FROM HIGGS TO DIHIGGS

18/JUNIO/2025 | **María Cepeda (CIEMAT)** | JORNADAS ICTEA

foto @ A. Lastra

HIGGS PHYSICS IN 2025

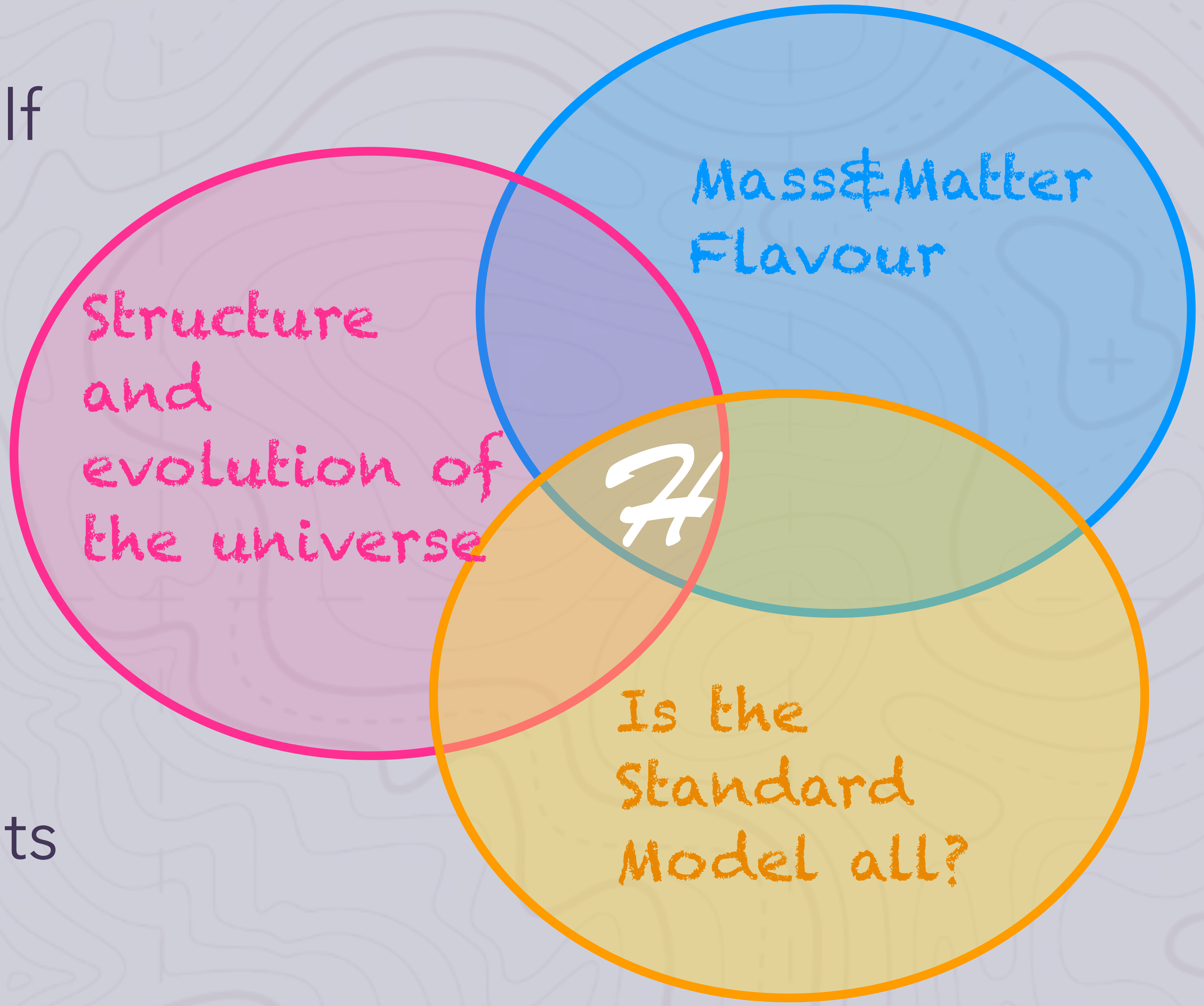
- **15 years since LHC started and 13 years since the Higgs discovery, CMS and ATLAS are dedicated to understanding the nature of the Higgs**
- We are 'lucky': a Higgs with m_H=125 implies that we can directly probe many of the decay modes (to bosons, hadrons, leptons), each with its own peculiarities (backgrounds, main systematics, challenges…)
- Many many results: impossible to cover them all!

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

- ✦**Precisely measuring its properties to test the SM boundaries**
- ✦**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**

NOT JUST ANOTHER PARTICLE...

- Only known fundamental scalar particle
- Gives mass to other particles, including itself
- Door to the unknown: what can we learn about BSM through the study of the Higgs boson?
- The central role of the Higgs in the SM makes it particularly sensitive to deviations coming from new physics. BSM will alter couplings, kinematics: we need to measure its properties precisely



NOT JUST ANOTHER PARTICLE...

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

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

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

Origin of quadratic divergences. Hierarchy problem

Possible instability depending on m_H

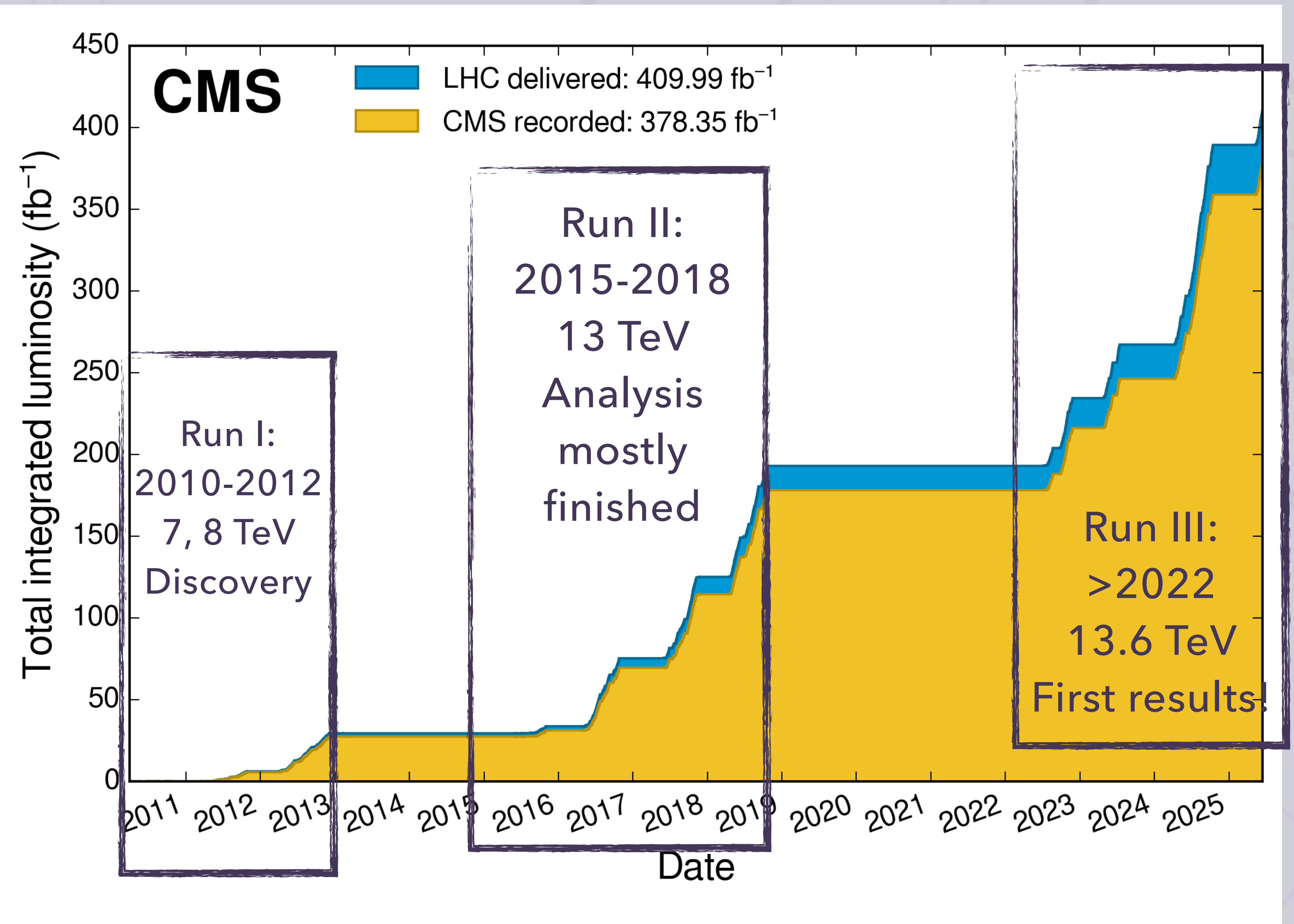
The flavour problem: large unexplained ratios of Y_{ij} Yukawa constants

Guido Altarelli, 2009

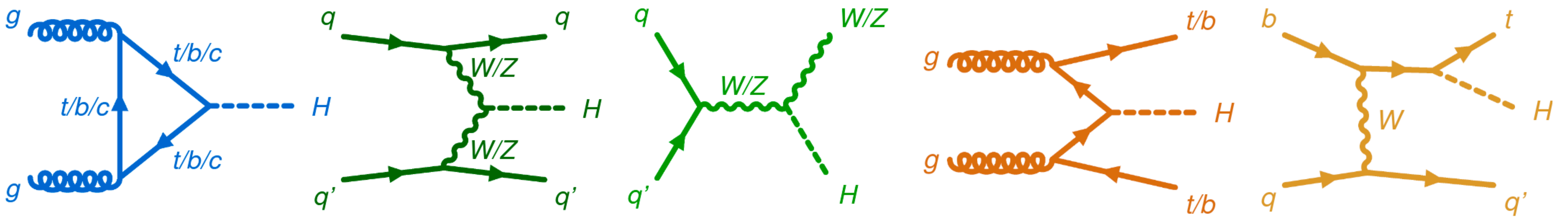

BSM?
HH and the Higgs Potential
EFT ?
Second Generation
Boosted topologies
Rare Production & DECAY
SM Couplings
Cross Sections
Mass, Spin, ...
Yukawa Interactions
DISCOVERY
A journey into the Higgs sector
foto @ JF.Sánchez Díaz

THE HIGGS LANDSCAPE TODAY AT A GLANCE

- **Run 2 analysis is (almost) complete** → >140 fb^{-1} at 13 TeV
- **Run 3 is underway** → First results with 13.6 TeV already public
  - → already > 300 fb^{-1} !
- **Wealth of precision measurements: testing SM boundaries**
  - → Inclusive and differential cross sections, Coupling fits
  - → EFT constraints
- Large statistics:
  - → **measurements in complicated, interesting phase-spaces**
  - → **rare and elusive signatures** starting to be within reach
- **Di-Higgs: exploring the self-coupling**
  - → Exclusion limits are closing in on SM range (~2.5x SM)
- **Analysis techniques in constant improvement** (Boosted objects, ML approaches, new EFT interpretations)
- **HL-LHC sensitivity reappraised for the the European Strategy**



HIGGS PRODUCTION AT THE LHC



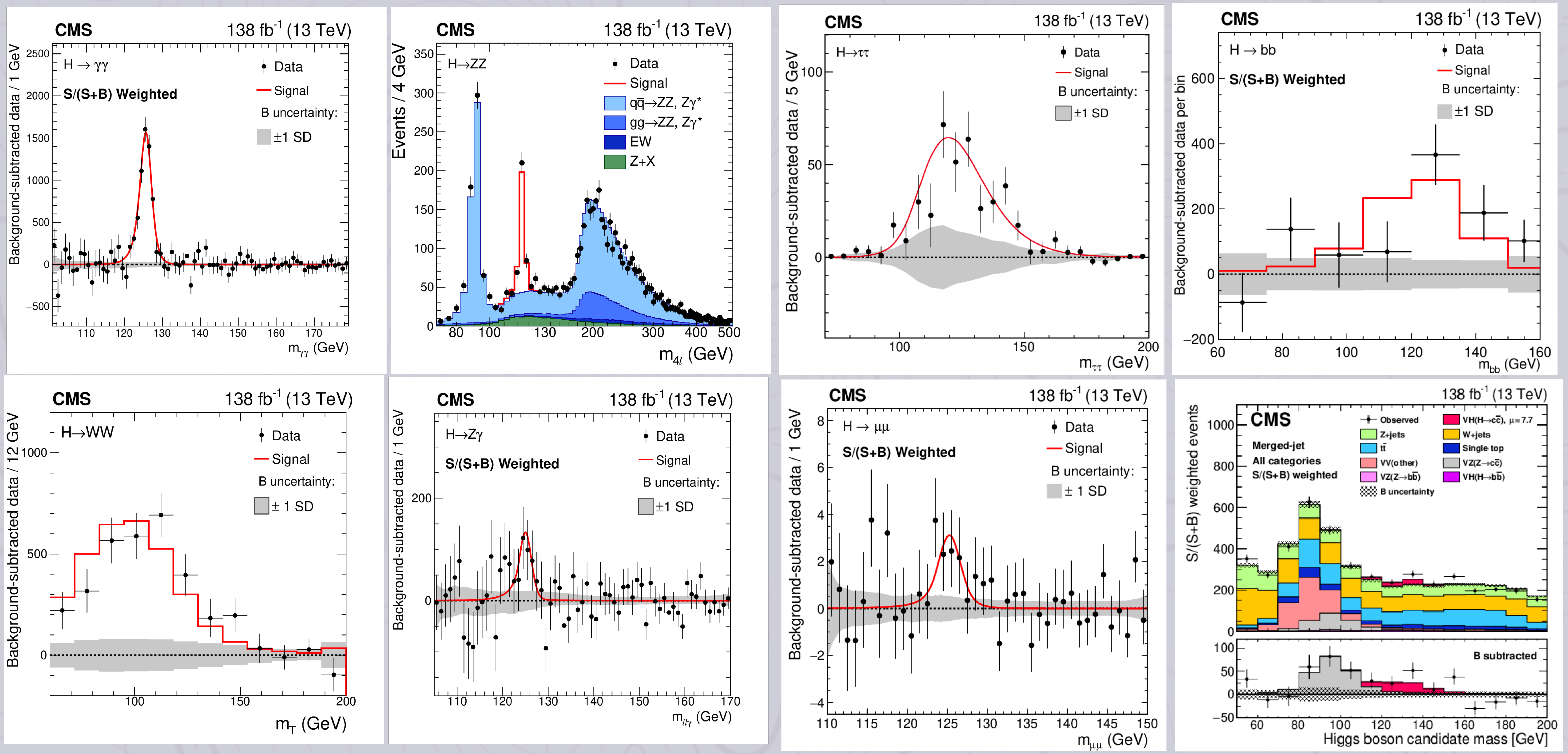
Gluon fusion (ggF) (87%)

Vector boson fusion (VBF) (7%)

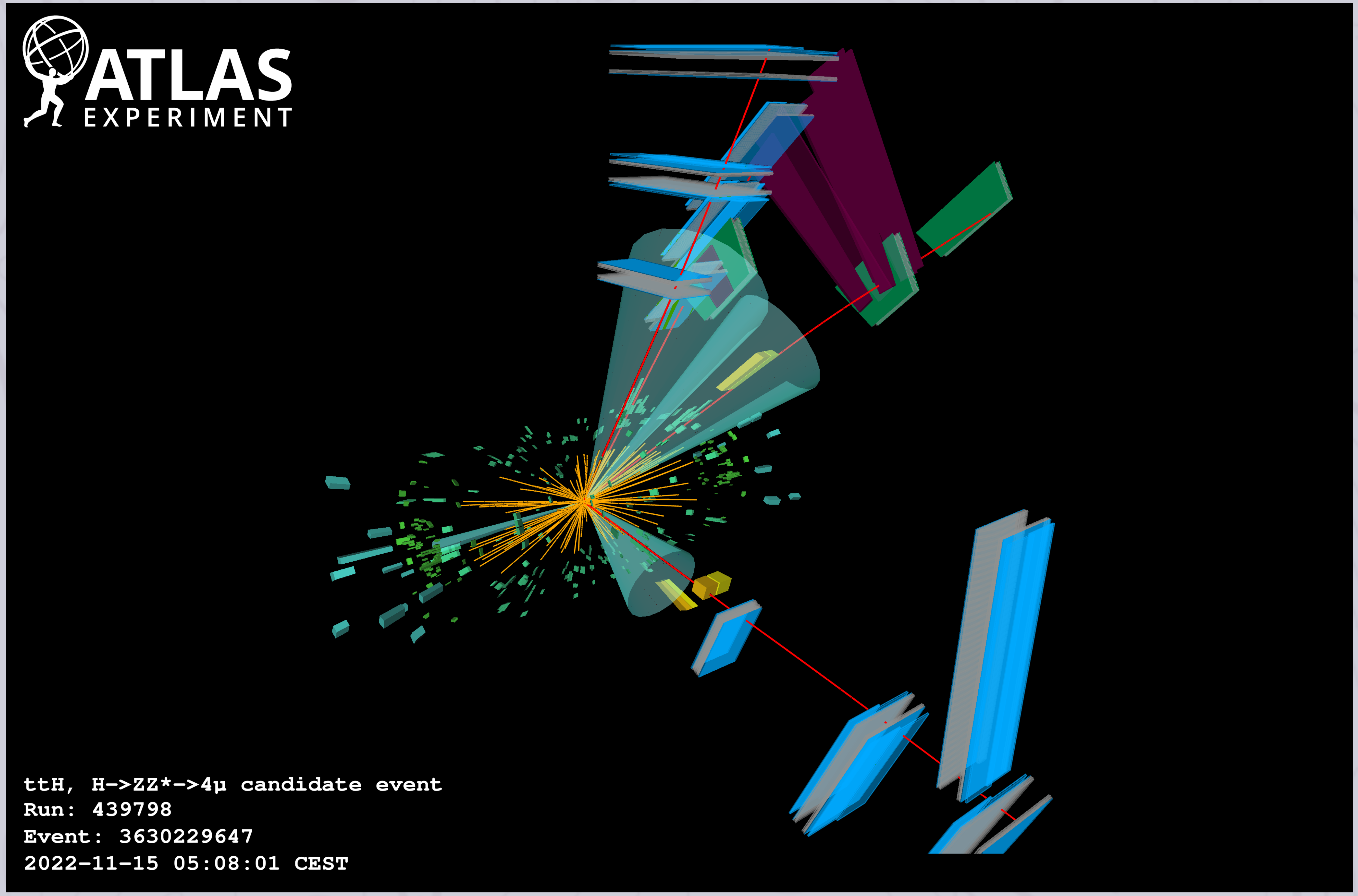
Vector boson associated production (VH) (4%)

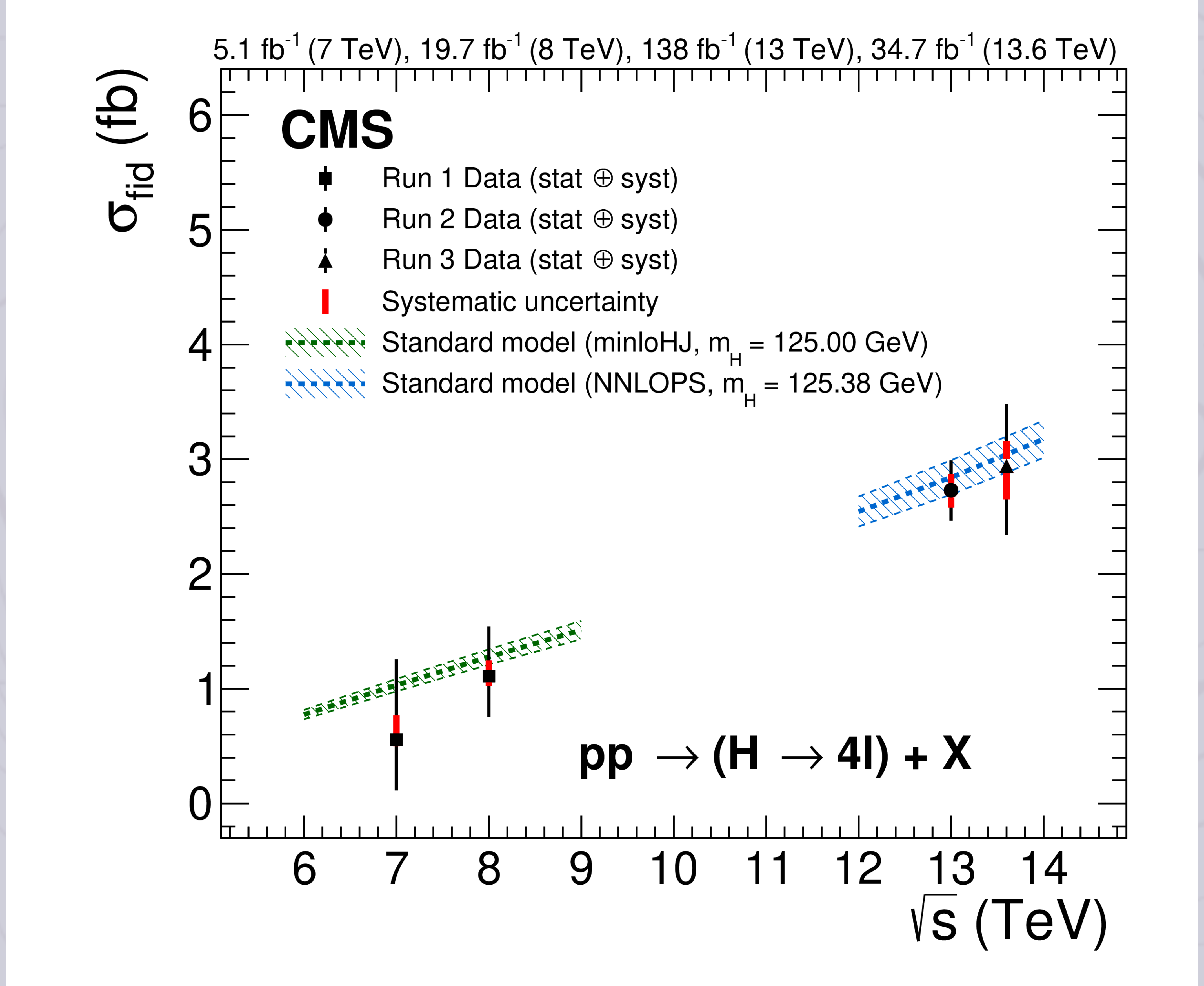
Top- and bottom-associated production, single-top production (2%)

THE FACES OF THE HIGGS IN RUN2...



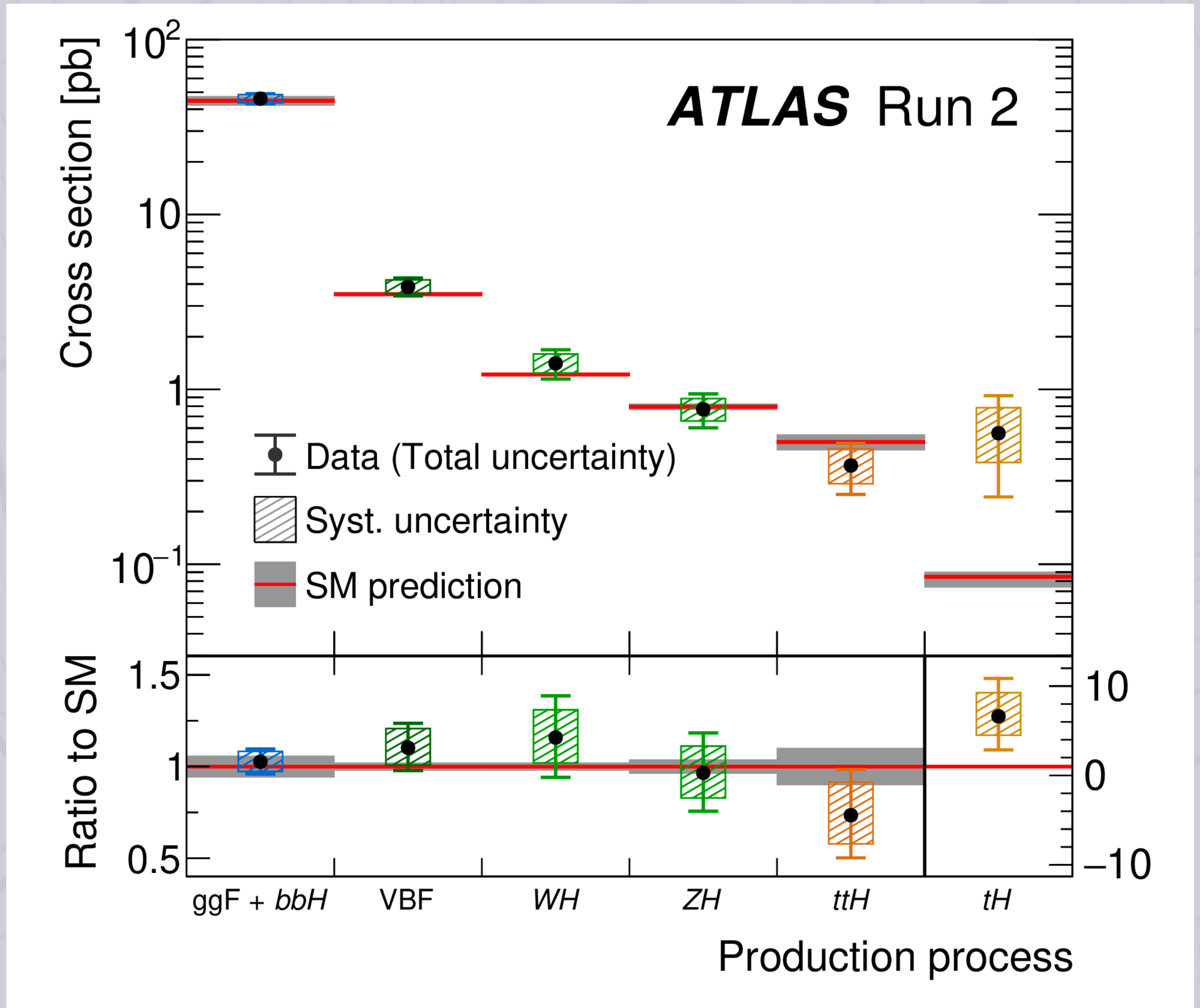
… AND IN RUN3

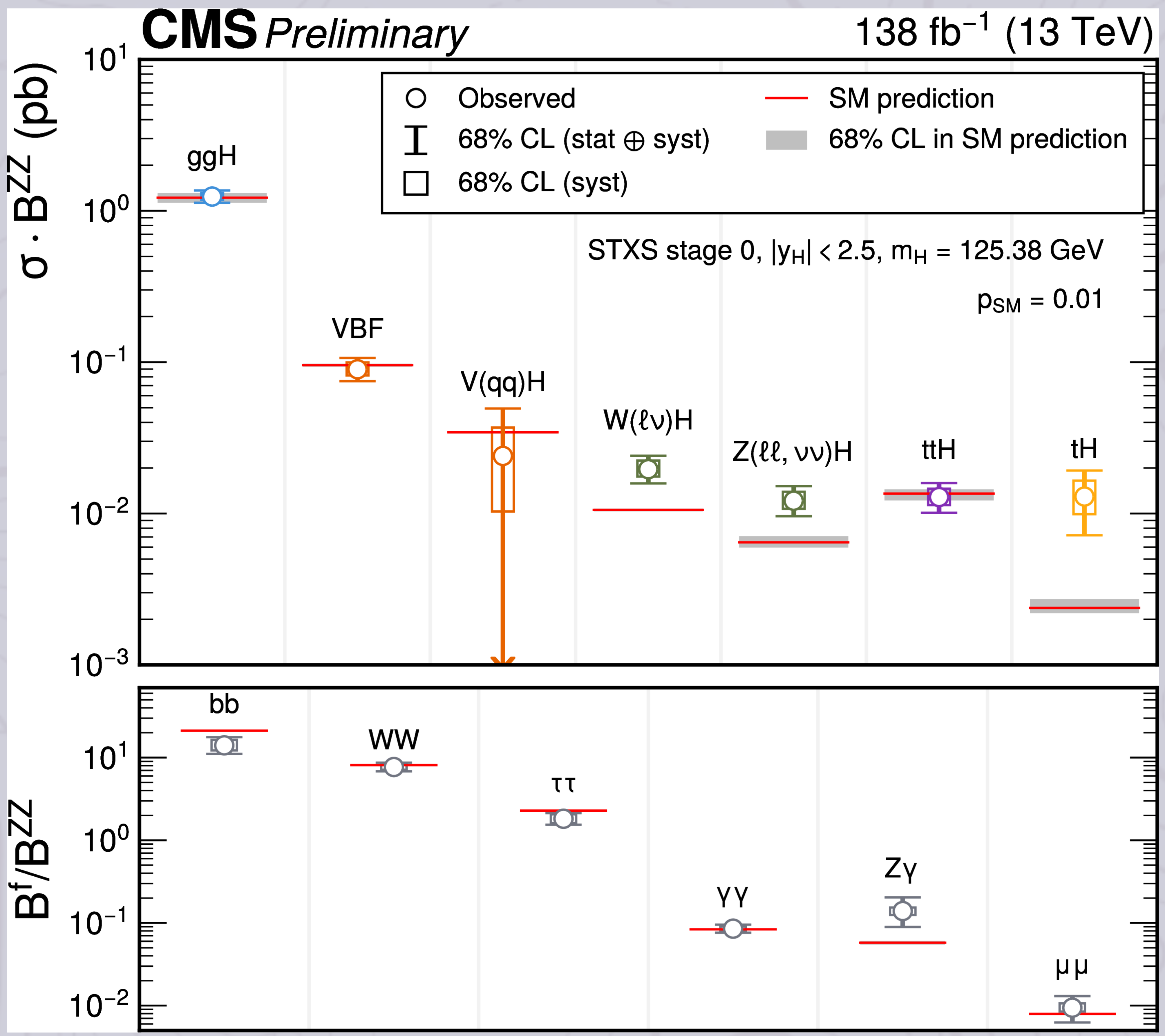




- Higgs Physics probed at 7, 8, 13 and 13.6 TeV: huge dataset for exploring Higgs physics

PRODUCTION X DECAY : ✓✓

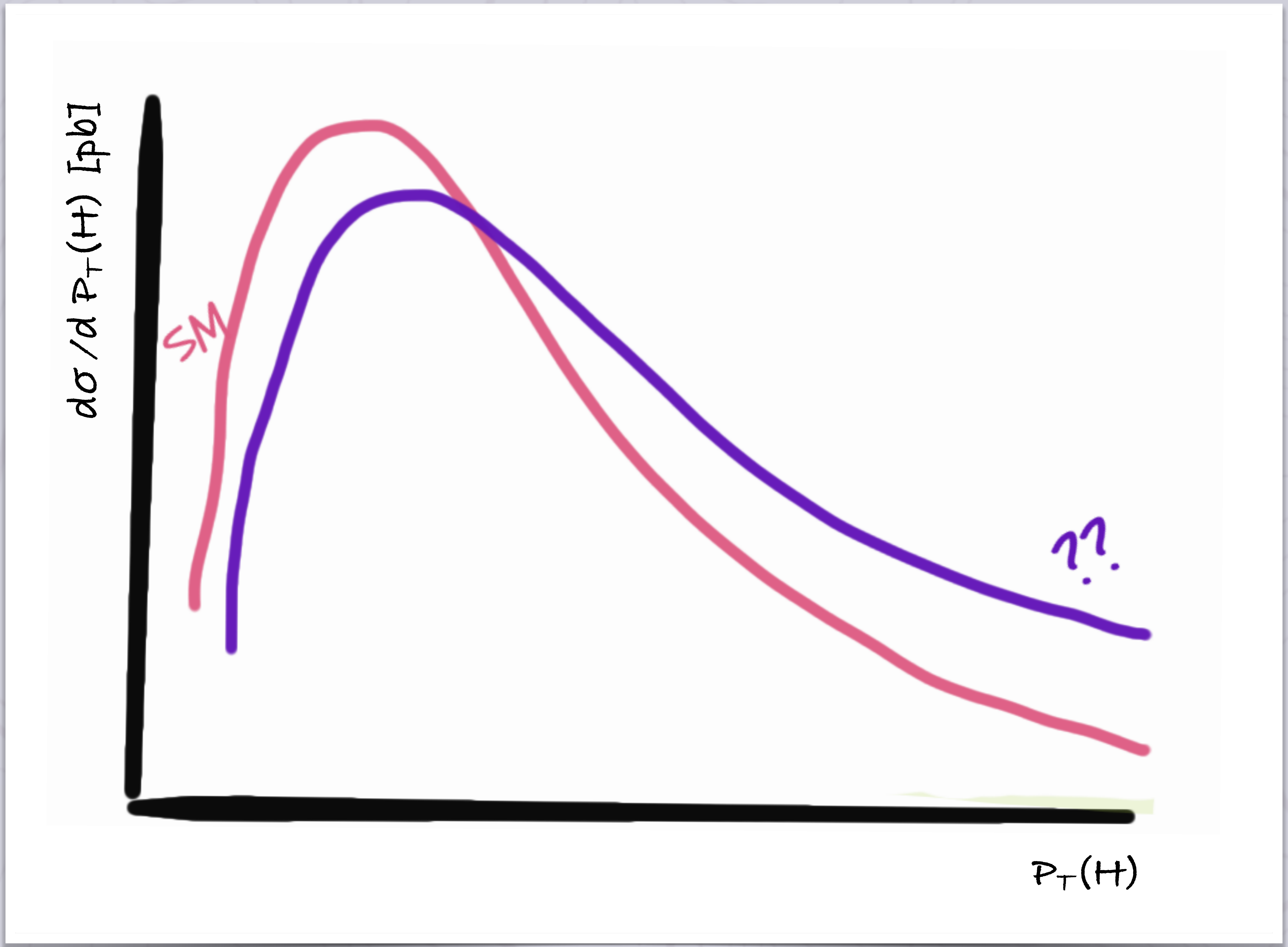




Inclusive cross section understood at the 6% already:

$$\mu_{CMS} = 1.014 \pm 0.054$$
$$\mu_{ATLAS} = 1.05 \pm 0.06$$

COUNTING IS ONLY THE BEGINNING…

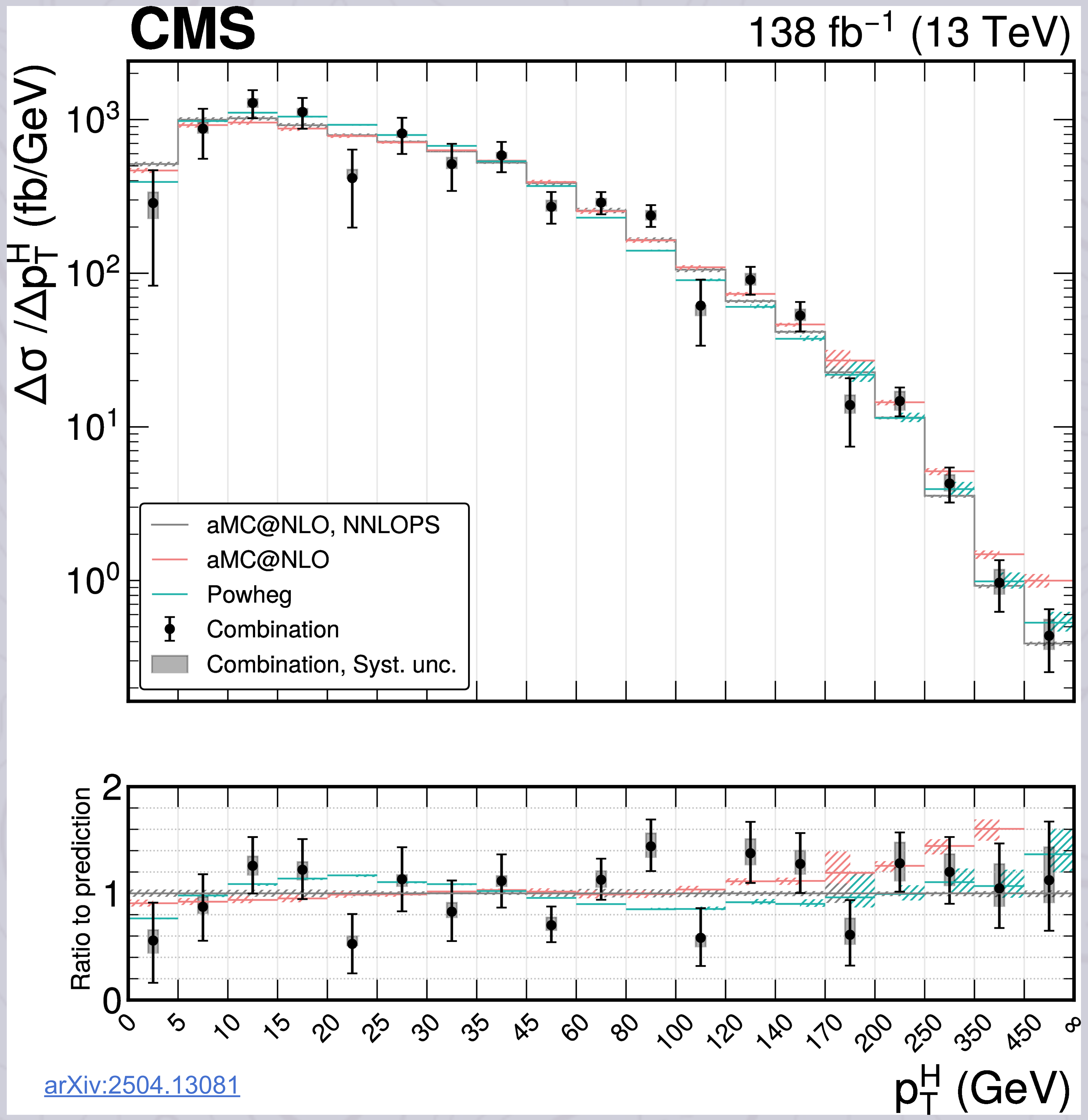


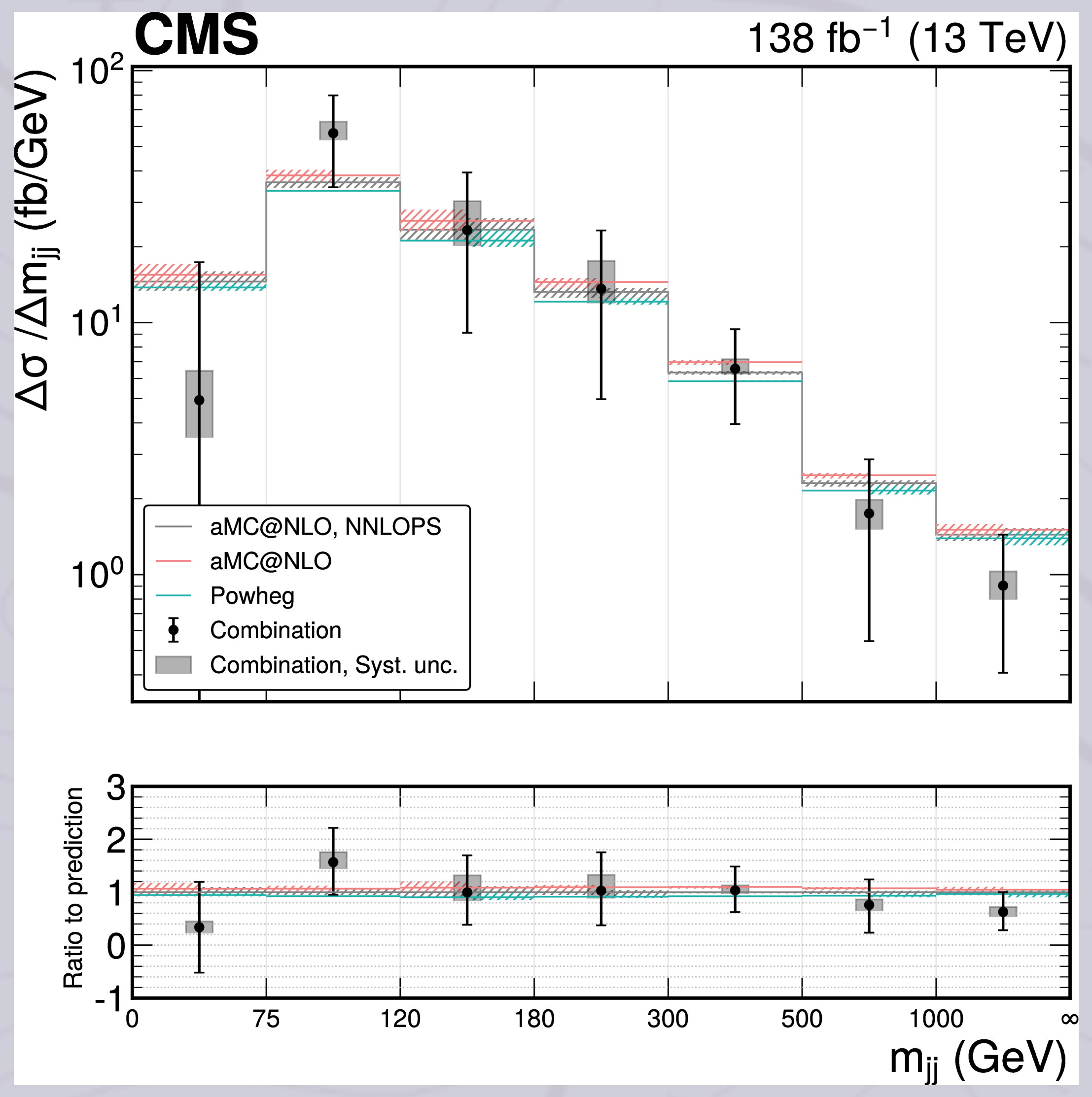
- Higgs kinematics can be modified by BSM physics

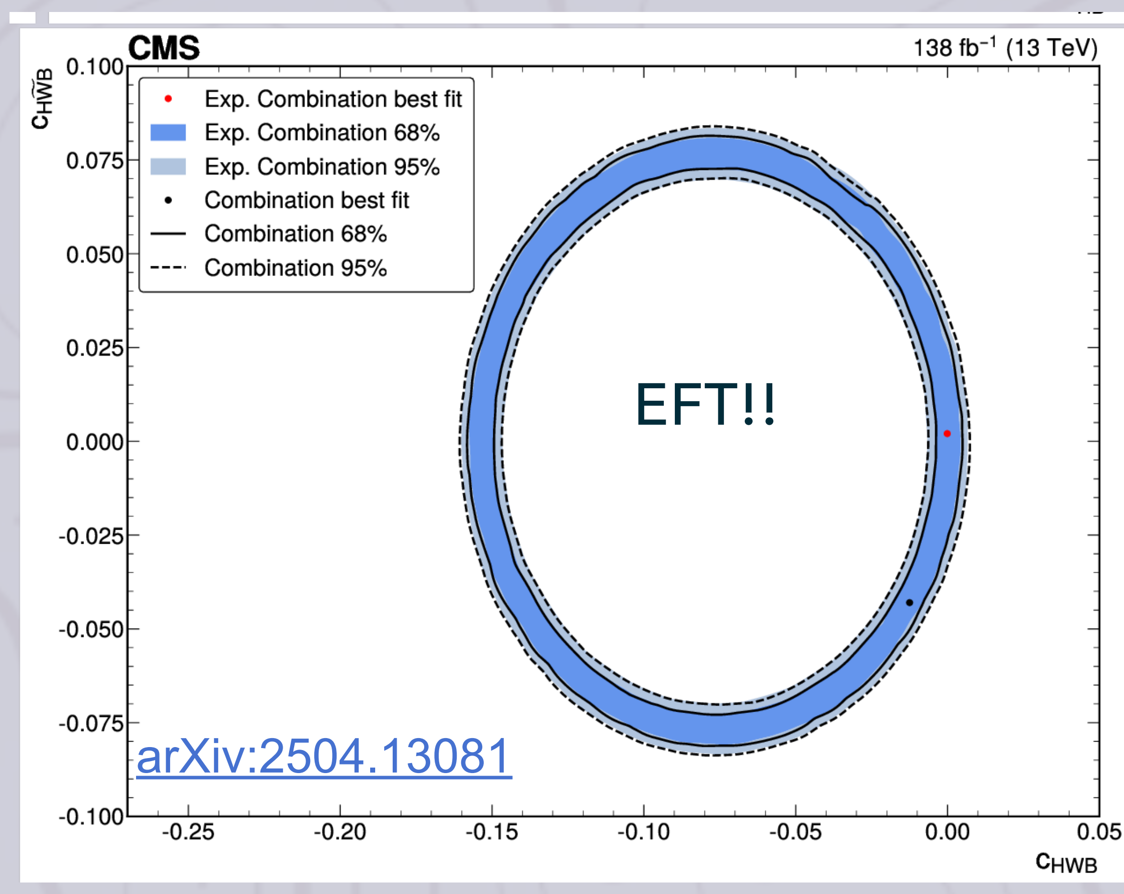
DIFFERENTIAL CROSS SECTIONS

- CMS Run2 combination of differential distributions (ZZ,WW,$\gamma\gamma$, $\tau\tau$). Many variables probed (pT, angular correlations, event topology…)

- **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



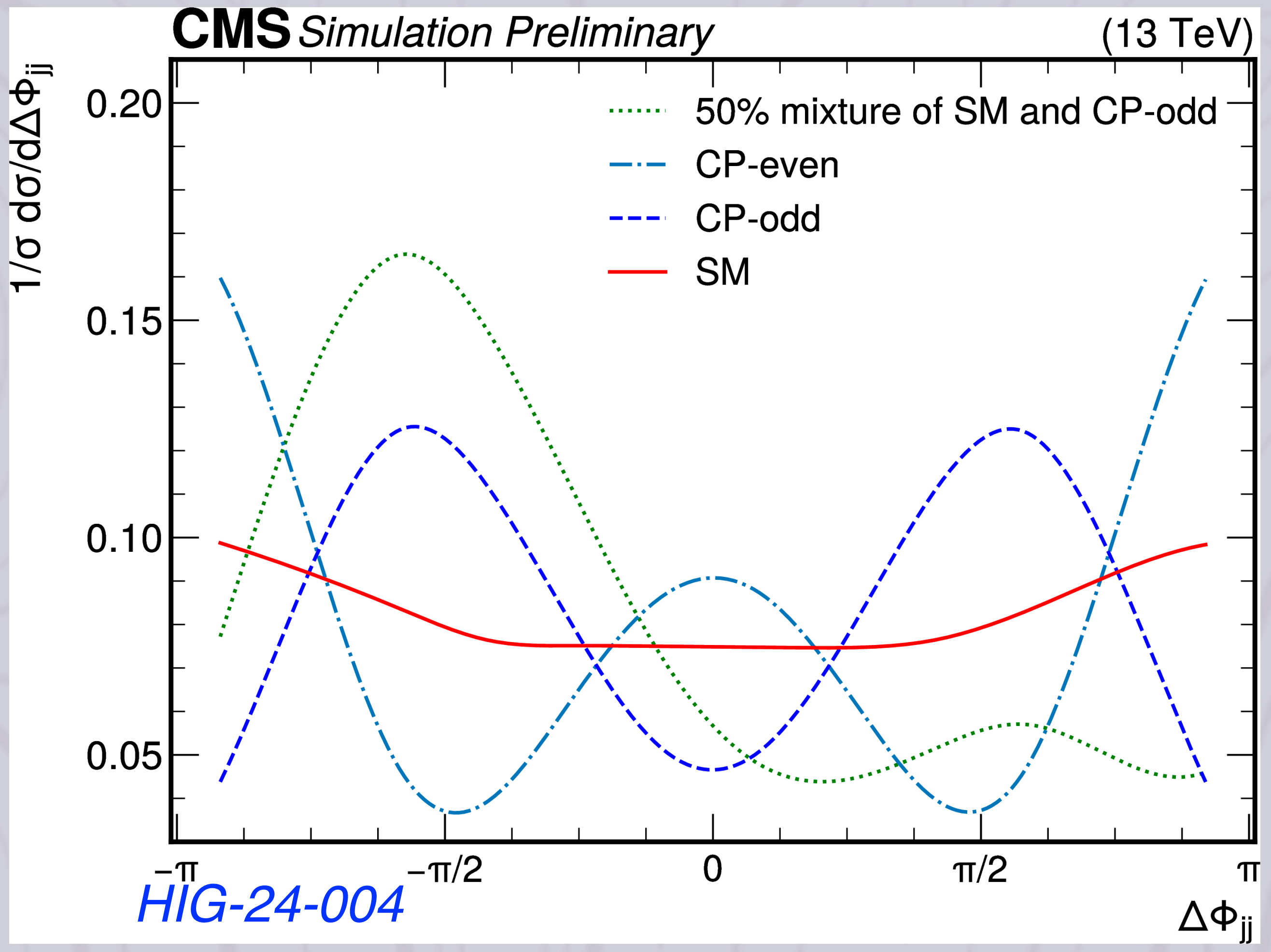




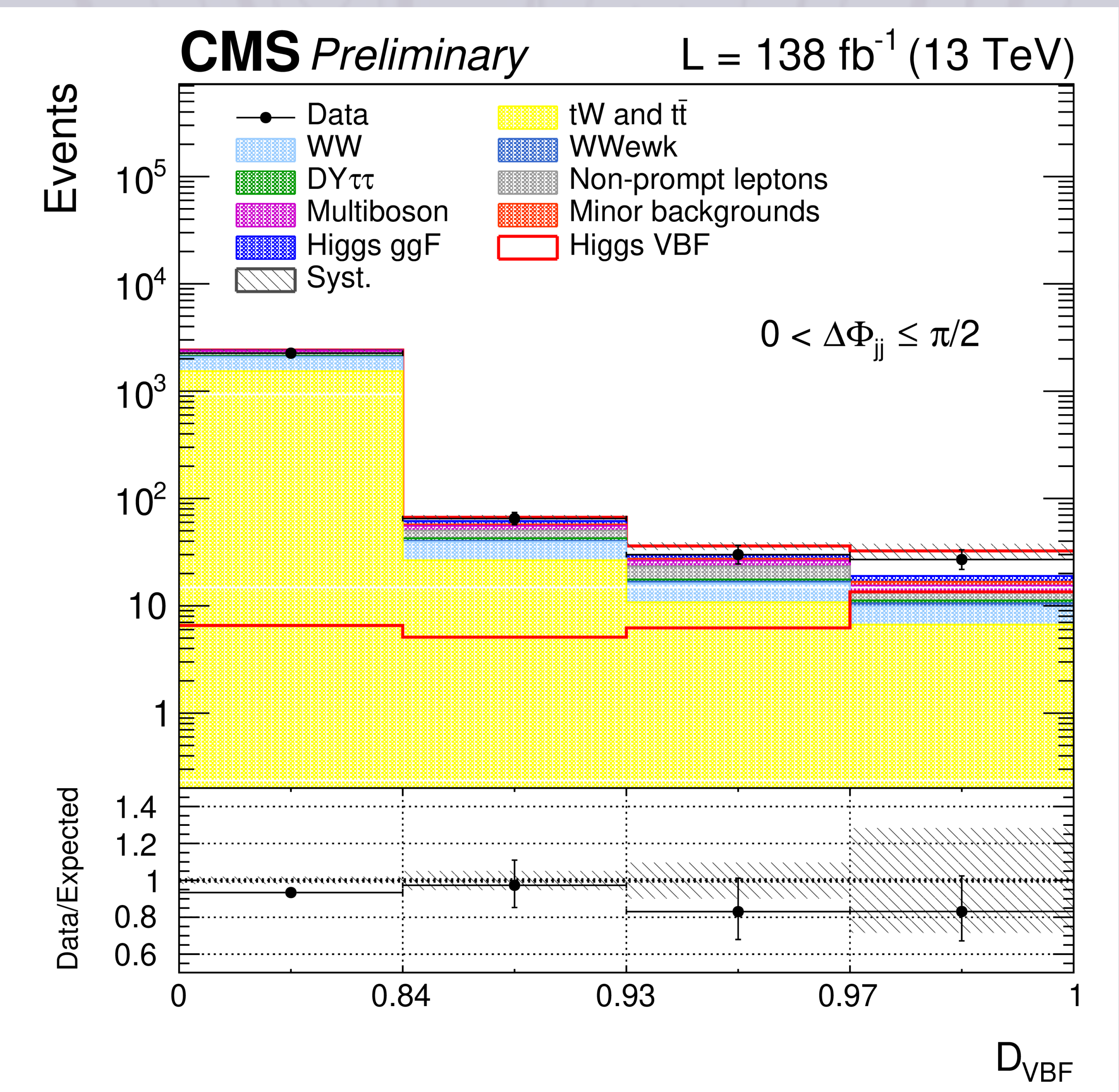
ZOOMING IN

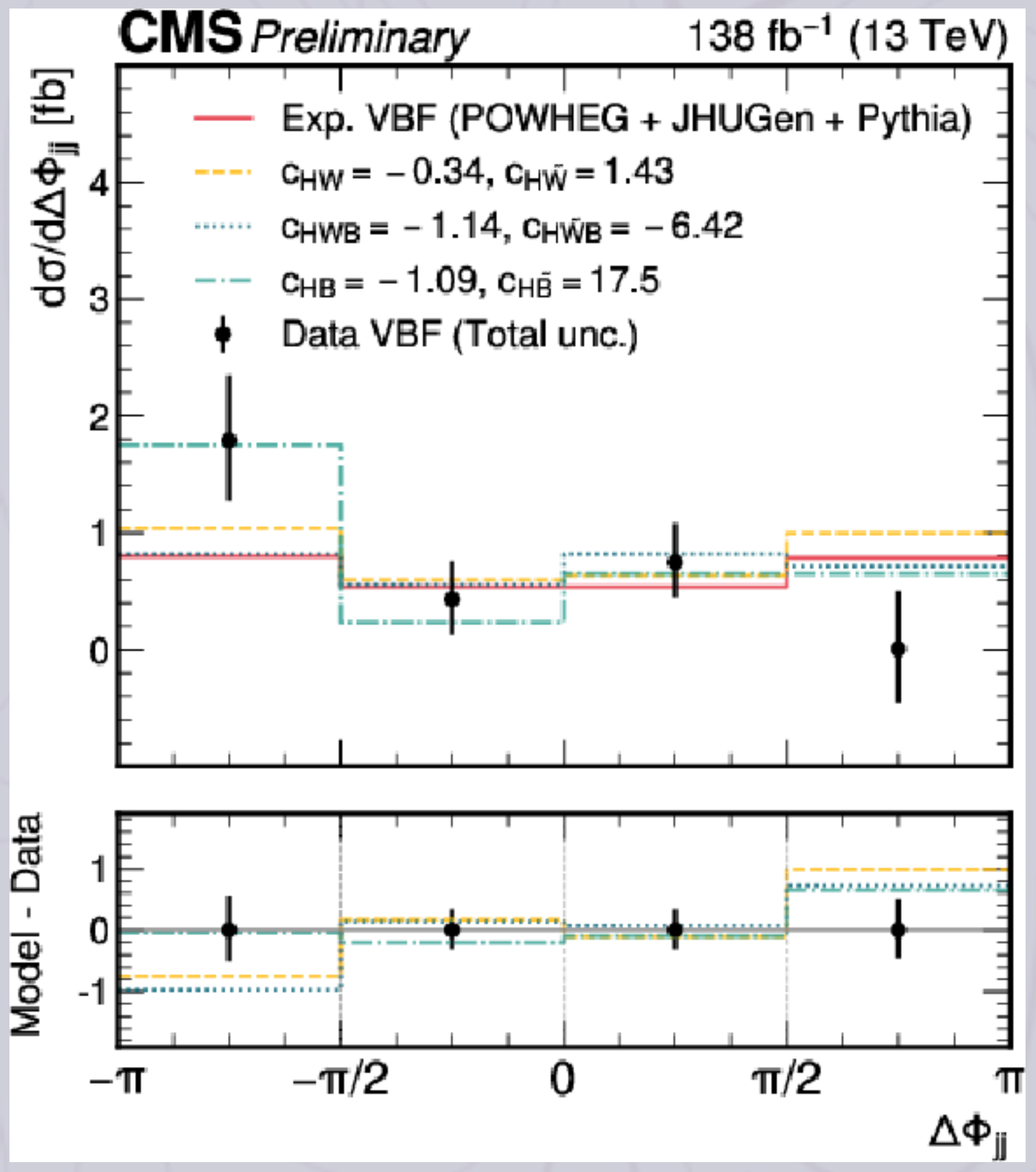
- Larger statistics: we can probe difficult phase-spaces, and exploit kinematic variables sensitive to new physics.

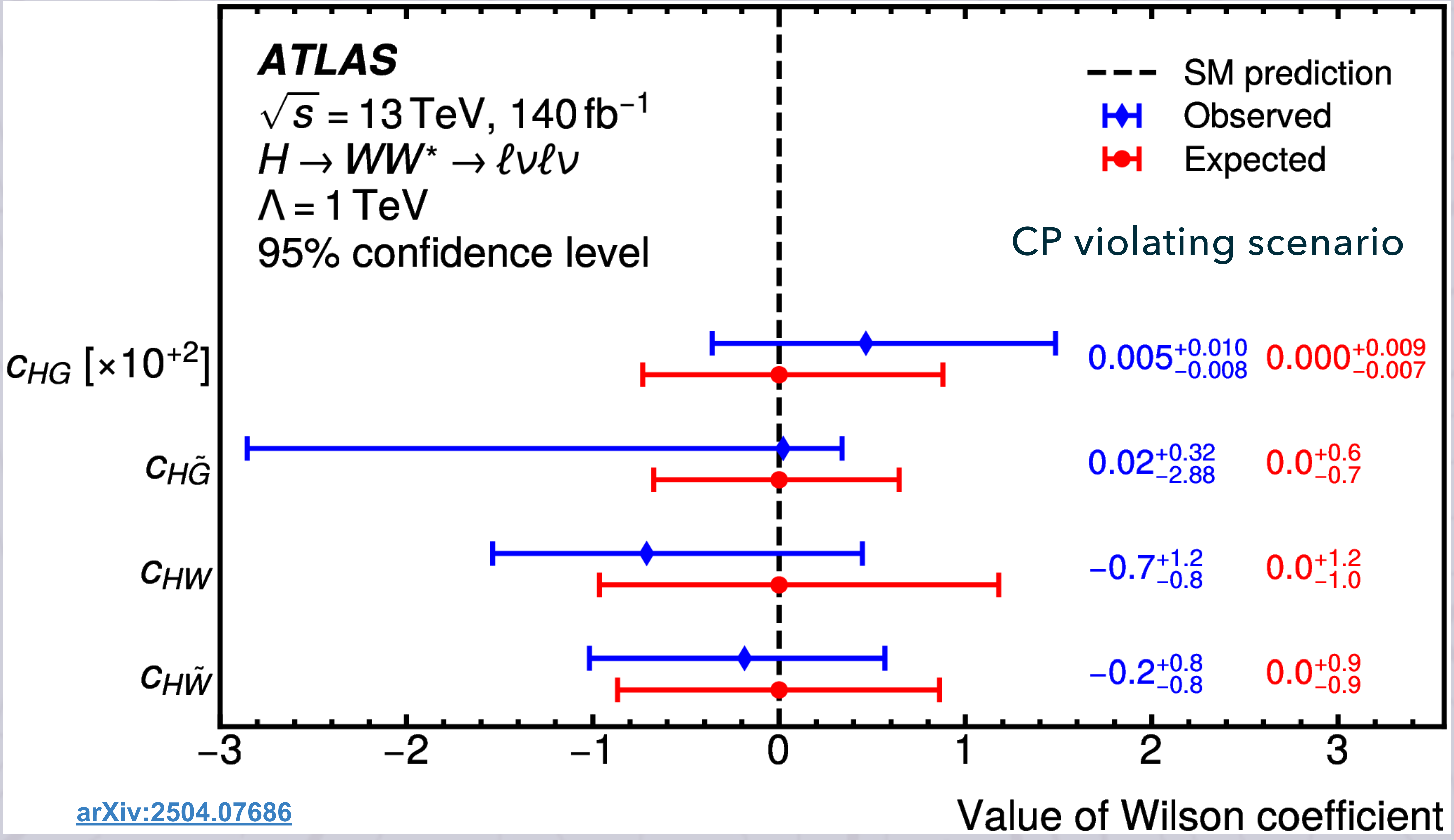
DIFFERENTIAL VBF HWW PRODUCTION



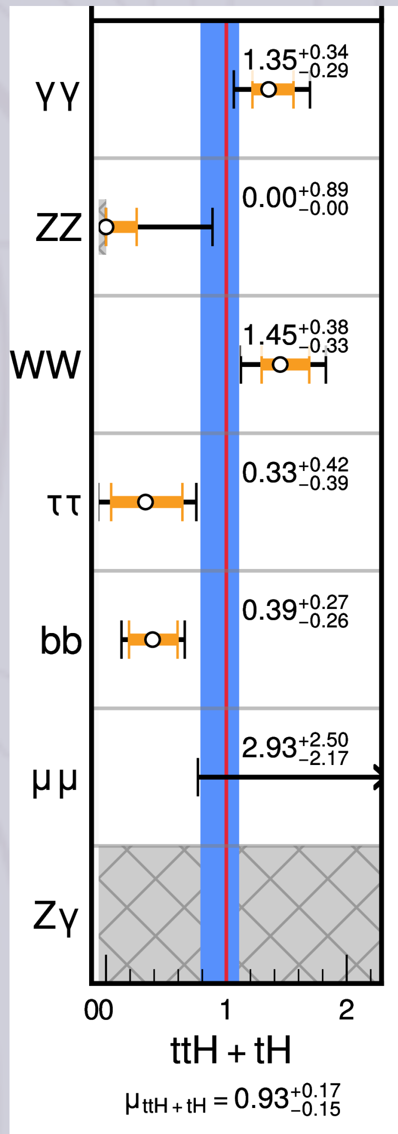
- **EFT Constraint from differential cross sections (in e$\mu\nu\nu$ in this case) as a function of the difference in azimuthal angle Δϕjj between the two jets.**
- ggF and VBF , both in CMS and ATLAS (*)
- Two approaches: Δϕjj vs STXS (Binned Differential Fiducial Xsec)
- Results interpreted as constraints of Higgs boson couplings in SMEFT



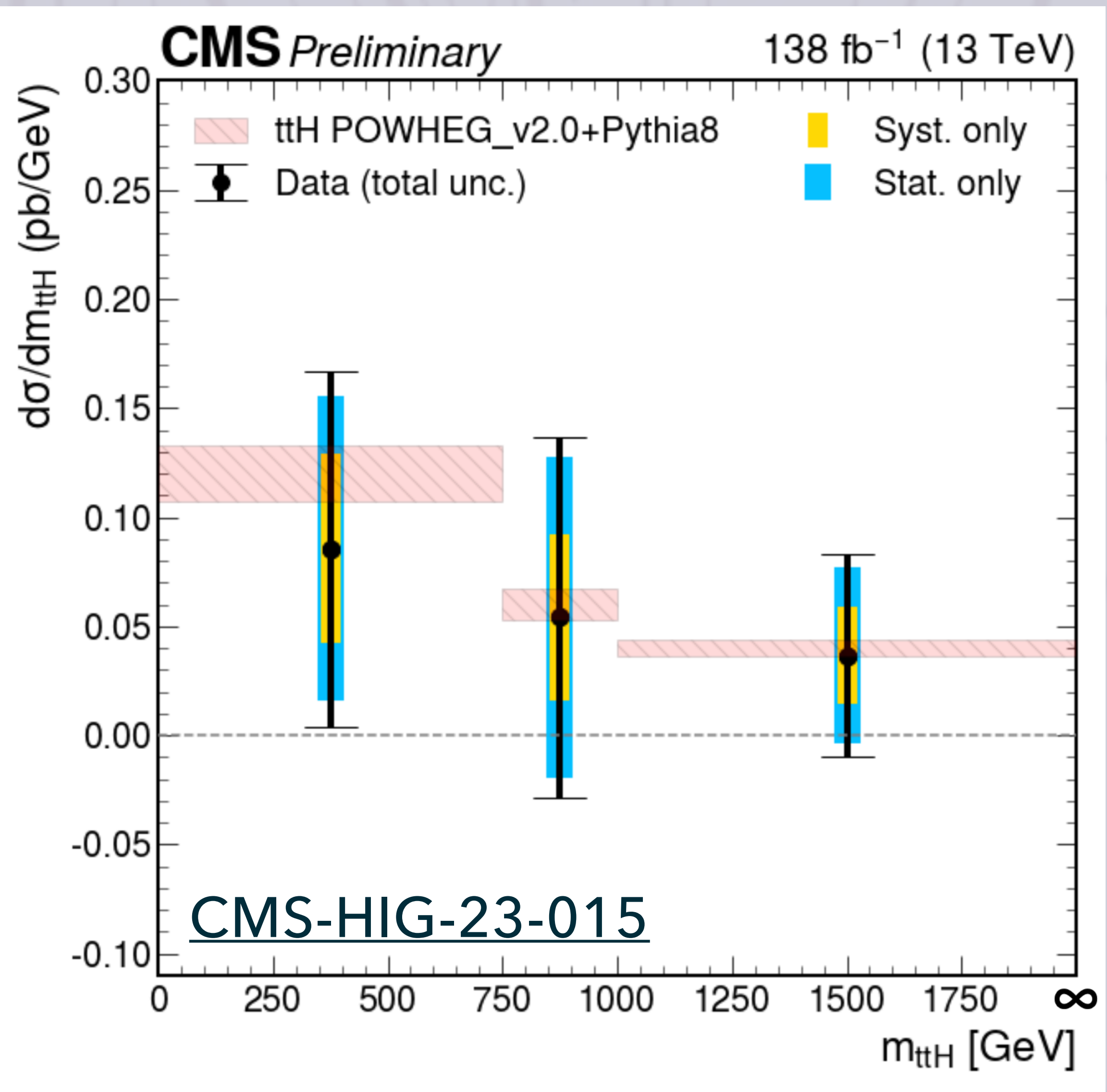


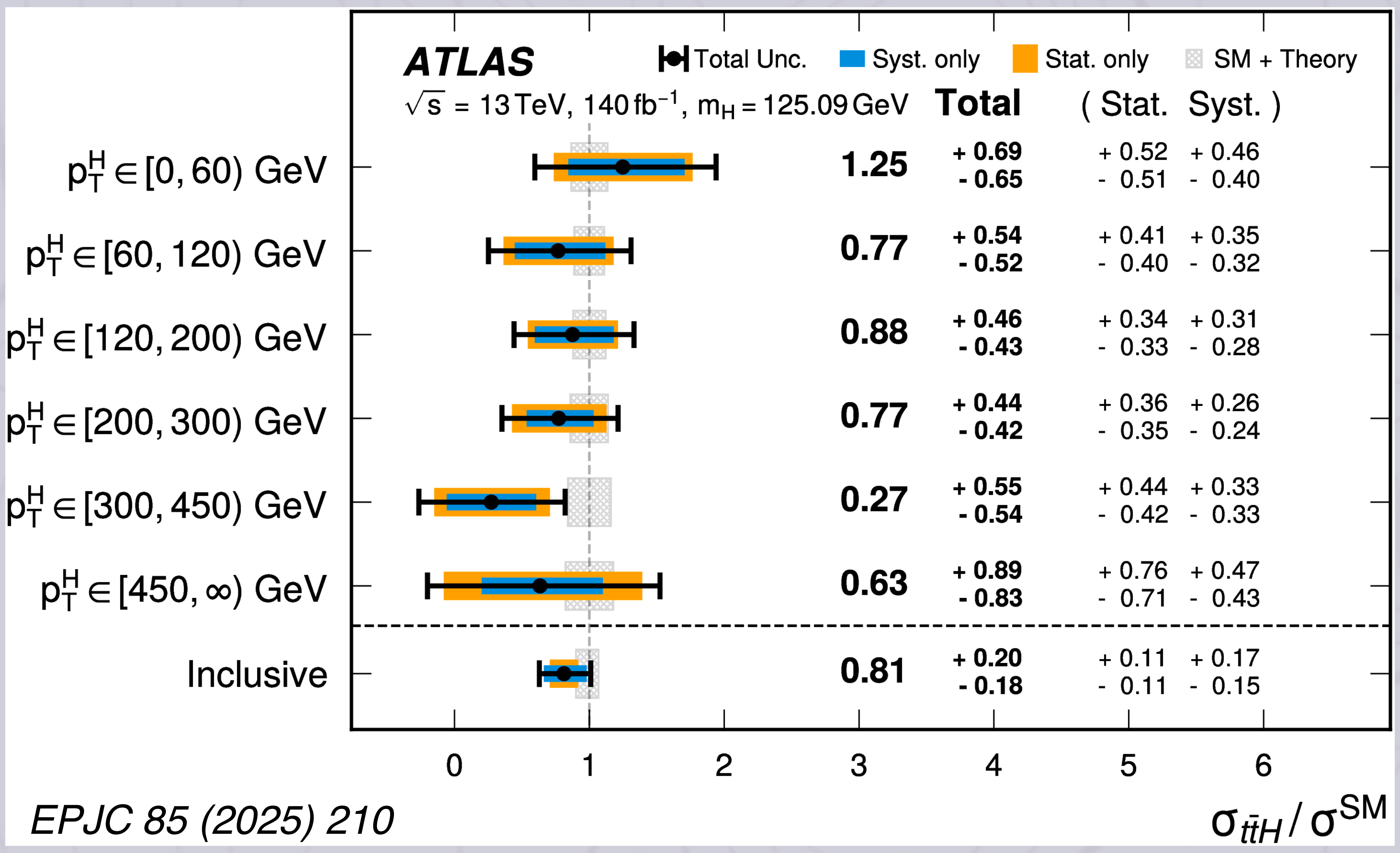


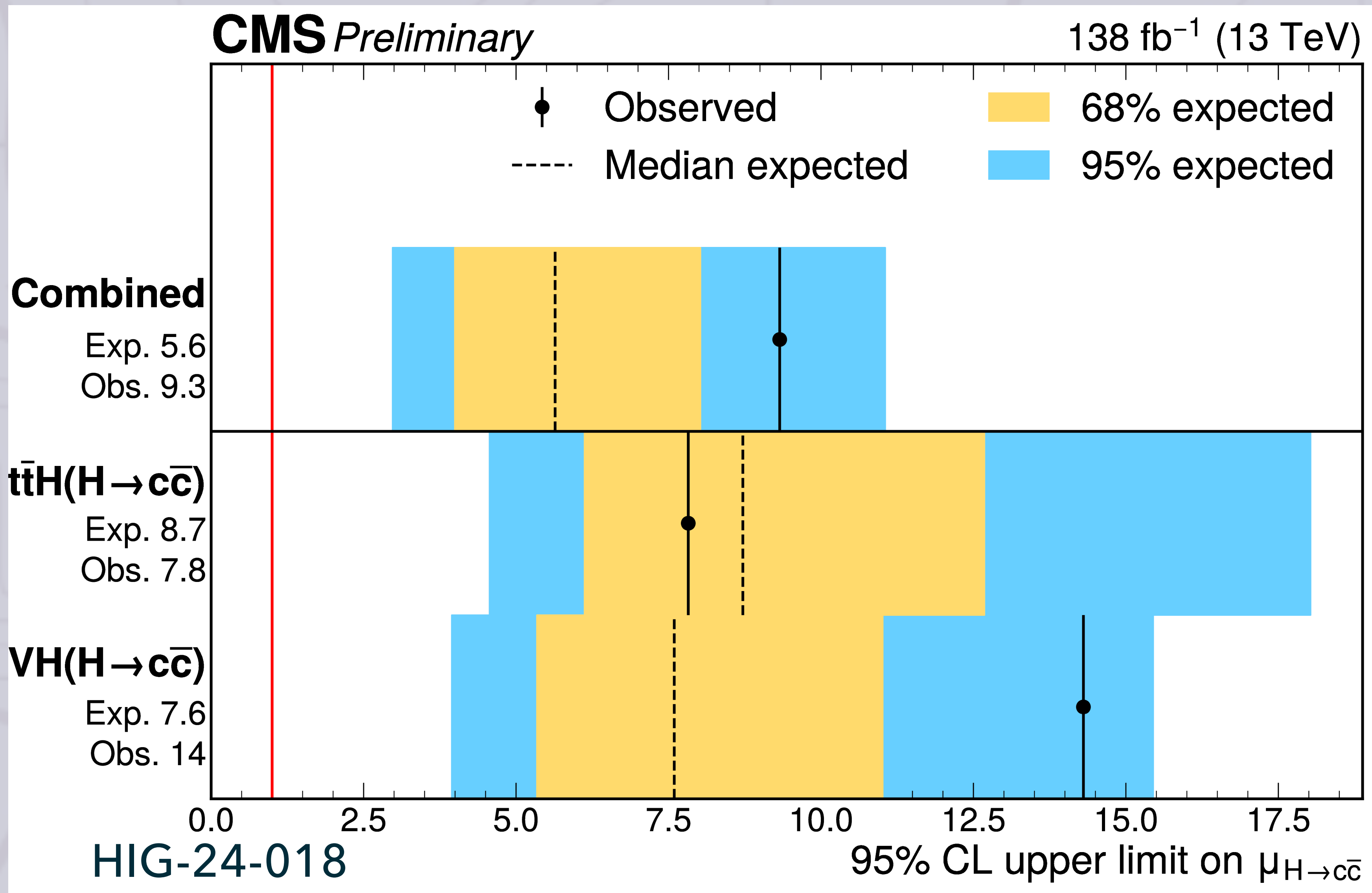
TTH PRODUCTION



- Well established: bb, $\gamma\gamma$, multilepton : differentials , probing properties like CP
- Some recent highlights :
  - Multilepton (WW+$\tau\tau$+…) differential measurement in CMS (m_{ttH} and p_TH), HIG-23-015
  - ttH Hbb: Inclusive + Differential measurement, at observation level (ttH Hbb in ATLAS 4.4sigmas)
  - **ttH Hcc? Joint Hbb+Hcc analysis by CMS ! ML techniques for flavor tagging and event classification. μ(ttH Hcc)<7.8 x SM**





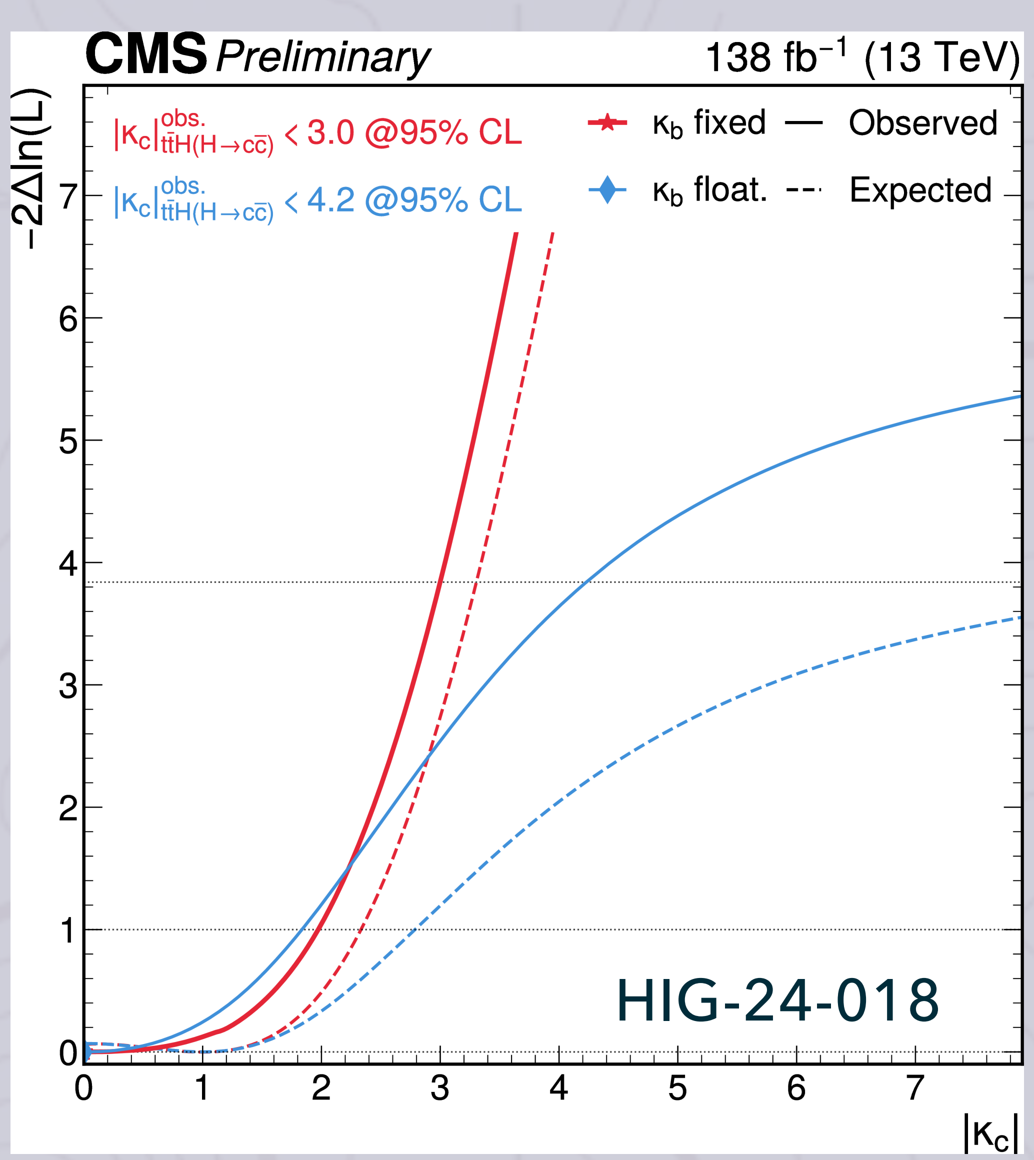


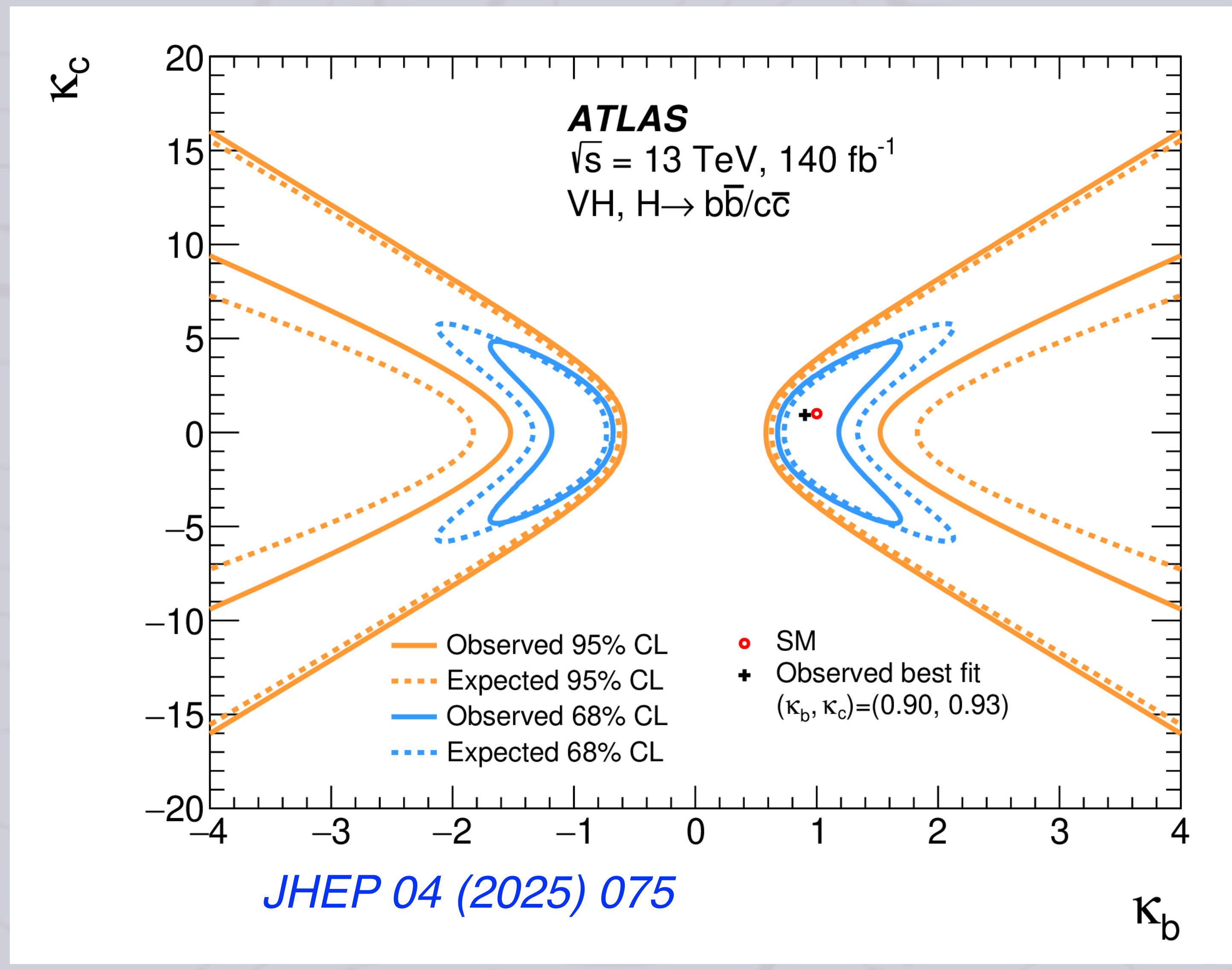
RARO, RARO

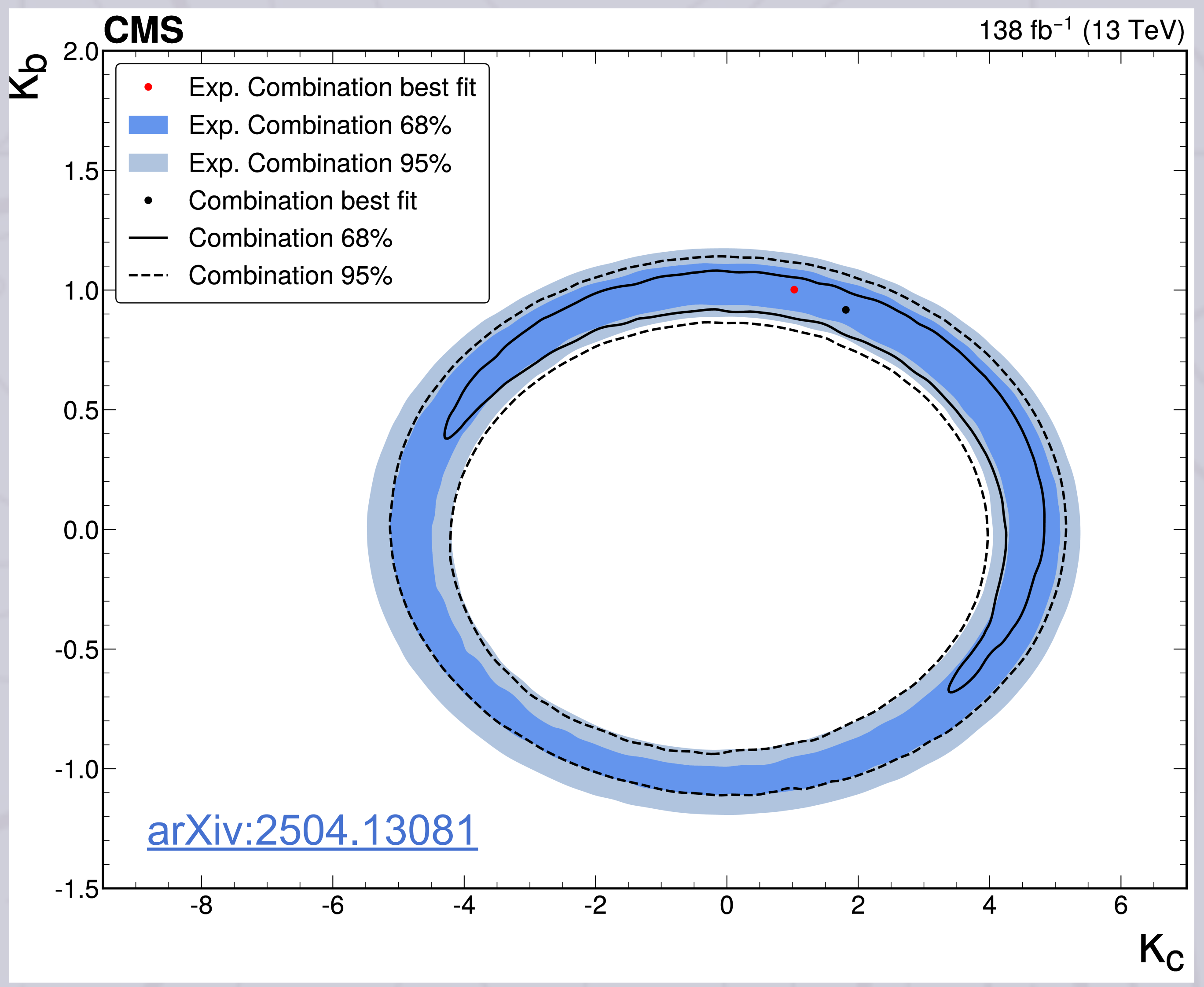
- We have only probed a fraction of the production phase-space
- While the number of observed decays has increased, many more still to be seen
- What's next?

WILL THE LHC REACH THE CHARM YUKAWA? YES!

- **Charm quark: only up quark for which we could possibly measure the branching ratio Br(H->cc)~3%**
  - Do up-type quarks get their mass from the same Higgs fields as down-type quarks and charged leptons?
- **Difficult measurement (not only statistics, we need to be able to identify charm jets!). Many avenues explored now!**
  - Direct: VH Hcc, ttH Hcc:
  - Associated production: H+c
  - H+γ : simultaneous constraint on light yukawas
  - Constraints from general Higgs pt differential
  - JPsiGamma
- **Best so far:** $|\kappa_c| < 3.5\ (2.7)$ **(ttH+VH)**

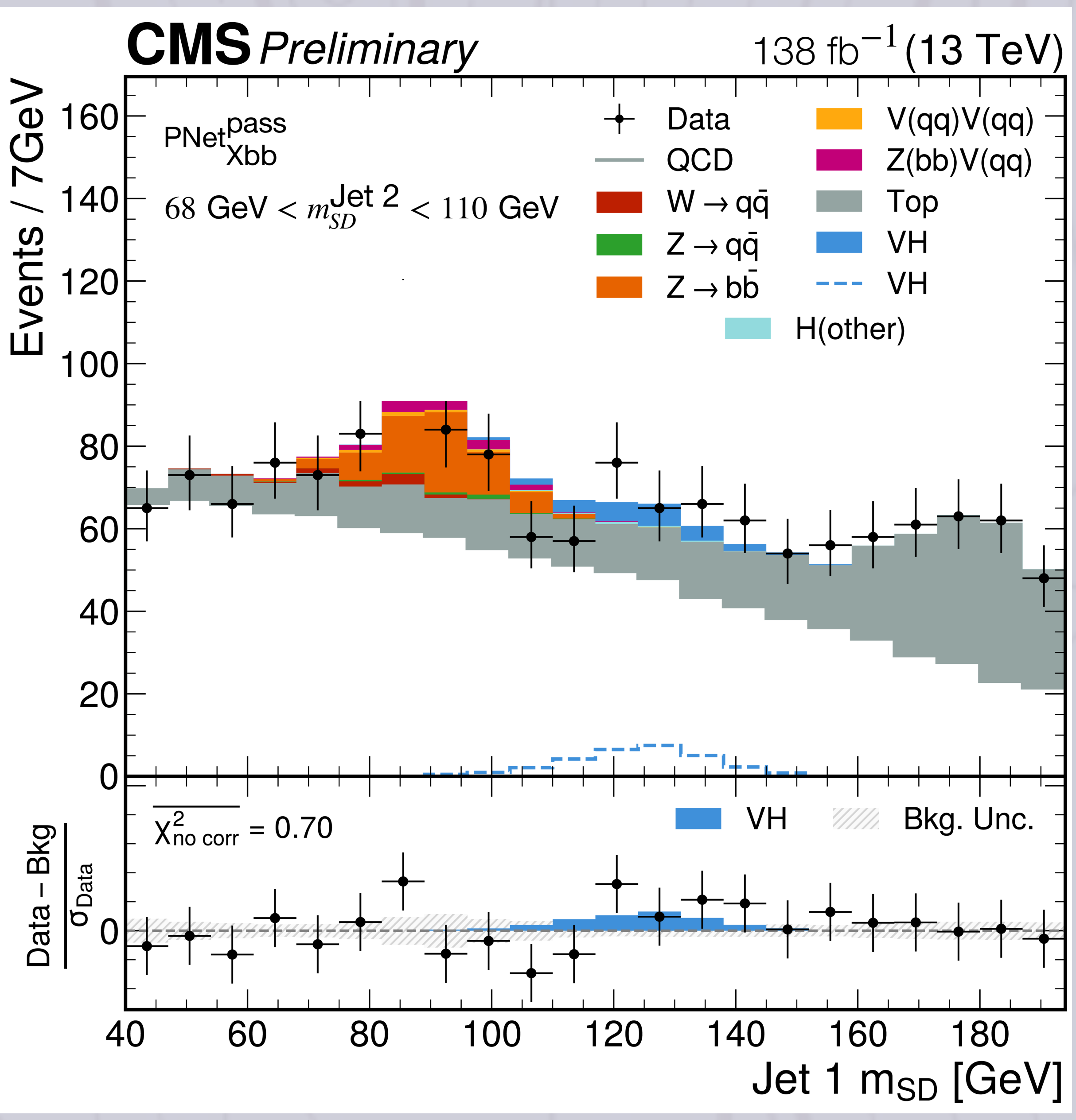


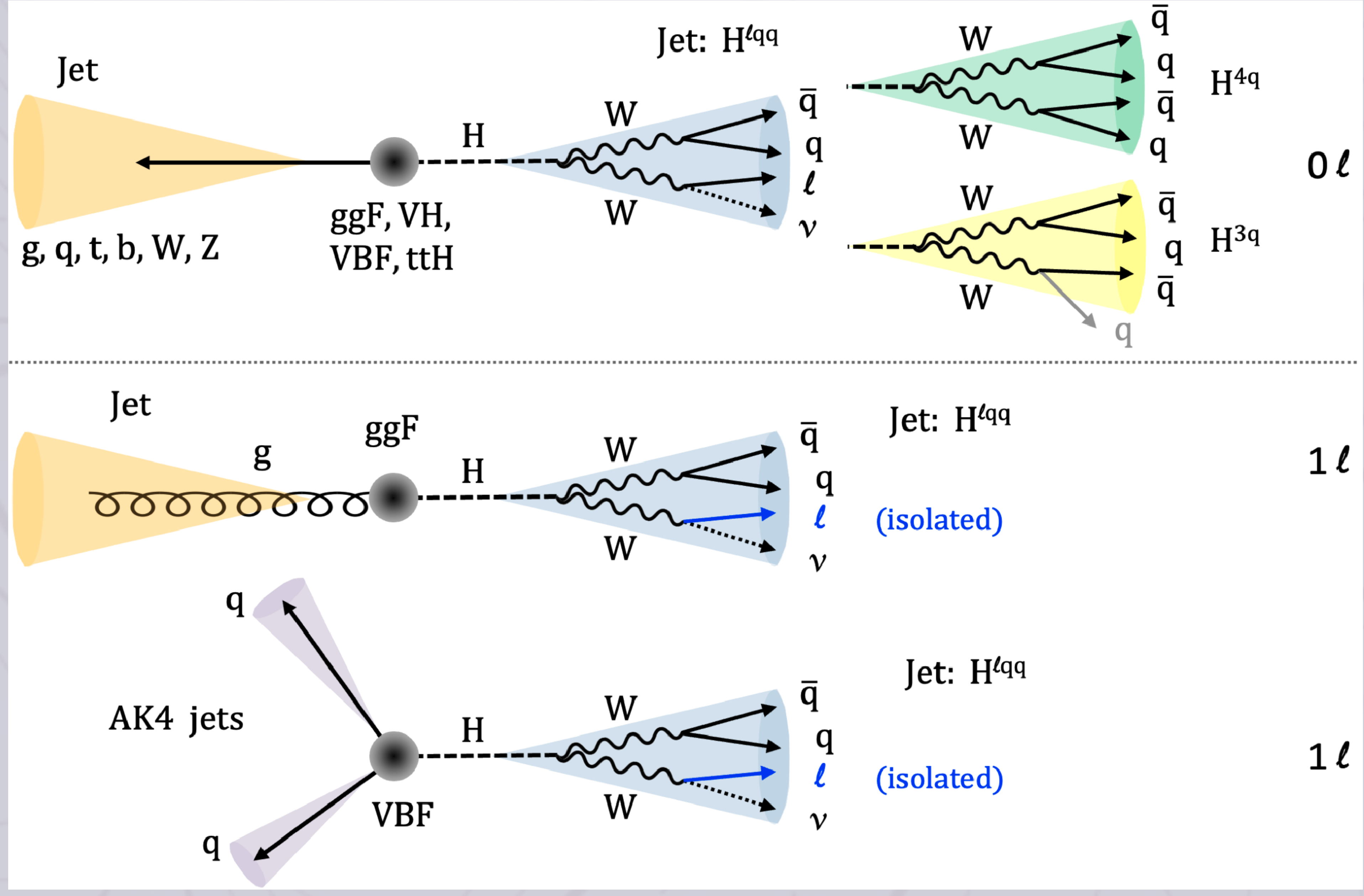


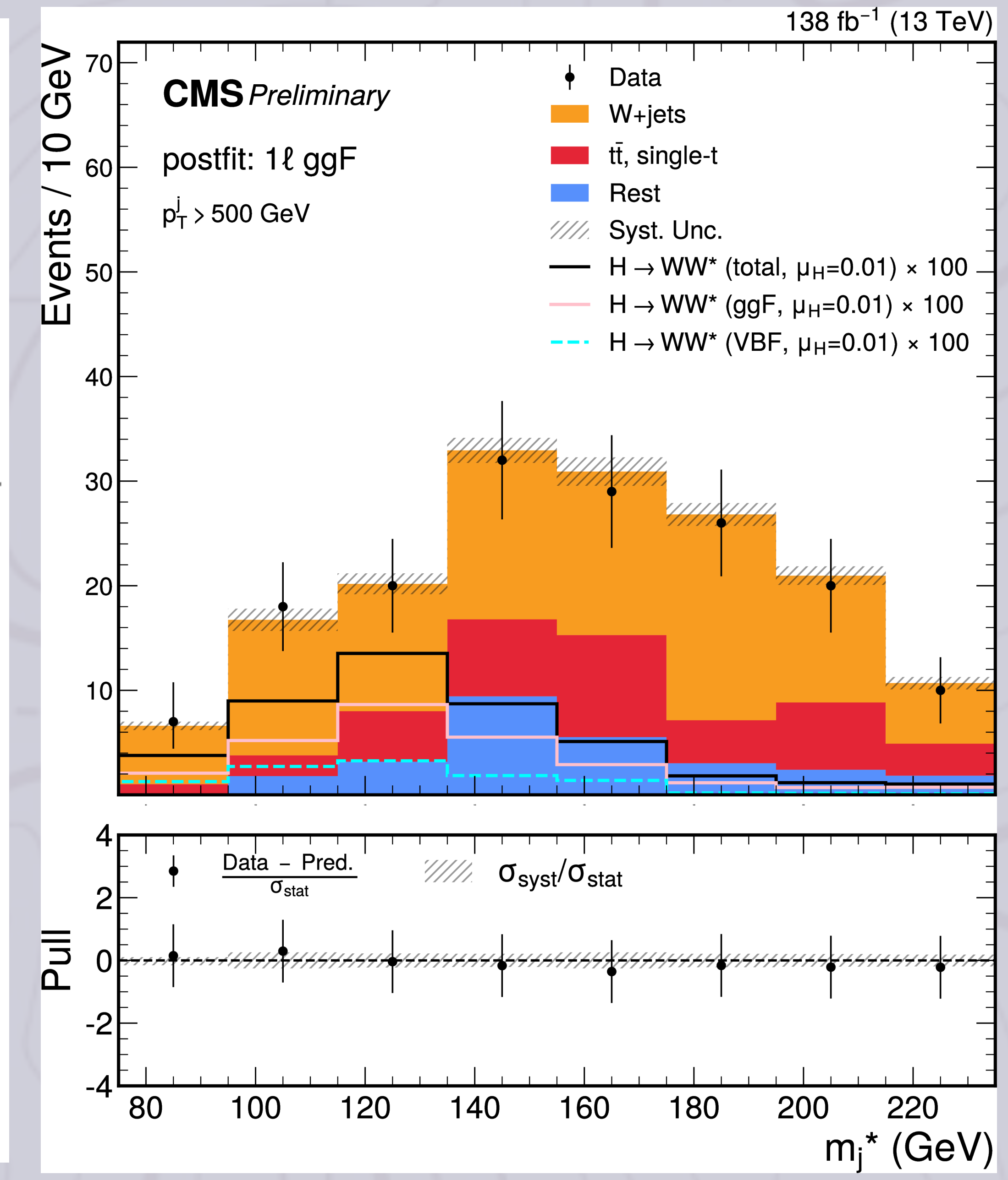


BOOSTED REGIMES AND ML TOOLS

- **The constant improvement in ML techniques have revolutionized the study of the high p_T phase space and continue to advance.** Besides the usual Hbb, Hcc and Htautau results:
  - Hbb, go beyond 1 boosted object: exploit the increased VH contribution at high pT(H) probing V(qq)H(bb) (> 450 GeV), with new techniques (ParticleNet-MD). CMS-HIG-24-017 : $\mu_{VH} = 0.72^{+0.75}_{-0.71}$
  - HWW!: Boosted techniques also applied to ggF+VBF in HWW! : , CMS-HIG-24-008. First example of boosted HWW signature. $\mu_H = 0.01^{+0.63}_{-0.48}$







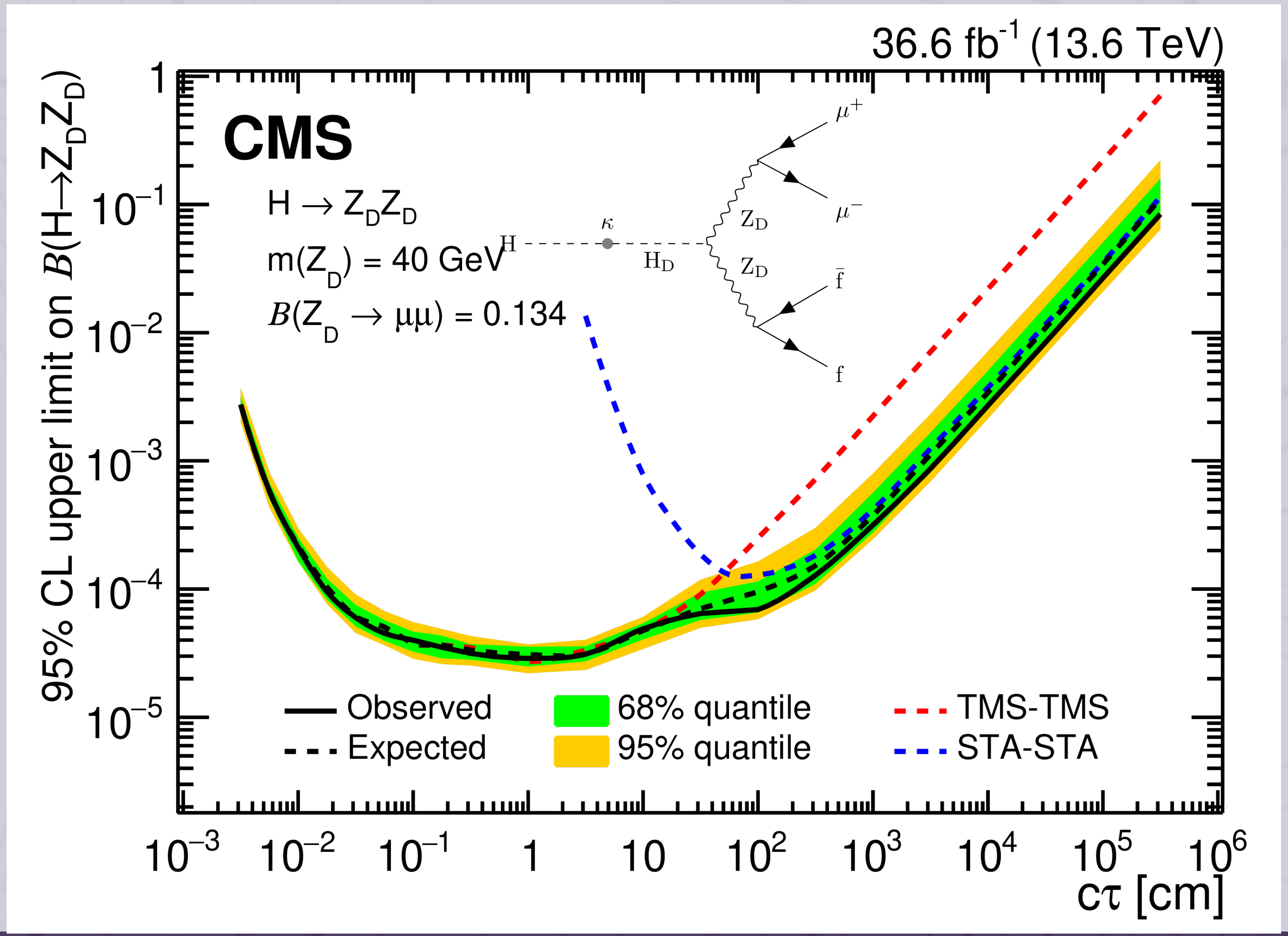
IMPOSSIBLE OR JUST VERY RARE?

- **We have not yet explored all the SM decays of the Higgs.** Some 'Rare' decays like MuMu or ZGamma are at evidence level already. For others, like decays to light quarks or ee, we can only set high upper limits, far away from the SM.
- Beyond the SM… **Why should we assume the Higgs boson follows the SM rules strictly?** Can it decay to the unexpected?
- We also **search directly for Higgs → BSM . eg: Dark Matter, LFV, light scalars, long-lived particles**

For example: direct searches for Higgs decays to **undetectable** particles ('invisible decays') → Does the Higgs boson couple to the **Dark Matter??**

CMS: Br(H_{inv}) < 15% (0.08%) , ATLAS: Br(H_{inv}) < 10.7% (0.077%)

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

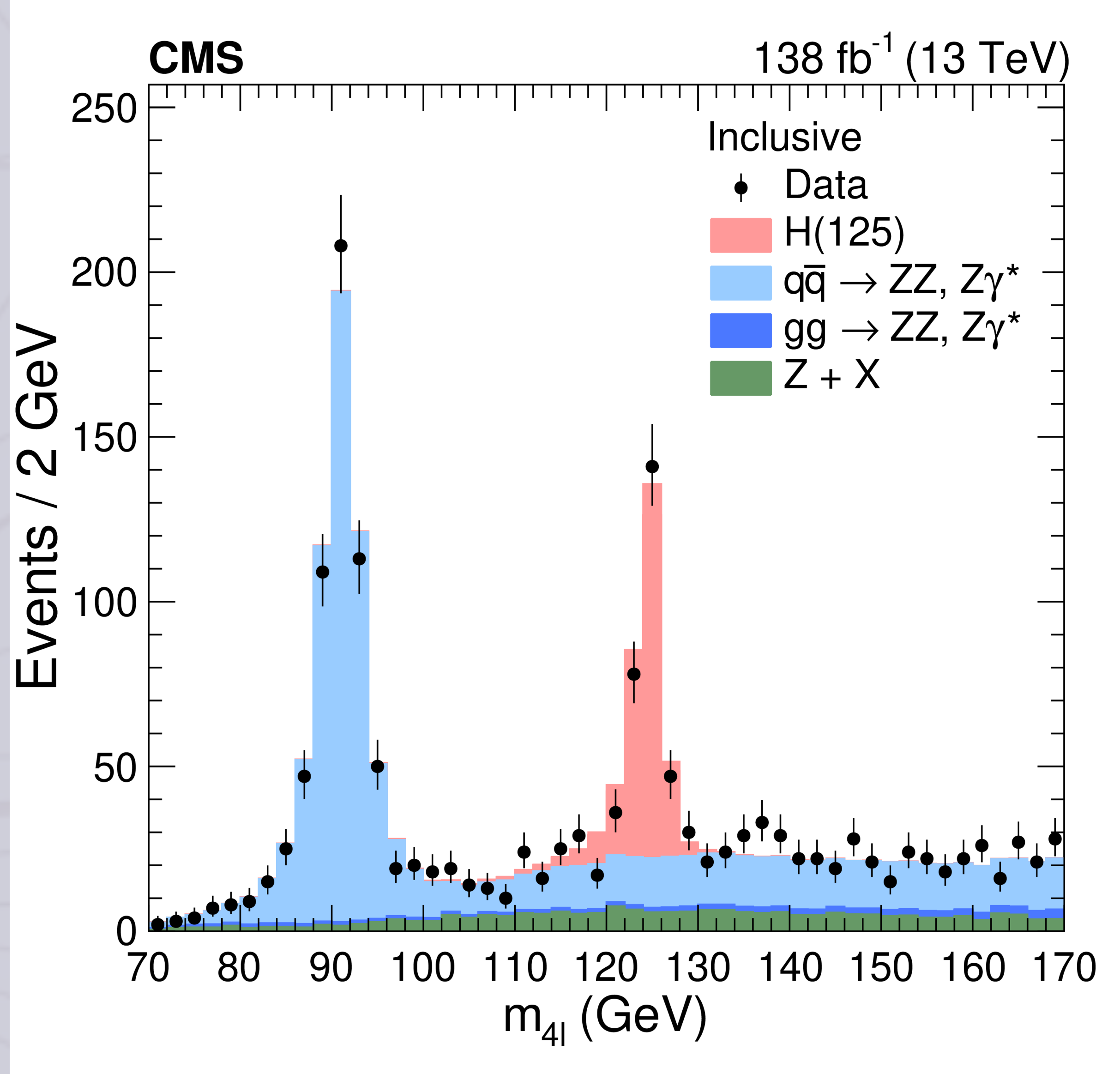


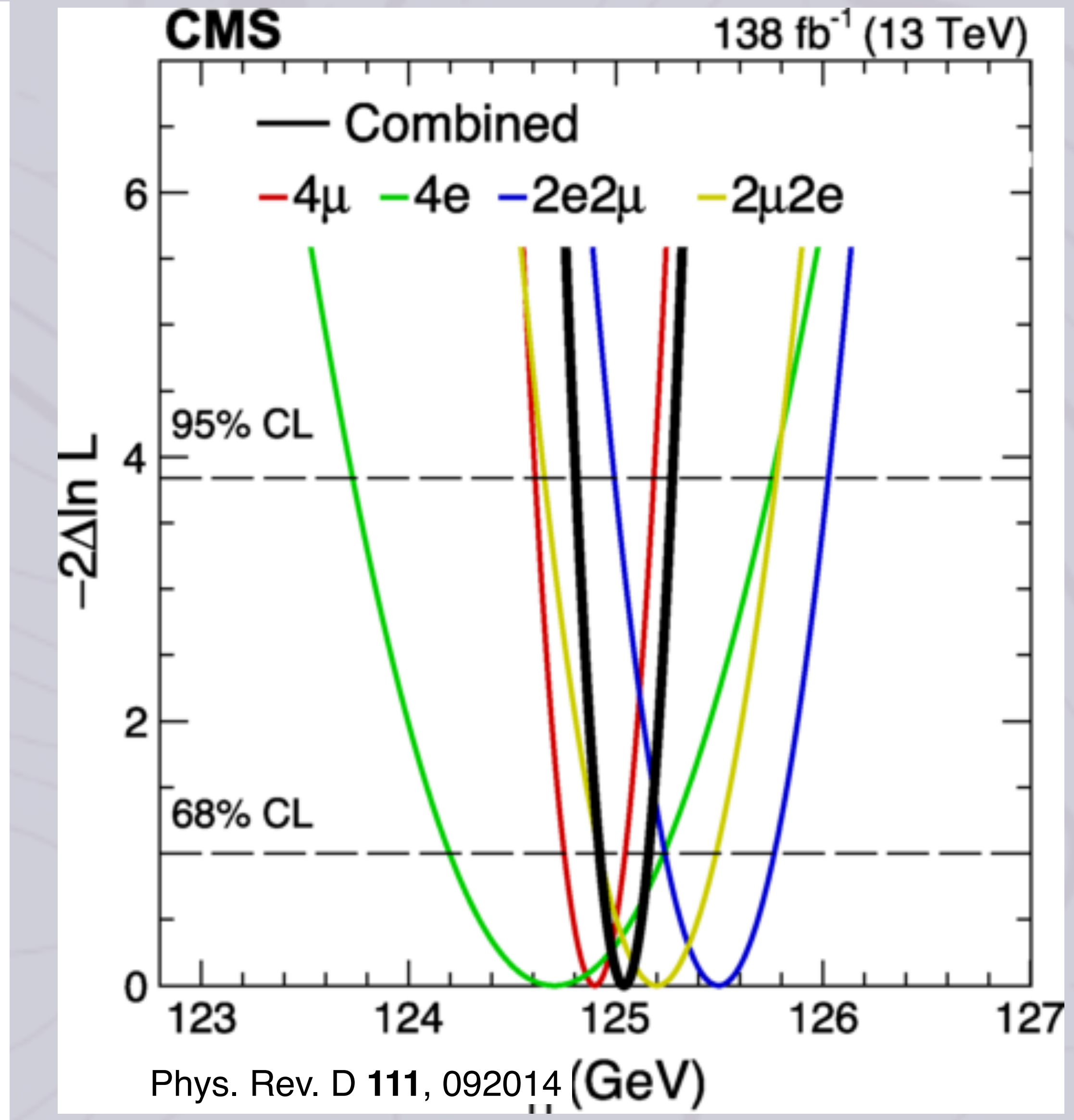
HIGGS PROPERTIES

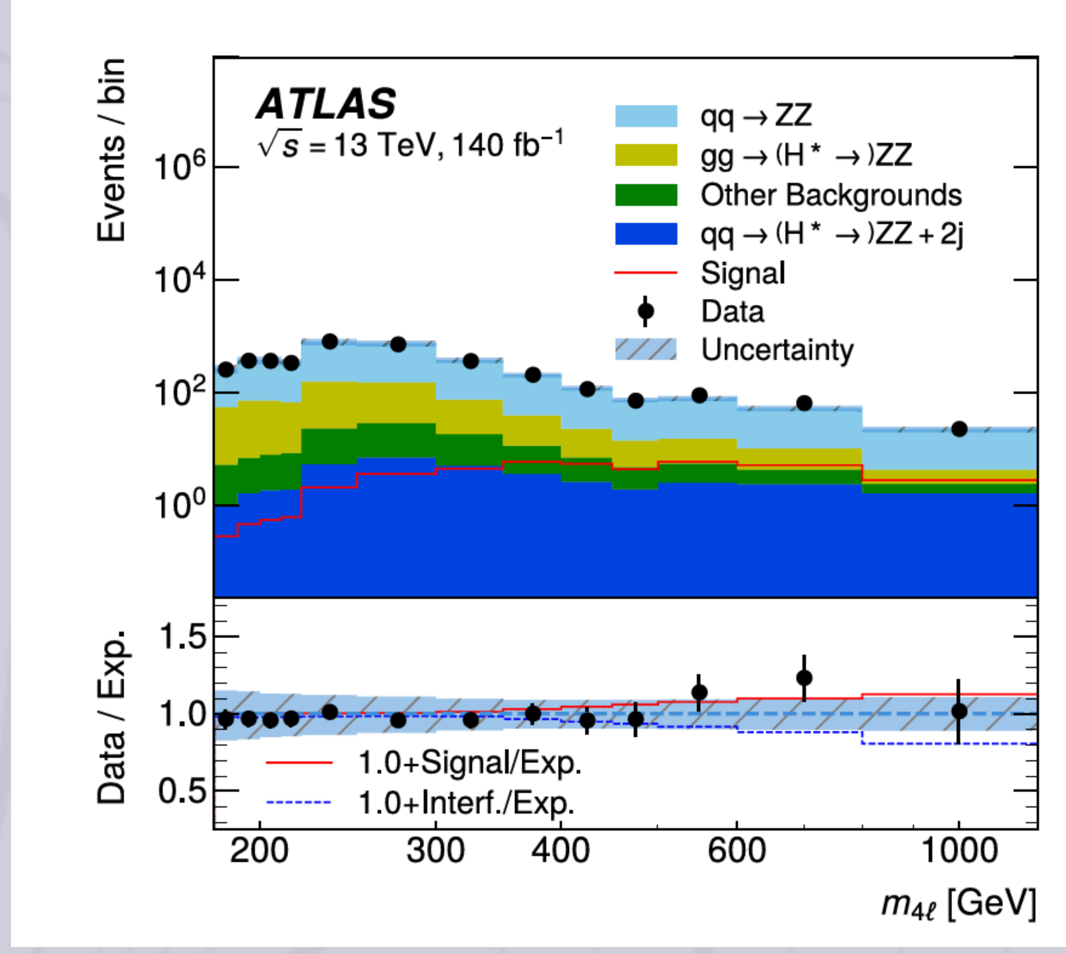
- We found 'a Higgs', but how well we can measure it? What can we learn about the SM through its properties?
- Precision as a probe of the unknown

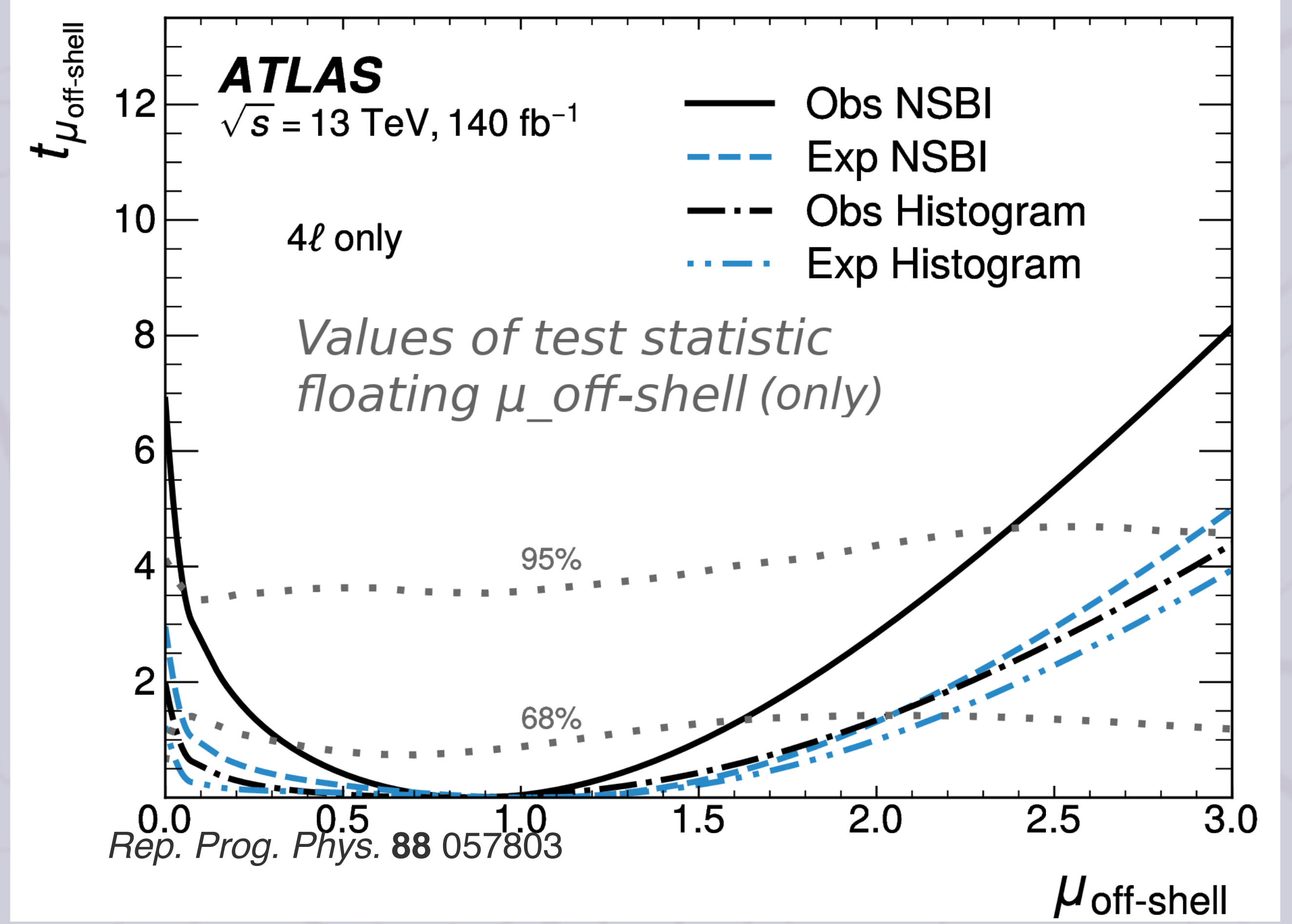
MEASURING MASS AND WIDTH

- **Mass: Free in the SM, now known to 0.1%**
  - Measured through 4l and also diphoton
  - Template fit of mH distribution, categorised by resolution
  - CMS Run1 + Run2:
    - $4l + \gamma\gamma\ (Run2\ 36\ \text{fb}^{-1}) : 125.38 \pm 0.14\ GeV$
    - $4l\ (Run2\ 138\ \text{fb}^{-1}) : 125.04 \pm 0.12\ GeV$
  - ATLAS Run1+Run2:
    - $4l + \gamma\gamma, > 140\ \text{fb}^{-1} : 125.11 \pm 0.11\ GeV$
- **Total Width: Very small in SM! (4 MeV)**
  - Direct measurement: <330 MeV (CMS, Run2, 95% CL)
  - Offshell/onshell measurements in Run2):
    - CMS: $3.0^{+2.0}_{-1.5}\ MeV$, ATLAS: $4.3^{+2.7}_{-1.9}\ MeV$
  - Width also constrained in HWW!
    - ATLAS: 13.1 MeV







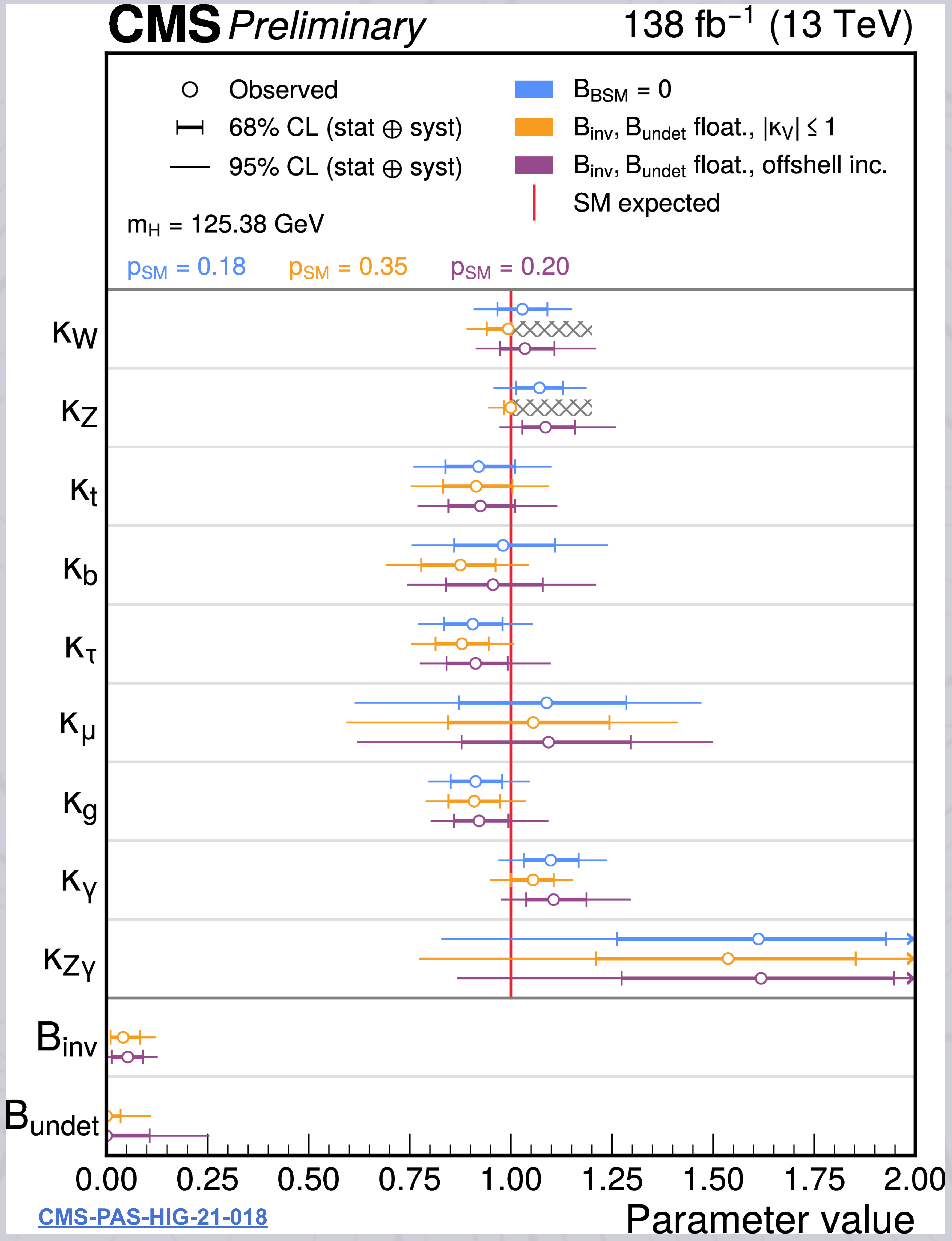


HIGGS COUPLINGS

- **What is the strength of the interaction of the Higgs to the different SM particles?**
  - Simplest approach: Kappa Framework

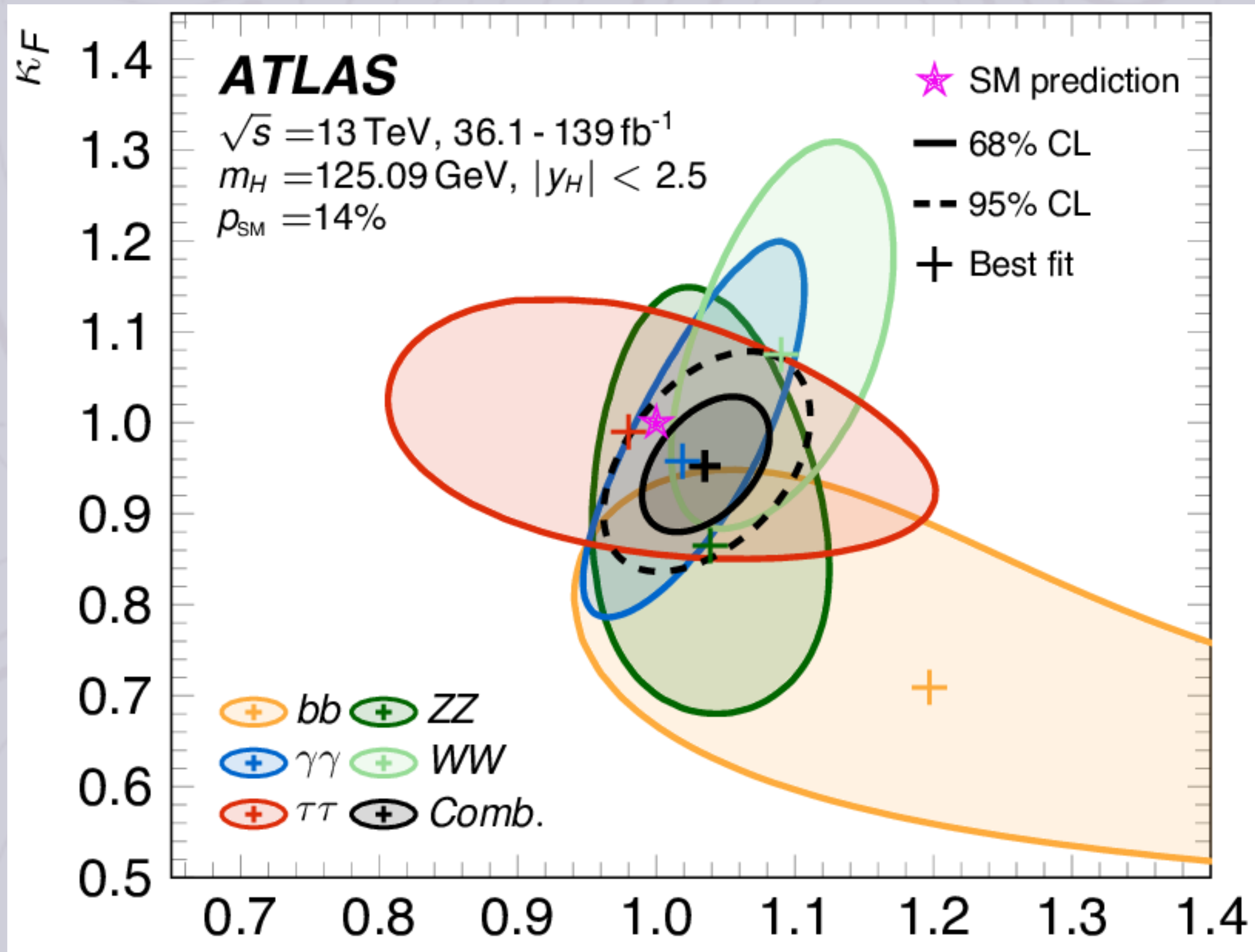
$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \qquad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

  - Simple parametrisation widely used by LHC experiments (not perfect, but very useful since it is close to what we measure)
  - With the full Run2 Combination (per experiment): 'Main' modes already known to 5-12% for the (~20%-30% for stat dominated $\mu\mu$, $Z\gamma$)
  - Ratios of couplings ($\lambda_{ij} = \kappa_i/\kappa_j$) to further control uncertainties

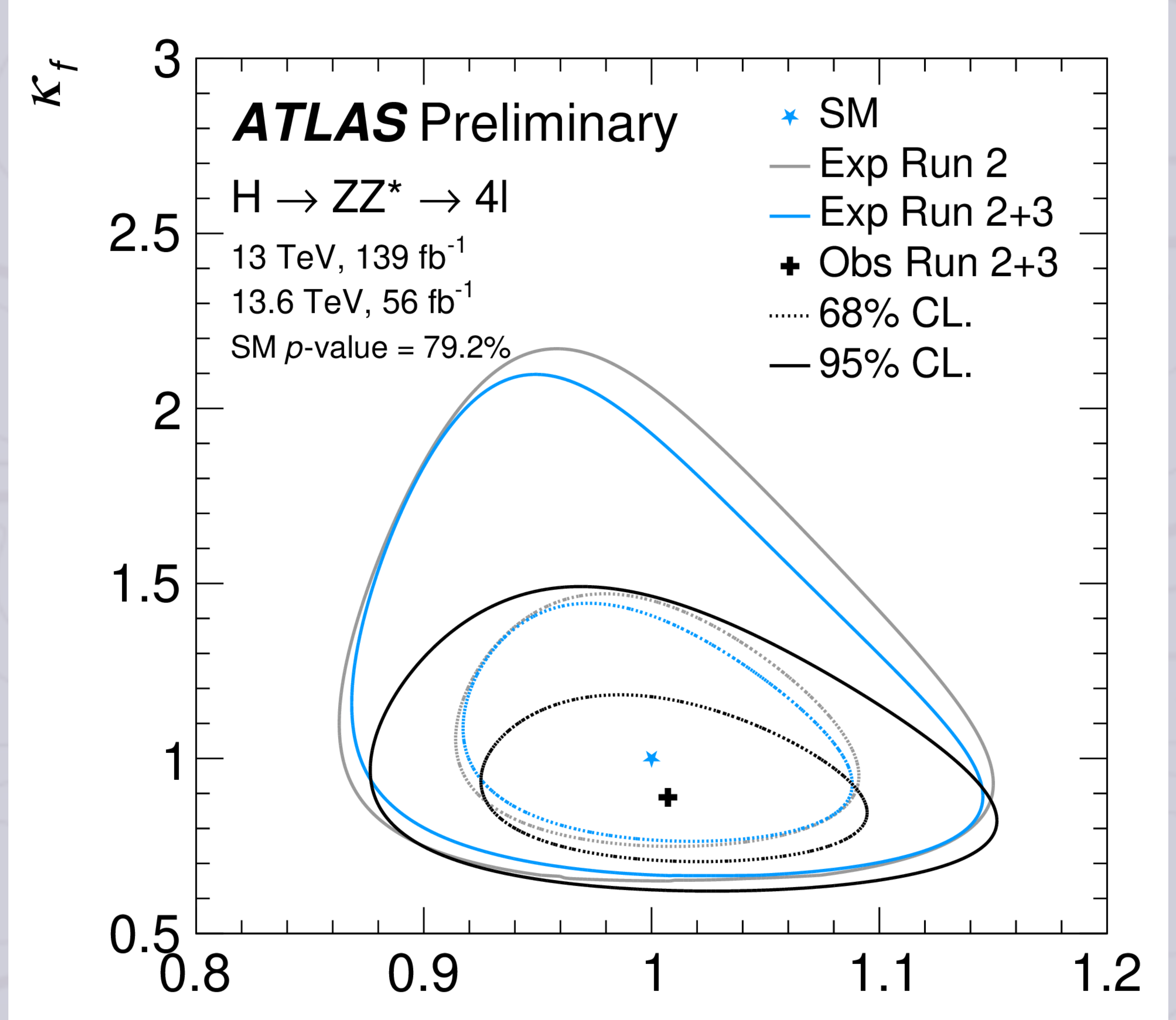


HIGGS COUPLINGS

- For the full view we need all channels: so far only Run2. First individual studies with Run2+Run3 arriving (eg, ATLAS HZZ , probing fermion vs boson coupling)



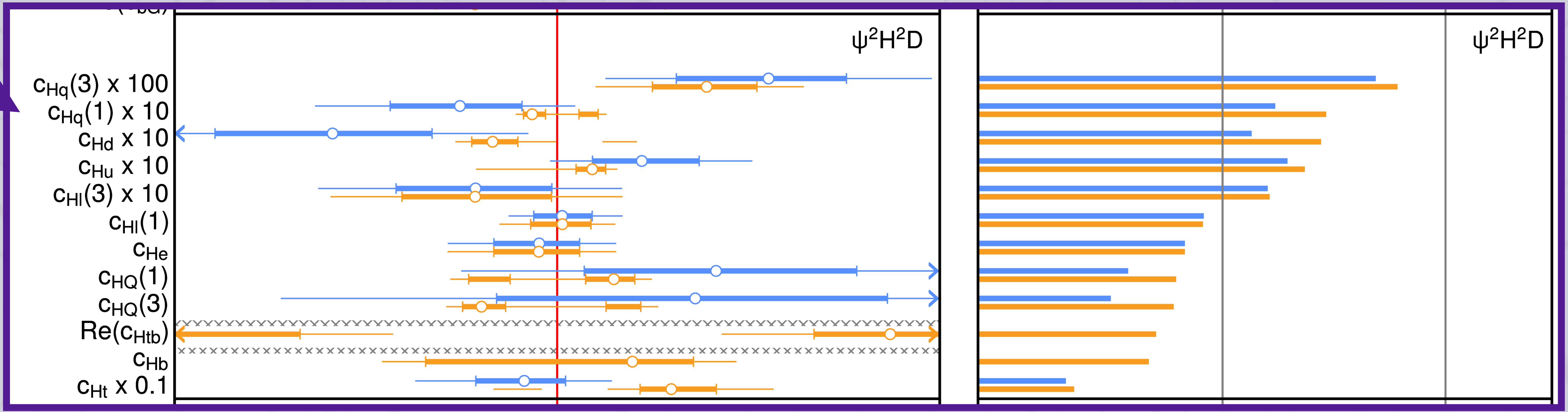
Nature 607 52 (2022)



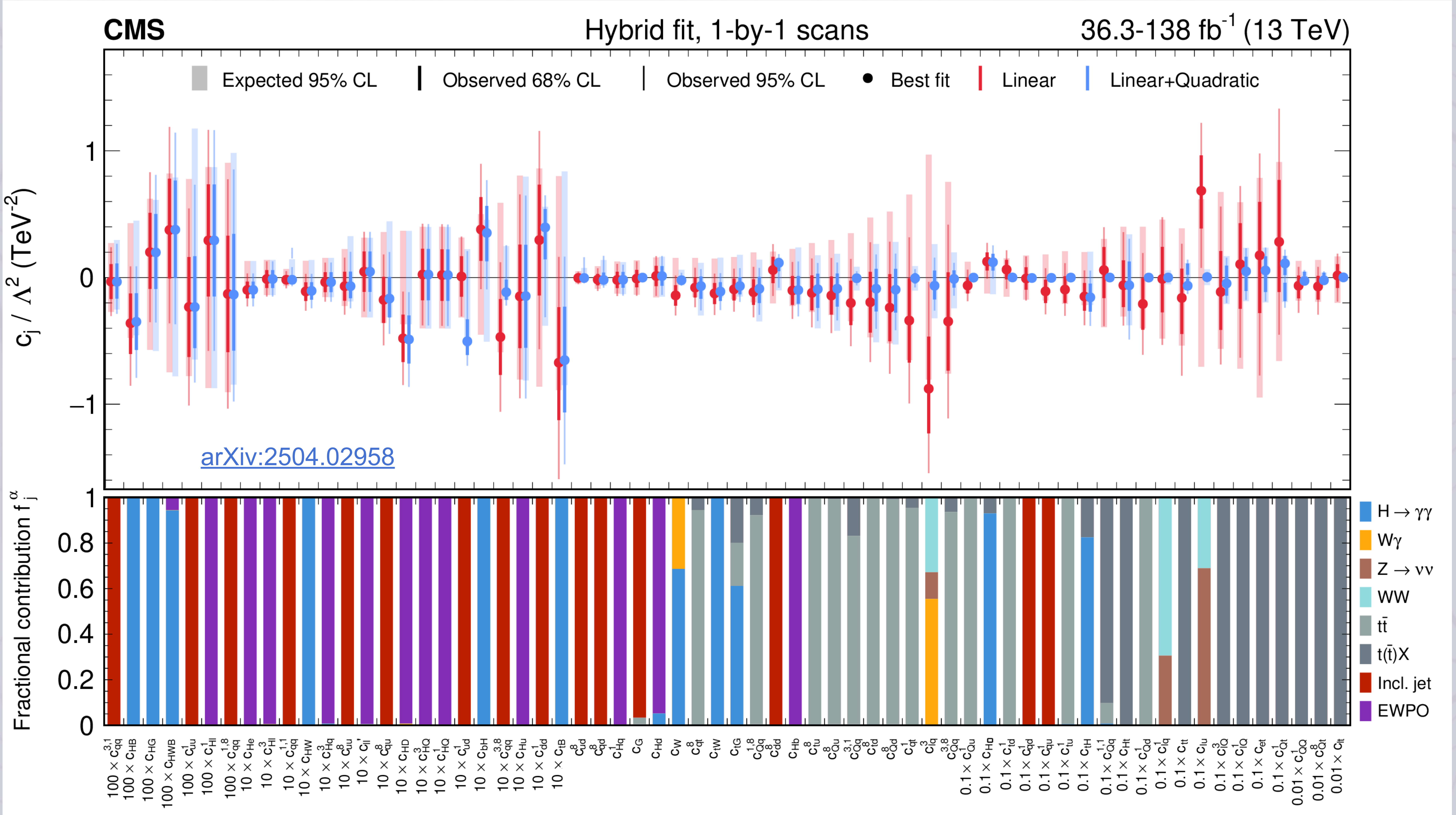
ATLAS-CONF-2025-002

BEYOND KAPPAS: SMEFT FITS

- We discussed constraints of specific SMEFT operators as a part of individual analyses
- We can also extract constraints on 43 Wilson Coefficients (linear and linear+quadratic parameterizations)
- The largest discrepancy from the SM is observed in the $c^{(3)}_{Hq}$ parameter (pSM = 0.01), driven by the observed excesses in the high-p_T(V) in WH and ZH leptonic STXS measurements.
- 17 independent directions in the SMEFT parameter space also constrained from the Higgs combination. Overall good agreement with SM (pvalue = 0.11).



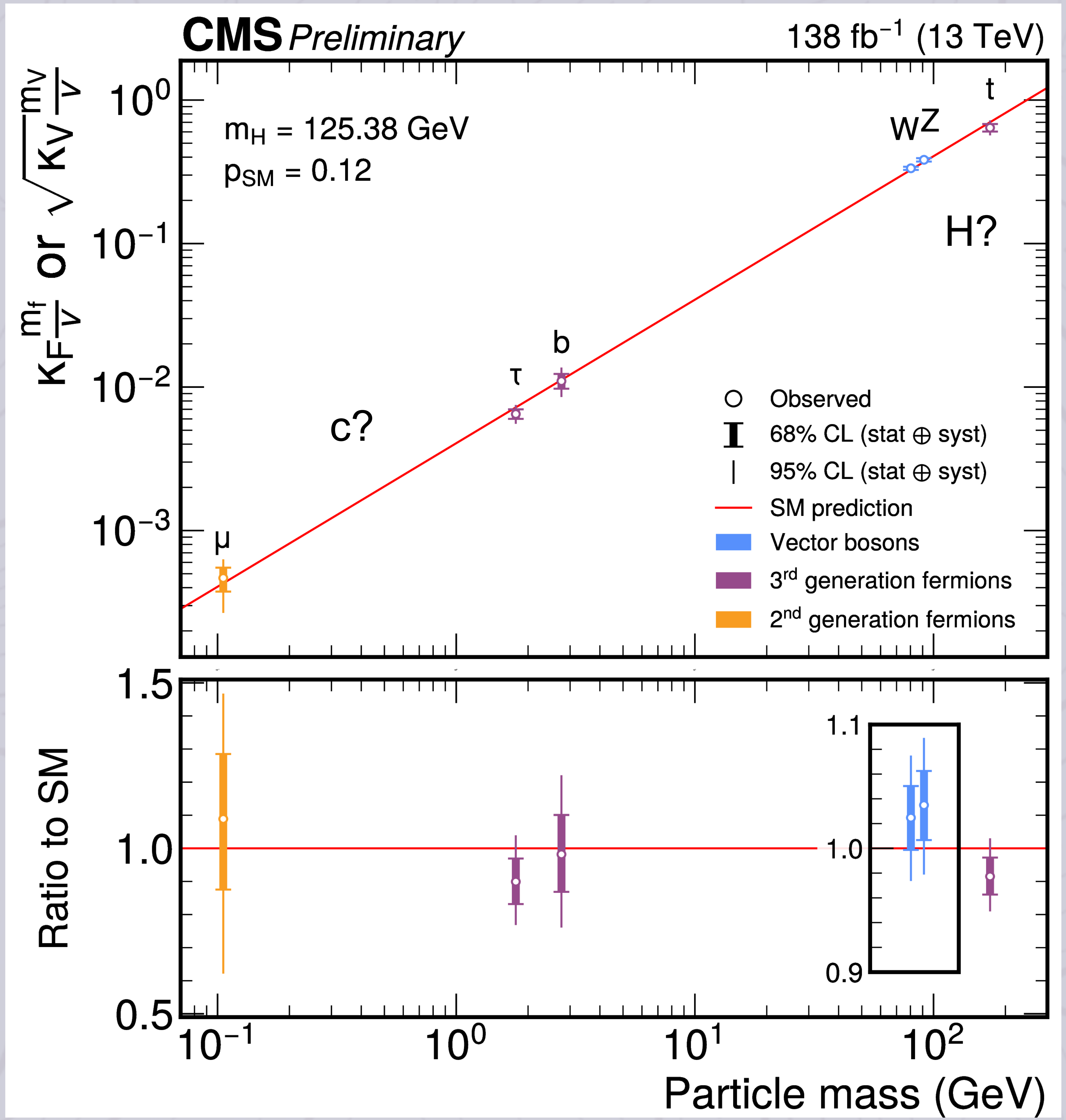
GLOBAL FITS: NOT ONLY HIGGS



- This goes beyond the topic of this talk… but for a full exploration of SMEFT, more input will be needed
- Both ATLAS and CMS are starting to do global fits incorporating top, EW and Higgs
- As an example, SMEFT constraints by CMS (arXiv:2504.02958) including Hgammagamma
- Constraints vary from 0.002 to 20 TeV^{-2}

VERY SM SO FAR..

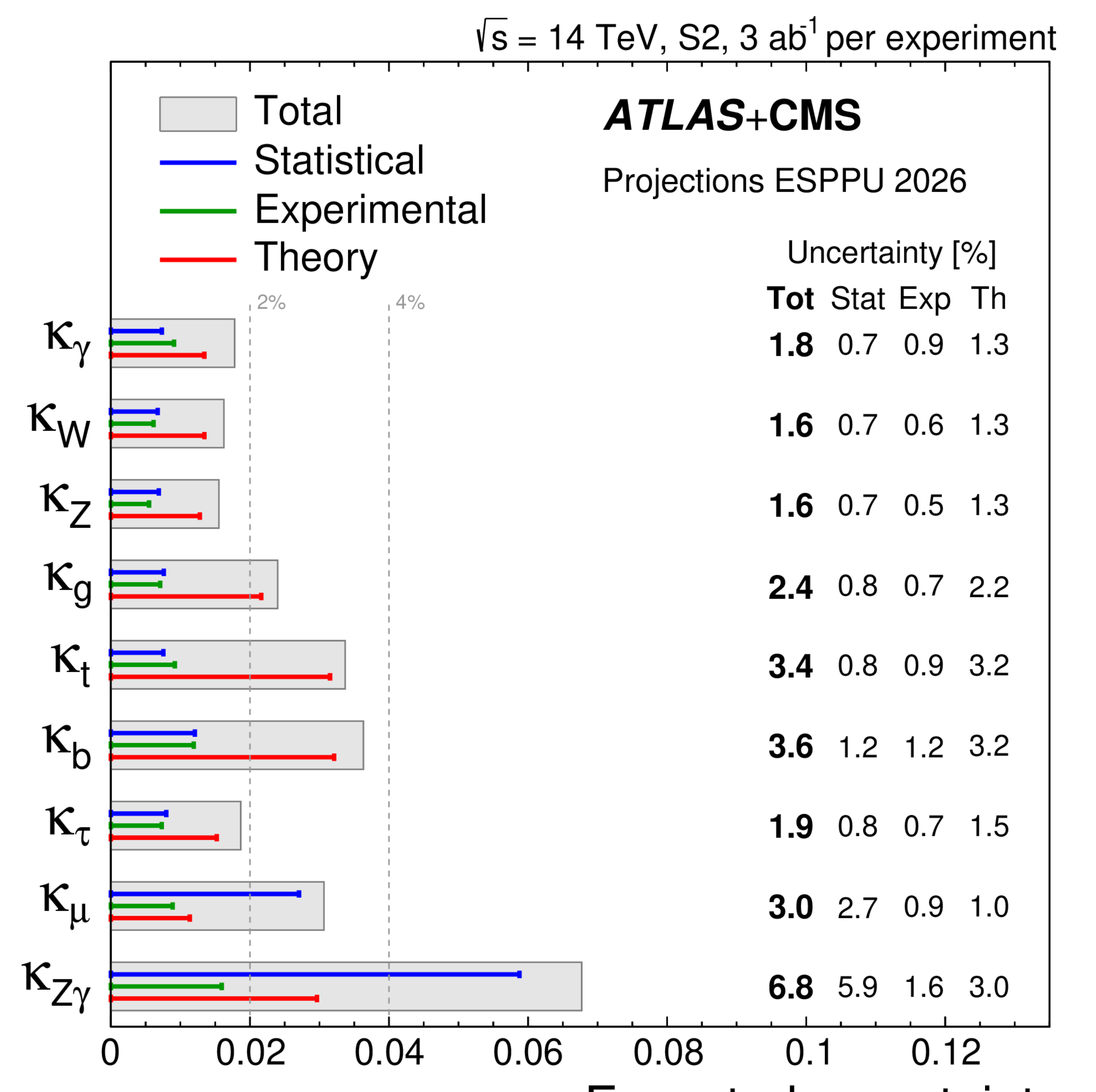
- So far the couplings we have measured are remarkably close to the SM predictions
- However, the picture is not yet complete (second generation, self coupling), and there is room for surprises (eg, what happens with DM?)
- Furthermore, even if the current direct and indirect searches for BSM in Extended Higgs Sectors (high mass, low mass, decay) so far confirm the SM, large phase-spaces remain to be covered
- More data, and further precision is needed.



MORE DATA IS COMING

We've explored a small fraction of the full HL-LHC dataset

LOOKING FORWARD: THE HL-LHC



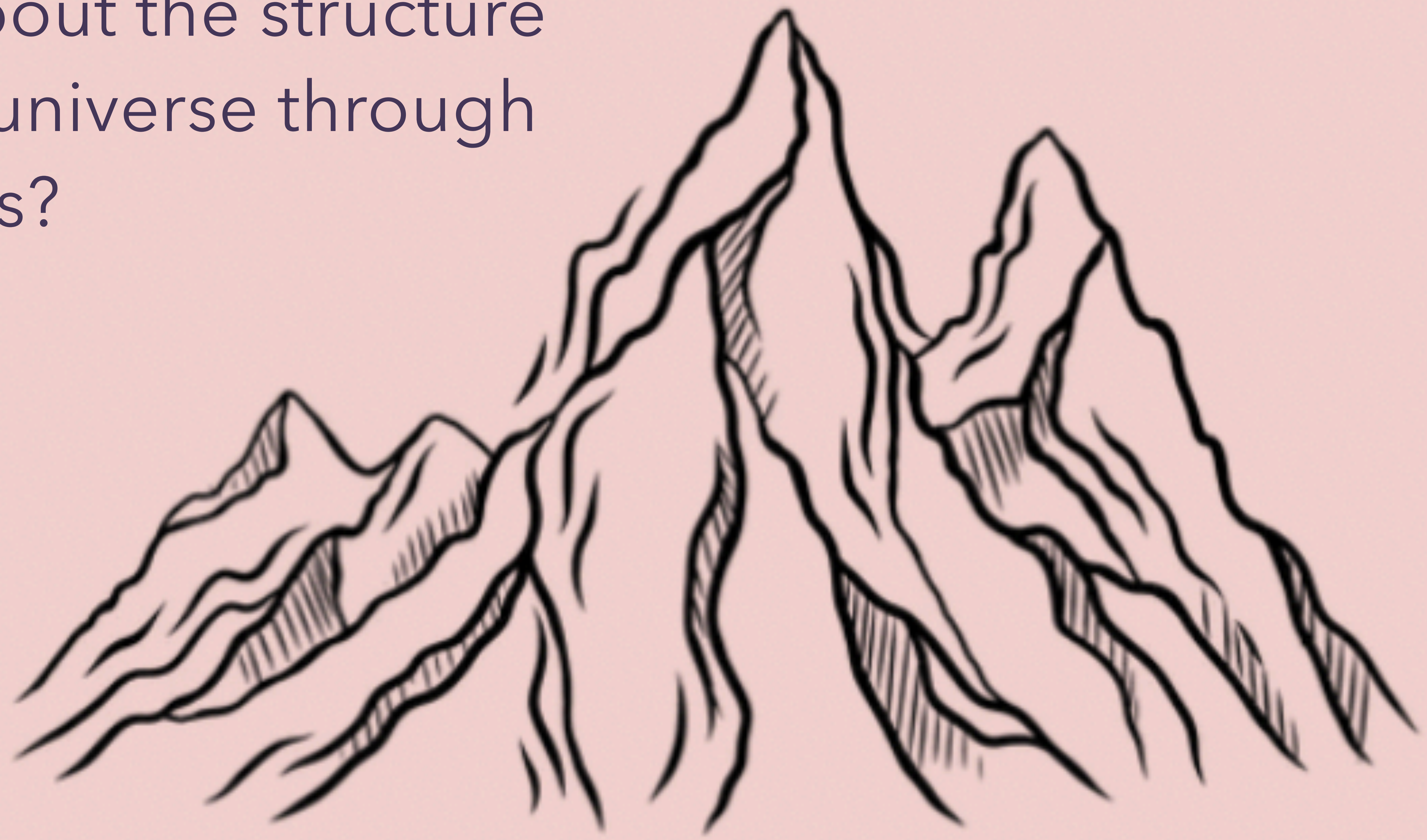
ATL-PHYS-PUB-2025-018

- Projections of Couplings updated for European Strategy, to be discussed next week in Venice

Open Symposium on the European Strategy for Particle Physics

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?

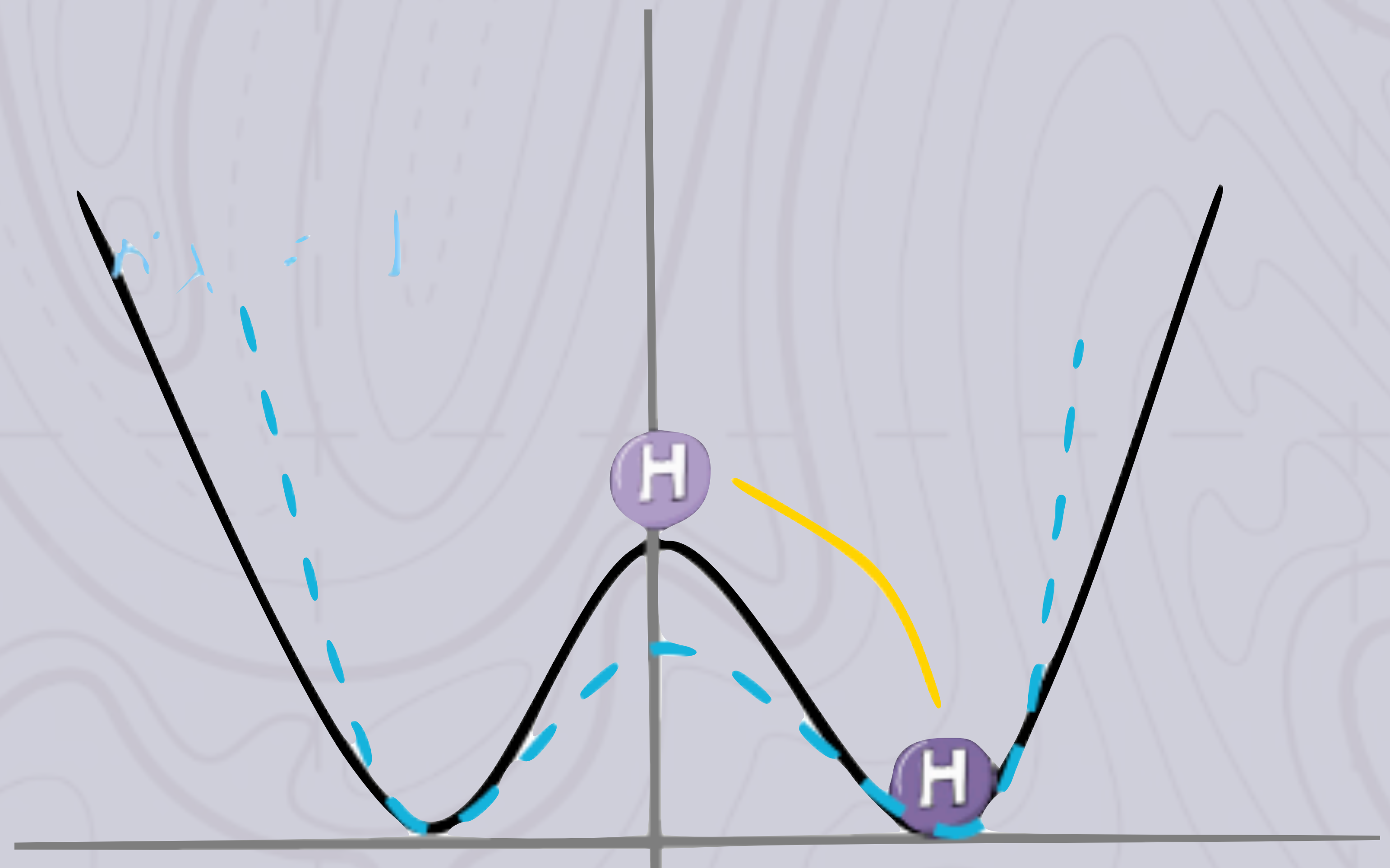


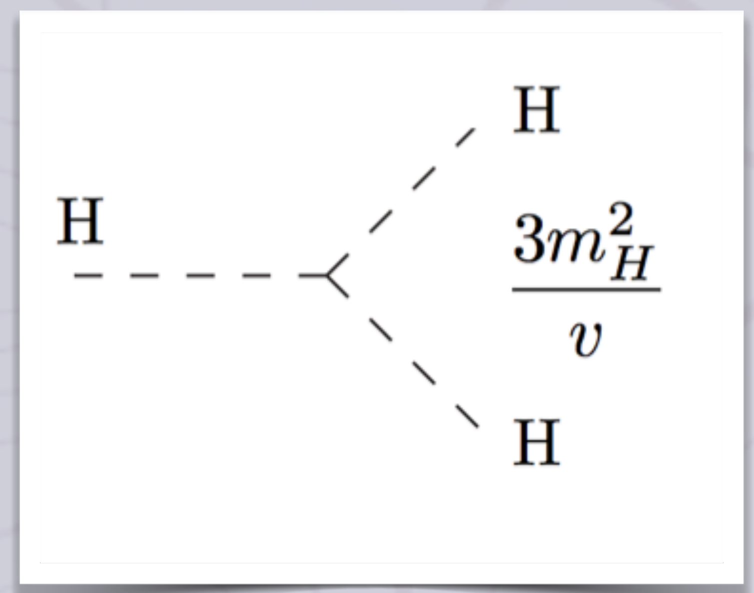
Diagram by Arely Cortes

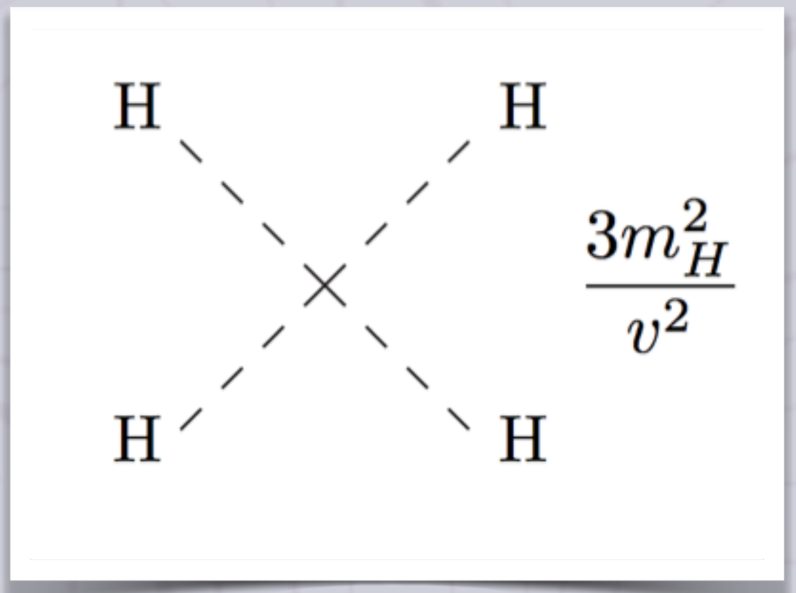
$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

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

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

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

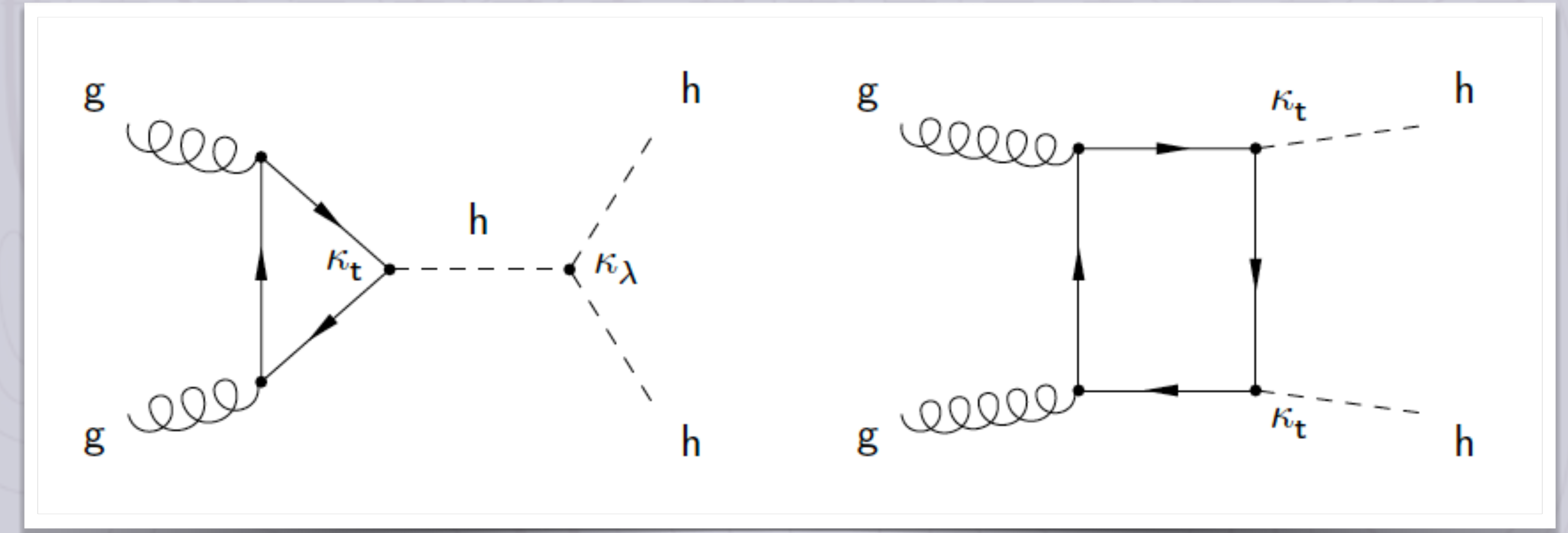


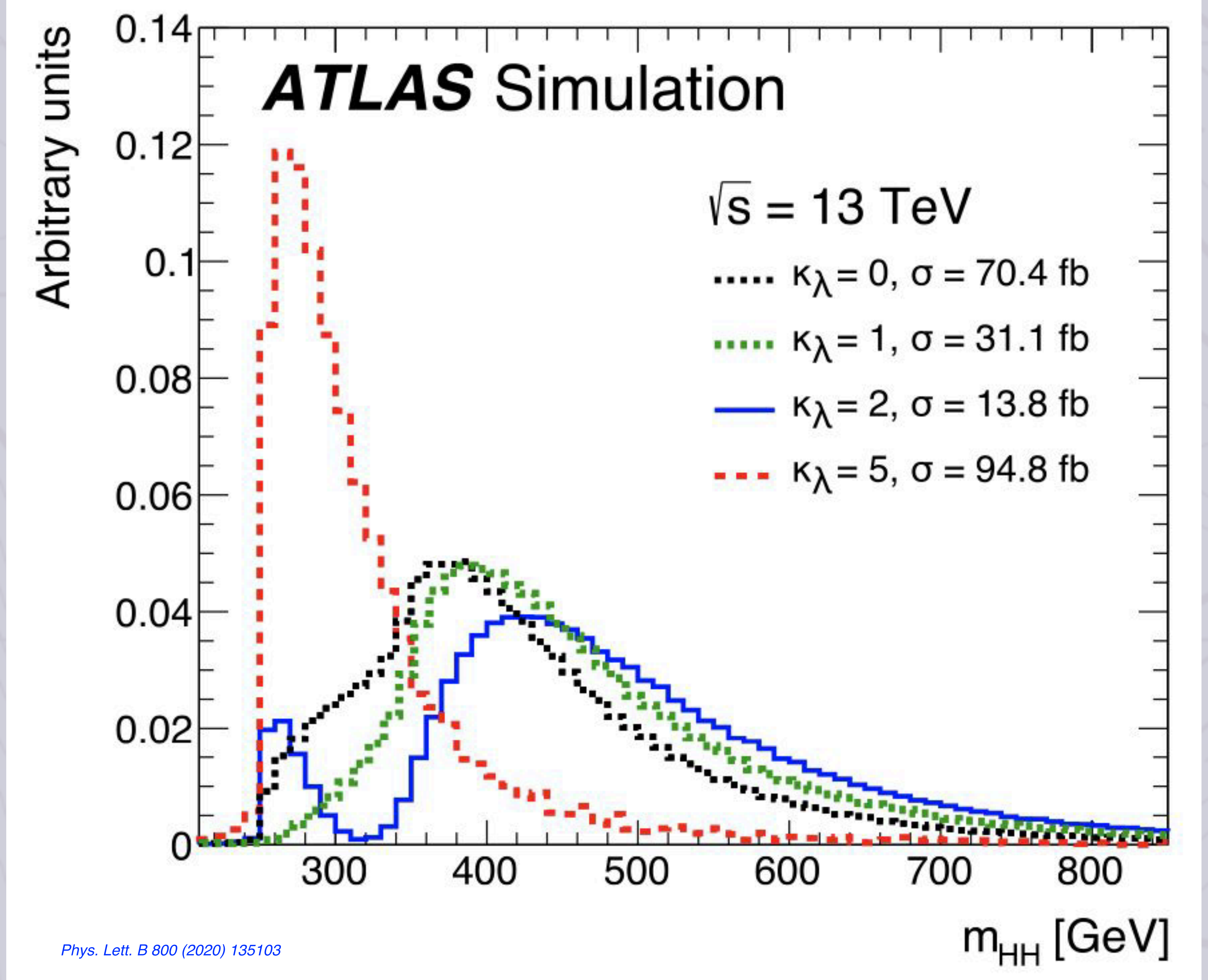


One of the key objectives for the LHC in this run and the future: narrowing down our understanding of the Higgs Potential through the search for HH production

LOOKING FOR HIGGS BOSON PAIRS

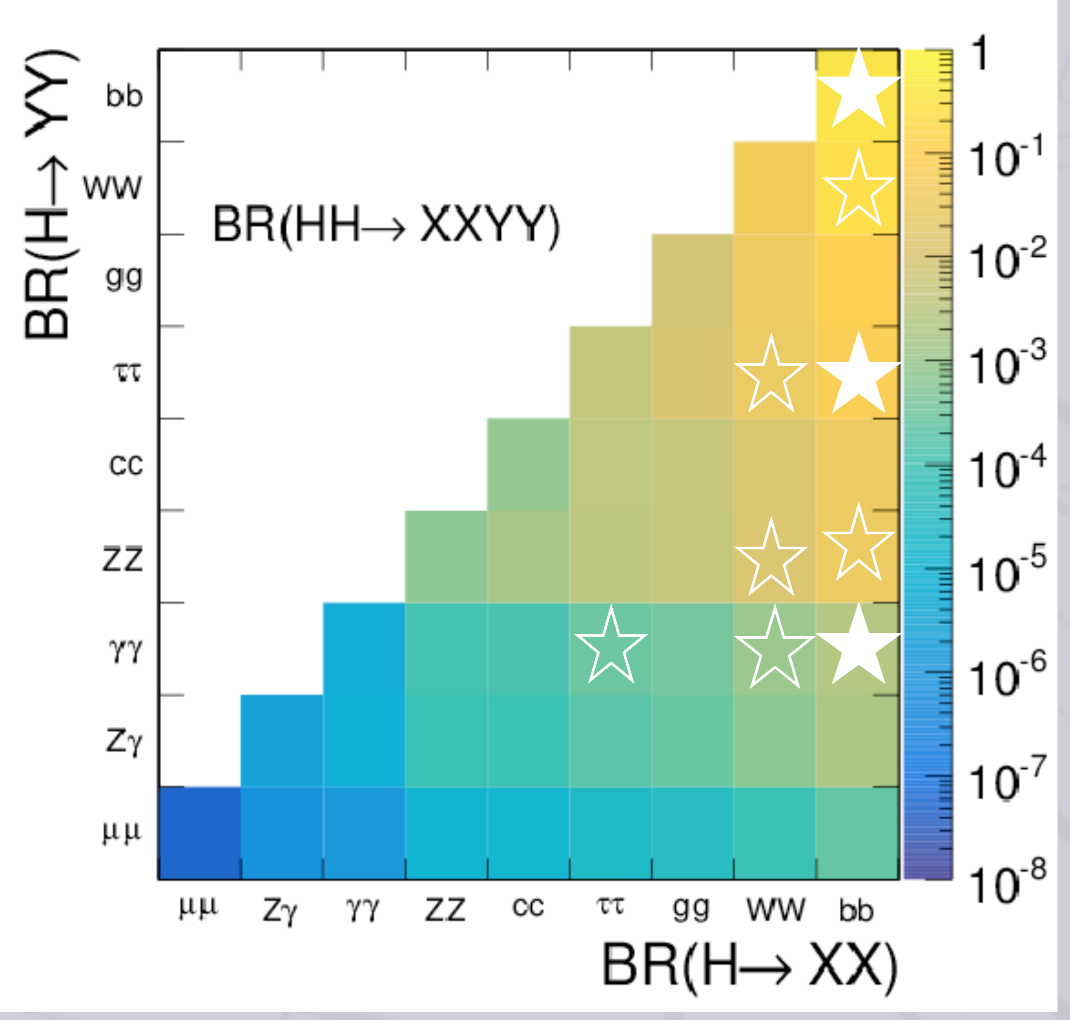
- **Simplest way to access the self coupling at LHC: through the production of Higgs boson pairs**
- Easiest does not mean easy! Very low cross section (σ~ 31 fb@13TeV): destructive interference between triangle and box diagrams
- Sensitive to BSM physics : *Small* changes of the couplings can lead to *large* changes in production

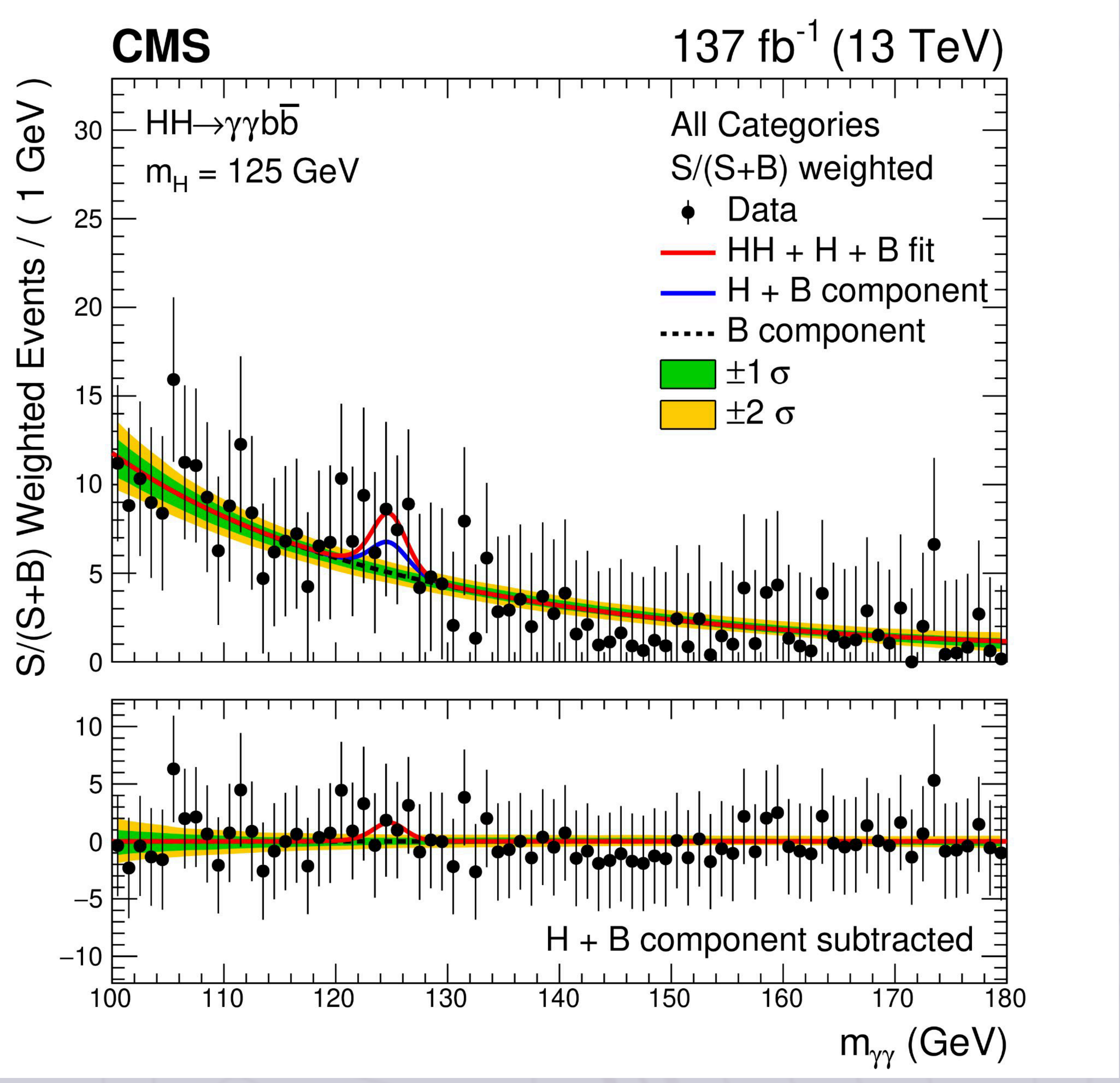


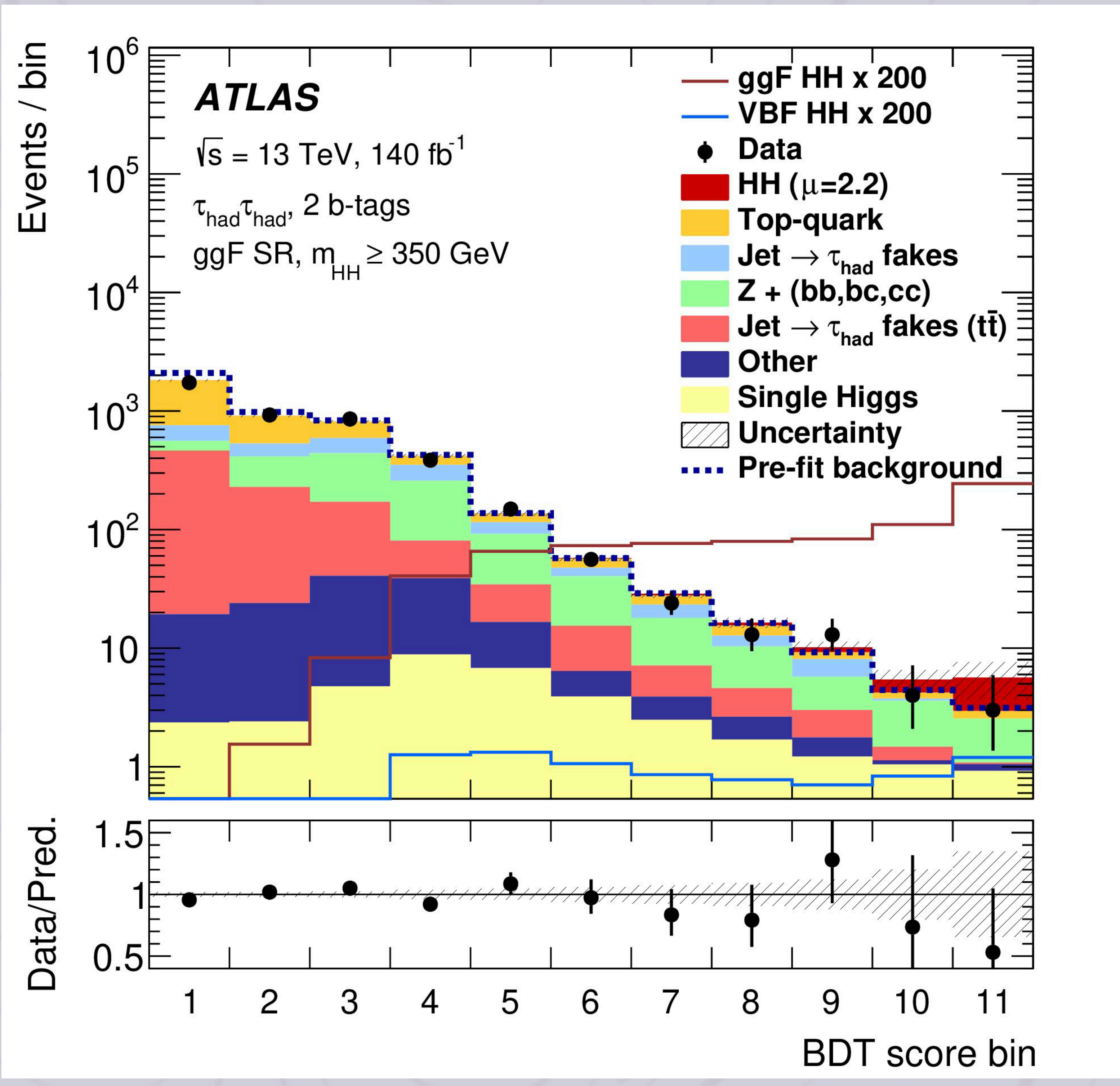


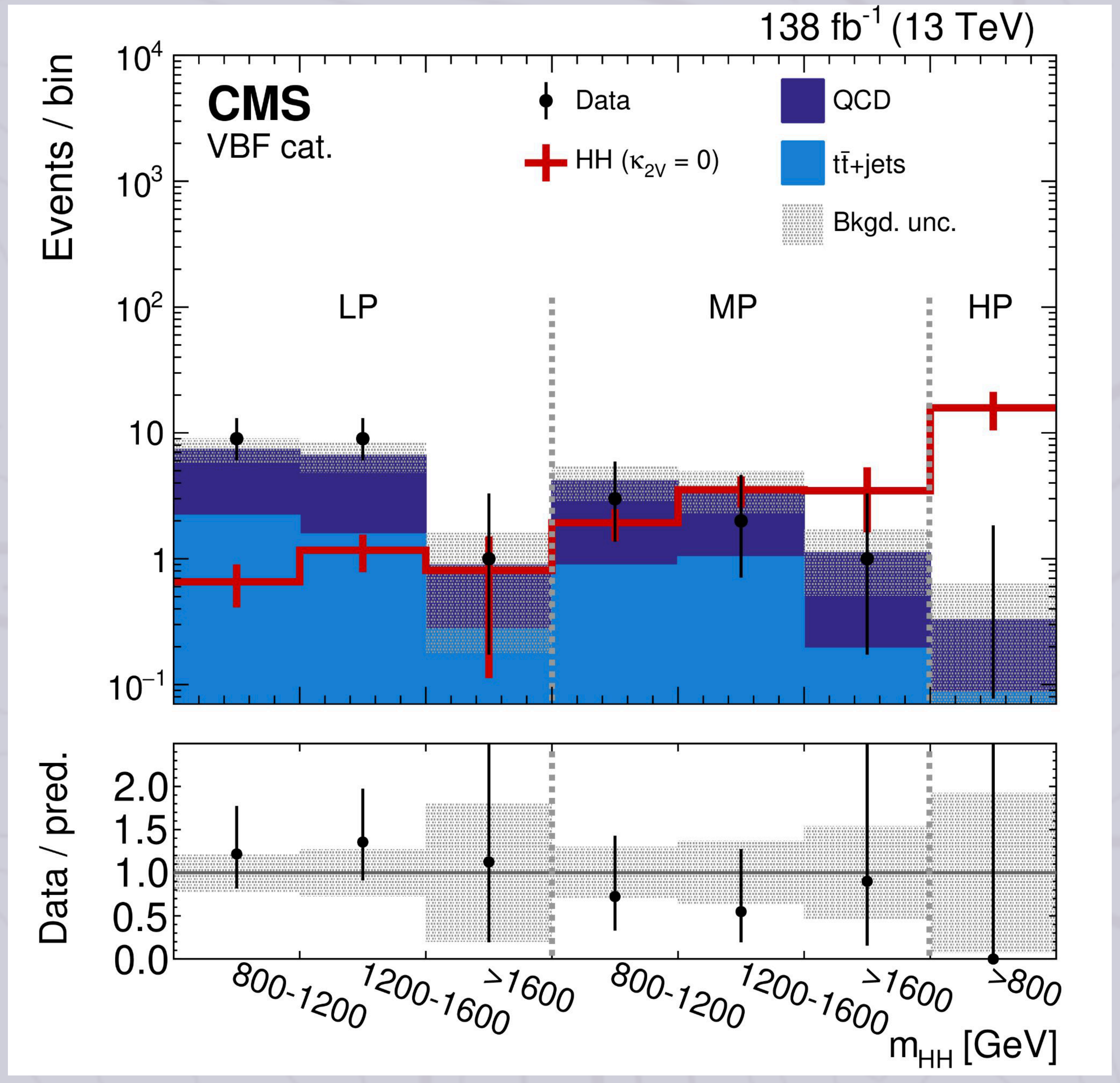
'GOLDEN' CHANNELS

- To study HH production we apply the tools perfected in single Higgs analysis… and some 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





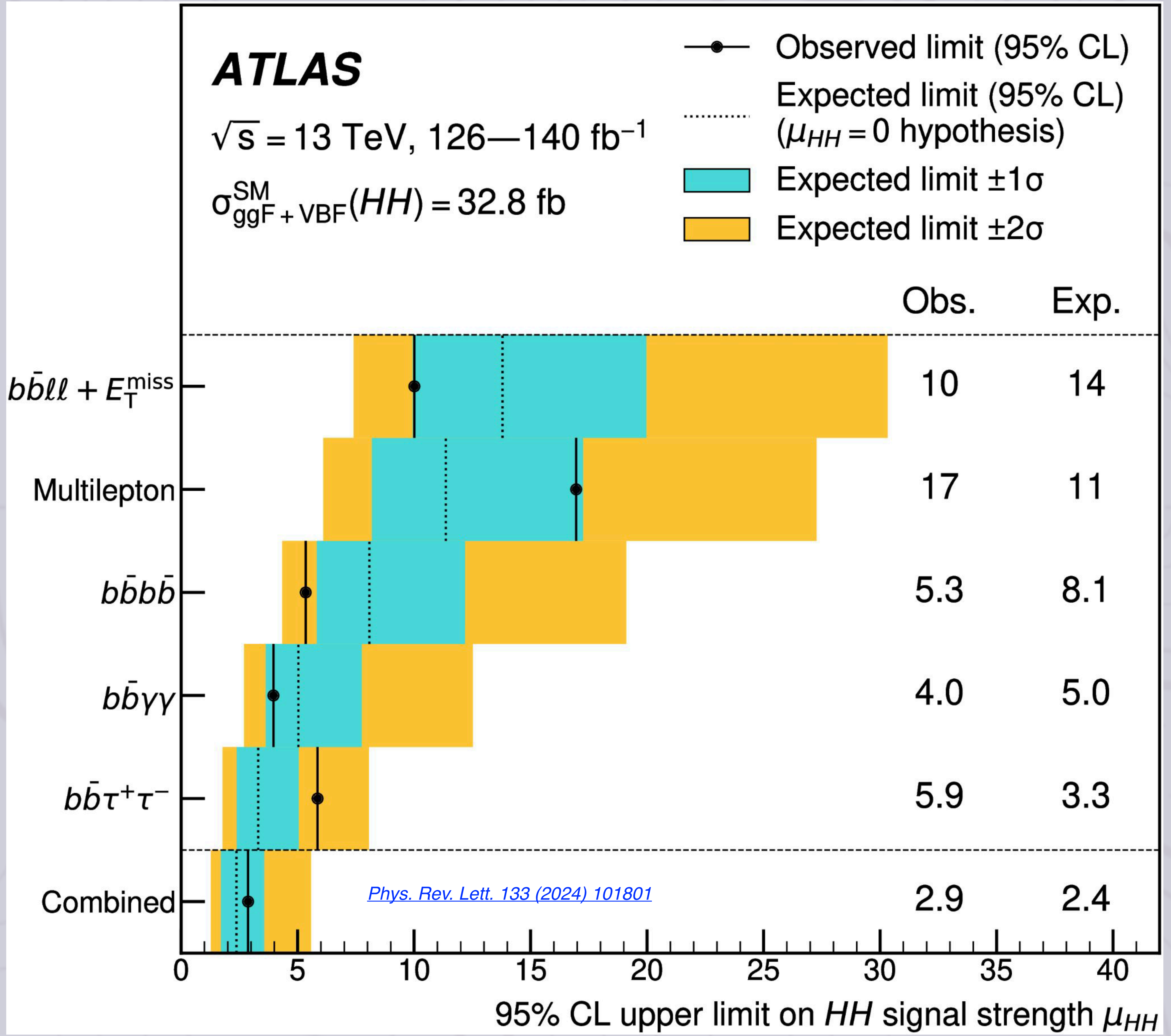


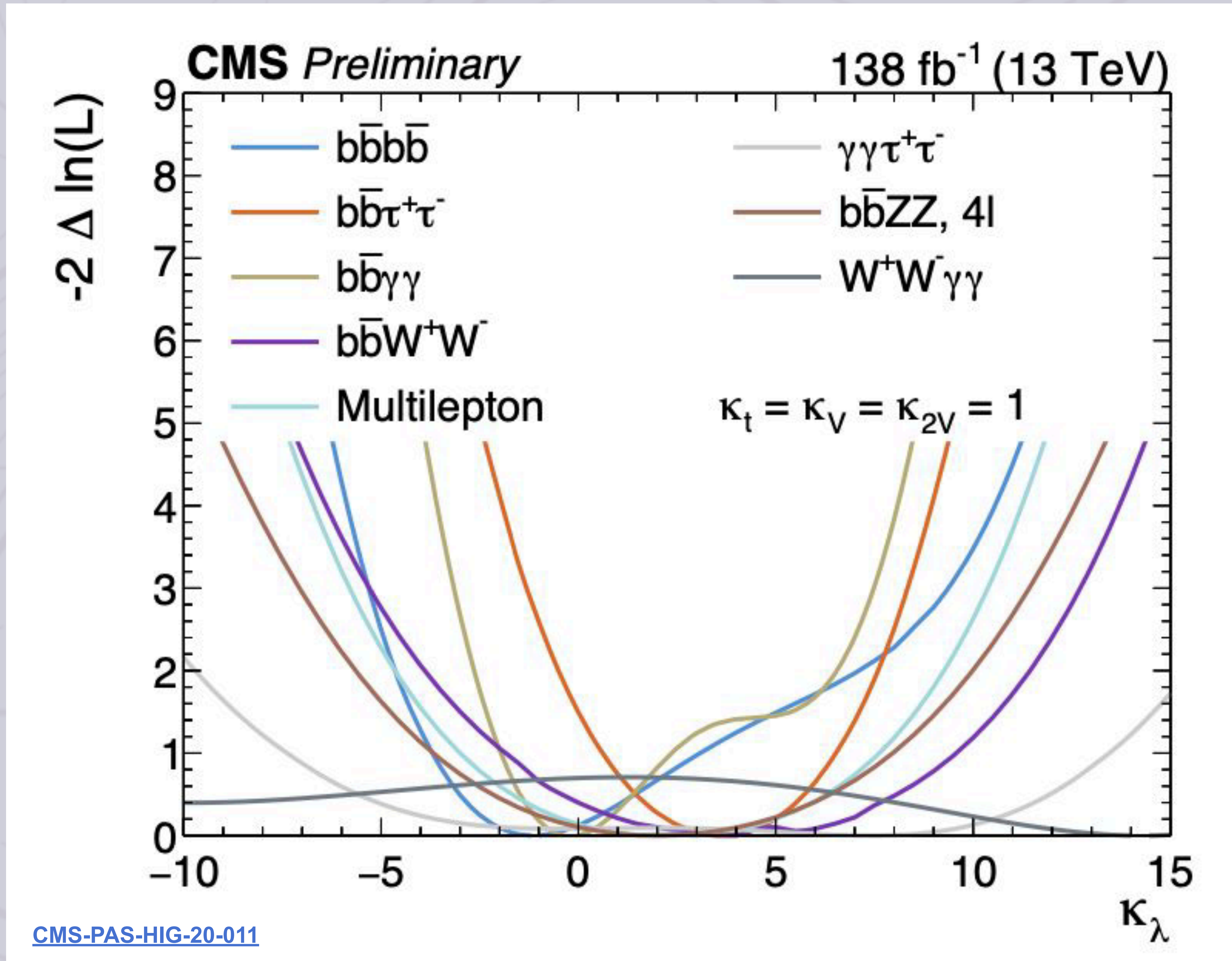


WHERE ARE WE?

With Run2 data analyzed, at 95%CL:

$$CMS: \quad \mu_{HH} < 3.5\ (2.5), \quad -1.40 < \kappa_\lambda < 6.43$$
$$ATLAS: \quad \mu_{HH} < 2.9\ (2.4), \quad -1.2 < \kappa_\lambda < 7.2$$





RUN3 !

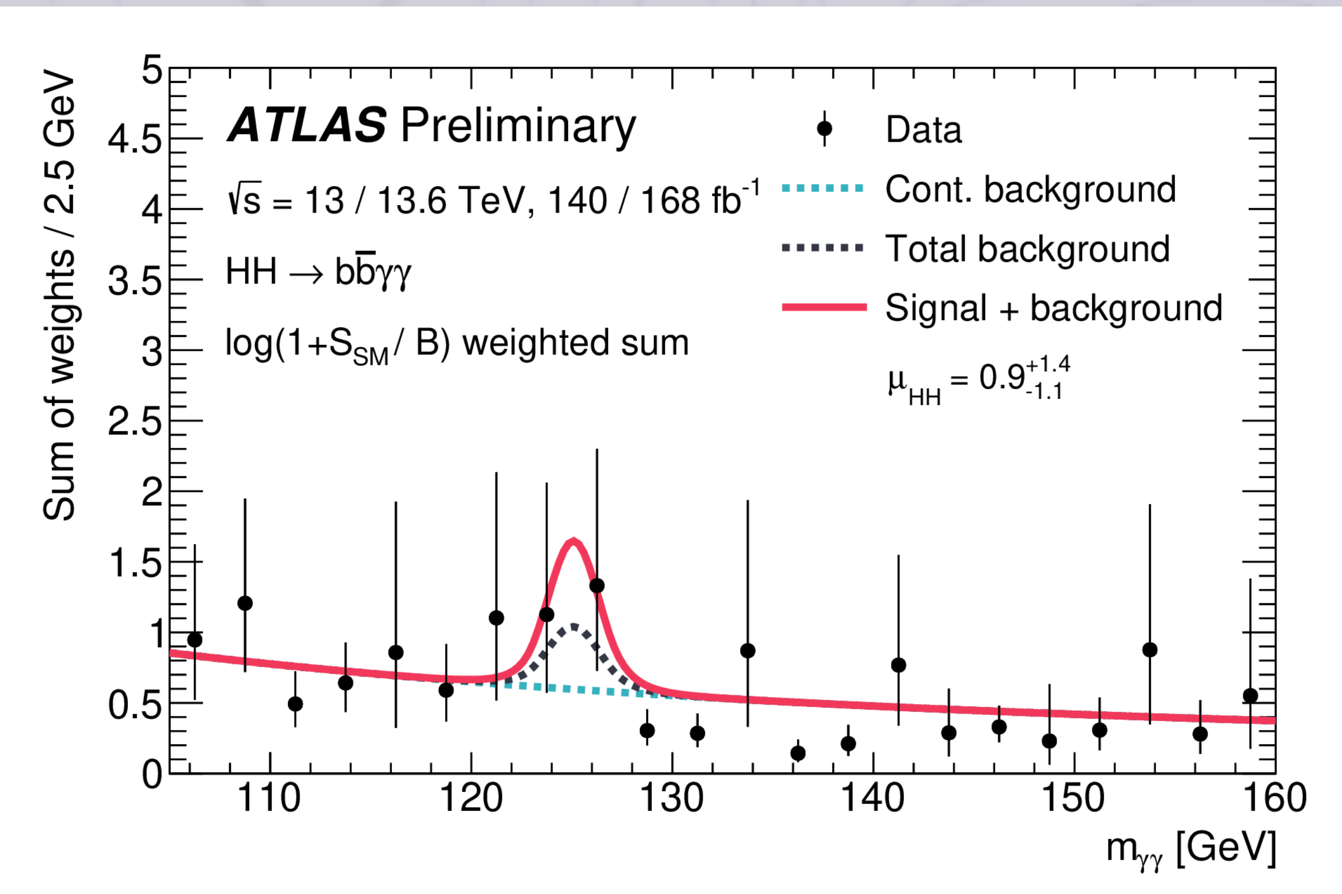

ATLAS
EXPERIMENT
Run: 456118
Event: 301264610
2023-07-08 06:59:42 CEST

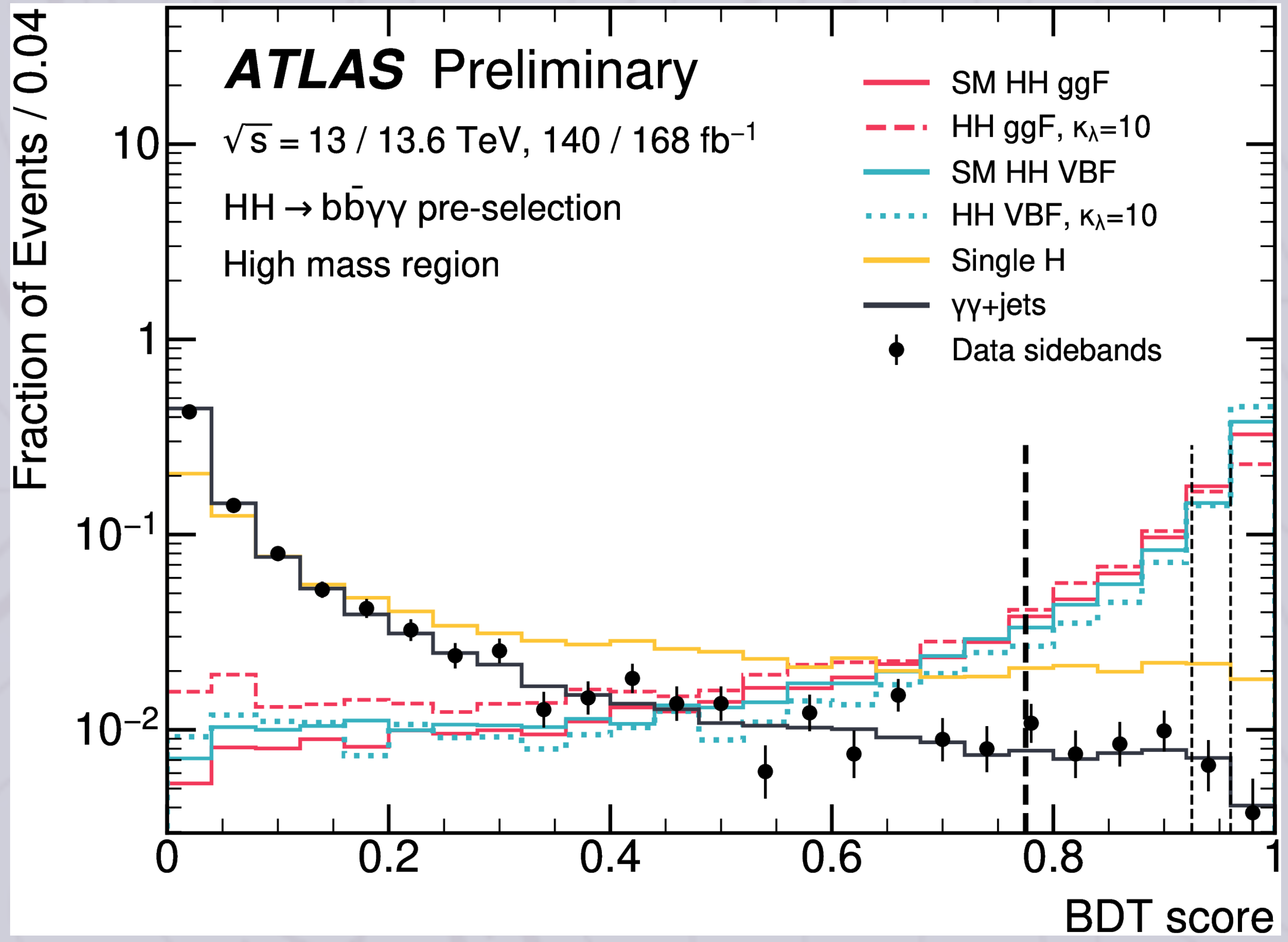
FIRST 308 fb^{-1} HH RESULT

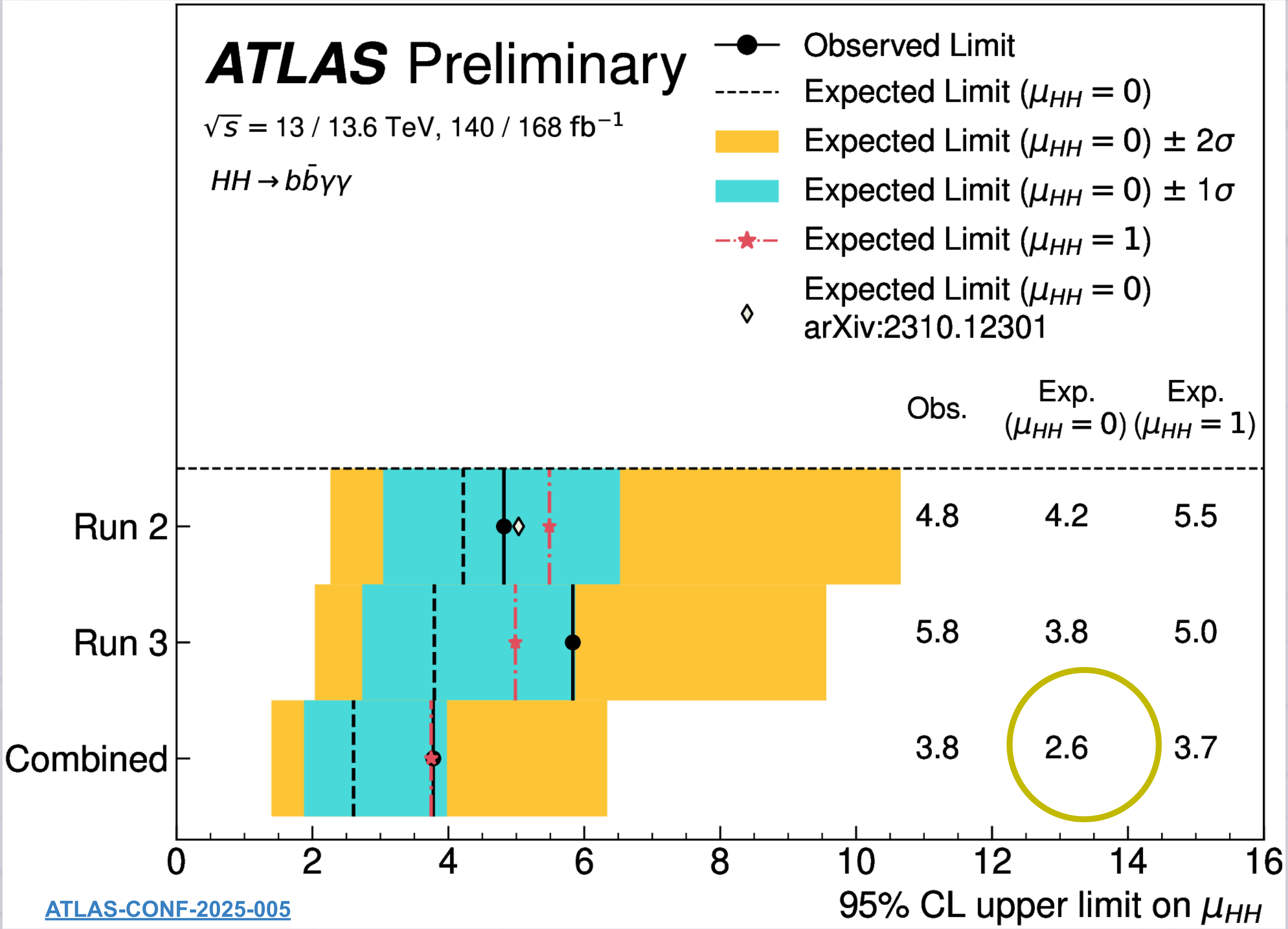
$$\mu_{HH} = 0.9^{+1.4}_{-1.1}$$

$$-1.7 < \kappa_\lambda < 6.6$$

at 95% CL

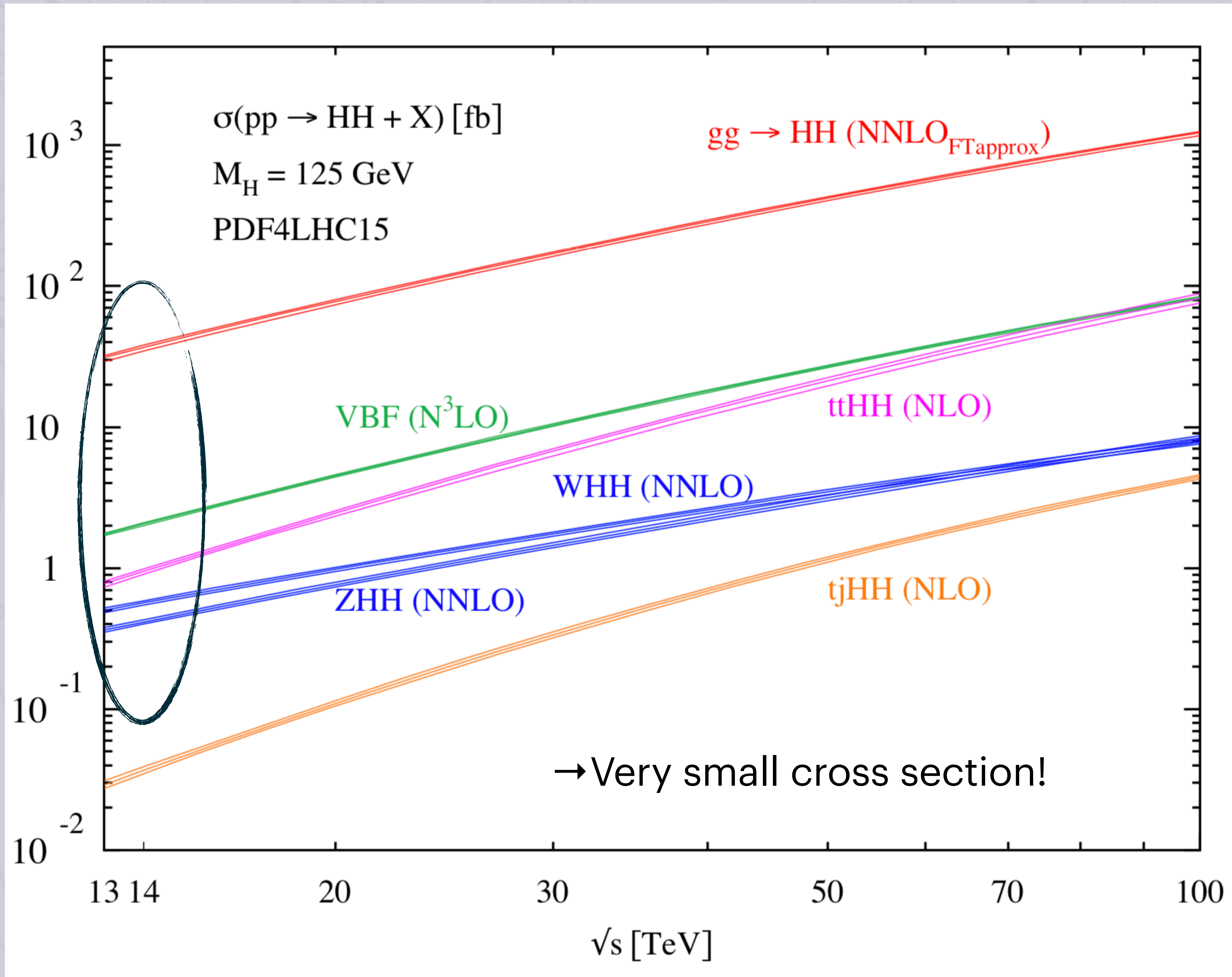


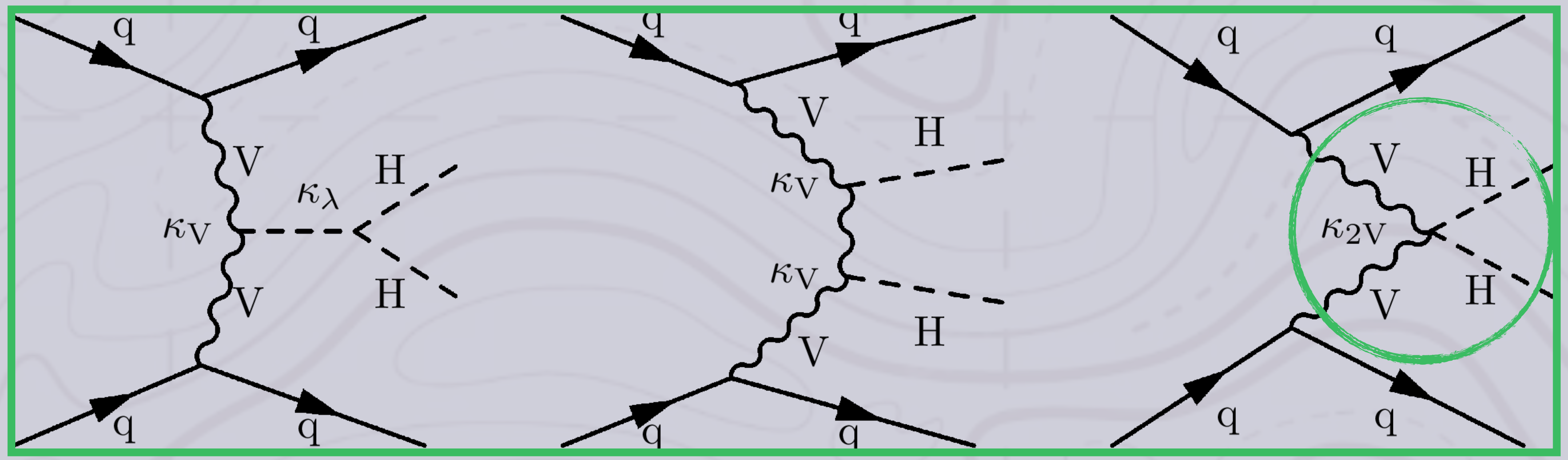


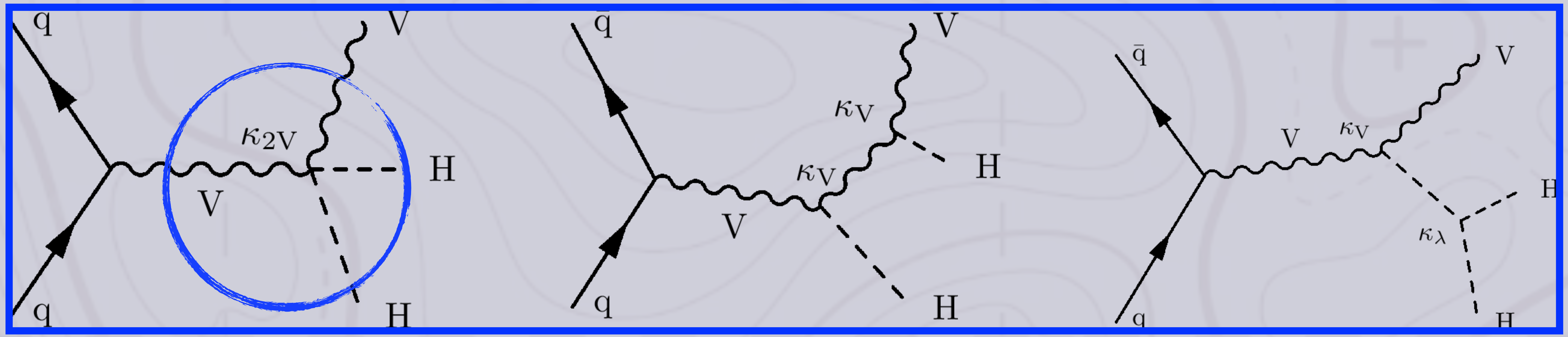


- Improvements + Statistics: single channel already at 2.6xSM - comparable to Run2 combination!

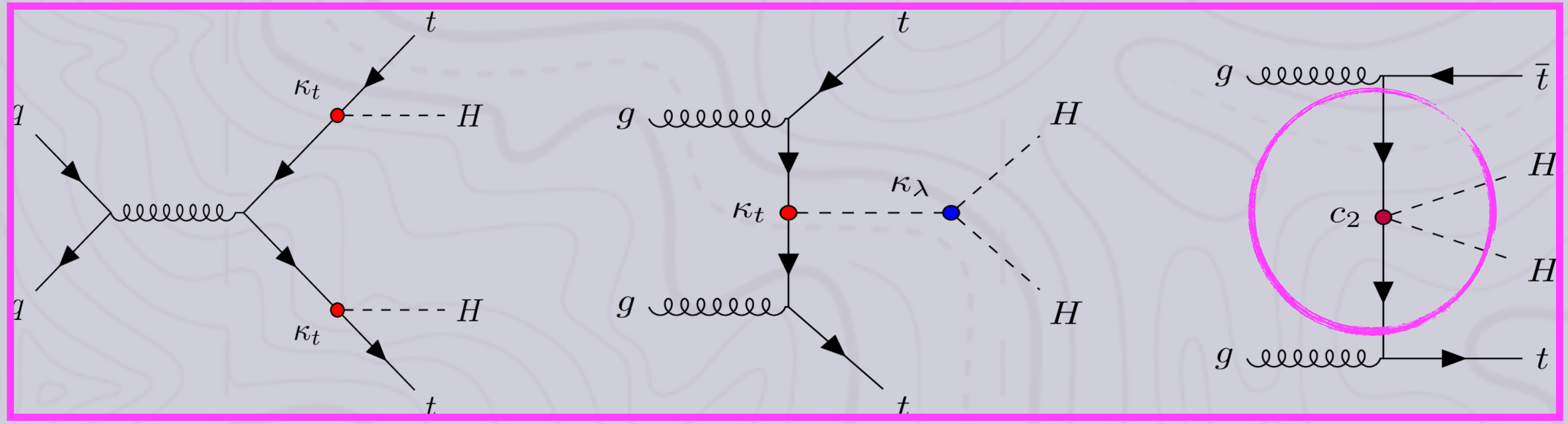
BEYOND GGF: VBFHH, TTHH AND VHH







JHEP 10 (2024) 061: VHH 4B



CMS-HIG-23-004 : CMS ttHH, bbgammagamma

VBFHH: PROBING K2V

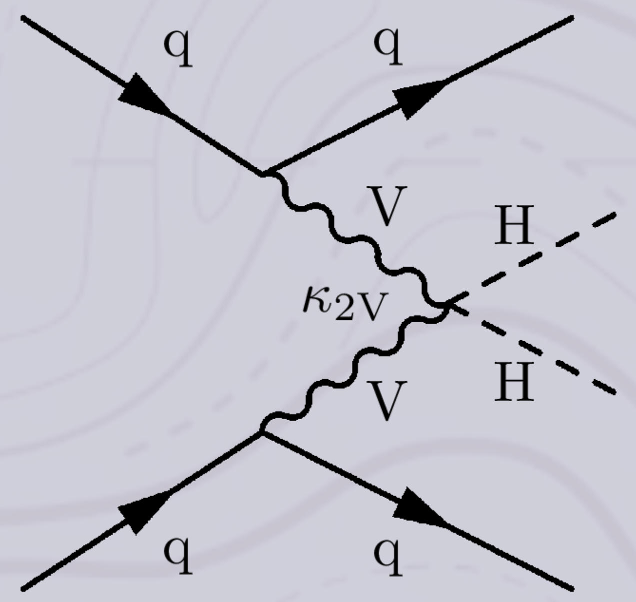
Tiny cross section in the SM, 1.7fb

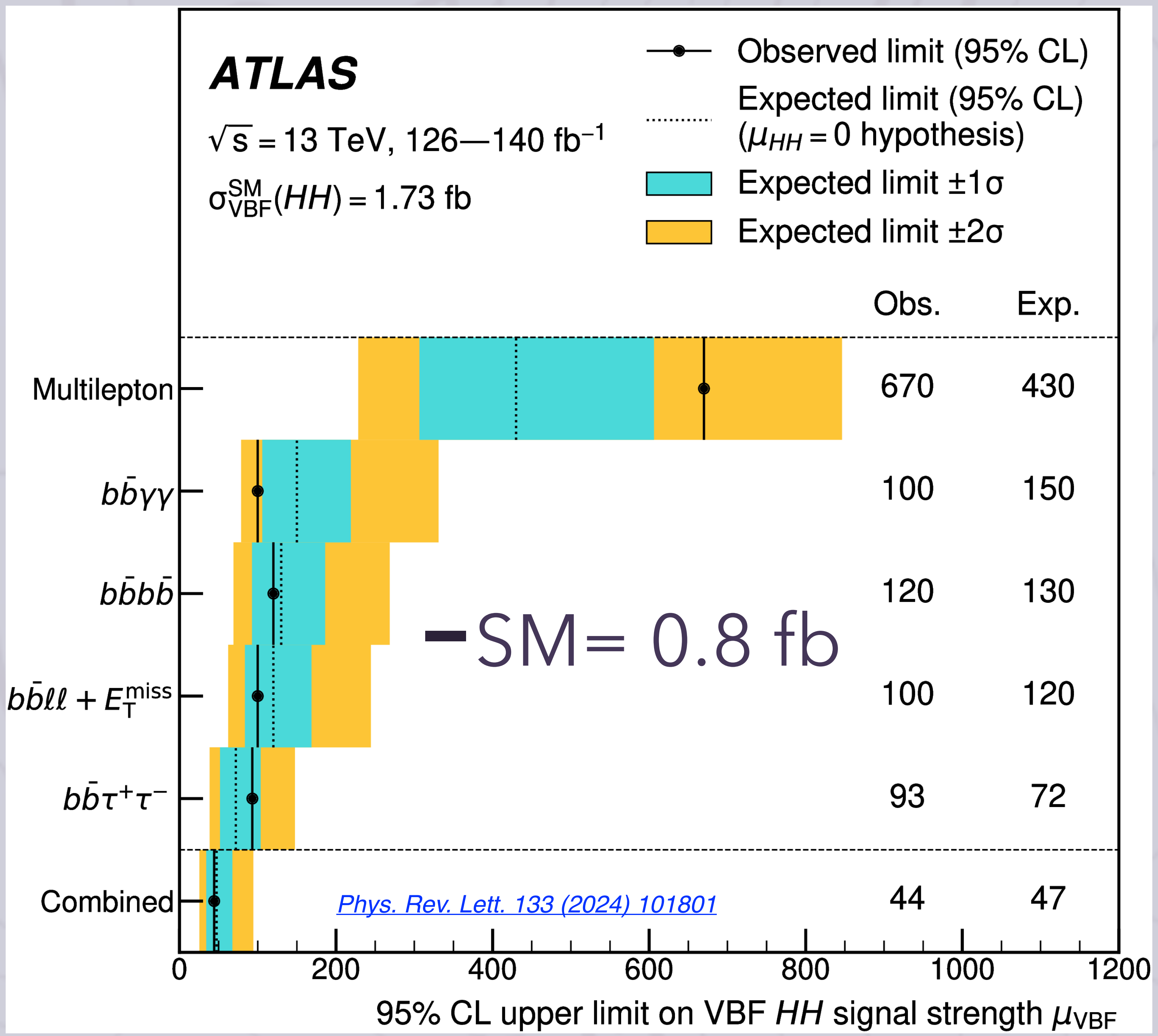
Access to coupling between two Higgs bosons and two Vector bosons (important in HEFT)

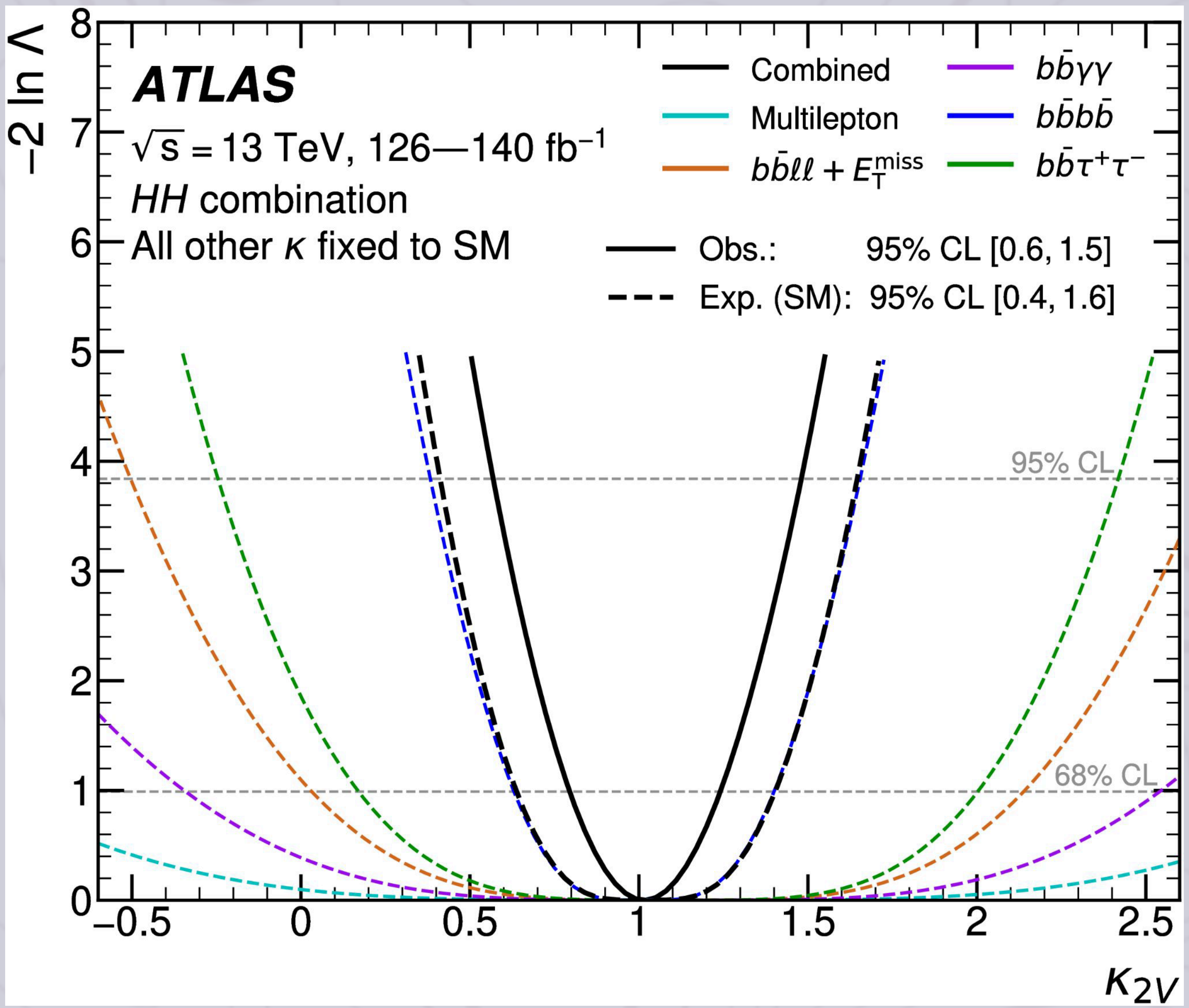
ATLAS: $\mu_{\mathrm{VBFHH}} < 44\ (47)$ $\quad 0.4 < \kappa_{2V} < 1.6$

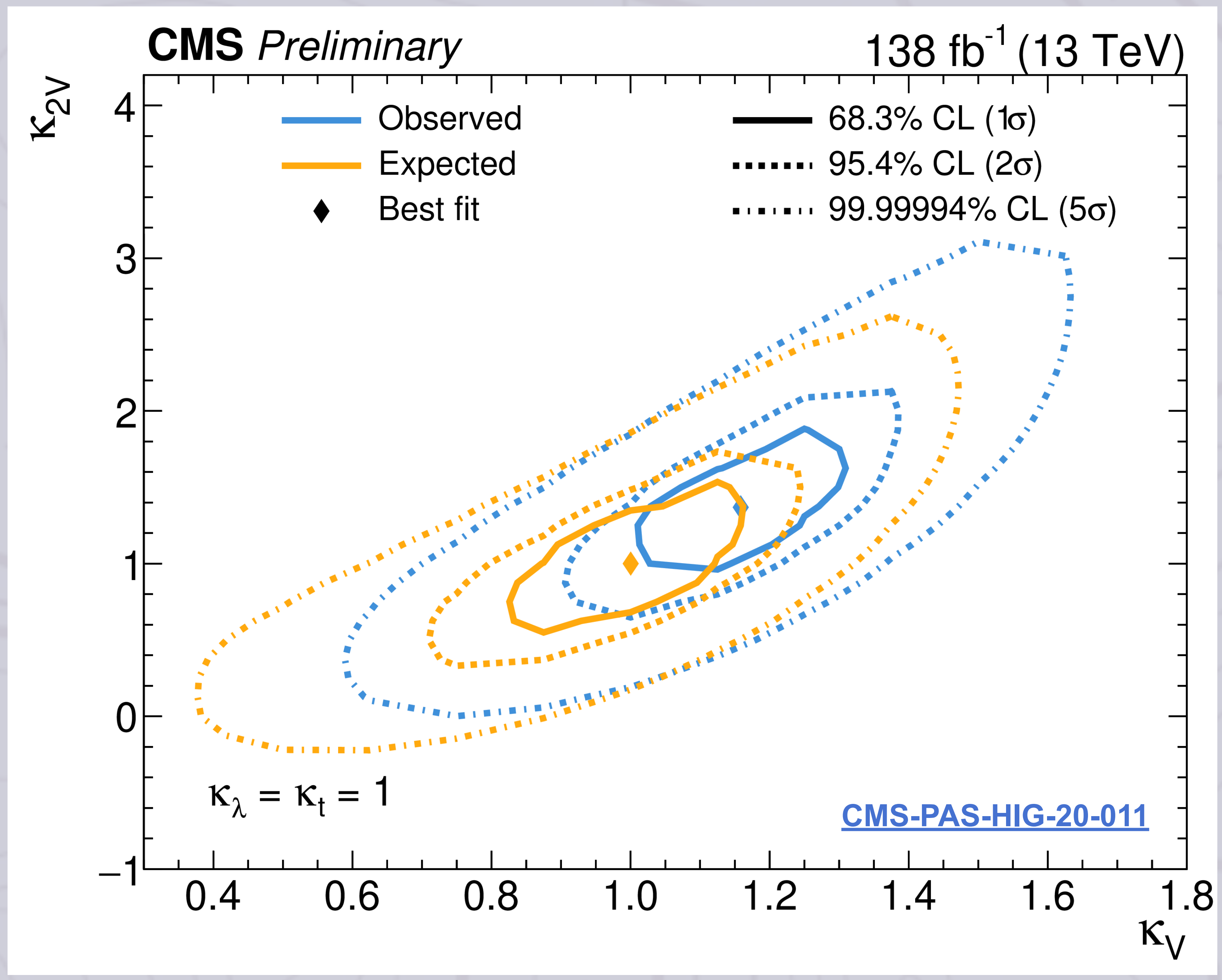
CMS: $\mu_{\mathrm{VBFHH}} < 79\ (91)$ $\quad 0.62 < \kappa_{2V} < 1.42$

at 95%CL





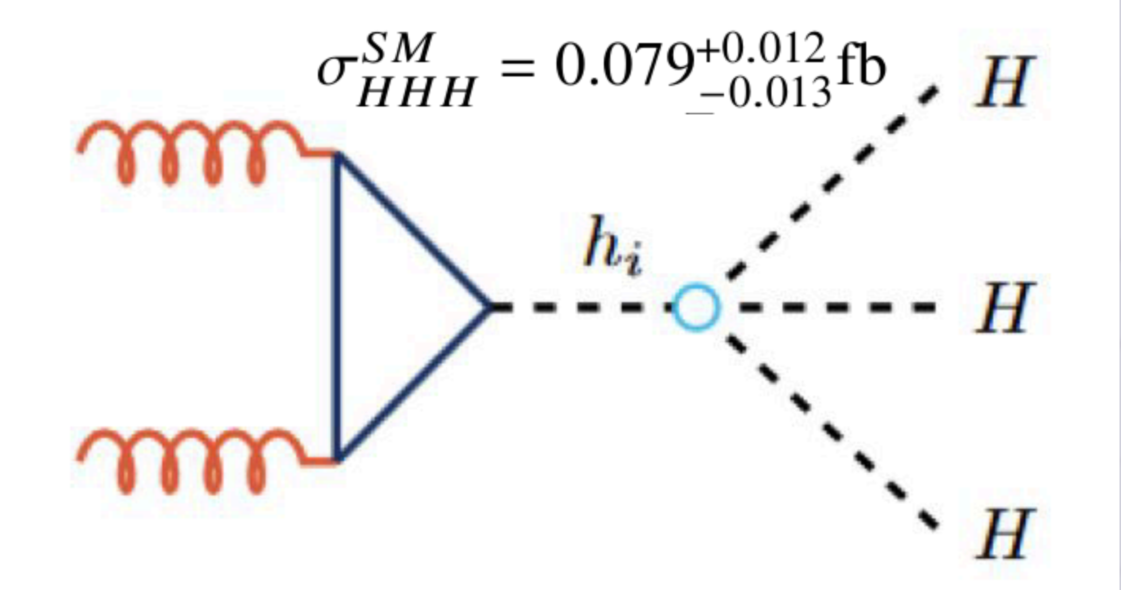


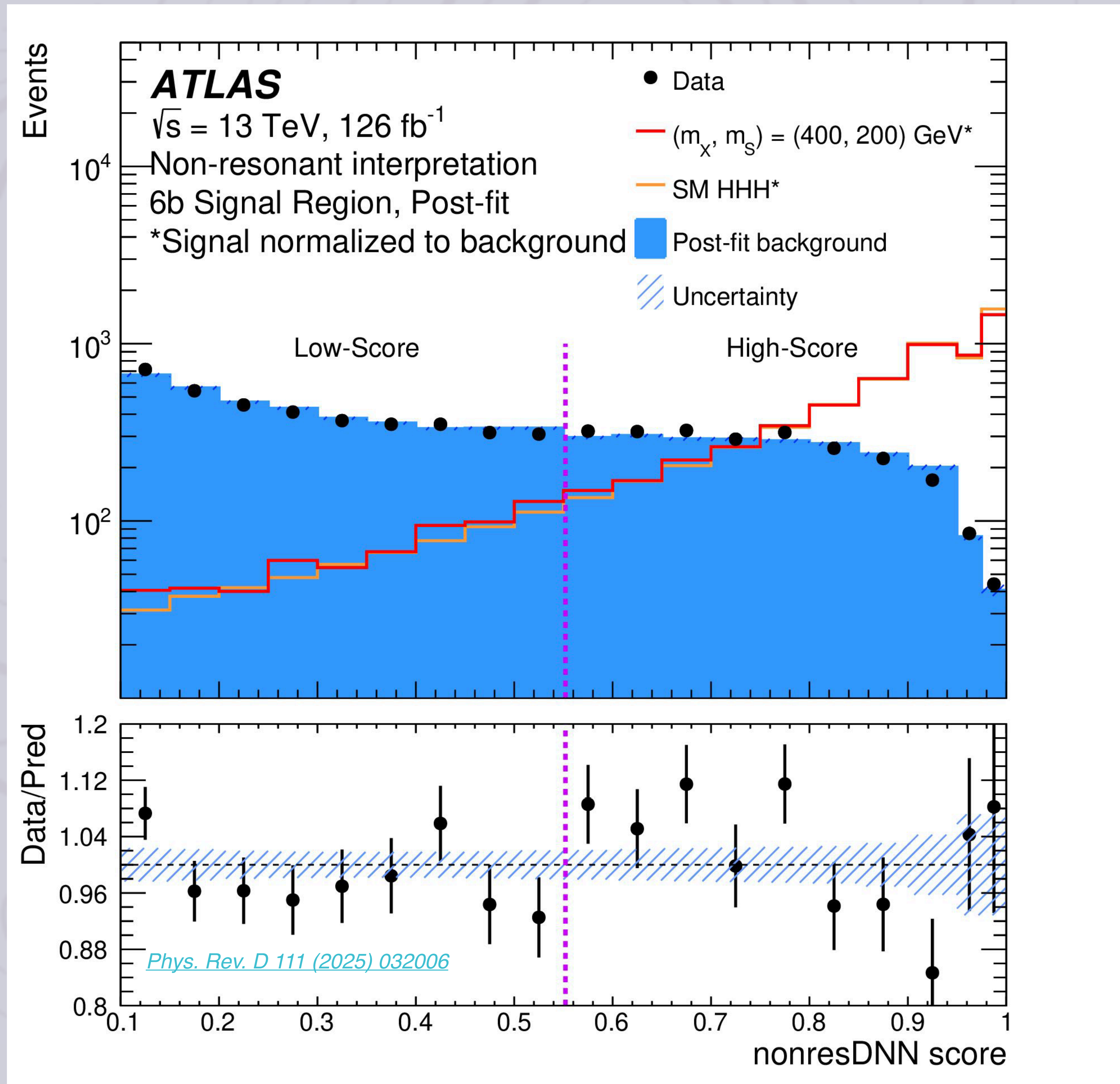


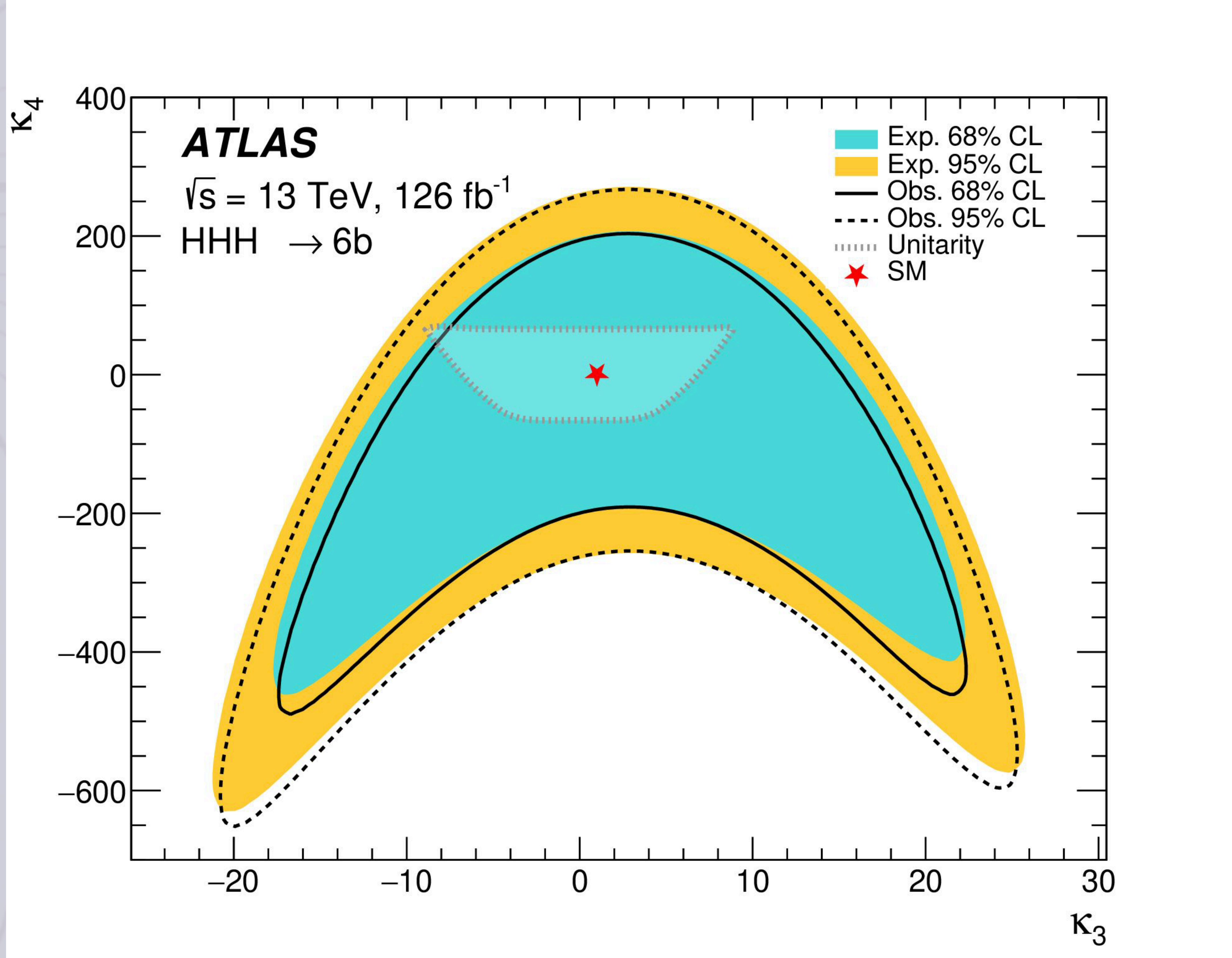
In VHH (JHEP 10 (2024) 061):$\mu_{VHH} < 294(124), -37.7 < \kappa_\lambda < 37.2, -12.2 < \kappa_{2V} < 13.5$, at 95%CL

THE QUEST FOR HHH?

- Very very small cross section, but **access to the quartic self-coupling (κ_4)**
- At the LHC: probe BSM scenarios
- First result, ATLAS, 6b μ< 760 (750) at 95% CL. More final states to come!



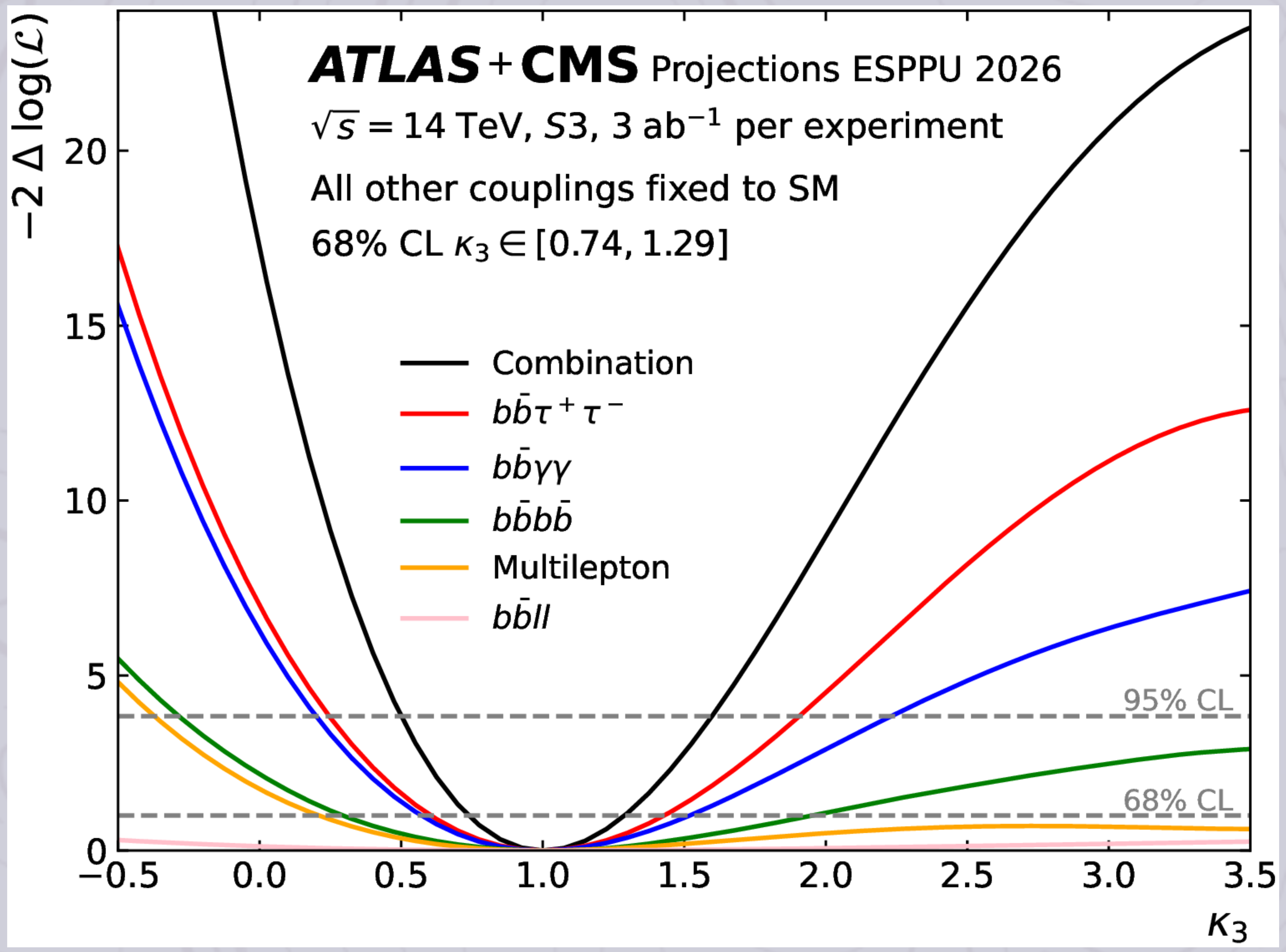


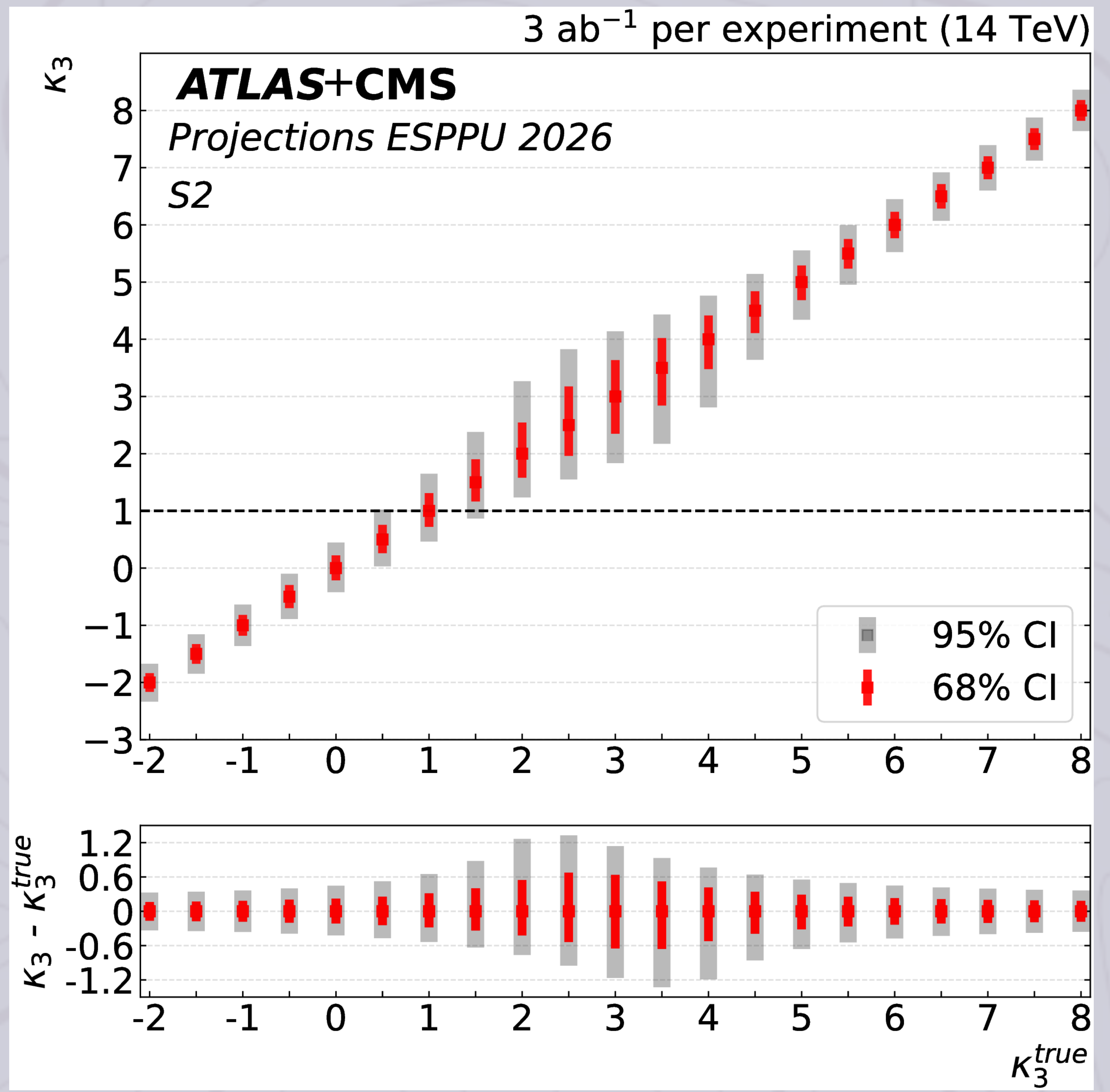


EXCEEDING EXPECTATIONS

- 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}**

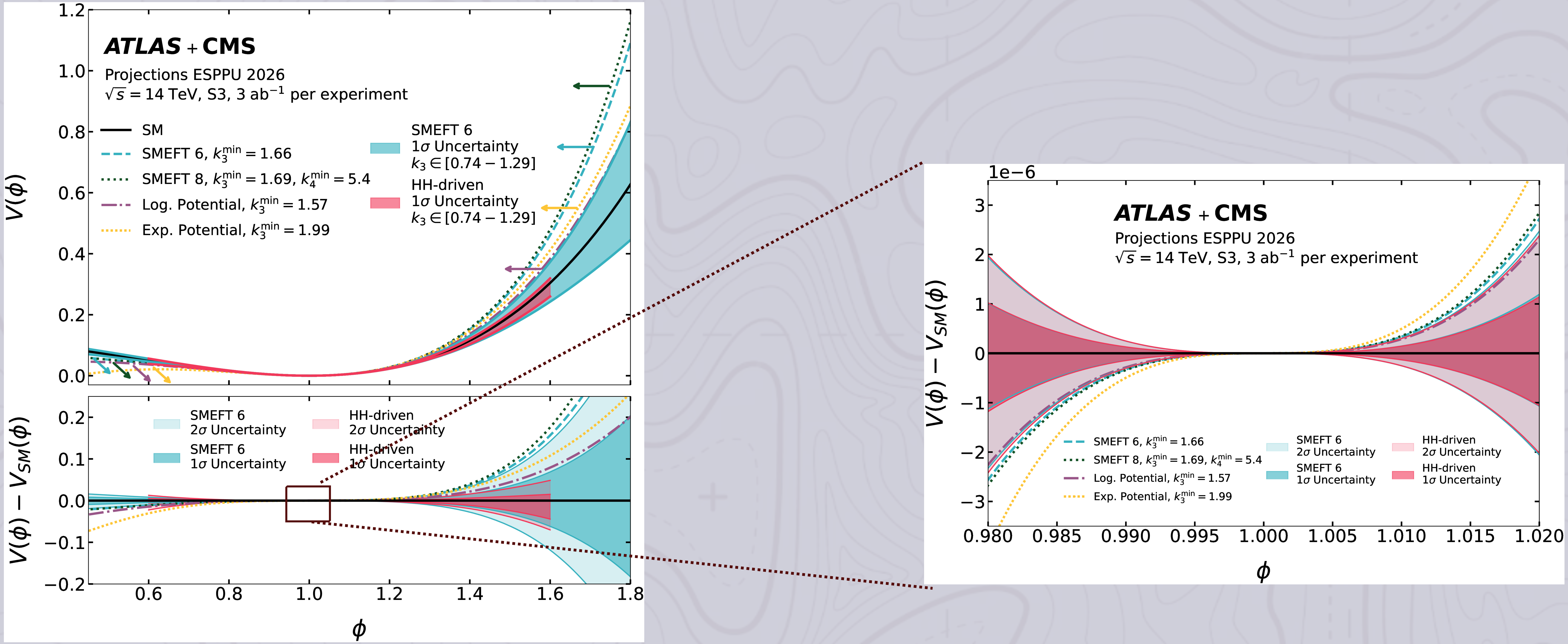
$$\kappa_\lambda \sim 1.0^{+0.29}_{-0.26} \; (3\text{ab}^{-1}, ATLAS + CMS)$$





MAPPING THE HIGGS POTENTIAL

- Sensitivity at the end of the HL-LHC of to fully exclude at 95% CL generic, high-scale new physics models that enable a strong first-order electroweak phase transition in the early universe




BSM?
HH and the Higgs Potential
Second
Generation
EFT ?
Boosted topologies
Rare Production
& Decay
SM Couplings
Cross Sections
Mass, Spin, ...
Yukawa
Interactions
Discovery
A journey into the Higgs sector
foto @ JF.Sánchez Díaz

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.**
  - I could only cover a fraction of the results! More in CMS and ATLAS.
- **Precisely mapping the Higgs sector will be one of the legacies of the LHC**
- With one Higgs at hand, one of the biggest challenges is finding a couple. **Measuring the self-coupling and understanding the Higgs potential, the HL-LHC final frontier?**
- The discussion of the distant future of particle physics relies on our understanding of Higgs physics today and in the near future. The LHC and HL-LHC are after all the first 'Higgs Factories'.. .


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

GRACIAS!

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DE CIENCIA, INNOVACIÓN
Y UNIVERSIDADES

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la Unión Europea

AGENCIA
ESTATAL DE
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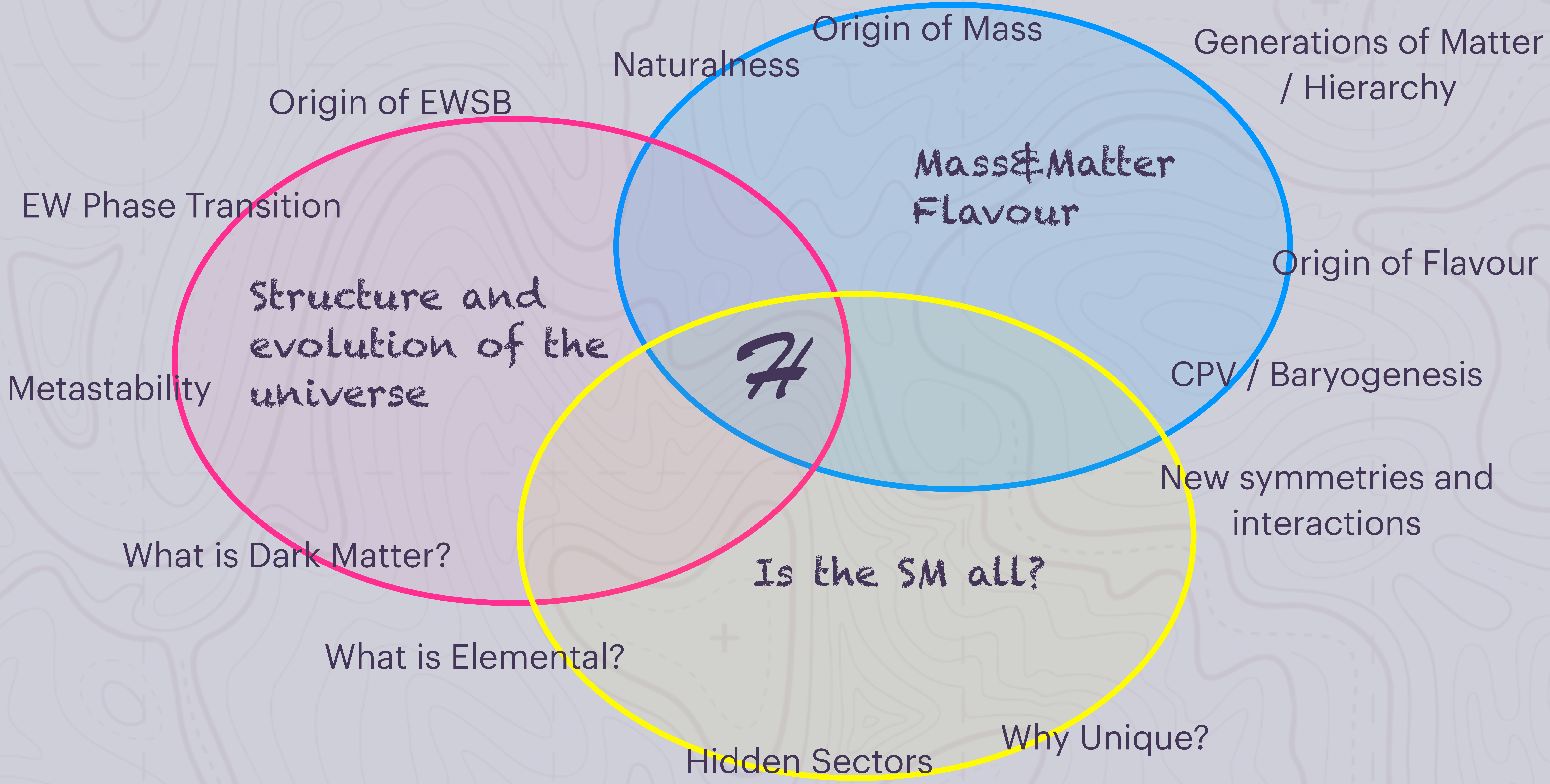
Generación de Conocimiento 2021: PID2021-122134NB-C21 and funded by MICIU/AEI/ 10.13039/501100011033 and ERDF A way of making Europe

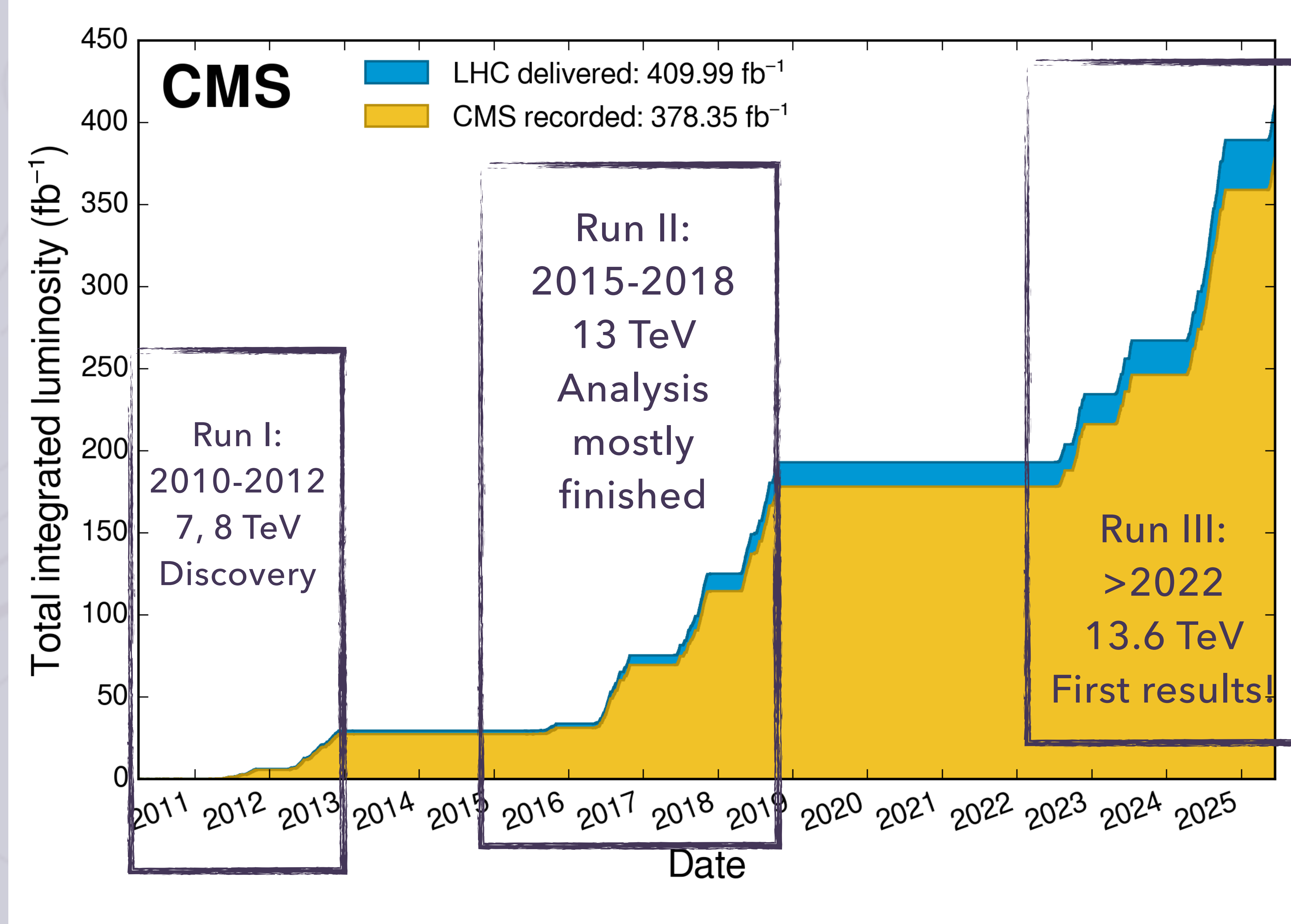
Consolidación Investigadora 2023: CNS2023-144781

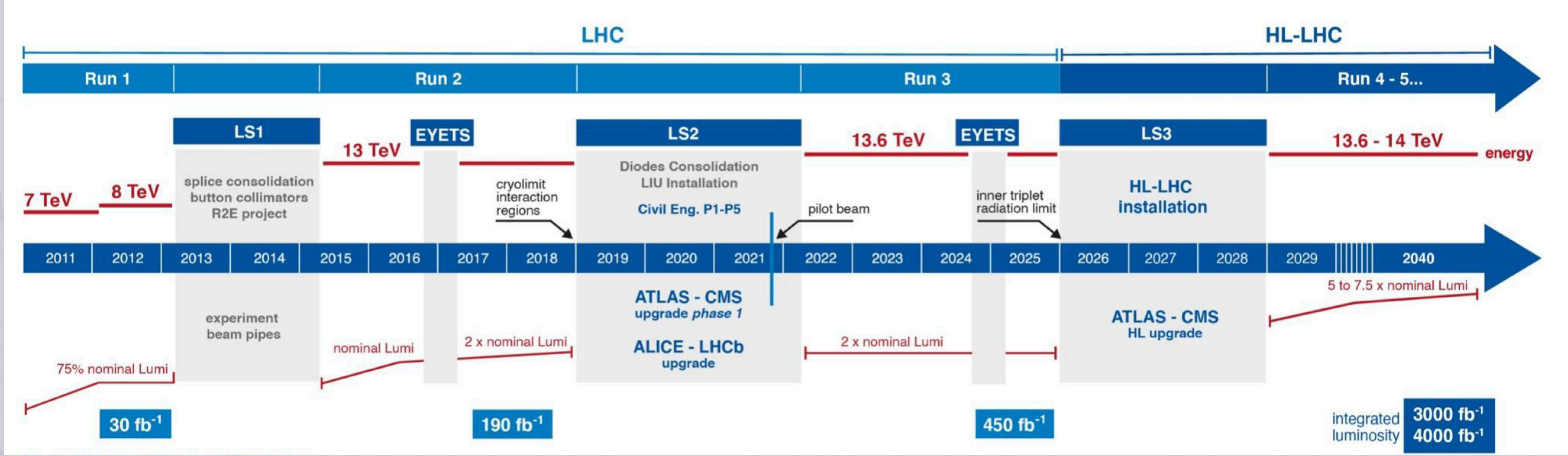
IN THE CENTER OF OUR QUESTIONS ABOUT MATTER



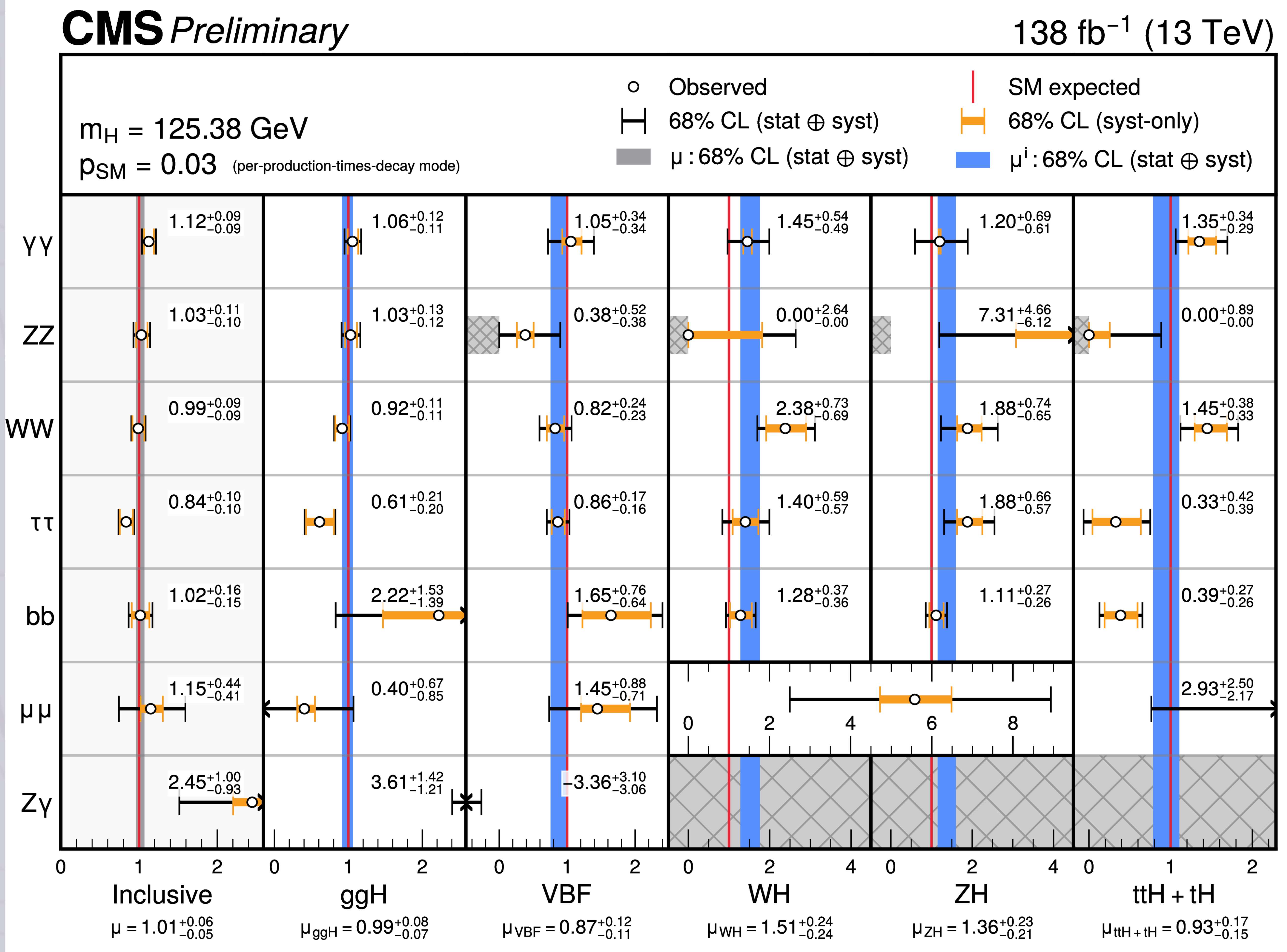
(* This is just an illustration, note that the different questions are more multifaceted than this shows)

- CMS&ATLAS are fantastic machines for exploring the Higgs in detail.
- In the past 10 years we have surpassed the expectations of how well we could measure the Higgs in this machine, and there is more to come.





GLOBAL VIEW OF HIGGS PRODUCTION



Combining the individual production and decay modes that have been measured so far we can achieve a comprehensive look at Higgs production

Inclusive cross section understood at the 6% level already

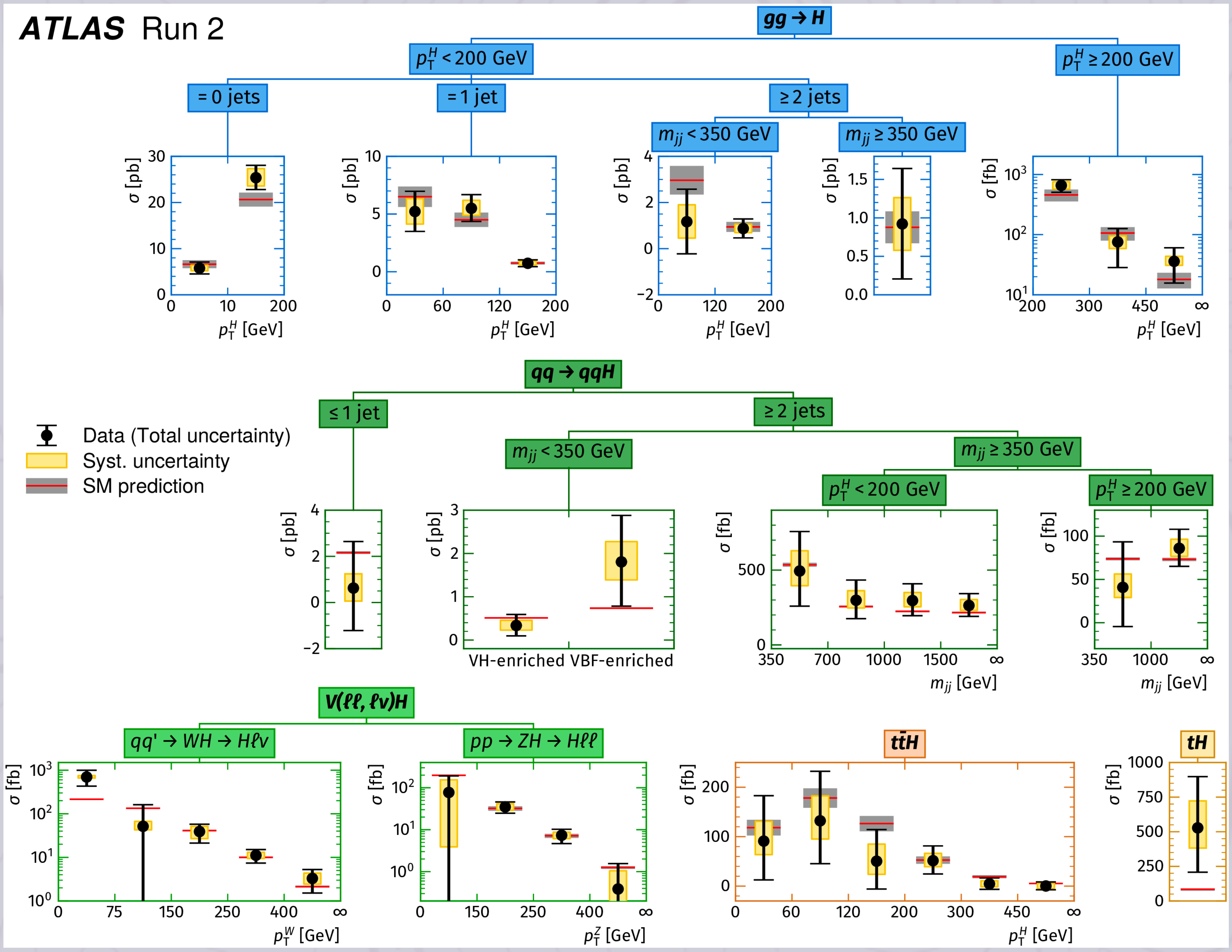
$$\mu_i^f \equiv \frac{\sigma_i \cdot \mathrm{BR}^f}{(\sigma_i \cdot \mathrm{BR}^f)_{\mathrm{SM}}} = \mu_i \times \mu^f$$

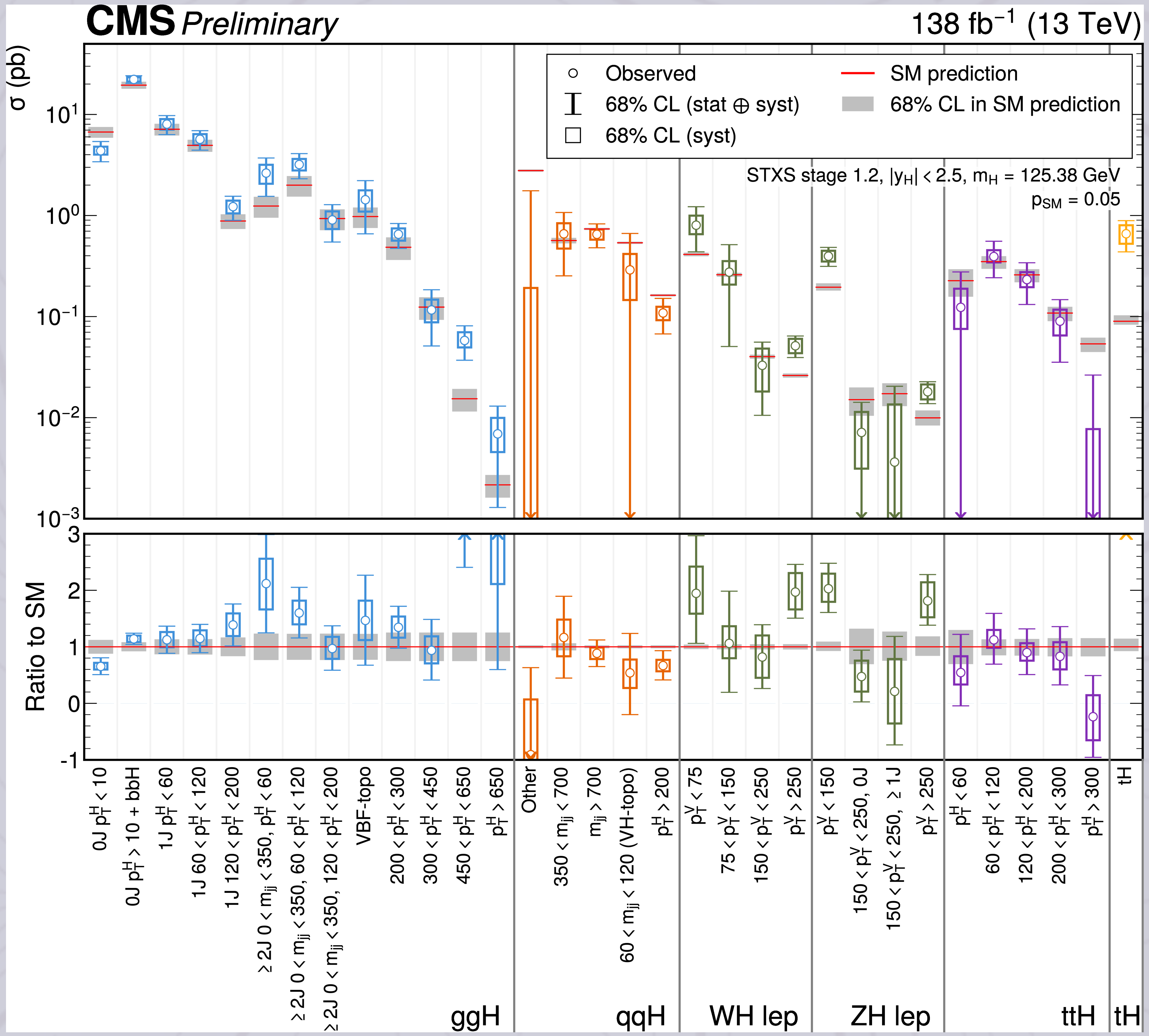
$$\mu_{CMS} = 1.014 \pm 0.054$$

$$\mu_{ATLAS} = 1.05 \pm 0.06$$

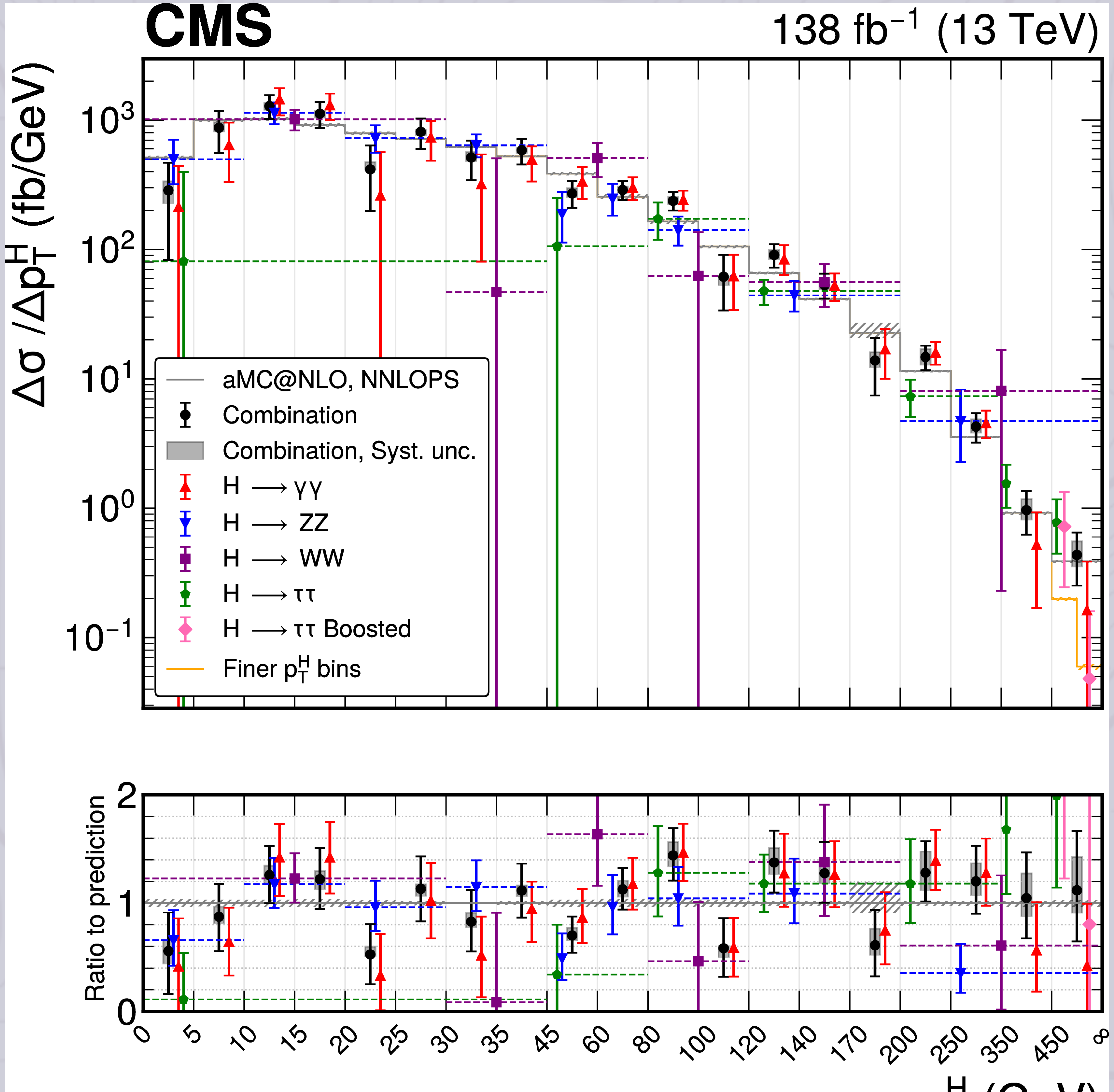
SIMPLIFIED TEMPLATE CROSS SECTIONS

- Alternative approach: measure cross sections separated into production modes, inclusively over the decays, in specific regions of phase-space, defined in terms of specific kinematic variables (p_T^H, m_{jj}, p_T^{Hjj}, p_T^V)
- STXS provide a largely model-independent way to test for BSM deviations in kinematic distributions.

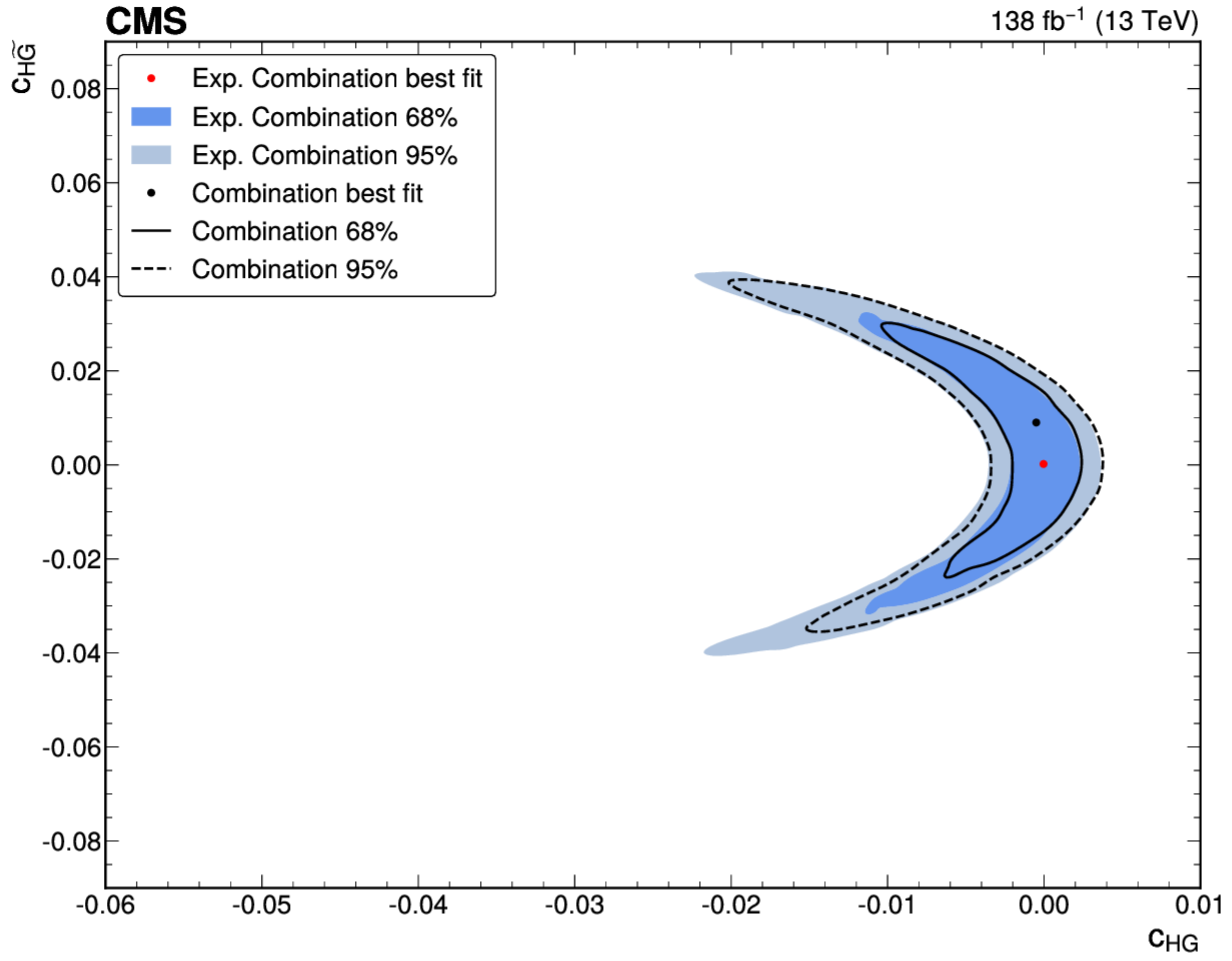


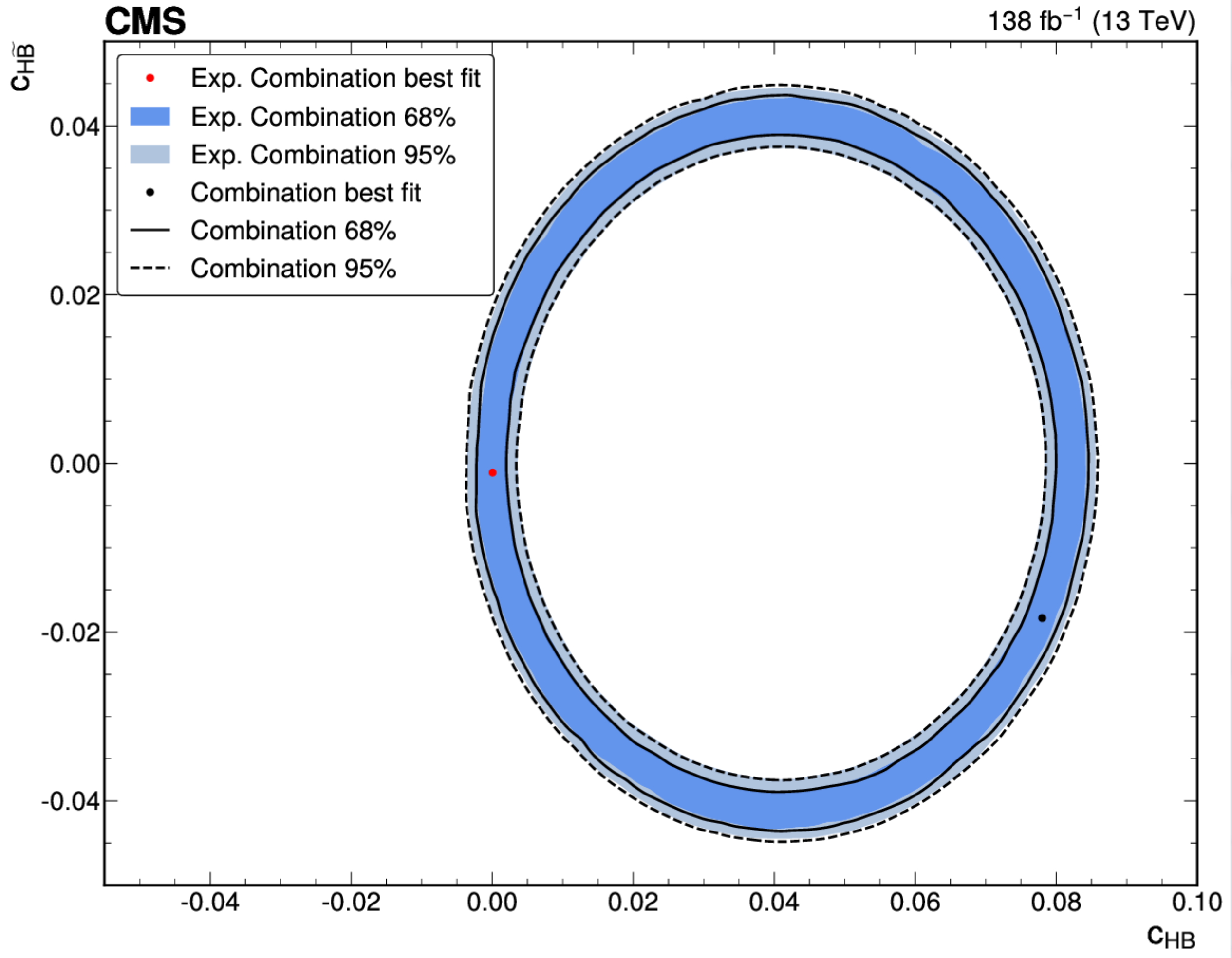


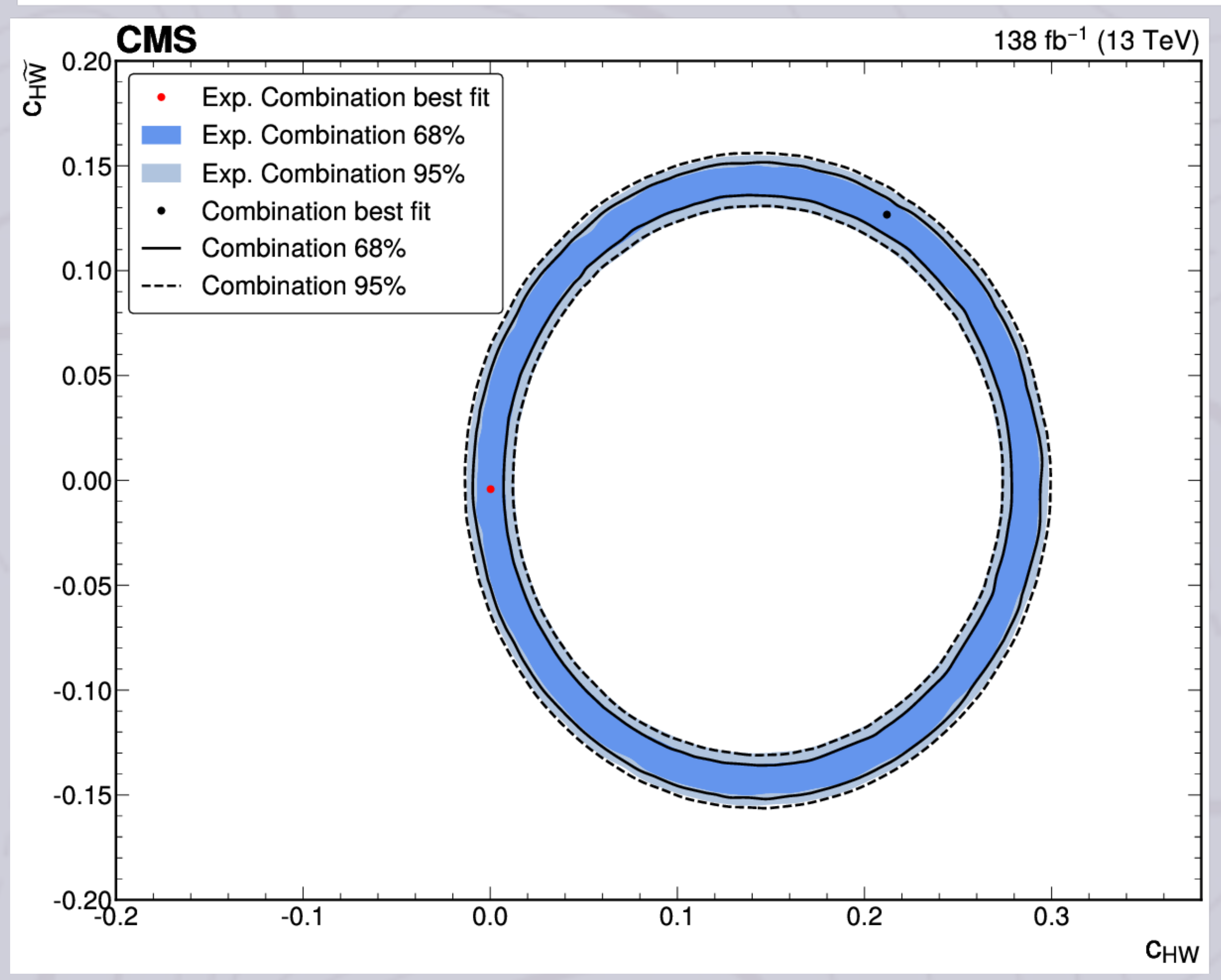
DIFFERENTIAL CROSS SECTIONS

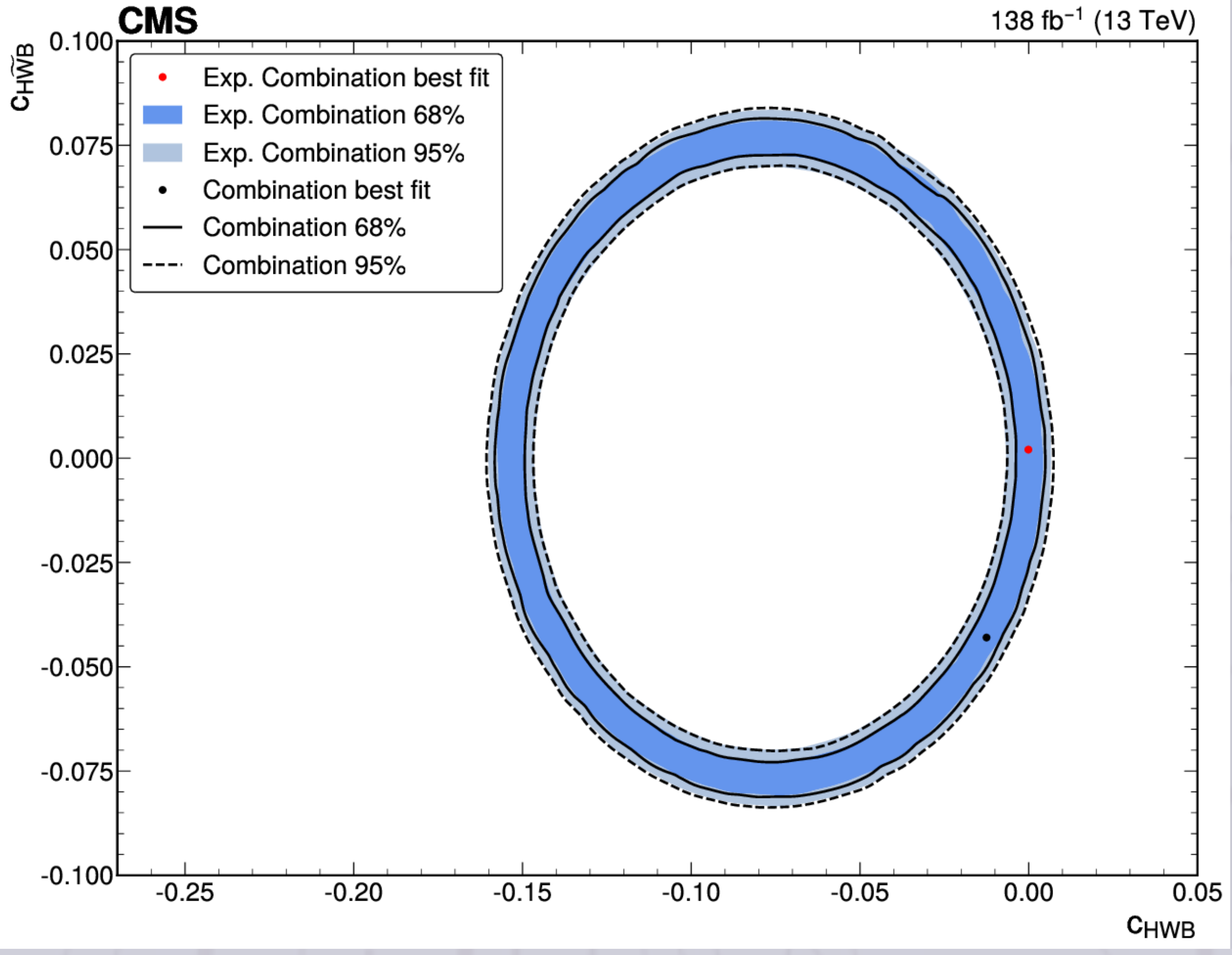


arXiv:2504.13081









DIFFERENTIAL CROSS SECTIONS

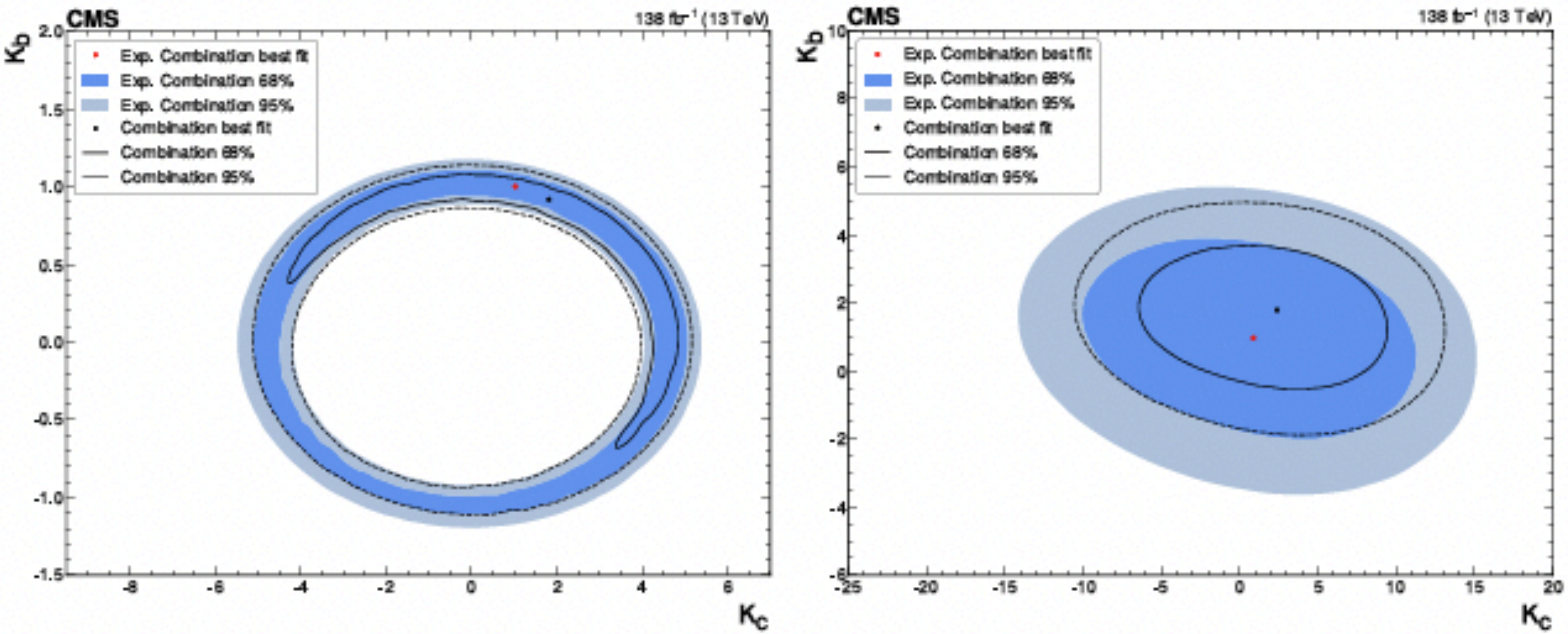
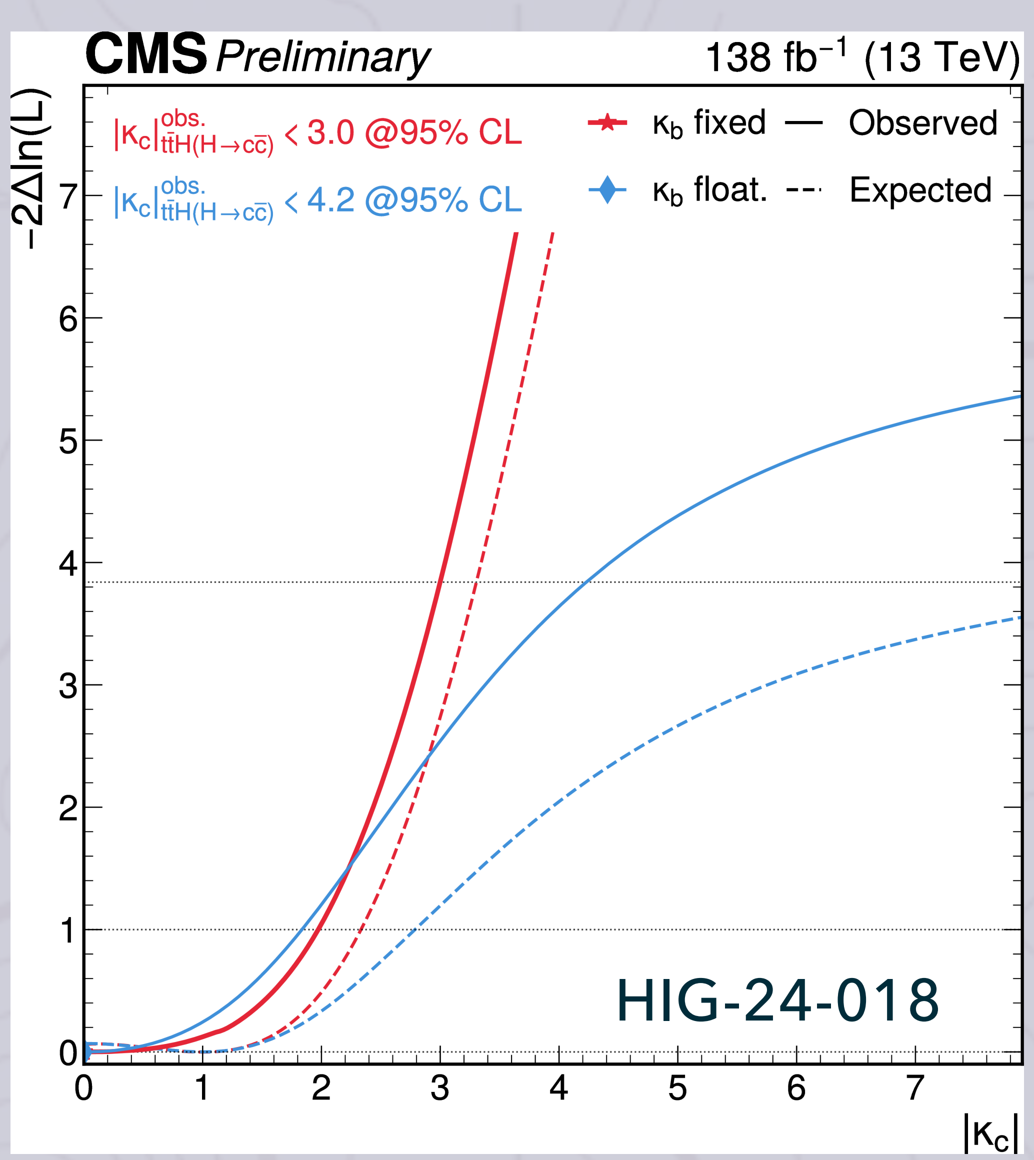
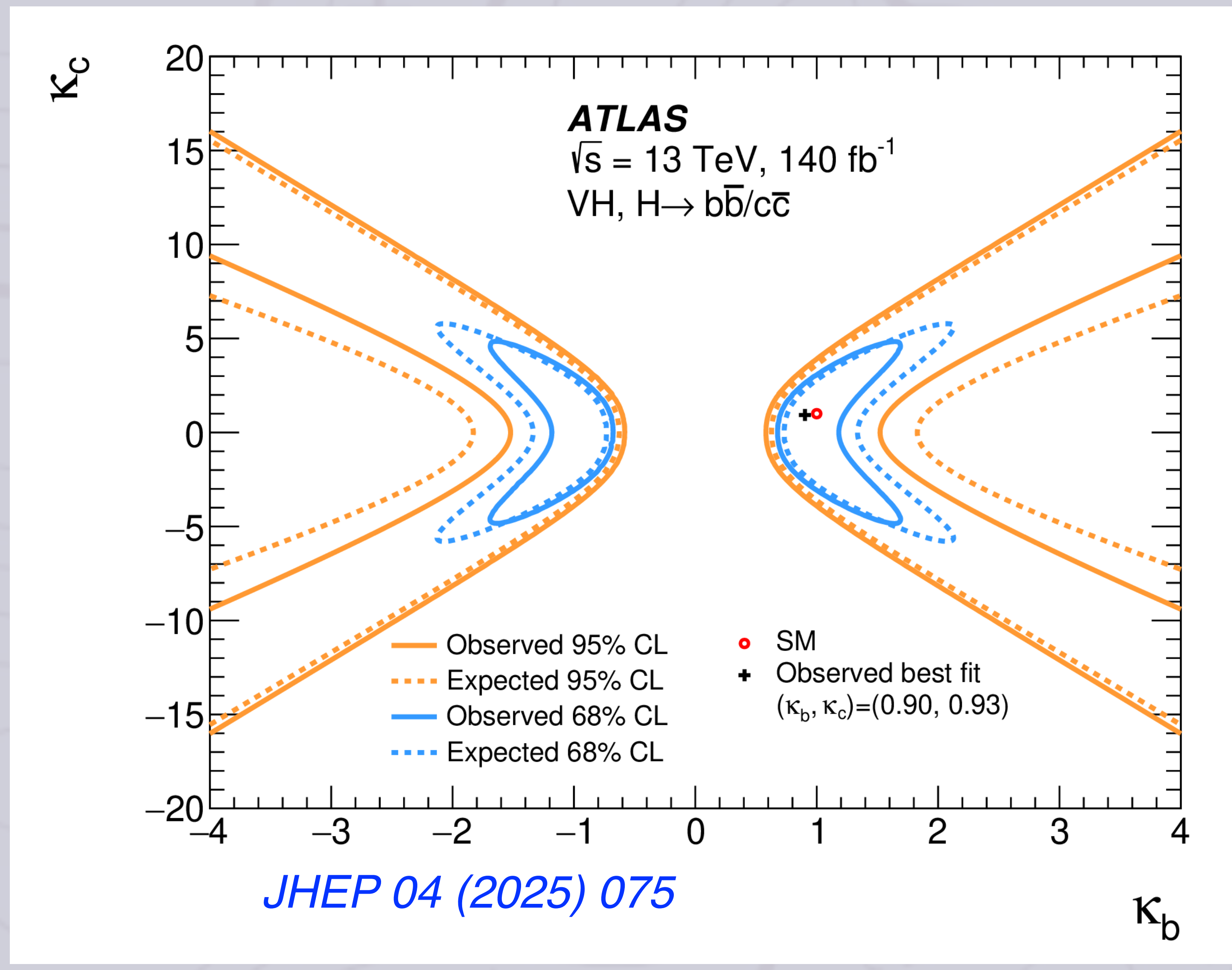


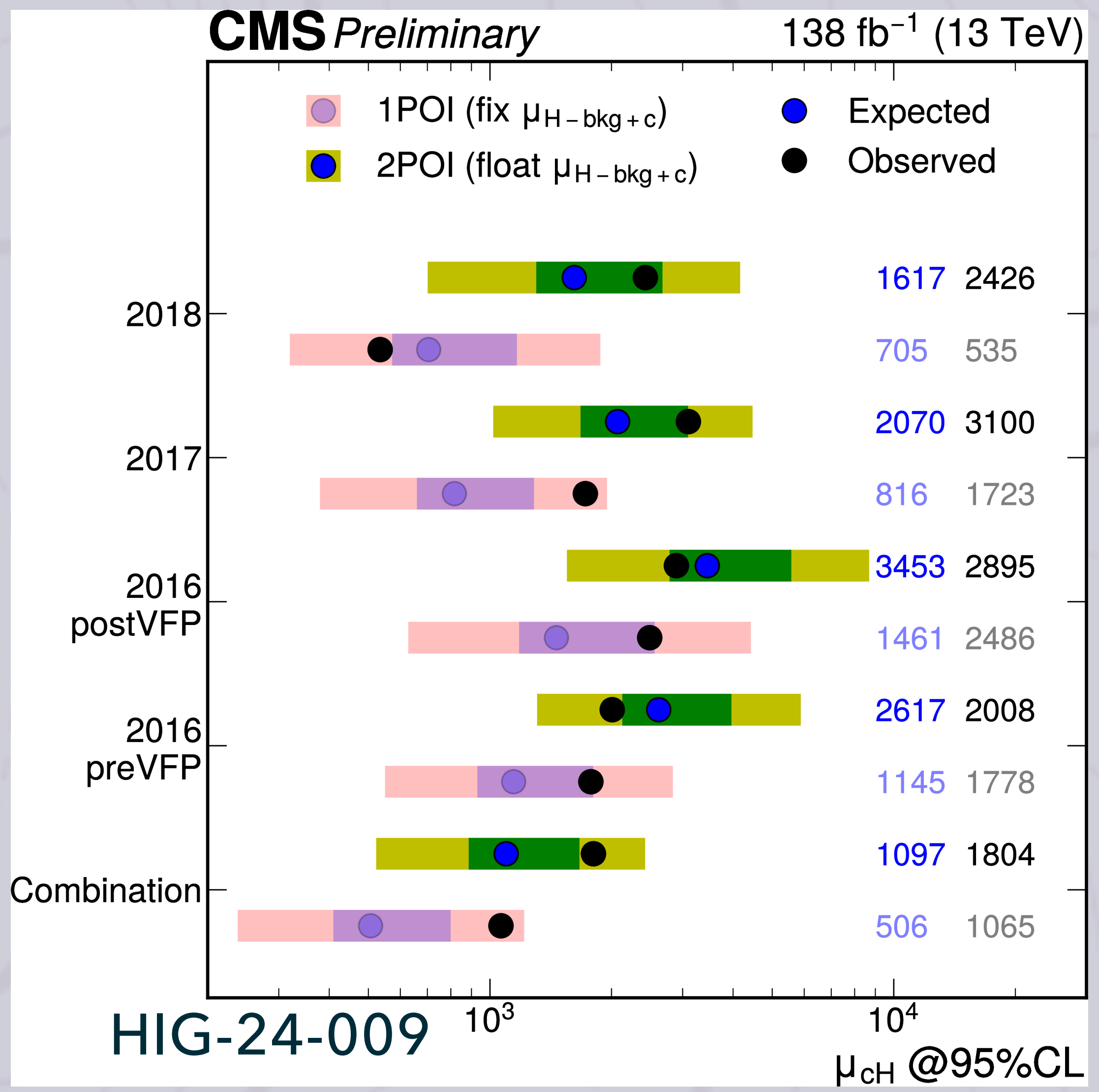
Figure 6: Observed and expected simultaneous fits for κ_b and κ_c, assuming a coupling dependence of the branching fractions (left) and with the branching fractions of the decay channels entering the combination implemented as nuisance parameters with no dependence on the couplings (right). The 68% and 95% CL contours are shown in solid and dashed lines for the observed data, with the expected contours indicated in blue.

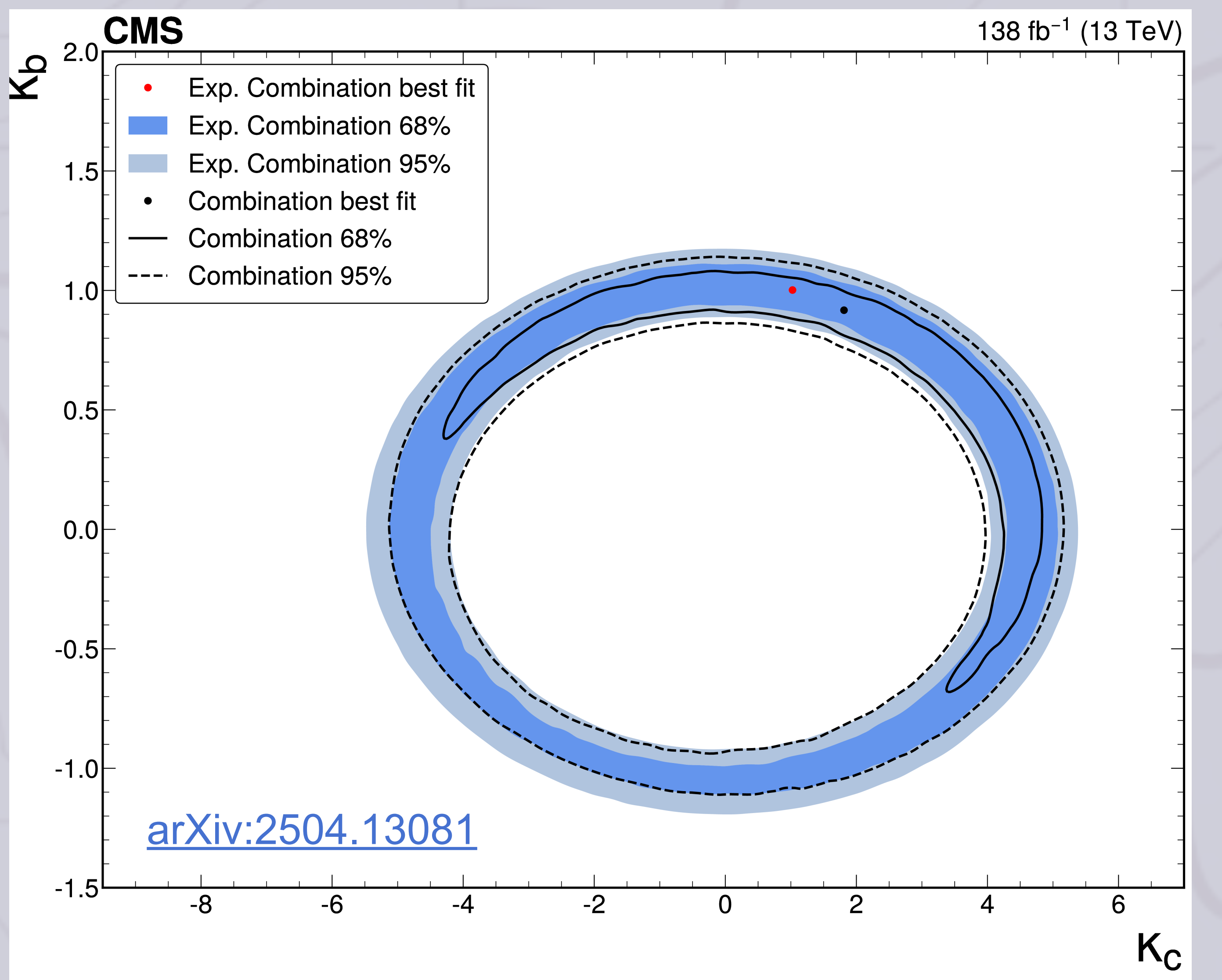
WILL THE LHC REACH THE CHARM YUKAWA? YES!

- **Charm quark: only up quark for which we could possibly measure the branching ratio Br(H->cc)~3%**
  - Do up-type quarks get their mass from the same Higgs fields as down-type quarks and charged leptons?
- **Difficult measurement (not only statistics, we need to be able to identify charm jets!). Many avenues explored now!**
  - **VH Hcc :**
    - CMS: μ(VH, Hcc) < 7.6(14)
    - ATLAS: μ(VH, Hcc) < 11.5 (10.6) and $|\kappa_c| < 4.2$ (300 better than their previous result!)
  - **ttH Hcc:**
    - (CMS) μ(ttH Hcc)<7.8 (8.7)and $|\kappa_c| < 3.5$ (2.7)
  - **H+c :** first probes by CMS in the HWW and H$\gamma\gamma$ channel. HWW: μ(cH, HWW)<1065 , $|\kappa_c| < 211(95)$. H$\gamma\gamma$: $|\kappa_c| < 38.1(72.5)$
  - **H+γ:** H4l, HIG-23-011: $-4.0 < \kappa_c < 3.4$ (floating all other couplings)
  - Constraints from general Higgs pt differential, weak unless assumptions on the branching ratios are added

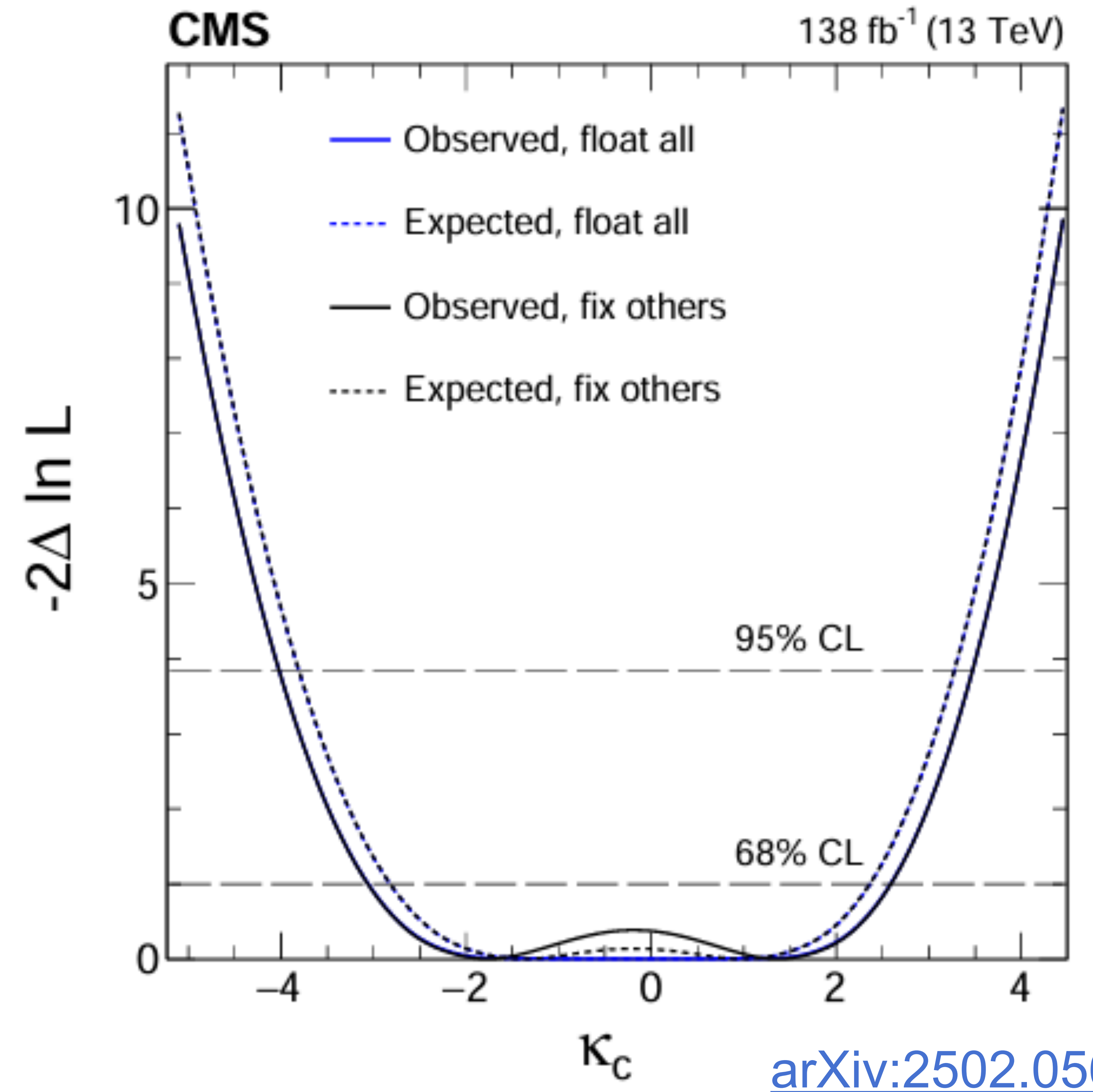








H+γ LIGHT YUKAWA CONSTRAINT



arXiv:2502.05665

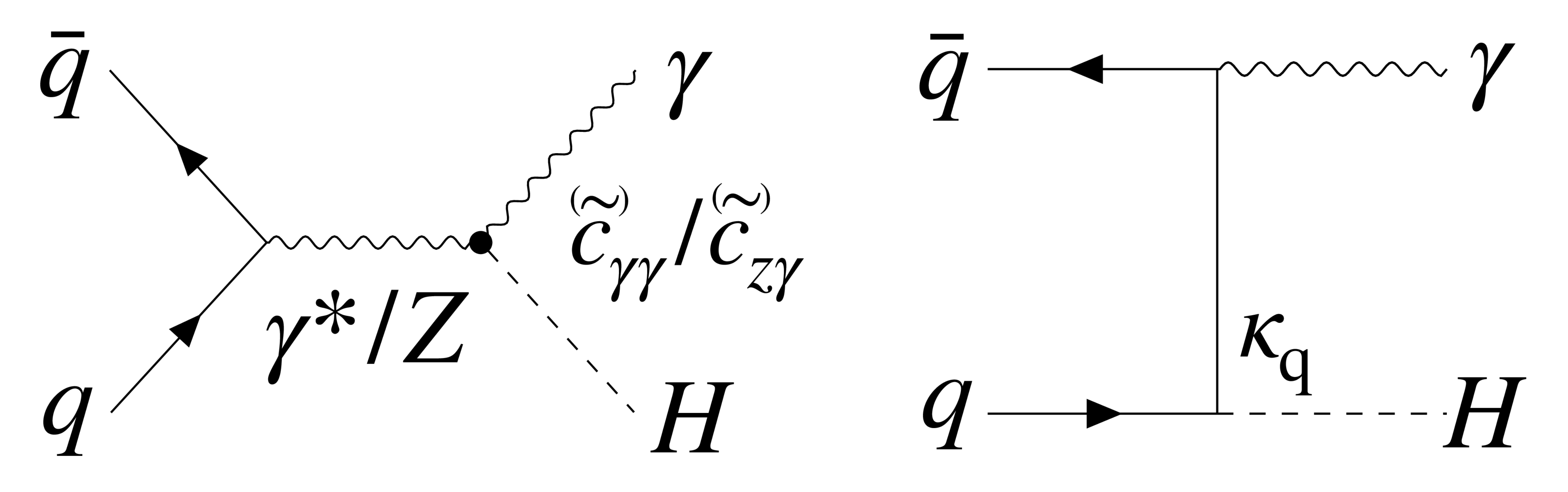
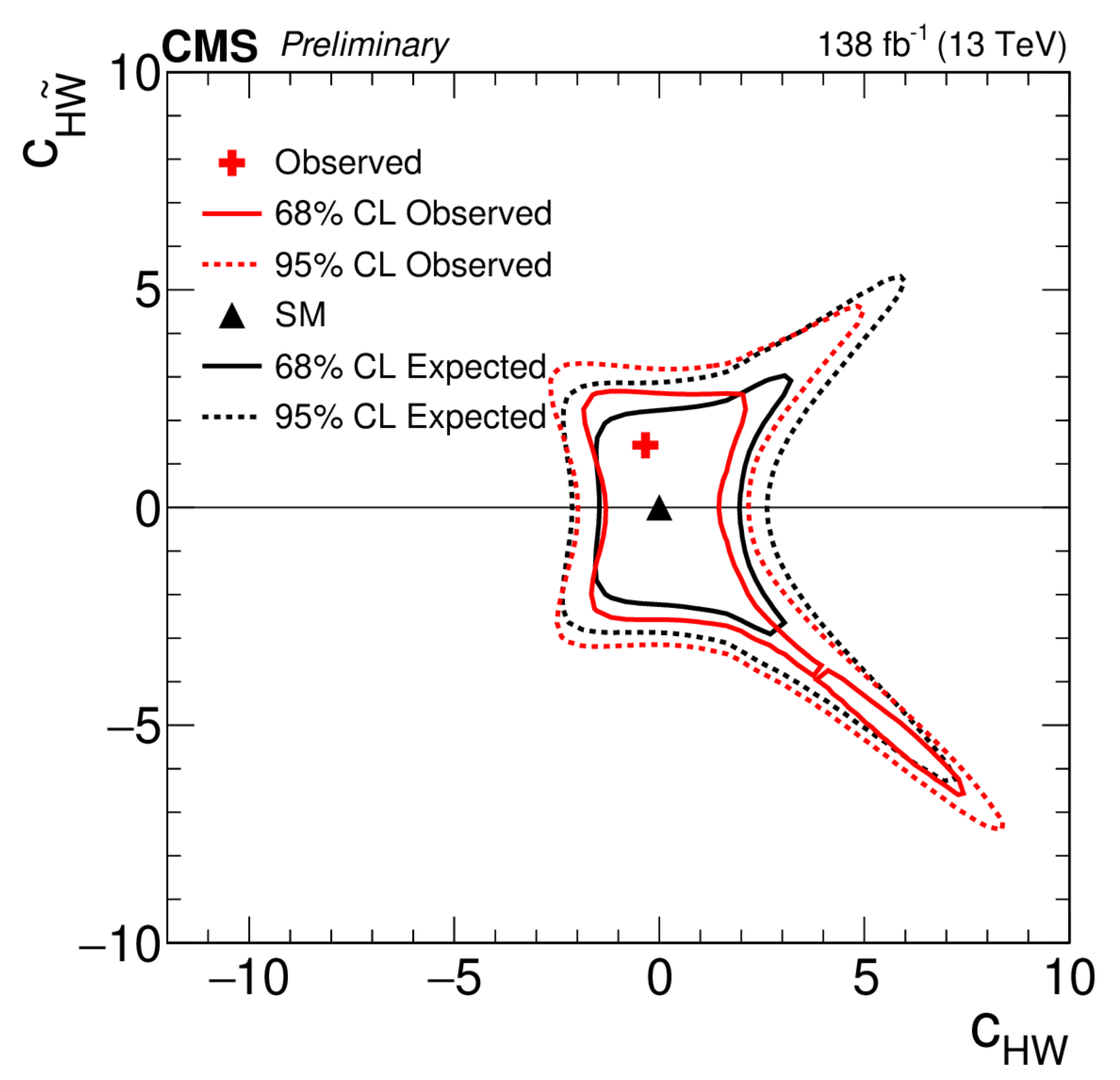


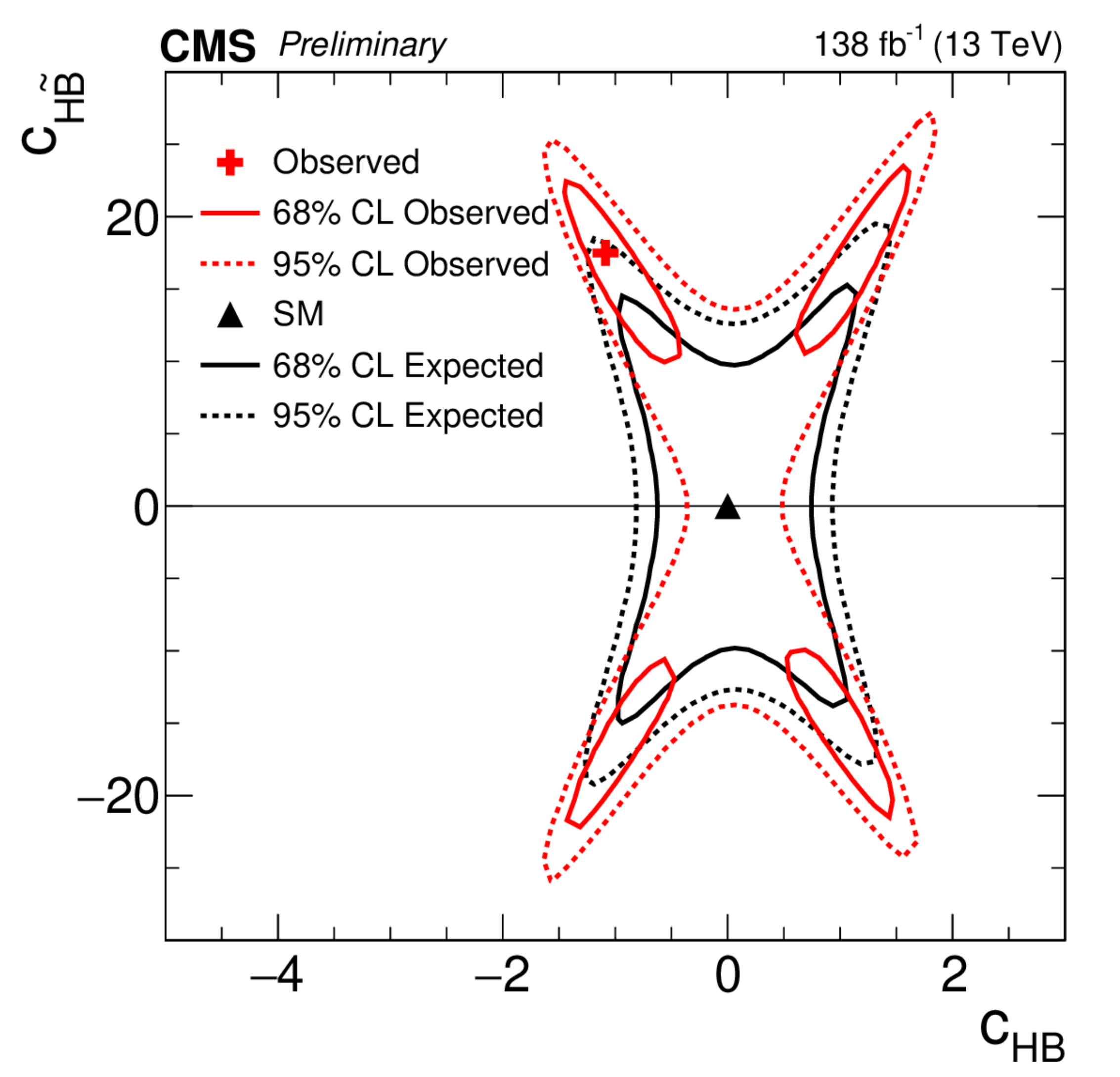
Table 3: Observed and expected constraints on the κ_u, κ_d, κ_s, and κ_c couplings are shown using the H $\to 4\ell$ channel. In one scenario, all couplings except the one being shown are fixed at their SM values. In the other scenario, the Yukawa couplings for the three other light quarks are left unconstrained, and BSM contributions are allowed. The 68% (central value with error bars) and 95% (bracketed range or upper limit) CL intervals are displayed.

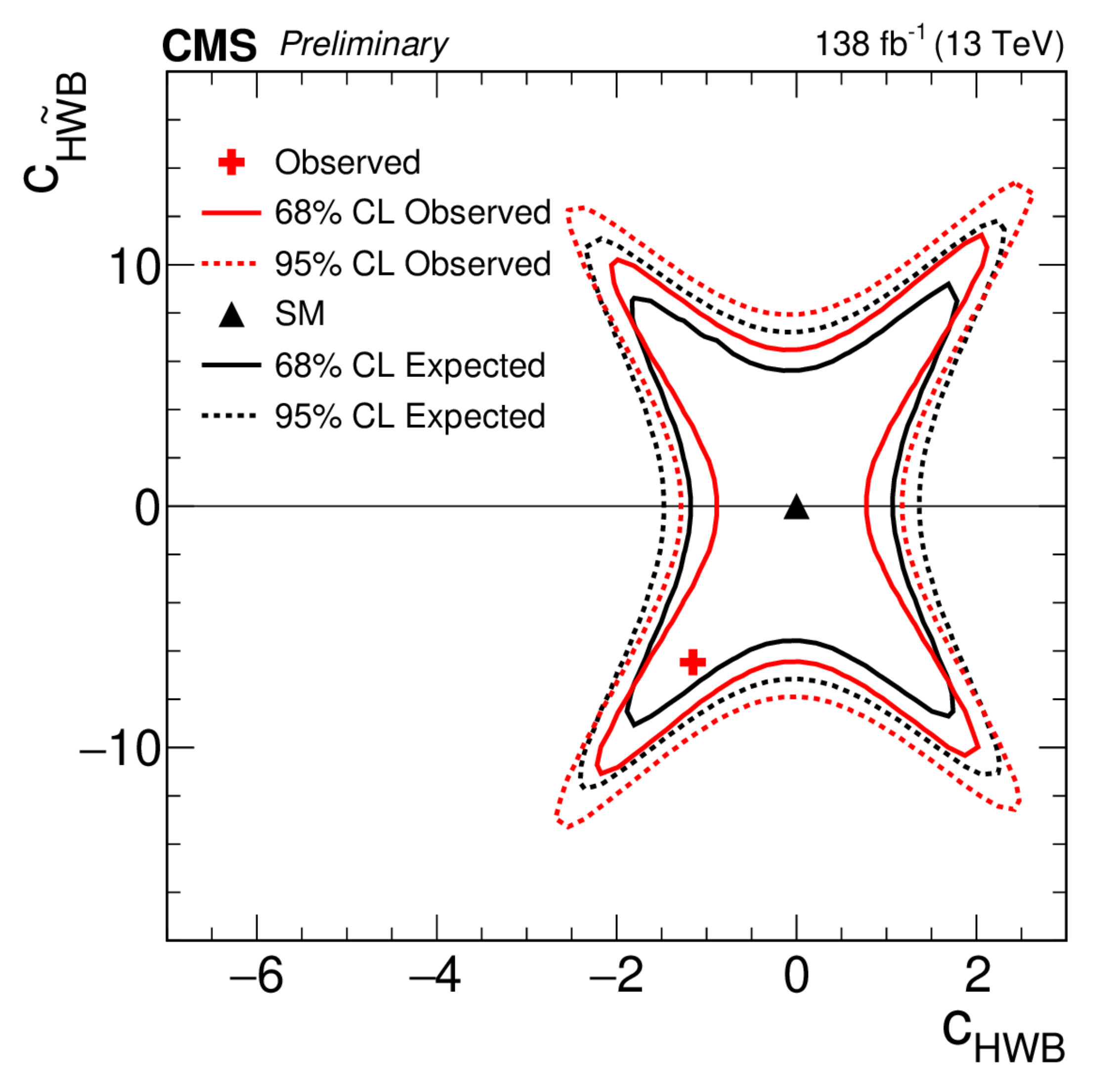
Parameter	Scenario	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
κ_u	float all	$(0.0 \pm 1.5) \times 10^3$	$[-2.4, 2.4] \times 10^3$	$(0.0 \pm 1.8) \times 10^3$	$[-2.6, 2.6] \times 10^3$
κ_u	fix others	$(0.0 \pm 1.4) \times 10^3$	$[-2.3, 2.3] \times 10^3$	$(0.0 \pm 1.6) \times 10^3$	$[-2.5, 2.5] \times 10^3$
κ_d	float all	$(0.0 \pm 7.1) \times 10^2$	$[-1.0, 1.0] \times 10^3$	$(0.0 \pm 7.4) \times 10^2$	$[-1.0, 1.0] \times 10^3$
κ_d	fix others	$(1.5^{+5.0}_{-8.0}) \times 10^2$	$[-9.7, 9.7] \times 10^2$	$(0.0 \pm 6.5) \times 10^2$	$[-9.7, 9.7] \times 10^2$
κ_s	float all	0^{+33}_{-34}	$[-46, 44]$	1^{+32}_{-31}	$[-44, 42]$
κ_s	fix others	11^{+19}_{-42}	$[-44, 42]$	1^{+26}_{-30}	$[-41, 40]$
κ_c	float all	$0.0^{+2.7}_{-3.0}$	$[-4.0, 3.4]$	$1.0^{+1.4}_{-3.8}$	$[-3.8, 3.2]$
κ_c	fix others	$1.4^{+1.2}_{-4.4}$	$[-4.0, 3.5]$	$1.0^{+1.3}_{-3.8}$	$[-3.8, 3.2]$
Γ_H^{BSM} (MeV)	float all	$0.0^{+0.9}_{-0.0}$	<1.6	$0.0^{+0.7}_{-0.0}$	<1.4

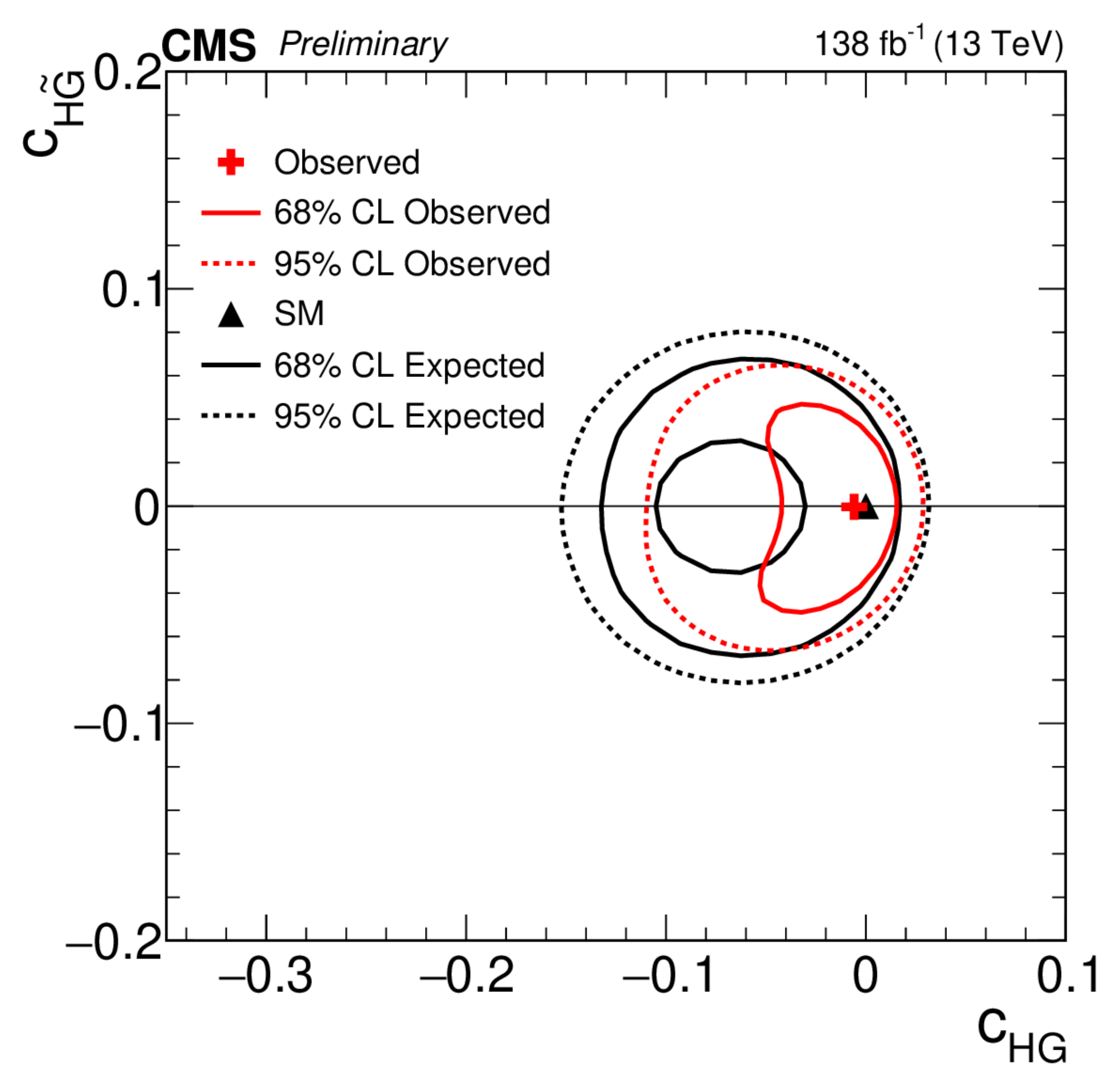
(Top and bottom yukawas constrained to SM, |k VV| ≤ 1)

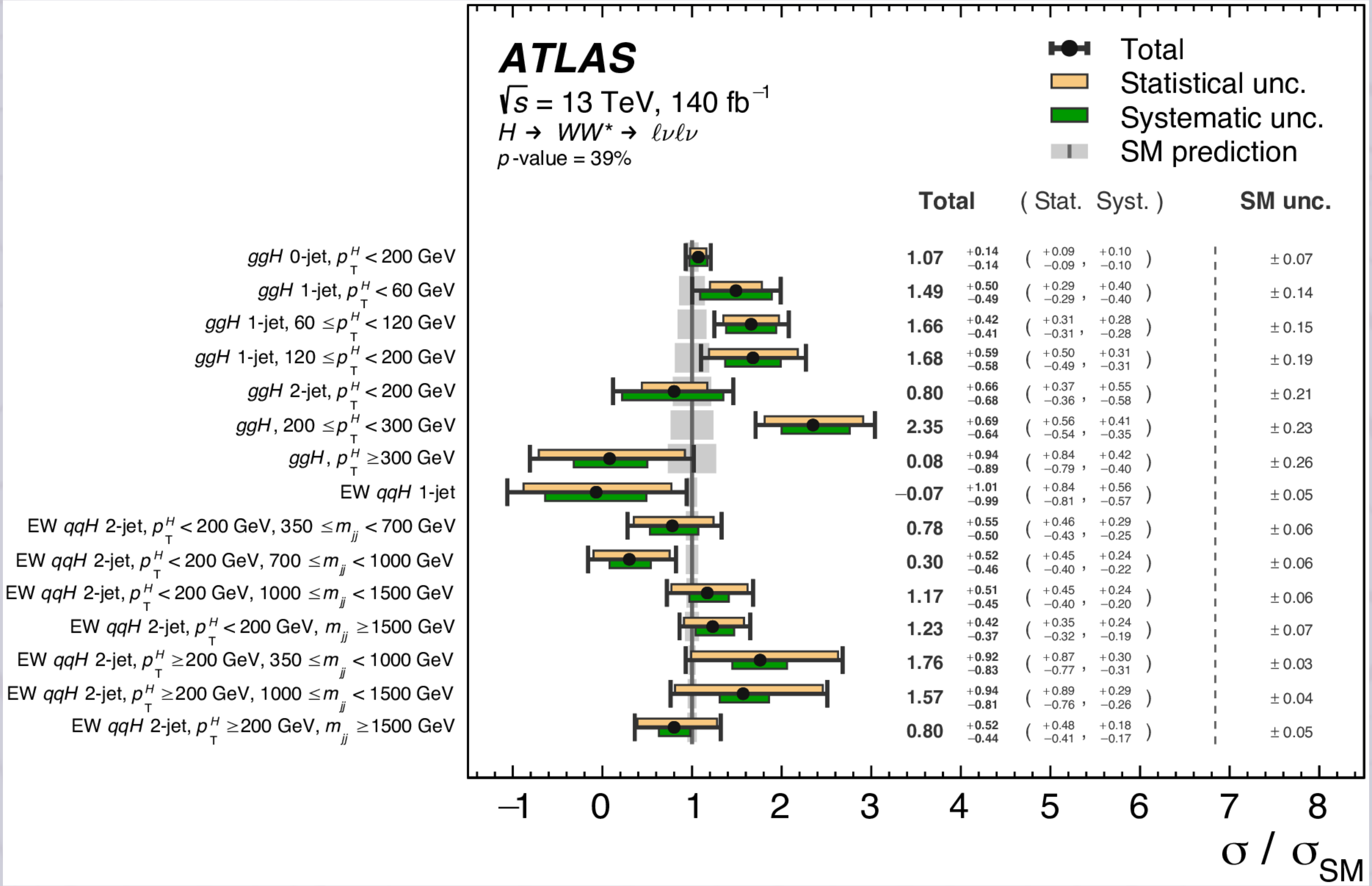
DIFFERENTIAL VBF HWW PRODUCTION

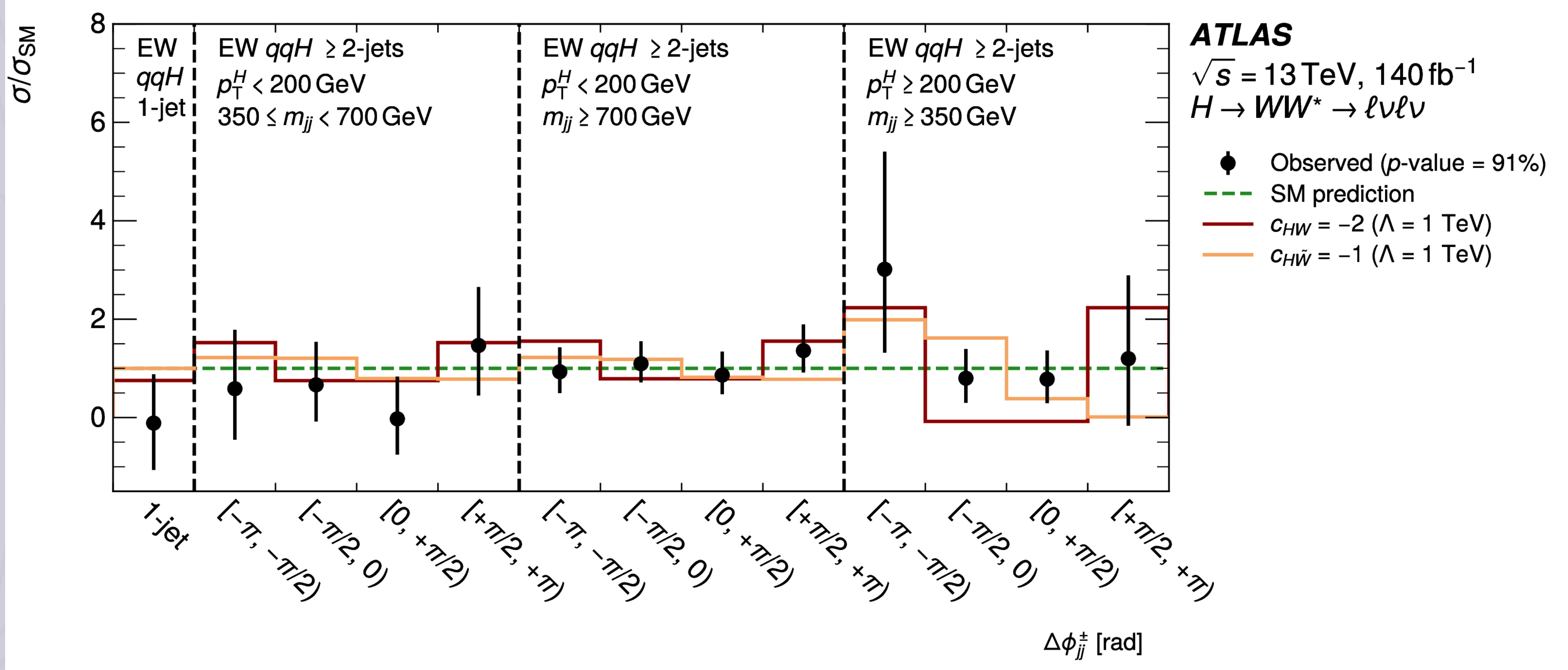








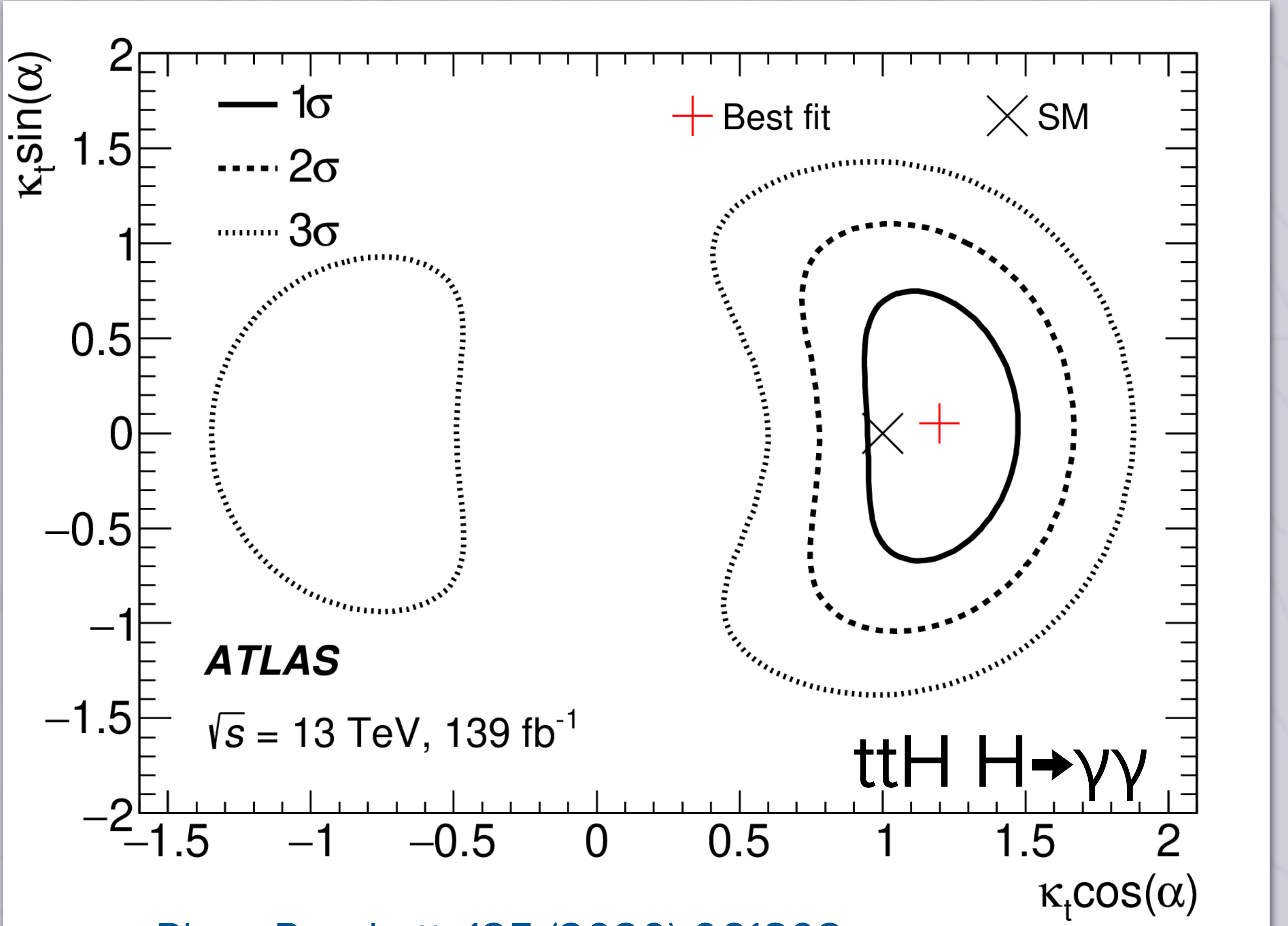




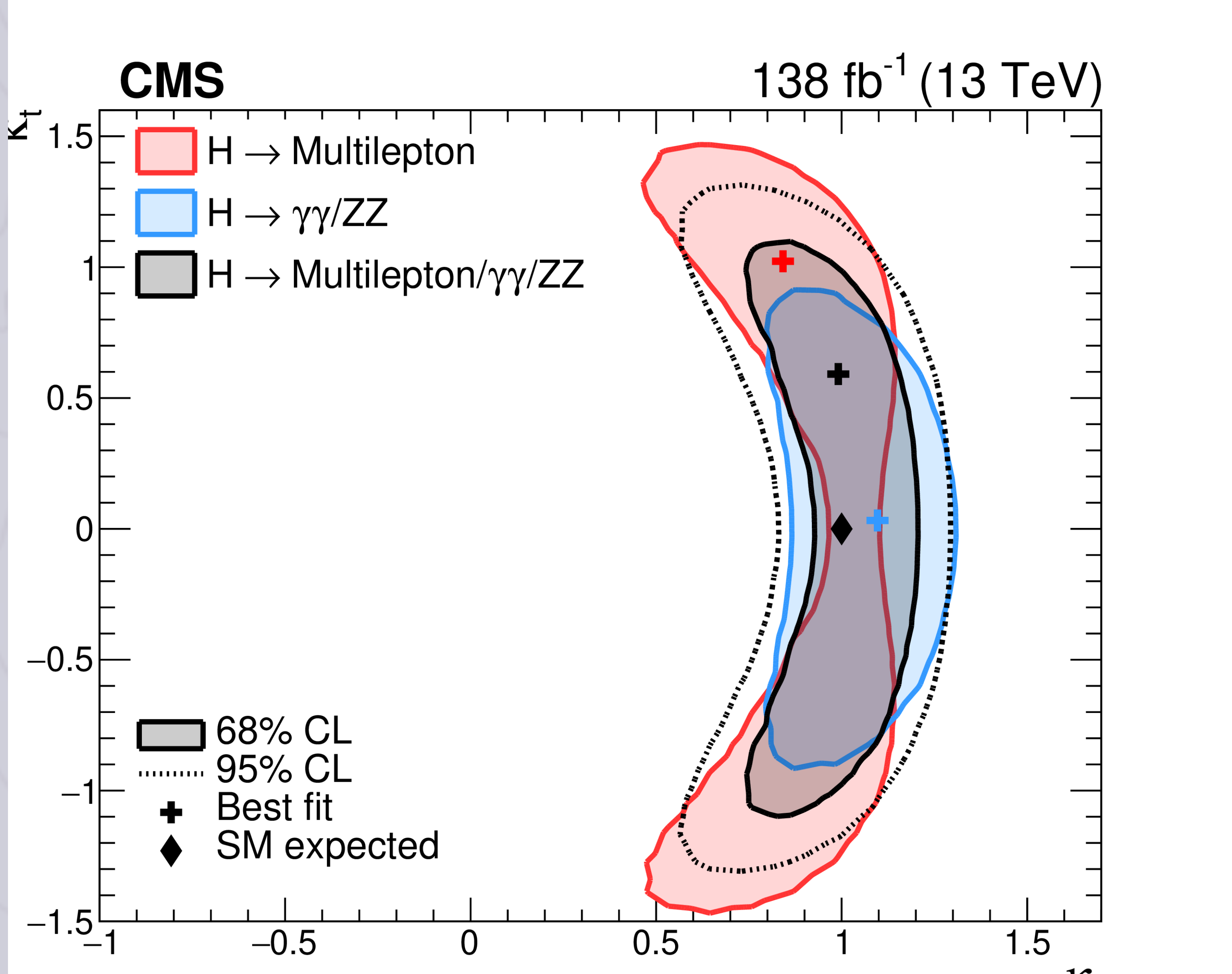
THE SCALAR NATURE OF THE HIGGS

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

- Spin-parity quantum number of Higgs boson consistent with the SM , $J^{cp} = 0^{++}$
- So far no surprises: good agreement with SM
- Plenty of searches for CP in practically all decay modes, exploring **production** and **decay.**
- Recent results exploring specific SMEFT coefficients (eg HWW, Hbb, already shown probes for specific CP observables)



Phys. Rev. Lett. 125 (2020) 061802



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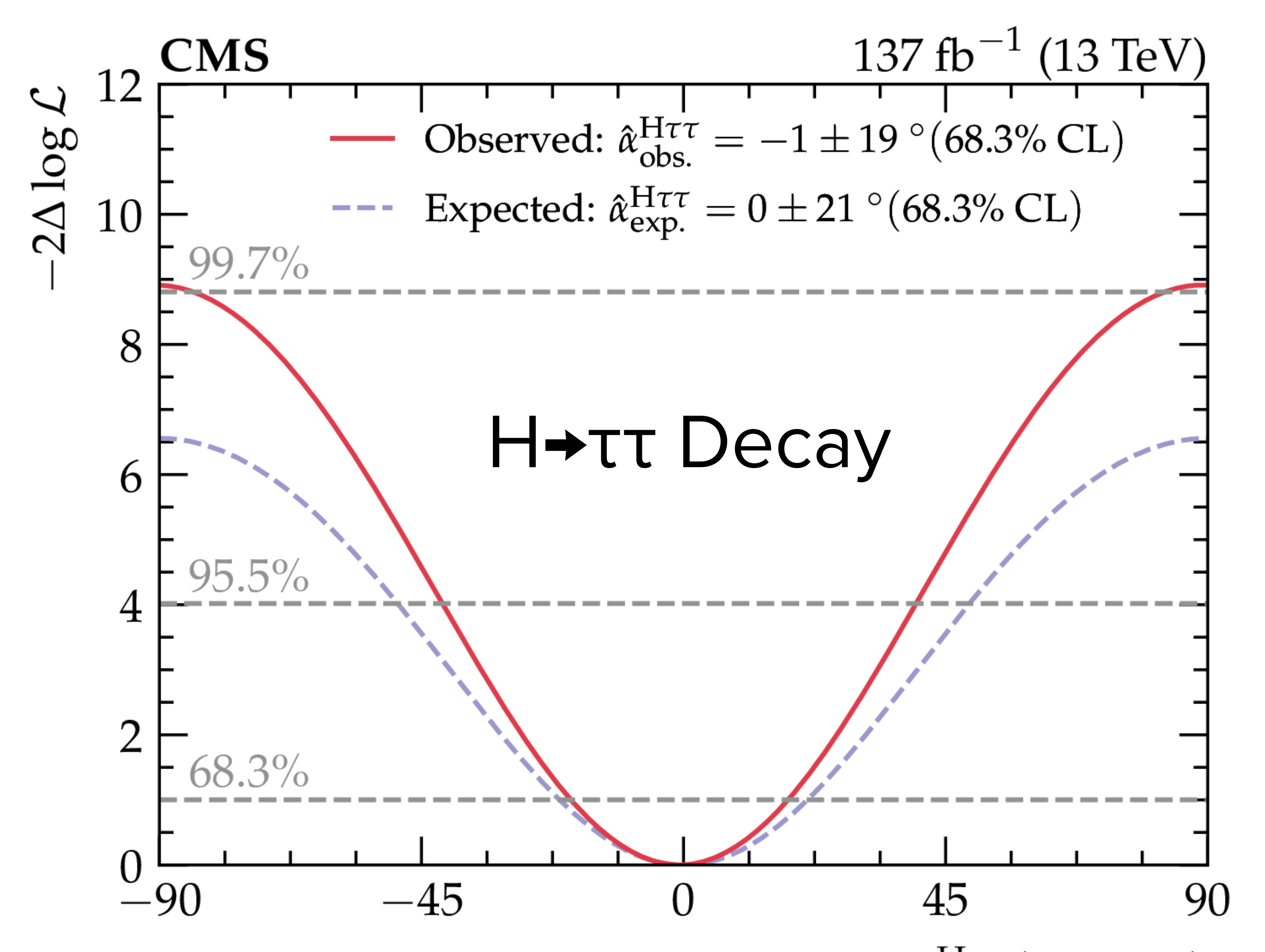

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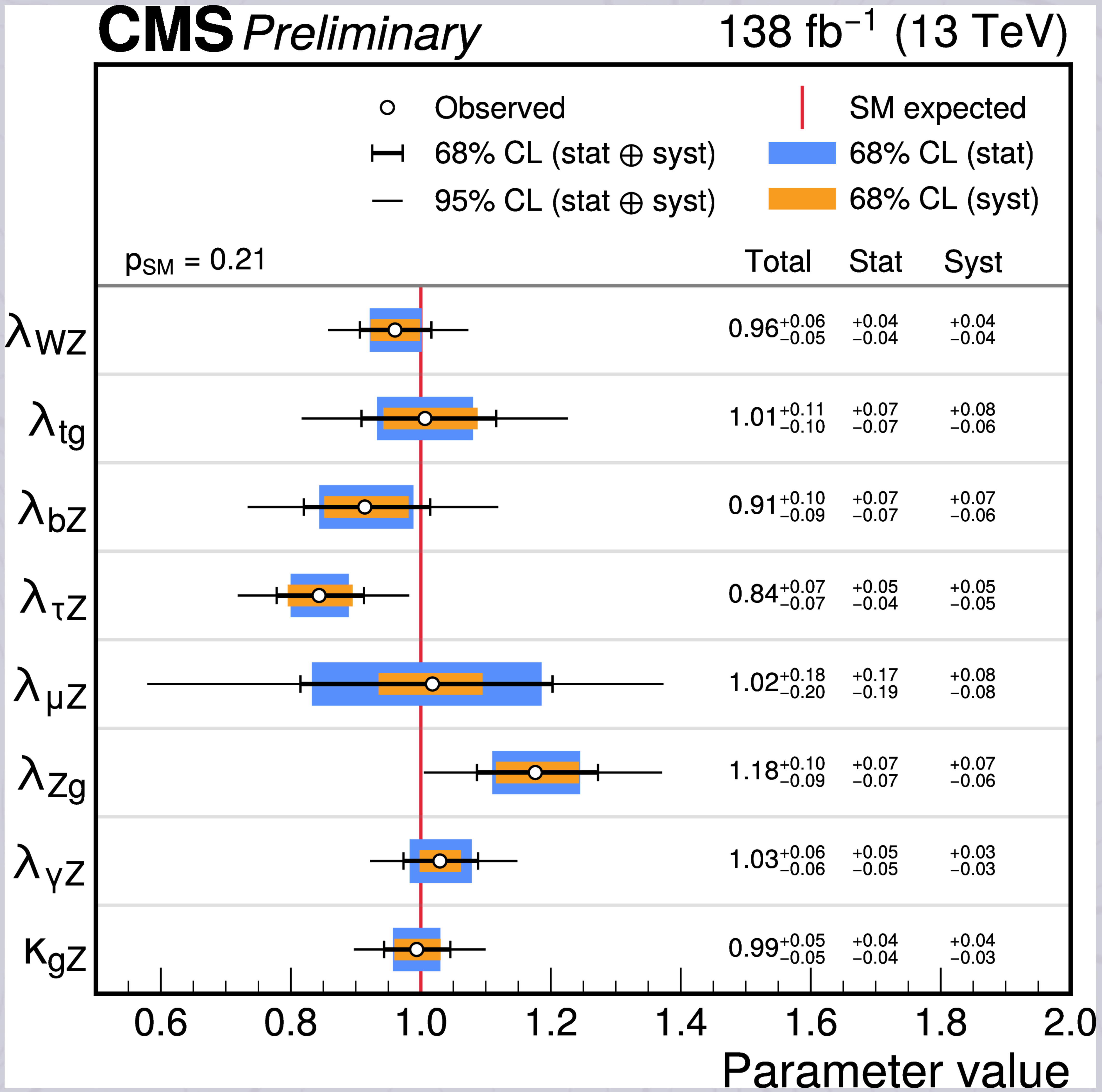
COUPLING RATIOS

- Ratios of couplings to control uncertainties.

$$\lambda_{ij} = \kappa_i/\kappa_j$$

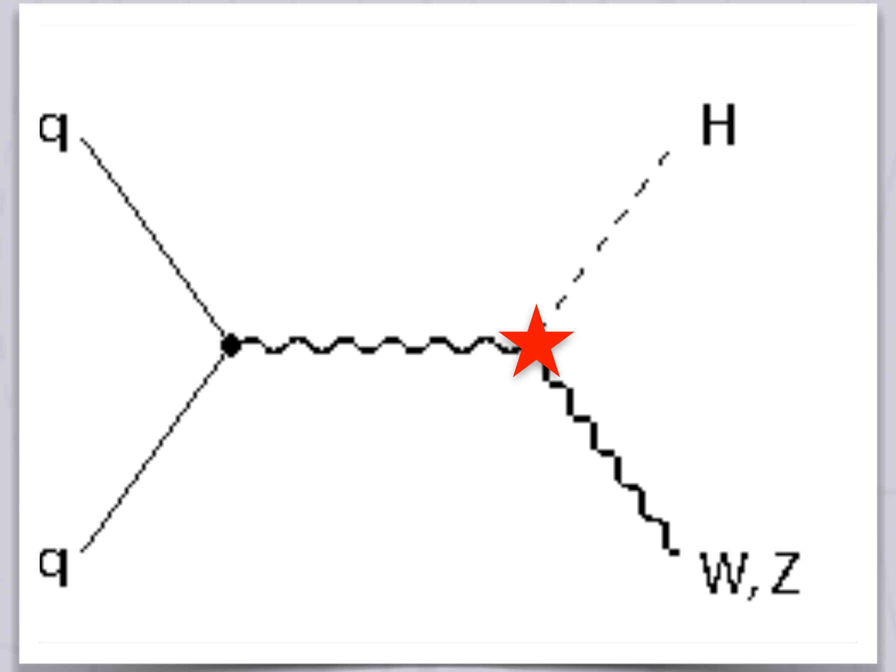
- Reference coupling (to account for changes in the total yield of specific processes, avoiding the need for assumptions on the Higgs boson total decay width): $\kappa_{gZ} = \kappa_g \kappa_Z / \kappa_H$

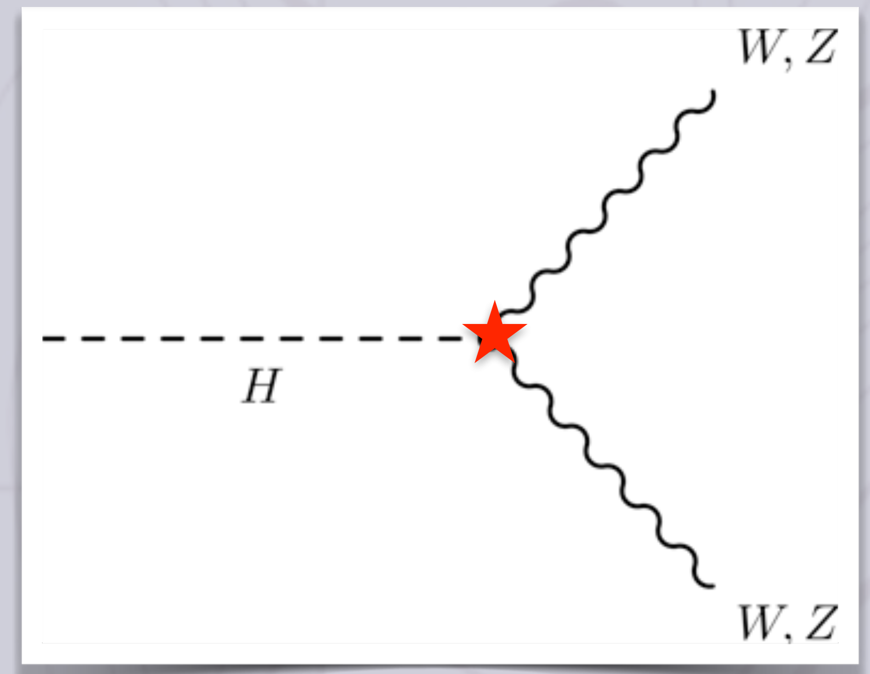


HIGGS COUPLINGS

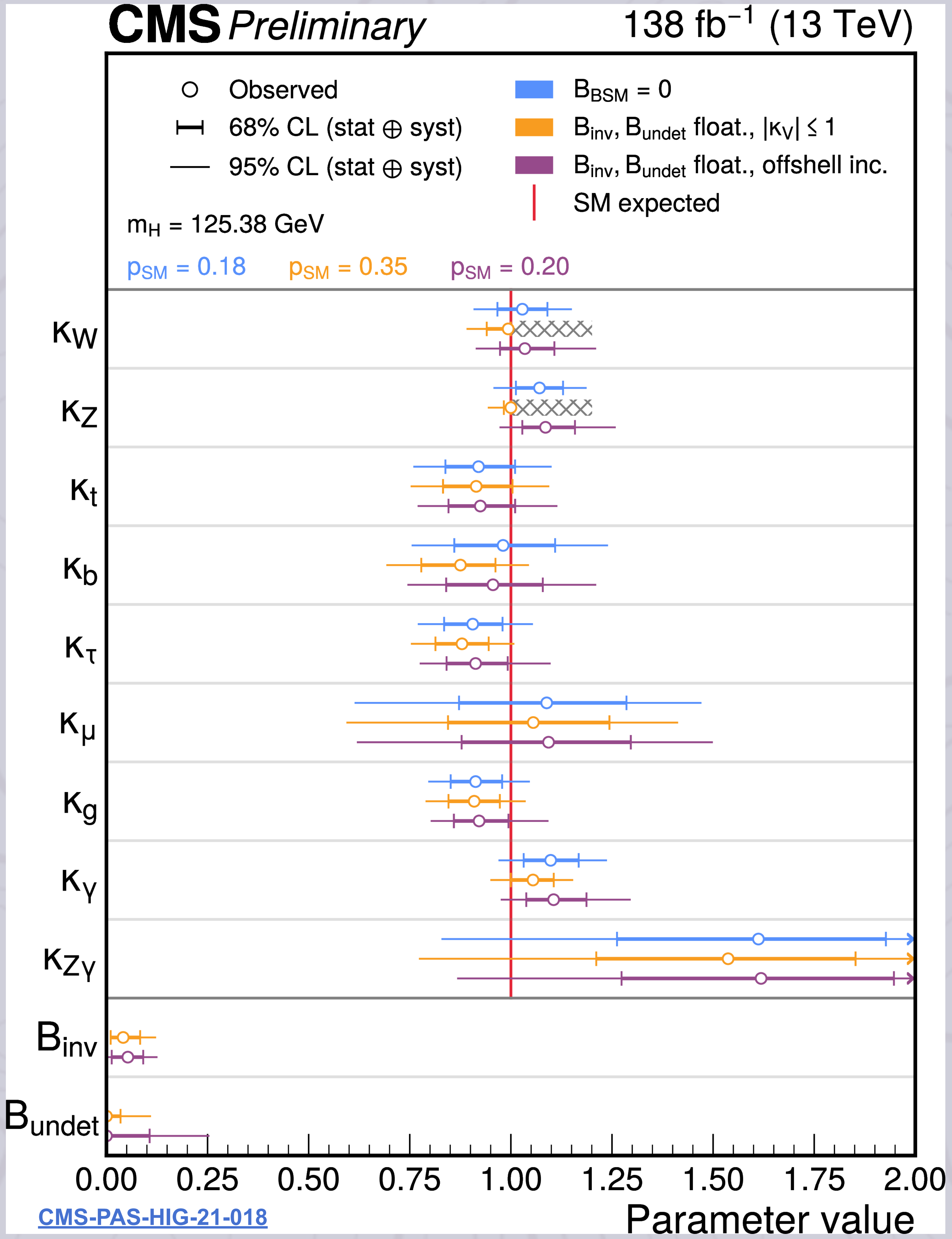
- **What is the strength of the interaction of the Higgs to the different SM particles?**
  - Kappa Framework: simple parametrisation widely used by LHC experiments (not perfect, but useful)

$$\kappa_j^2 = \sigma_j/\sigma_j^{SM} \qquad \kappa_j^2 = \Gamma^j/\Gamma^j_{SM}$$

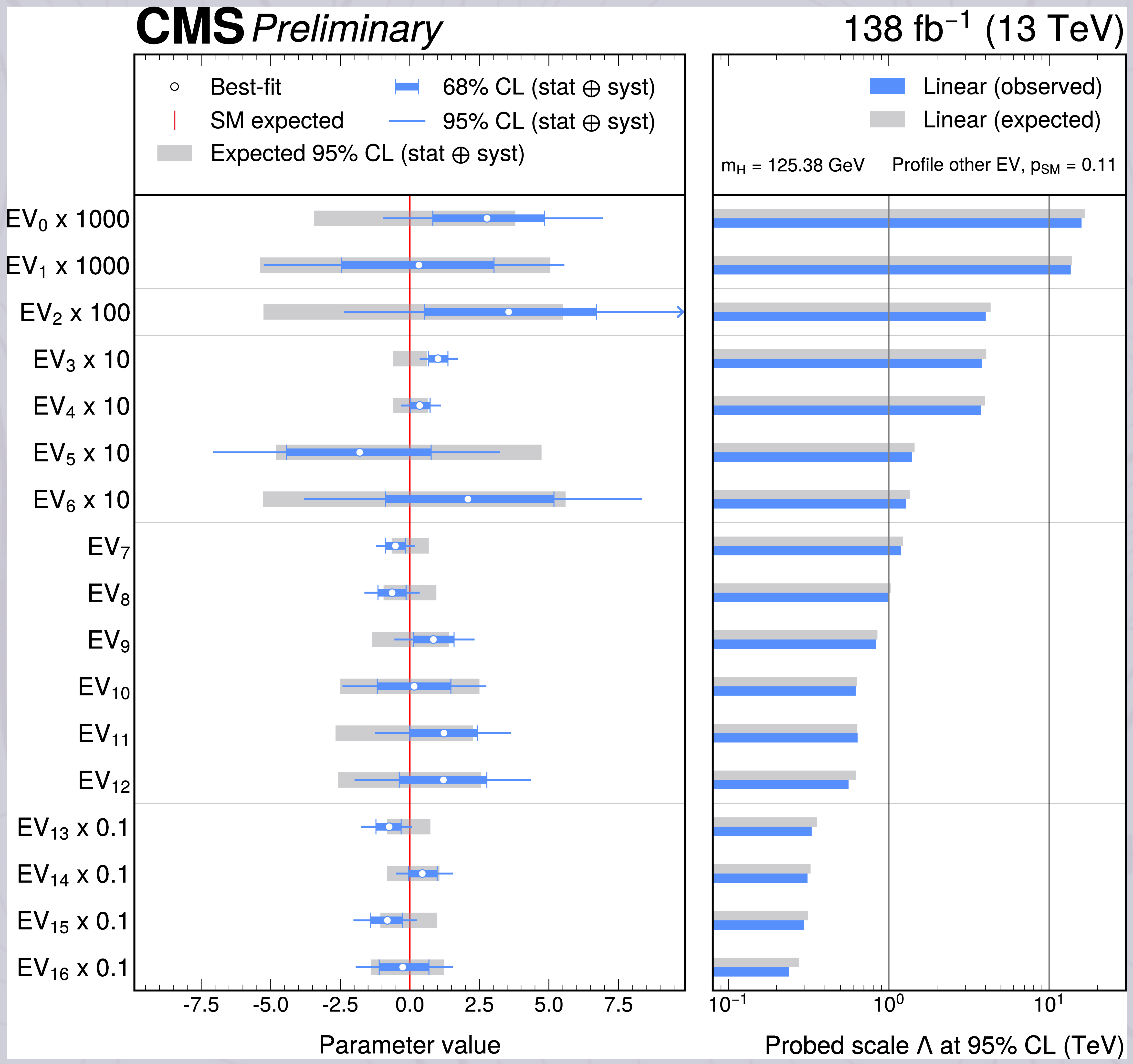




  - Different scenarios considered: tree level couplings only, including effective loops, assuming no BSM decays, or allowing invisible and undetected contributions to the total width
- **With the full Run2 Combination (per experiment): 'Main' modes already known to 5-12% for the (~20%-30% for stat dominated $\mu\mu$, Zγ)**

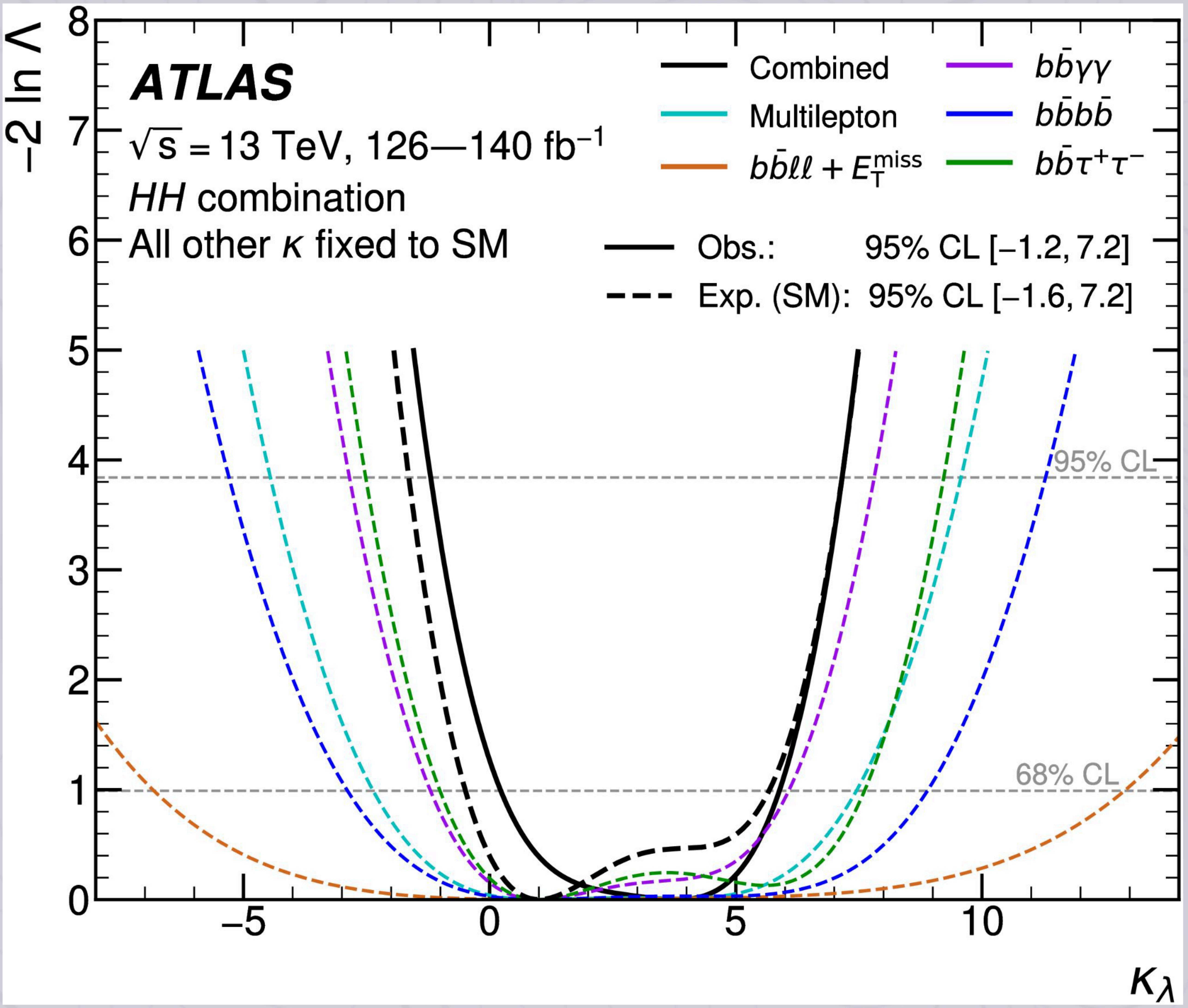


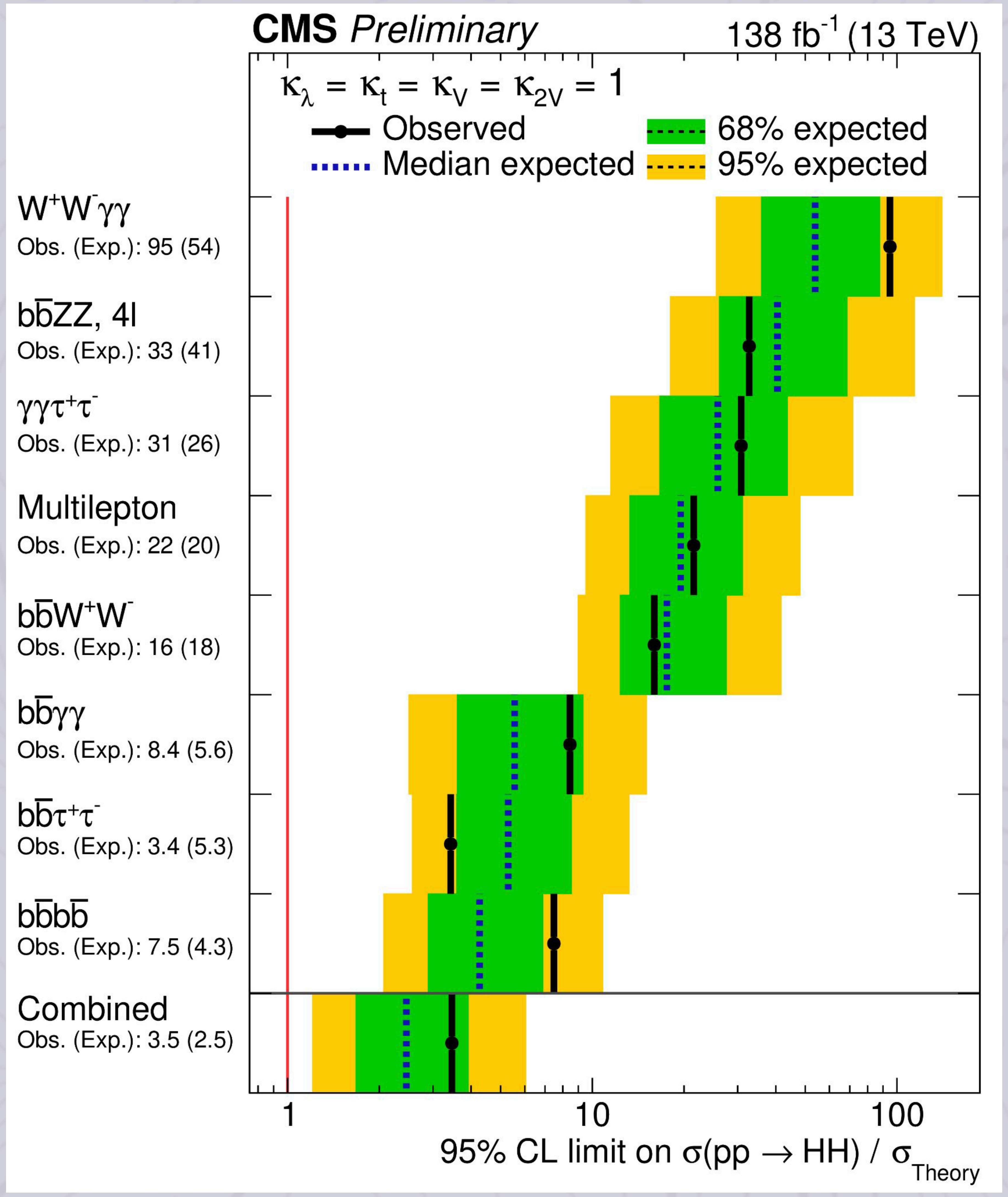
BEYOND KAPPAS: SMEFT FITS



- We discussed constraints of specific SMEFT operators as a part of individual analysis
- We can also extract constraints on 43 Wilson Coefficients (linear and linear+quadratic parameterizations)
- The largest discrepancy from the SM is observed in the $c^{(3)}_{Hq}$ parameter (pSM = 0.01), driven by the observed excesses in the high-p_T(V) in WH and ZH leptonic STXS measurements.
- 17 independent directions in the SMEFT parameter space constrained (eigenvectors, EV) from the Higgs combination. Overall good agreement with SM (pvalue = 0.11).

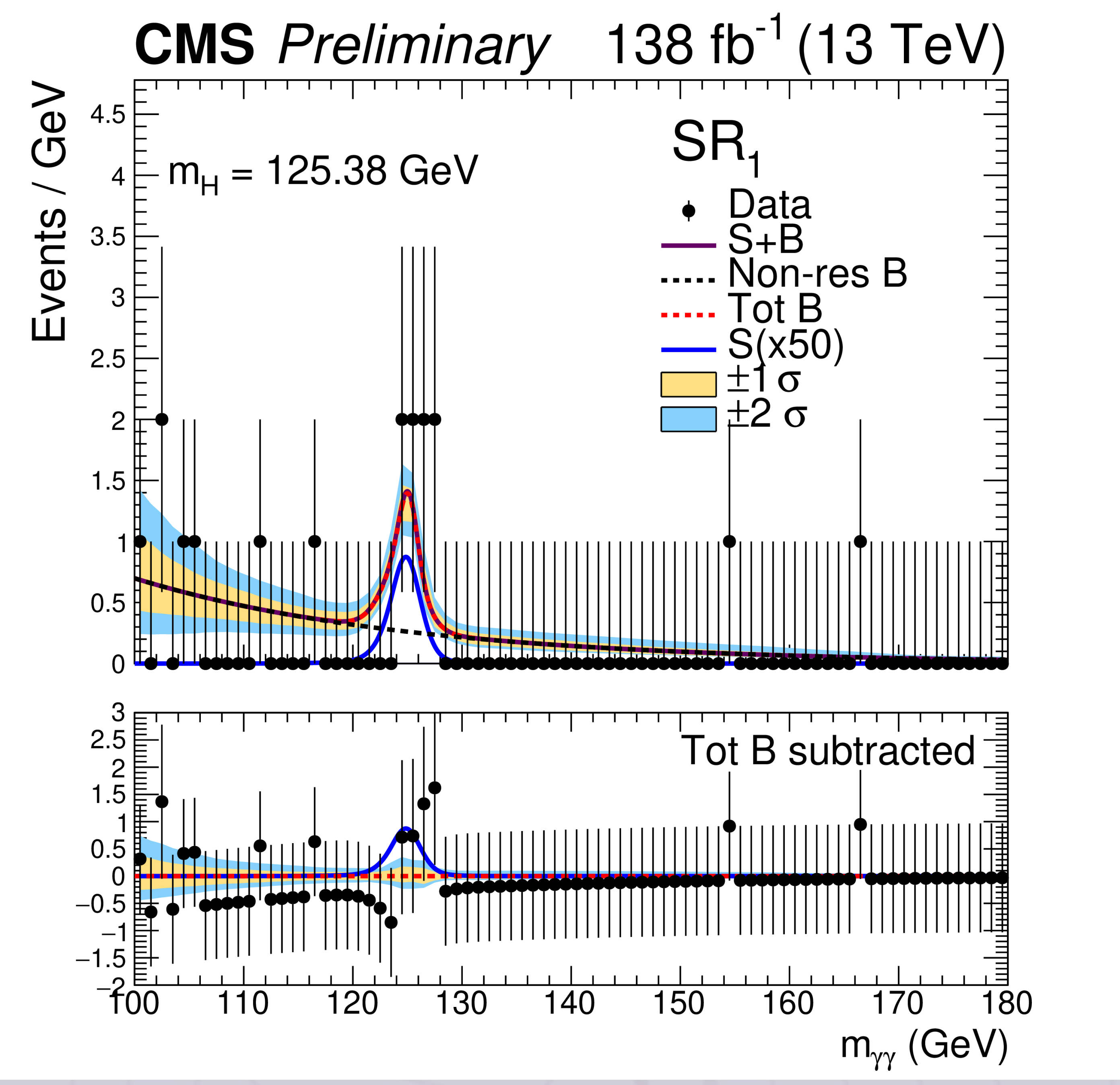
WHERE ARE WE?

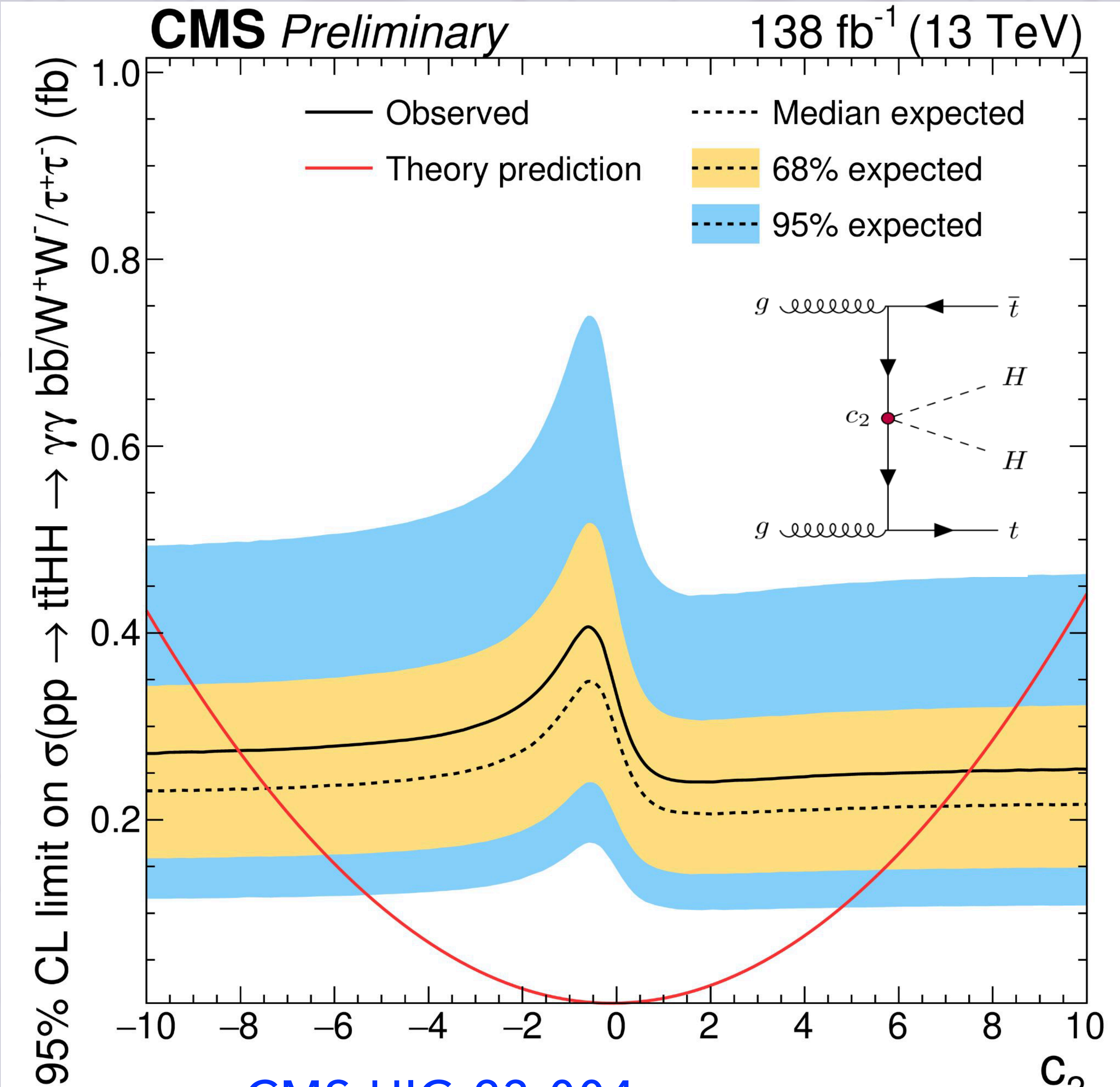

ATLAS
$\sqrt{s}$ = 13 TeV, 126—140 fb^{-1}
HH combination
All other κ fixed to SM
Combined
Multilepton
$b\bar{b}\ell\ell + E_T^{miss}$
$b\bar{b}\gamma\gamma$
$b\bar{b}b\bar{b}$
$b\bar{b}\tau^+\tau^-$
Obs.: 95% CL [−1.2, 7.2]
Exp. (SM): 95% CL [−1.6, 7.2]
95% CL
68% CL
−2 ln Λ
κ_λ


CMS Preliminary
138 fb^{-1} (13 TeV)
$\kappa_\lambda = \kappa_t = \kappa_V = \kappa_{2V} = 1$
Observed
Median expected
68% expected
95% expected
$W^+W^-\gamma\gamma$
Obs. (Exp.): 95 (54)
$b\bar{b}ZZ$, 4l
Obs. (Exp.): 33 (41)
$\gamma\gamma\tau^+\tau^-$
Obs. (Exp.): 31 (26)
Multilepton
Obs. (Exp.): 22 (20)
$b\bar{b}W^+W^-$
Obs. (Exp.): 16 (18)
$b\bar{b}\gamma\gamma$
Obs. (Exp.): 8.4 (5.6)
$b\bar{b}\tau^+\tau^-$
Obs. (Exp.): 3.4 (5.3)
$b\bar{b}b\bar{b}$
Obs. (Exp.): 7.5 (4.3)
Combined
Obs. (Exp.): 3.5 (2.5)
95% CL limit on σ(pp → HH) / σ_{Theory}

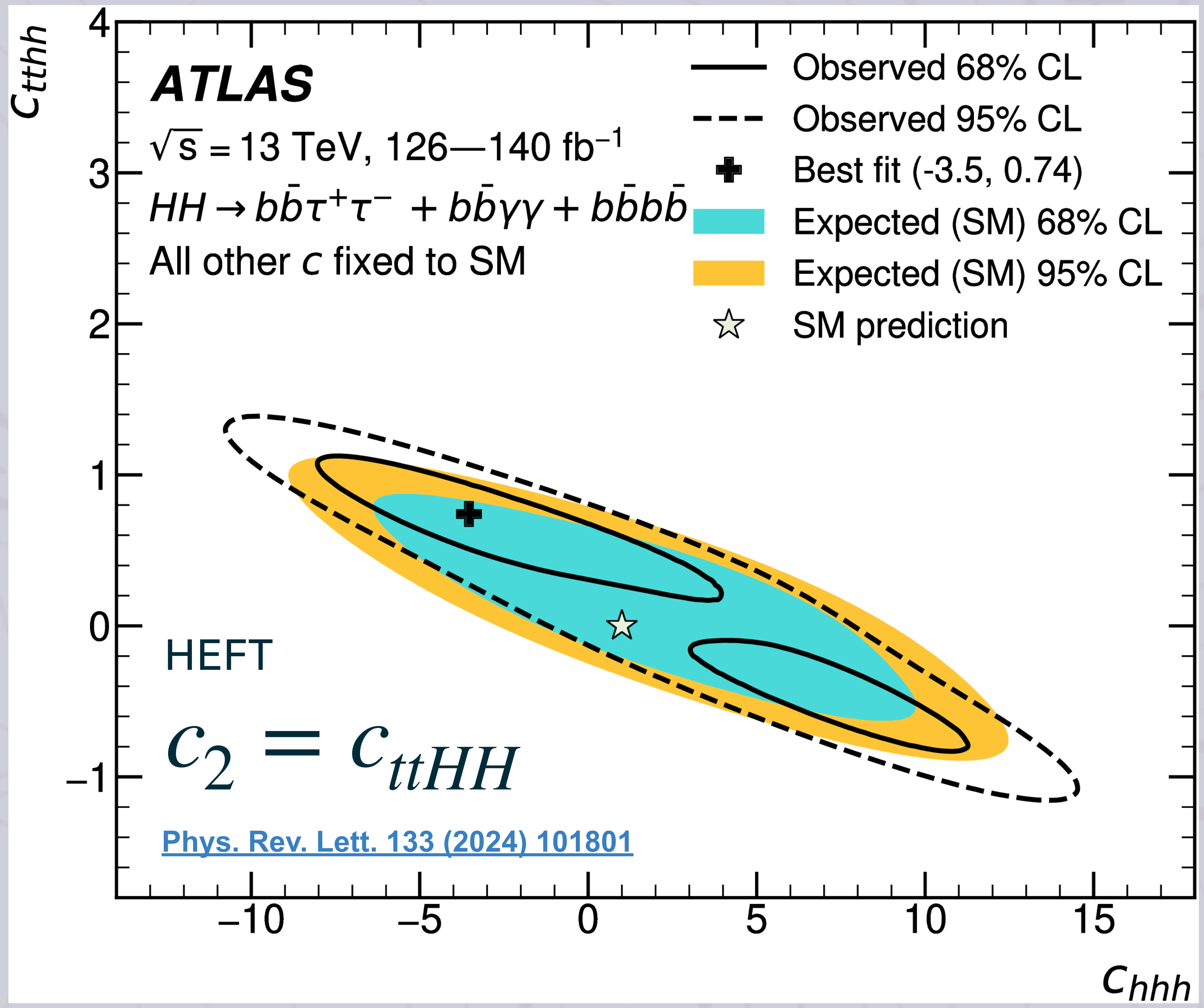
TTHH AND C2

- First limit on ttHH production (SM= 0.8 fb), exploiting the Hγγ channel : $\mu_{ttHH} < 119.4(85.9)$ at 95%CL
- Direct constraint on c2 (contact interaction between two Higgs bosons and two top quarks): $-8.0 < c_2 < 7.5$
  - Indirect constraints from ggHH in HEFT: $-0.19 < c_2 < 0.7\ (ATLAS),\ -0.28 < c_2 < 0.59\ (CMS)$
- Resonant production probes 2HDM and VLQ production (no signal observed, $m_{H2} < 265\ GeV\ (tan\beta = 0.8)$ $m_{T'} < 1100(1500)\ GeV$)





CMS-HIG-23-004



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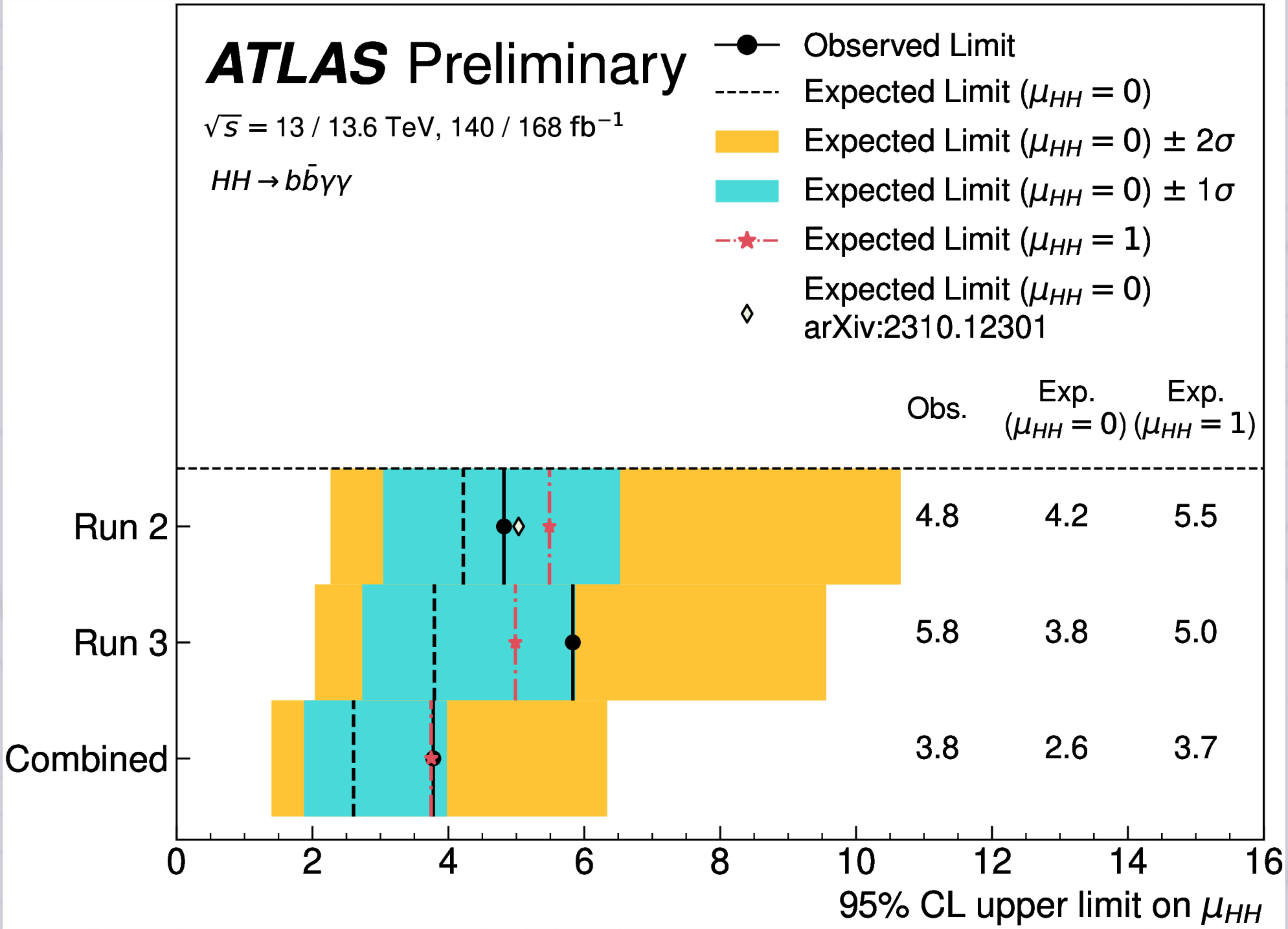
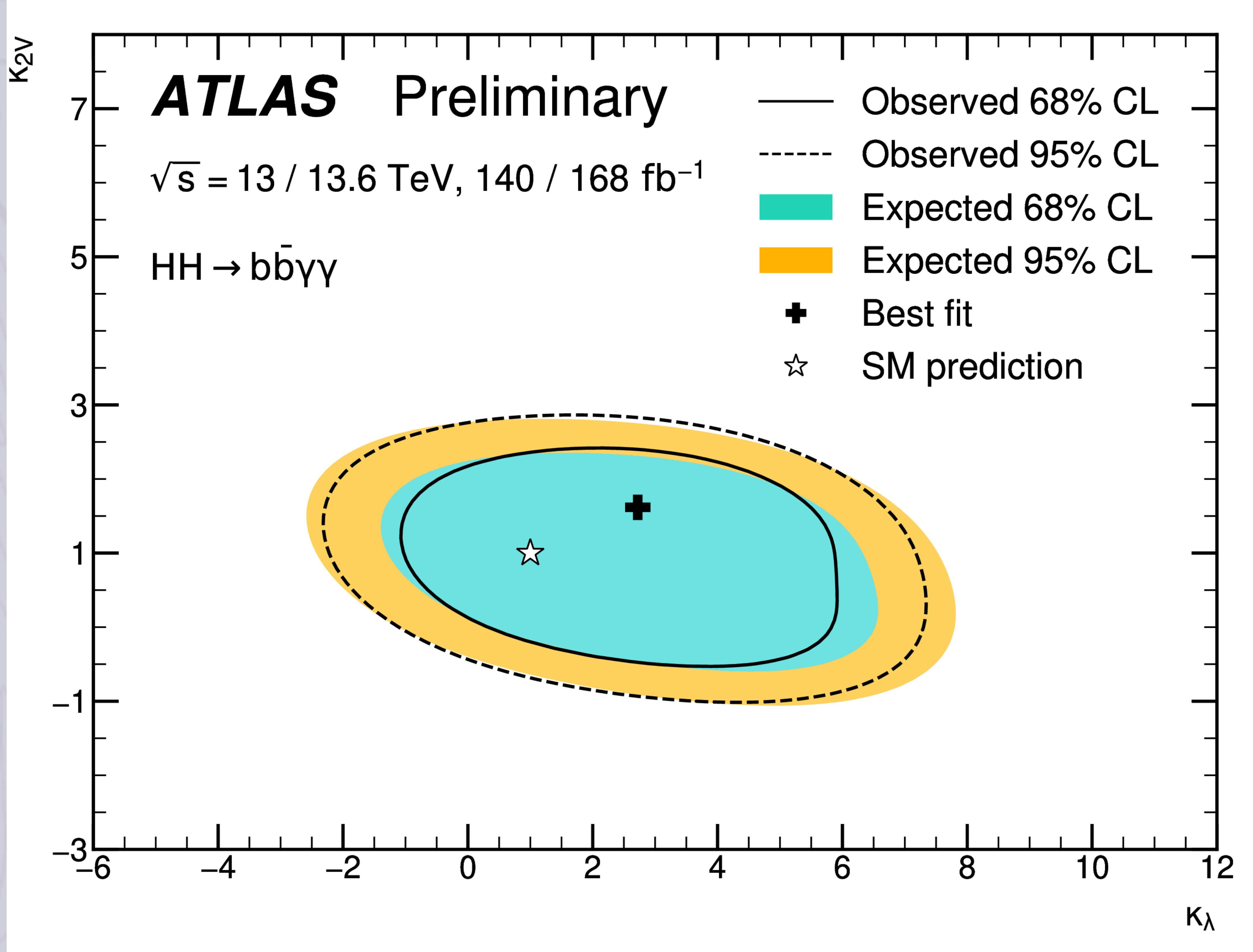
RUN3: HH BBGAMMAGAMMA

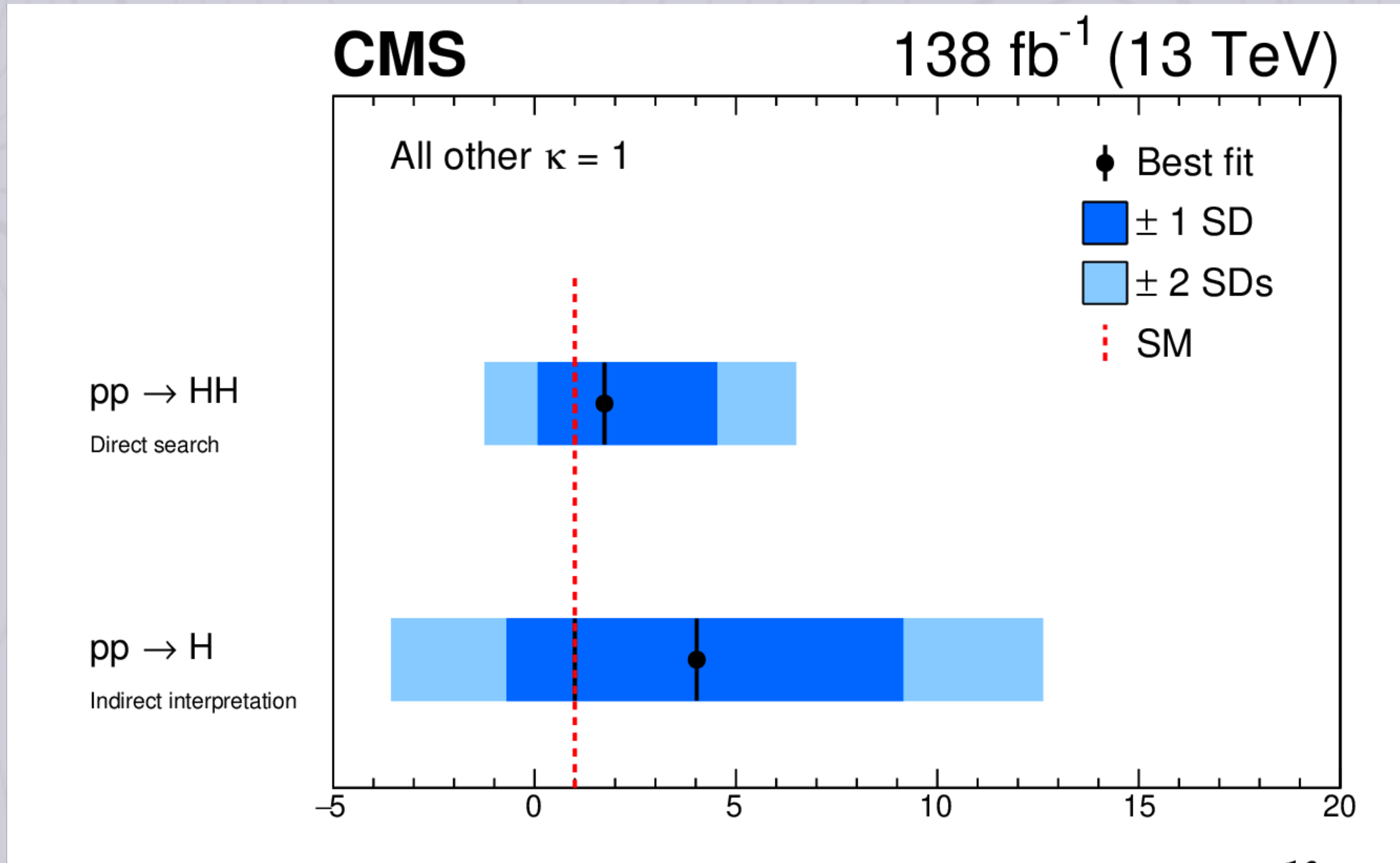
- ATLAS bbgg



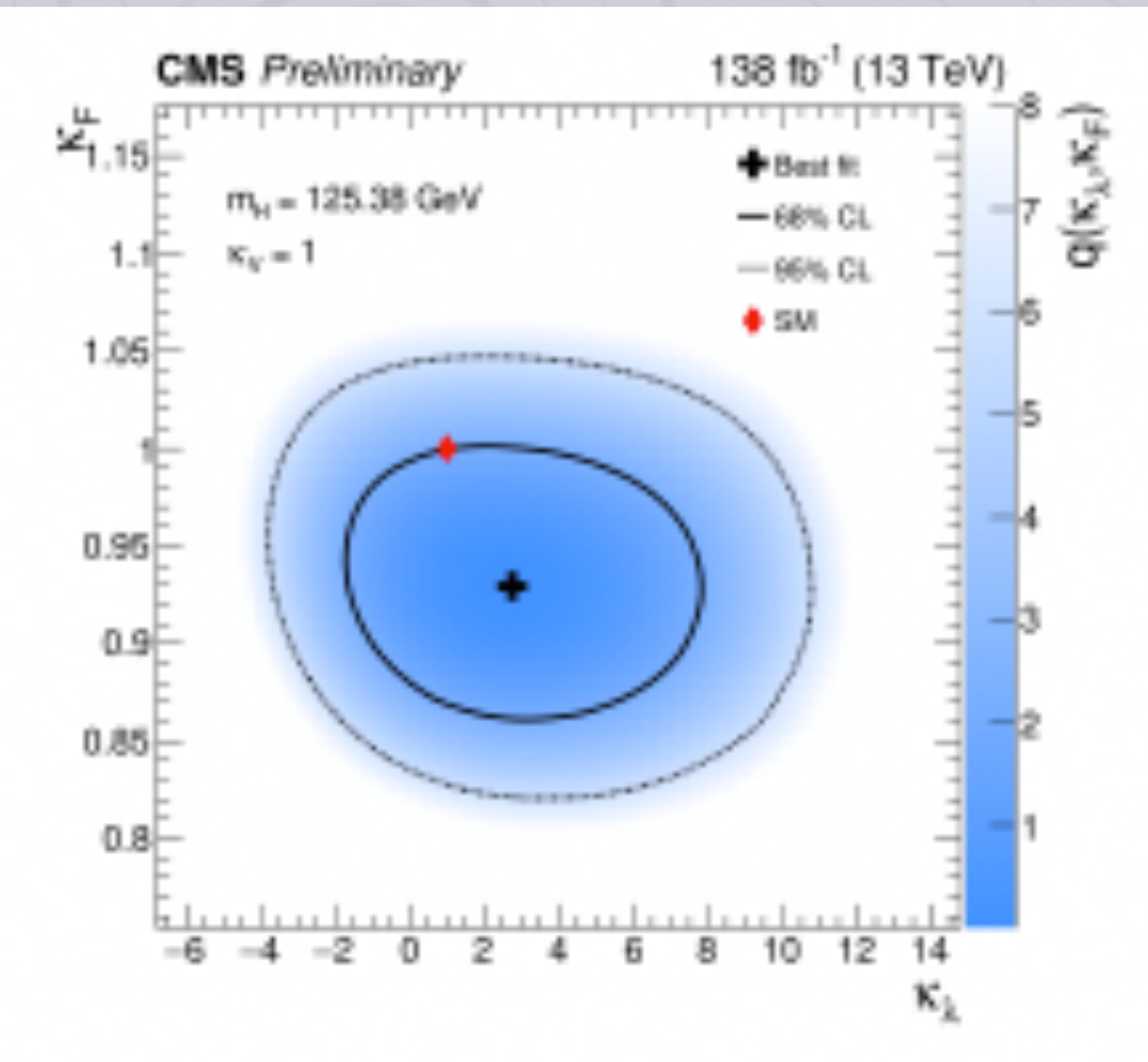


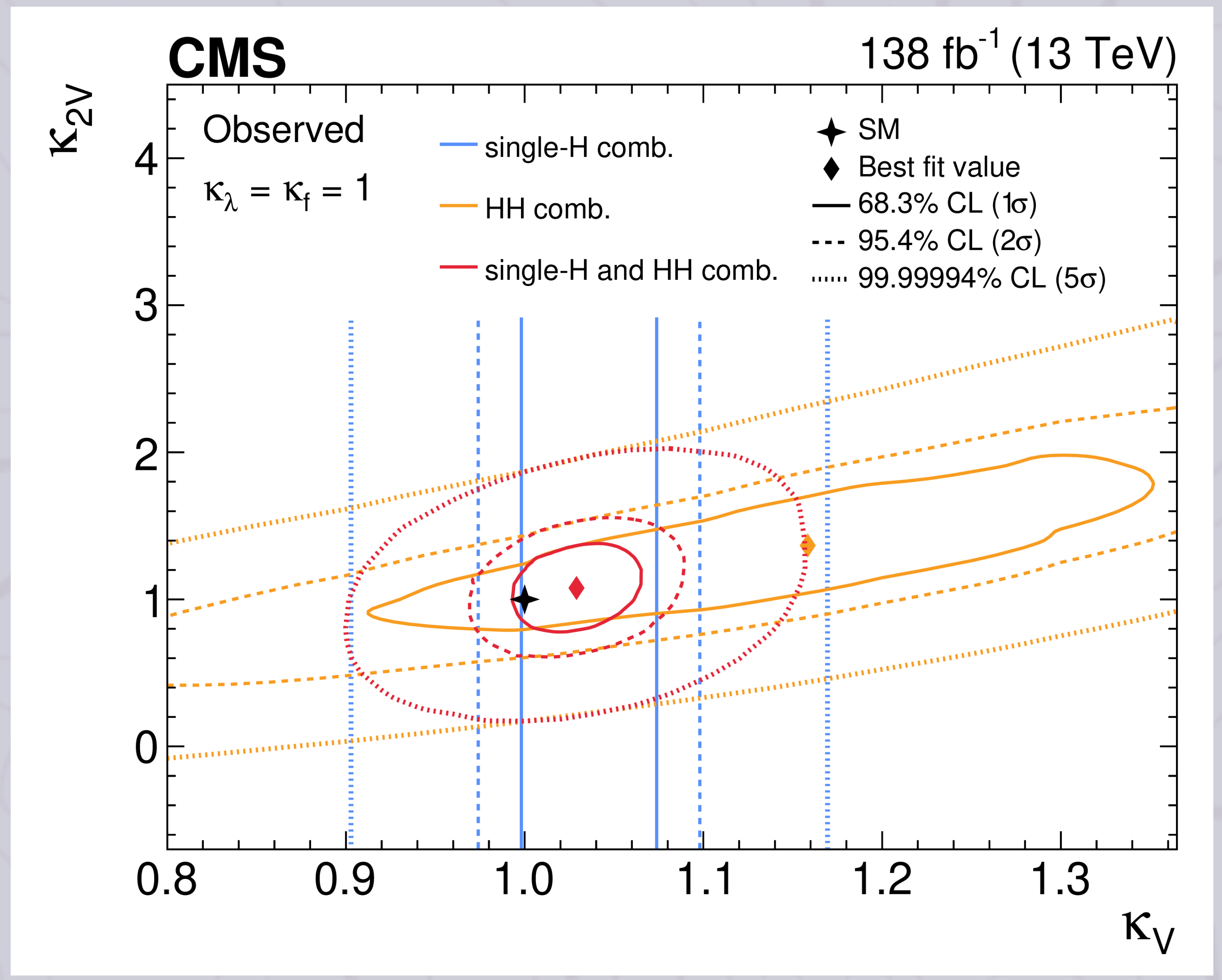
K3 FROM SINGLE HIGGS

- It is possible to constrain the self coupling from single Higgs analysis. In the recent CMS combination: $\kappa_\lambda \in [-3.3, 9.6]\ at\ 95\,\%\,CL$ in HIG-21-018
  - Weaker than HH
- Combining H and HH: full access to parameterization. Correlations between couplings.
  - Example: kV vs k2V in Phys. Lett. B 861 (2025) 139210

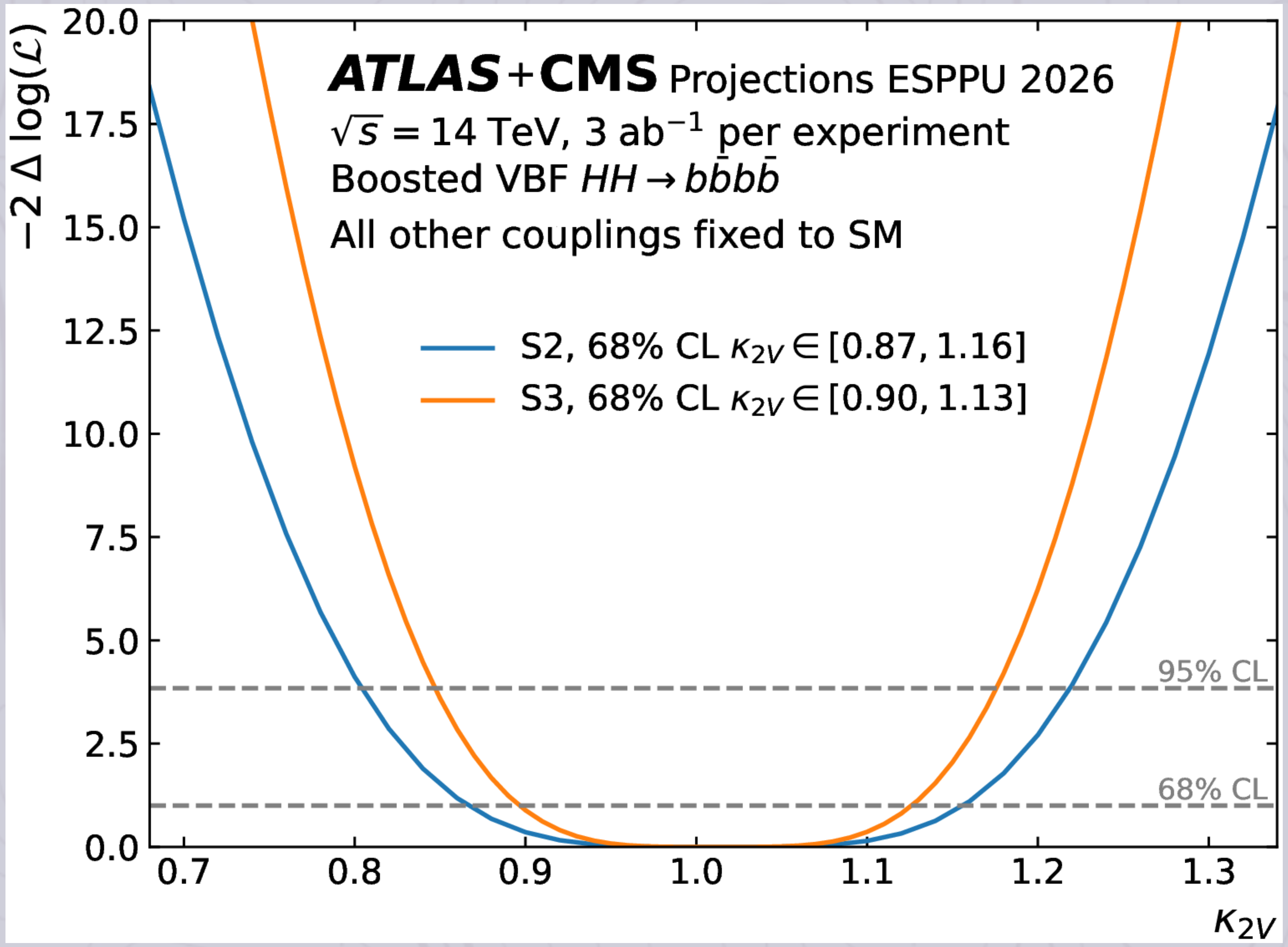


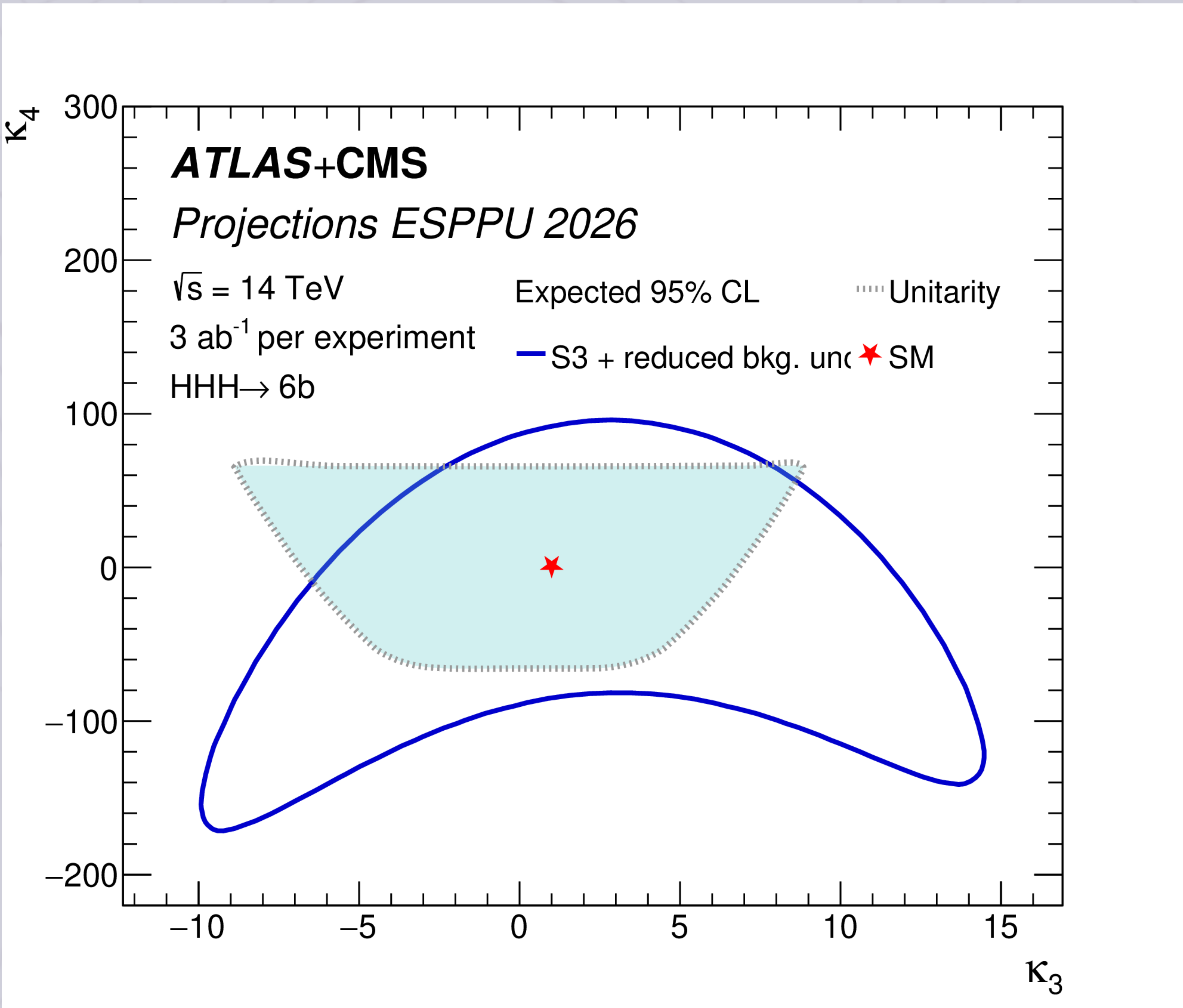
From Nature Paper, 2020, slightly old numbers but still same idea





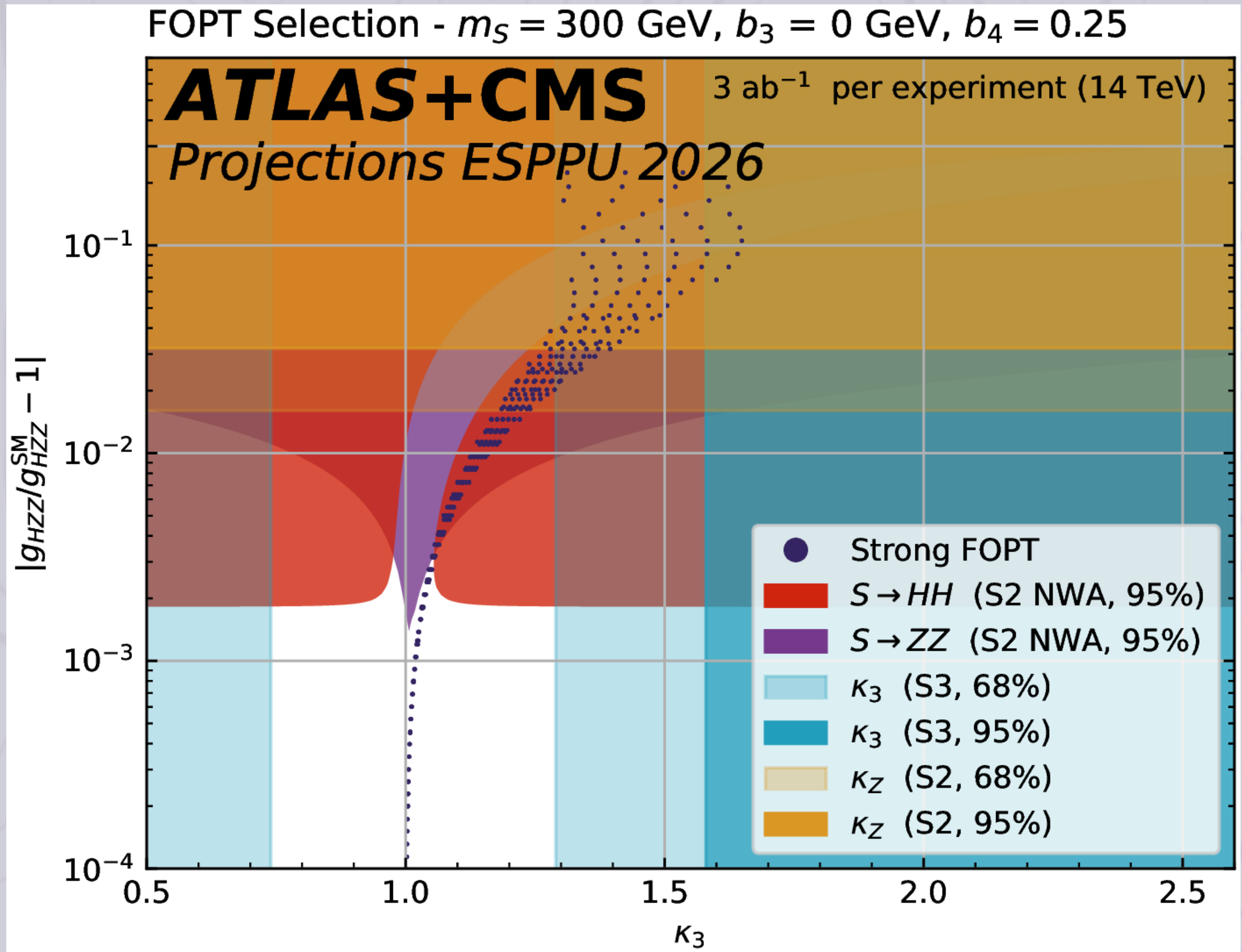
MORE HL PROJECTIONS



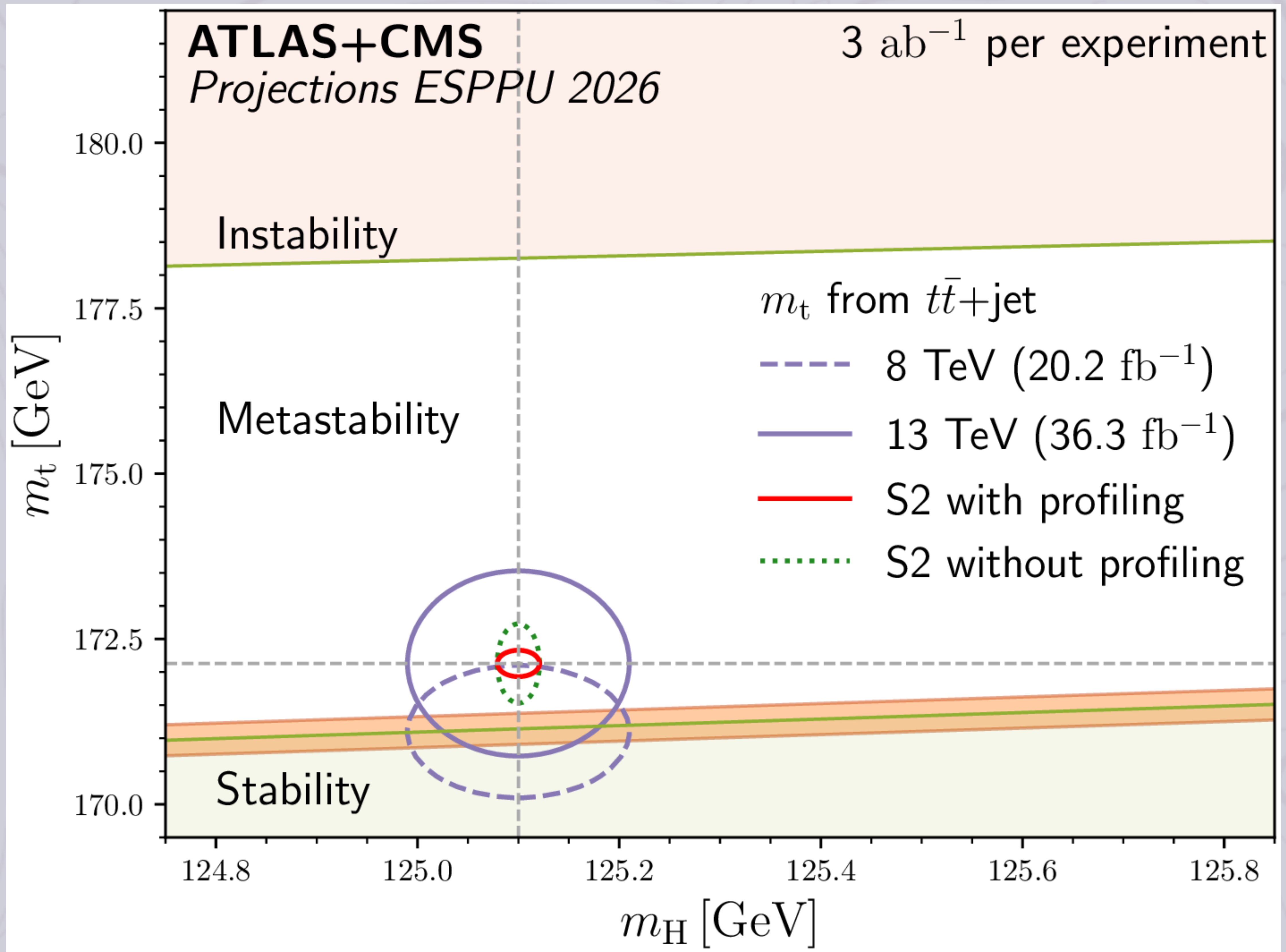


HL-LHC: BSM AND HH

- Bounds on the heavy scalar model, in the plane of the scalar portal coupling. The dark blue points show the area where a strong first-order phase transition in the early universe is possible within the scalar singlet model



- (Meta)stability of the universe: Higgs vs top mass after the HL-LHC



VH PRODUCTION

- **A similar approach can be followed in VH: from STXS & Differentials to EFT interpretations.**

- In HWW: VH differentials in ATLAS, arXiv:2503.19420 (no EFT)

- In Hbb:

  - SMEFT constraints to the Wilson coefficients of six relevant operators $(c_{Hq}^{(1)}, c_{Hq}^{(3)}, c_{Hu}, c_{Hd}, g_2^{ZZ}, g_4^{ZZ})$. Recent result by CMS: JHEP 03 (2025) 114

  - CP: Extension of the STXS measurement of WH, Hbb to prove CP. $c_{H\tilde{W}}$ in [-0.62, 0.85] at 95% CL (ATL-PHYS-PUB-2025-022)