FROM HIGGS TO DIHIGGS

19/NOV/2025

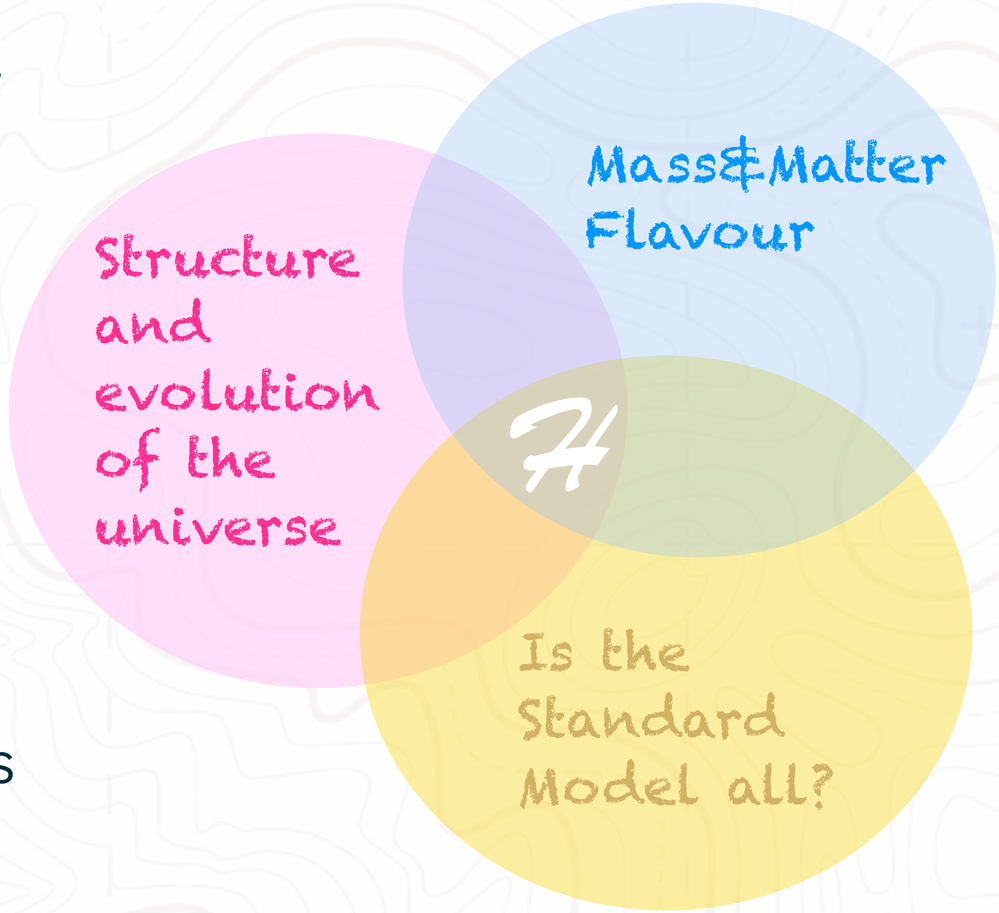
María Cepeda (CIEMAT)

CPAN, VALENCIA

foto @ A. Lastra

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

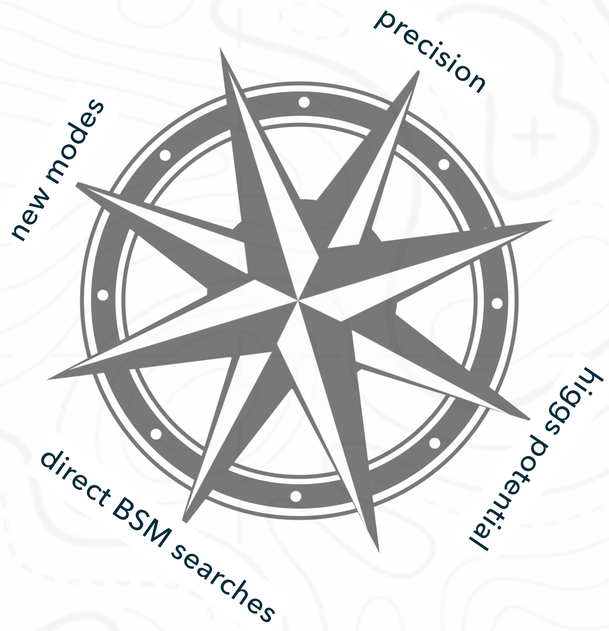


HIGGS PHYSICS IN 2025

- 15 years since LHC started and 13 years since the Higgs discovery, CMS and ATLAS are dedicated to understanding the nature of the Higgs

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




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

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

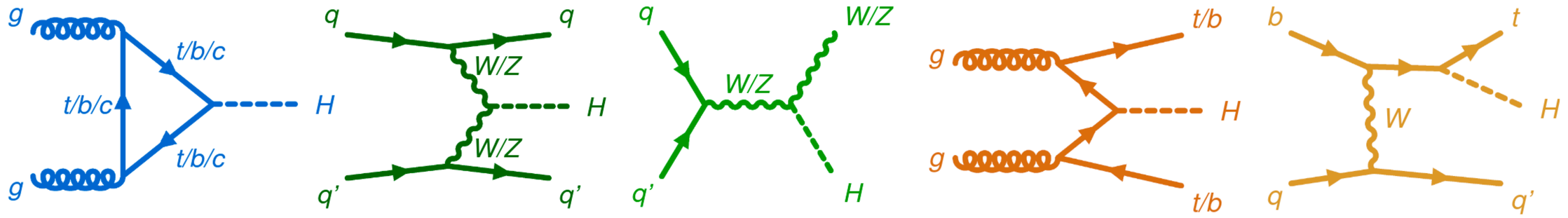
The Higgs Potential

Searches for HH and HHH

Impossible to cover all the recent Higgs measurements by ATLAS and CMS in 25'
This is just a small selection

MEASUREMENT OF HIGGS PROPERTIES

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



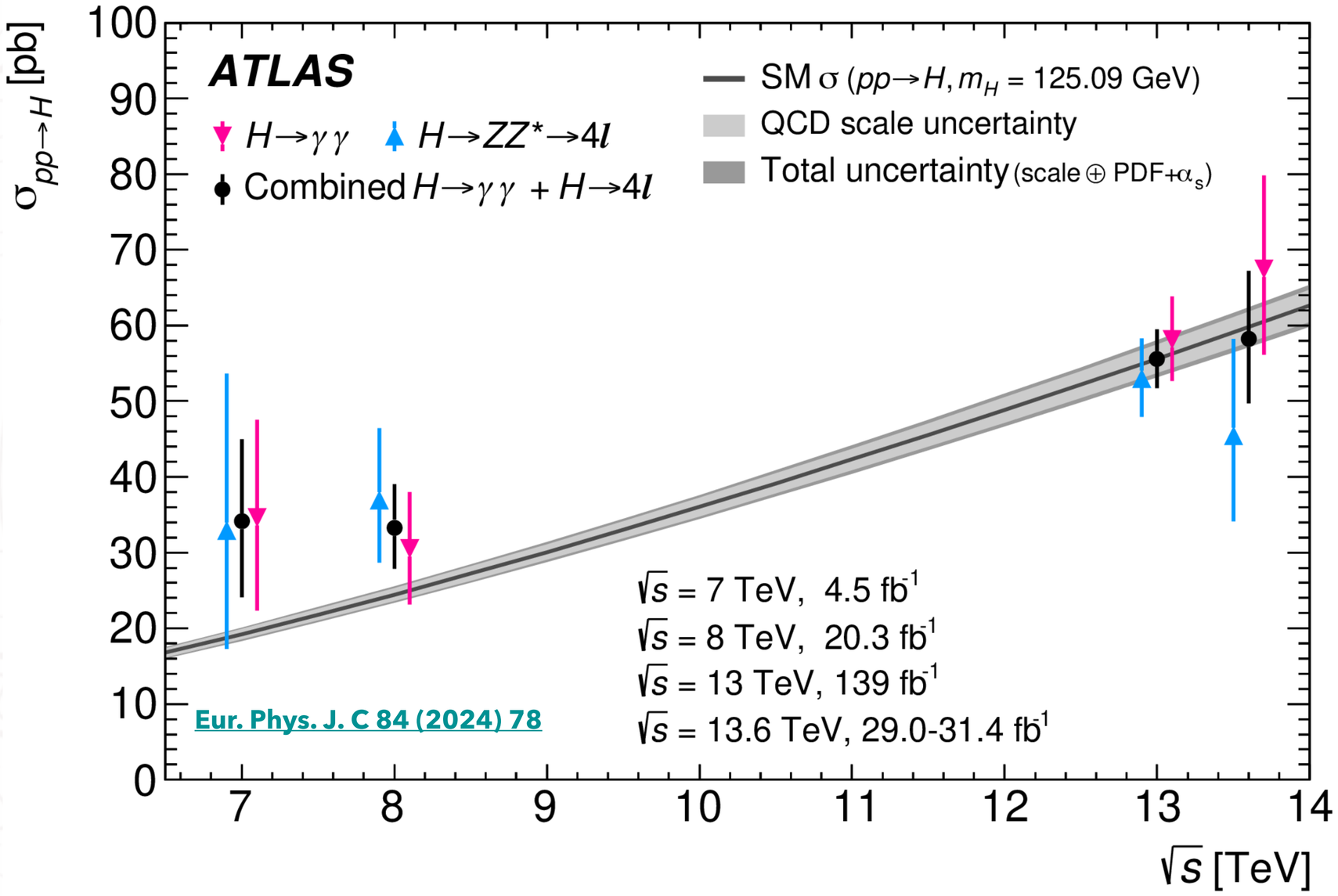
Gluon fusion (ggF) (87%)

Vector boson fusion (VBF) (7%)

Vector boson associated production (VH) (4%)

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

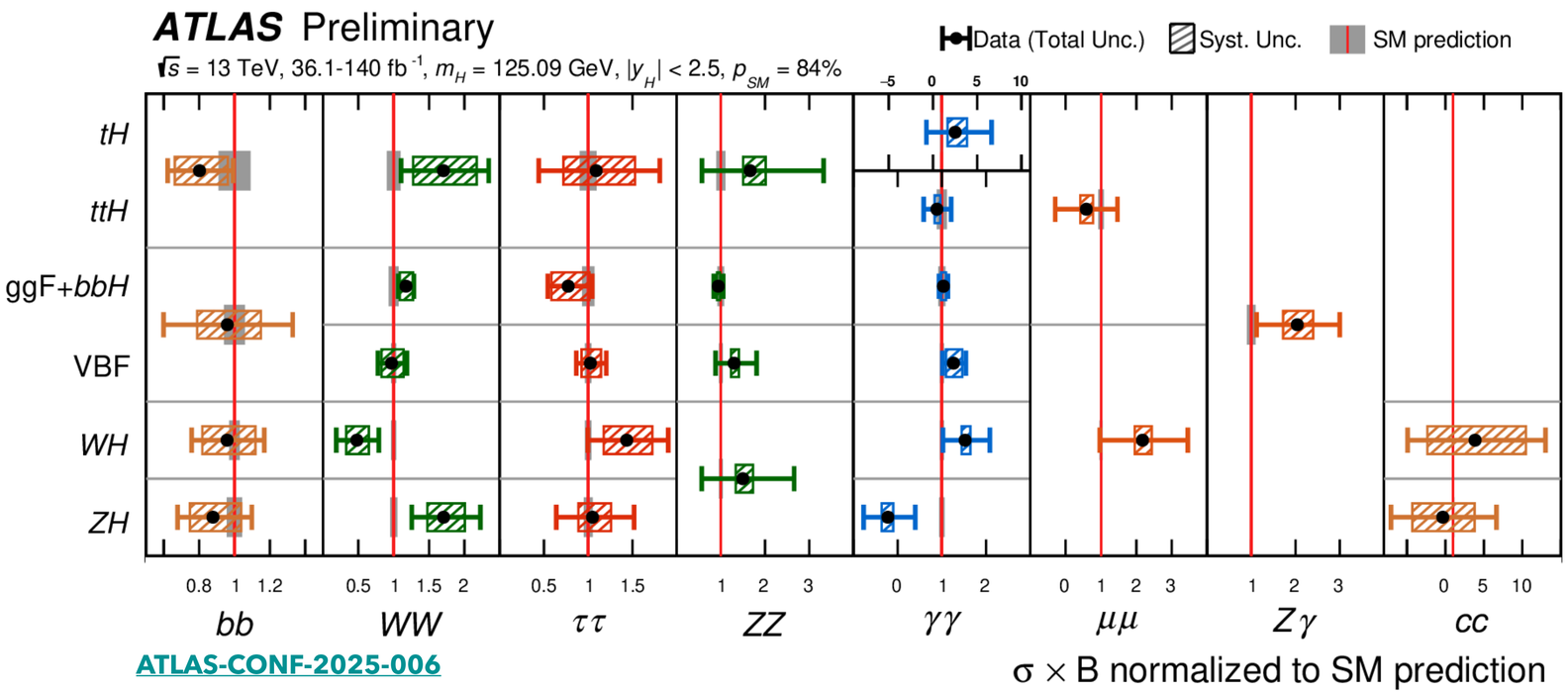
MEASURING HIGGSES FROM RUN1 TO RUN3



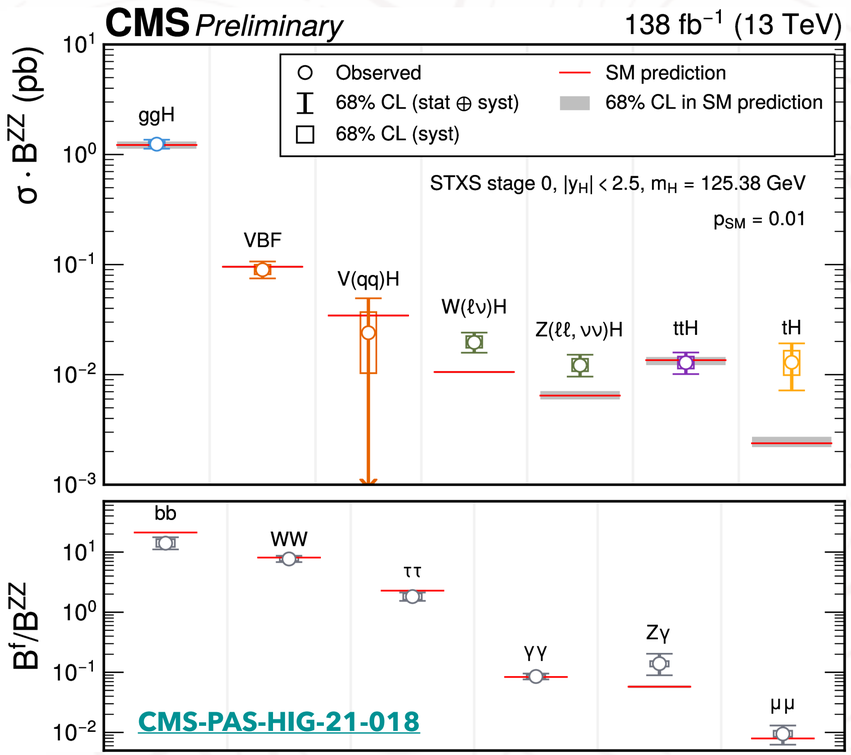
Eur. Phys. J. C 84 (2024) 78

Huge dataset to understand the Higgs Sector !

PRODUCTION X DECAY

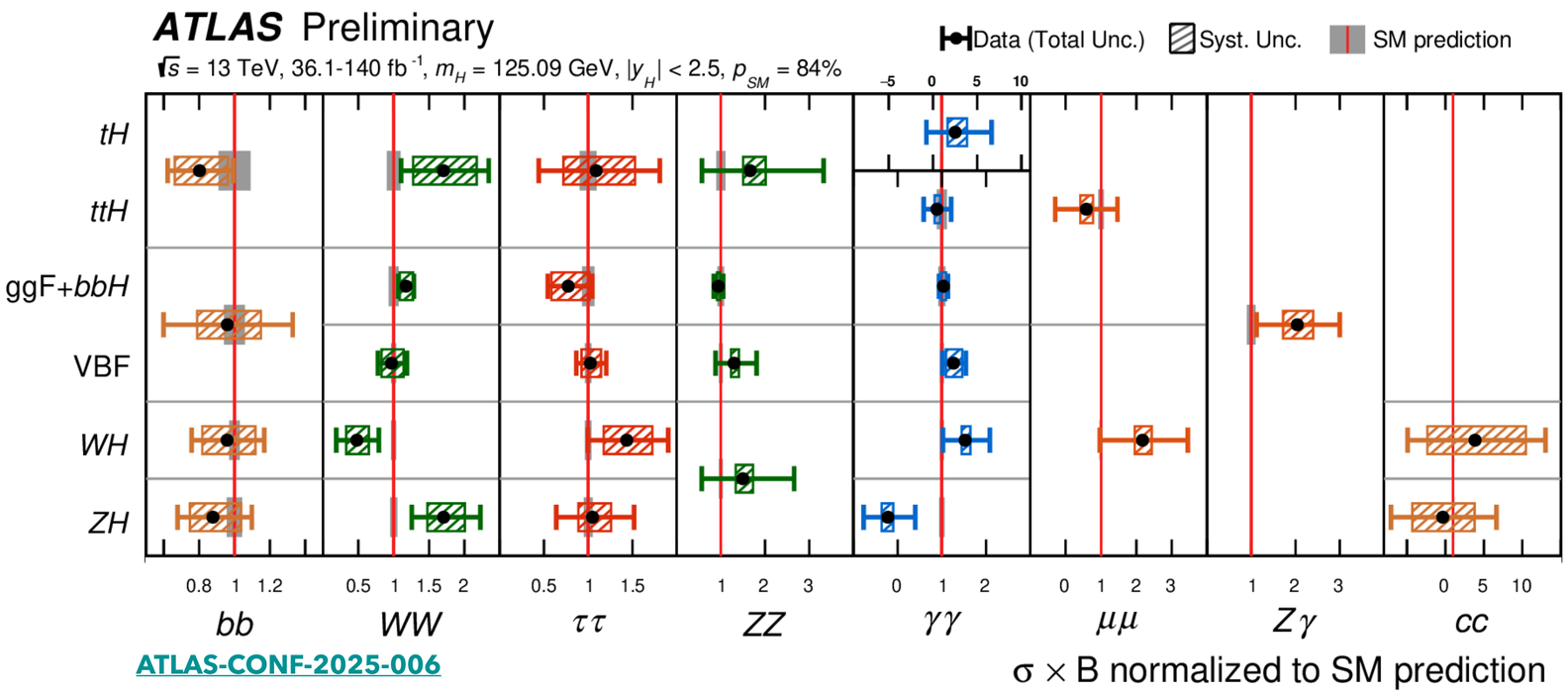


ATLAS-CONF-2025-006



CMS-PAS-HIG-21-018

PRODUCTION X DECAY : ✓✓



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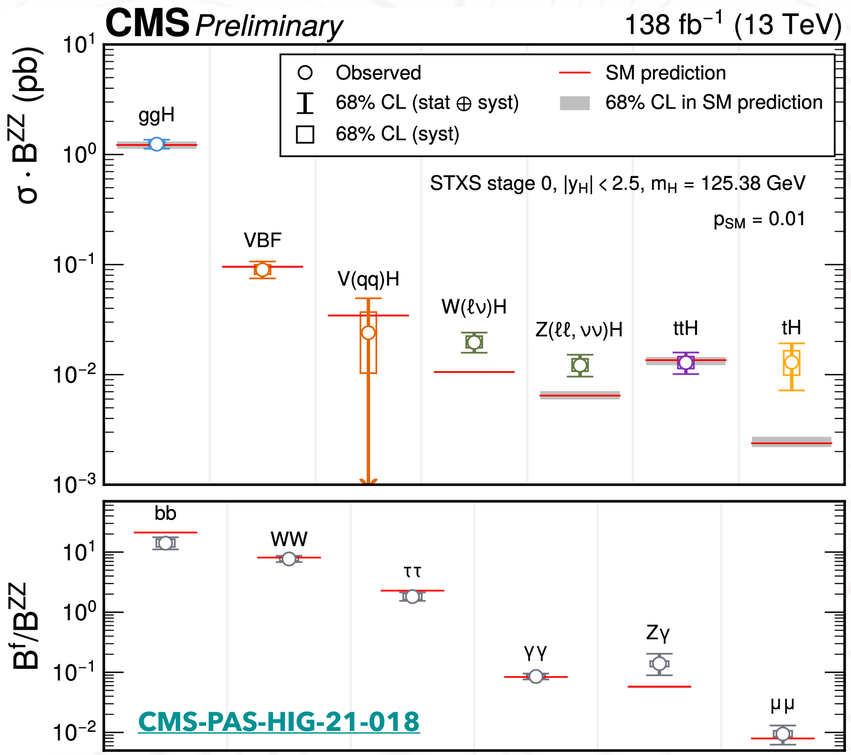

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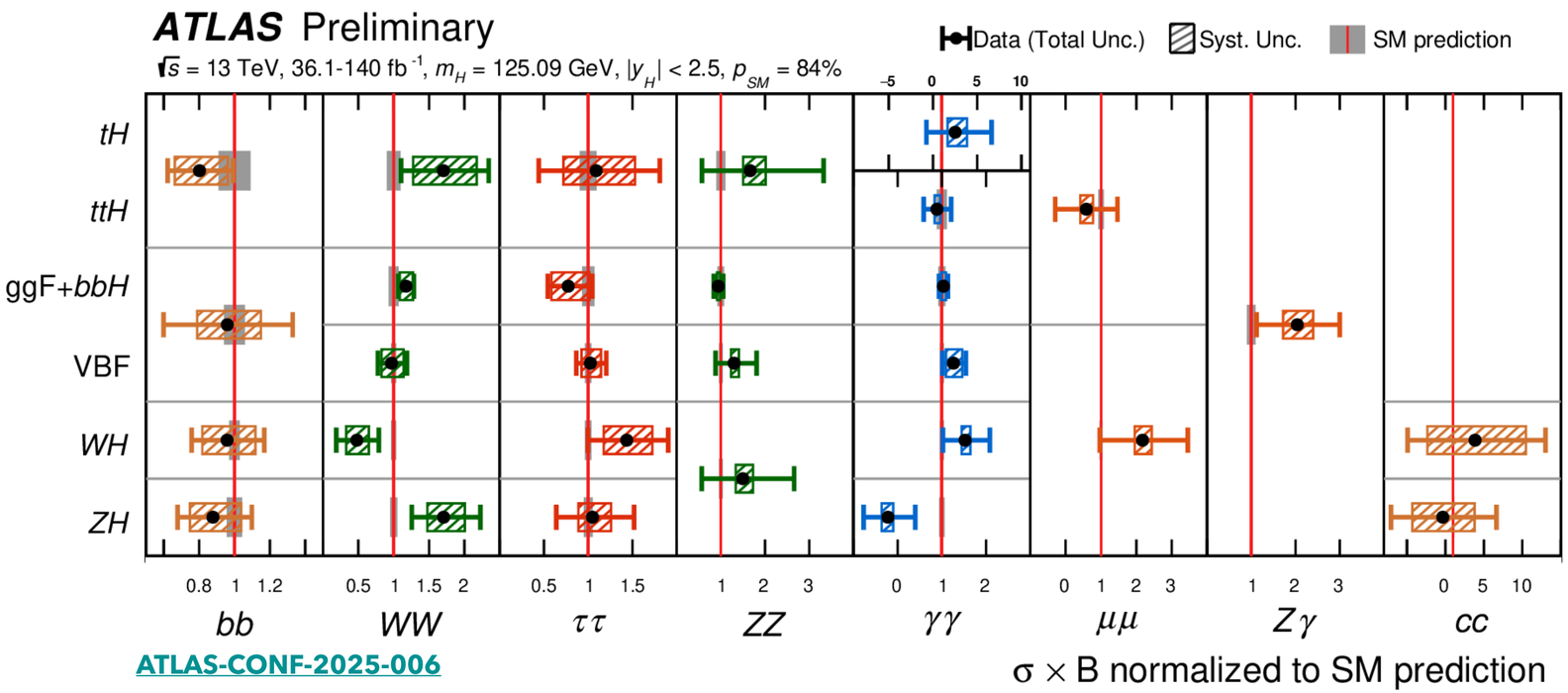

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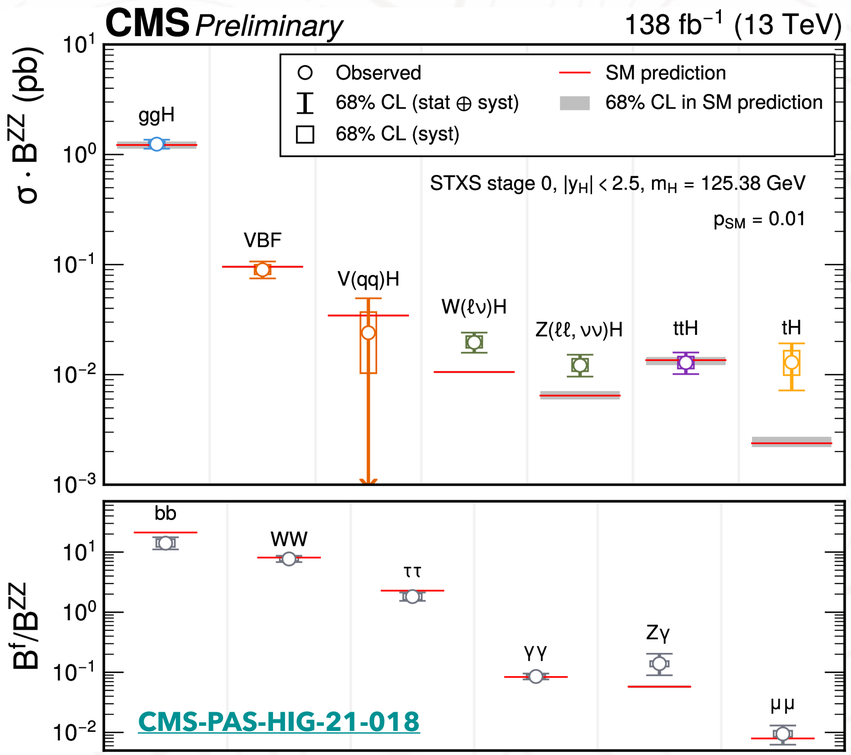

CMS-PAS-HIG-21-018

Inclusive cross section understood at the 6% already:

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

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

MEASURING MASS AND WIDTH

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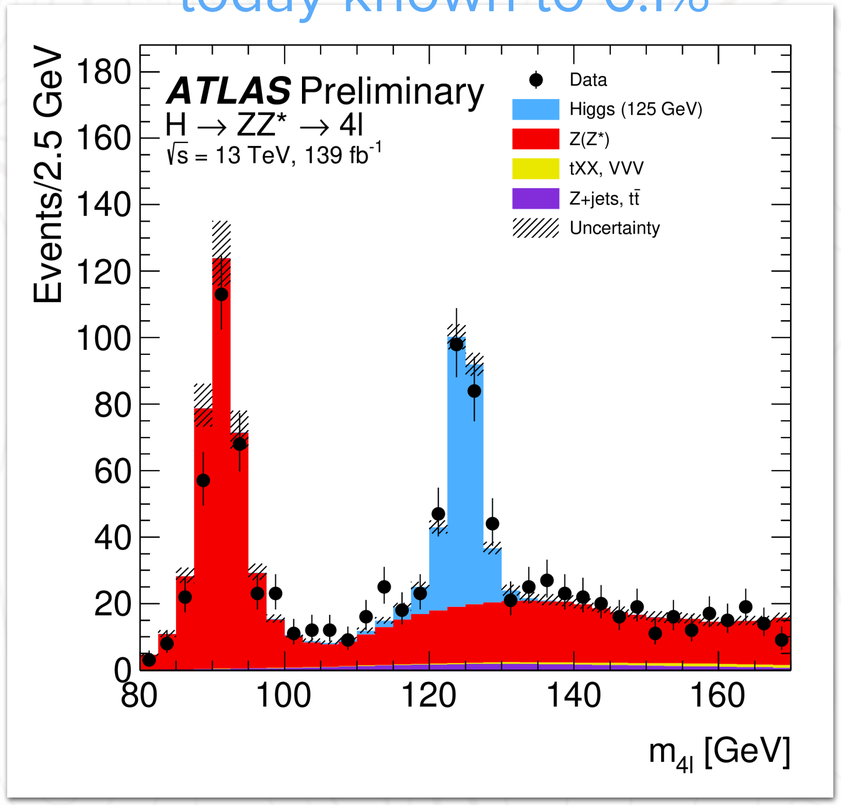
Mass

Free in the SM,
today known to 0.1%



$CMS\ (4l\ Run2\ 138\ \mathrm{fb}^{-1}) : 125.04 \pm 0.12\ GeV$

$ATLAS\ (4l + \gamma\gamma, > 140\ \mathrm{fb}^{-1}) : 125.11 \pm 0.11\ GeV$

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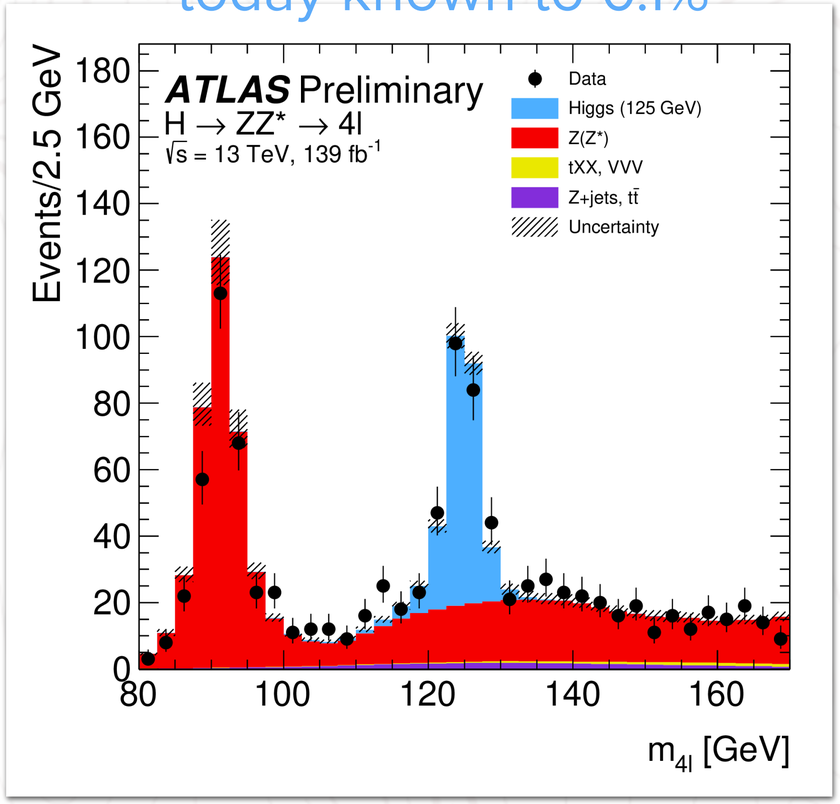

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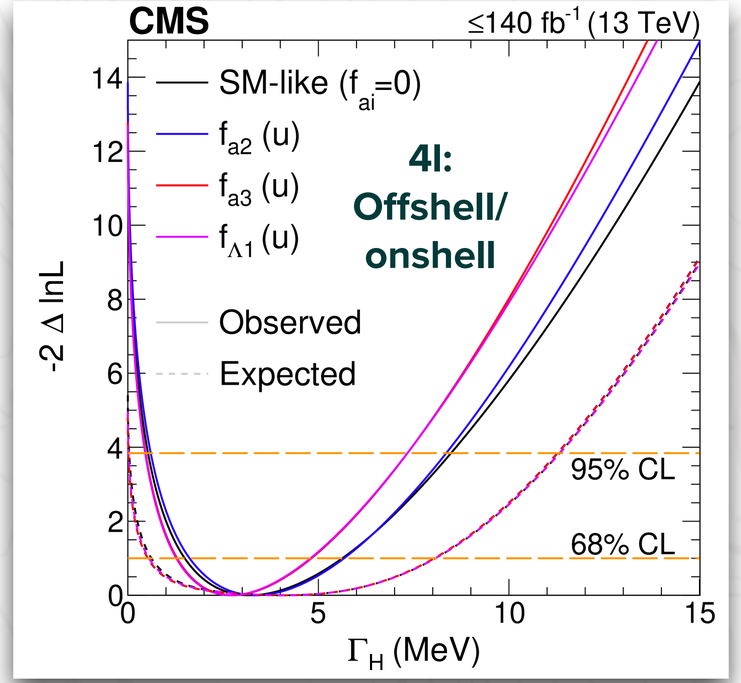
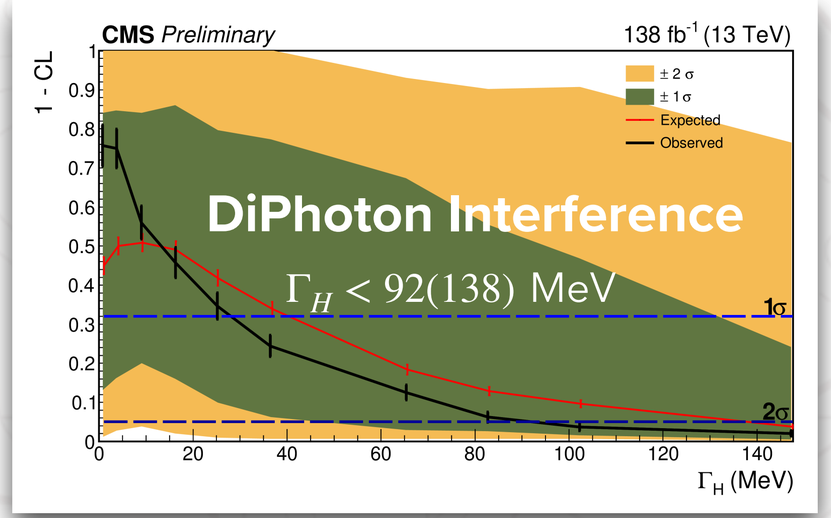
Total Width

Very small in SM! (4 MeV). Run2 ~45%



$\Gamma_H = 3.2^{+2.0}_{-1.5}$ MeV (CMS, 4l)

$\Gamma_H = 4.3^{+2.7}_{-1.9}\ MeV$ (ATLAS, 4l)



Direct in 4l: < 300 MeV (CMS)
Width from offshell: also in HWW (ATLAS: < 13.1 MeV (95%CL) , CMS: $3.0^{+2.7}_{-2.2}\ MeV$) and tttt vs ttH (ATLAS, < 450 (75) MeV, 95%CL)

Interference between gg→H→$\gamma\gamma$ and the continuum gg→$\gamma\gamma$ and qg →q$\gamma\gamma$: CMS-HIG-25-004

HIGGS COUPLINGS

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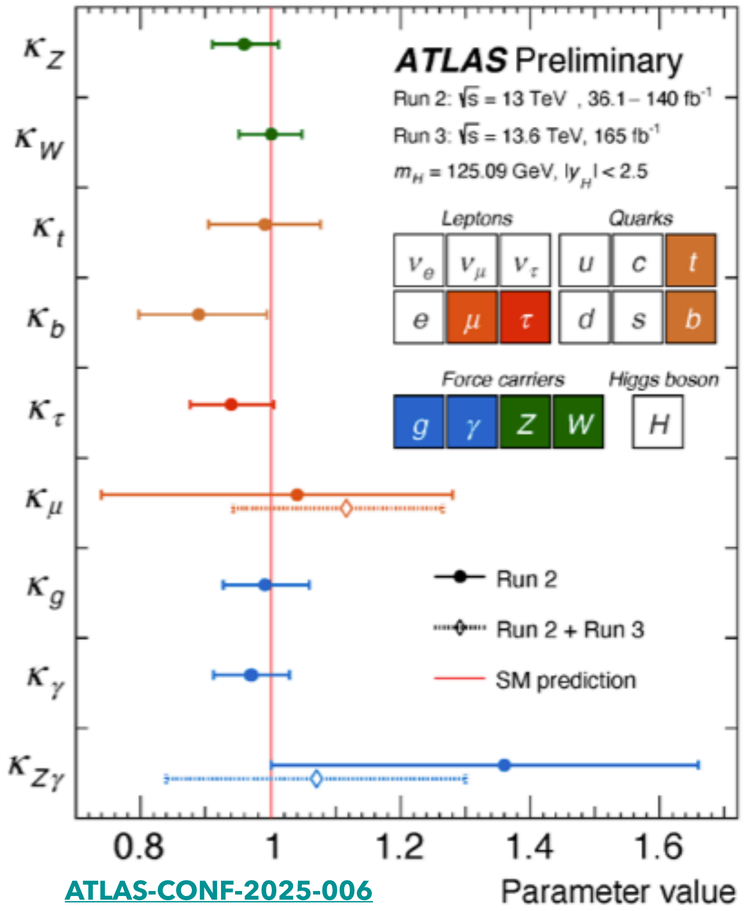
- With the full Run2 Combination (per experiment): 'Main' modes already known to 5-12% (~20%-30% for stat dominated $\mu\mu$, $Z\gamma$)
- Importance of theoretical uncertainties!

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



ATLAS-CONF-2025-006

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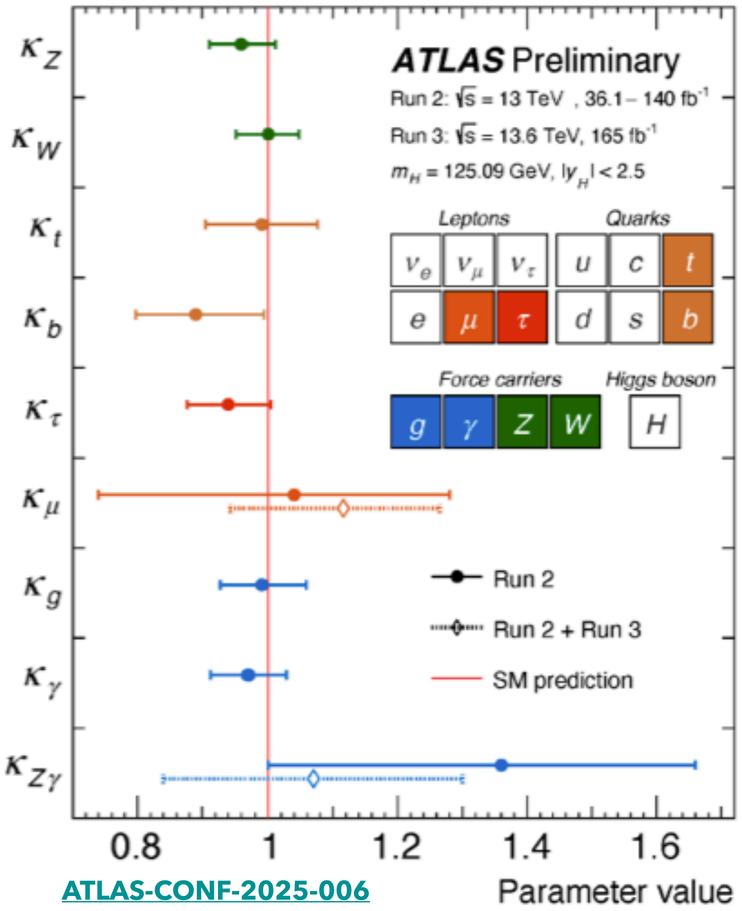
- Importance of theoretical uncertainties!
- Control systematic uncertainties: ratios of couplings ($\lambda_{ij} = \kappa_i/\kappa_j$)

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



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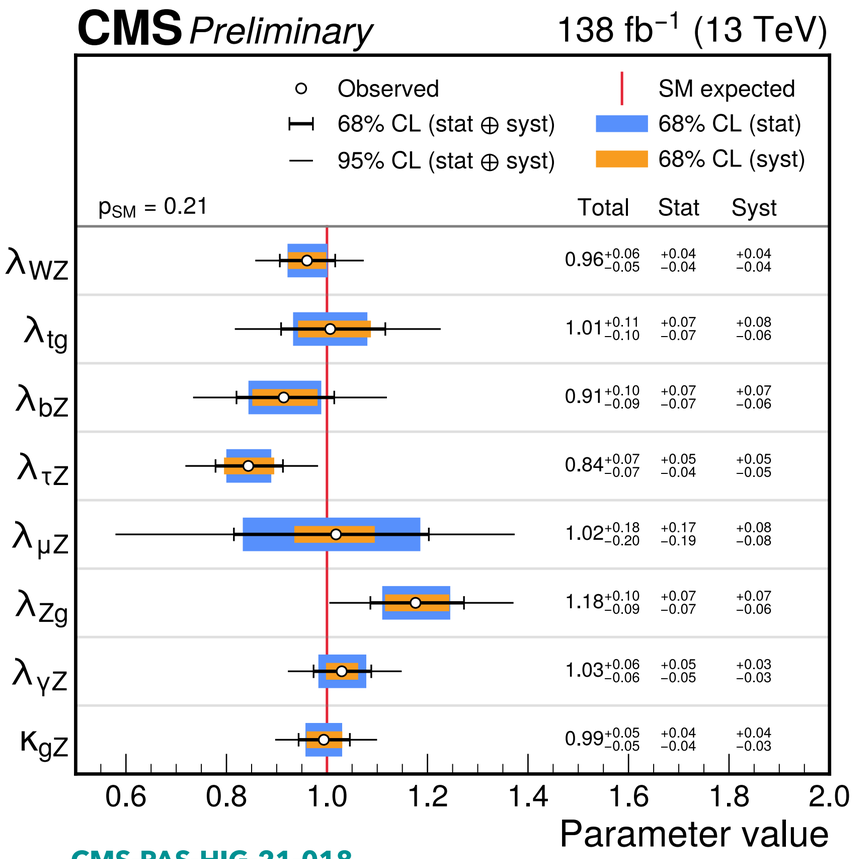
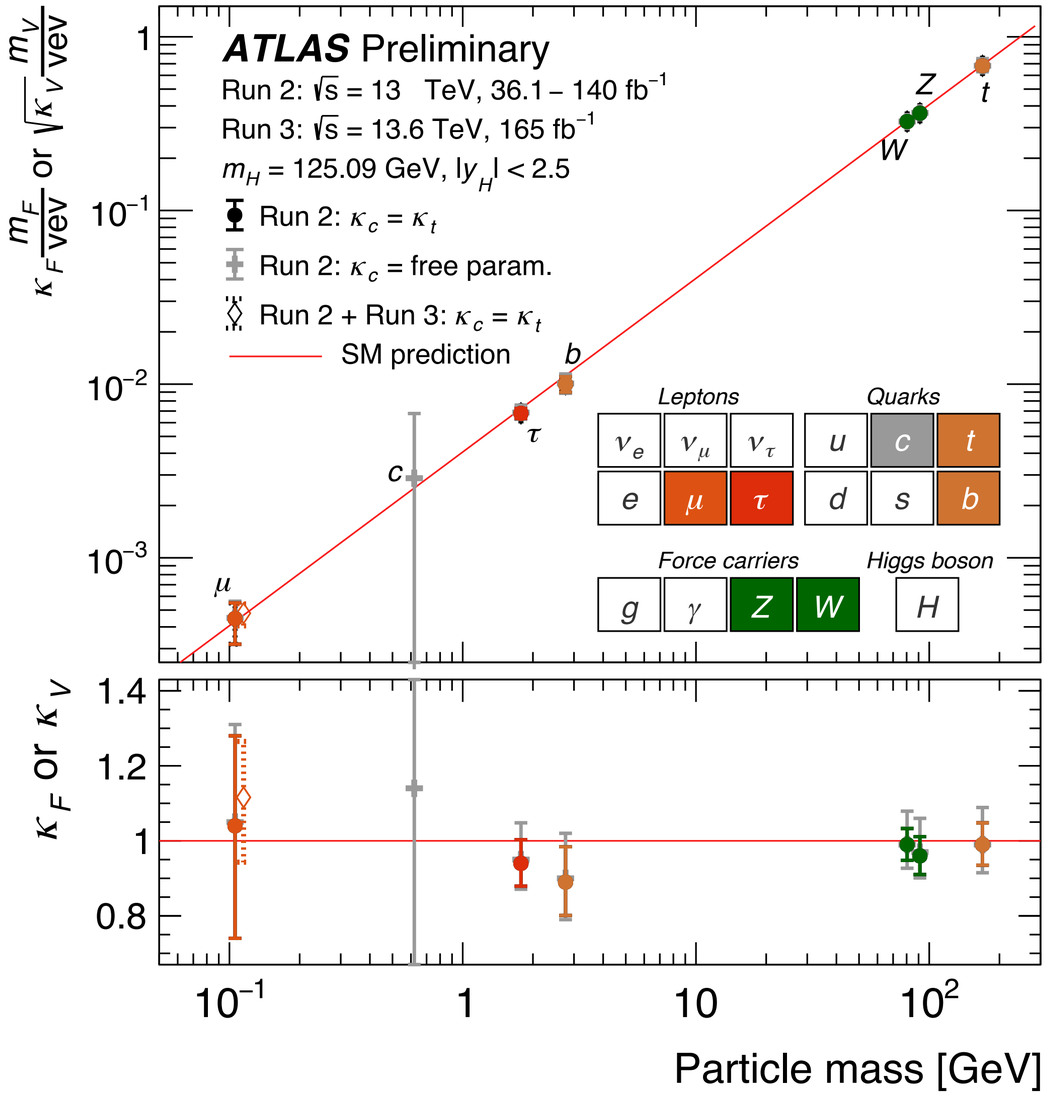


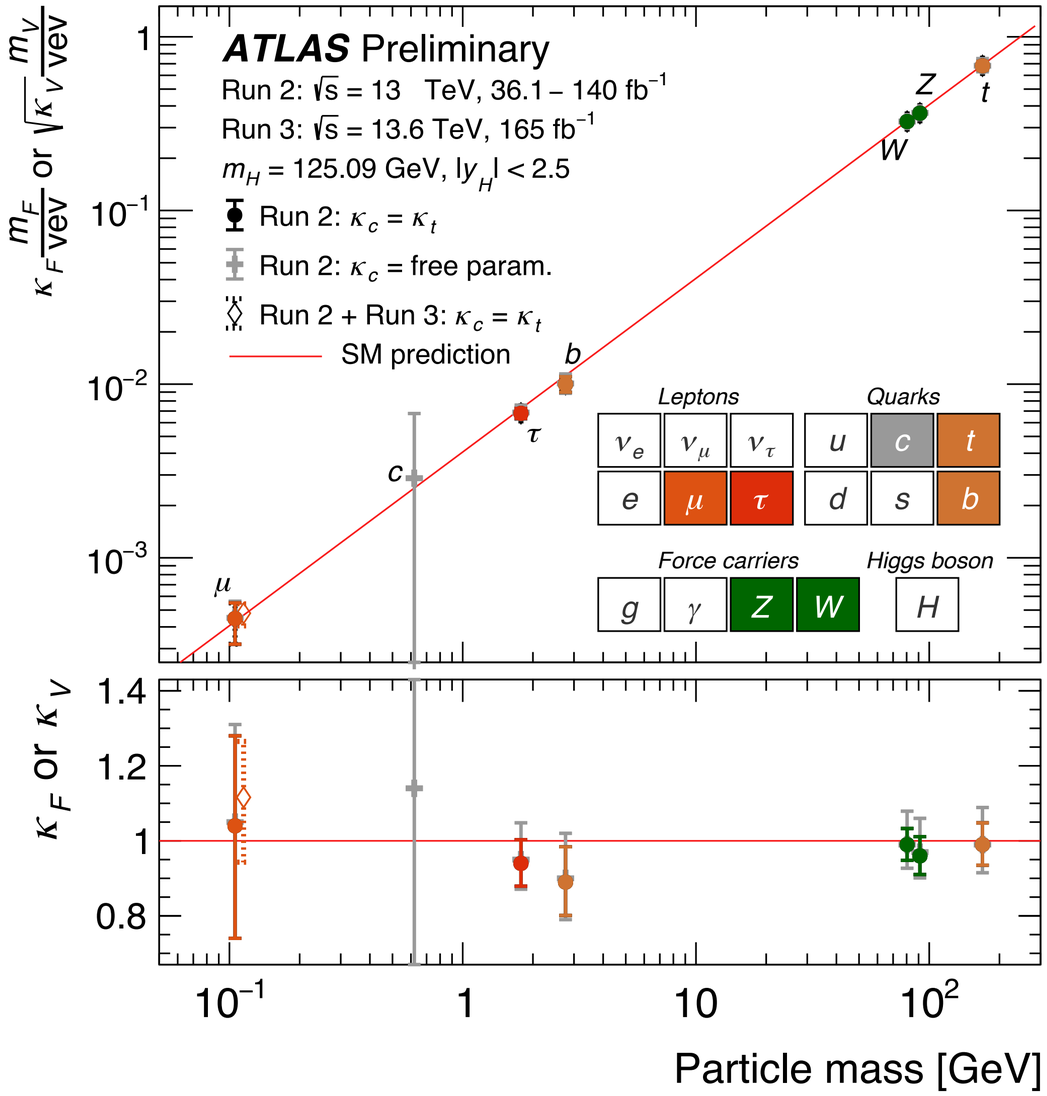
CMS-PAS-HIG-21-018

STILL A LOT TO UNDERSTAND



STILL A LOT TO UNDERSTAND

- So far the couplings we have measured are remarkably close to the SM predictions
- However, the picture is not 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



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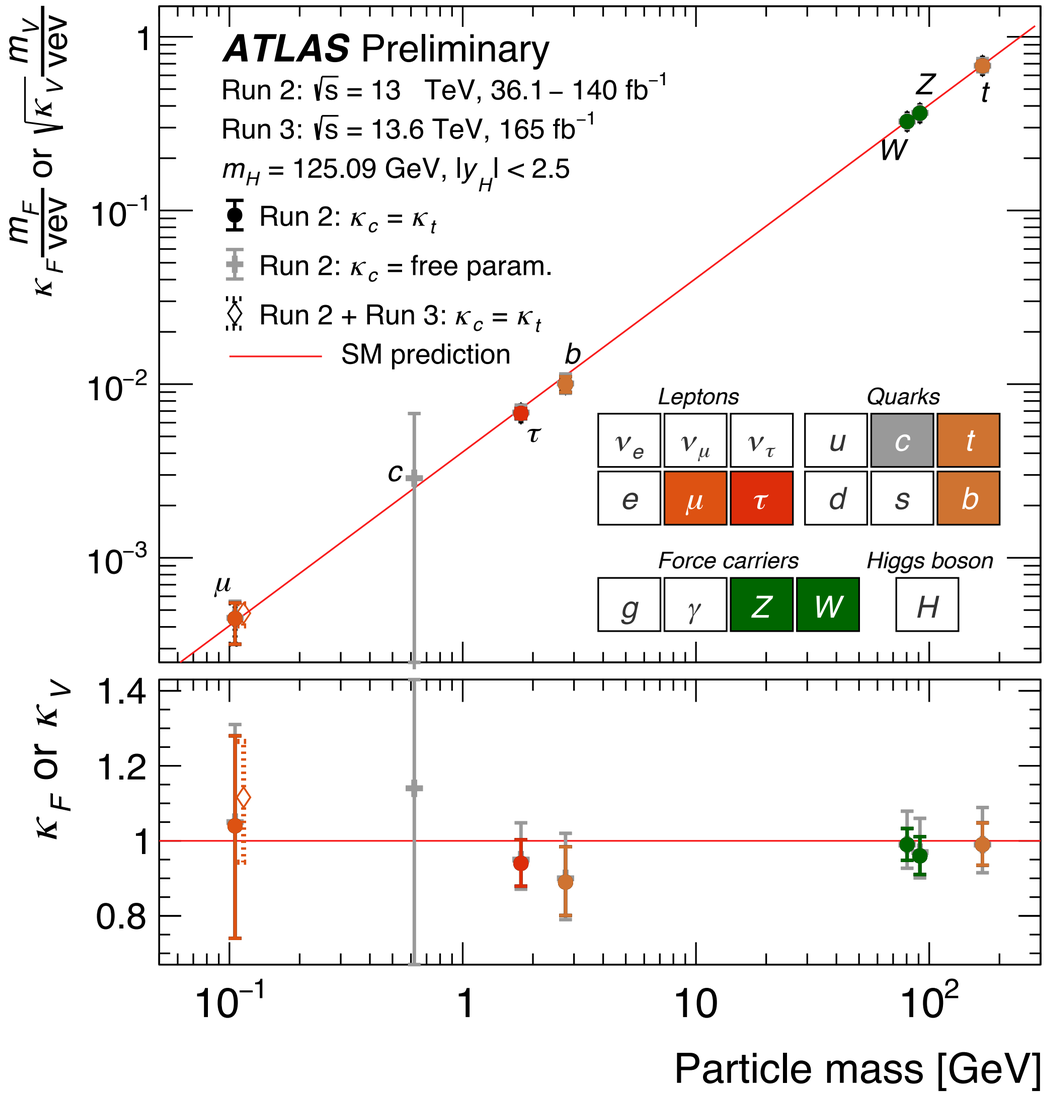
- **What are we learning from Run2 and Run3 data?**

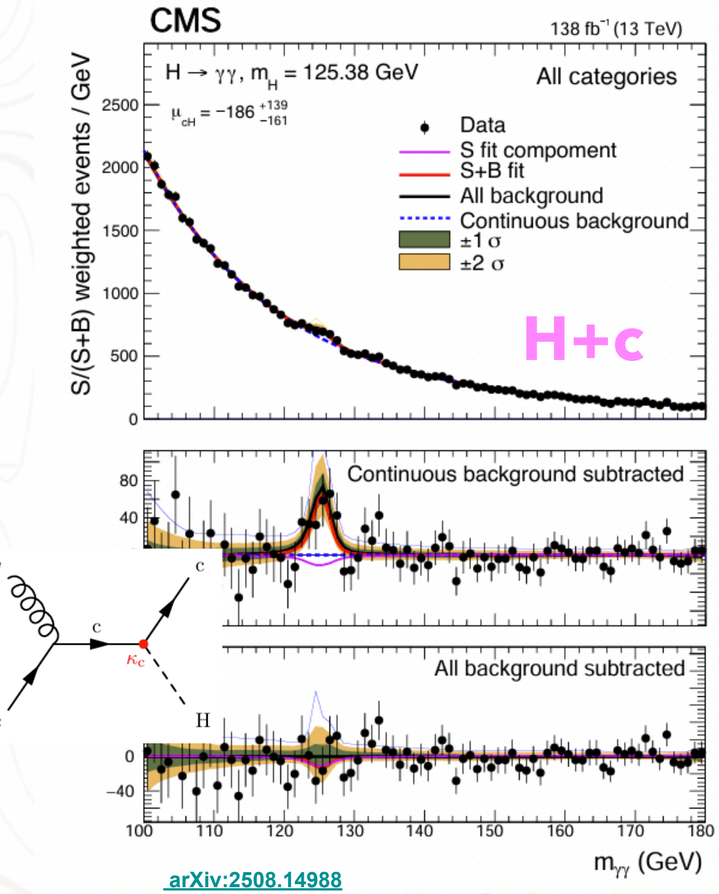


ZOOMING IN

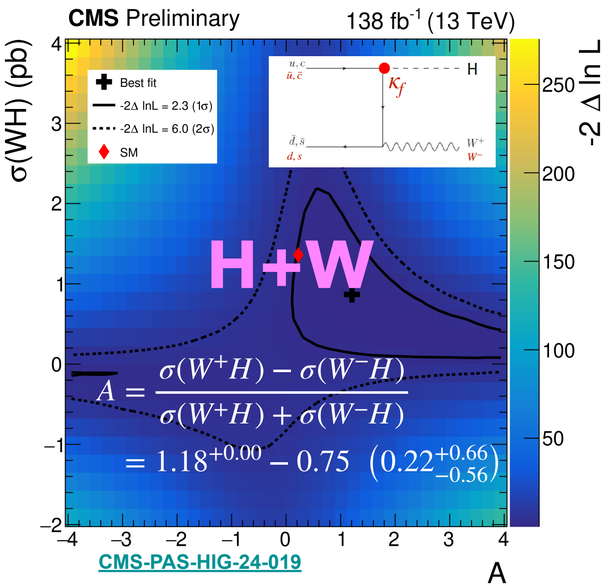
- Larger statistics! we can probe difficult phase-spaces, and exploit kinematic variables sensitive to new physics.
- Beyond the main production modes: search for new decays
- New physics through precision in measurements

RARER AND RARER PRODUCTION MODES

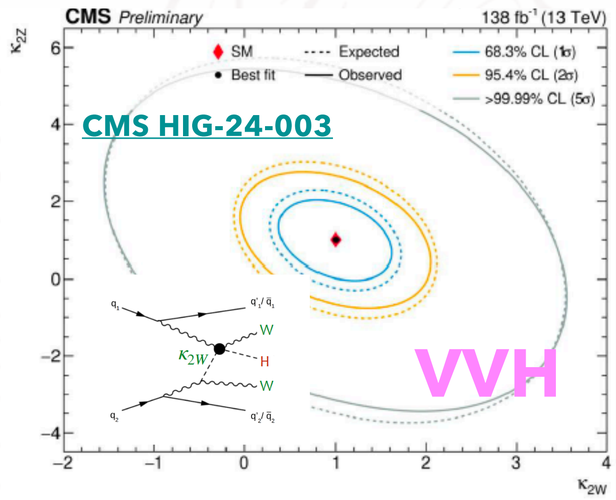
Associated production (H+W, H+c, H+b, H+γ...)

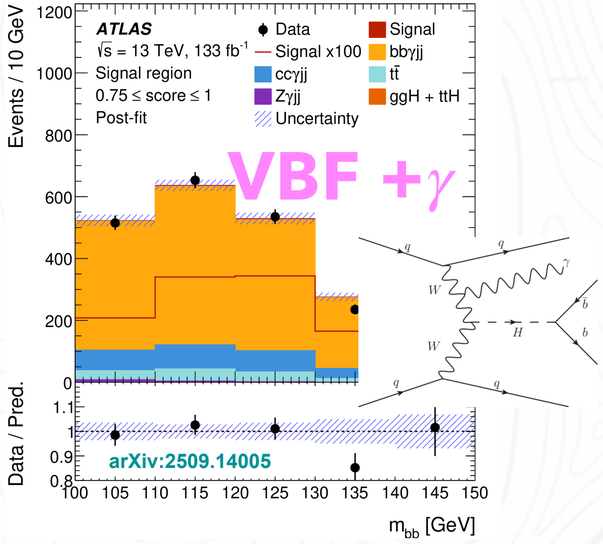


arXiv:2508.14988

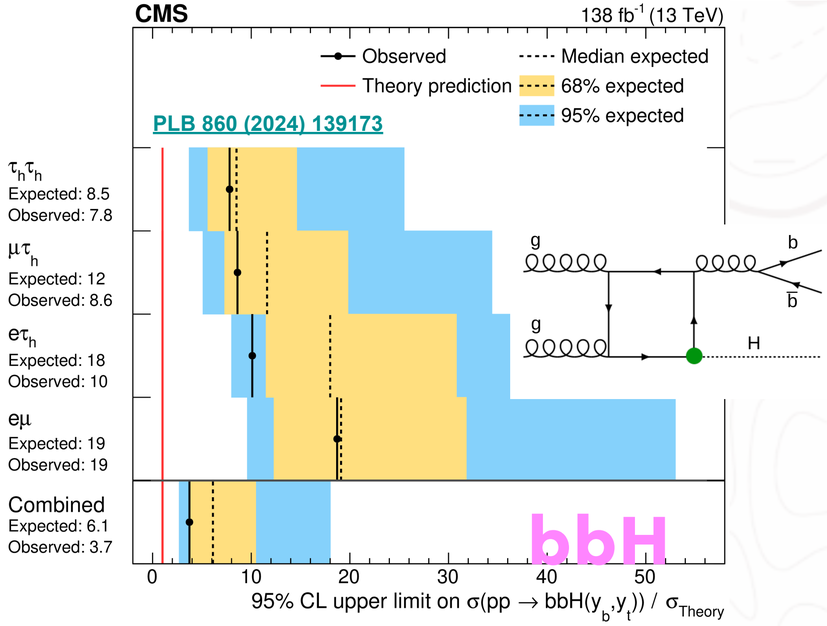


CMS-PAS-HIG-24-019



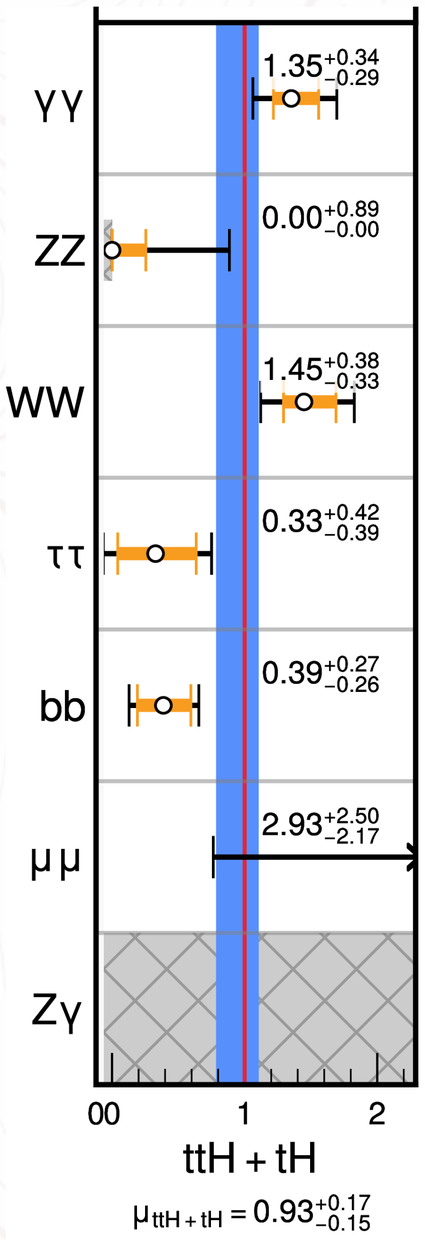


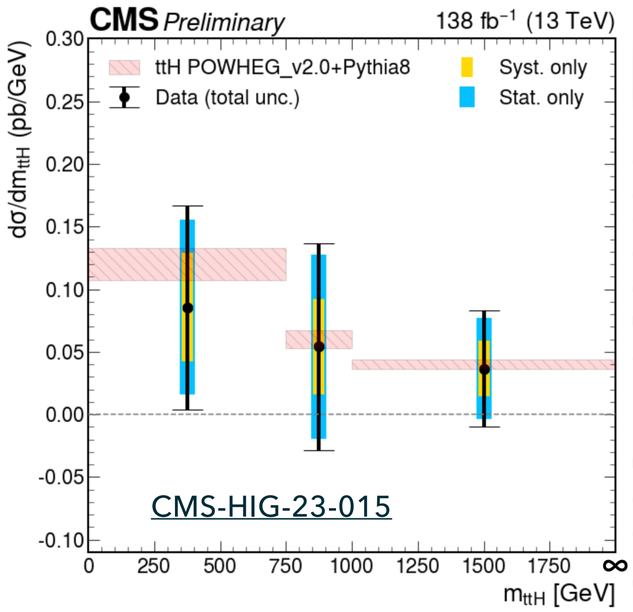
arXiv:2509.14005

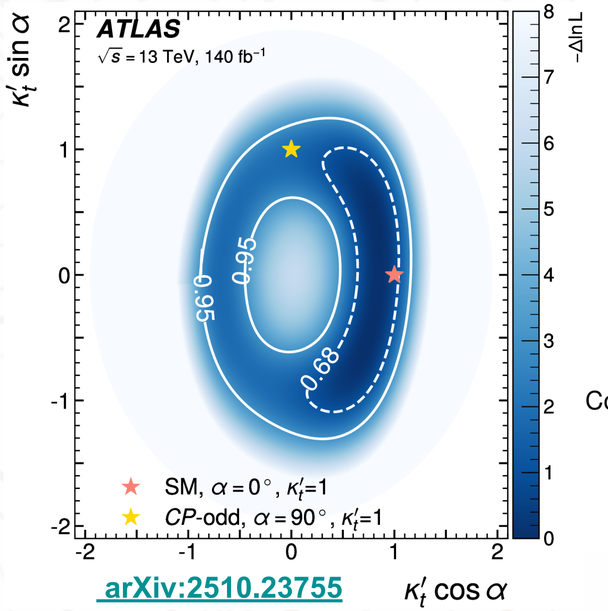


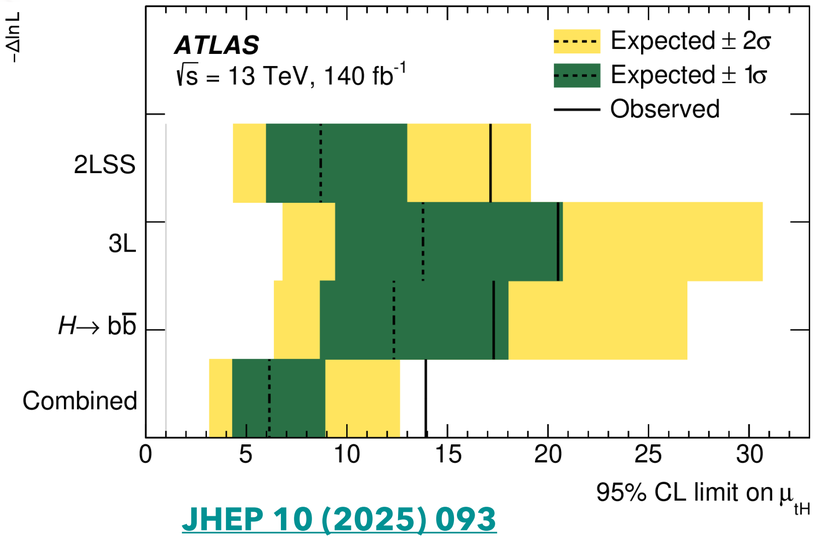
TTH/TH PRODUCTION

- **ttH: from a rare mode to the measurement regime**
  - Multilepton (WW+$\tau\tau$+…) differential and CP measurements
  - Now also Hbb vs Hcc! (CMS-HIG-24-018)
- **tH: getting closer to SM sensitivity, with some tension.**
  - New result by ATLAS - μ_{tH} = 8.1 ± 2.6 (stat.) ± 2.0 (syst.)



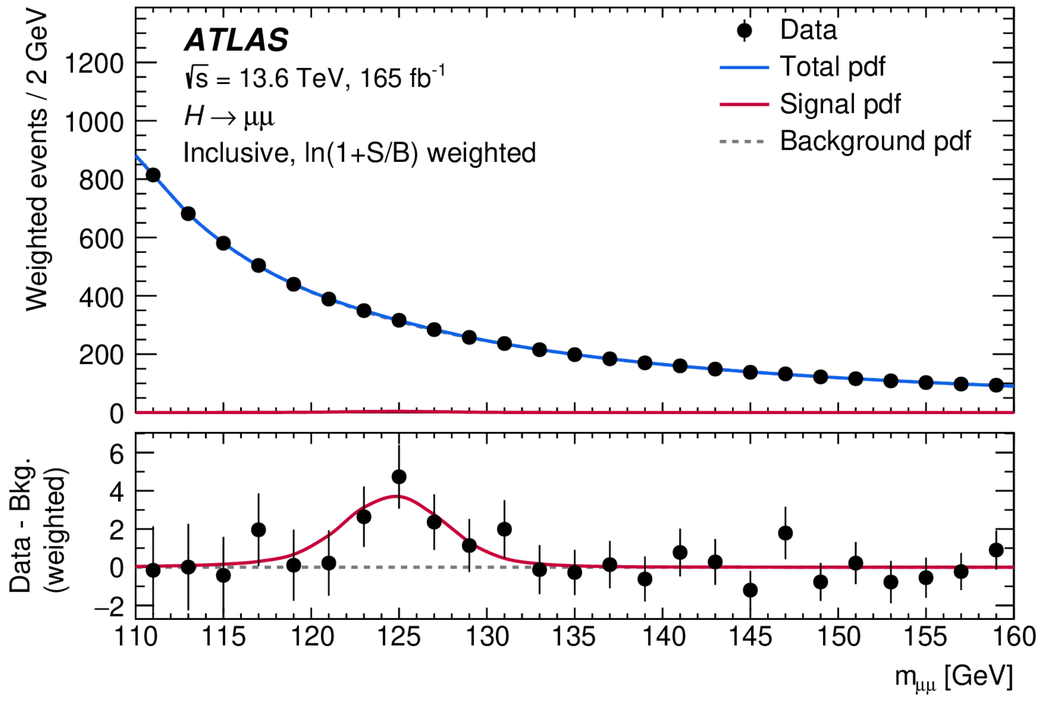






RARE DECAYS: EVERY FB^{-1} COUNTS

$H \to \mu\mu$

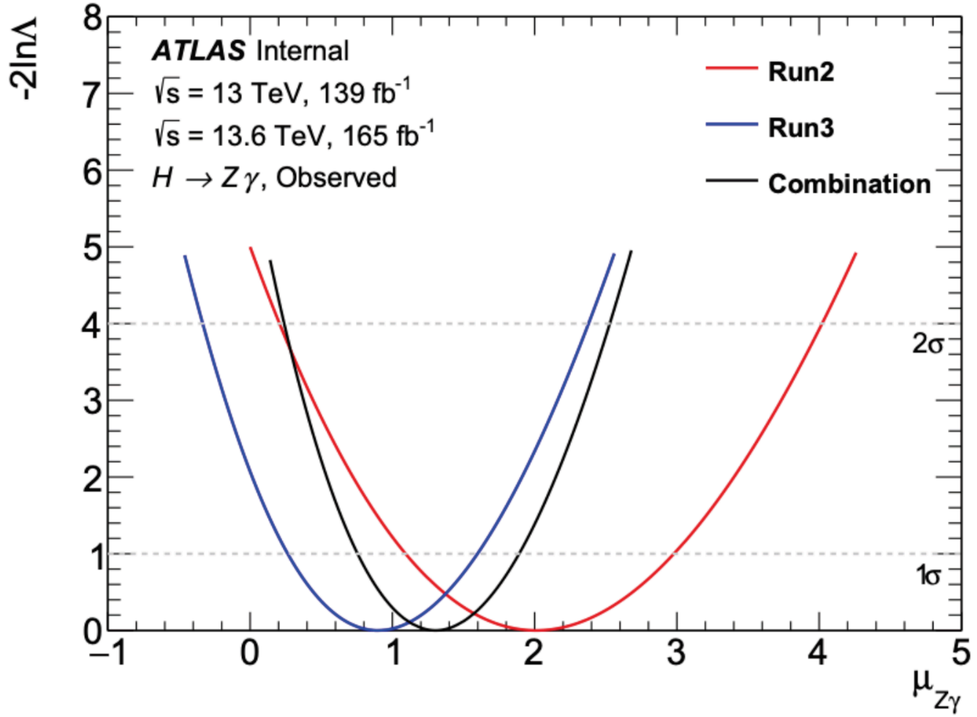


Run2+Run3 ATLAS (arXiv:2507.03595):

3.4σ (2.5 exp) , μ = 1.4 ±0.4

CMS Run2 (JHEP 01 (2021) 148): μ =1.2±0.4, 3σ (2.5 exp)

$H \to Z\gamma$



Evidence in Run2 with ATLAS+CMS (PRL 132 (2024) 021803):

μ =2.2±0.7, 3.4σ (1.6 exp SM)

Run2+Run3 ATLAS (arXiv:2507.12598):-

2.5σ (1.0 exp SM) , μ = 1.3 ±0.5

HOW CHARMING IS THE HIGGS?

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- **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?

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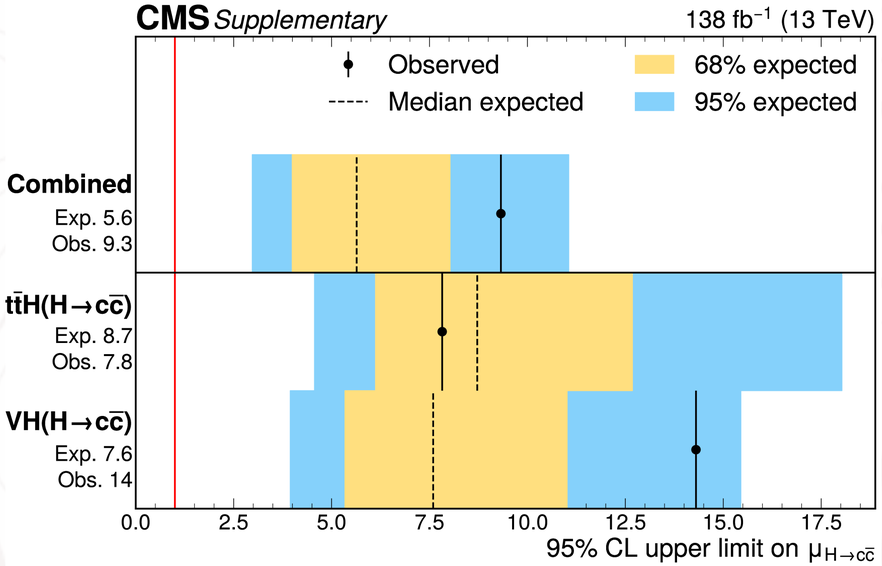
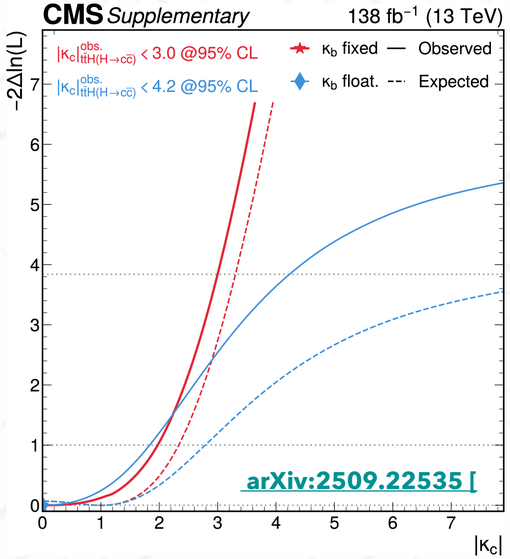
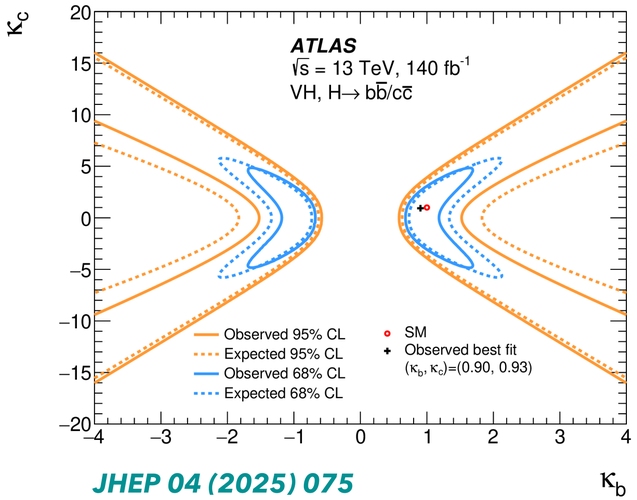
- Once considered impossible at the LHC!
- Despite the difficulties, we are narrowing down the hunt, exploiting innovations in tagging:
  - **CMS, ttH Hcc + VH cc:** $|\kappa_c| < 3.5\ (2.7)$ **(95%CL)**
  - **ATLAS VH cc:** $|\kappa_c| < 4.2\ (4.1)$ **(95%CL)**
  - Other probes: H+c, H+γ, H→ψ(nS)γ , constraints from general Higgs pt differentials







JHEP 04 (2025) 075

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→Meson+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 → BSM . eg: Dark Matter, LFV, light scalars, long-lived particles**

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

- CMS: Br(H→inv) < 15% (8%) (EPJC 83 (2023) 933)
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New avenues: Dark Sectors, Long Lived decays, interesting reconstruction opportunities

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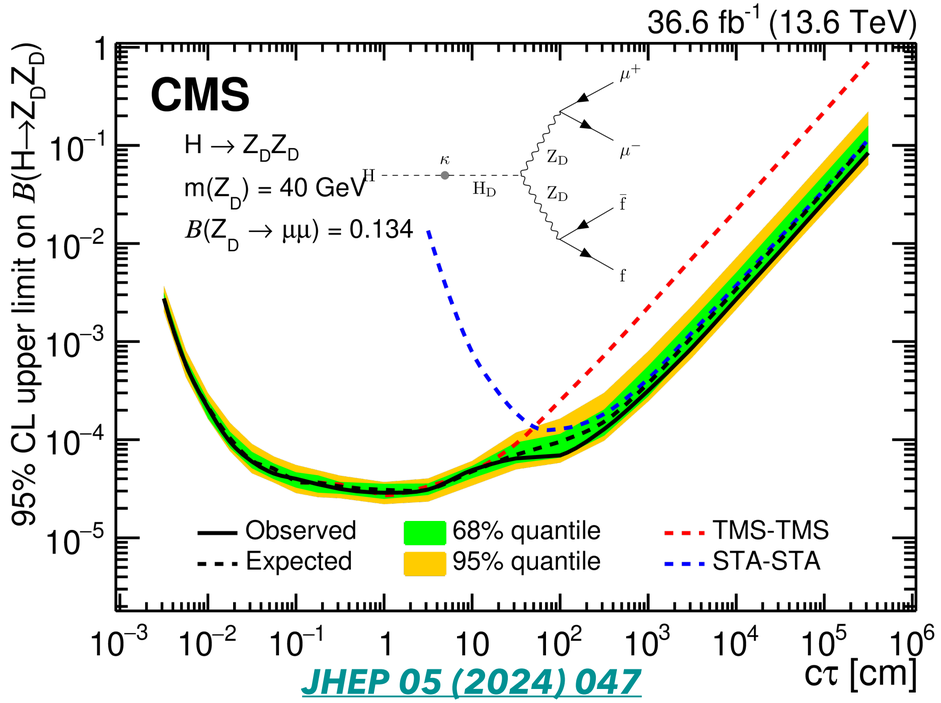
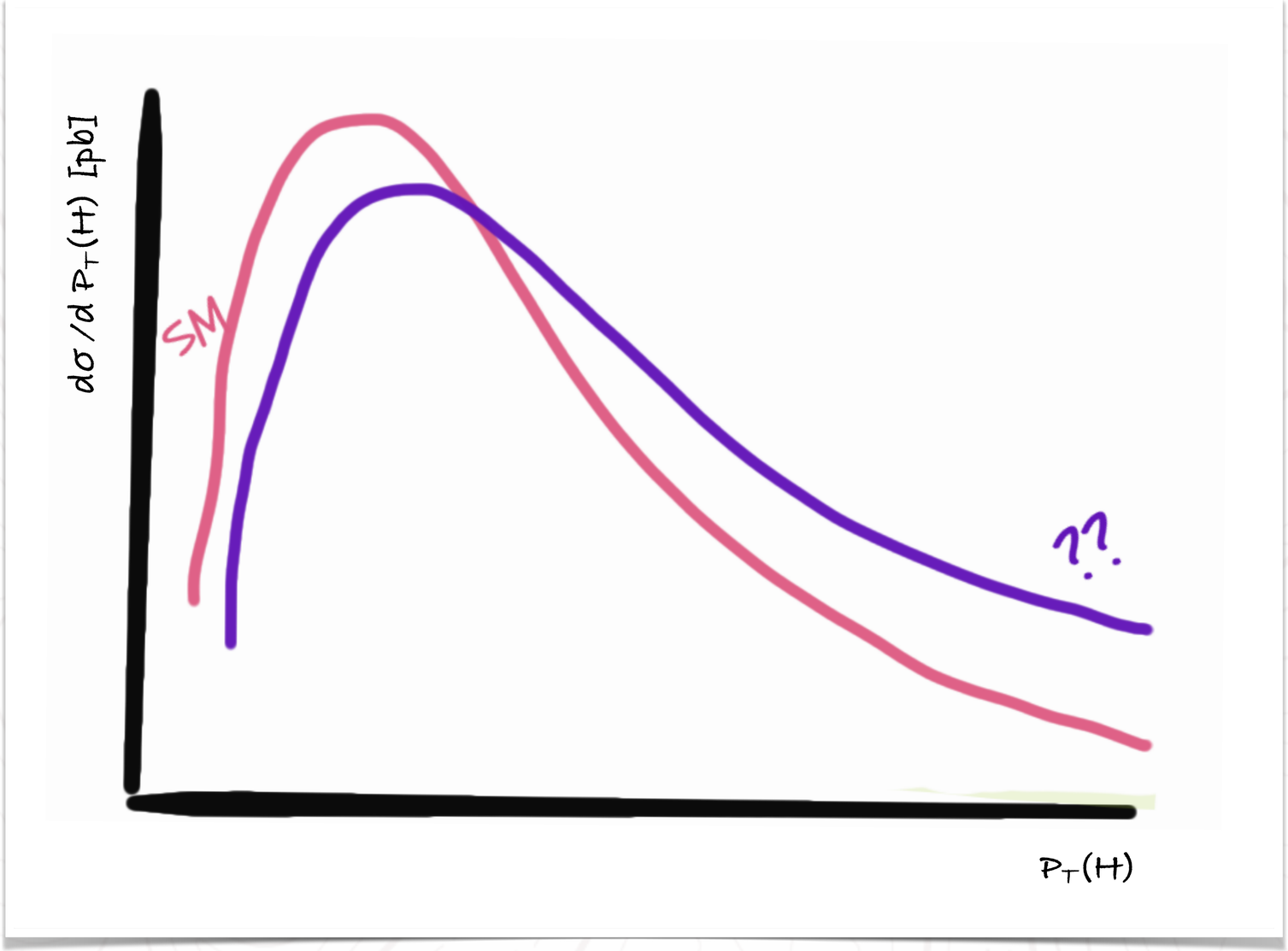


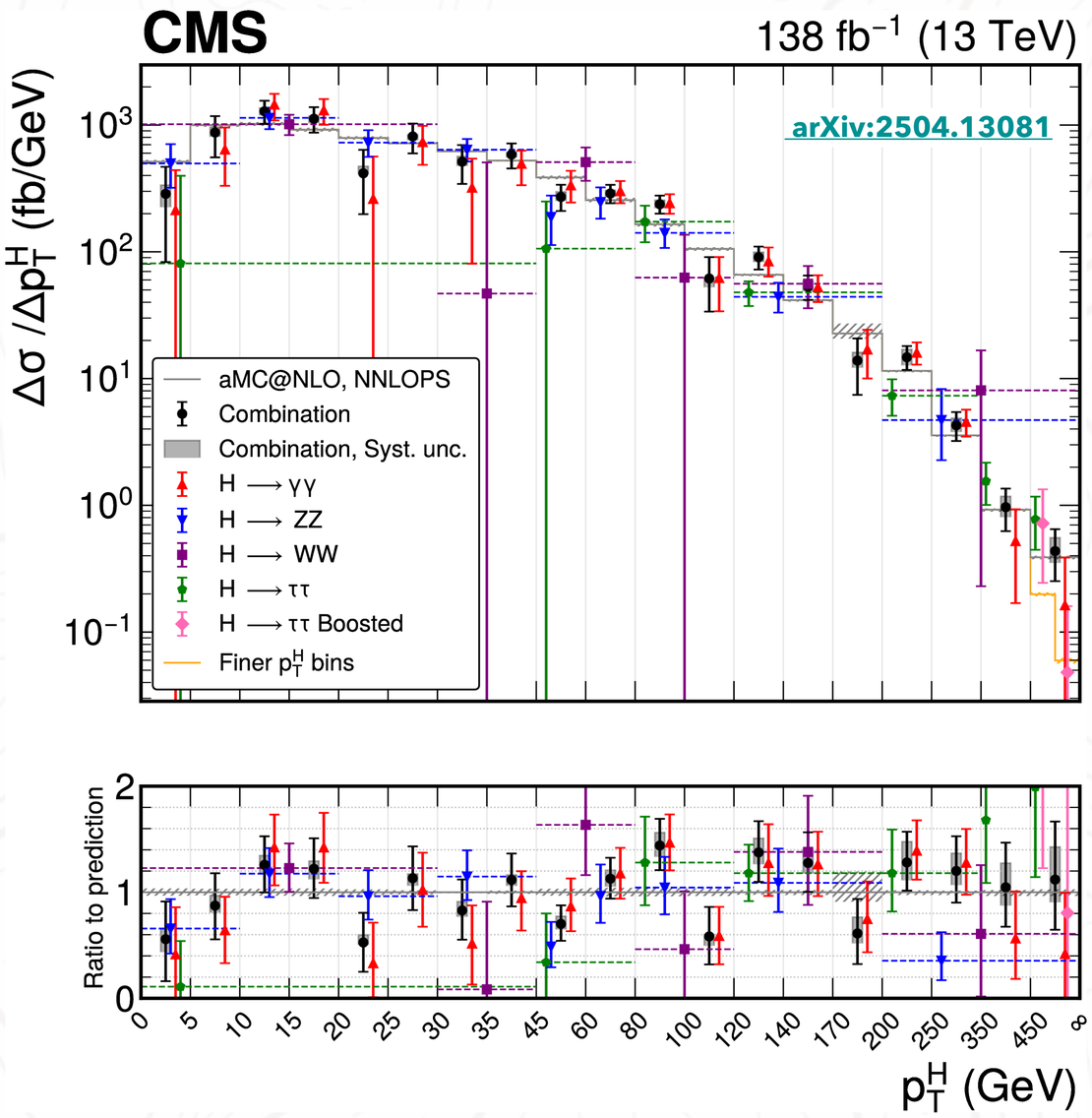
JHEP 05 (2024) 047

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



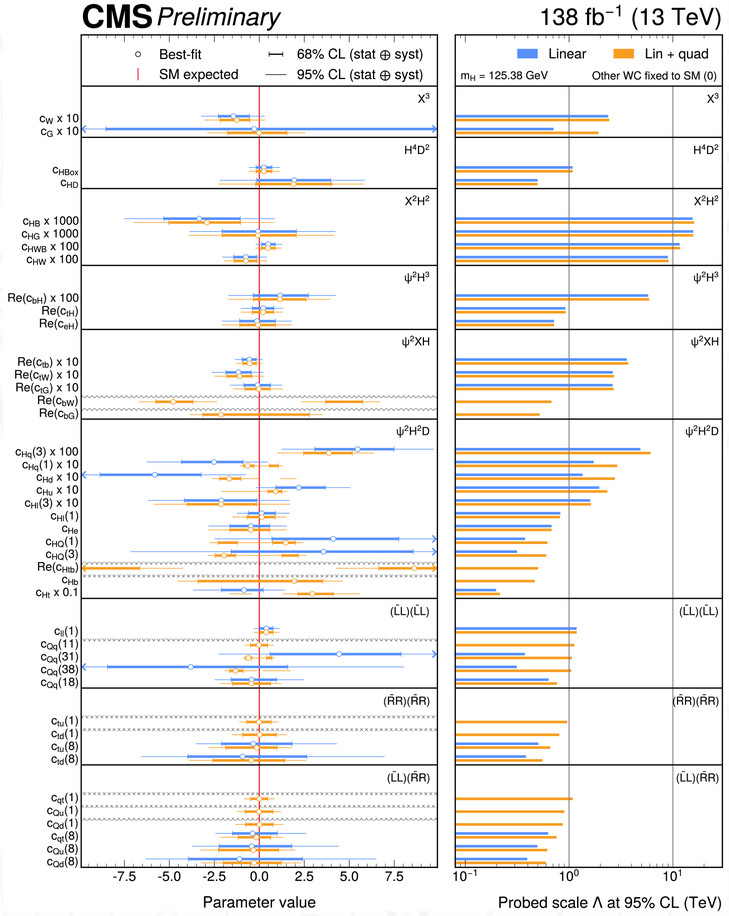
DIFFERENTIAL DISTRIBUTIONS



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

BEYOND KAPPAS: EFT CONSTRAINTS



CMS-PAS-HIG-21-018

- 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

ATL-PHYS-PUB-2025-031

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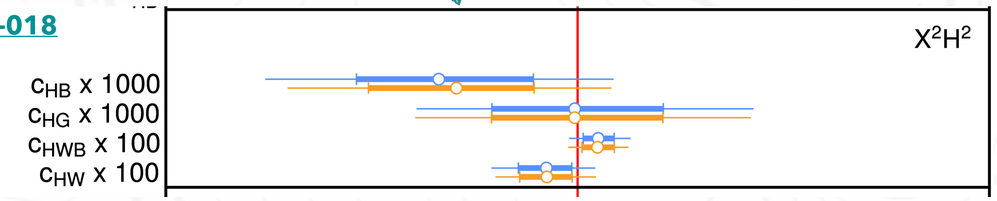
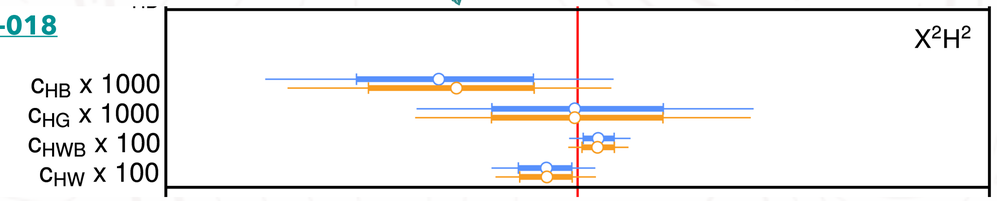


ATL-PHYS-PUB-2025-031

BEYOND KAPPAS: EFT CONSTRAINTS

CMS-PAS-HIG-21-018



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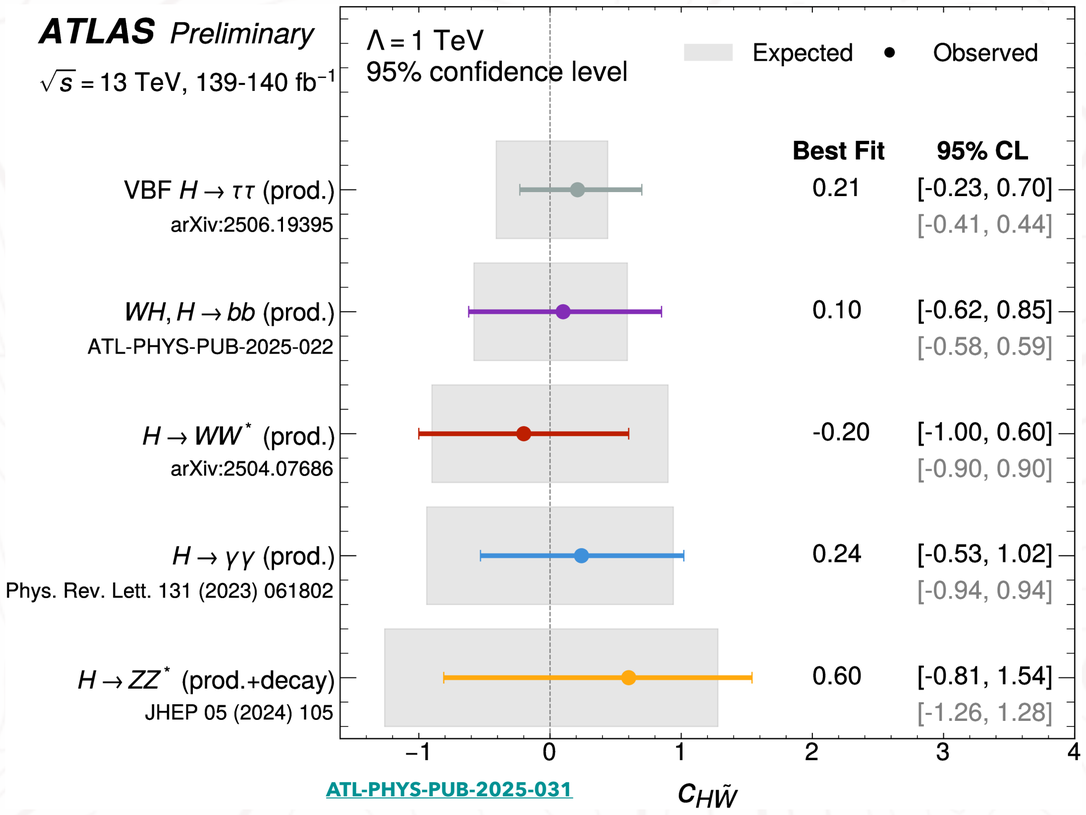


ATL-PHYS-PUB-2025-031

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?

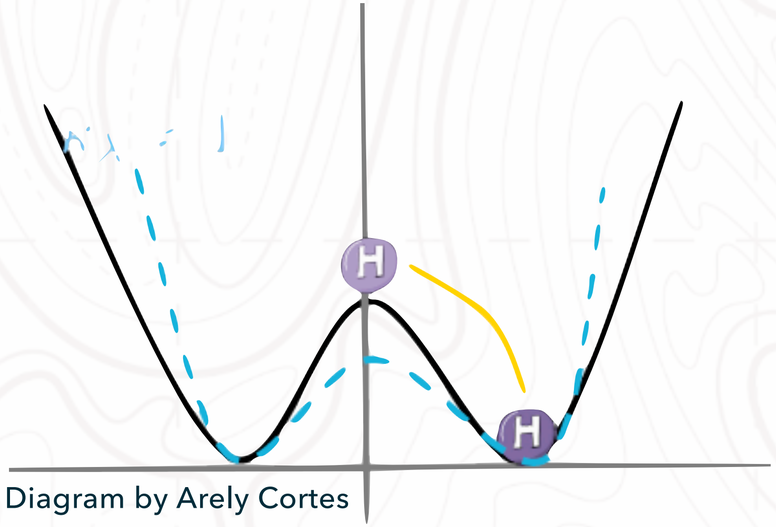


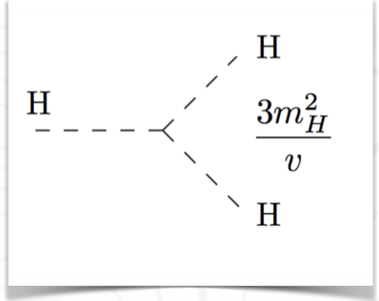
Diagram by Arely Cortes

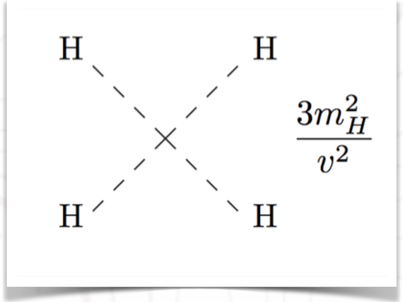
$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

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

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

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

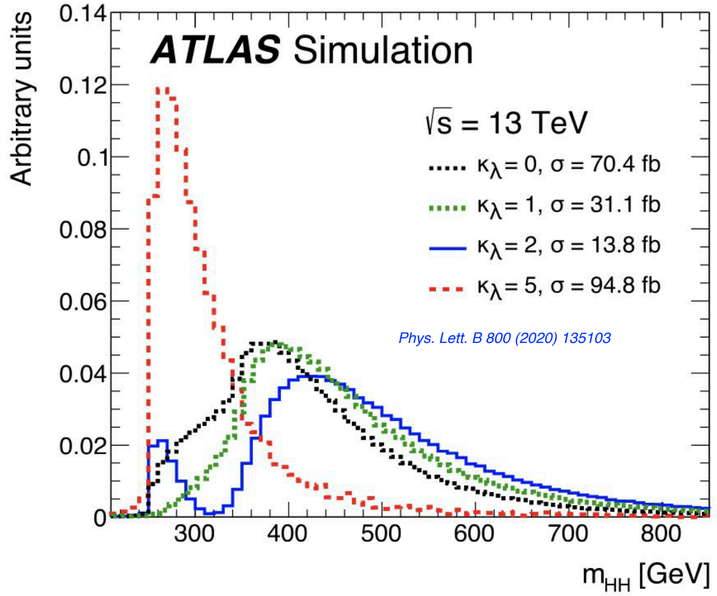


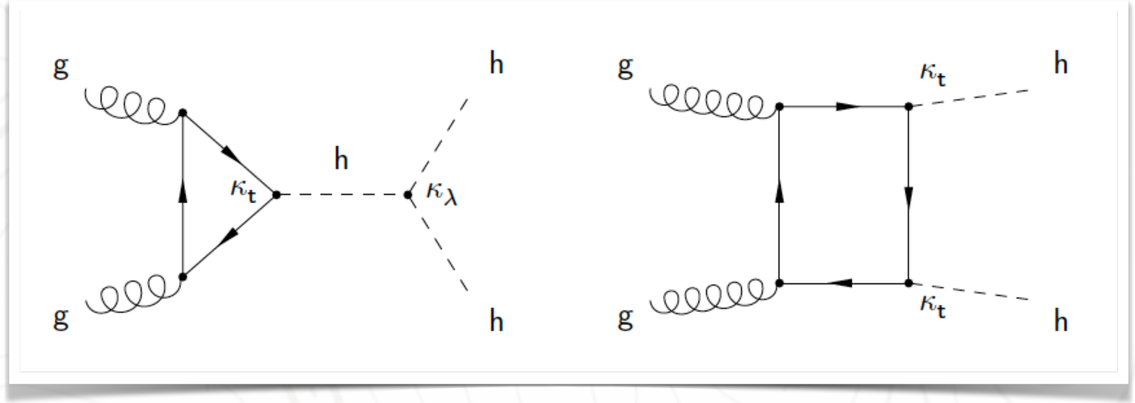


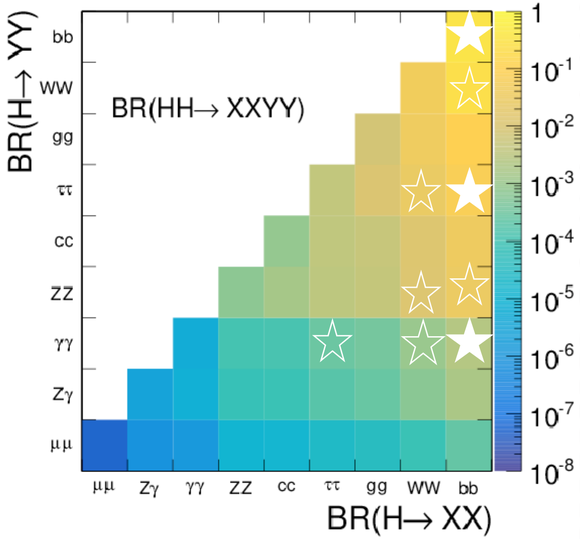
One of the key objectives for the LHC in this run and the future: narrowing down our understanding of the Higgs Potential through the search for HH production

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! Tiny 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**
- Large choice of final states: exploit everything we know from studying single Higgs, profit from combinations of largish branching ratio with good S/B discrimination
- Dominated by ggHH, but also probing qqHH, VHH, ttHH







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

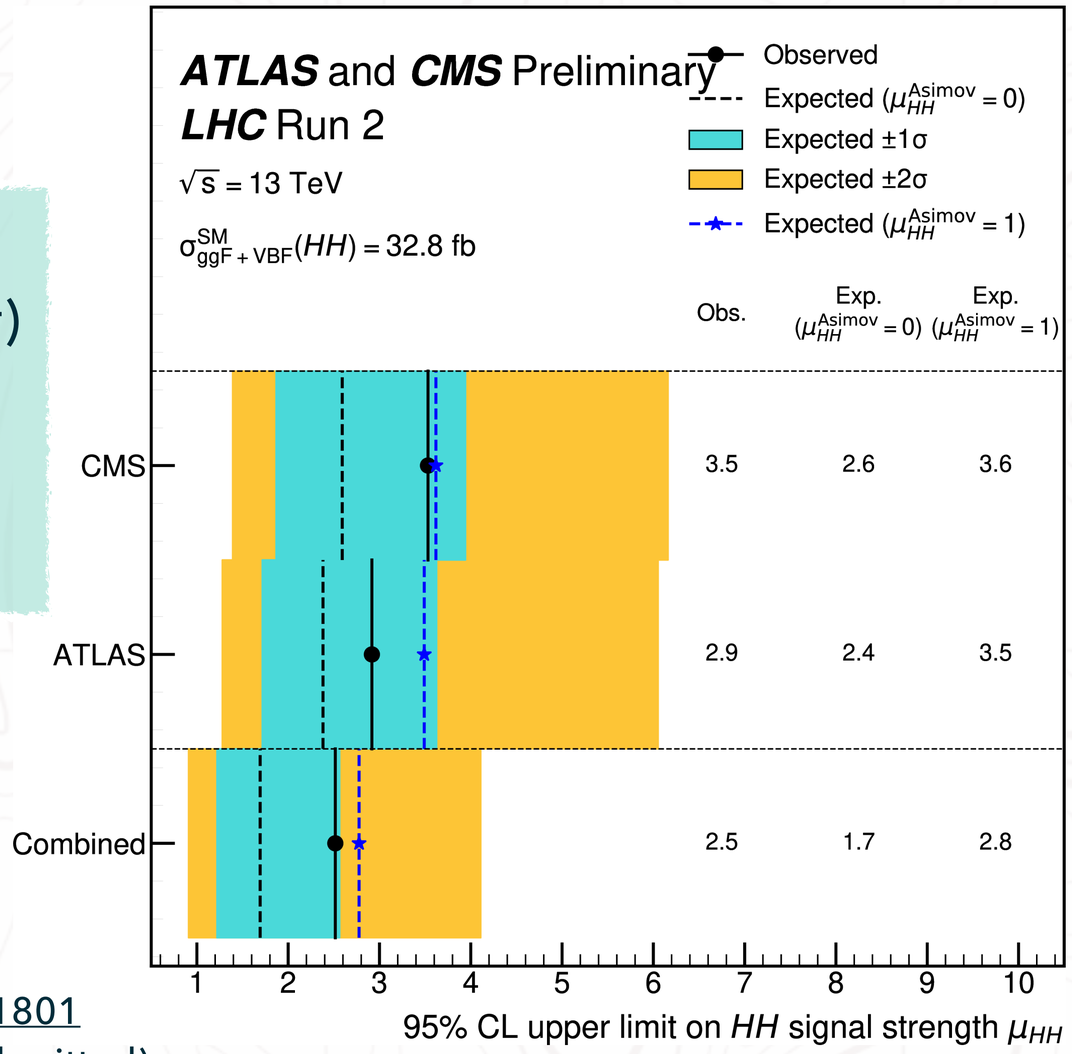
WHERE ARE WE? FIRST LHC HH COMBINATION

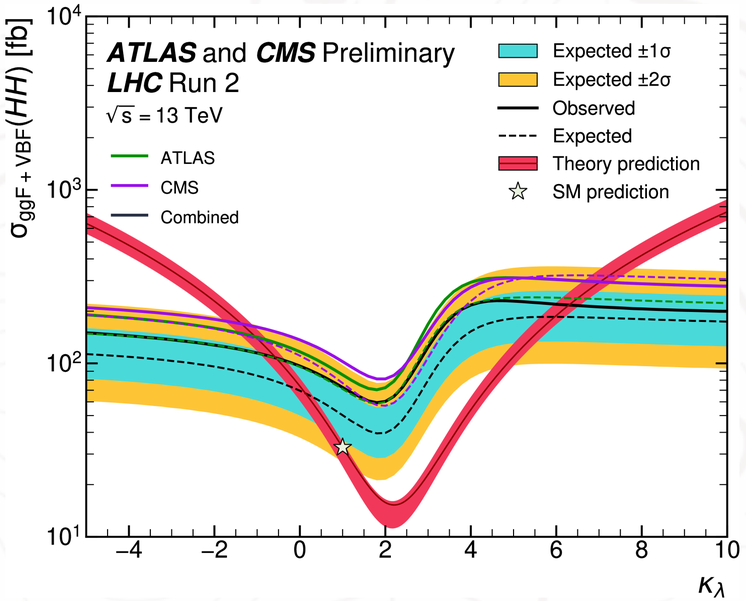
$\mu_{HH} < 2.5$ @ 95% CL

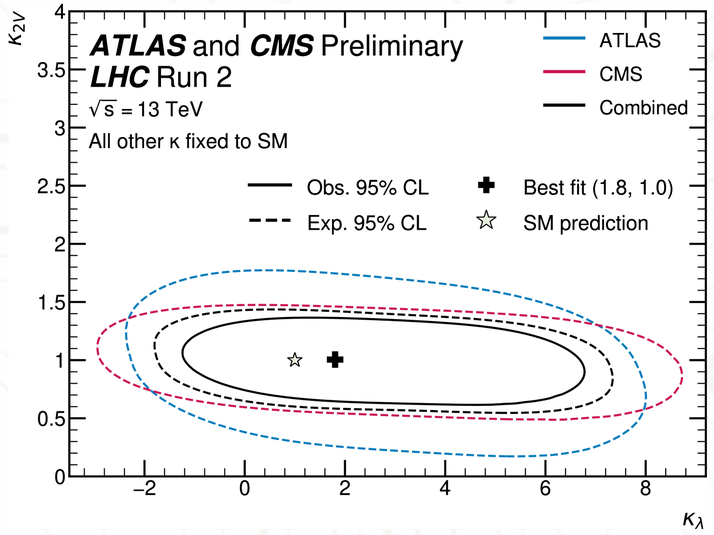
$<\mu_{HH}> = 0.8^{+0.9}_{-0.7}$ (1.1 σ)

$-0.71 < \kappa_\lambda < 6.1$

$0.73 < \kappa_{2V} < 1.3$







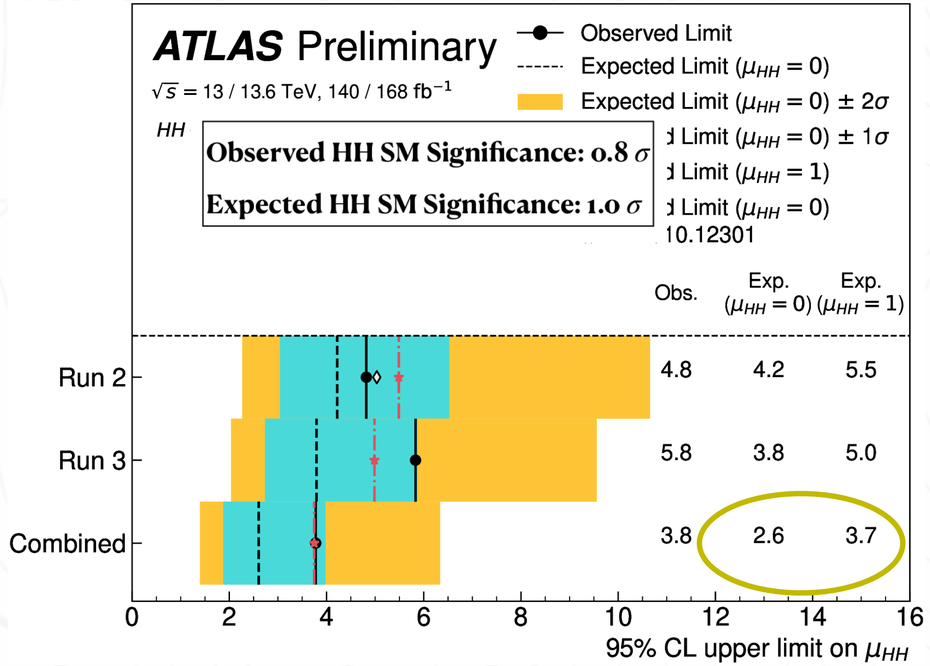
ATLAS Run2: PRL 133 (2024) 101801

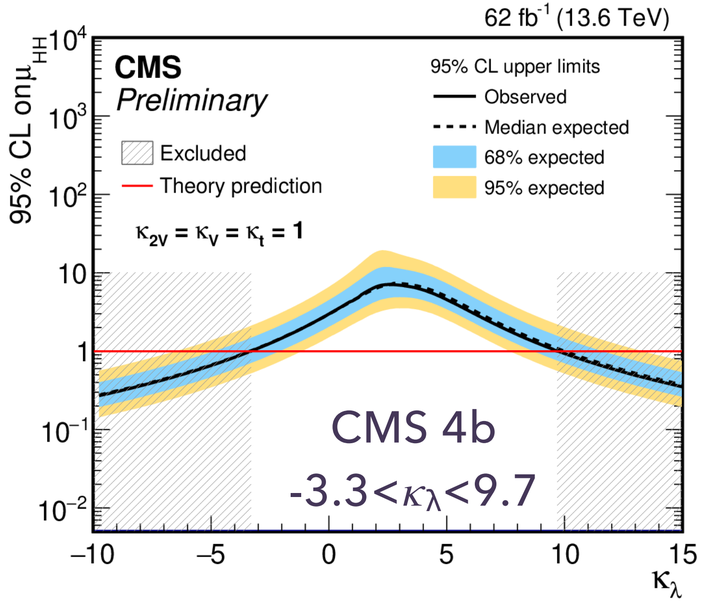
CMS Run2: CMS-HIG-20-011 (submitted)

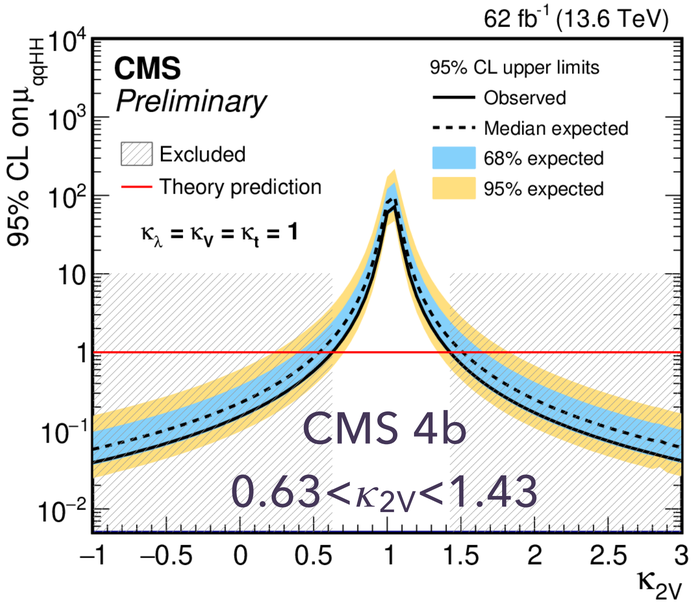
ATLAS+CMS Conf Note: CMS-HIG-25-014

FIRST LOOK AT RUN3 HH DATA

- Exploiting the new statistics, but not only!
  - 2b2γ: ATLAS arXiv:2507.03495 , CMS HIG-25-007 . 4b: CMS HIG-24-010
- New analysis techniques, new triggers: huge potential to be untapped.
- Single channels in Run3 approach full Run2 combination in sensitivity



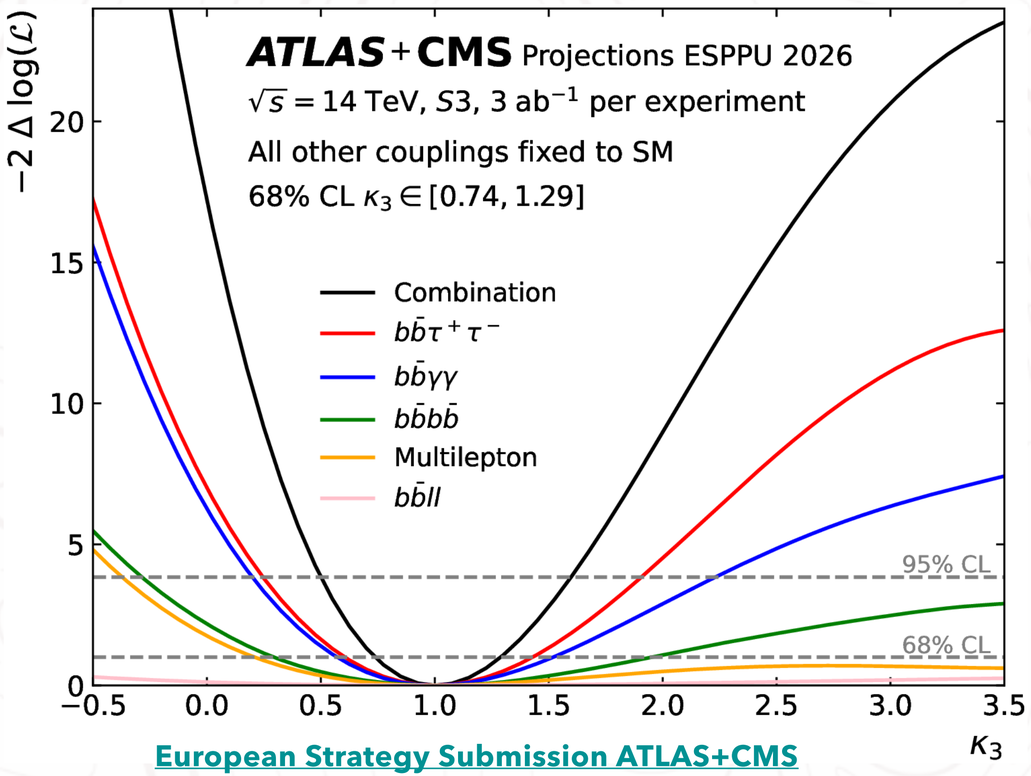




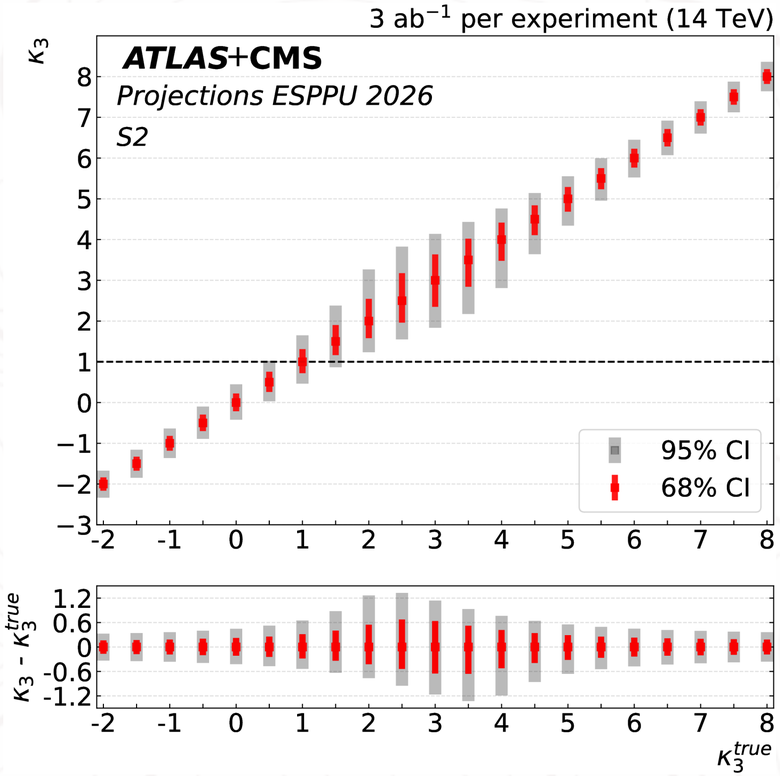
EXCEEDING EXPECTATIONS

- 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}**

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

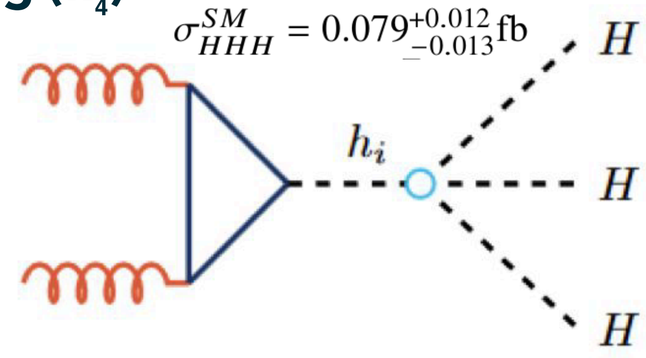


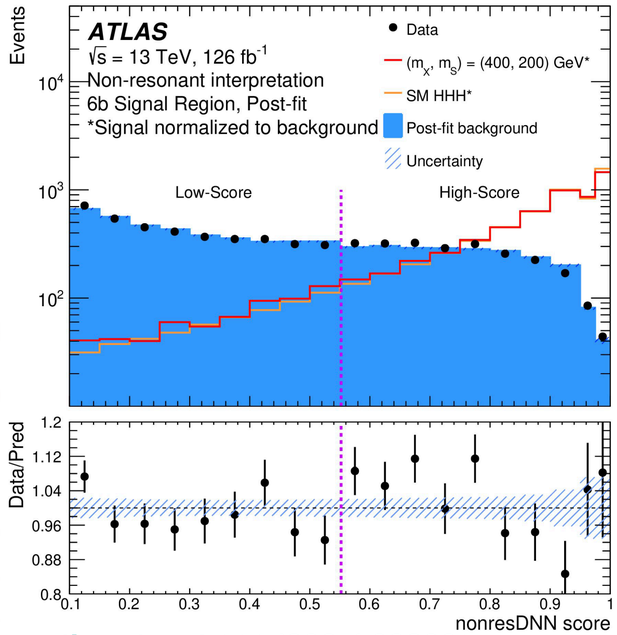
European Strategy Submission ATLAS+CMS



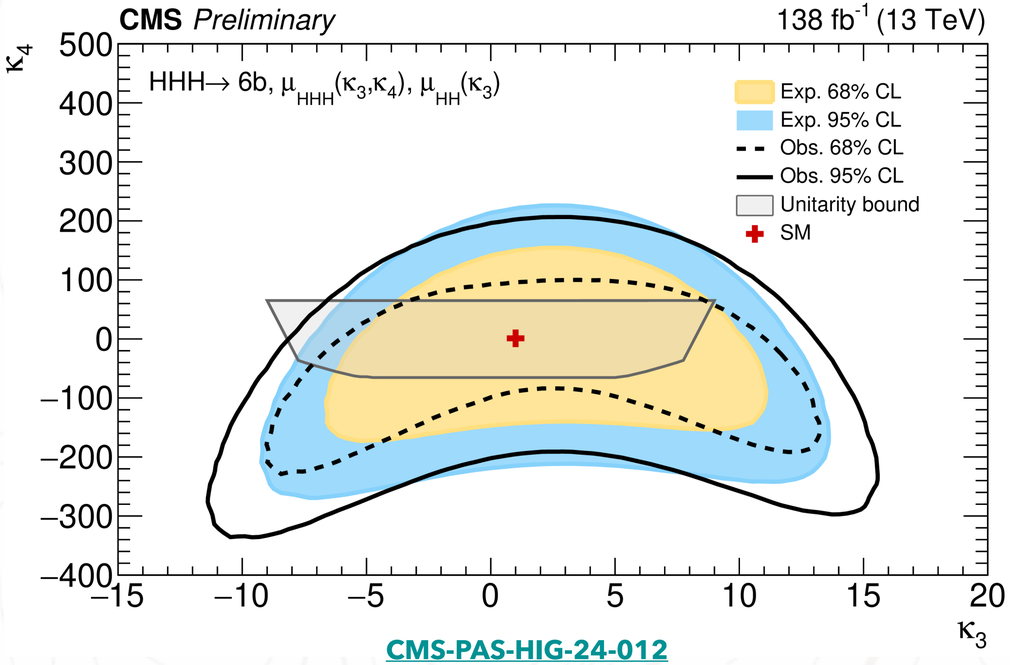
THE QUEST FOR HHH

- 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 μ< 760 (750) at 95% CL , CMS: μ< 588 (572), at 95% CL
  - 4b2gamma (CMS) μ< 3400 (2086) at 95% CL

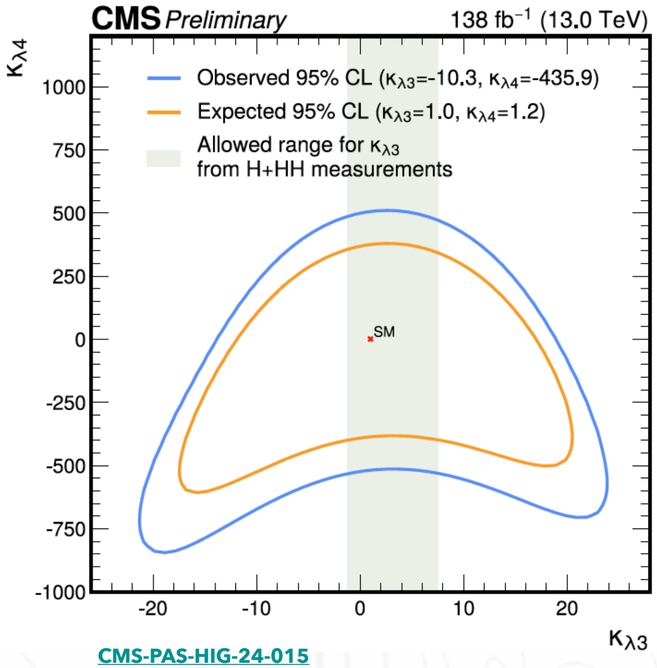




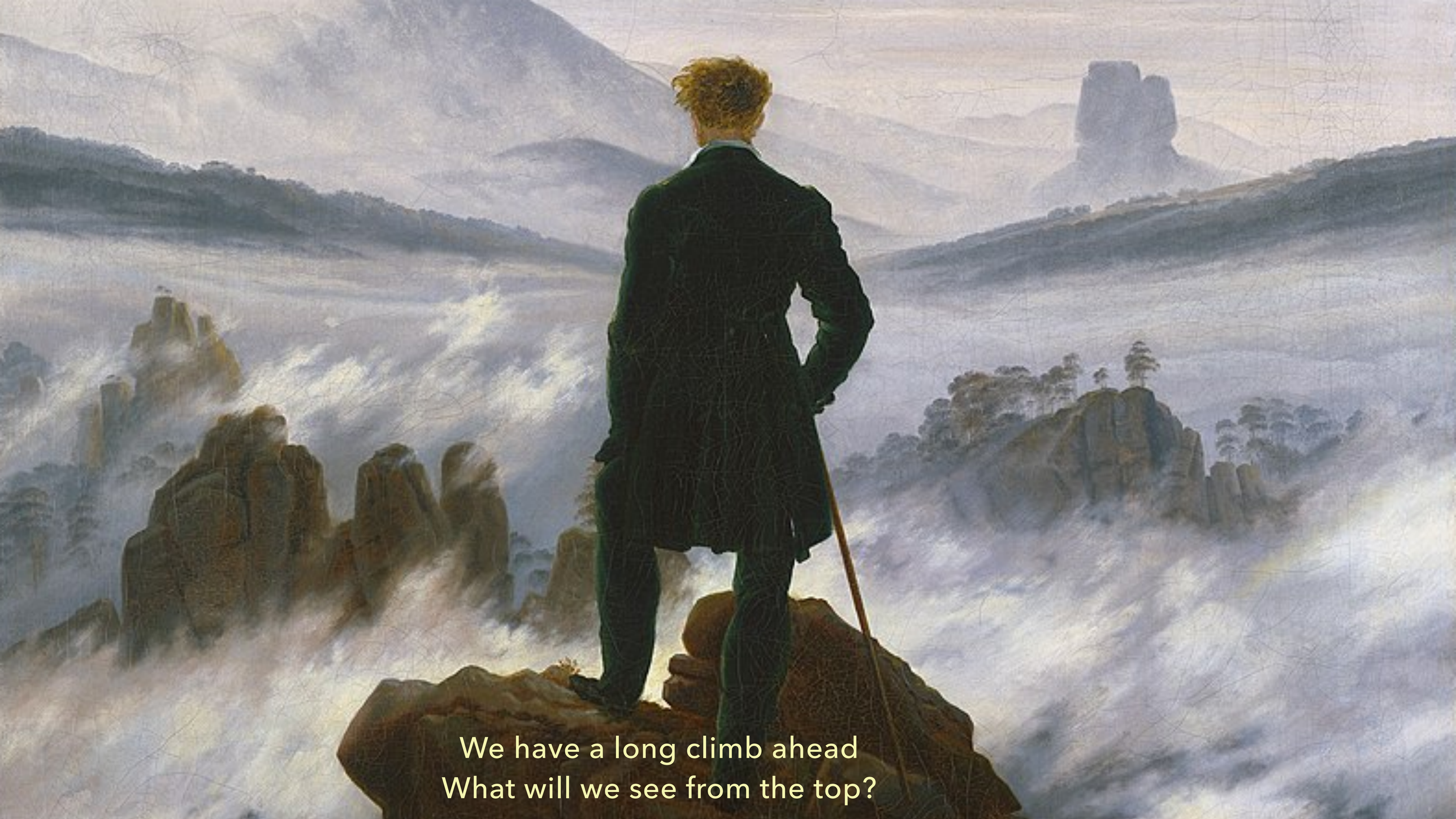
Phys. Rev. D 111 (2025) 032006



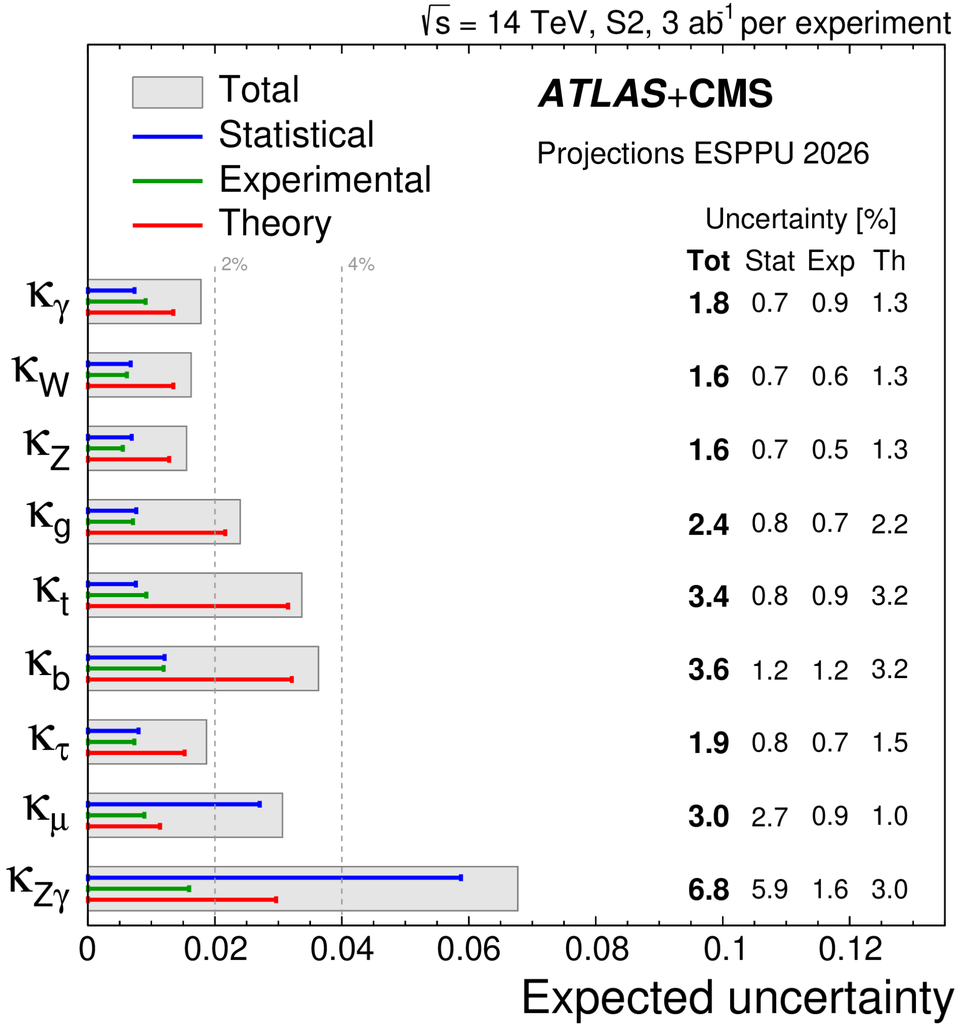
CMS-PAS-HIG-24-012

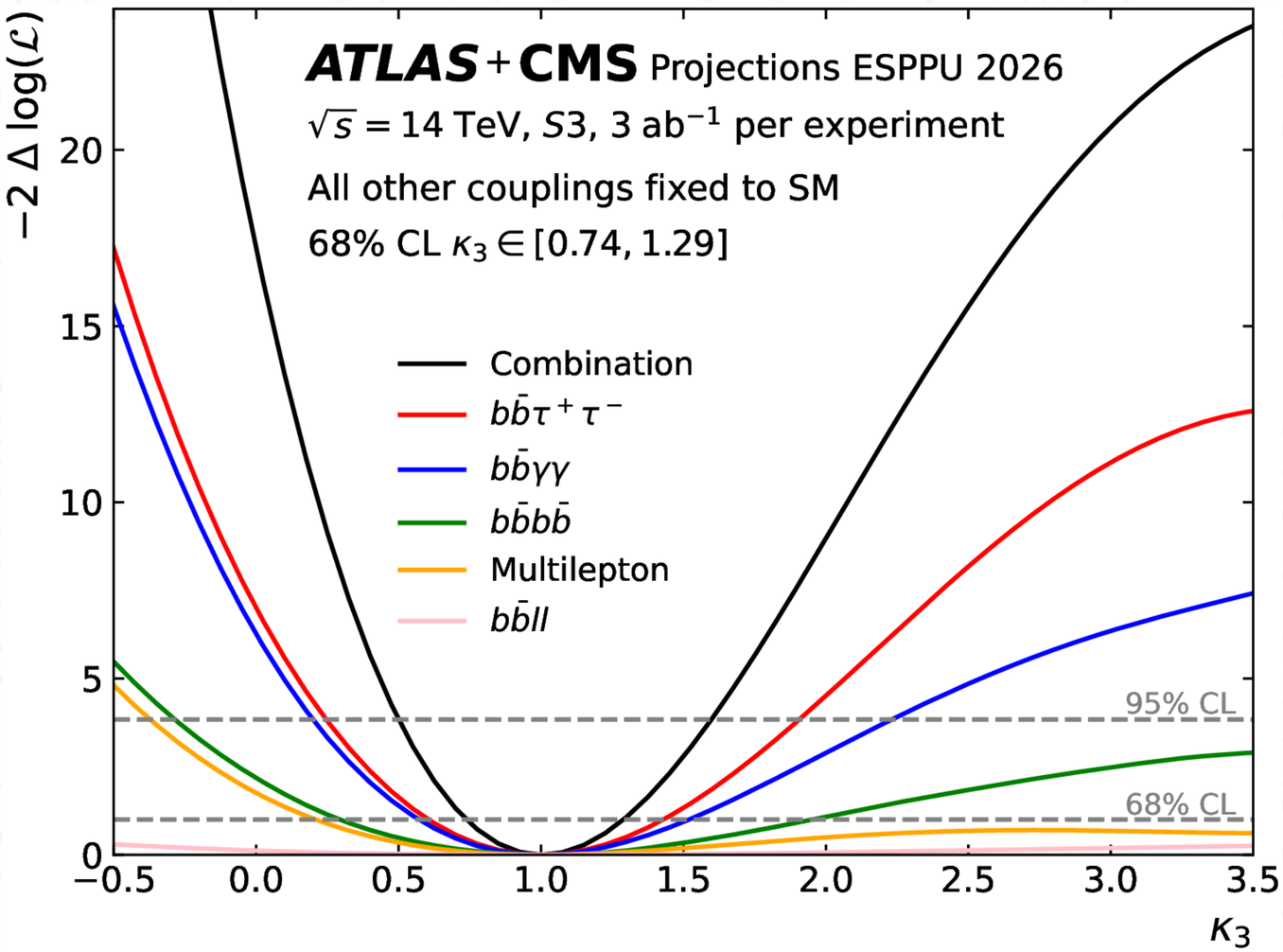


CMS-PAS-HIG-24-015


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

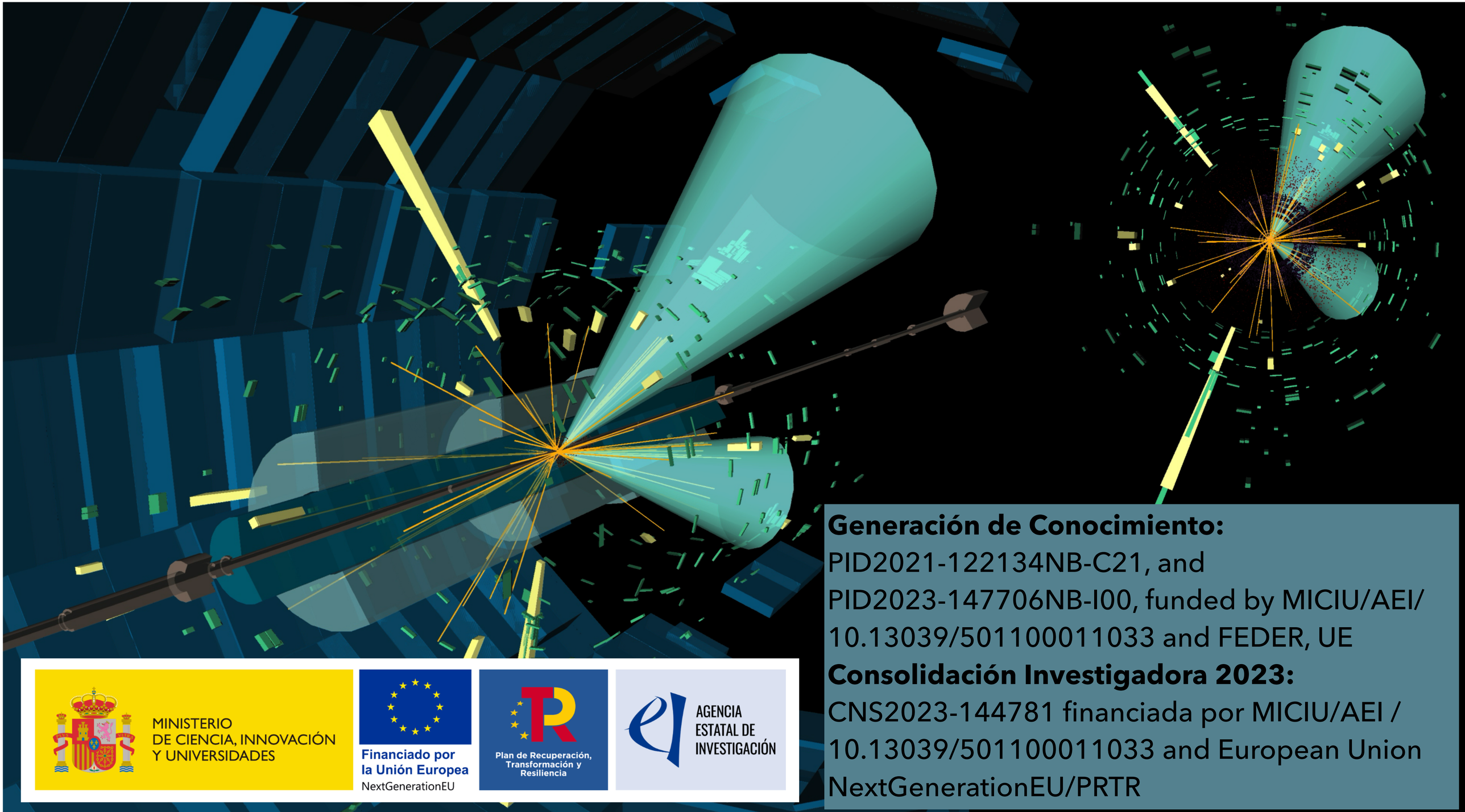
AT THE END OF THE LHC ROAD...





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.
- 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 that 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:
PID2021-122134NB-C21, and
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
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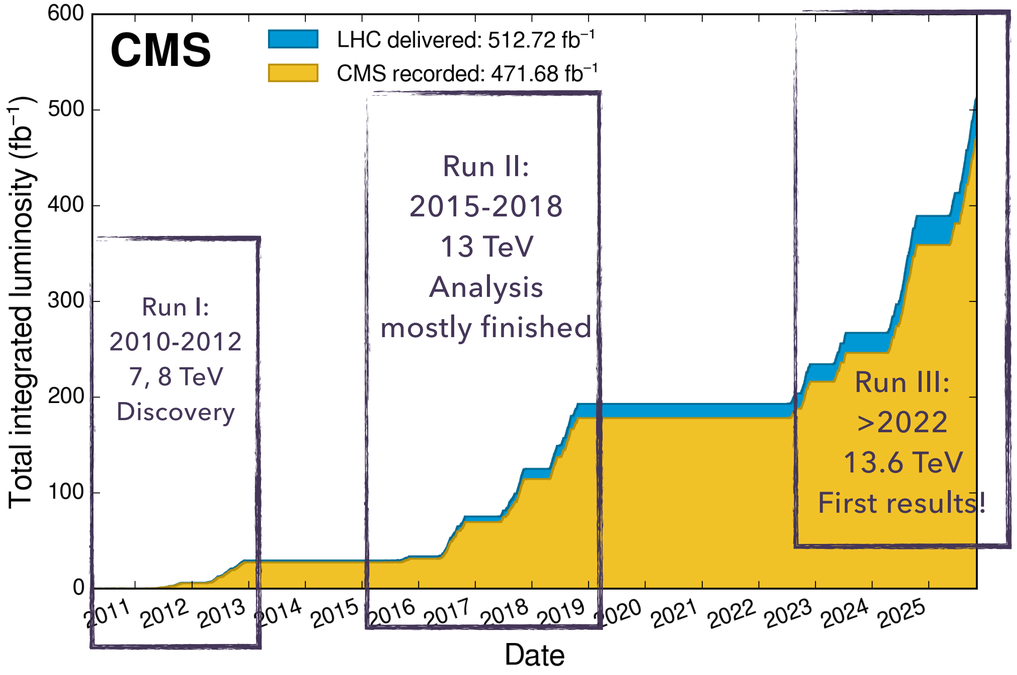
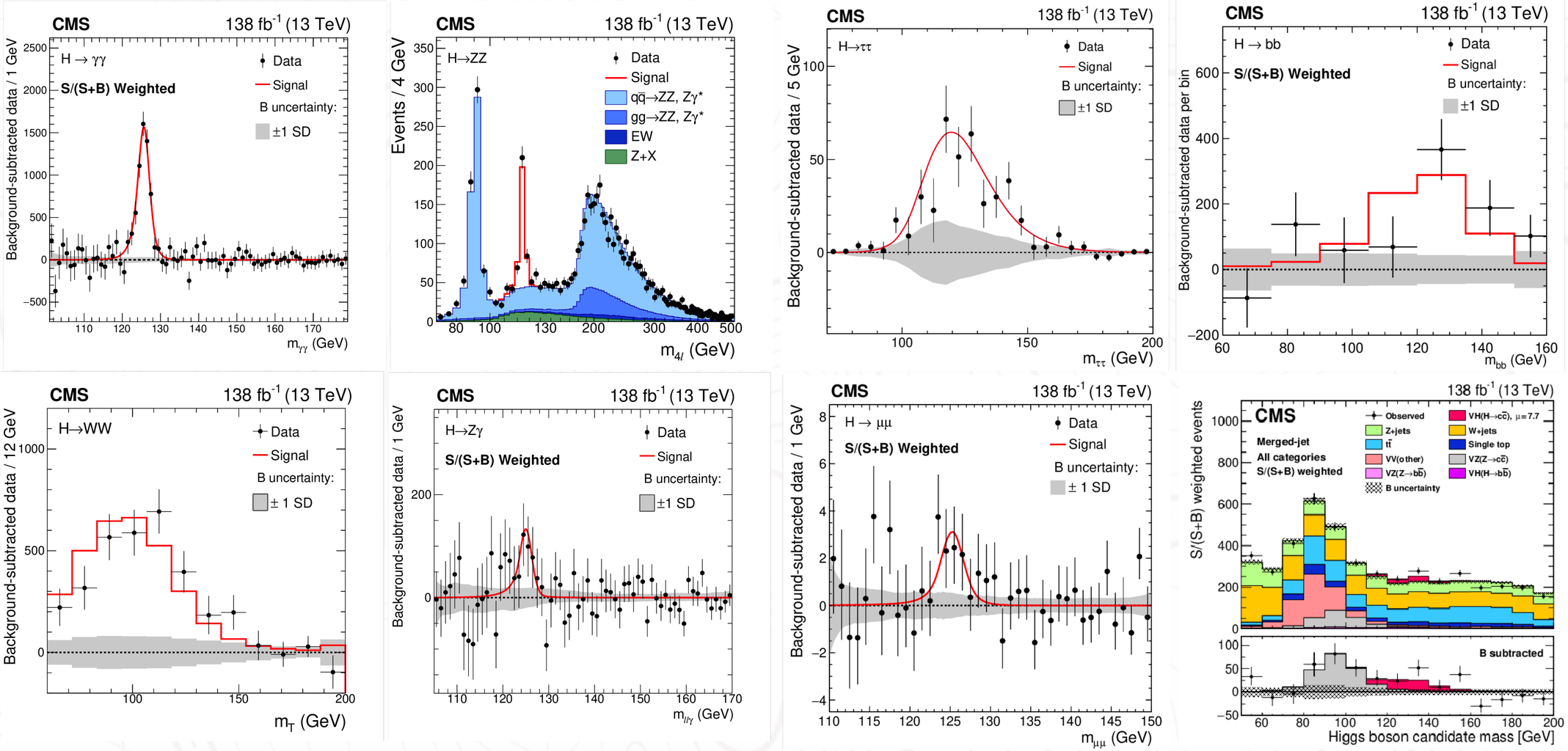
ESTATAL DE
INVESTIGACIÓN

THE HIGGS LANDSCAPE TODAY AT A GLANCE

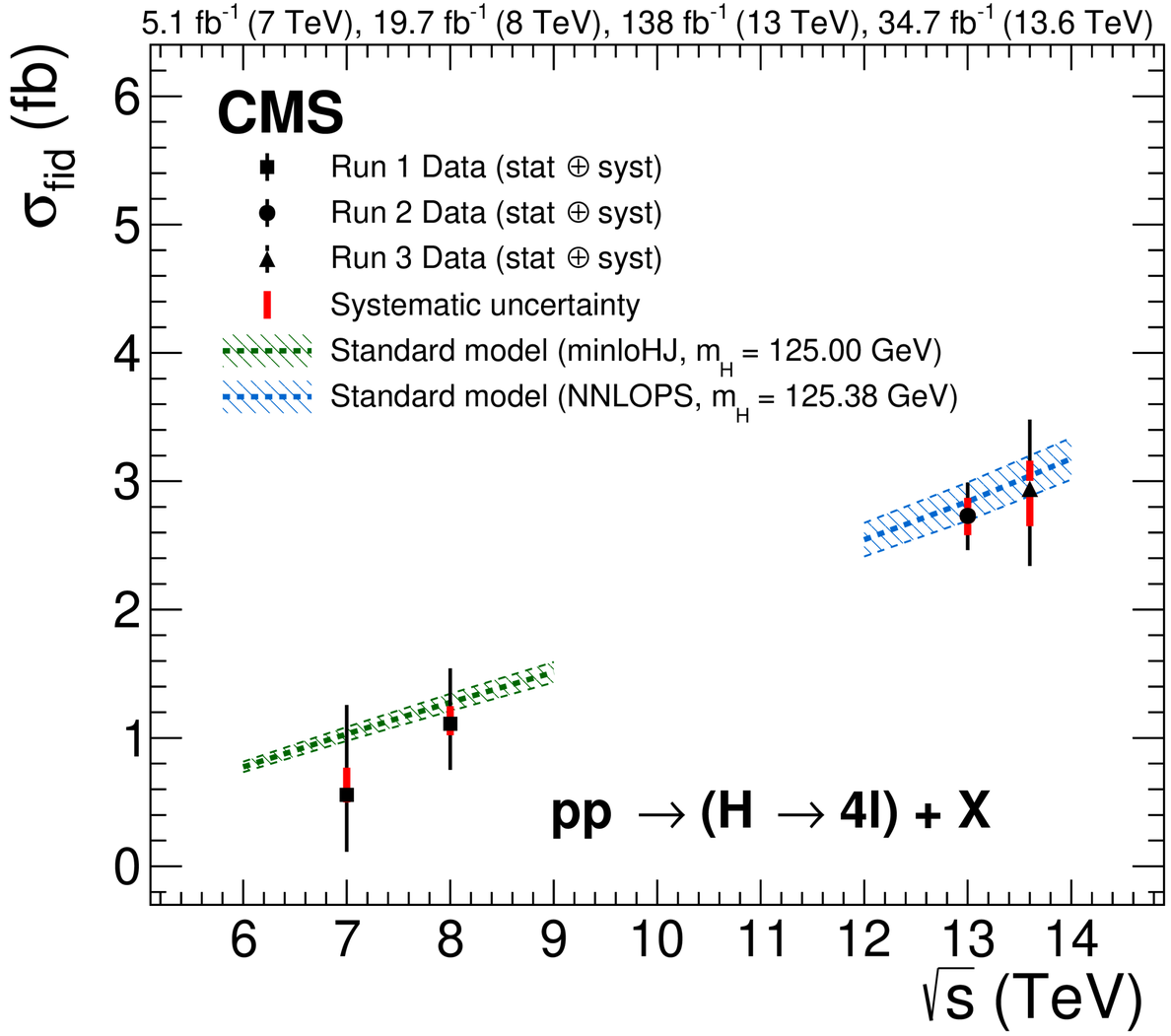
- **Run 2 analysis is (almost) complete** → ~140 fb^{-1} at 13 TeV
- **Run 3 analysis underway** → > 300 fb^{-1} at 13.6 TeV!
- **Wealth of precision measurements: testing SM boundaries**
  - → Inclusive and differential cross sections, Coupling fits
  - → EFT constraints
- **Large statistics:**
  - → measurements in complicated phase-spaces
  - → rare decays and elusive signatures 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**

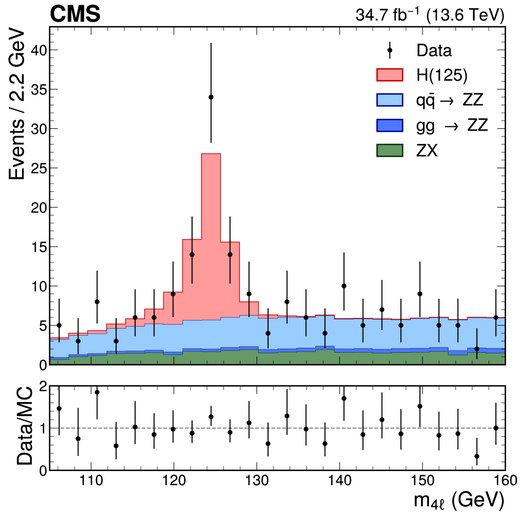


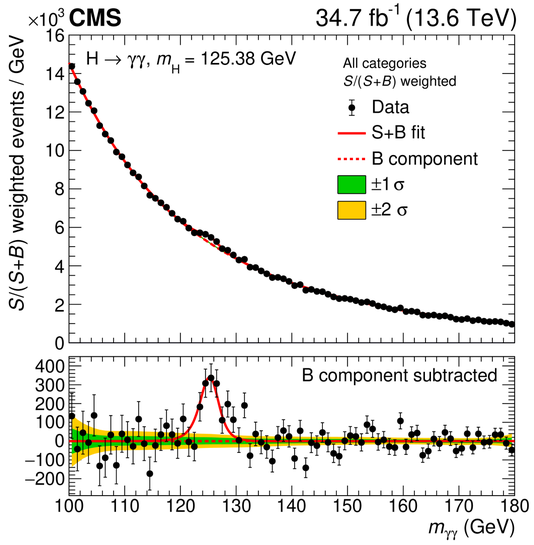
THE FACES OF THE HIGGS IN RUN2…



7, 8, 13… AND 13.6 TeV







- HZZ (JHEP 05 (2025) 079) :

  - $\sigma_{fid}(H \to ZZ \to 4l) = 3.09 \pm 11^{+0.27}_{-0.24}$ fb

- and H$\gamma\gamma$ (arXiv:2504.17755)

  - $\sigma_{fid}(H \to \gamma\gamma) = 74 \pm 11\,(\text{stat})\,^{+5}_{-4}\,(\text{syst})$ fb

HOW WELL DO WE KNOW THE HIGGS MASS?

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- **Free parameter in the SM**
- Known to permil level already!

(Through $H \to ZZ \to 4l$ and $H \to \gamma\gamma$)

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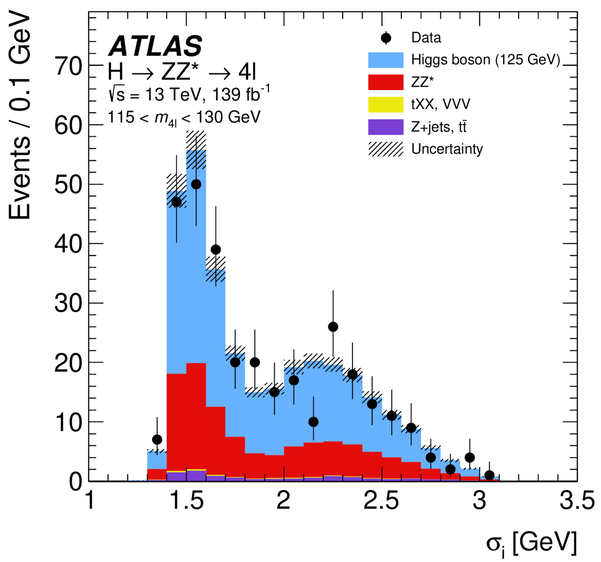
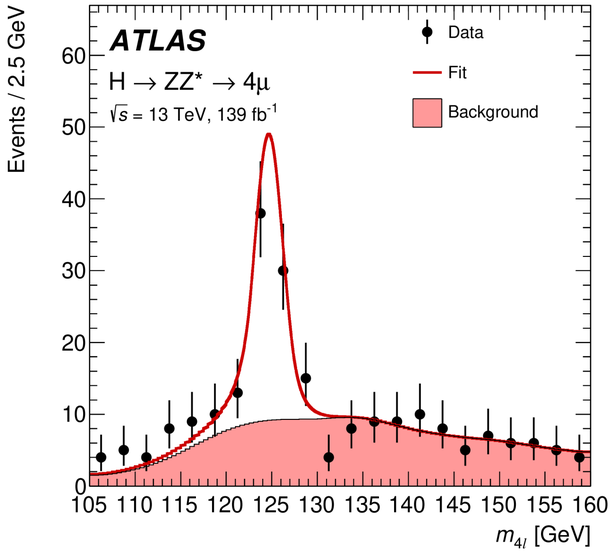
- Precision directly linked to the reconstruction (energy scale and resolution) of photons and leptons
  - Huge experimental effort to measure momentum/ energy scale, calibration and resolution very precisely
- Template fit of mH distribution, categorised by resolution





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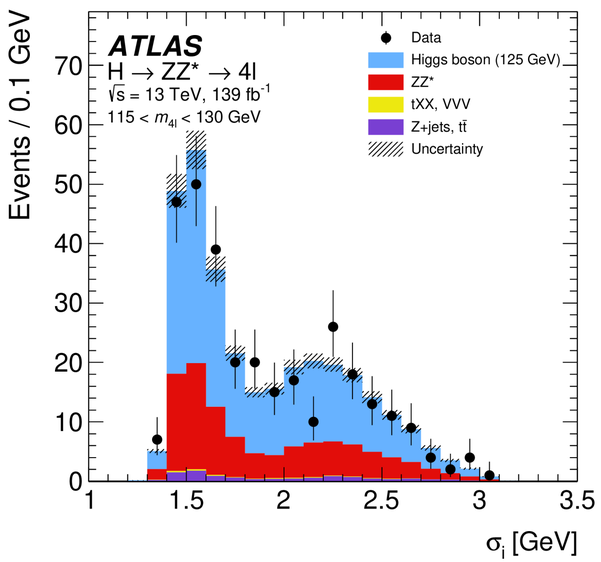
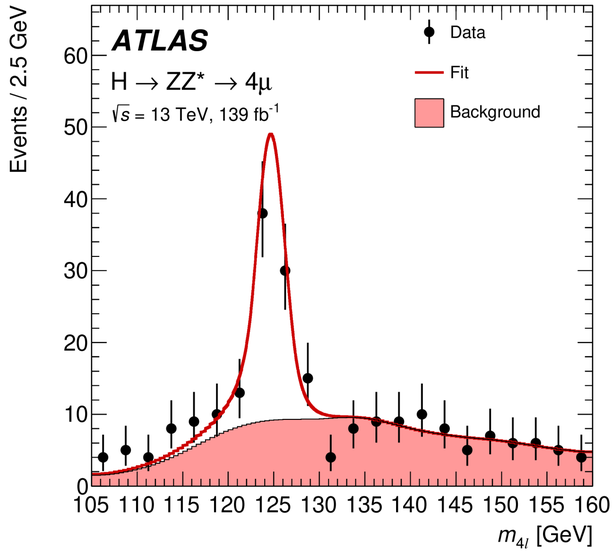
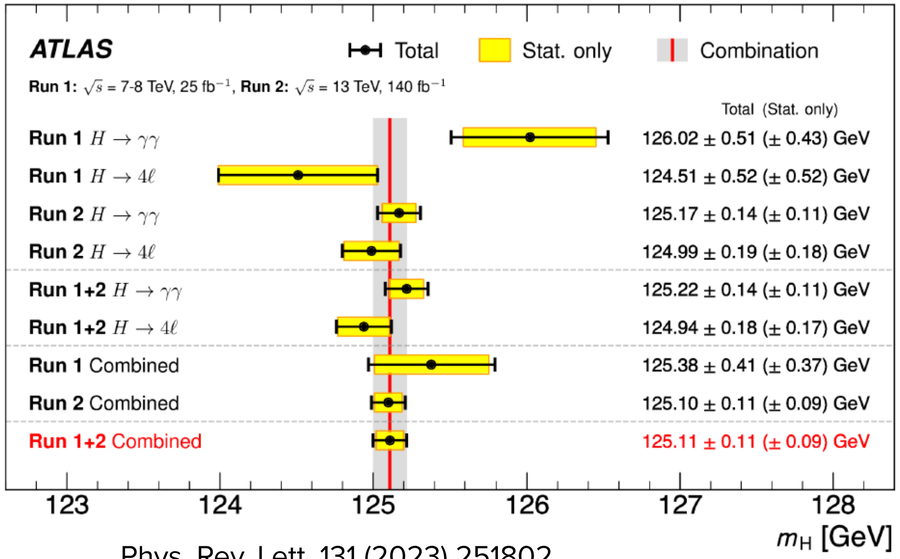
- Precision directly linked to the reconstruction (energy scale and resolution) of photons and leptons
  - Huge experimental effort to measure momentum/ energy scale, calibration and resolution very precisely
- Template fit of mH distribution, categorised by resolution

- Latests CMS Run1 + Run2:
  - $4l + \gamma\gamma$ $(Run2\ 36\ \text{fb}^{-1})$: $125.38 \pm 0.14\ GeV$
  - $4l$ $(Run2\ 138\ \text{fb}^{-1})$: $125.04 \pm 0.12\ GeV$

- Latest ATLAS Run1+Run2:
  - $4l + \gamma\gamma, > 140\ \text{fb}^{-1}$: $125.11 \pm 0.11\ GeV$







Phys. Rev. Lett. 131 (2023) 251802

WIDTH FROM OFF-SHELL/ON-SHELL

- Main channel: H→ZZ
  - CMS PRD 111 (2025) 092014: $3.0^{+2.0}_{-1.5}\ MeV$
  - ATLAS RPOP 88 057803: $4.3^{+2.7}_{-1.9}\ MeV$
- Evidence for off shell production

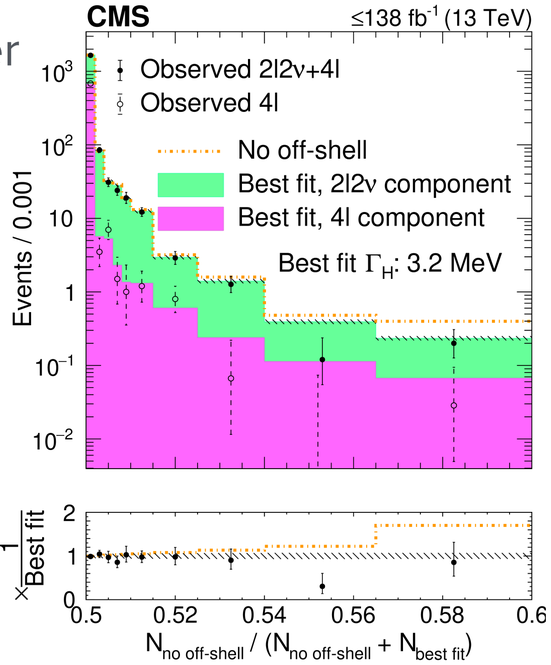
$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H},$$

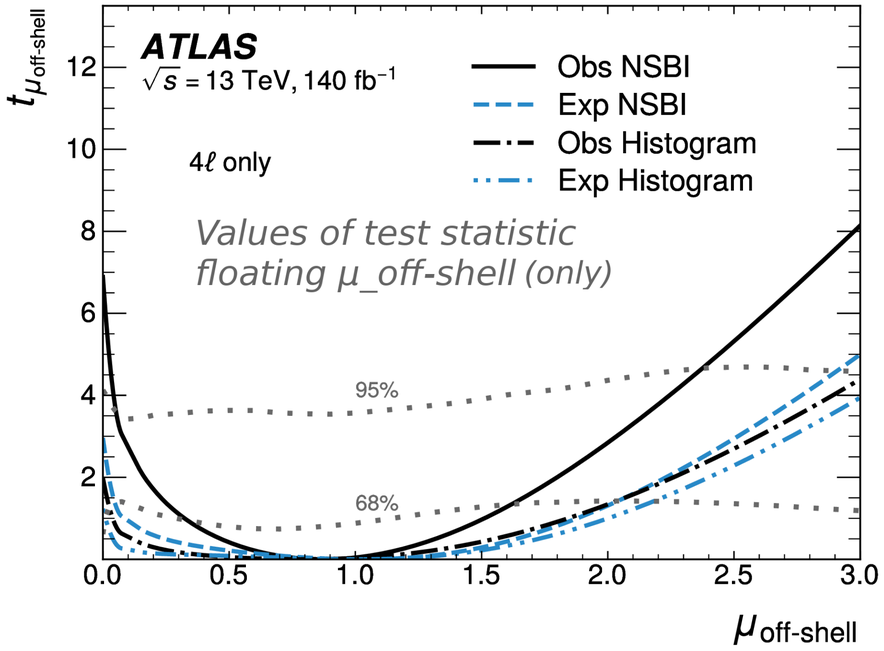
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H} \quad \text{and} \quad \sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}.$$

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

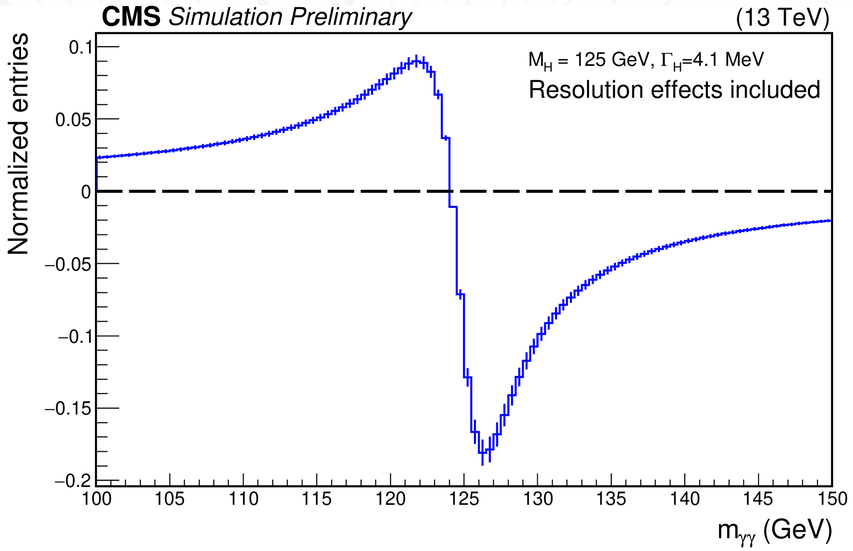
$m_{ZZ} > m_{ZZ}$ *(Off-shell production)*

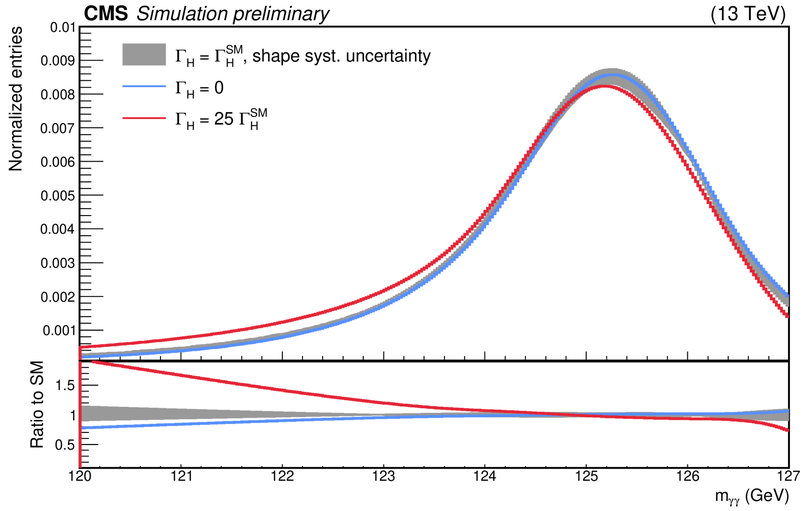
- Offshell/onshell idea can also be applied to other channels (only limits)
  - HWW, (ATLAS, arXiv:2504.07710): < 13.1 MeV (95%CL)
  - HWW, (CMS HIG-24-011): : $3.0^{+2.7}_{-2.2}\ MeV$
  - tttt and ttH (ATLAS ATLAS PLB 861 (2025) 139277): < 450 MeV (95%CL)
- Other methods to probe the width are less stringent, e.g., mass interference in gamma gamma channel





WIDTH FROM DIPHOTON INTERFERENCE

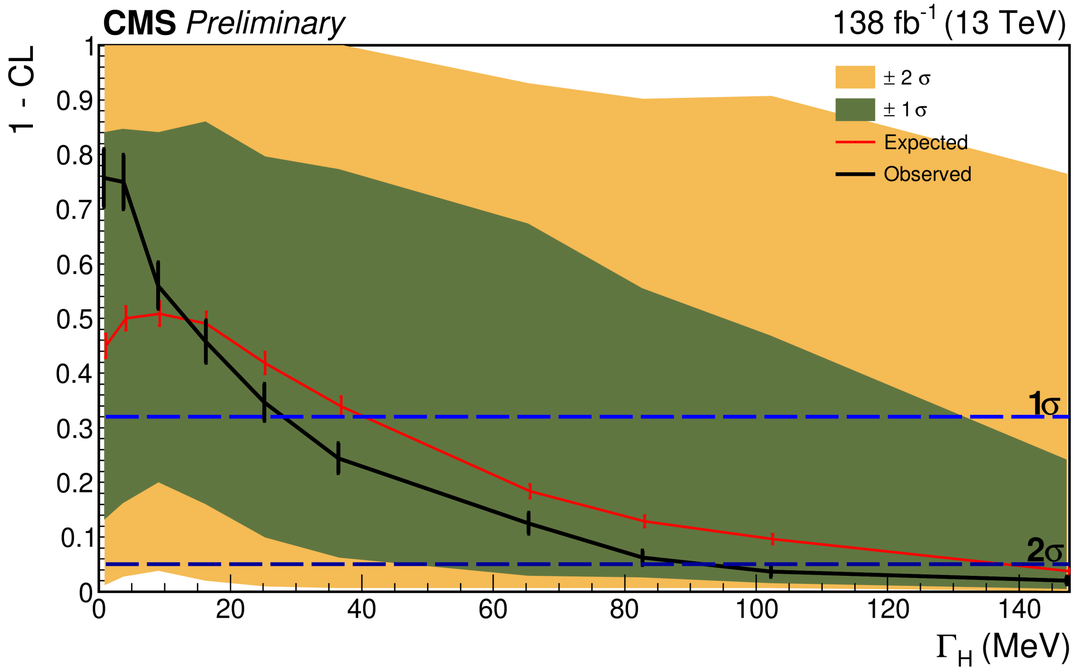




- Constraint on Γ_H from the diphoton mass through the interference between gg→H→$\gamma\gamma$ (aMC@NLO) and the QCD continuum gg→$\gamma\gamma$ and qg →q$\gamma\gamma$ (NLO sherpa)

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

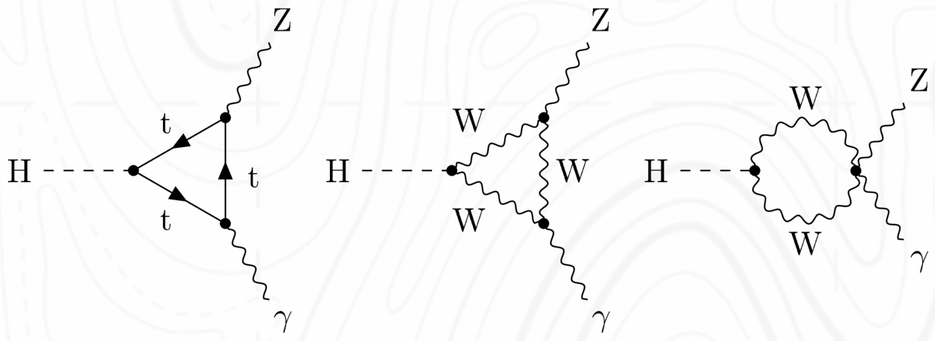
$$d\sigma/dm_{\gamma\gamma} = (\mu_{\gamma\gamma} - c_{g\gamma})\, S + c_{g\gamma}(S + I) + \sum_{i \neq ggF} \mu_i S_i + B(m_{\gamma\gamma})$$



$\Gamma_H < 92(138)$ MeV

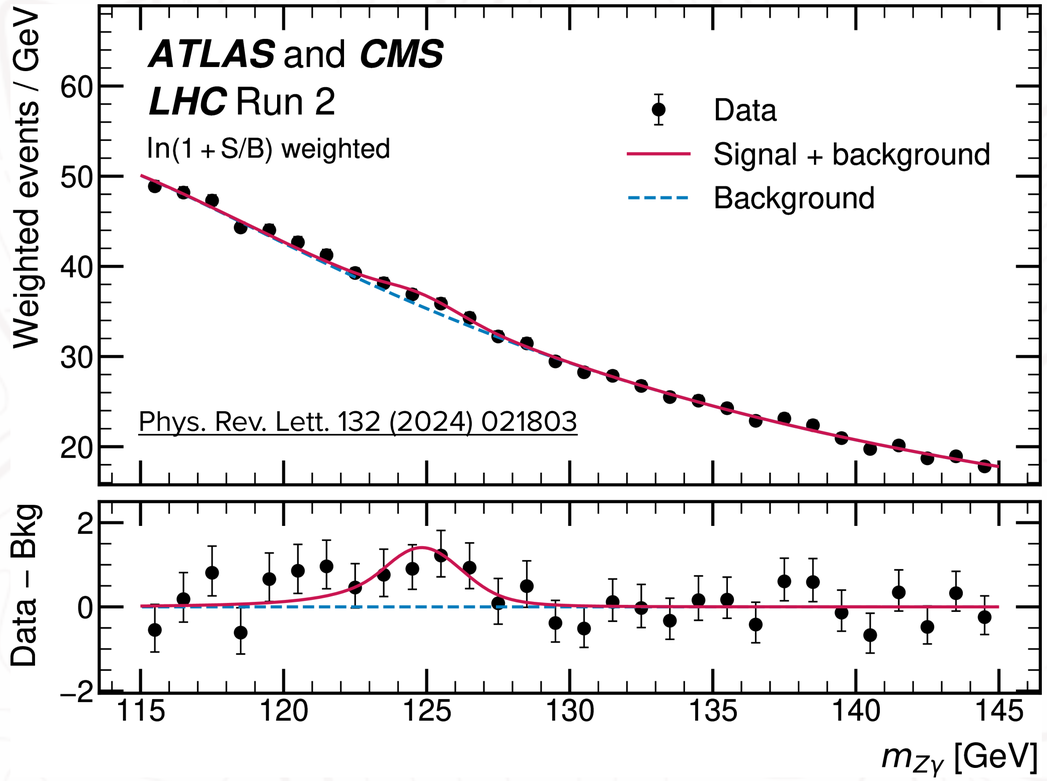
CMS PAS HIG-25-004

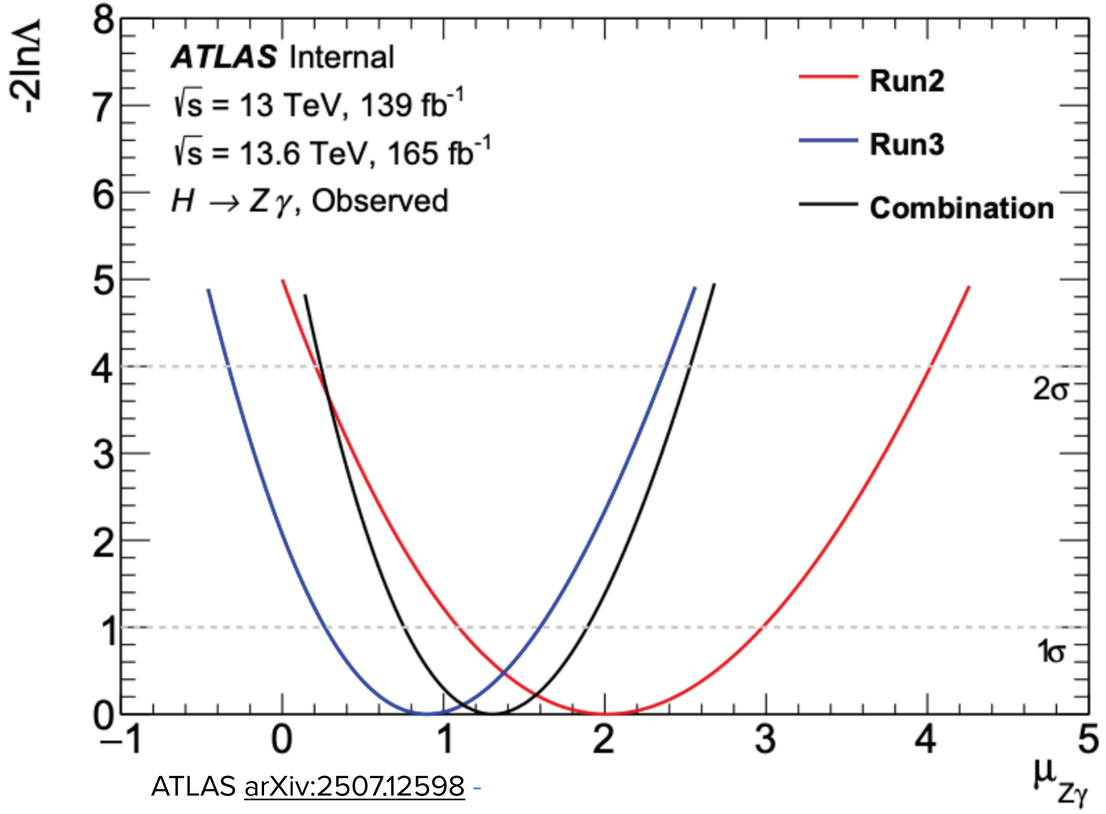
EVIDENCE FOR ZGAMMA



Evidence in Run2 with ATLAS+CMS: μ =2.2±0.7, 3.4σ (1.6 exp SM)

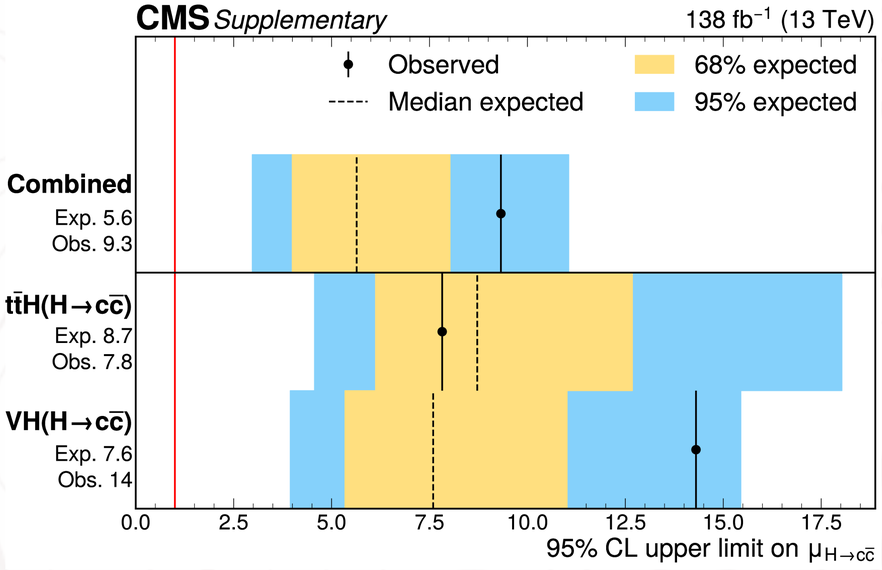
Run2+Run3 ATLAS: 2.5σ (1.0 exp SM) , μ = 1.3 ±0.5





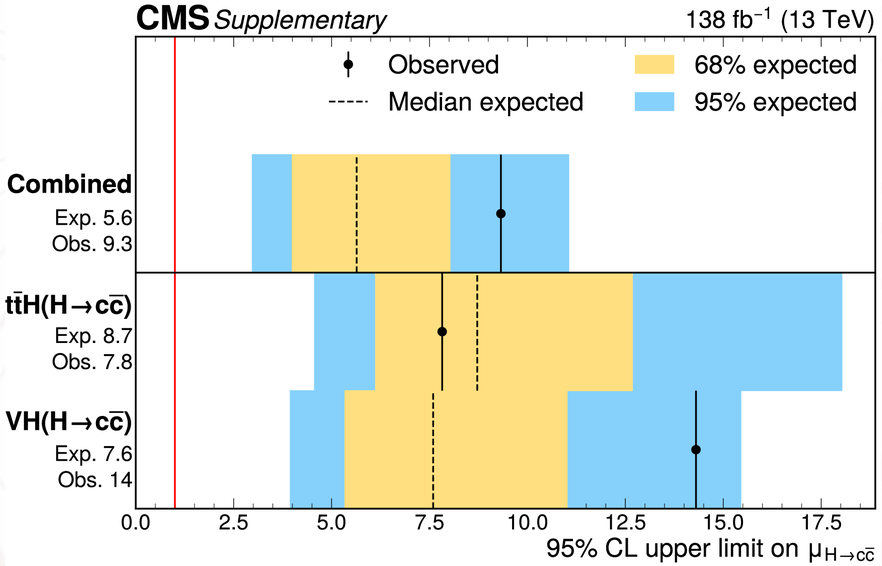
ATLAS arXiv:2507.12598 -

HOW CHARMING IS THE HIGGS?



HOW CHARMING IS THE HIGGS?

- **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?
- **Once considered impossible at the LHC!**



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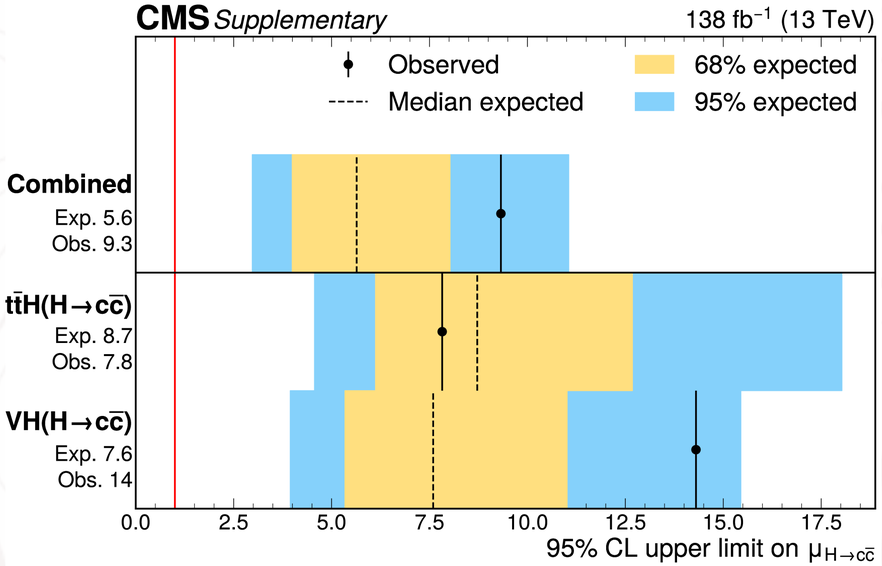
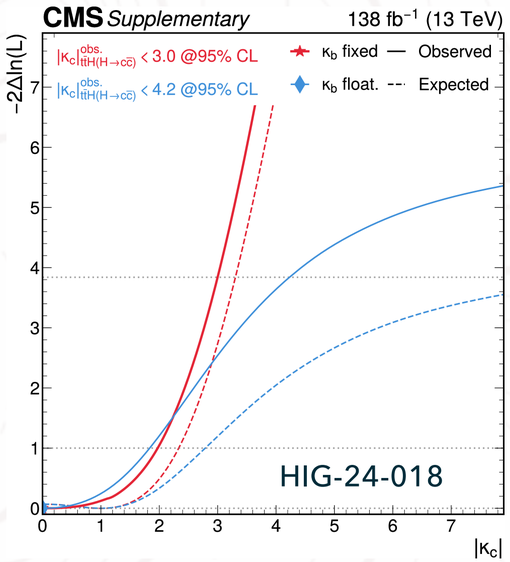
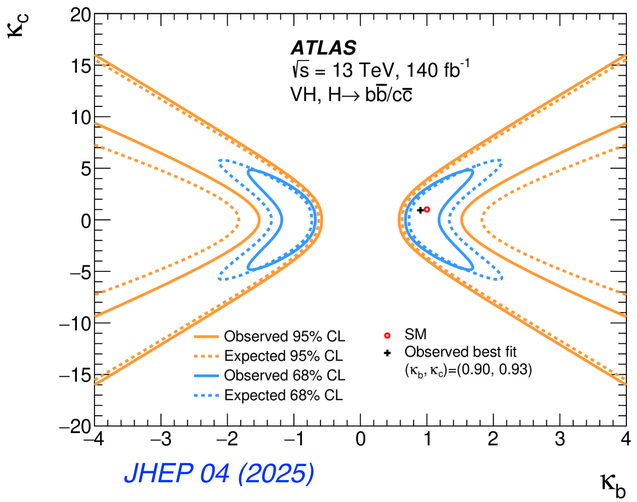
  - Do up-type quarks get their mass from the same Higgs fields as down-type quarks and charged leptons?
- **Once considered impossible at the LHC!**
- **Despite the difficulties, we are narrowing down the hunt with an combined attack from all directions**
  - **Direct:**
    - **CMS, ttH Hcc + VH cc:** $|\kappa_c| < 3.5\ (2.7)$ (95%CL)
    - **ATLAS VH cc:** $|\kappa_c| < 4.2\ (4.1)$ (95%CL)
  - **H+c :** probes by in HWW (μ(cH, HWW)<1065 , $|\kappa_c| < 211(95)$) and Hγγ: $|\kappa_c| < 38.1(72.5)$. ATLAS: xsec measurement in H+c , Hgg.
  - **H+γ:** $-4.0 < \kappa_c < 3.4$ (floating all other couplings)
  - H→ψ(nS)γ : $-166 < \kappa_c < 208$
  - Constraints from general Higgs pt differentials
- **Best so far:** $|\kappa_c| < 3.5\ (2.7)$ **(ttH+VH, CMS)**



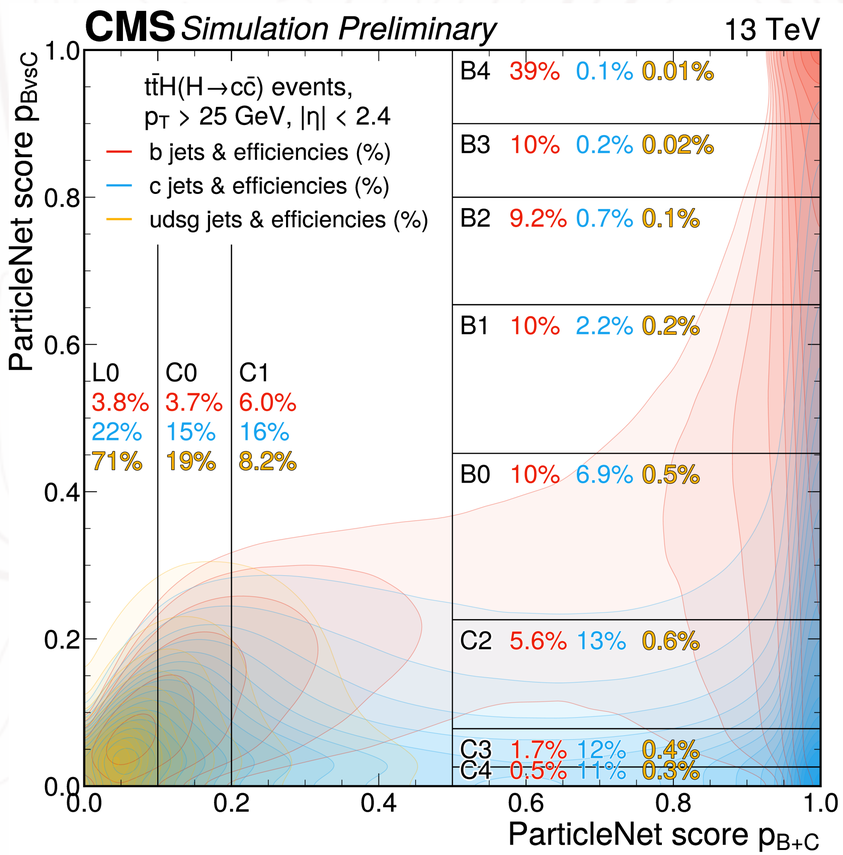


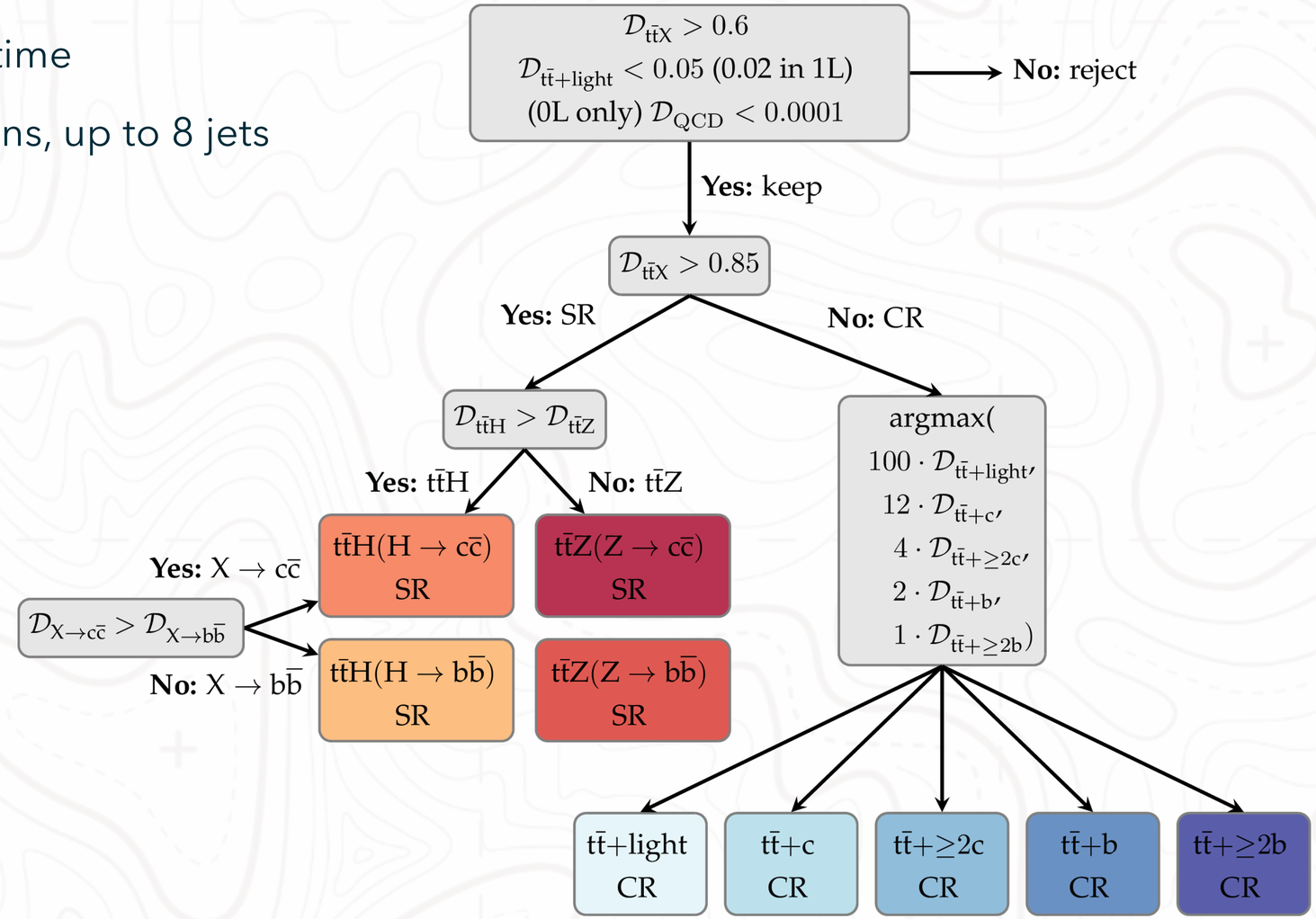


JHEP 04 (2025)

TTH, H→CC AND H→BB

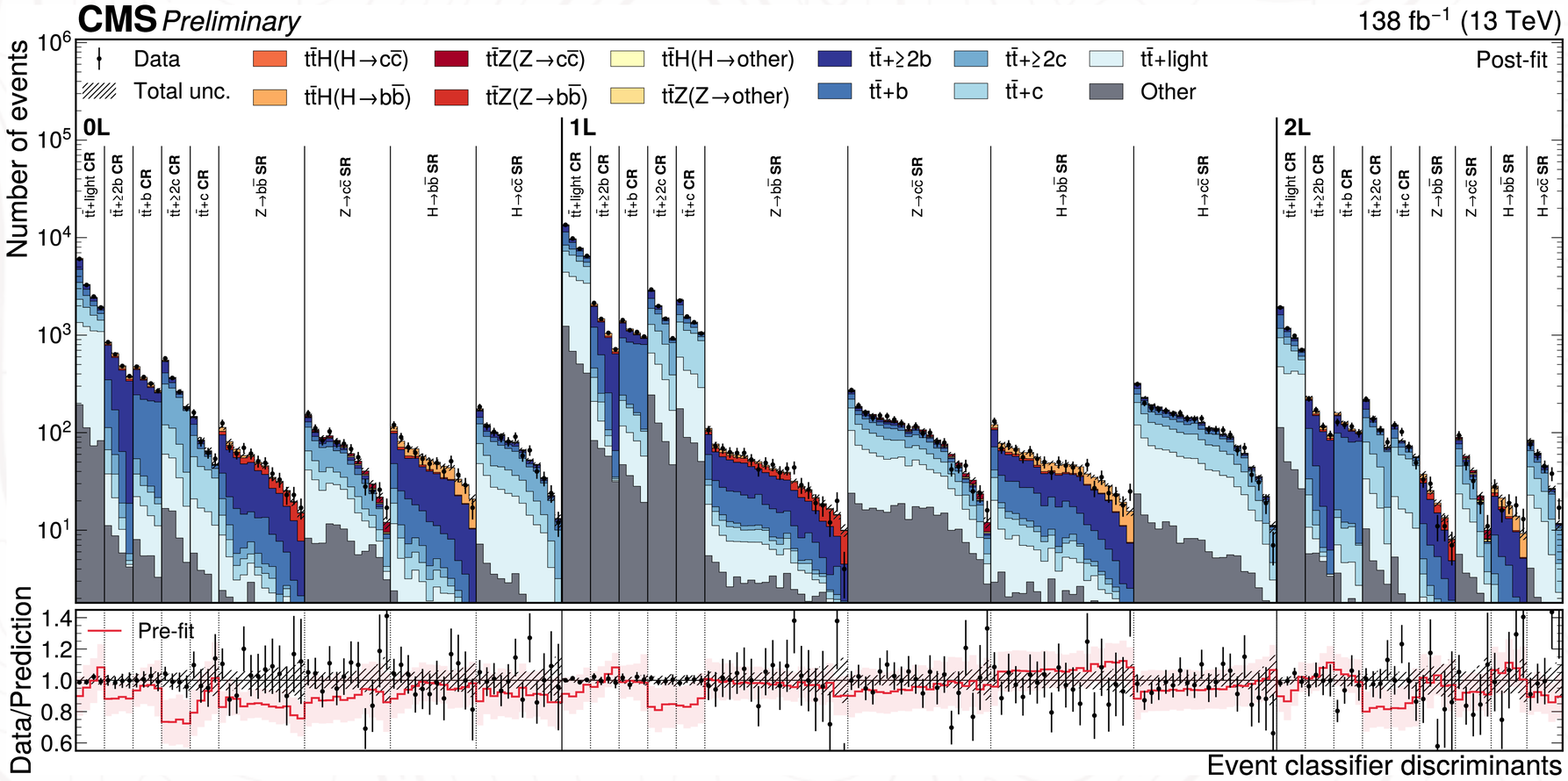
- State of the art tagger: PNet (GNN , up to 2x improvement in b-rejection wrt to previous tagger)
- Tackles ttH ttZ , cc and bb at the same time
- Very challenging final state, 0,1,2 leptons, up to 8 jets

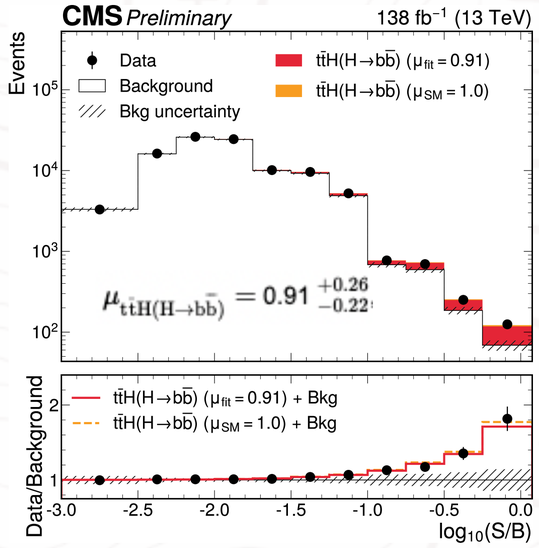


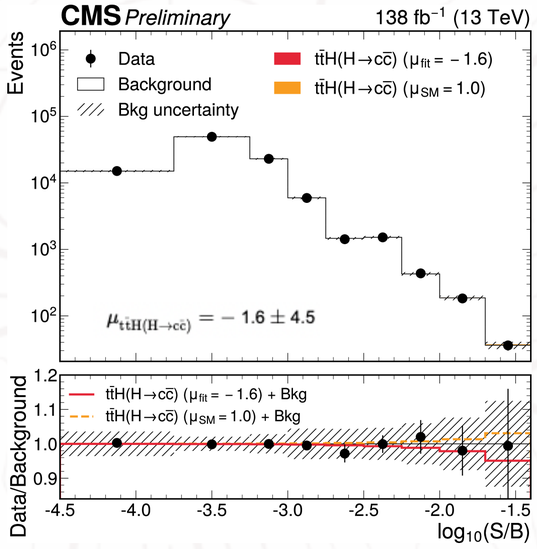


TTH, H→CC AND H→BB

- Signal strength extracted through a simultaneous fit to the discriminators targeting tt+jets, ttH Hcc, ttH Hbb, Zcc, Zbb
- Stat dominated, followed by theory uncertainty on tt+≥1c background

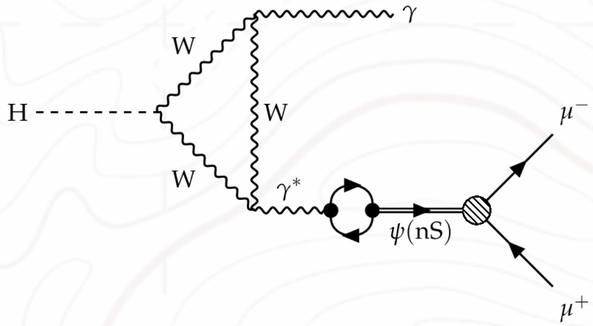


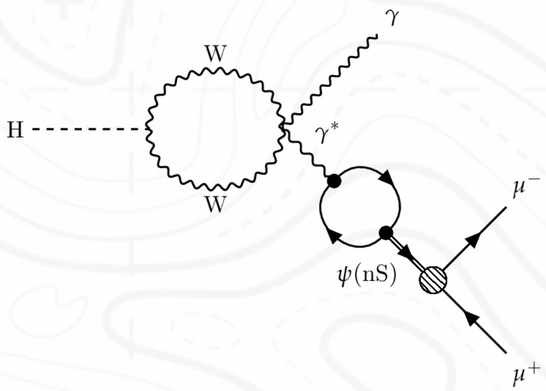


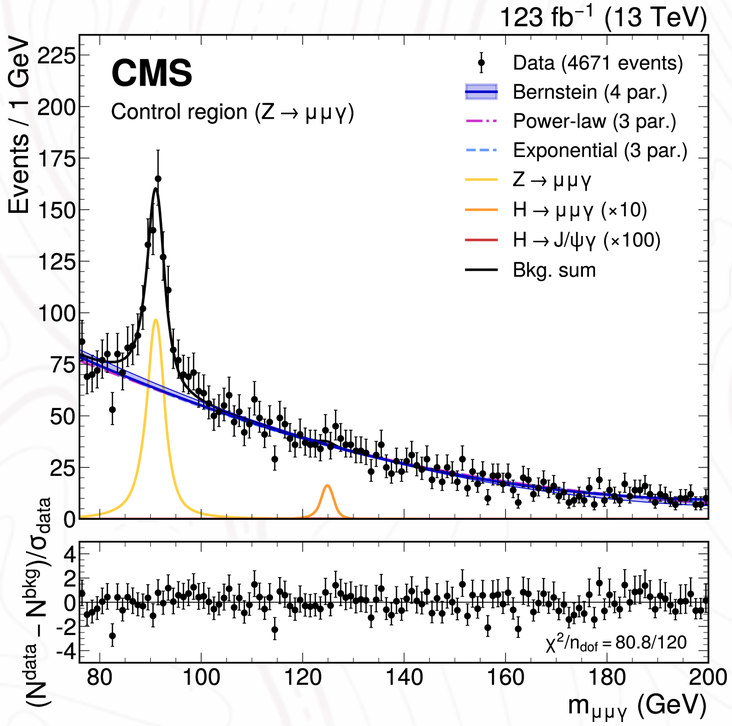


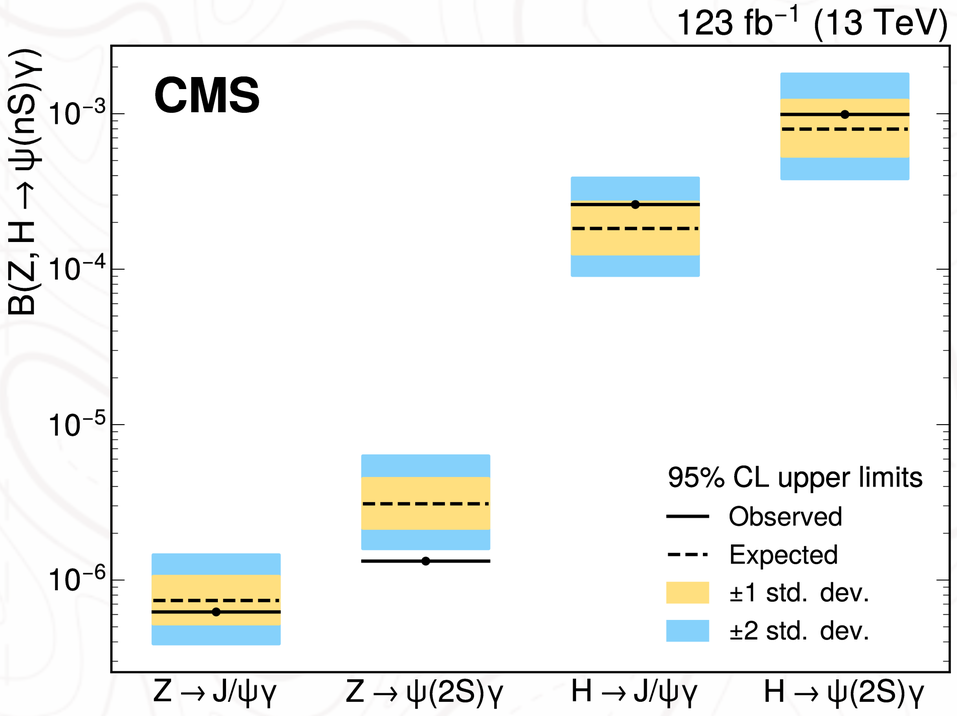
H→Ψ(nS)γ

- Rare decay study + Alternative probe of charm coupling
  - Sensitive to the sign of the coupling
- Final state. $\mu\mu\gamma$. Excellent resolution: very clean, but statistically dominated
- Study of Higgs and Z in parallel:





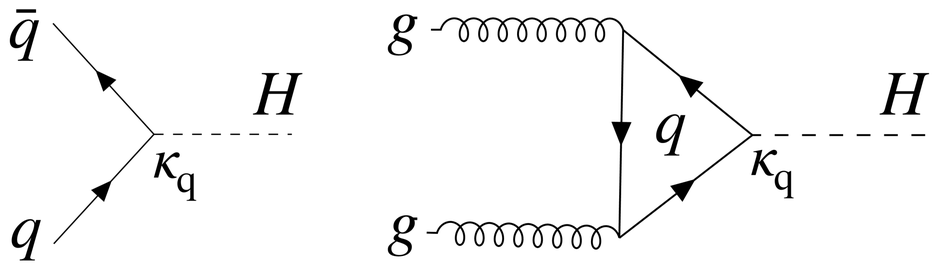


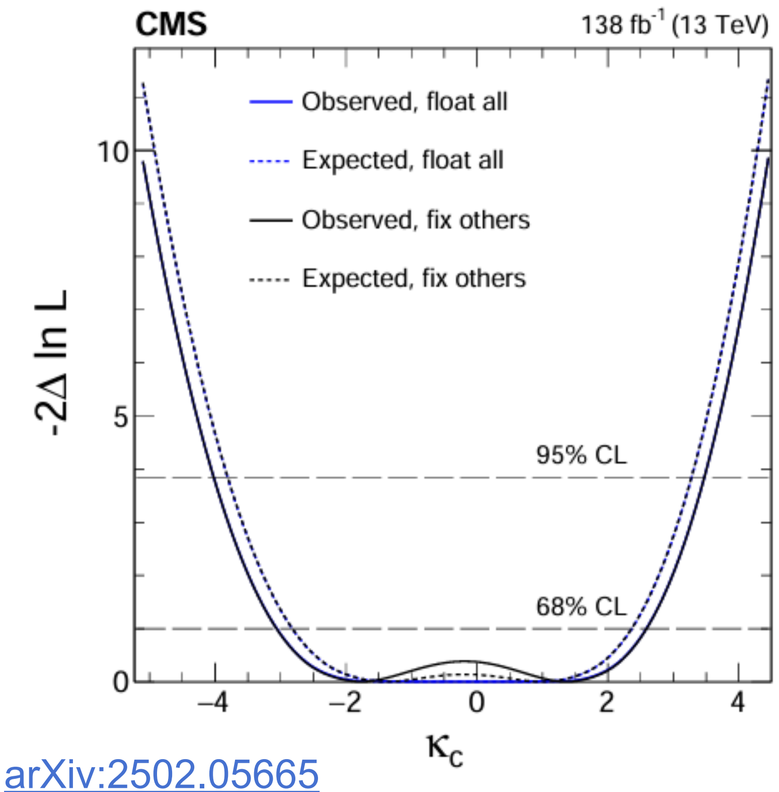


- Constraint on charm coupling: $-166 < \kappa_c < 208$

LIGHT YUKAWA CONSTRAINTS FROM 4L

- Indirect Constraints on Light Yukawa in the 4l channel
- Looking for changes in production rate (both ggF and qqH)



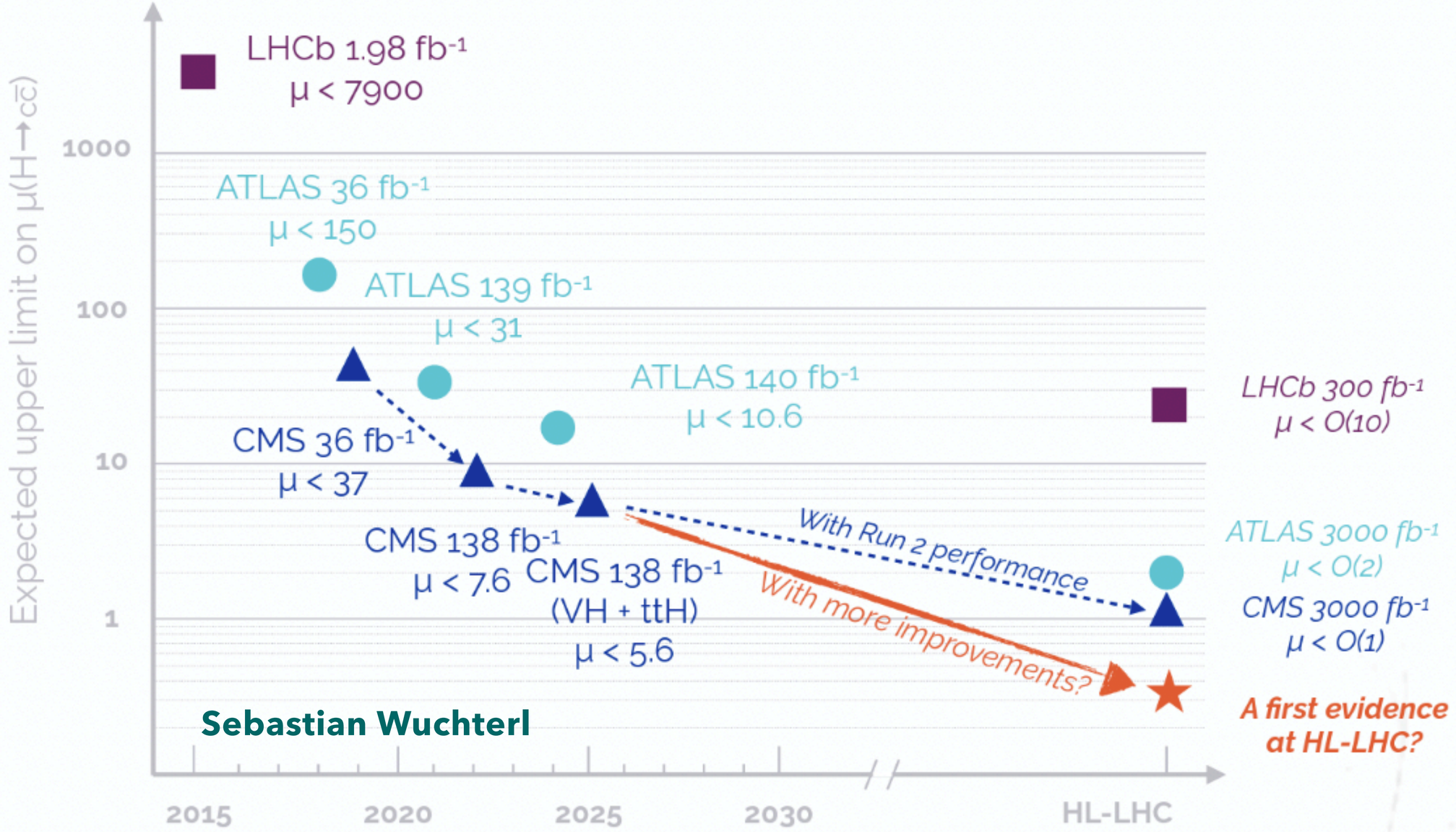


Parameter	Scenario	Observed 68% CL	Observed 95% CL	Expected 68% CL	Expected 95% CL
κ_u	float all	$(0.0 \pm 1.5) \times 10^3$	$[-2.4, 2.4] \times 10^3$	$(0.0 \pm 1.8) \times 10^3$	$[-2.6, 2.6] \times 10^3$
κ_u	fix others	$(0.0 \pm 1.4) \times 10^3$	$[-2.3, 2.3] \times 10^3$	$(0.0 \pm 1.6) \times 10^3$	$[-2.5, 2.5] \times 10^3$
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

arXiv:2502.05665

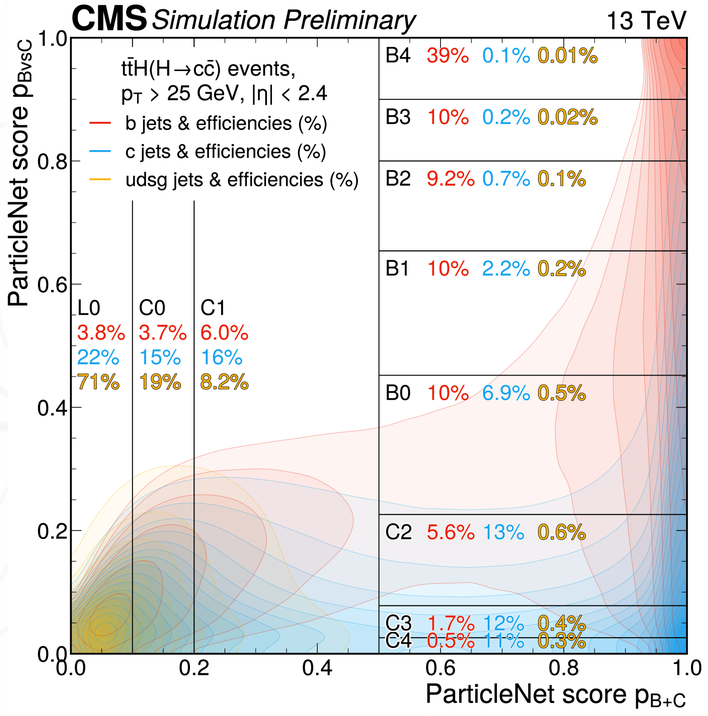
(Top and bottom yukawas constrained to SM, |k VV| ≤ 1)

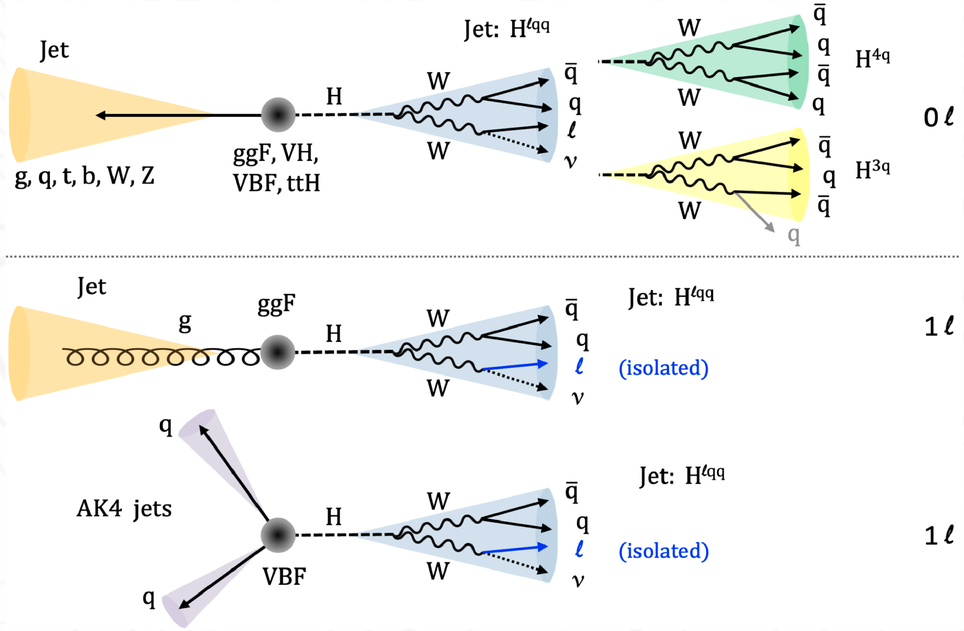
MAKING THE IMPOSSIBLE POSSIBLE

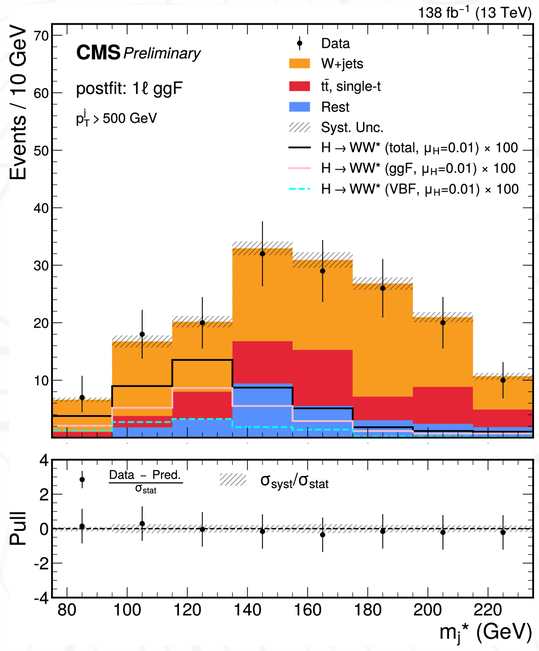


BOOSTED REGIMES AND ML TOOLS

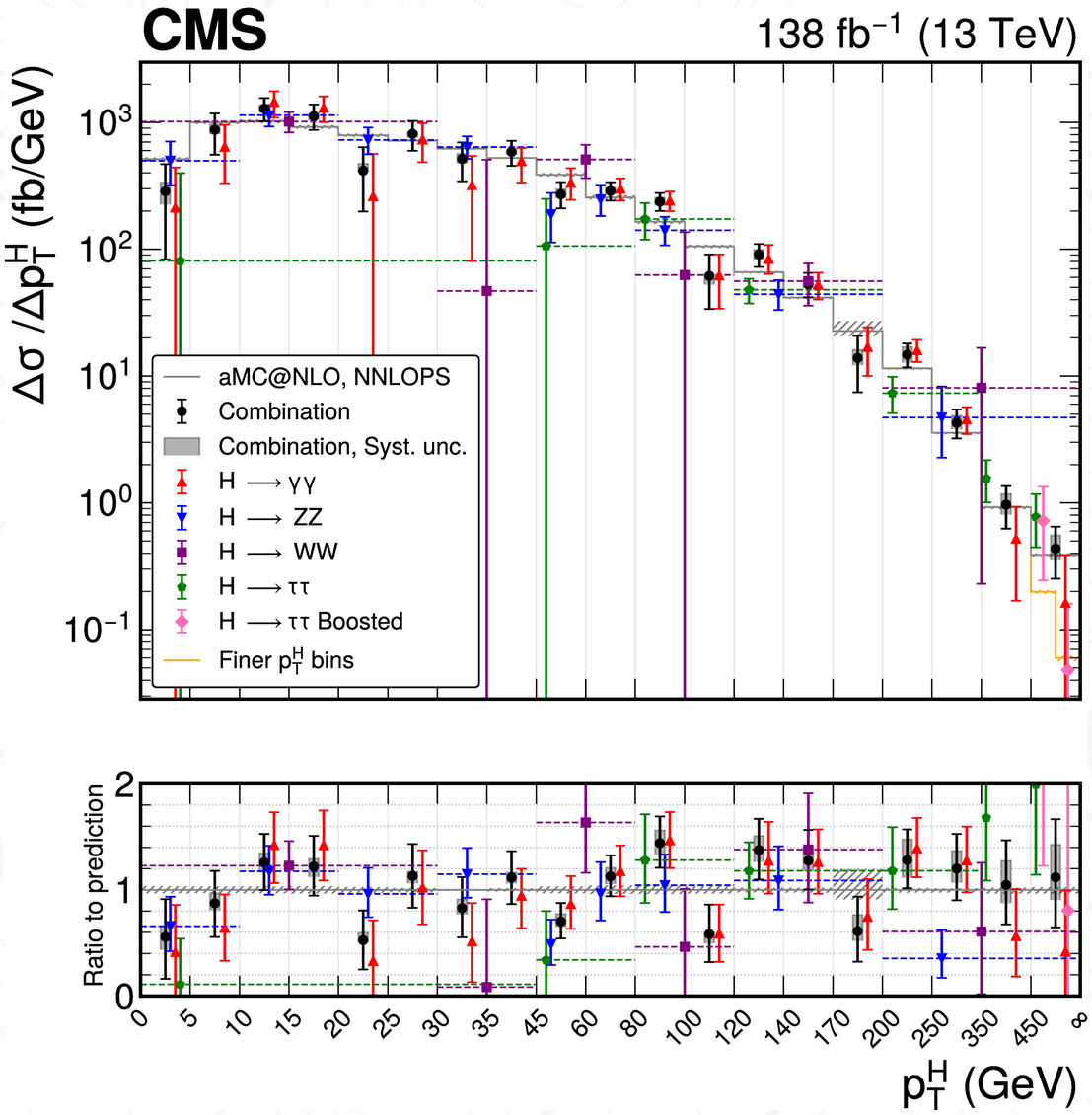
- **The constant improvement in ML techniques have revolutionized the study of the high p_T phase space and continue to advance.**
  - The revolution in Hcc in recent years comes from development of innovative algorithms - tagging and selection.
  - But that is not all! Hbb, Htautau, HWW… Expect more in the future. Examples:
    - 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. $\mu_H = 0.01^{+0.63}_{-0.48}$

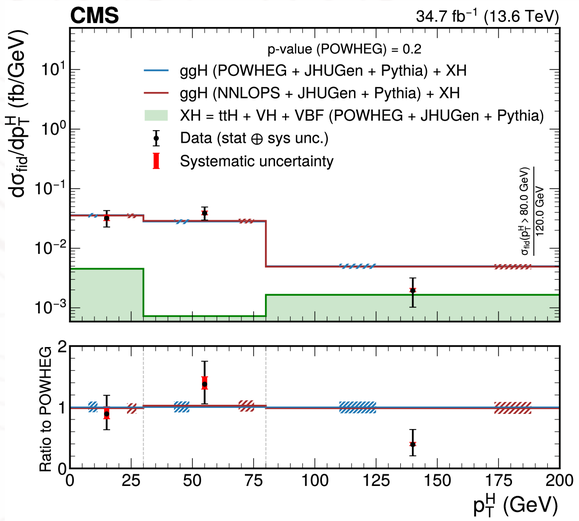


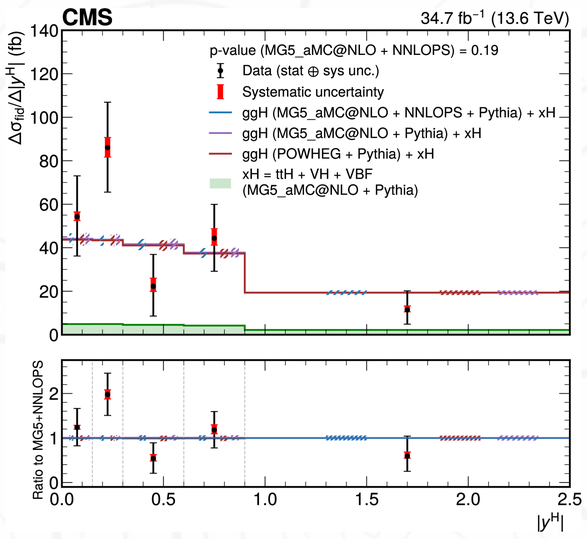




DIFFERENTIAL CROSS SECTIONS

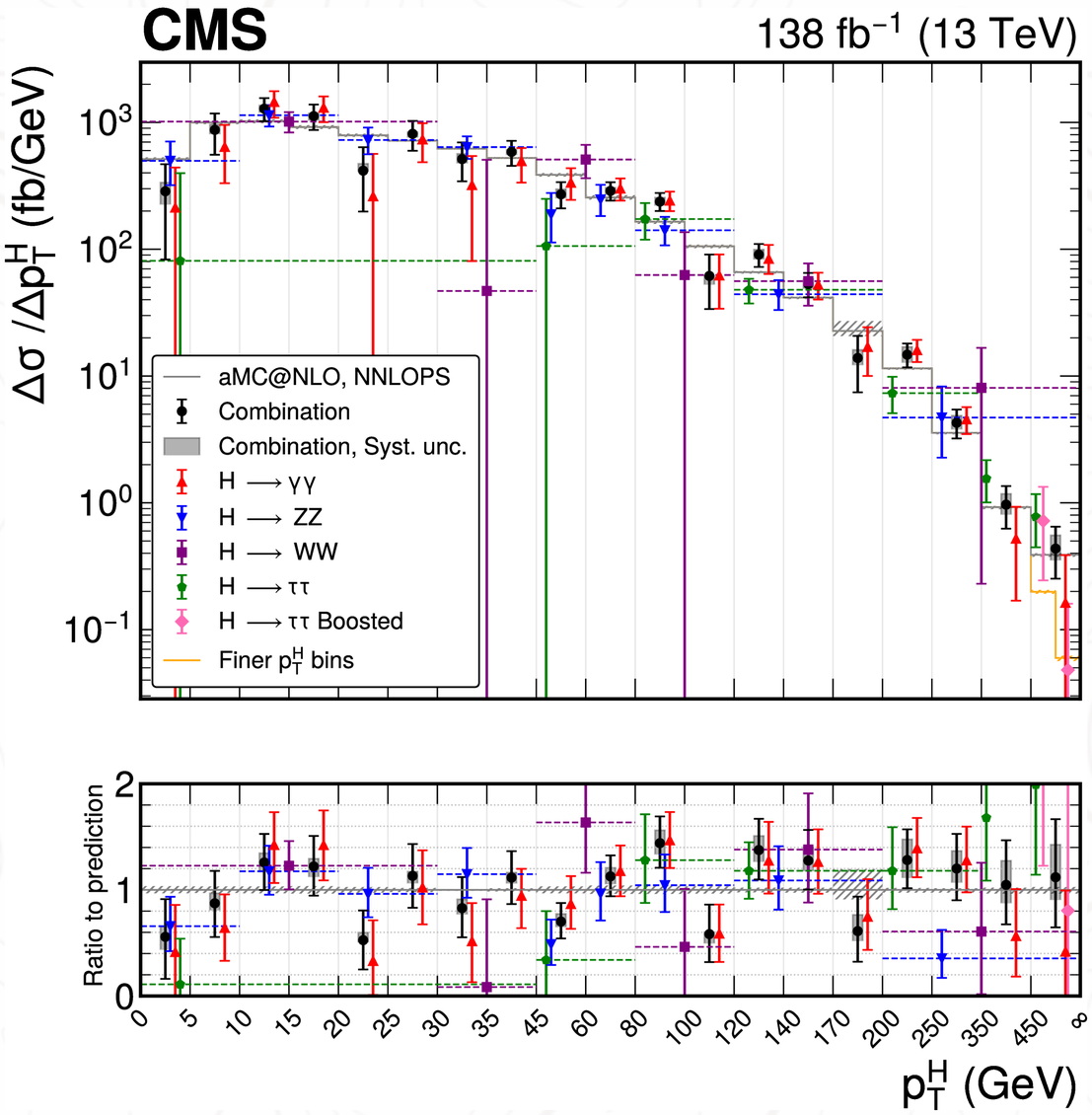


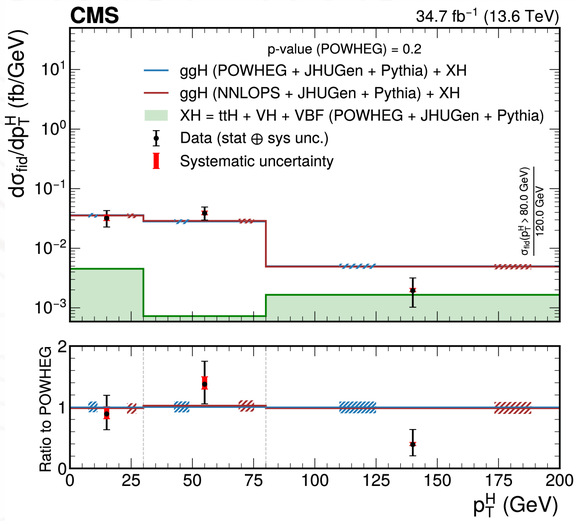


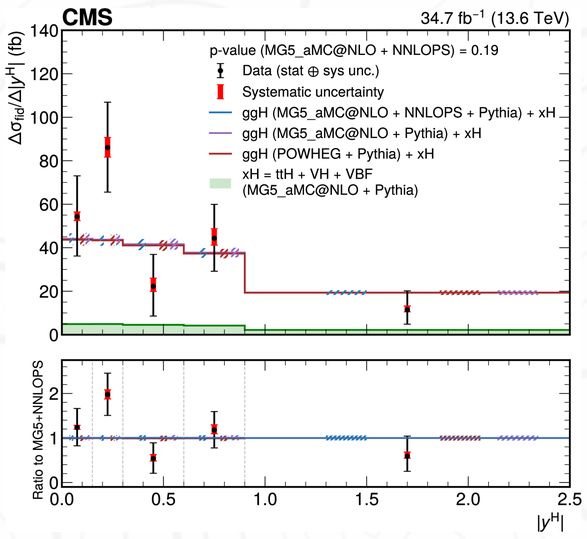


DIFFERENTIAL CROSS SECTIONS

- CMS Run2 combination of differential distributions (ZZ,WW,$\gamma\gamma$, $\tau\tau$). Many variables probed (pT, angular correlations, event topology…)
- First Run3 results in 4l and diphoton

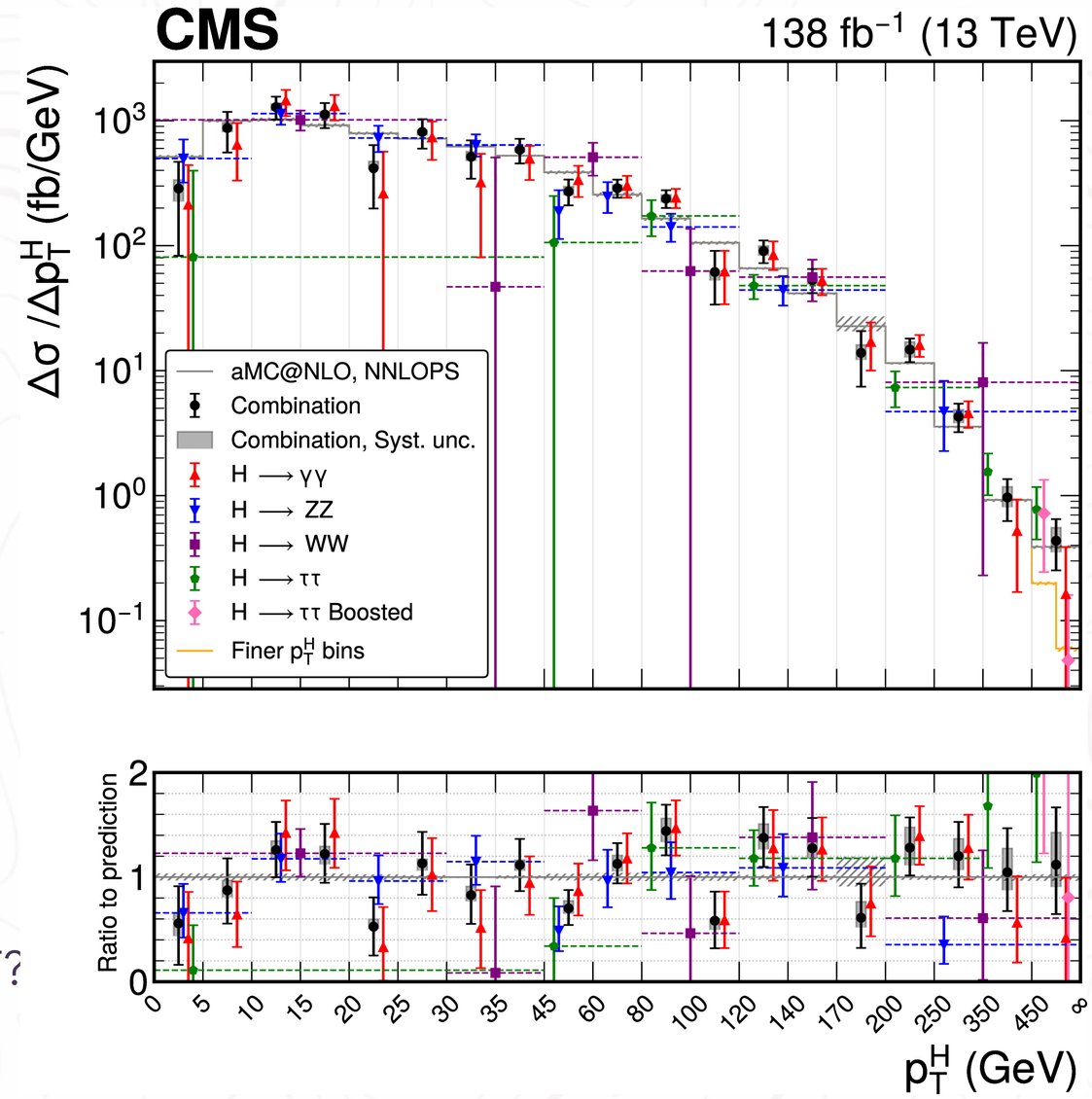


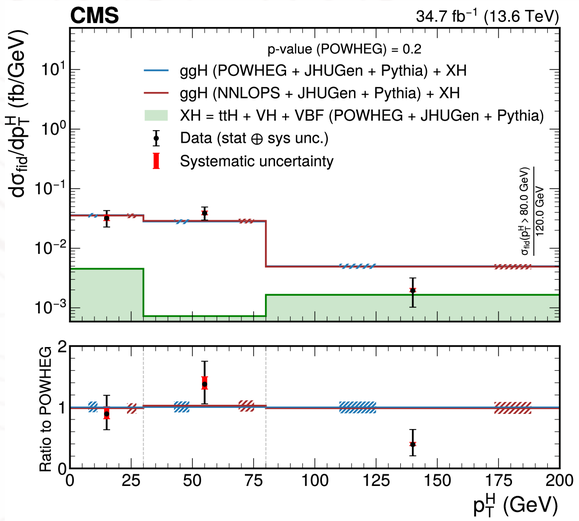


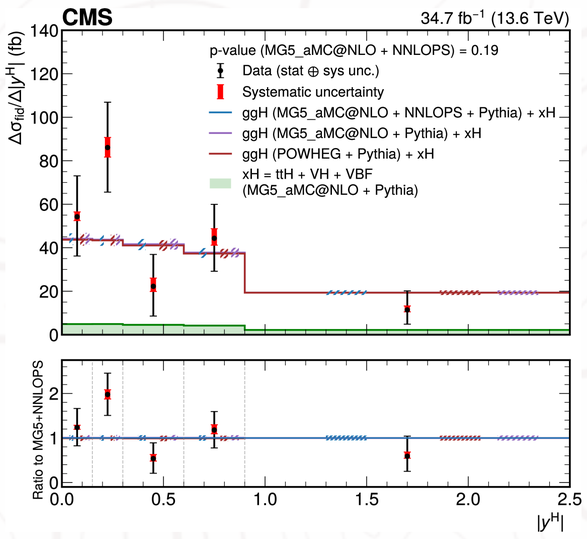


DIFFERENTIAL CROSS SECTIONS

- CMS Run2 combination of differential distributions (ZZ,WW,$\gamma\gamma$, $\tau\tau$). Many variables probed (pT, angular correlations, event topology…)
- First Run3 results in 4l and diphoton
- **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

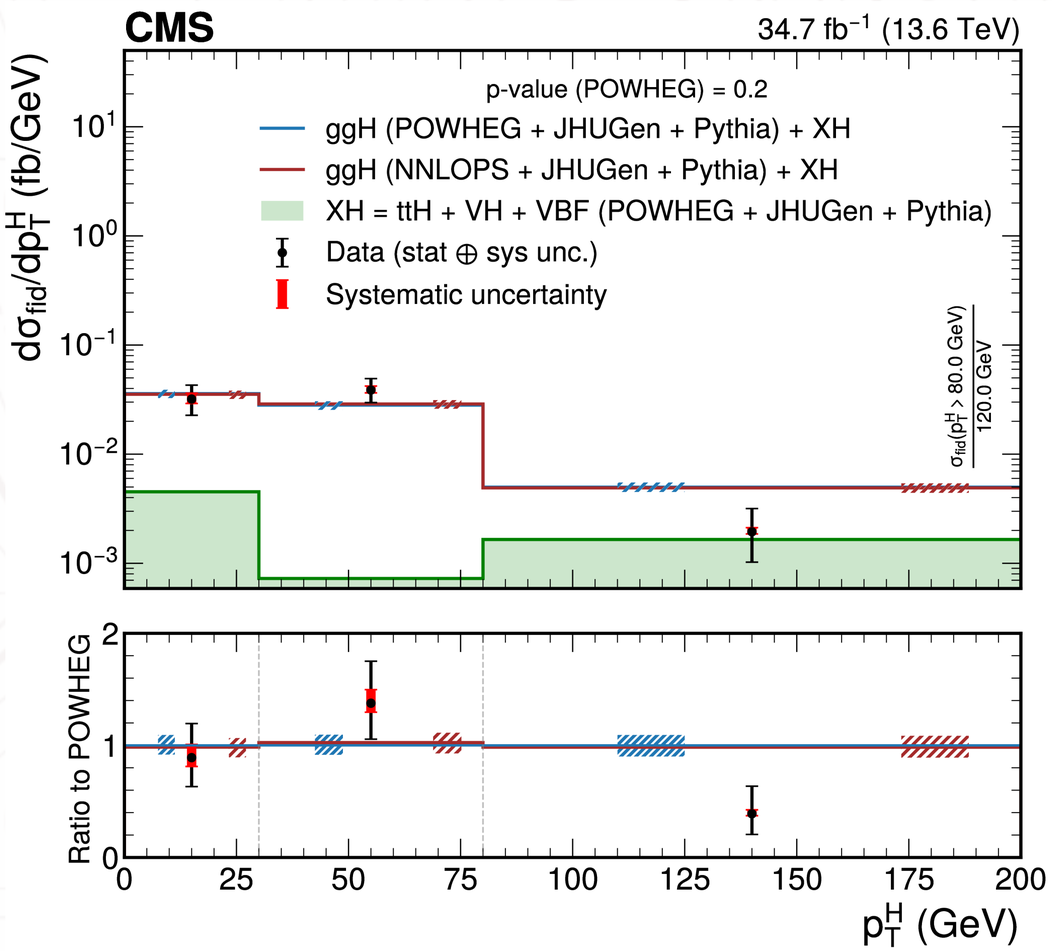


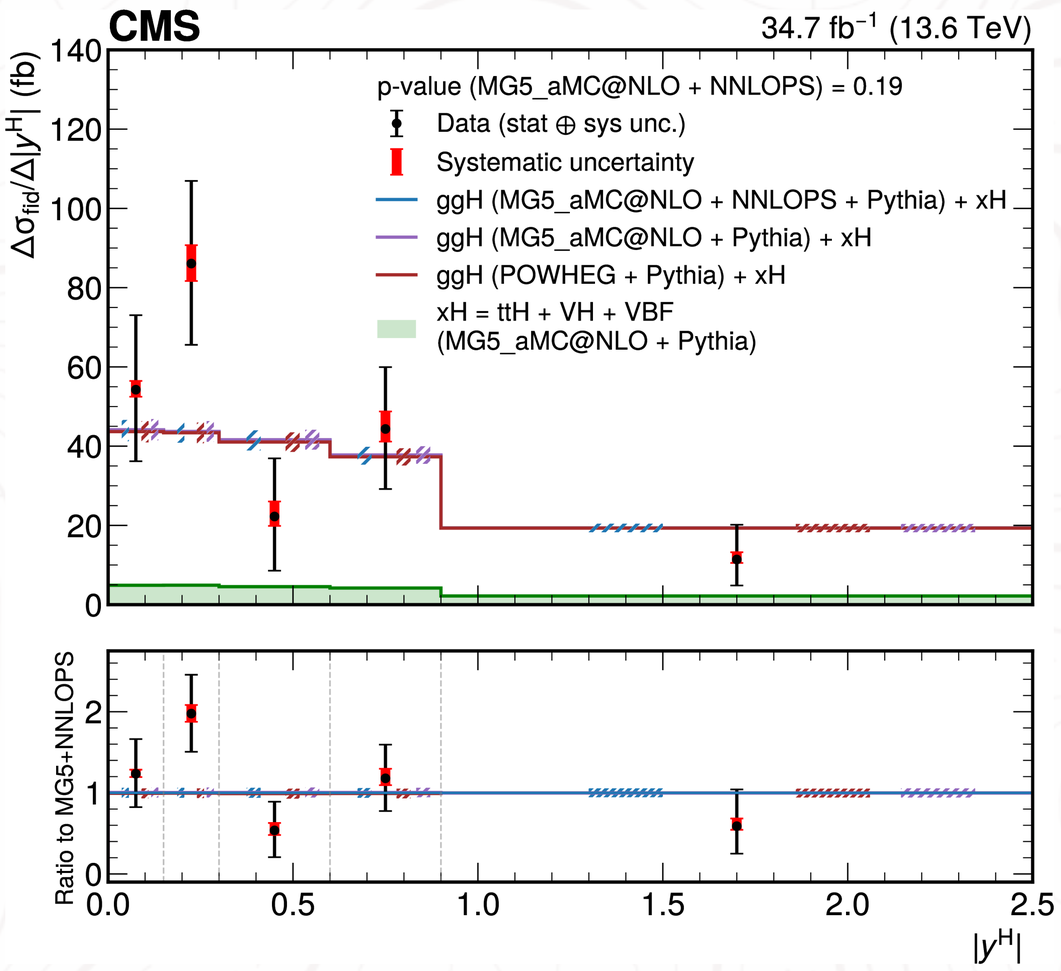




DIFFERENTIALS AT 13.6 TEV

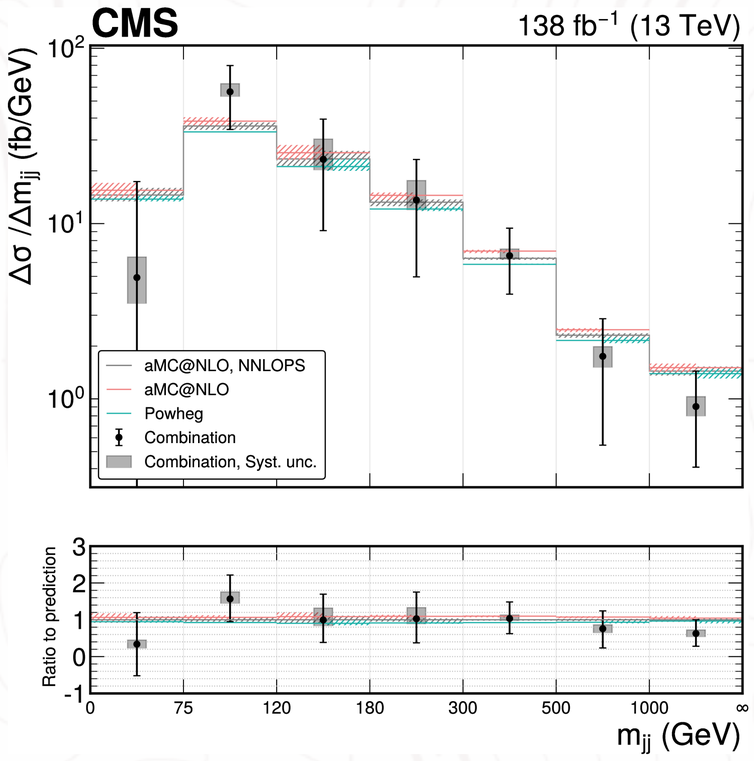
- HZZ (JHEP 05 (2025) 079): Differential p_T^H , y_H
- $H\gamma\gamma$ (arXiv:2504.17755): Differential p_T^H , y_H , N_{Jets}, p_T lead jet

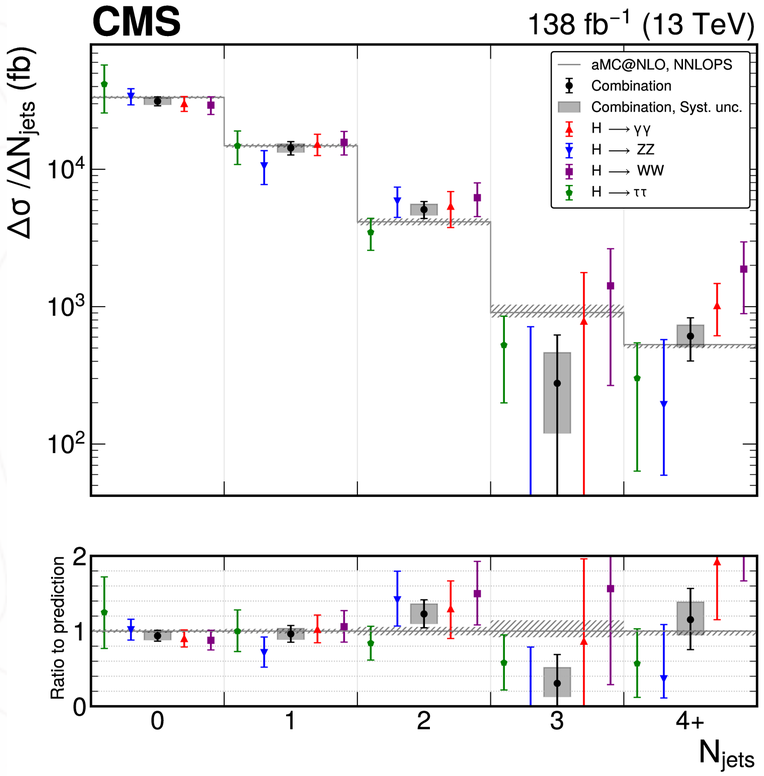


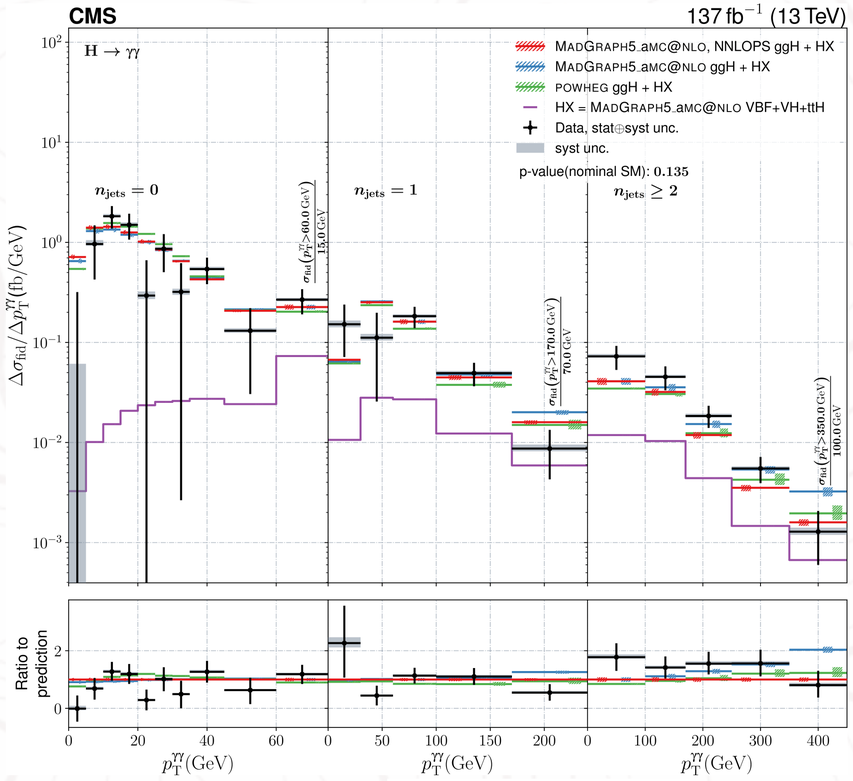


NOT ONLY P_T...

- Many variables probed: pt, eta of the products or of the Higgs, number of jets in the event and other global topological variables, angular correlations…)
- Besides the combination, the individual channels have even more variables (and in some cases double differentials)





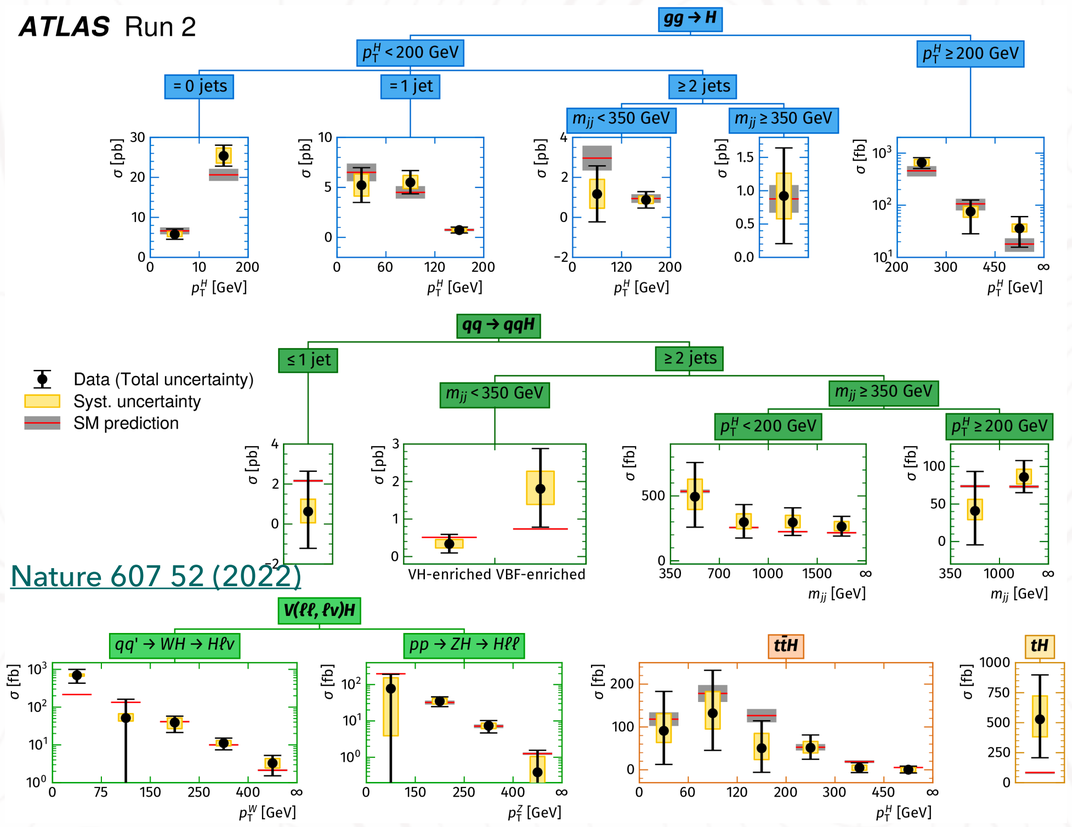


arXiv:2504.13081

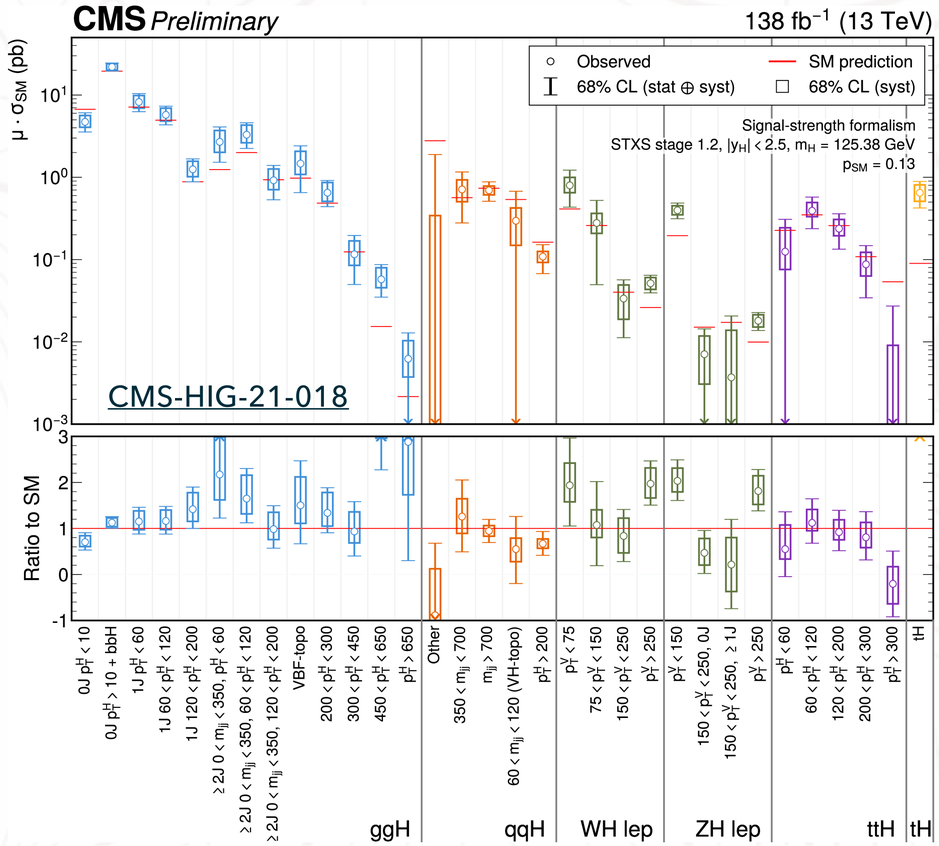
JHEP 07 (2023) 091

SIMPLIFIED TEMPLATE CROSS SECTIONS

- "Simplified Template Cross Sections" approach: Measure cross sections separated into production modes, inclusively over the Higgs decays, in specific regions of phase-space ("bins"), defined in terms of specific kinematic variables (p_T^H, m_{jj}, p_T^{Hjj}, p_T^V)
- Largely model-independent way to test for BSM deviations in kinematic distributions.



Nature 607 52 (2022)



PRECISION IN HIGGS COUPLINGS

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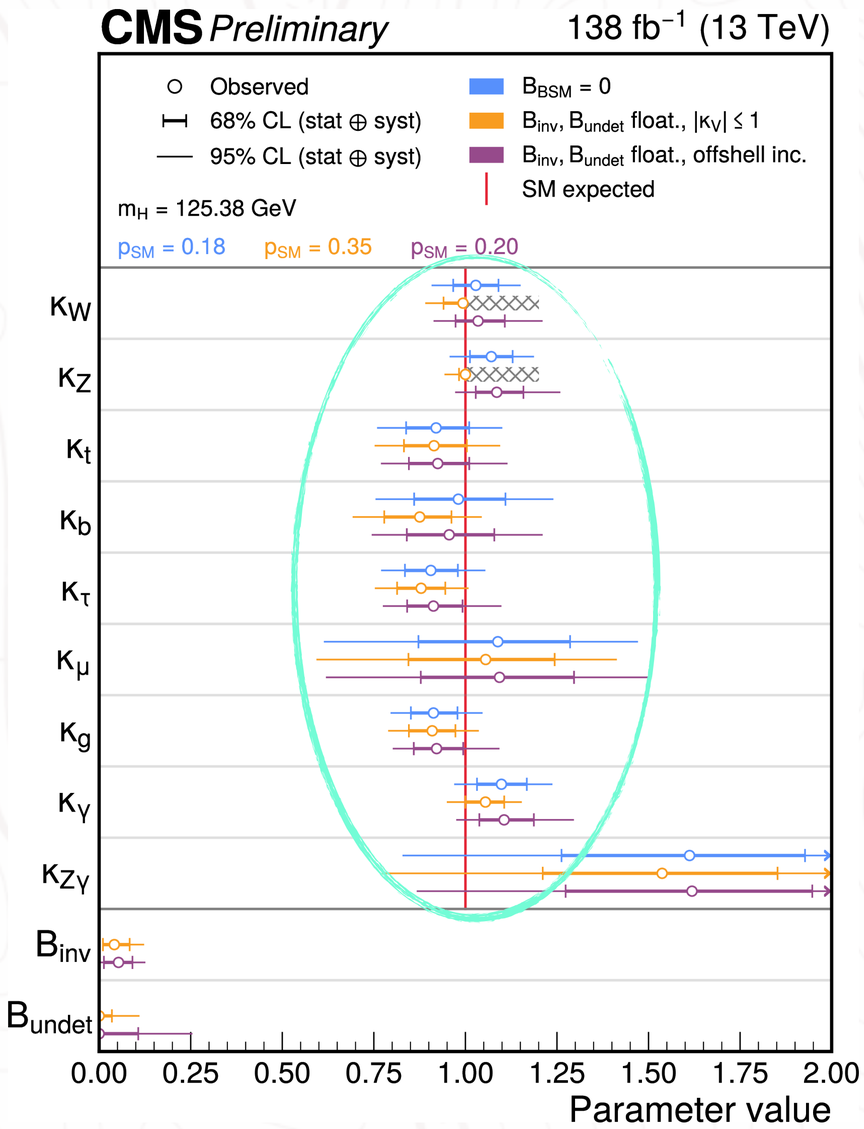

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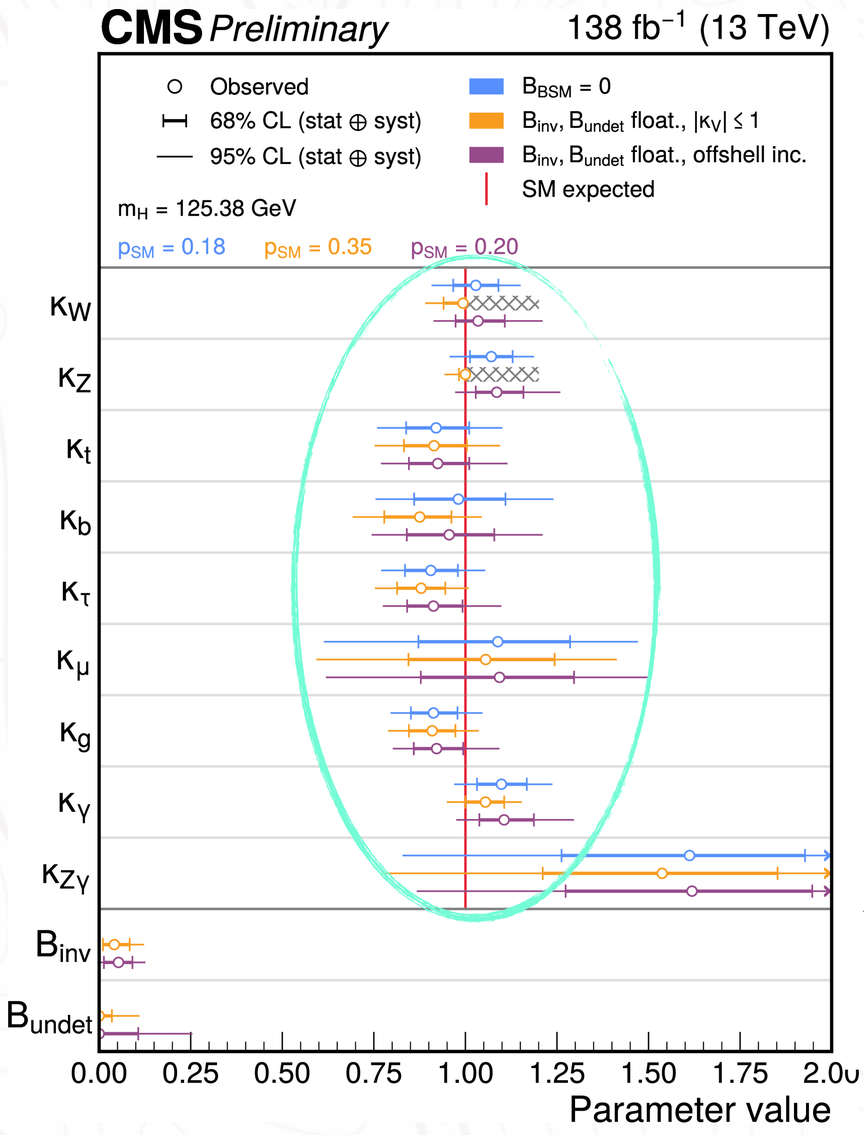
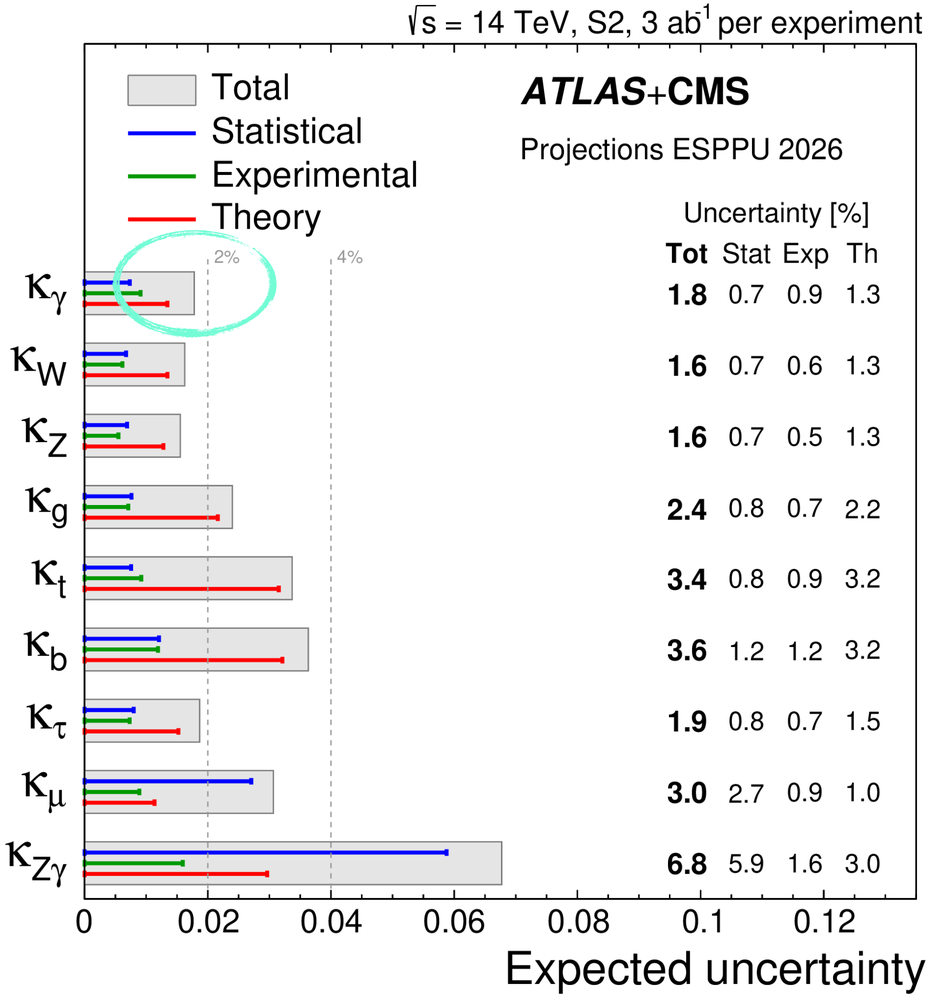
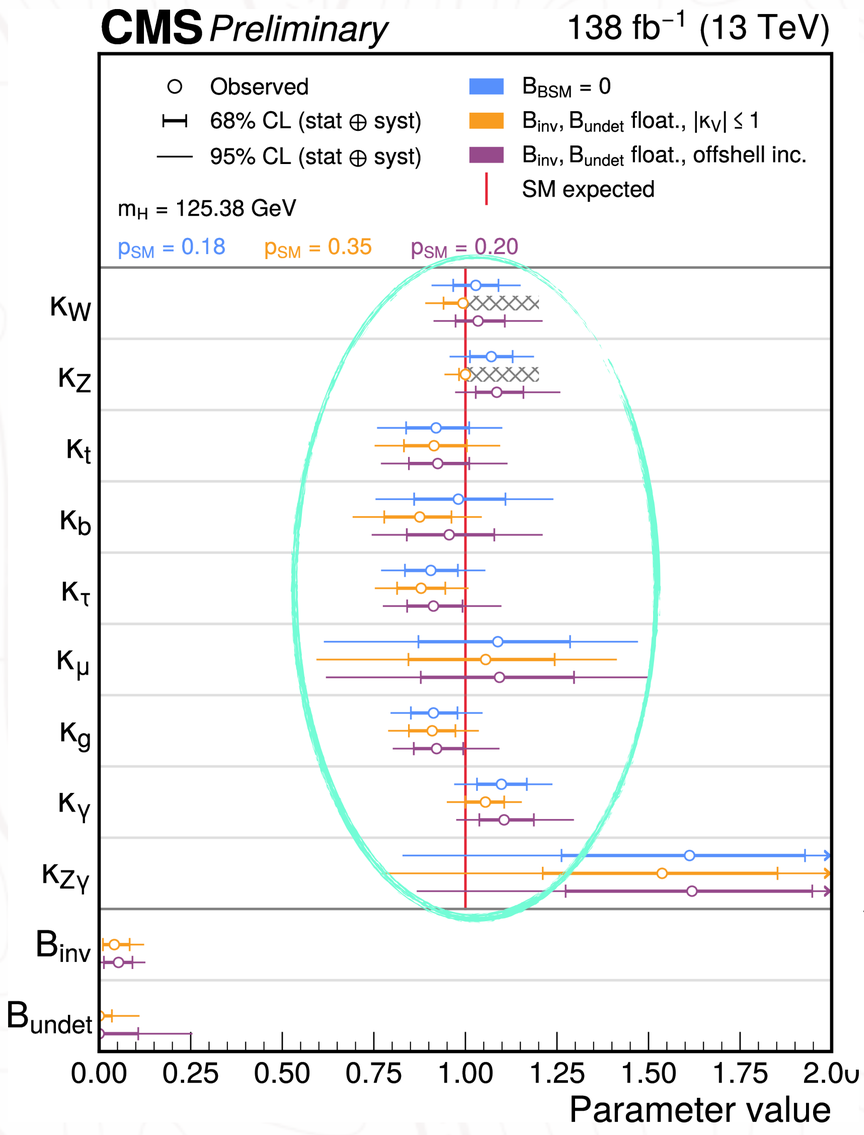
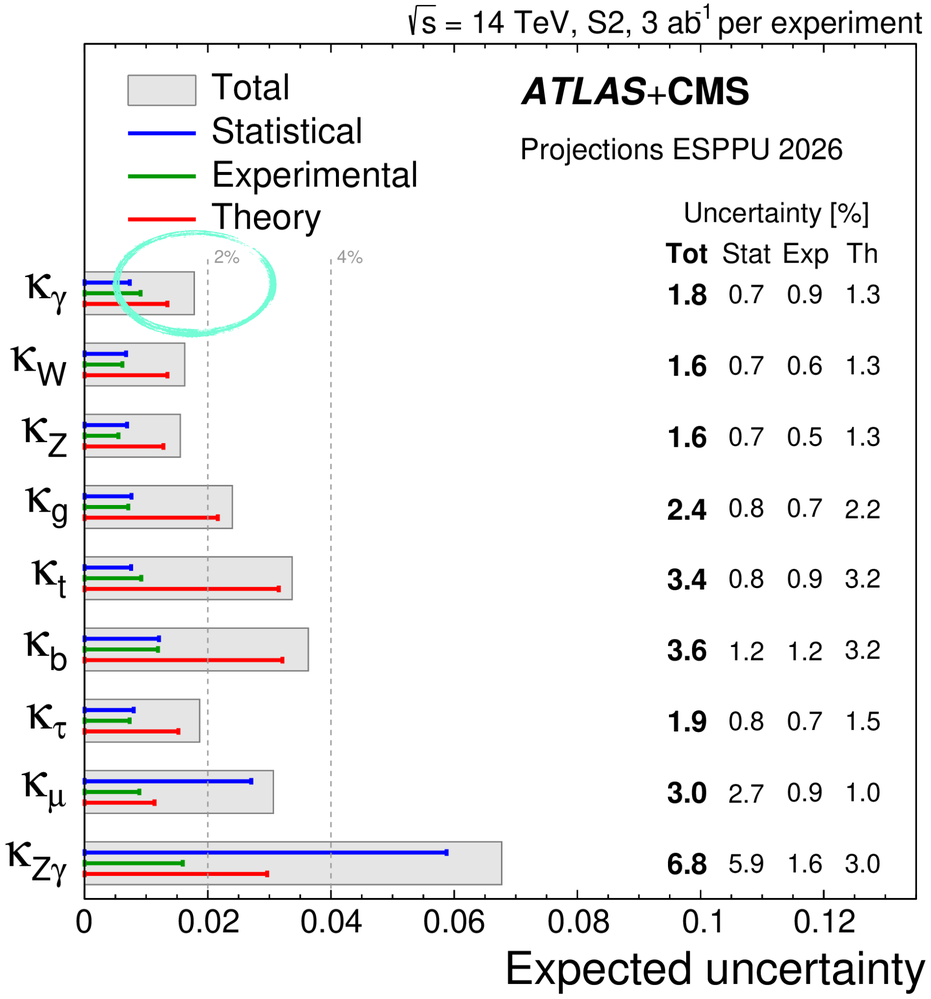




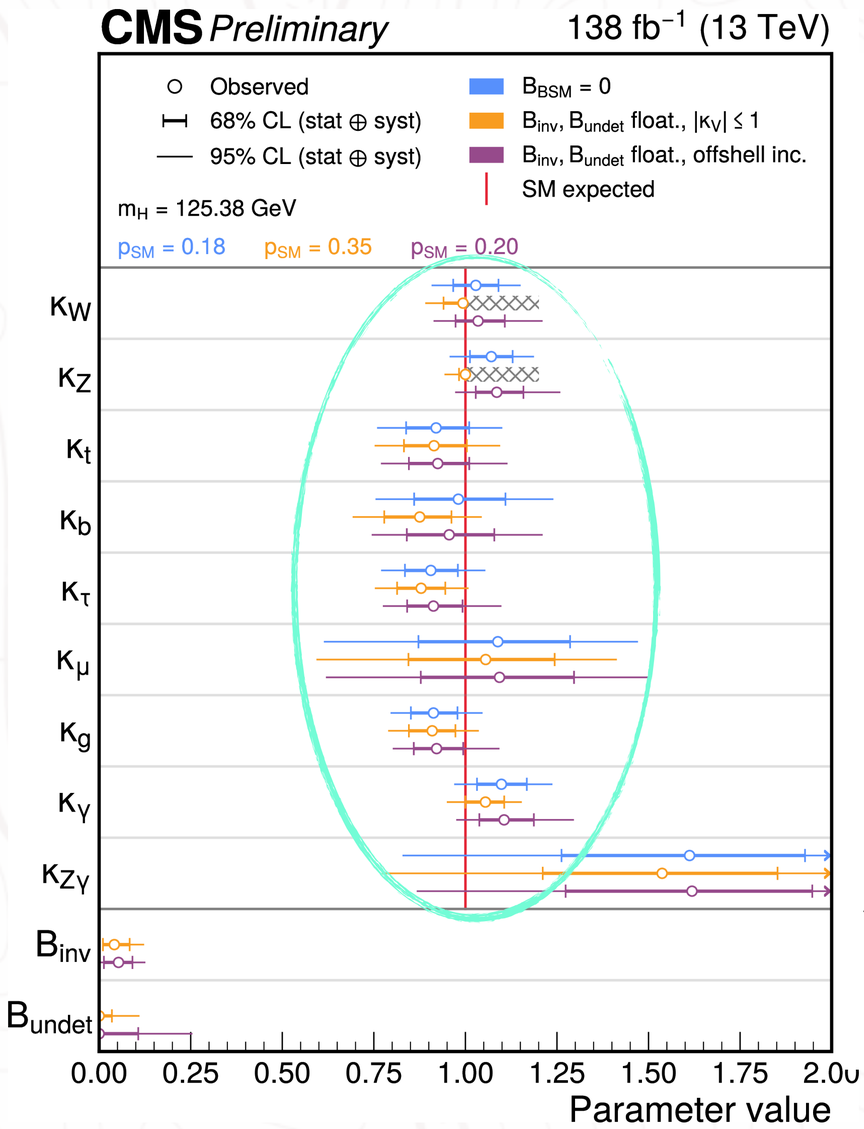
PRECISION IN HIGGS COUPLINGS

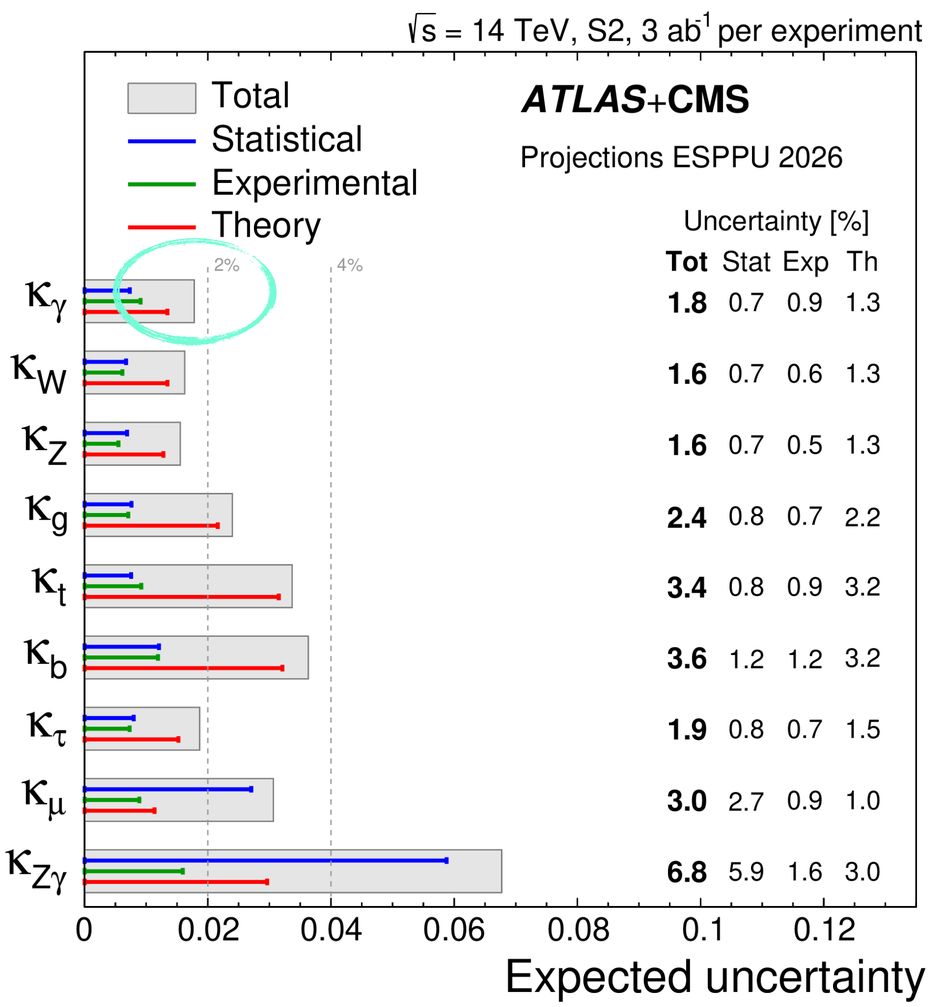


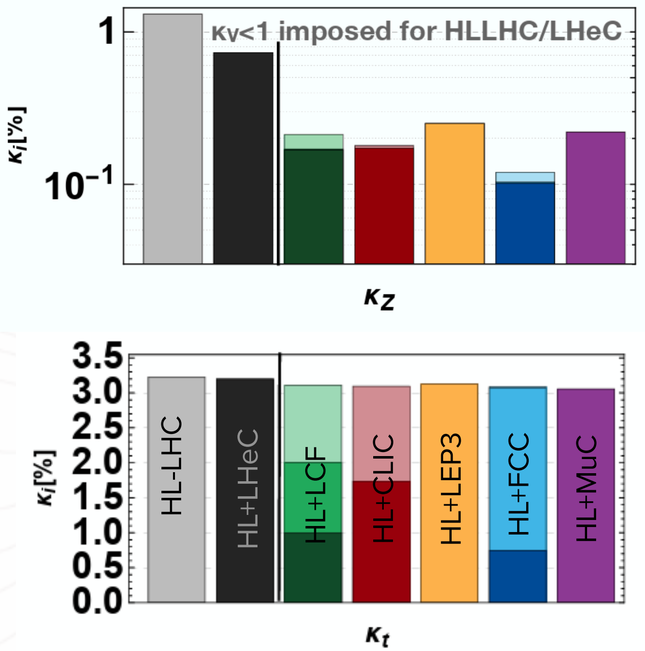


Experimental challenge: improve our measurements.
Theoretical challenge: improve the predictions!

PRECISION IN HIGGS COUPLINGS





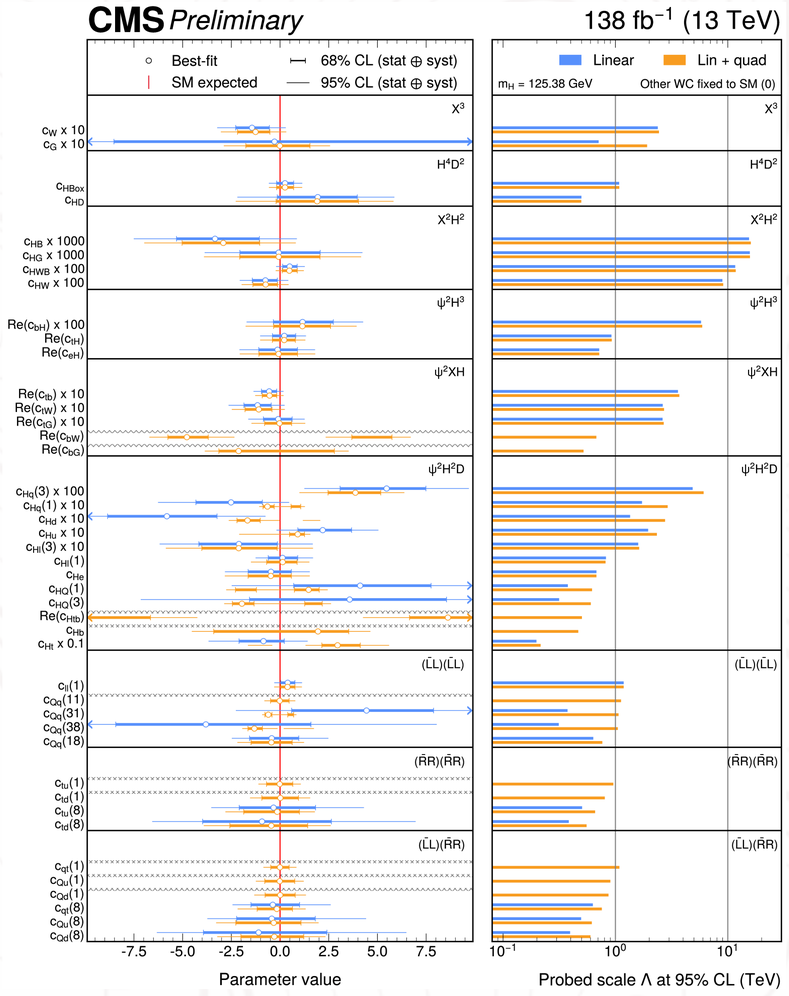


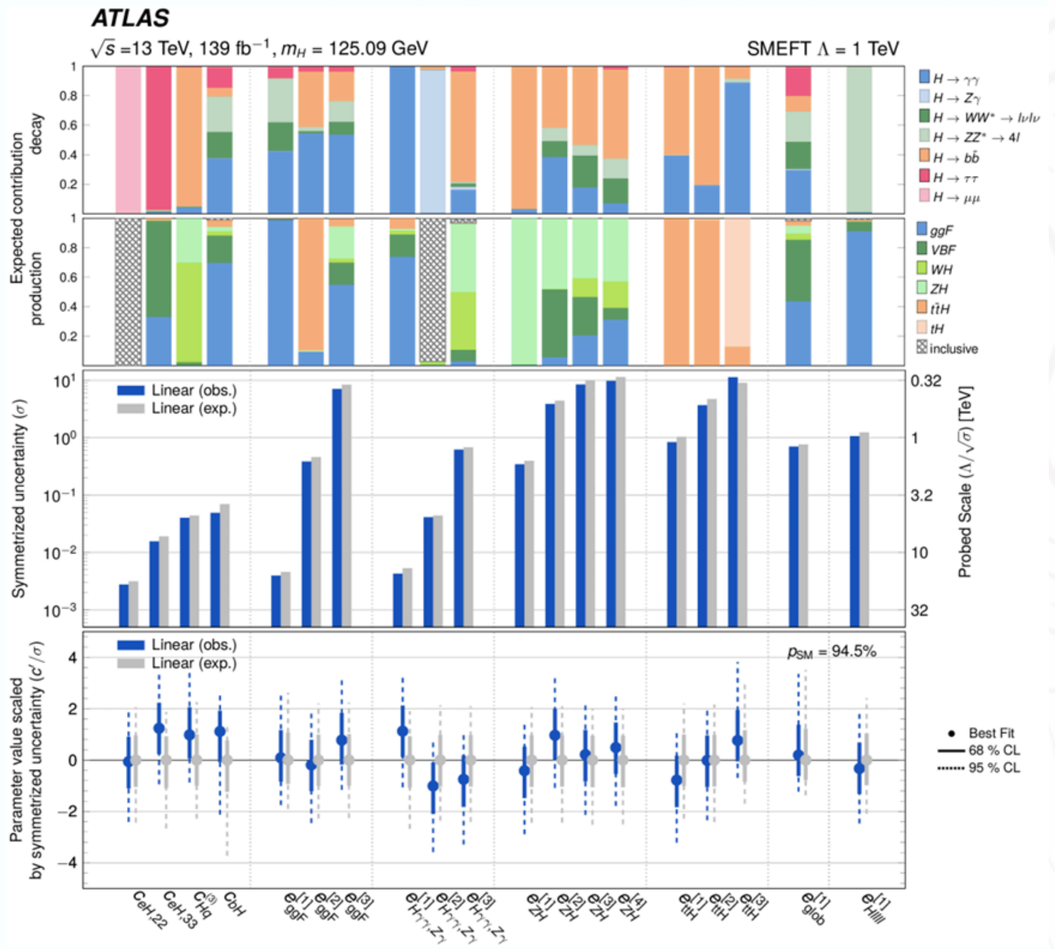
(Projections From Venice Symposium)

Experimental challenge: improve our measurements.
Theoretical challenge: improve the predictions!

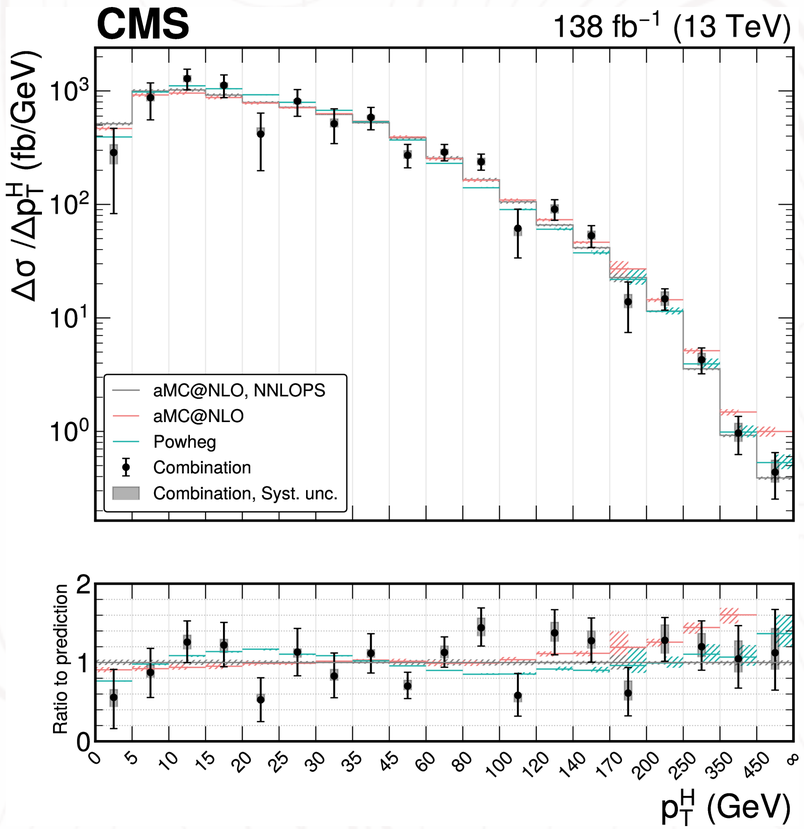
BEYOND KAPPAS: SMEFT FITS

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



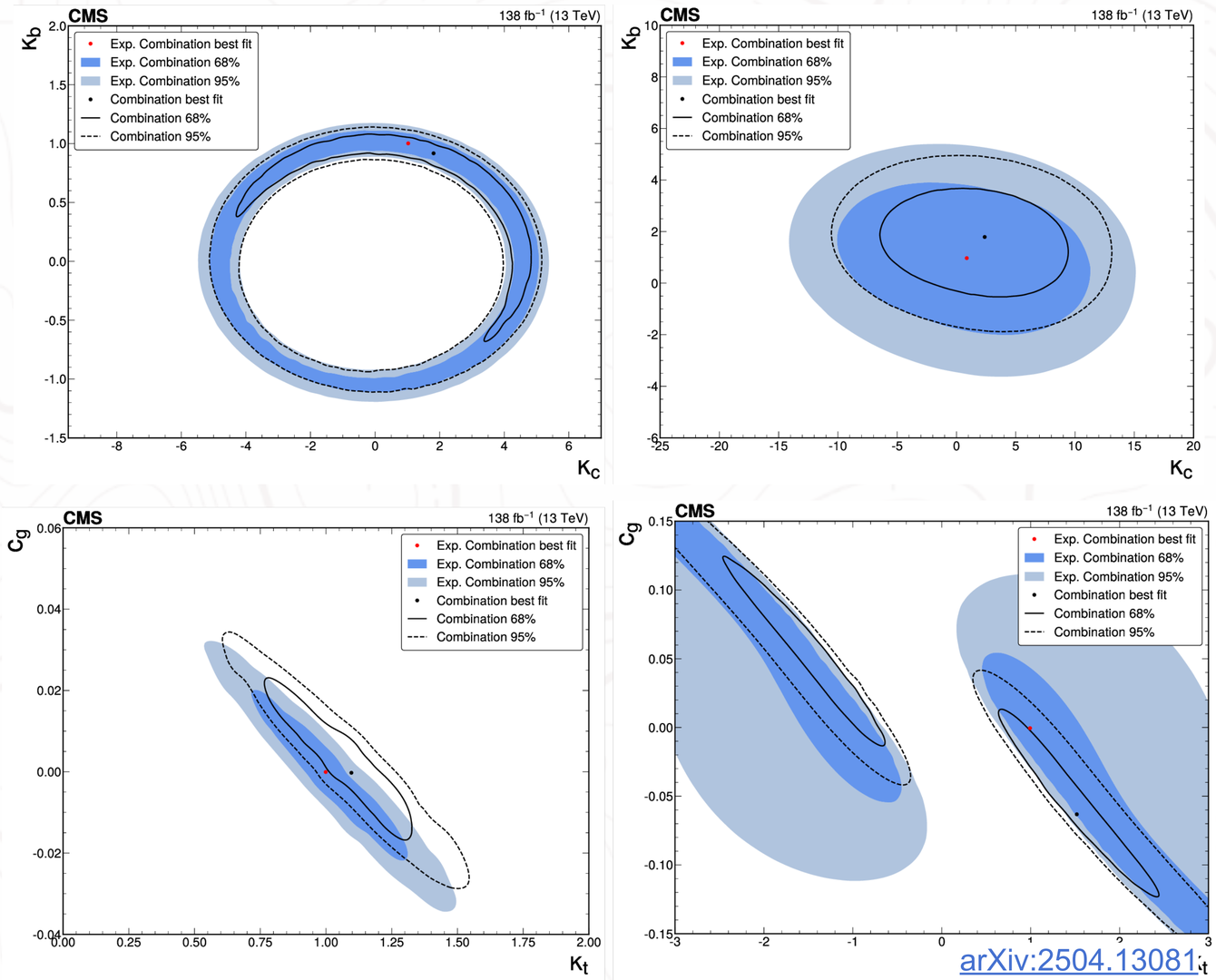


CONSTRAINTS FROM DIFFERENTIALS



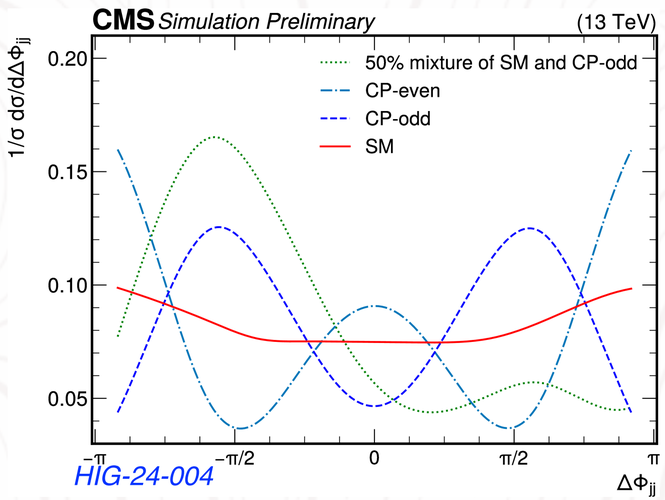
Assuming coupling dependence of the branching fractions

Branching ratios are nuisance parameters



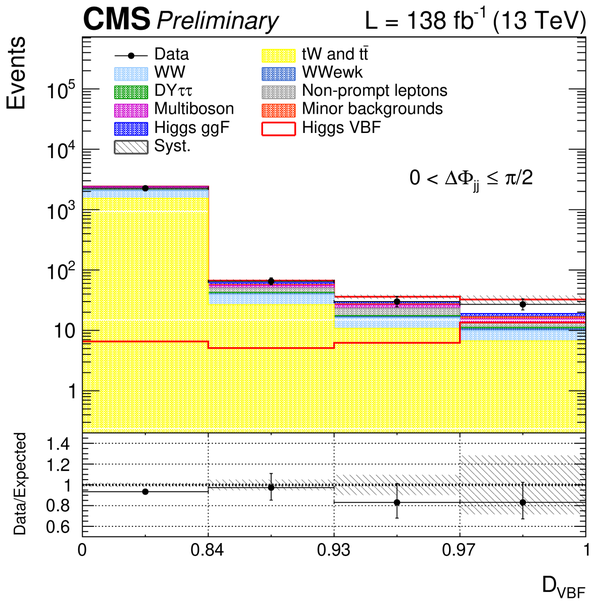
arXiv:2504.13081

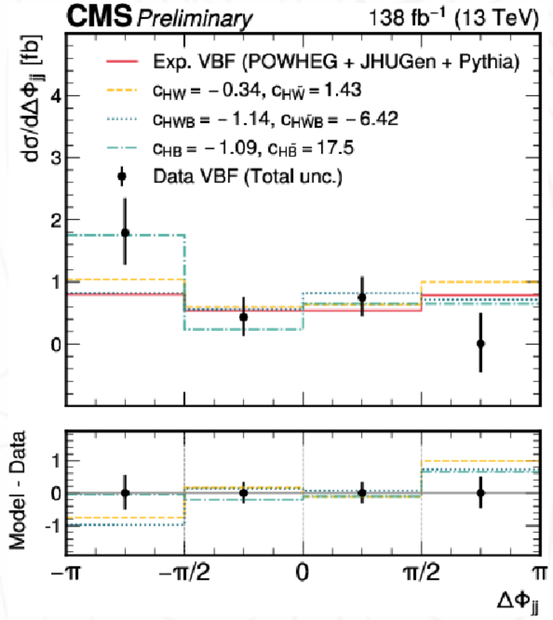
EXAMPLE: DIFFERENTIAL VBF HWW PRODUCTION

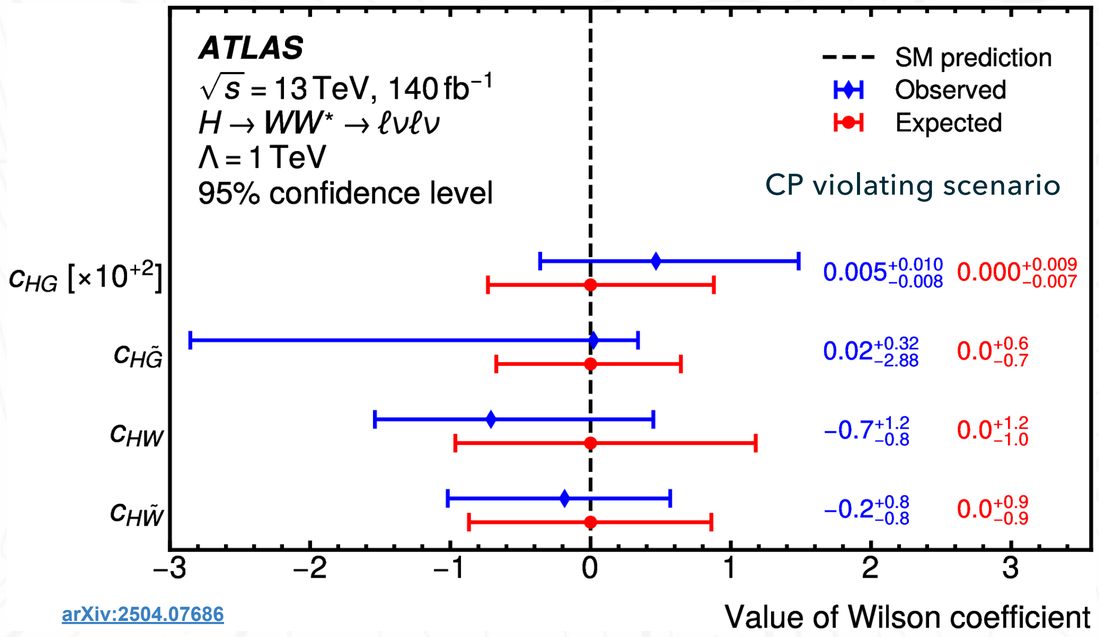


HIG-24-004

- **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





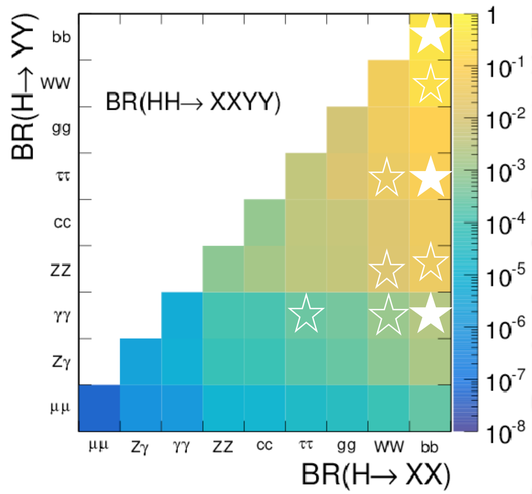


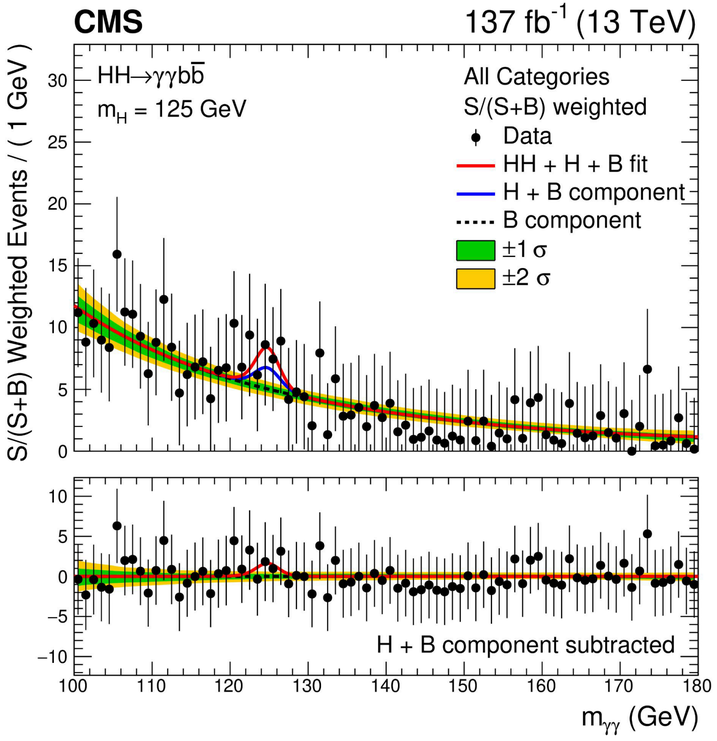
arXiv:2504.07686

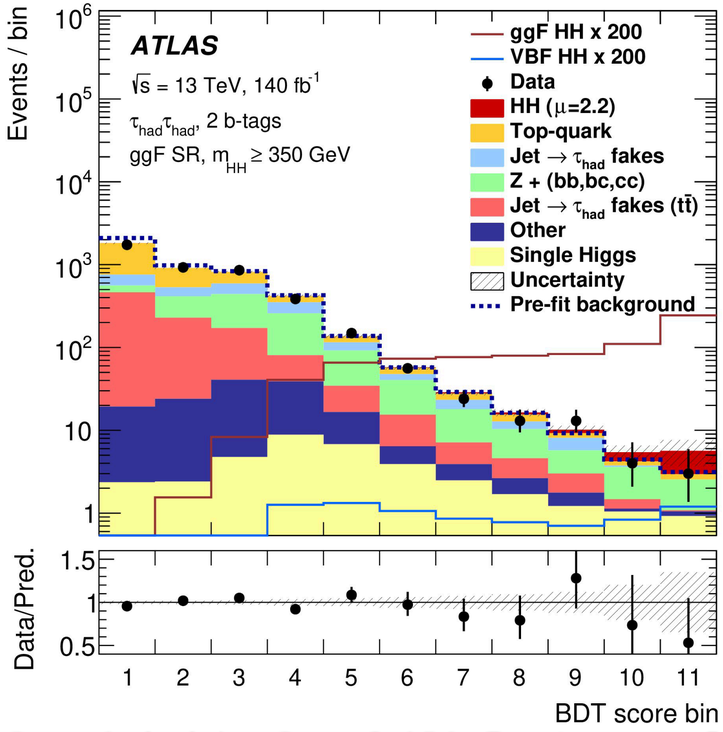
(*) VH , HWW differentials in ATLAS, arXiv:2503.19420 (no EFT)

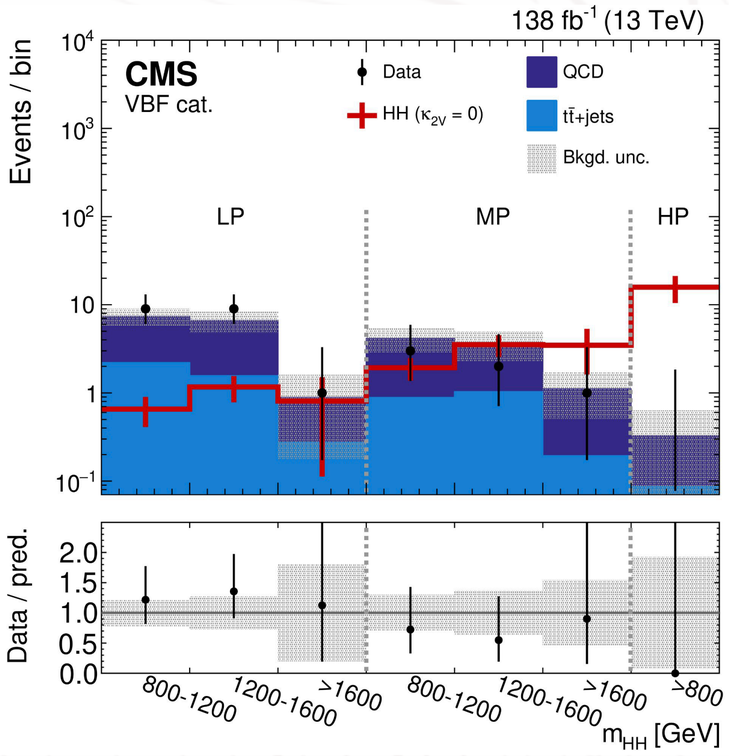
‘GOLDEN’ CHANNELS

- 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







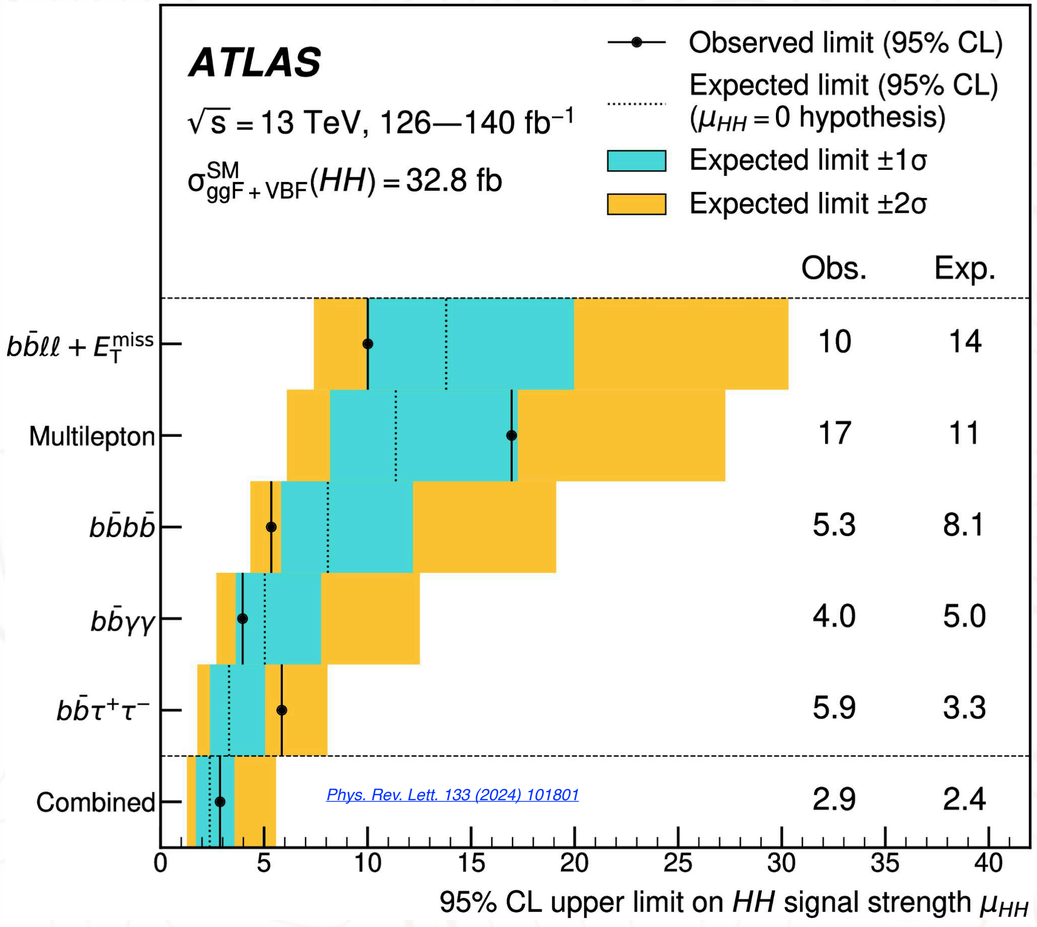


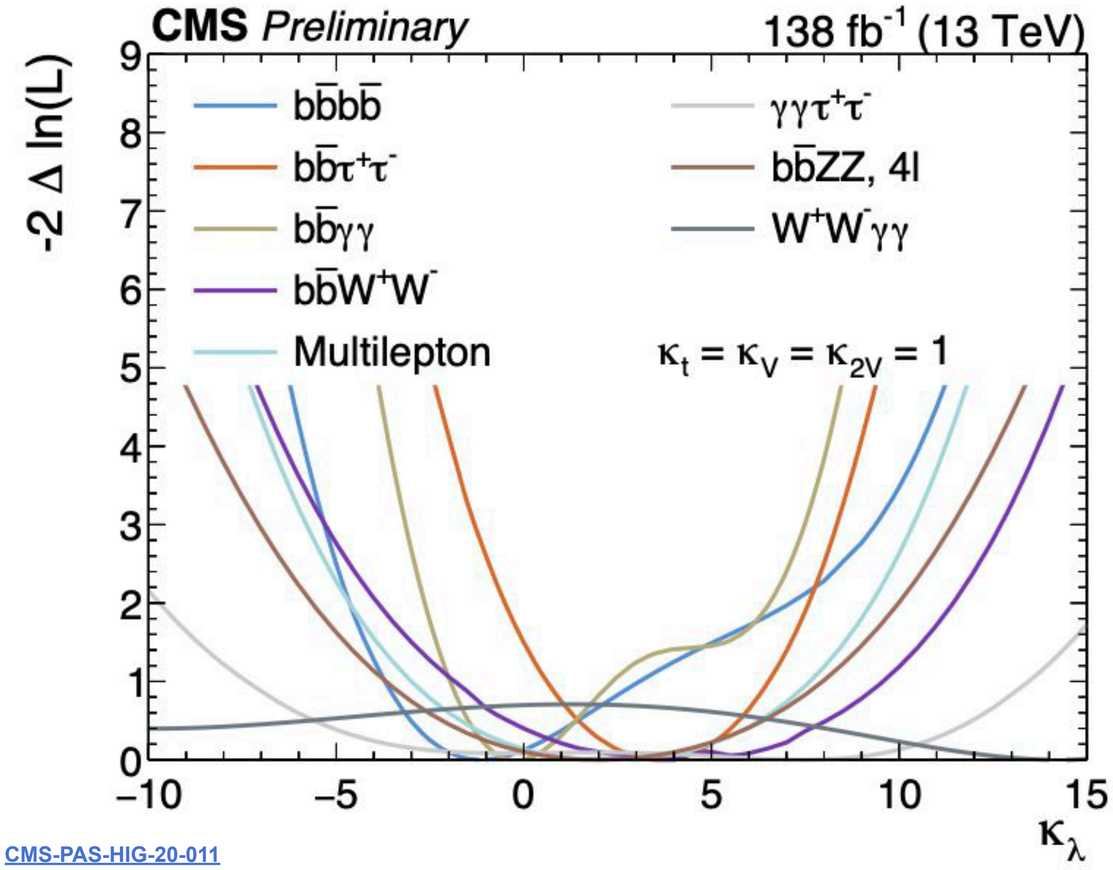
WHERE ARE WE?

With Run2 data analyzed, at 95%CL:

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

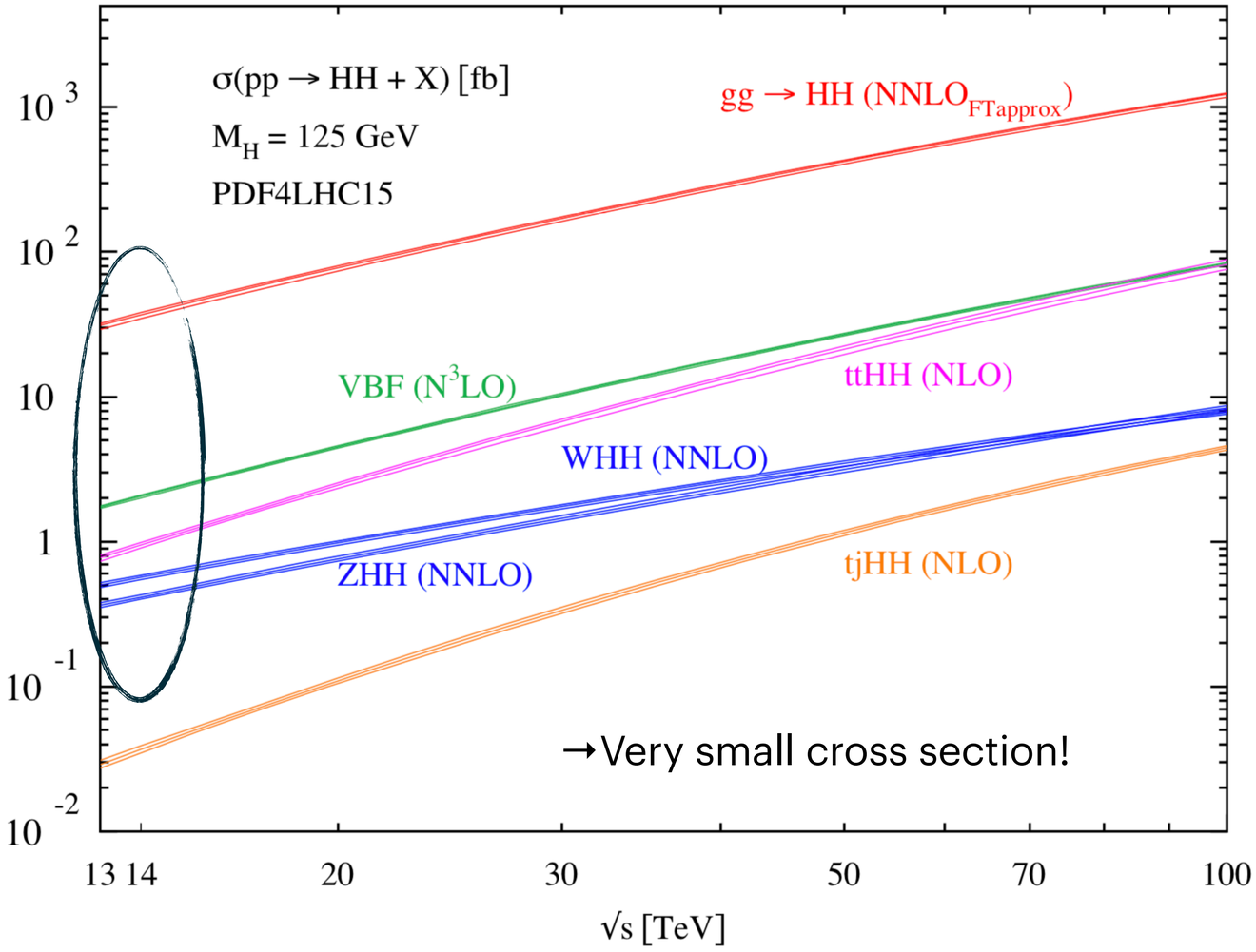
$$ATLAS: \quad \mu_{HH} < 2.9\ (2.4), \quad -1.2 < \kappa_\lambda < 7.2$$

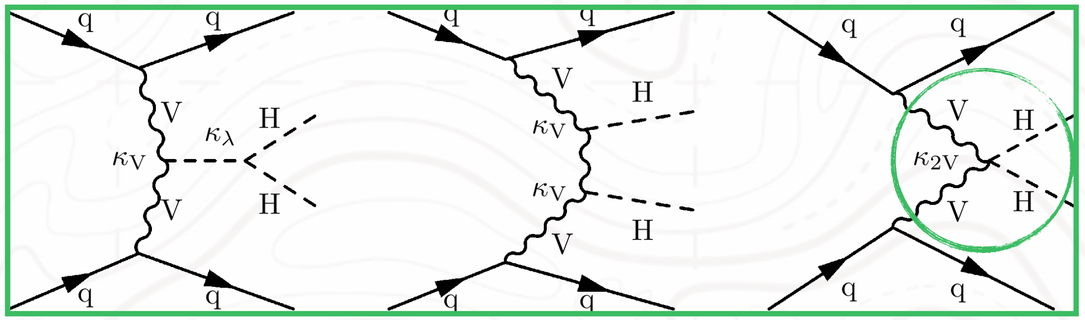


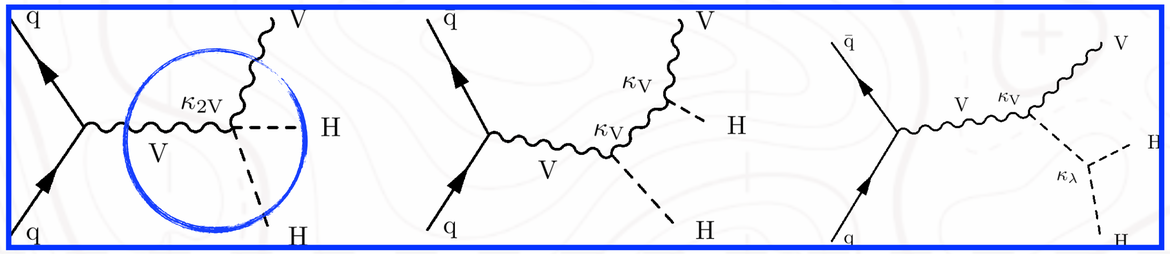


CMS-PAS-HIG-20-011

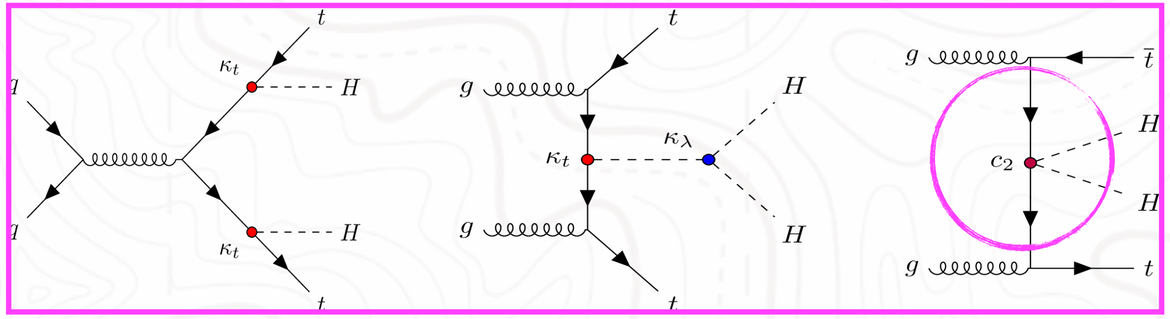
BEYOND GGF: VBFHH, TTHH AND VHH







JHEP 10 (2024) 061: VHH 4B



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

VBFHH: PROBING K2V

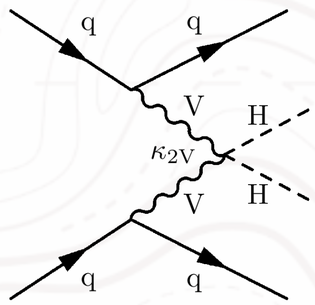
Tiny cross section in the SM, 1.7fb

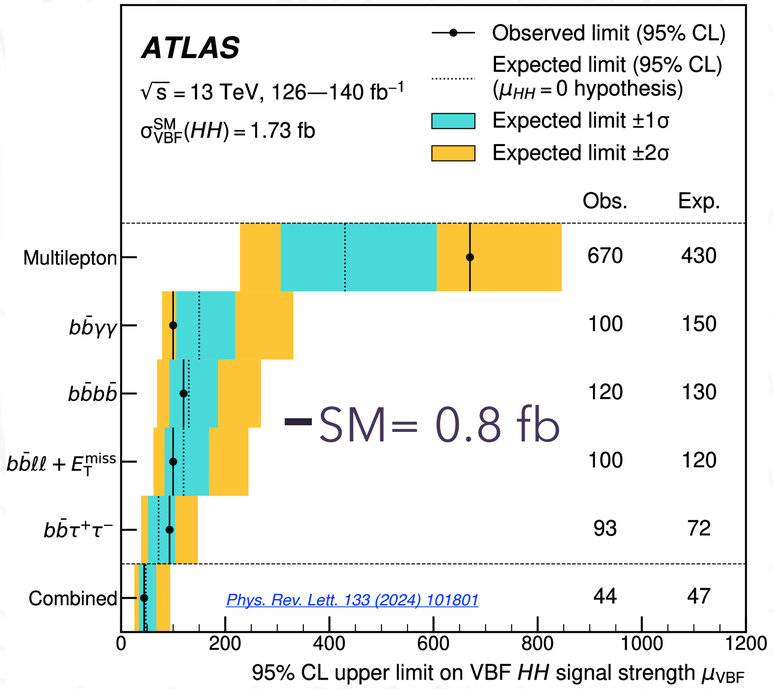
Access to coupling between two Higgs bosons and two Vector bosons (important in HEFT)

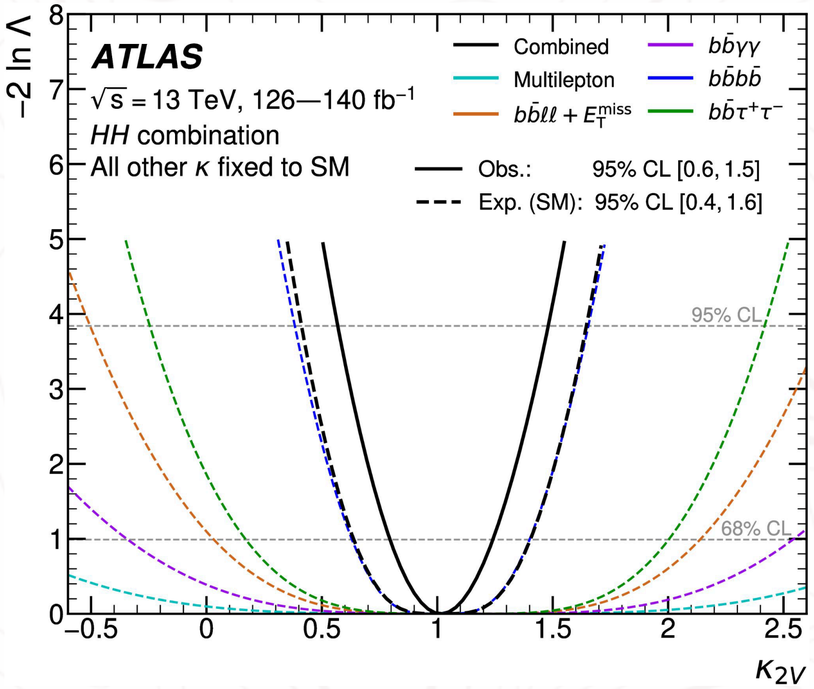
ATLAS: $\mu_{\mathrm{VBFHH}} < 44\ (47)$ $\quad 0.4 < \kappa_{2V} < 1.6$

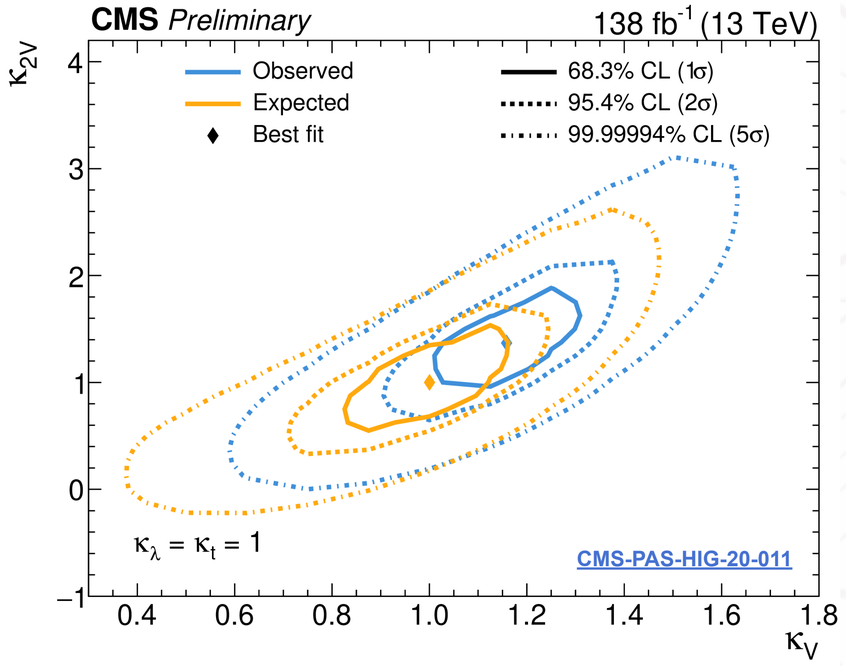
CMS: $\mu_{\mathrm{VBFHH}} < 79\ (91)$ $\quad 0.62 < \kappa_{2V} < 1.42$

at 95%CL



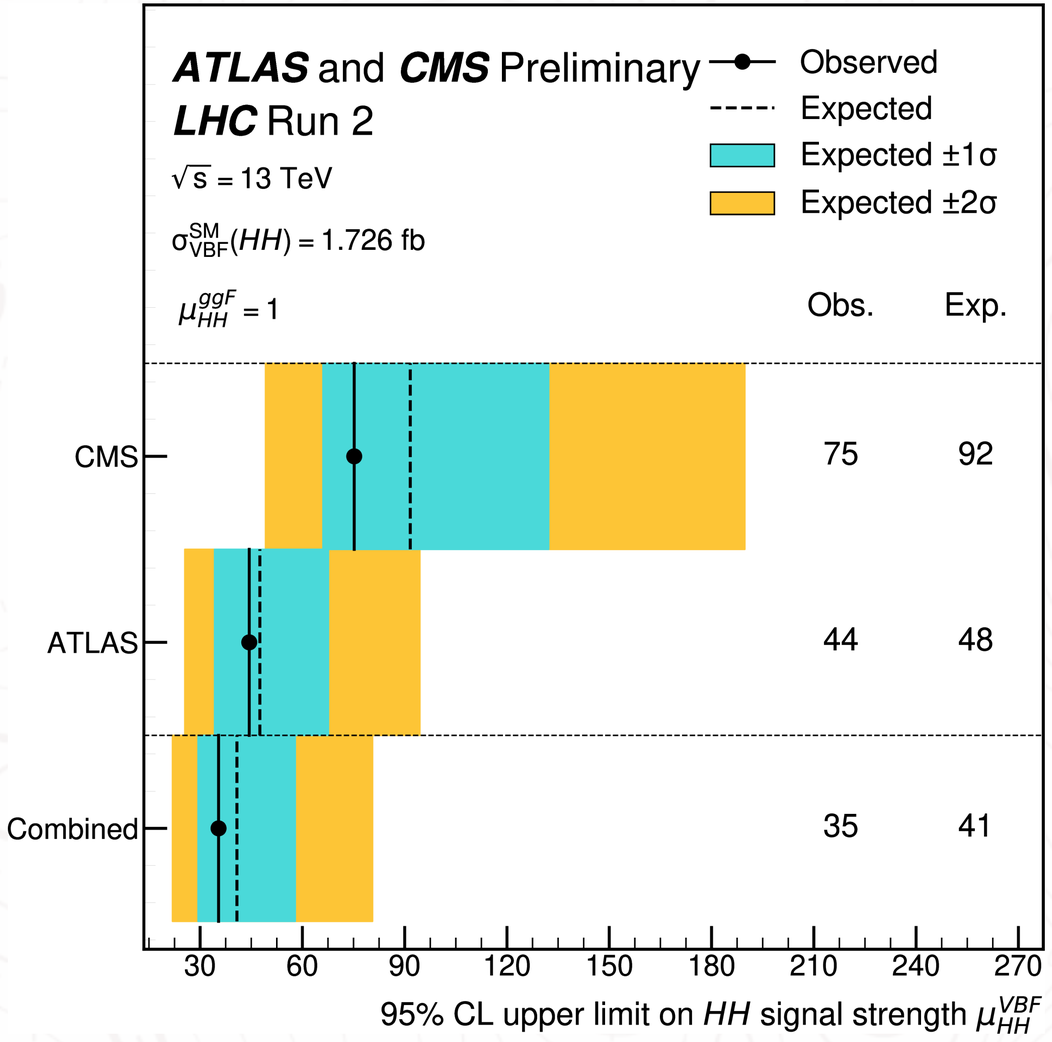


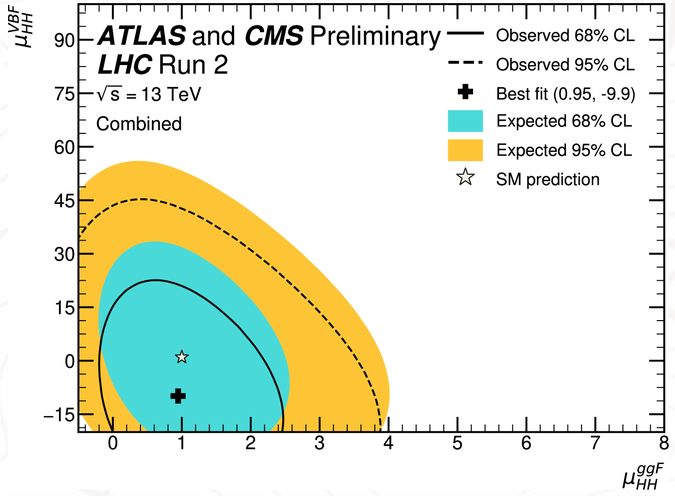


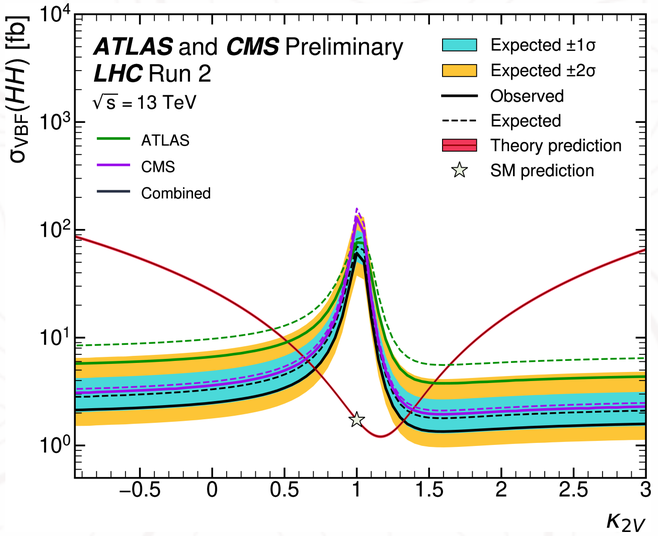


In VHH (JHEP 10 (2024) 061):$\mu_{VHH} < 294(124)$, $-37.7 < \kappa_\lambda < 37.2$, $-12.2 < \kappa_{2V} < 13.5$, at 95%CL

VBF HH IN THE COMBINATION







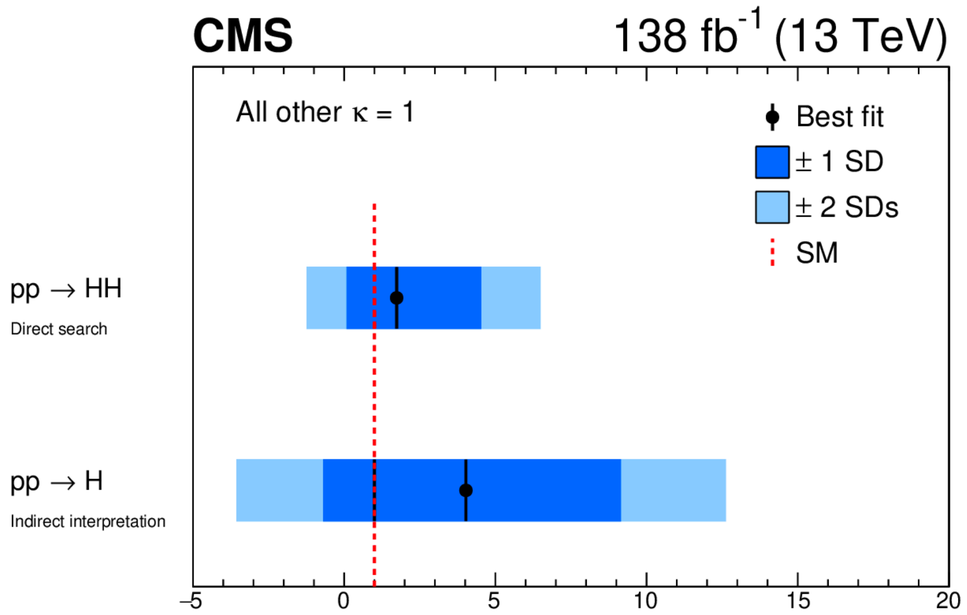
HH COMBINATION

	Channel	Details	Expected			Observed		
			μ_{HH}	κ_λ	κ_{2V}	μ_{HH}	κ_λ	κ_{2V}
ATLAS	bbbb	[none-none-none,none-none-none]	< 8.1	$[-5.3, 12]$	$[0.38, 1.7]$	< 5.4	$[-3.4, 11]$	$[0.55, 1.5]$
	bb$\tau\tau$	[none-none-none]	< 3.3	$[-2.6, 9.2]$	$[-0.24, 2.4]$	< 5.8	$[-3.3, 9.1]$	$[-0.51, 2.7]$
	bb$\gamma\gamma$	[none-none-none]	< 5.2	$[-3.0, 7.9]$	$[-1.1, 3.3]$	< 4.1	$[-1.6, 7.0]$	$[-0.48, 2.7]$
	bb$\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$	[none-none-none]	< 14	$[-11, 17]$	$[-0.50, 2.7]$	< 9.6	$[-6.5, 13]$	$[-0.19, 2.4]$
	Multileptons	[none-none-none]	< 11	$[-4.5, 9.6]$	$[-1.9, 4.1]$	< 17	$[-6.4, 12]$	$[-2.5, 4.7]$
	Combined	[41]	< 2.4	$[-1.7, 7.2]$	$[0.41, 1.7]$	< 2.9	$[-1.3, 7.2]$	$[0.57, 1.5]$
CMS	bbbb	[29,31]	< 4.3	$[-4.6, 12]$	$[0.63, 1.4]$	< 7.0	$[-5.0, 12]$	$[0.66, 1.4]$
	bb$\tau\tau$	[33]	< 5.4	$[-4.2, 11]$	$[-0.64, 2.8]$	< 3.5	$[-1.9, 8.9]$	$[-0.32, 2.5]$
	bb$\gamma\gamma$	[35]	< 5.7	$[-3.5, 8.8]$	$[-0.94, 3.1]$	< 8.7	$[-3.5, 8.0]$	$[-1.4, 3.6]$
	bbWW	[none-none-none-none]	< 19	$[-9.4, 16]$	$[-1.4, 3.5]$	< 15	$[-6.1, 13]$	$[-1.0, 3.1]$
	Multileptons	[39]	< 20	$[-8.0, 12]$	$[-2.5, 4.6]$	< 22	$[-5.8, 10]$	$[-3.4, 5.6]$
	Combined	[42]	< 2.6	$[-2.2, 8.0]$	$[0.63, 1.4]$	< 3.5	$[-1.4, 6.6]$	$[0.66, 1.4]$
ATLAS + CMS combined			< 1.7	$[-1.3, 6.7]$	$[0.66, 1.4]$	< 2.5	$[-0.71, 6.1]$	$[0.73, 1.3]$

		κ_λ			κ_{2V}		
		Best fit	68% CL	95% CL	Best fit	68% CL	95% CL
ATLAS	Observed	3.5	[0.11, 5.9]	[-1.3, 7.2]	1.0	[0.80, 1.2]	[0.57, 1.5]
	Expected	1.0	[-0.55, 5.7]	[-1.7, 7.2]	1.0	[0.64, 1.4]	[0.41, 1.7]
CMS	Observed	1.6	[-0.04, 4.6]	[-1.4, 6.6]	1.0	[0.83, 1.2]	[0.66, 1.4]
	Expected	1.0	[-0.86, 6.4]	[-2.2, 8.0]	1.0	[0.78, 1.3]	[0.63, 1.4]
Combination	Observed	1.8	[0.36, 4.6]	[-0.71, 6.1]	1.0	[0.87, 1.2]	[0.73, 1.3]
	Expected	1.0	[-0.27, 5.2]	[-1.3, 6.7]	1.0	[0.79, 1.2]	[0.66, 1.4]

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
- 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