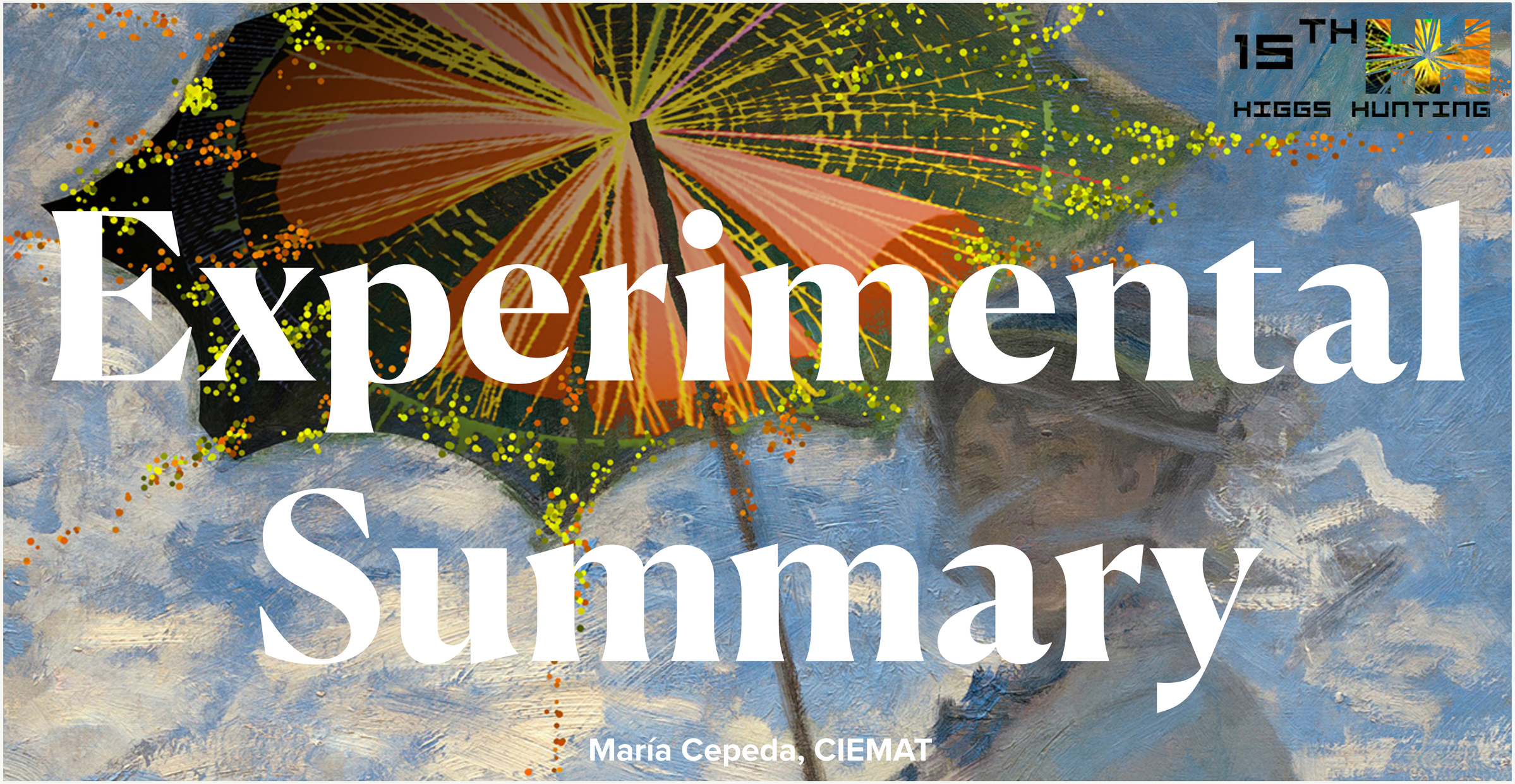


Experimental Summary

María Cepeda, CIEMAT

In Summary…

- This has been an amazing conference - thanks to all the speakers, experimental and theorists alike, for all the results, ideas and discussions
- We have been very busy exploring the Higgs Sector!
- **15 years of Higgs Huntings, and the Higgs community is buzzing with new results: so many interesting topics and discussions condensed in three days that to make them justice them in a few slides is an impossible task.**
- Since I cannot cover all… I'll pick some (biased) topics

Cross Sections, Couplings, Properties

New methods: new phase spaces, improved sensitivity

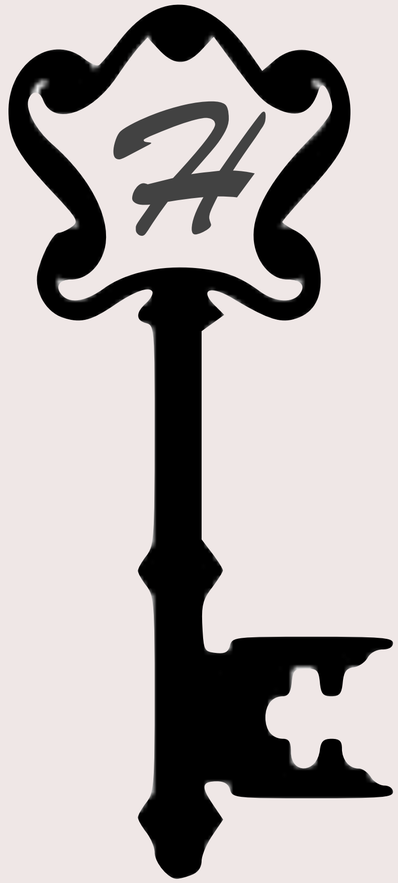
Charm and Rare Decays

CP and EFT

HH and the Potential

BSM?

Keystone of the Standard Model ?

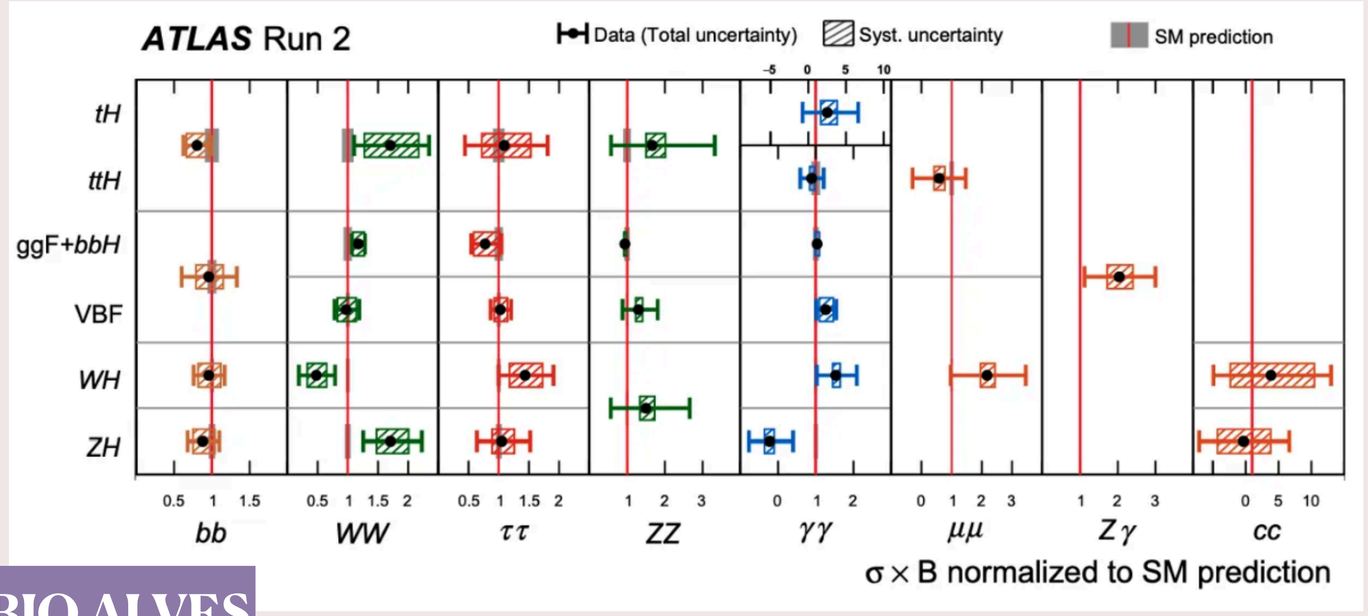


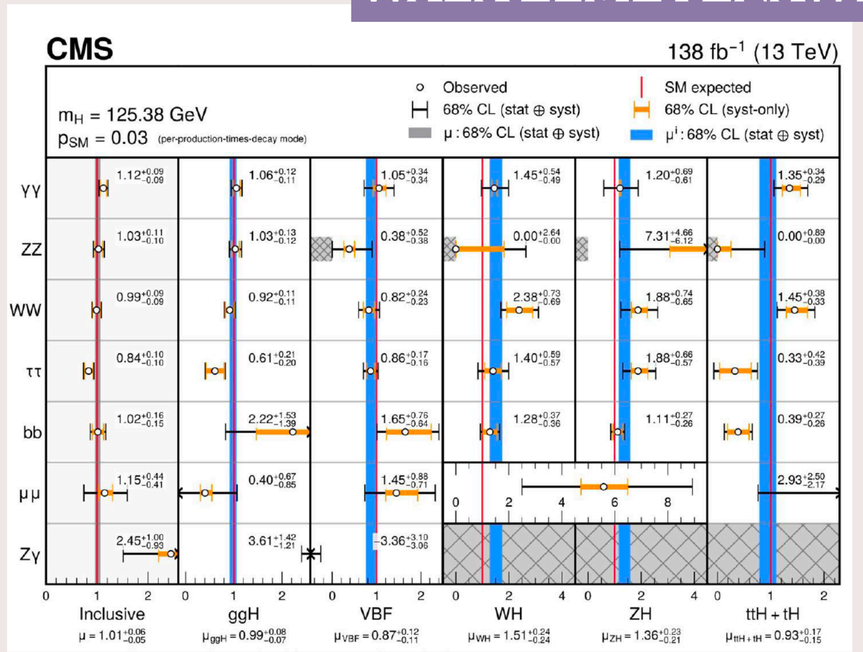
Or key to the portals of BSM?

Measuring Higgs Properties

Cross Sections...

WALA ELMETENAWEE





FABIO ALVES

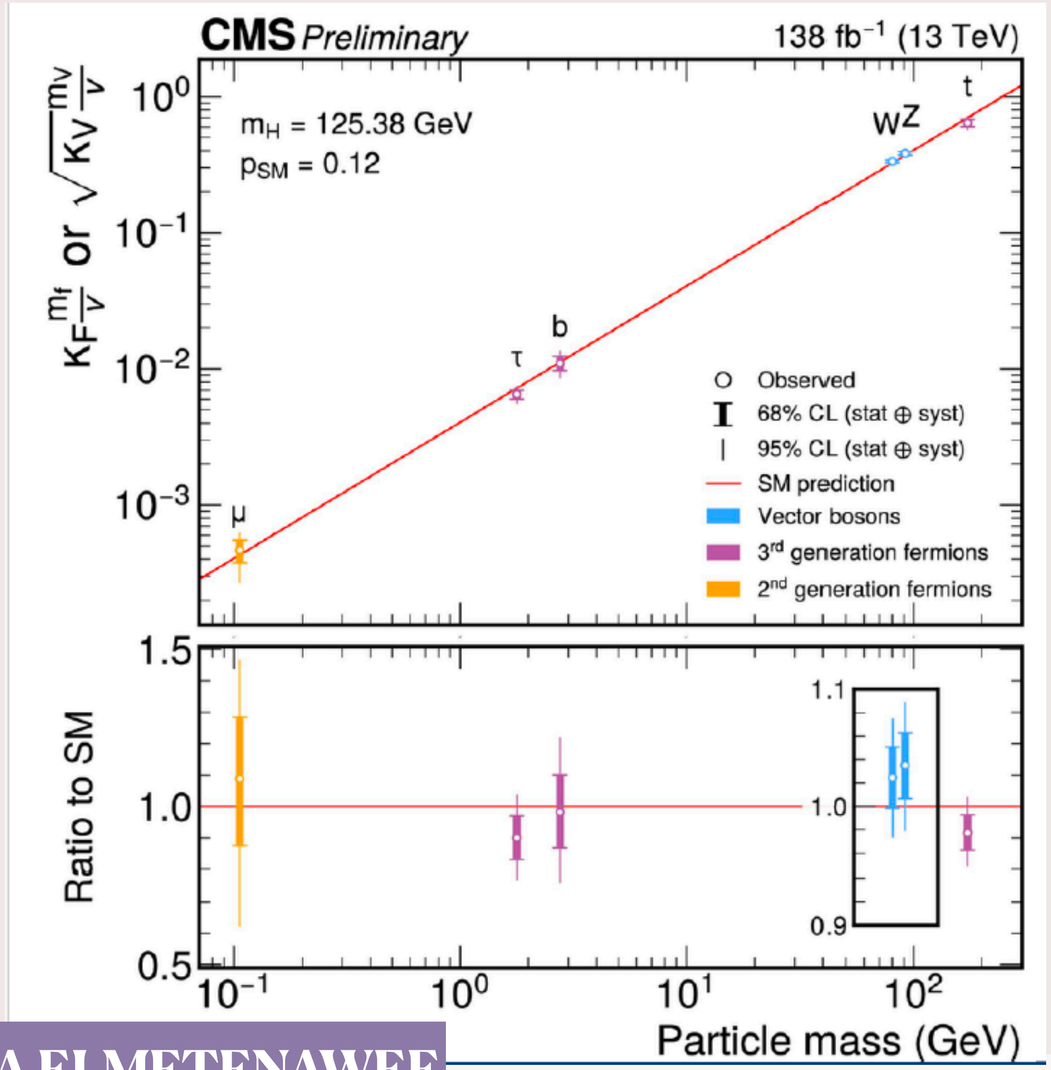
- Run2 Combinations updated with new channels and interpretations
- Through examination of Higgs Production: impressive agreement with the SM
- Precision on main modes down to 5-10%

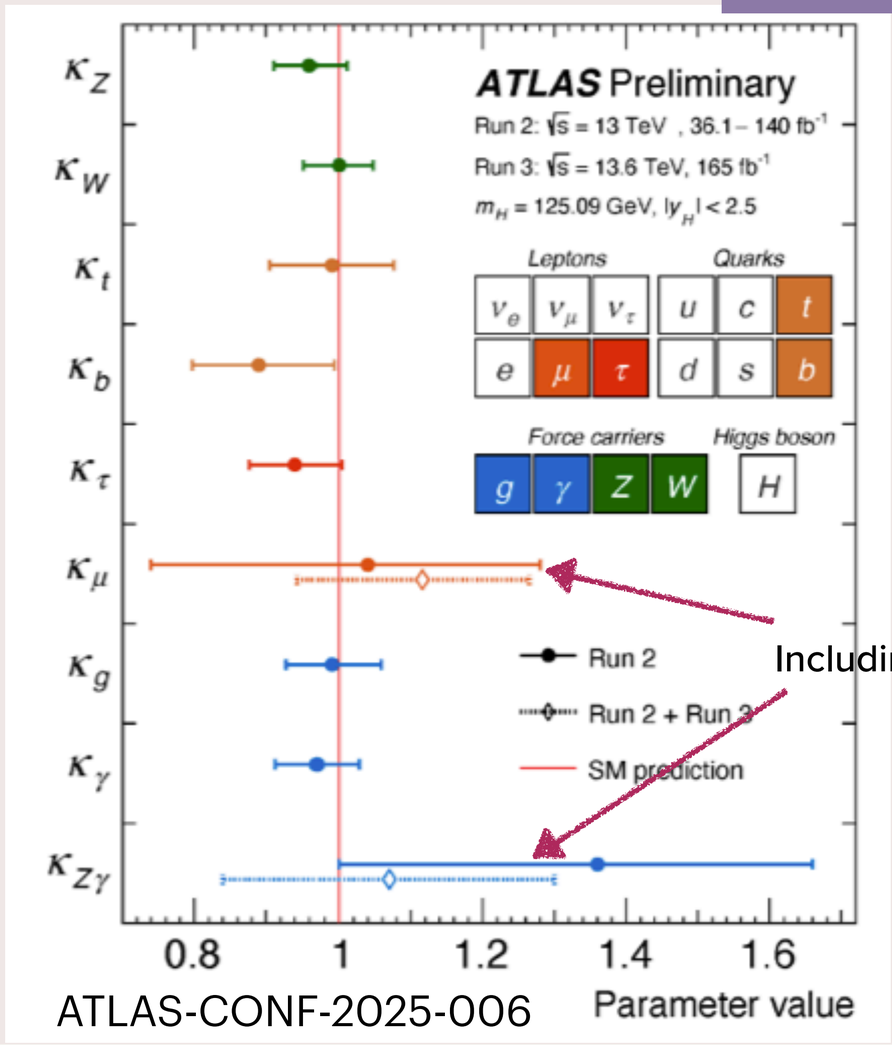
$$\mu_{if} = \frac{(\sigma_i \times B_f)}{(\sigma_i^{SM} \times B_f^{SM})} = 1.023 \pm 0.028\ (\text{stat.})\ ^{+0.026}_{-0.025}\ (\text{exp.})\ ^{+0.039}_{-0.036}\ (\text{sig. theo.})\ \pm 0.012\ (\text{bkg. theo.})$$

(ATLAS: 10% improvement on global mu compared to Nature paper)

...and Couplings!

FABIO ALVES



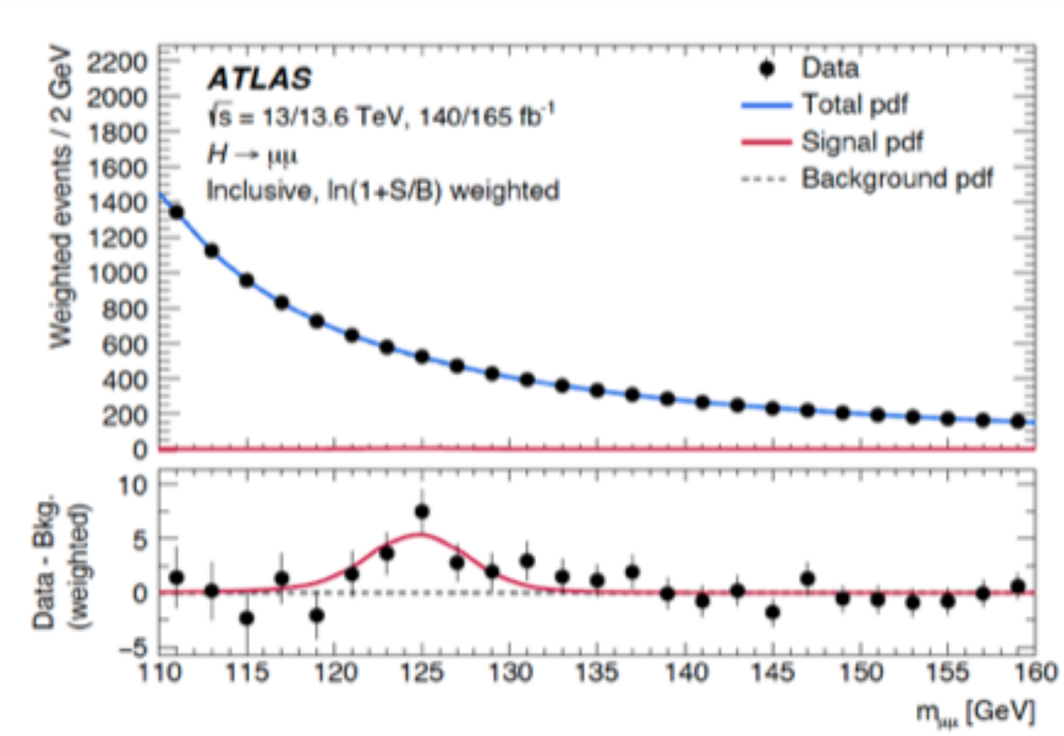


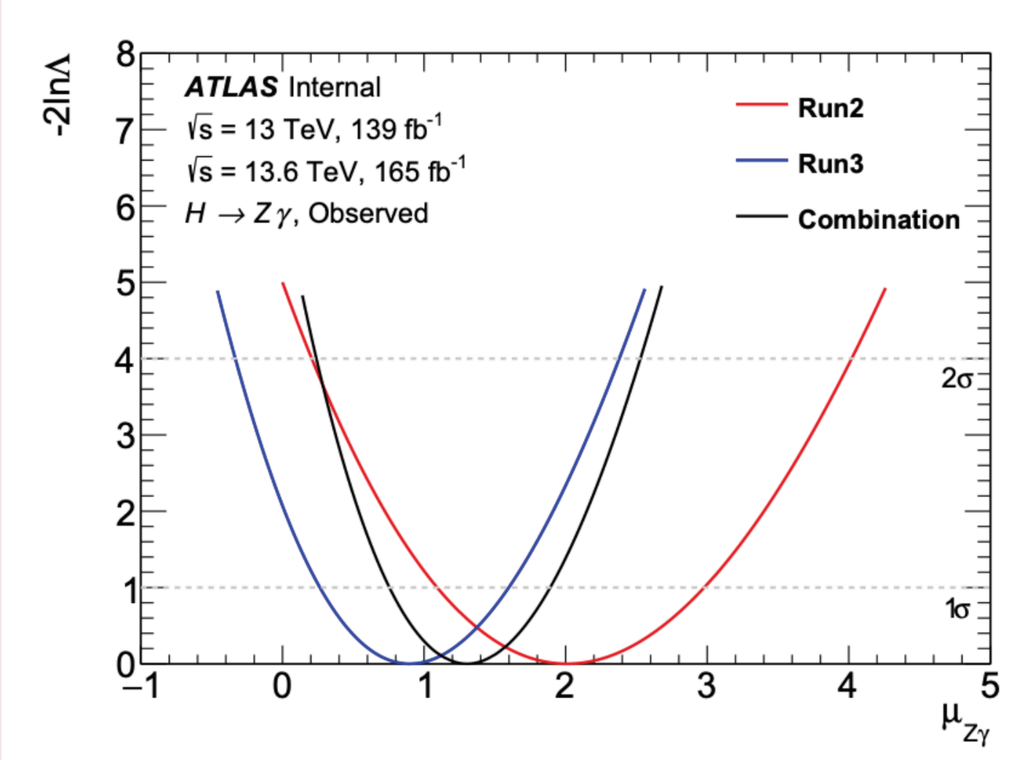
Including Run3 Data!

ATLAS-CONF-2025-006

WALA ELMETENAWEE

Rare Decays: exploiting Run3 (22+23+24) data





Run2+Run3 ATLAS: **3.4σ (2.5 exp)** , μ = 1.4 ±0.4

CMS Run2 : μ =1.2±0.4, 3σ (2.5 exp)

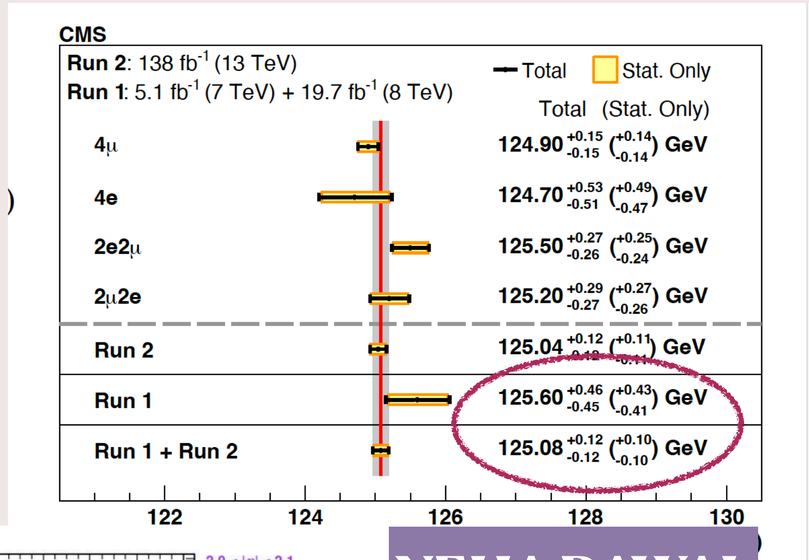
Run2+Run3 ATLAS: 2.5σ (1.0 exp SM) , μ = 1.3 ±0.5

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

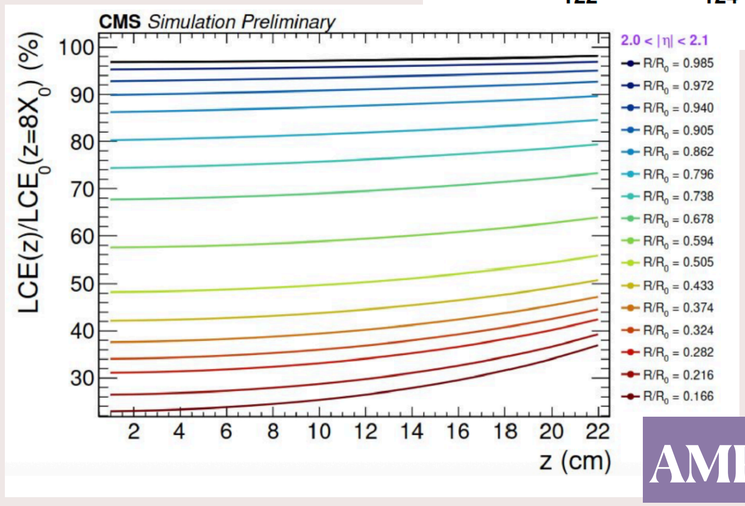
STEFANO MANZONI

Pinning down the mass

- Known better than 0.1%!

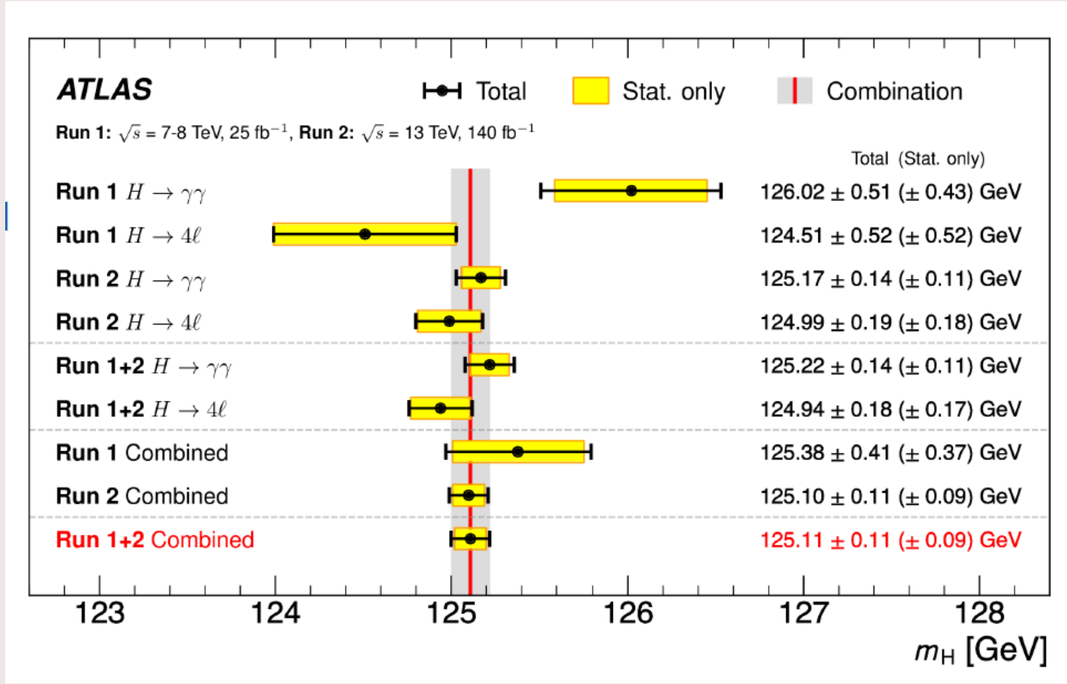


NEHA RAWAL



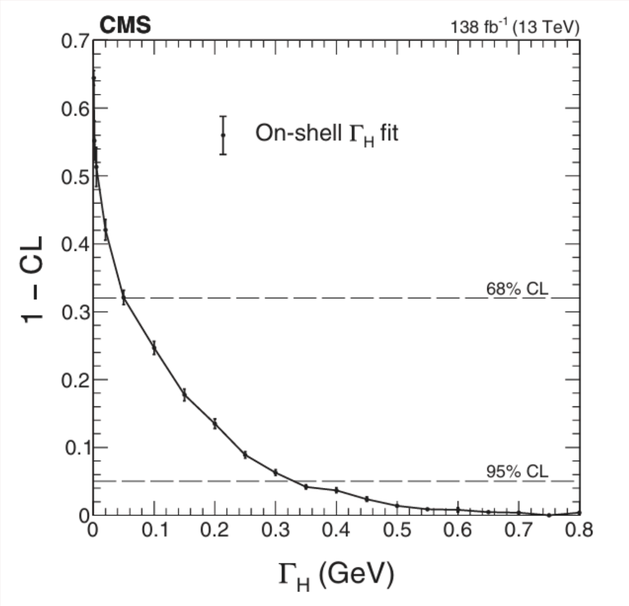
AMRUTHA KRISHNA

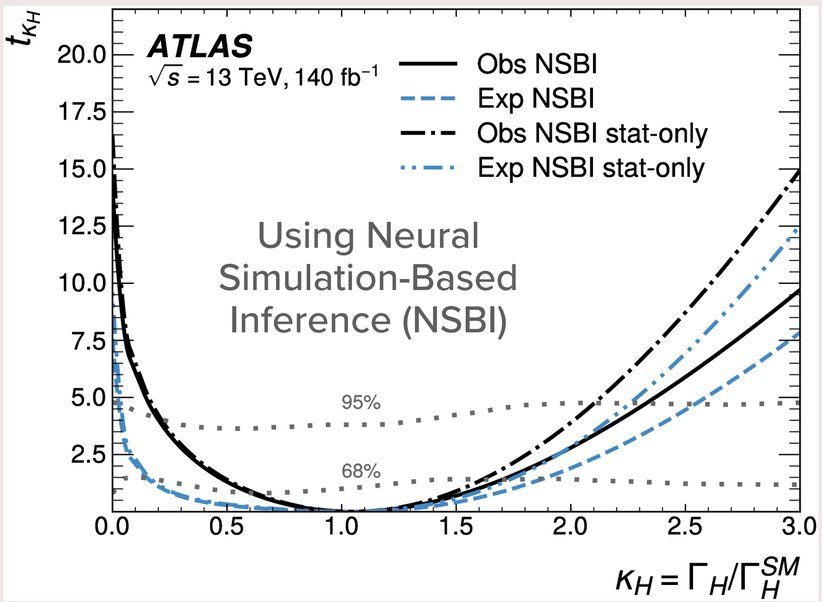
- Precision measurements: improvement in calibration and control over systematics is key

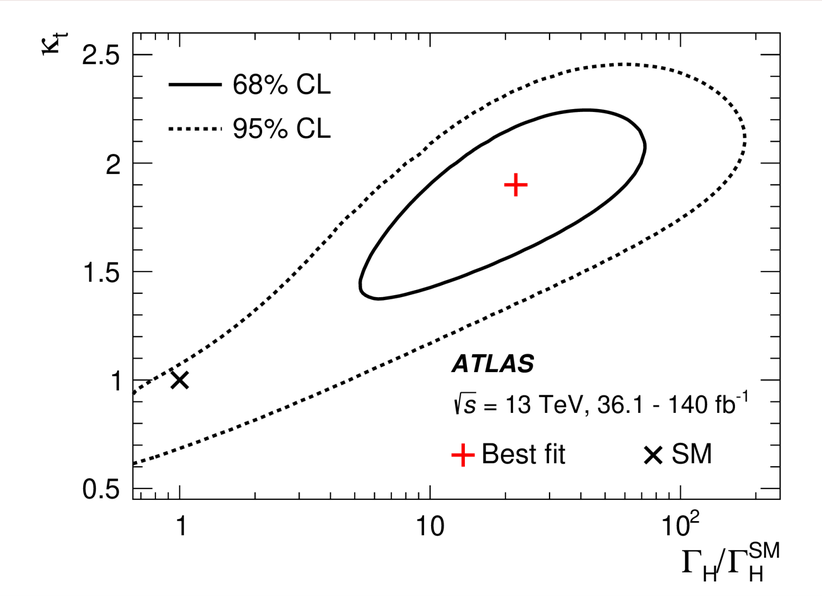


ELISE LE BOULICAUT ENNIS

Narrowing down the Width







Direct, from 4l:

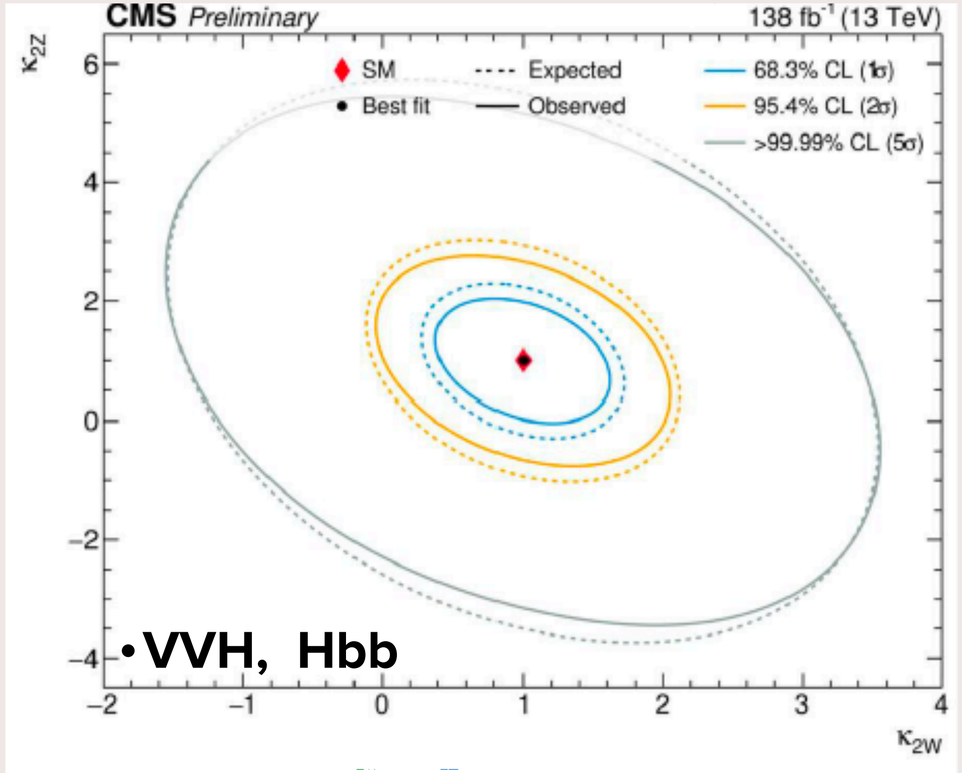
Γ_H< 50 (330) MeV at 68% (95%) C.L.

- **HZZ Offshell/Onshell:**
  - CMS: $3.0^{+2.0}_{-1.5}\ MeV$
  - ATLAS: $4.3^{+2.7}_{-1.9}\ MeV$
- HWW: ATLAS < 13 MeV

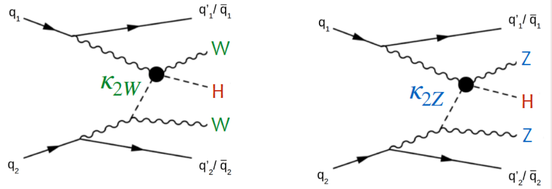
- **With tops! 4top (off shell) / ttH (on shell)**
  - Γ_H<450 (75) MeV
  - Dominated by Theo systematics
  - Resolved loops: Γ_H< 160 (55) MeV

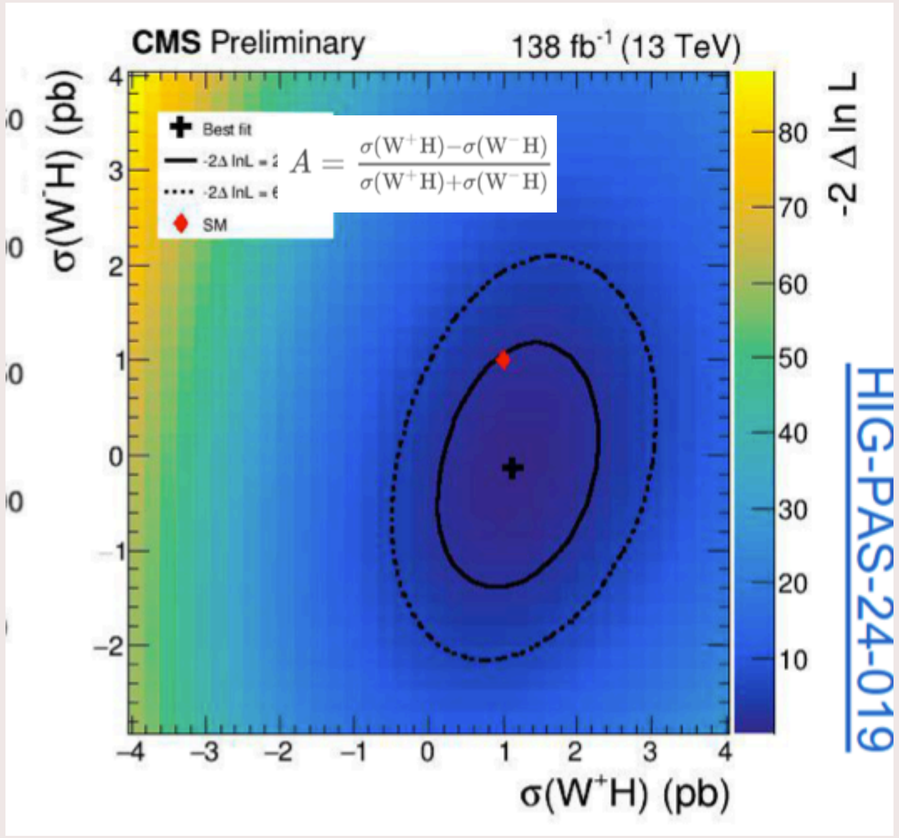
AMRUTHA KRISHNA NEHA RAWAL ELISE LE BOULICAUT ENNIS YANGFAN ZHANG

Also rarer and rarer production modes



- VVH, Hbb





- Charge Asymmetry in $H\tau\tau$

$$A = \frac{\sigma(W^+H)-\sigma(W^-H)}{\sigma(W^+H)+\sigma(W^-H)}$$

WALA ELMETENAWEE

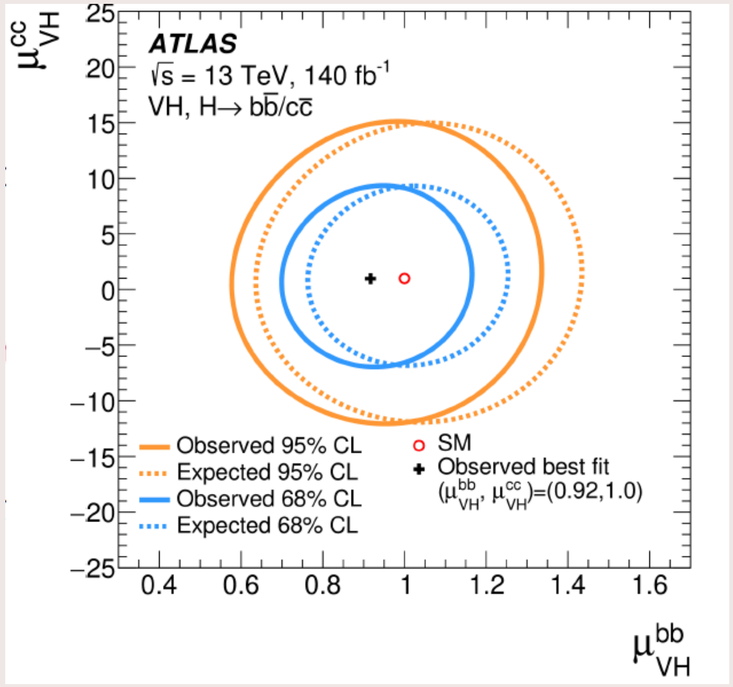
Charming the Higgs

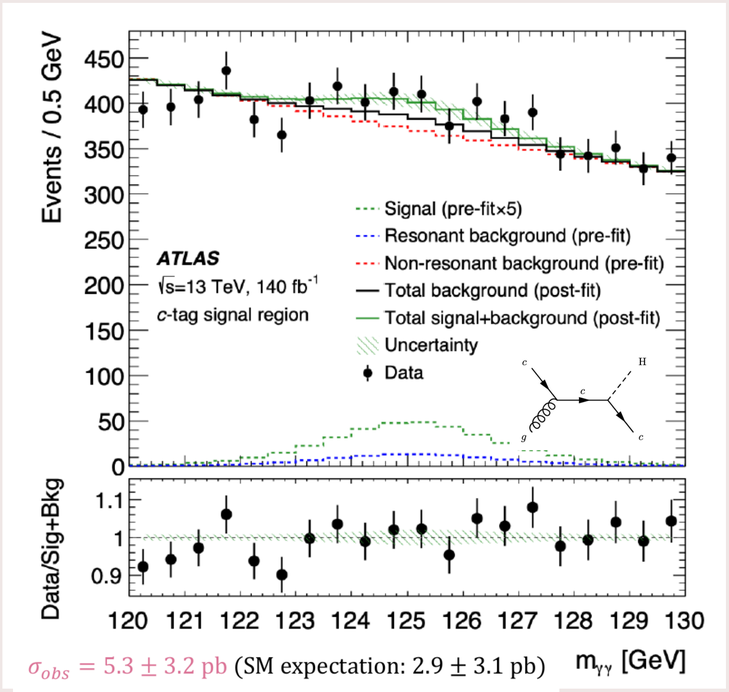
The hunt for the charm coupling

GRETA BRIANTI

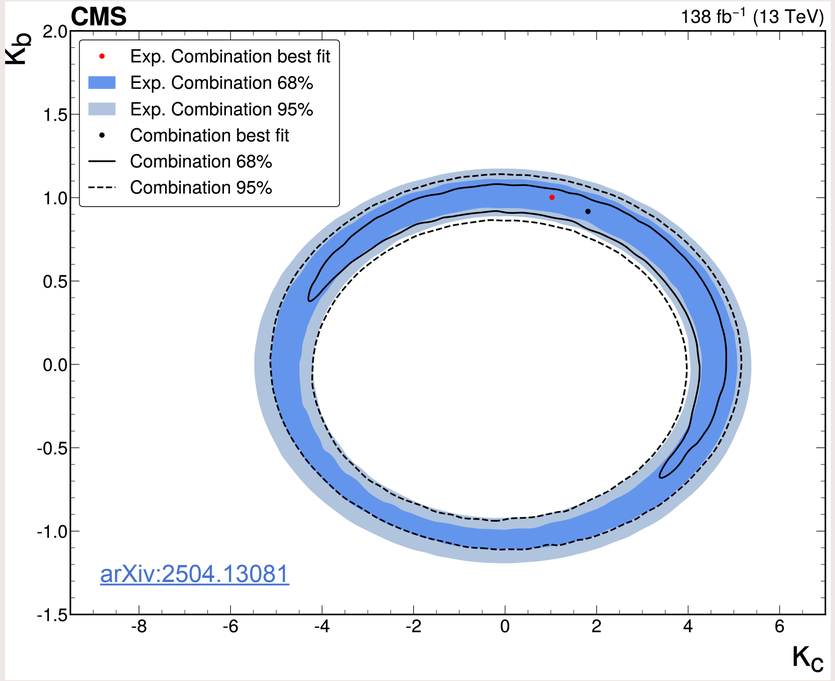
ANGELA ZAZA

Will the HL-LHC be the first in measuring the charm coupling? Different approaches & techniques keep changing the landscape - all still with Run2 data results





$\sigma_{obs} = 5.3 \pm 3.2$ pb (SM expectation: 2.9 ± 3.1 pb)



Direct: VH, ttH, ggF, VBF?

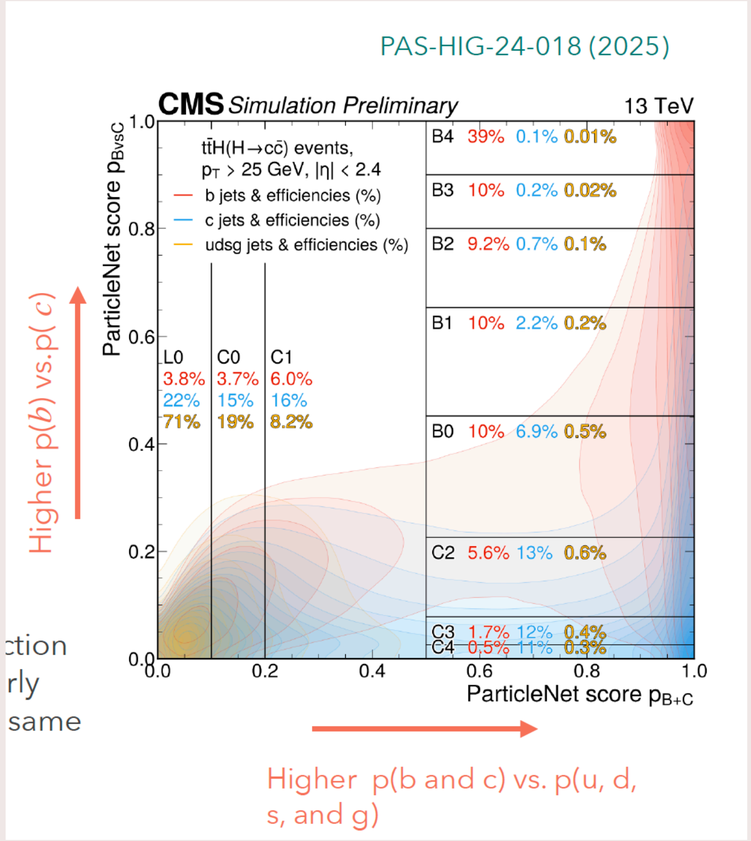
H+c

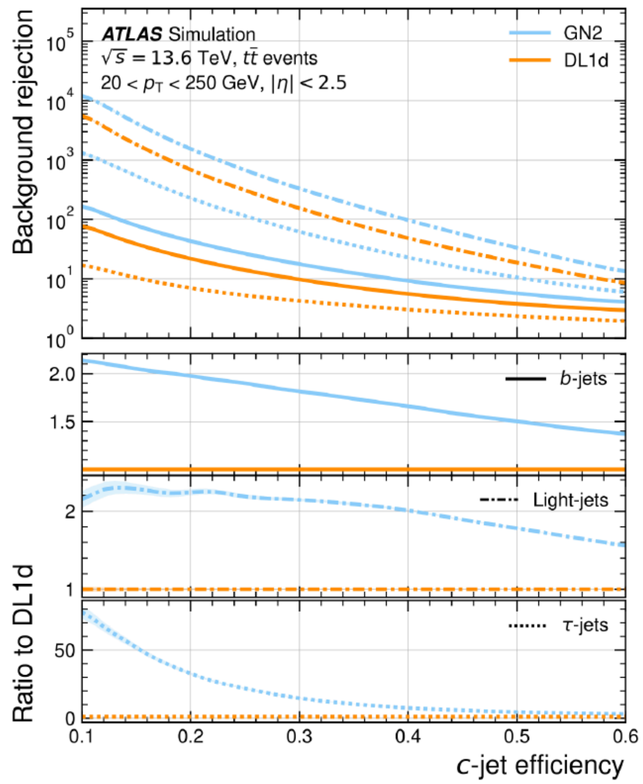
Other indirect, eg from differentials

The hunt for the charm coupling

- **Direct: Difficult measurement (not only statistics, we need to be able to identify charm jets!).**
- **Constant improvement in performance in recent years coming from new techniques**
- **Improvement in techniques is the key: ML to the rescue.**

PAS-HIG-24-018 (2025)





- For example in CMS: ParticleNet for tagging + PartT for discrimination

MARIA MAZZA

GRETA BRIANTI

The hunt for the charm coupling

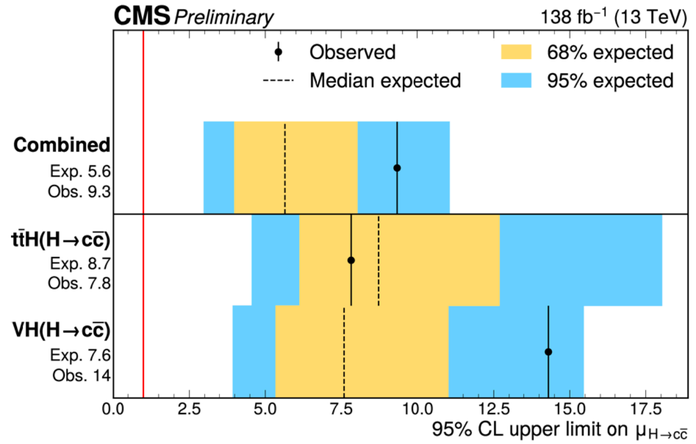
- Direct: Difficult measurement (not only statistics, we need to be able to identify charm jets!).
- Constant improvement in performance in recent years coming from new techniques
- Improvement in techniques is the key: ML to the rescue.
- **Impressive new result by CMS probing ttH:**
  - **ttH at the level of VH!**
  - **Can the HL-LHC measure Kc ?**

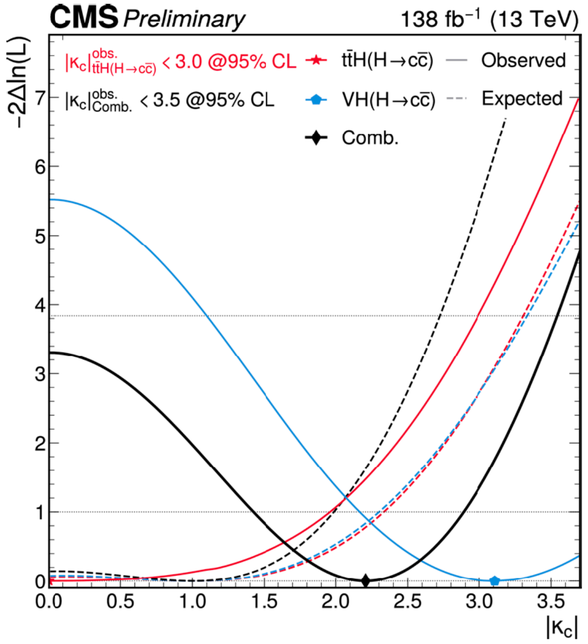
VH and ttH combination:

$\mu_{Hcc} < 9.3\ (5.6) \quad @95\%CL$

$|k_c| < 3.5\ (|k_c| < 2.7) \quad @95\%CL$

→ **Best result to date!**





ANGELA ZAZA

HL-LHC Projection

Projection on **VH→cc** combination by **ATLAS** and **CMS**

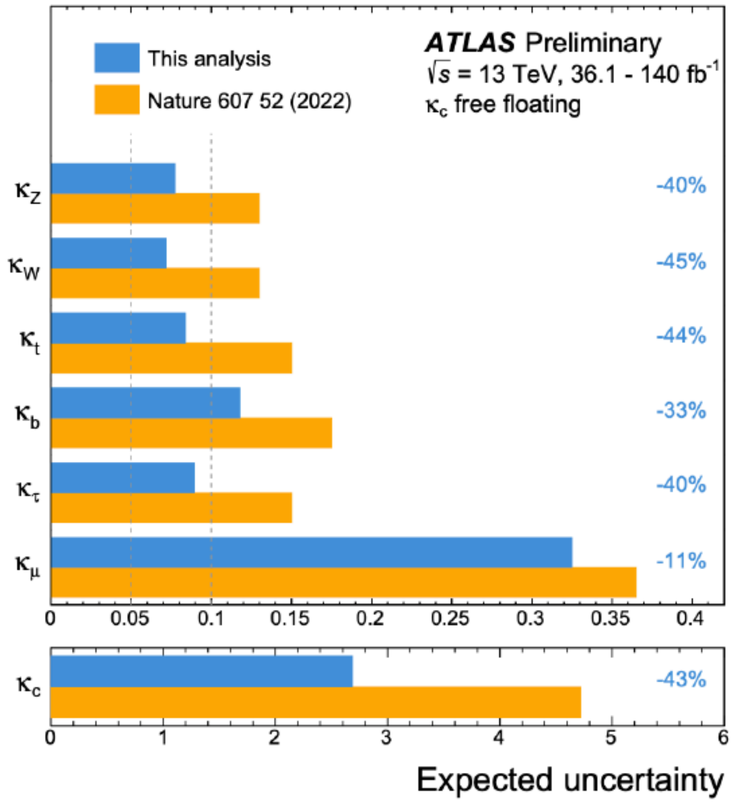
$|k_c| < 1.5 \quad @95\%CL$

ATL-PHYS-PUB-2025-018
CMS-HIG-25-002

Impact of κ_c on the combination

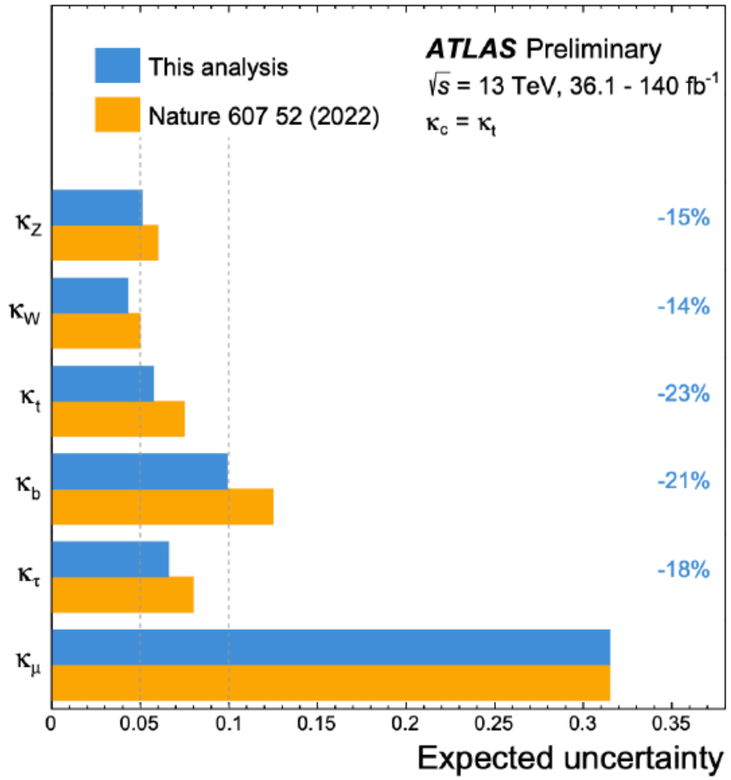
FABIO ALVES

κ_c as fit parameter



Reduction of 43% on exp. κ_c uncertainty (improved VH, H(cc) constraints)

Assuming $\kappa_c = \kappa_t$



Reduction of 23% on exp. κ_t uncertainty

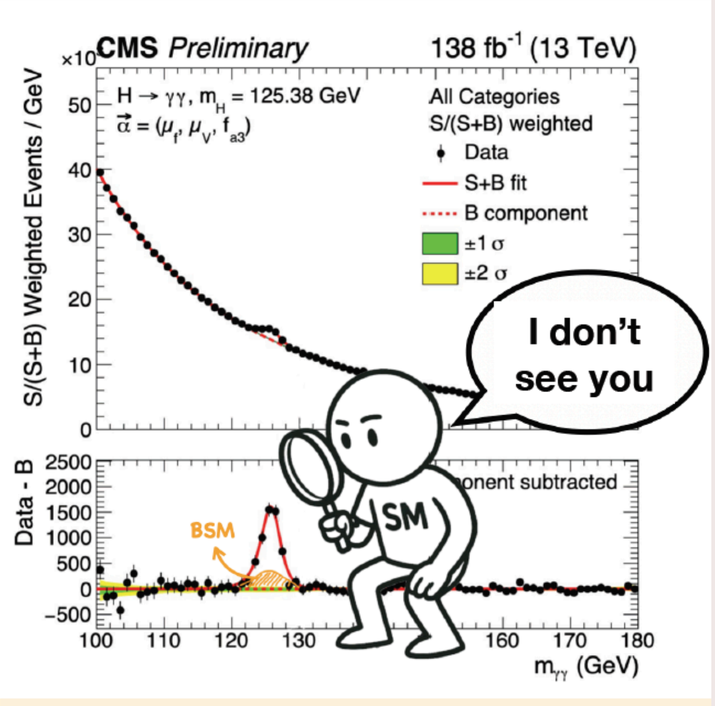
14

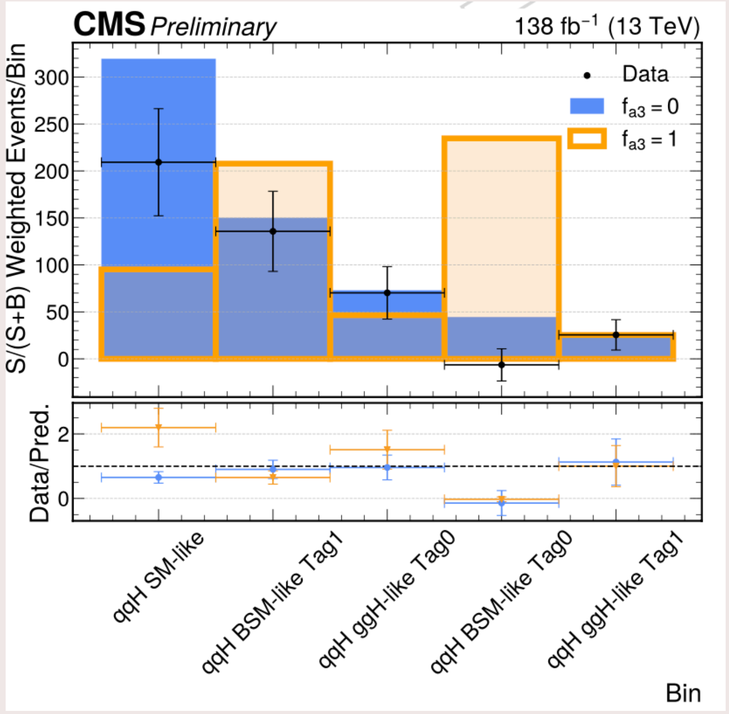
EFTs everywhere

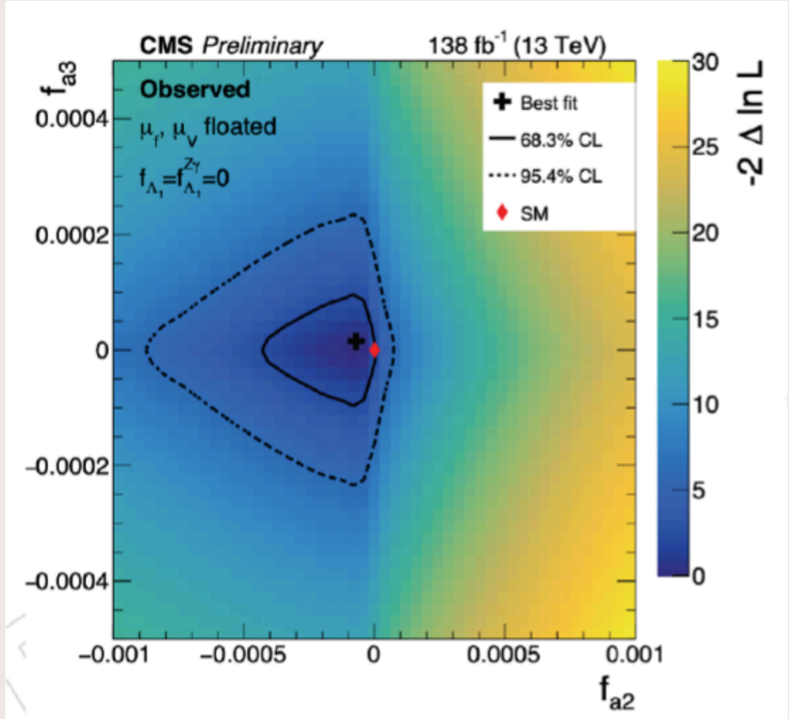
Anomalous Couplings with H→$\gamma\gamma$

FEDERICA DE RIGGI

- Vibrant field, many directions and channels being explored today
- Example: CMS Hgammagamma study. Statistically dominated.



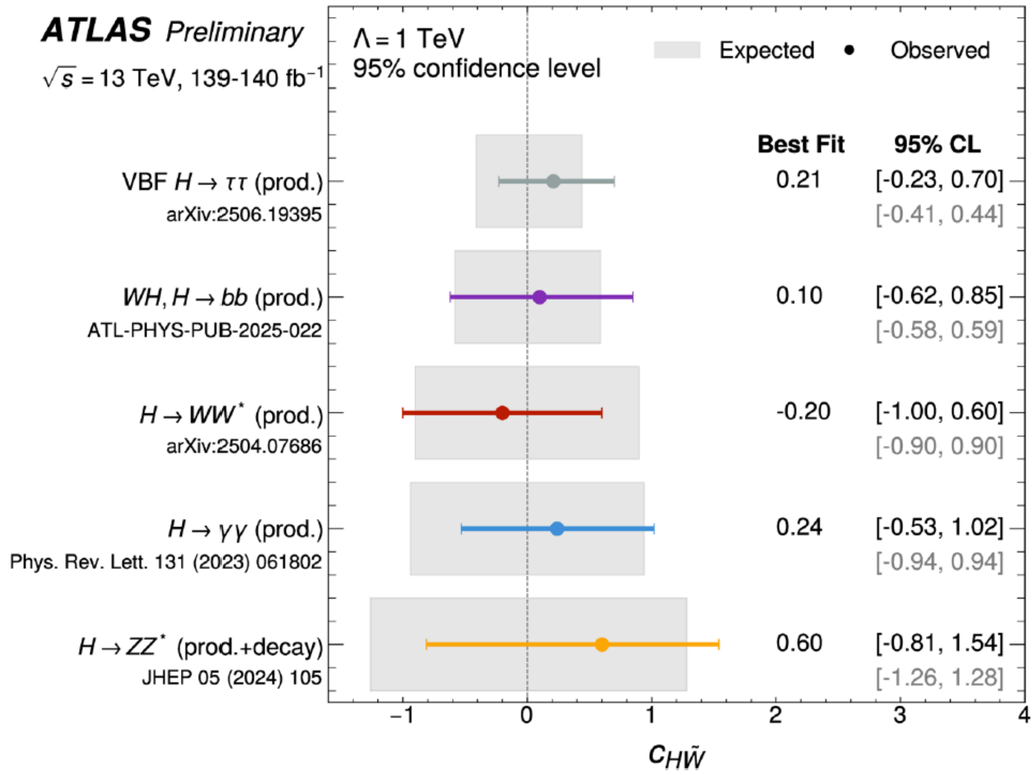




Three-dimensional categorization ($D_{0^-}^{ggH}$, D_{STXS}^{ggH}, D_{CP}^{ggH}) in **30 bins**

CP was truly the star this year...

Summary of constraints on $c_{H\tilde{W}}$:



ELISE LE BOULICAUT ENNIS

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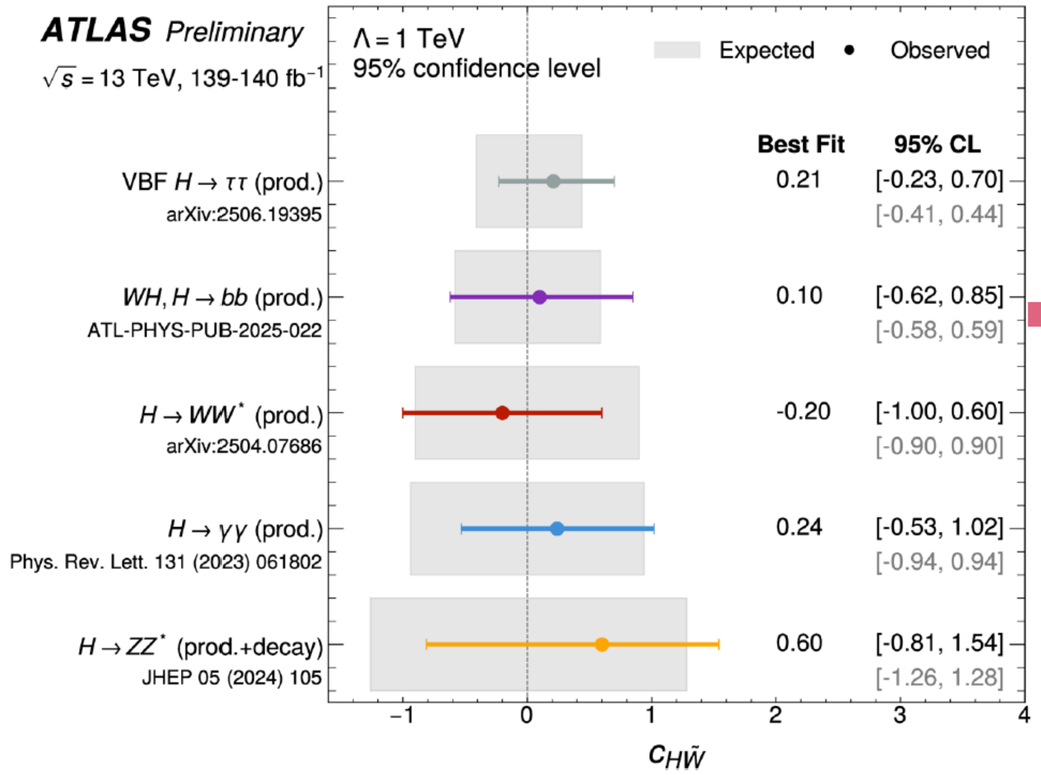
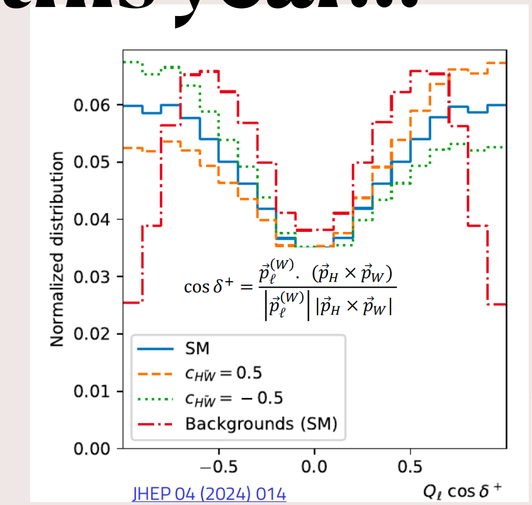


ELISE LE BOULICAUT ENNIS

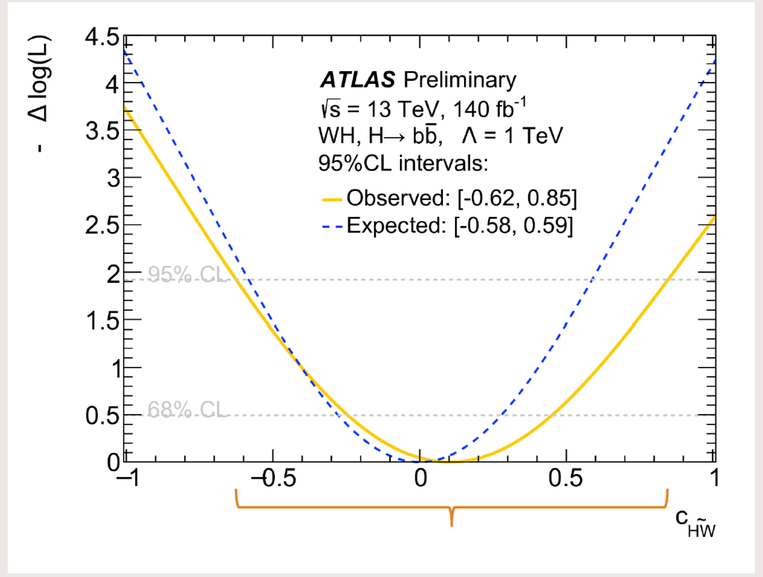


JHEP 04 (2024) 014

HWW vertex in WH(bb)

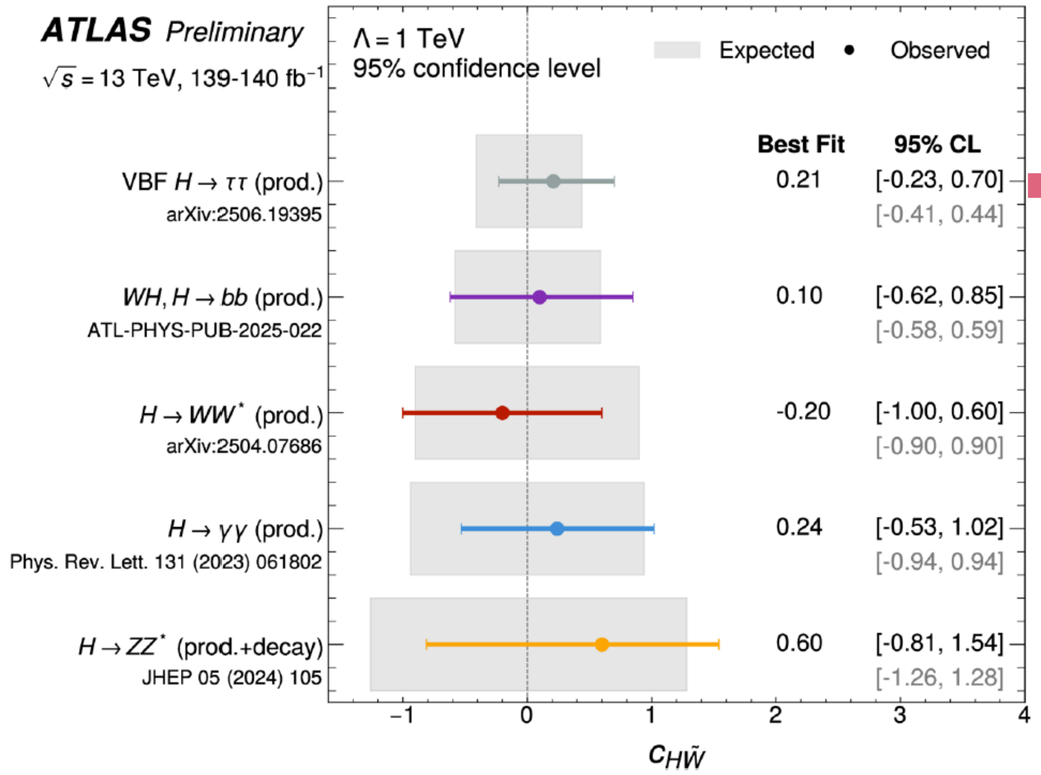
STXS based

RICARDO BARRUÉ

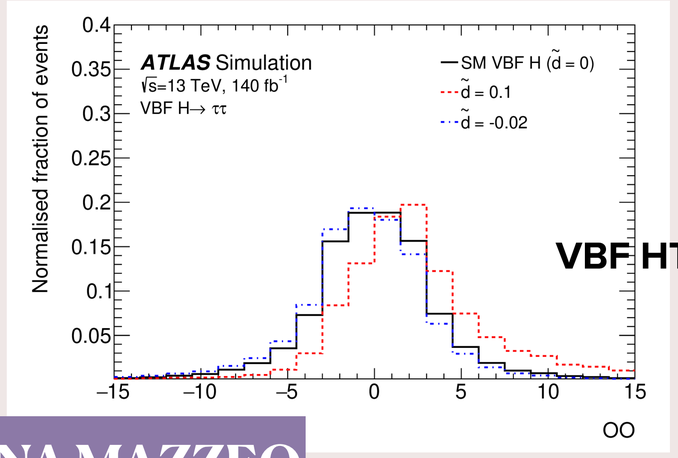


CP was truly the star this year...

Summary of constraints on $c_{H\tilde{W}}$:

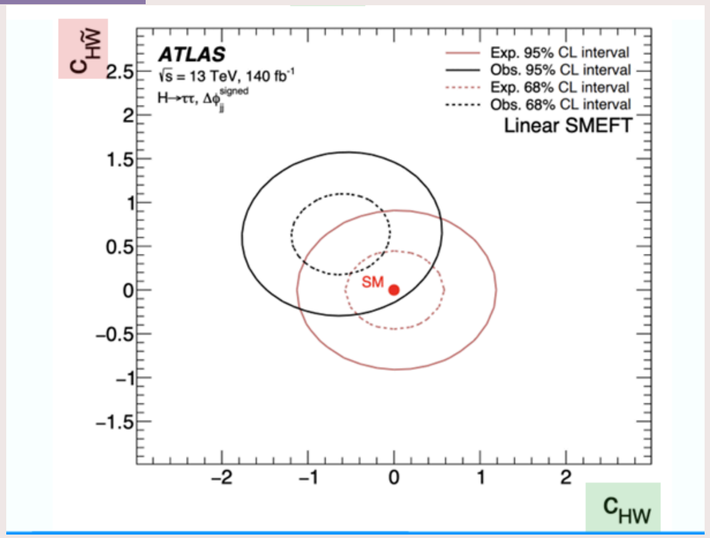


ELISE LE BOULICAUT ENNIS



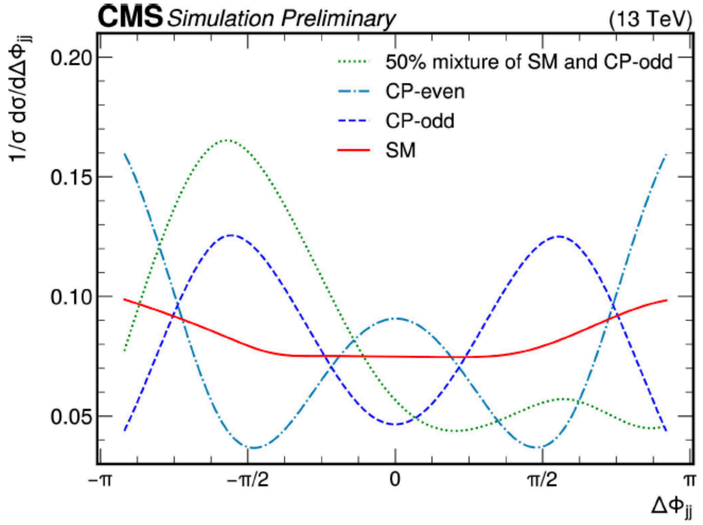
VBF HTauTau

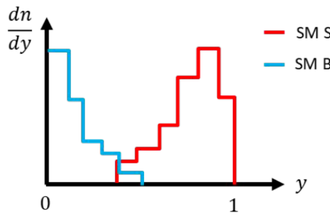
ELENA MAZZEO

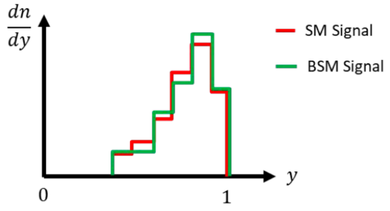


CP was truly the star this year...

$$\Delta\Phi_{jj} = \phi_{j_k} - \phi_{j_l} \quad \text{with} \quad \eta_{j_k} > \eta_{j_l}$$

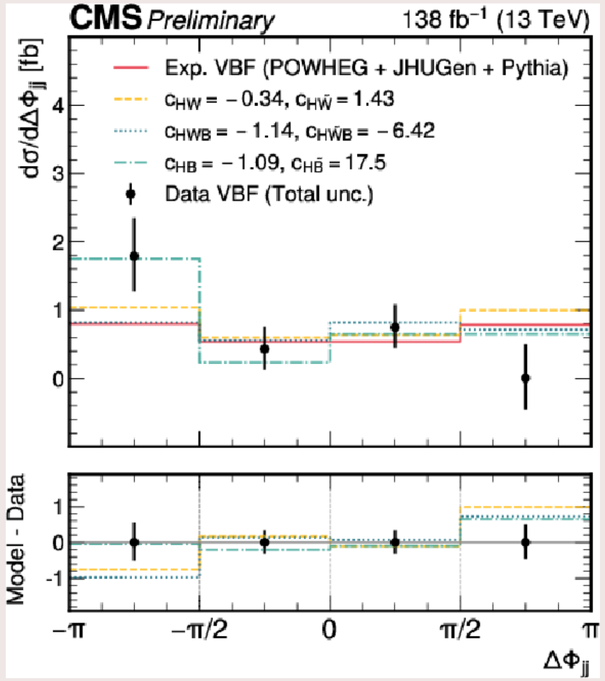


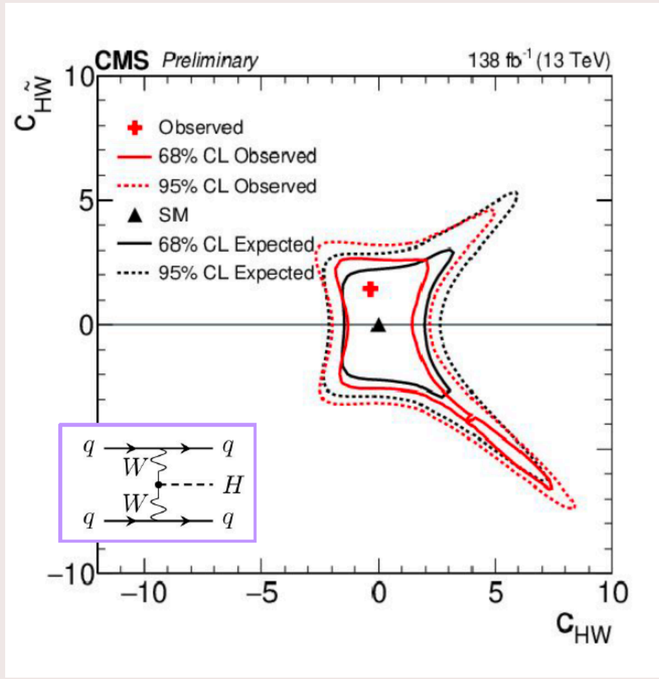




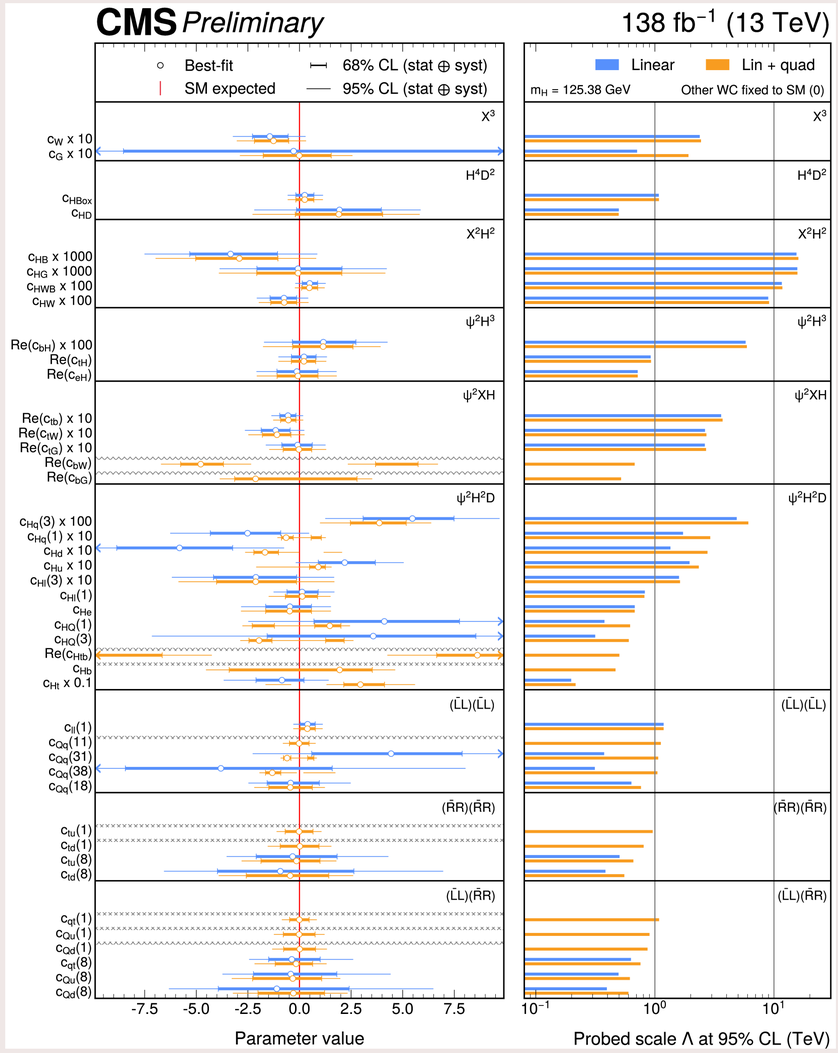
- **EFT Constraint from differential cross sections (in WH(Hbb) in this case) as a function of the difference in azimuthal angle Δϕjj between the two jets.**

BENEDETTA CAMAIANI





SMEFT Fits from the Combination

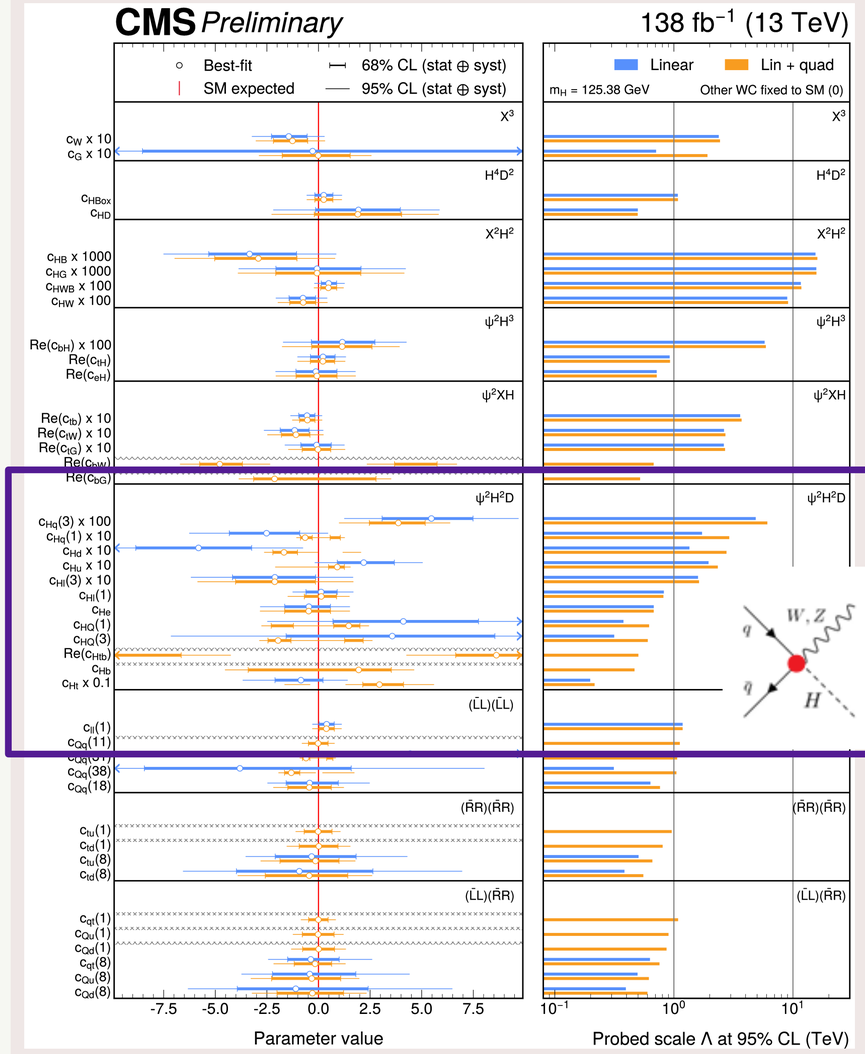


- Combination of measurements in simplified template cross section (STXS) framework → interpreted in terms of SMEFT operators

SUMAN CHATTERJEE

- CMS: 43 Coefficients Fitted
- 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.

SMEFT Fits from the Combination



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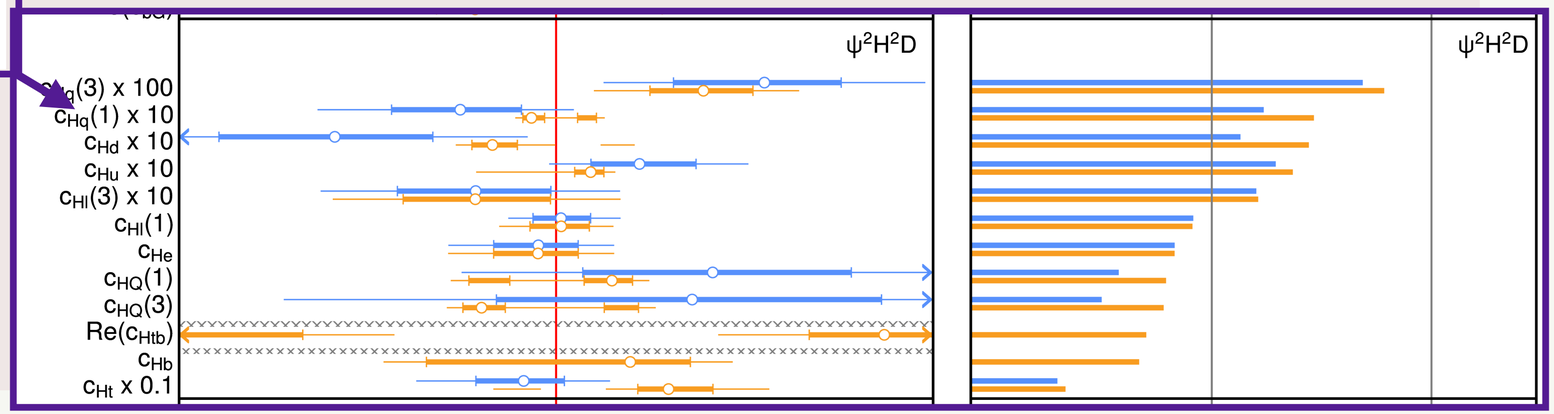
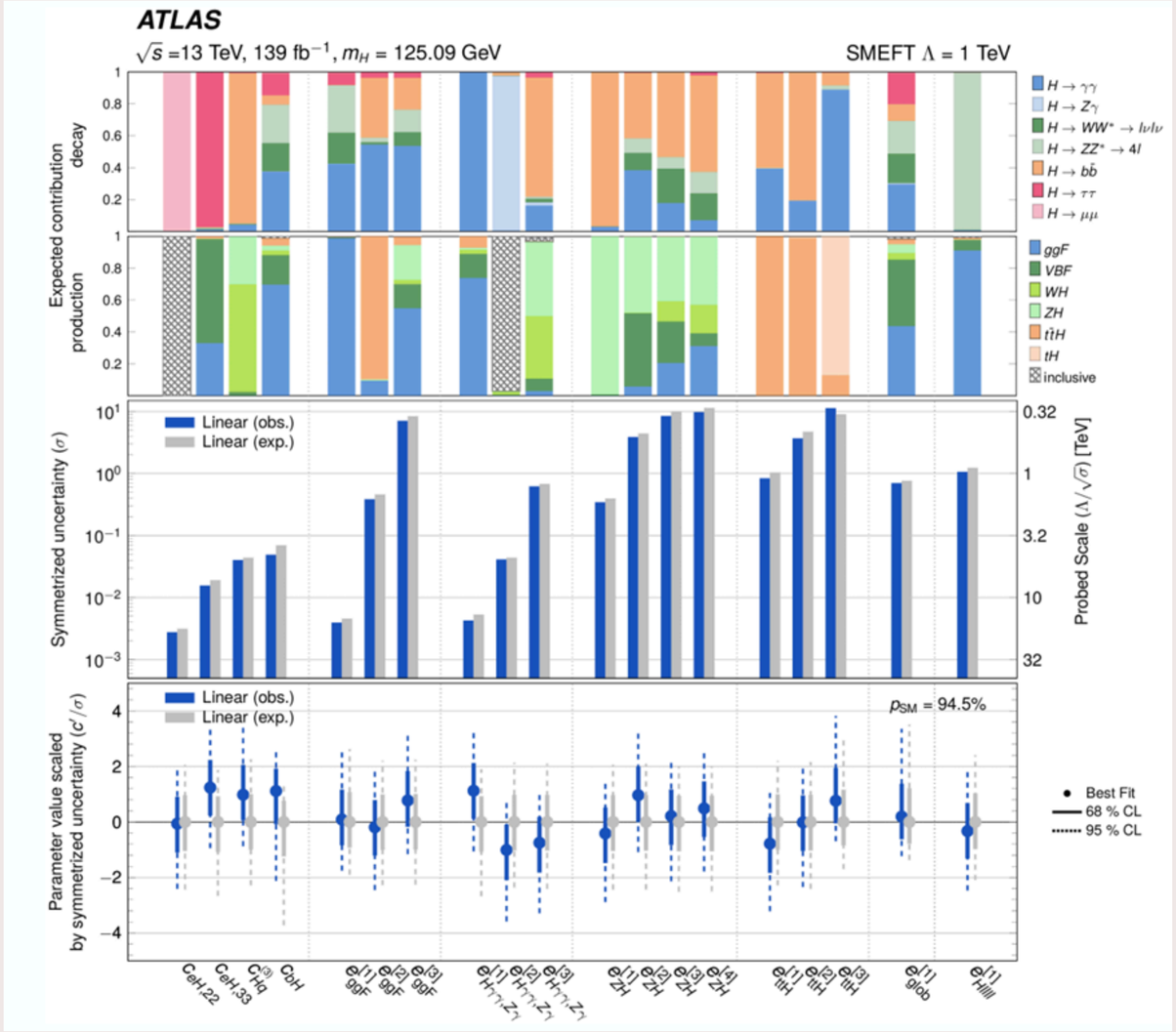
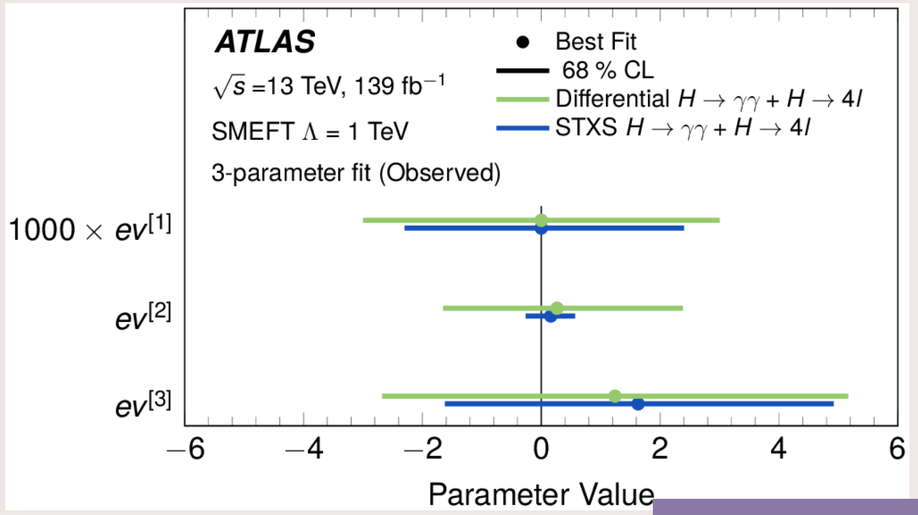


SMEFT Fits from the Combination



- STXS Fit: 19 parameters
- Differential Cross Section: 3 parameters, ev[1], ev[2], ev[3] (Mostly C_{HG}, C_{tG}, C_{tH})
- STXS has typically better sensitivity than differential measurement (able to separate production and decay modes)



ELENA MAZZEO

Mapping the Higgs Potential

Seeing double: HH

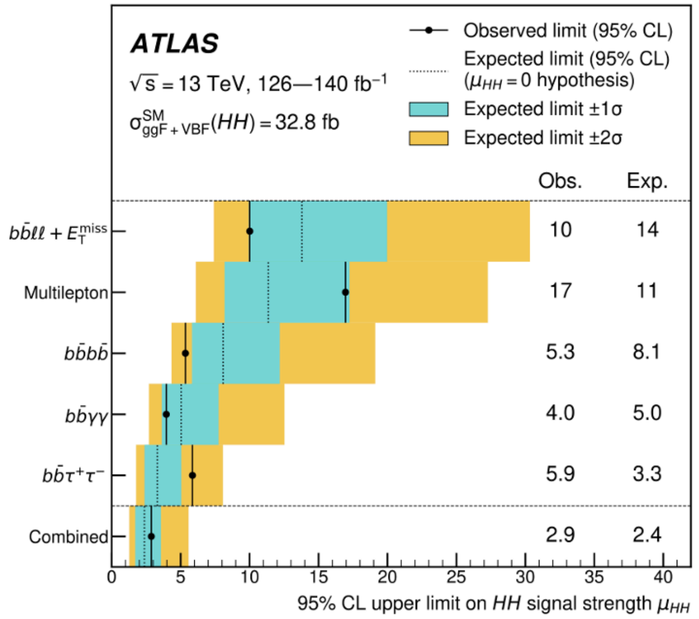
LORENZO SANTI

LEONIDAS PAIZANOS

With Run2 data analyzed, at 95%CL:

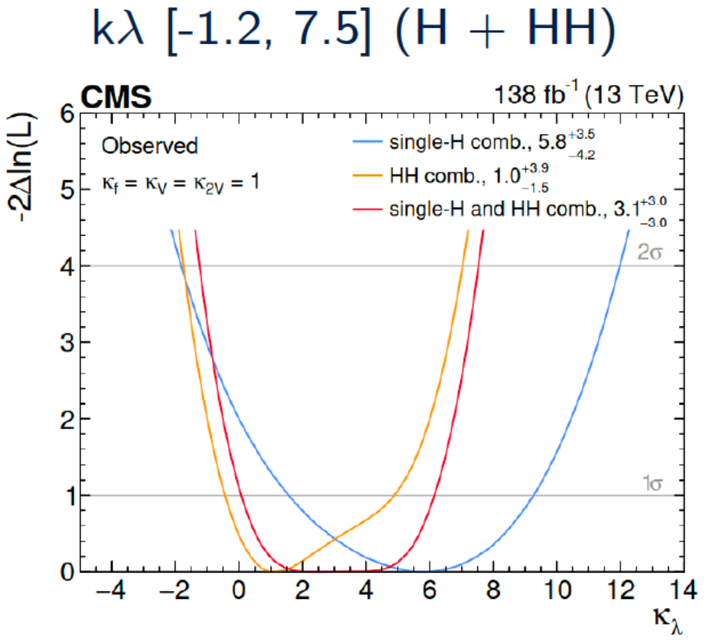
$$CMS: \quad \mu_{HH} < 3.5\ (2.5), \quad -1.39 < \kappa_\lambda < 7.02$$

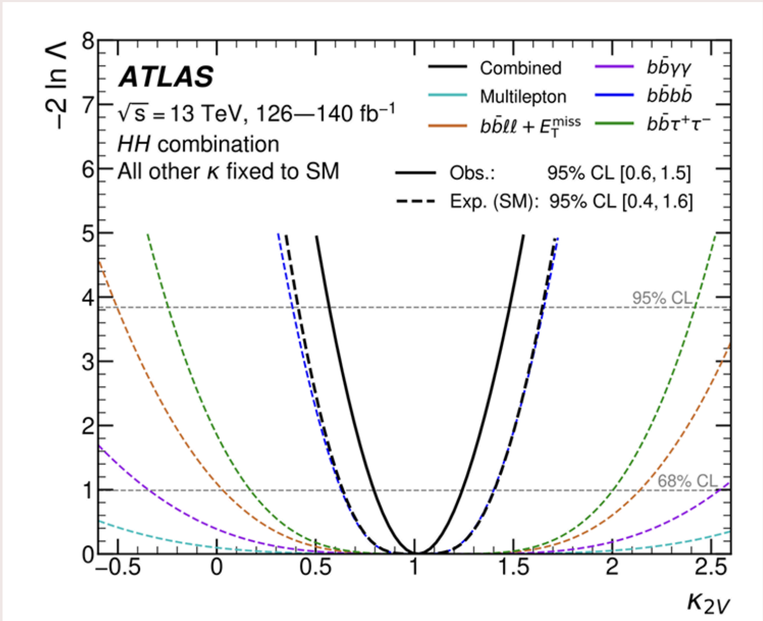
$$ATLAS: \quad \mu_{HH} < 2.9\ (2.4), \quad -1.2 < \kappa_\lambda < 7.2$$



Observed HH SM Significance: 0.4 σ

Expected HH SM Significance: 1.0 σ



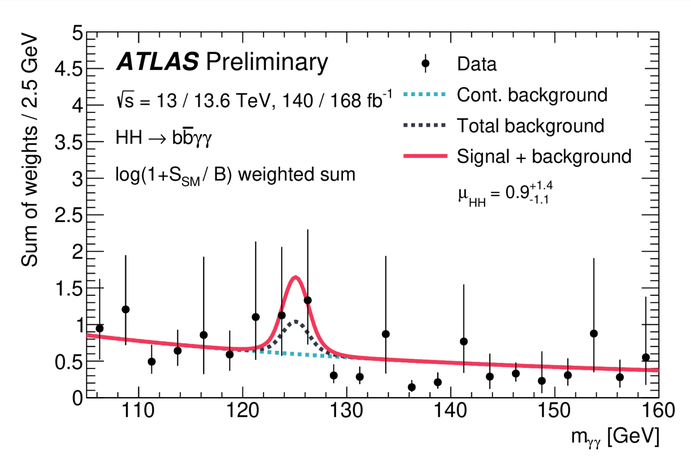


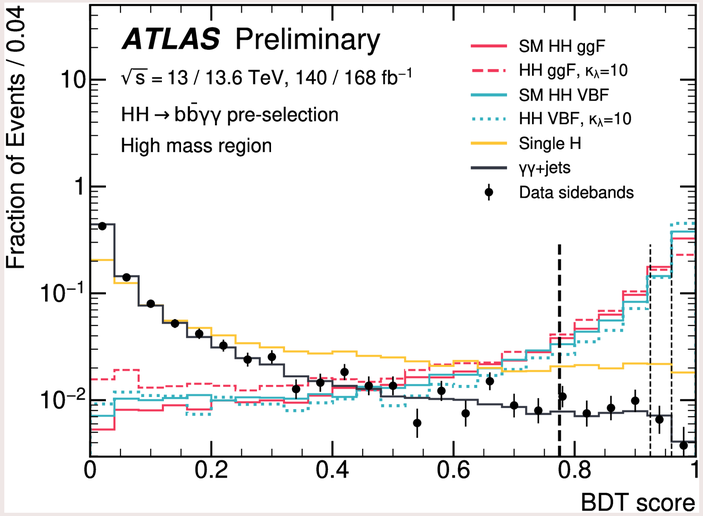
CMS HIG-20-011

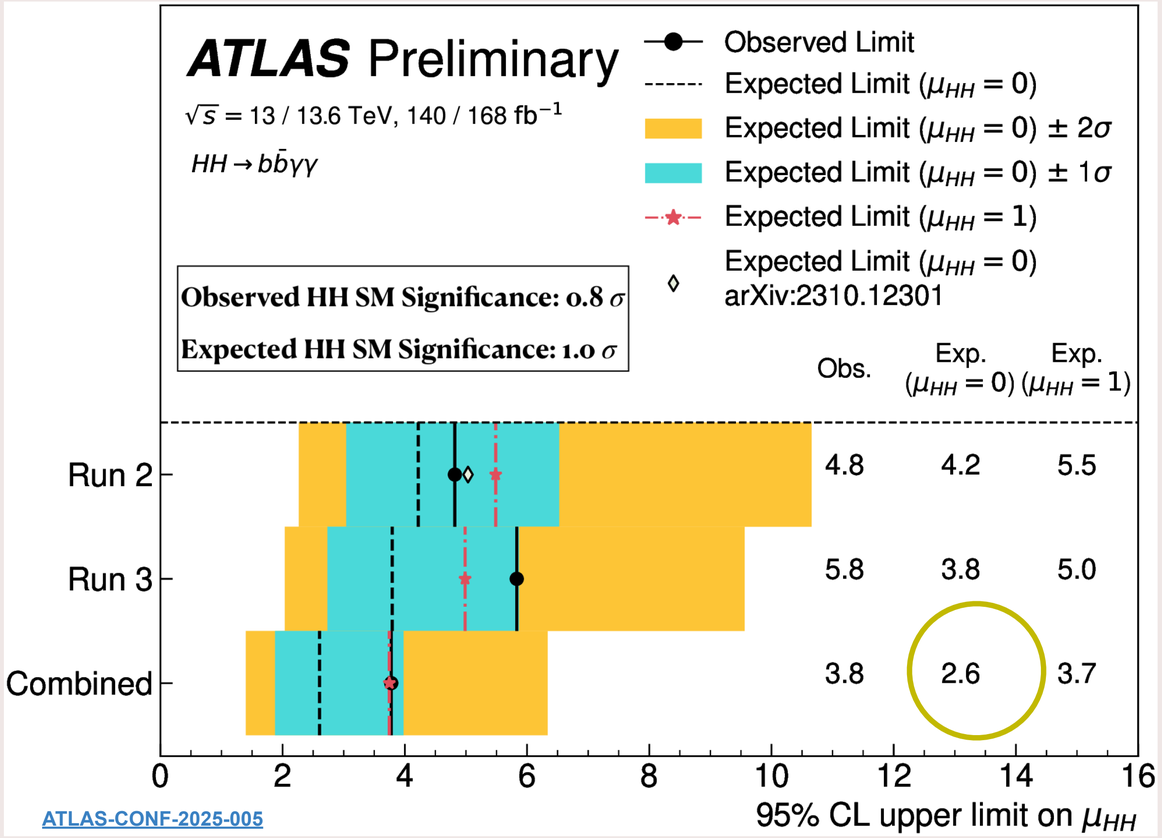
The First 308 fb^{-1} HH Result

LORENZO SANTI

$$\mu_{HH} = 0.9^{+1.4}_{-1.1} \quad -1.7 < \kappa_\lambda < 6.6 \quad \text{at 95\% CL}$$

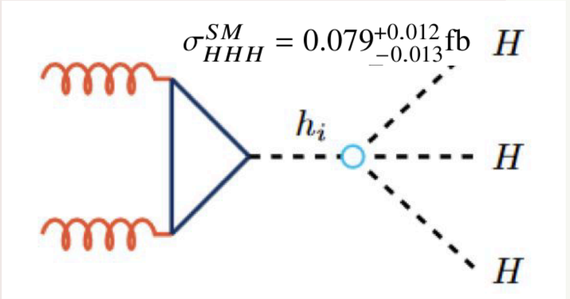






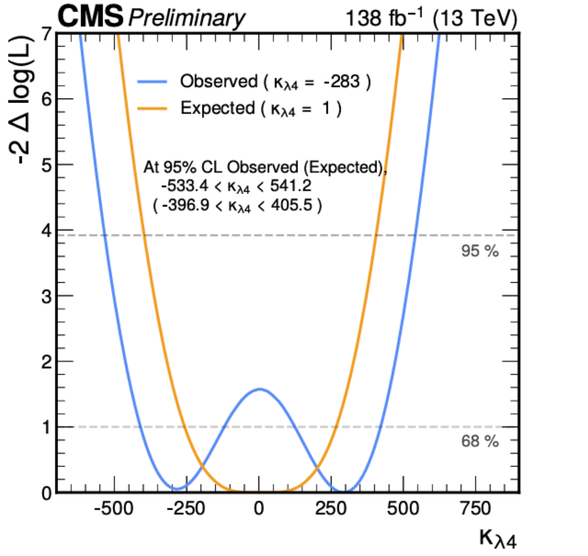
- Improvements + Statistics: single channel already at 2.6xSM - comparable to Run2 combination!

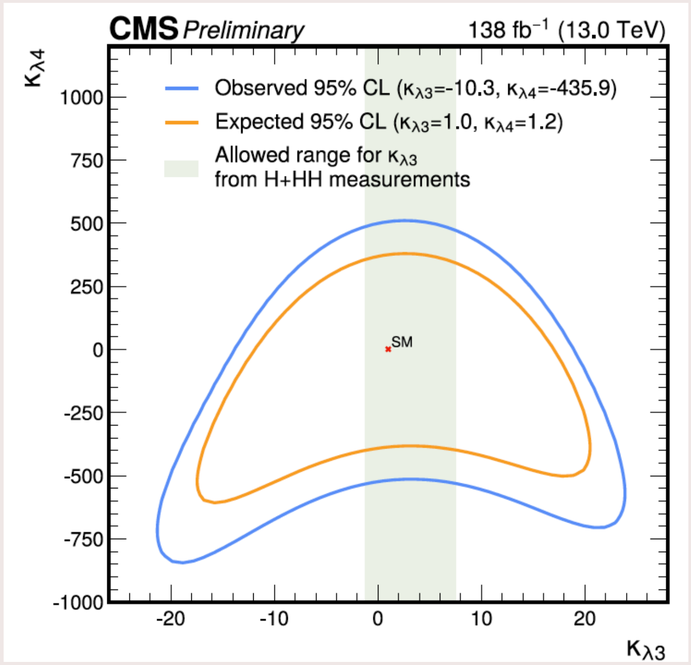
The quest for HHH?

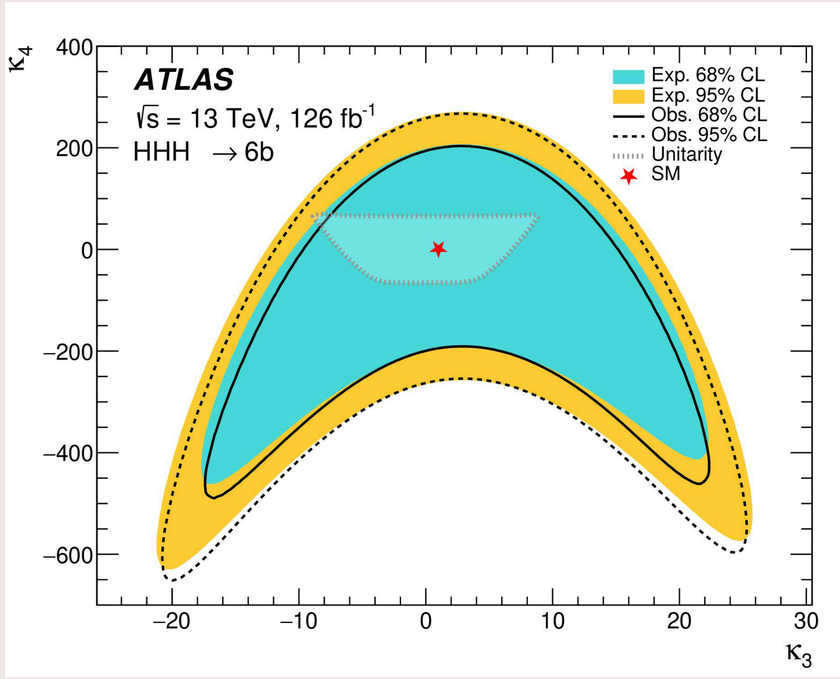


- Very very small cross section, but **access to the quartic self-coupling (κ_4)**
- At the LHC: probe BSM scenarios
- First results, 6b (ATLAS) μ< 760 (750) at 95% CL and 4b2gamma (CMS) μ< 3400 (2086) at 95% CL

$-533(-397) < k_{\lambda 4} < 541(406)$





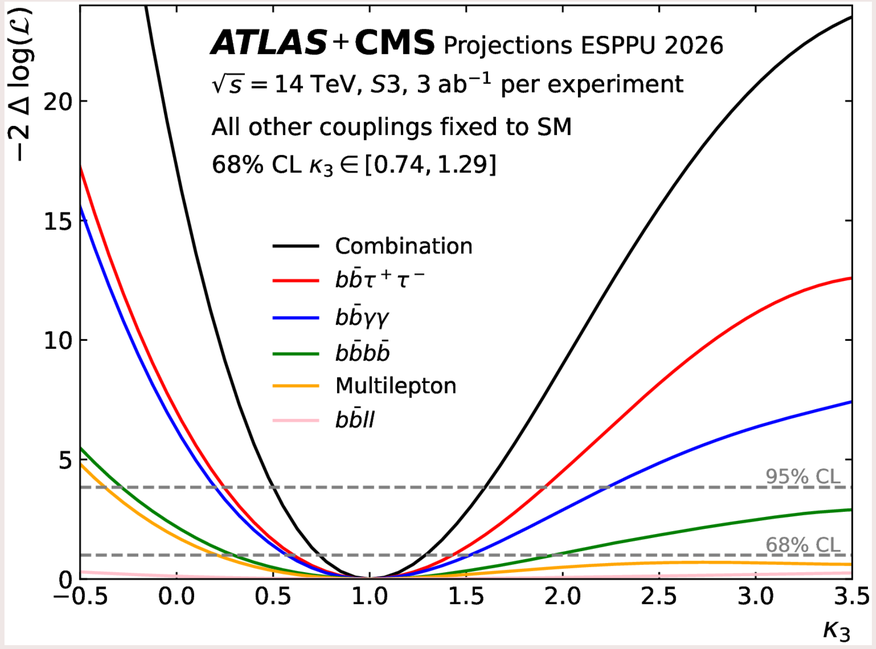


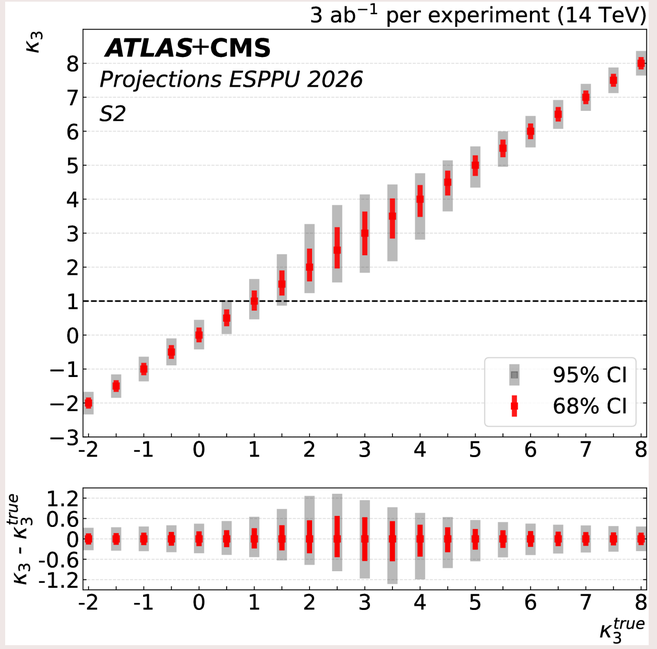
Exceeding expectations

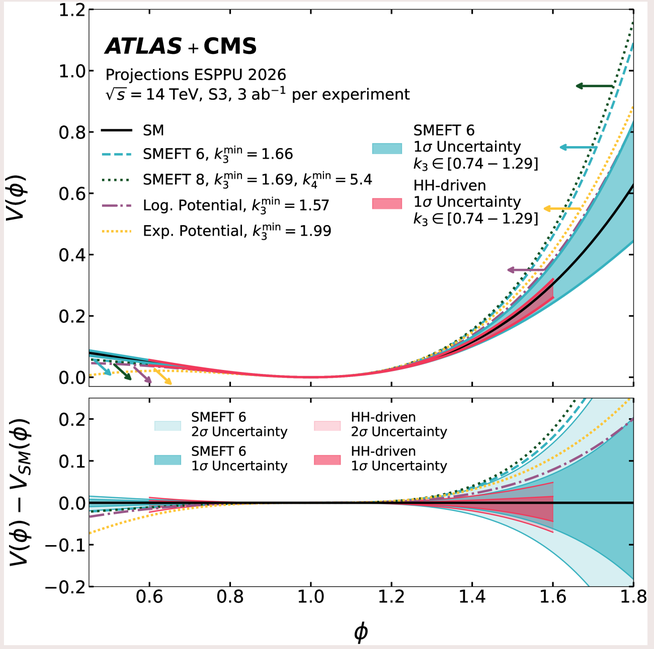
- When discussing HH we look forward to future runs - remembering that analysis outpace the projections!
  - Observation in combination already at 2 ab-1
  - Over 4 sigmas per experiment at 3 ab-1

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

LORENZO SANTI

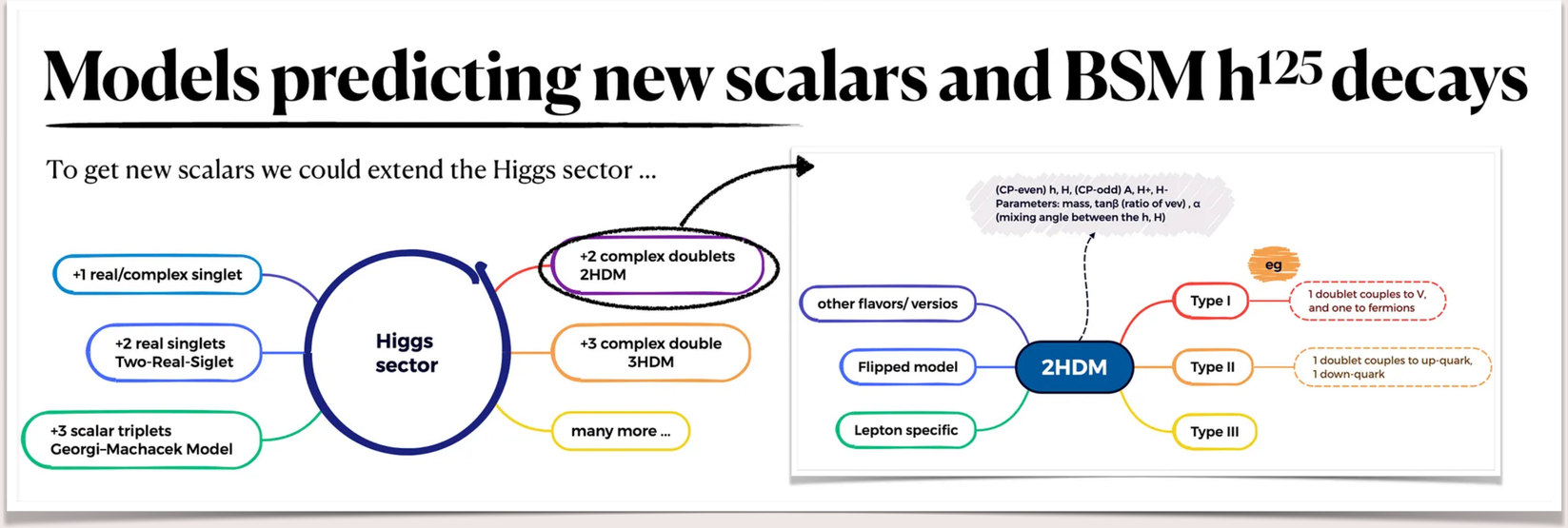






BSM, Where are you?

Higgs Partners?



ELENI SKORDA

SIDDESH SAWANT

While we scrutinize Run3, we are still squeezing all the physics from the Run2 datasets

Pushing the searches forward we want to go beyond what we did before:

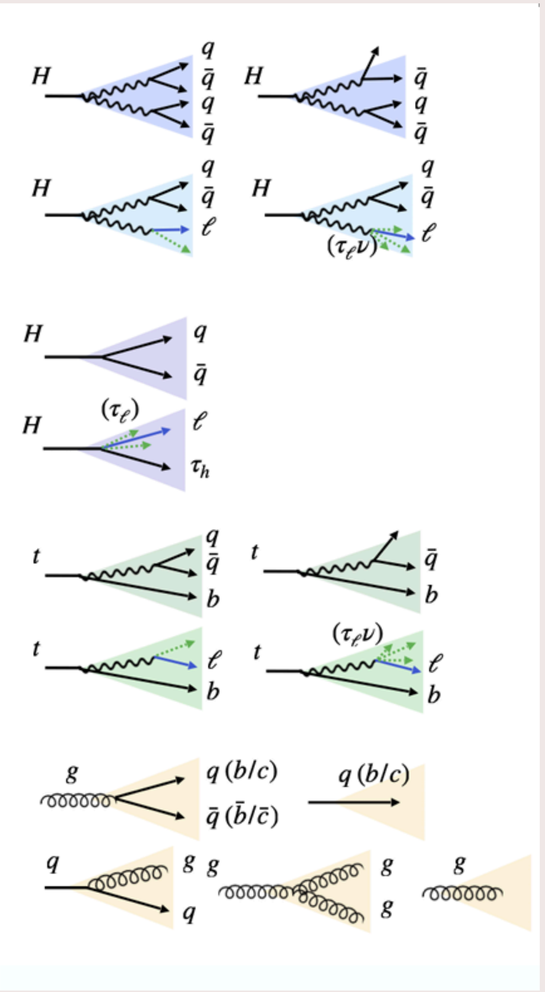
➡Look for new phase-spaces, **exploit new techniques (new taggers, boosted objects, scouting / long lived techniques…)**

Too many searches shown to discuss all of them, some examples…

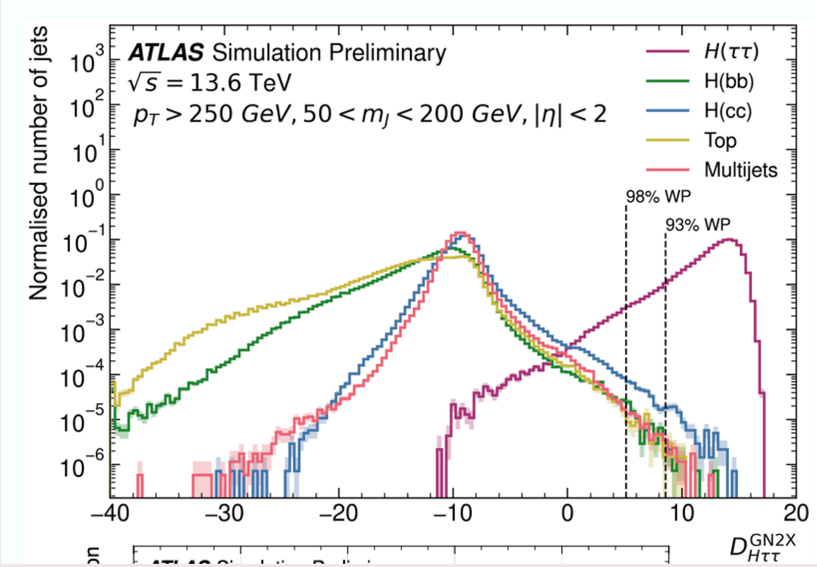
New tools

ANDREA SCIANDRA

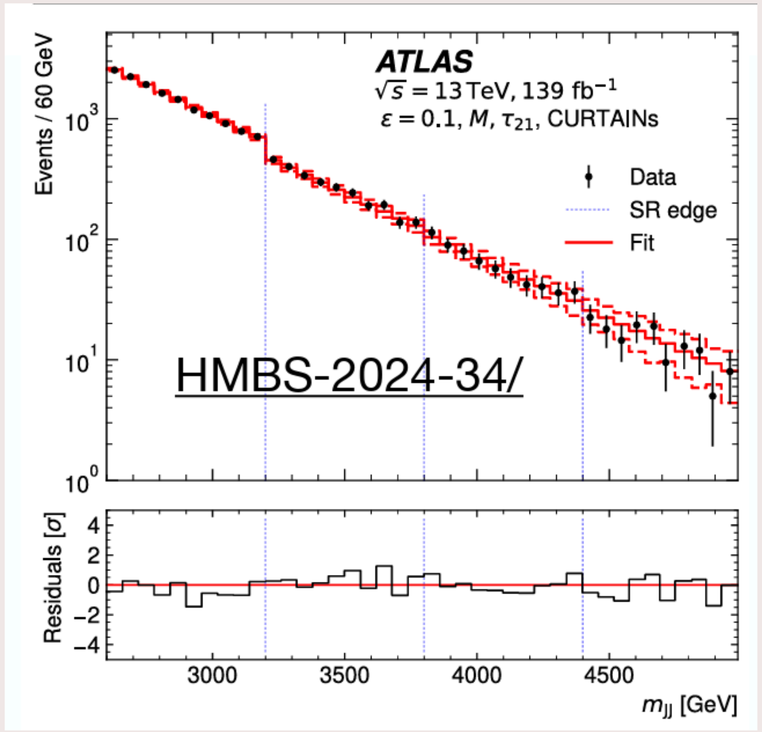
MARIA MAZZA



➡Understanding complex, merged objects using ML, at low and high momentum



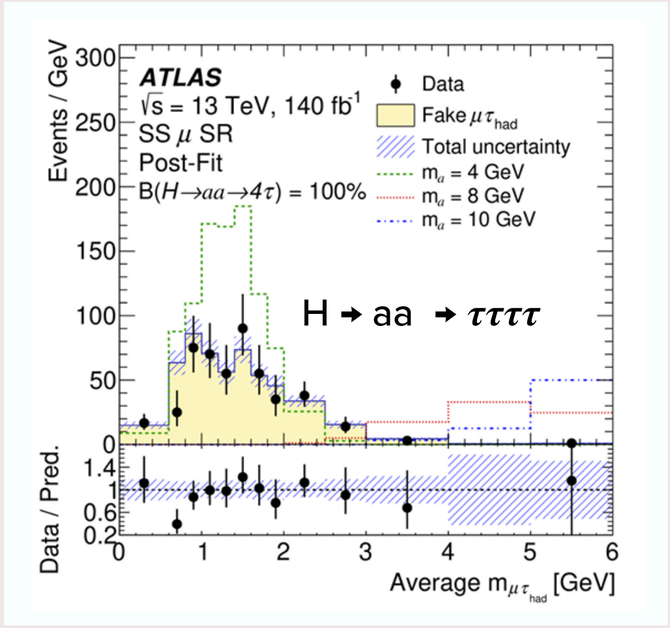
➡Scouting, analysis directly at trigger level? (Eg: inclusive phi->ditau , from 20-60 GeV, see CMS-EXO-24-012)

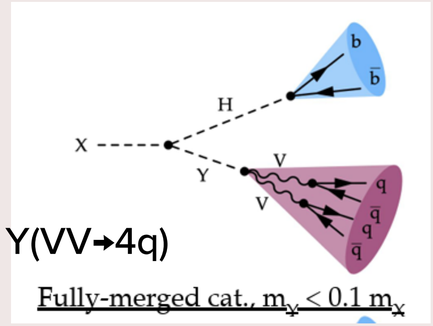


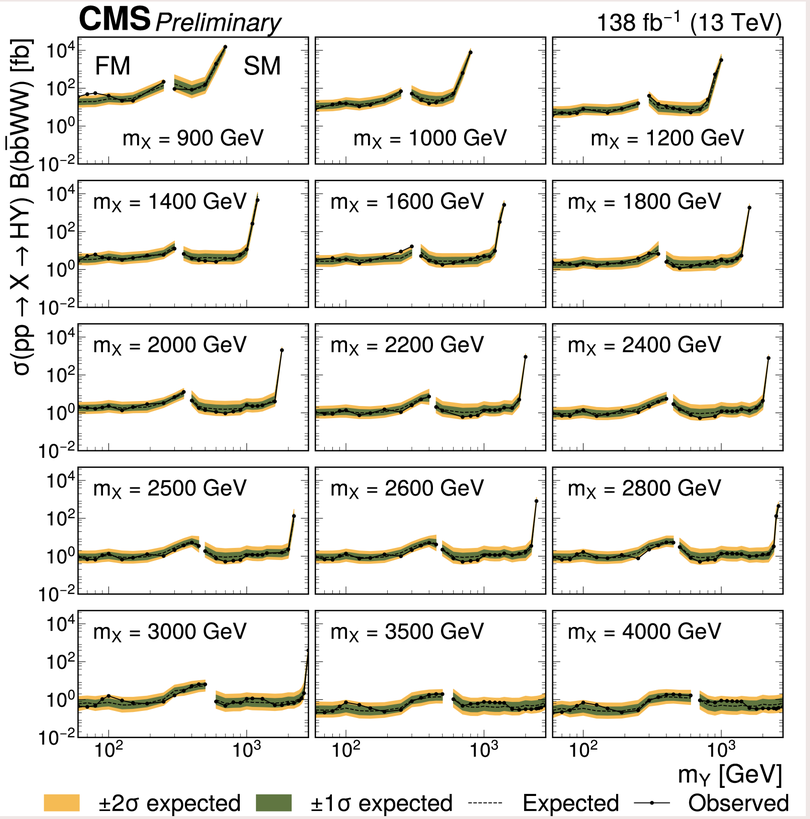
➡Looking for ‘anomalies’ - what can ML see? Eg: Weakly Supervised Anomaly Detection for Light Di-Jet Resonance

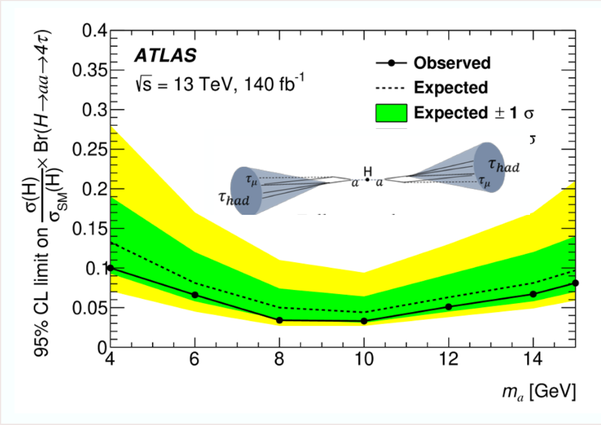
Going Boosted

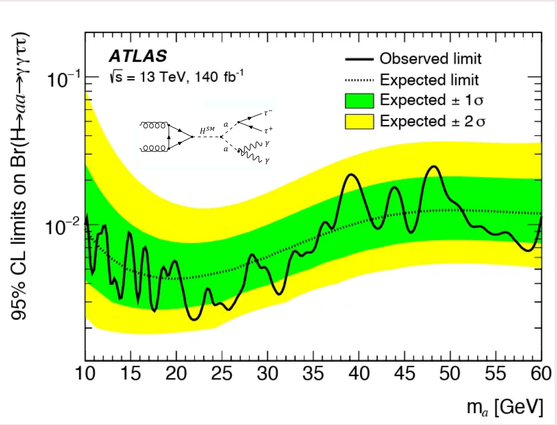
Exploiting the variety of new techniques to reconstruct boosted objects in h→aa decays AND Resonant Searches











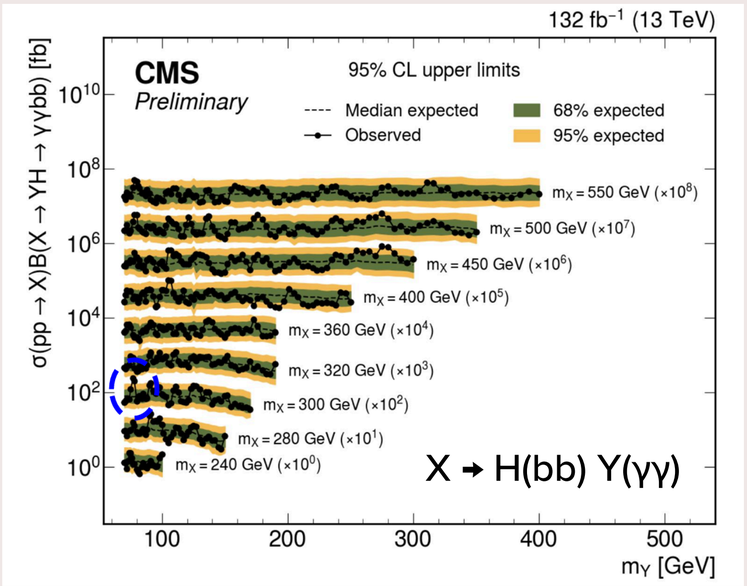
ELENI SKORDA
ANDREA SCIANDRA
GADI NINIO
SIDDESH SAWANT
MARIA MAZZA

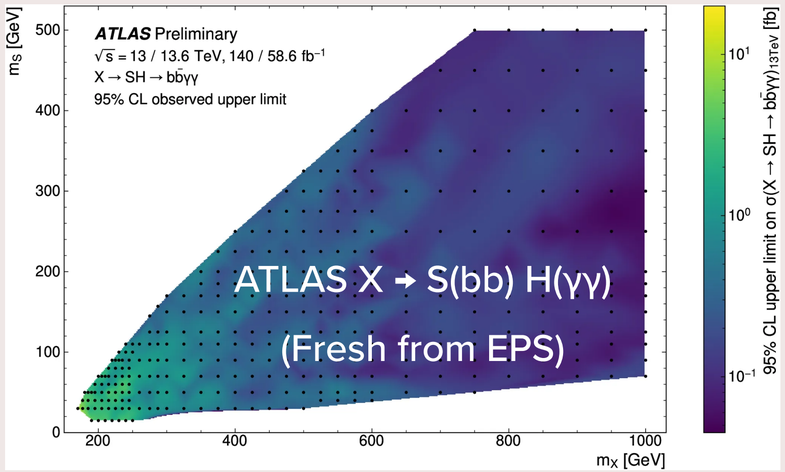
HY Resonances

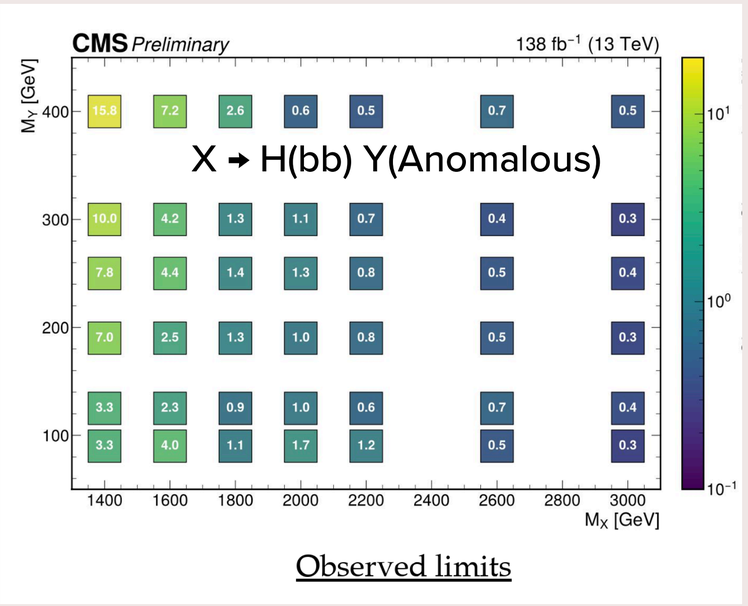
SIDDESH SAWANT

Few years ago, switching from the standard X→HH to X→HY searches was high on the wishlist from our theory friends

We delivered! In a variety of final states, from the obvious to more and more complicated (Y→Anomalous, Y→MET). And while the picture is not complete, the searches are ongoing… and improving.

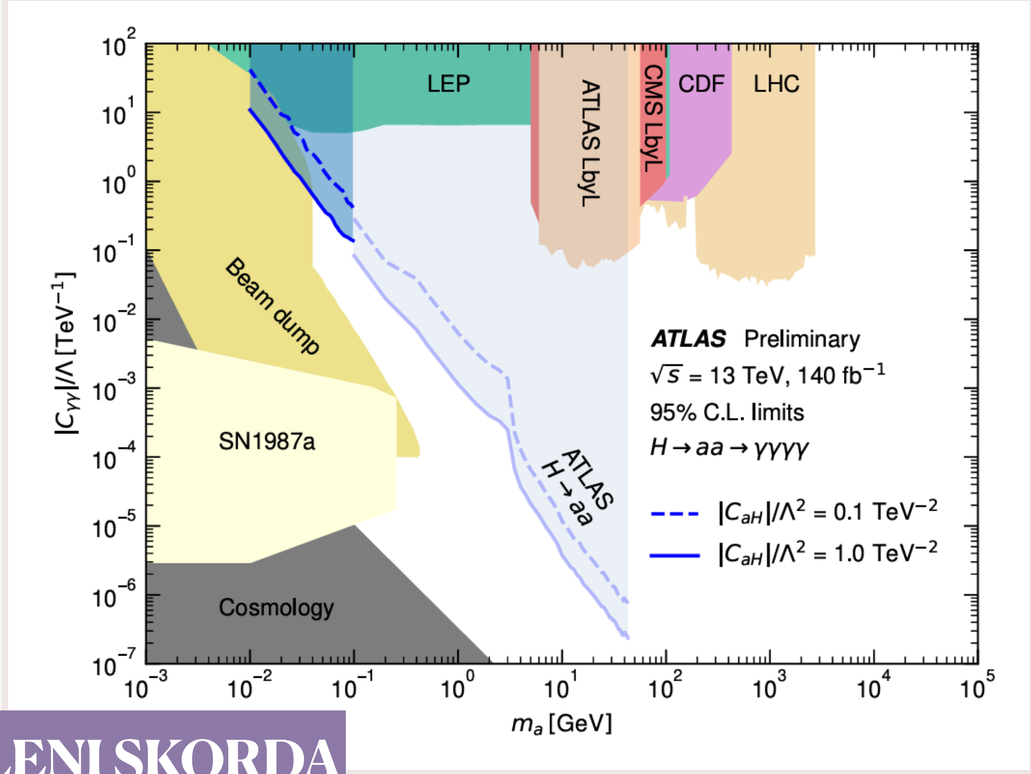


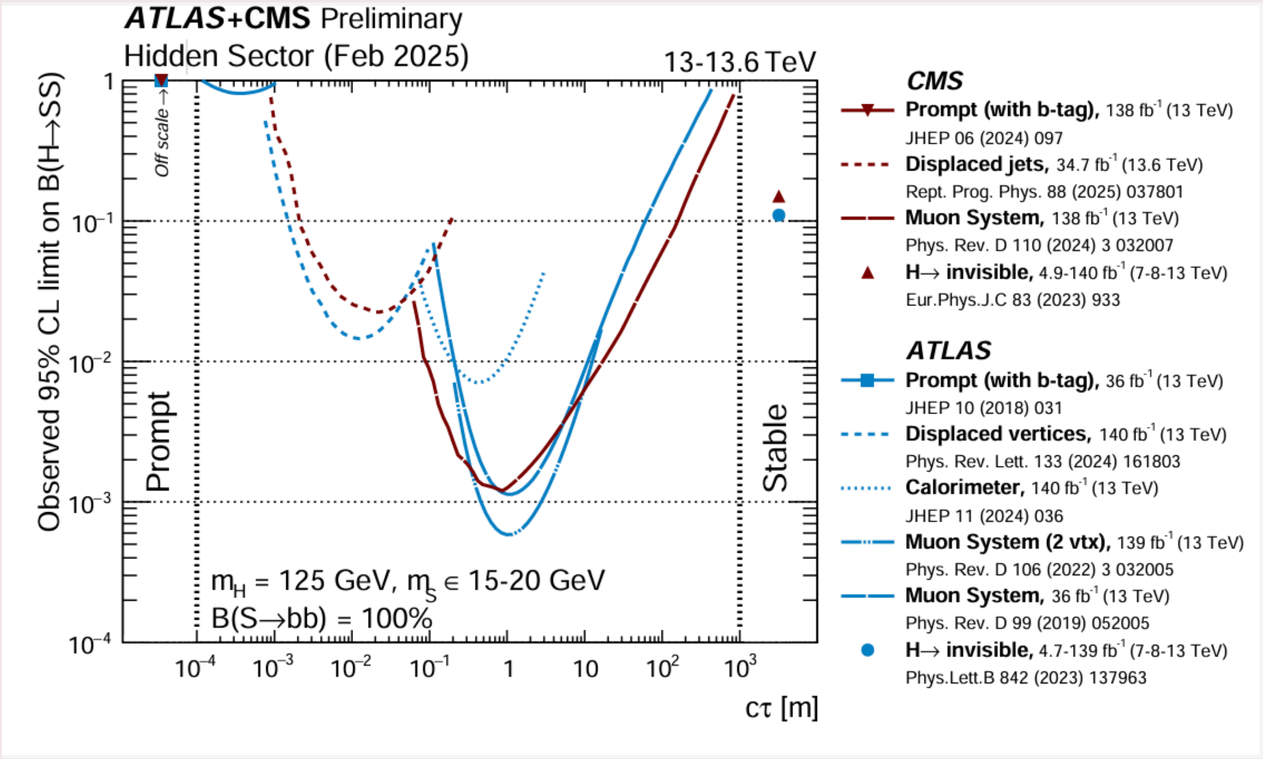




Observed limits

Exotic Decays: Long Lived?





ELENI SKORDA

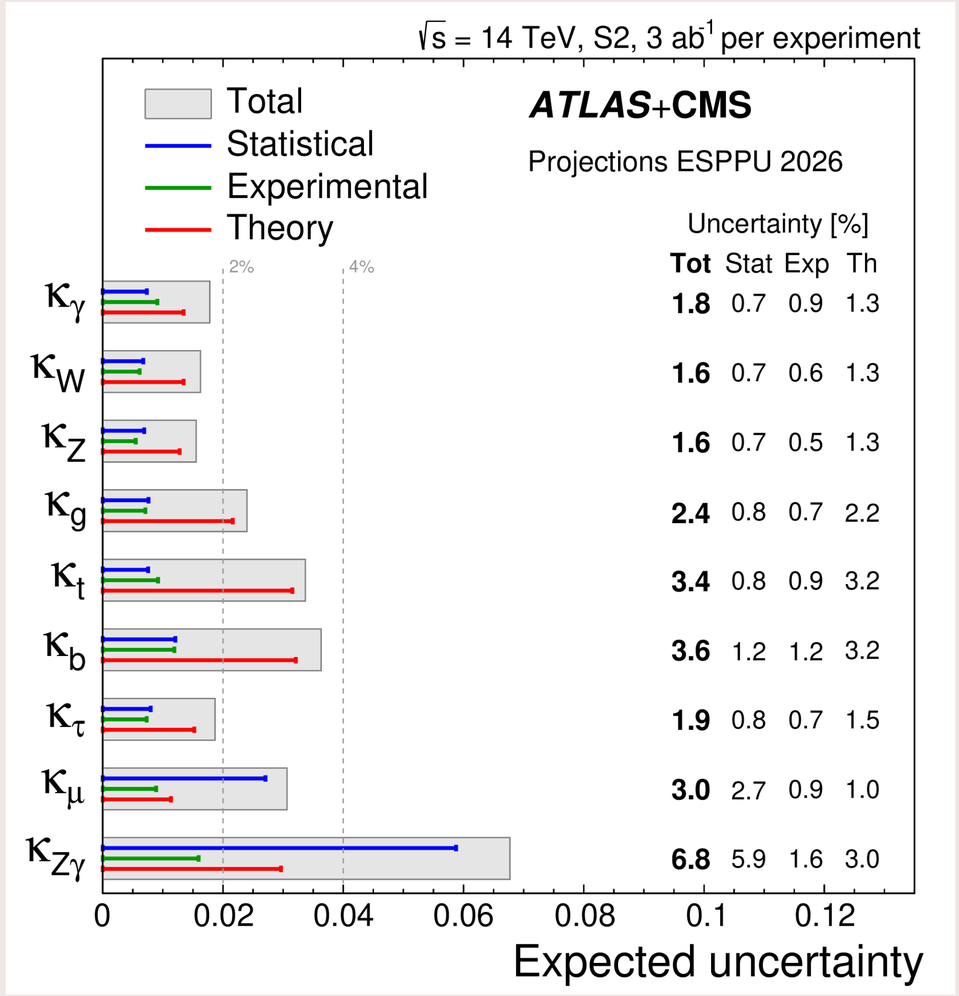
Reinterpretation of previous result, to lower masses and including long lived

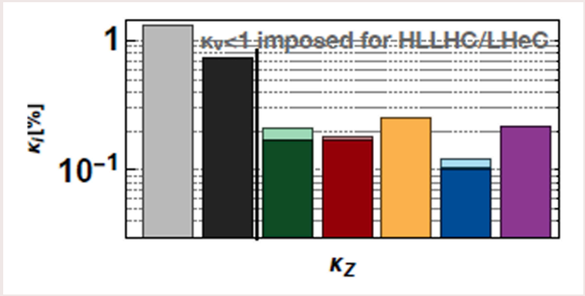
Lively area with many developments!

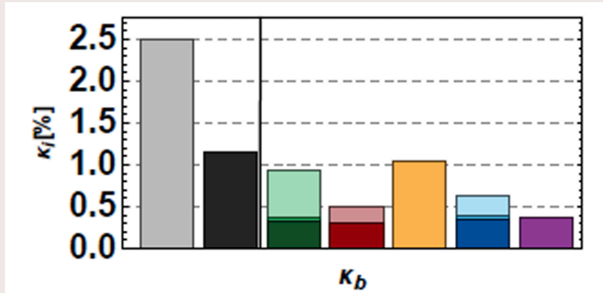
Comparing directly ATLAS and CMS...

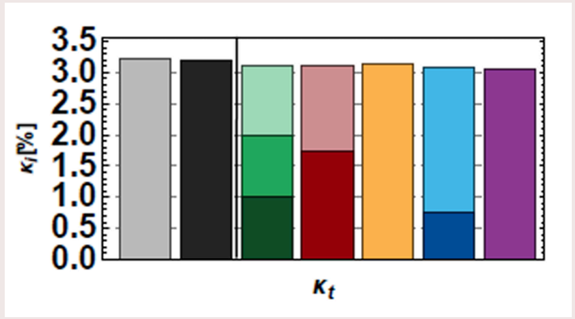
Future

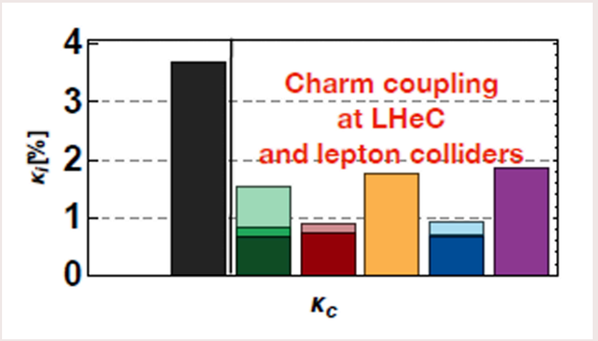
The future of couplings

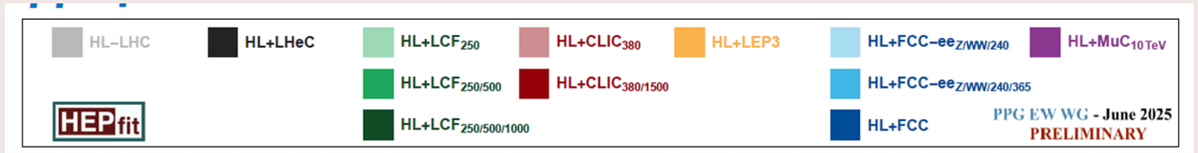








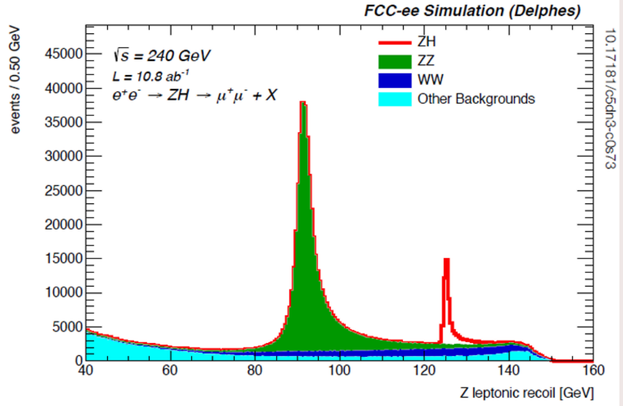


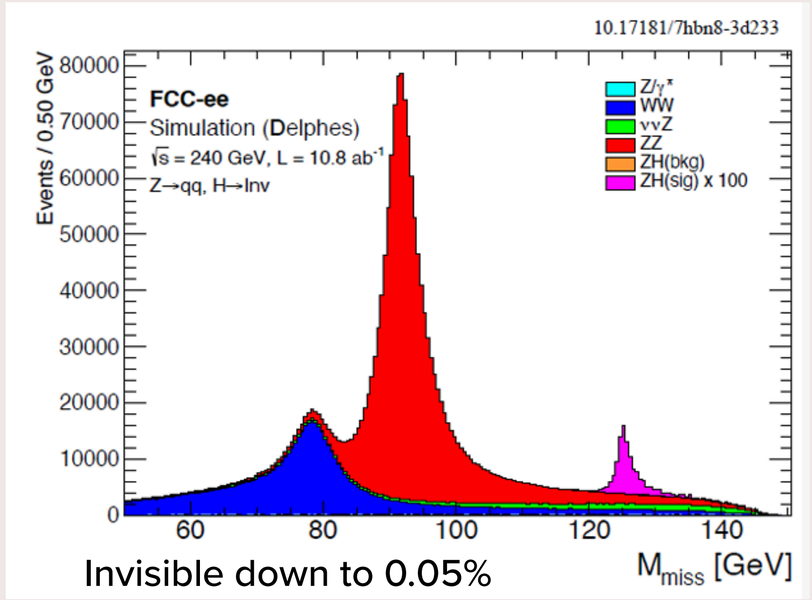


FCC-INT always provides the best precision

The future of measurements

Precision on total xsect:
0.3% FCC, 0.8% LC, 0.6% LEP3





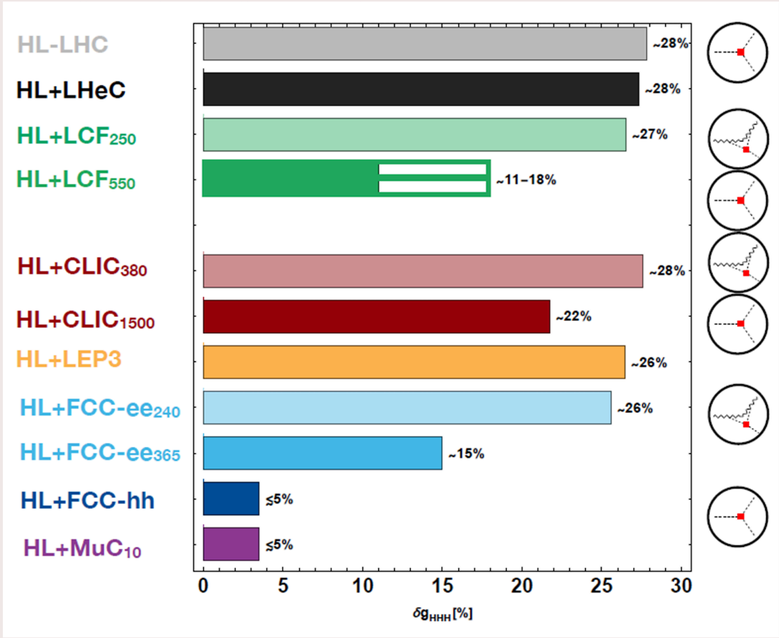
Invisible down to 0.05%

HL-LHC: 21 MeV
FCC-ee: 3 MeV
Linear collider: 12 MeV
LEP3: 15 MeV

Higgs mass estimates

Access to charm (1.5-2.5 %)

Potential access to electron yukawa at FCCee ?



Beyond Higgs - precision measurements in e+e-: Z pole, top and W, QCD, Flavor Physics

We have a "Plan A"

FCCee

FCChh

High luminosity

Energies up to top threshold

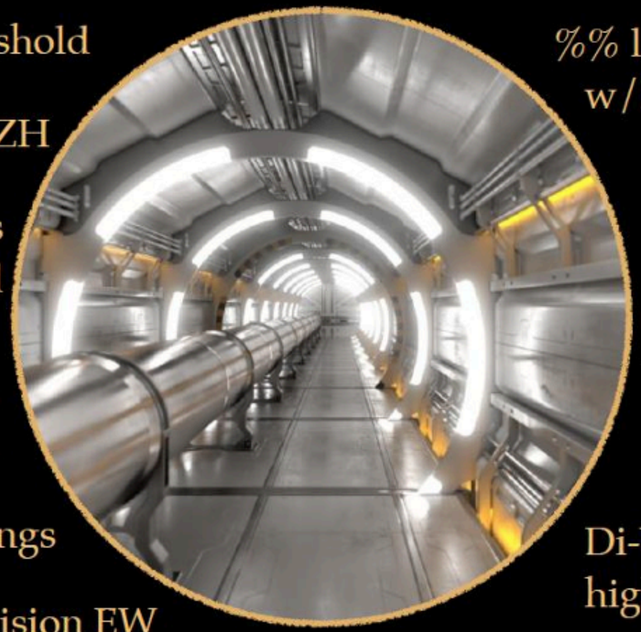
Easy transition between Z, WW, ZH

% to %% level precision on Higgs couplings (except top), stats limited

Best precision on Higgs couplings of all e+e- options

Possible 1st generation couplings

TeraZ run for precision EW



%% level precision on Higgs w/FCCee, ttH production

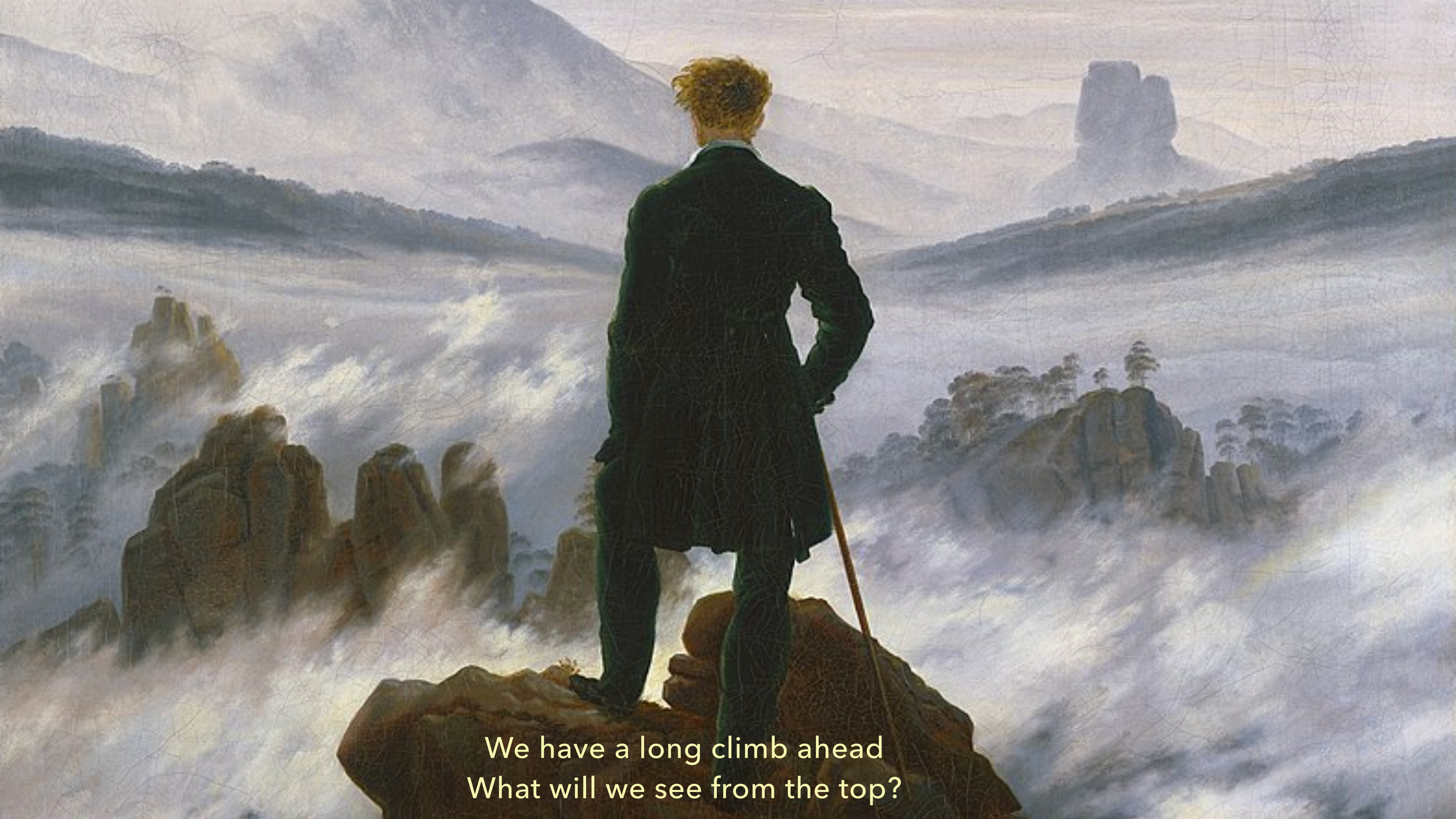
% level precision on Higgs self-coupling

Access to rare decays and high pT distributions with strong BSM potential

Di-boson measurements at high energy

Combined precision top results

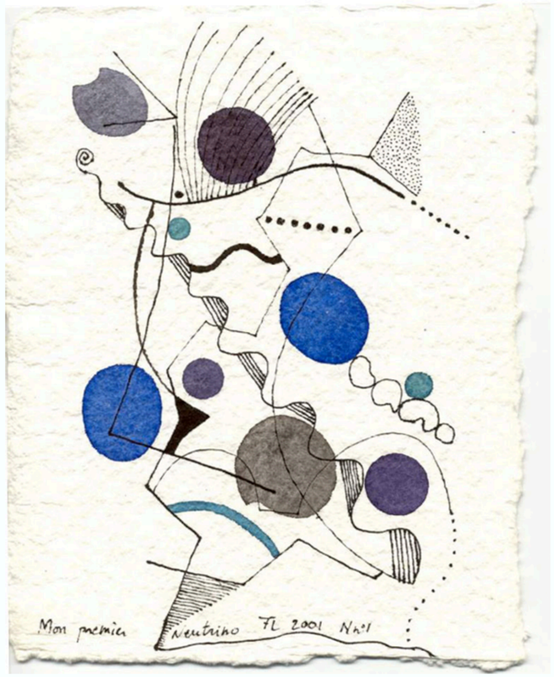
24

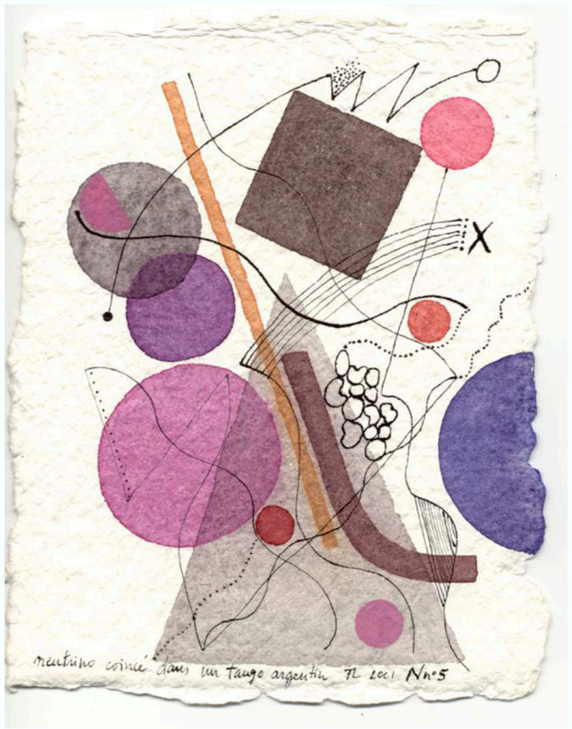

We have a long climb ahead
What will we see from the top?

15 years of Hunting Higgses

- 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, and the journey goes on.
- Today, the Higgs is **one of our best tools to discover new physics** (direct or indirectly).
- With Run2 analysis still arriving (including updates to the combinations!), we are deep in the analysis of Run3 datasets, with 13.6 TeV results starting to come
- To go beyond our current results both experiments are invested in M**L developments in tagging, reconstruction, and inference: improving sensitivity for future analysis way beyond statistics**
  - This week we have discussed heard about their impact in charm, boosted phase-spaces, the exploration of CP… and this is not the end of the story, more to come!
  - One of the biggest challenges for the future is is finding a couple of Higgses: 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. Precisely mapping the Higgs sector will be the legacy of the LHC, a stepping stone for the future machines. The future looks bright for the Higgs, and we should work together to make it brighter!

Thank you for a great conference!





Pierre Ramond

Funding acknowledgement:

Generación de Conocimiento: PID2020-116262RB-C41, PID2021-122134NB-C21, and ID2023-147706NB-I00, funded by MICIU/AEI/ 10.13039/501100011033 and FEDER, UE

Consolidación Investigadora 2023: CNS2023-144781 financiada por MICIU/AEI /10.13039/501100011033 and European Union NextGenerationEU/PRTR

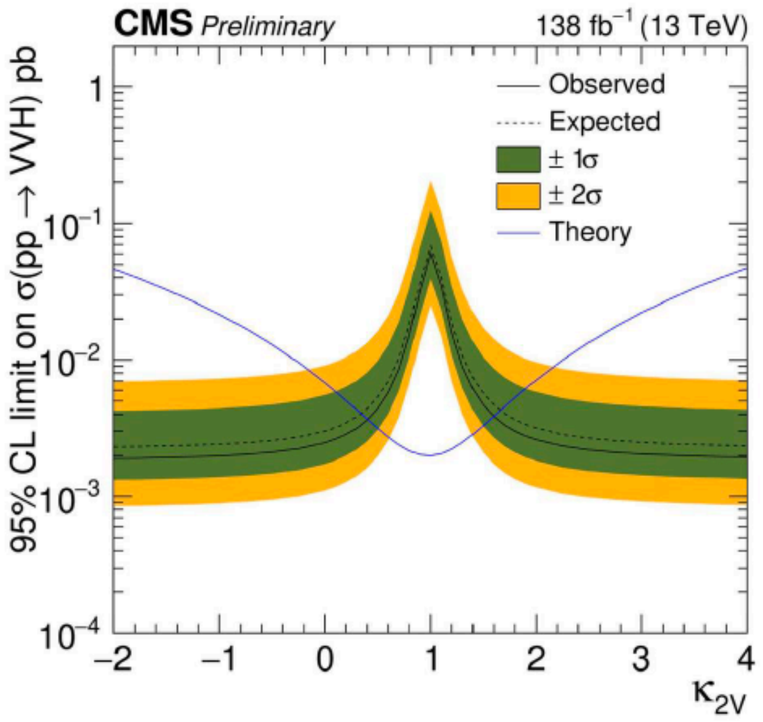
EWK VVH, Hbb

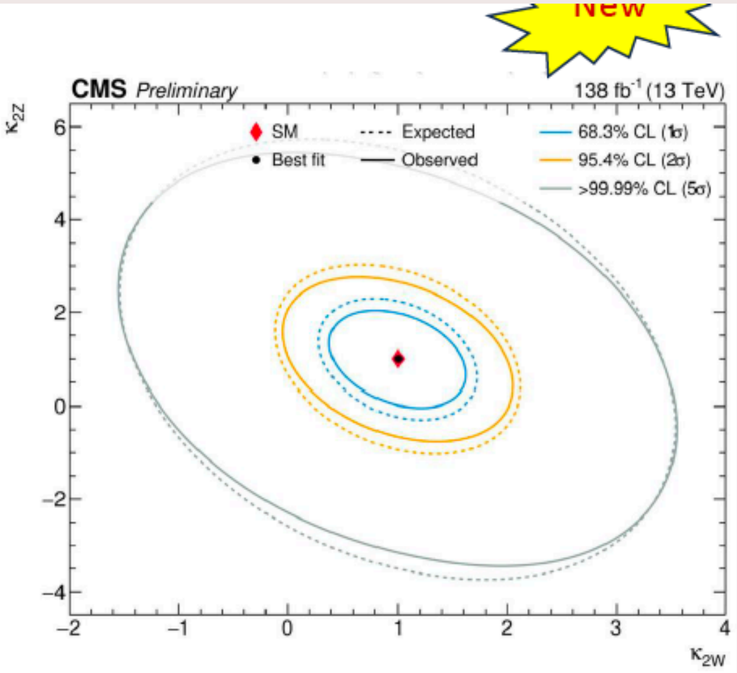
- Set limit on K_{2v} - approaching current constraints from di-Higgs:

  $0.41 < \kappa_{2V} < 1.59$

- Produced current tightest limits on K_{2W} and K_{2Z} : $0.17 < \kappa_{2W} < 1.80$

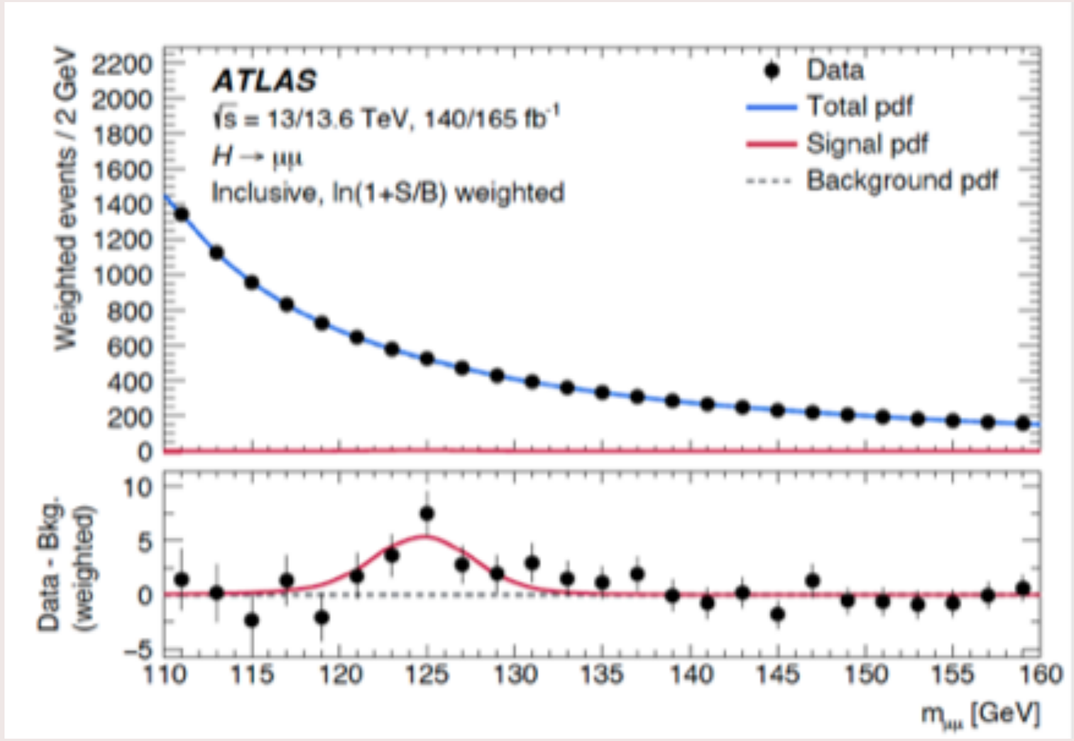
  $-0.37 < \kappa_{2Z} < 2.37$

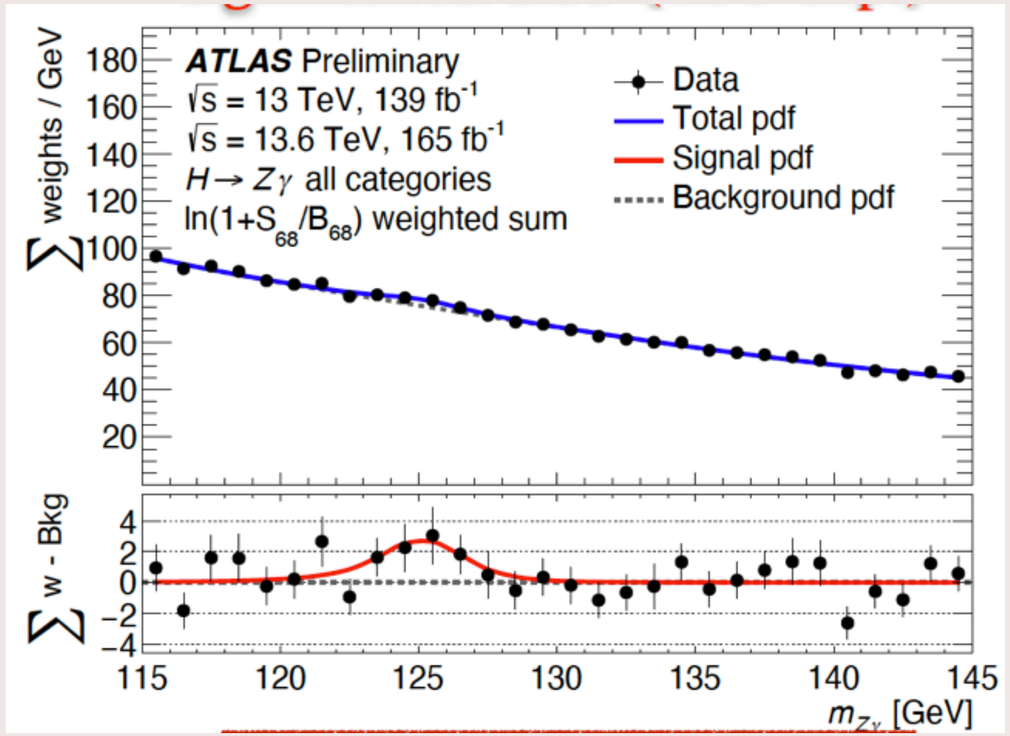




HIG-PAS-24-003

Rare Decays: exploiting Run3 (22+23+24) data





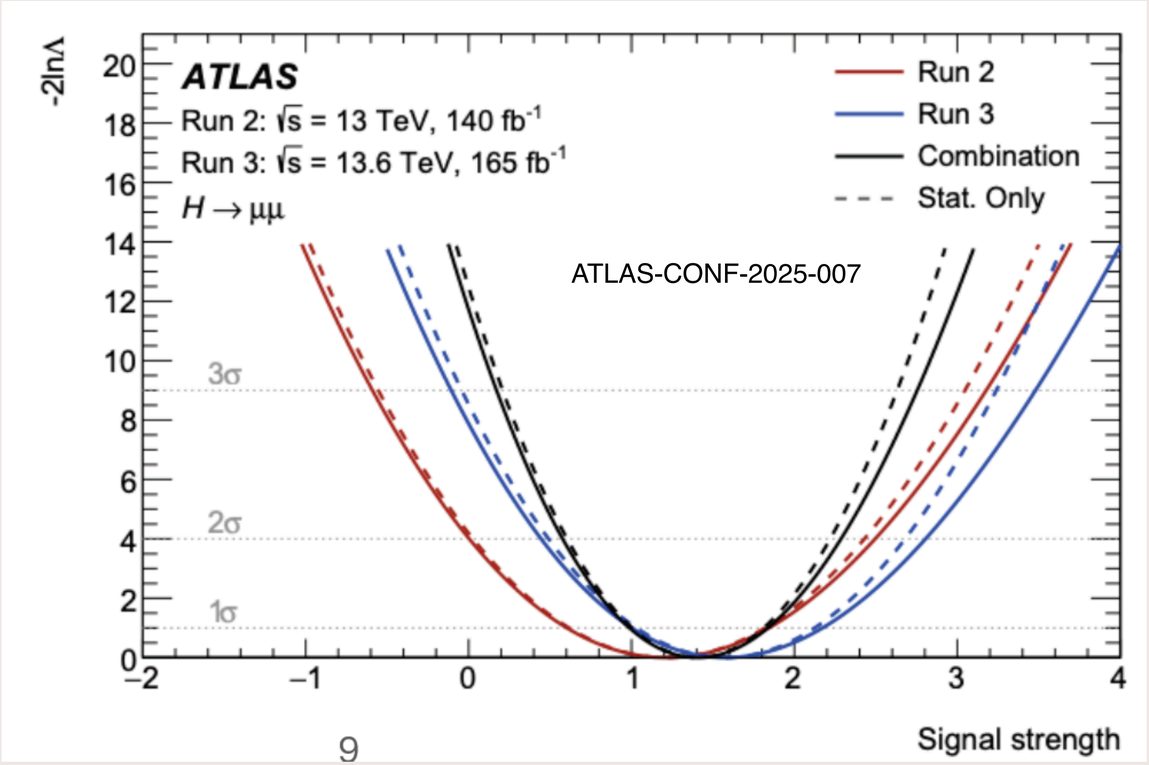
Run2+Run3 ATLAS: 3.4σ (2.5 exp) , μ = 1.4 ±0.4

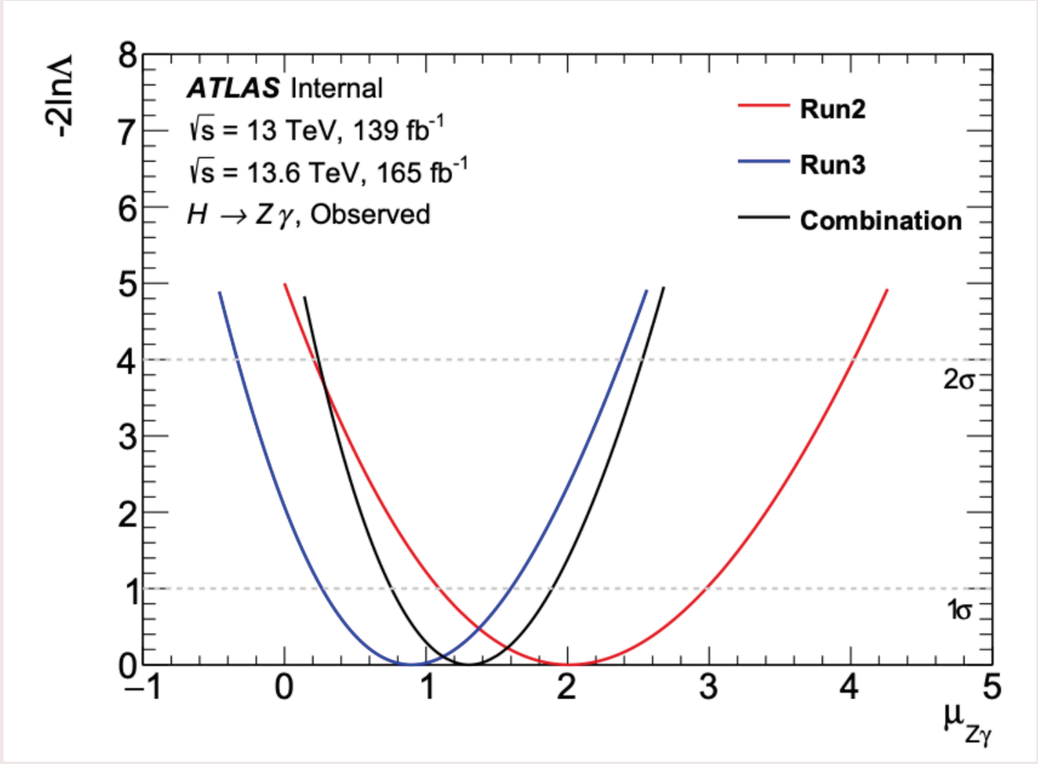
Run2+Run3 ATLAS: 2.5σ (1.0 exp SM) , μ = 1.3 ±0.5

CMS Run2 : μ =1.2±0.4, 3σ (2.5 exp)

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

Rare Decays: exploiting Run3 (22+23+24) data





Run2+Run3 ATLAS: 3.4σ (2.5 exp) , μ = 1.4 ±0.4

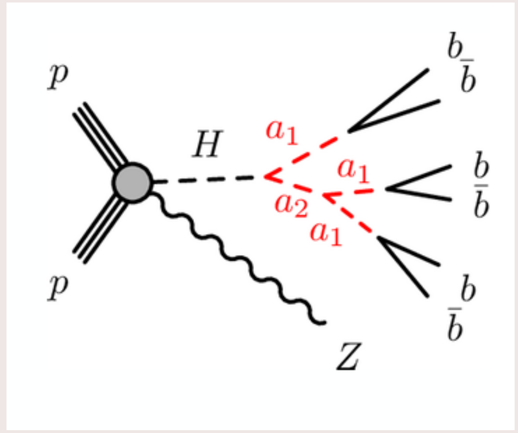
CMS Run2 : μ =1.2±0.4, 3σ (2.5 exp)

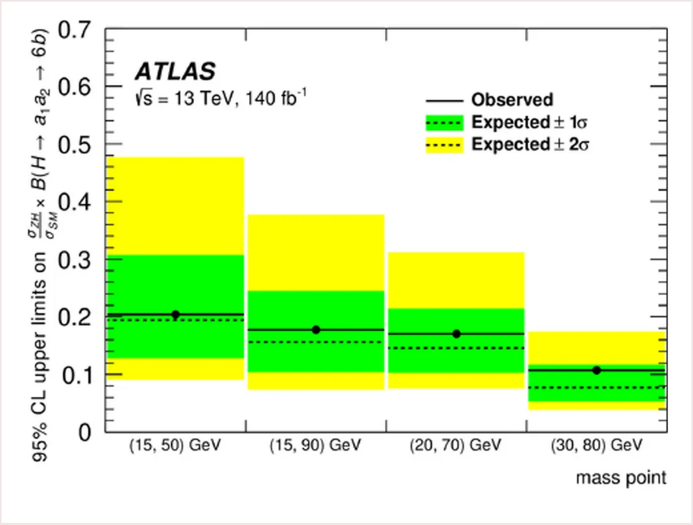
Run2+Run3 ATLAS: 2.5σ (1.0 exp SM) , μ = 1.3 ±0.5

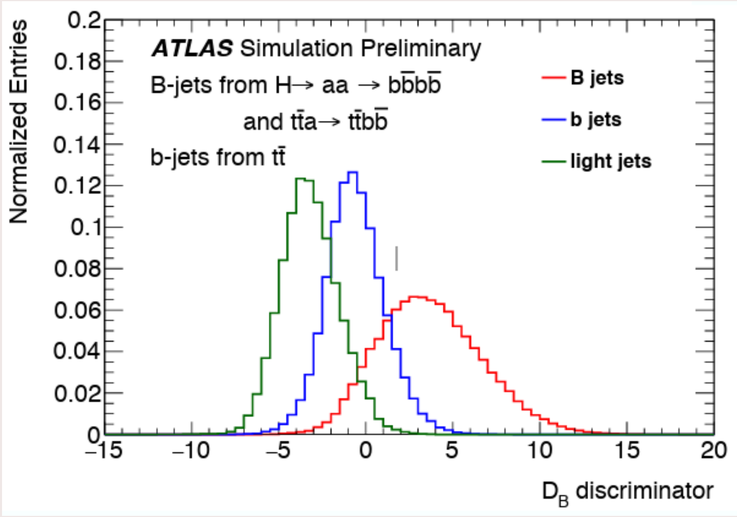
ATLAS+CMS Run2 : μ =2.2±0.7, 3.4σ (1.6 exp SM)

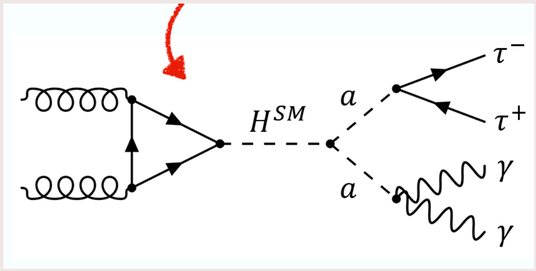
ELENI SKORDA
ANDREA SCIANDRA
GADI NINIO

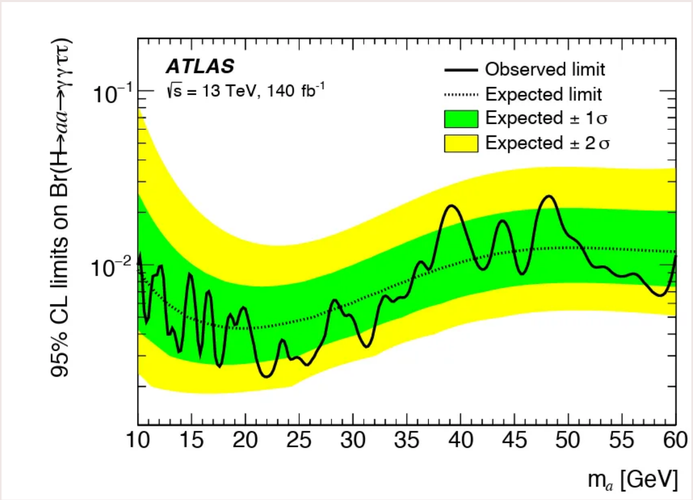
Boosted

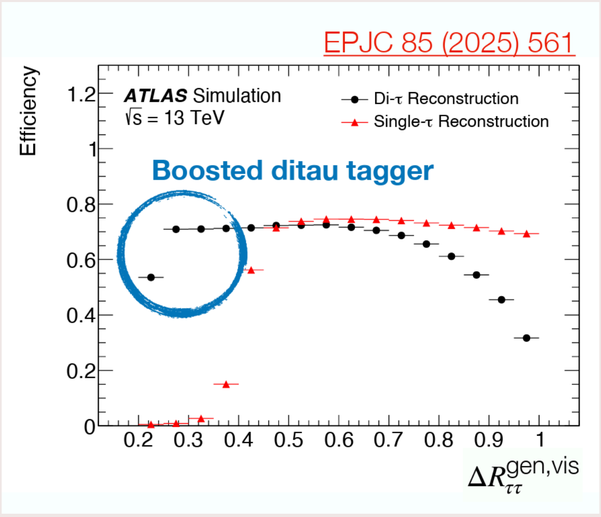






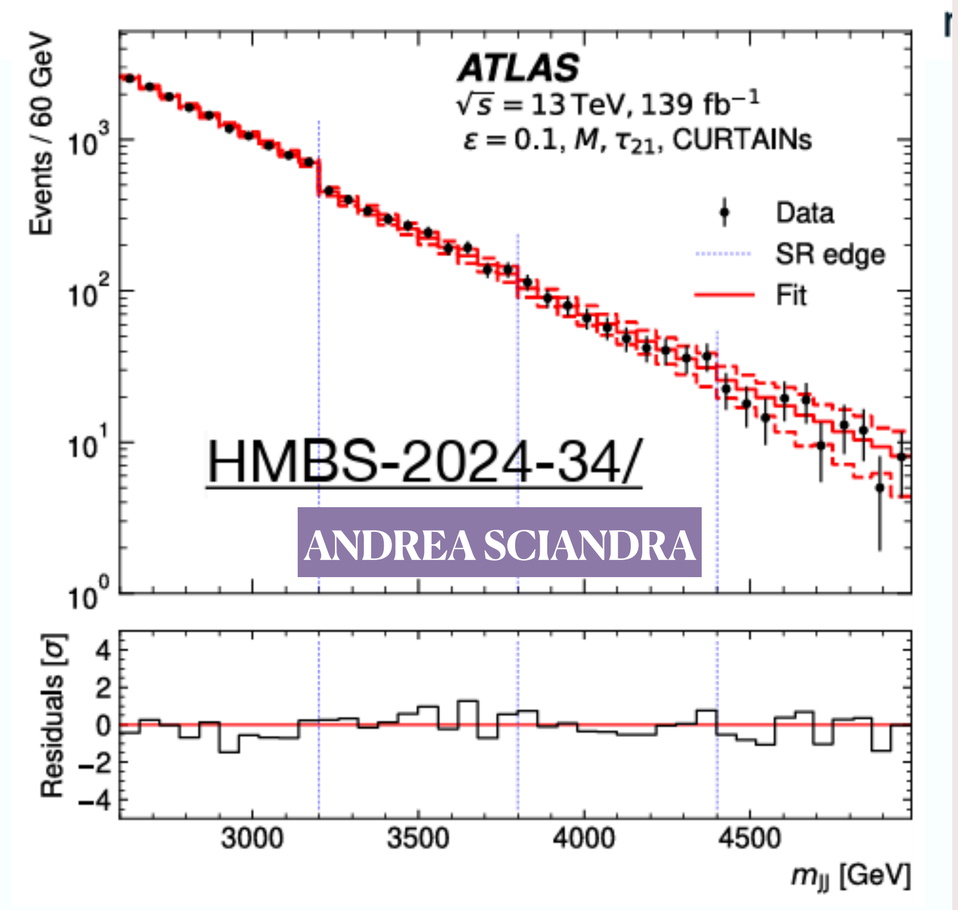






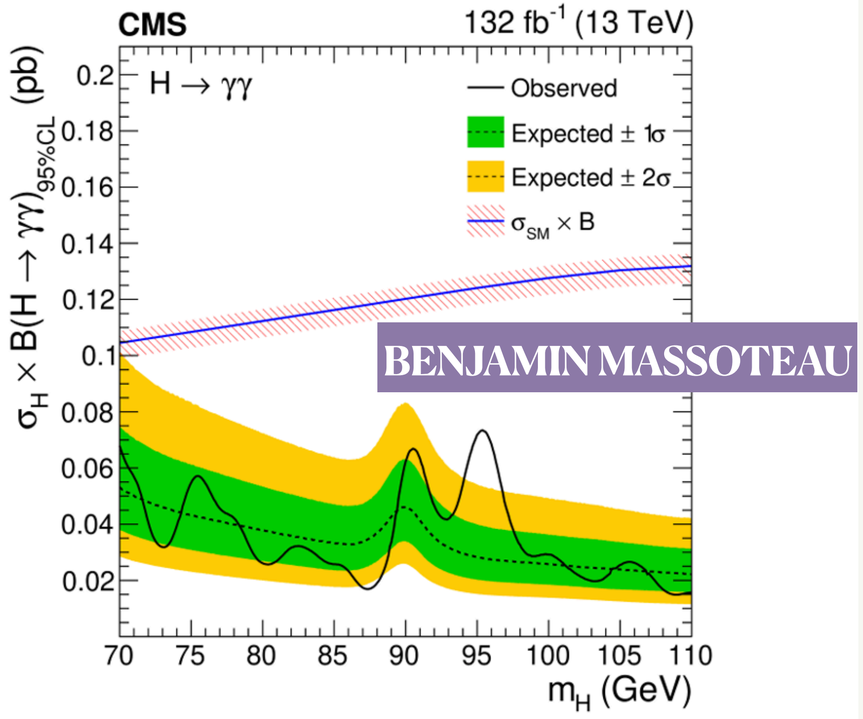
BSM

Weakly supervised Anomaly Detection to search for narrow resonance in di-jet events



Low mass Hgammagamma

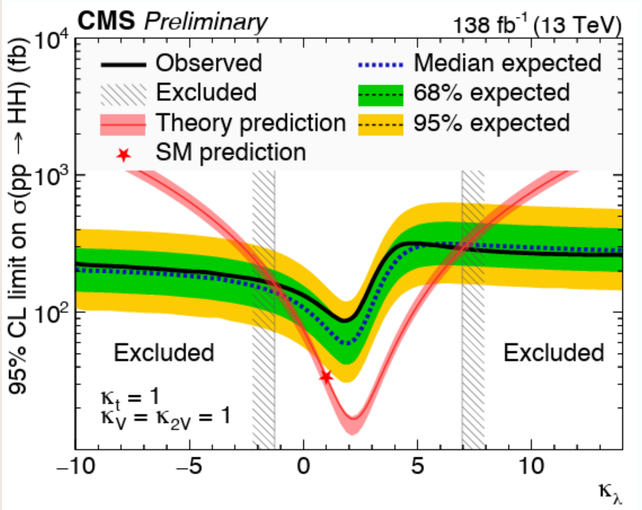
Absolute 95% CL upper limits on $\sigma \times BR$



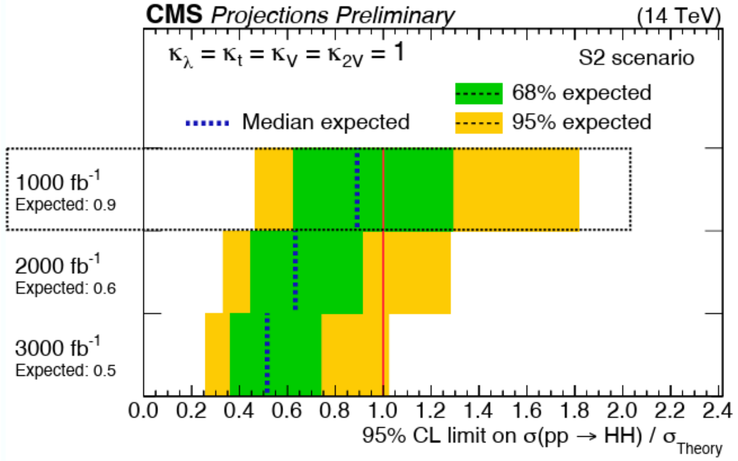
Almost there?

ROBERTO SALERNO

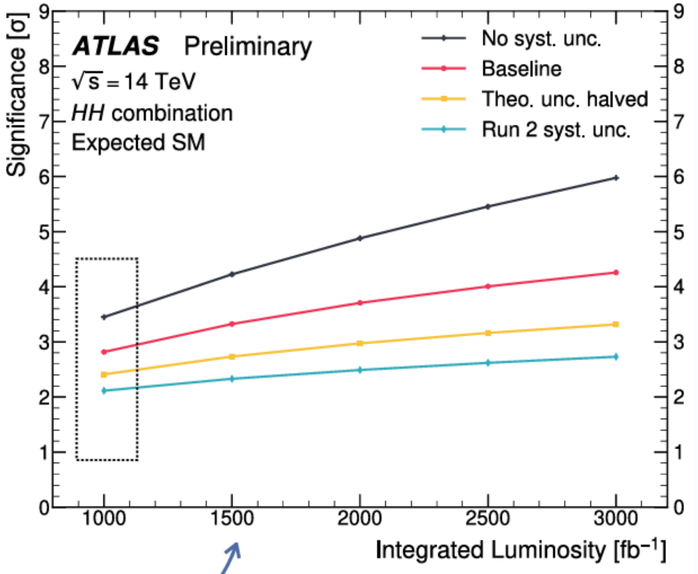
Sensitivity to exclude of $\lambda_{HHH} = 0$ by the the end of Run3



95% CL sensitivity for HH production combining ATLAS and CMS. Sensitivity with single experiment?



HH evidence at the end of Run3 combining ATLAS and CMS?



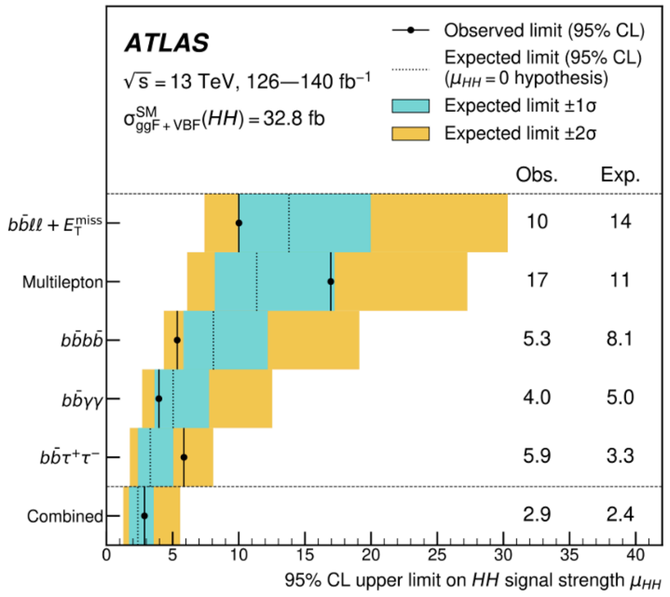
Single experiment 1000/fb projection as a gauge of two experiments combinations

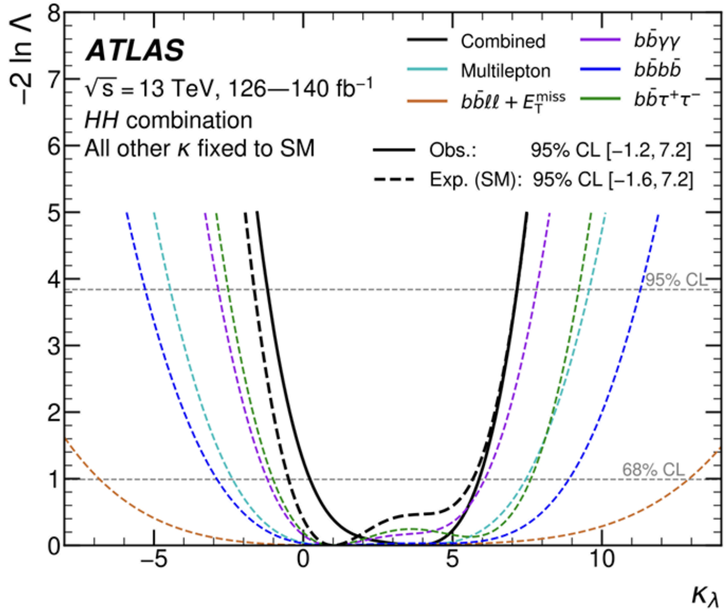
Seeing double: HH

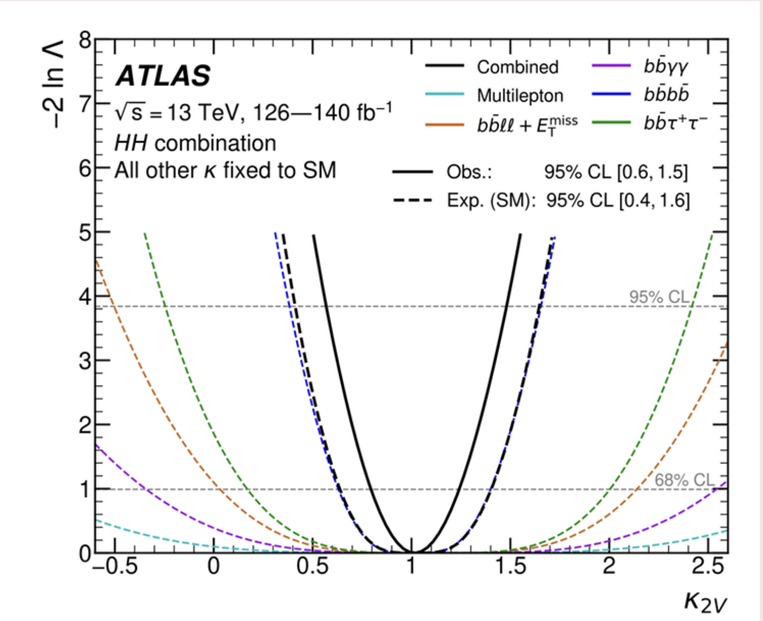
With Run2 data analyzed, at 95%CL:

$$CMS: \quad \mu_{HH} < 3.5\ (2.5), \quad -1.39 < \kappa_\lambda < 7.02$$

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







Observed HH SM Significance: 0.4 σ

Expected HH SM Significance: 1.0 σ

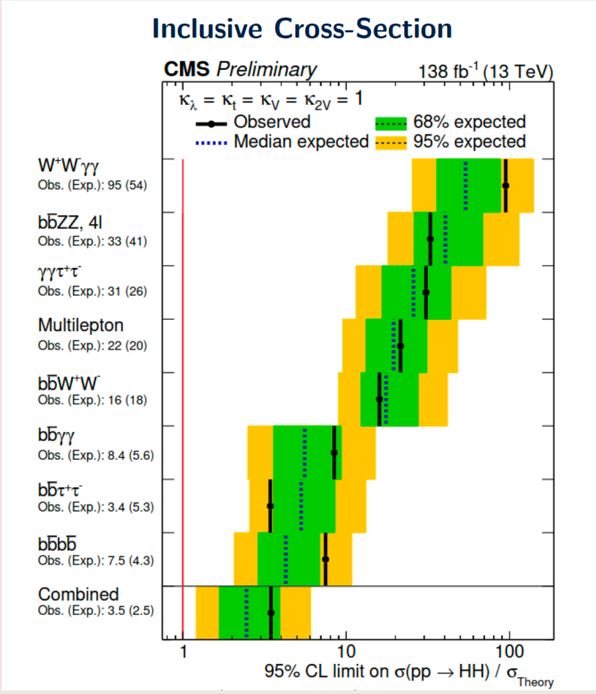
LORENZO SANTI

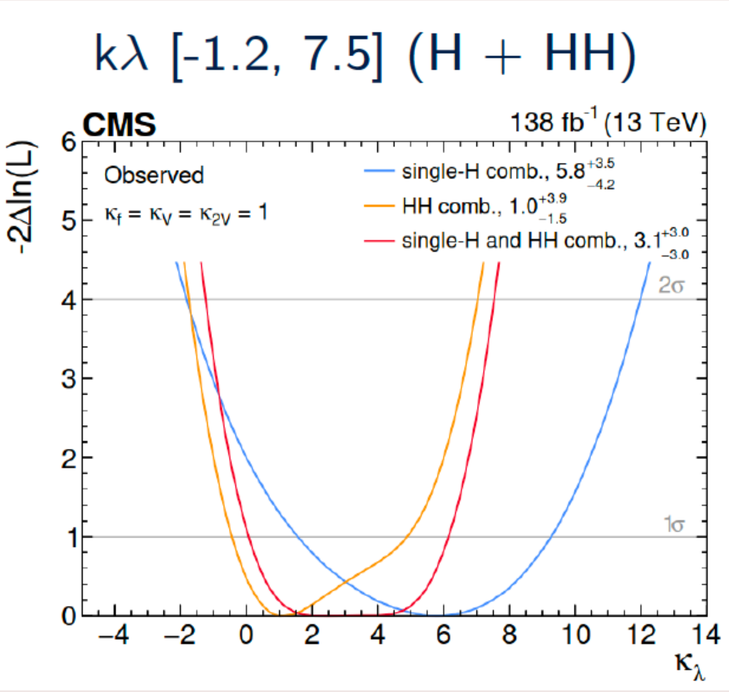
Seeing double: HH

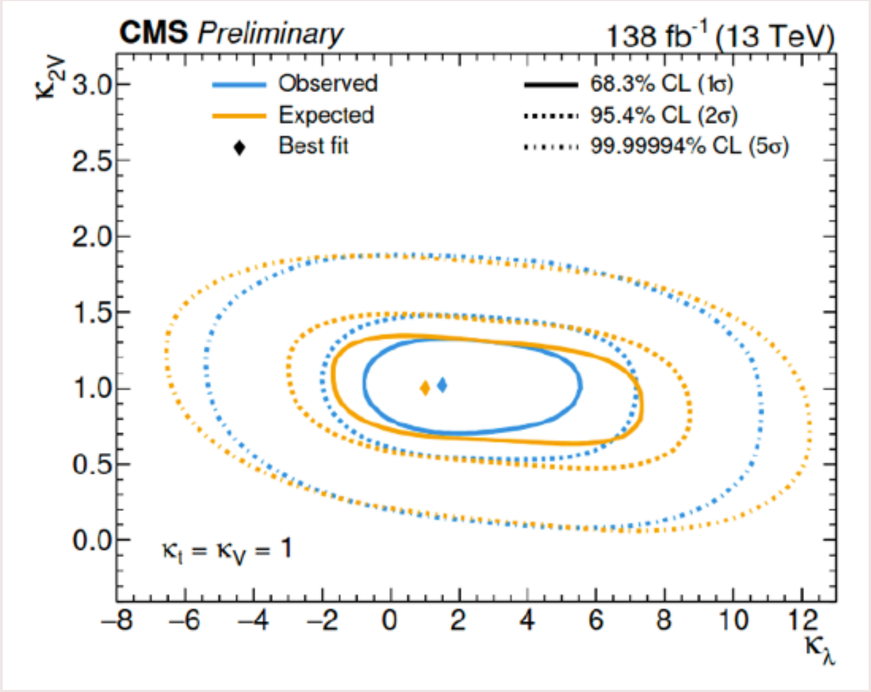
With Run2 data analyzed, at 95%CL:

$$CMS: \quad \mu_{HH} < 3.5\ (2.5), \quad -1.39 < \kappa_\lambda < 7.02$$

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





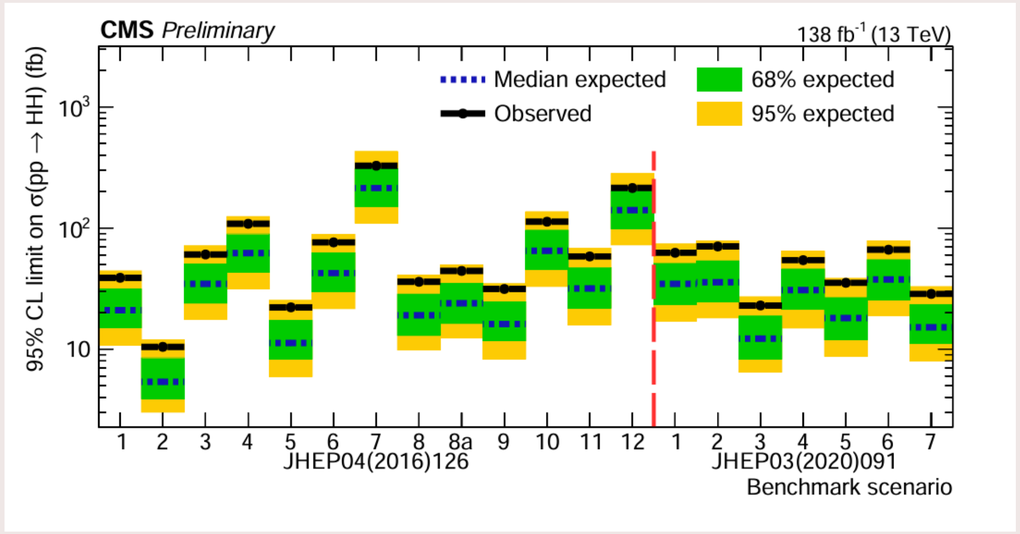


LEONIDAS PAIZANOS

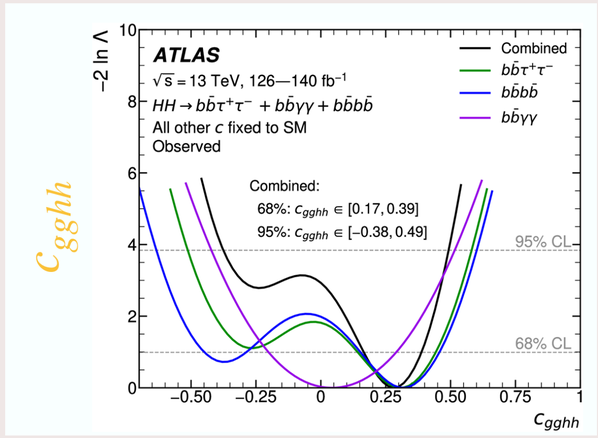
HEFT interpretation of HH results

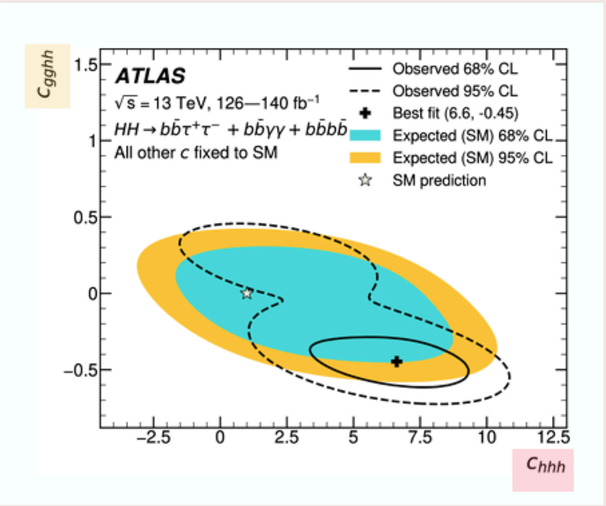
HEFT

- Highlights **new physics** effects in **Higgs couplings**.
  - Defined **independently** from **SU(2)$_L$ doublet** structure.
- Regime of validity **wider w.r.t. SMEFT**.
  - Particularly useful in regions of phase space where **BSM effects are still weakly constrained** (e.g. HH production).



LEONIDAS PAIZANOS

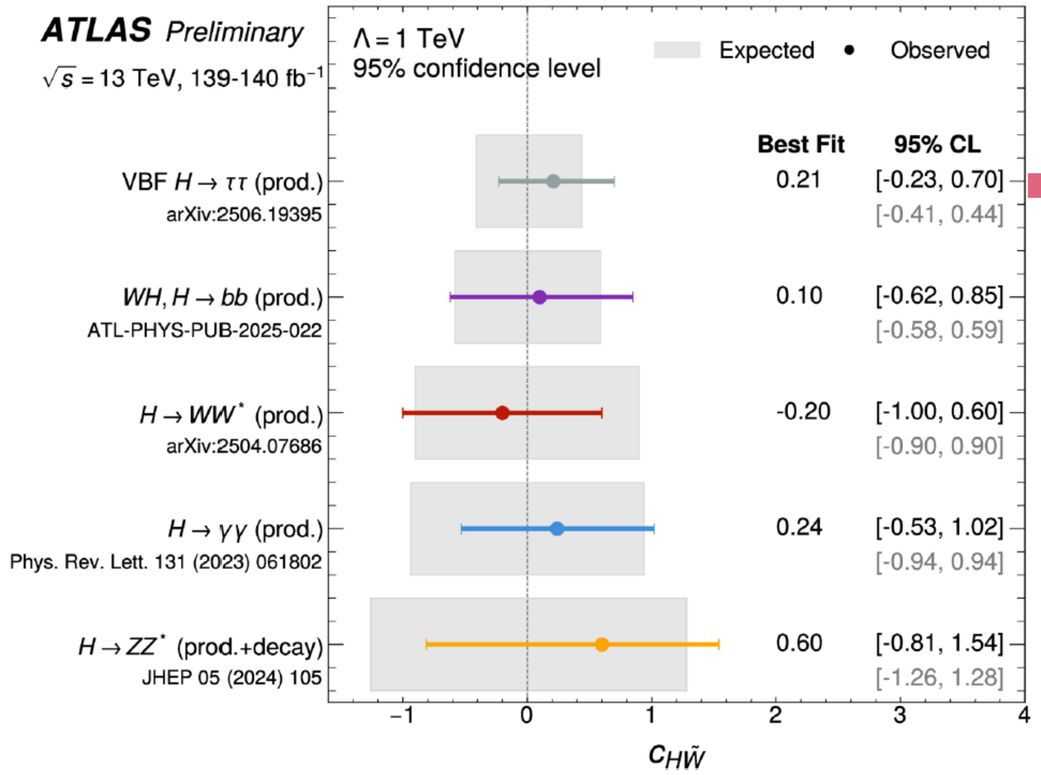


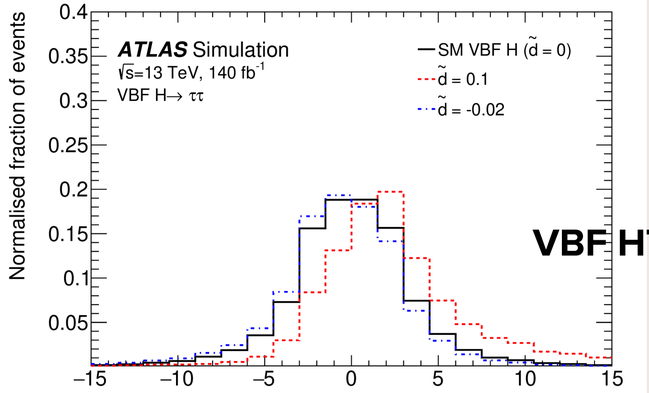


ELENA MAZZEO

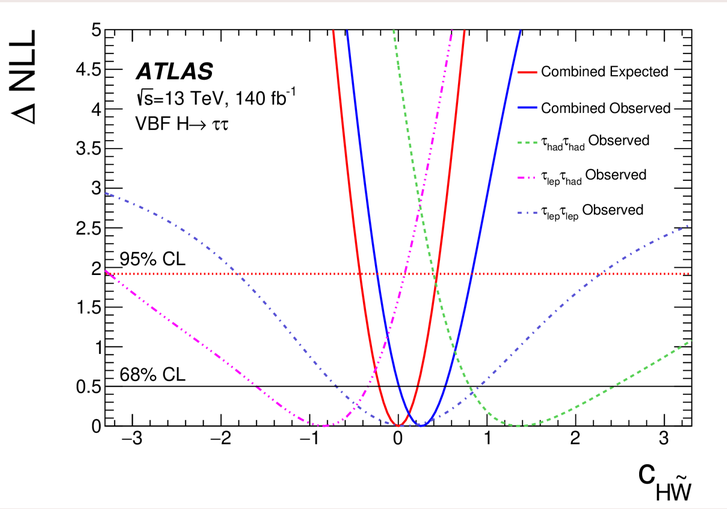
CP was truly a star this year...

Summary of constraints on $c_{H\tilde{W}}$:



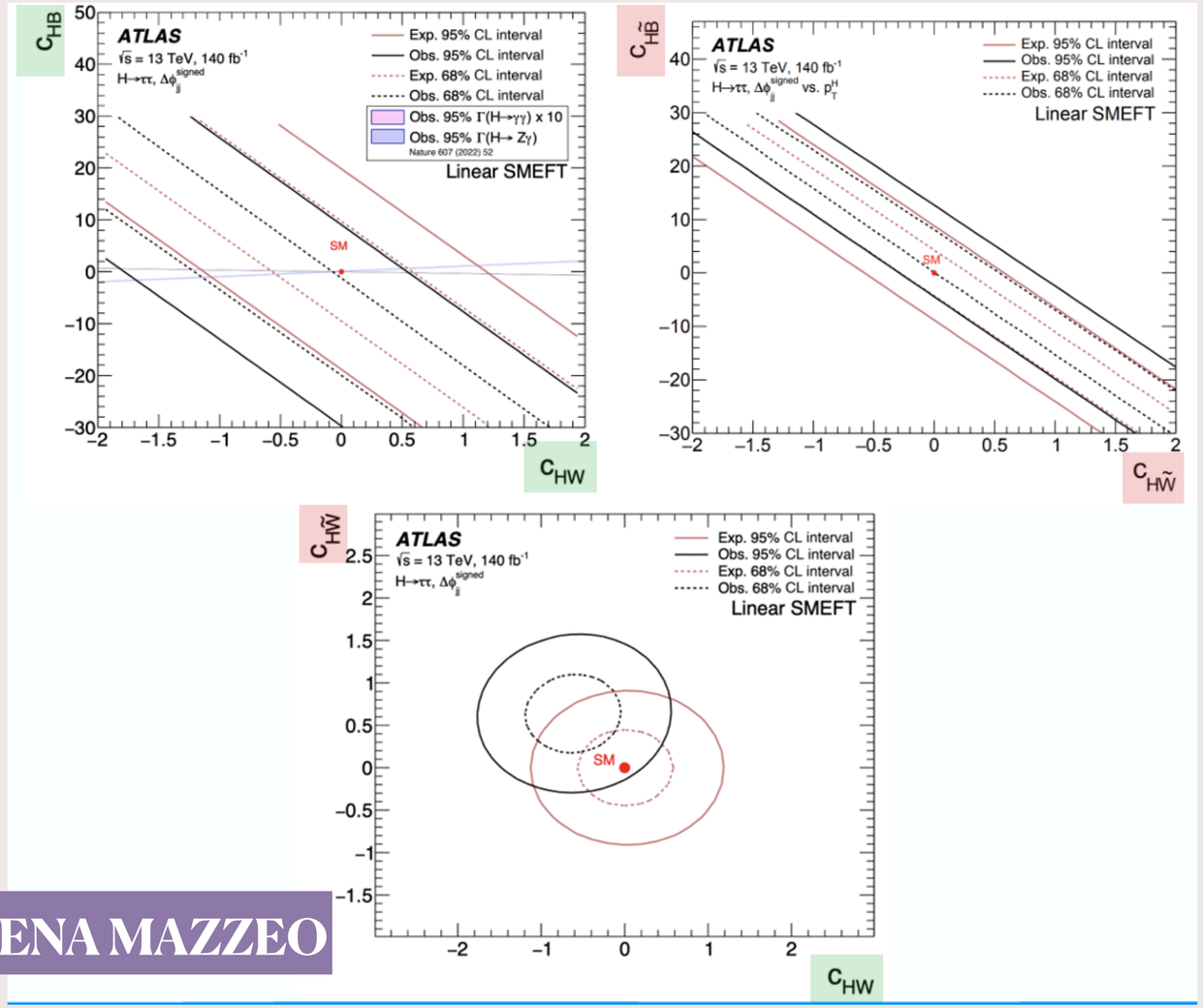


VBF HTauTau



ELISE LE BOULICAUT ENNIS

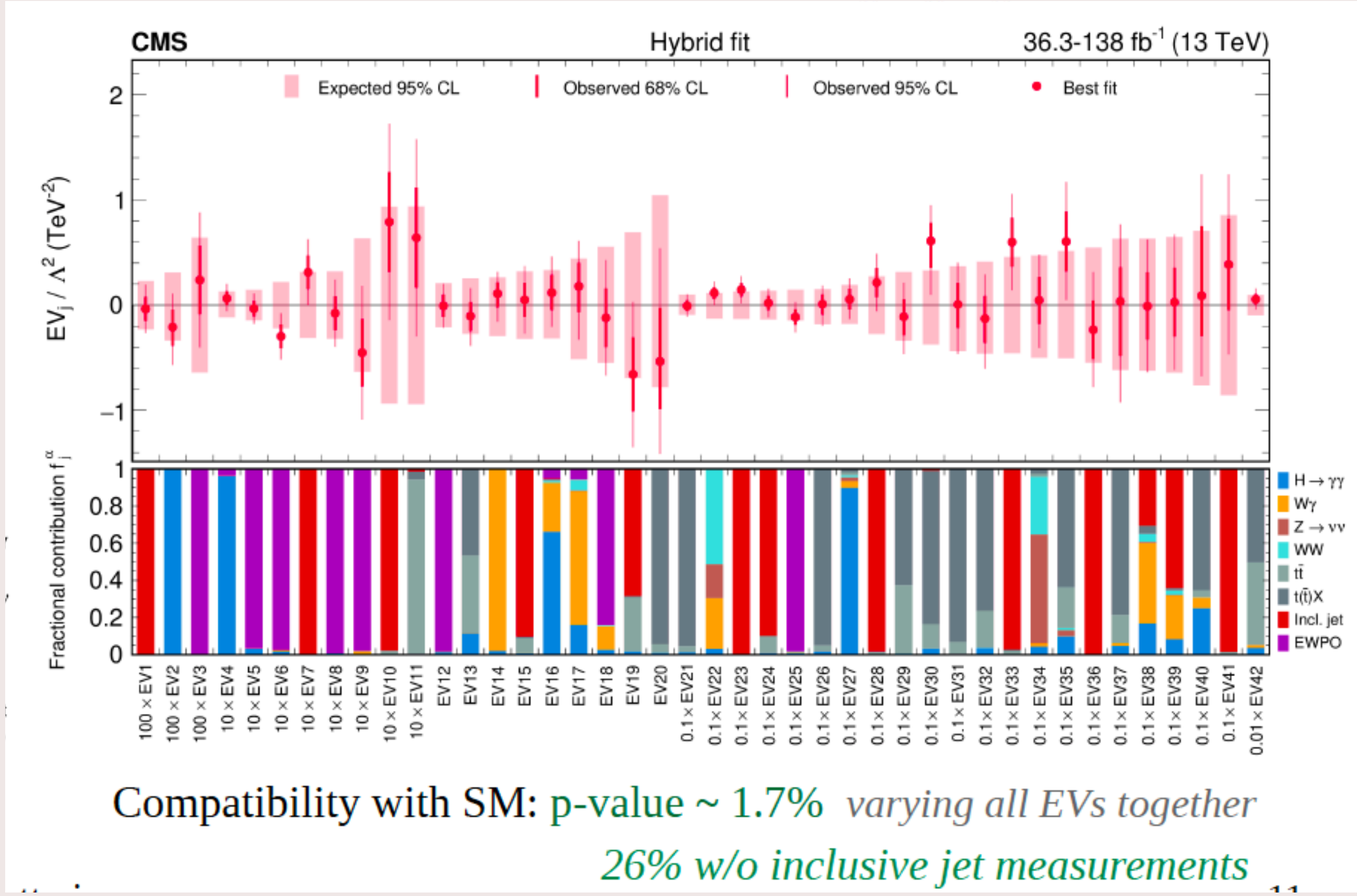
Probing CP: Also in two dimensions



- (C_{HW}, C_{HB}) and ($C_{H\tilde{W}}$, $C_{H\tilde{B}}$) **planes**:
  - Effects of the **two operators cancel out** in one "**flat direction**" in the 2-dimensional plane.
    - **No sensitivity** there!
    - **Crucial** to **combine** with other analyses, which have a different "flat direction".
- (C_{HW}, $C_{H\tilde{W}}$) **plane**:
  - The two **operators modify differently** the $\Delta\phi_{jj}^{signed}$ **shape**.
    - **Effects** do **not cancel out**.
    - **No loss of sensitivity**.

ELENA MAZZEO

EFTs: everything together?



Compatibility with SM: p-value ~ 1.7% *varying all EVs together*

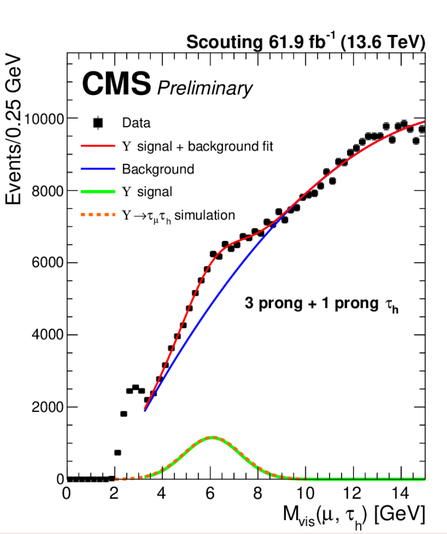
26% w/o inclusive jet measurements

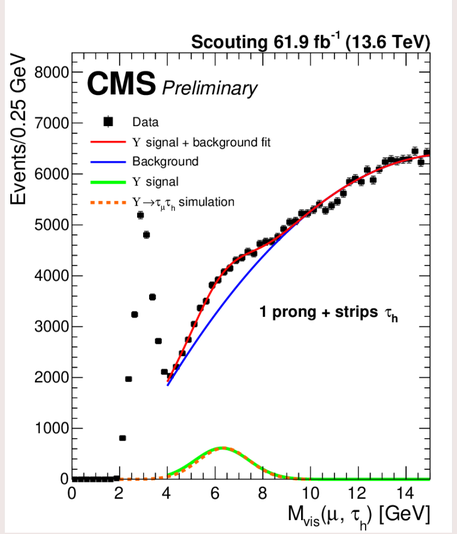
- Both ATLAS and CMS are starting to do global fits incorporating top, EW and Higgs
- ATLAS (older): ATL-PHYS-PUB-2022-037

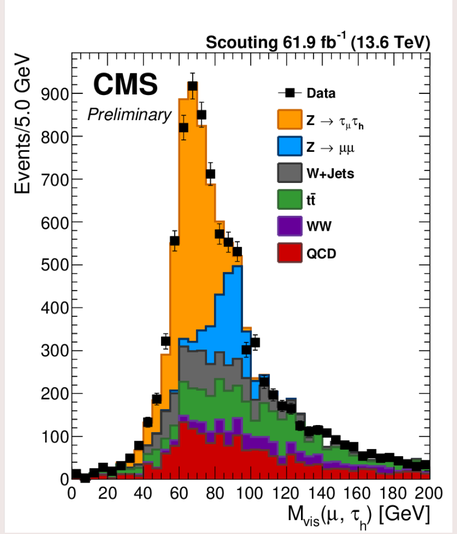
SUMAN CHATTERJEE

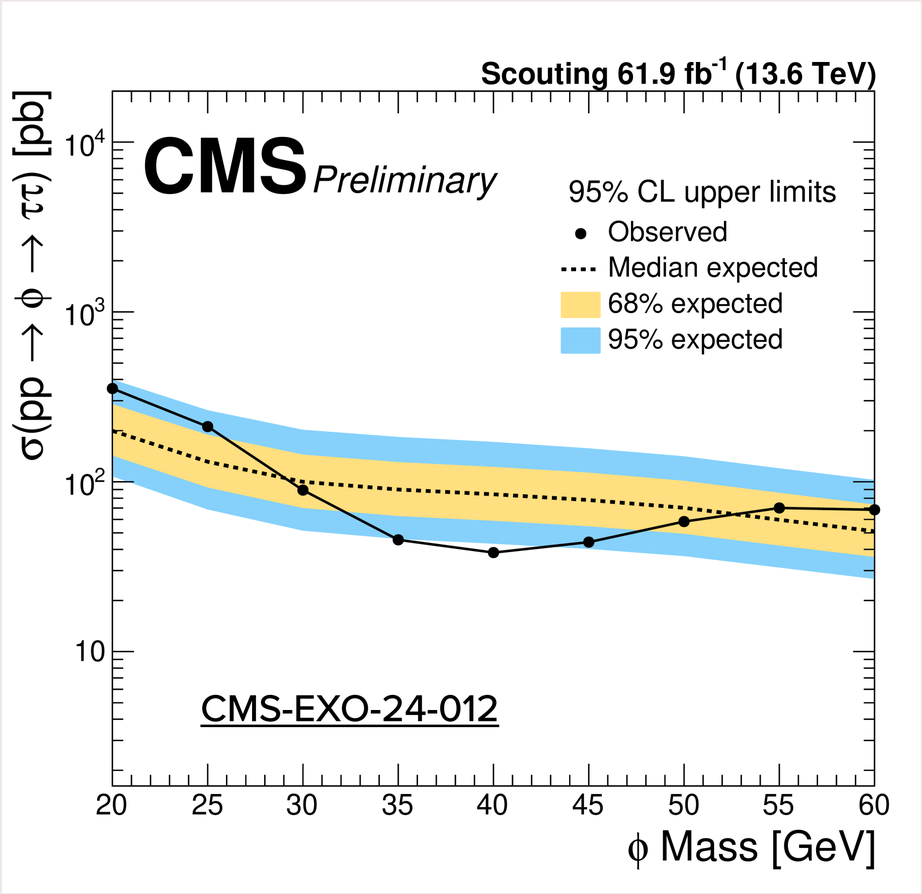
Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Differential cross sections	STXS bins [54]	✓
$W\gamma$	Fiducial differential cross sections	$p_T^\gamma \times \lvert\phi_f\rvert$ [33]	✓
$Z \to \nu\nu$	Fiducial differential cross sections	p_T^Z	✓
WW	Fiducial differential cross sections	$m_{\ell\ell}$	✓
$t\bar{t}$	Fiducial differential cross sections	$m_{t\bar{t}}$	×
$t(\bar{t})X$	Direct EFT	Yields in regions of interest	✓
Inclusive jet	Fiducial differential cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A_{FB}^{0,\ell}$, $A_{FB}^{0,c}$, $A_{FB}^{0,b}$ [36]	×

Scouting: inclusive ditau









- High-rate data-stream with low trigger thresholds and a compact data format
- Offline-like hadronic reconstruction at trigger level
- Reaches very low tau momentum