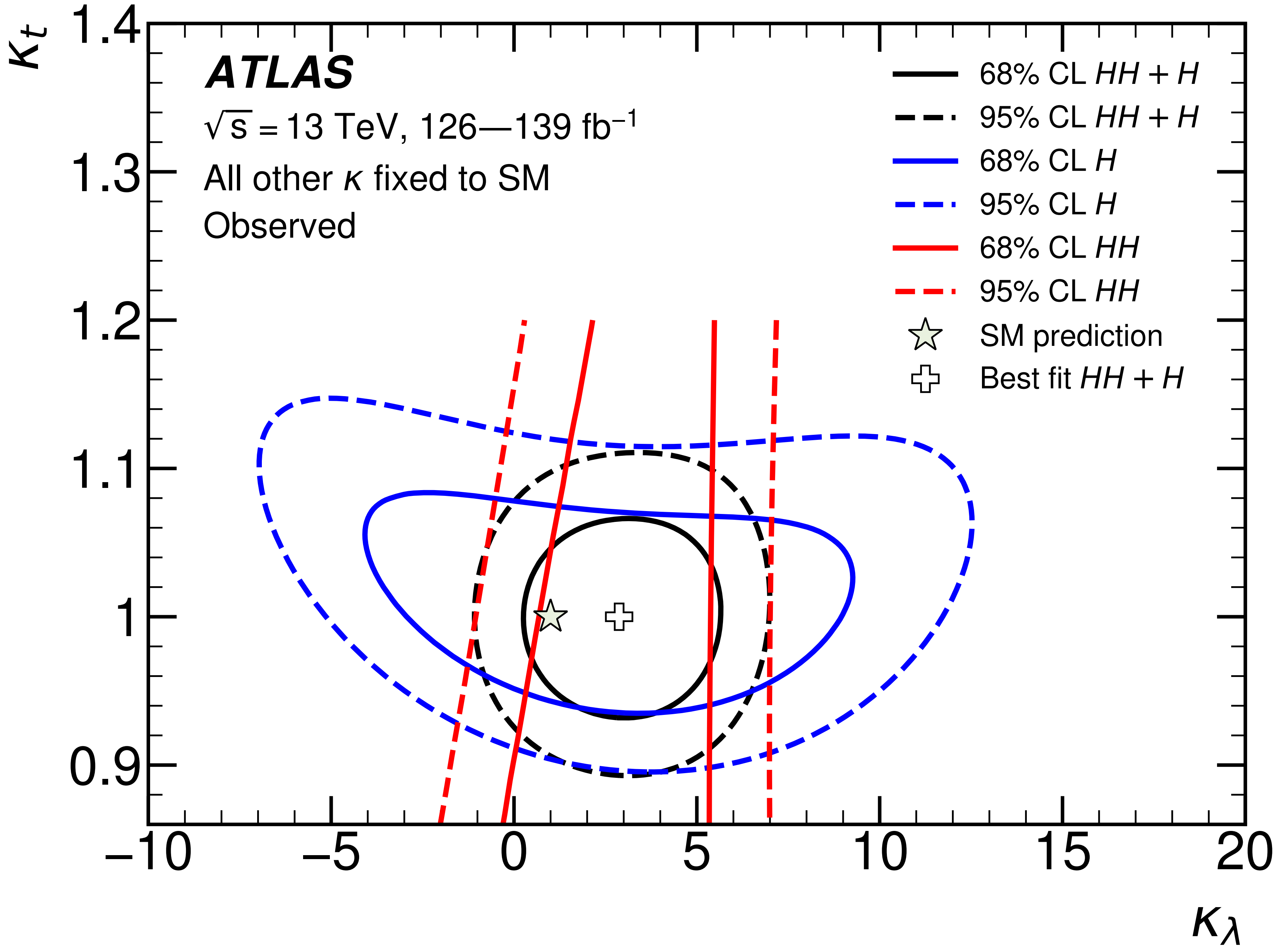
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value$^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-*H* combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+*H* combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+*H* combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+*H* combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

model independent limit

double-Higgs decay channels are combined with single-Higgs boson cross-section measurements assuming κ_λ is the only source of physics beyond the SM

- Using the **combined** measurement (assuming κ_λ only source of physics BSM), **values outside** $-0.4 < \kappa_\lambda < 6.3$ are **excluded** at **95% CL** (exp. $-1.9 < \kappa_\lambda < 7.6$)
- This **study** provides the **most stringent constraints** on Higgs boson self-interactions to date





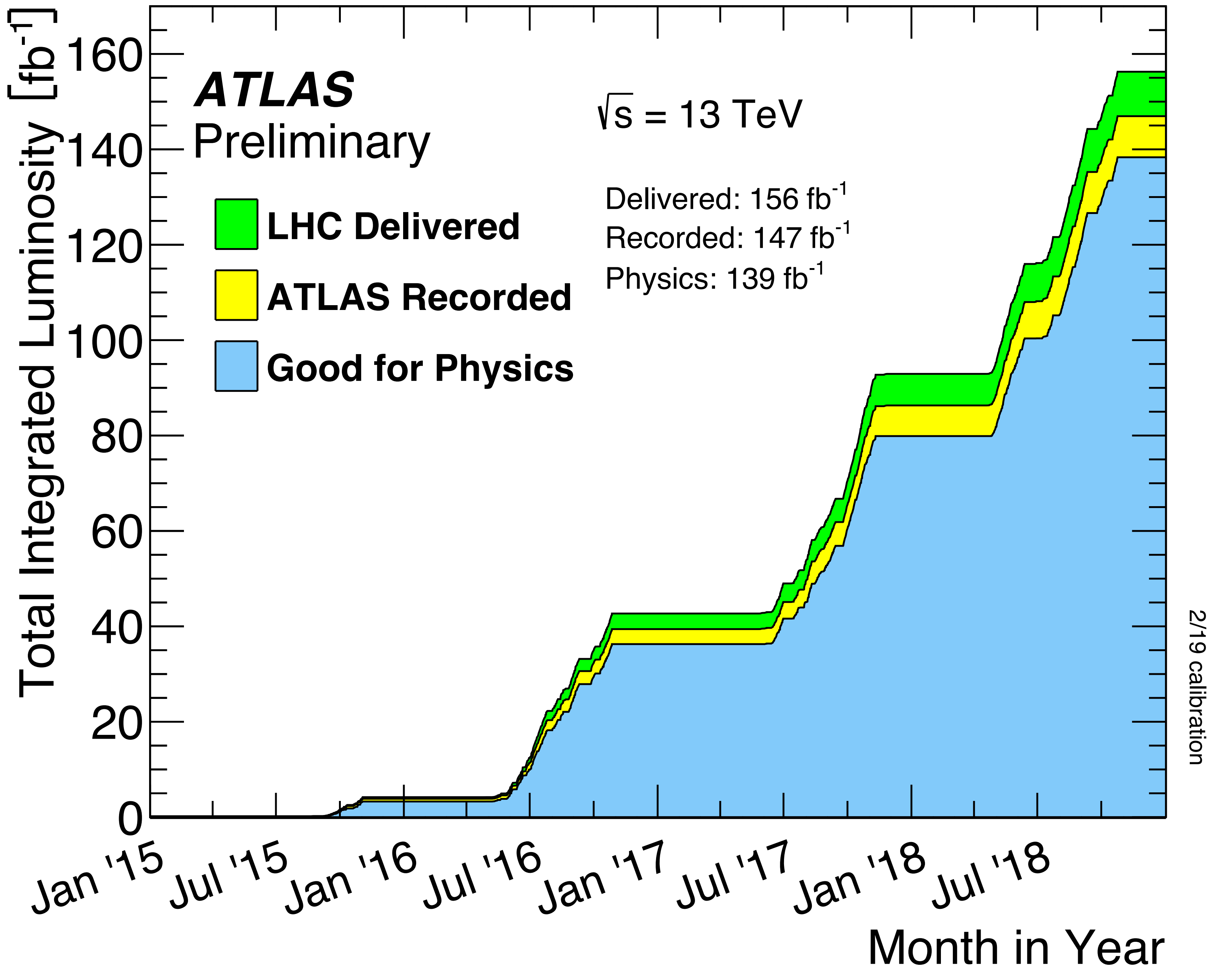
Conclusions

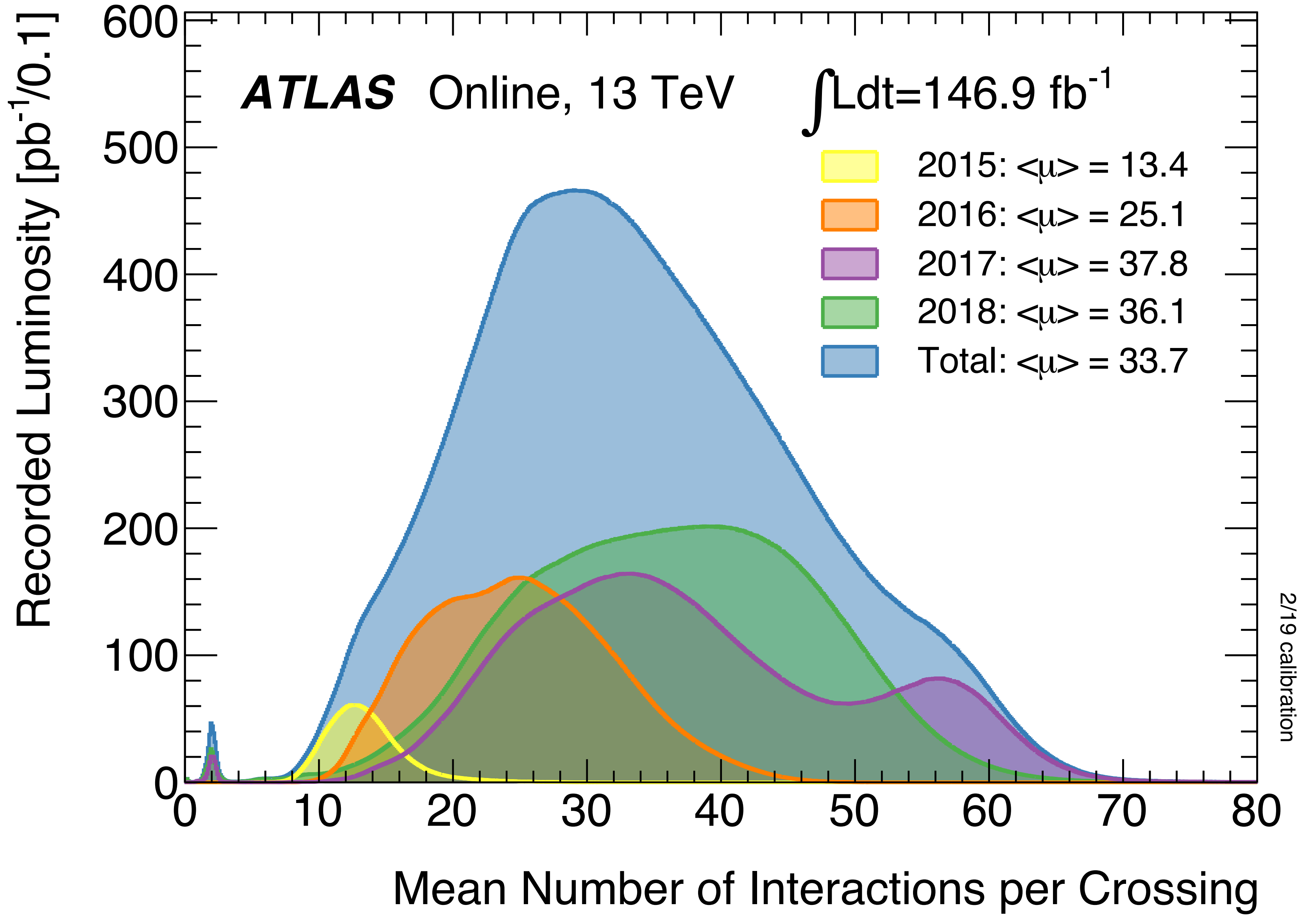
- We are **10 years after the Higgs boson discovery**
  - Most up to date **results** of its **properties** were presented
- **Gauge couplings** to vector bosons (W, Z) and γ and **Yukawa couplings** to 3rd generation fermions (t, b, τ) are **experimentally confirmed**
- **Achieved** less than **10% precision** (total uncertainties) in a few individual channels but others still **dominant by statistical uncertainties**
  - *Improvement in Run3*
  - *Aiming for **percent-level precision at HL-LHC***
- **STXS** regions allows stronger constraints on BSM & **SMEFT** well **advanced**
- The best **constraints** on ***HH*** signal strength and $\boldsymbol{\kappa_\lambda}$ to date from ATLAS
- So far, **Higgs complies with SM predictions**

Backup

Run 2

- Run2 data-taking successfully finished in 2018
- 139 fb^{-1} of 13 TeV proton-proton collision data collected by ATLAS in total after data quality (DQ) requirements thanks to the excellent LHC performance





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Run 3

Slightly higher CM energy, double luminosity of Run 2

Channel	13.6 / 13 TeV	14 / 13.6 TeV
H (ggF)	**7%**	6%
HH	**11%**	7%
tt	**11%**	6%
ttH	**13%**	7%
tttt	**19%**	11%
SUSY stop (1.2–1.5 TeV)	**20–30%**	14–19%
Z' (5–6 TeV)	**50–70%**	30–40%
QBH (9.5 TeV)	**250%**	100%

LHC risk analysis found training to 7 TeV unreasonable
→ 6.8 TeV was decided in 2021

Calendar Year	2022	2023 / 2024			
Machine efficiency	25 %	50 %			
Bunch population $[10^{11}]$ at FT	1.4	1.8			
Collisions at IP1 and IP5	2736	2736		2484	
Norm. emittance at FT $[\mu m]$	1.8	1.8	2.5	1.8	2.5
Levelling time [h]	5.3	12.1	11.4	10.2	9.3
Optimal fill length [h]	10.7	15.5	15.0	13.7	13.3
Integrated luminosity/year $[fb^{-1}]$	35.4	84.4	83.6	81.2	80.1

Table 3: Performance estimate at 6.8 TeV for 2022 and 2023/2024, considering various possible beam parameters in 2023/2024, assuming a turn around time of 4.5 h, 130 days of pp run per year, and an effective cross-section of 100 mb. The impact of the finite β^* steps during β^*-levelling is neglected, degrading at the percent level or less the performance of each year (e.g. corresponding to a reduction of the 2022 and 2023/2024 performance by $0.3 - 0.4\,fb^{-1}$ and $1.1 - 1.2\,fb^{-1}$, respectively, assuming a β^* step of the order of 5 %, see [34] for more details).

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