Recent Higgs results from the LHC

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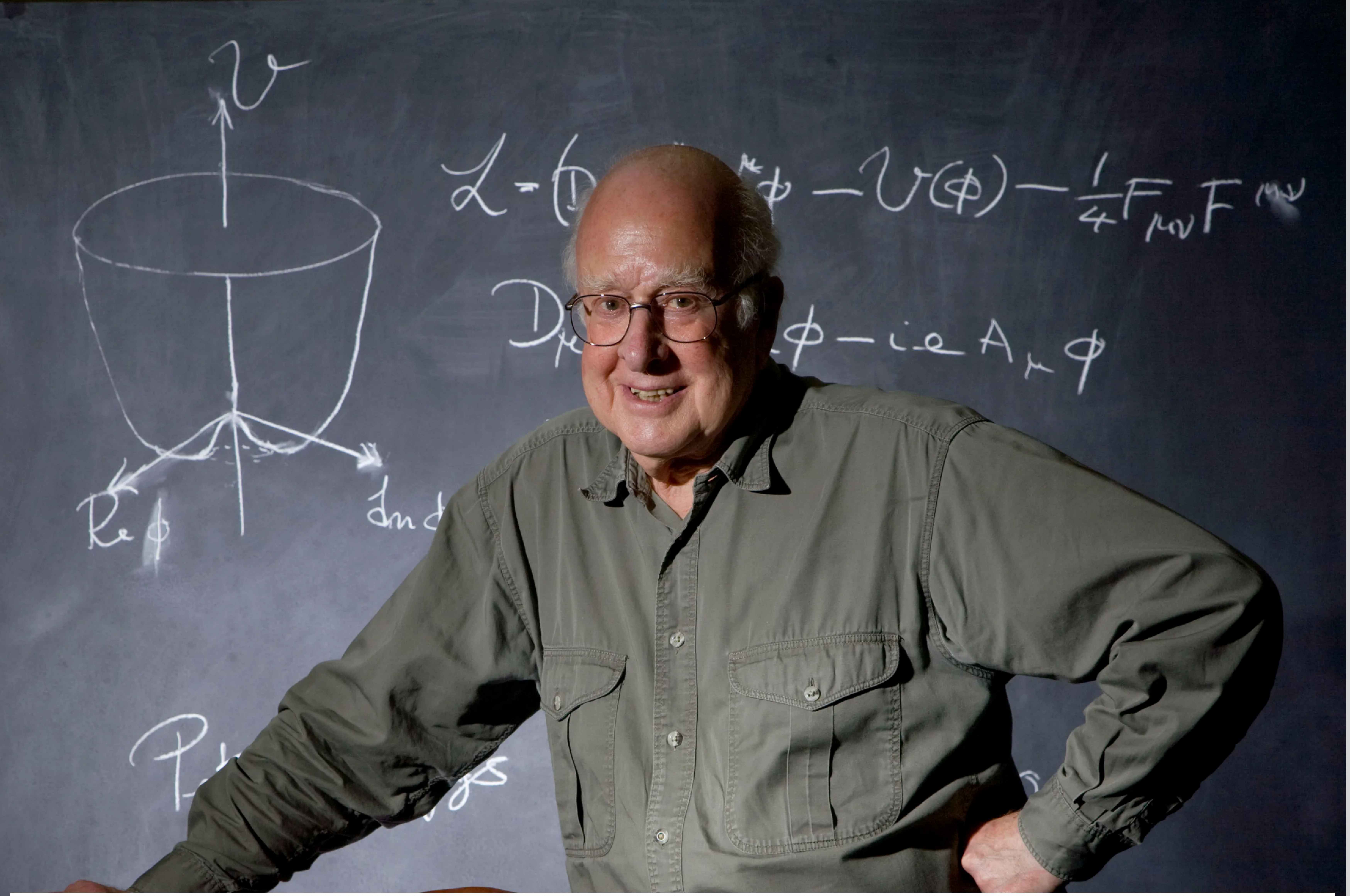
on behalf of the ATLAS and CMS Collaborations

MAX-PLANCK-INSTITUT FÜR PHYSIK

ATLAS EXPERIMENT

CMS

Corfu Summer Institute: Workshop on Standard Model and Beyond / Corfu, Greece / Aug 25 - Sep 04, 2024



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In Memoriam

Peter Ware Higgs

(1929 - 2024)

It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons.[8]

Higgs boson physics

Discovery of a unique scalar particle at the LHC in 2012
opened a new path to resolving some of the key open questions in the Standard Model.

$$\mathscr{L}_{\text{Higgs}} = |D_\mu \phi|^2 + \psi_i \, y_{ij} \, \psi_j \, \phi + h.c. - V(\phi) \quad + \sum C_i^{(d)} \mathcal{O}_i^{(d)} / \Lambda^{d-4} + \ldots$$

Why is the electroweak interaction so much stronger than gravity? Why is there a large range of fermion masses?

Higgs production and decay rates; coupling strengths to vector bosons and fermions.

What is the origin of dark matter? Are there new particles interacting with the Higgs boson?

Higgs portal to dark sector or to other new particles, probed via total Higgs decay width or exotic decays.

What is the exact structure of the Higgs potential? Is there a connection to the evolution of the Universe?

Higgs mass, Higgs self-interaction in Higgs pair production or via loop effects in single-Higgs production.

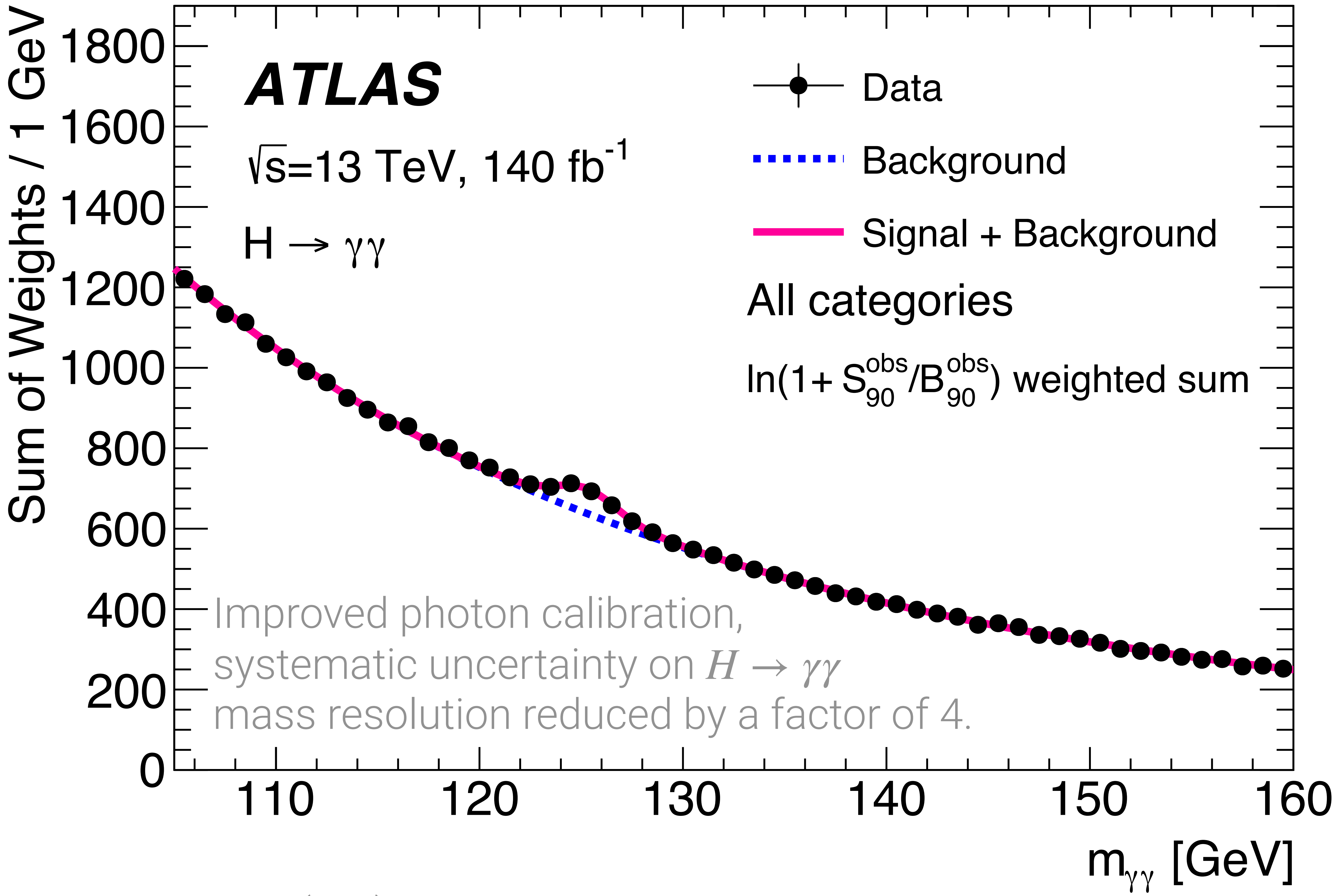
What is the origin of matter-antimatter asymmetry? Are there any extensions of the Higgs sector?

Anomalous Higgs couplings (e.g. CP violation), affecting also differential distributions.

Complementary to Higgs boson property measurements: direct searches for new (Higgs) particles.

Current state-of-the-art results

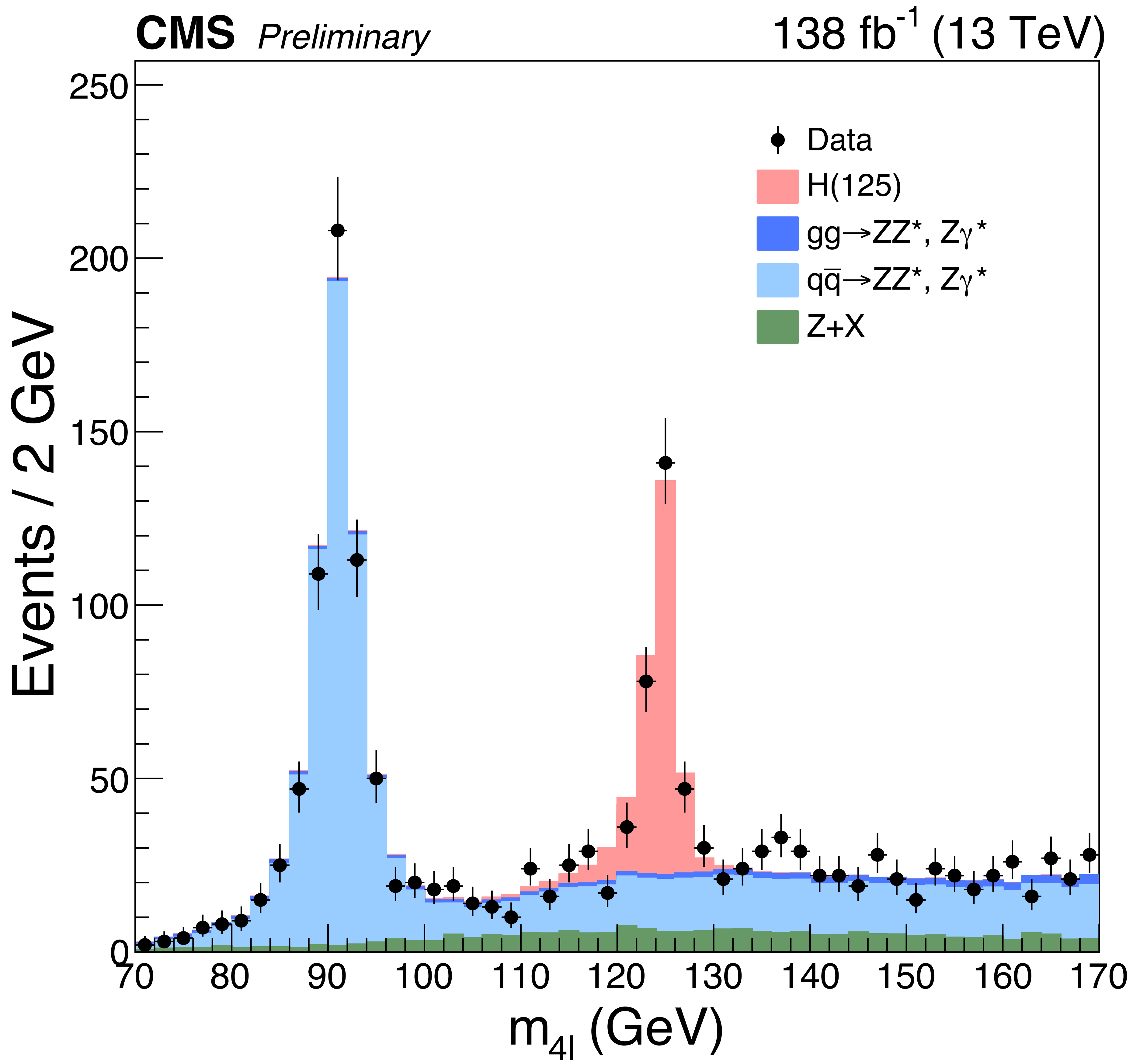
Higgs boson mass



ATLAS: PRL 131 (2023) 251802

Most precise measurement to date (ATLAS $4\ell + \gamma\gamma$):

$$m_H = 125.11 \pm 0.09\ \text{(stat)} \pm 0.06\ \text{(syst)}\ \text{GeV}$$



CMS-PAS-HIG-21-019 (Sep 2023)

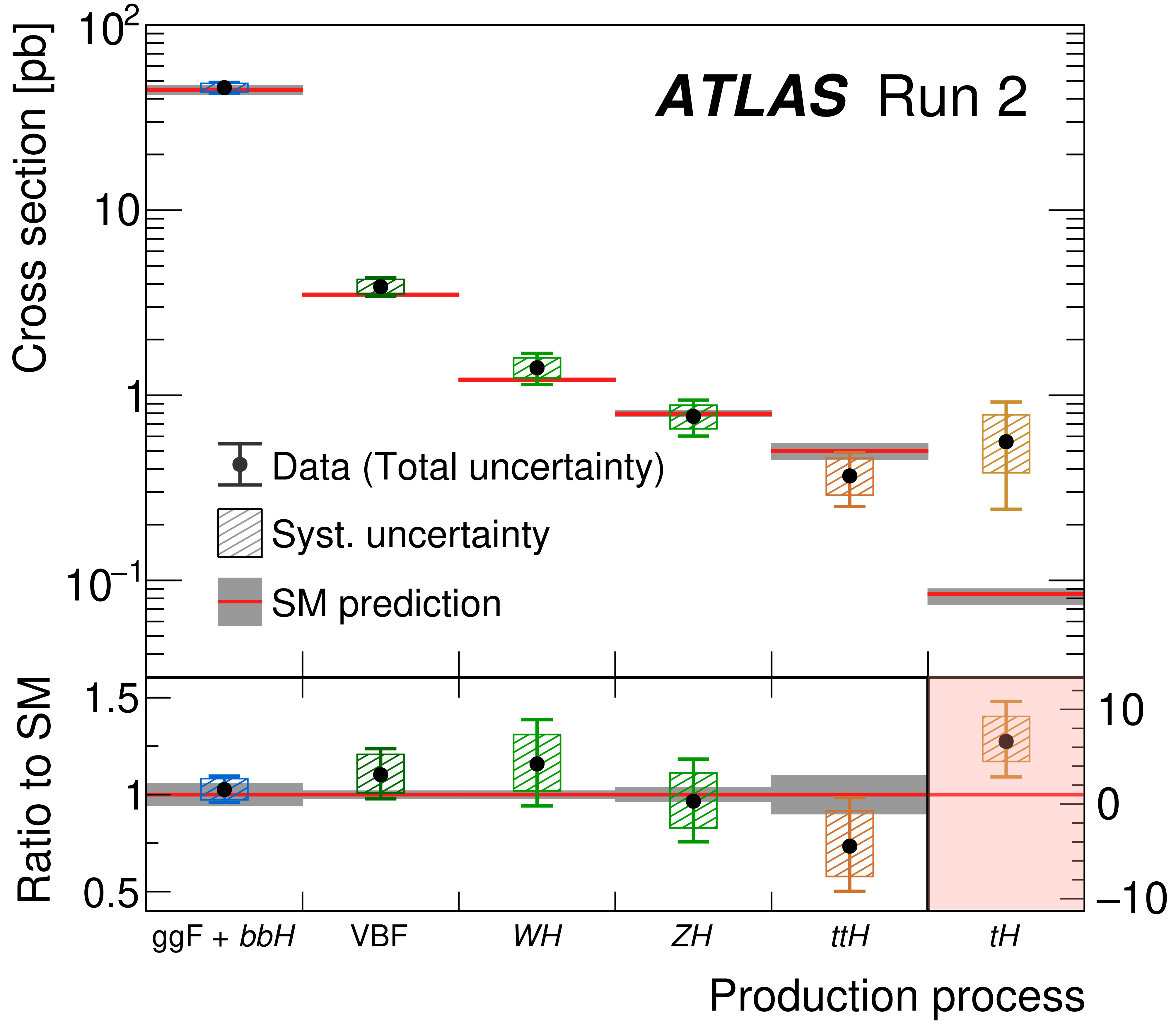
Most precise single measurement (CMS $H \to 4\ell$):

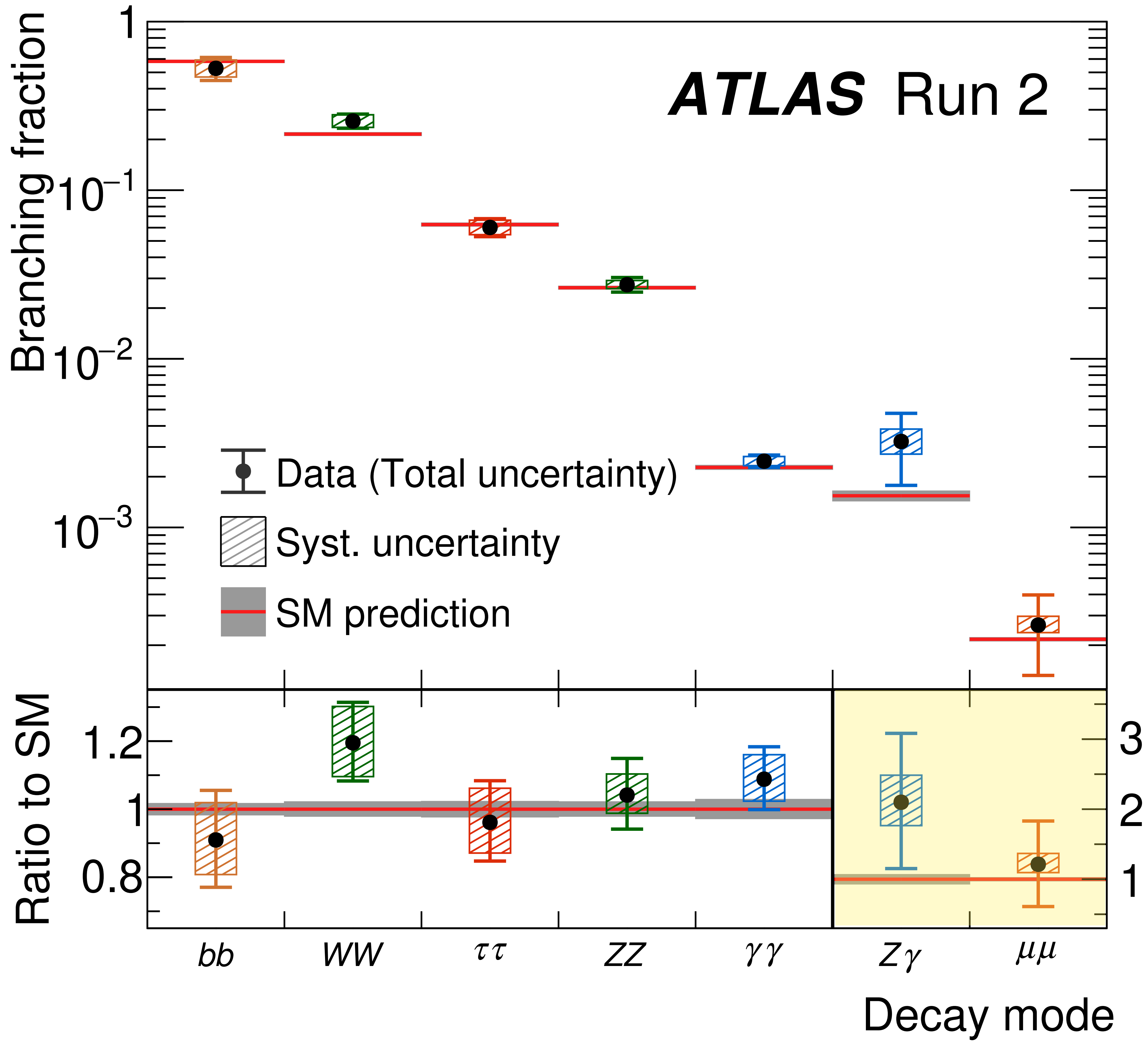
$$m_H = 125.08 \pm 0.10\ \text{(stat)} \pm 0.05\ \text{(syst)}\ \text{GeV}$$

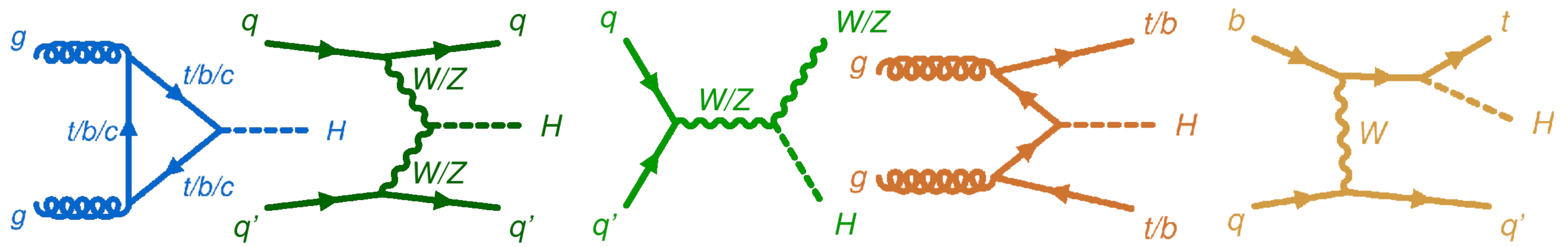
Mass measurement precision: < 1‰ .

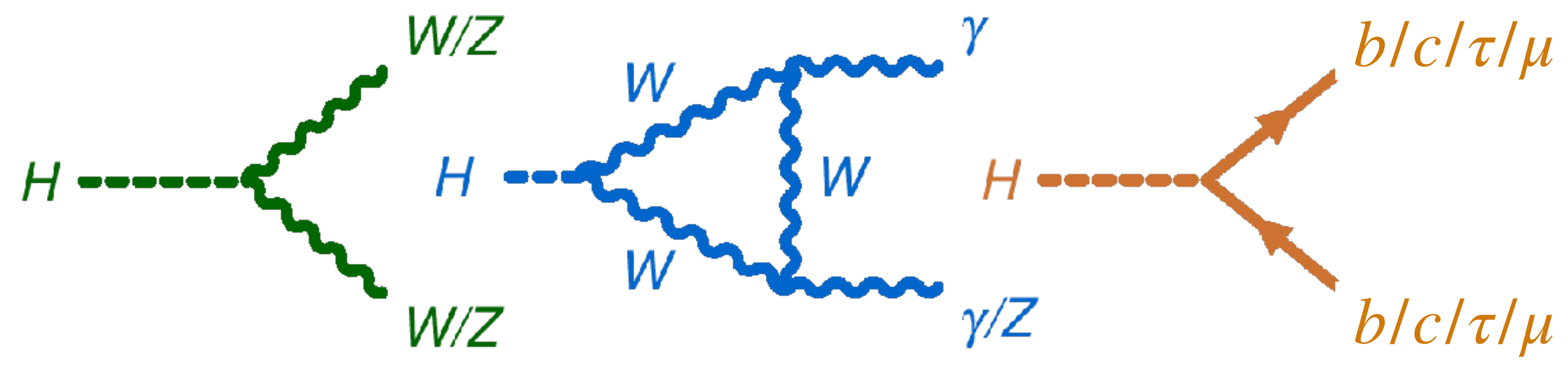
Higgs boson production and decays

ATLAS: Nature 607 (2022) 52 , CMS: Nature 607 (2022) 60





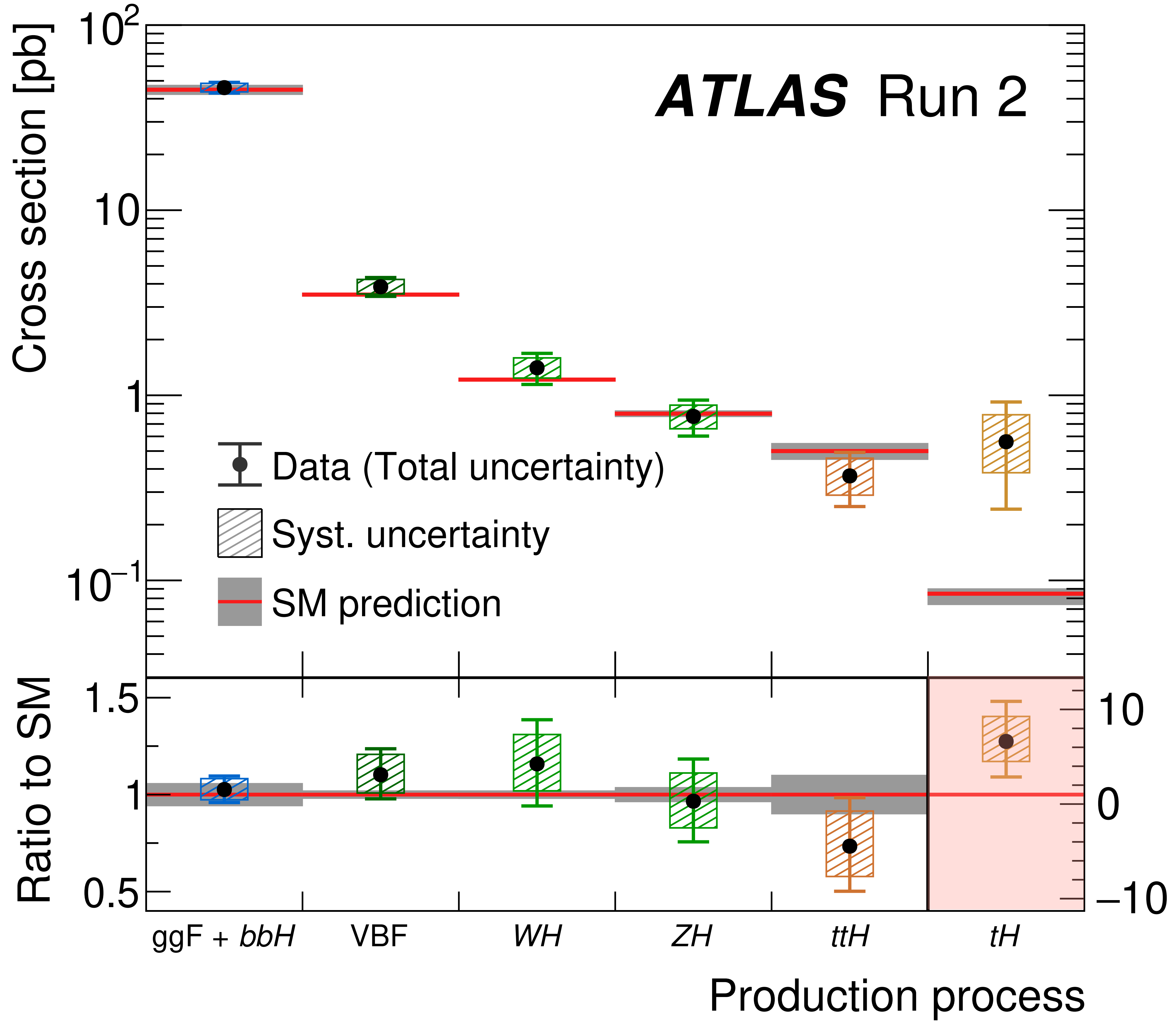


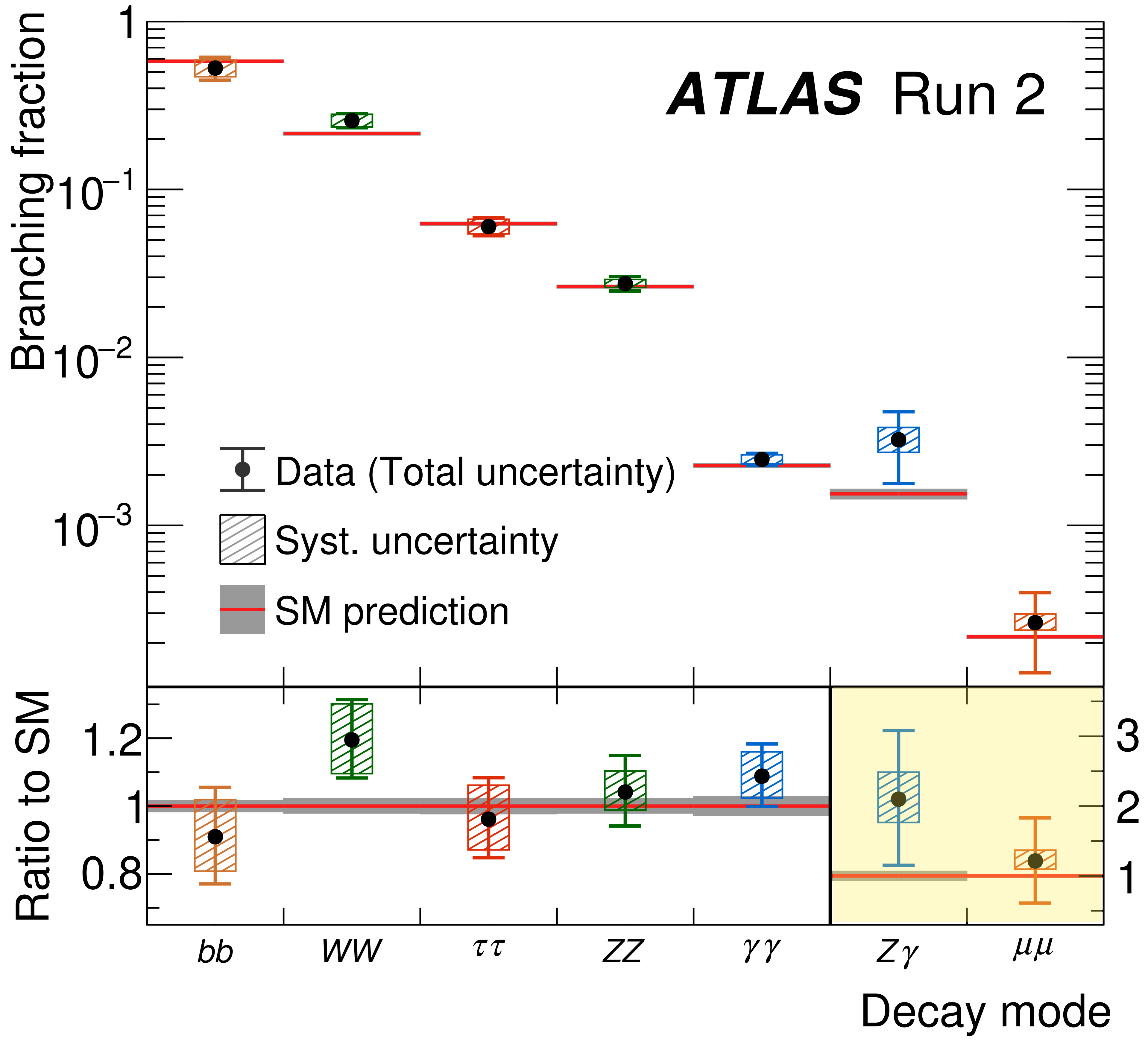


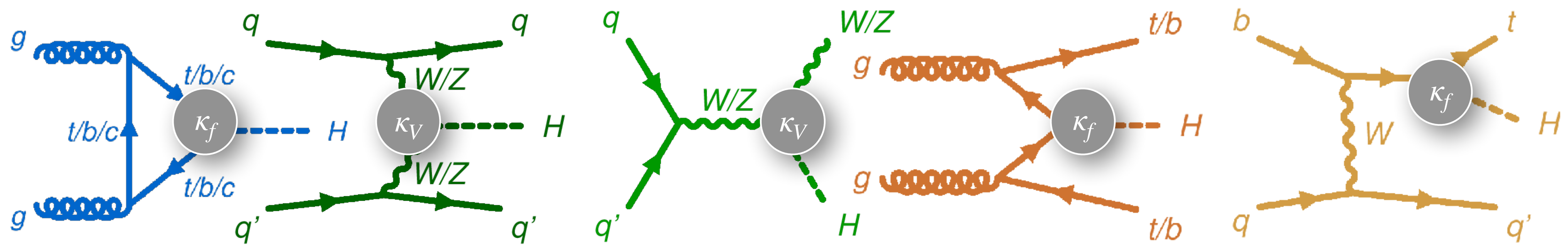
Main production and decay processes observed, measured with 10% - 20% precision.

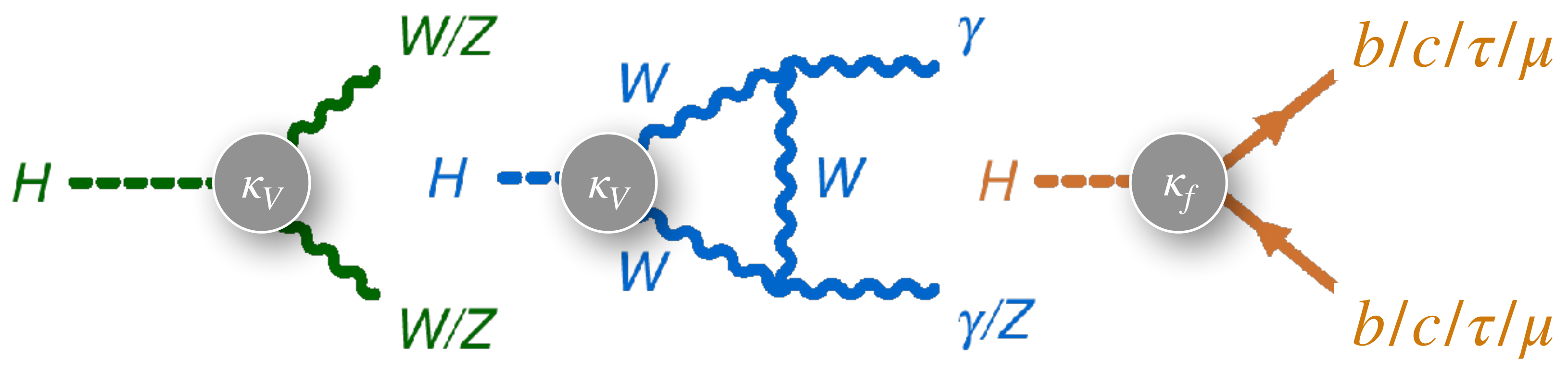
Higgs boson production and decays

ATLAS: Nature 607 (2022) 52 , CMS: Nature 607 (2022) 60





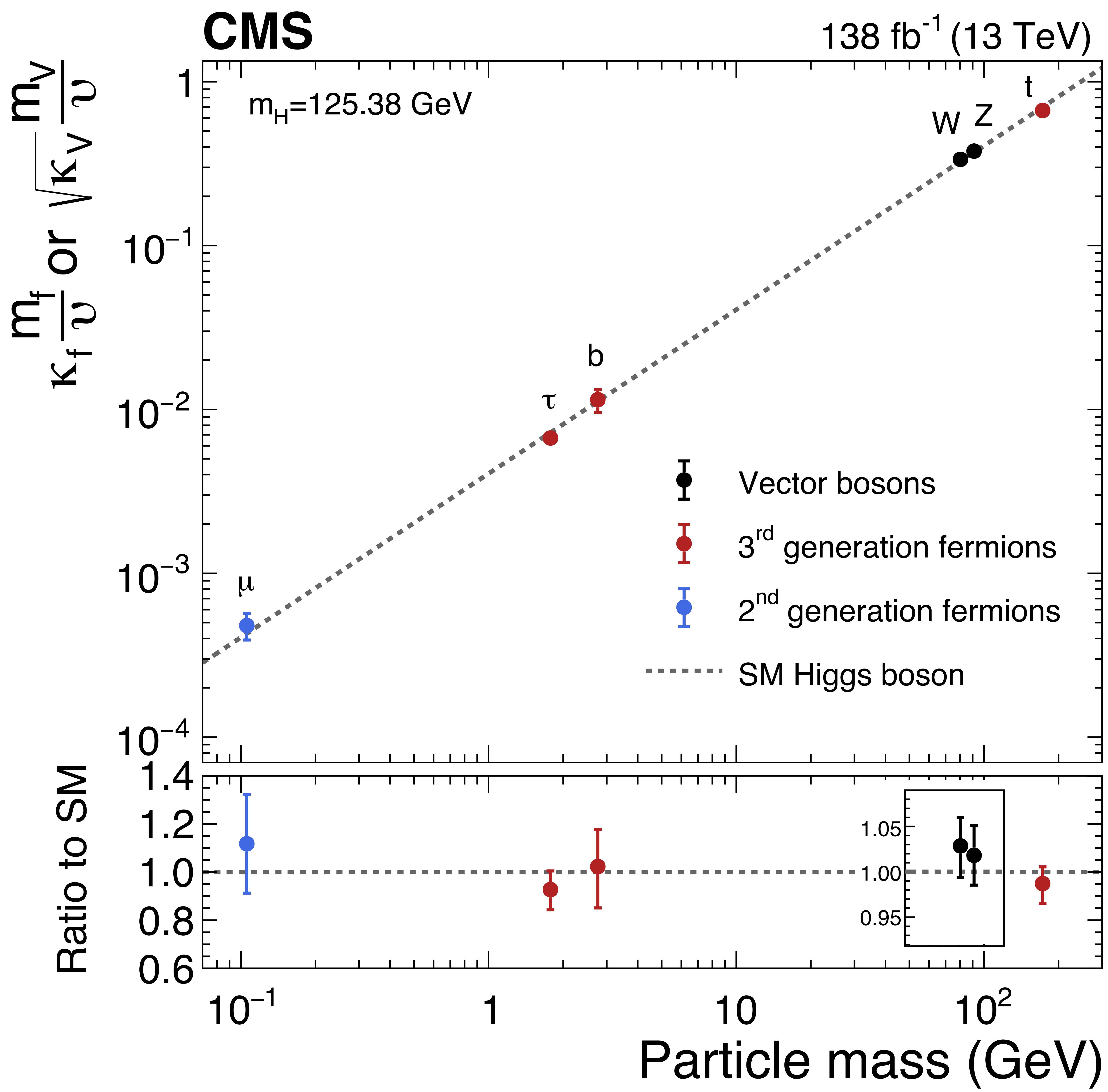


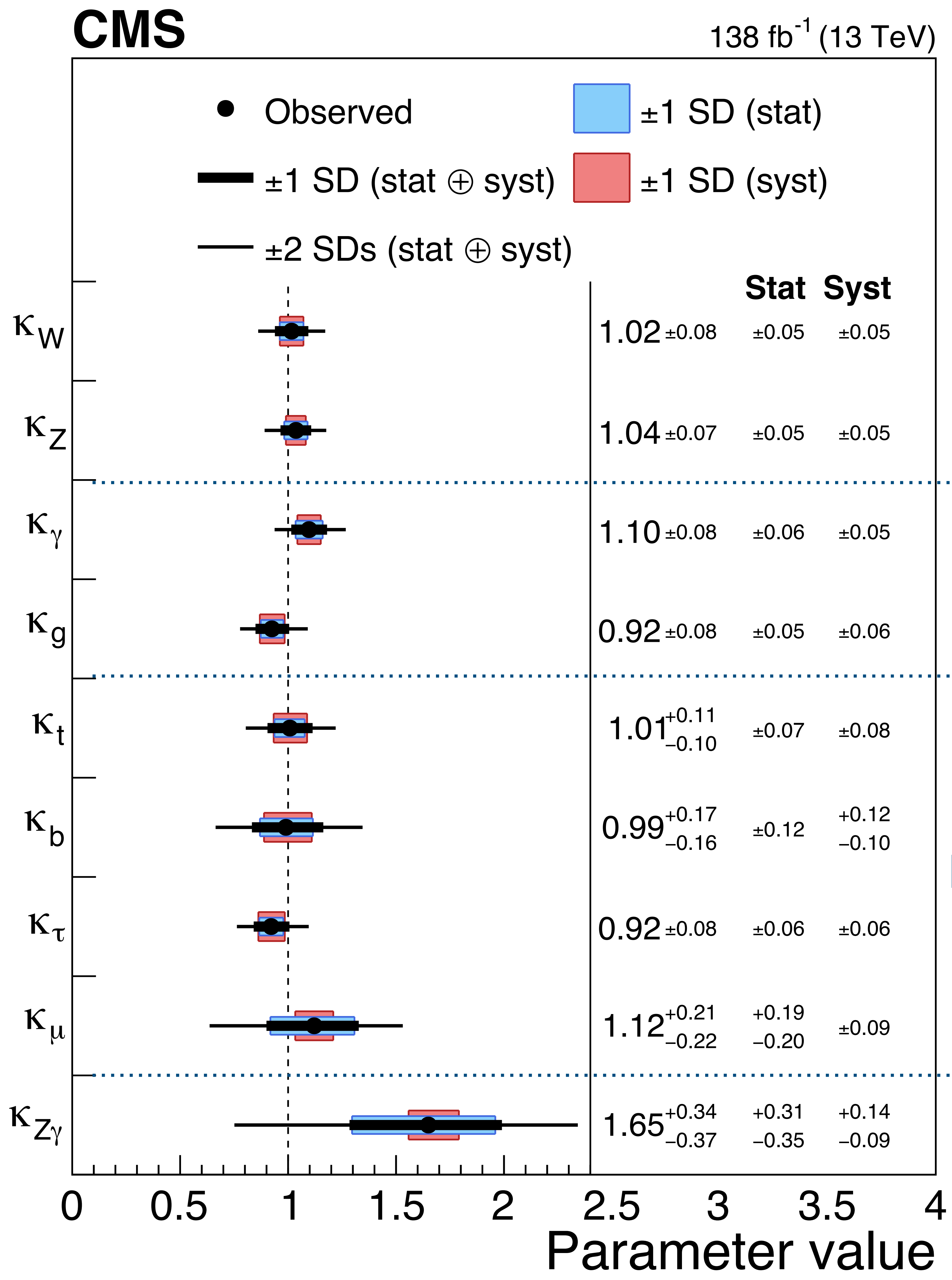


Main production and decay processes observed, measured with 10% - 20% precision.

Higgs boson coupling strengths

ATLAS: Nature 607 (2022) 52 , CMS: Nature 607 (2022) 60





Vector bosons: 8%.

Effective (loops): 8%.

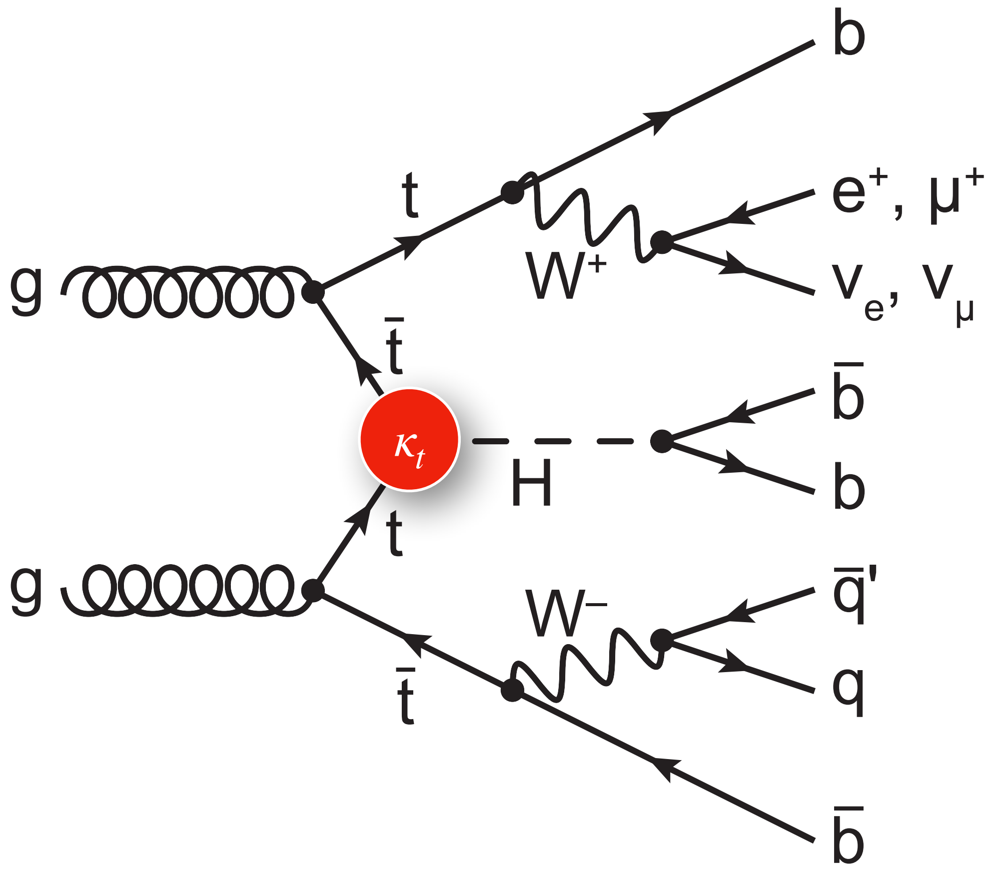
Fermions: 10 - 20%.

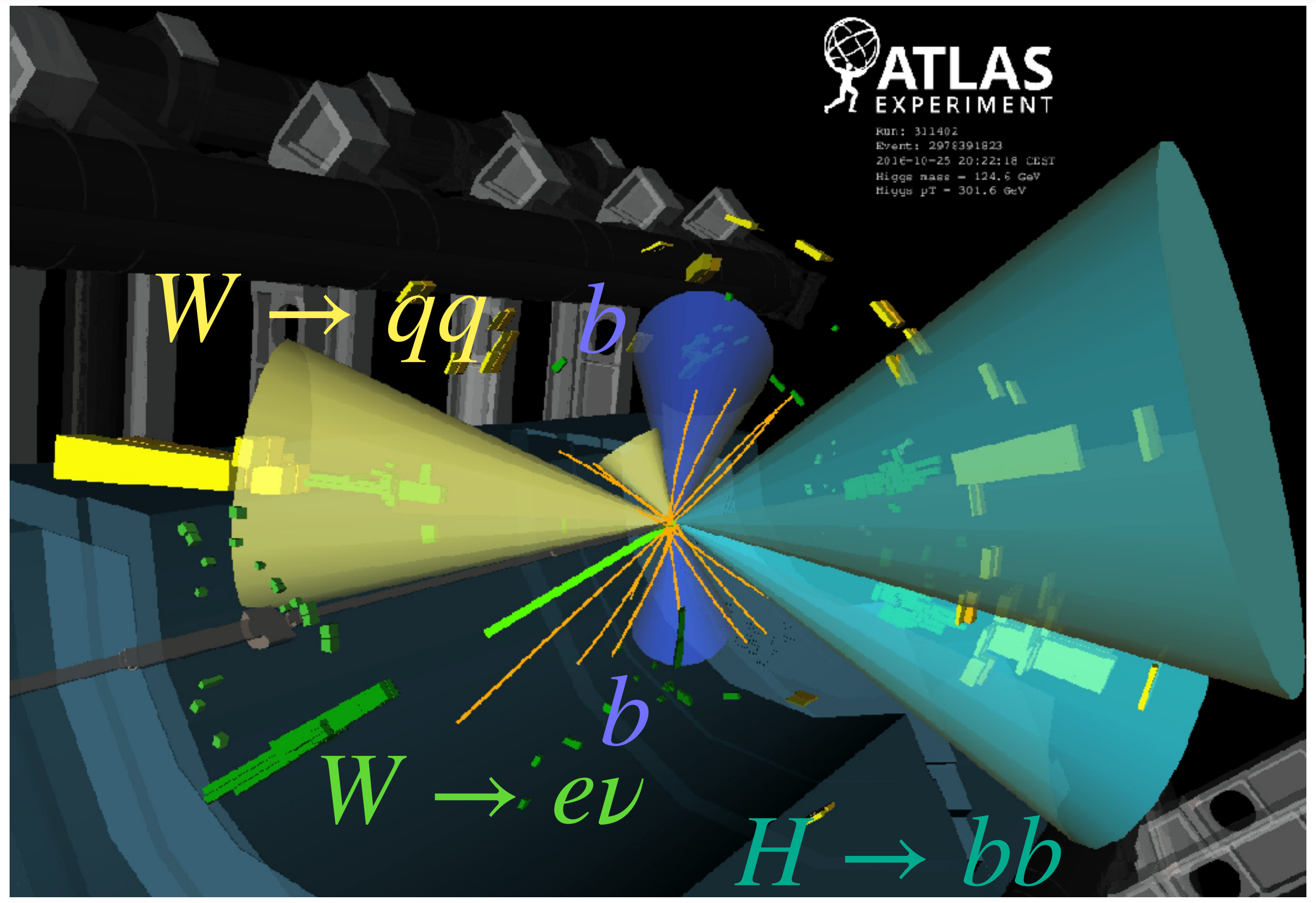
Evidence by CMS, JHEP 01 (2021) 148.

Evidence by ATLAS+CMS, PRL 132 (2024) 02183.

Spotlight on Higgs interactions with fermions

ATLAS final Run 2 $ttH(bb)$ production measurement





NEW ATLAS: arXiv:2407.10904, submitted to EPJC

Access to the top-Yukawa coupling at tree-level.

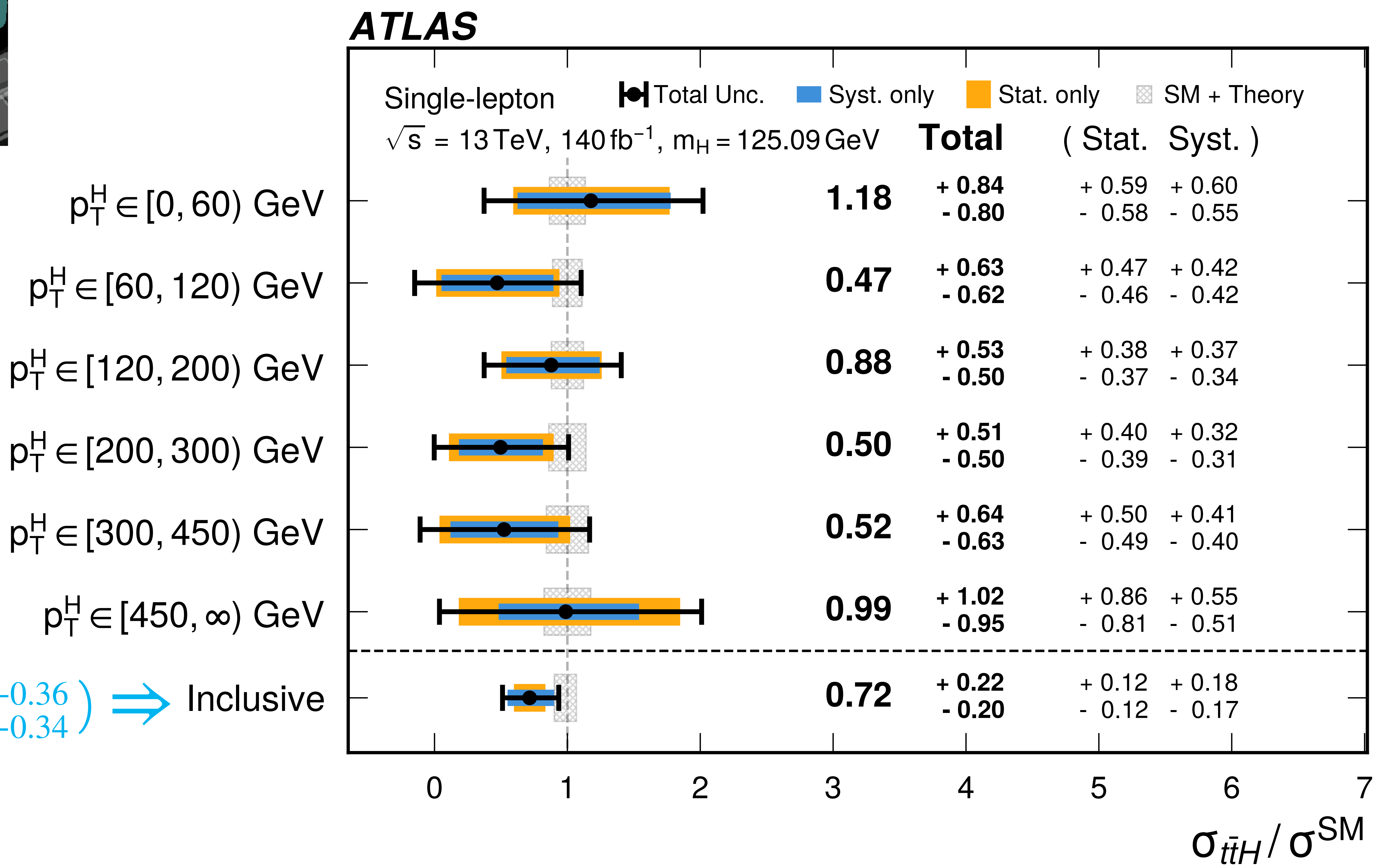
Complex final state:
4 b-jets and 2 W bosons (1or 2 charged leptons).

ATLAS re-analysis of the full Run 2 dataset:

- Improved b-tagging (many developments over past years).
- Increased signal acceptance due to looser b-tagging.
- Improved $tt + jets$ background modeling.
- Neural-network-based event categorization.

Observed (expected) signal significance: 4.6 σ (5.4 σ)

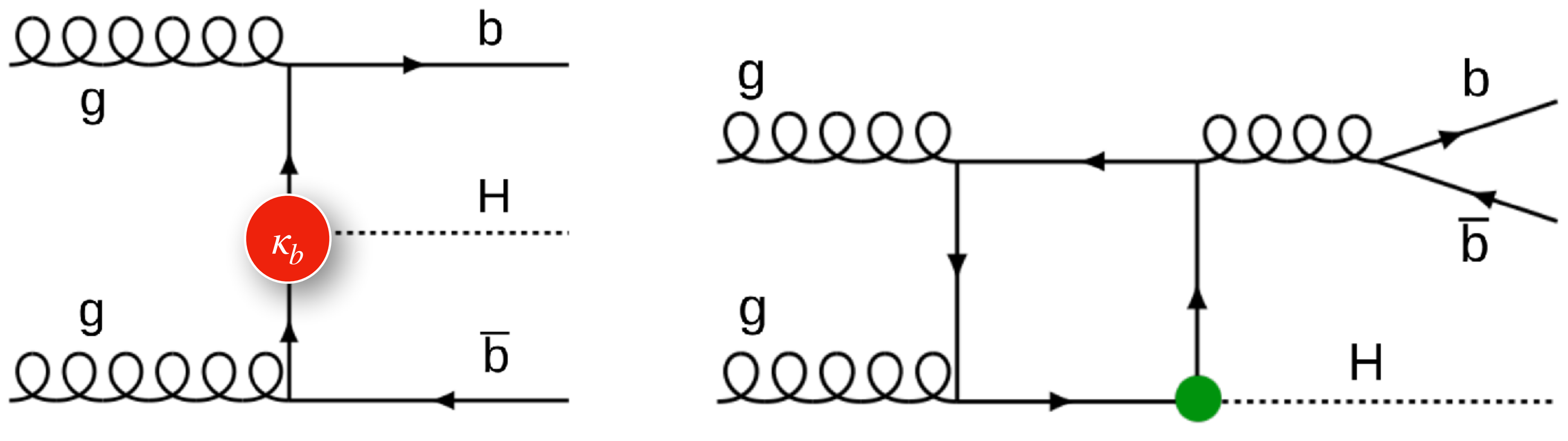
Measurement precision strongly improved (previously $0.35^{+0.36}_{-0.34}$) $\Rightarrow$



Most precise ttH cross-section measurement in a single decay channel.

CMS results with similar sensitivity: $\mu_{ttH} = 0.33 \pm 0.26$ (arXiv:2407.10896, submitted to JHEP)

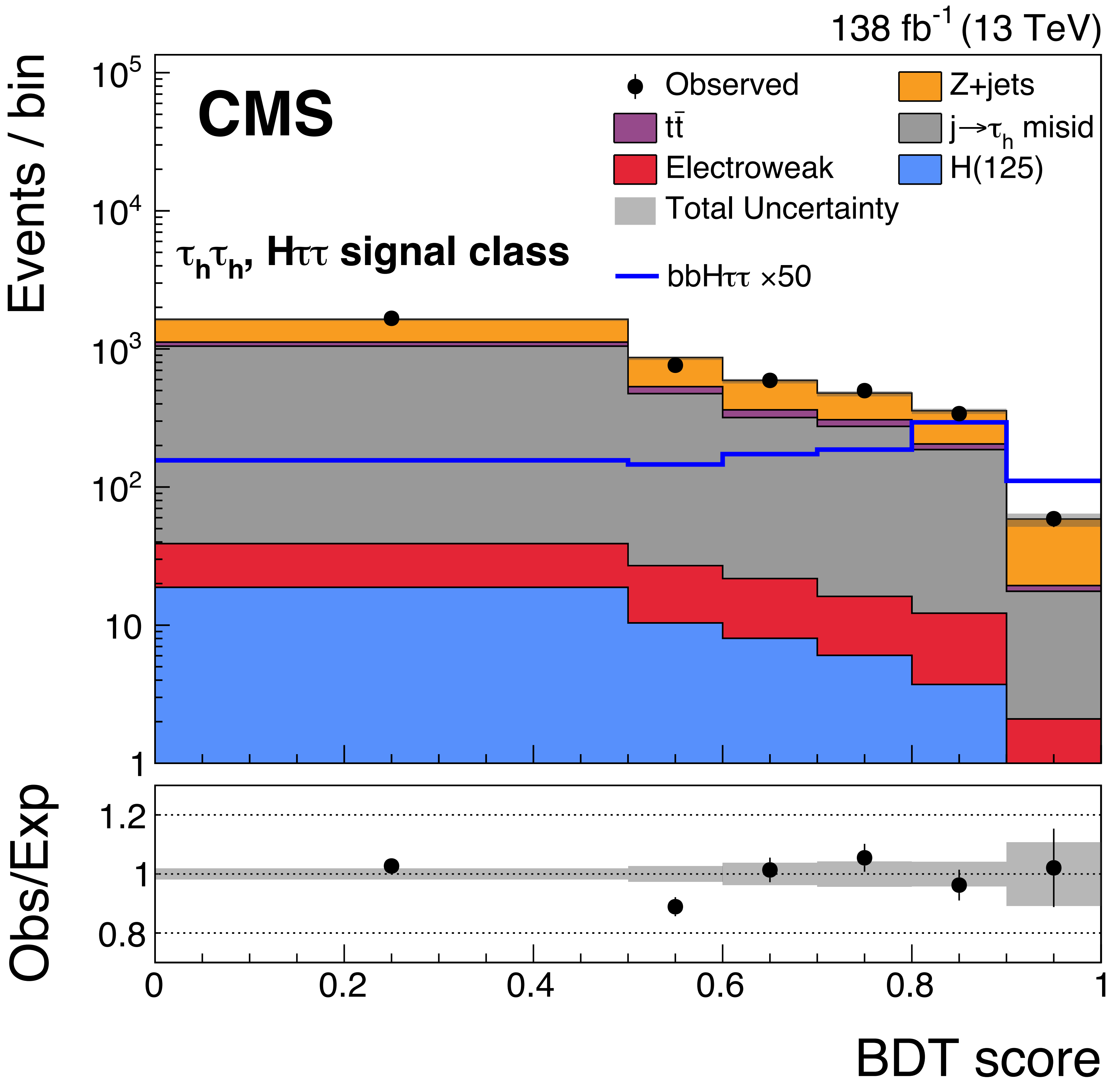
First search for the bbH production (CMS)

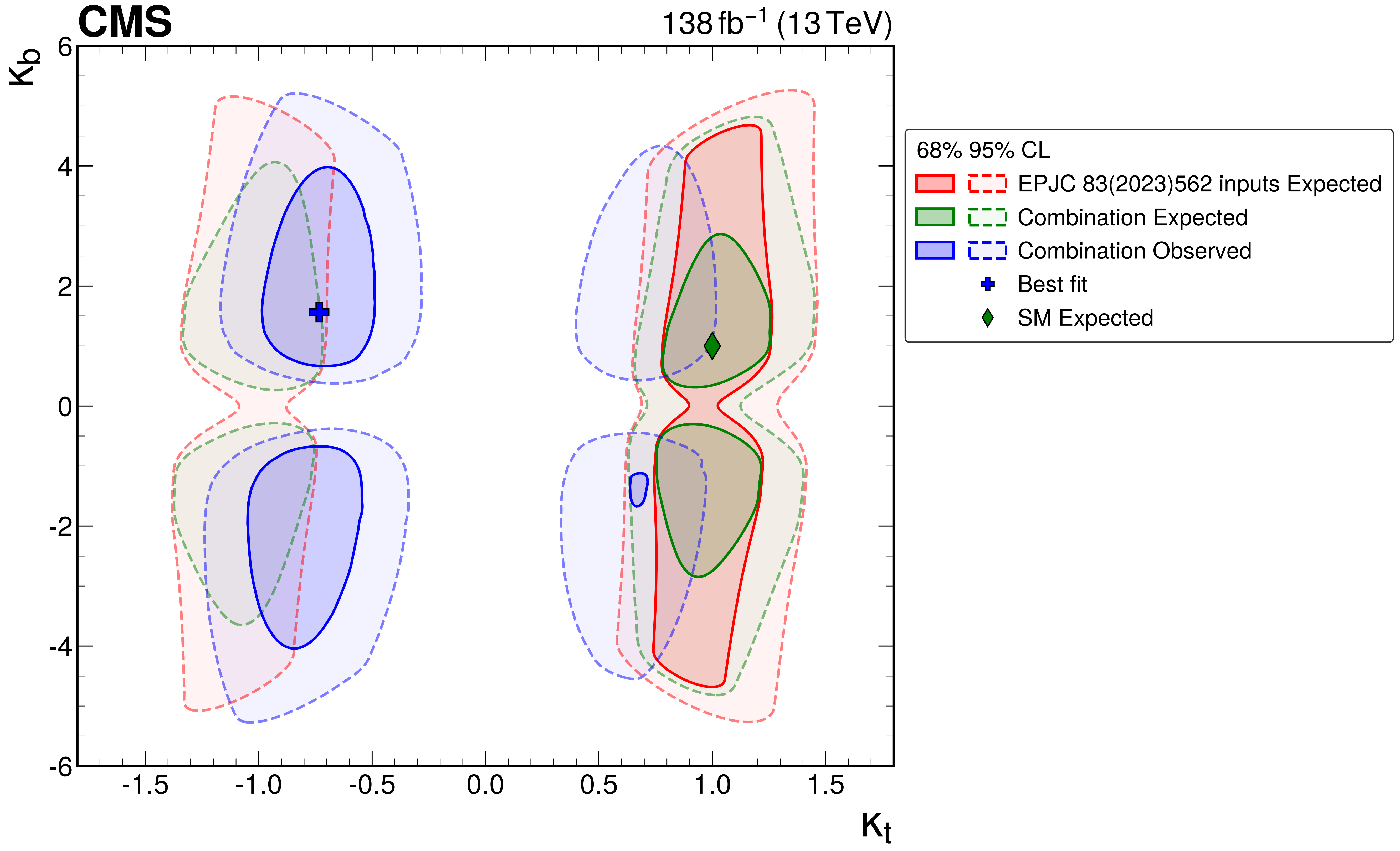


CMS: arXiv:2408.01344, submitted to PLB

Final states with $\mathrm{H} \to \tau\tau$ and $\mathrm{H} \to \mathrm{WW}$ decays.
Larger background compared to the ttH search.

Destructive interference to bbH from top-quark loops:
correlated measurement of top- and b-quark couplings.



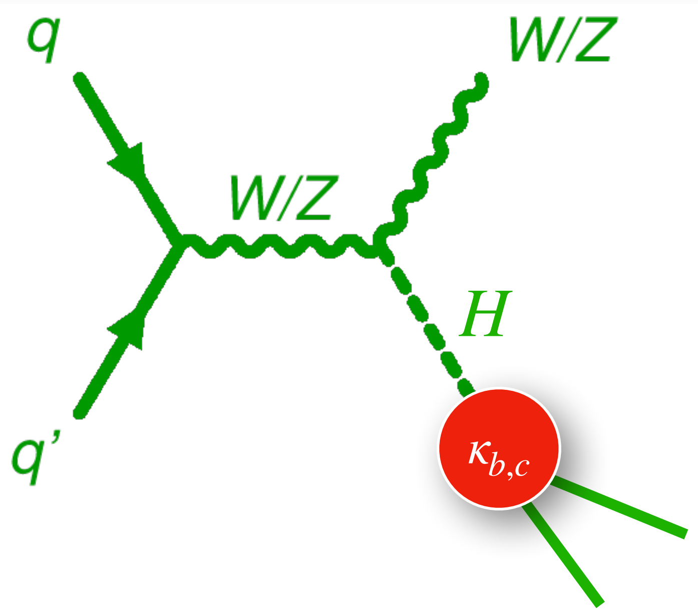


Observed (expected) upper limit on the signal strength at 95% CL: 3.7 (6.1) times the SM.

ATLAS final Run 2 VH(bb, cc) measurement

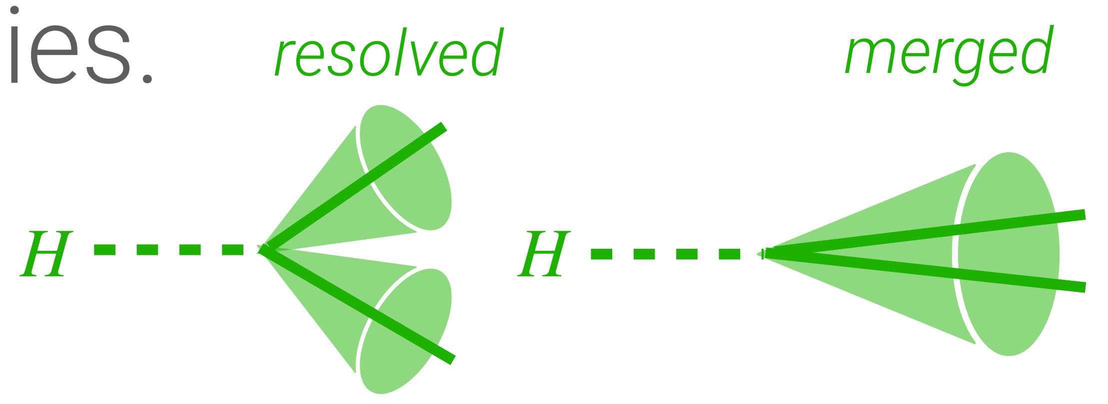
NEW

ATLAS-CONF-2024-010



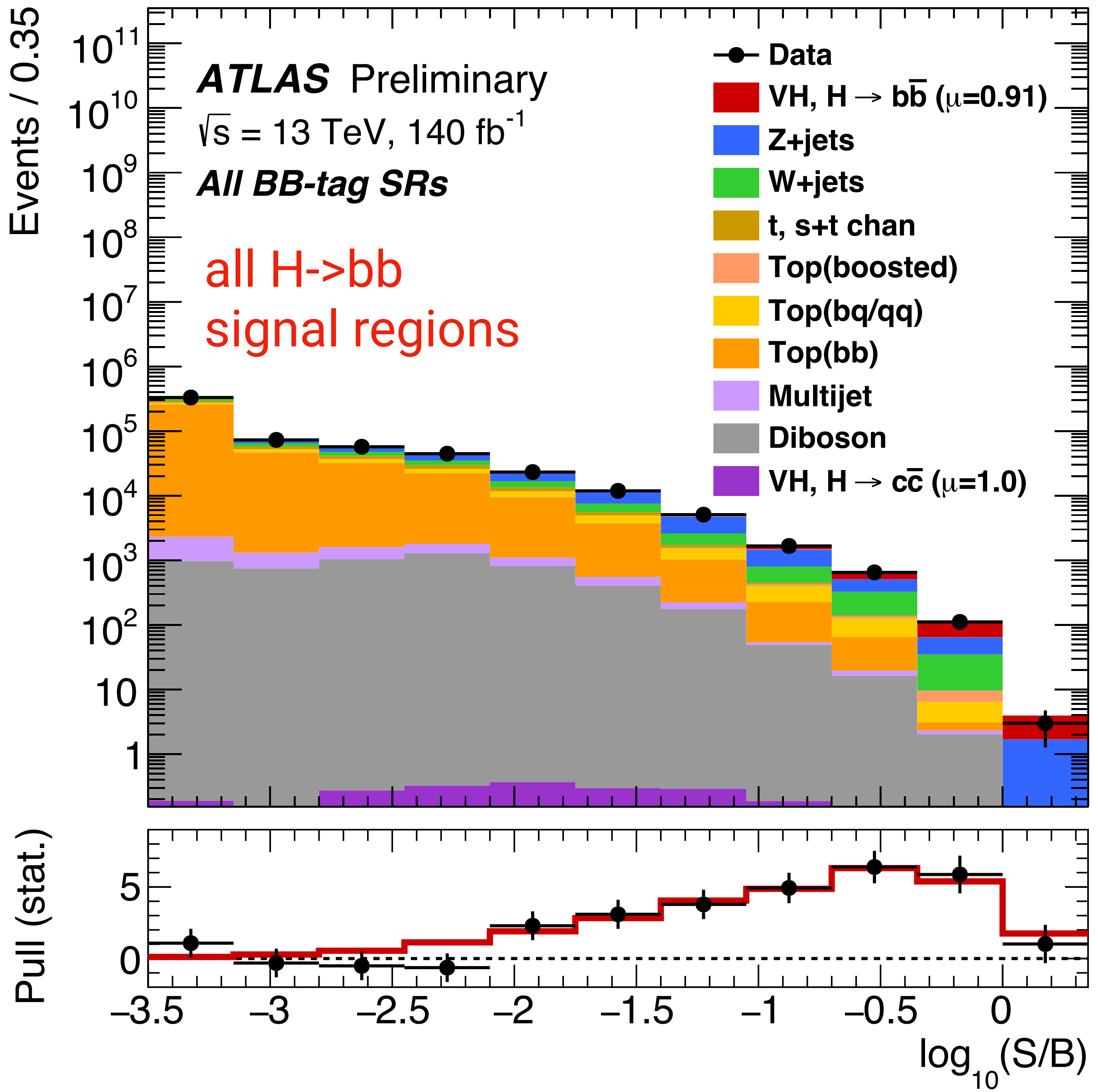
VH is the most sensitive production mode to access the **H → bb** and **H → cc** decays.

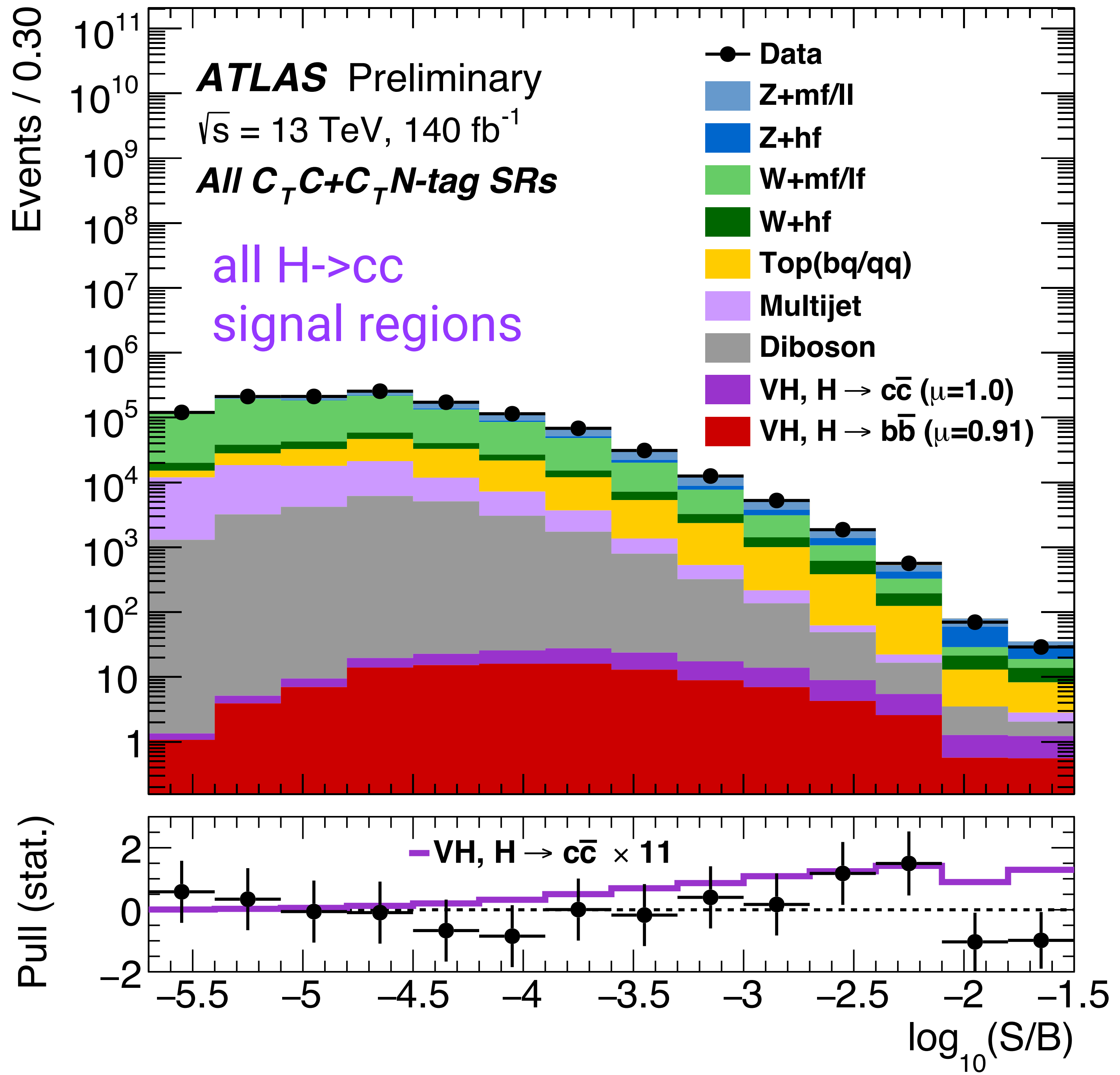
Final states with 0, 1 or 2 charged leptons from vector boson decays; considering both the resolved and merged Higgs decay topologies.



ATLAS re-analysis of previous VH(bb) and VH(cc) measurements:

- better reconstruction and calibration of leptons and jets
- improved flavor tagging, combining b- and c-jet identification
- optimized multivariate discriminants; used for the first time also for **H → cc** searches

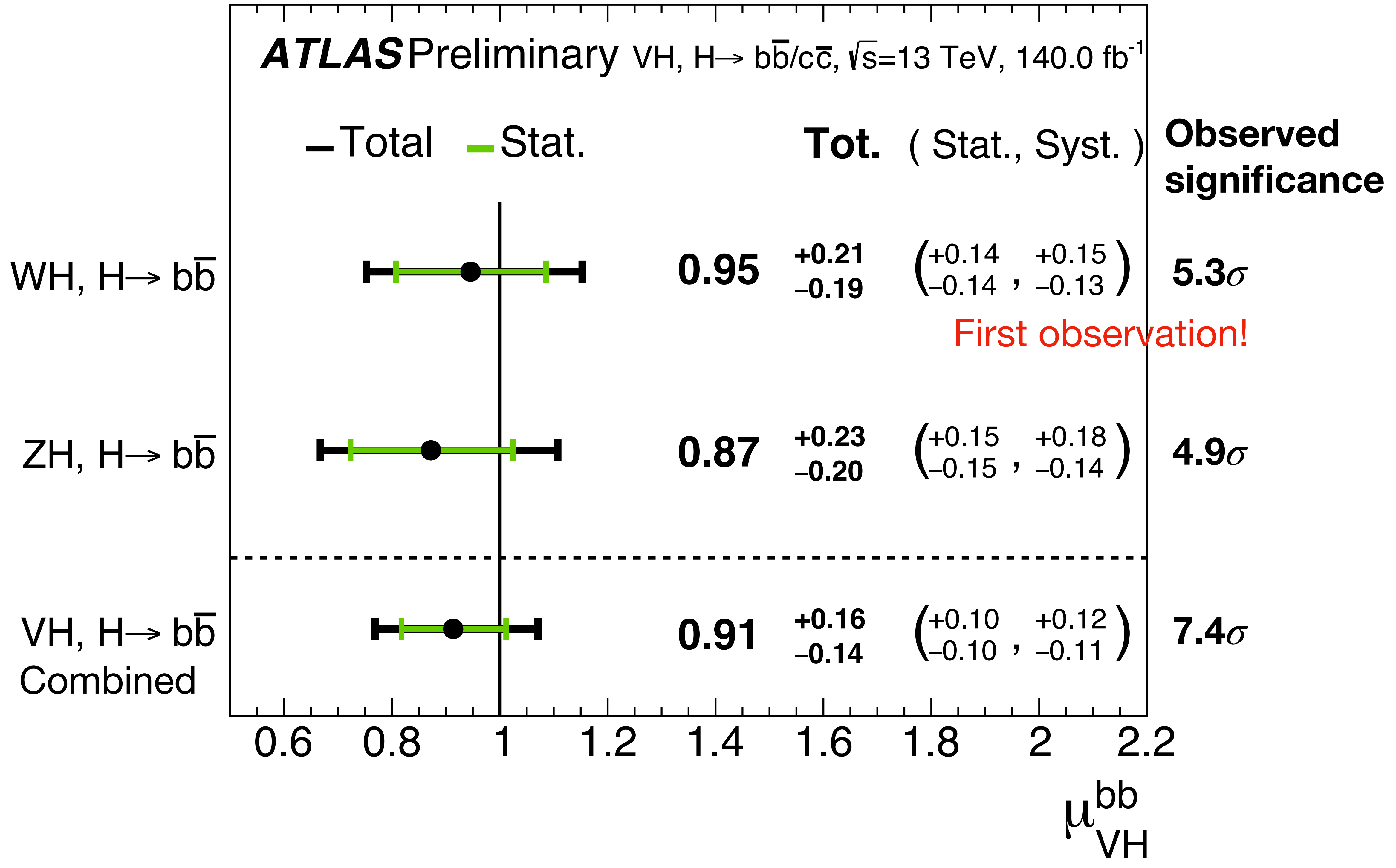


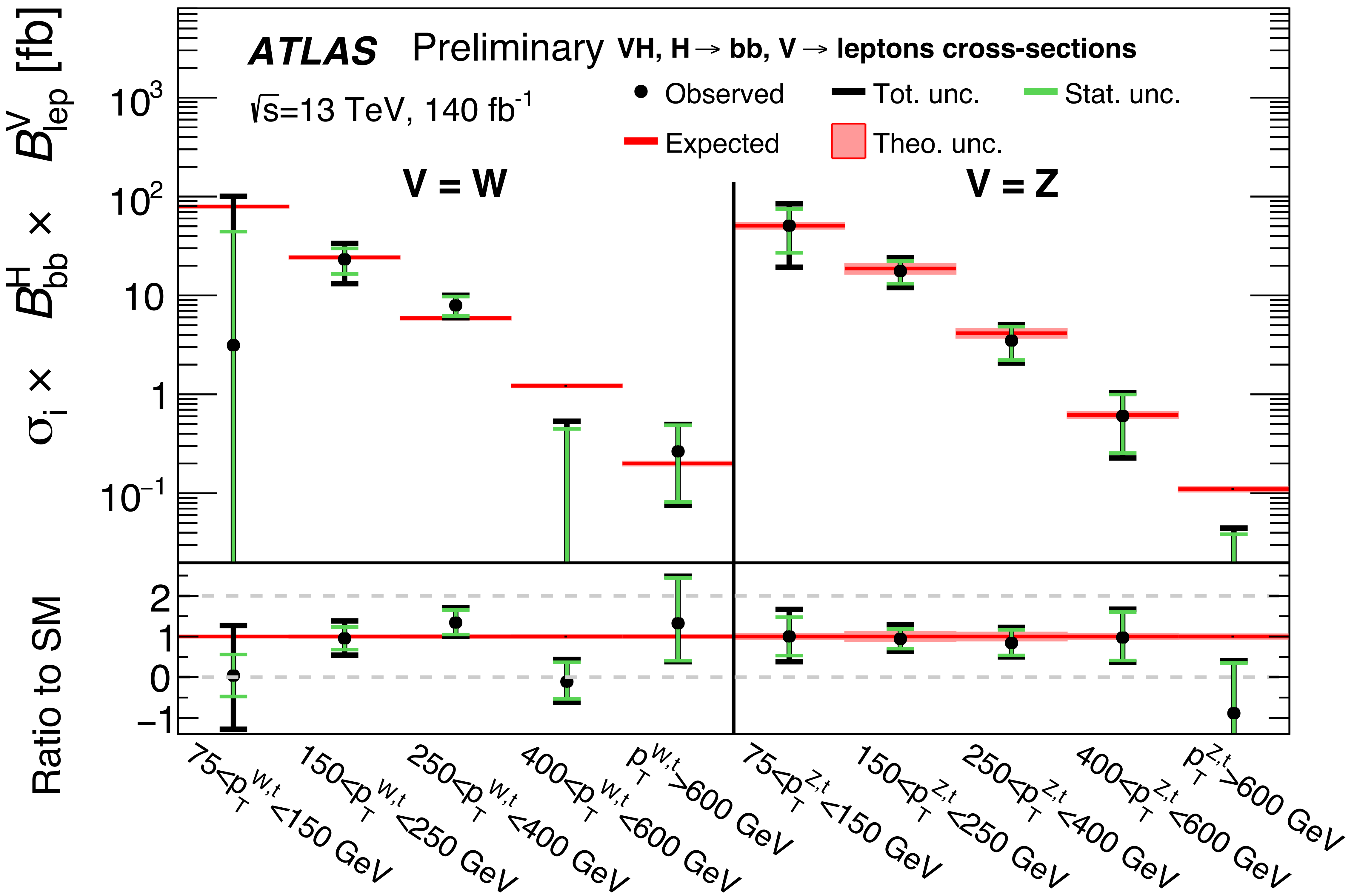


ATLAS Final Run 2 VH(bb) measurement

NEW

ATLAS-CONF-2024-010





Results compatible with the SM.

More granular p_T^H spectrum, up to 600 GeV.

Most precise VH(bb) measurement to date, uncertainties reduced by up to 20%.

CMS results with similar sensitivity: PRD 109 (2024) 092011

$\mu_{VH} = 1.15^{+0.22}_{-0.20}$, observed VH signal significance: 6.3σ

ATLAS & CMS $\mathbf{VH(cc)}$ measurements

ATLAS: ATLAS-CONF-2024-010, CMS: PRL 131 (2023) 041801, PRL 131 (2023) 061801

Including both the resolved and the merged $\mathbf{H} \to \mathbf{cc}$ decay topologies.

CMS:

Best measurement sensitivity.

$\mu_{VH(cc)} < 14$ @ $95\,\%$ CL (7.6 expected)

$1.1 < |\kappa_c| < 5.5$ @ $95\,\%$ CL

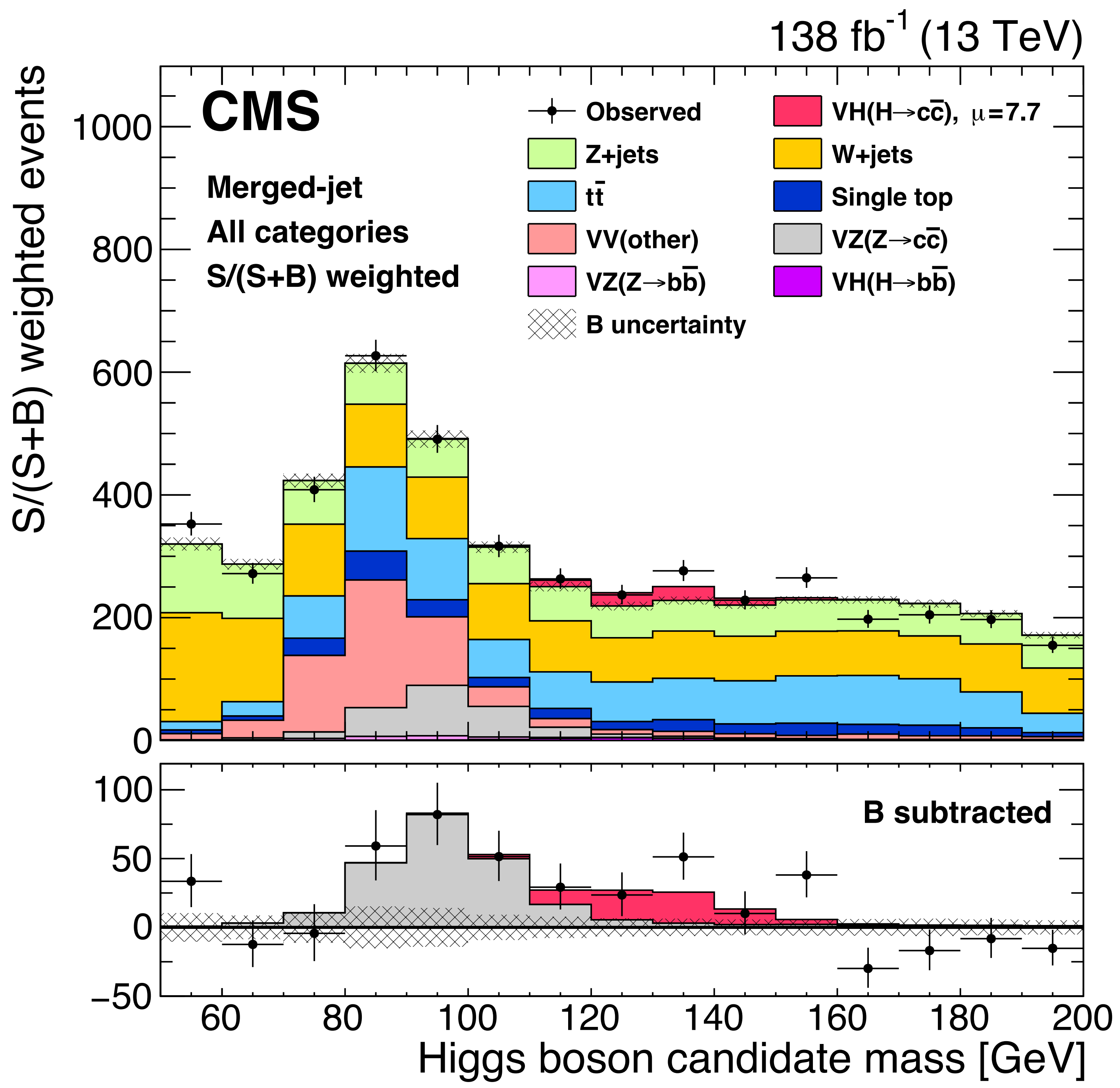
NEW **ATLAS:**

Best limit to date.

Factor 2.5 improvement w.r.t. previous ATLAS limit.

$\mu_{VH(cc)} < 11.3$ @ $95\,\%$ CL (10.4 expected)

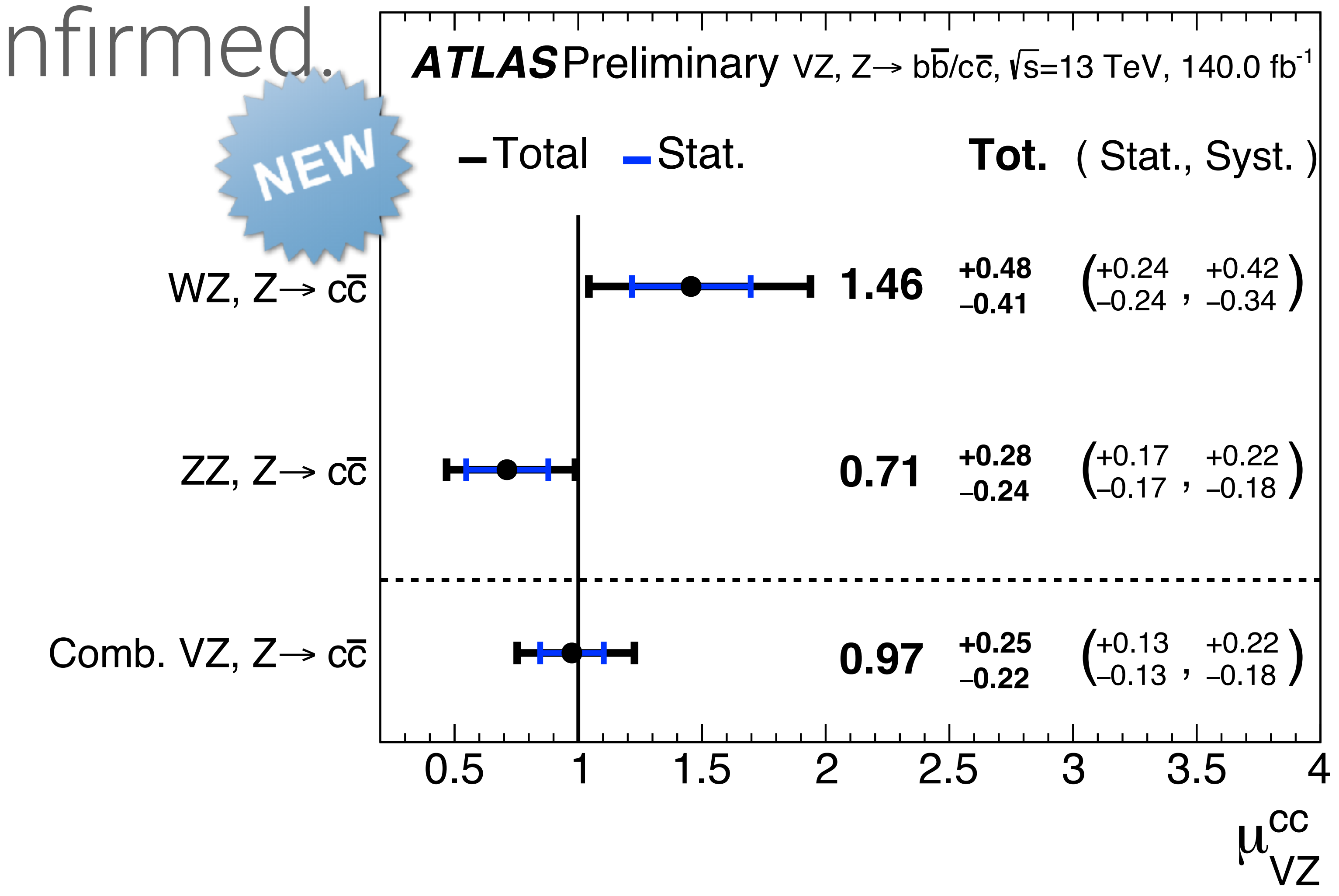
$|\kappa_c| < 4.2$ @ $95\,\%$ CL



Validation via $\mathbf{VZ, Z} \to \mathbf{cc}$ diboson processes.

CMS: First observation of $\mathbf{Z} \to \mathbf{cc}$ decays in hadron collisions.

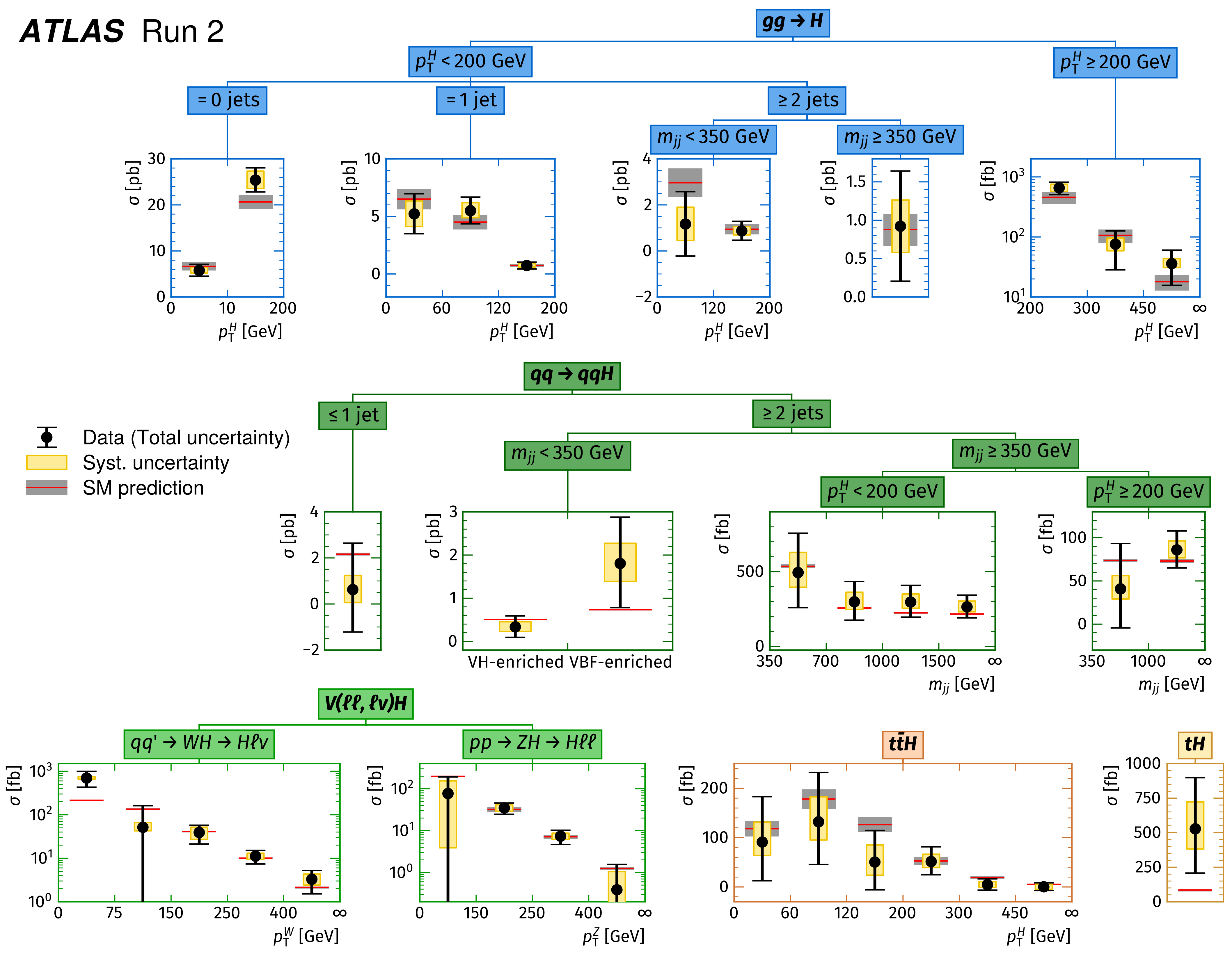
ATLAS: $\mathbf{Z} \to \mathbf{cc}$ observation confirmed.



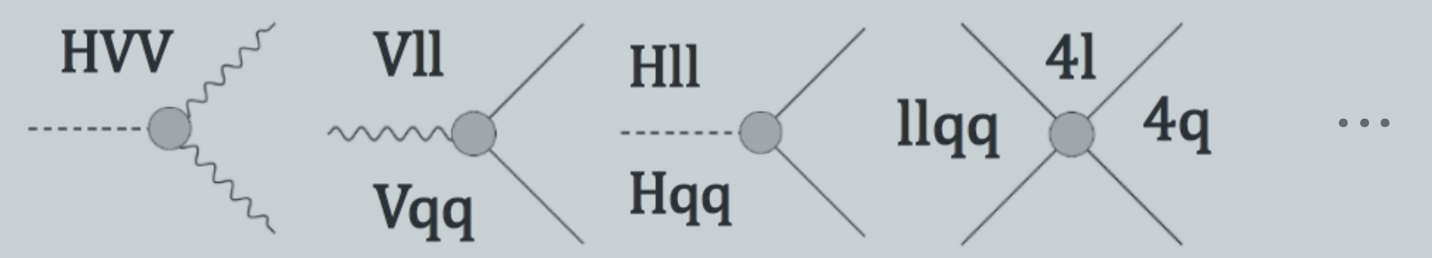
Going differential in search for anomalies

Effective Field Theory interpretations of STXS measurements

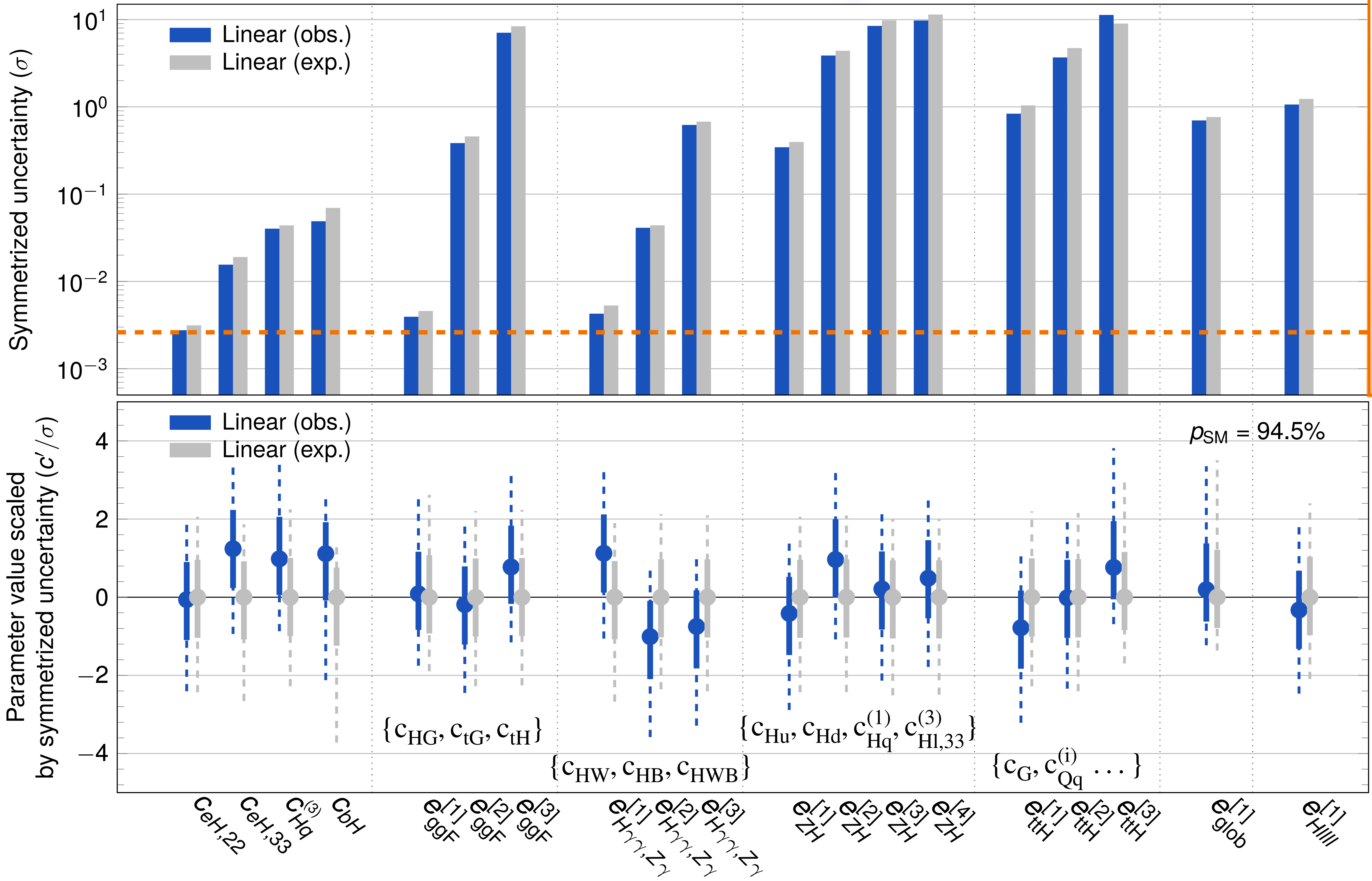
Nature 607 (2022) 52

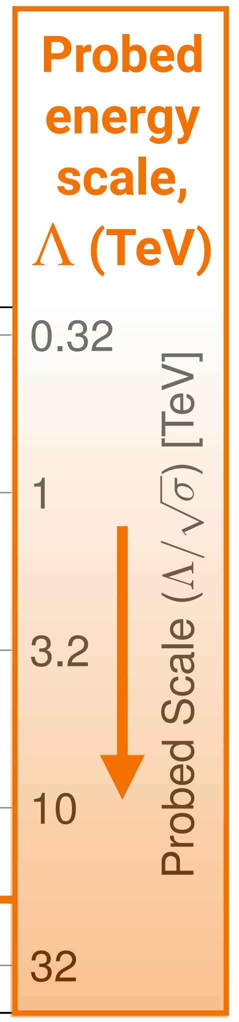


$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM}^{(d=4)} + \sum_{i=1}^{n_d} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathscr{O}_i^{(d)}$$



ATLAS: arXiv:2402.05742, submitted to JHEP



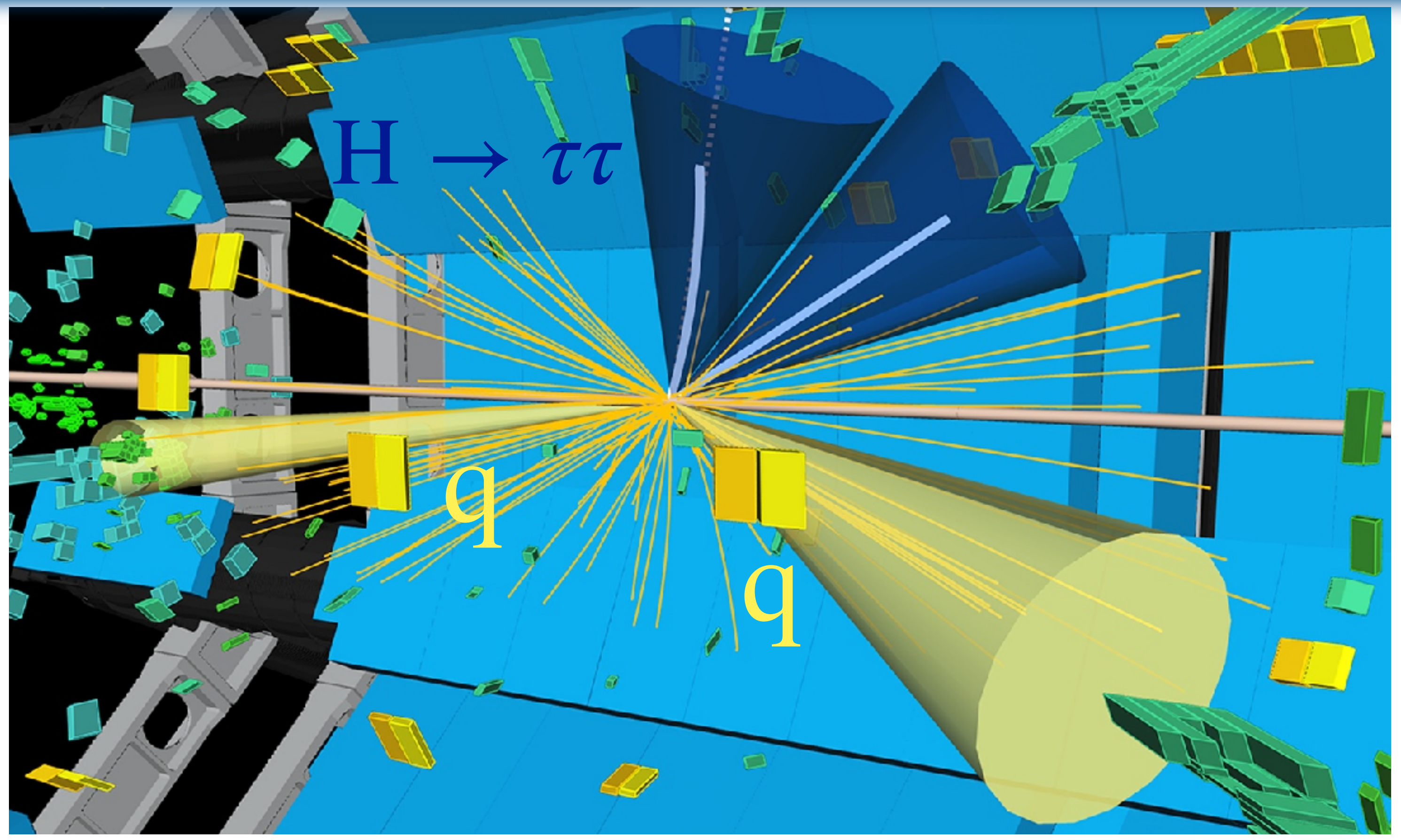


Similar interpretations by CMS (HEL EFT framework):
CMS-PAS-HIG-19-005

ATLAS final Run 2 $\mathrm{H} \rightarrow \tau\tau$ measurement

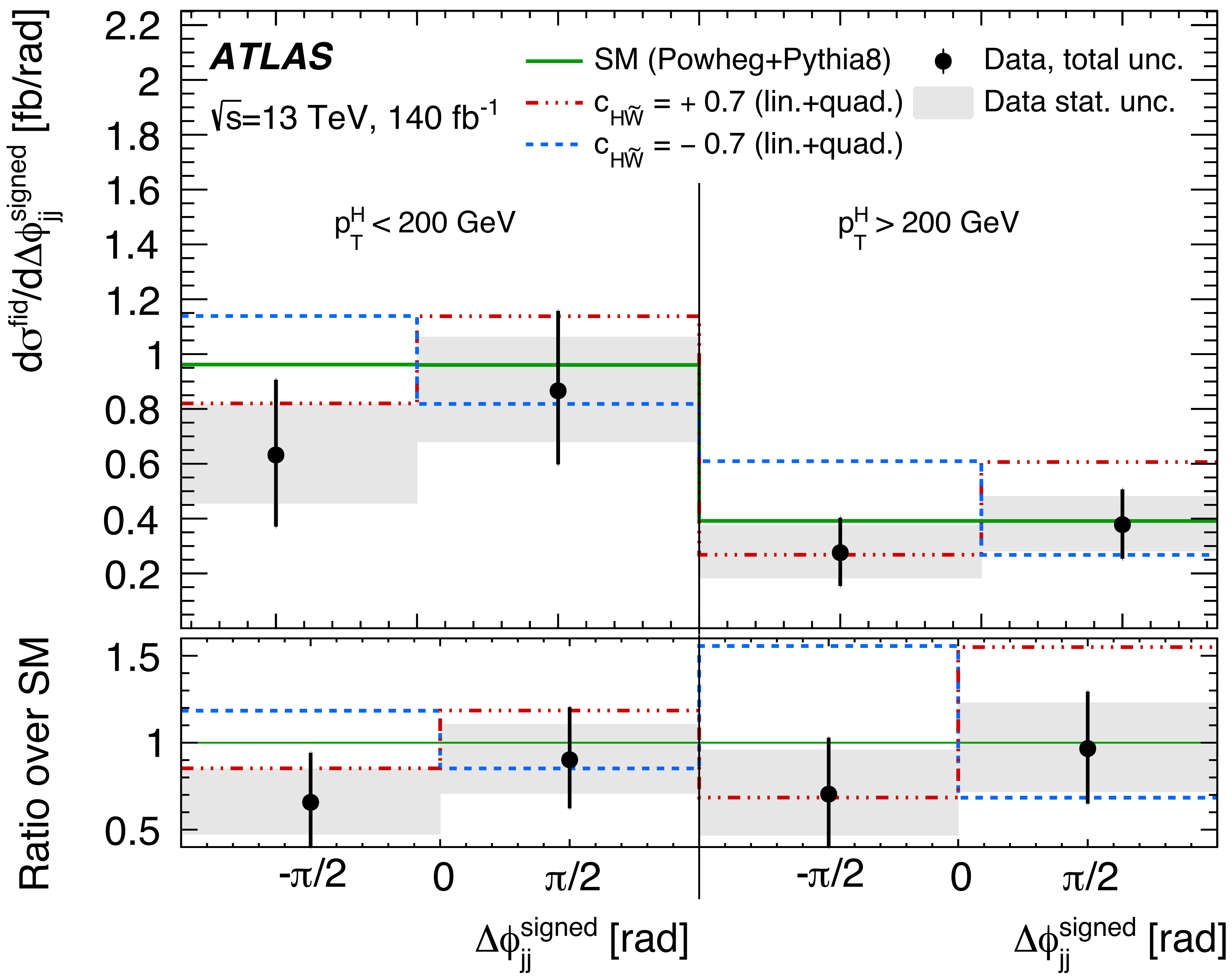
NEW

ATLAS: arXiv.2407.16320, submitted to JHEP

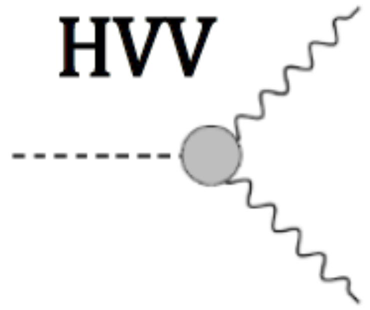


ATLAS re-analysis of full Run 2 $\mathrm{H} \rightarrow \tau\tau$ data:

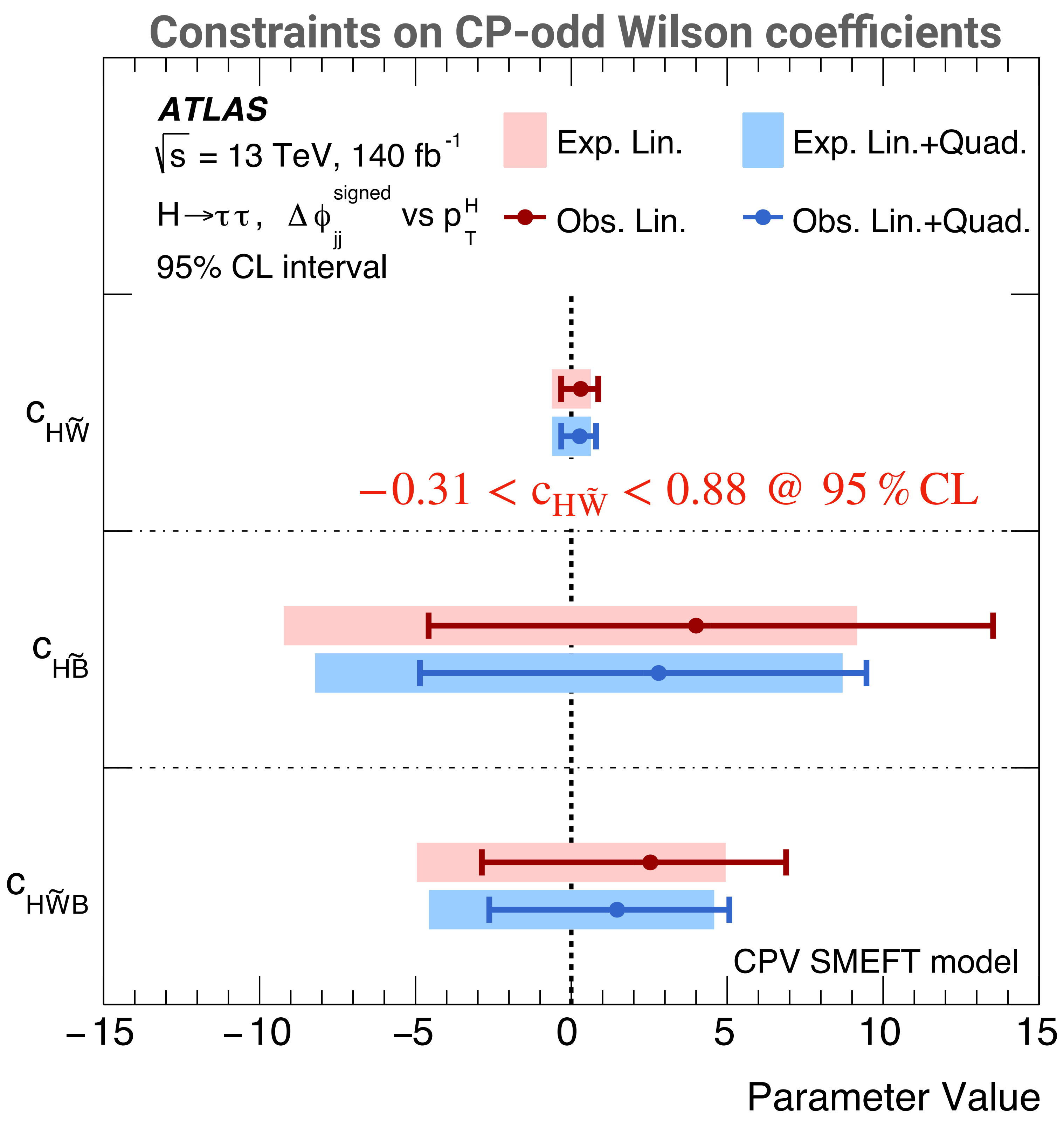
- Most precise single measurement of *VBF*: $\mu_{\mathrm{VBF}} = 0.93^{+0.17}_{-0.15}$
- More granular STXS measurements for *VBF* and *ttH* production modes.
- First $\mathbf{VBF\ H} \rightarrow \tau\tau$ differential measurements by ATLAS.



Constraints on individual CP-even and CP-odd SMEFT parameters.



✔ Observables have only a small dependence on quadratic SMEFT terms.



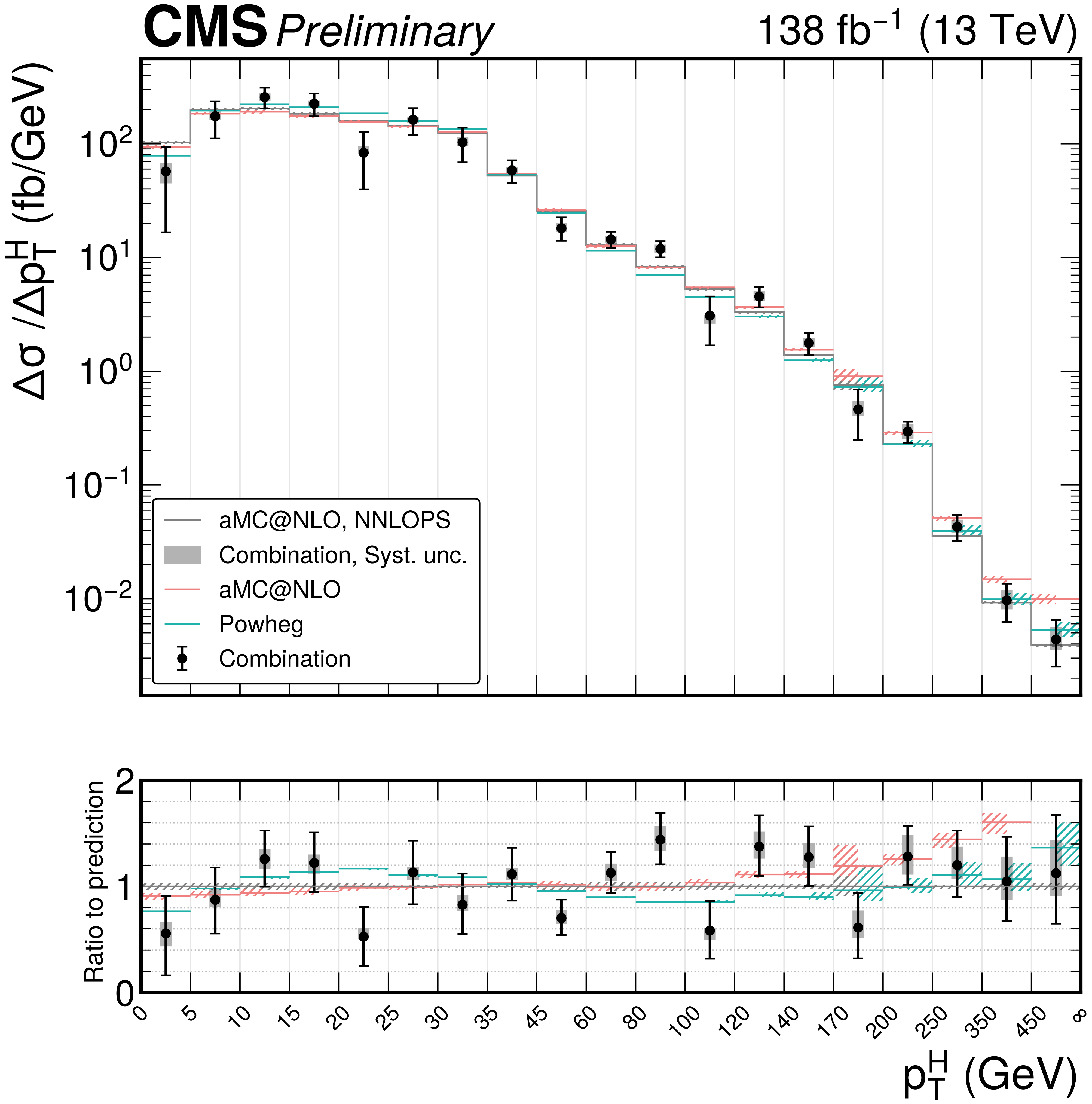
CMS combination of Run 2 differential measurements

NEW

CMS-PAS-HIG-23-013

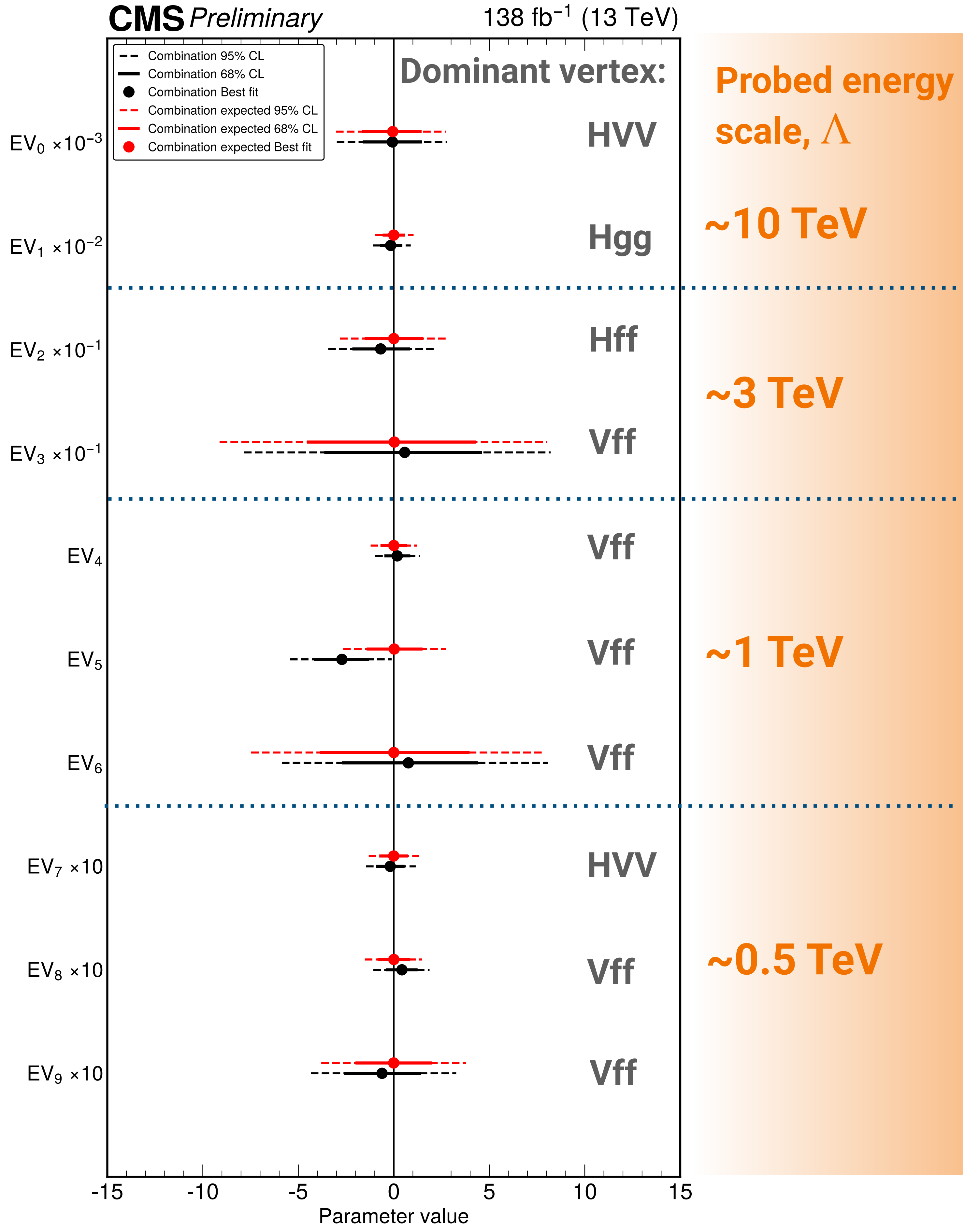
Combining differential distributions measured in four decay channels: $\gamma\gamma, \mathrm{ZZ}, \mathrm{WW}, \tau\tau$.

Observables: $\mathrm{p_T^H}, |\mathrm{y_H}|, \mathrm{N_{jets}}, \mathrm{p_T^{j1}}, \mathrm{m_{jj}}, |\Delta\eta_{jj}|, \Delta\phi_{jj}, \tau_C^j$. Interpretation within the **kappa** and **SMEFT** frameworks.

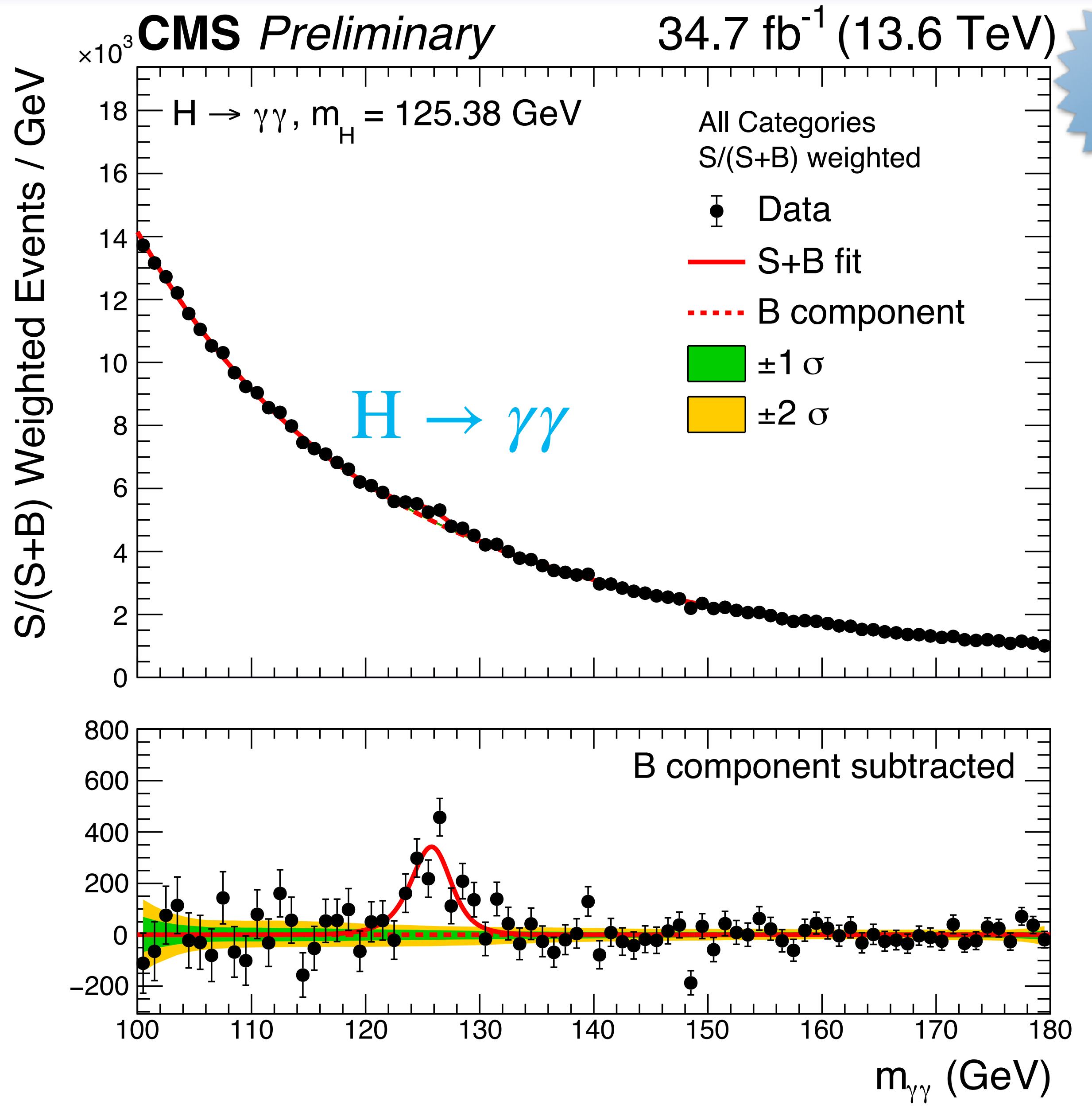


⇒

E.g. powerful constraints on linear combinations of CP-even SMEFT Wilson coefficients.



CMS Run 3 differential cross-section measurements

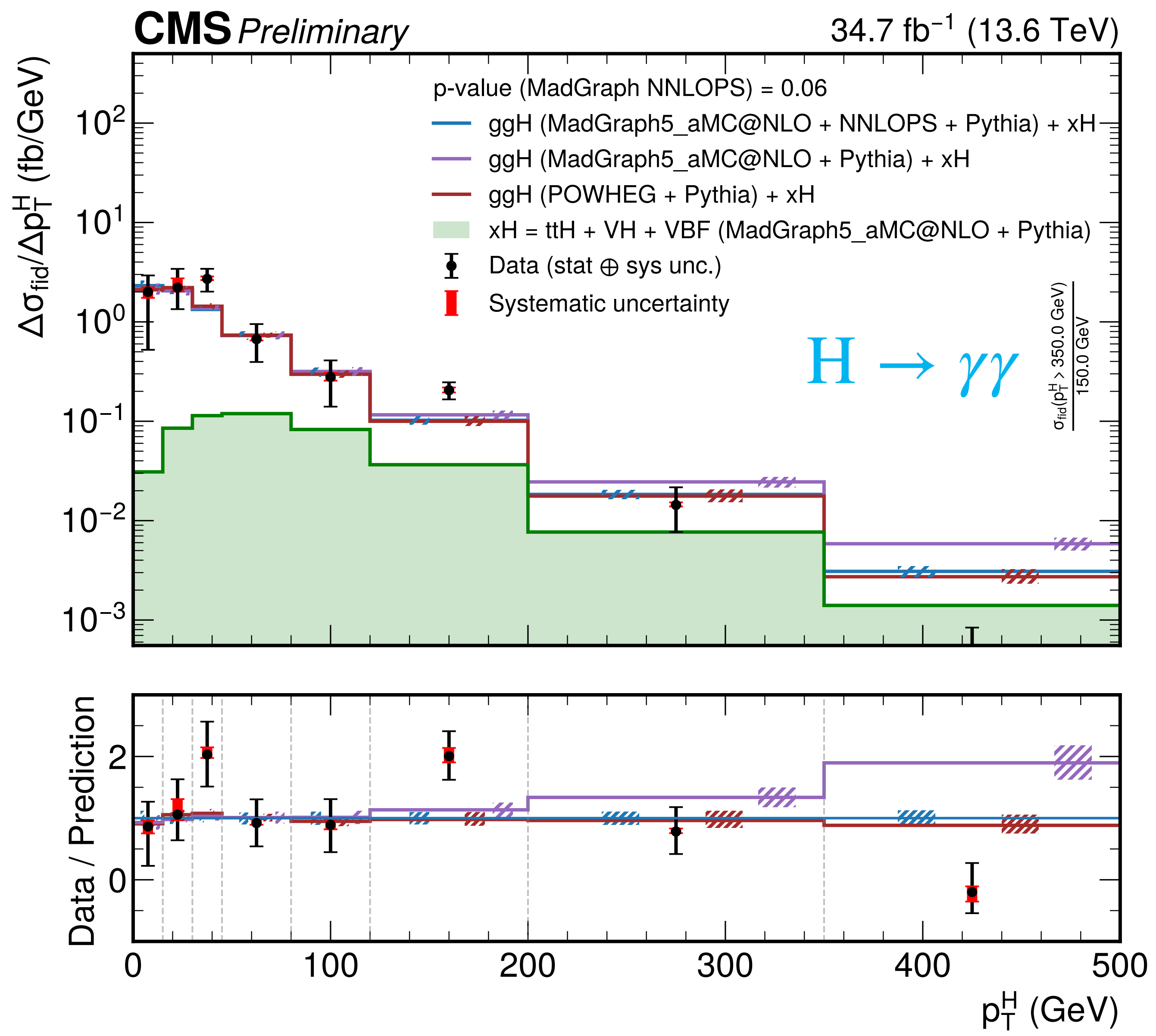


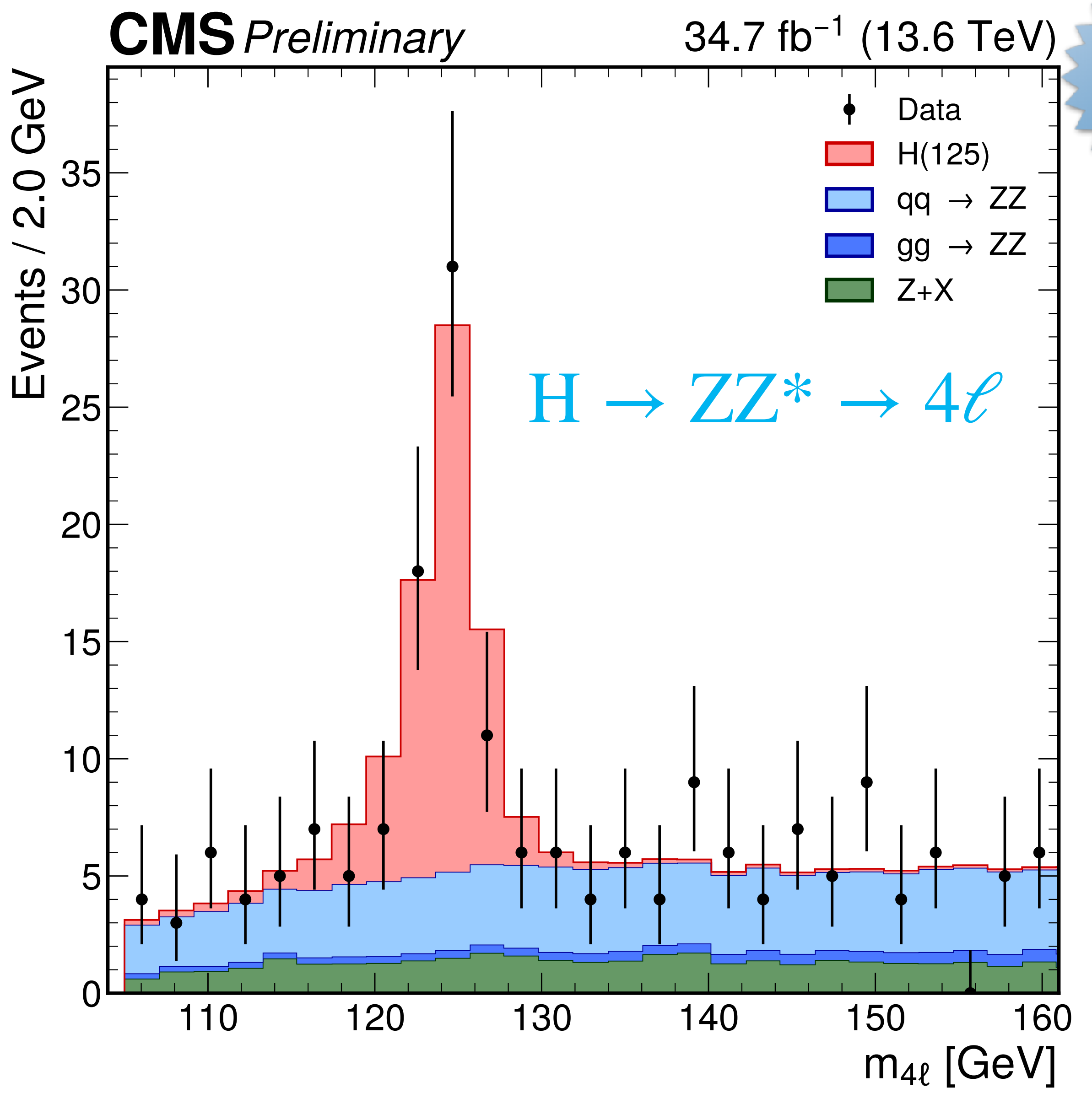
CMS-PAS-HIG-23-014

$$\sigma_{\gamma\gamma}^{\text{fiducial}} = 78 \pm 11 \text{ (stat) } {}^{+6}_{-5} \text{ (syst) fb}$$

SM : 67.8 ± 3.8 fb

Comparable precision to the corresponding total and fiducial ATLAS Run 3 measurements:
EPJC 84 (2024) 78

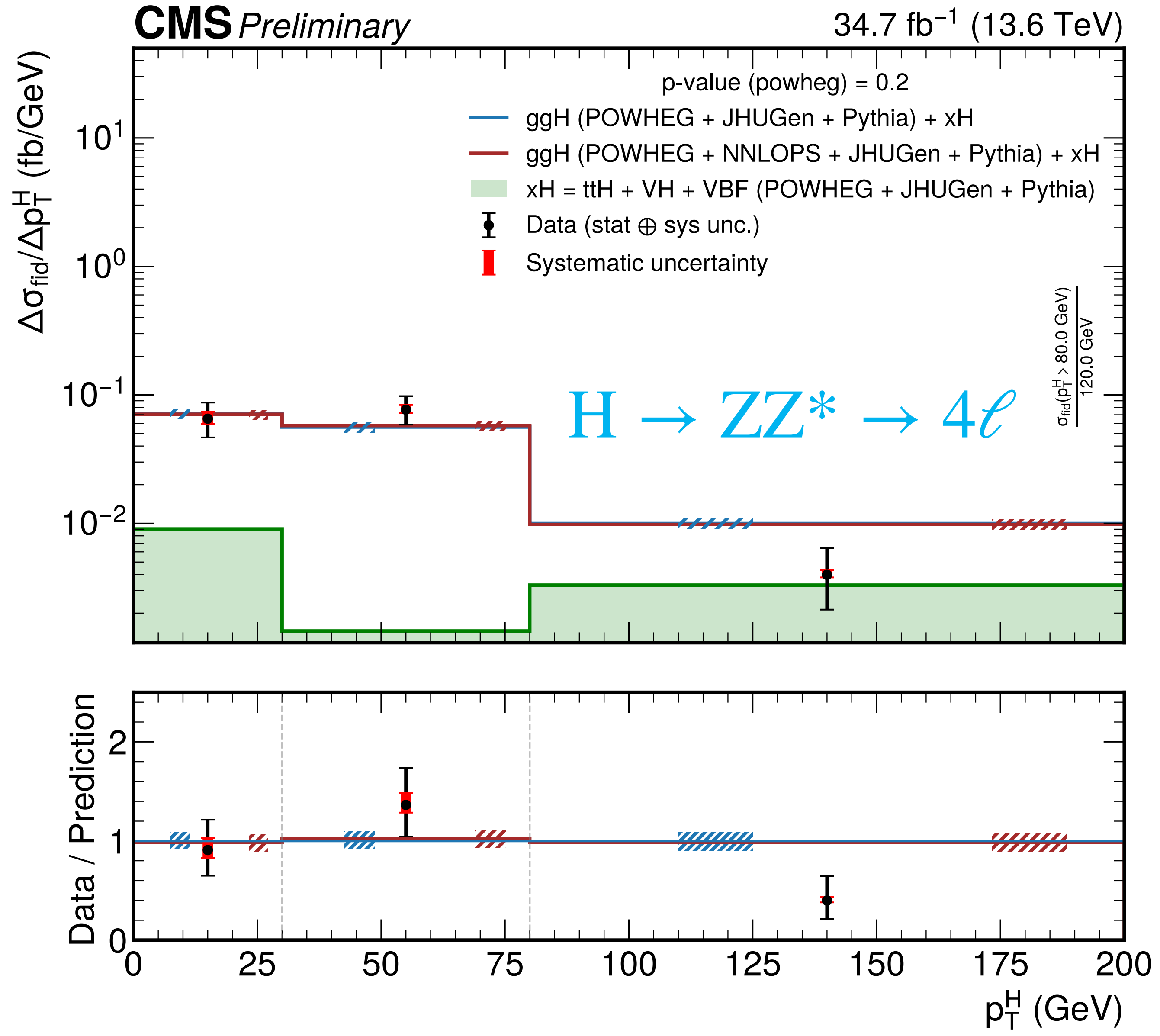




CMS-PAS-HIG-24-013

$$\sigma_{4\ell}^{\text{fiducial}} = 2.94 \; {}^{+0.53}_{-0.49} \text{ (stat) } {}^{+0.29}_{-0.22} \text{ (syst) fb}$$

SM : $3.09 \; {}^{+0.39}_{-0.31}$ fb

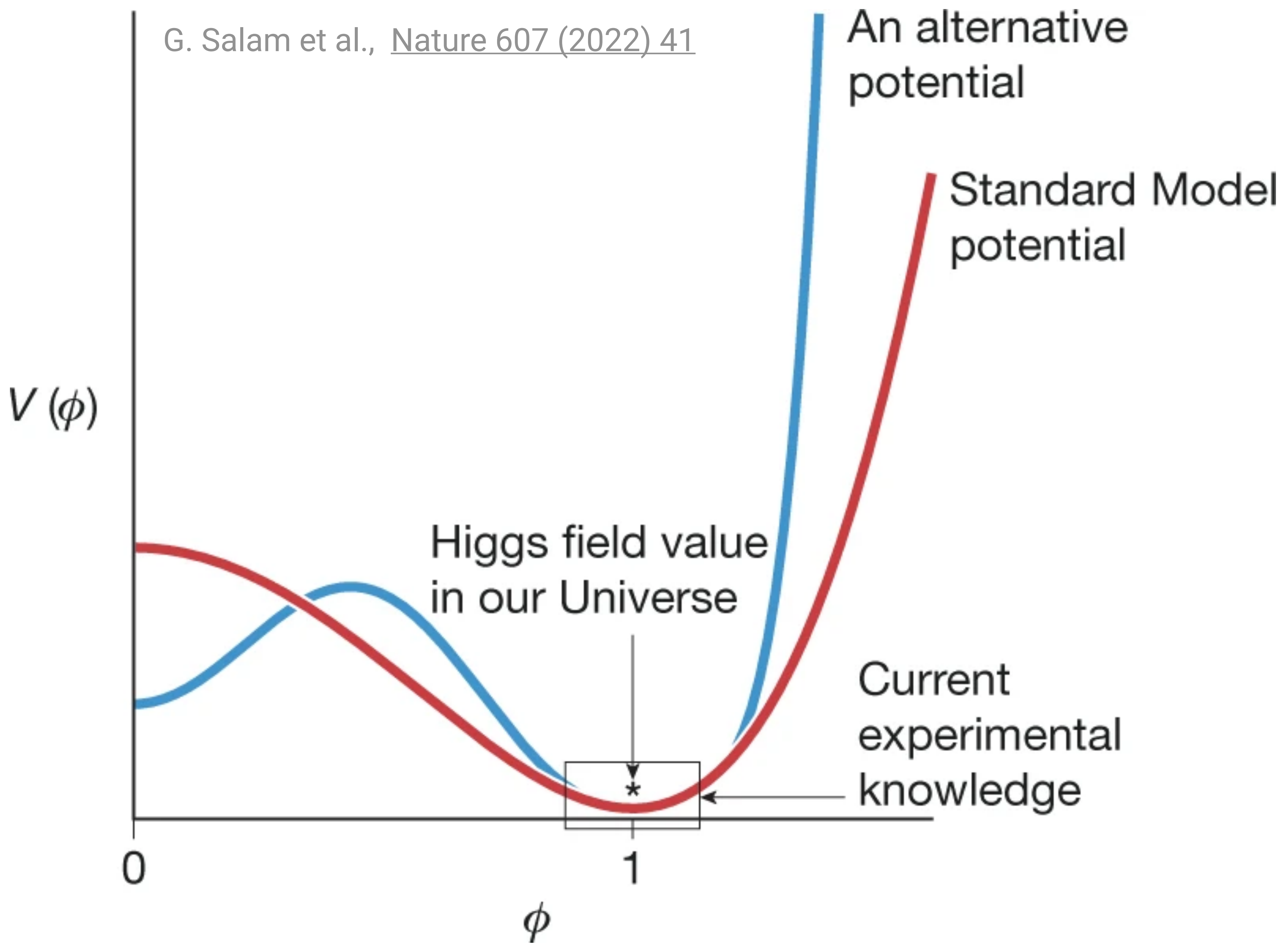


All measurements in good agreement with SM predictions.

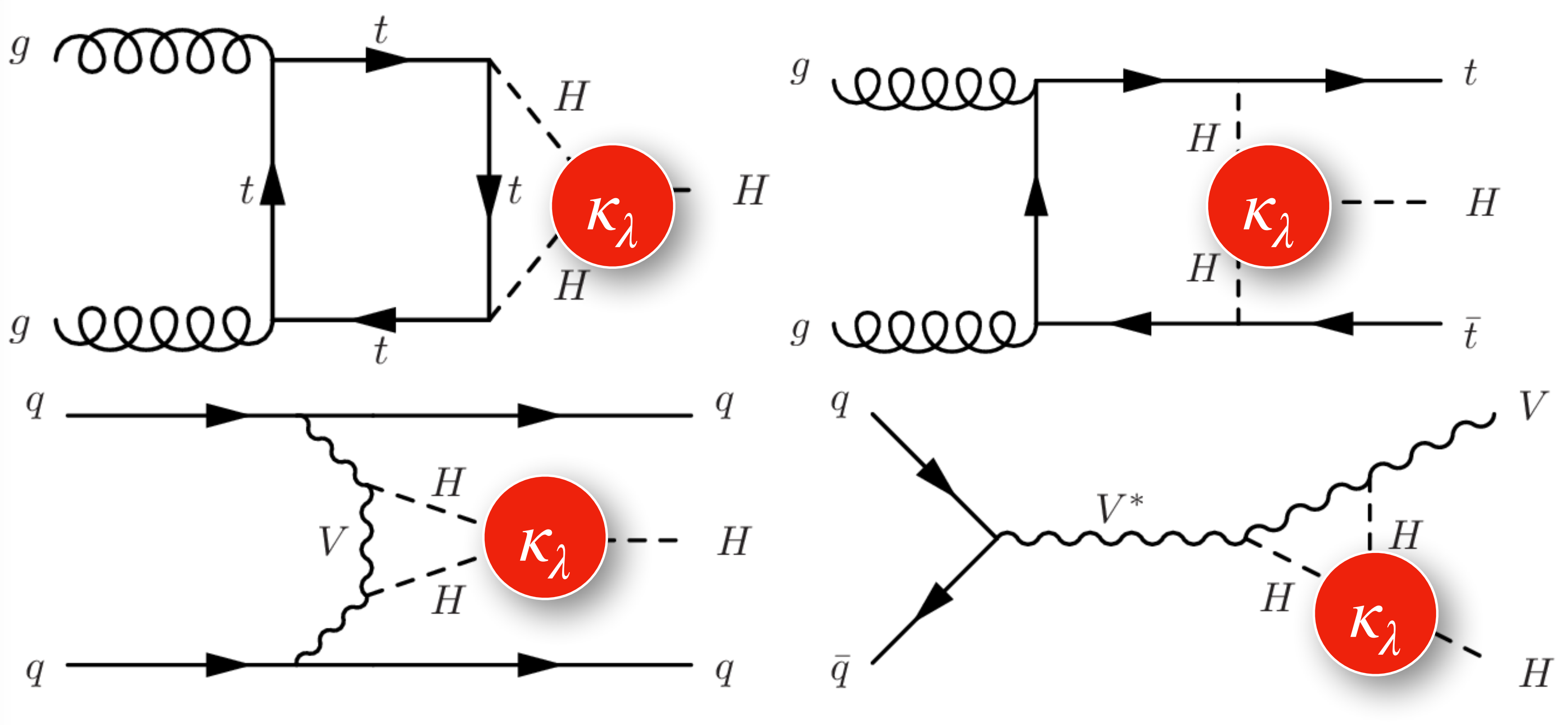
Higgs self-interaction

Higgs self-interactions

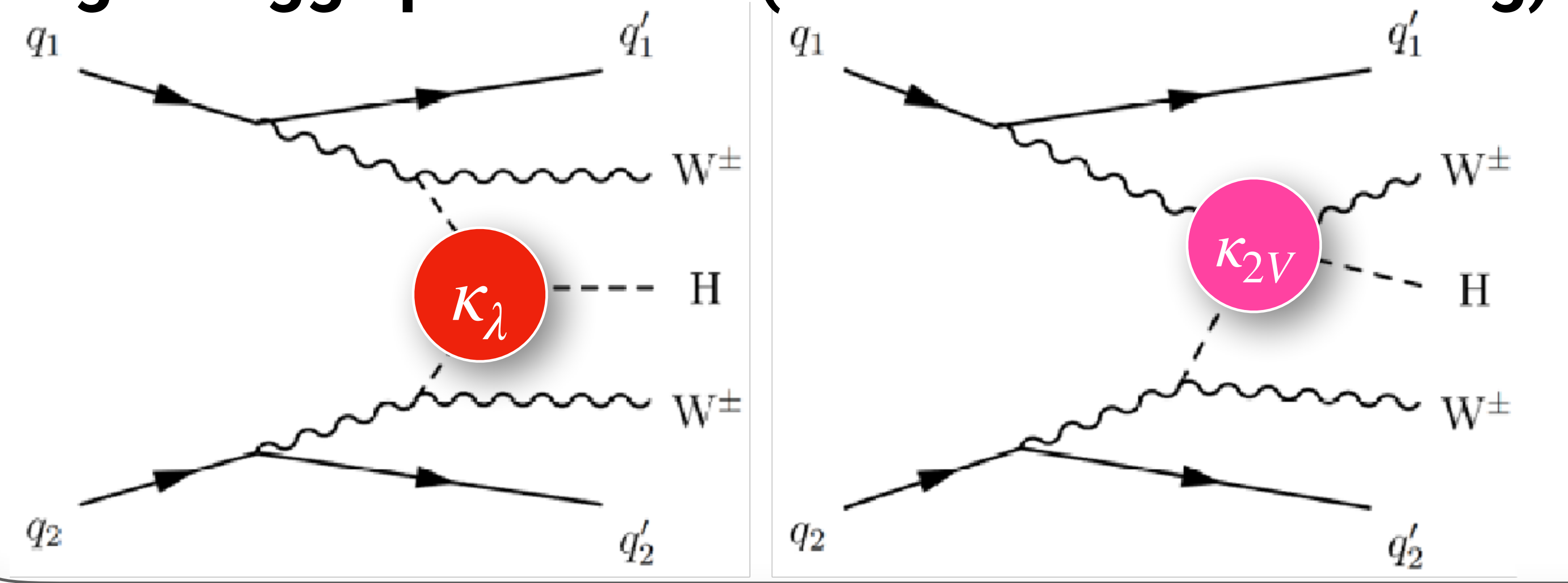
Processes with Higgs self-interactions can probe the structure/stability of the Higgs potential.



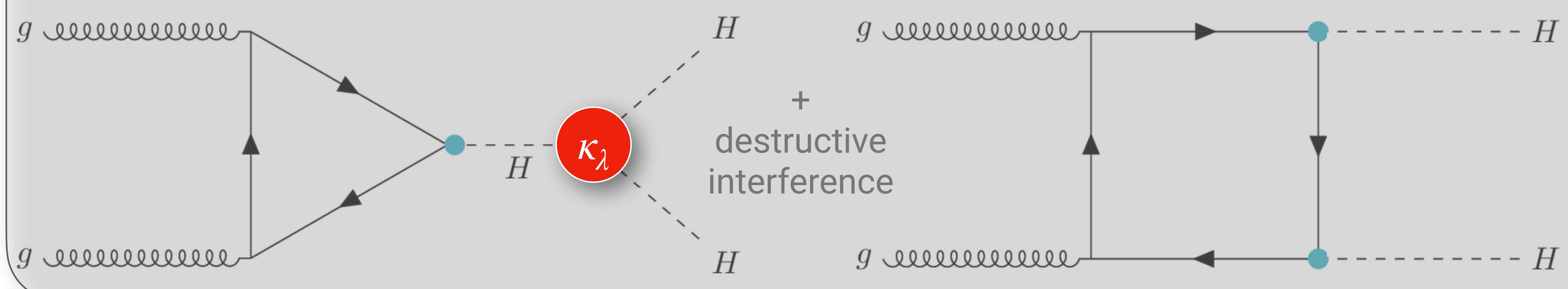
Single-Higgs production (ggH, VBF, VH, ttH)



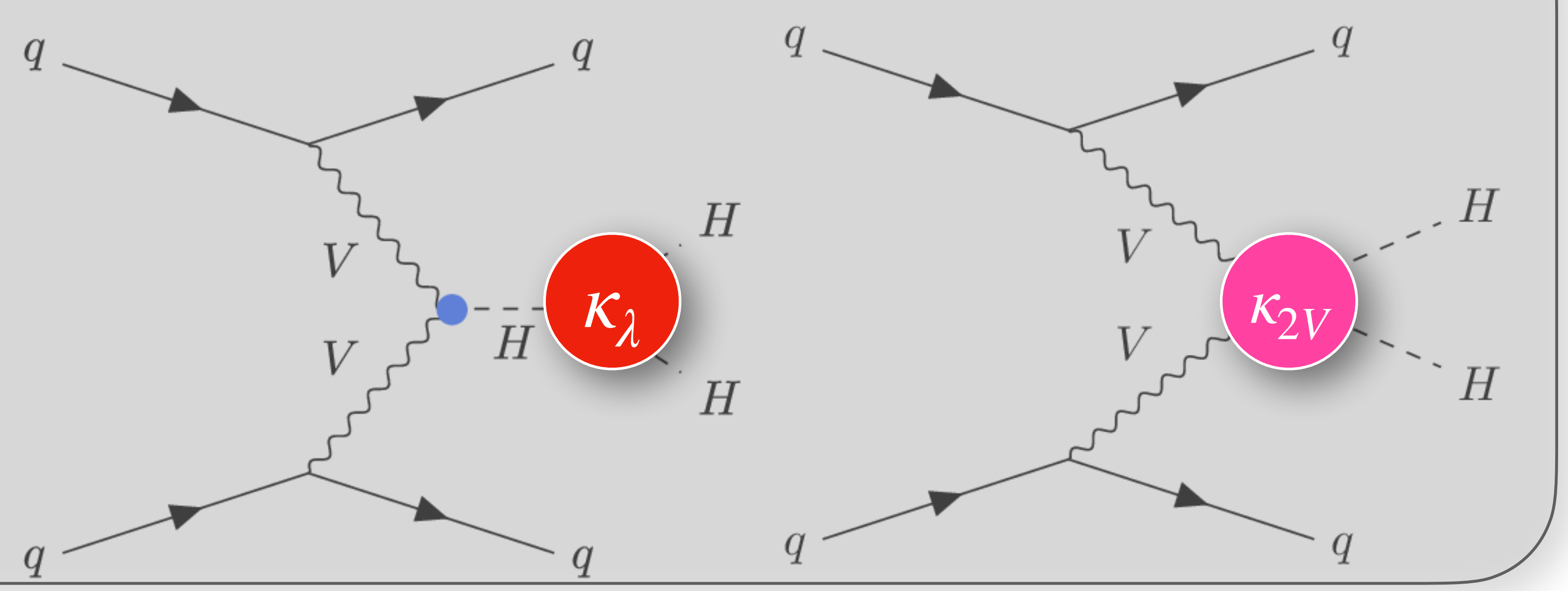
Single-Higgs production (vector boson scattering)



Higgs pair production (gluon fusion)



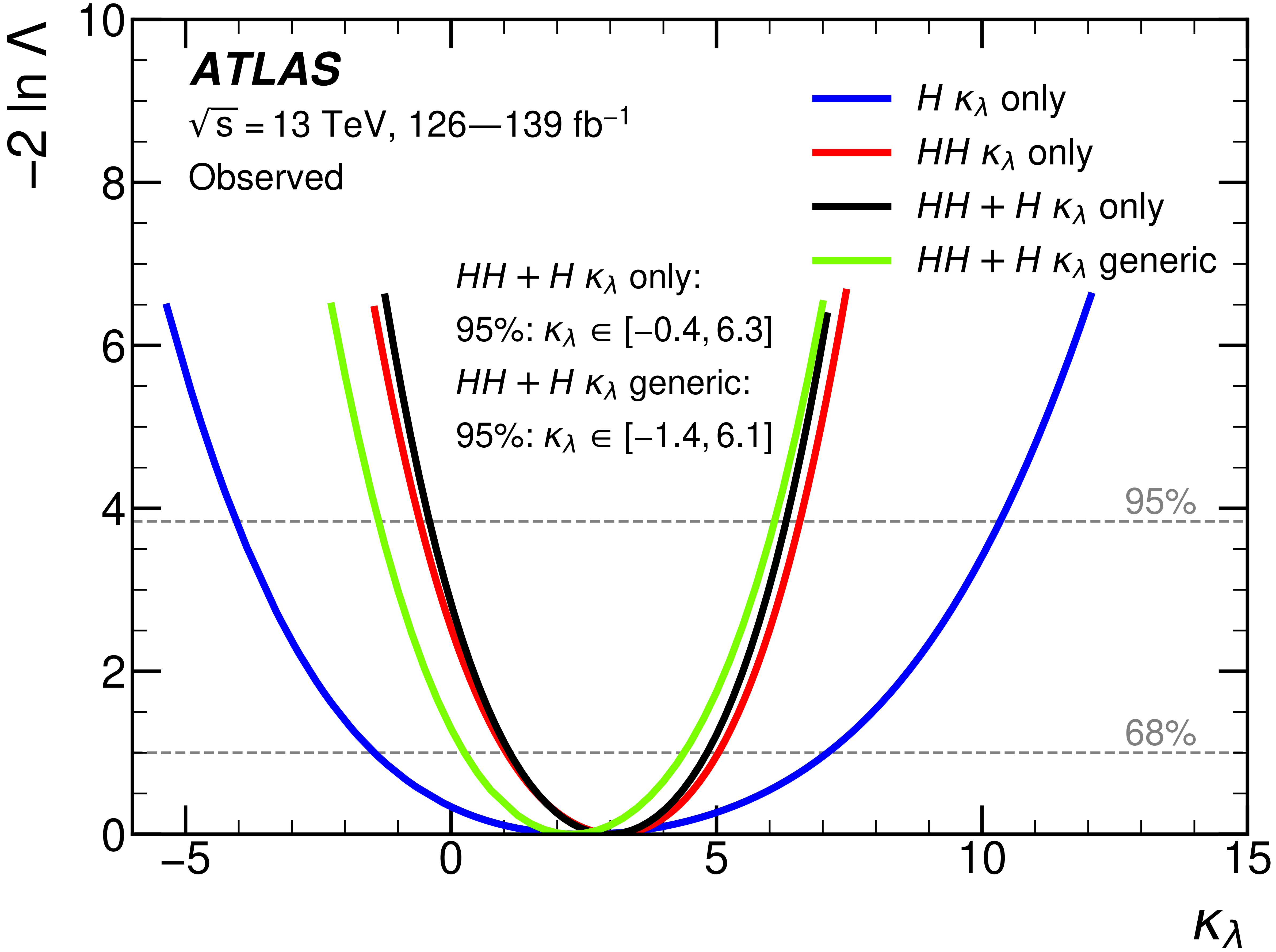
Higgs pair production (VBF)

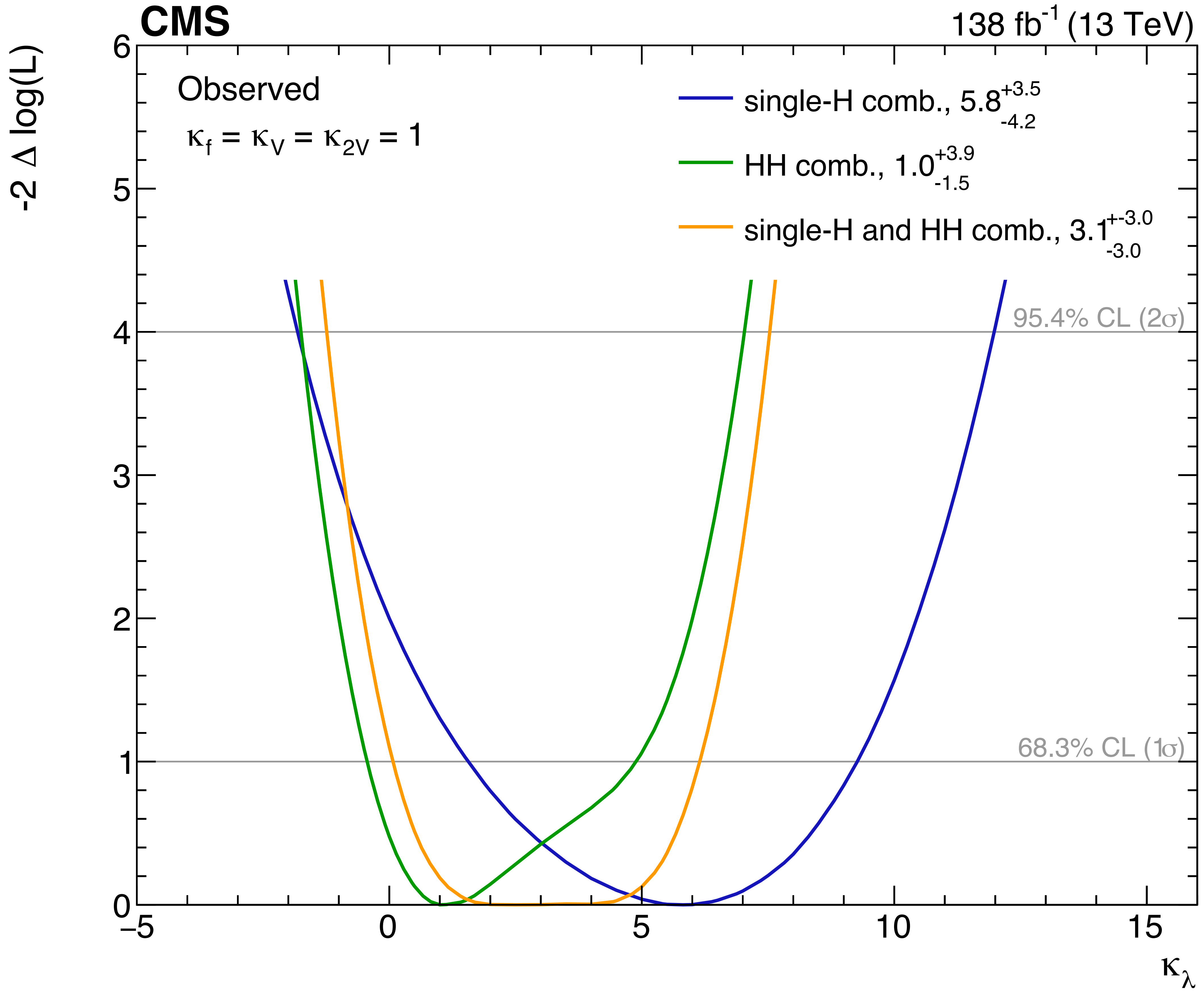


Combination of HH and single-Higgs analyses

ATLAS: PLB 843 (2023) 137745

CMS: arXiv:2407.13554, submitted to PLB





With free-floating single-Higgs couplings ($\kappa_V, \kappa_t, \kappa_b, \kappa_\tau$) :

$-1.4 < \kappa_\lambda < 6.1$ @ 95 % CL observed
($-2.2 < \kappa_\lambda < 7.7$ @ 95 % CL expected)

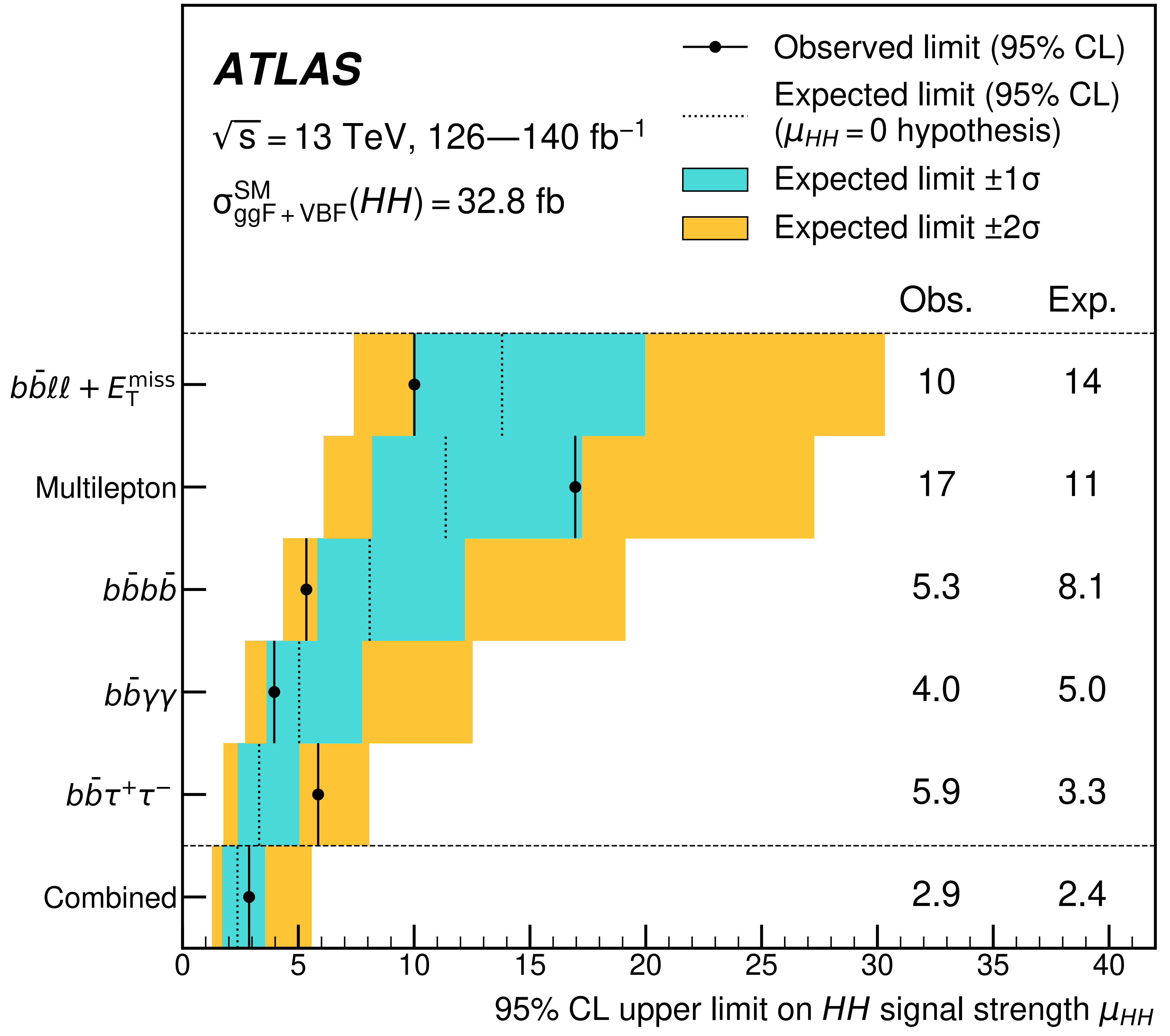
$-1.4 < \kappa_\lambda < 7.8$ @ 95 % CL observed
($-2.3 < \kappa_\lambda < 7.7$ @ 95 % CL expected)

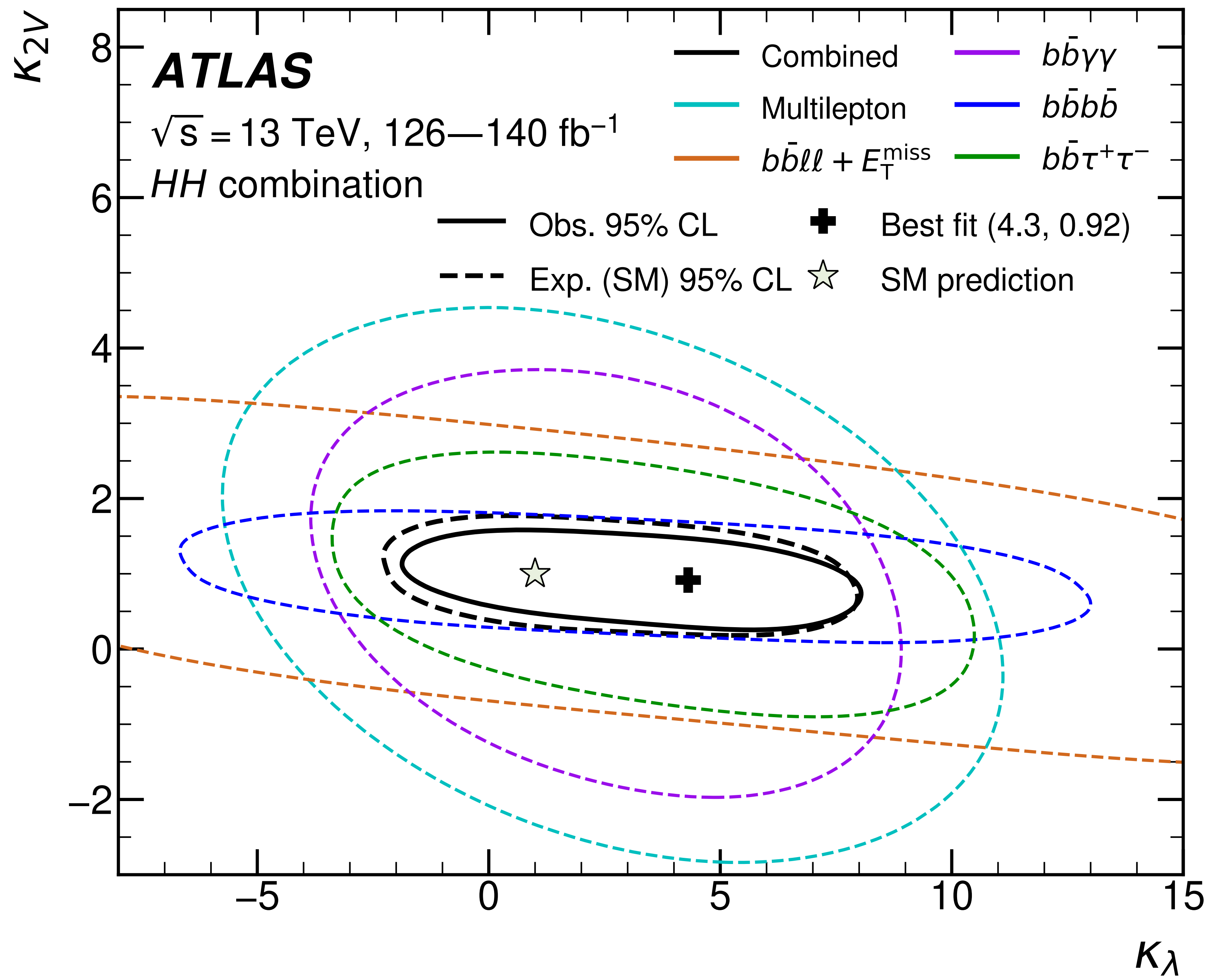
ATLAS combined Run 2 HH search

NEW

ATLAS: arXiv.2406.09971, submitted to PRL

Combination of results from **bbbb, bb$\gamma\gamma$, bb$\tau\tau$, bb$\ell\ell$ + E_T^{miss}** & **multilepton** decay channels.





$-1.2 < \kappa_\lambda < 7.2$ @ 95 % CL observed

($-1.6 < \kappa_\lambda < 7.2$ @ 95 % CL expected)

Currently best expected sensitivity from **HH**.

$0.6 < \kappa_{2V} < 1.5$ @ 95 % CL observed

($0.4 < \kappa_{2V} < 1.6$ @ 95 % CL expected)

Boosted **VBF HH → bbbb** channel most sensitive.

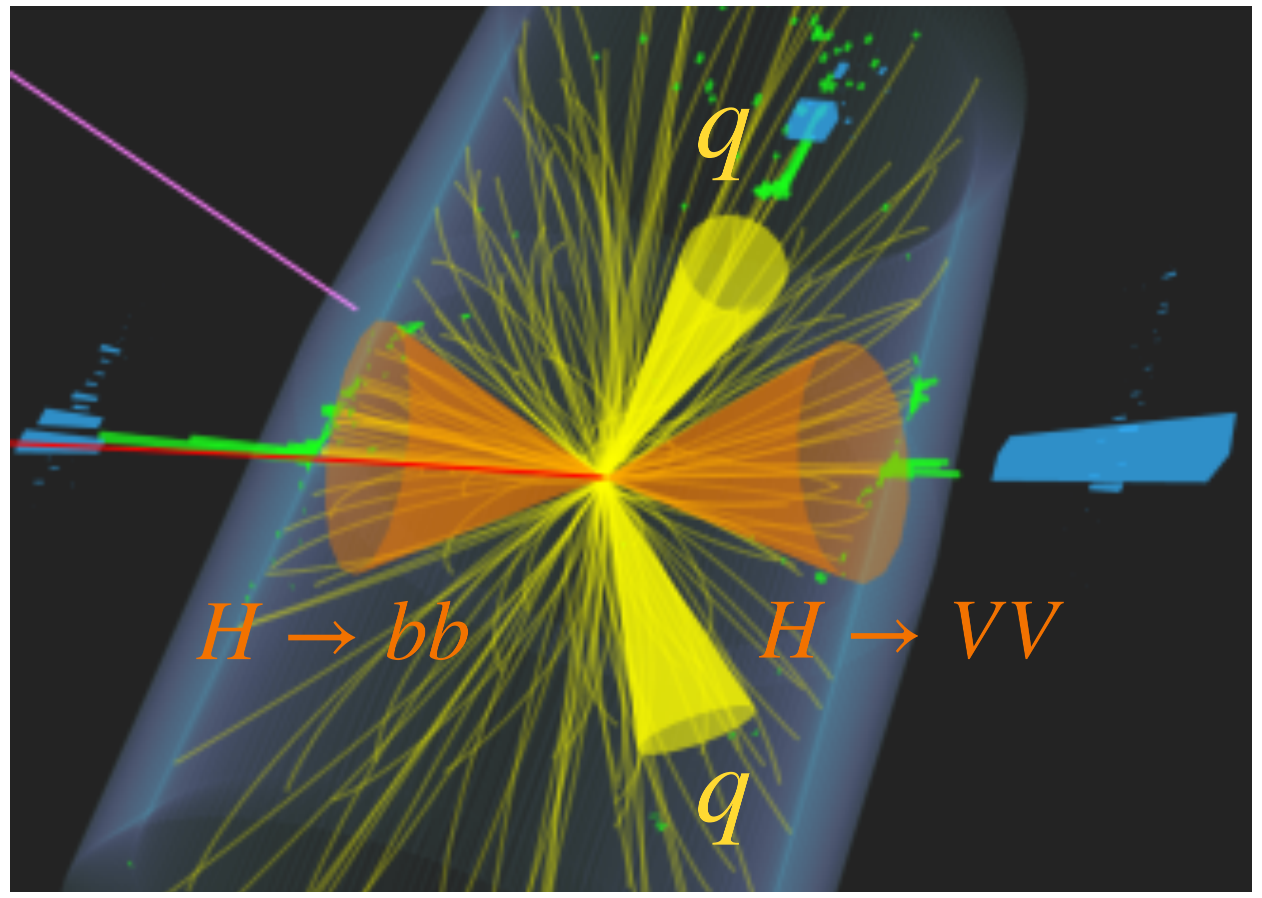
Comparable CMS results: Nature 607 (2022) 60, arXiv:2407.13554

Current best constraint on κ_{2V},

$0.67 < \kappa_{2V} < 1.38$ @ 95 % CL observed

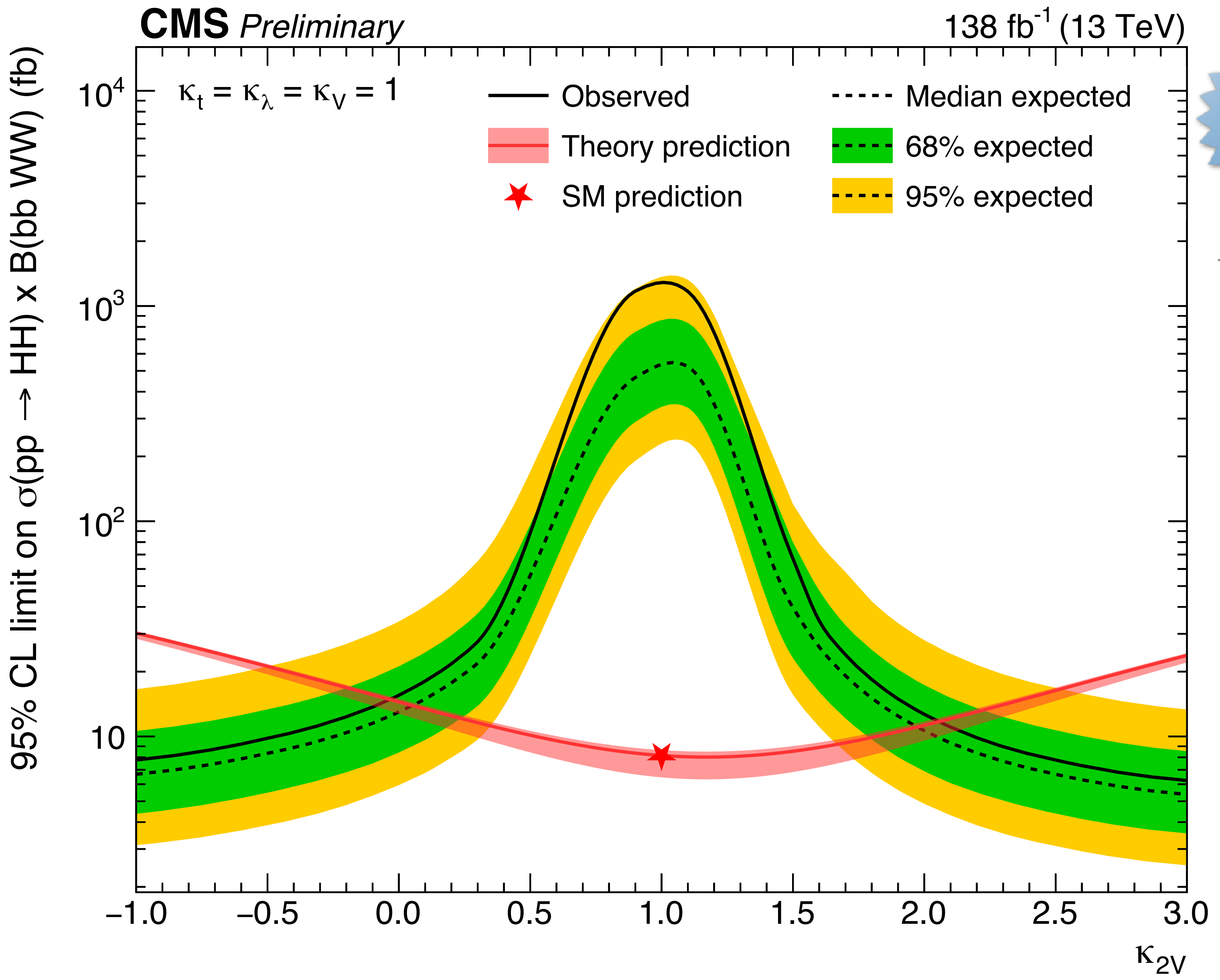
CMS: Additional measurements constraining κ_{2V}

Boosted VBF HH → bbVV channel



Highly energetic Higgs pair production with merged decay topologies.

Employing a new $\mathrm{H \to VV \to qqqq}$ tagging.



NEW

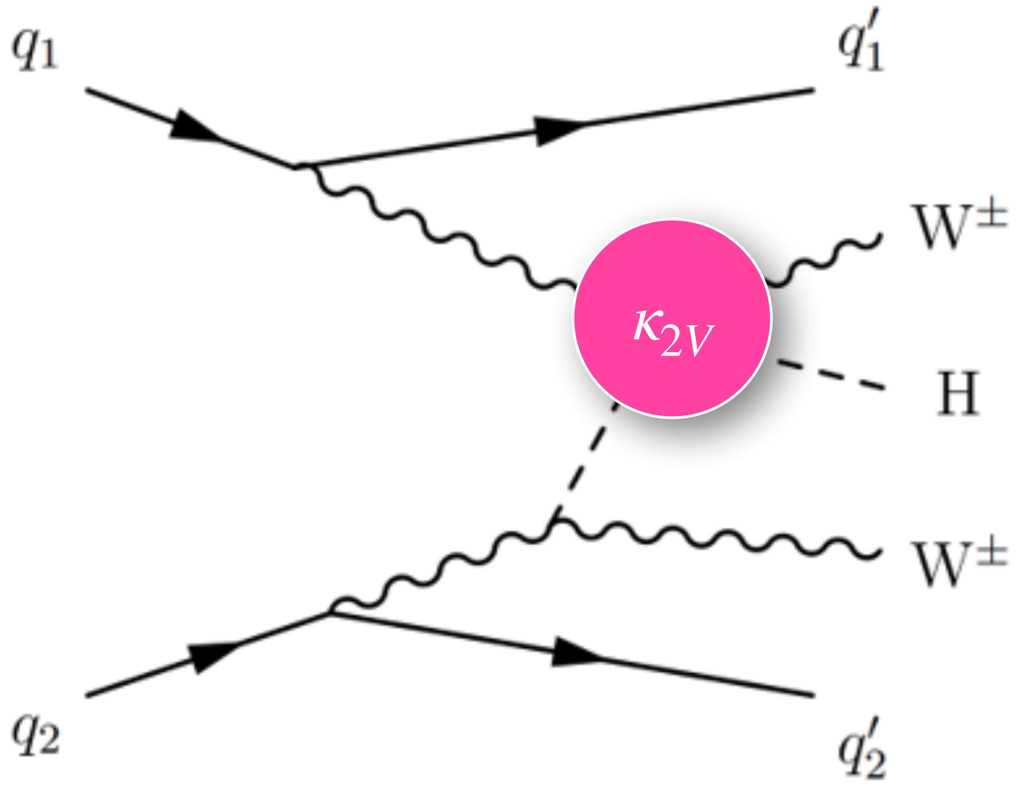
CMS-PAS-HIG-23-012

Competitive sensitivity.

$$-0.04 < \kappa_{2V} < 2.05 \ @ \ 95\,\% \,\mathrm{CL\ observed}$$
$$0.05 < \kappa_{2V} < 1.98 \ @ \ 95\,\% \,\mathrm{CL\ expected}$$

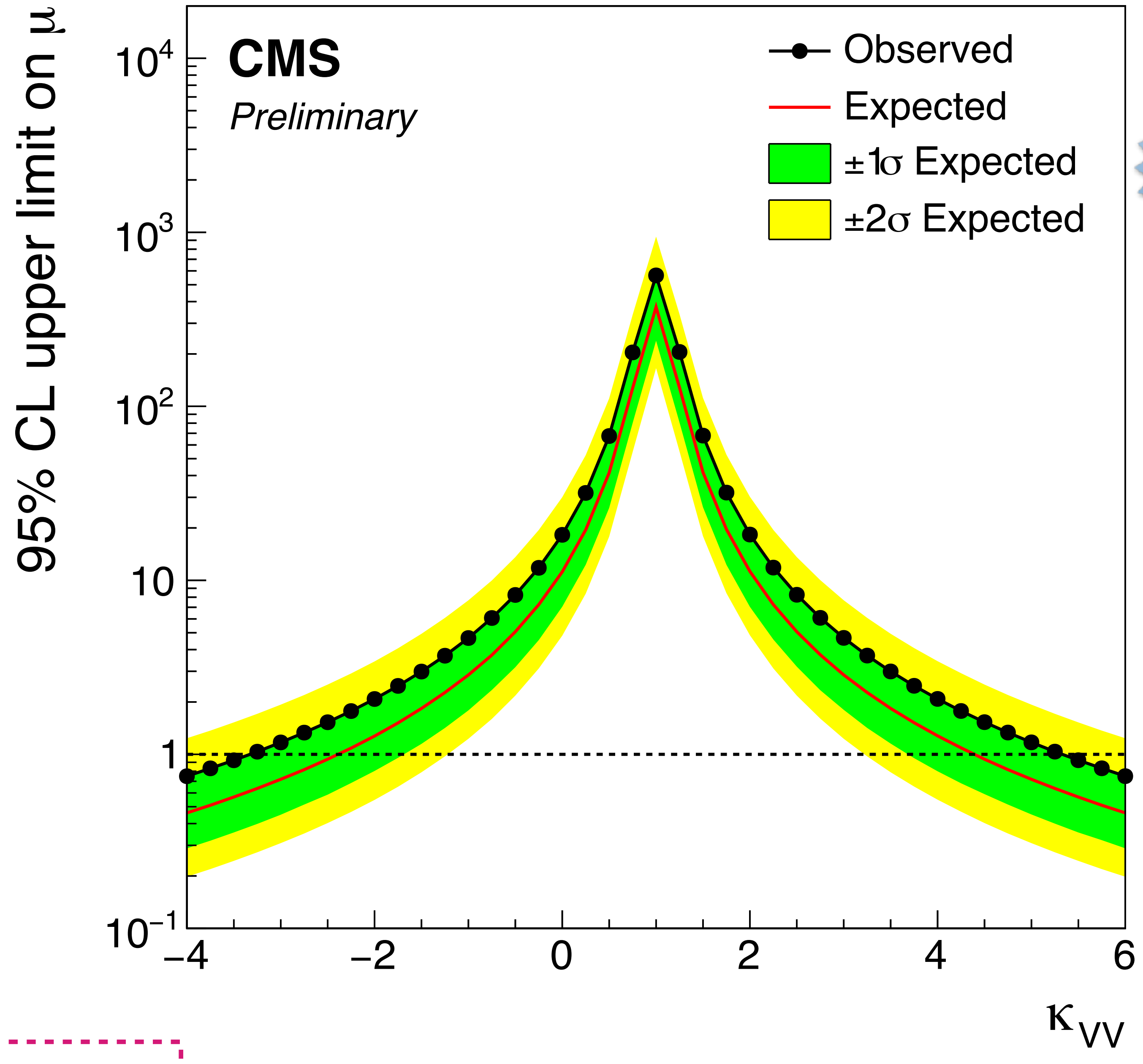
Current best observed limit: $0.67 < \kappa_{2V} < 1.38$.

VBS WWH(bb) channel



Higgs production via vector boson scattering also sensitive to κ_{2V} .

Final state with boosted $\mathrm{H \to bb}$ decays.



NEW

CMS-PAS-HIG-24-001

First VBS-based κ_{2V} constraints.

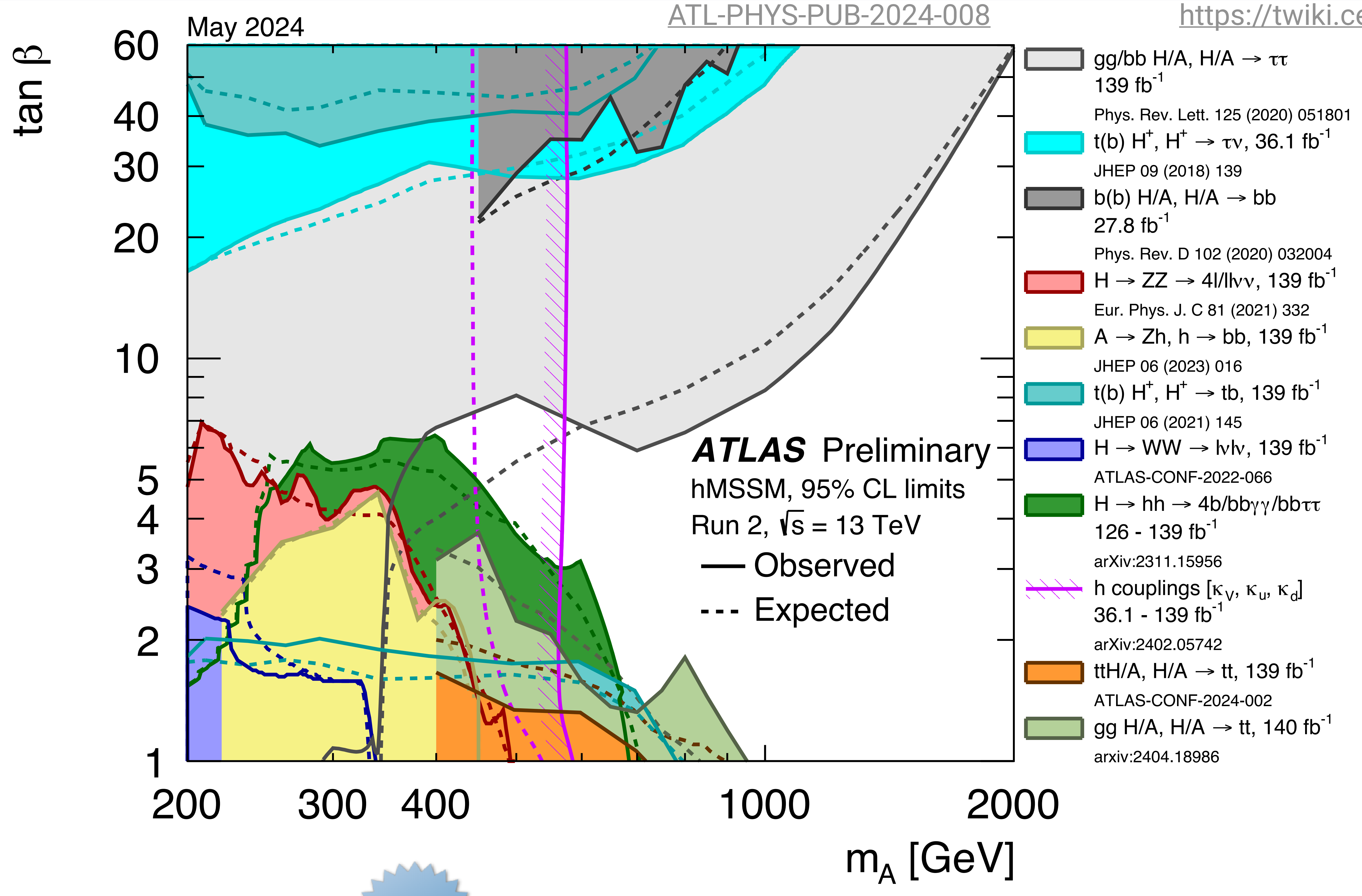
Possible improvements by adding other final states.

$$-3.3 < \kappa_{2V} < 5.3 \ @ \ 95\,\% \,\mathrm{CL\ observed}$$
$$-2.4 < \kappa_{2V} < 4.4 \ @ \ 95\,\% \,\mathrm{CL\ expected}$$

Direct searches for Higgs sector extensions

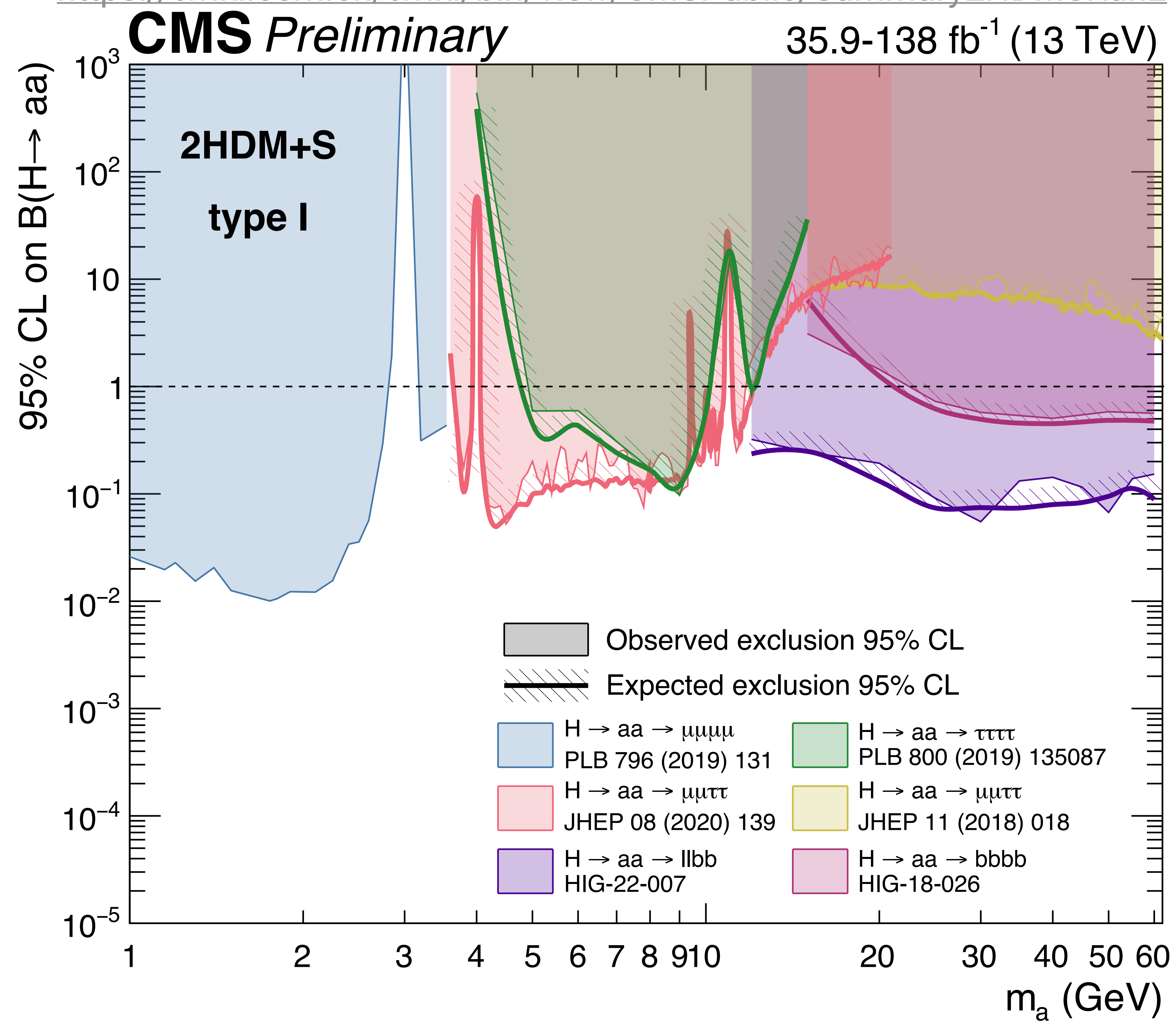
Just a selection of recent summary plots…

ATL-PHYS-PUB-2024-008



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG#NEW_Summary_of_MSSM_Higgs_Boson

https://twiki.cern.ch/twiki/bin/view/CMSPublic/Summary2HDMSRun2



… and a few NEW individual measurements:

	Analysis	Reference	Energy range
ATLAS	h → aa → bb$\tau\tau$	arXiv:2407.01335	m_a: 12 - 60 GeV
ATLAS	$H^\pm$ → cs	arXiv:2407.10096	$m_{H\pm}$: 60 - 160 GeV
ATLAS	Combined charged Higgs search	arXiv:2407.10798	$m_{H\pm(GM)}$: 200 - 1000 GeV
CMS	H → ZZ → 4ℓ	CMS-PAS-HIG-24-002	m_H: 130 - 3000 GeV
CMS	A → Zh($\tau\tau$)	CMS-PAS-HIG-22-004	m_A: 225 - 800 GeV
CMS	ϕ → bb	CMS-PAS-SUS-24-001	m_φ: 125 - 1800 GeV

Summary

Extensive Higgs physics program performed by ATLAS and CMS.

Many legacy results with the Run 2 data, with improved analysis techniques.

- Mass measurement precision: better than 1‰.
- Coupling strengths to vector bosons: 5-10% precision.
- Coupling strengths to third-generation fermions: 10-20% precision.
- Searches for anomalous couplings probing energy scales of up to 10 TeV.
- Higgs pair production measurement approaching the SM sensitivity.

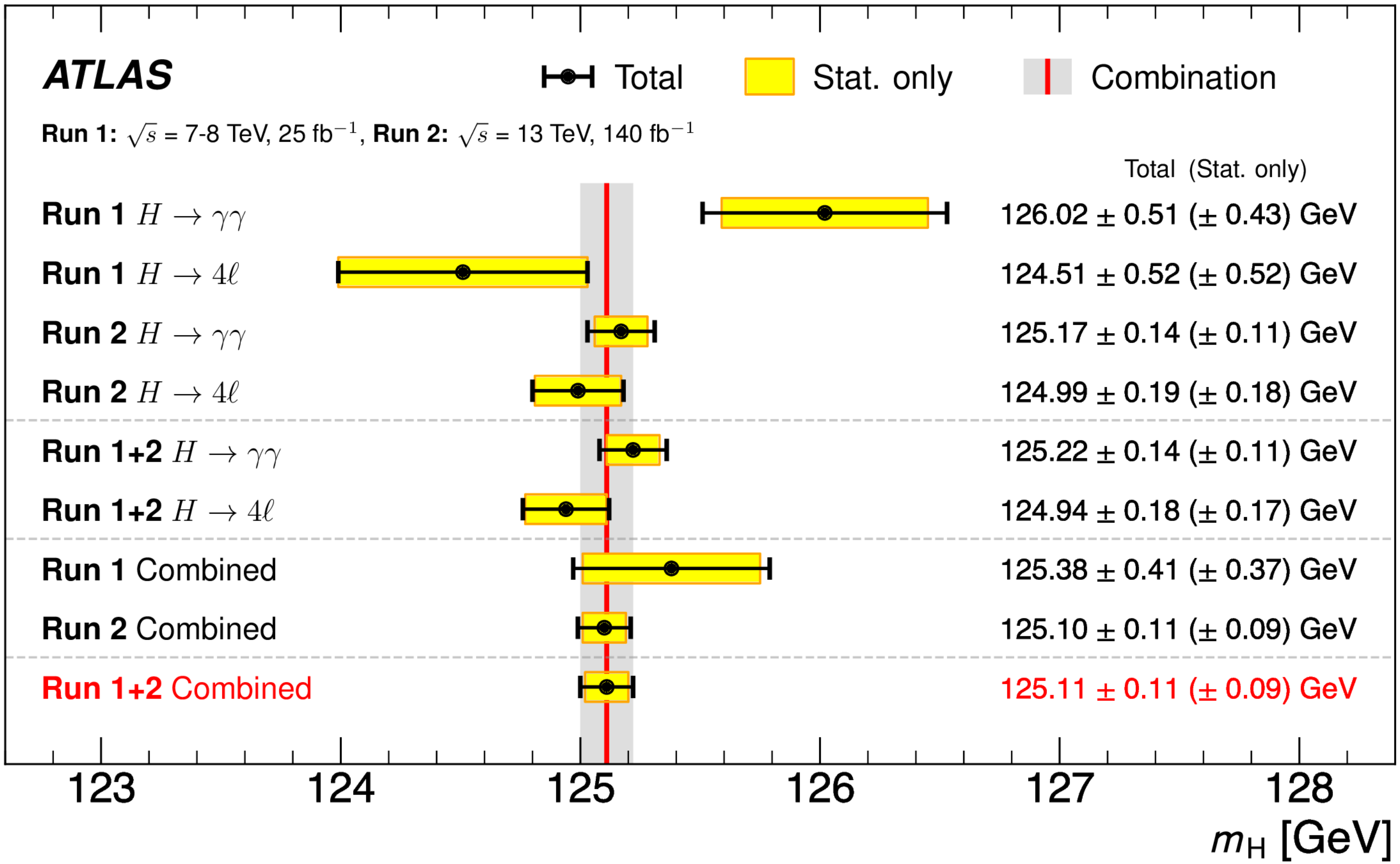
Run 2 analyses finishing. ATLAS+CMS combinations for the final Run 2 legacy.
Focus is now shifting to Run 3 data.

Backup

Backup:
Current state-of-the-art results

Higgs boson mass measurement by ATLAS

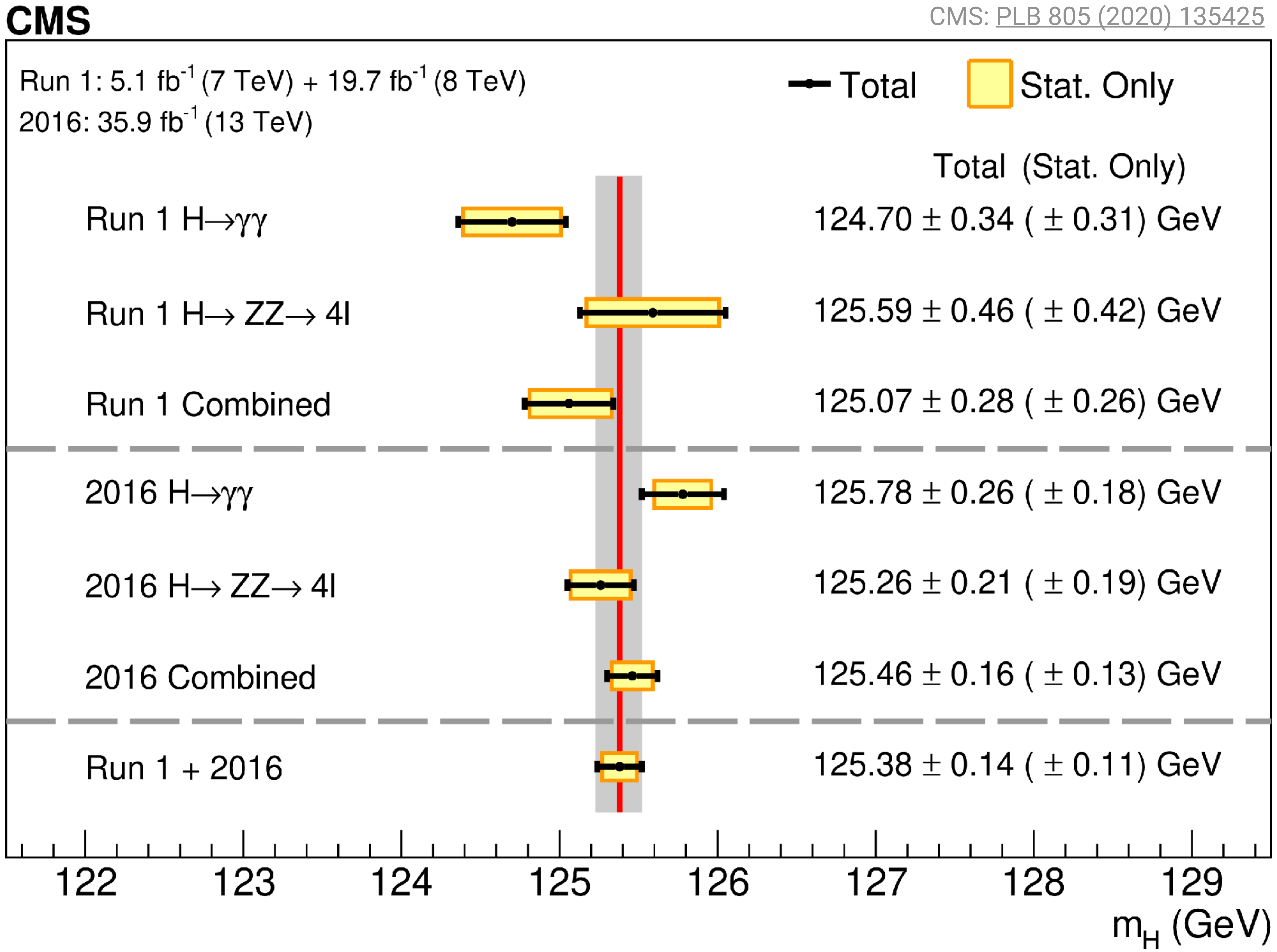
ATLAS: PRL 131 (2023) 251802



Higgs boson mass measurement by CMS

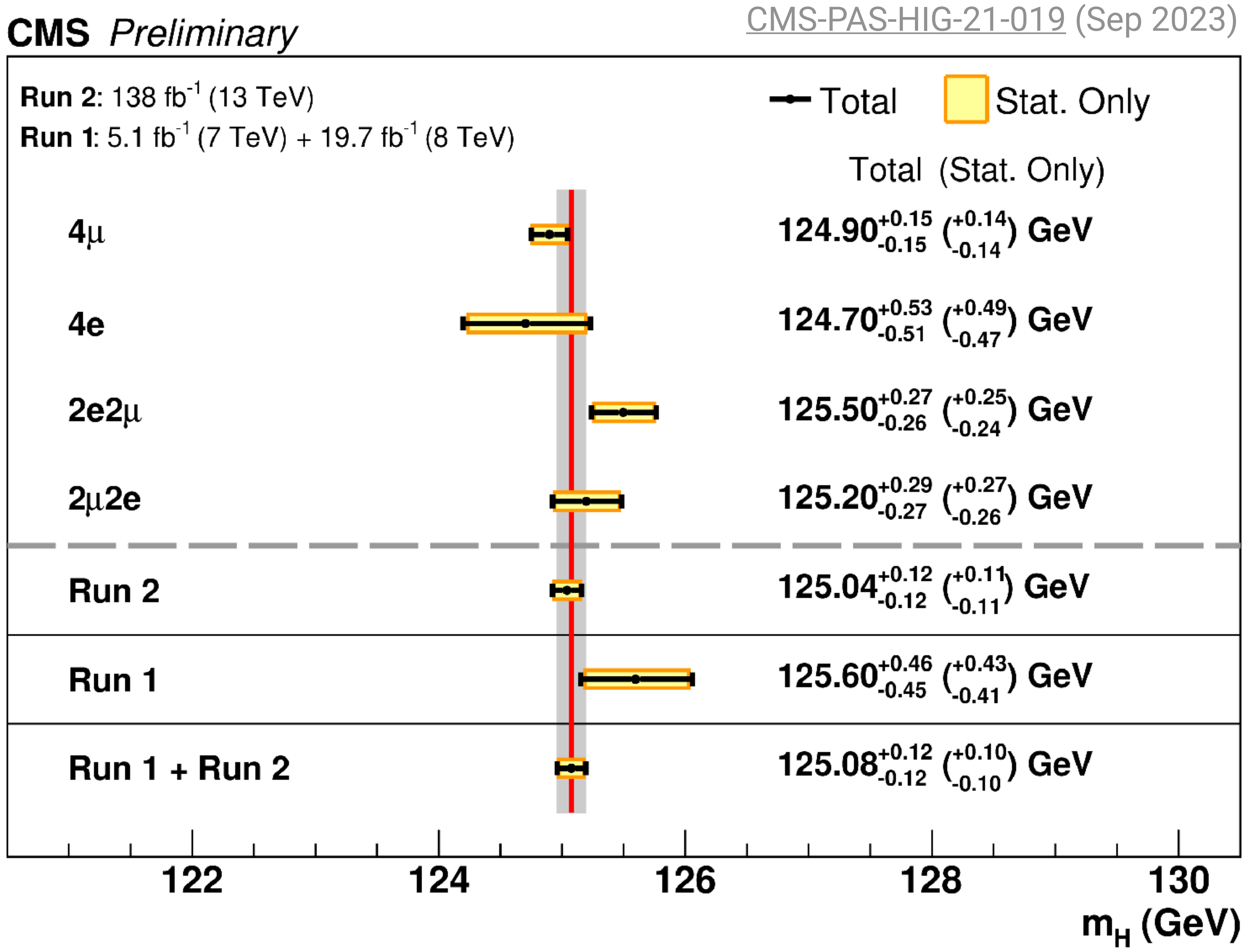
Combination $4\ell + \gamma\gamma$ with partial Run 2 data

CMS: PLB 805 (2020) 135425



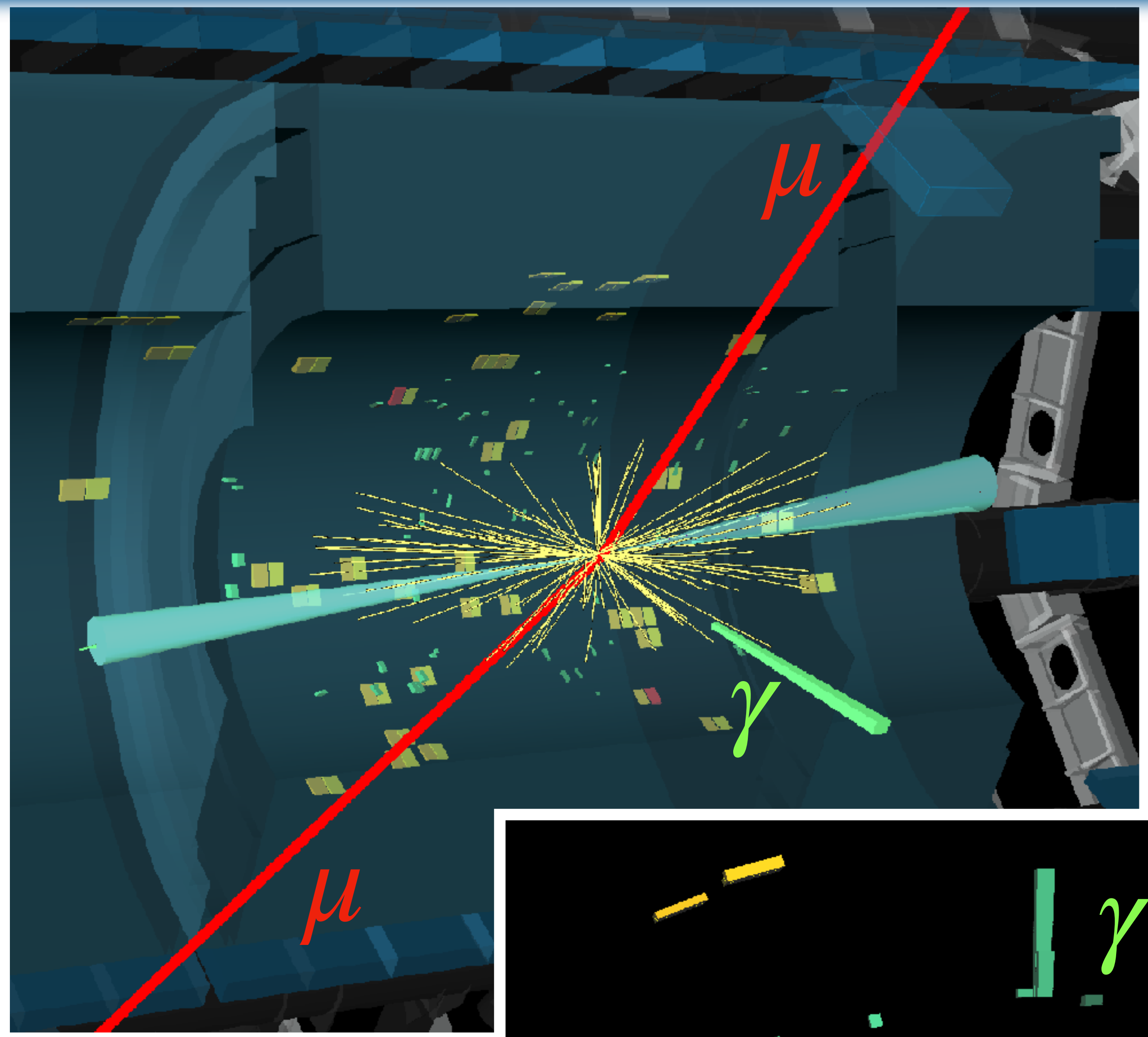
4ℓ channel only, with full Run 2 data

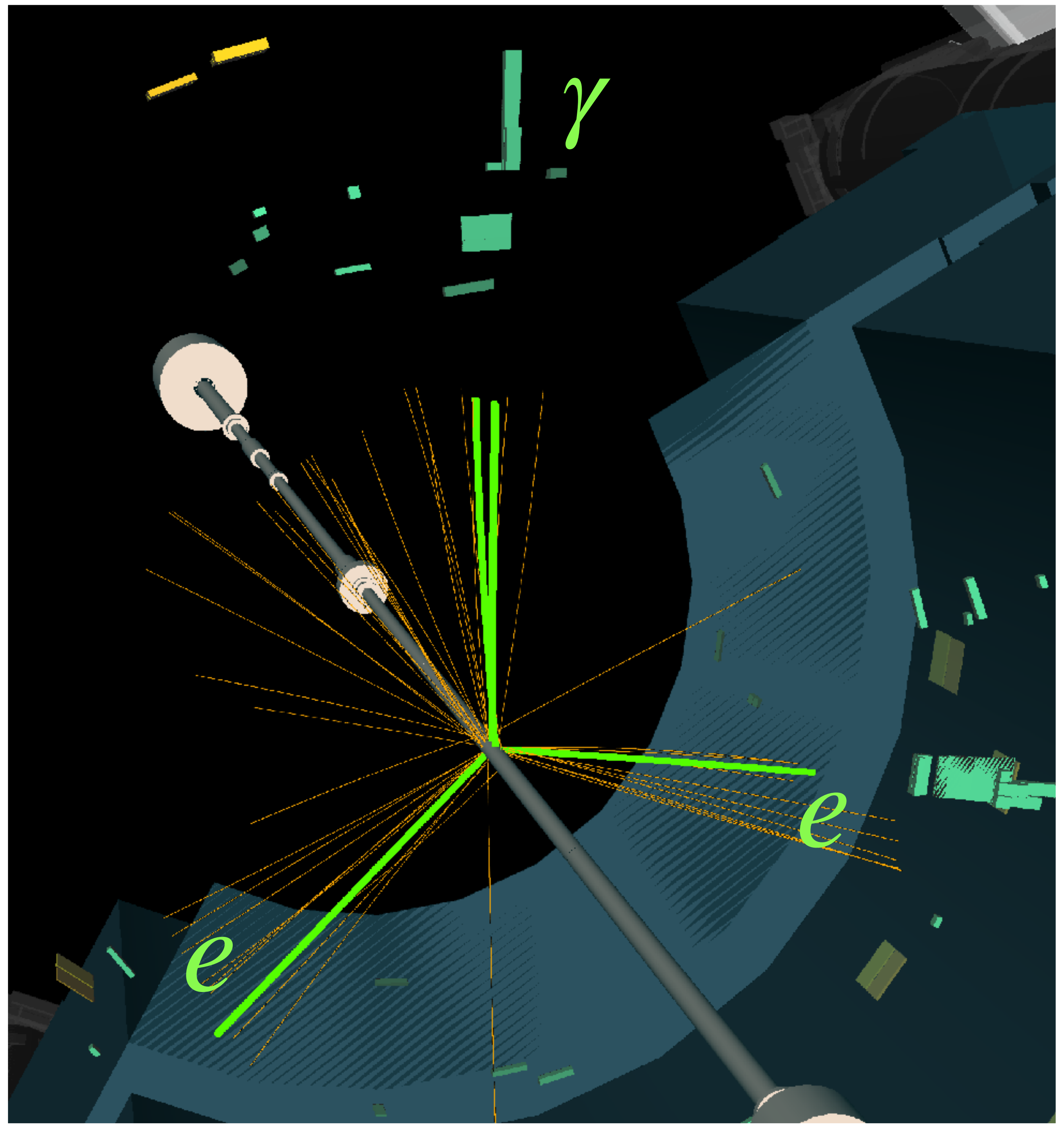
CMS-PAS-HIG-21-019 (Sep 2023)

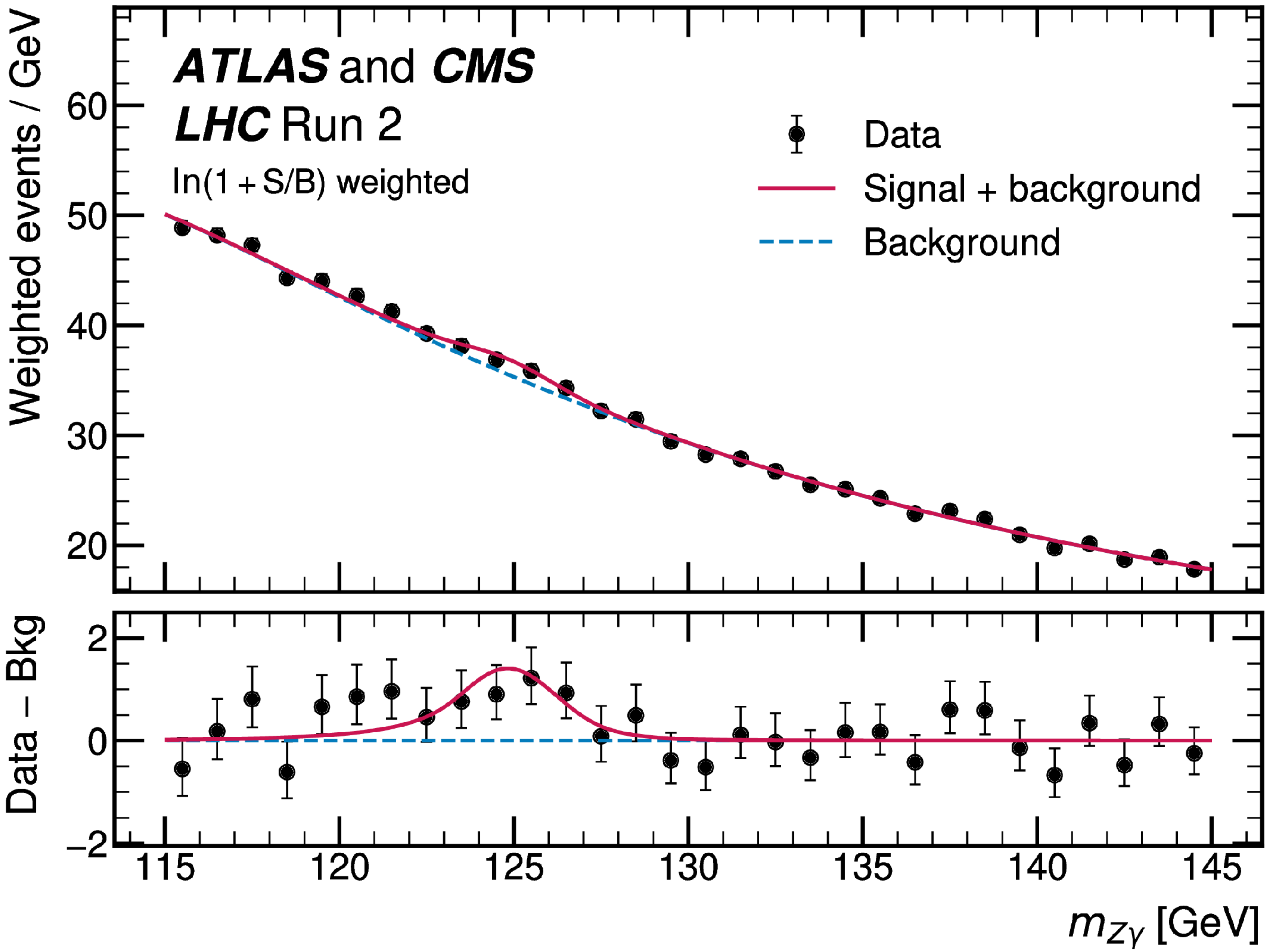


Evidence for the $\mathbf{H} \rightarrow Z\gamma$ decay

ATLAS & CMS: PRL 132 (2024) 021803





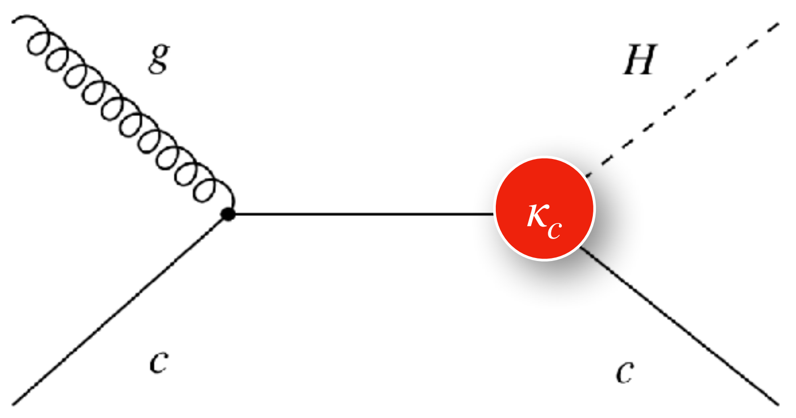


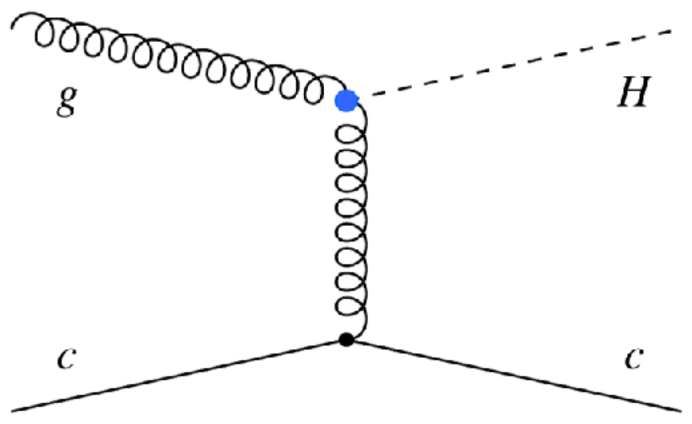
Observed (expected) signal significance: 3.4 σ (1.6 σ).

Backup:
Spotlight on Higgs interactions with fermions

First search for $\mathrm{H+c}$ production (ATLAS, CMS)

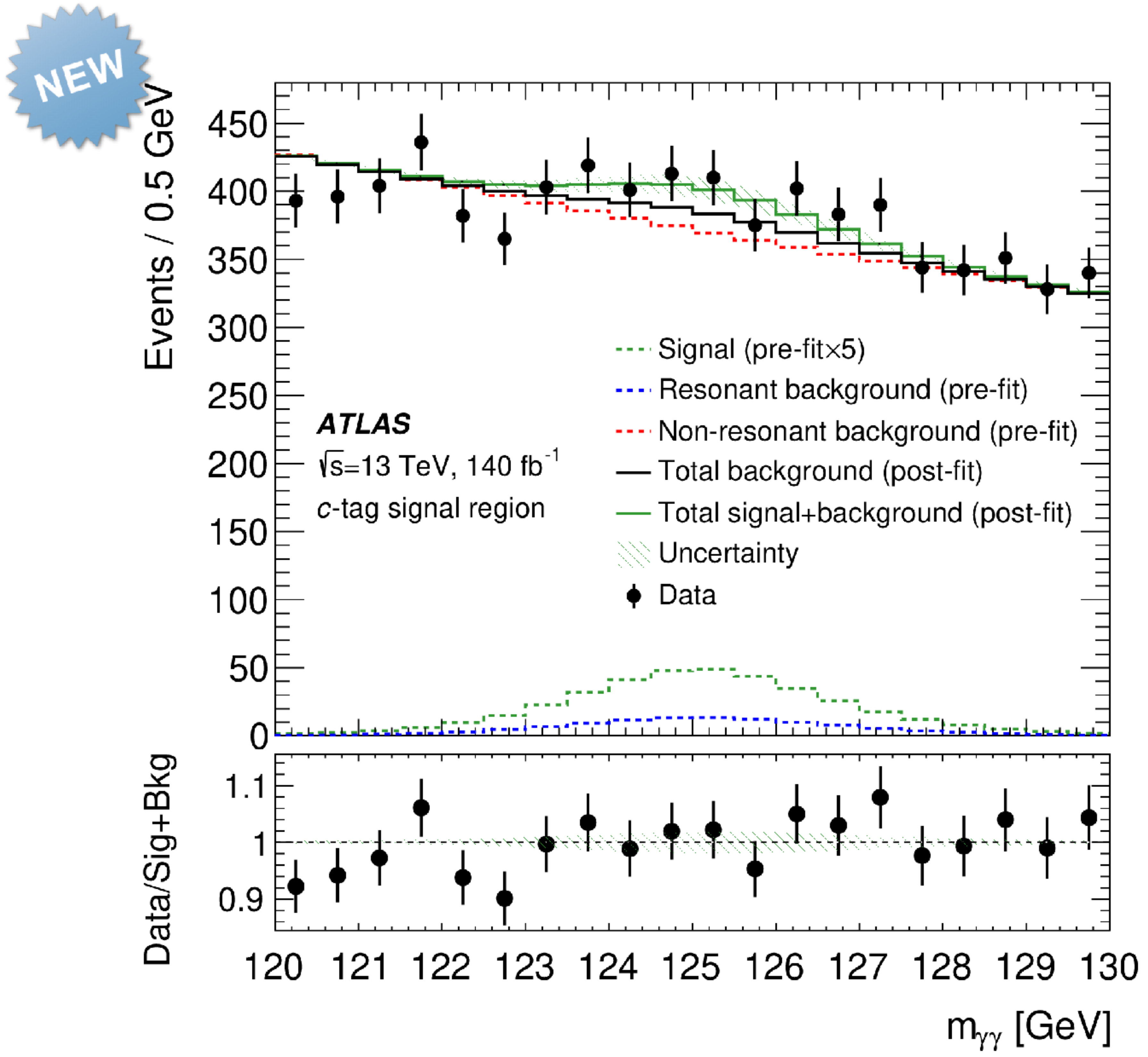
ATLAS: arXiv:2407.15550, submitted to JHEP, CMS: CMS-PAS-HIG-23-010

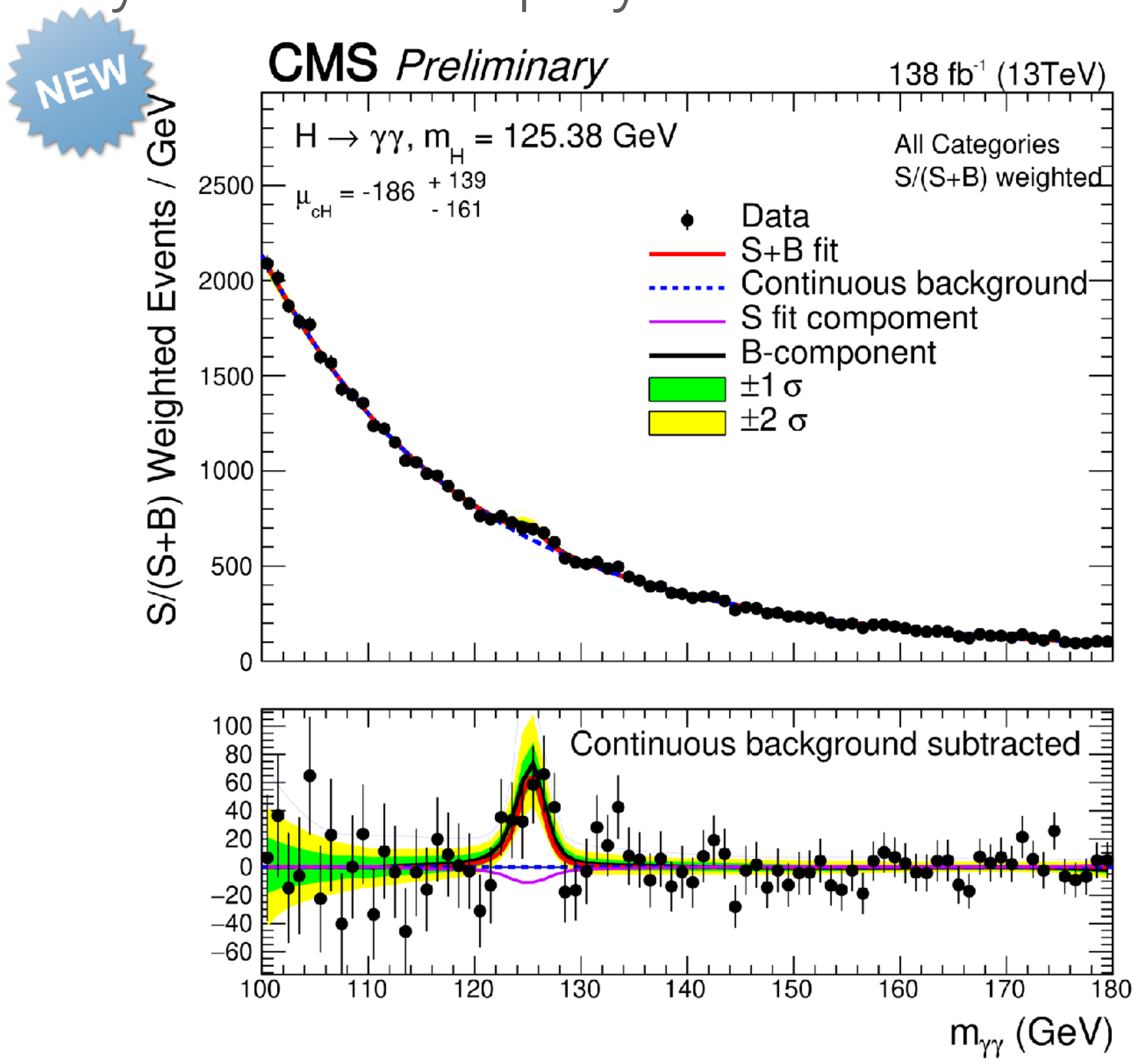




Production sensitive to κ_c ,
but with a large background of other non-κ_c processes.

$\mathrm{H} \to \gamma\gamma$ decay channel employed to minimize the background.





ATLAS measures the inclusive $\mathrm{H+c}$ production: $\sigma_{\mathrm{H+c}} < 10.4\ \mathrm{pb}\ @\ 95\,\%\,\mathrm{CL}\ (8.6\ \mathrm{expected})\ ;\ \sigma^{\mathrm{SM}}_{\mathrm{H+c}} = 2.9\ \mathrm{pb}$

CMS measures the κ_c-dependent part: $\mu_{\mathrm{cH}} < 243\ @\ 95\,\%\,\mathrm{CL}\ (355\ \mathrm{expected})\ ;\ |\kappa_c| < 38.1\ @\ 95\,\%\,\mathrm{CL}\ (72.5\ \mathrm{exp.})$

Backup:
Total Higgs decay width

Higgs width constraints from the 4-top-quark production

Experimental Higgs mass resolution is 30 times worse than the SM decay width prediction of 4.1 MeV.

Decay width constrained by combining on-shell and off-shell Higgs production measurements:

$$\left.\begin{array}{l}\sigma^{\mathrm{on-shell}}_{\mathrm{gg\to H\to ZZ}} \propto \mu_{\mathrm{ggH}}/(\mathrm{m_H}\Gamma_\mathrm{H}) \\ \sigma^{\mathrm{off-shell}}_{\mathrm{gg\to H\to ZZ}} \propto \mu_{\mathrm{ggH}}/(\mathrm{m^2_{ZZ}})\end{array}\right\}$$

Assuming $\mu^{on-shell}_{ggH} = \mu^{off-shell}_{ggH}$ and similar for μ_{VBF} $\Rightarrow$

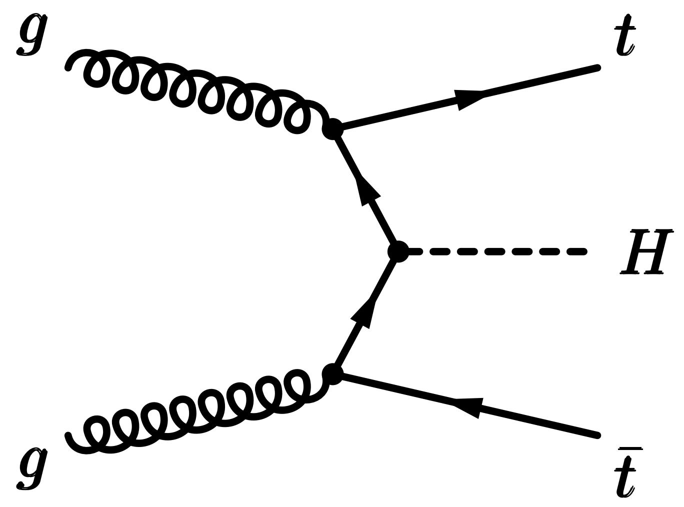
ATLAS $ZZ^{(*)}$: $\Gamma_\mathrm{H} < 10.2\ \mathrm{MeV}\ @\ 95\,\%\,\mathrm{CL}$ PLB 846 (2023) 138223

CMS $ZZ^{(*)}$: $\Gamma_\mathrm{H} < 7.9\ \mathrm{MeV}\ @\ 95\,\%\,\mathrm{CL}$ CMS-PAS-HIG-21-019

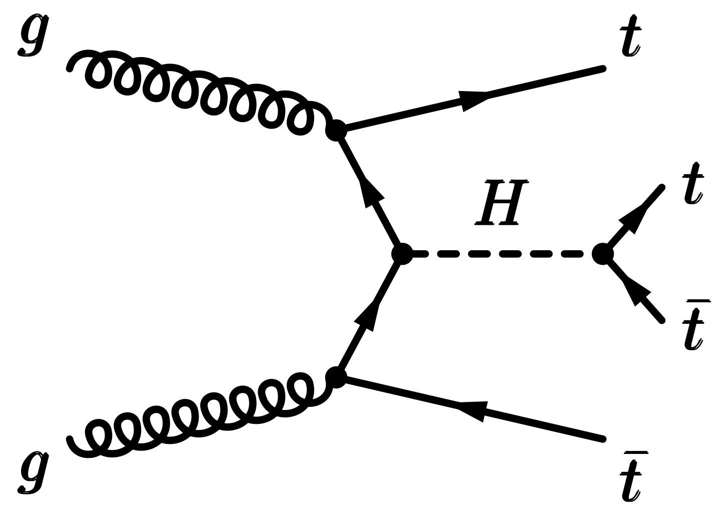
Recent complementary approach (ATLAS): top-quark-induced on-shell and off-shell Higgs production.

ATLAS: arXiv:2407.10631, submitted to PLB

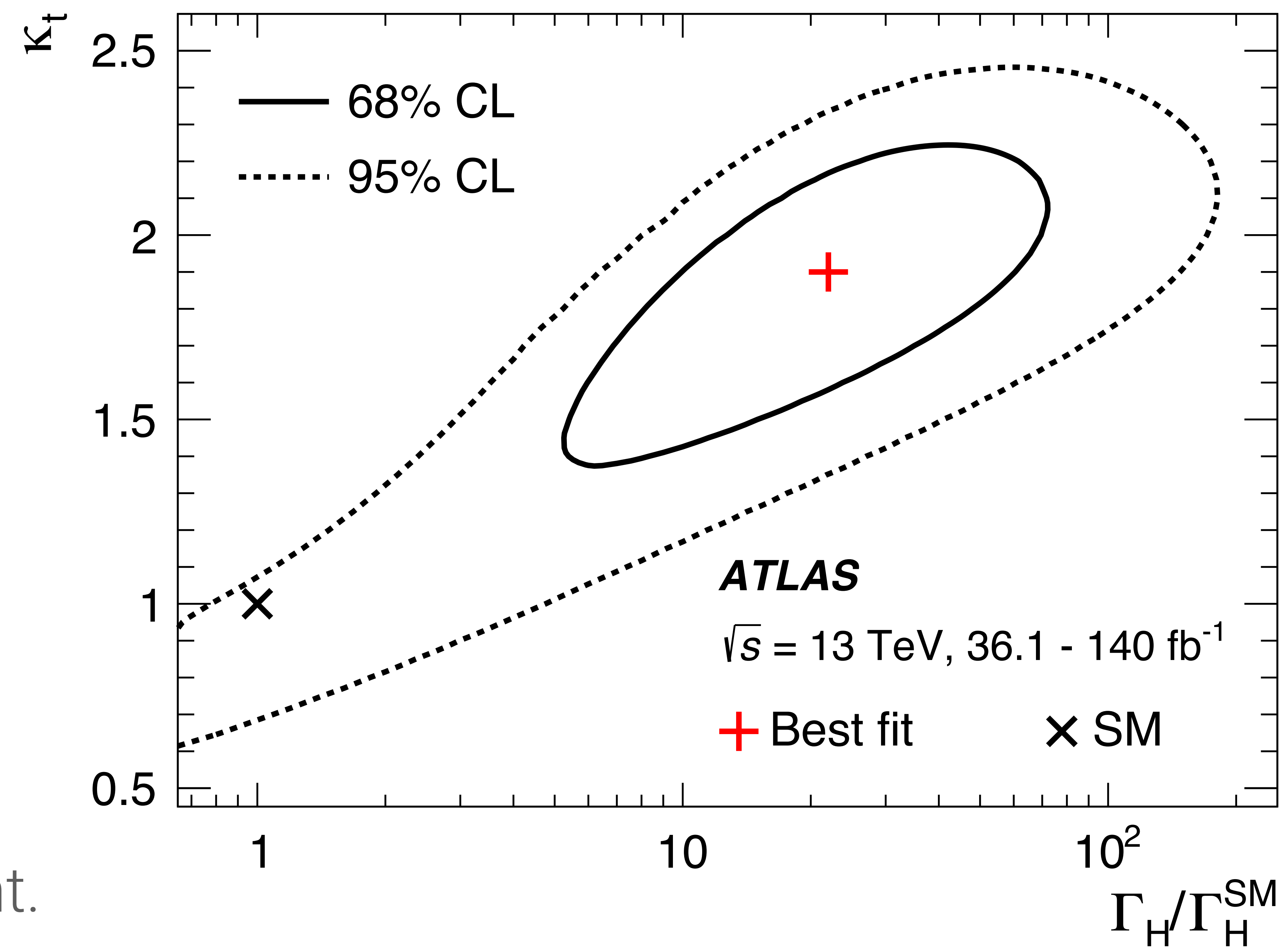
NEW



$\sigma^{\mathrm{on-shell}}_{\mathrm{pp\to ttH}} \propto \kappa_t^2/\Gamma_\mathrm{H}$



$\sigma^{\mathrm{off-shell}}_{\mathrm{pp\to 4t}} \propto \mathrm{f}(\kappa_t^2)$



Assumption:

top-Yukawa coupling is the same in on-shell and off-shell processes.

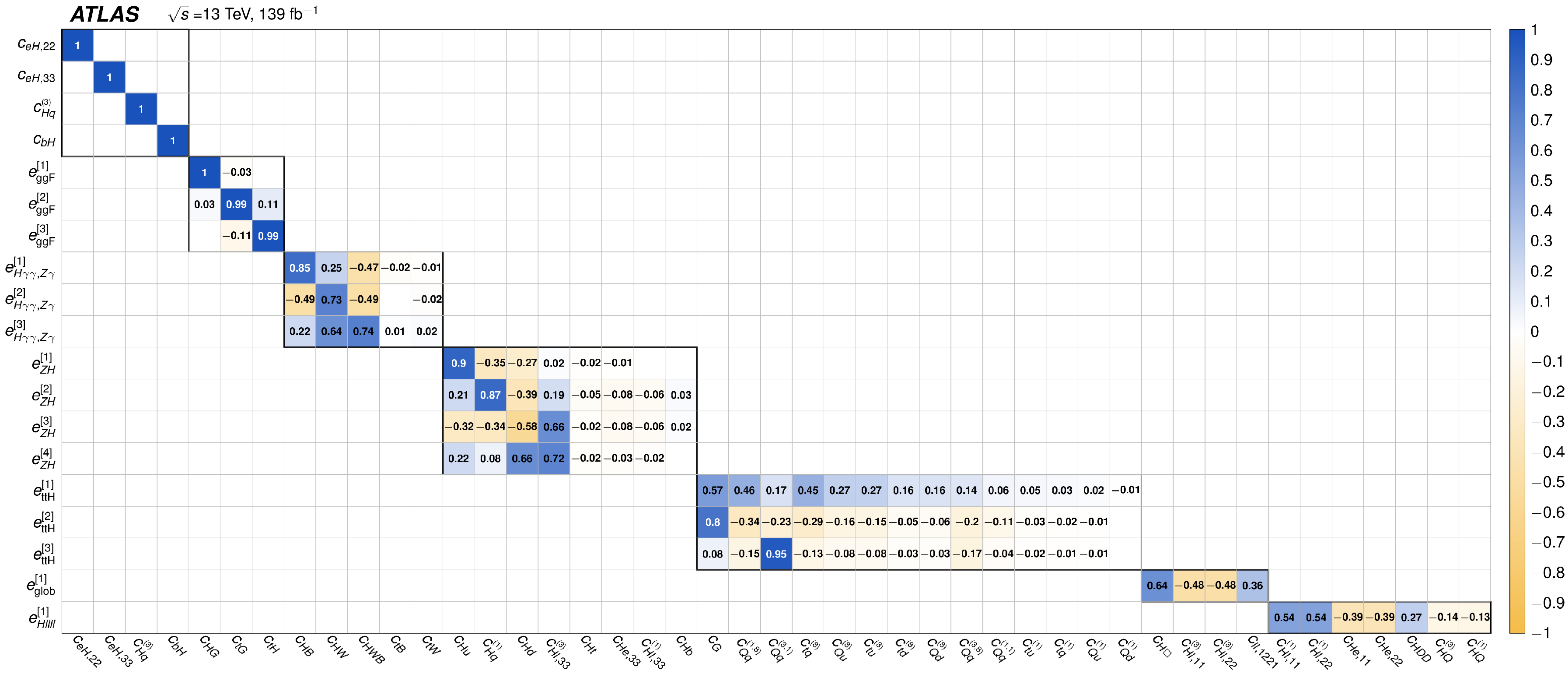
Other couplings constrained by combined on-shell Higgs measurement.

Γ_H < 450 MeV (exp. 75 MeV) @ 95% CL. Larger observed due to observed excess in $\mathrm{pp} \to \mathrm{tttt}$.

Backup:
Going differential in search for anomalies

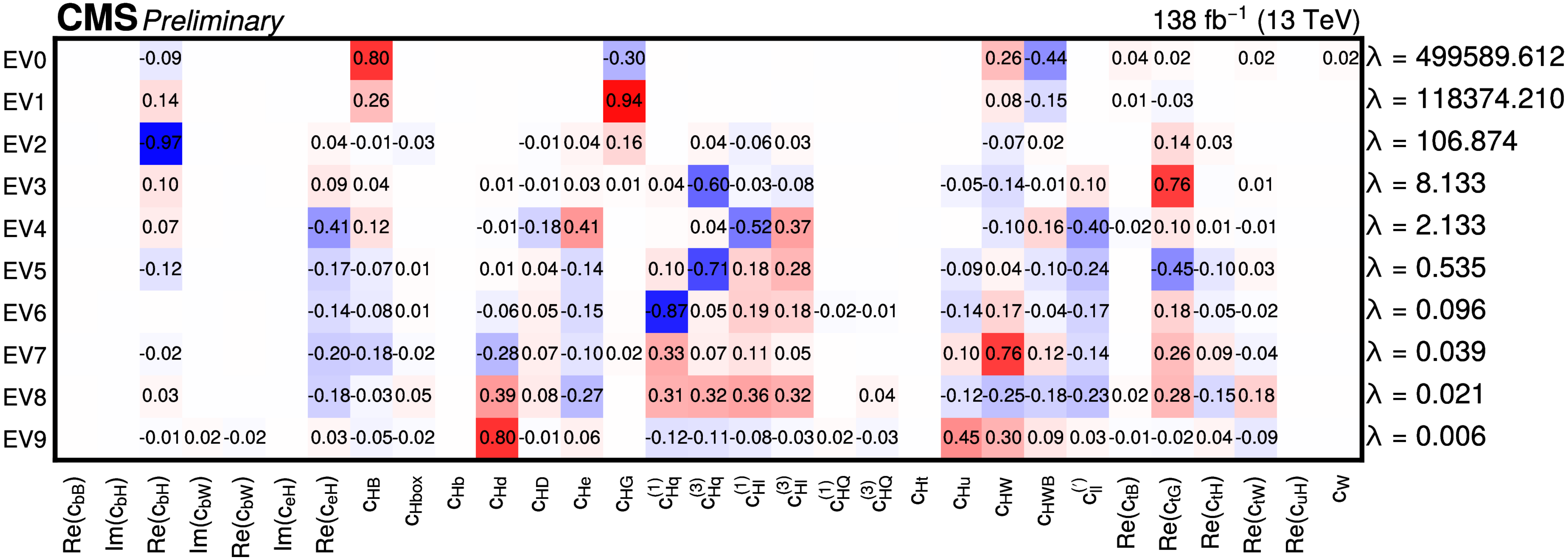
ATLAS: PCA-based SMEFT eigenvector decomposition (STXS)

ATLAS: arXiv:2402.05742, submitted to JHEP



CMS: PCA-based SMEFT eigenvector decomposition (differential)

CMS-PAS-HIG-23-013



Backup:
Higgs self-interaction

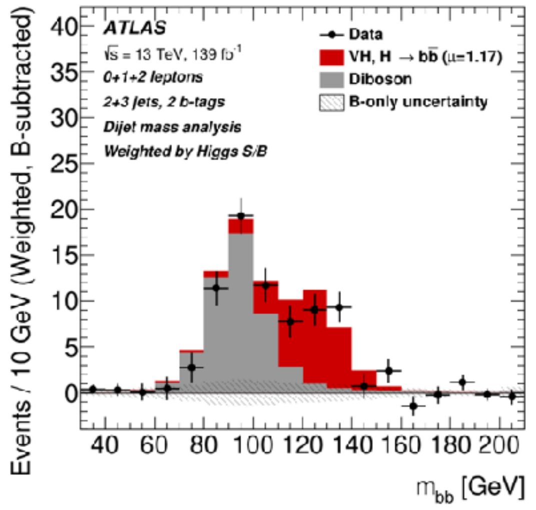
Searches for Higgs pair production

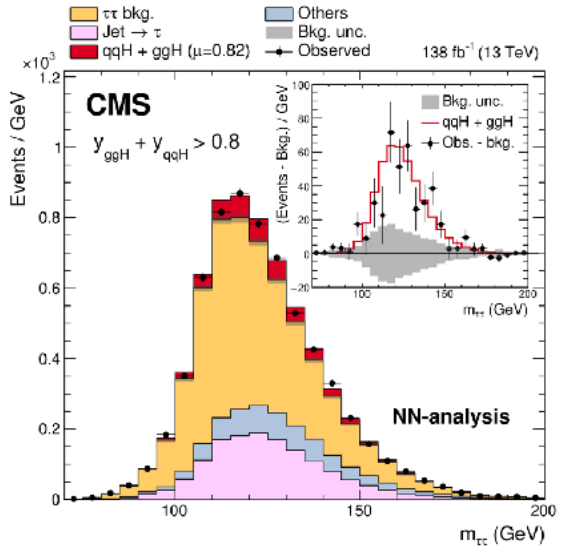
Summary compiled by N.Berger, ICHEP 2024

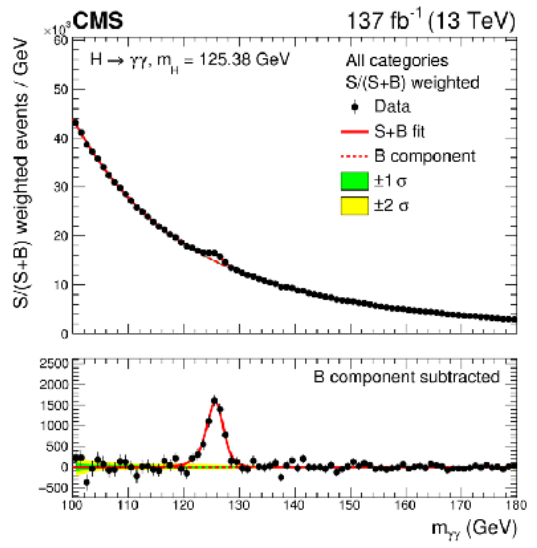
	H→bb	H→ττ	H→γγ	H→WW|ZZ
H→bb (58%)	**HH→bbbb (34%)** μ < 3.9 (CMS)			
H→ττ (6.3%)	**HH→bbττ (7.3%)** μ < 3.3 (CMS)	**HH→ττττ**		
H→γγ (0.23%)	**HH→bbγγ (0.26%)** μ < 4.0 (ATLAS)	**HH→ττγγ**	**HH→γγγγ**	
H→WW|ZZ (24%)	**HH→bbVV (25%)** μ < 14 (CMS)	**HH→ττVV**	**HH→γγVV**	**HH→VVVV**

HH→multileptons μ < 17 (ATLAS)

Best current 95% CL observed upper limits on μ are shown



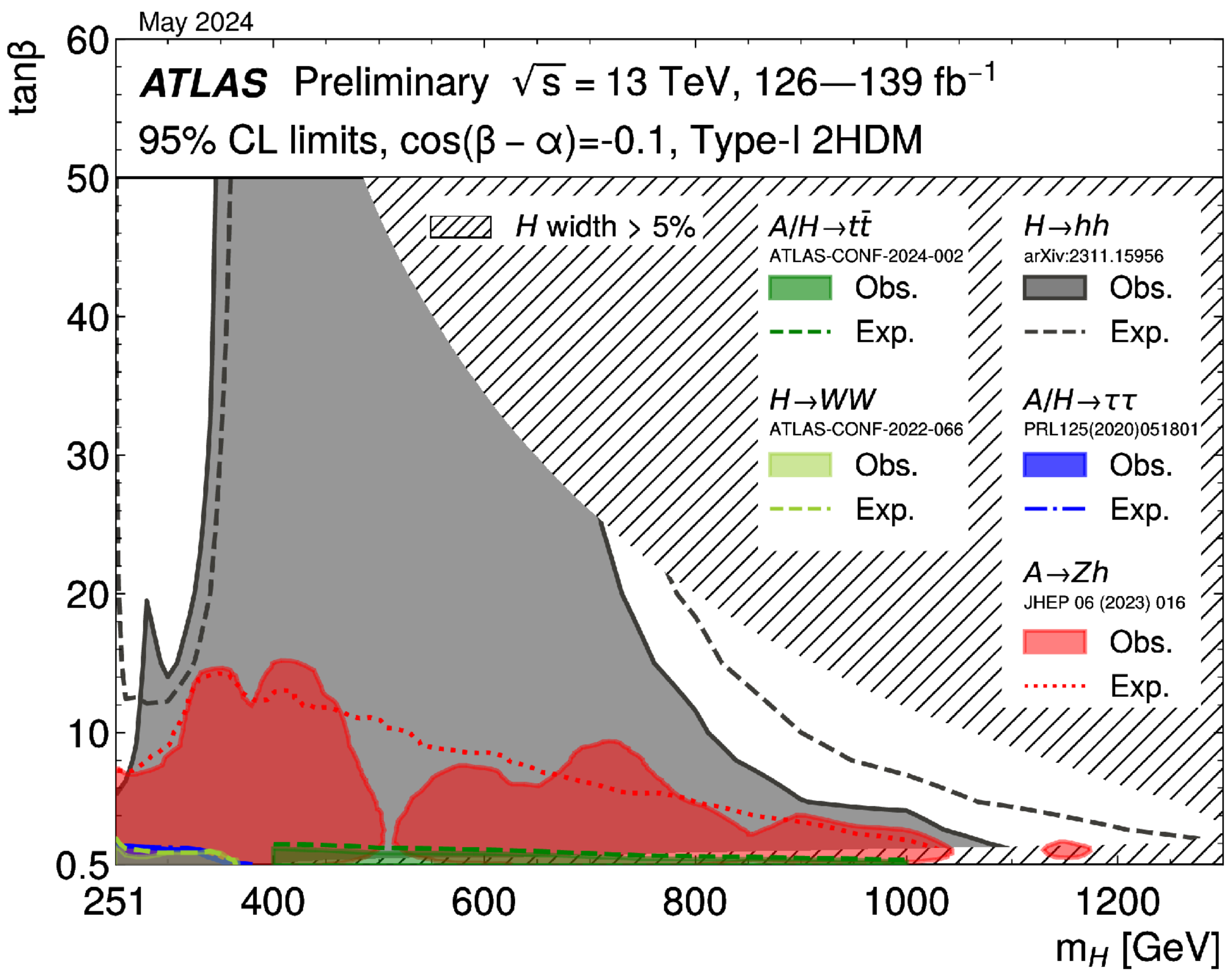


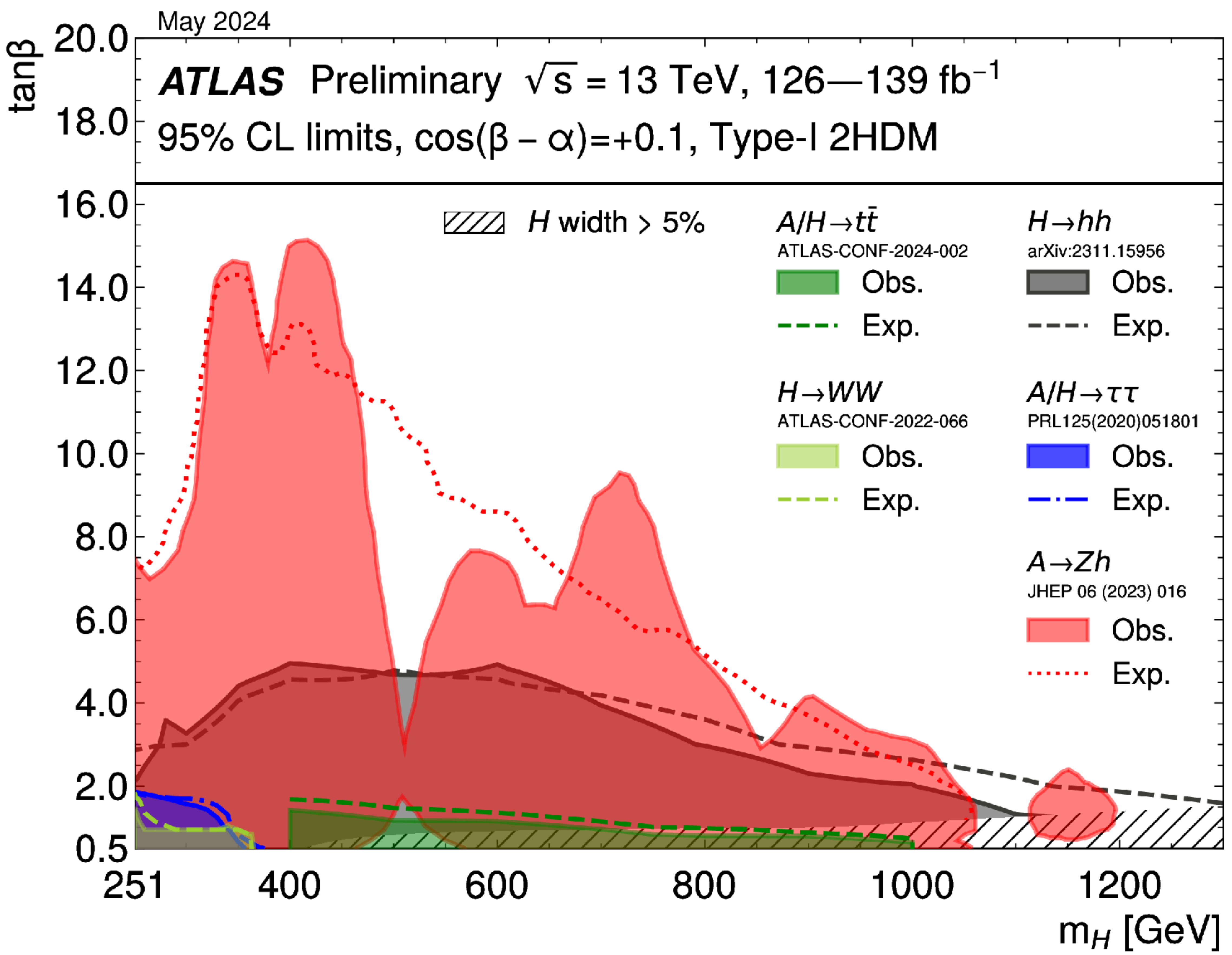


Backup:
Direct searches for Higgs sector extensions

ATLAS: Recent summary plots

ATL-PHYS-PUB-2024-008





Recent summary plots: ATLAS & CMS comparison

ATL-PHYS-PUB-2024-008

https://twiki.cern.ch/twiki/pub/CMSPublic/SummaryResultsHIG/MSSM_limits_hMSSM_Mar2023.png