



A JOURNEY INTO THE HIGGS SECTOR

21/APRIL/2026

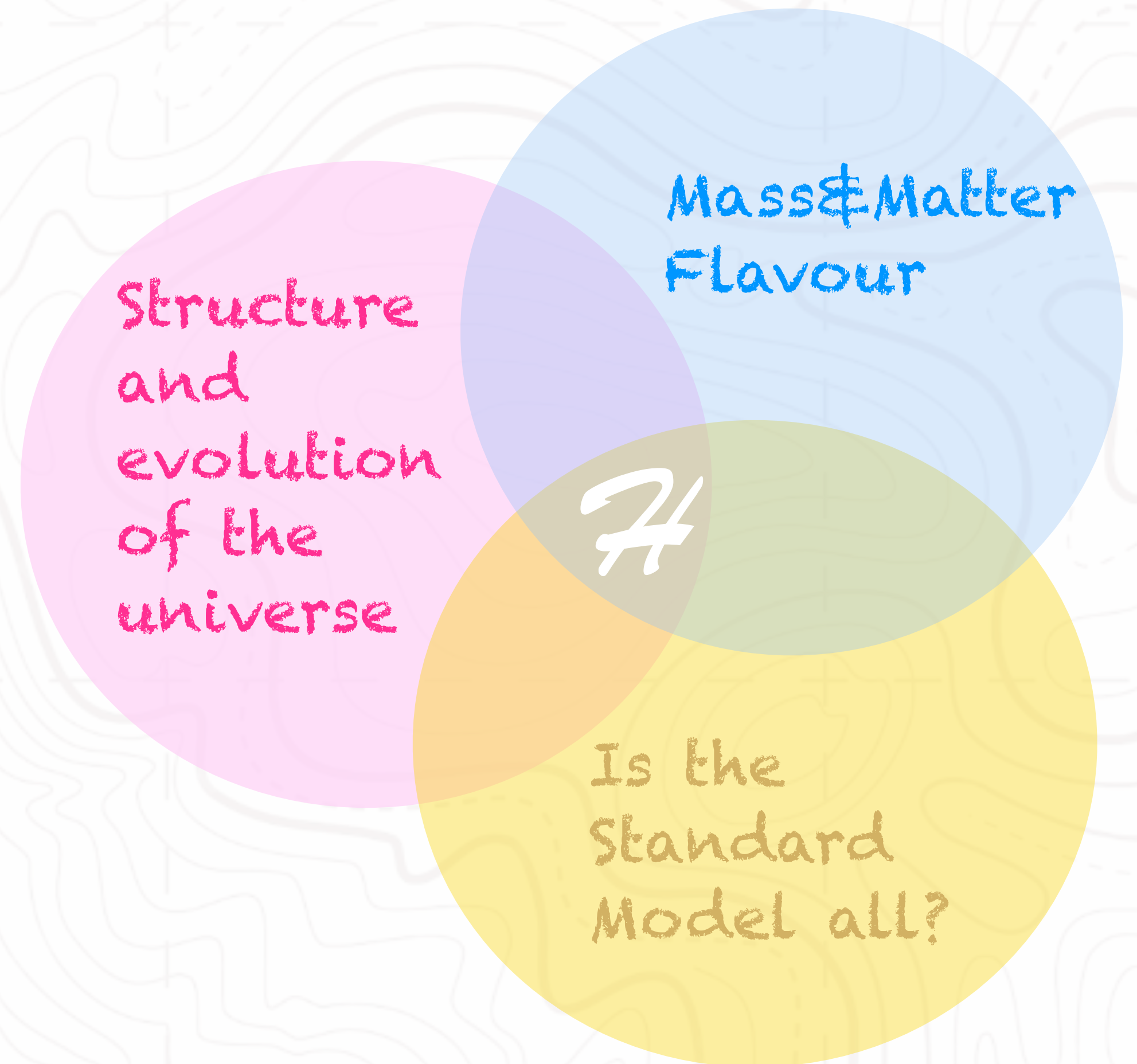
María Cepeda (CIEMAT)

U. SIEGEN

NOT JUST ANOTHER PARTICLE...

Studying the nature of the Higgs Boson at the LHC addresses some of the main questions in fundamental physics

- Why do particles have mass?
- Why does the universe exist in its current form?
- Is there new physics beyond the standard model (BSM) ?



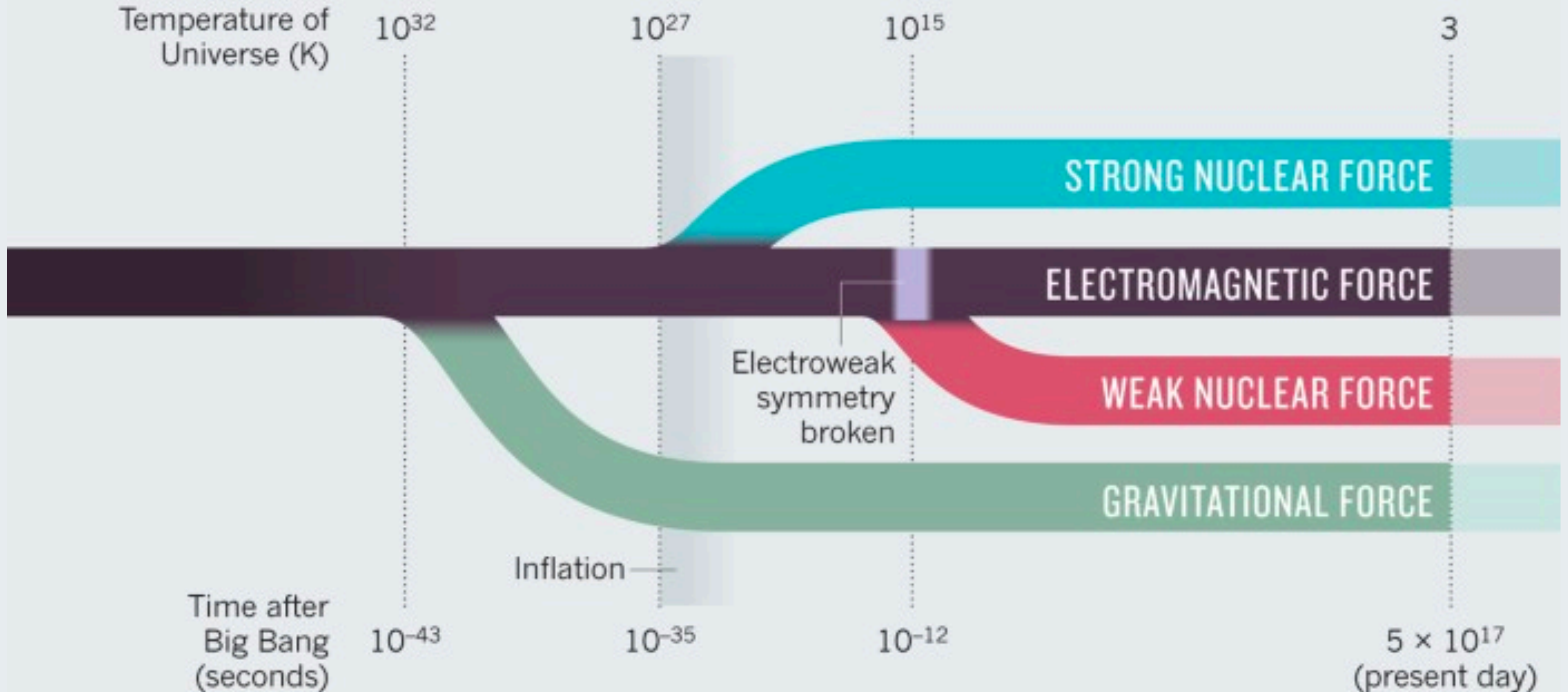
Let's start by briefly
remembering what is
the Higgs Field...



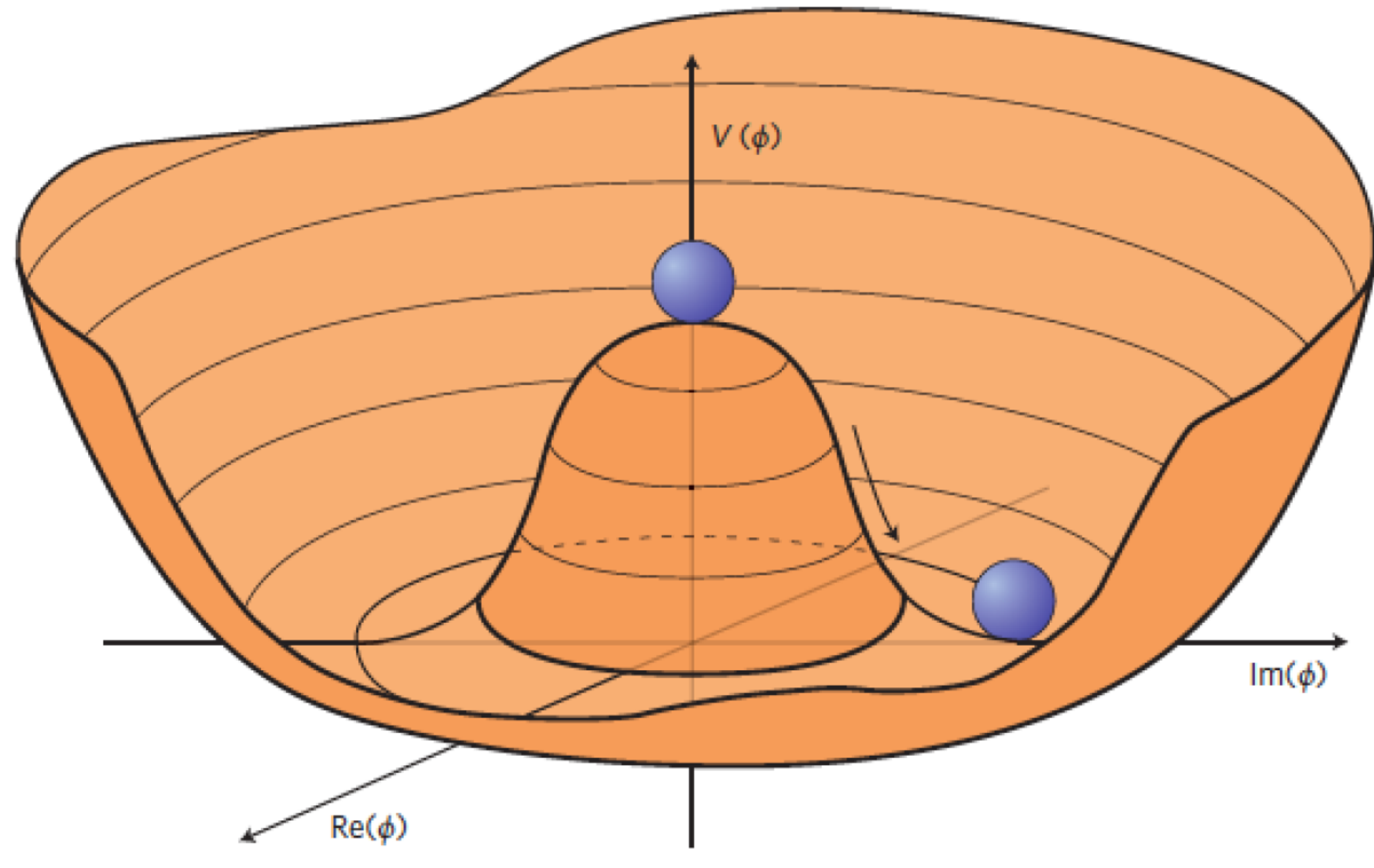
Illustration by Michele Sclafani for Quanta Magazine

FUNDAMENTAL FORCES

After the Big Bang, the four forces divided as the cooling Universe underwent phase transitions. The Higgs boson broke the symmetry between the electromagnetic and weak nuclear forces.



THE HIGGS MECHANISM

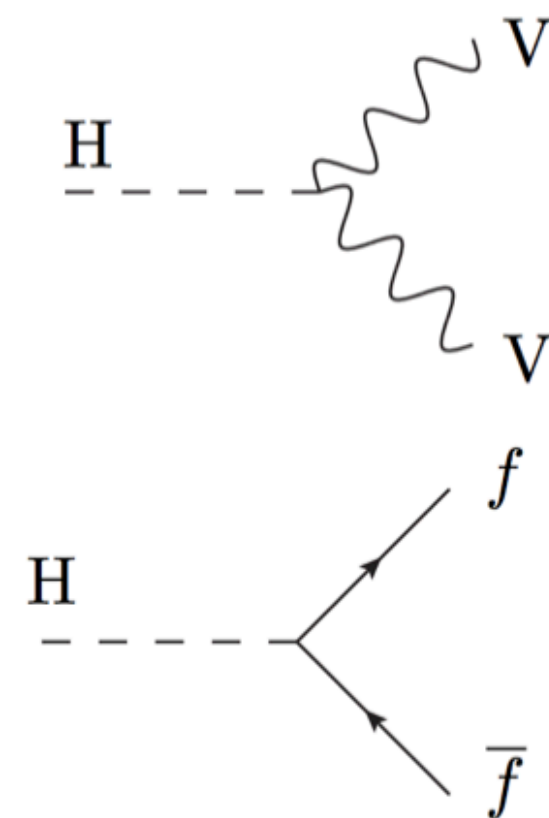


- Electro-Weak Symmetry Breaking: mass of W, Z (photons massless)
- Prediction of the relation between the gauge boson masses and their couplings
- Prediction of a new boson, the Higgs
- What about fermion masses? Yukawa couplings!

$$\mathcal{L} = |D_\mu \Phi|^2 - \mu^2 \Phi^2 - \lambda \Phi^4$$

For $\mu^2 < 0$, minimum $v = \sqrt{-\frac{\mu^2}{2\lambda}}$

$$\mathcal{L}_{Y_i} = y_i h f_L^i f_R^i + h.c. \text{ with } y_i = \frac{m_i}{v}$$



$$\frac{2m_V^2}{v}$$

$$+ |D_\mu \phi|^2$$

$$\frac{m_f}{v}$$

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi$$

$$\frac{3m_H^2}{v}$$

$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

WHY SO IMPORTANT?

The main problems of the SM show up in the Higgs sector

$$V_{Higgs} = V_0 - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2 + [\bar{\psi}_{Li} Y_{ij} \psi_{Rj} \phi + h.c.]$$

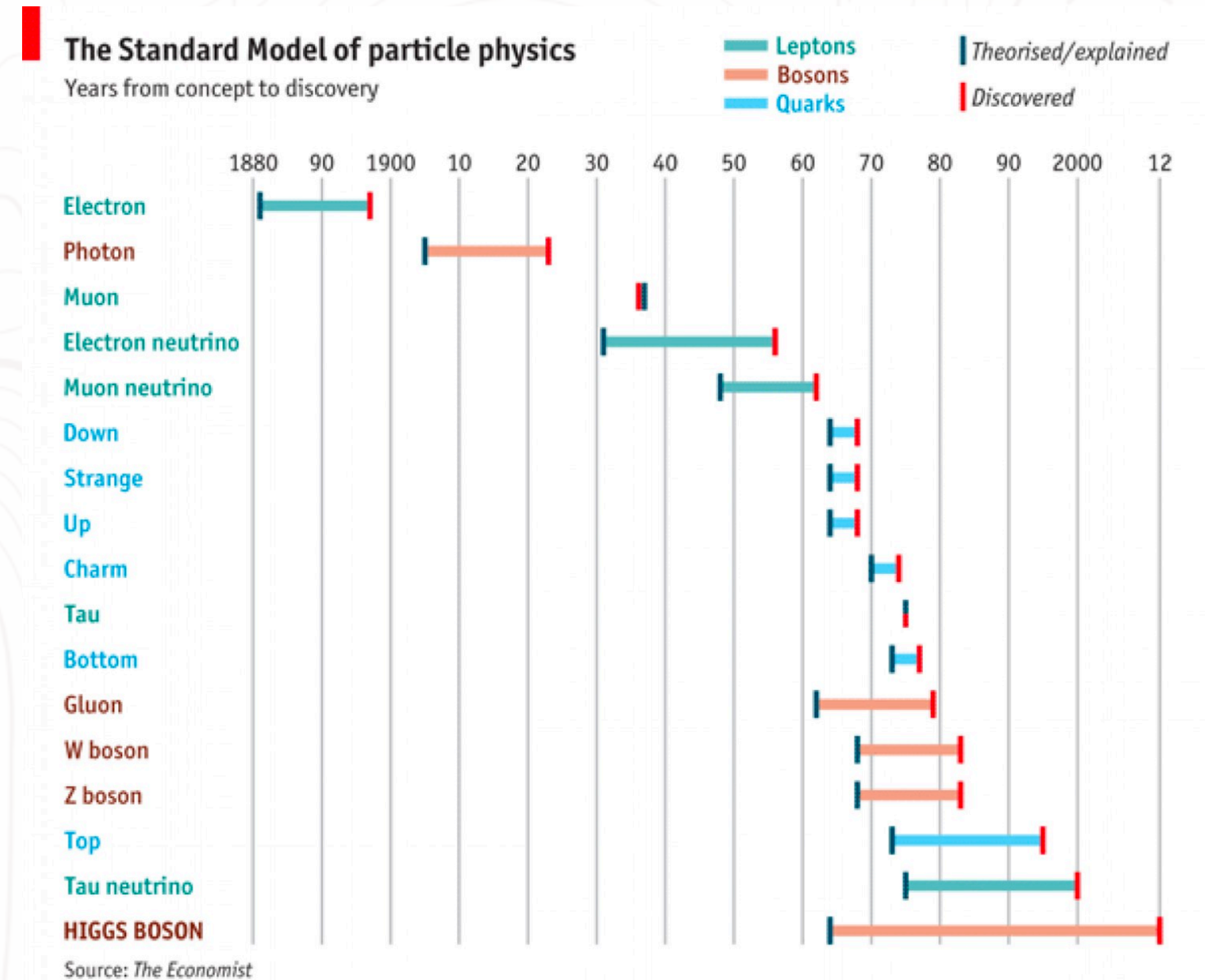
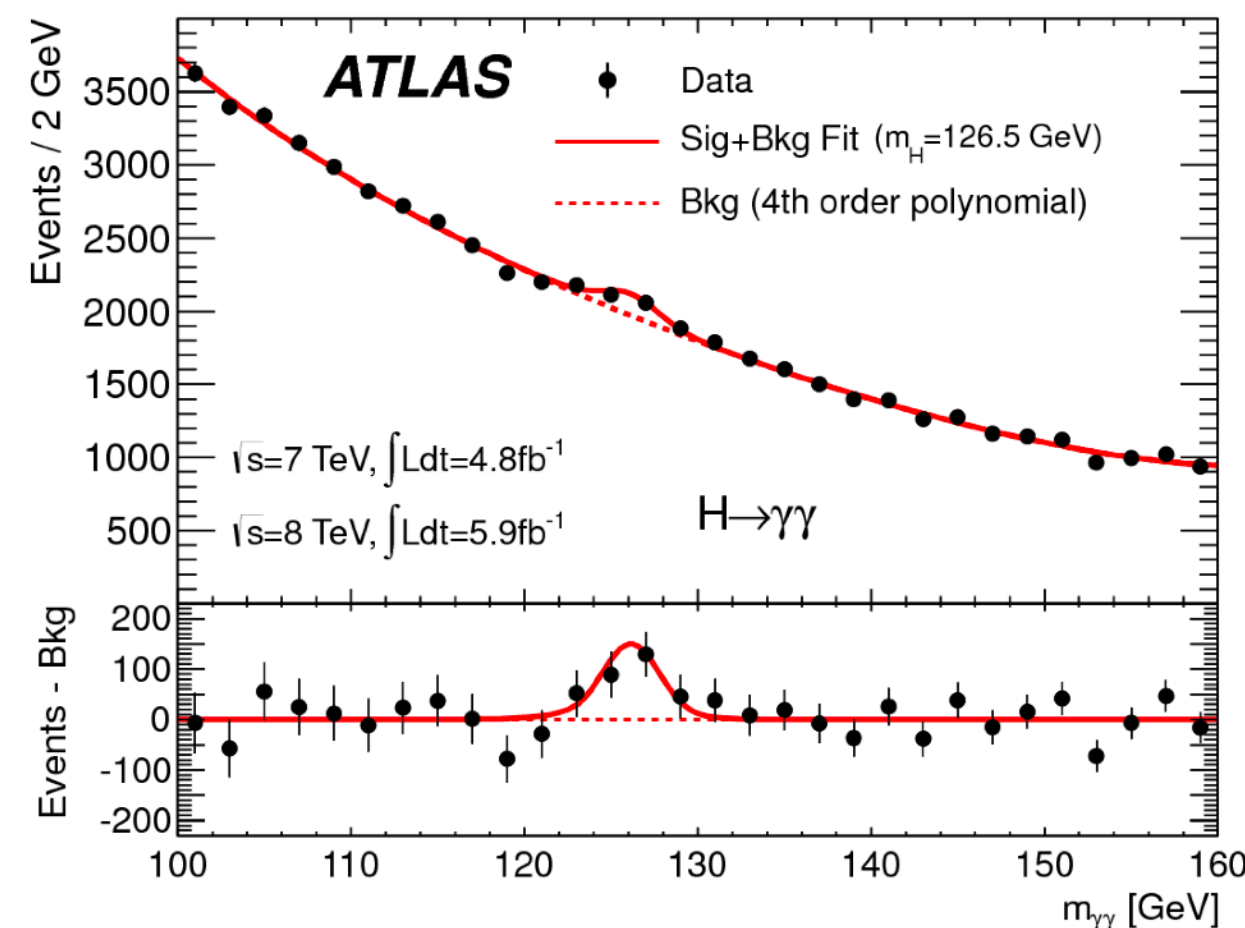
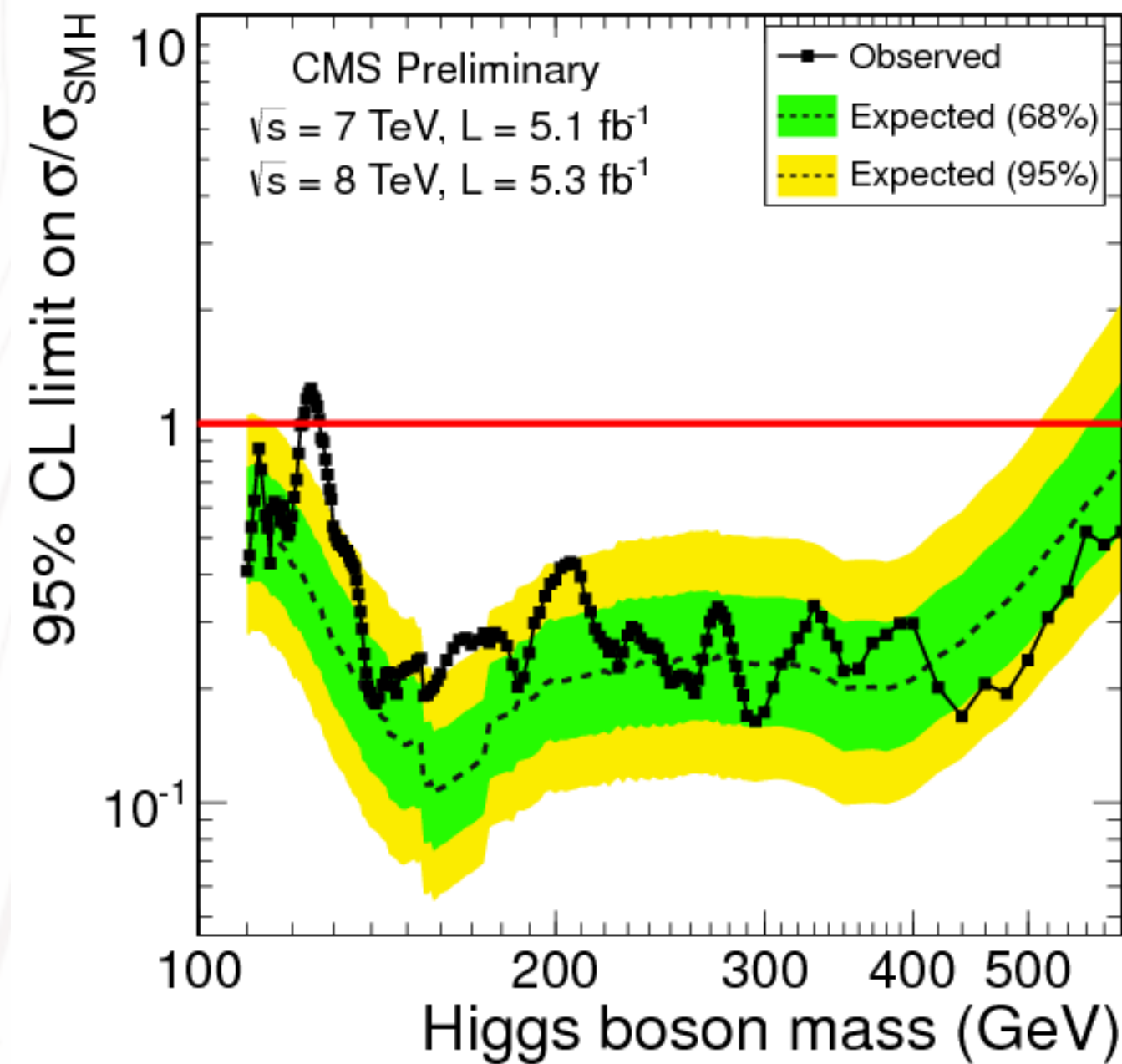
Vacuum energy
 $V_{0exp} \sim (2.10^{-3} \text{ eV})^4$

Possible instability
depending on m_H

Origin of quadratic
divergences.
Hierarchy problem

The flavour problem:
large unexplained ratios
of Y_{ij} Yukawa constants

At the time the LHC started, finding the Higgs, the “last piece” of the SM, was the top priority for particle physics: without it, no SM!



 BSM?

HH AND THE HIGGS POTENTIAL

BOOSTED TOPOLOGIES

SECOND
GENERATION

EFT

RARE PRODUCTION
& DECAY

SM COUPLINGS

CROSS SECTIONS

YUKAWA
INTERACTIONS

MASS, SPIN, ...

OBSERVATION

A JOURNEY INTO THE HIGGS SECTOR

HIGGS PHYSICS IN 2026

- **16 years since LHC started and 14 years since the Higgs discovery, CMS and ATLAS are dedicated to understanding the nature of the Higgs**

ATLAS and CMS are true 'Higgs machines', exploring all possible directions in the Higgs sector:

- ◆ **Precisely measuring its properties to test the SM boundaries**
- ◆ **Studying all accessible decay modes**
- ◆ **Pushing to the limits of the measurable phase-space, chasing down rarer production and decay modes**
- ◆ **Probing the Higgs potential, to connect to the big scale**
- ◆ **Searching for new physics through and with the Higgs**



OUTLINE

MEASUREMENT OF HIGGS PROPERTIES

CrossSections, Couplings, Mass, Width

NEW PHASE-SPACES

Rare prod and decay. Charming the Higgs

FROM PRECISION TO NEW PHYSICS

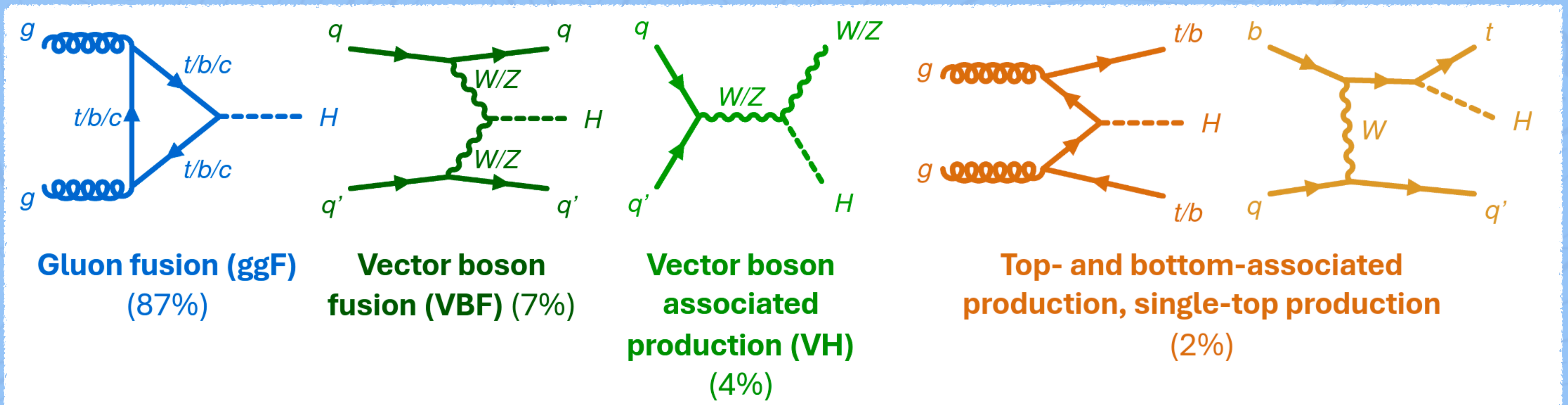
Differentials, STXS, EFTs

THE HIGGS POTENTIAL

Searches for HH and HHH

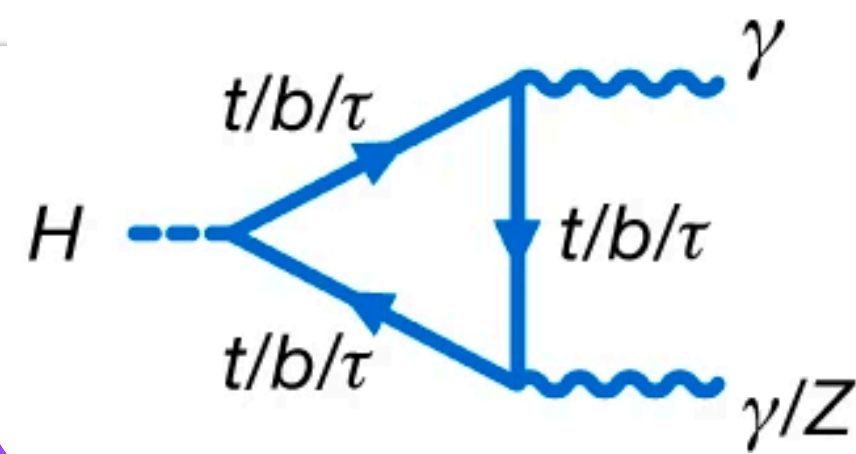
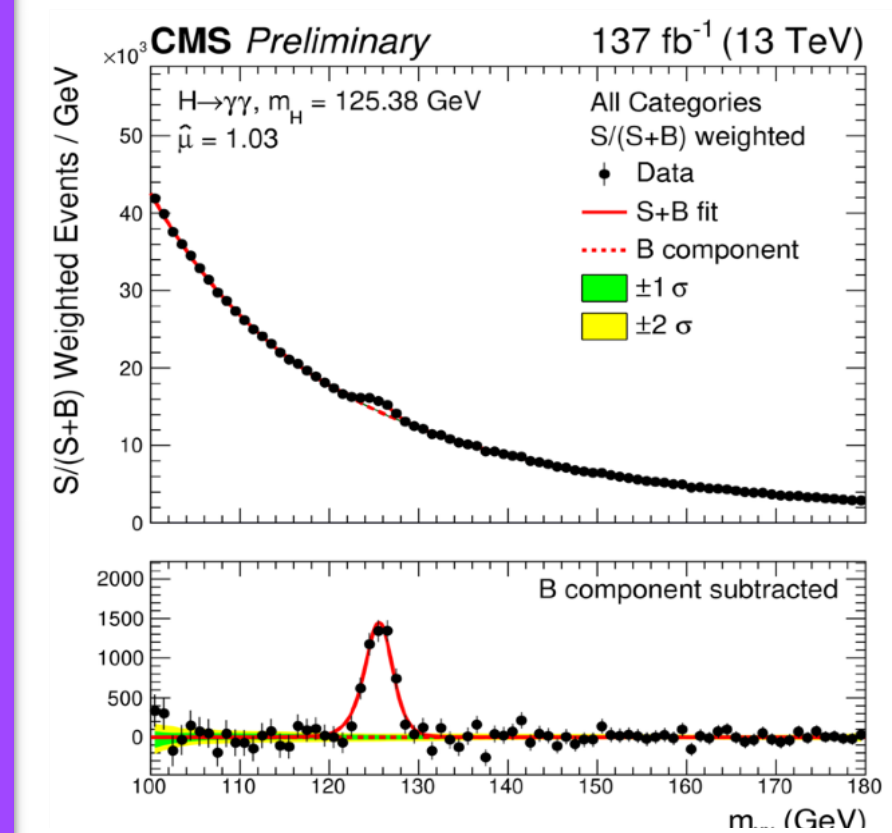
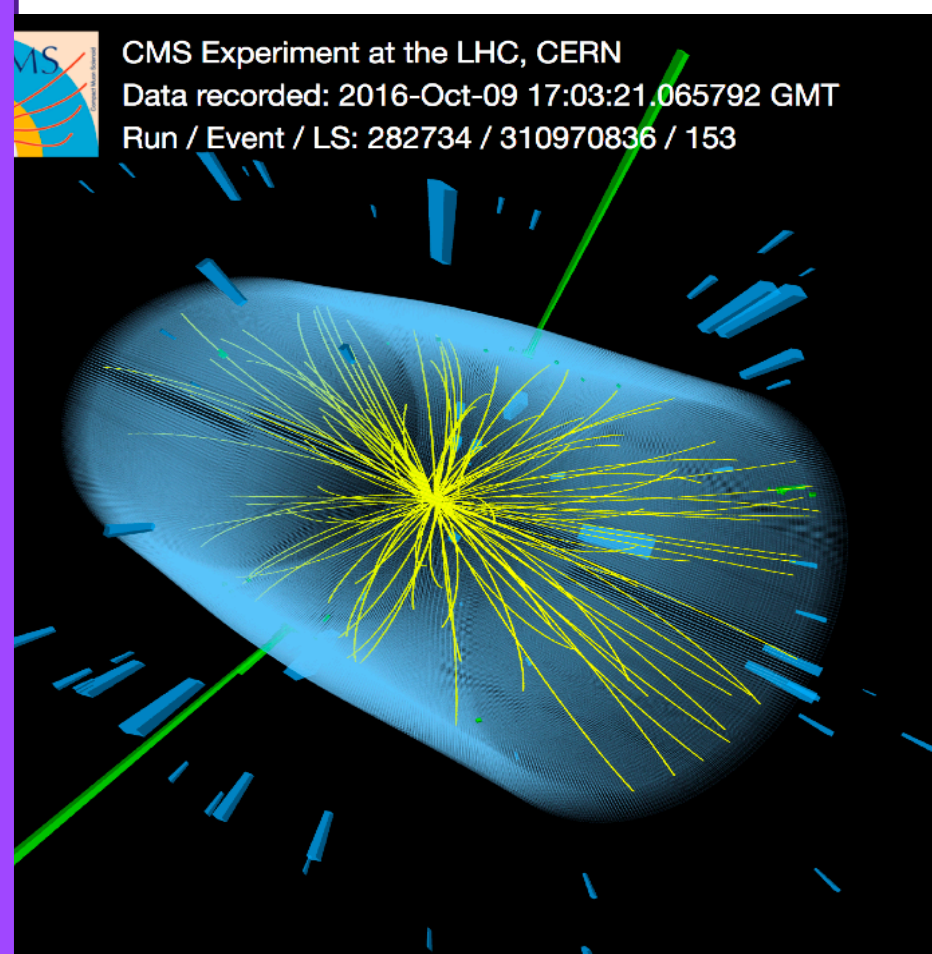
MEASUREMENT OF HIGGS PROPERTIES

- We found 'a Higgs', but how well we can measure it?
- How is it produced, how does it decay, what kind of particle is it?



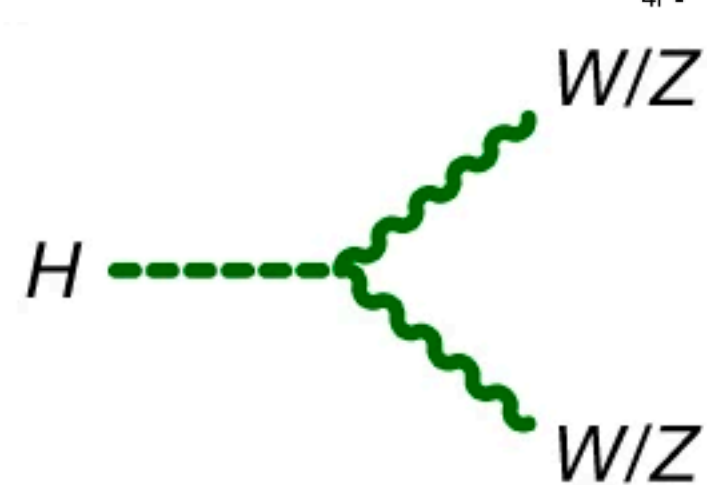
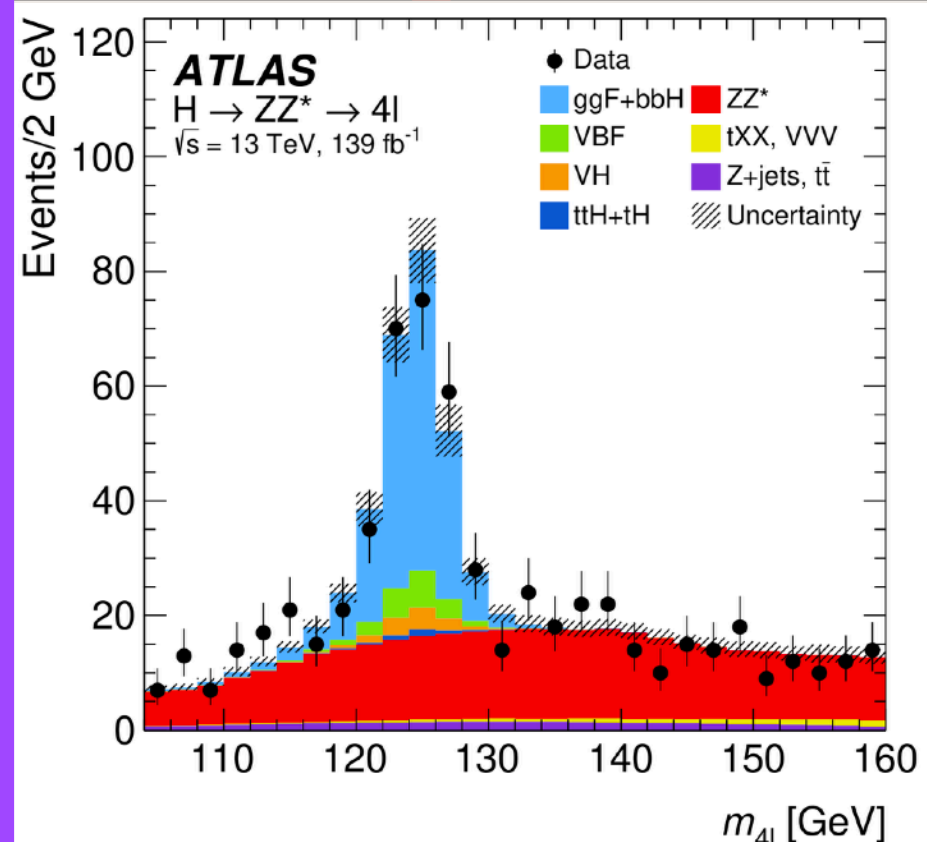
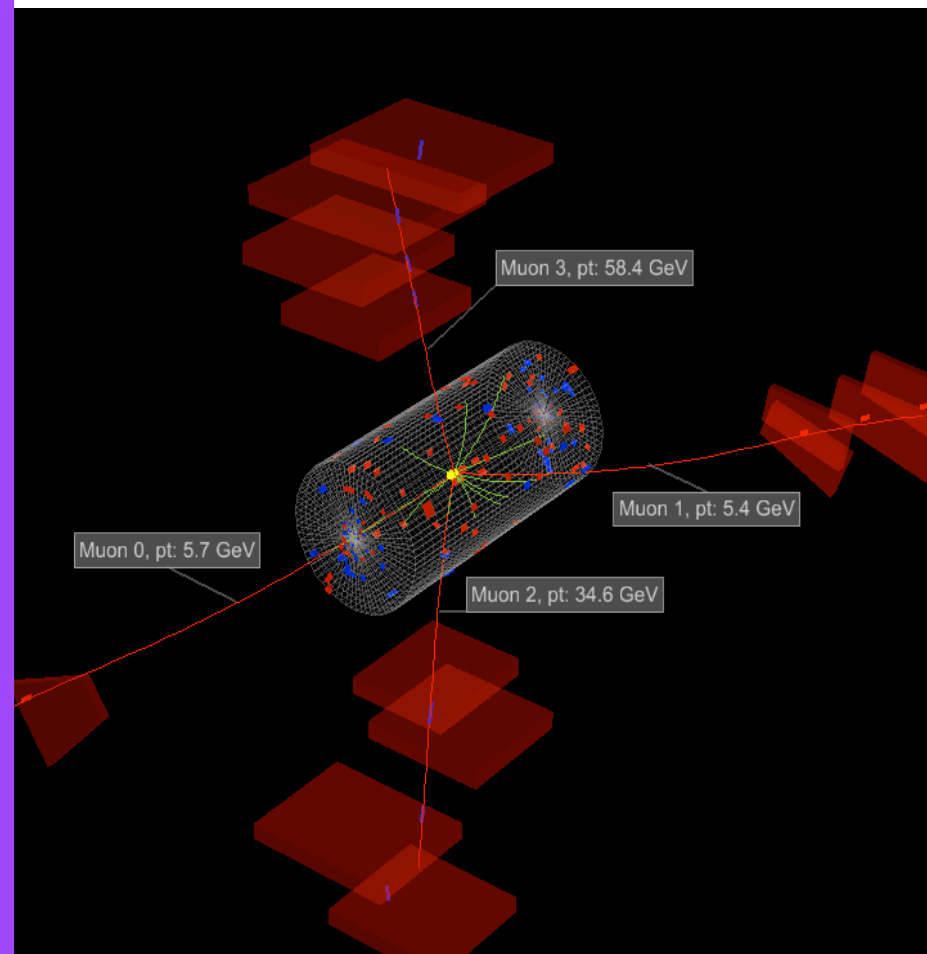
$$H \rightarrow \gamma\gamma$$

Br~0.2%



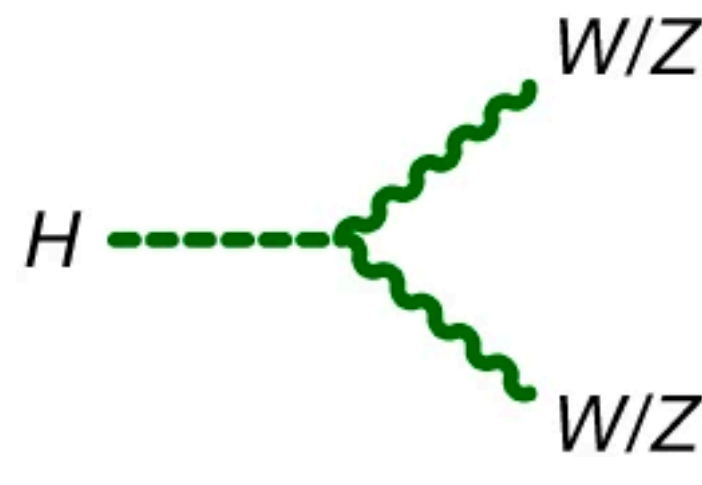
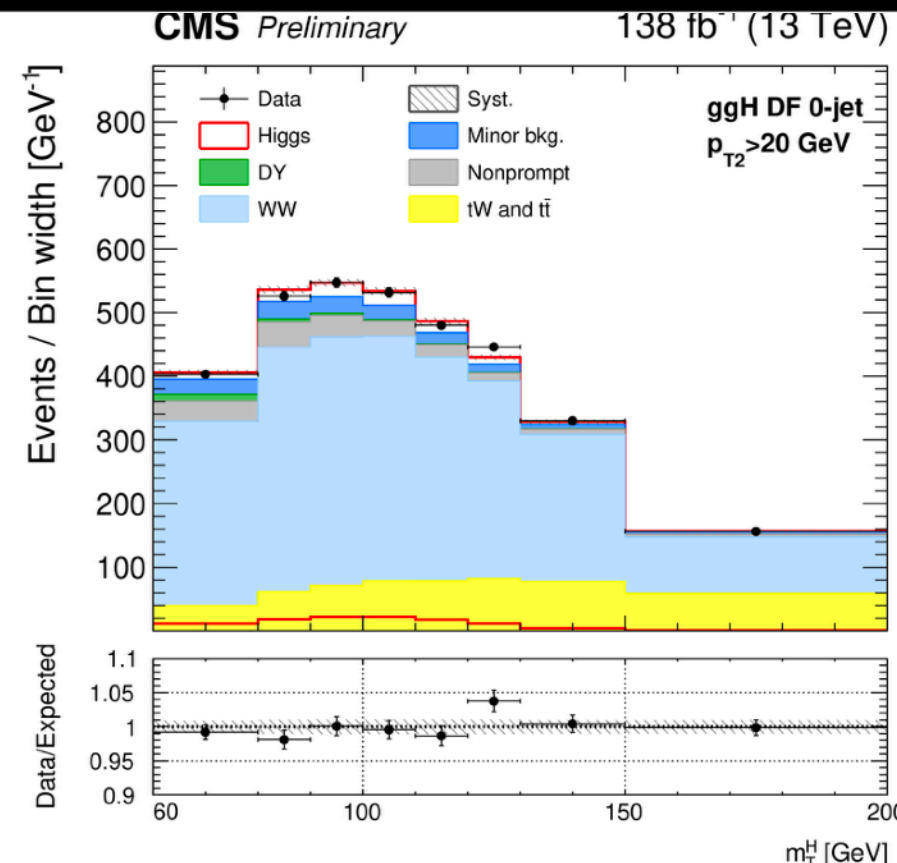
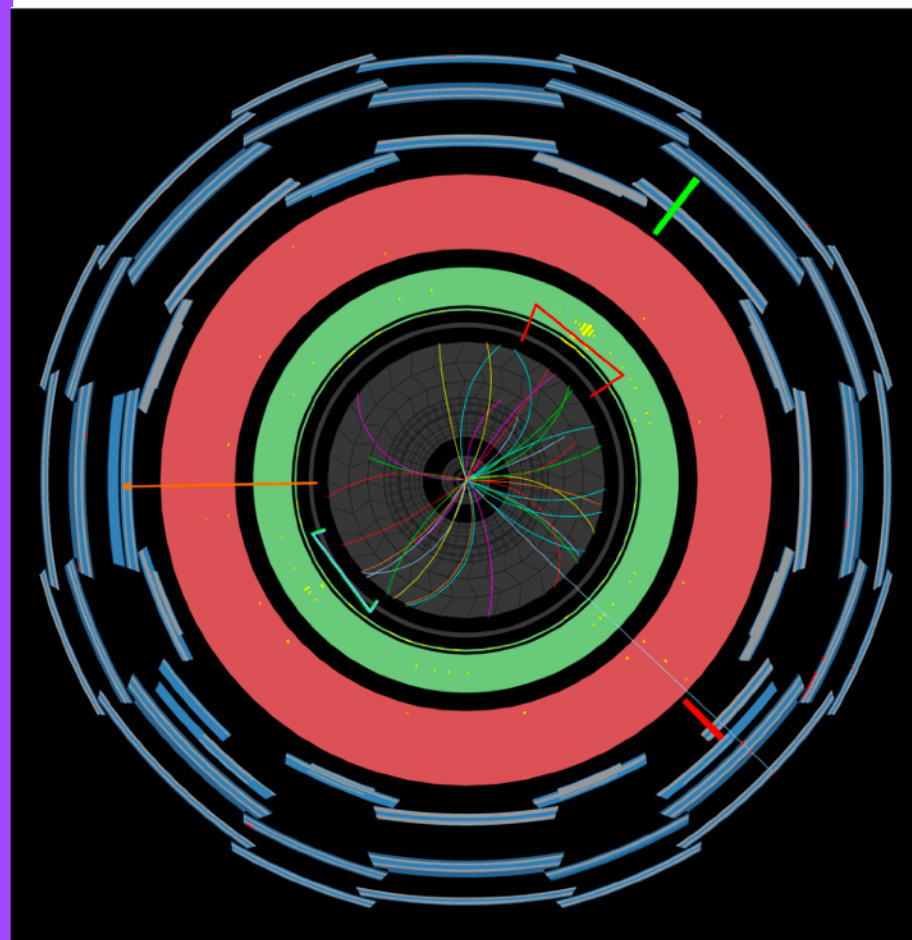
$$H \rightarrow ZZ$$

Br~3%



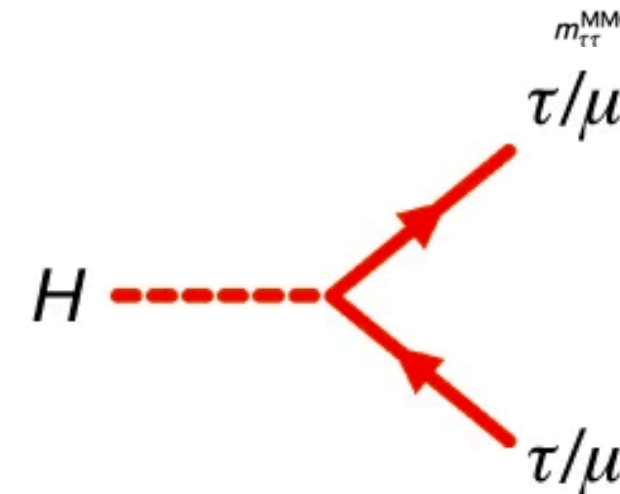
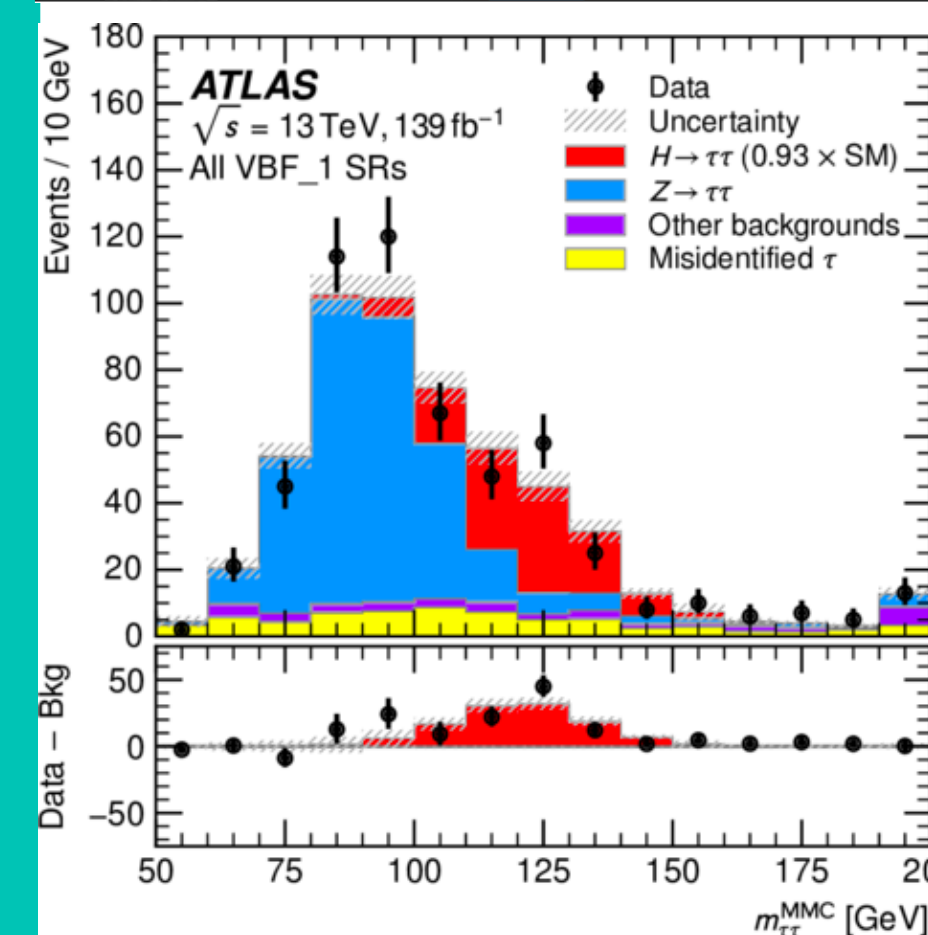
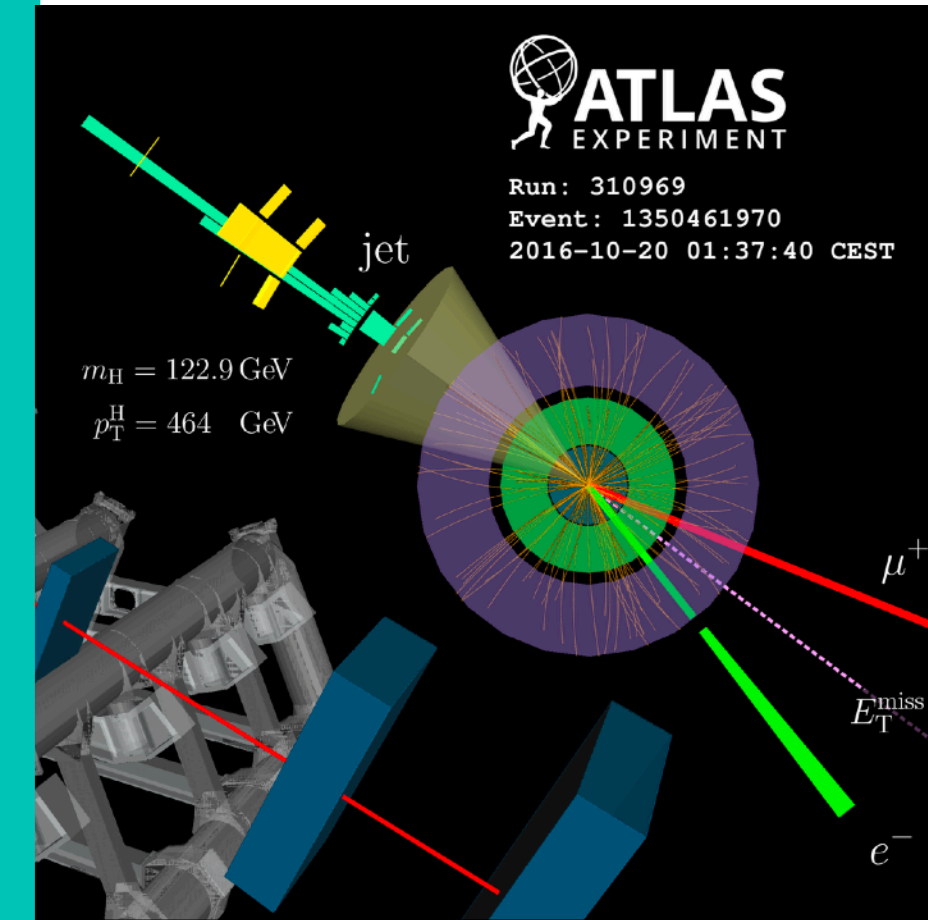
$$H \rightarrow WW$$

Br~21%



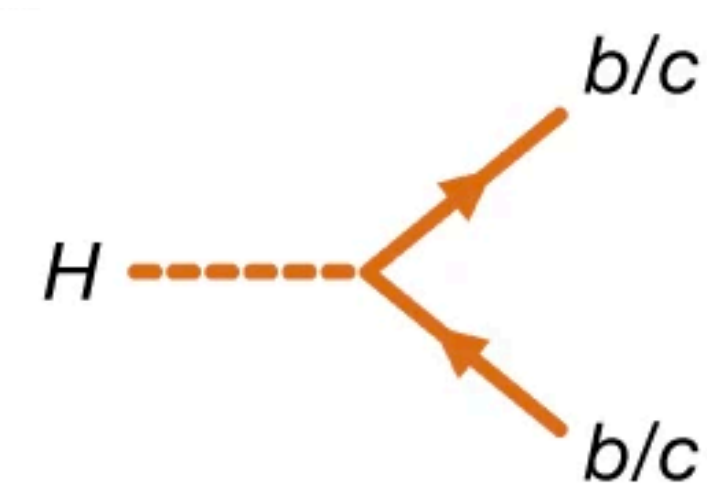
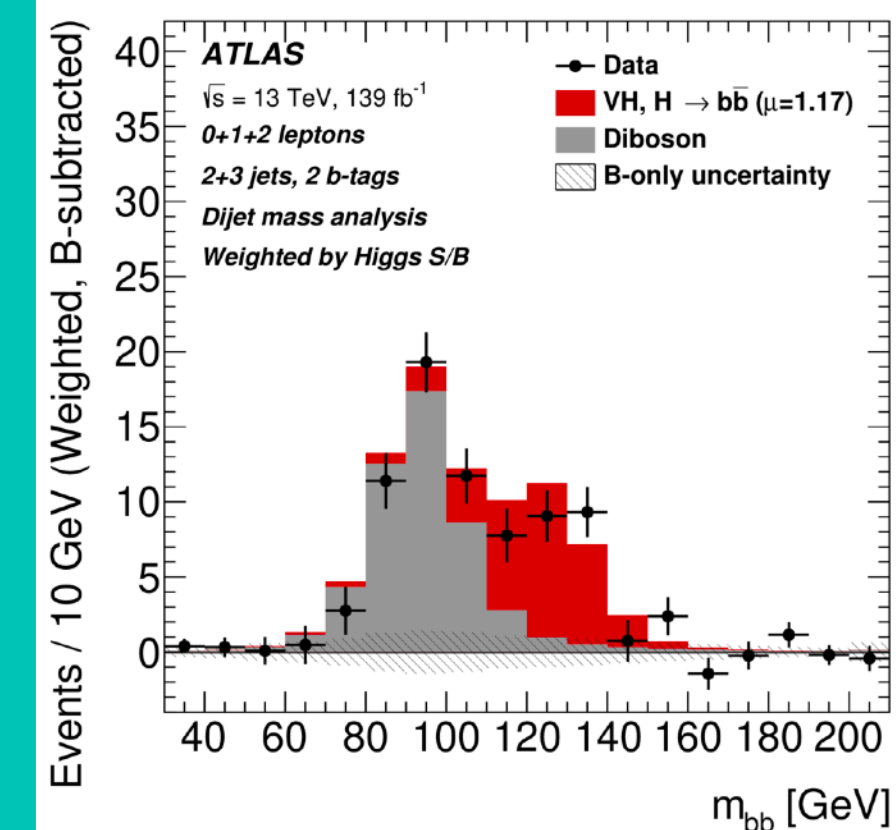
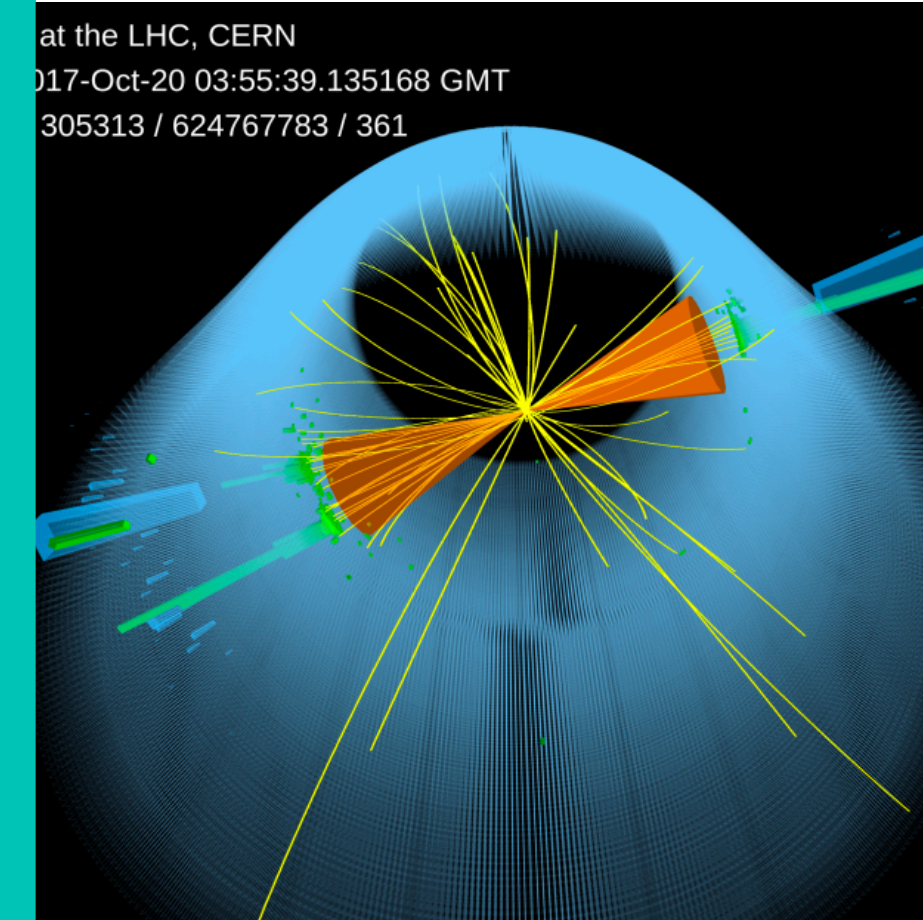
$$H \rightarrow \tau\tau$$

Br~6%

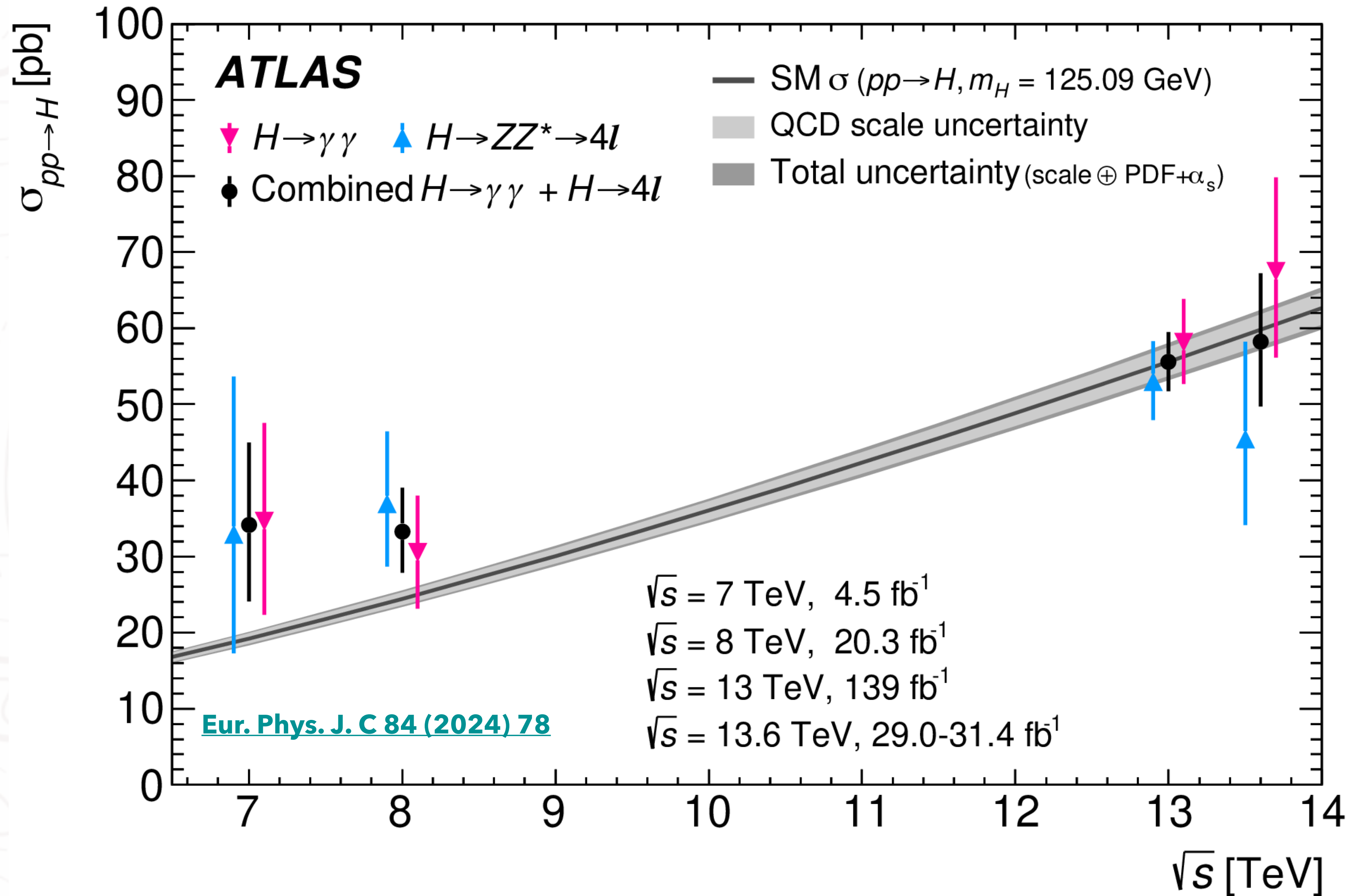


$$H \rightarrow bb$$

Br~58%

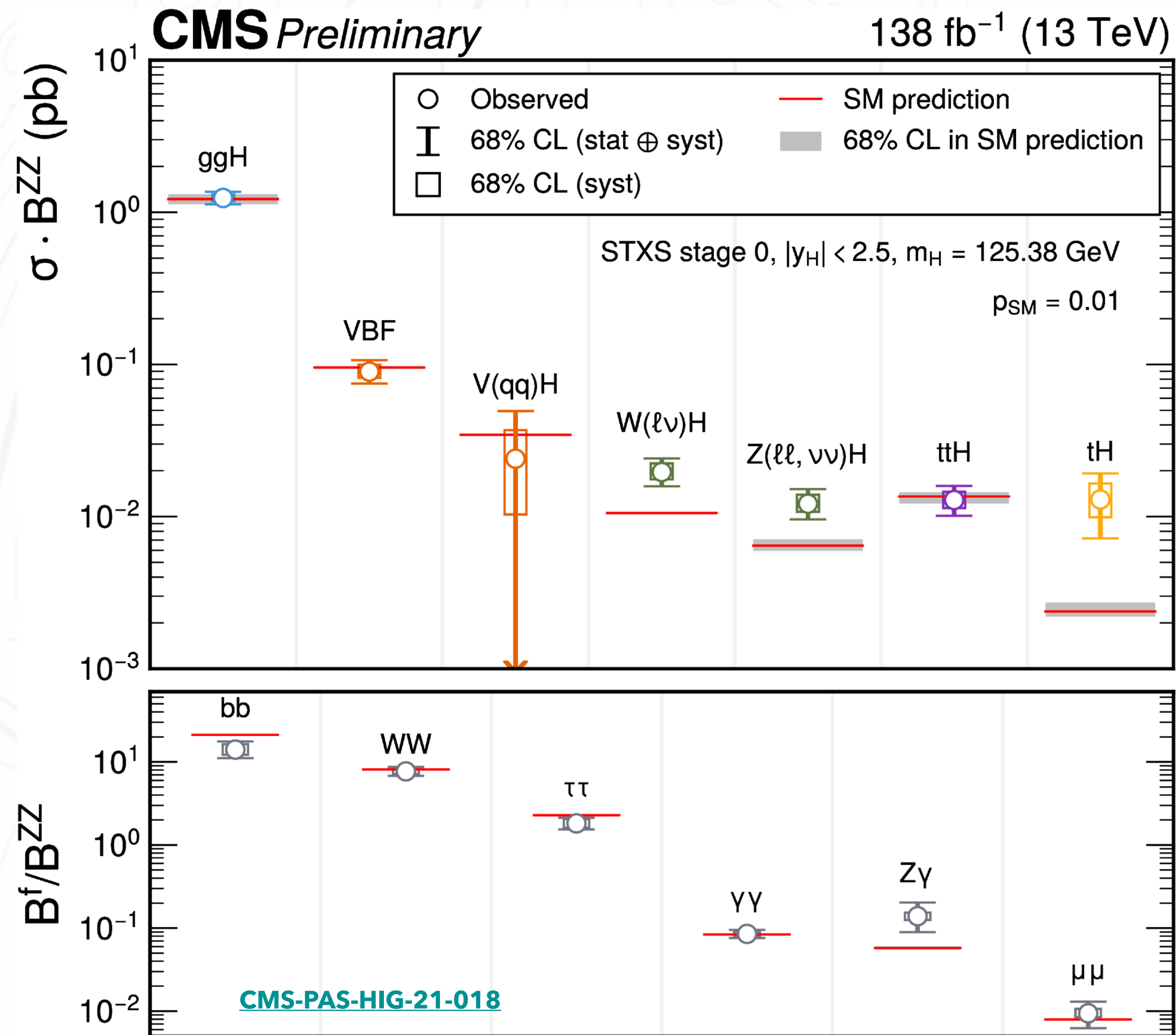


CROSS SECTION MEASUREMENTS ACROSS LHC RUNS

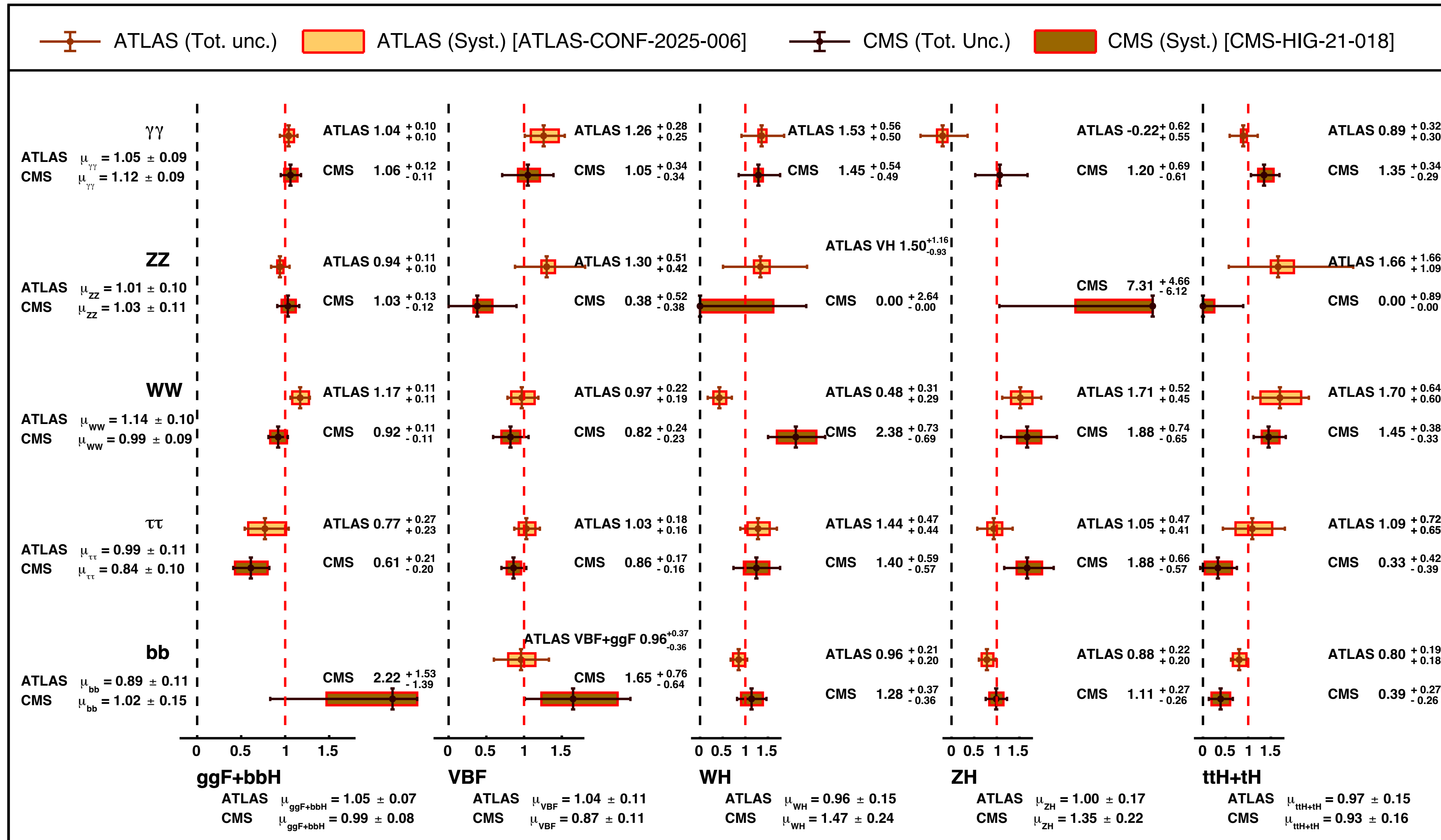


Huge dataset to understand the Higgs Sector !

PRODUCTION X DECAY : ✓✓



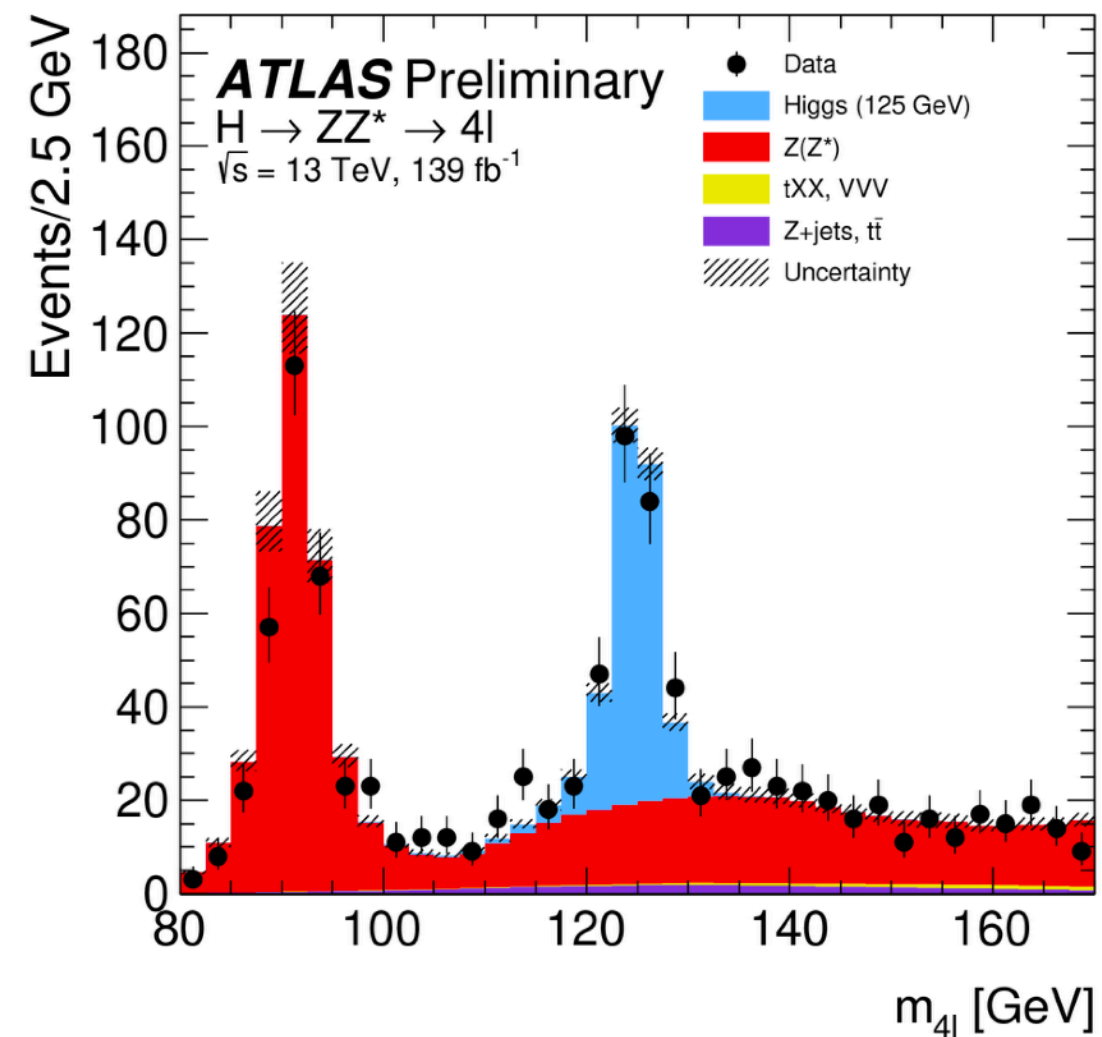
MEASURING THE STRENGTH OF THE HIGGS SIGNAL



$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}}$$

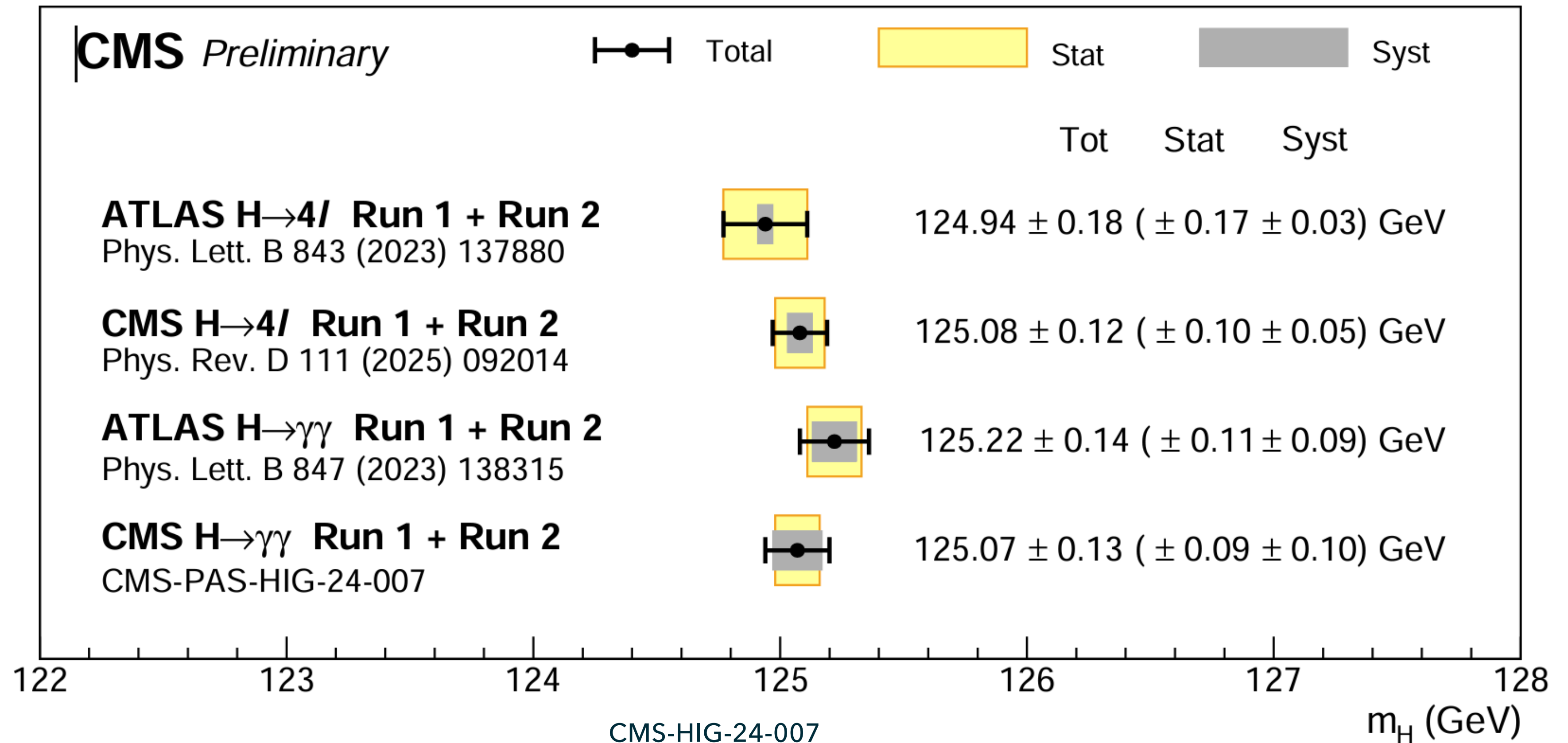
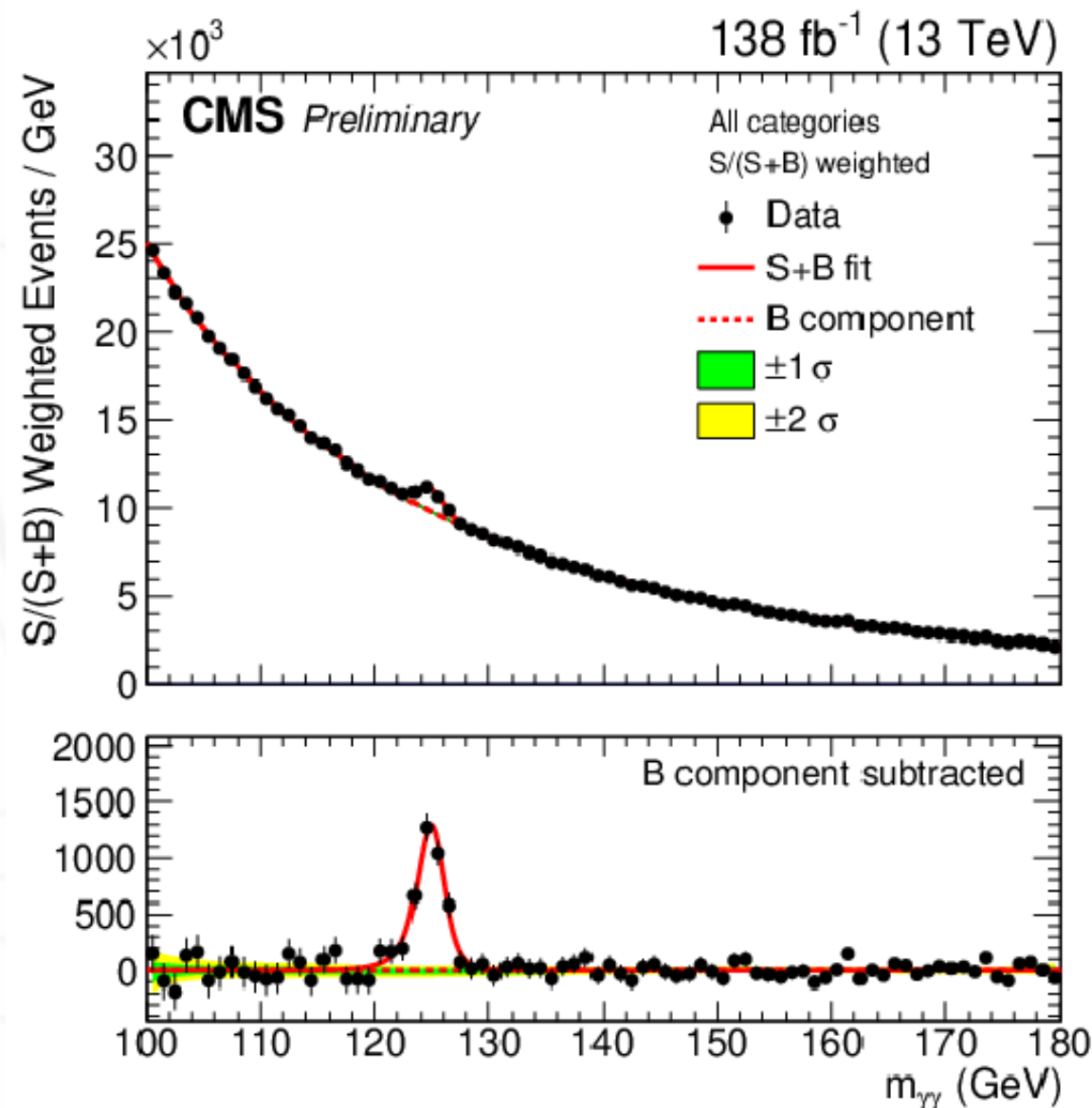
- Combining all channels in one single fit
- All major channels consistent with $\mu \approx 1$
- Precision ~5-10%
- Inclusive cross section understood at the 6% already

HOW WELL DO WE KNOW THE HIGGS MASS?



Free in the SM
 Known today to the 0.1%

5.1 fb⁻¹ (7 TeV) + 19.7 fb⁻¹ (8 TeV) + 138 fb⁻¹ (13 TeV)



HOW WELL DO WE KNOW THE HIGGS WIDTH?

$$\Gamma_H \propto \text{lifetime}^{-1}$$

Very small in SM! (4 MeV)

- Difficult to measure. Much smaller than detector resolution!
- Main avenue at LHC measure through **relative on-shell and off-shell production rates**

- CMS: $3.0^{+2.0}_{-1.5} \text{ MeV}$

- ATLAS: $4.3^{+2.7}_{-1.9} \text{ MeV}$

- Other methods to probe the width are less stringent, e.g., mass interference in gamma gamma channel

$$m_{ZZ} \sim m_H$$

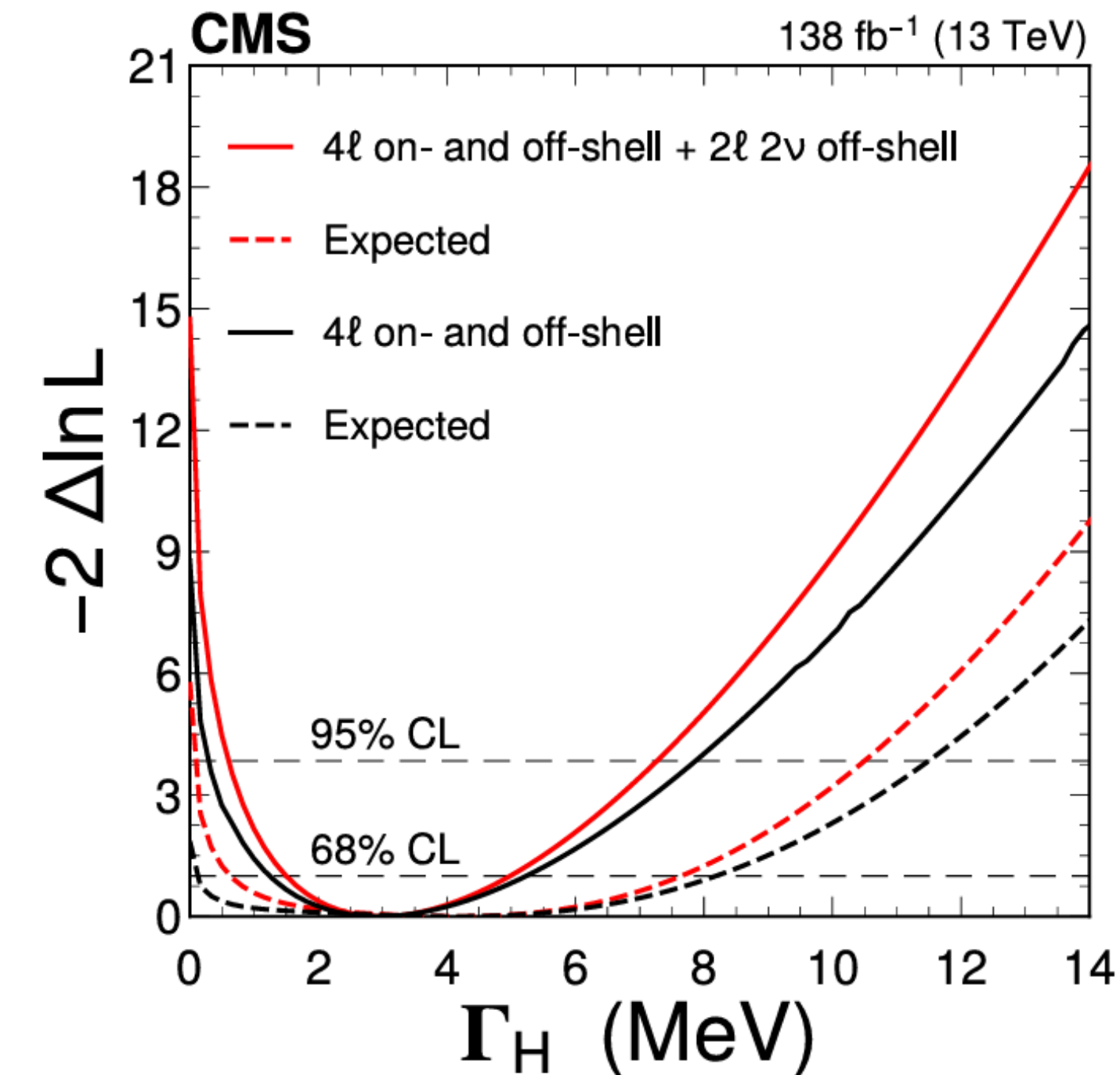
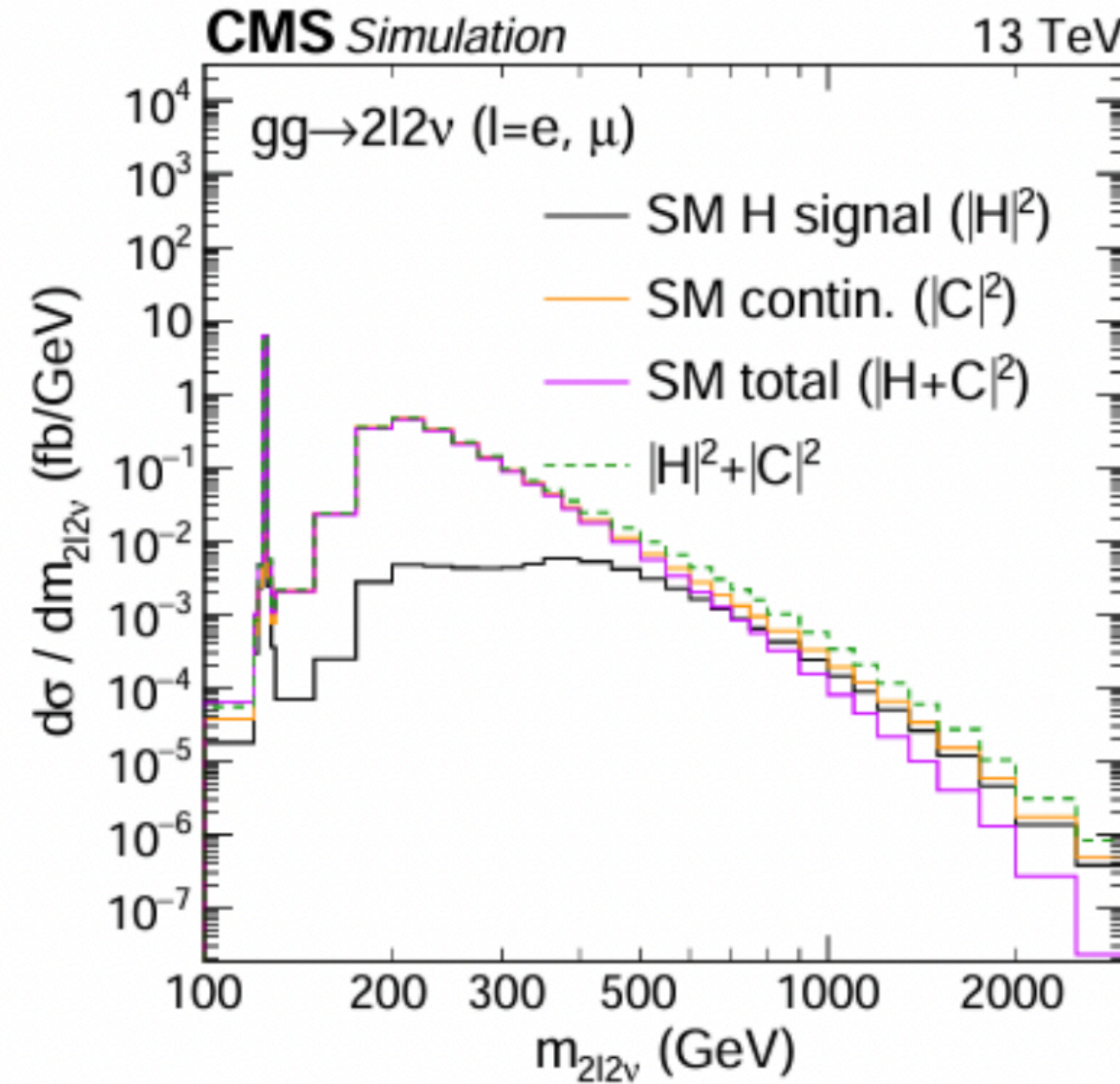
(On-shell production)

$$\sigma_j^{\text{on-shell}} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_j^{\text{on-shell}}$$

$$m_{ZZ} > m_{ZZ}$$

(Off-shell production)

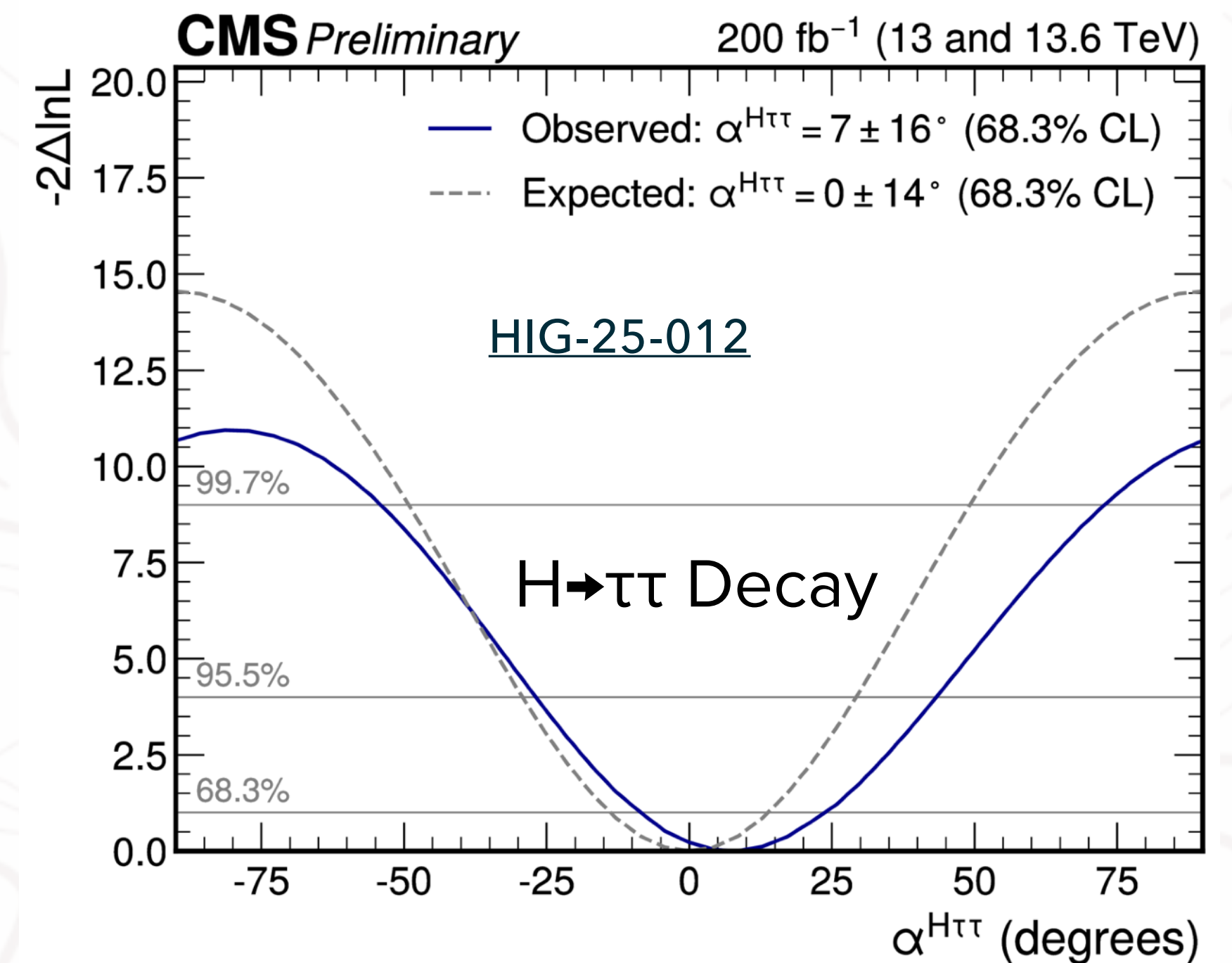
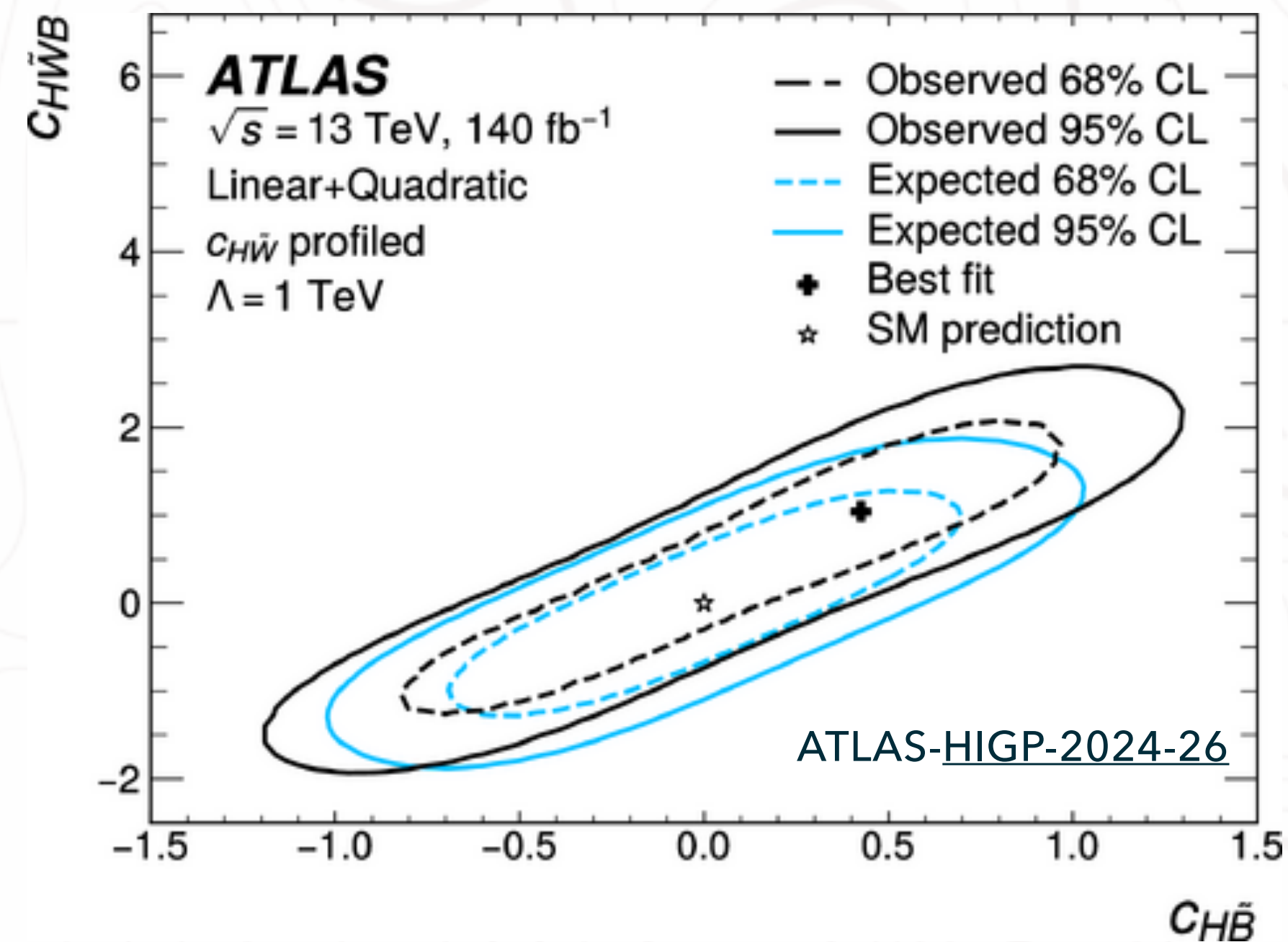
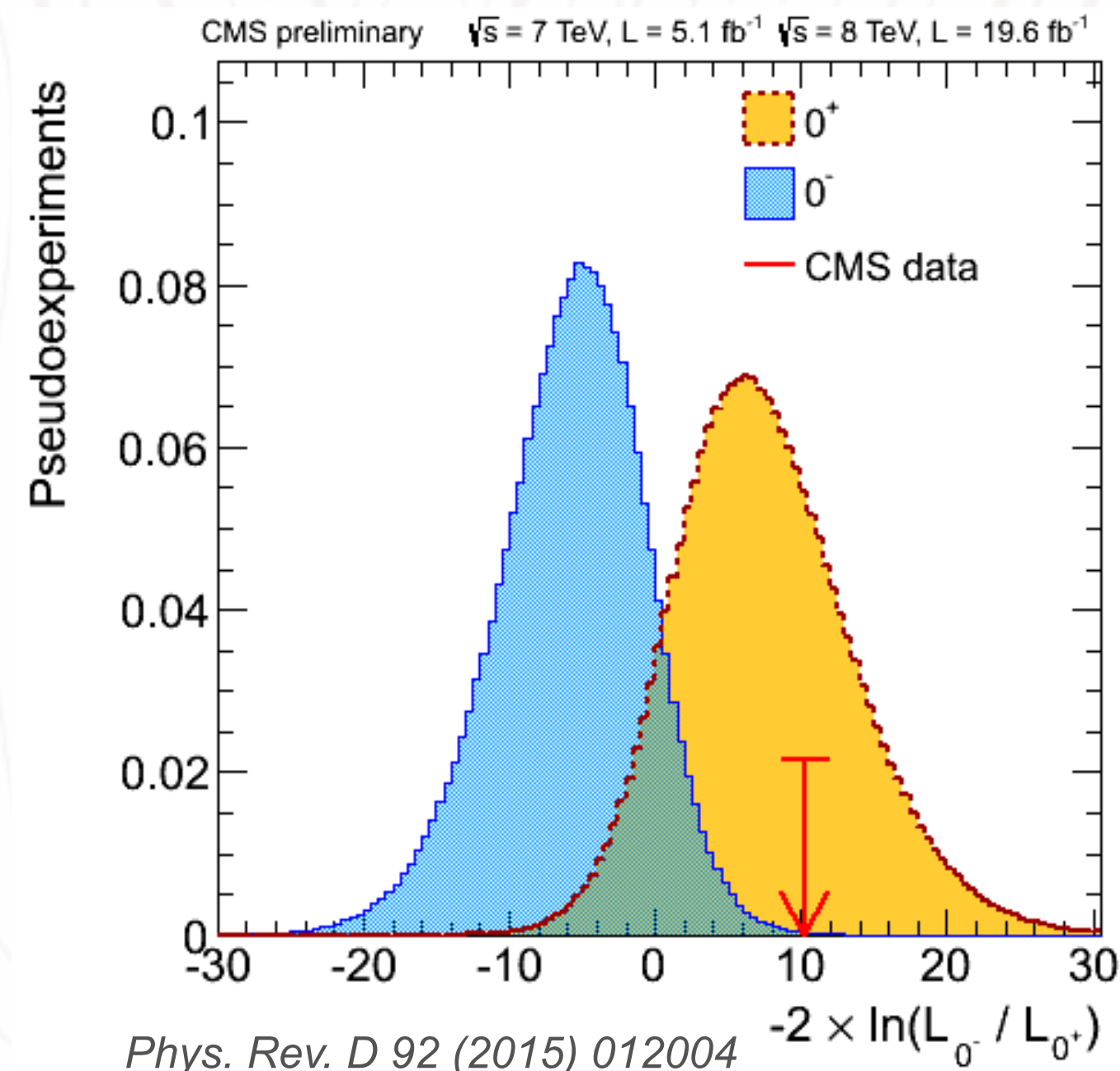
$$\sigma_j^{\text{off-shell}} \propto g_p^2 g_d^2 \propto \mu_j^{\text{on-shell}} \Gamma_H$$



SPIN AND CP

Does the Higgs sector have a new source of Charge-Parity violation?

- Spin-parity quantum number of Higgs boson consistent with the SM, $J^{CP} = 0^{++}$
- Plenty of recent searches for CP in production and decay. Results also expressed in terms of SMEFT coefficients.

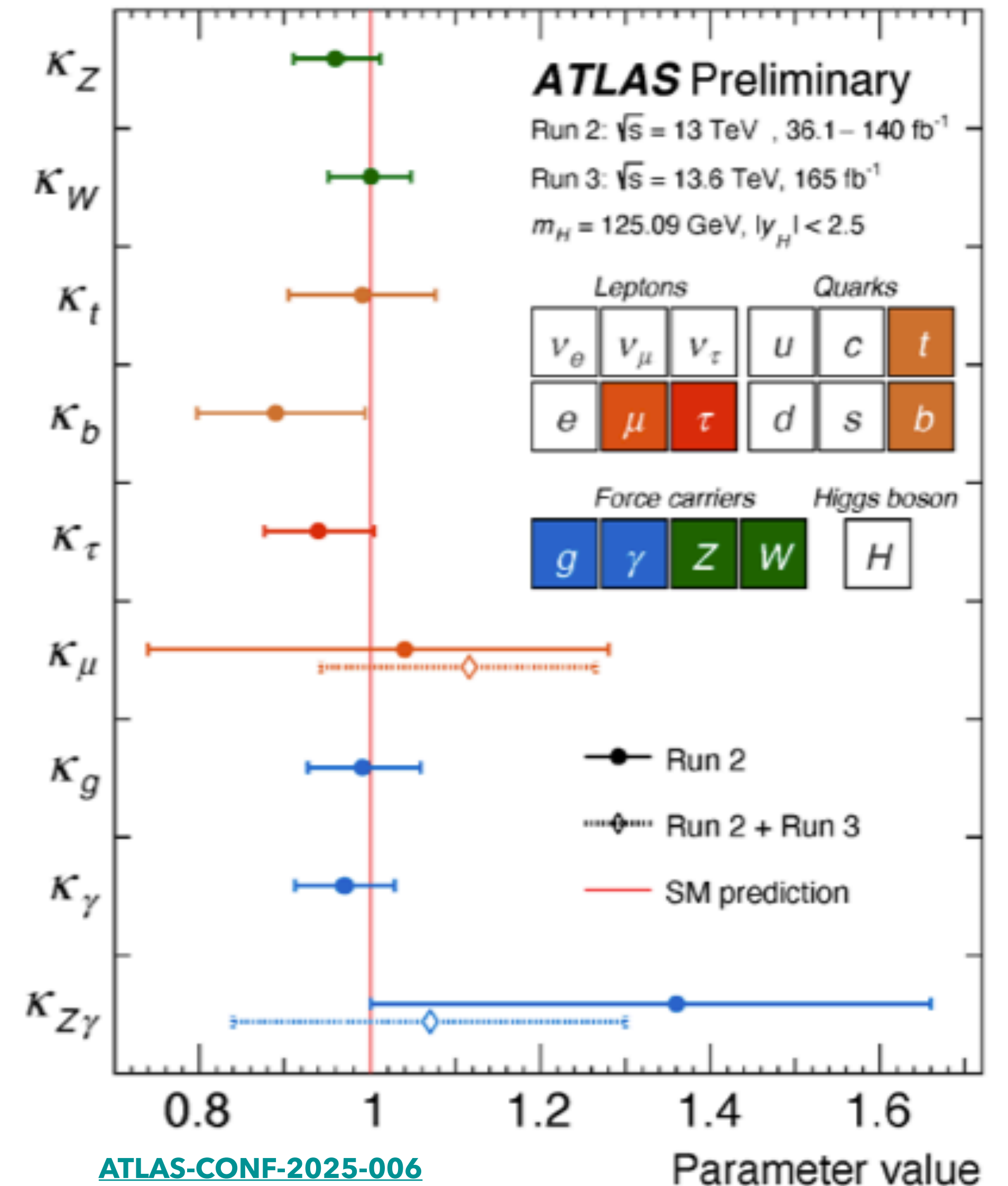


HOW STRONGLY DOES THE HIGGS INTERACT WITH MATTER?

- **Higgs Couplings:** strength of the interaction of the Higgs to the different SM particles
- **Kappa framework:** simple parameterization, widely used at LHC, which connects well to our measurements

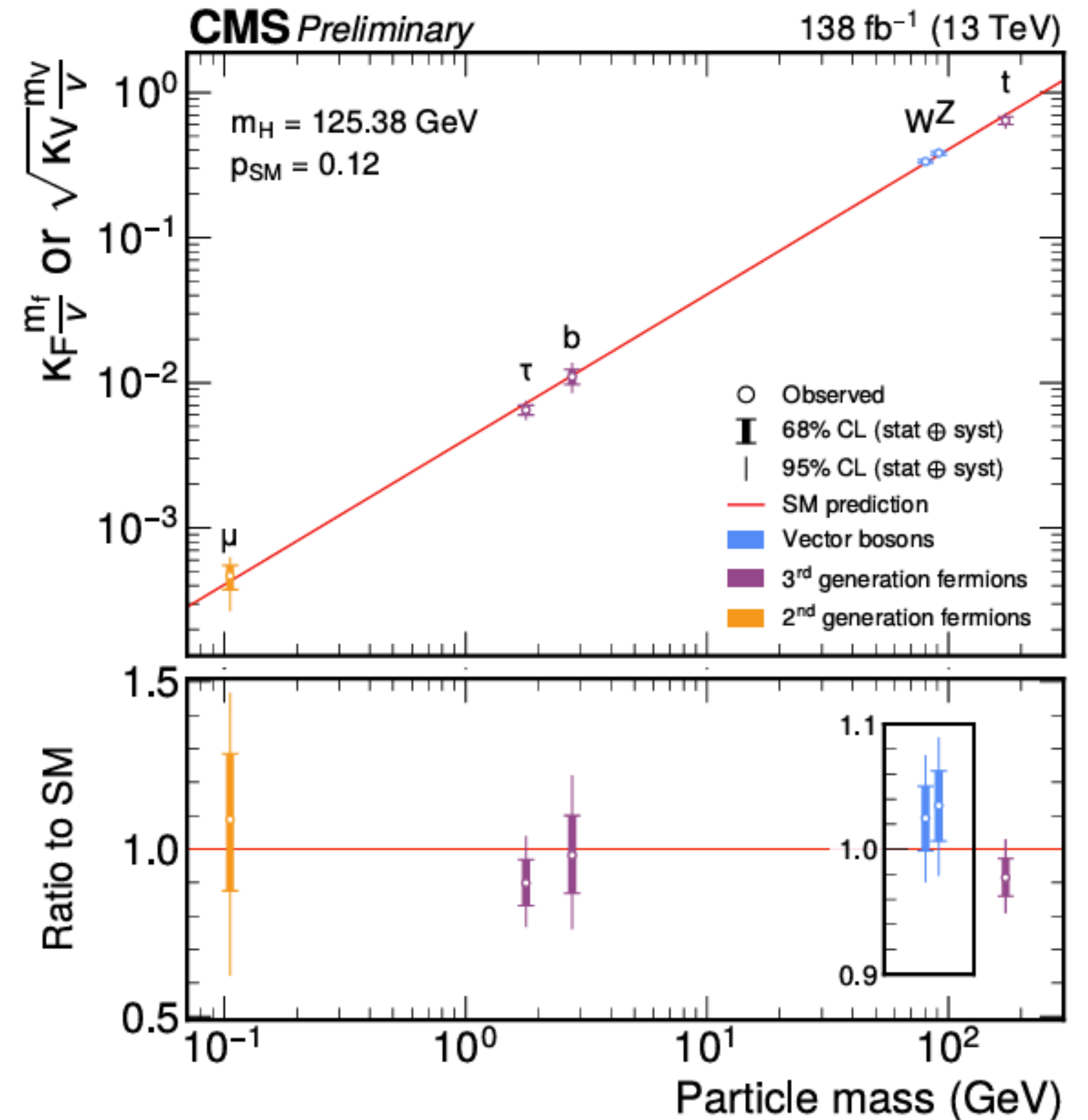
$$\kappa_j^2 = \sigma_j / \sigma_j^{SM} \quad \kappa_j^2 = \Gamma^j / \Gamma_{SM}^j$$

- With the full Run2 Combination (per experiment): ‘Main’ modes already known to 5-12% (~20%-30% for stat dominated $\mu\mu, Z\gamma$)
- Importance of theoretical uncertainties!



STILL A LOT TO UNDERSTAND

- So far the couplings we have measured are remarkably close to the SM predictions
- But the picture is not complete! (second generation, self coupling)
- Large phase-spaces remain to be covered
- **What are we learning from Run2 and Run3 data?**



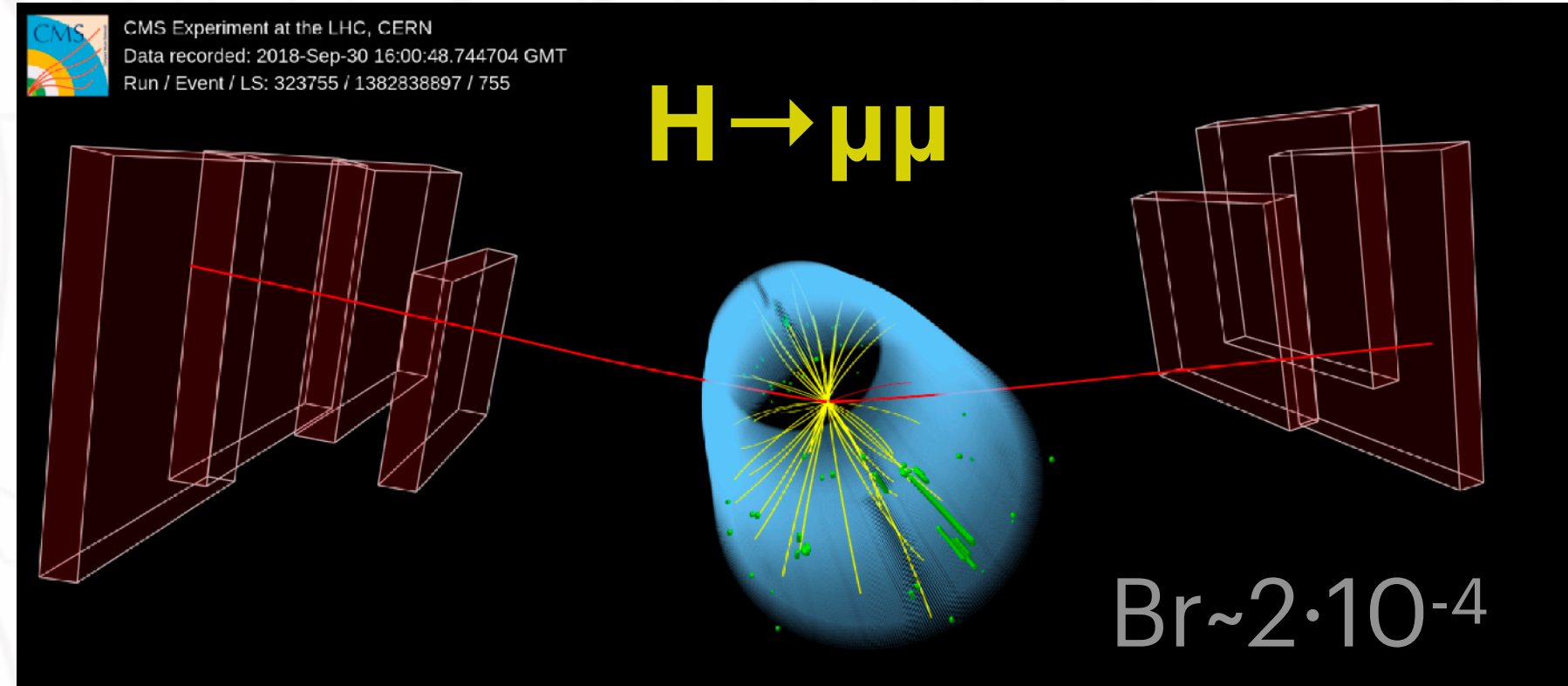
ZOOMING IN

- **Larger statistics! we can probe difficult phase-spaces, and exploit kinematic variables sensitive to new physics.**
- **Beyond the main production and decay modes**
- **New physics through precision in measurements**

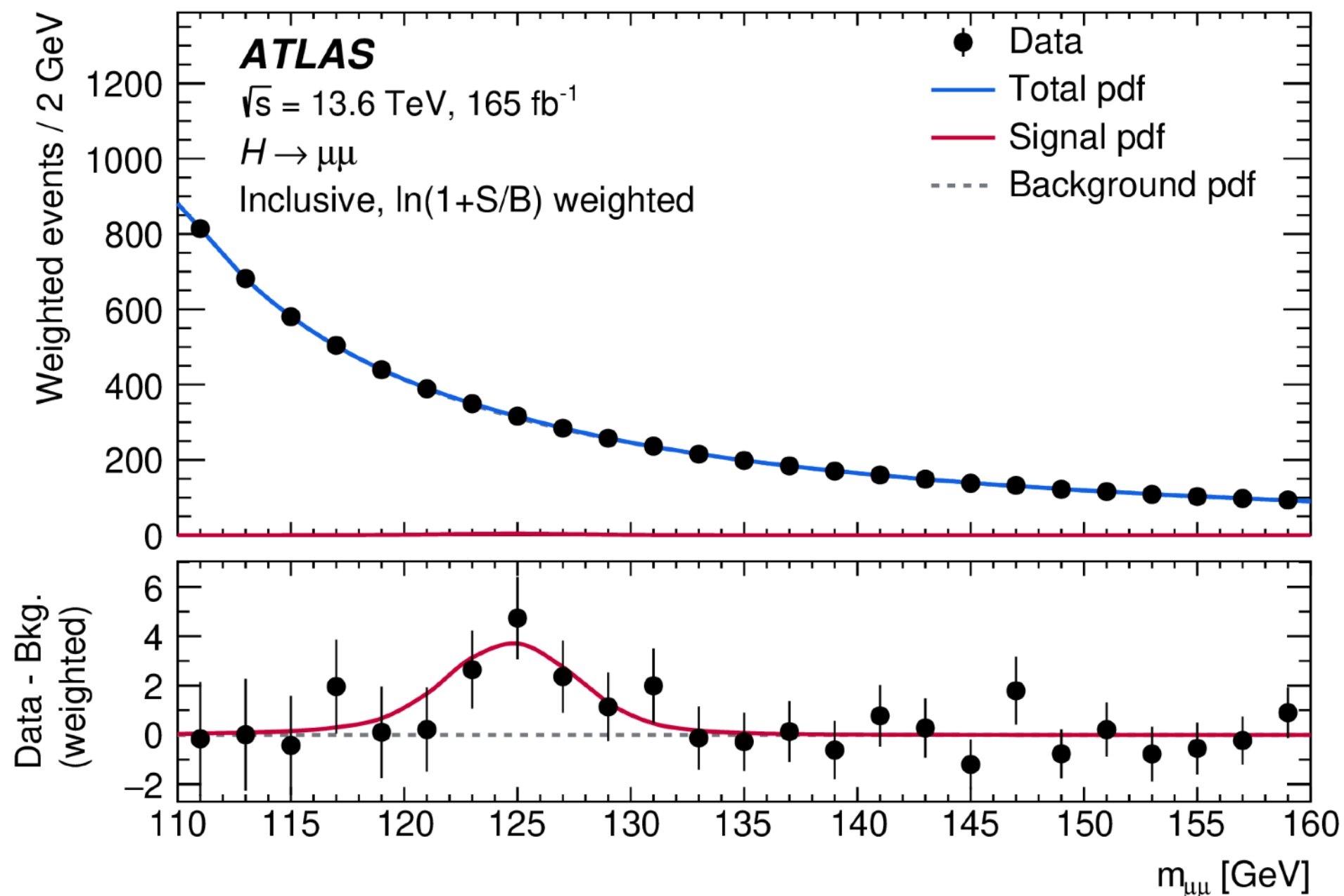
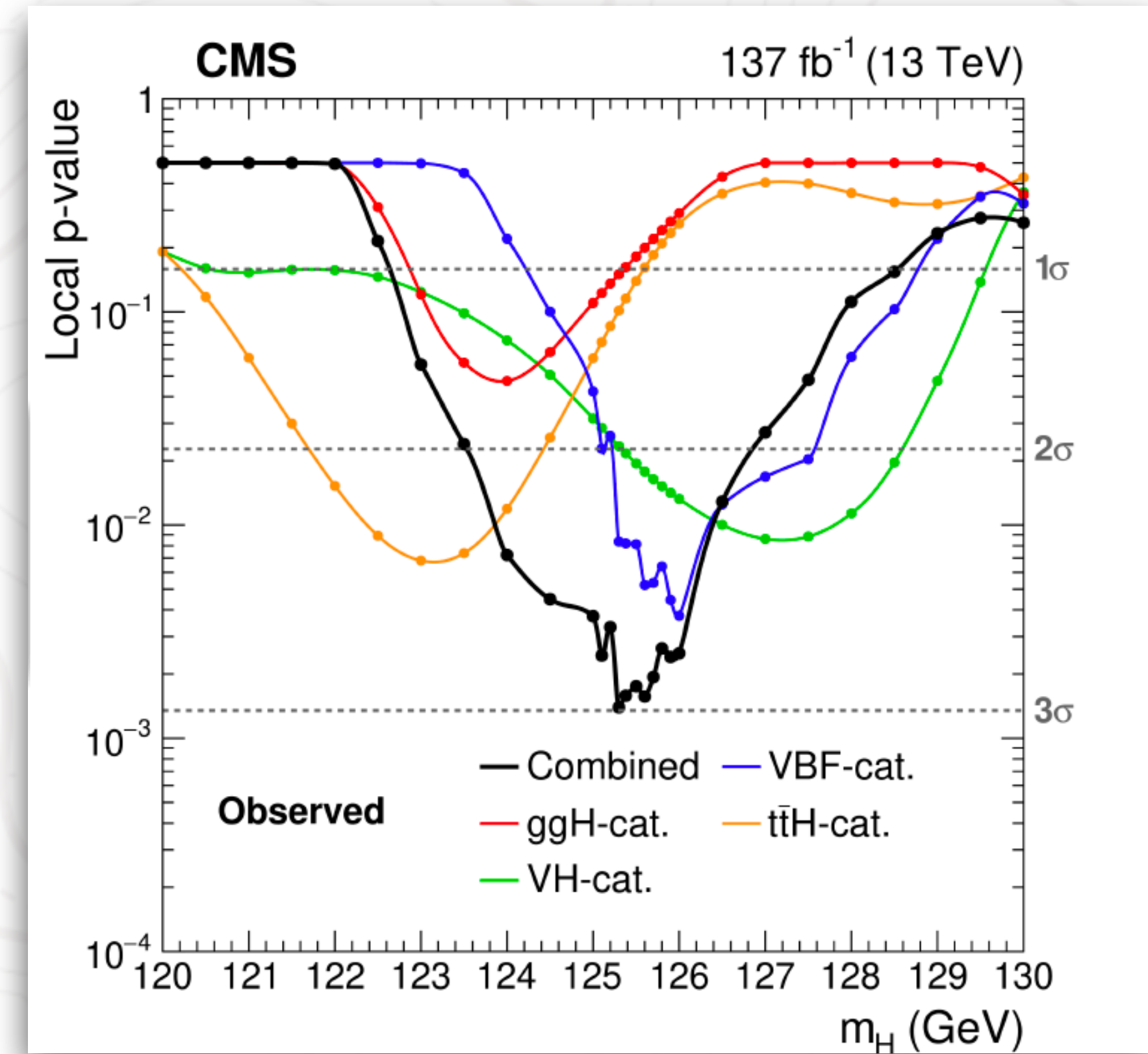


+

DO ALL SM FAMILIES GET THEIR MASS FROM THE SAME HIGGS FIELD?



Evidence for the coupling to the second generation already with Run2 data!



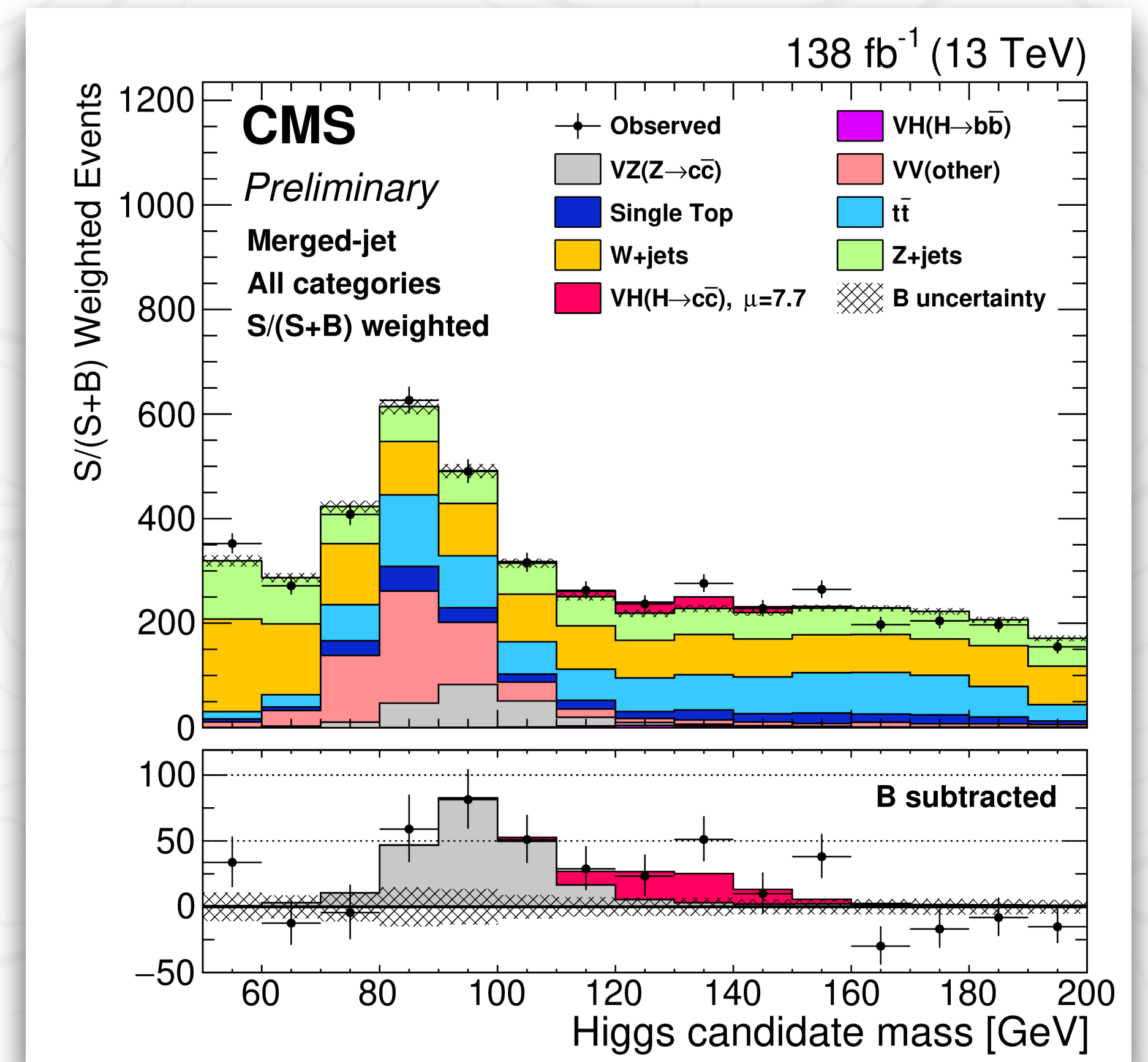
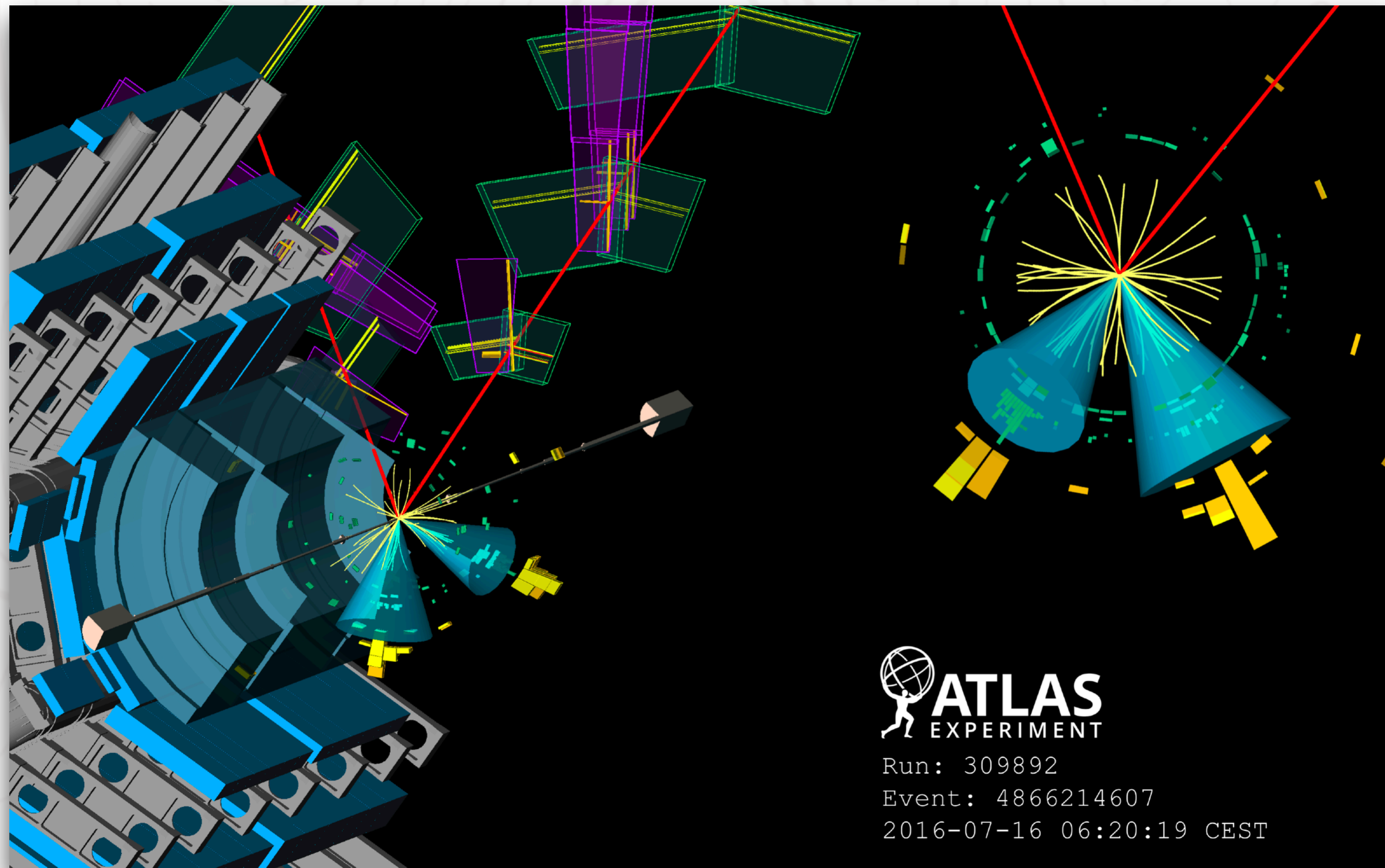
Rare decays: every fb^{-1} counts. Incorporating Run3 statistics is critical here.

CMS (Run2): $\mu = 1.19^{+0.40}_{-0.39} (\text{stat})^{+0.15}_{-0.14} (\text{syst}) \rightarrow 3.0(2.5)\sigma$

ATLAS (Run2+early Run3): $\mu = 1.2 \pm 0.4 \rightarrow 3.4\sigma (2.5 \text{ exp})$

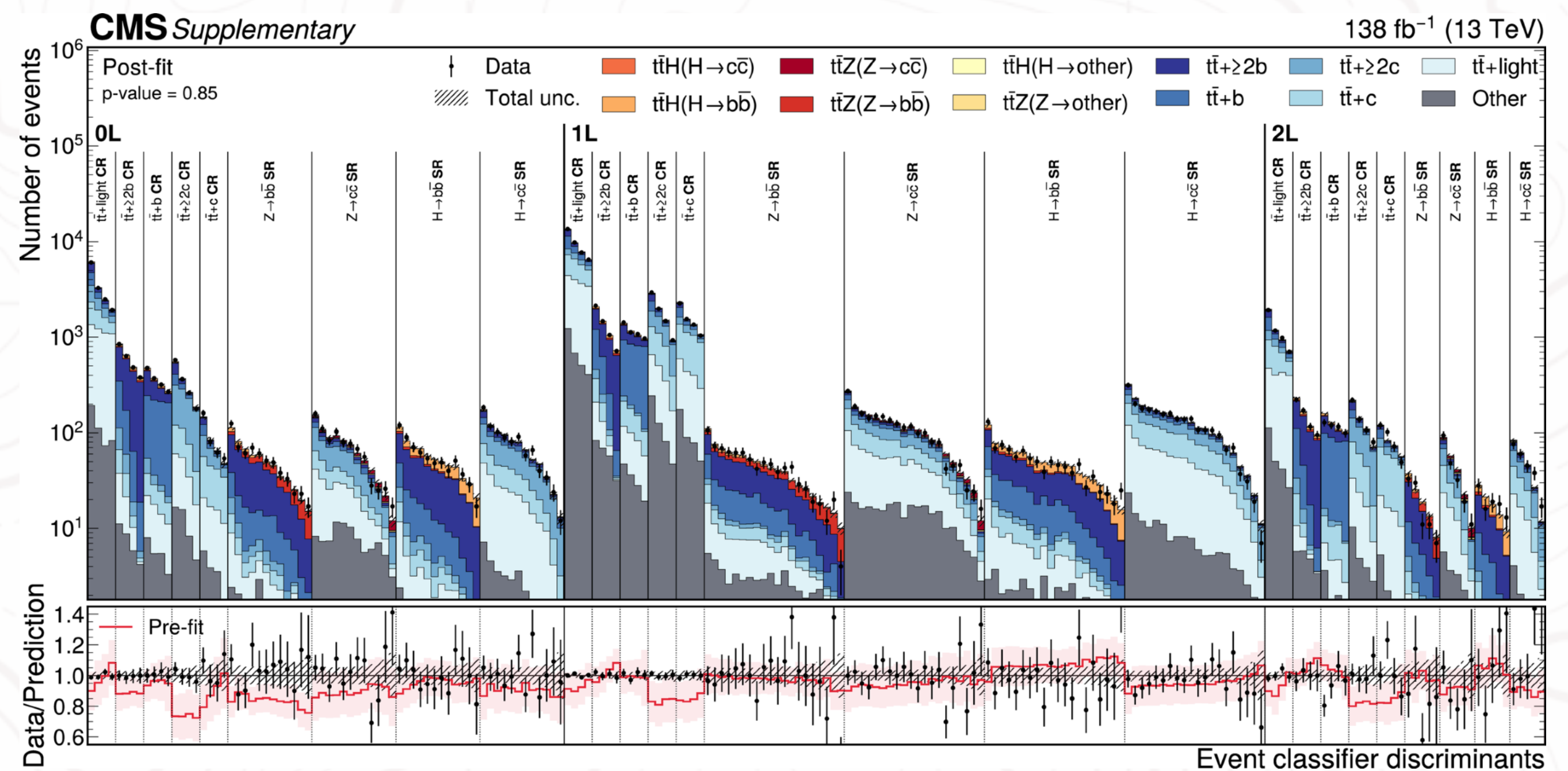
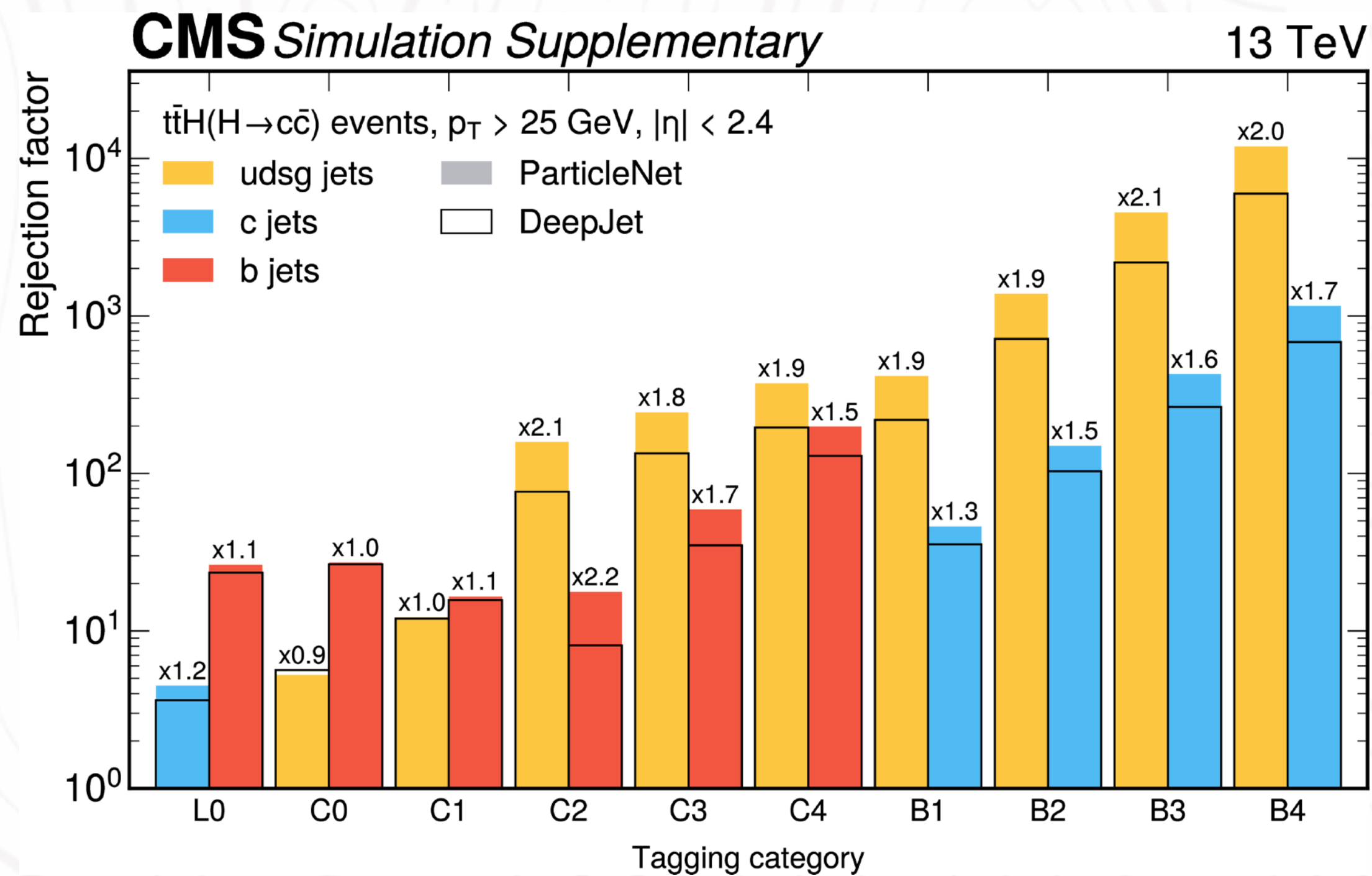
HOW CHARMING IS THE HIGGS?

- Charm quark: only up quark for which we could possibly measure the branching ratio $\text{Br}(H \rightarrow cc) \sim 3\%$
 - Do up-type quarks get their mass from the same Higgs fields as down-type quarks and charged leptons?
 - Difficult measurement: we need to be able to identify charm jets. Tagging and ML to the rescue.



EXPLOITING ML TO LOOK FOR DIFFICULT SIGNALS

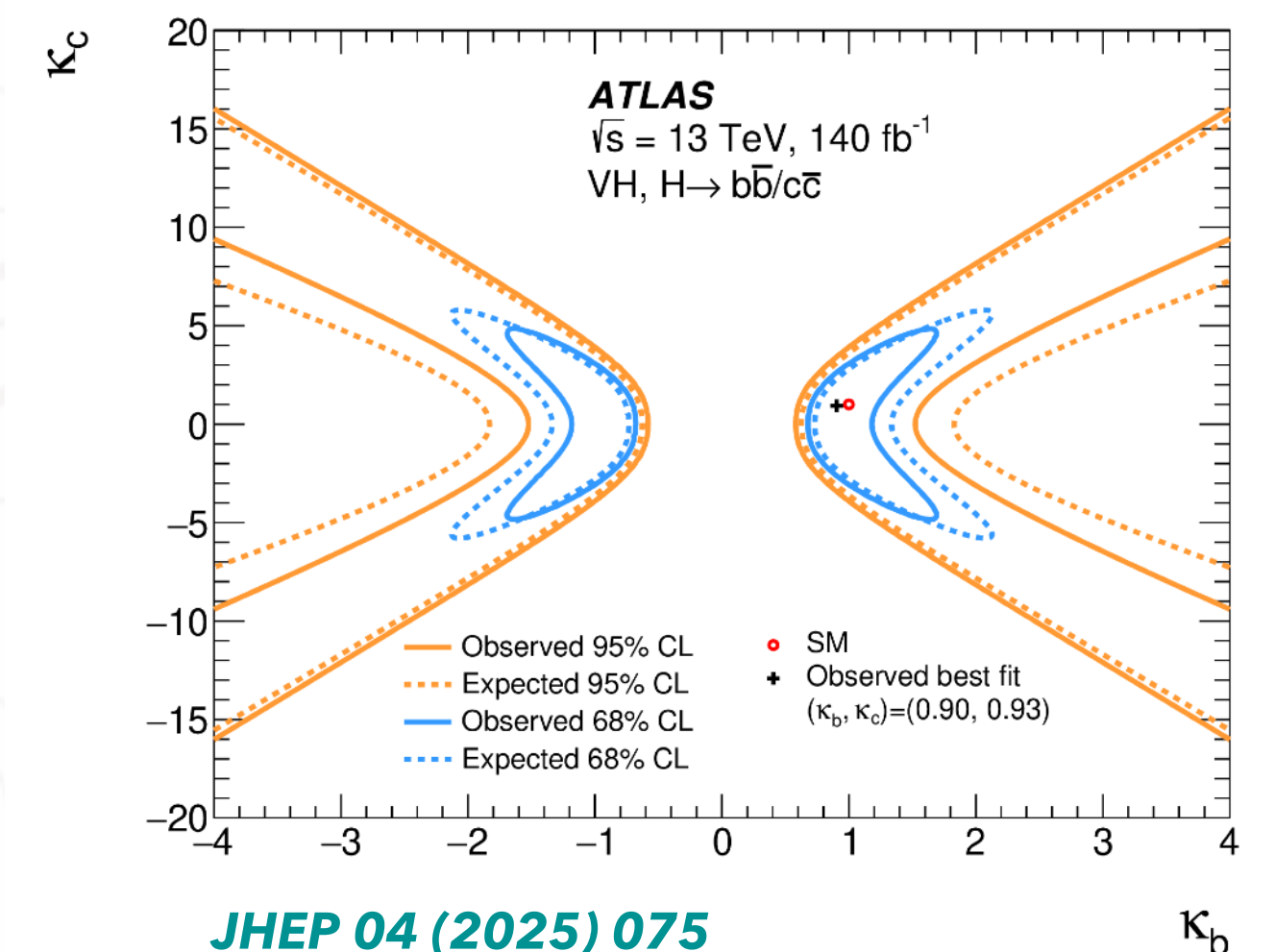
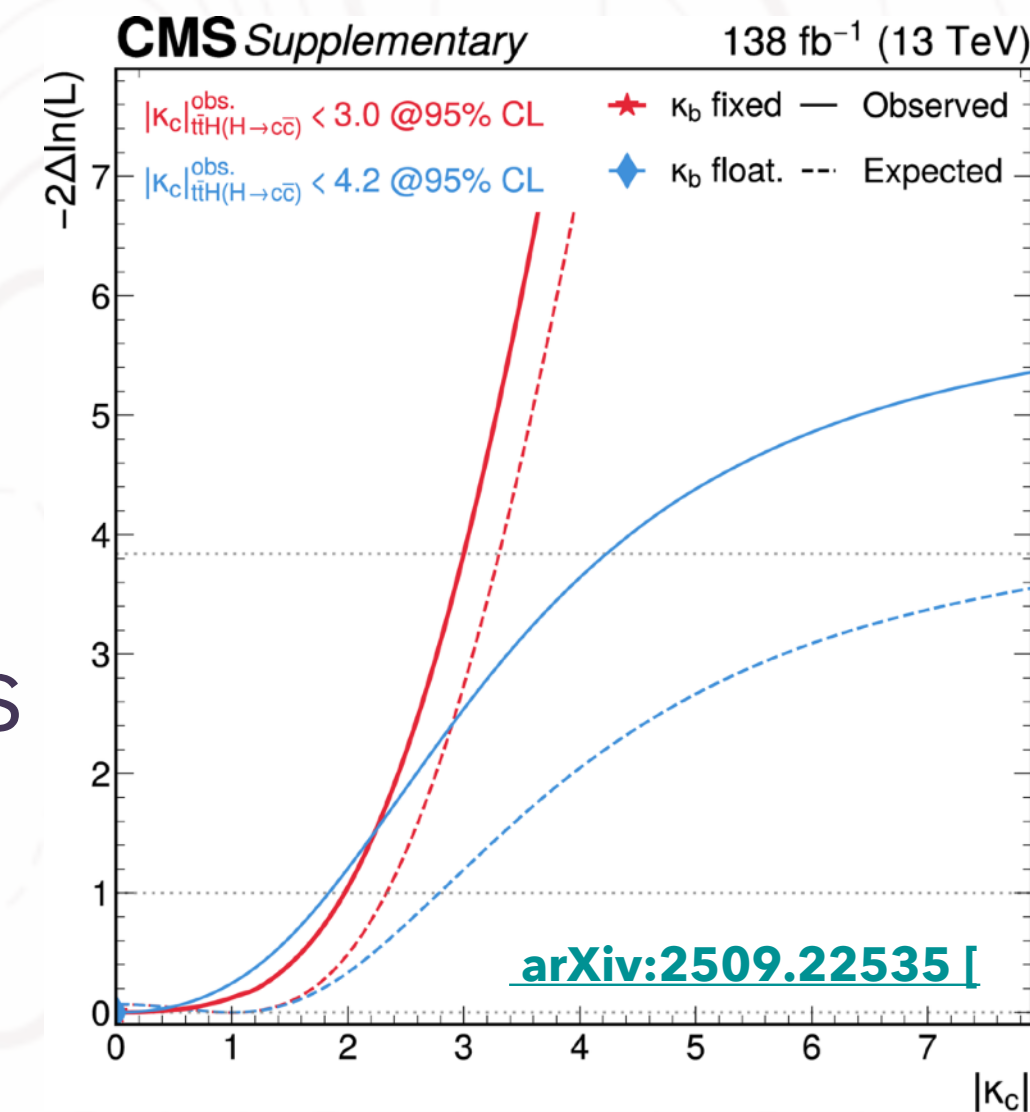
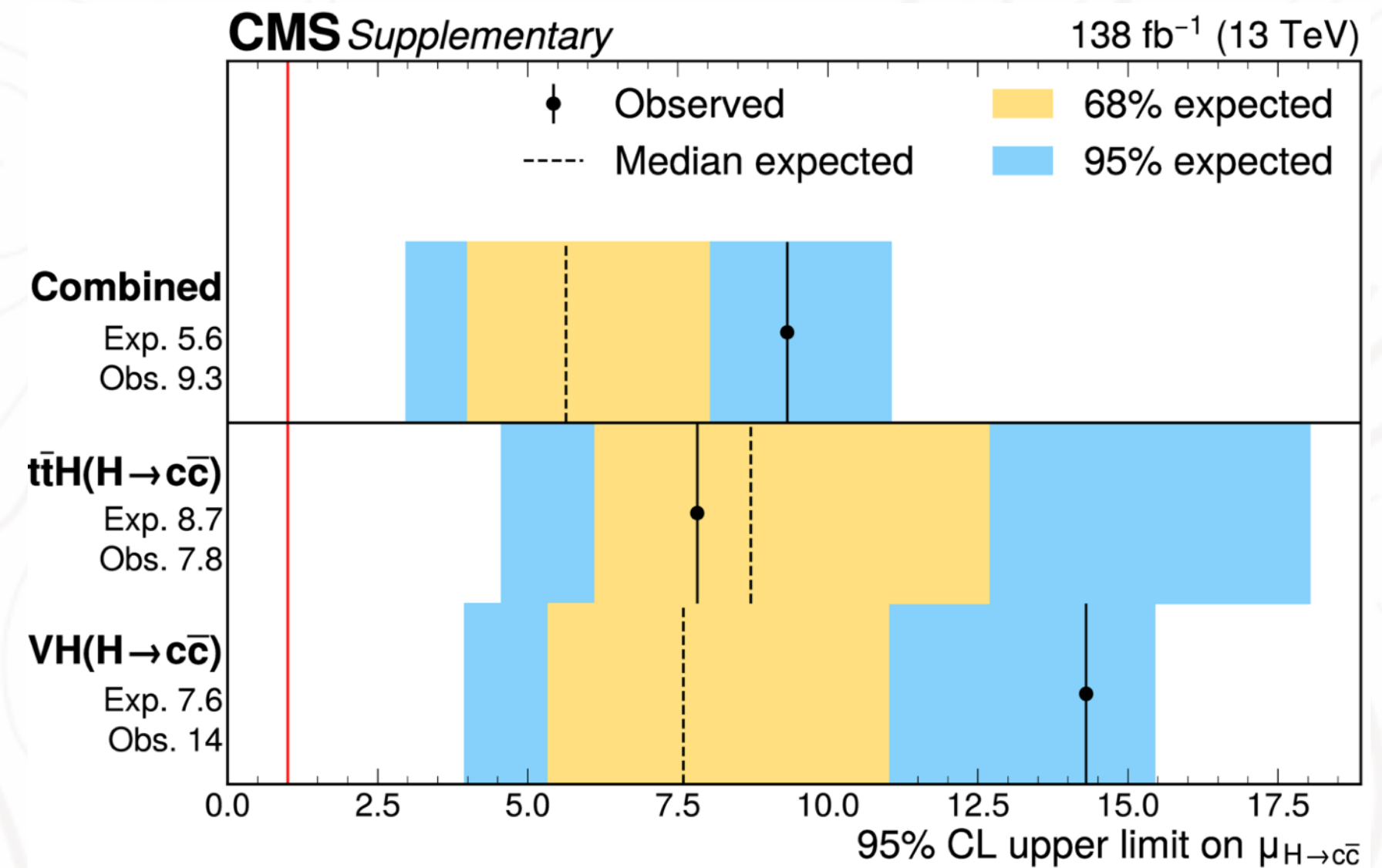
- Huge improvements in recent years in the study of the charm coupling: exploiting innovations in flavour tagging and in signal/background discrimination with dedicated ML approaches
- Game changer: originally "impossible" channels now lead to measurements



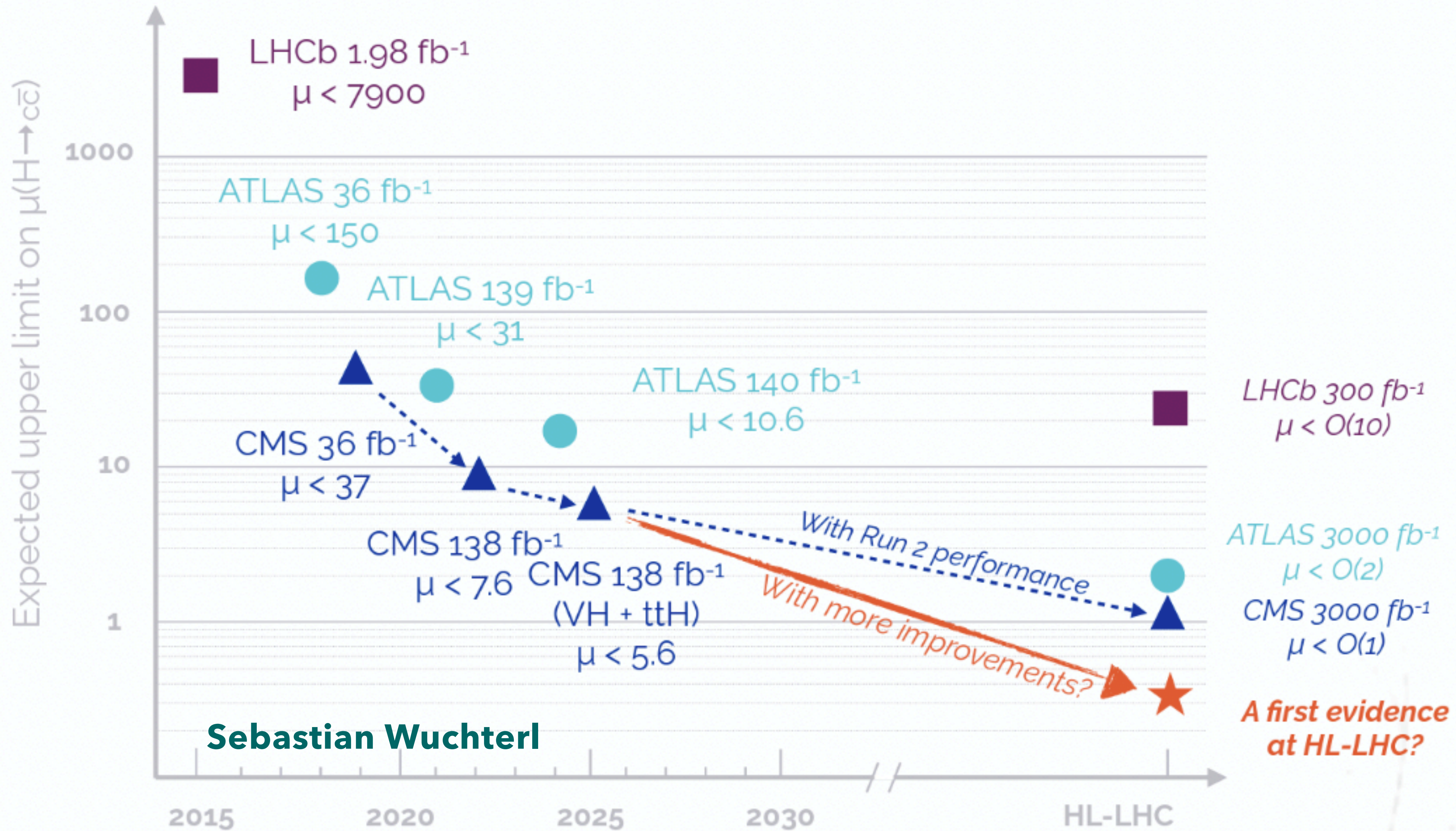
THE HUNT FOR THE CHARM

- **CMS, $t\bar{t}H$ Hcc + VH cc : $|\kappa_c| < 3.5$ (2.7)**
- **ATLAS VH cc : $|\kappa_c| < 4.2$ (4.1)**
(At 95%CL)

- Many other probes: $H+c$, $H+\gamma$, $H \rightarrow \psi(nS)\gamma$, constraints from general Higgs pt differentials,...
- All with the goal of answering a question: will the LHC measure the Higgs coupling to the charm?



MAKING THE IMPOSSIBLE POSSIBLE



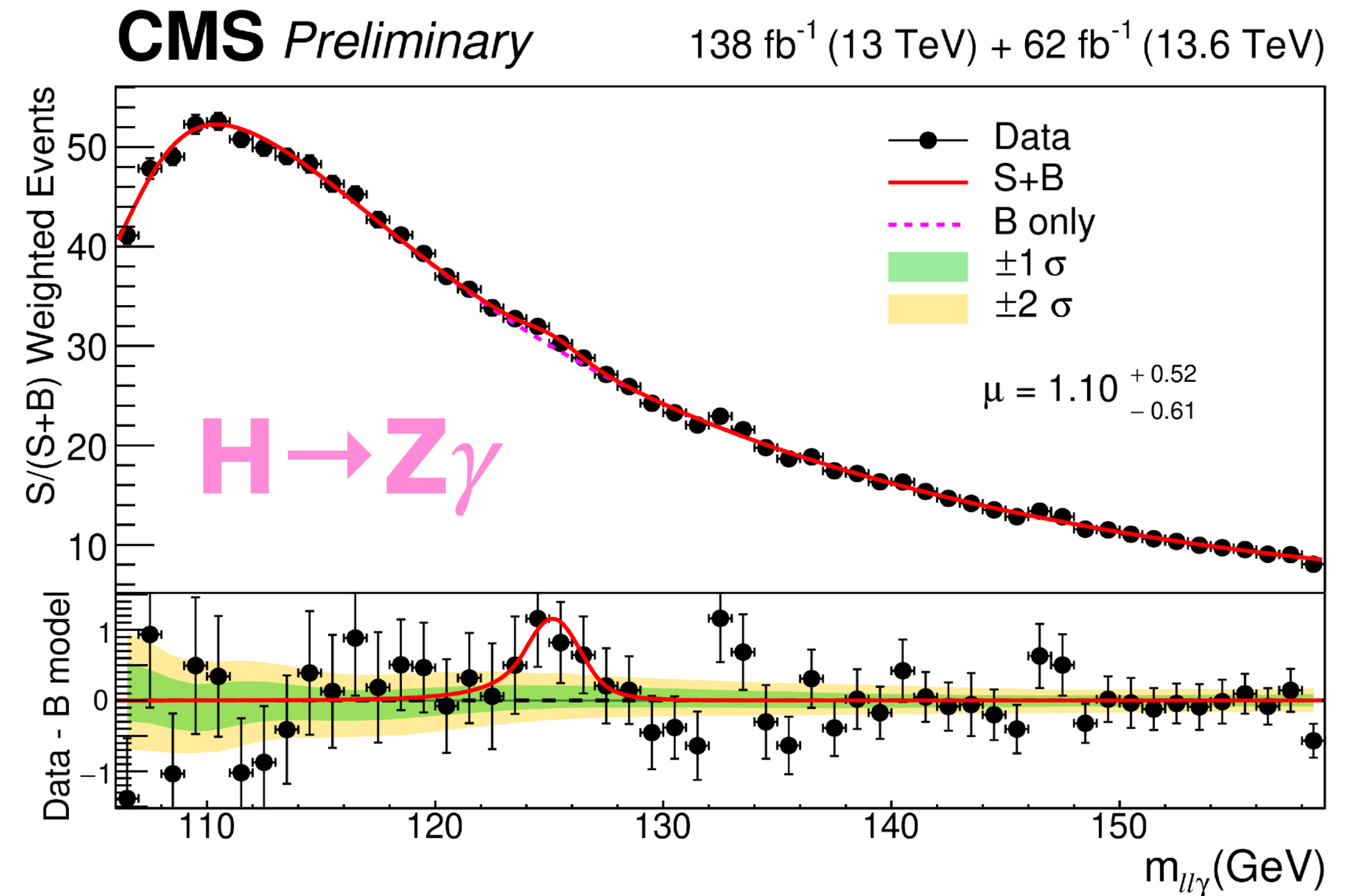
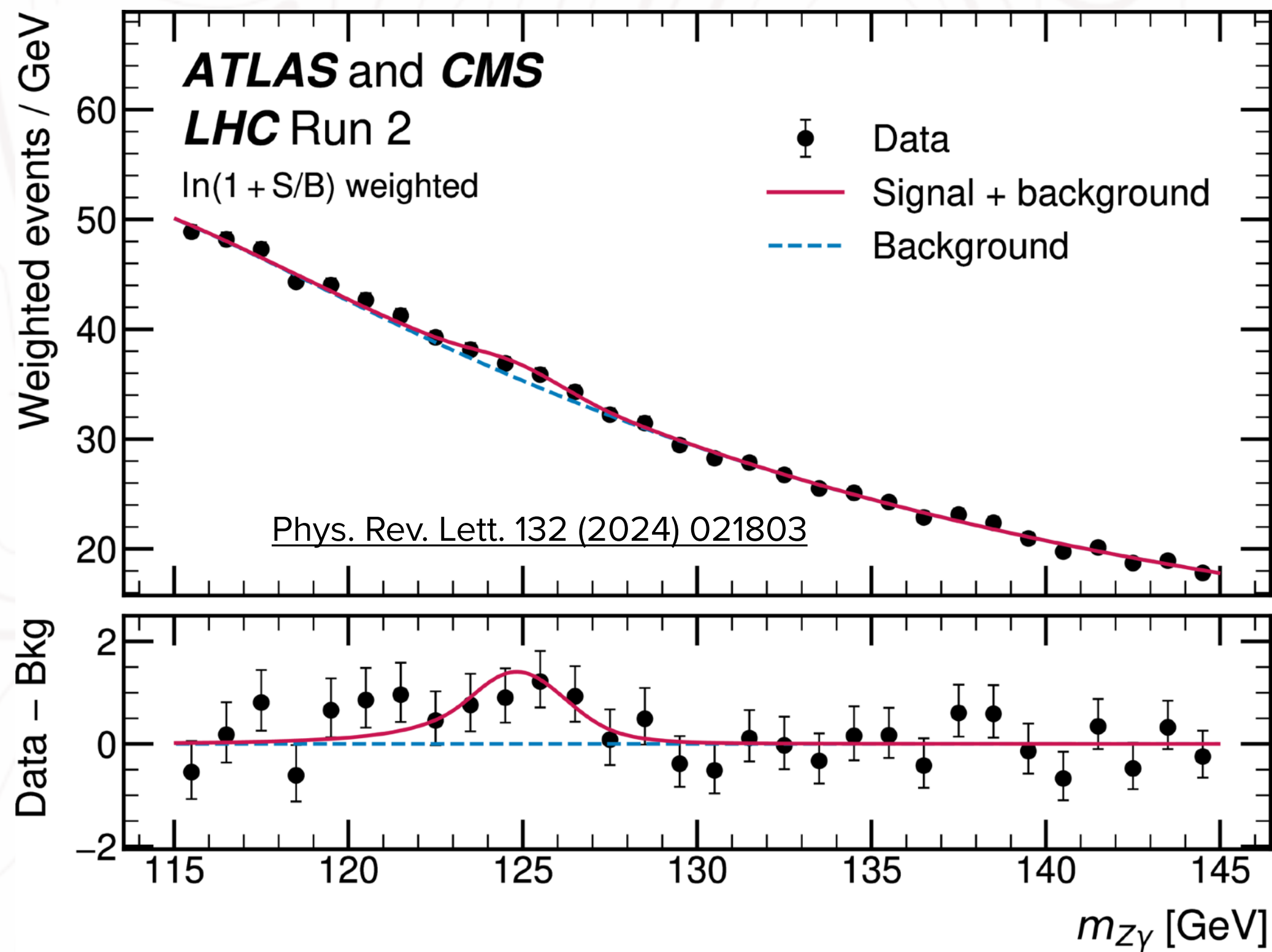
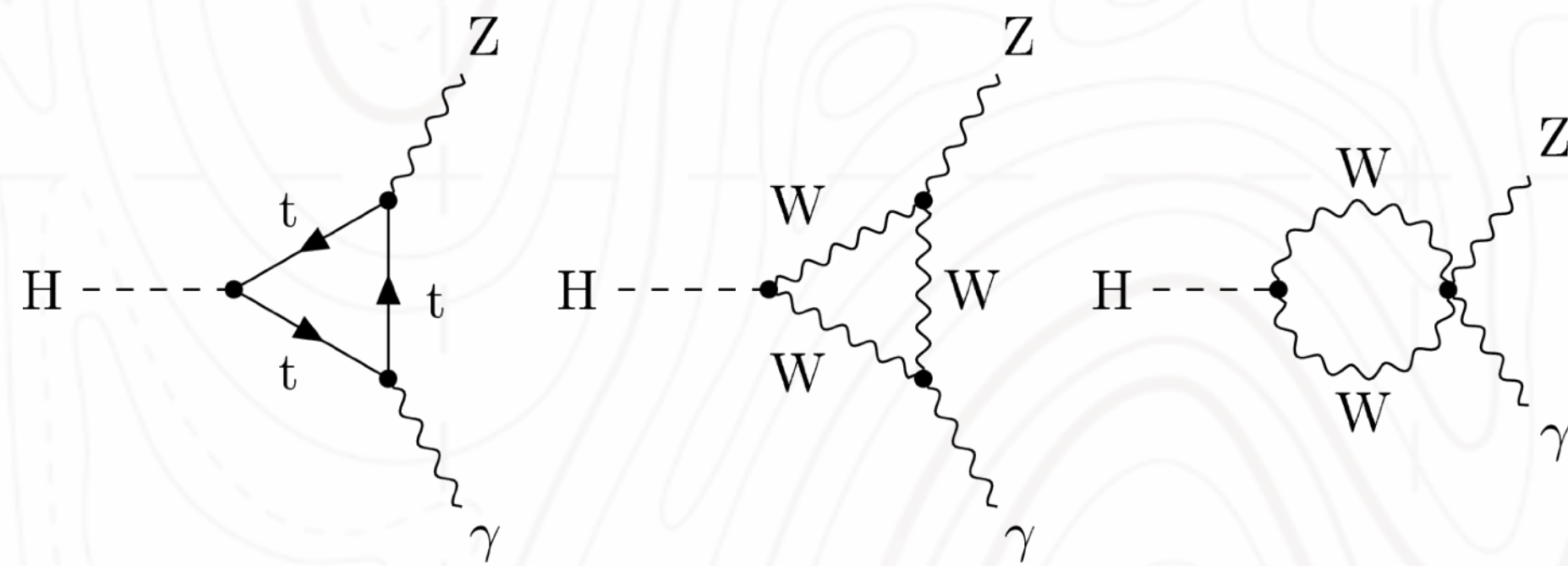
EVIDENCE FOR ZGAMMA

Evidence in Run2 with ATLAS+CMS: $\mu = 2.2 \pm 0.7$, 3.4σ (1.6 exp SM)

Run2+Run3?

ATLAS : 2.5σ (1.9 exp SM), $\mu = 1.3^{+0.6}_{-0.51}$

CMS 1.9σ (2.3 exp SM) , $\mu = 1.1^{+0.52}_{-0.61}$



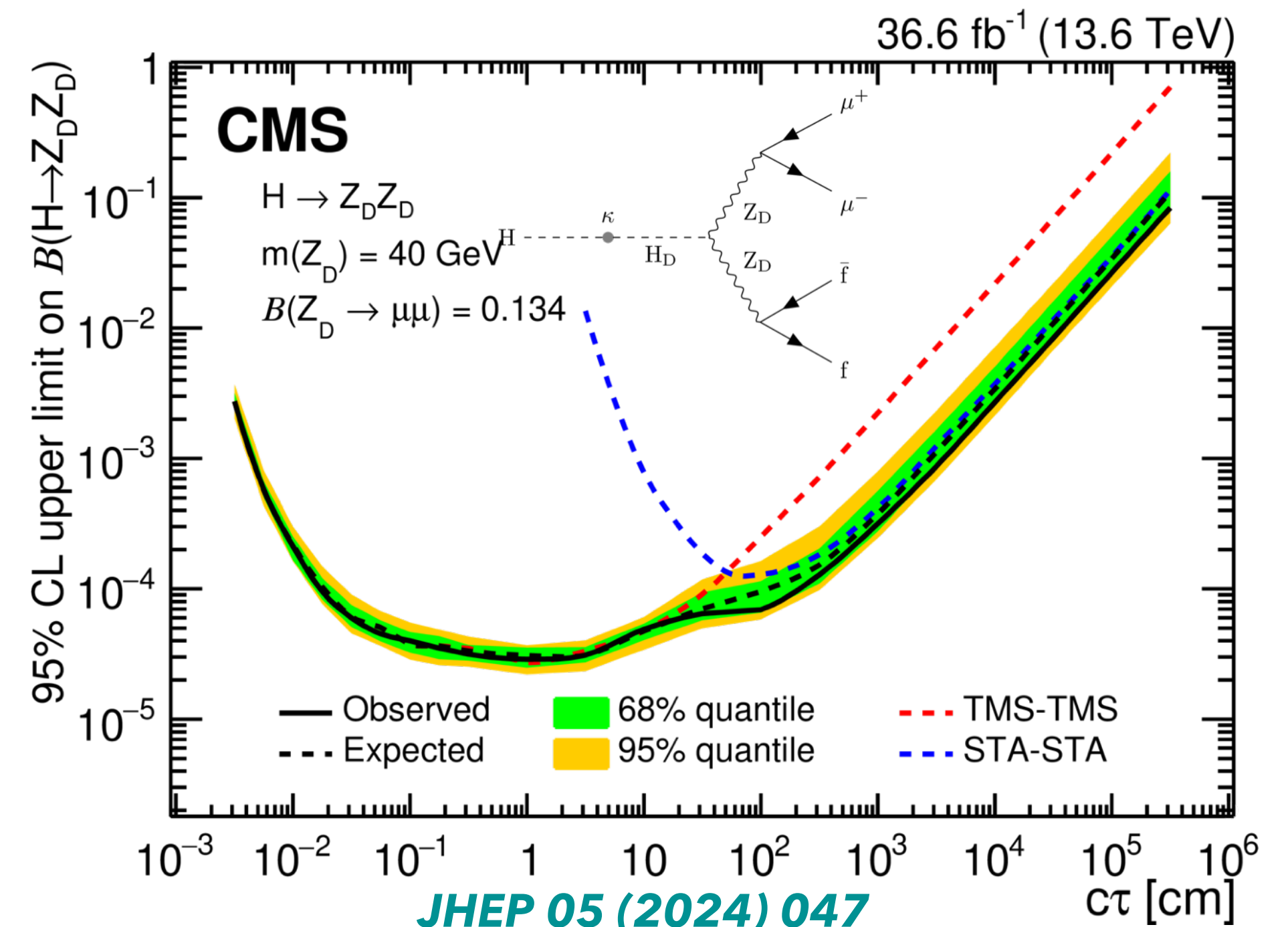
IMPOSSIBLE OR JUST EXTREMELY RARE?

- **We have not yet explored all the SM decays of the Higgs.**
 - Searches for many rare decay modes existing or ongoing, directly (eg $H \rightarrow \text{Meson} + \text{Photon}$) or indirectly
 - For many, like decays to light quarks or ee , we can only set high upper limits, far away from the SM
- But **why should we assume the Higgs boson follows the SM rules?** Can it decay to the unexpected?
- We also **search directly for Higgs \rightarrow BSM . eg: Dark Matter, LFV, light scalars, long-lived particles**

“Higgs Invisible”: Searches for Higgs decays to Dark Matter particles. At 95% CL, with Run2:

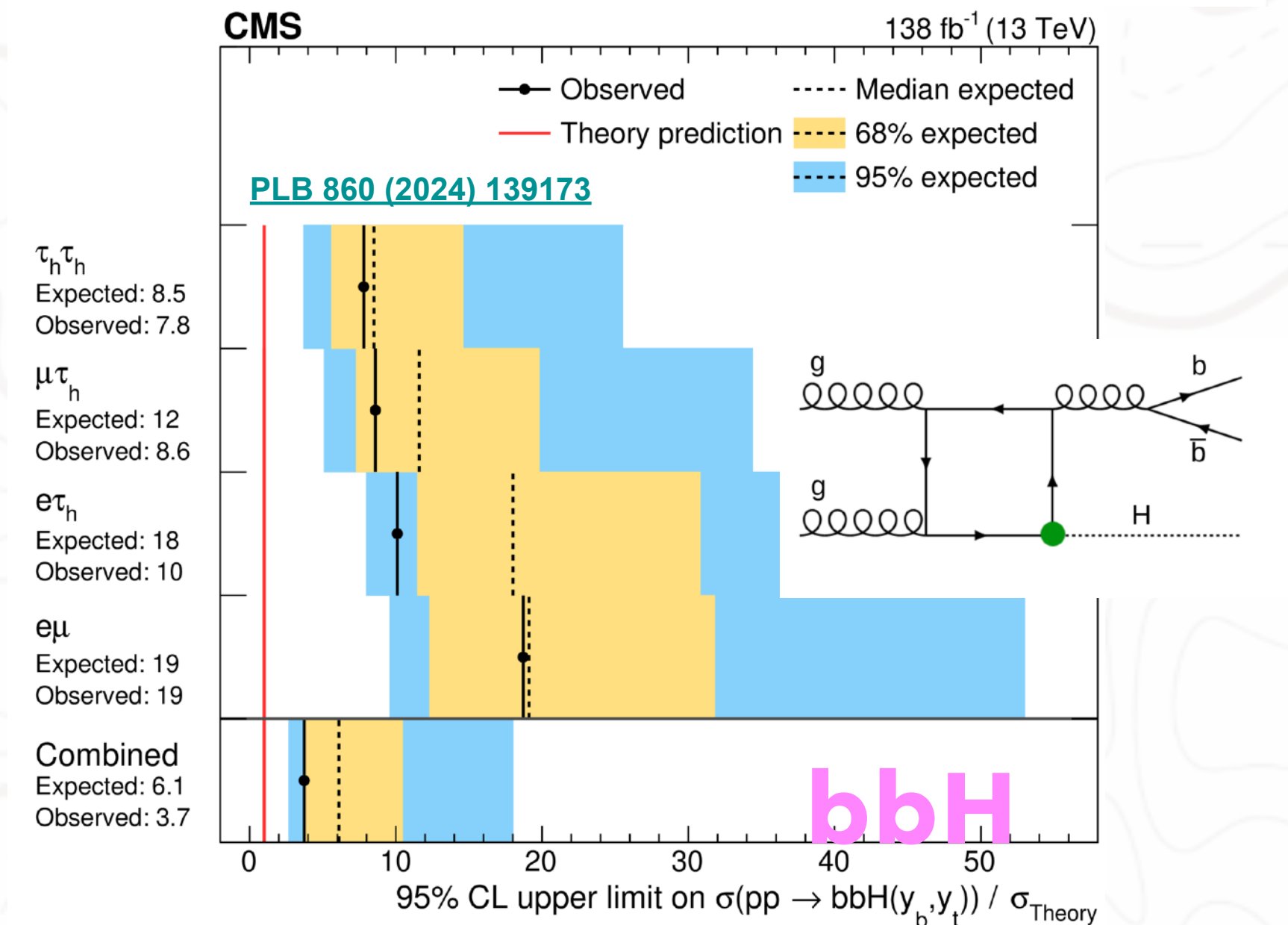
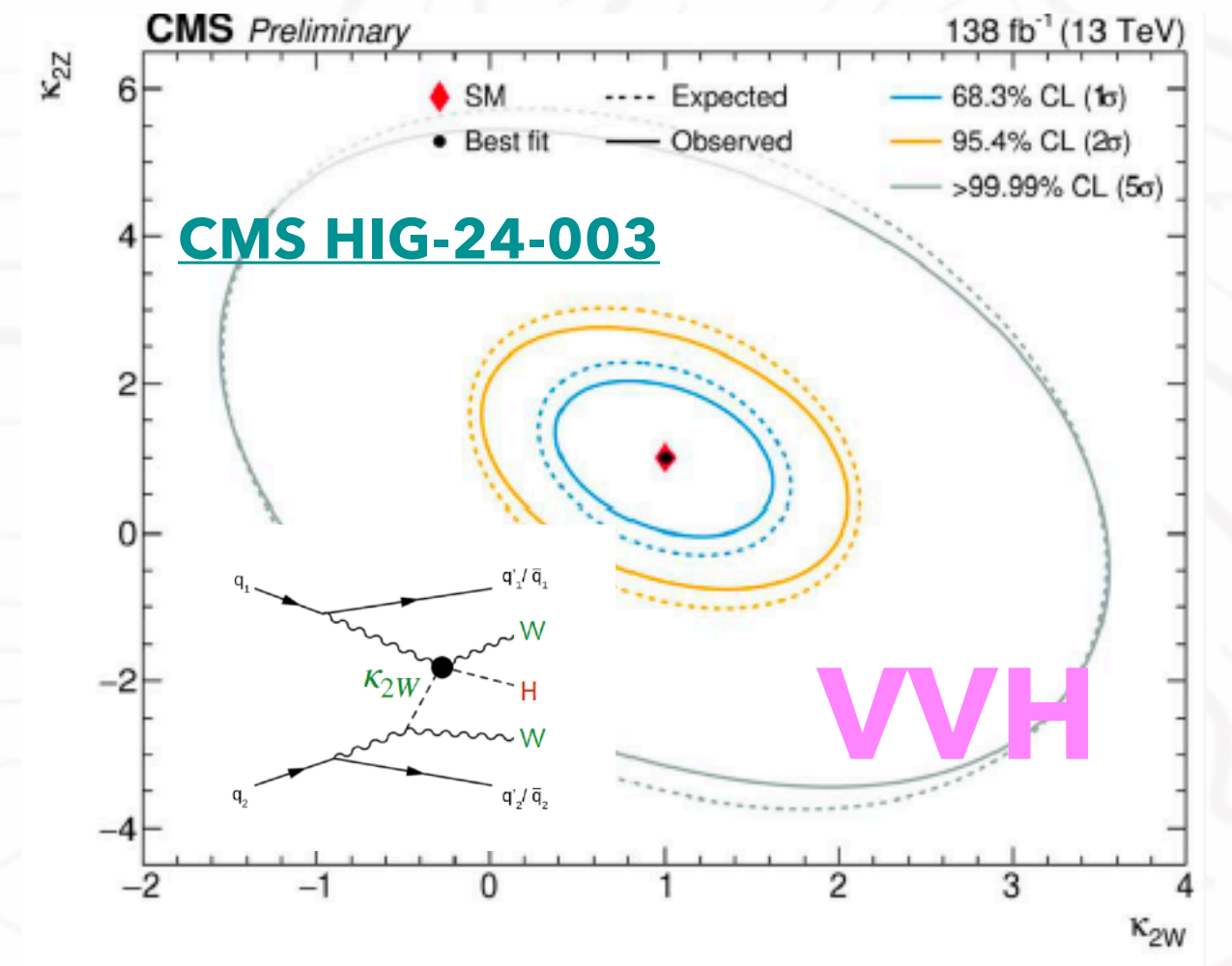
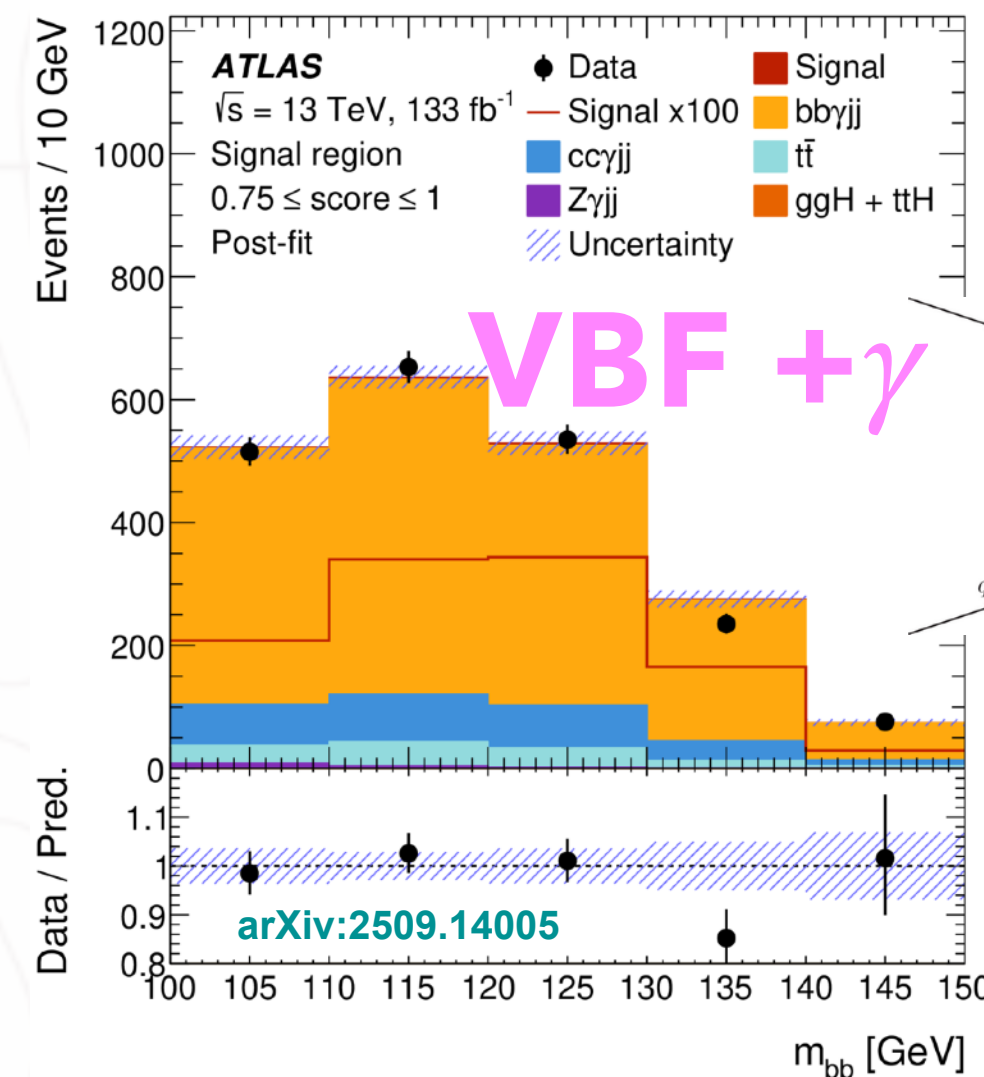
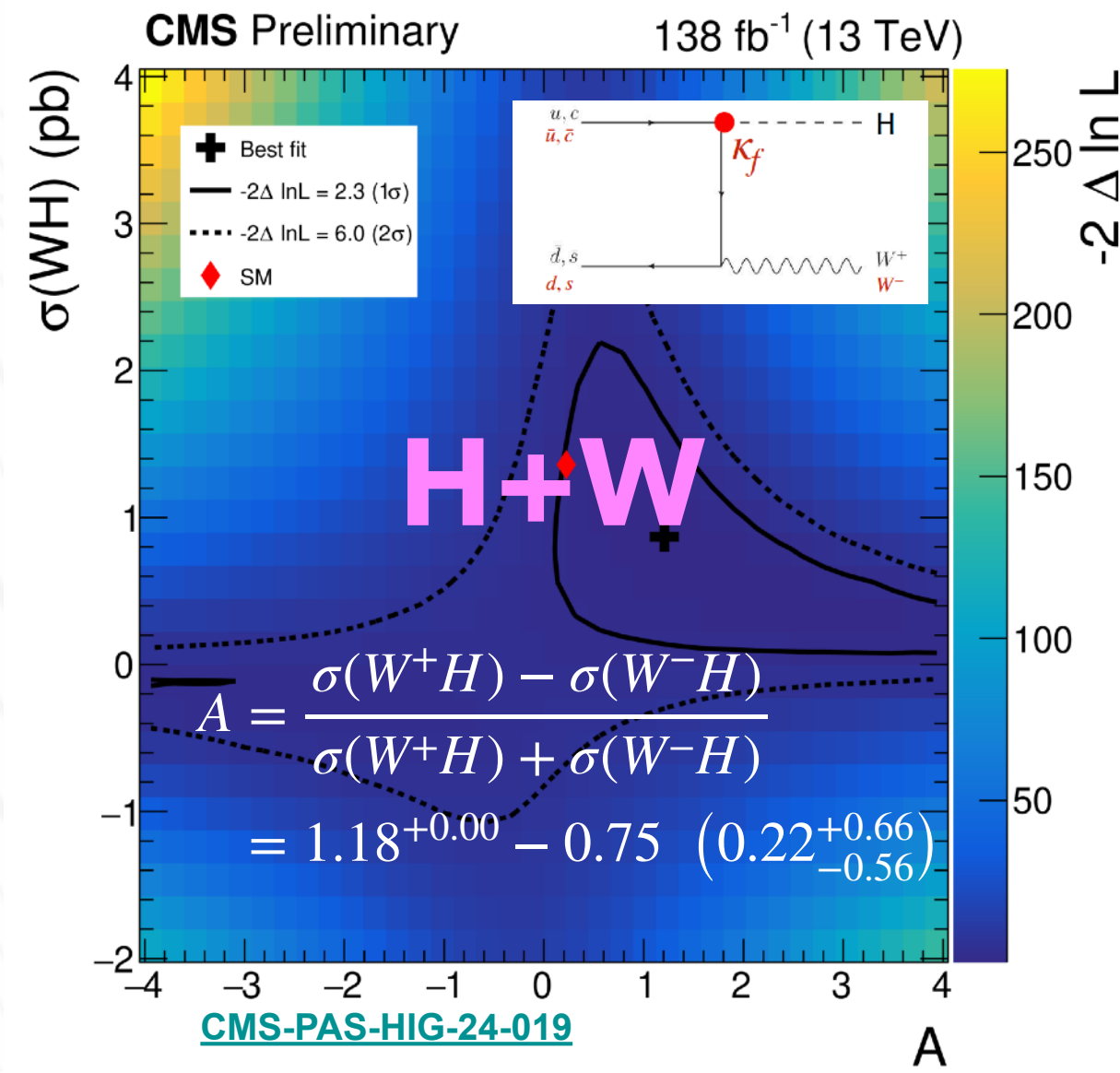
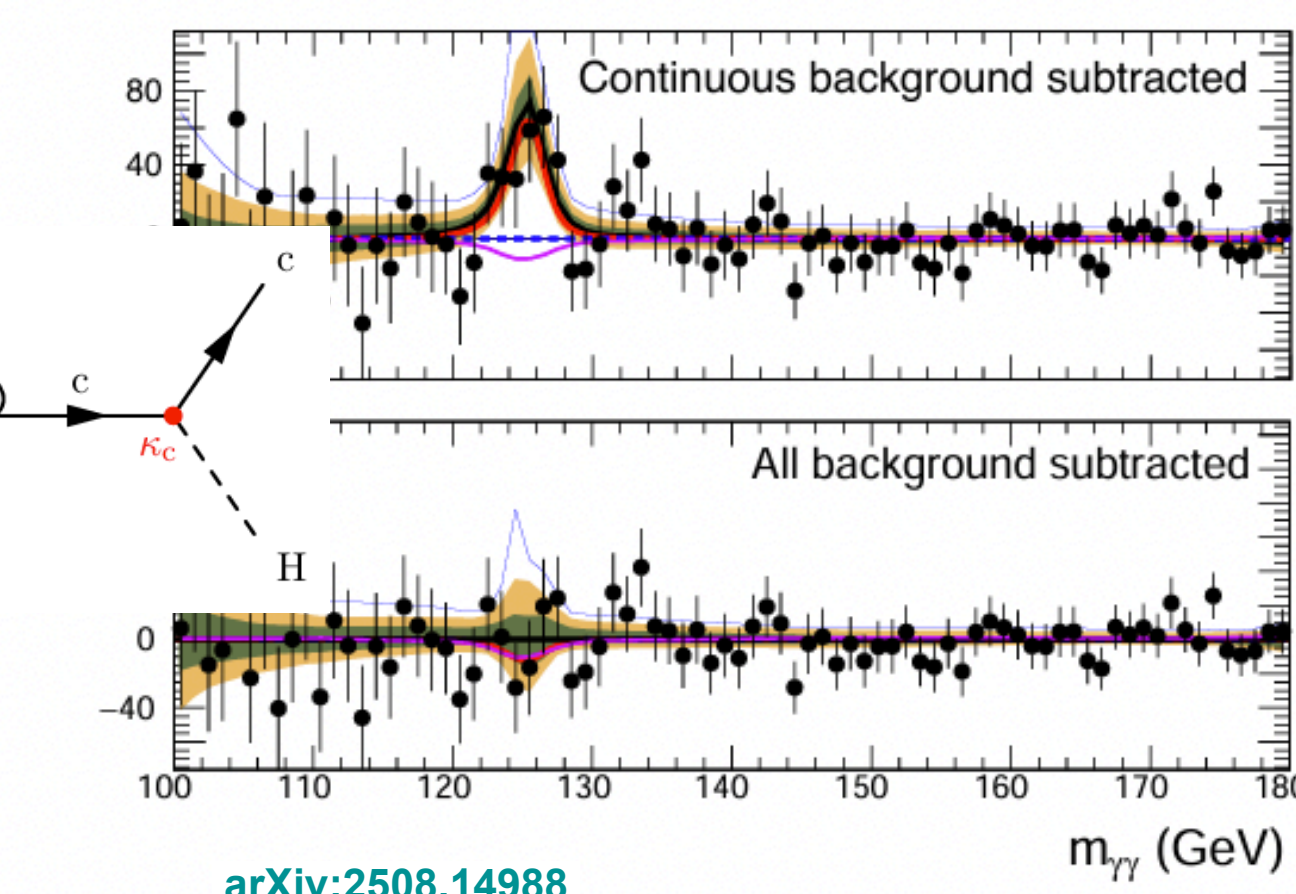
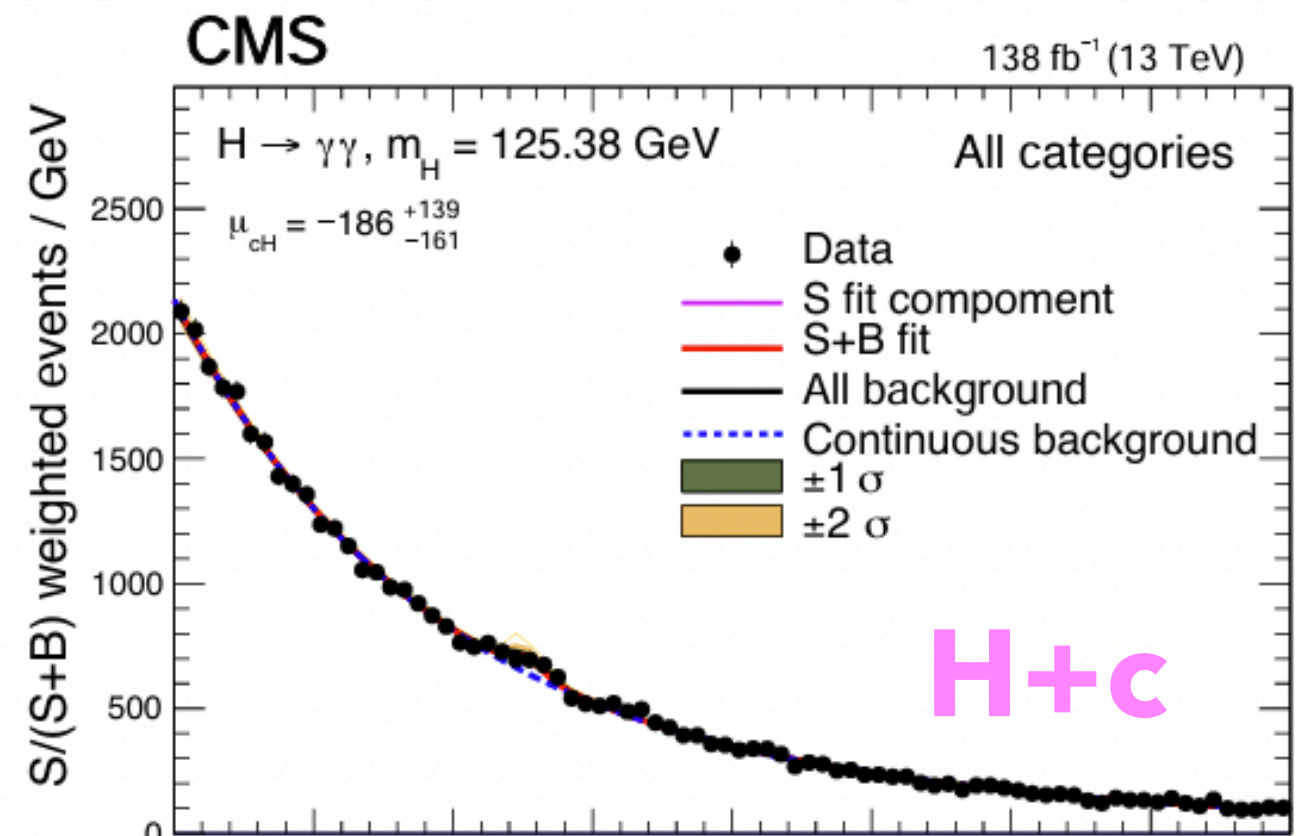
- CMS: $\text{Br}(H \rightarrow \text{inv}) < 15\%$ (8%) ([EPJC 83 \(2023\) 933](#))
- ATLAS: $\text{Br}(H \rightarrow \text{inv}) < 10.7\%$ (7.7%) ([PLB 842 \(2023\) 137963](#))

New avenues: Dark Sectors, Long Lived decays, interesting reconstruction opportunities



RARER AND RARER PRODUCTION MODES

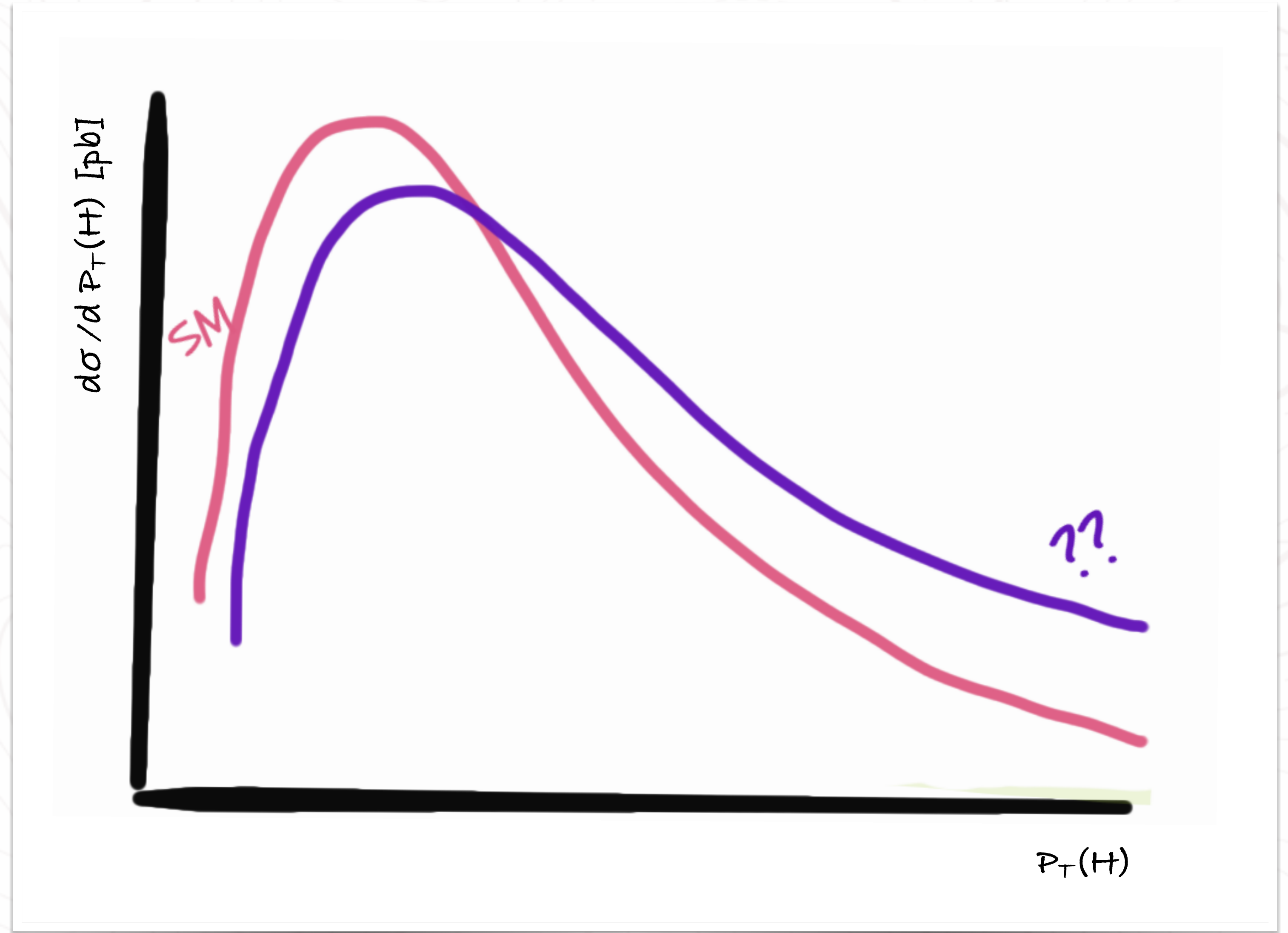
Associated production
(H+W, H+c, H+b, H+ γ ...)



COUNTING WAS ONLY THE BEGINNING...

■ Higgs kinematics can be modified by BSM physics

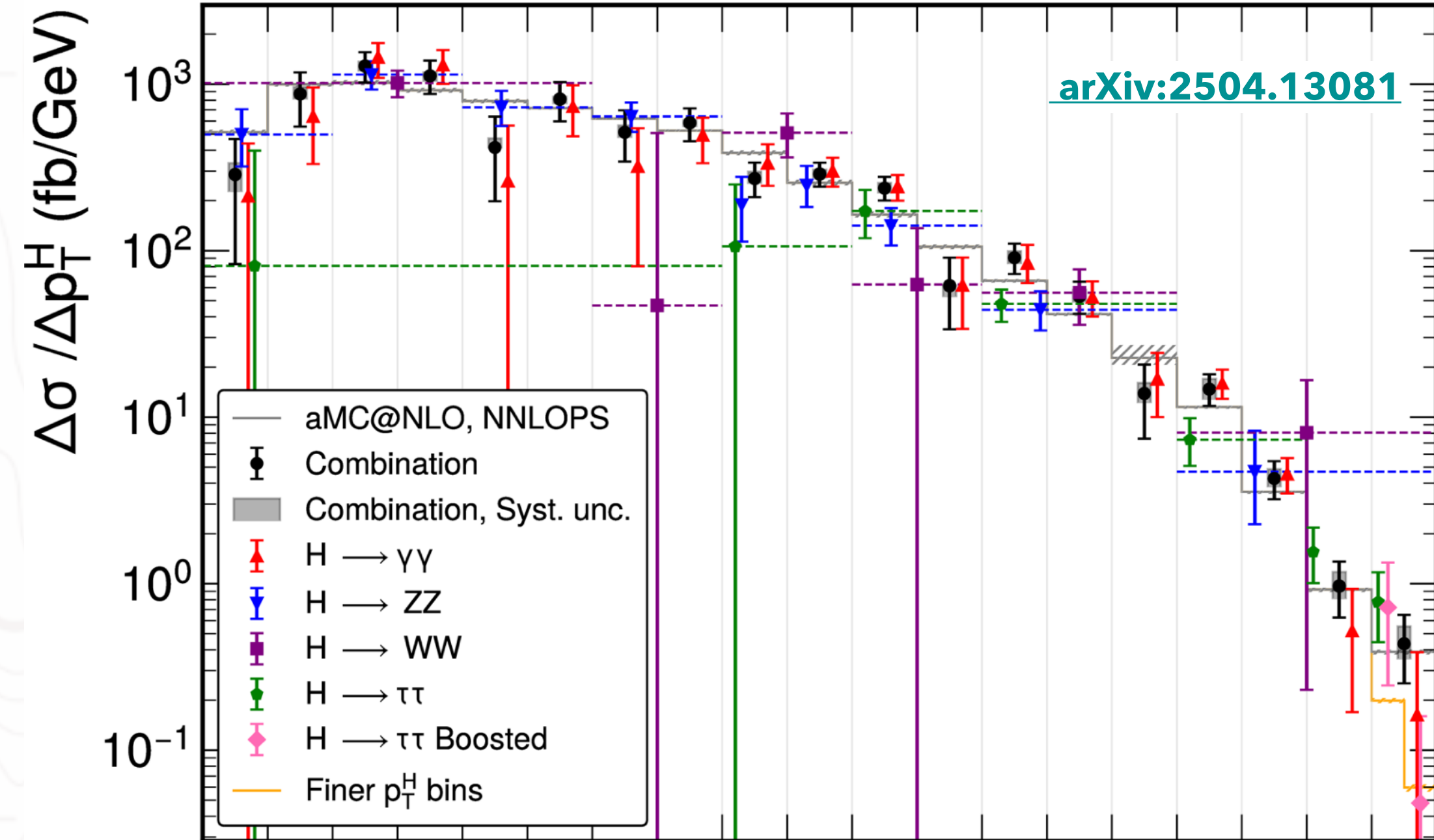
- Do the current MC tools model the Higgs behaviour correctly?
- Complex phase-spaces: how high can we reach in Higgs PT?
- Indirect constraints on BSM



DIFFERENTIAL DISTRIBUTIONS

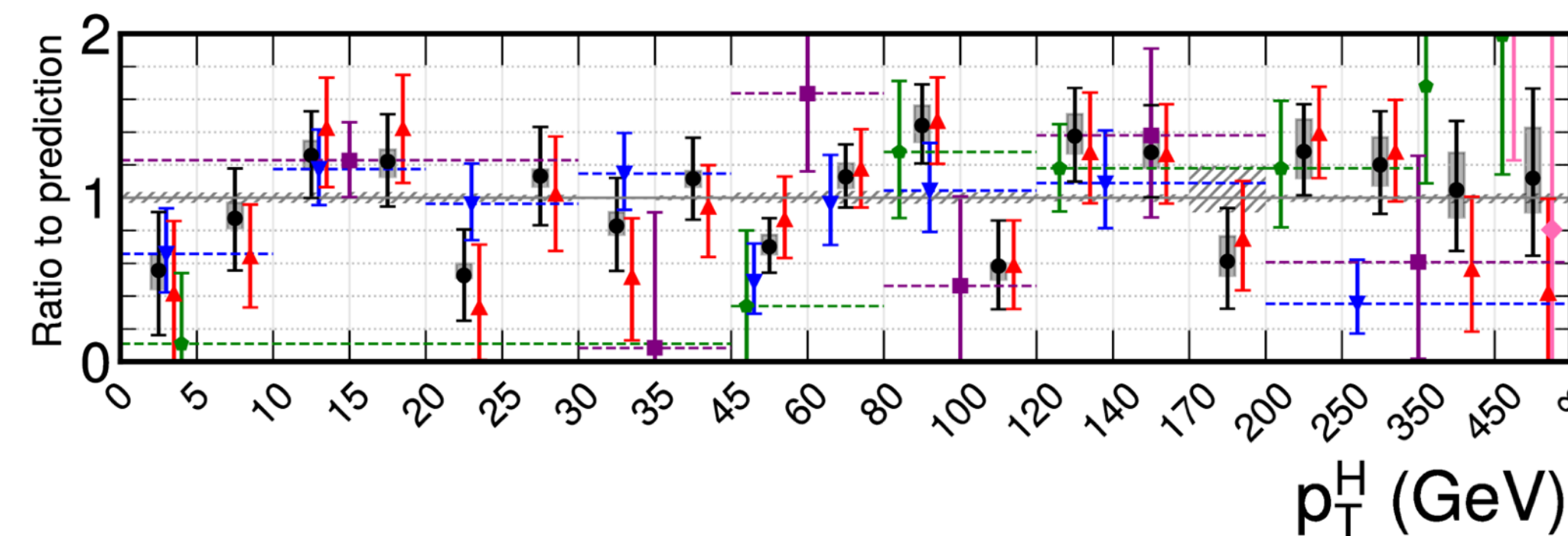
CMS

138 fb⁻¹ (13 TeV)

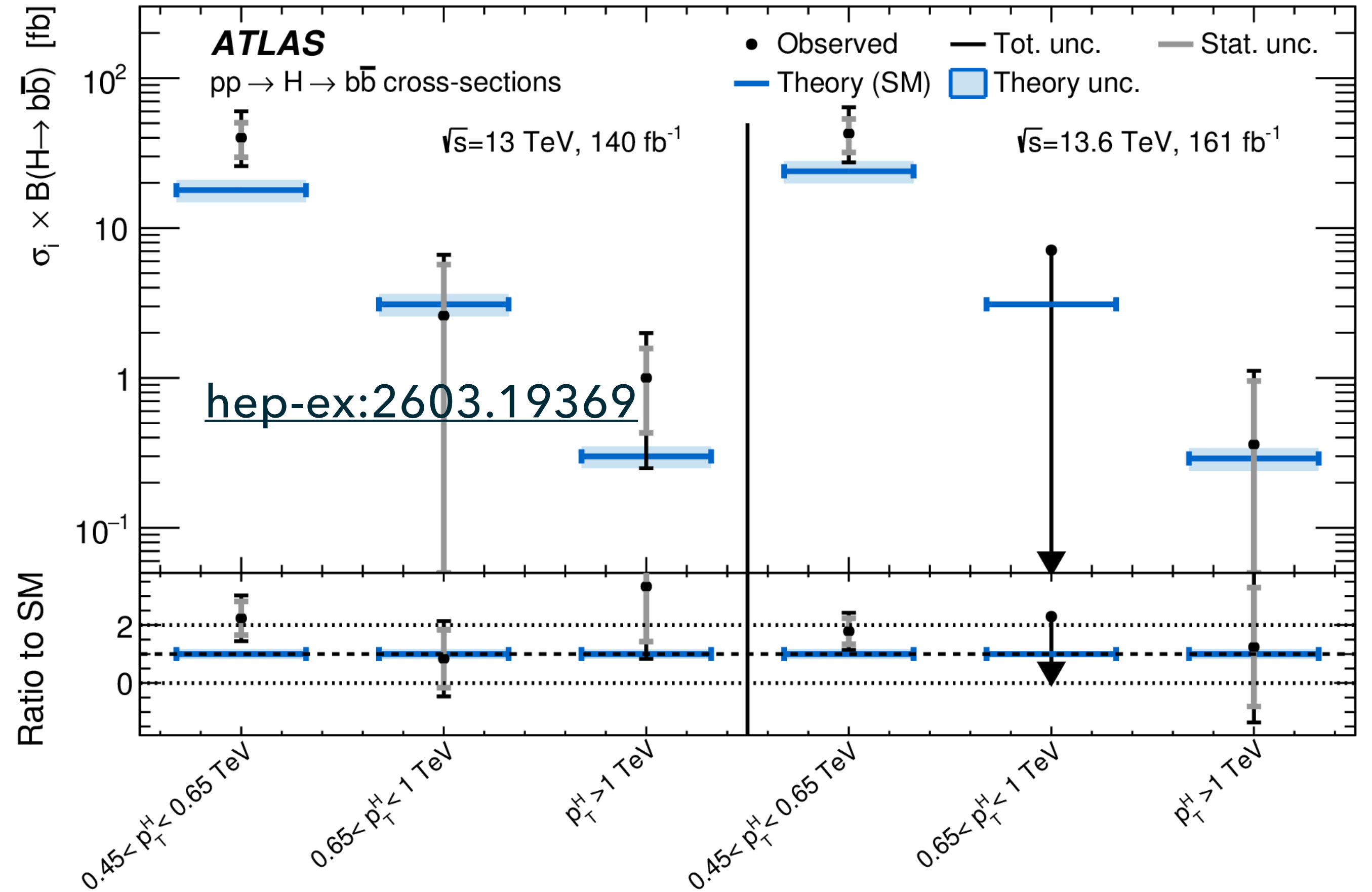
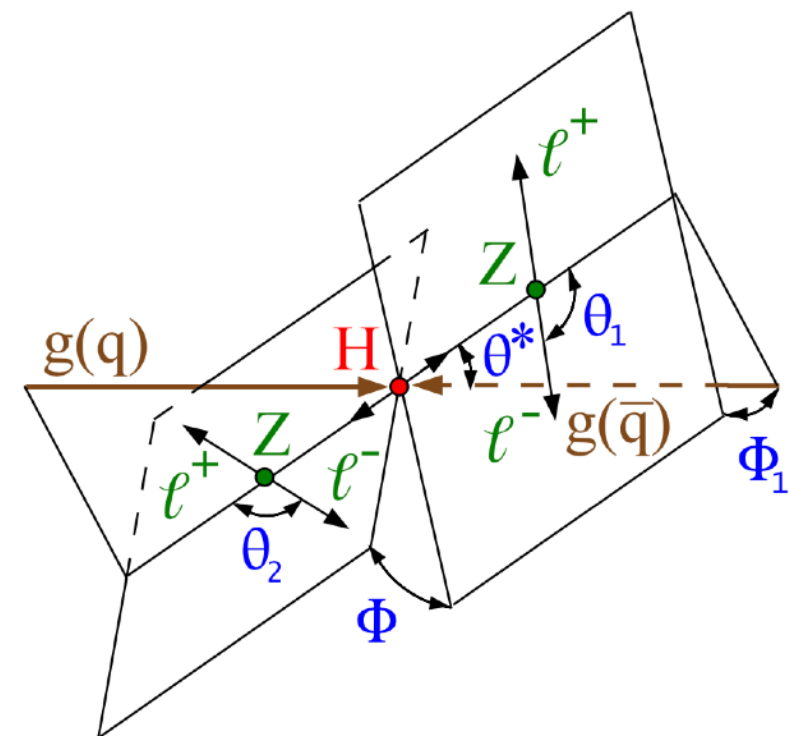
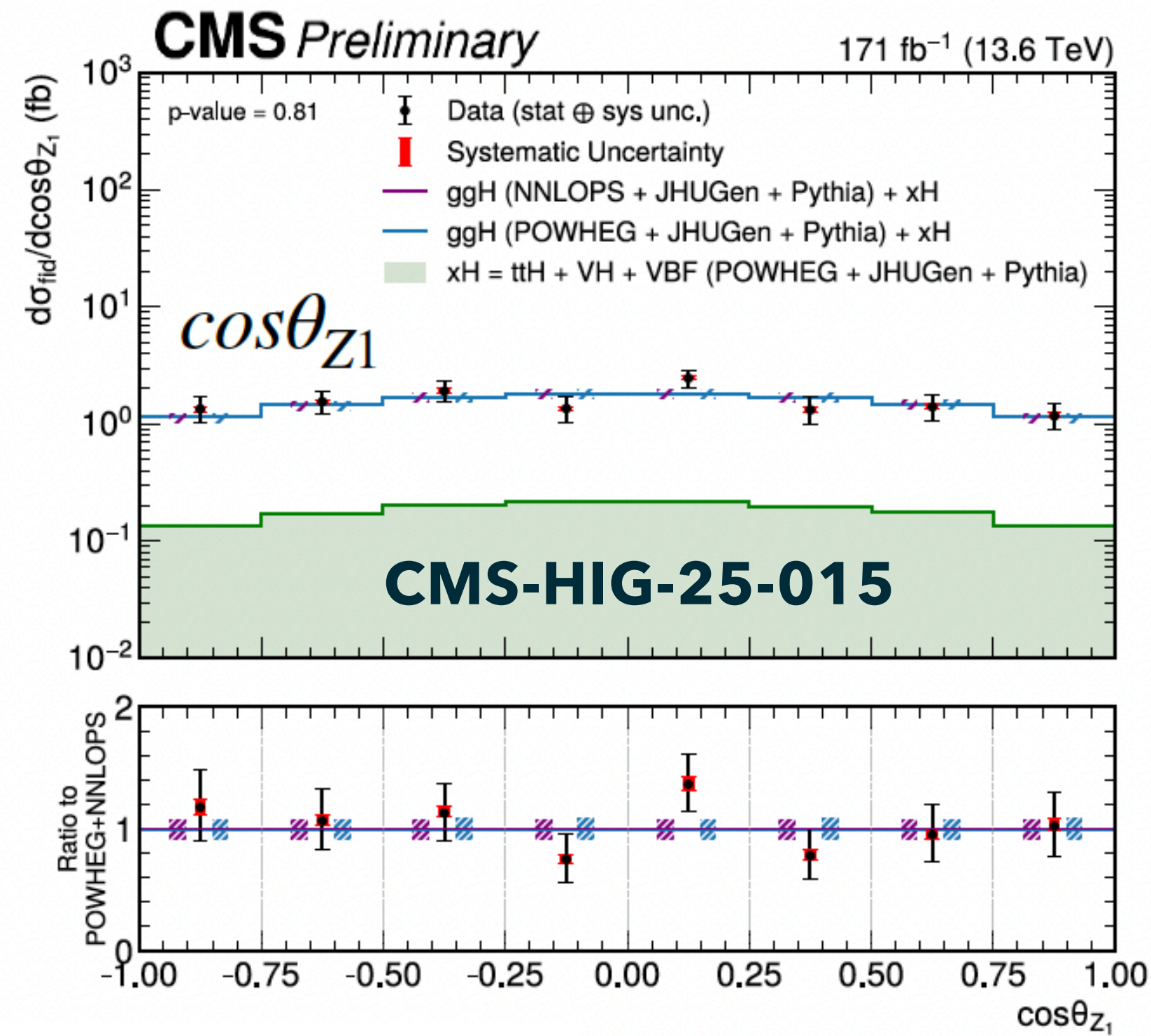


Many variables probed. Detailed map of Higgs Kinematics

Another approach: STXS (binned fiducial cross sections, in backup). Largely model-independent way to test for BSM deviations



MAPPING THE HIGGS PHASESPACE



— Studying interesting variables (eg kinematics) & regimes (eg High PT)

EFFECTIVE FIELD THEORY INTERPRETATIONS

- The precision of these differential / STXS measurements can be interpreted in EFT scenarios
- From global fits to analyses targeting a dedicated observable, growing field, many new results

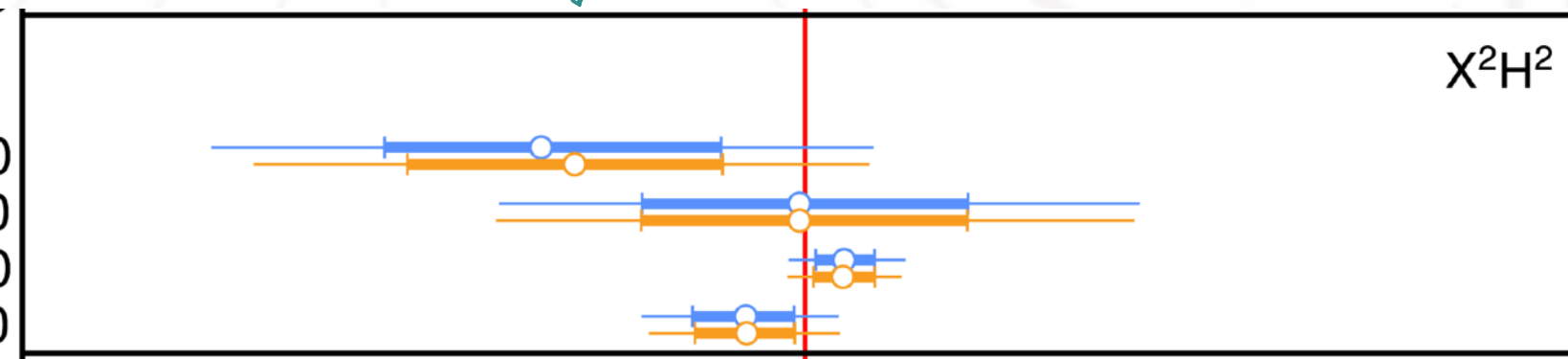
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} \mathcal{O}_j^{(8)} + \dots,$$

CMS Preliminary 138 fb⁻¹ (13 TeV)



CMS-PAS-HIG-21-018

CHB X 1000
CHG X 1000
CHWB X 100
CHW X 100



$H \rightarrow ZZ^*$ (prod.+decay)

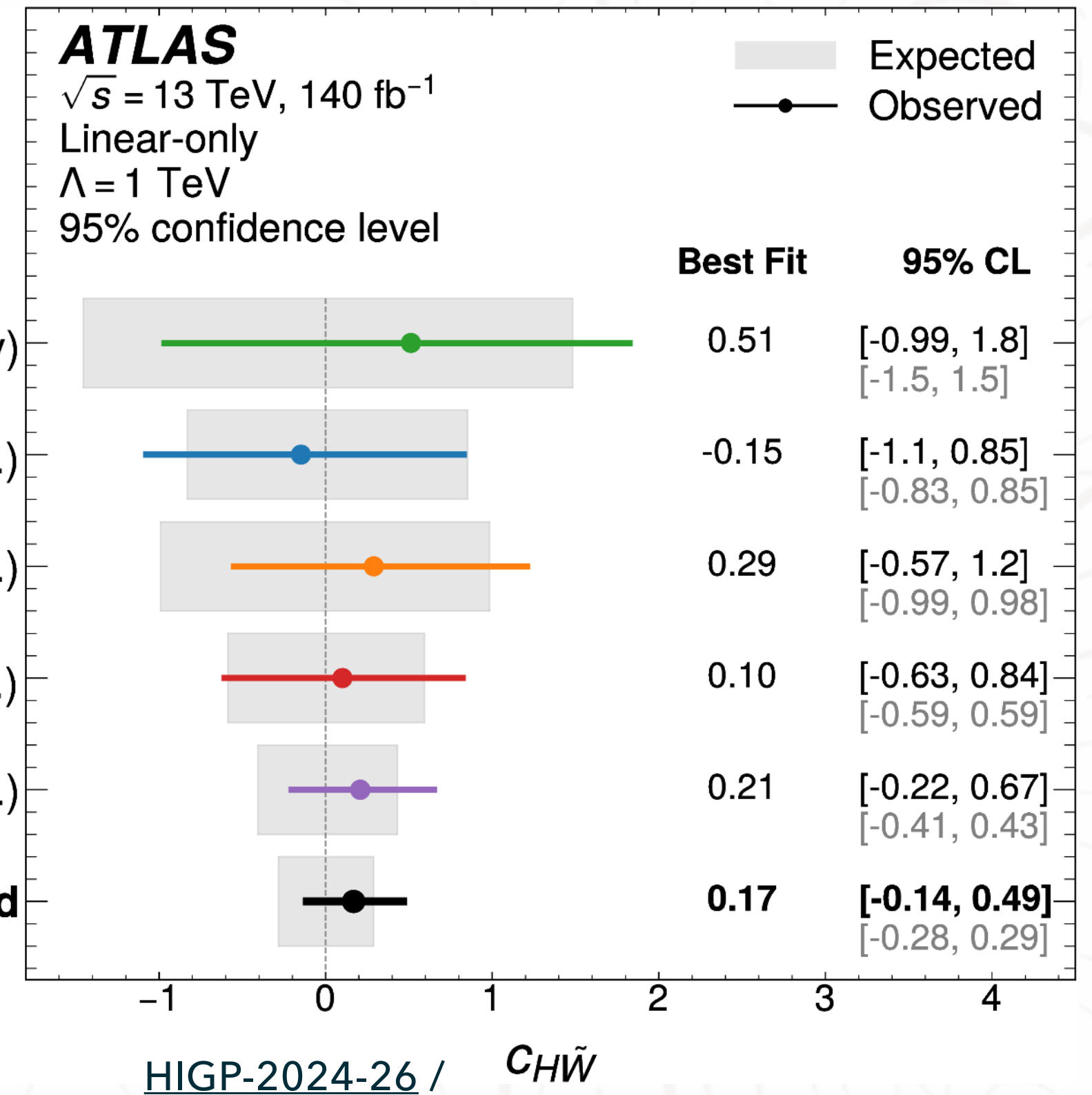
$H \rightarrow WW^*$ (prod.)

$H \rightarrow \gamma\gamma$ (prod.)

$WH, H \rightarrow b\bar{b}$ (prod.)

VBF $H \rightarrow \tau\tau$ (prod.)

Combined



TWO HIGGSES?

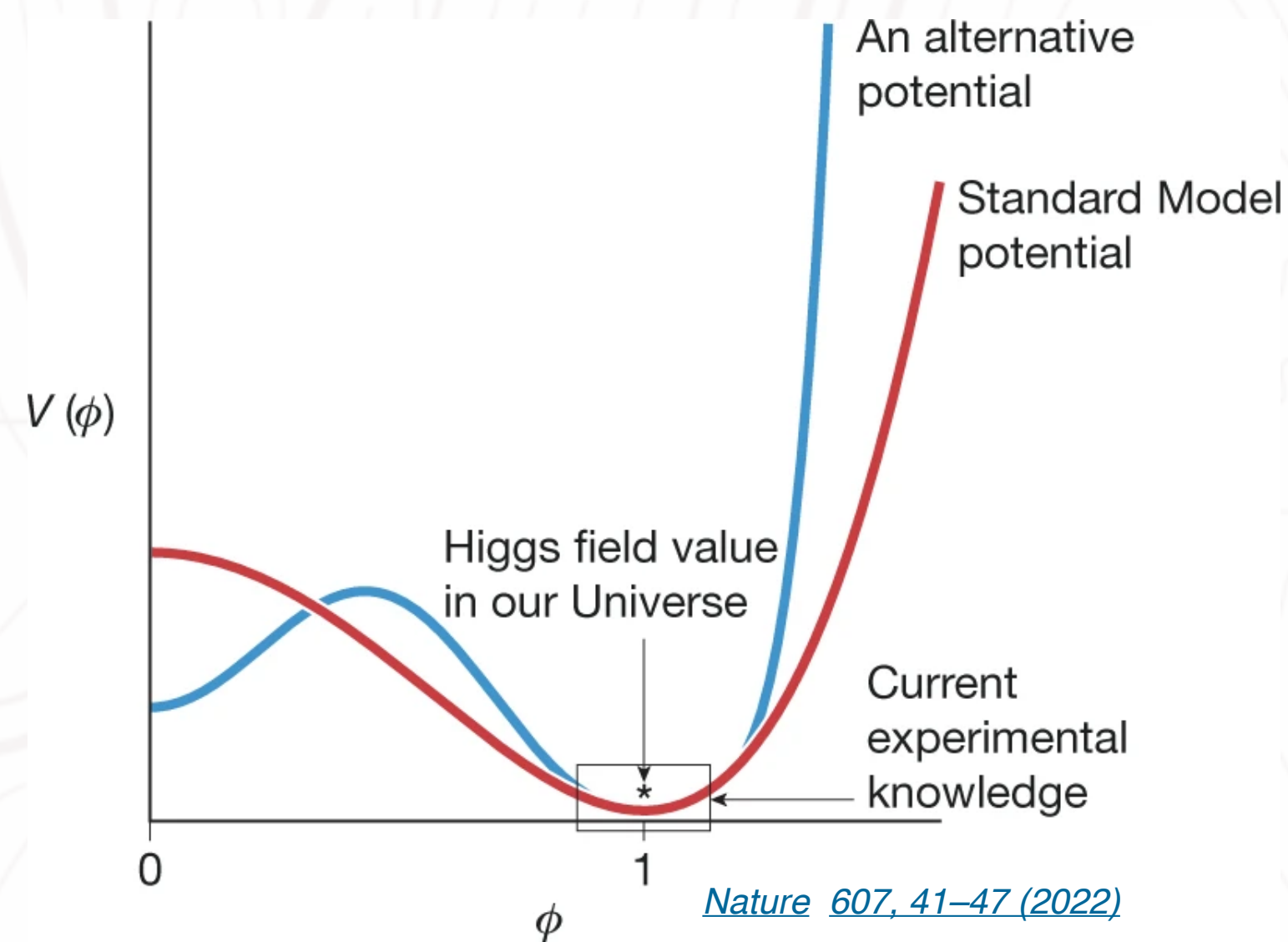
- **The next frontier: the self-coupling and the Higgs Potential**
- **What can we learn about the structure and evolution of the universe through the study of the Higgs?**



PROBING THE HIGGS POTENTIAL

Studying the Higgs boson transcends particle physics: understanding the Higgs Potential and the vacuum connects with the structure of the Universe

- Is there a deep reason for the apparent metastability of the Higgs vacuum?
- Is there a connection between the Higgs/EWSB and baryogenesis, Dark Matter, or inflation?
- What happens at the EW phase transition during the Big Bang?

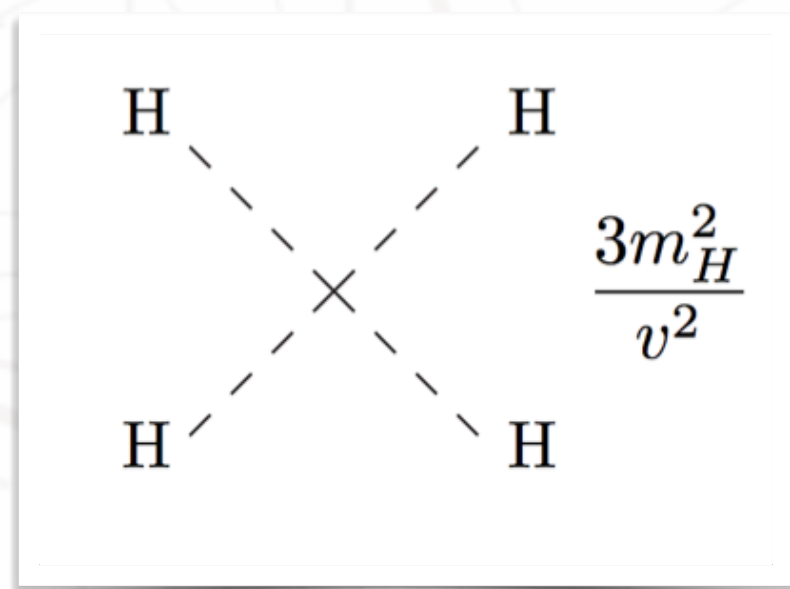
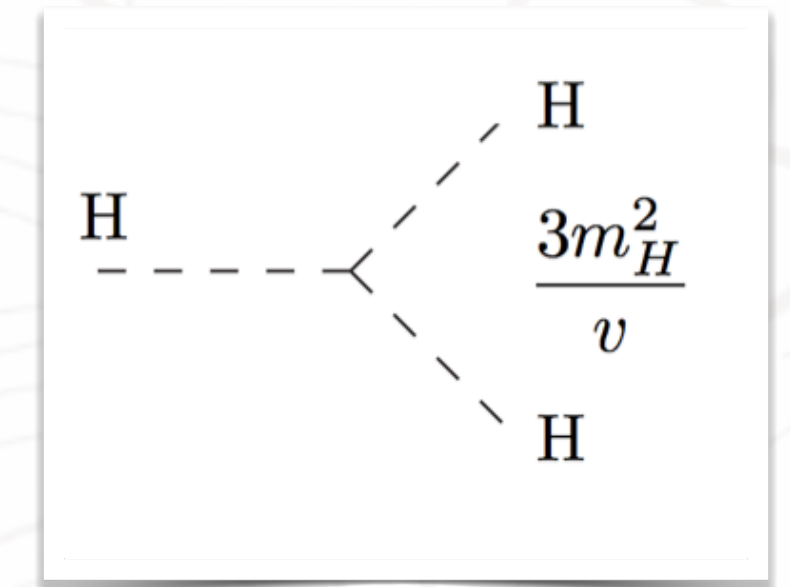


$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$V = V_0 + \frac{m_H^2}{2} h^2 + \lambda_3 \nu h^3 + \frac{1}{4} \lambda_4 h^4 - \frac{\lambda_4}{4}$$

$$\lambda_{SM} = m_H^2 / 2v^2 \approx 0.13$$

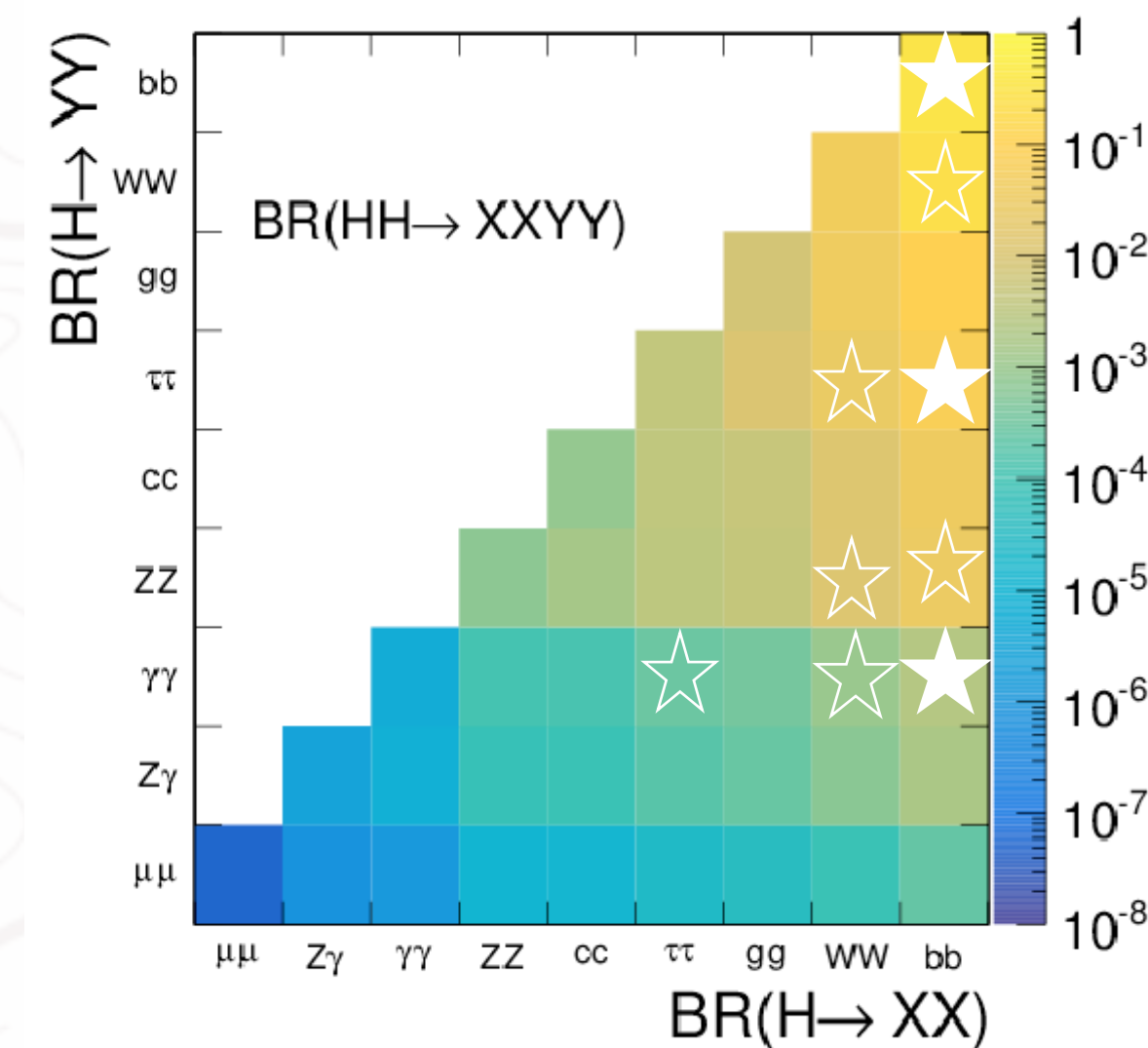
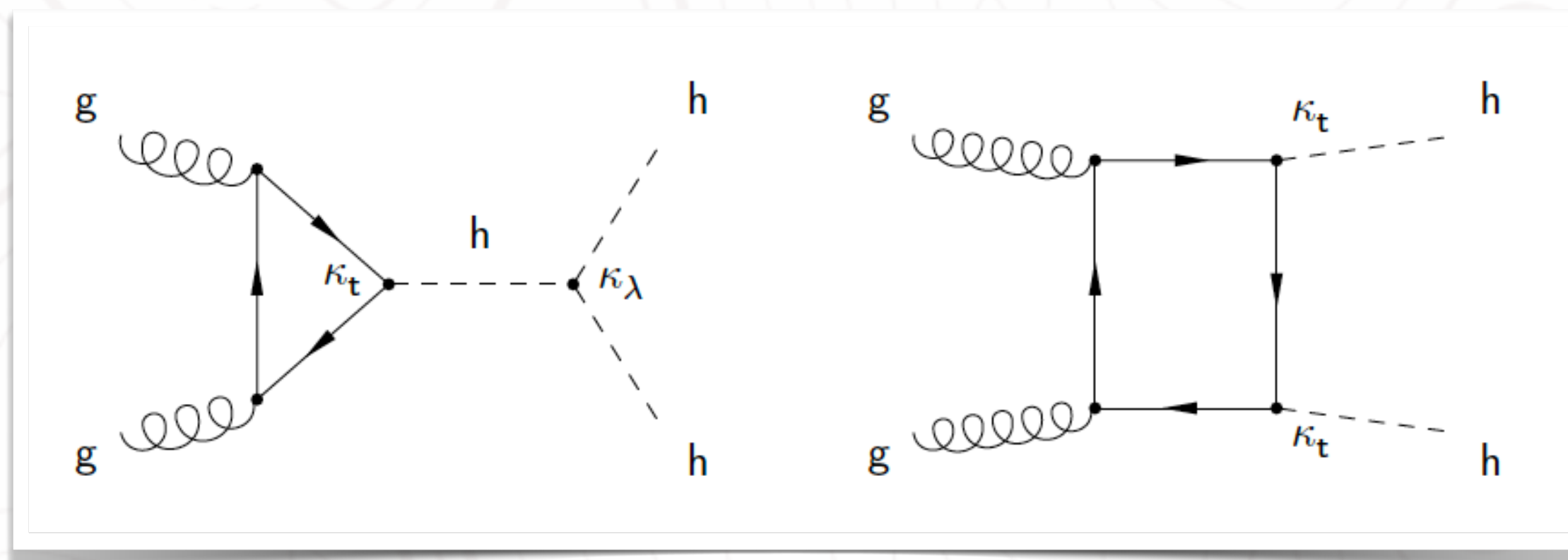
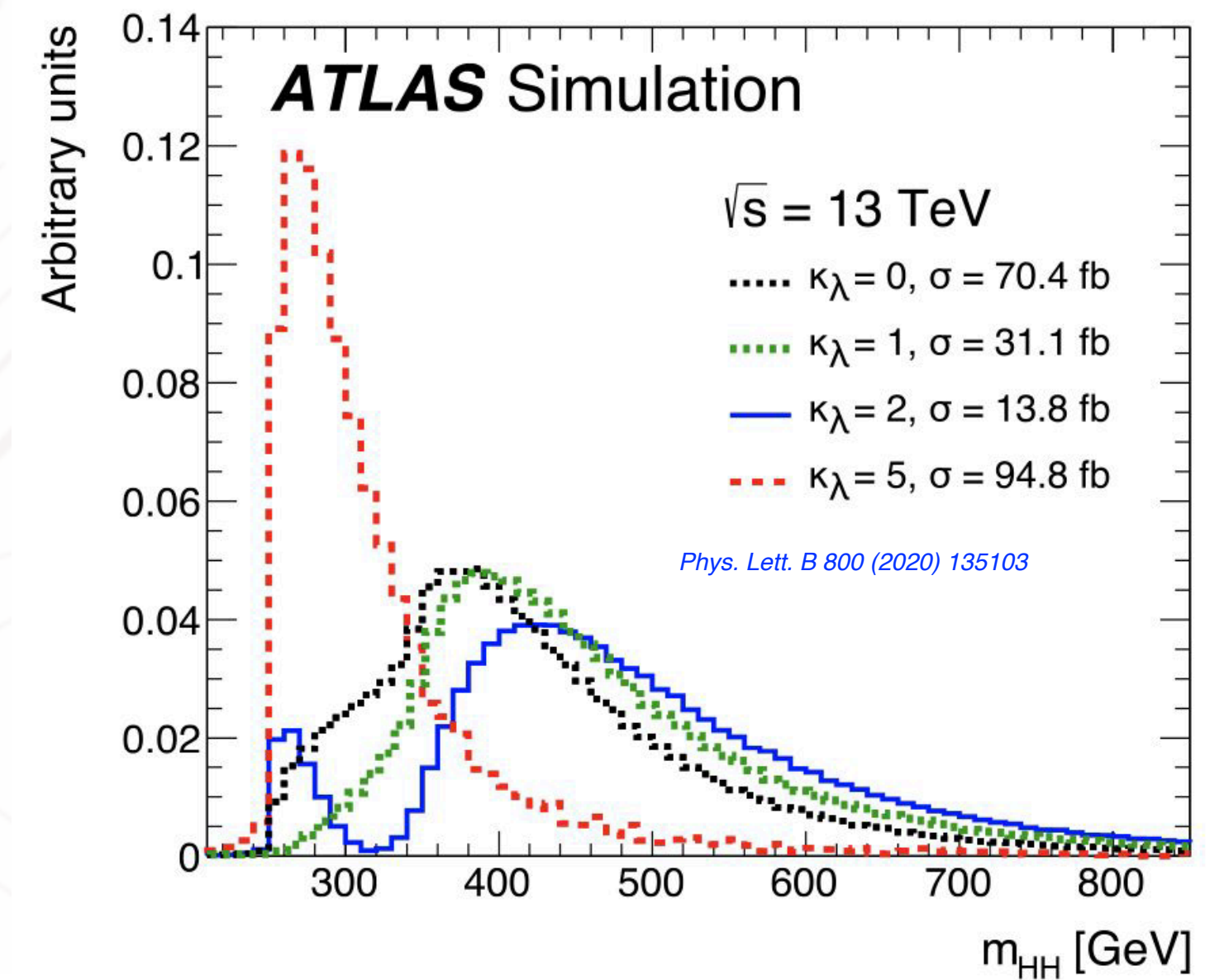
$$\kappa_\lambda = \lambda / \lambda_{SM}$$



One of the key objectives for the LHC: narrowing down our understanding of the Higgs Potential through the search for HH production

LOOKING FOR HIGGS BOSON PAIRS

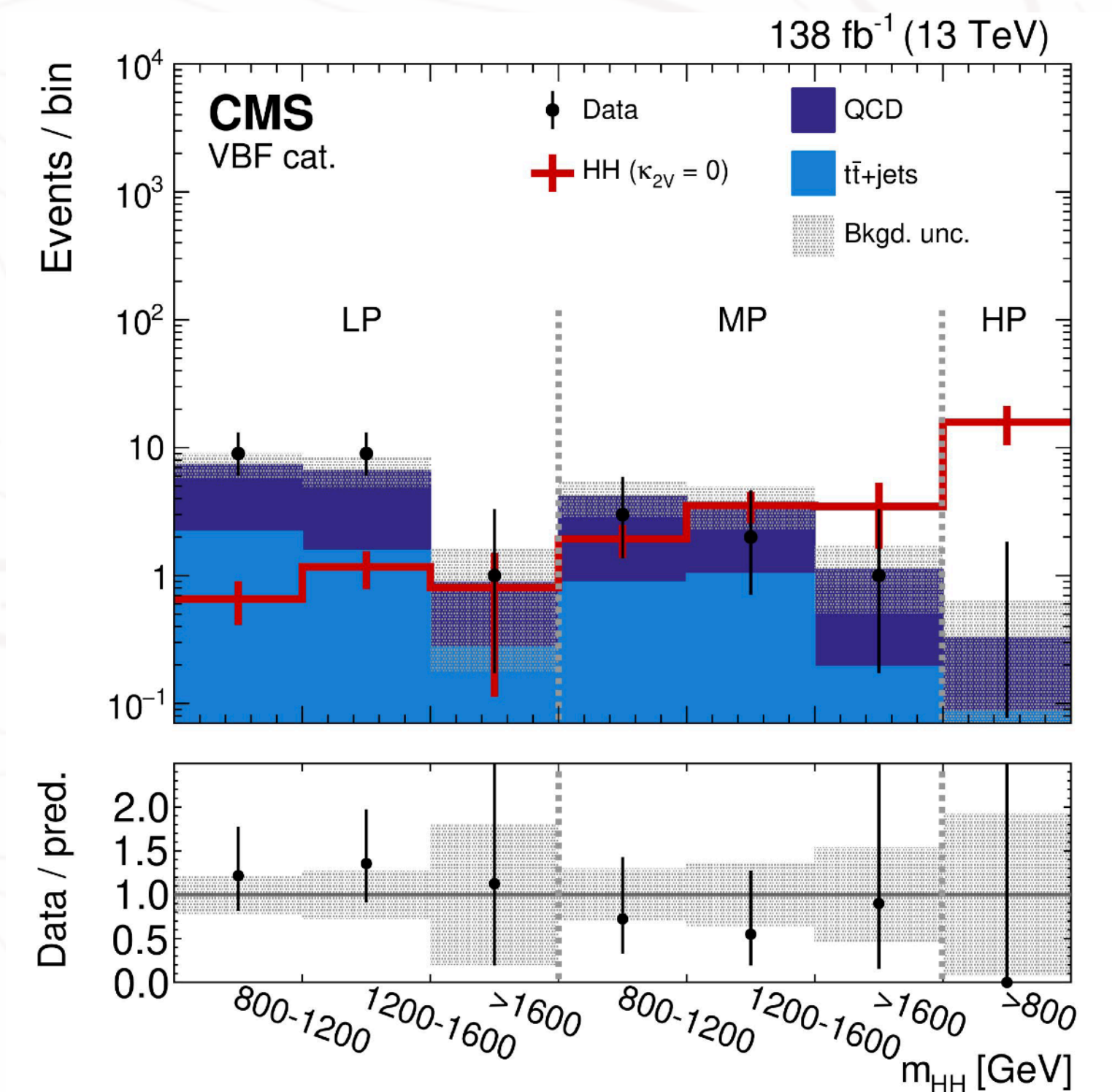
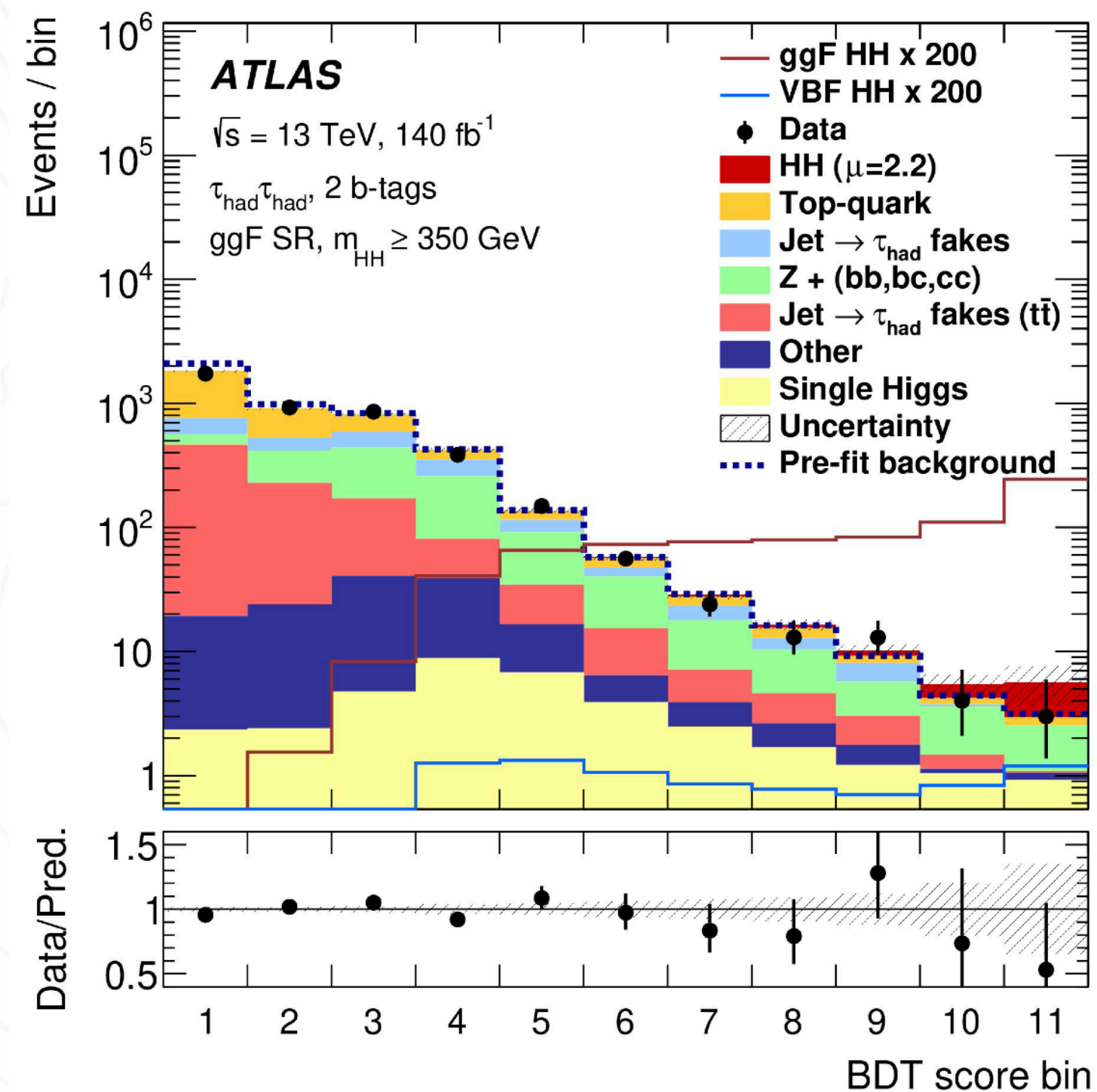
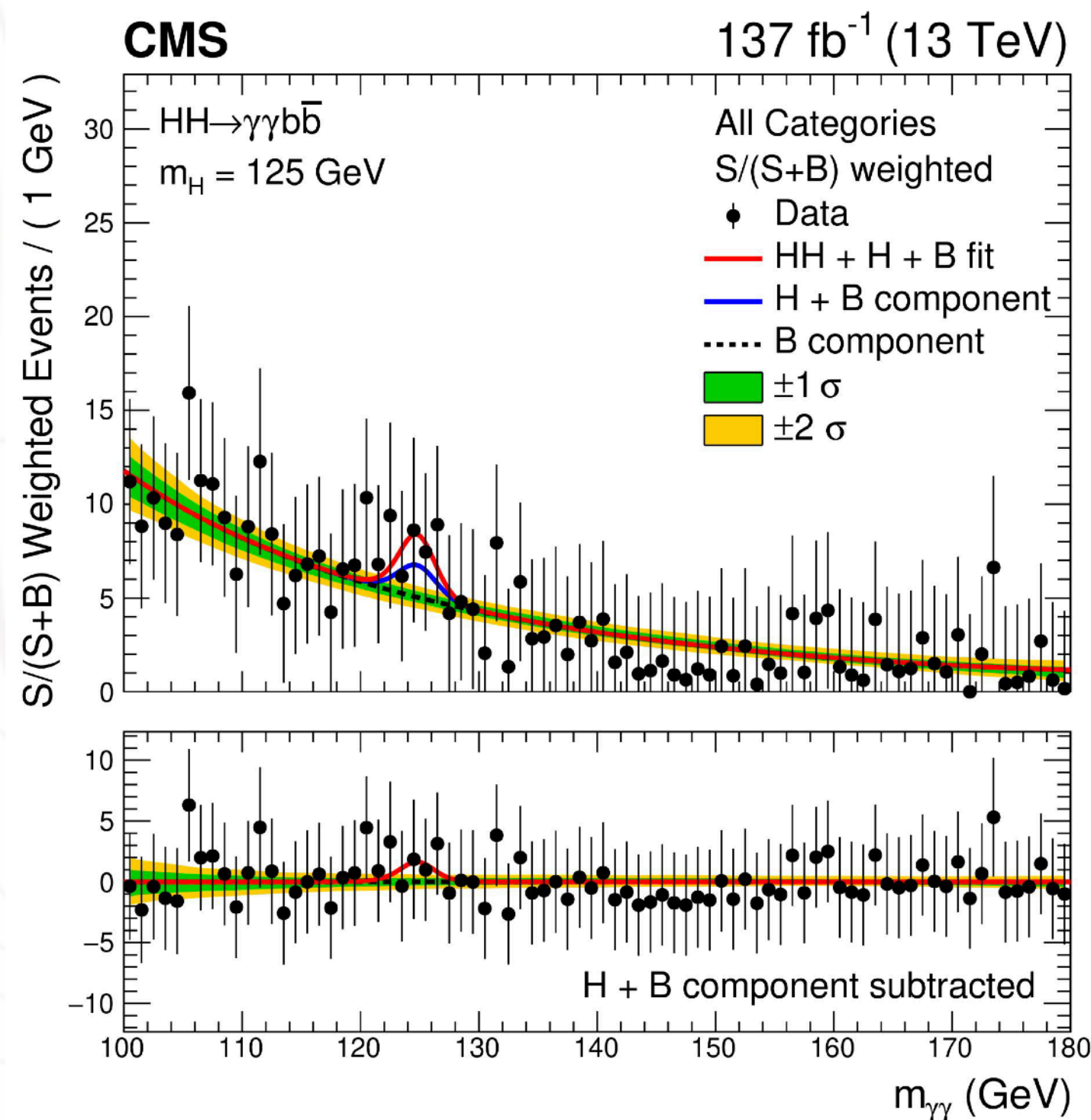
- Simplest way to access the self coupling at LHC: through the production of Higgs boson pairs
- Easiest does not mean easy! **Tiny cross section** ($\sigma \sim 31 \text{ fb@13TeV}$): destructive interference between triangle and box diagrams
- **Sensitive to new physics**: *Small* changes of the couplings can lead to *large* changes in production



Sensitivity driven by $bb\gamma\gamma$, $bb\tau\tau$, $4b$

'GOLDEN' CHANNELS

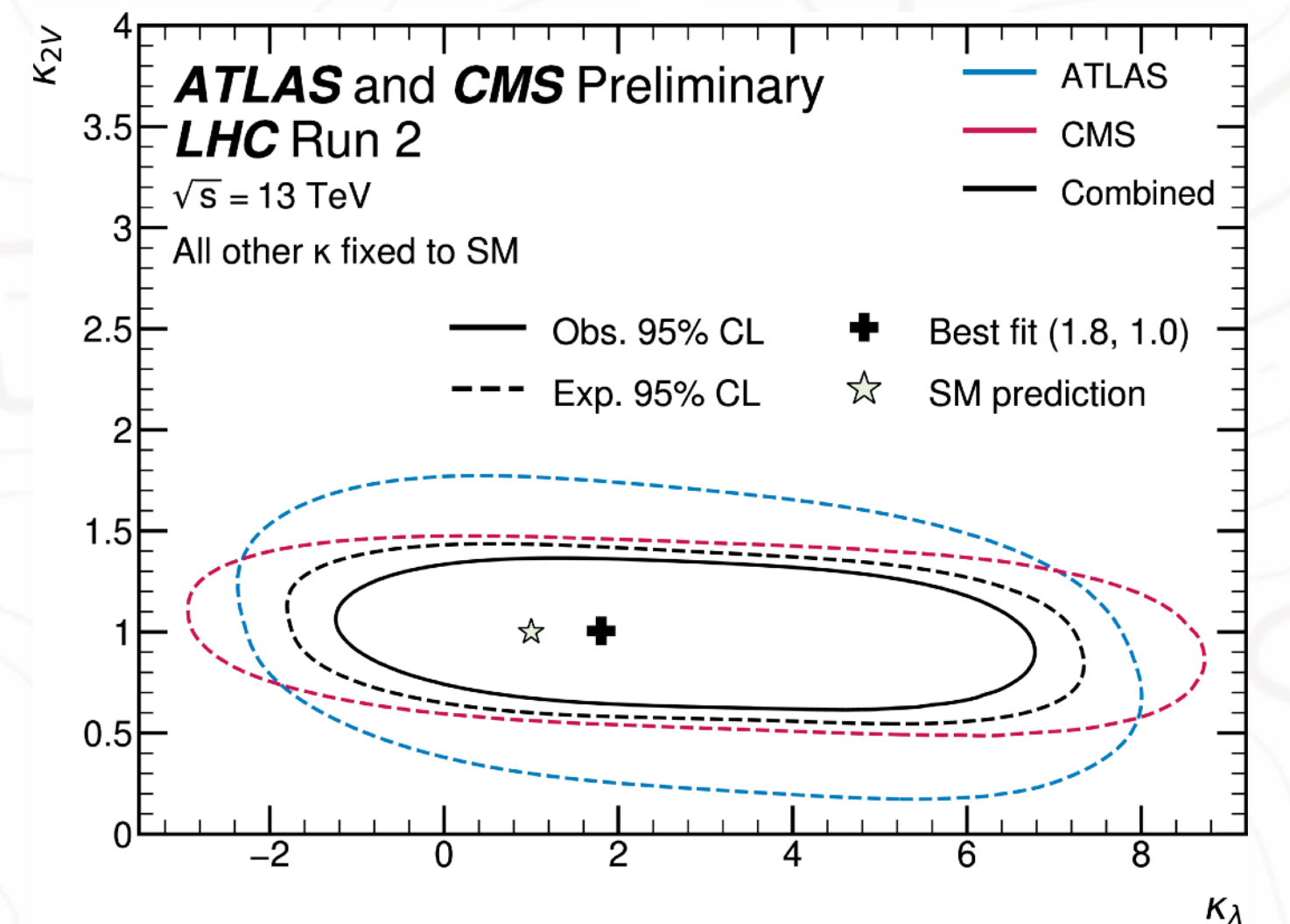
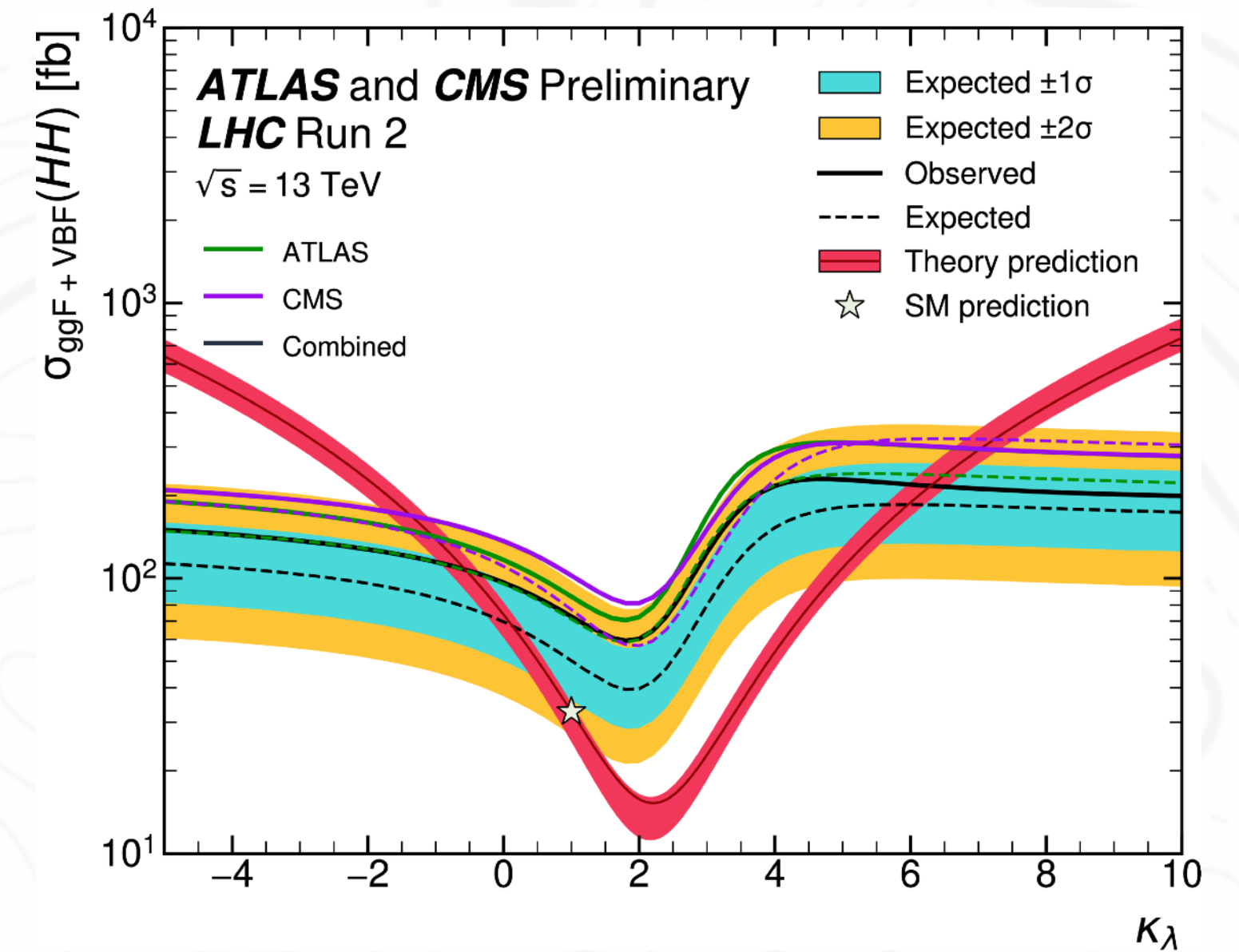
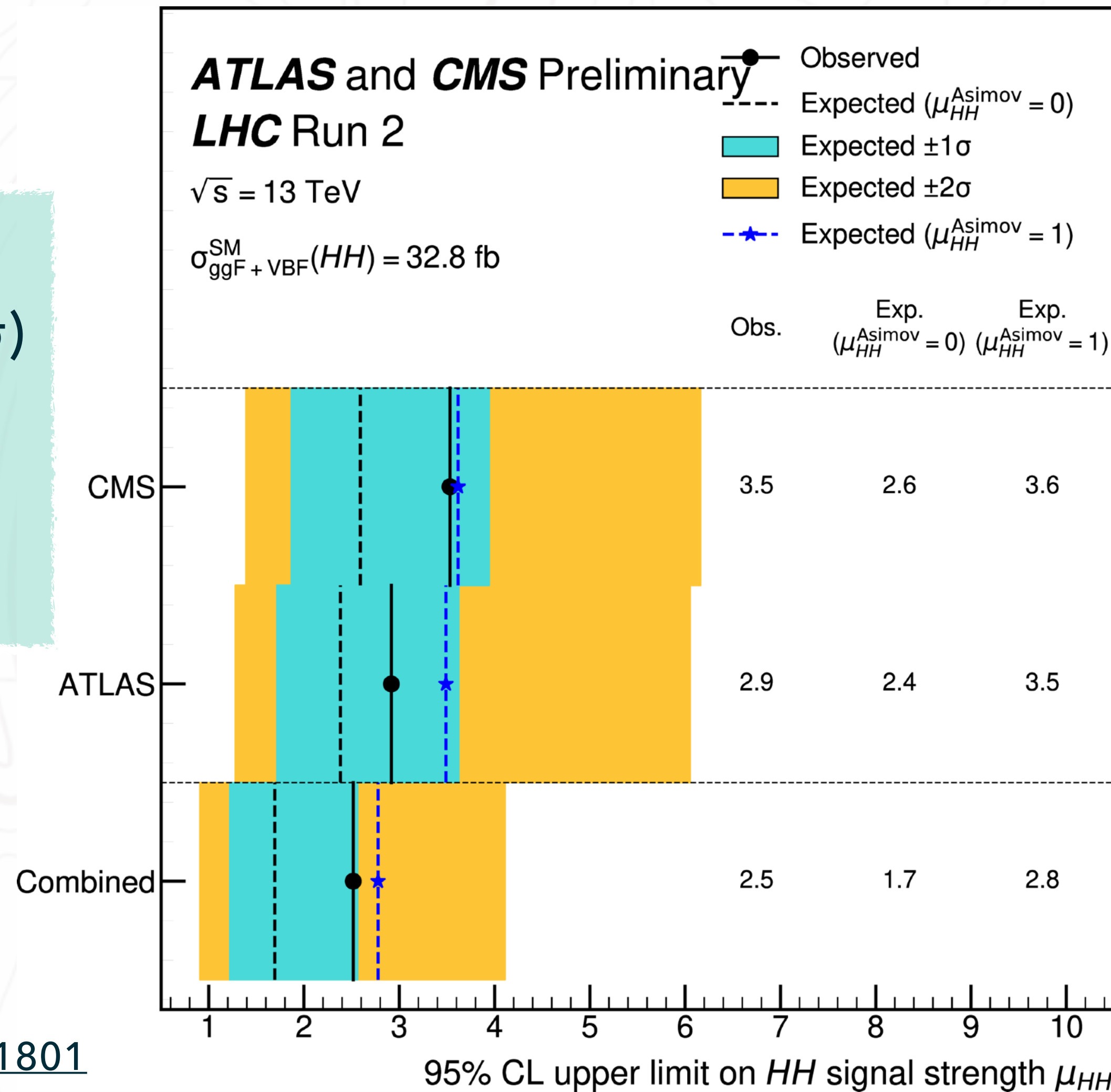
- To study HH production we apply the tools perfected in single Higgs analysis... and more
- Elaborated selection algorithms and categorization, background modeling (and here single Higgs is a background!), heavy use of ML techniques, boosted techniques to zoom in complicated phase spaces...
- Three main channels which exploit high Hbb branching ratio lead the sensitivity



WHERE ARE WE? FIRST LHC HH COMBINATION

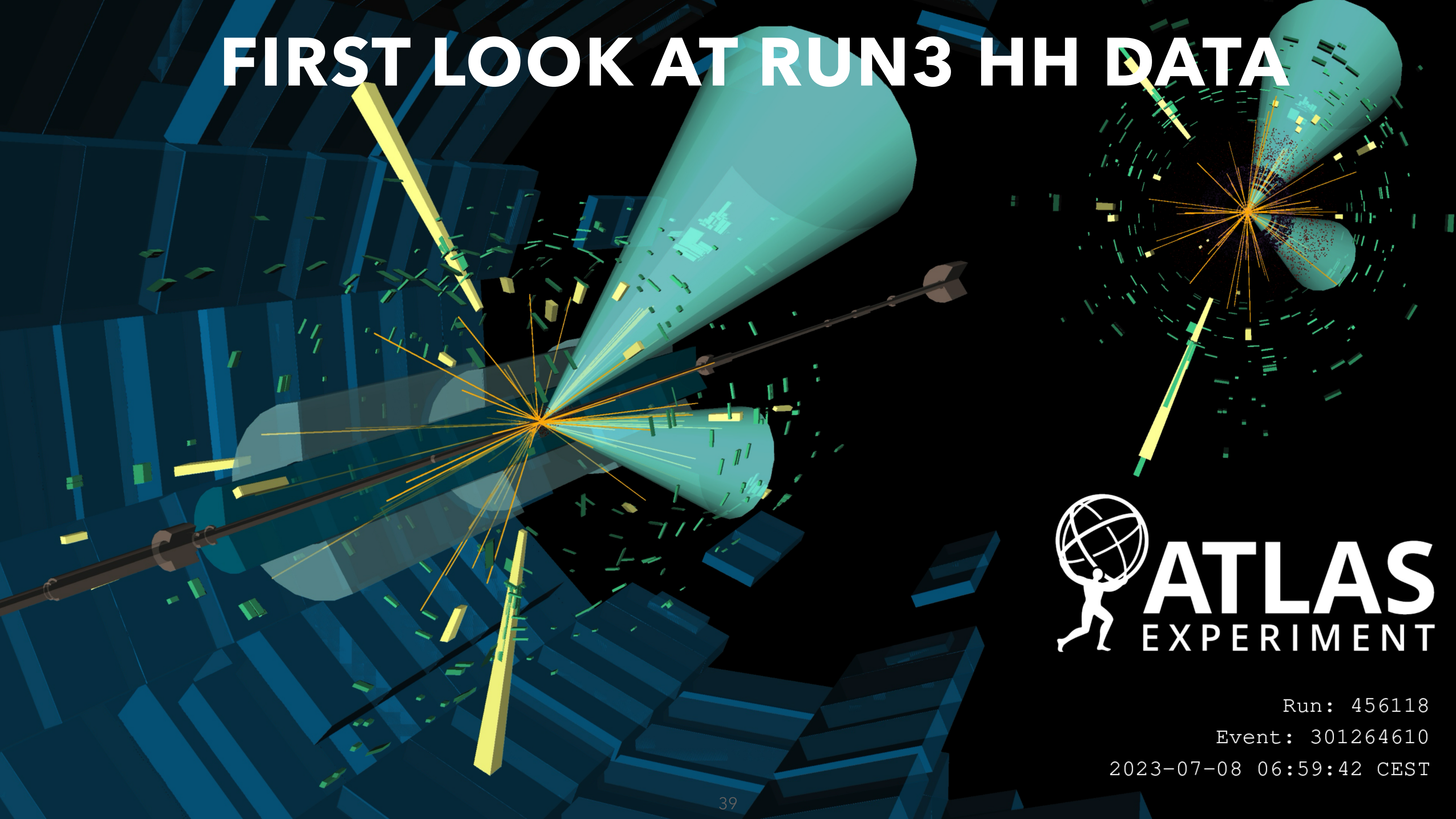
$\mu_{HH} < 2.5 @ 95\% CL$
 $\langle \mu_{HH} \rangle = 0.8^{+0.9}_{-0.7} (1.1 \sigma)$

$-0.71 < \kappa_\lambda < 6.1$
 $0.73 < \kappa_{2V} < 1.3$



ATLAS Run2: [PRL 133 \(2024\) 101801](#)
 CMS Run2: [CMS-HIG-20-011 \(submitted\)](#)
 ATLAS+CMS Conf Note: [CMS-HIG-25-014](#)

FIRST LOOK AT RUN3 HH DATA



ATLAS
EXPERIMENT

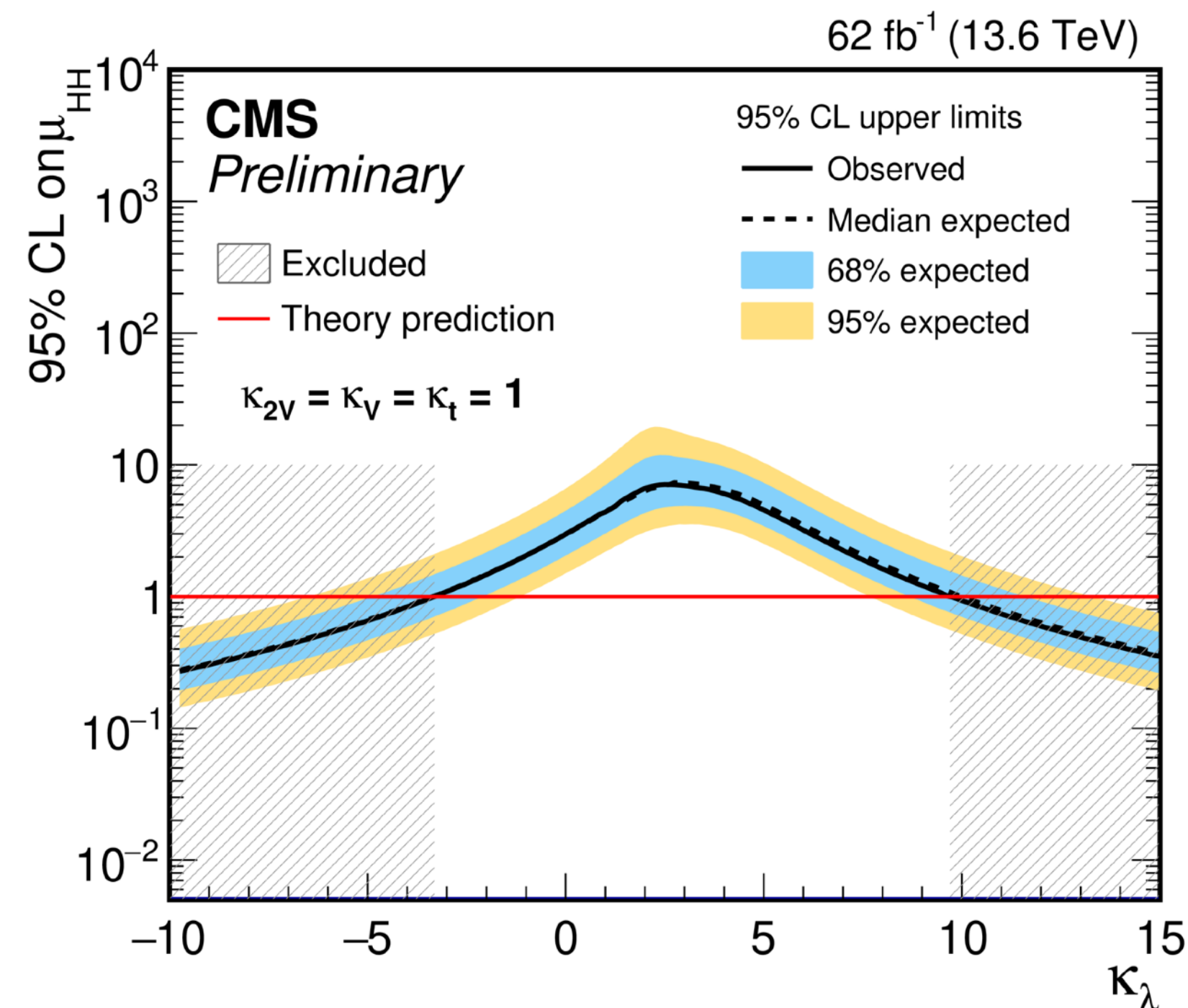
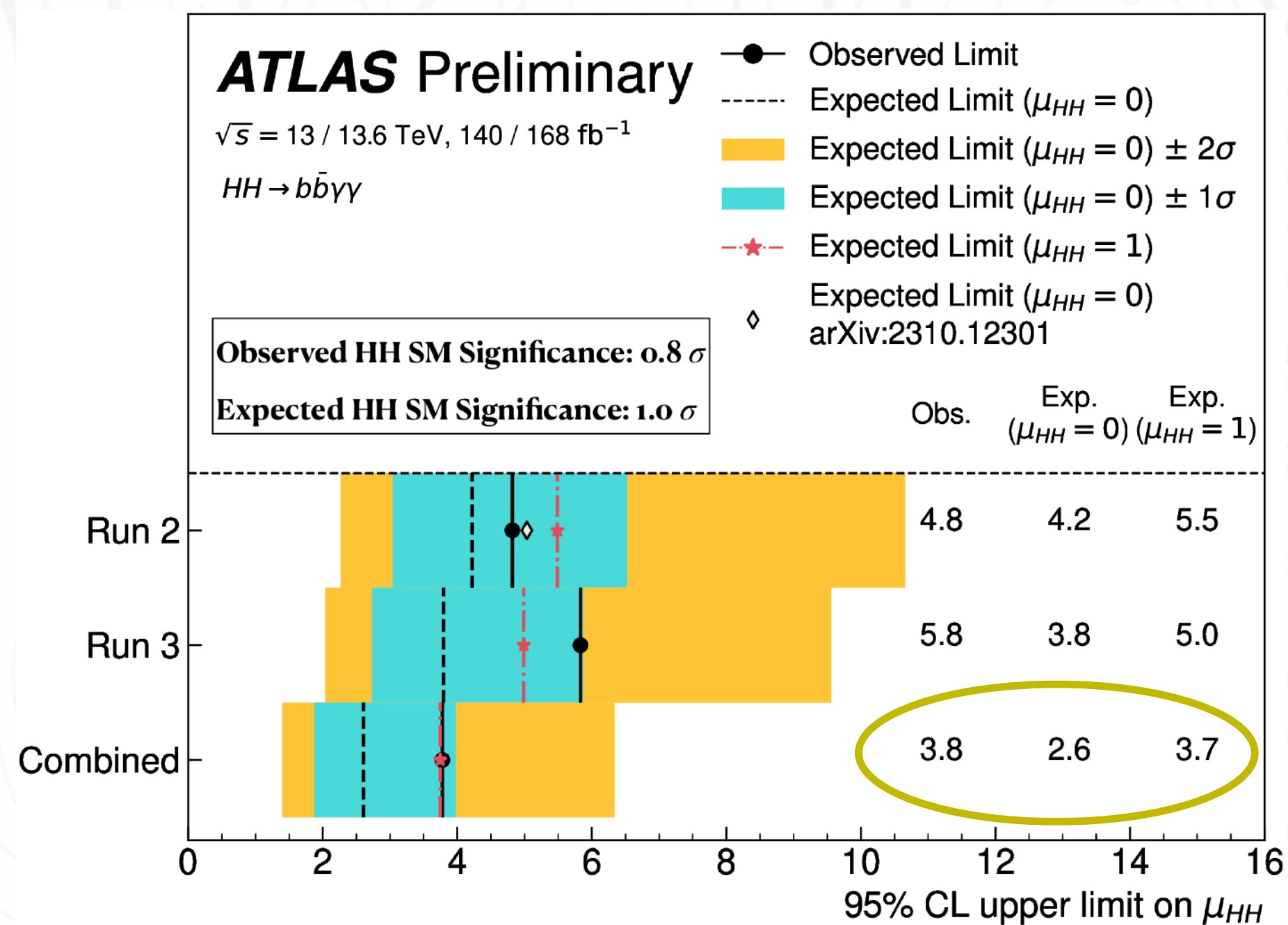
Run: 456118

Event: 301264610

2023-07-08 06:59:42 CEST

FIRST LOOK AT RUN3 HH DATA

- Exploiting the new statistics, but not only!
- New analysis techniques (improved object identification, new ML techniques for signal extraction, new triggers specifically targeting HH production...): huge potential to be untapped.
- Single channels in Run3 approach full Run2 combination in sensitivity



First analyses to arrive :

- 2b2 γ : [ATLAS-HIGP-2025-10](#), [CMS HIG-25-007](#)
- 4b: [CMS HIG-24-010](#)
- 2b2W: [CMS-HIG-25-018](#).

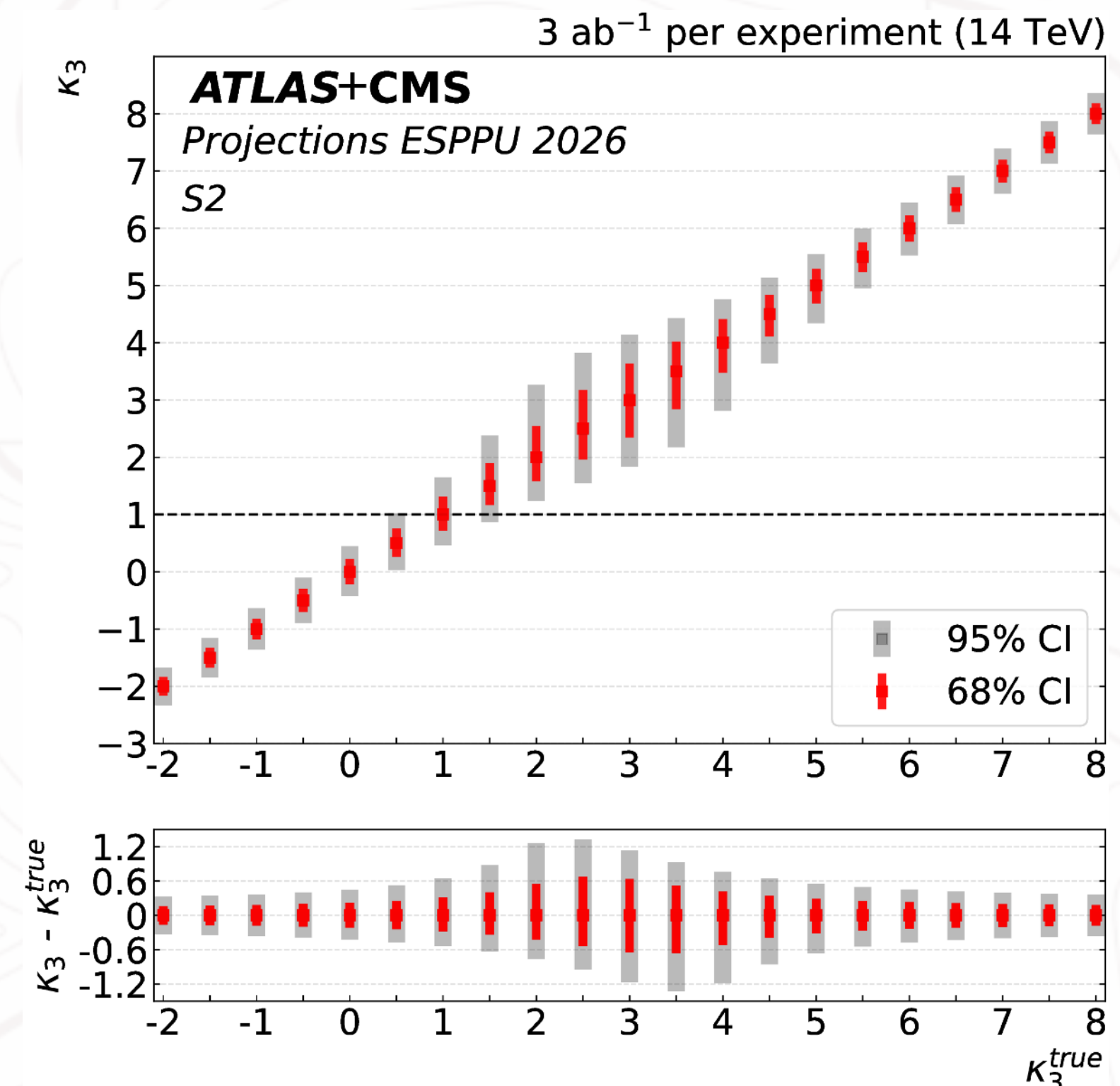
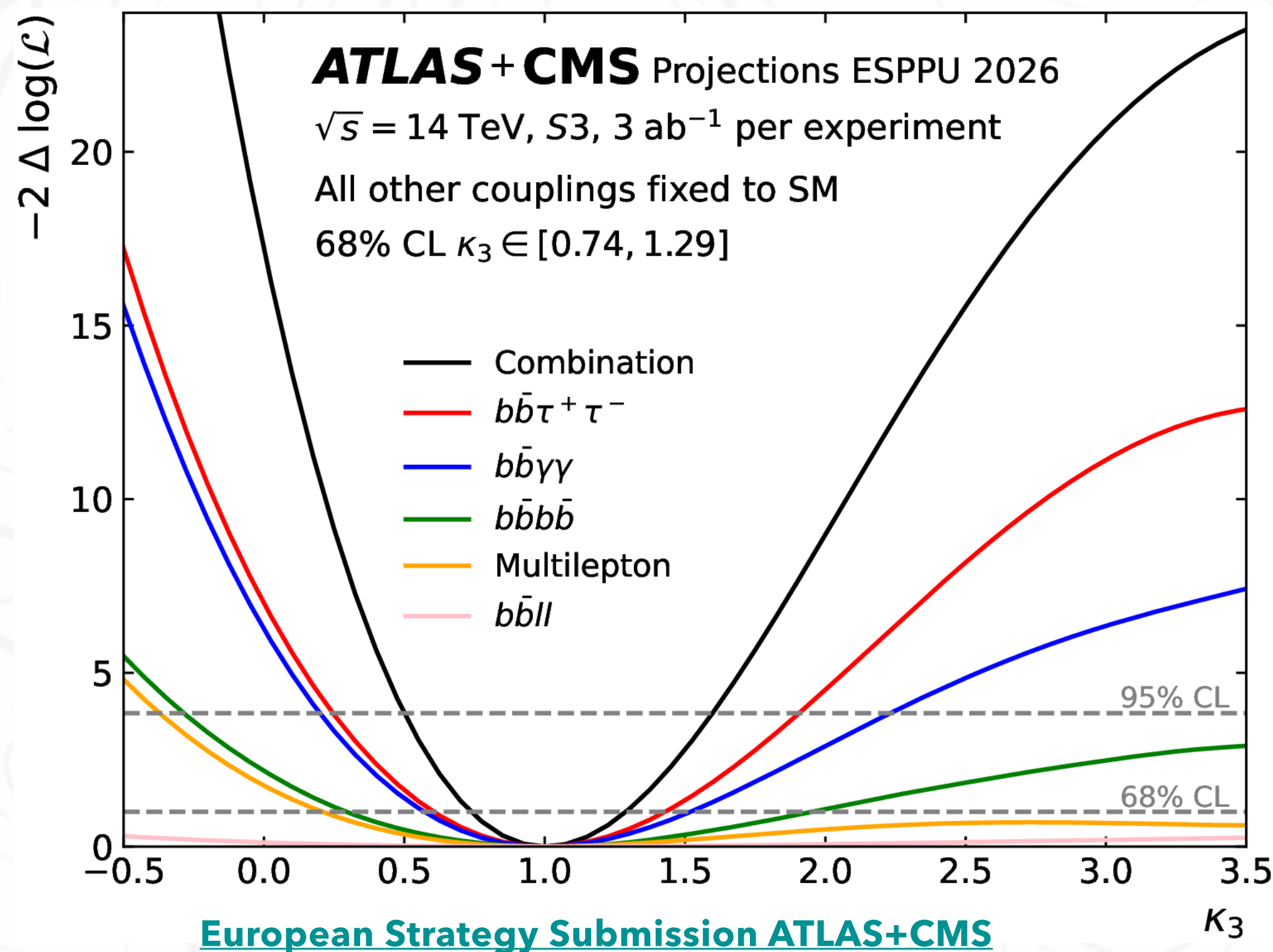
Many more soon!

EXCEEDING EXPECTATIONS

- When discussing HH we look forward to future runs - remembering that analysis outpace the projections!

▪ **Observation in combination already at 2 ab⁻¹**

▪ **Over 4 sigmas per experiment at 3 ab⁻¹** $\kappa_\lambda \sim 1.0^{+0.29}_{-0.26}$ (3ab⁻¹, ATLAS + CMS)



 BSM?

HH AND THE HIGGS POTENTIAL

BOOSTED TOPOLOGIES

SECOND
GENERATION

EFT

RARE PRODUCTION
& DECAY

SM COUPLINGS

CROSS SECTIONS

YUKAWA
INTERACTIONS

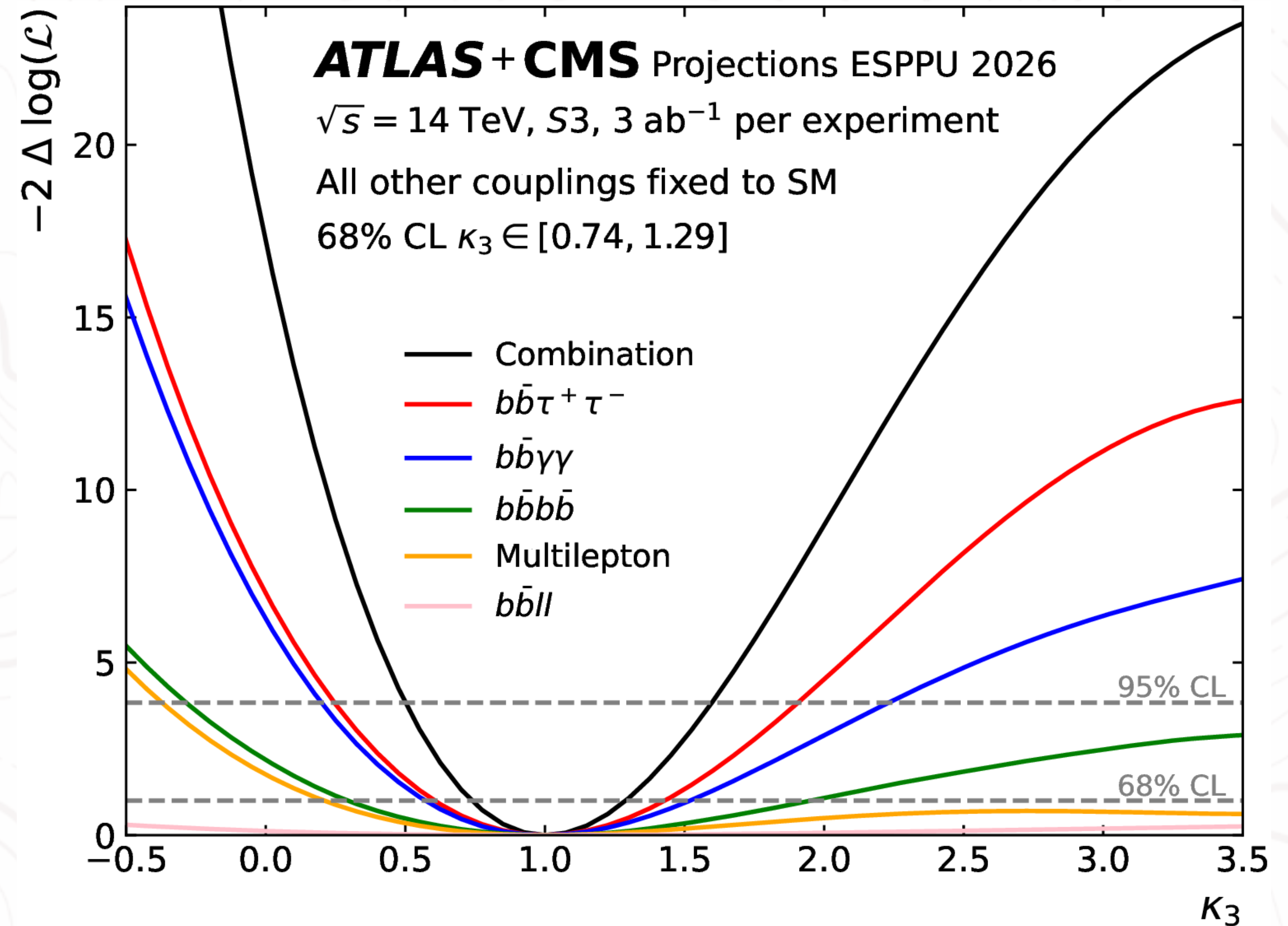
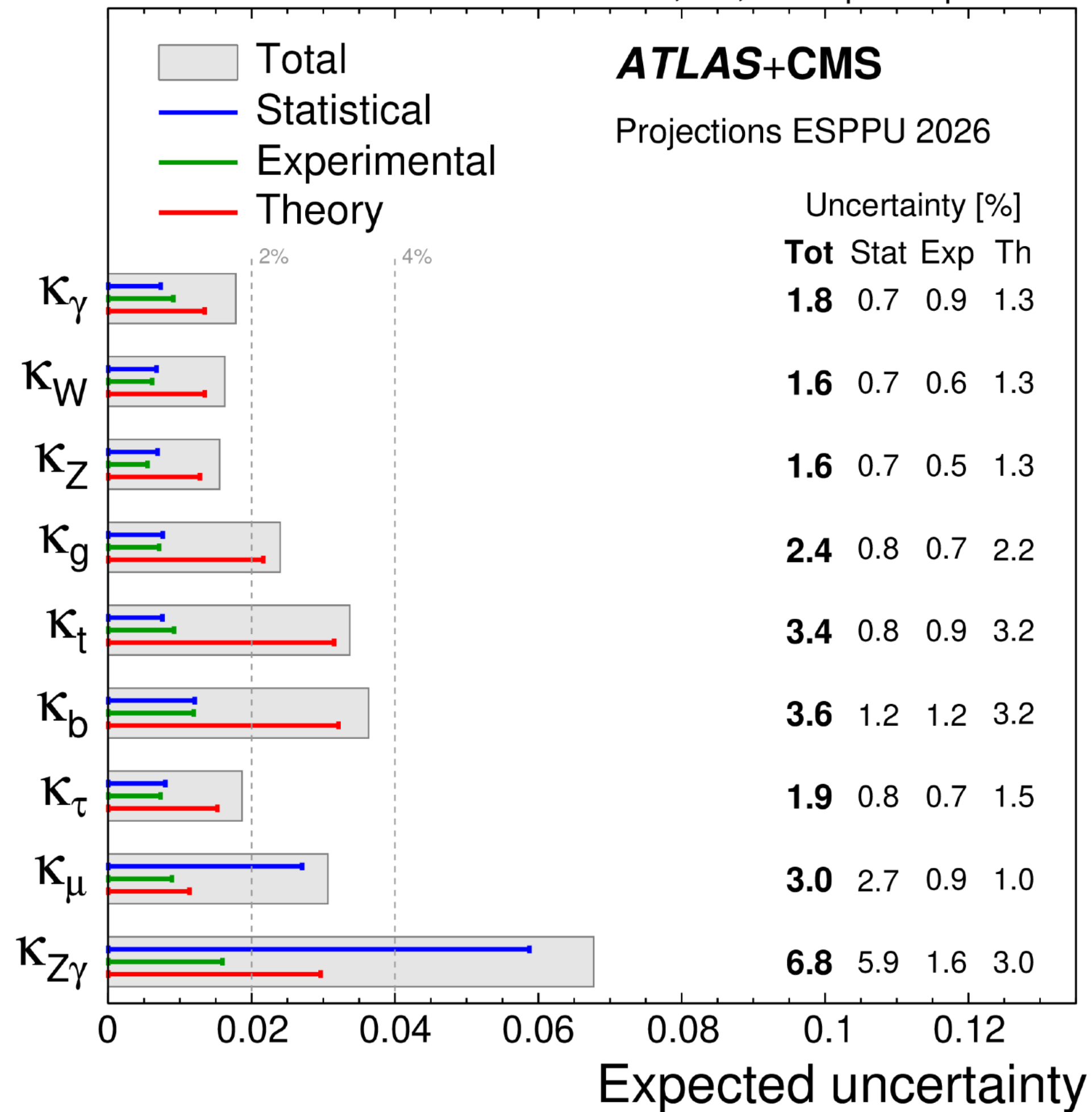
MASS, SPIN, ...

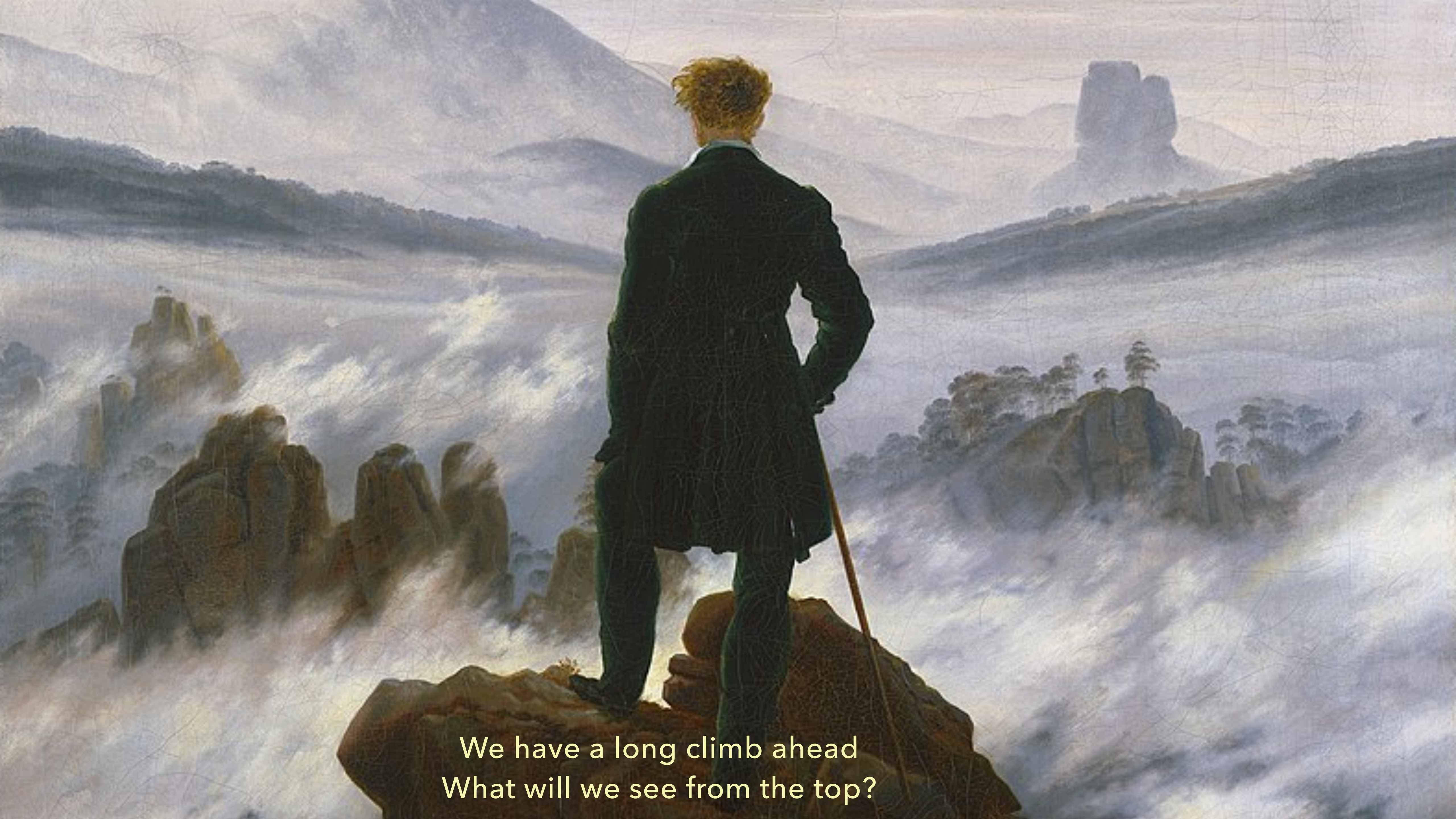
DISCOVERY

A JOURNEY INTO THE HIGGS SECTOR

AT THE END OF THE LHC ROAD...

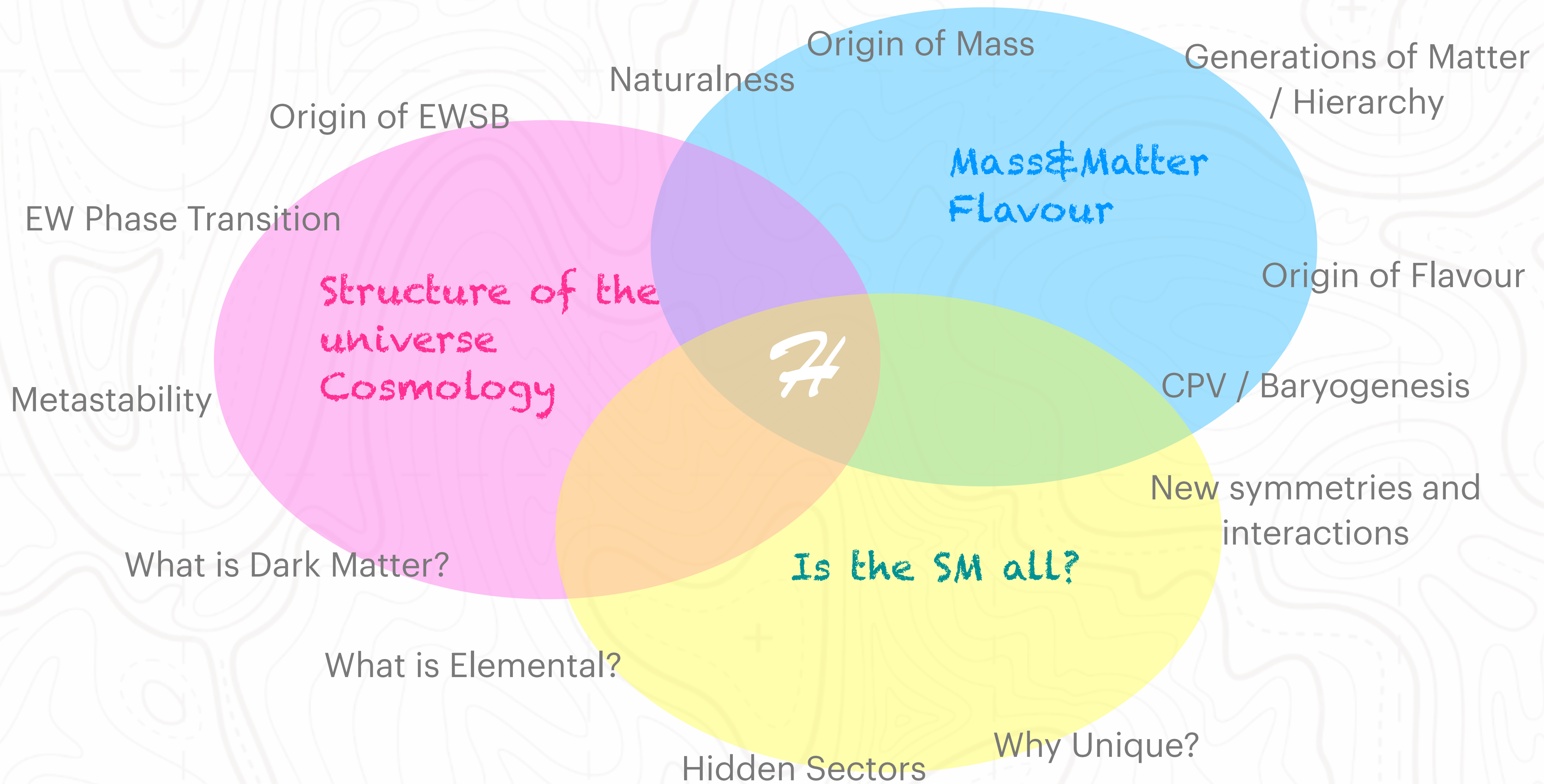
$\sqrt{s} = 14$ TeV, S2, 3 ab^{-1} per experiment





We have a long climb ahead
What will we see from the top?

KEYSTONE IN THE SM



TOWARDS HIGGS PRECISION

- The study of the Higgs boson is more alive than ever. The landscape has changed dramatically: from searches and discovery to really understanding its nature: the journey goes on. Today, it is **one of our best tools to discover new physics** (direct or indirectly).
- CMS and ATLAS have scrutinized the Run2 dataset, with a treasure of measurements of its properties. Run3 results are underway.
- To go beyond our current results both experiments are invested in ML developments in tagging, reconstruction, and inference: improving sensitivity way beyond statistics
- With one Higgs at hand, the next big challenge is finding two. **Measuring the self-coupling and understanding the Higgs potential, the HL-LHC final frontier?**
- Beyond our current machine, the future is coming and we need to prepare for it. **Mapping the Higgs sector will be the legacy of the LHC, and a stepping stone for the next machines.**
More precision than what the LHC can provide is needed, and as we uncover uncharted territory more interesting questions will arise. The future looks bright for Higgs studies!



Generación de Conocimiento: PID2023-147706NB-I00, funded by MICIU/AEI/ 10.13039/501100011033 and FEDER, UE
Consolidación Investigadora 2023: CNS2023-144781 financiada por MICIU/AEI /10.13039/501100011033 and European Union NextGenerationEU/PRTR

WIDTH FROM OFF-SHELL/ON-SHELL

- Main channel: $H \rightarrow ZZ$

- [CMS PRD 111 \(2025\) 092014](#): $3.0^{+2.0}_{-1.5} \text{ MeV}$

- [ATLAS RPOP 88 057803](#): $4.3^{+2.7}_{-1.9} \text{ MeV}$

- Evidence for off shell production

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(m_{ZZ}^2 - m_H^2)^2 + m_H^2 \Gamma_H^2}$$

$$\sigma_{gg \rightarrow H \rightarrow ZZ}^{\text{on-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{m_H \Gamma_H} \quad \text{and} \quad \sigma_{gg \rightarrow H^* \rightarrow ZZ}^{\text{off-shell}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{(2m_Z)^2}$$

$m_{ZZ} \sim m_H$ (On-shell production) $m_{ZZ} > m_{ZZ}$ (Off-shell production)

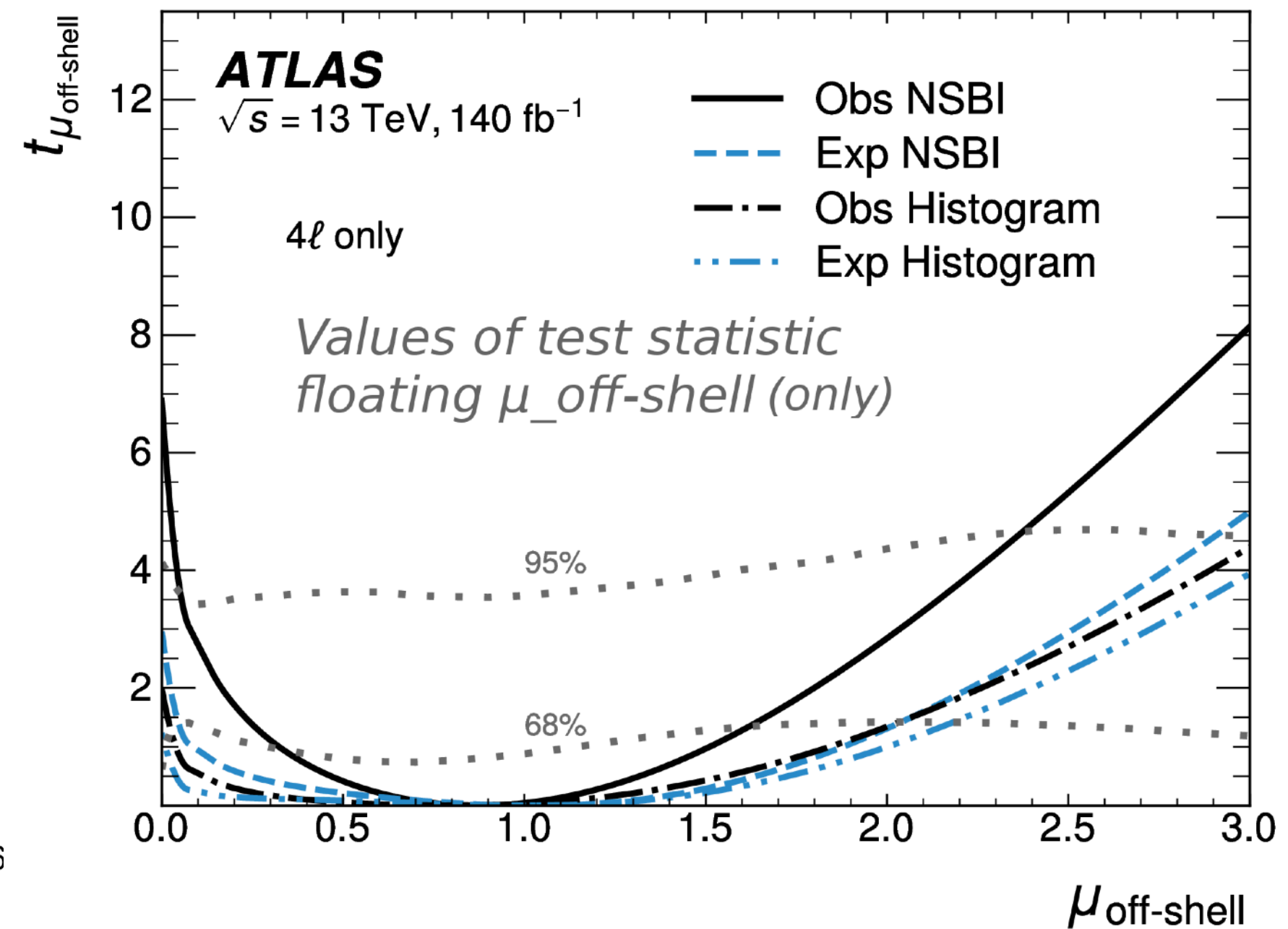
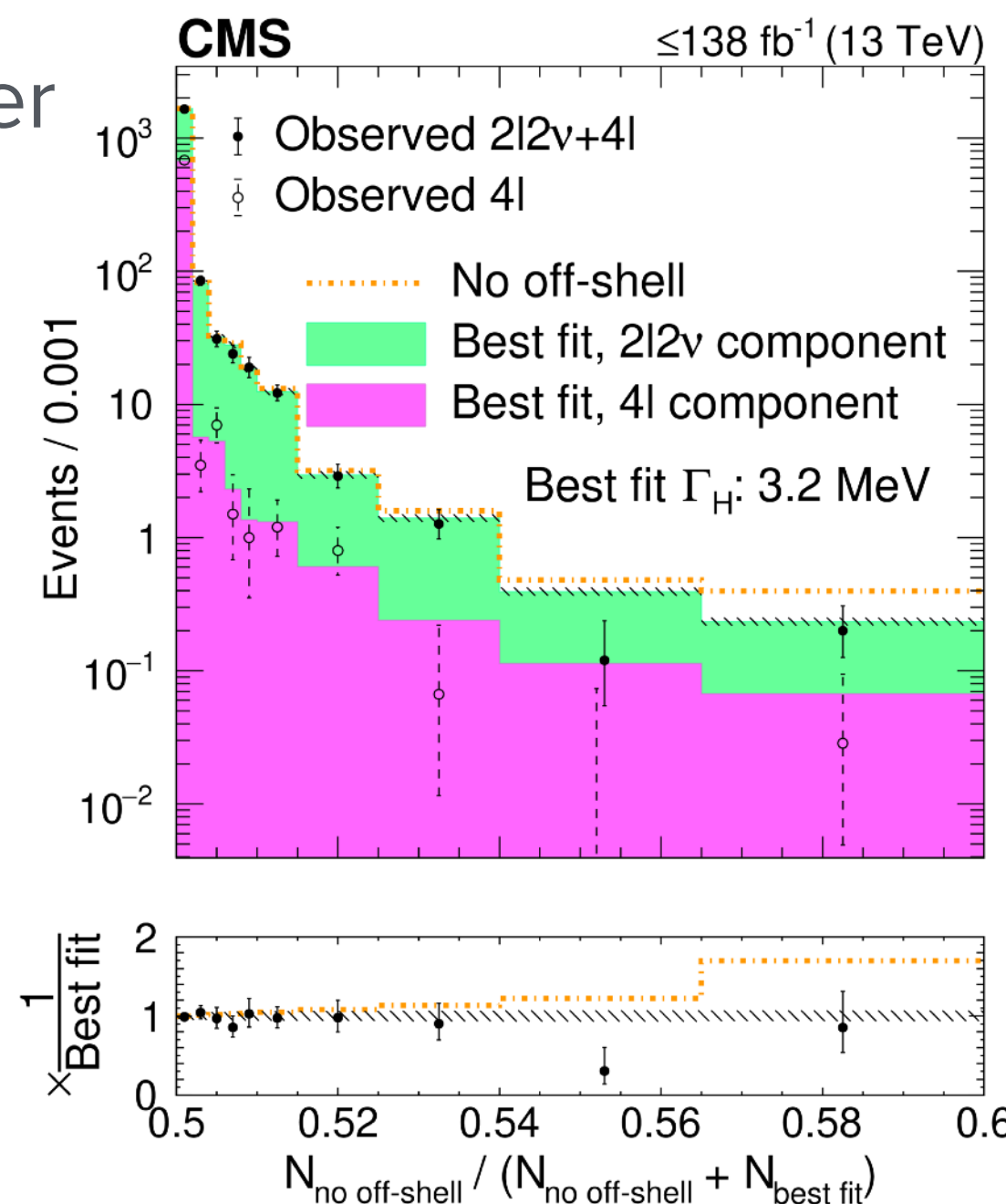
- Offshell/onshell idea can also be applied to other channels (only limits)

- HWW, ([ATLAS, arXiv:2504.07710](#)): $< 13.1 \text{ MeV}$ (95%CL)

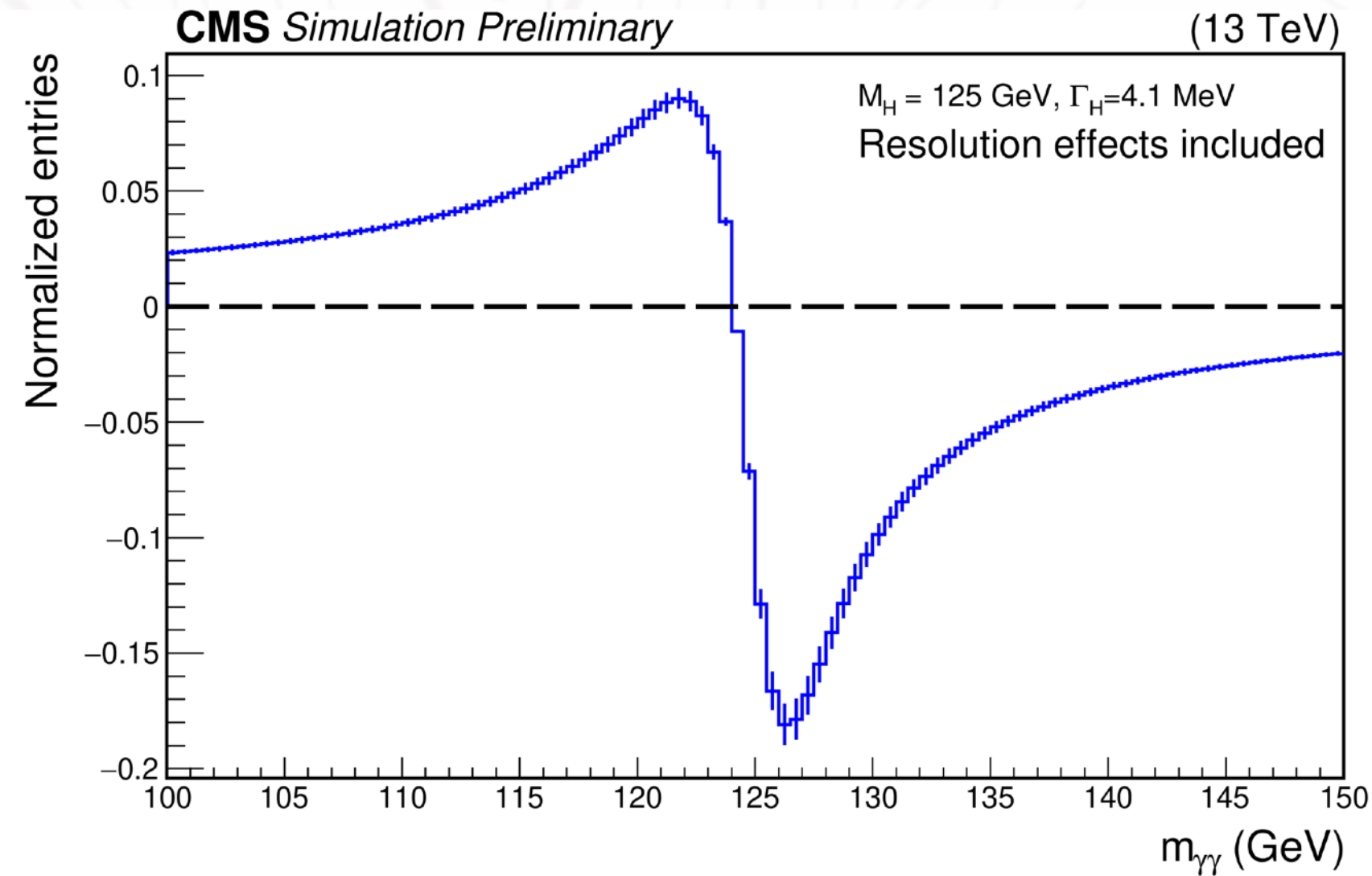
- HWW, ([CMS HIG-24-011](#)): $3.0^{+2.7}_{-2.2} \text{ MeV}$

- tttt and ttH ([ATLAS ATLAS PLB 861 \(2025\) 139277](#)): $< 450 \text{ MeV}$ (95%CL)

- Other methods to probe the width are less stringent, e.g., mass interference in gamma gamma channel



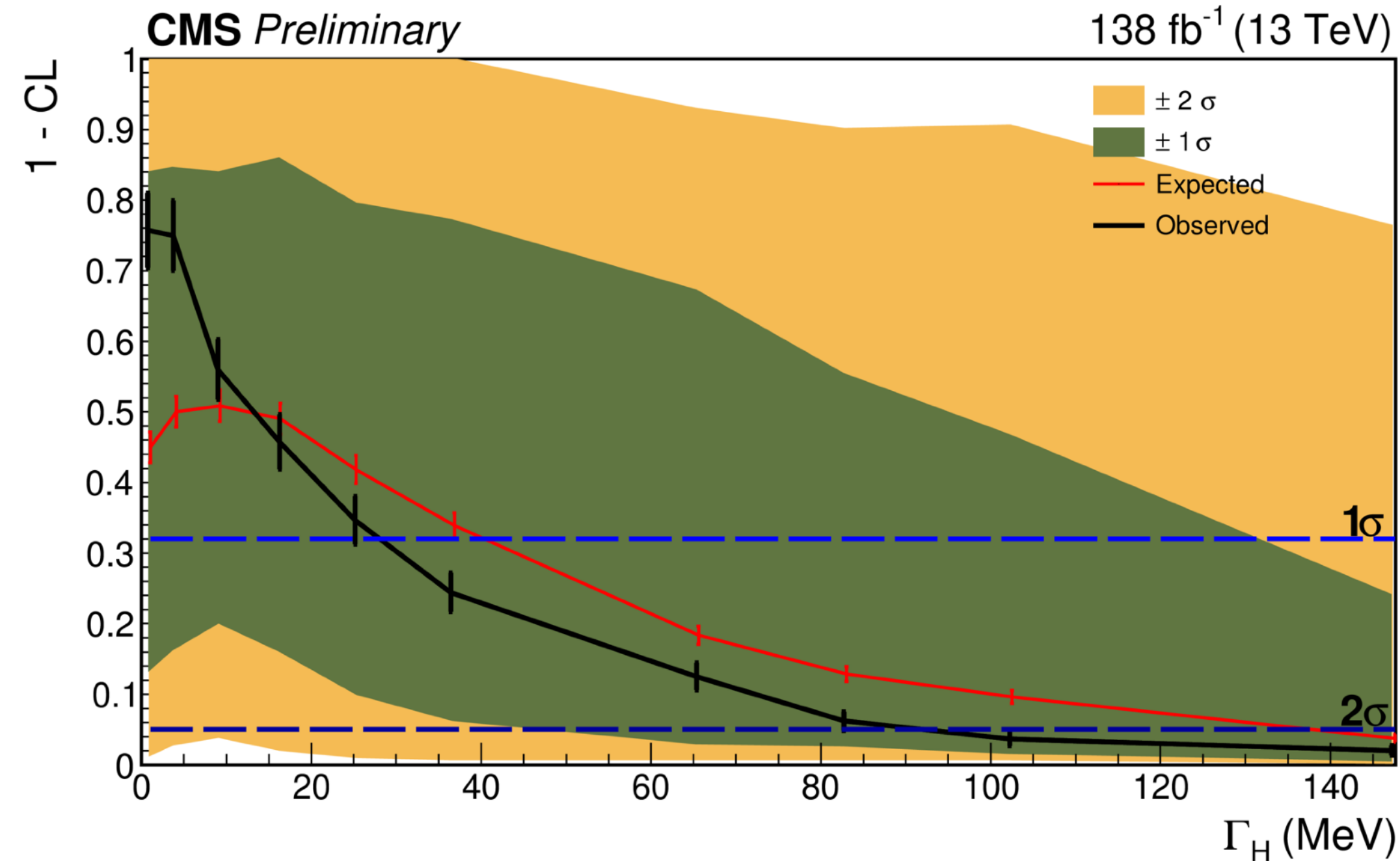
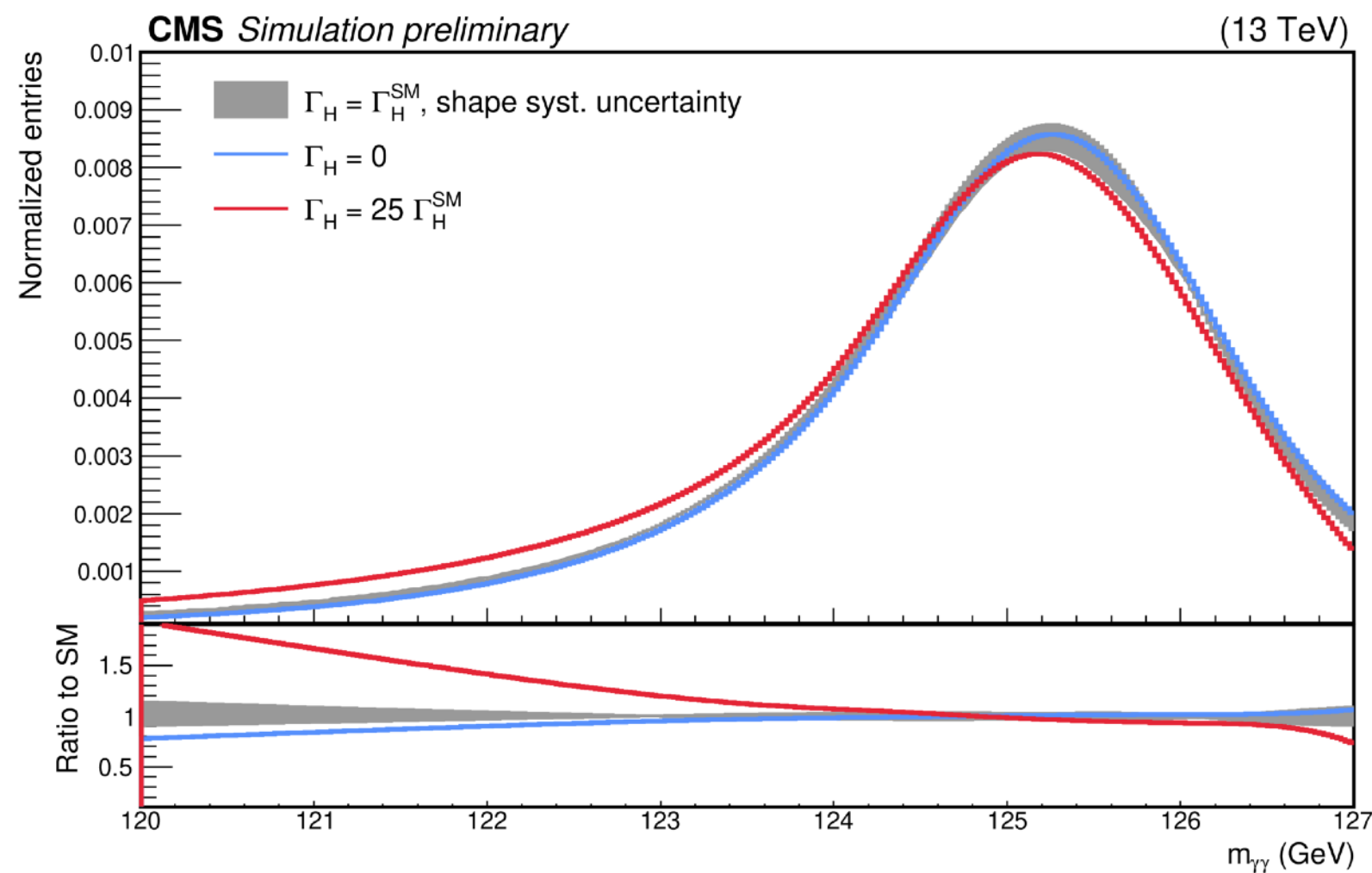
WIDTH FROM DIPHOTON INTERFERENCE



- Constraint on Γ_H from the diphoton mass through the interference between $gg \rightarrow H \rightarrow \gamma\gamma$ (aMC@NLO) and the QCD continuum $gg \rightarrow \gamma\gamma$ and $qg \rightarrow q\gamma\gamma$ (NLO sherpa)

$$c_{g\gamma} = \sqrt{\mu_F \Gamma_H / \Gamma_H^{SM}}$$

$$d\sigma/dm_{\gamma\gamma} = (\mu_{\gamma\gamma} - c_{g\gamma})S + c_{g\gamma}(S + I) + \sum_{i \neq gg} \mu_i S_i + B(m_{\gamma\gamma})$$

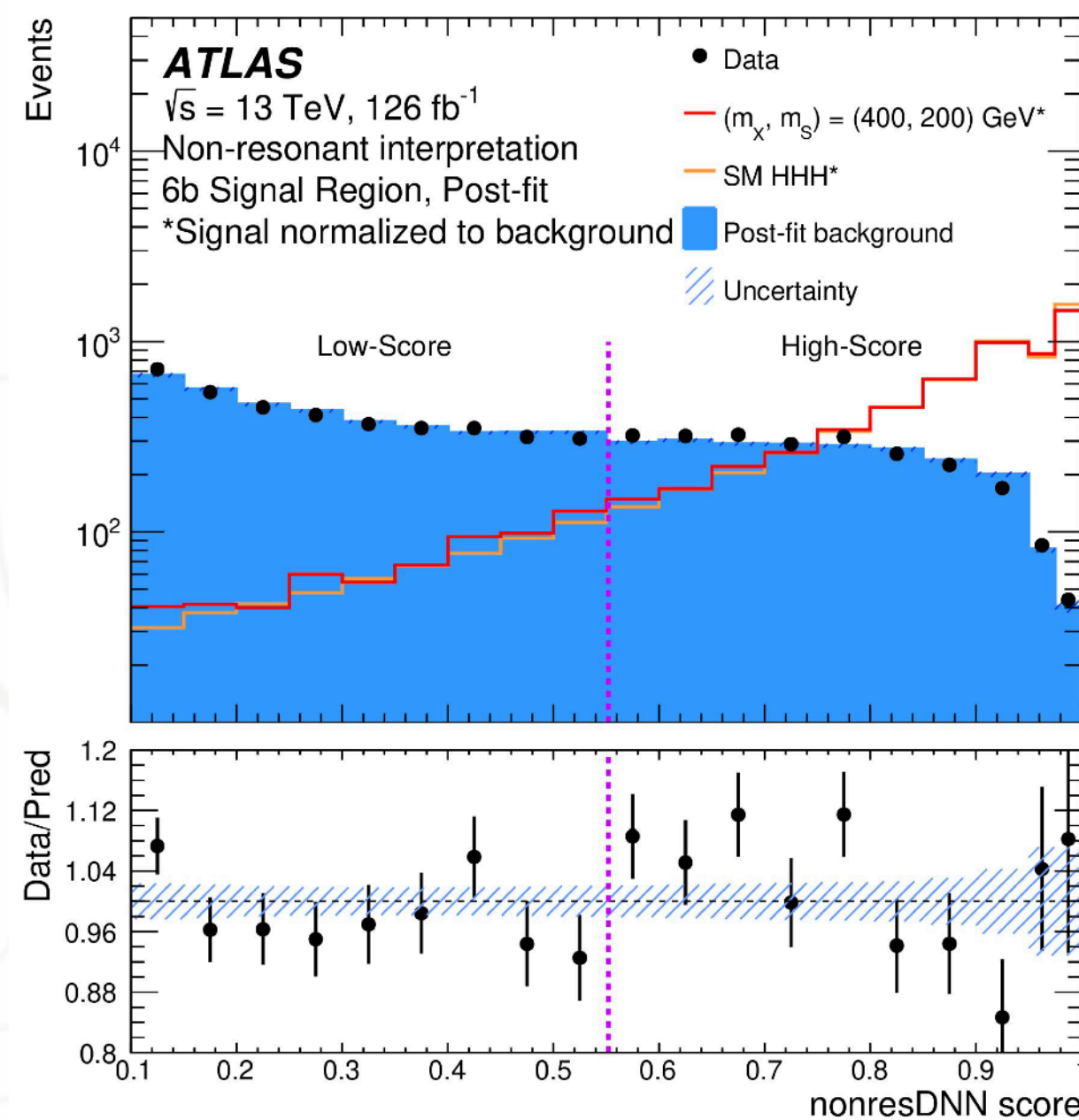
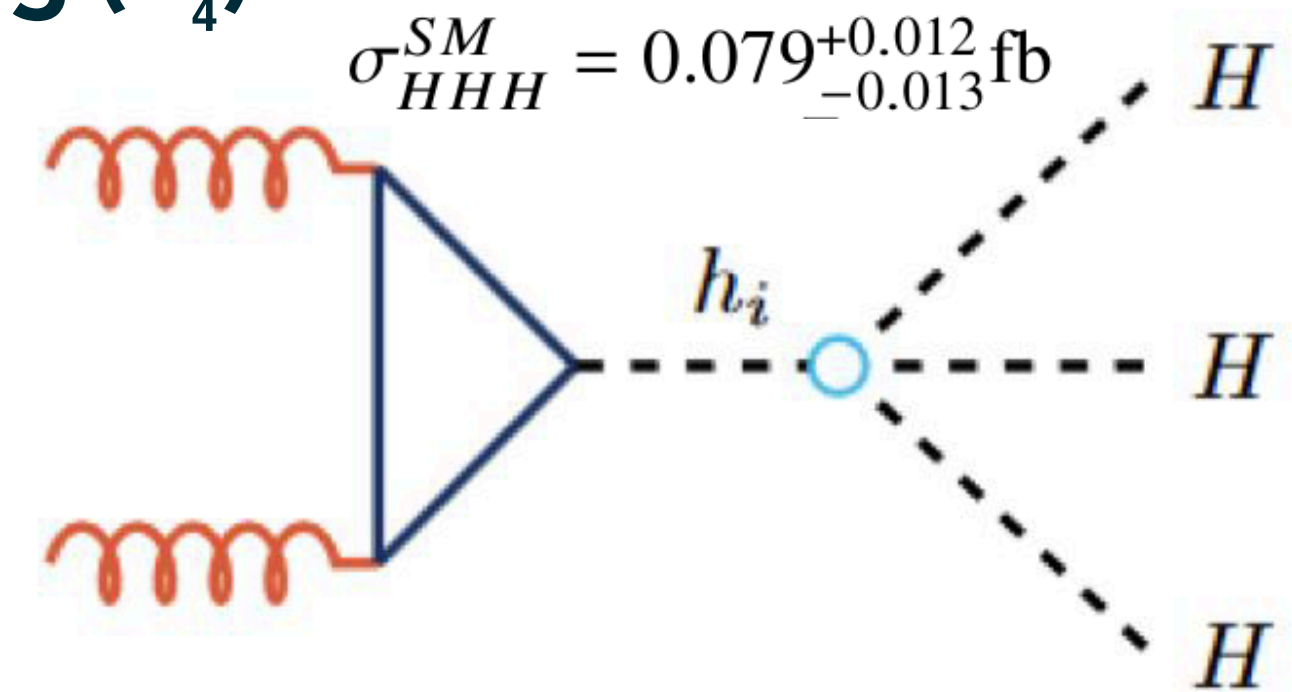


$\Gamma_H < 92(138) \text{ MeV}$

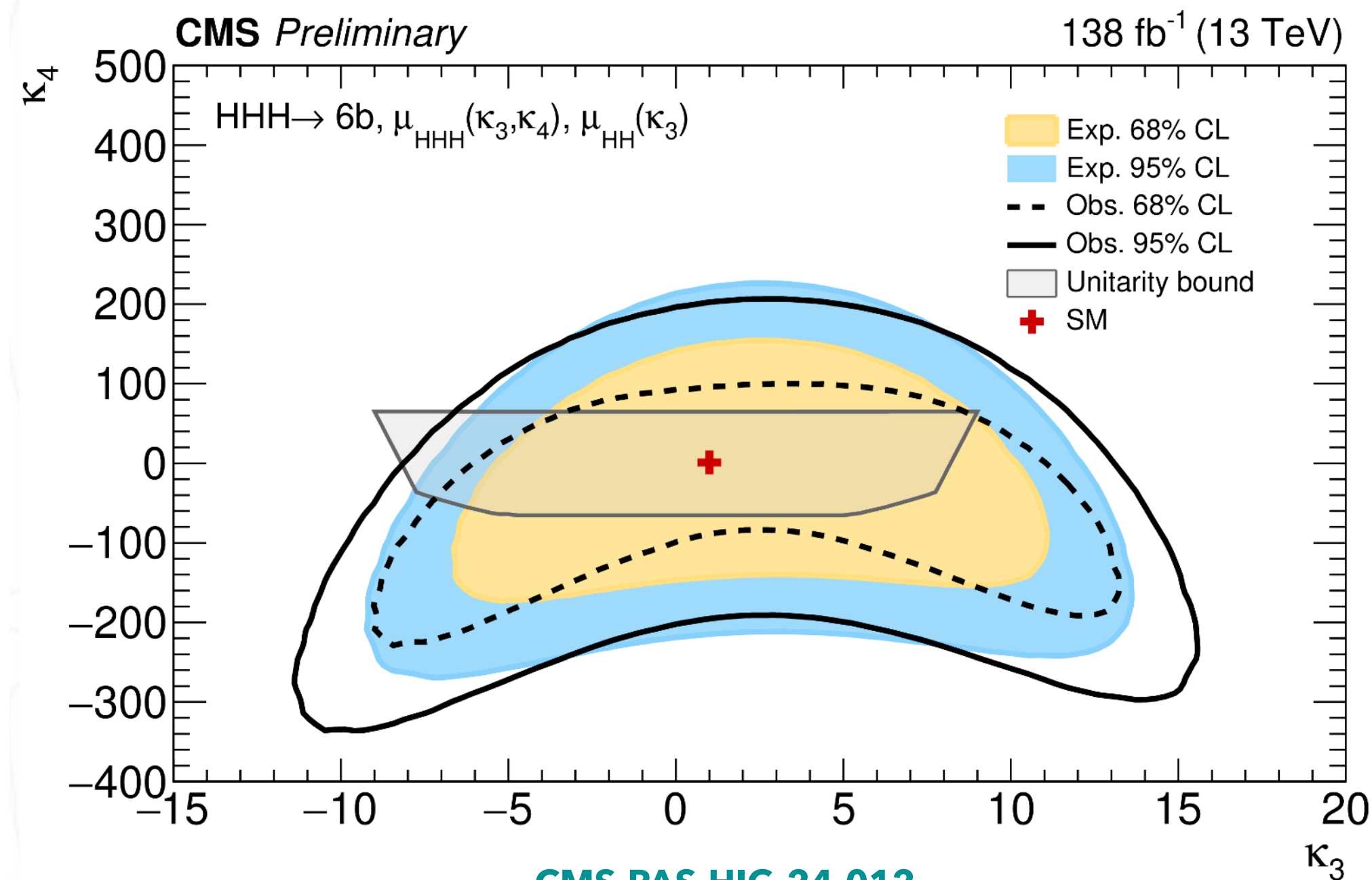
CMS PAS HIG-25-004

THE QUEST FOR HHH

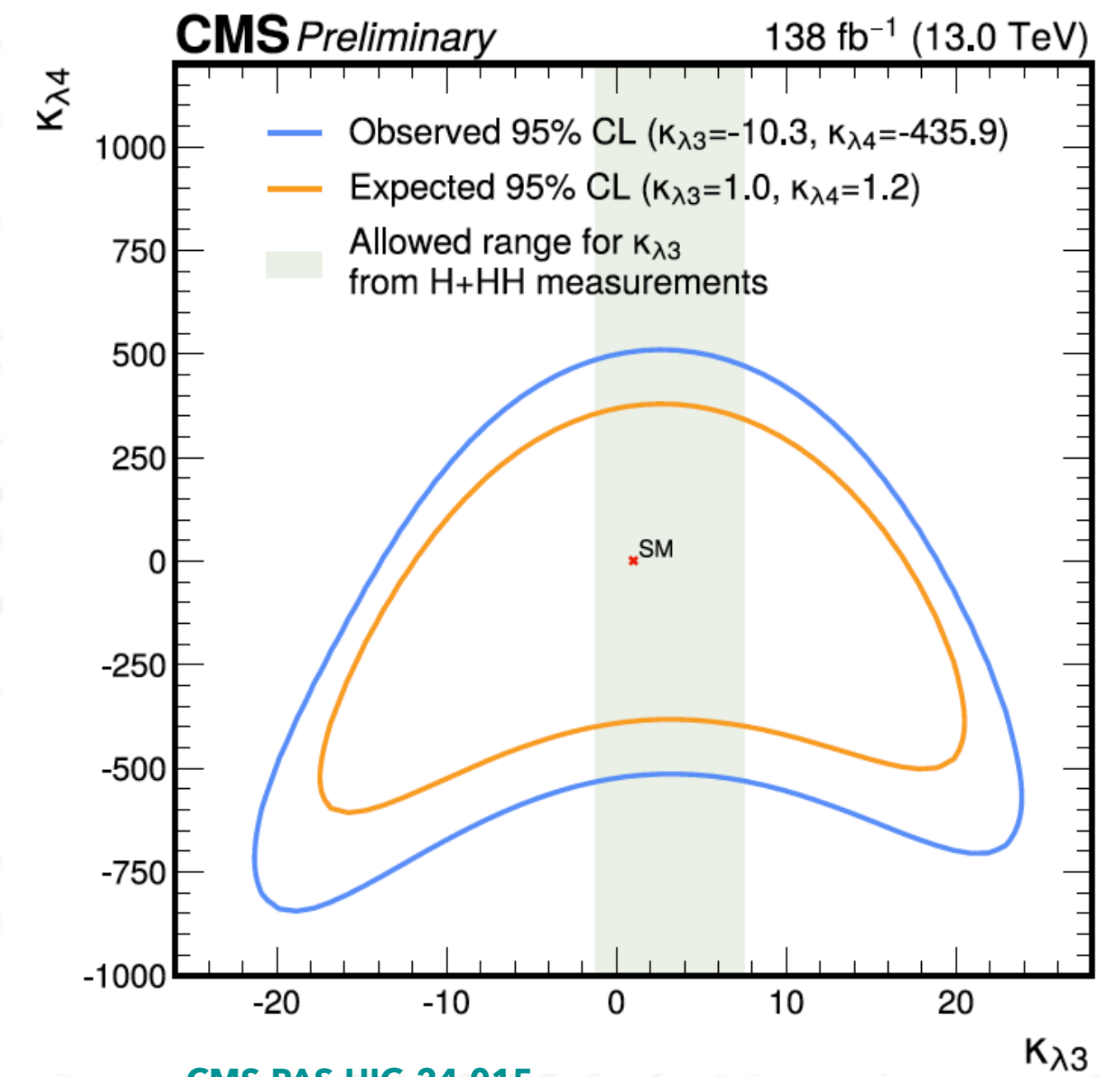
- Very very very small cross section, but **access to the quartic self-coupling (κ_4)**
- At the (HL-)LHC: probe BSM scenarios
- First results:
 - 6b: ATLAS $\mu < 760$ (750) at 95% CL, CMS: $\mu < 588$ (572), at 95% CL
 - 4b2gamma (CMS) $\mu < 3400$ (2086) at 95% CL



[Phys. Rev. D 111 \(2025\) 032006](#)



[CMS-PAS-HIG-24-012](#)



[CMS-PAS-HIG-24-015](#)