ATLAS and CMS Higgs measurements

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on behalf of the ATLAS and CMS experiments

PASCOS 2024, 29th International Symposium on Particles, String and Cosmology
July 7-13 2024, Quy Nhơn, Việt Nam

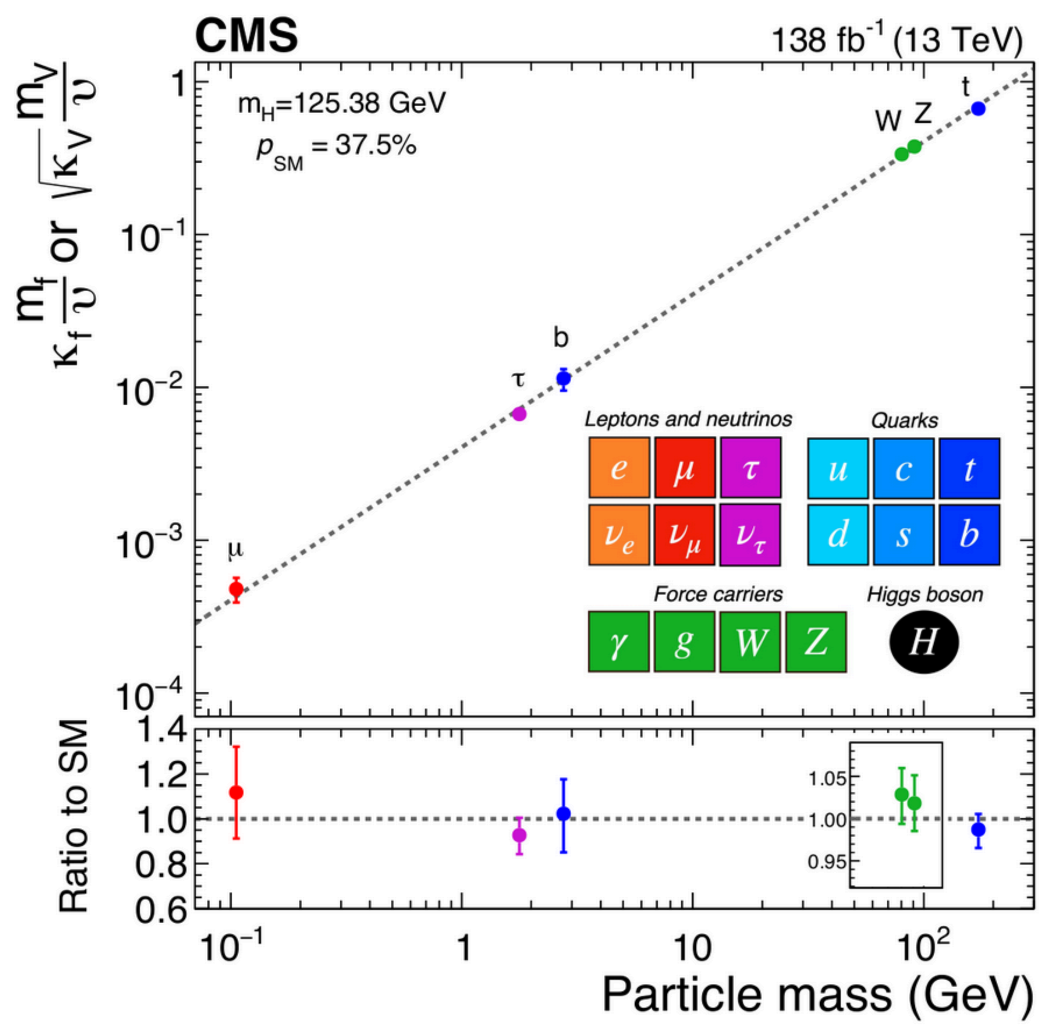
Higgs boson

Discovered in 2012

Higgs mechanism expected to give mass to particles…

Boson couplings ↪

Fermion couplings ↪



Couplings (or $\sqrt{\ }$) proportional to the mass of the coupled particle…

Over three orders of magnitude

- Great precision from LHC's Run 2 data
- So far excellent compatibility with theory

What Else?

Higgs decays

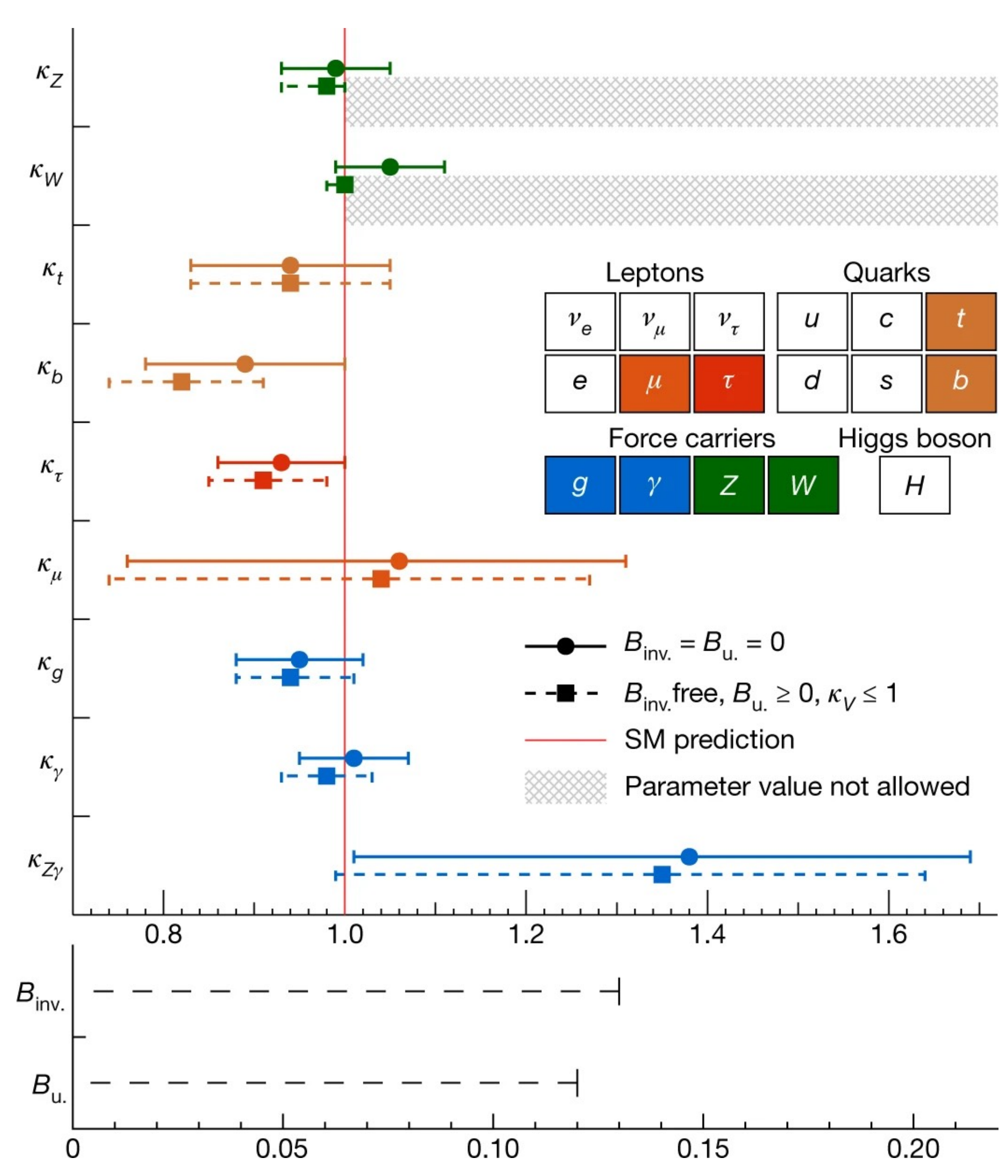
10 years after discovery

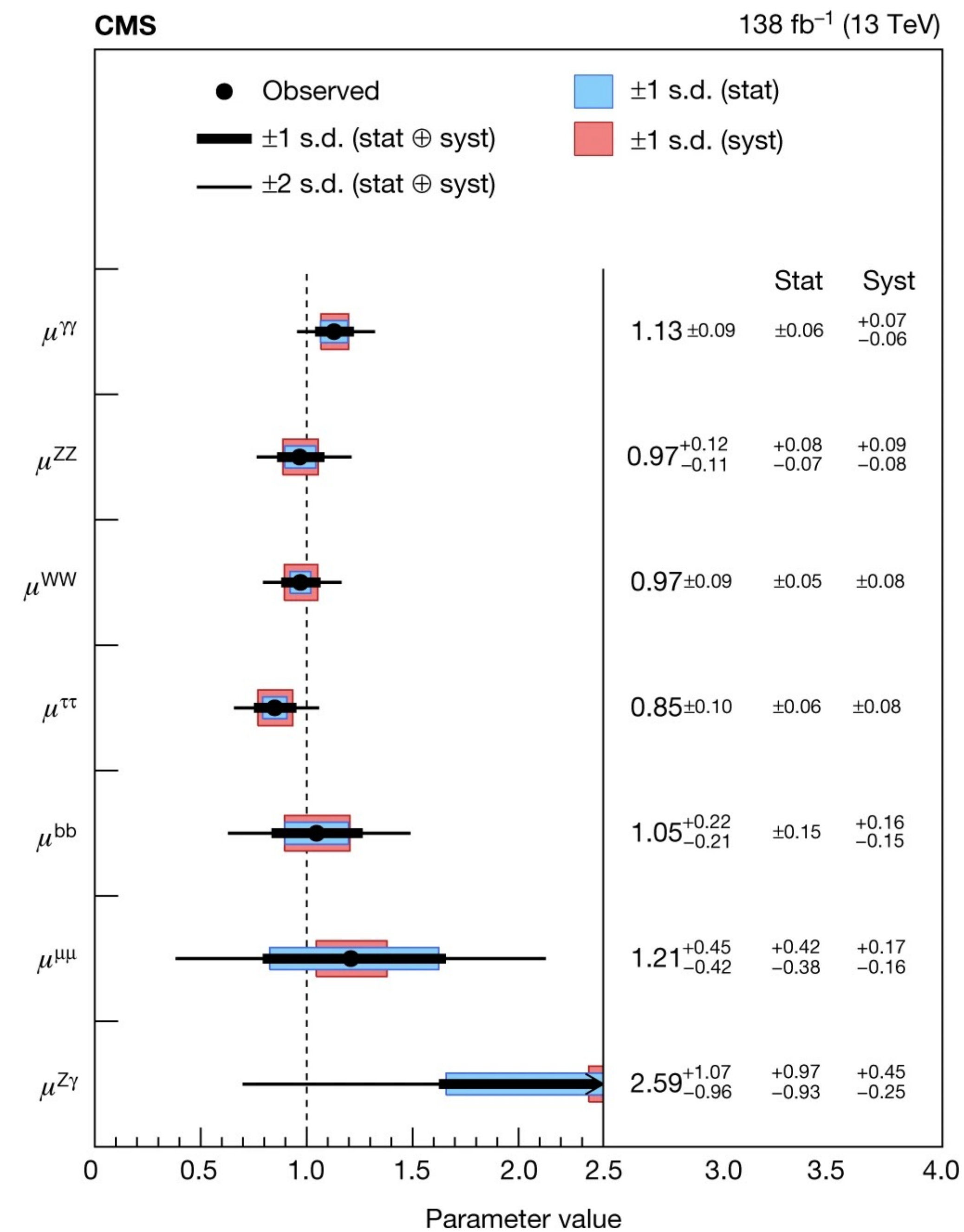
Nature 607 (2022) 52

Nature 607 (2022) 60

Couplings to **bosons** and **3rd generation fermions** are known with a precision of ~**10%**

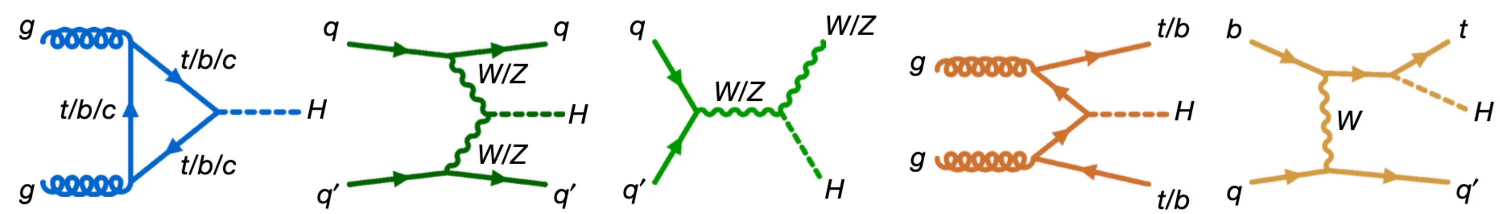
Evidence only for H → $\mu\mu$





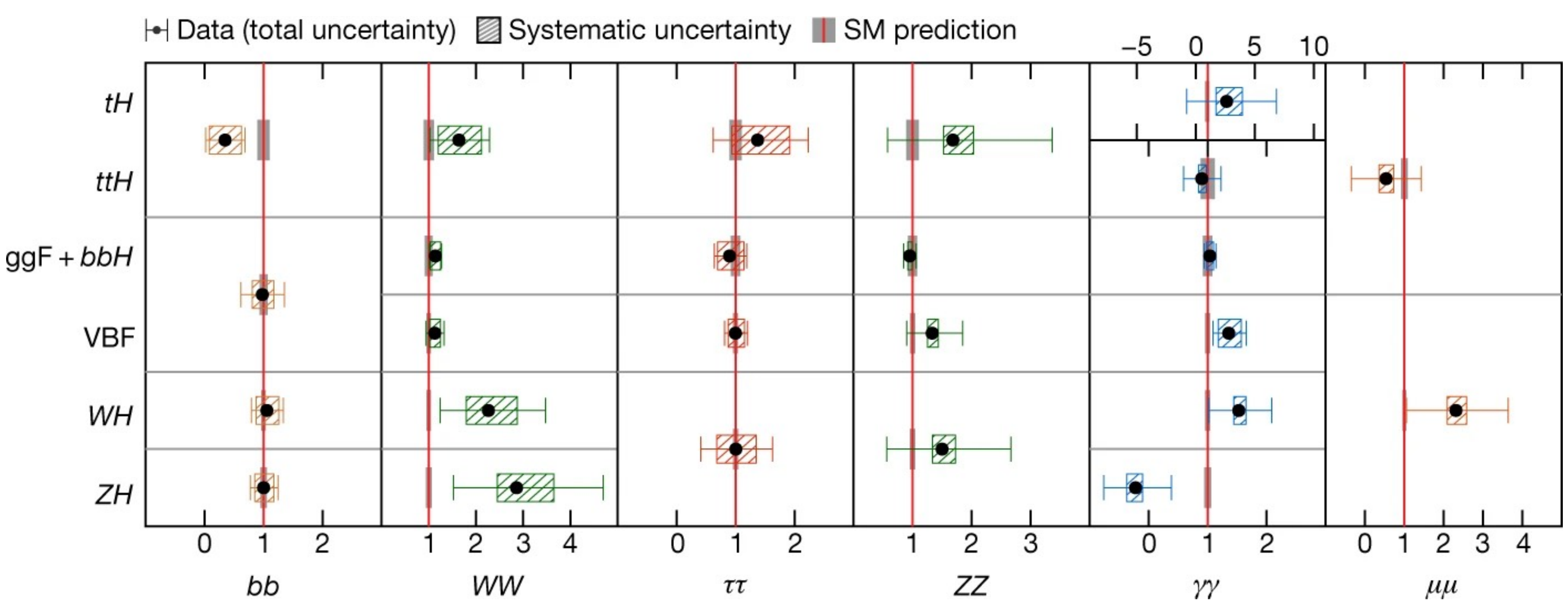
Higgs production modes

10 years after discovery



[Nature 607 (2022) 52](#)

[Nature 607 (2022) 60](#)



Global signal strength modifiers

μ = 1.05 ± 0.06 (ATLAS)

μ = 1.002 ± 0.057 (CMS)

Observation of the usual production modes ggH, VBF, VH, ttH

Higgs decays 2nd generation of fermions

H→$\mu\mu$: evidence for CMS (3.0σ)

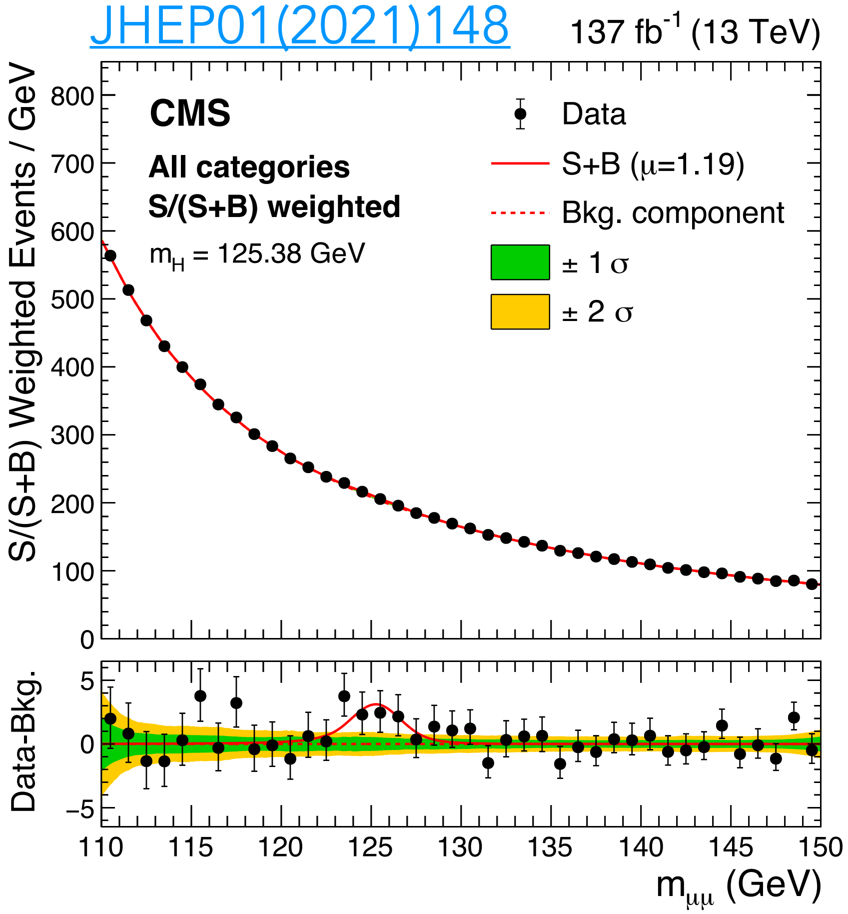
Narrow resonance over falling background
Track refitting to PV and FSR energy recovery
to improve mass resolution (1.5-2.1 GeV)

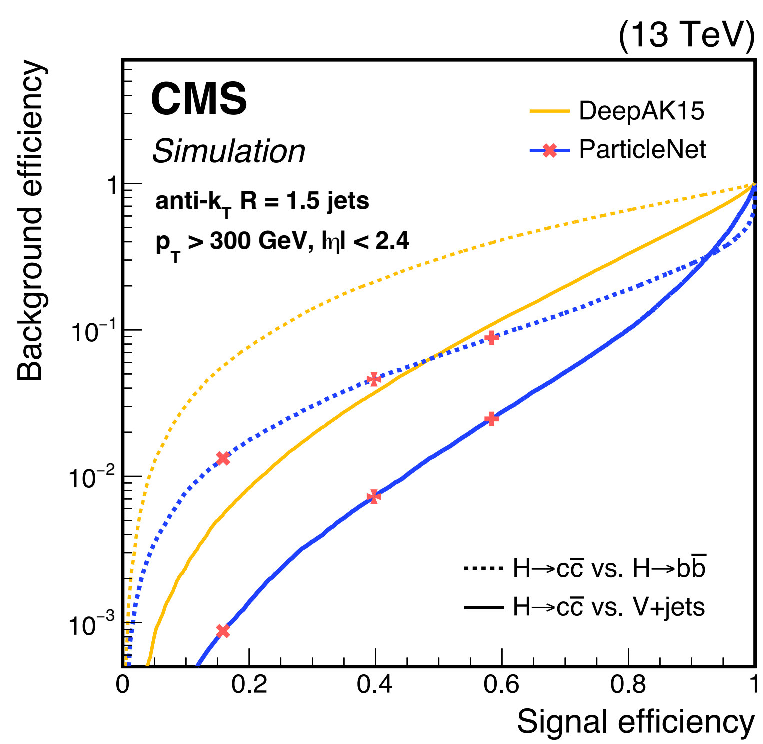
H→cc: being searched for in VH production

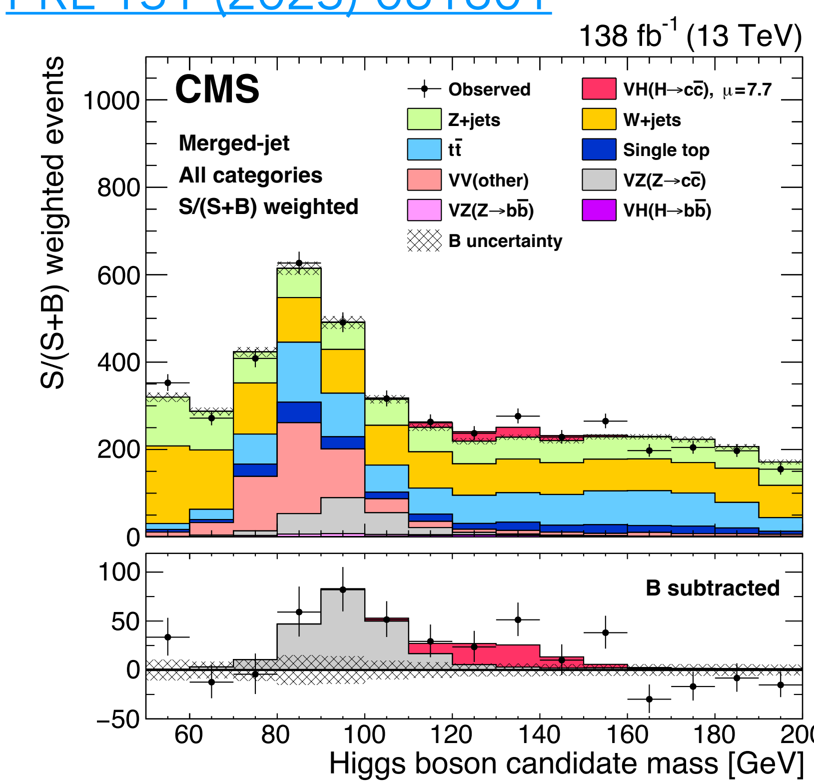
Excellent progress on machine learning side!
5x better rejection with [ParticleNet]

[PRL 131 (2023) 061801]

[JHEP01(2021)148]







Boosted and resolved, regressions all over the place (mass, E…)
Expected limit 7.6 x SM
1.1 < $\lvert\kappa_c\rvert$ < 5.5 ($\lvert\kappa_c\rvert$ < 3.4)

[PLB 812 (2021) 135980]

ATLAS: 2.0σ (1.7σ)

[Eur. Phys. J. C 82 (2022) 717]

ATLAS: $\lvert\kappa_c\rvert$ < 8.5 (12.4) at 95% CL

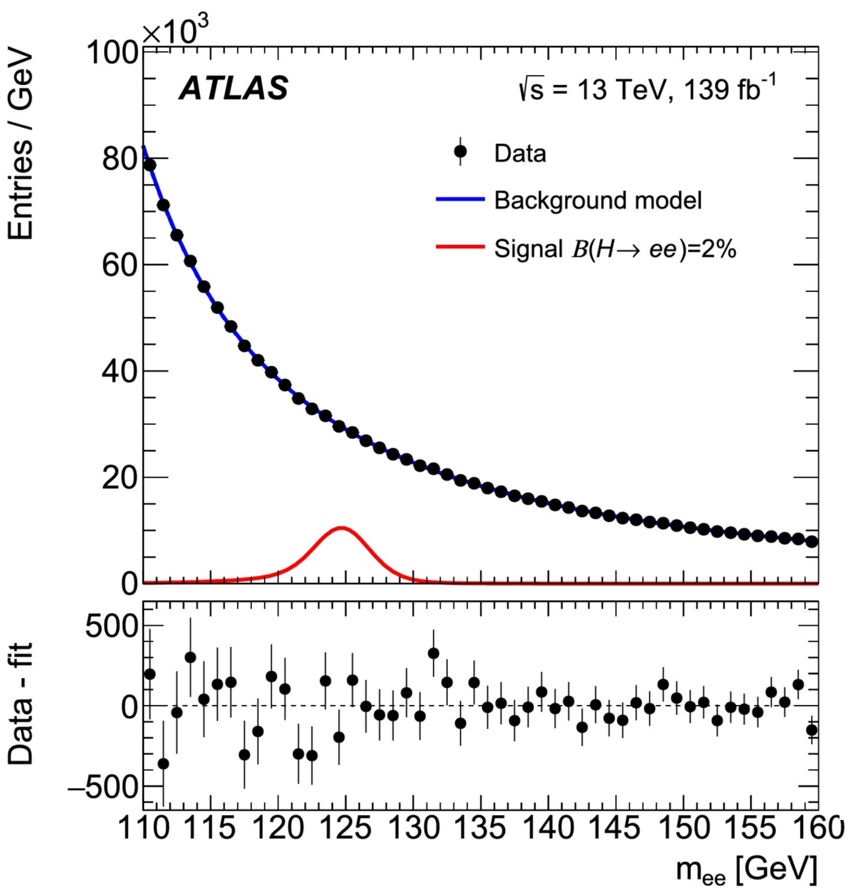
Higgs decays 1st generation of fermions

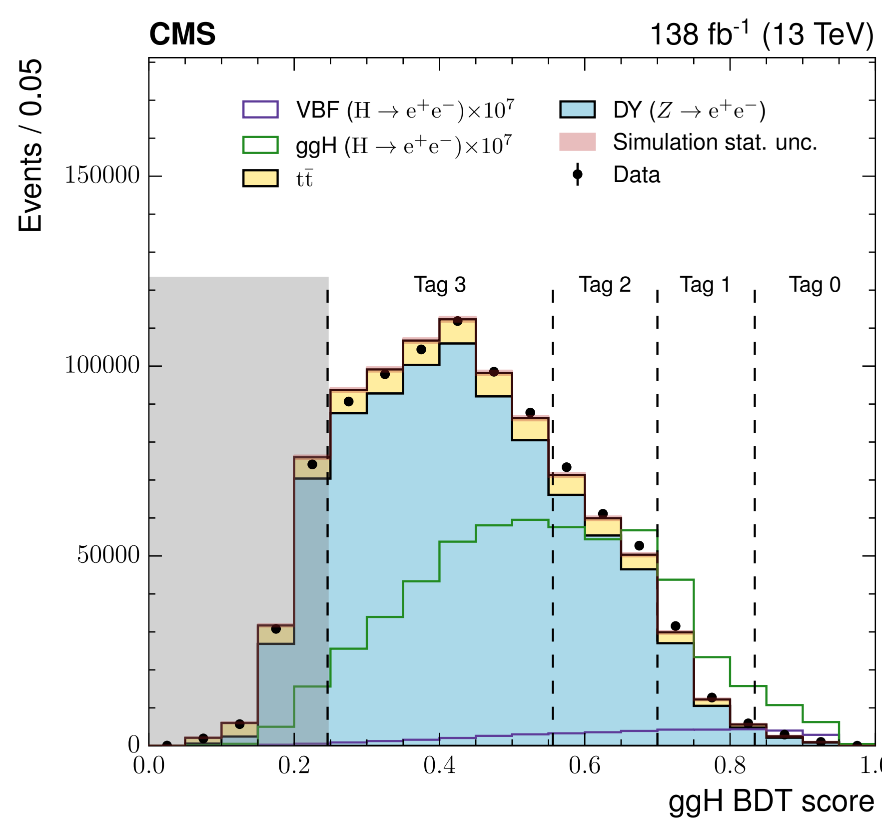
Upper limits: BR(H → ee) < $3.6.10^{-4}$ ($3.5.10^{-4}$) at 95%CL - ATLAS
BR(H → ee) < $3.0.10^{-4}$ ($3.0.10^{-4}$) at 95%CL - CMS

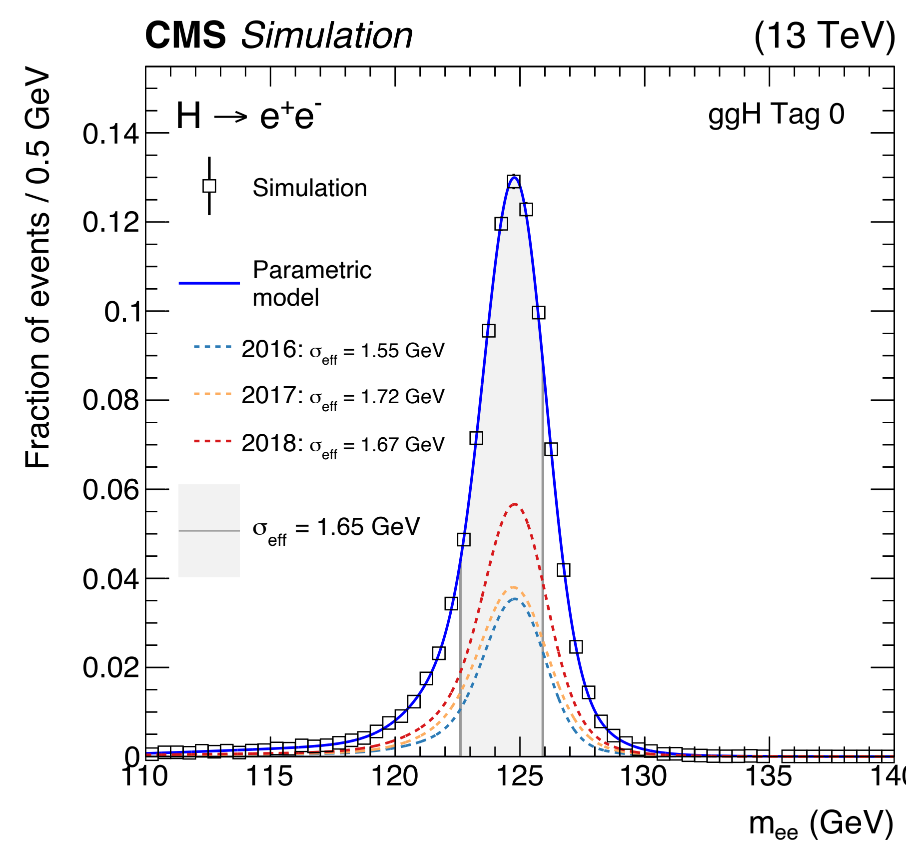
Far from the SM BR(H → ee) ~5.10^{-9}…

j.physletb.2019.135148

PLB 846 (2023) 137783







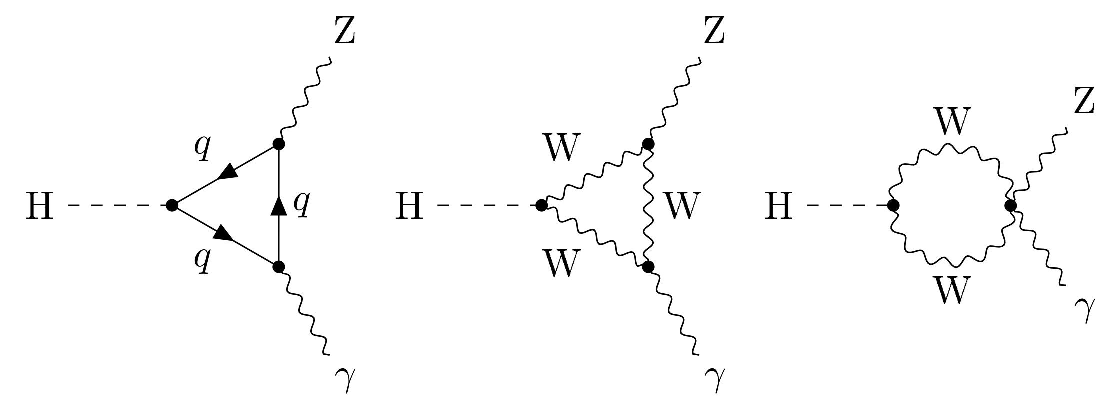
Similar strategy than H → μμ

BR(H → eμ)< $6.2.10^{-5}$ ($5.9.10^{-5}$)

Fit to m(ee) distribution in different event categories:
4 targeting gluon fusion, 2 targeting VBF production

H → $Z\gamma$

Rare decay, branching ratio of 0.15%.
Indirect probe of BSM physics in the loops

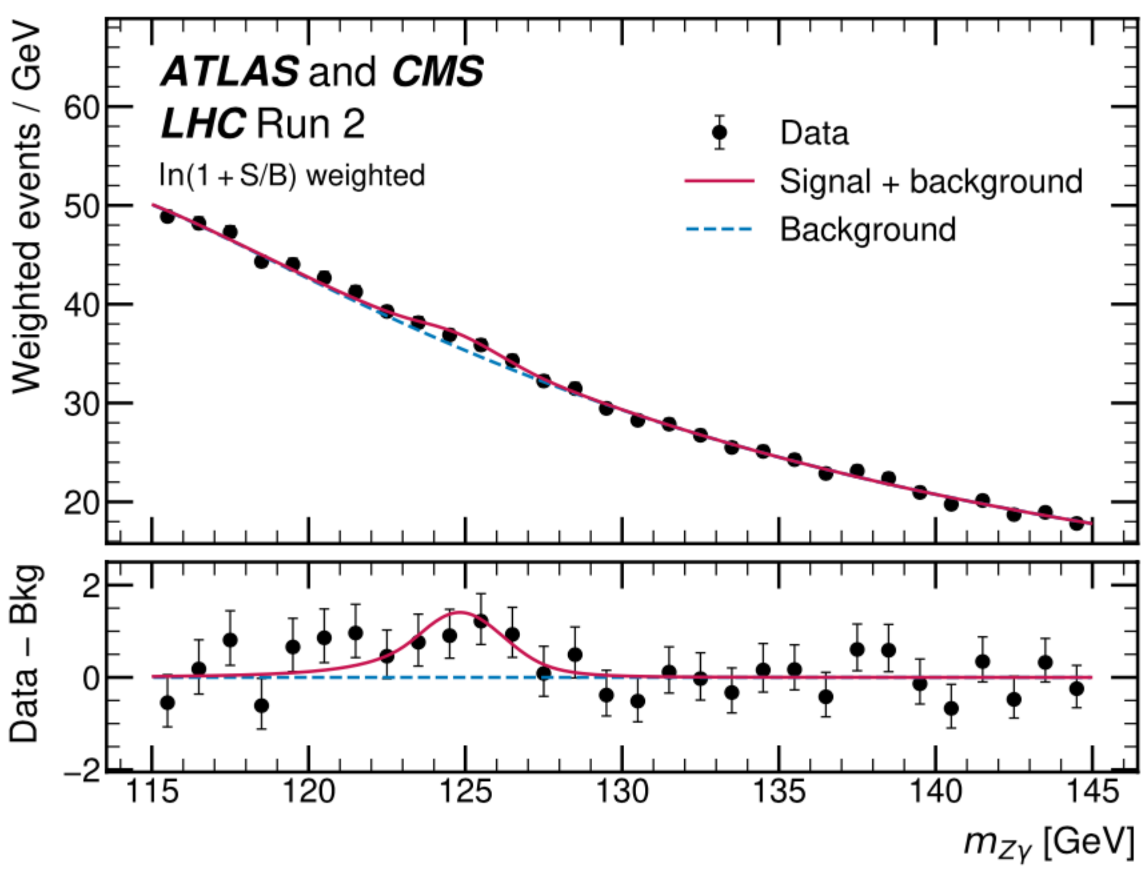


First evidence at 3.4σ (1.6σ) thanks to ATLAS+CMS combination!

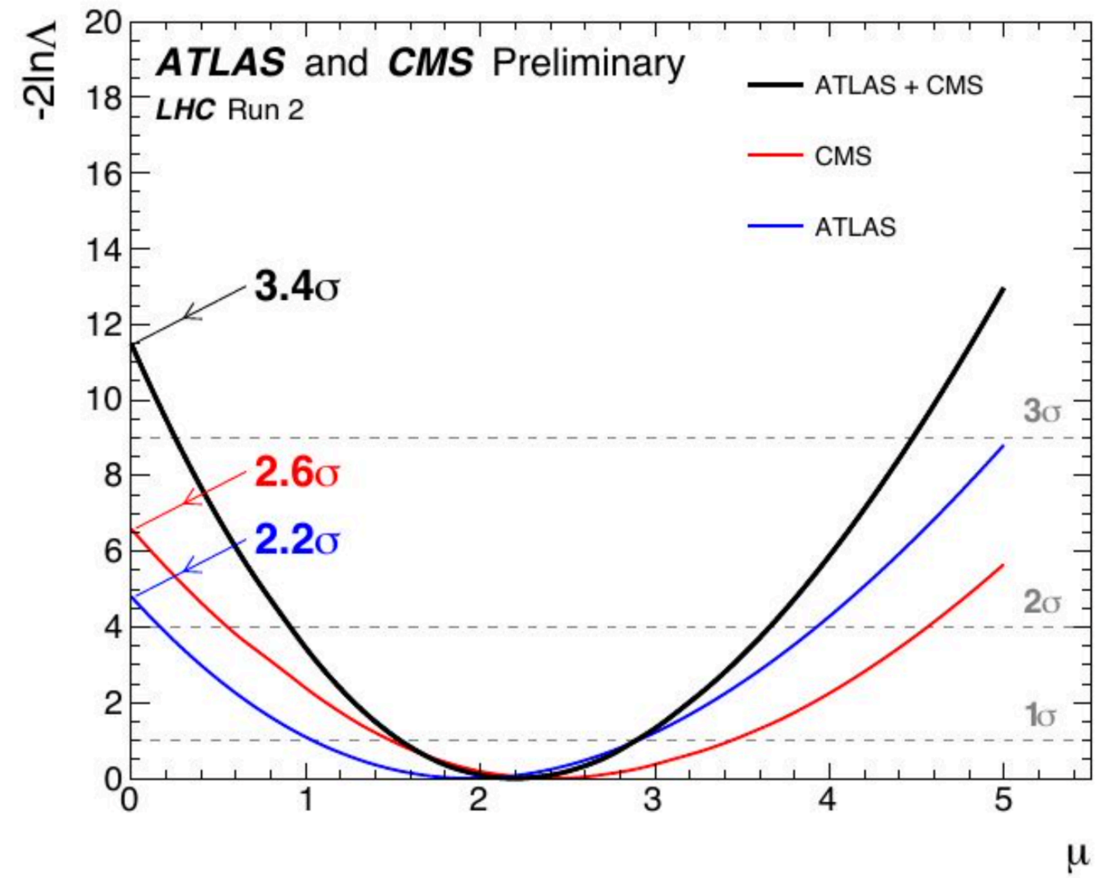
μ = 2.2 ± 0.7
1.9σ away from the SM prediction

Both experiments observe a modest excess of 2.2-2.6σ

PRL 132 (2024) 021803



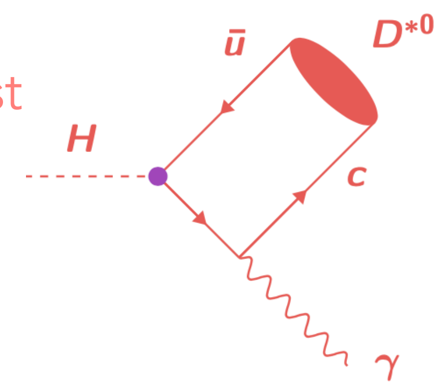
Classical bump hunt in m($\ell\ell\gamma$)



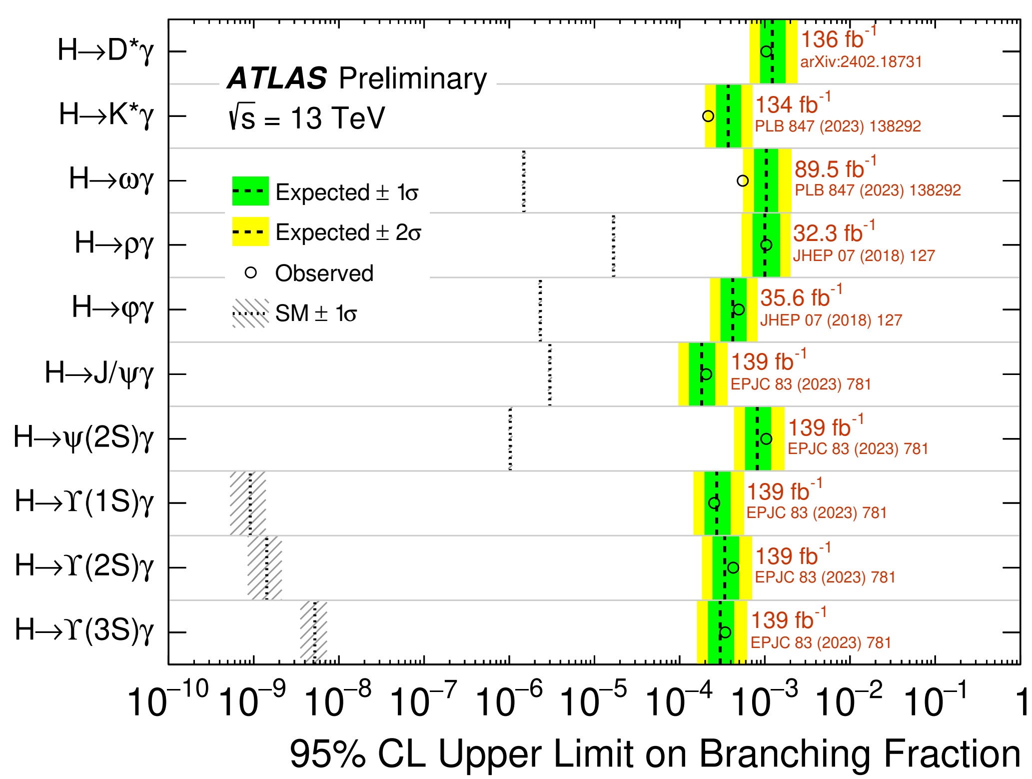
Rare decays to probe quark Yukawas

$H \to K^{*0}, D^{*0}, B_s^{*0}, B^{*0}\gamma$ are clean probes of **flavour changing Yukawa interactions**

Example D^{*0}, rarest decay in the SM (~10^{-27})



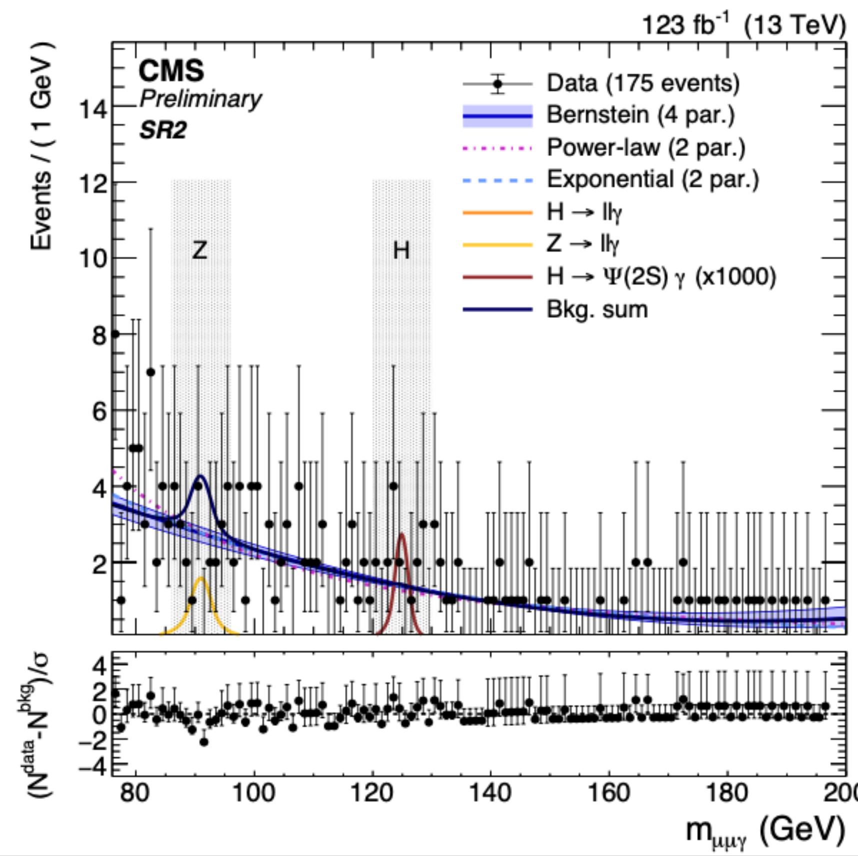
Broad range of rare decays being scrutinised…



[ATL-PHYS-PUB-2023-004]

Radiative Higgs boson decays to charmonium to probe charm Yukawa

H → ψ(nS) γ, ψ(nS) → $\mu^+\mu^-$



Comparable limits on BR and κ_c/κ_γ constraints obtained by ATLAS and CMS

-157 < κc /κγ < 199 at 95%CL [CMS-PAS-SMP-22-012]

-133 < κc /κγ < 175 at 95%CL [Eur. Phys. J. C 83 (2023) 781]

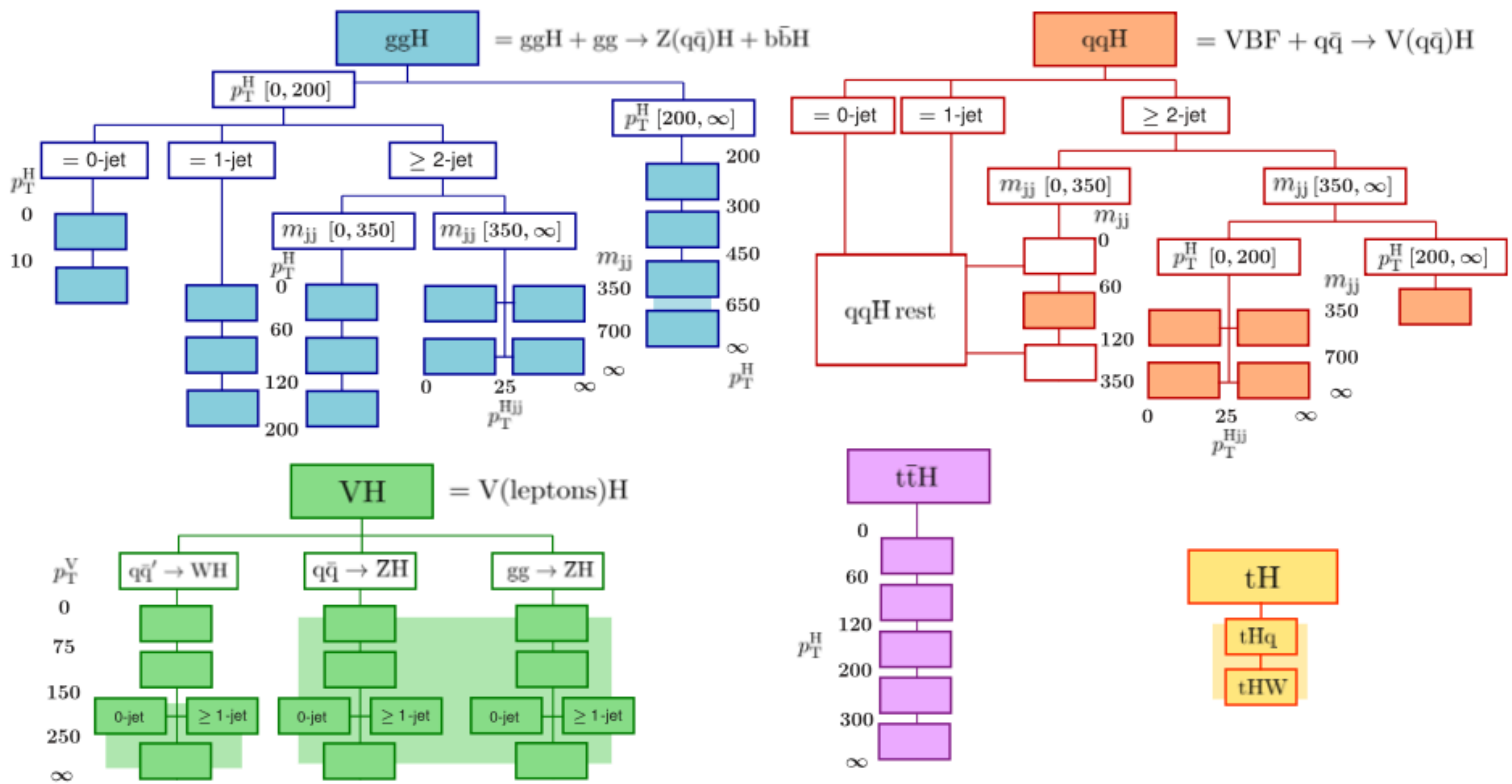
Combining decay modes and production modes

STXS measurements

Measurement in **bins of production mode** and **kinematic/jet multiplicity bins**
To probe the **kinematic dependance of SM** & look for **BSM effects in tails**

→ Useful for combinations and consistent treatment of theory uncertainties

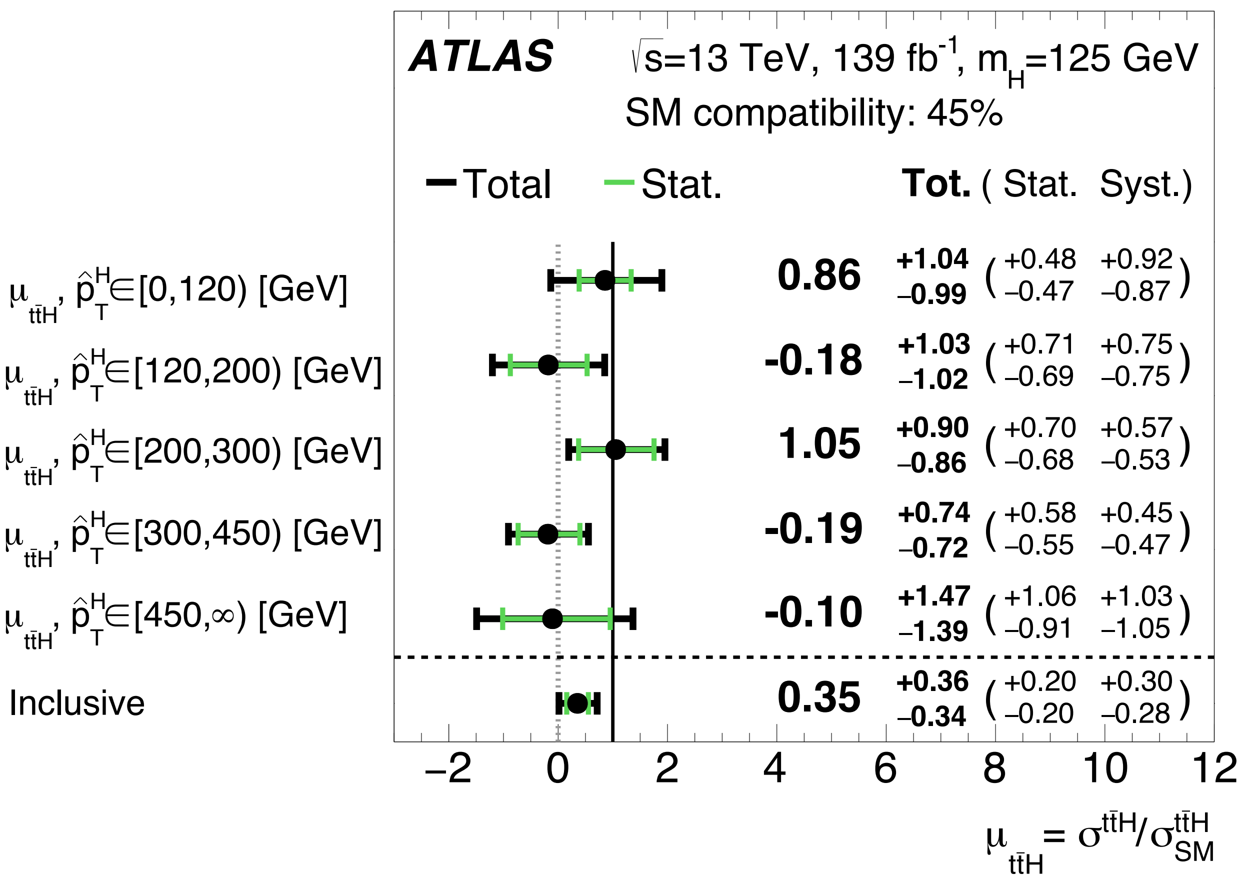
LHC Higgs WG - STXS 1.2



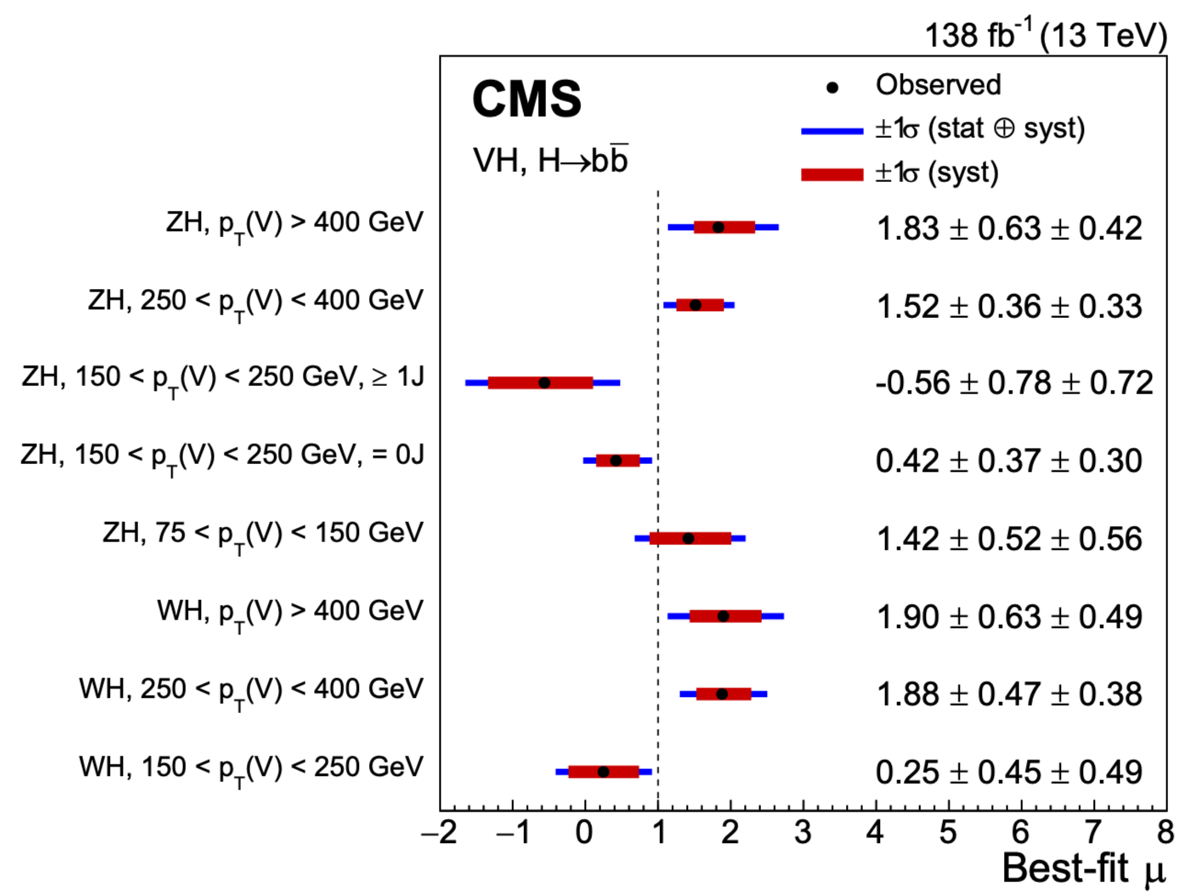
STXS measurements

First STXS 1.2 - with merged bins - in Nature papers

Recent updates for instance for H→bb, ttH and VH



[PRD 109 (2024) 092011](PRD 109 (2024) 092011)

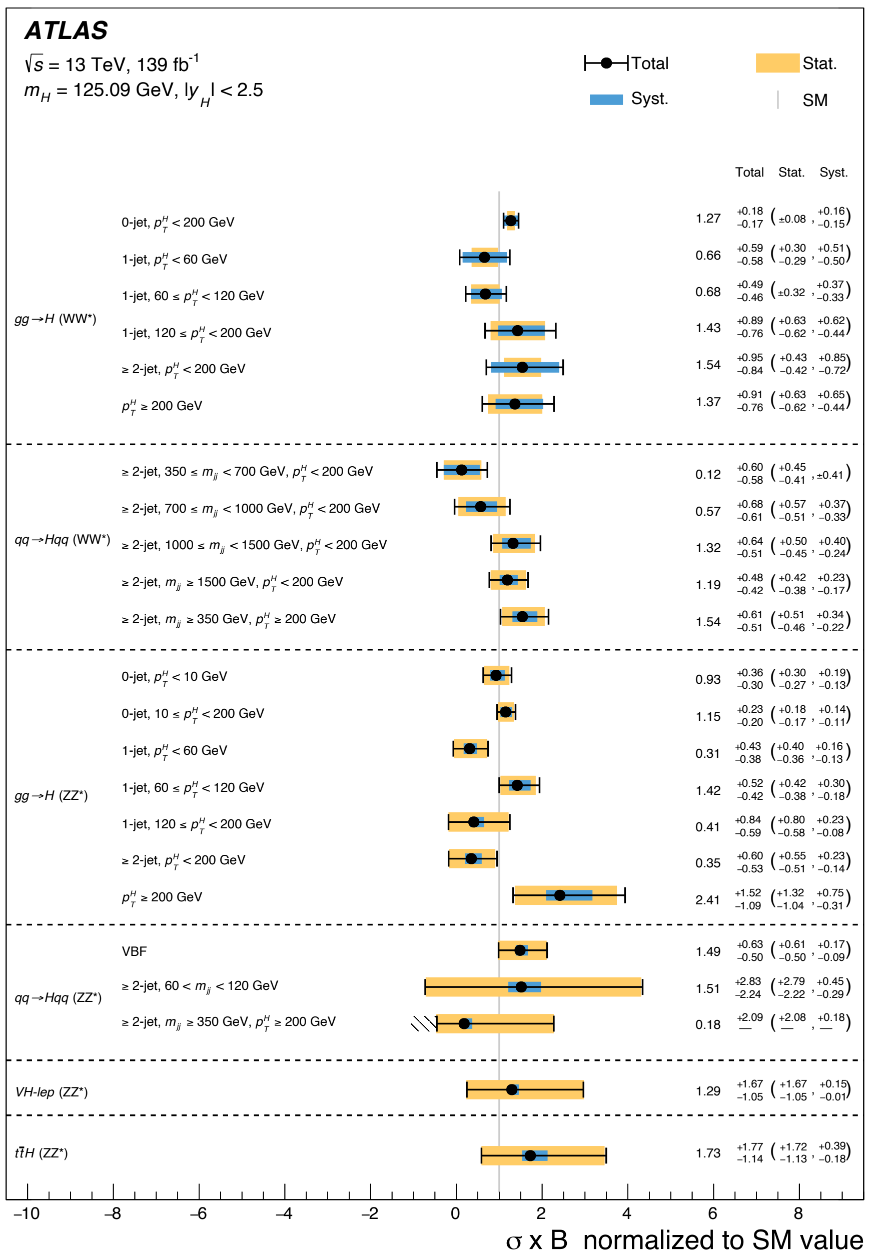


JHEP 06 (2022) 97

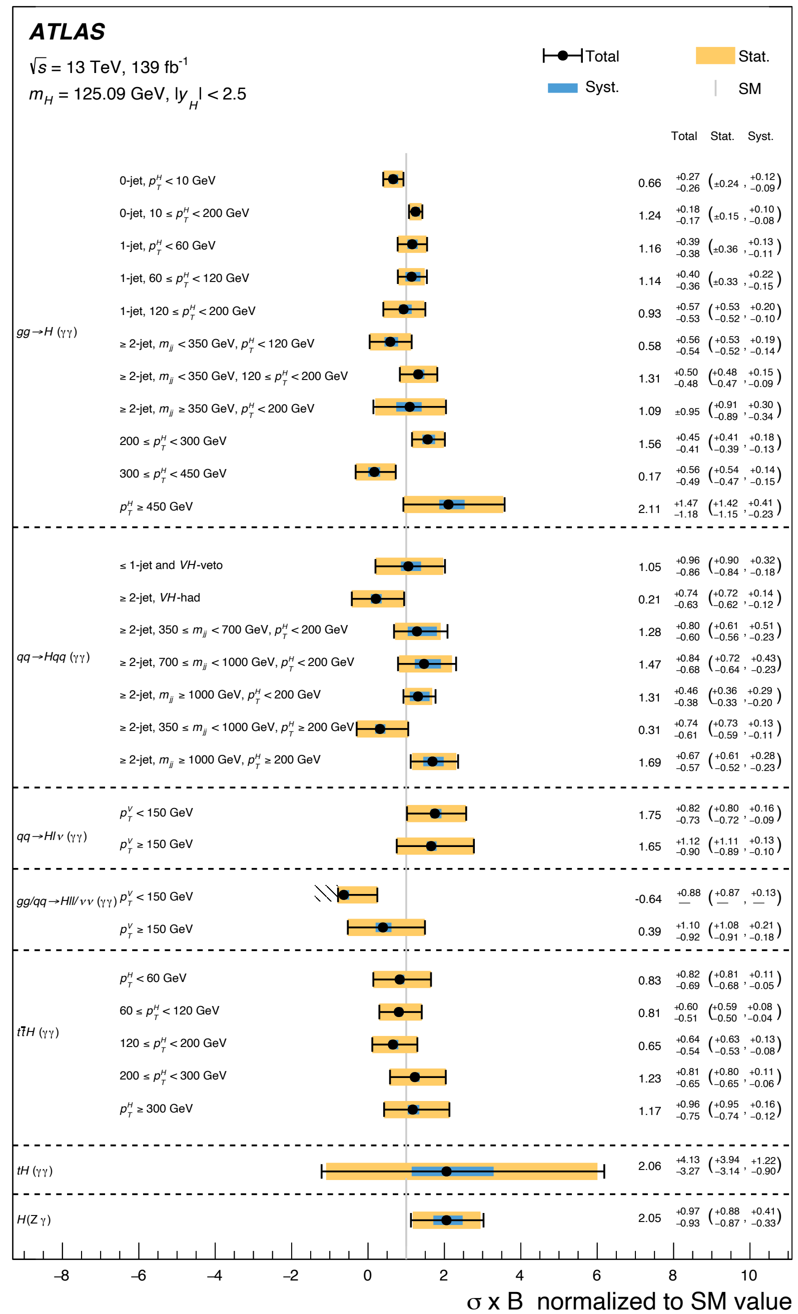
STXS measurements

[arXiv:2402.05742v1 sub. to JHEP](https://arxiv.org/abs/2402.05742v1)

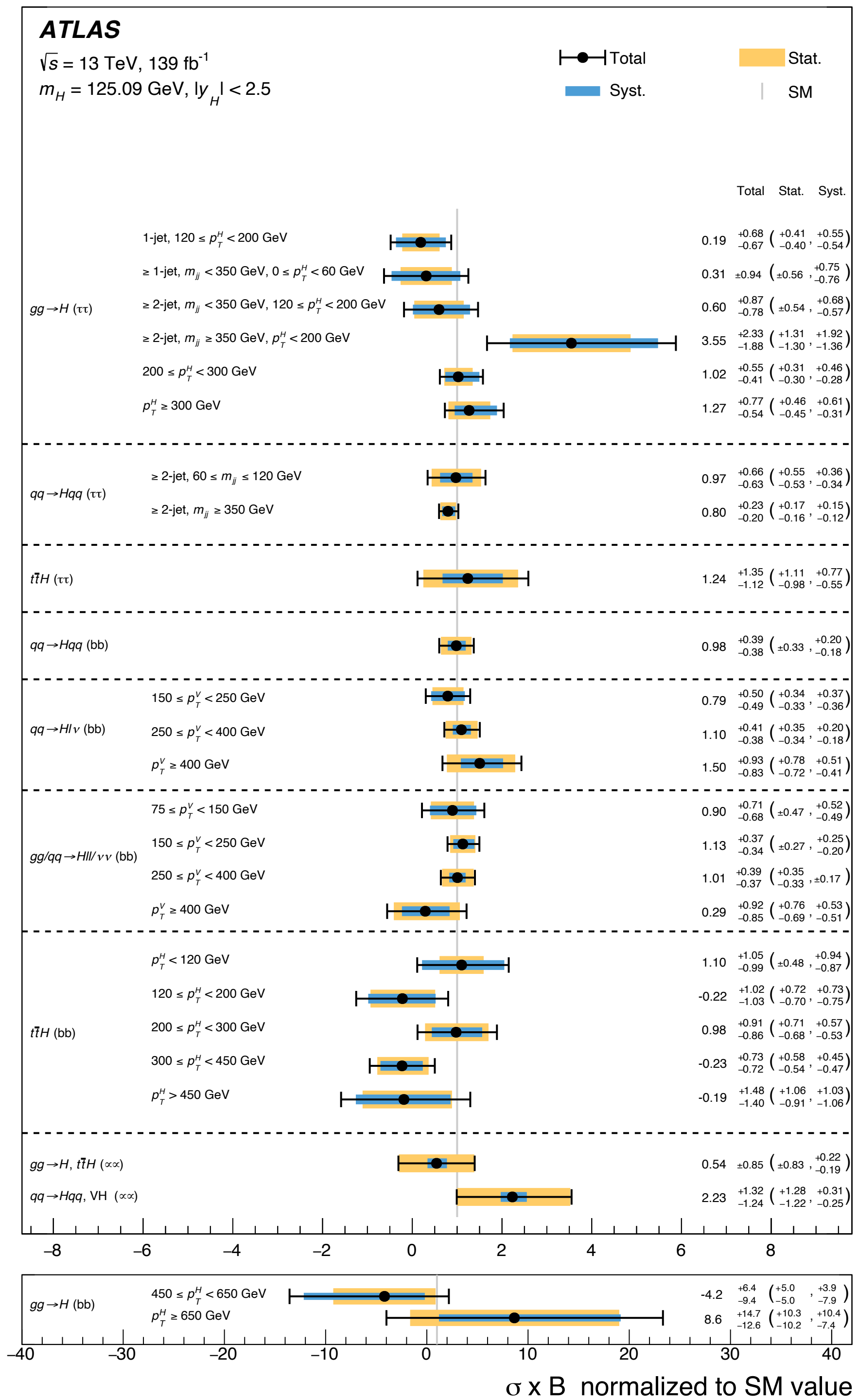
$H \rightarrow WW^*$ and $H \rightarrow ZZ^*$



$H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$



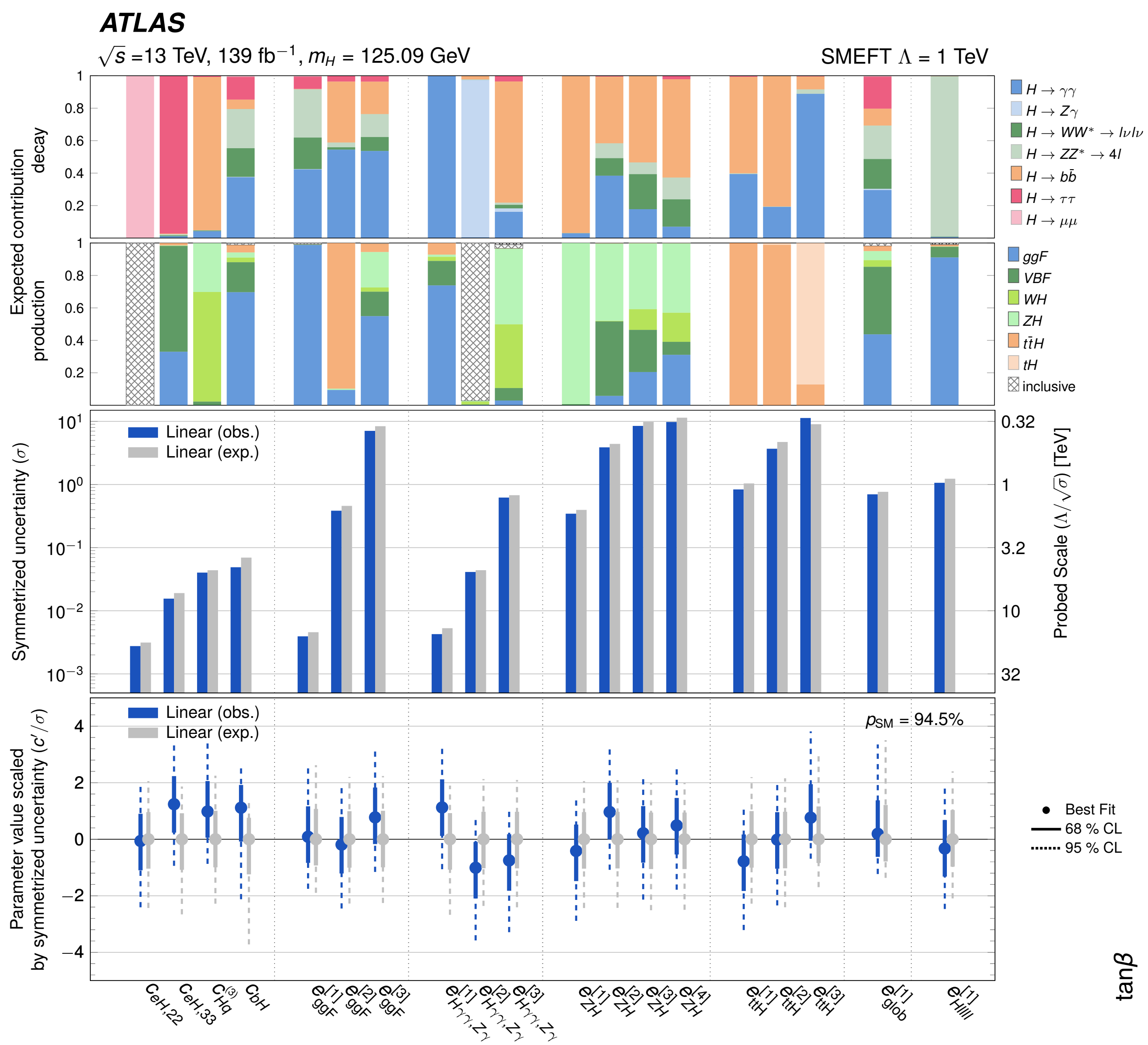
$H \rightarrow \tau\tau$, $H \rightarrow b\bar{b}$ and $H \rightarrow \mu\mu$



ttH multileptons not included, 78 signal yields extracted

p-value of 99.4% to be compatible with SM

STXS measurements



p-value of 94.5% to be compatible with SM

[arXiv:2402.05742v1 sub. to JHEP](https://arxiv.org/abs/2402.05742)

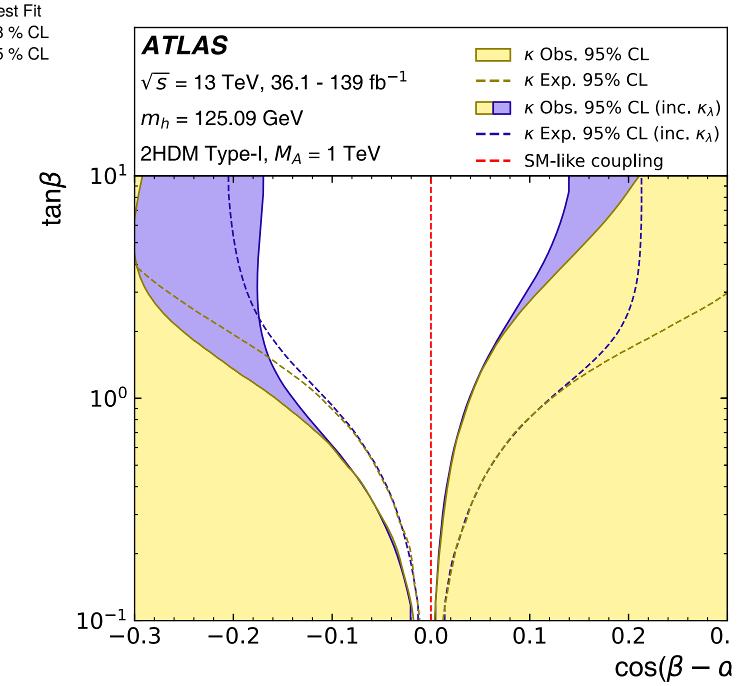
STXS measurements reinterpreted with EFT approach

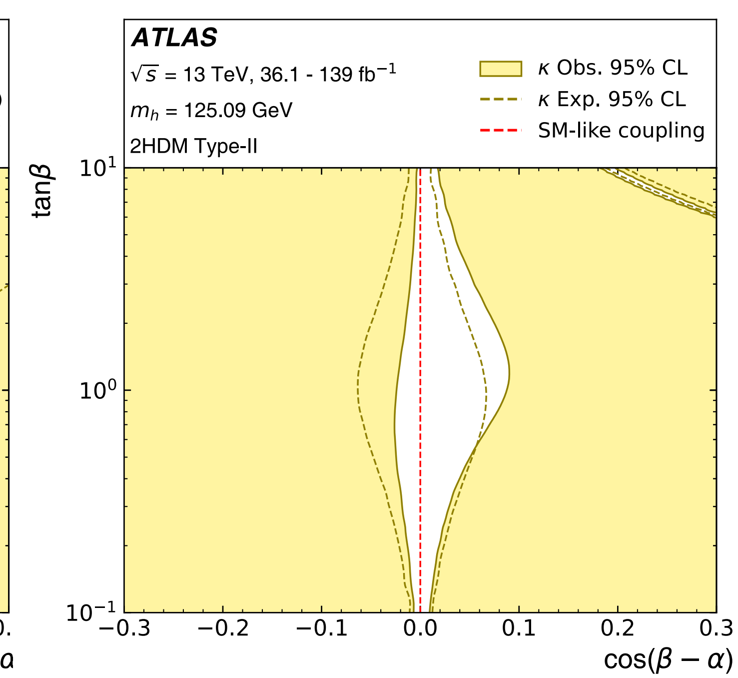
Input measurements don't allow to constrain all dim 6 Wilson coefficients simultaneously

→ 19 linear combinations in rotated basis

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d=6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d=8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots,$$

And reinterpretation in MSSM (7 new benchmarks) and different 2HDM models…





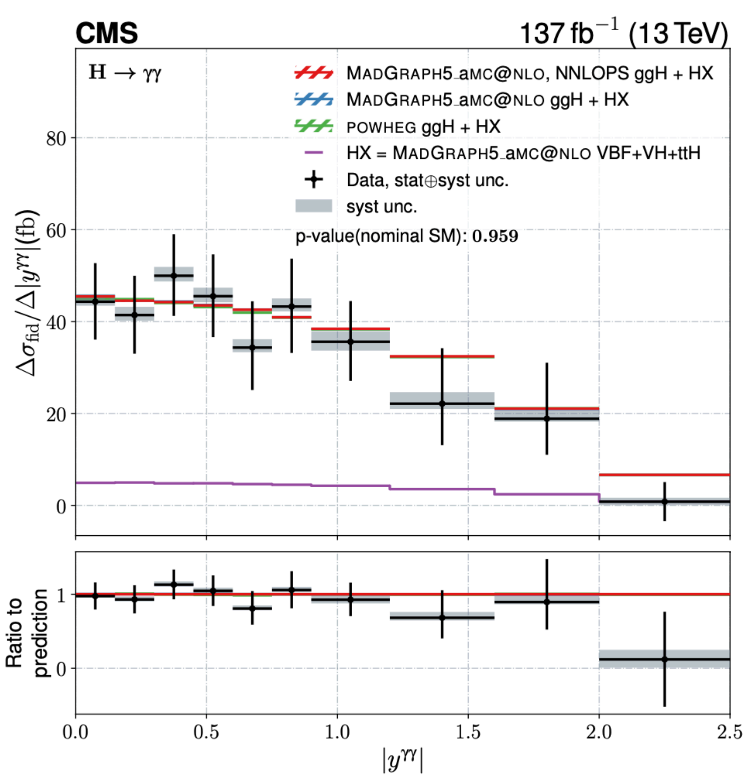
Differential measurements

Fiducial measurements to avoid extrapolations, **unfolded** for selection efficiencies and resolution effects

Check kinematics & variables sensitive to new physics

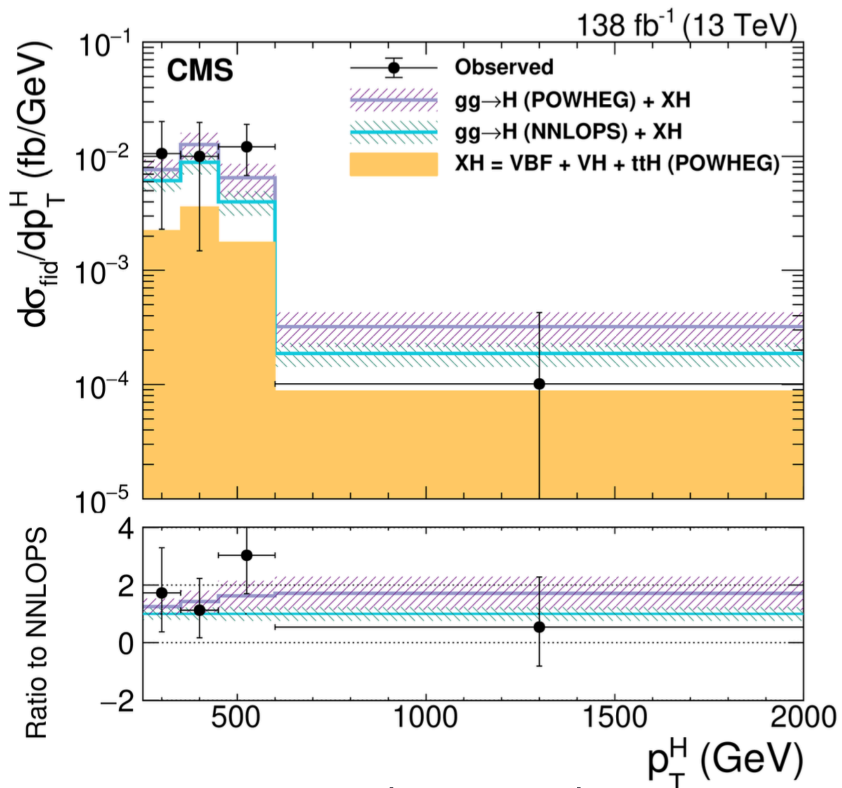
Measurements available for H $\rightarrow \gamma\gamma$, H $\rightarrow ZZ^*$, H $\rightarrow \tau\tau$, H $\rightarrow WW$, H $\rightarrow b\bar{b}$…

JHEP 07 (2023) 091



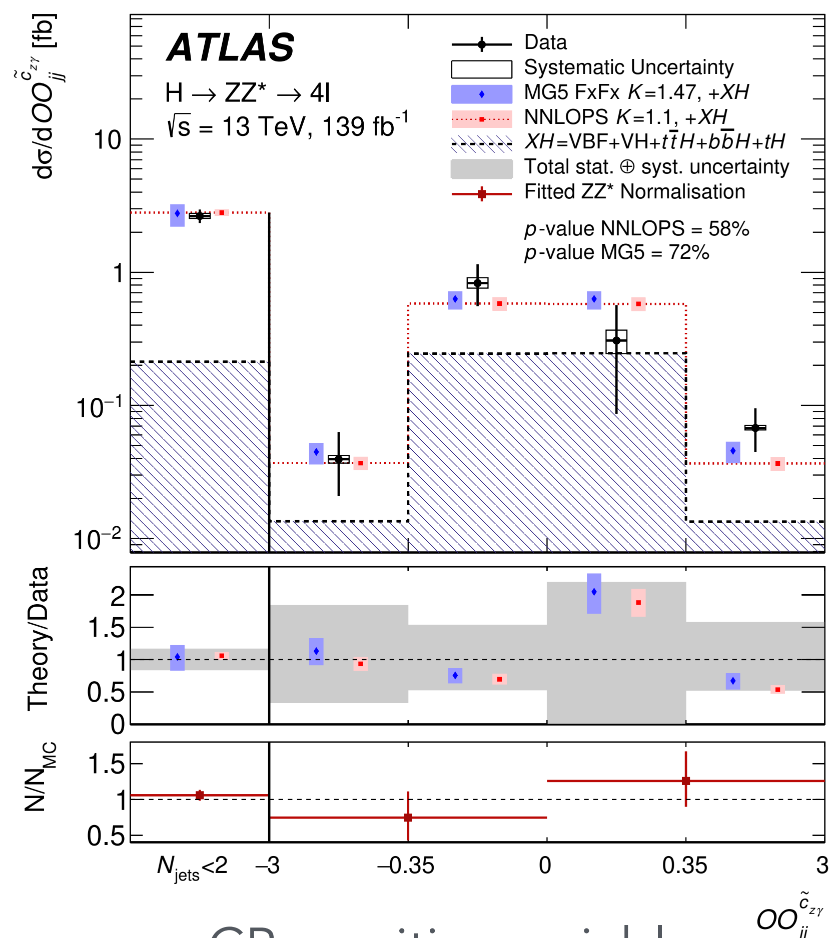
Higgs rapidity in H $\rightarrow \gamma\gamma$

arxiv.2403.20201 sub. PLB



Higgs pT in boosted τ topologies

Eur. Phys. J. C 80 (2020) 942



CP sensitive variable in H $\rightarrow ZZ^*$

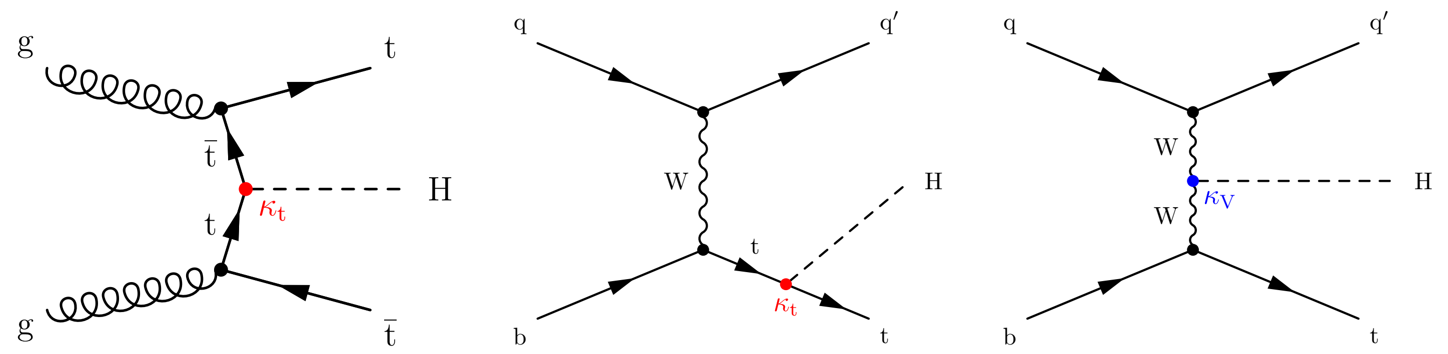
H $\rightarrow WW$ (ATLAS) Phys. Rev. D 108 (2023) 072003

H $\rightarrow \tau\tau$ non boosted (CMS) Phys. Rev. Lett. 128 (2022) 081805

H $\rightarrow b\bar{b}$ (CMS) JHEP 12 (2020) 085

ttH and tH measurements

2018: First observation combining main decay modes Run1 + Run2 (2016)
2018: Observation in the multilepton final state
2020: Observation in H → γγ

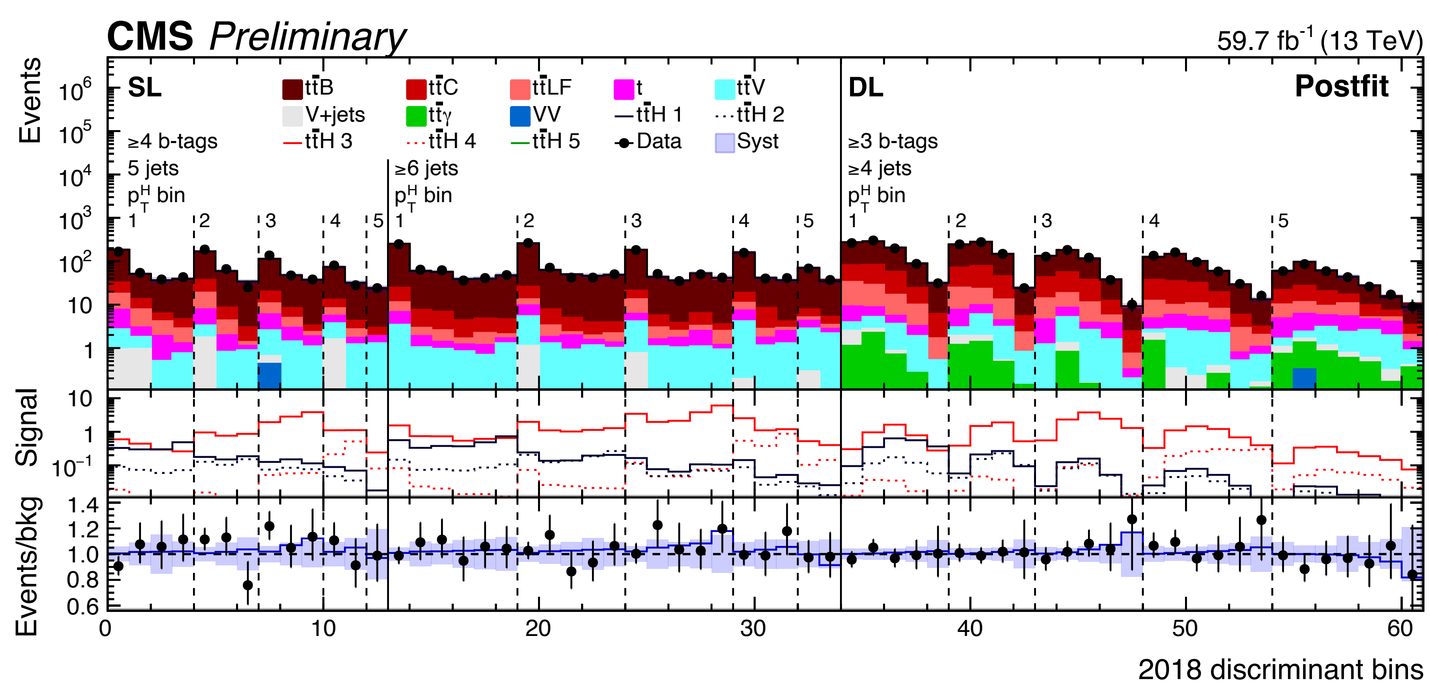


Latest Run 2 result: ttH,H→bb for ATLAS and CMS

Common treatment of difficult irreducible tt+bb background

Comparable sensitivity to ttH in multileptons but μ ~ 0.3

CMS-PAS-HIG-19-011



Usage of machine learning and categorisation

μ = 0.35 ± 0.20 (stat) ± 0.29 (syst) (ATLAS)
μ = 0.33 ± 0.17 (stat) ± 0.21 (syst) (CMS)

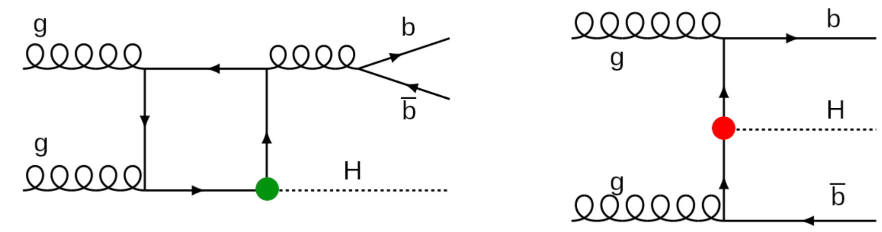
Associated b quark production

CMS-PAS-HIG-23-003

3% of the total production cross section

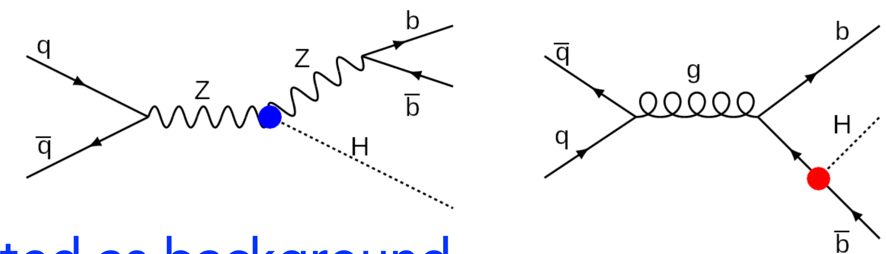
gluon fusion with gluon→bb splitting and b-fusion

Accuracy of theoretical prediction of b-fusion of only 40%



interferences between b-fusion and gluon fusion

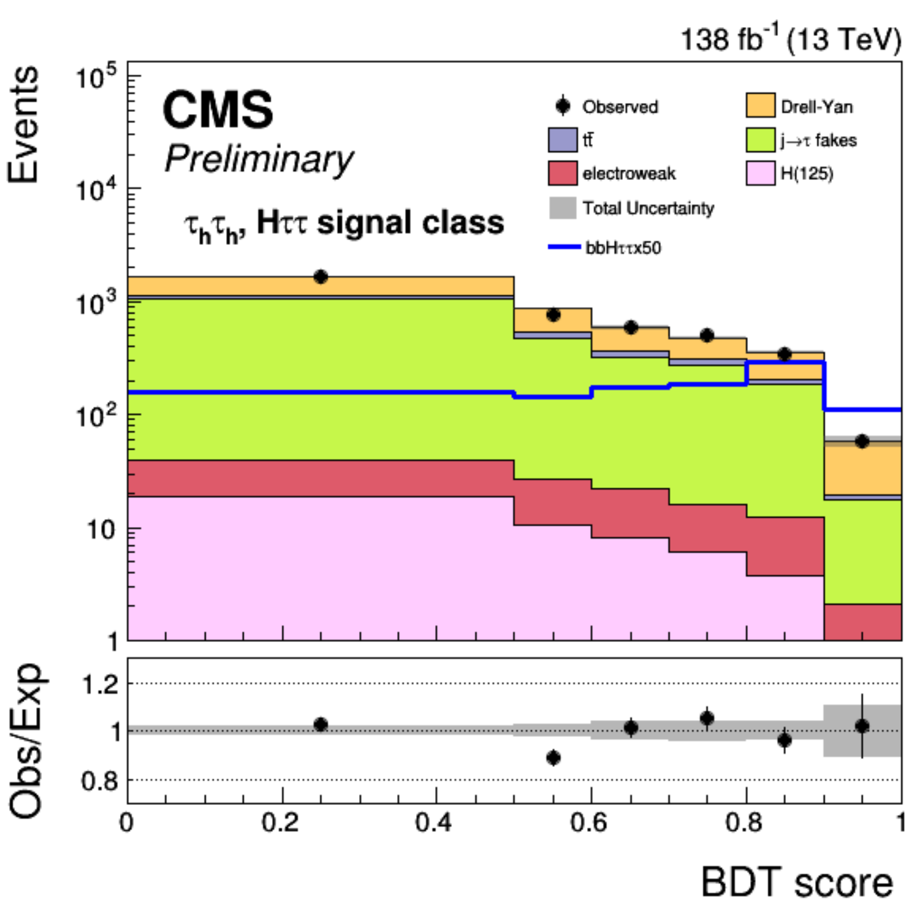
Upper limits: 3.7 (6.1) x SM at 95%CL

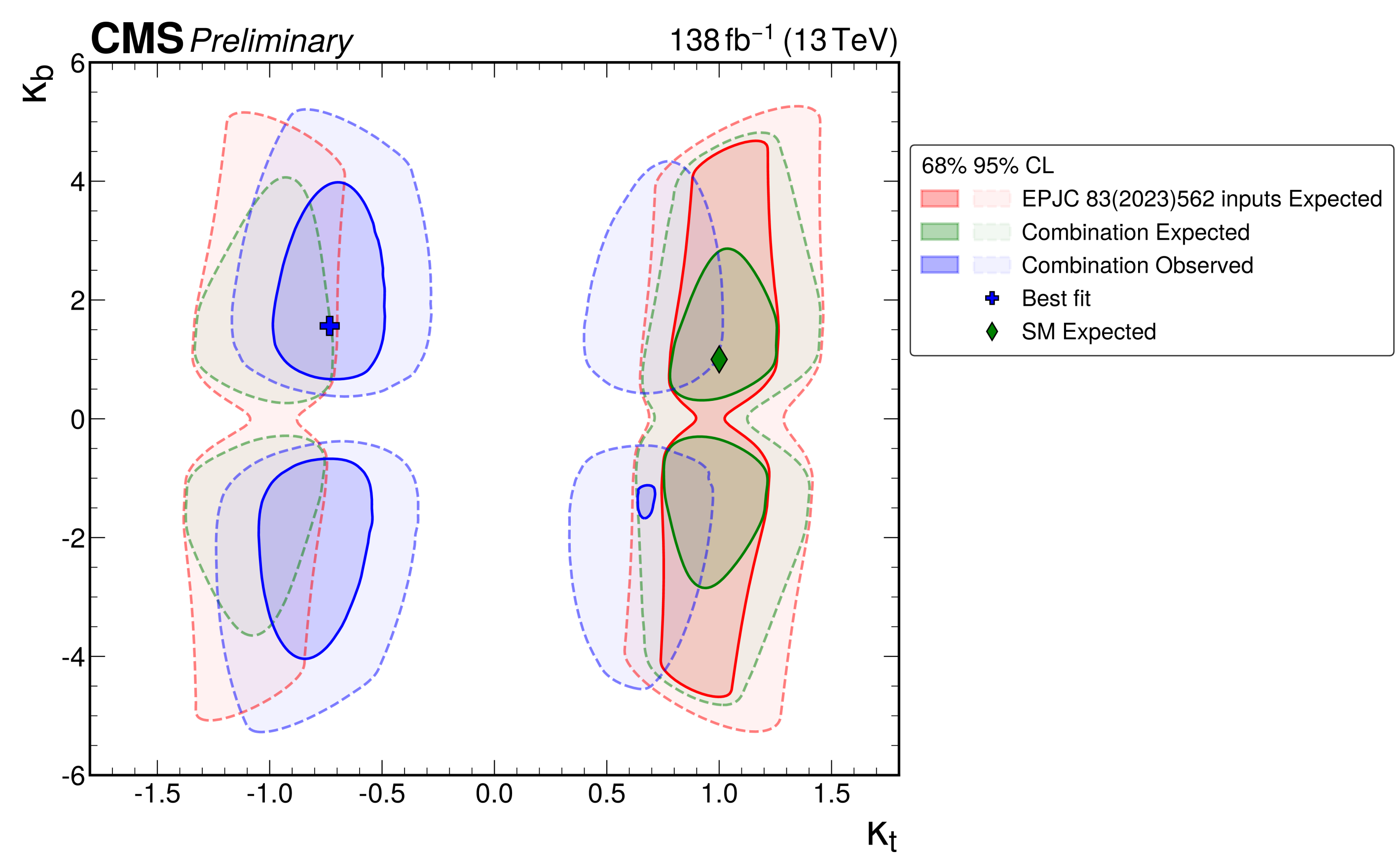


ZH treated as background

$\tau\tau$ final states (including WW)

Allows to constrain relative sign of κ_b and κ_t





Electroweak VH measurement

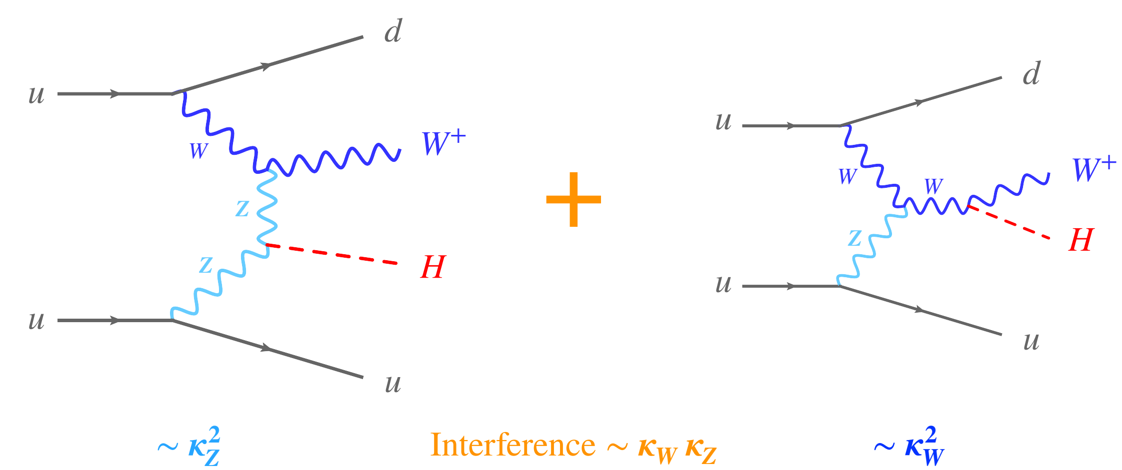
Vector Boson Scattering

arXiv:2402.00426
arXiv:2405.16566

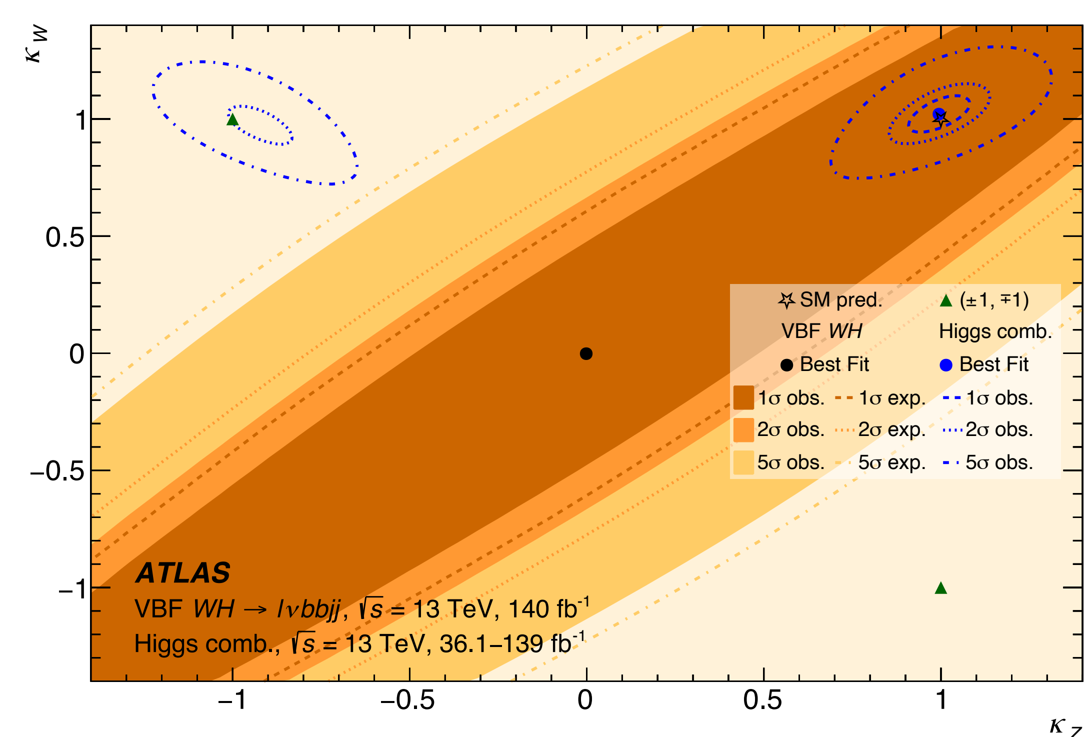
VH measurements traditionally performed in V to 2 leptons and H to fermions (large BR)

VBS production gives access to relative sign of κ_Z and κ_W

ATLAS and CMS both exclude $\kappa_W/\kappa_Z < 0$ beyond 5σ in H $\rightarrow b\bar{b}$ final states



$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z\,\kappa_W\,\Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$



Inclusive cross section measurement

Run 3 - 13.6 TeV

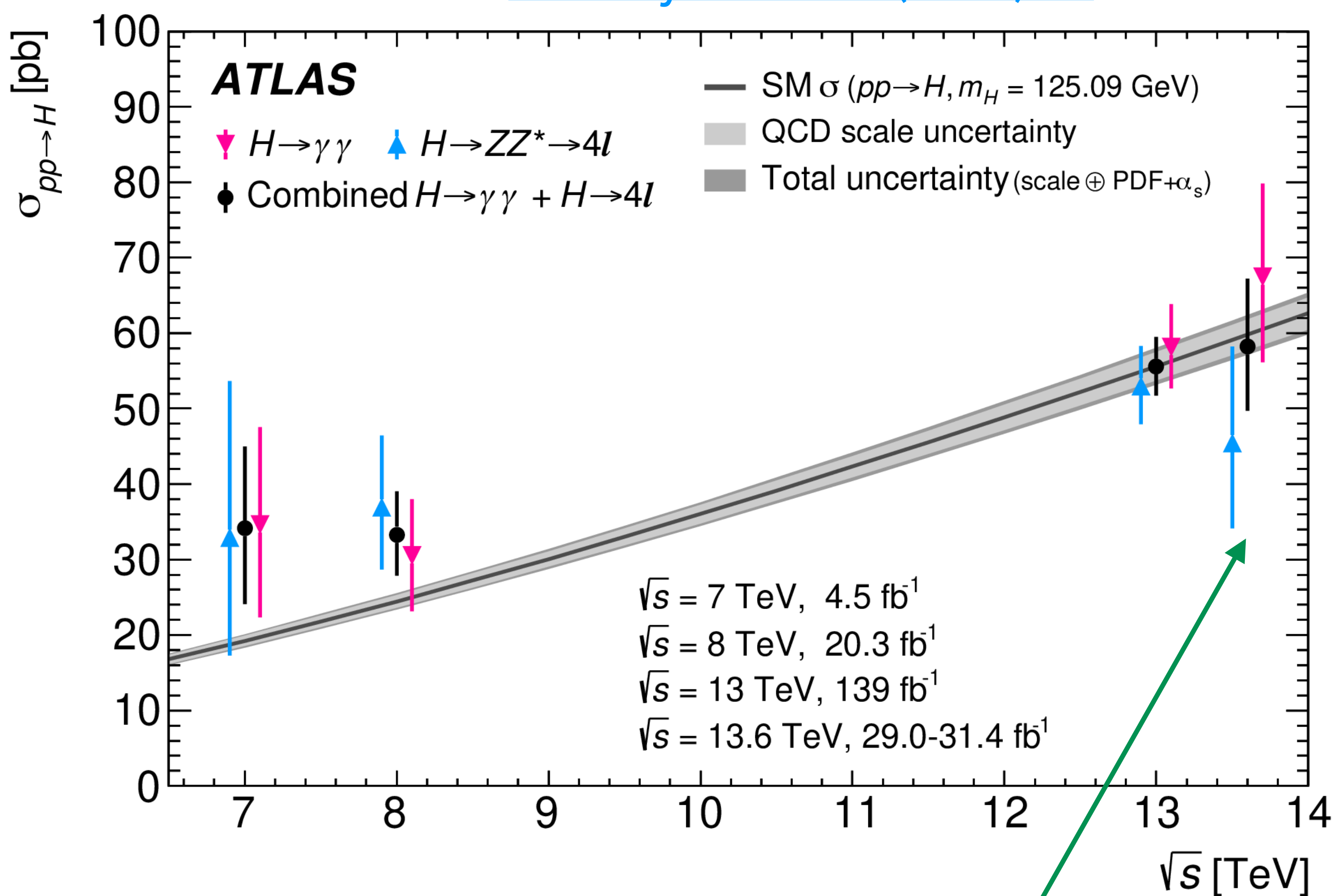
Fiducial inclusive cross sections with 2022 ATLAS Run 3 data

- $H \to \gamma\gamma$ (29.0 fb^{-1})
- $H \to ZZ^* \to 4$ (31.4 fb^{-1})

Extrapolation to full phase space

- σ(pp→H) = 58.2 ± 8.7 pb
- σ(pp→H) SM = 59.9 ± 2.6 pb

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



First Run 3 uncertainty is ~15%
Twice Run 2 for now

Mass, width and CP violation

H $J = 0$

was H^0

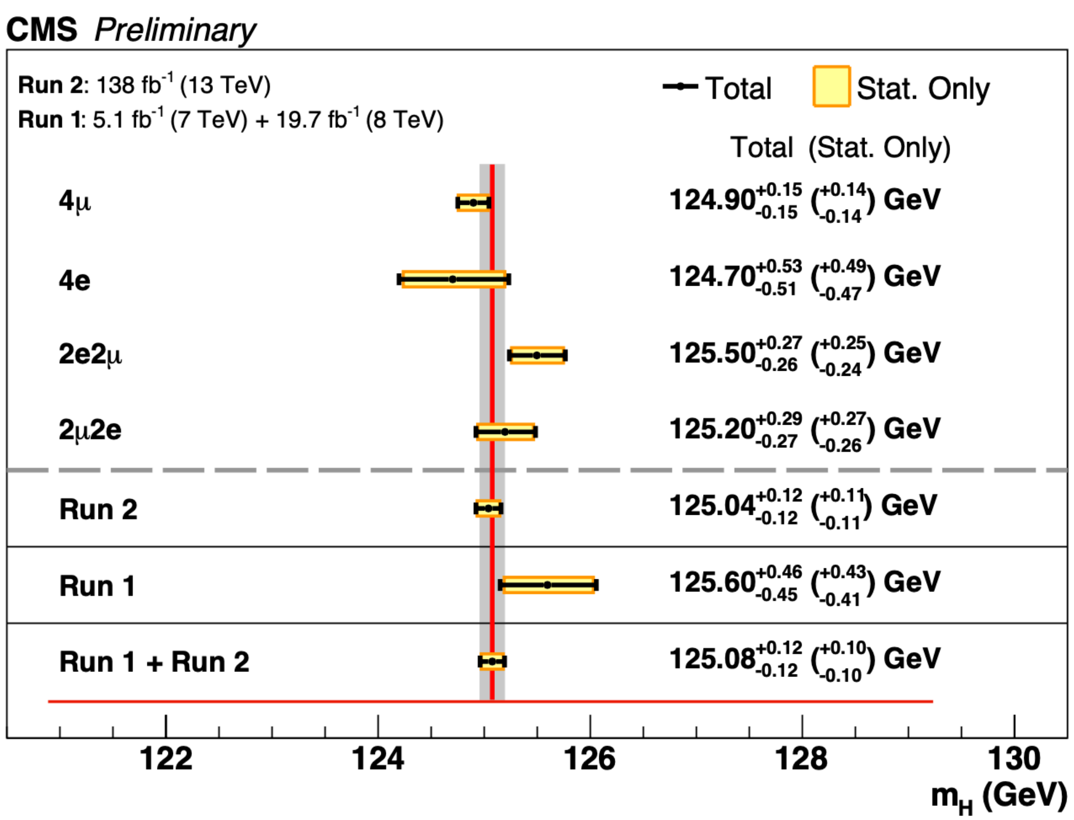
Mass $m = 125.20 \pm 0.11$ GeV (S = 1.4)
Full width $\Gamma = 3.7^{+1.9}_{-1.4}$ MeV (assumes equal on-shell and off-shell effective couplings)

Higgs boson mass

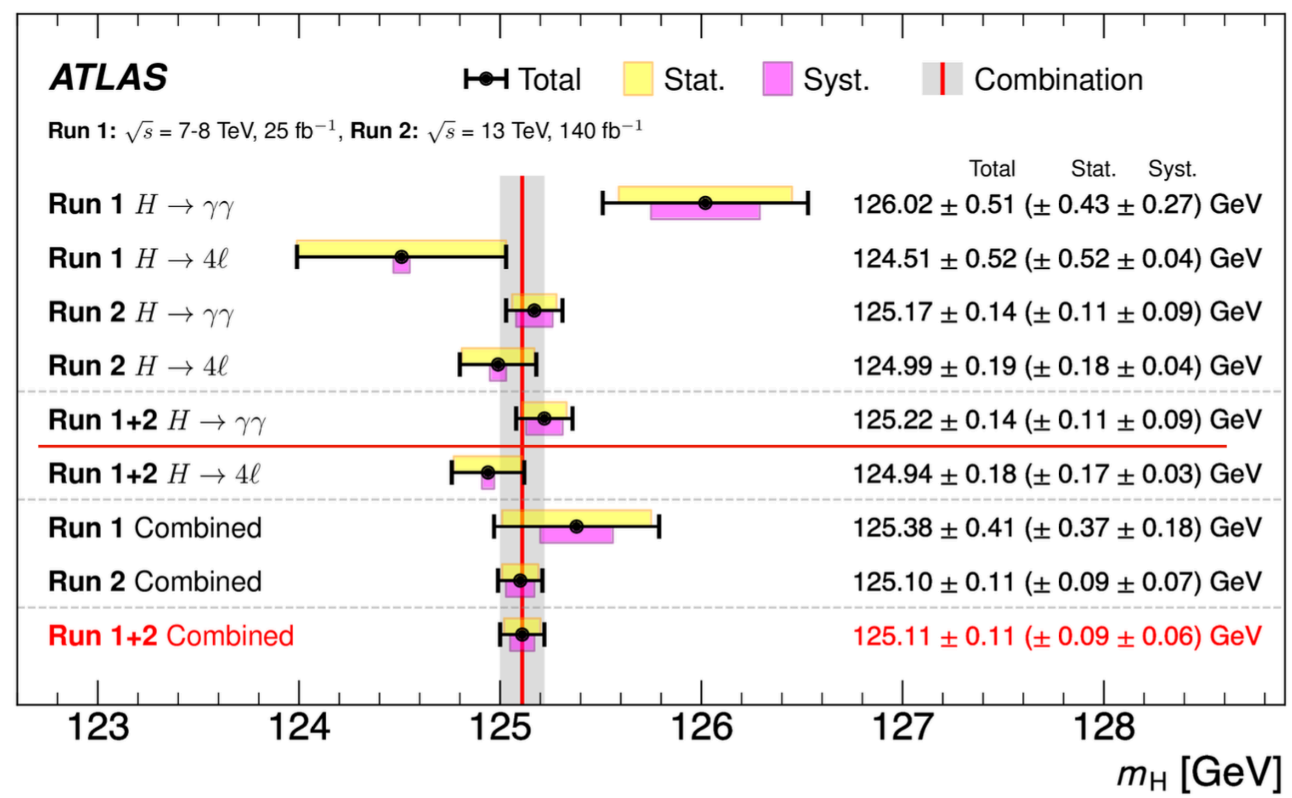
Mass from channels with best resolutions: H $\rightarrow \gamma\gamma$ and H $\rightarrow ZZ^* \rightarrow 4\ell$
Multiple categories with different resolutions
Reaching 0.1% precision

M_H = 125.08 ± 0.12 GeV (CMS 4 leptons)
Best single measurement! [JHEP 08 (2023) 040]

M_H = 125.17 ± 0.14 GeV (ATLAS di-photon)
M_H = 125.11 ± 0.11 GeV (ATLAS, Best combination!)



$\sigma(m4\ell)$ improved by 3-8%: constraint to common vertex (with beam spot constraint) of the 4 lepton tracks + 9 $\delta4\ell/m4\ell$ categories



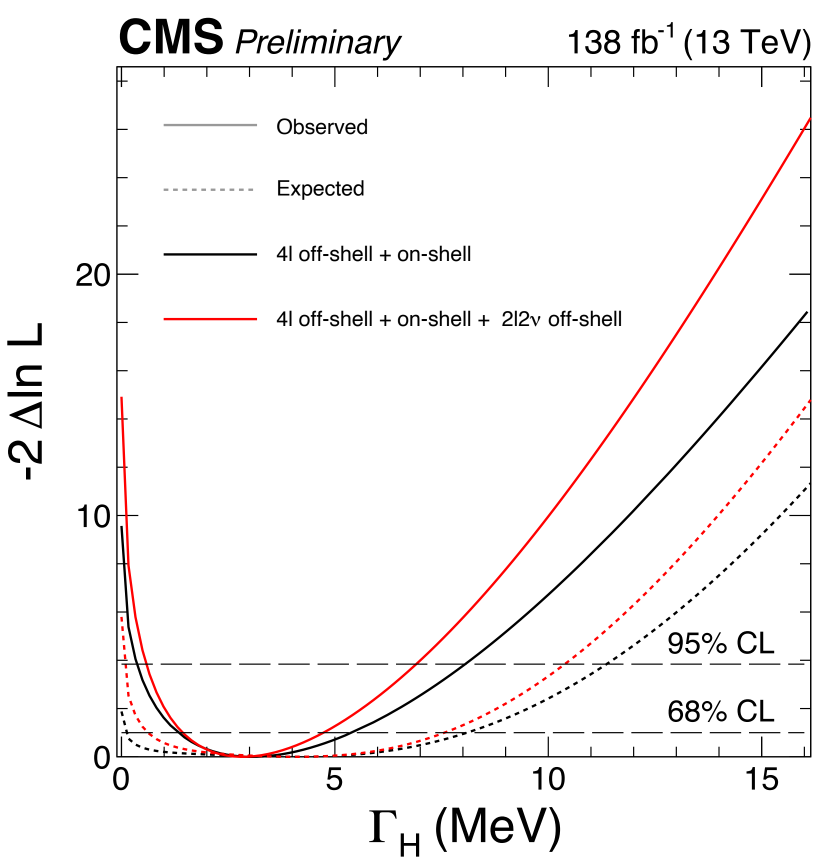
Higgs boson width

On- & off-shell ratio gives access to the Higgs boson width
Assuming same couplings to on- and off-shell Higgs

$$\mu^{\text{on}}_{ZZ} \equiv \frac{\sigma_h \times \text{BR}(h \to ZZ \to 4\ell)}{[\sigma_h \times \text{BR}(h \to ZZ \to 4\ell)]_{\text{SM}}} \sim \frac{\kappa^2_{ggh}\,\kappa^2_{hZZ}}{\Gamma_h/\Gamma_h^{\text{SM}}}$$

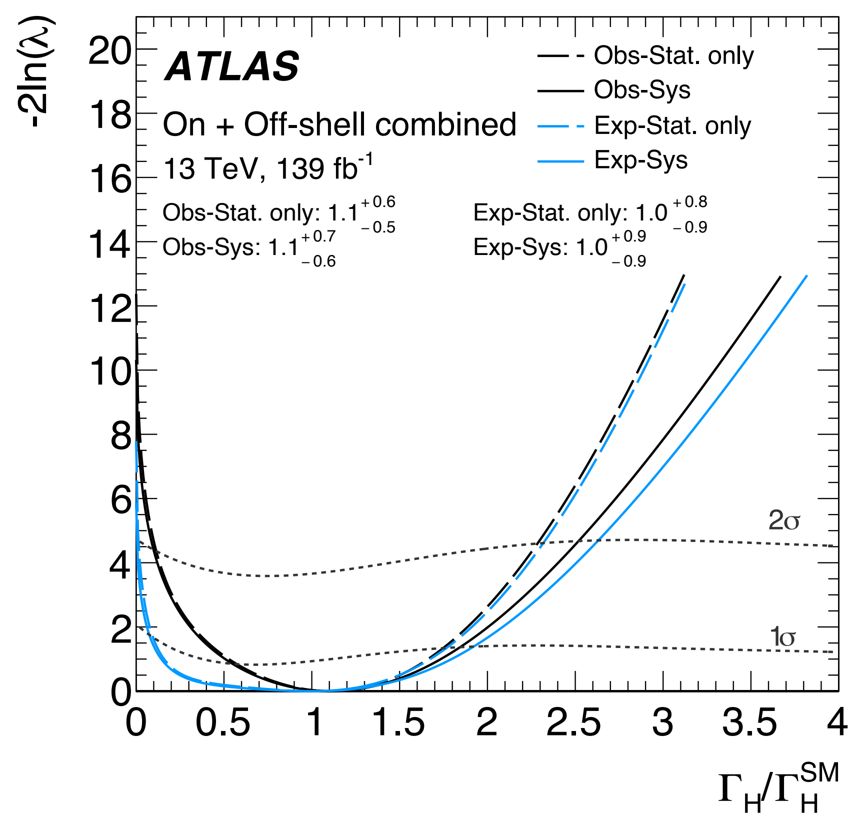
$$\mu^{\text{off}}_{ZZ} \equiv \frac{\text{d}\bar{\sigma}_h}{[\text{d}\bar{\sigma}_h]_{\text{SM}}} \sim \kappa^2_{ggh}(\hat{s})\,\kappa^2_{hZZ}(\hat{s})$$

JHEP 08 (2023) 040



$$\Gamma_H = 2.9^{+1.9}_{-1.4} \text{ @ 68\% CL}$$

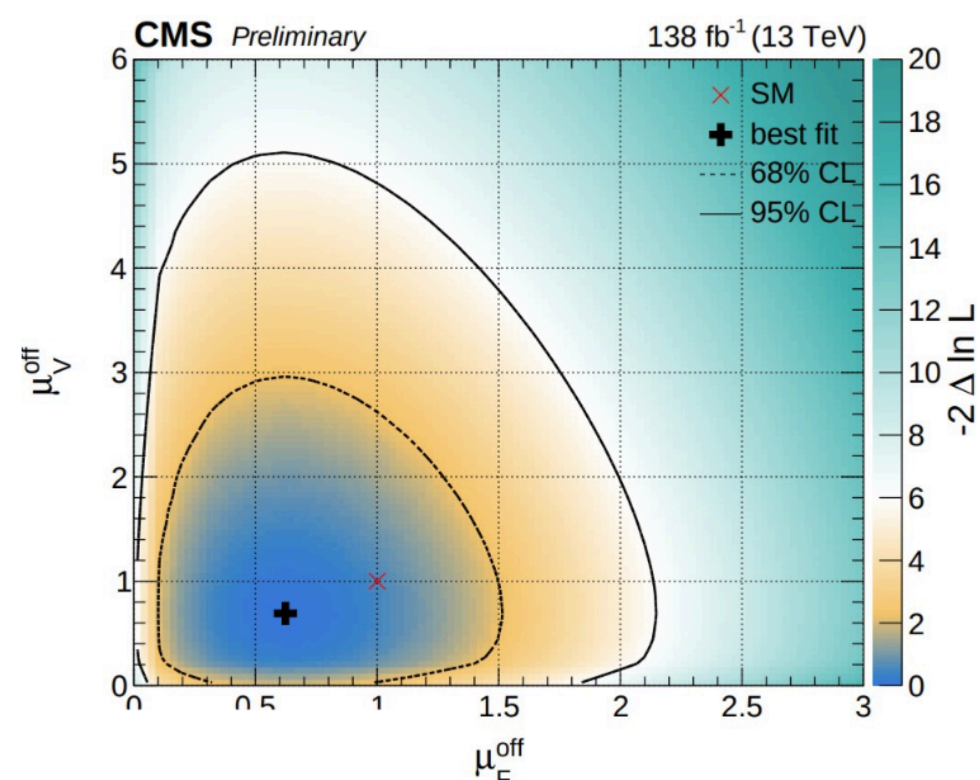
PLB 846 (2023) 138223



$$\Gamma_H = 4.5^{+3.3}_{-2.5} \text{ @ 68\% CL}$$

JHEP 08 (2023) 040

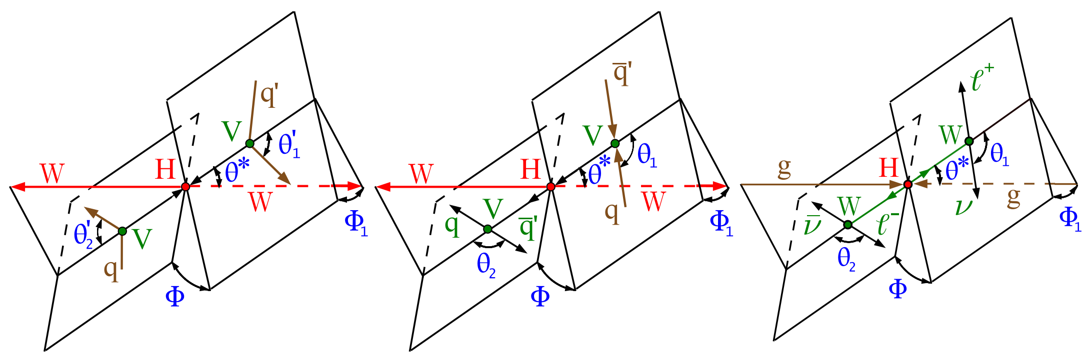
Off-shell region: m(4ℓ) > 220 GeV
+ combination with m($2\ell2\nu$)



+ direct constraint $\Gamma_H <$ 330 MeV
@ 95% CL from 4ℓ mass

Measurement is statistically limited
Main uncertainties related to dominant qq → (Z/γ*)(Z/γ*) → 4ℓ background modelling

CP violation - bosonic couplings



Tree level CP-even coupling (=0 if absent in SM)

CP-even anomalous higher order couplings

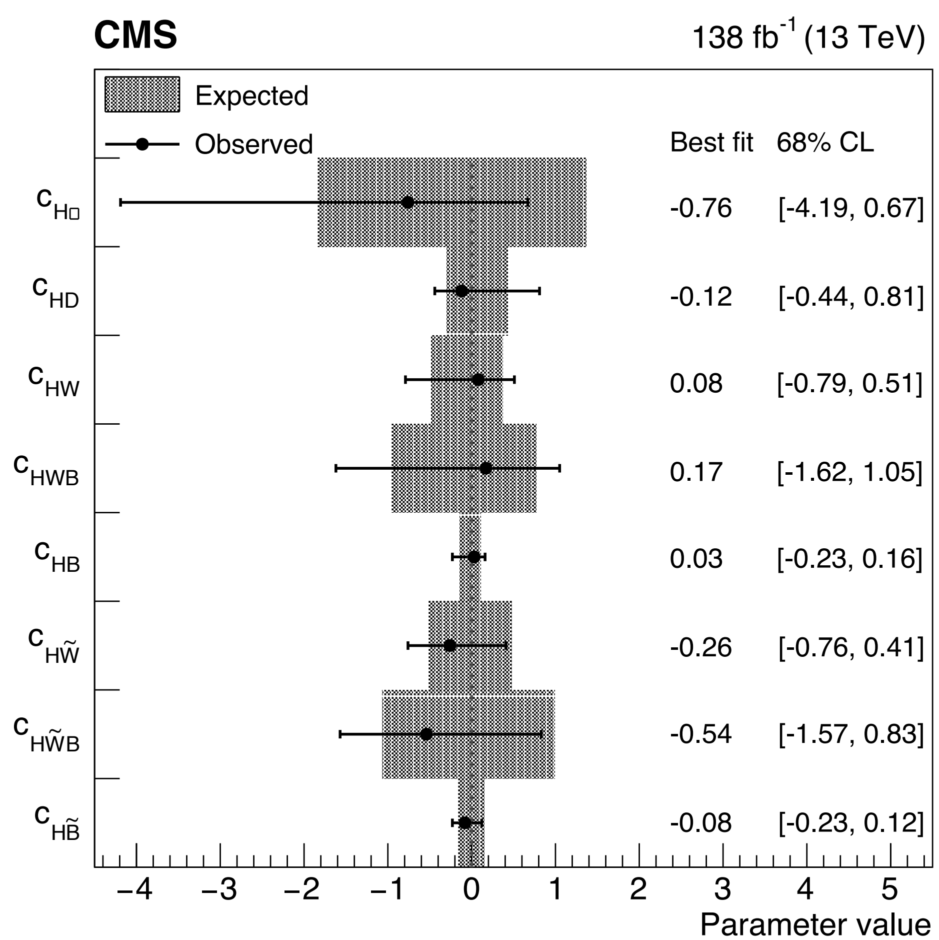
$$\mathscr{A}(HVV) \simeq \left[a_1^{VV} + \frac{k_1^{VV} q_1^2 + k_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} + \frac{k_3^{VV} (q_1 + q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_V^2 \varepsilon_{V1}^* \varepsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

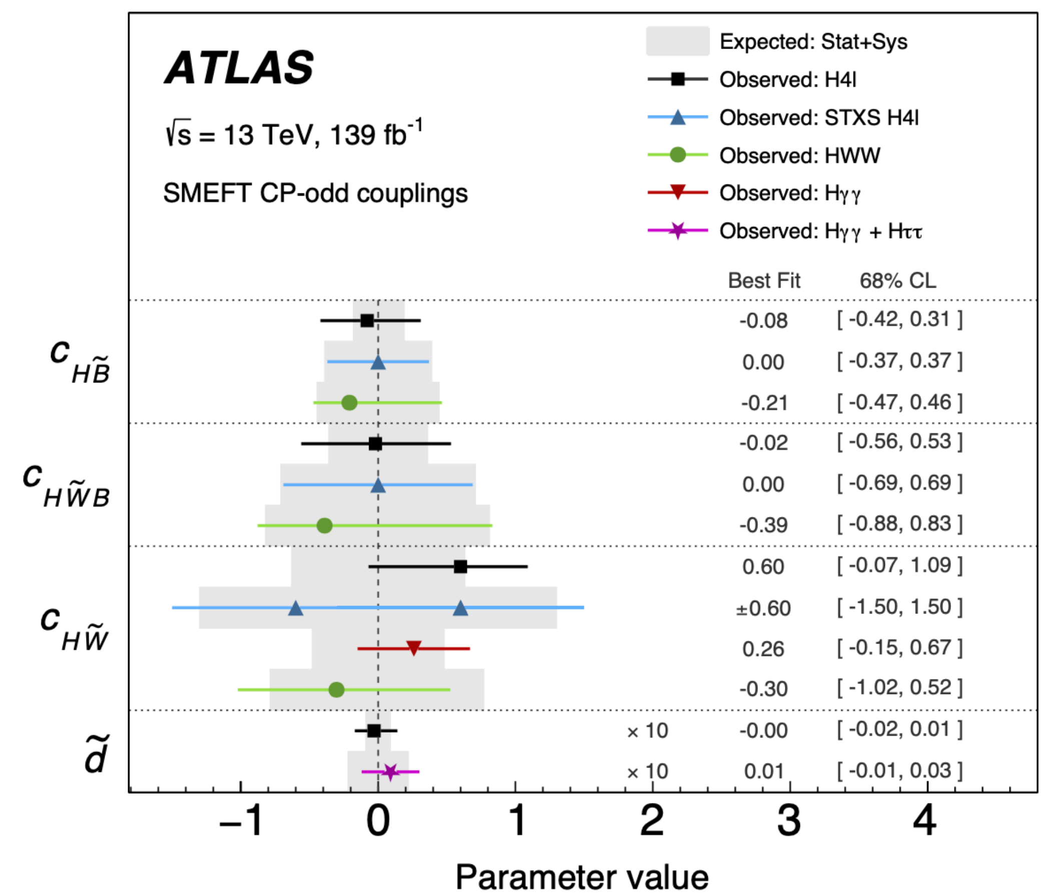
CP-even anomalous coupling

CP-odd anomalous coupling

MELA discriminants in H→WW - ggH, VBF, VH production
EFT interpretations

Optimal observables in VBF (many channels),
And H→ZZ, H→WW decays
EFT interpretations





CMS-PAS-HIG-22-008 acc. JHEP

JHEP05(2024)105

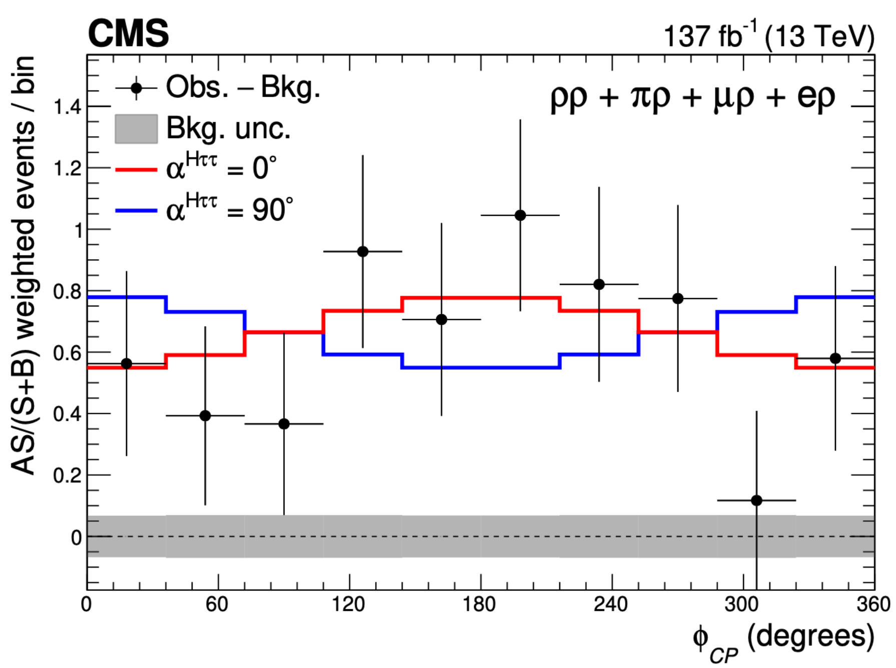
CP violation - fermionic couplings

Generalised Yukawa coupling, CP violation can occur at tree level!

$$L_Y = -\frac{m_l \phi}{\nu}(\kappa_l \overline{\psi_l}\psi_l + \tilde{\kappa}_l \overline{\psi_l} i\gamma_5 \psi_l) \qquad f_{cp}^{Hll} = \frac{|\tilde{\kappa}_l|^2}{|\kappa_l|^2 + |\tilde{\kappa}_l|^2} = \sin^2(\alpha^{Hll})$$

Angle between tau decay planes gives access to α^{Hll}
Several techniques depending on τ decay mode $\mu^{\pm}, e^{\pm}, \pi^{\pm}, \rho^{\pm}, a_1^{1pr,3pr}$

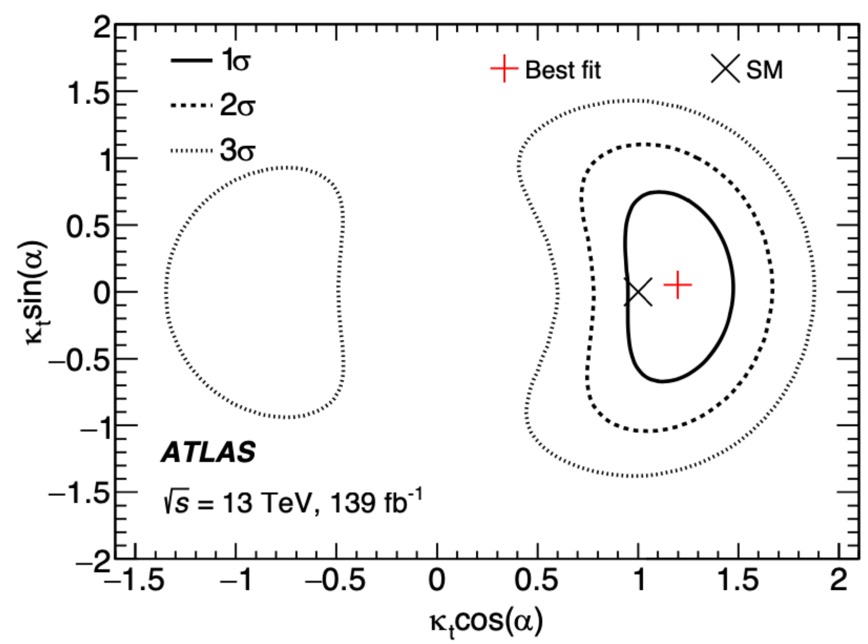
Overall weighted distribution



CMS → pure CP-odd hypothesis excl. at 3.0σ (2.6σ)
JHEP 06 (2022) 012 → α(Hττ) = -1 ± 19°

ATLAS → pure CP-odd hypothesis excl. at 3.4σ (2.1σ)
Eur. Phys. J. C 83 (2023) 563 → α(Hττ) = 9 ± 16°

Top Yukawa CP structure probed in $t\bar{t}H, H \to 4l, \gamma\gamma$ and ggH loop with top quark dominance and also in $t\bar{t}H, H \to b\bar{b}$



CMS → pure CP-odd hypothesis excl. at 3.2σ (ttH,4l,$\gamma\gamma$)
Phys. Rev. D 104 (2021) 052004
→ pure CP-odd hypothesis excl. at 1.0σ (ttH,bb)
CMS-PAS-HIG-19-011

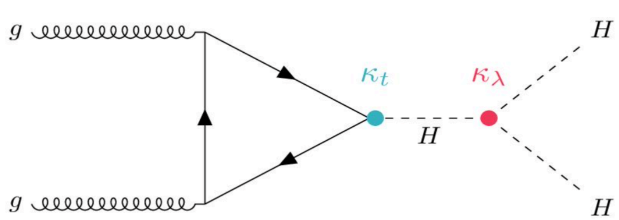
ATLAS → pure CP-odd hypothesis excl. at 3.9σ (ttH,$\gamma\gamma$)
Phys. Rev. lett. 125 (2020) 061802
→ pure CP-odd hypothesis excl. at 1.2σ (ttH,bb)
Phys. Lett. B 849 (2024) 138469

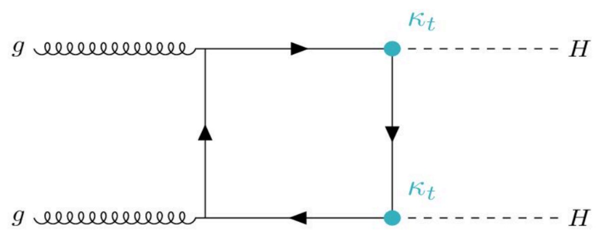
Towards the Higgs self-coupling

Towards the Higgs self-coupling

Di-Higgs production allows to probe the **shape of the Higgs potential** by measuring the trilinear **self-coupling** λ of the Higgs boson

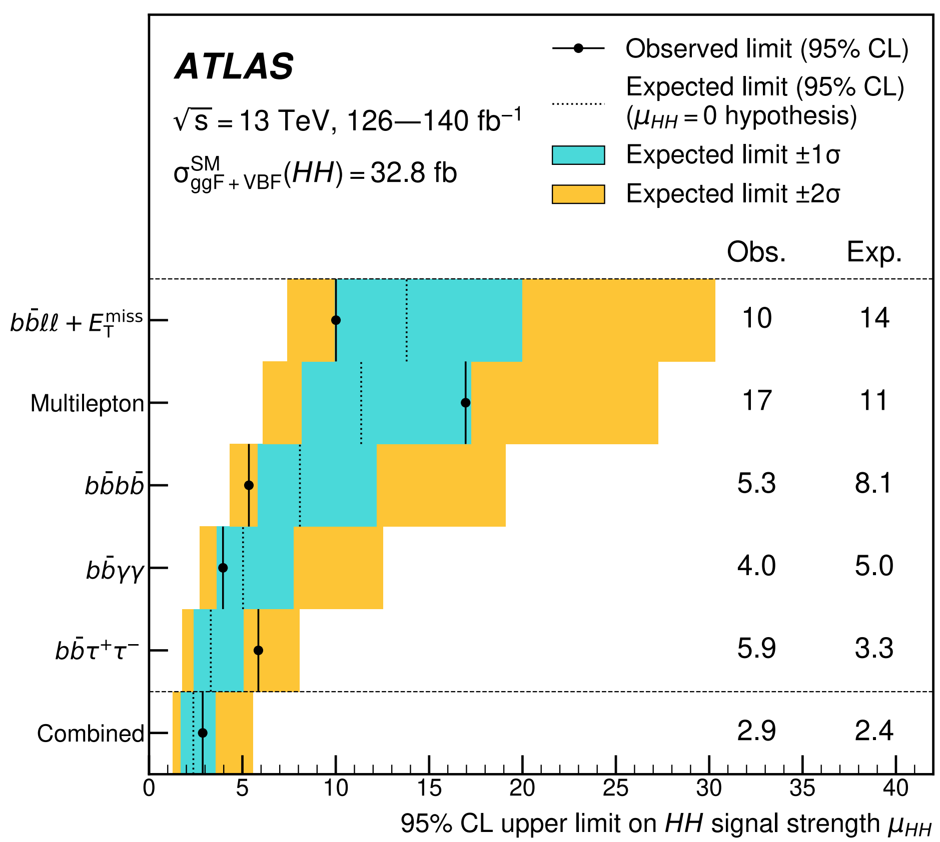
$$V(H) = \frac{1}{2}m_{\rm H}^2 H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$



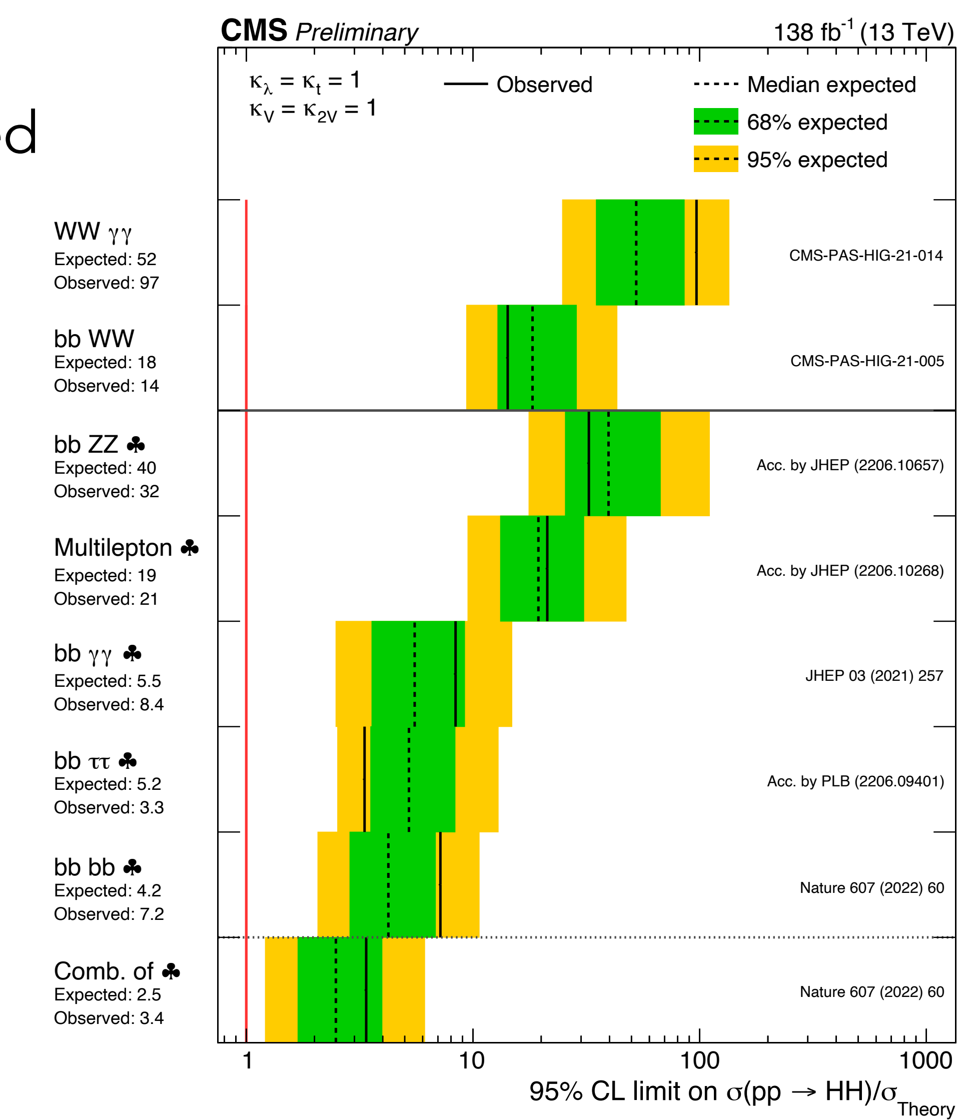


But destructive interference between triangle and box diagrams: small x-sec…

No golden channel, combination between many channels needed



3 leadings channels ($bb\gamma\gamma$, $bb\tau\tau$, bbbb) are reaching limits close to ~5 x SM

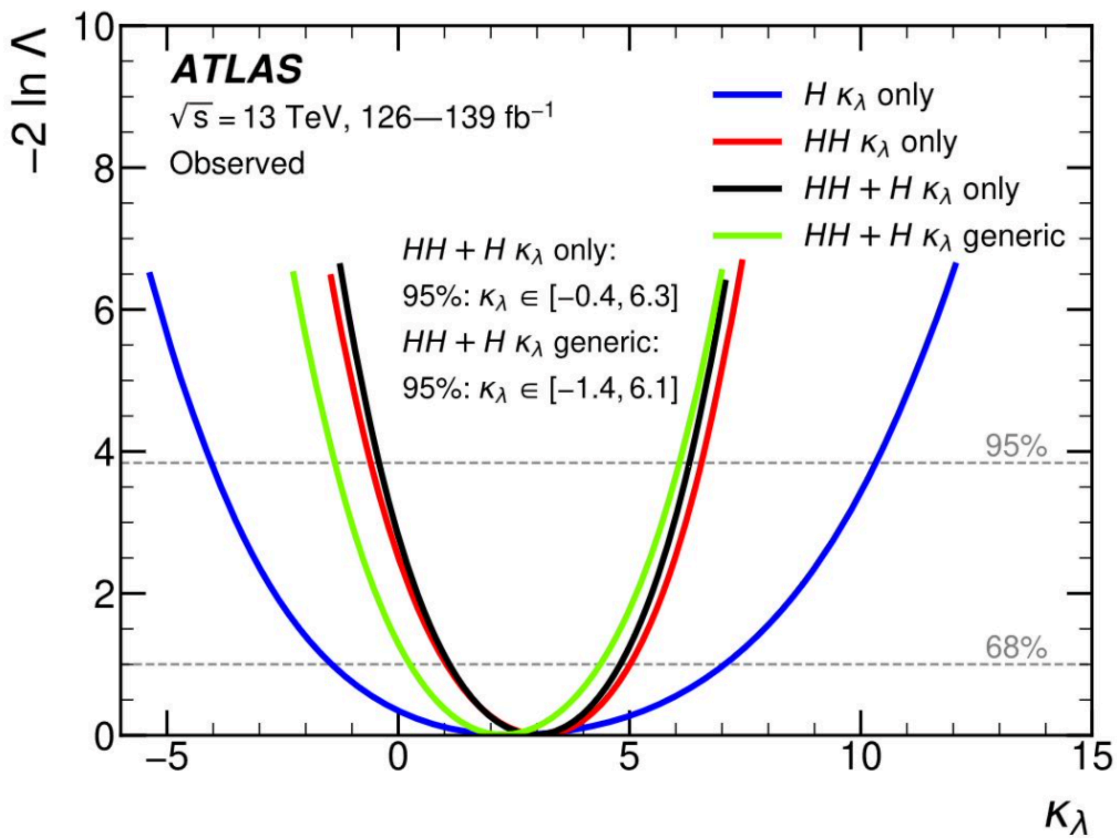


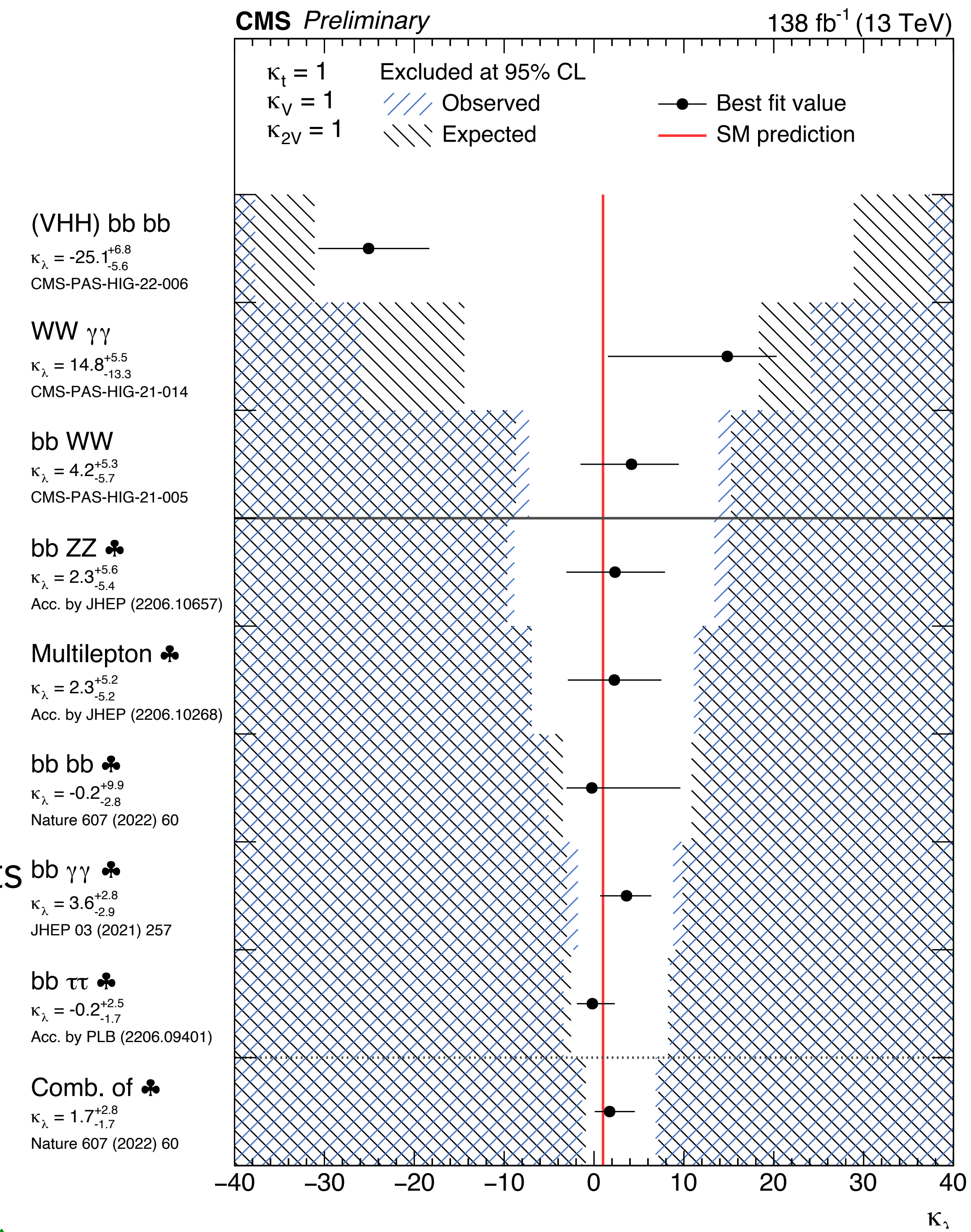
Global combinations leading to ~2.5-3 x SM

Towards the Higgs self-coupling

[Higgs_PAG_Summary_Plots](#)
[CMS-PAS-HIG-23-006](#)

[Phys. Lett. B 843 (2023)](#)





Combination with single Higgs measurements (sensitive to λ through NLO EW corrections)

ATLAS: $-1.4<\kappa_\lambda<6.1$ ($-2.2<\kappa_\lambda<7.7$)
CMS: $-2.3<\kappa_\lambda<7.8$ ($-1.4<\kappa_\lambda<7.8$)

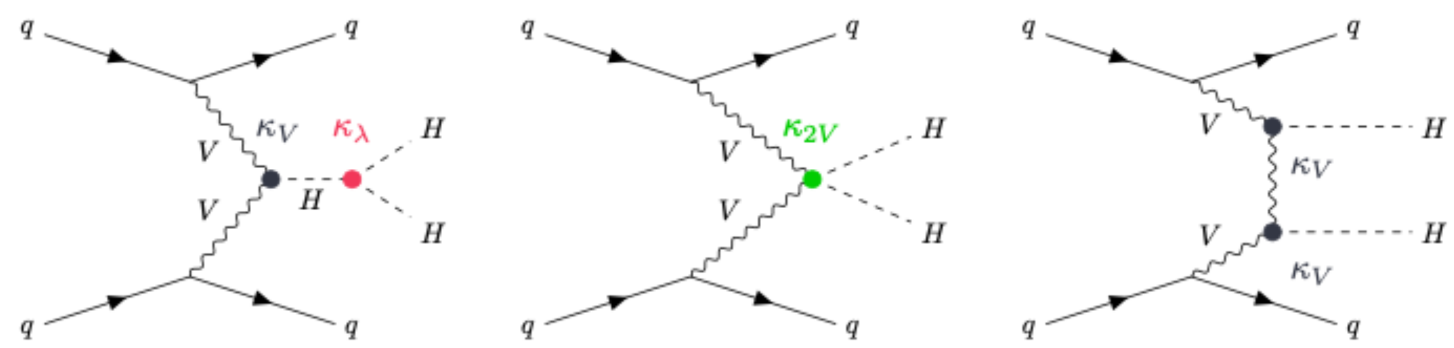
(*) with many free floating couplings (κ_λ generic)

From x-sec limit

From likelihood result with 1σ error

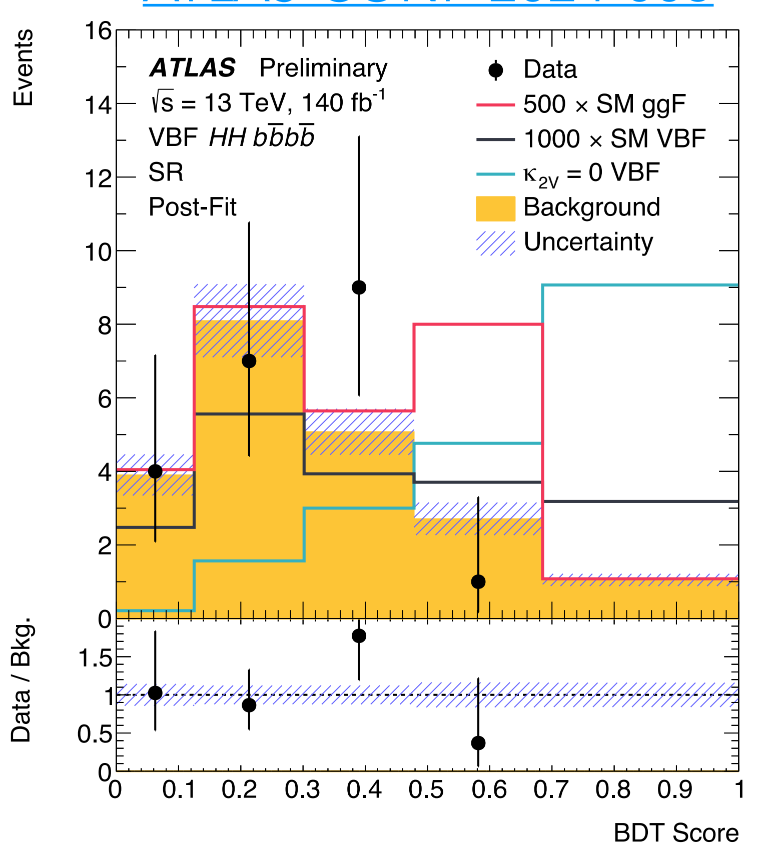
Towards the Higgs self-coupling

VBF HH production allows to constrain κ_{2V}

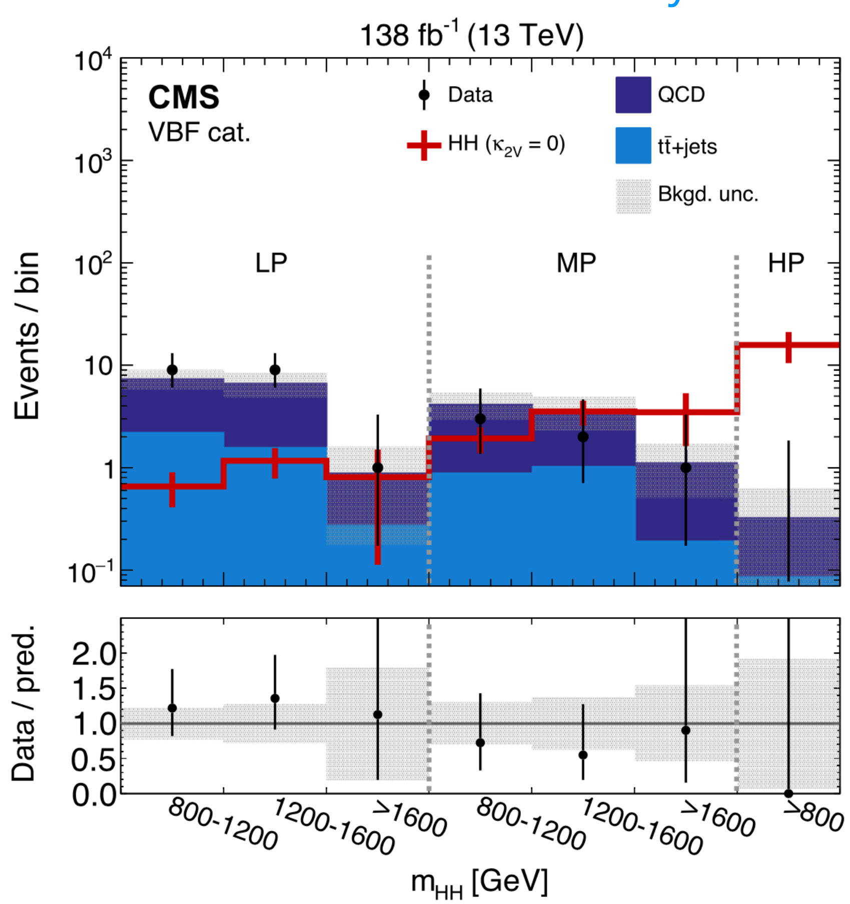


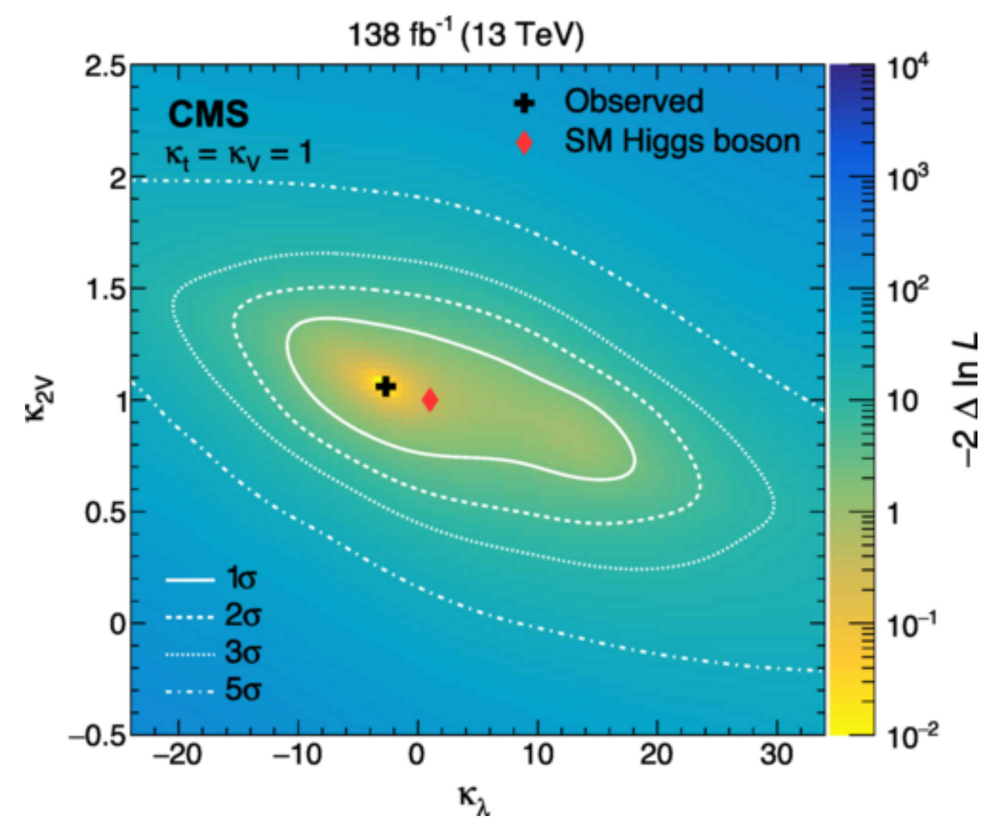
HH → bbbb boosted analyses from ATLAS and CMS exclude both κ_{2V}= 0 with significances of respectively 3.4σ (2.9σ) and 6.3σ

ATLAS-CONF-2024-003



Phys. Rev. Lett. 131 (2023)





BDT to select κ_{2V}= 0

m_{HH} in low (LP), medium (MP), high (HP) purity regions

Conclusion & Outlook

Great progress in Higgs measurement properties since its discovery!

Higgs boson mass not predicted by SM, but is **now known to 1 permille precision!**
Higgs width compatible with SM with reasonable assumptions (using off-shell production)

Higgs couplings to gauge bosons, top, tau measured with <10% uncertainty

No sign of CP violation: many measurements performed, in bosonic and fermonic couplings, direct measurements and EFT approach

Rare decays being chased, can give insight to Yukawa couplings, H→meson γ, H $\rightarrow \psi(nS)\gamma$

STXS interpretation and many differential measurements performed to assess the full picture

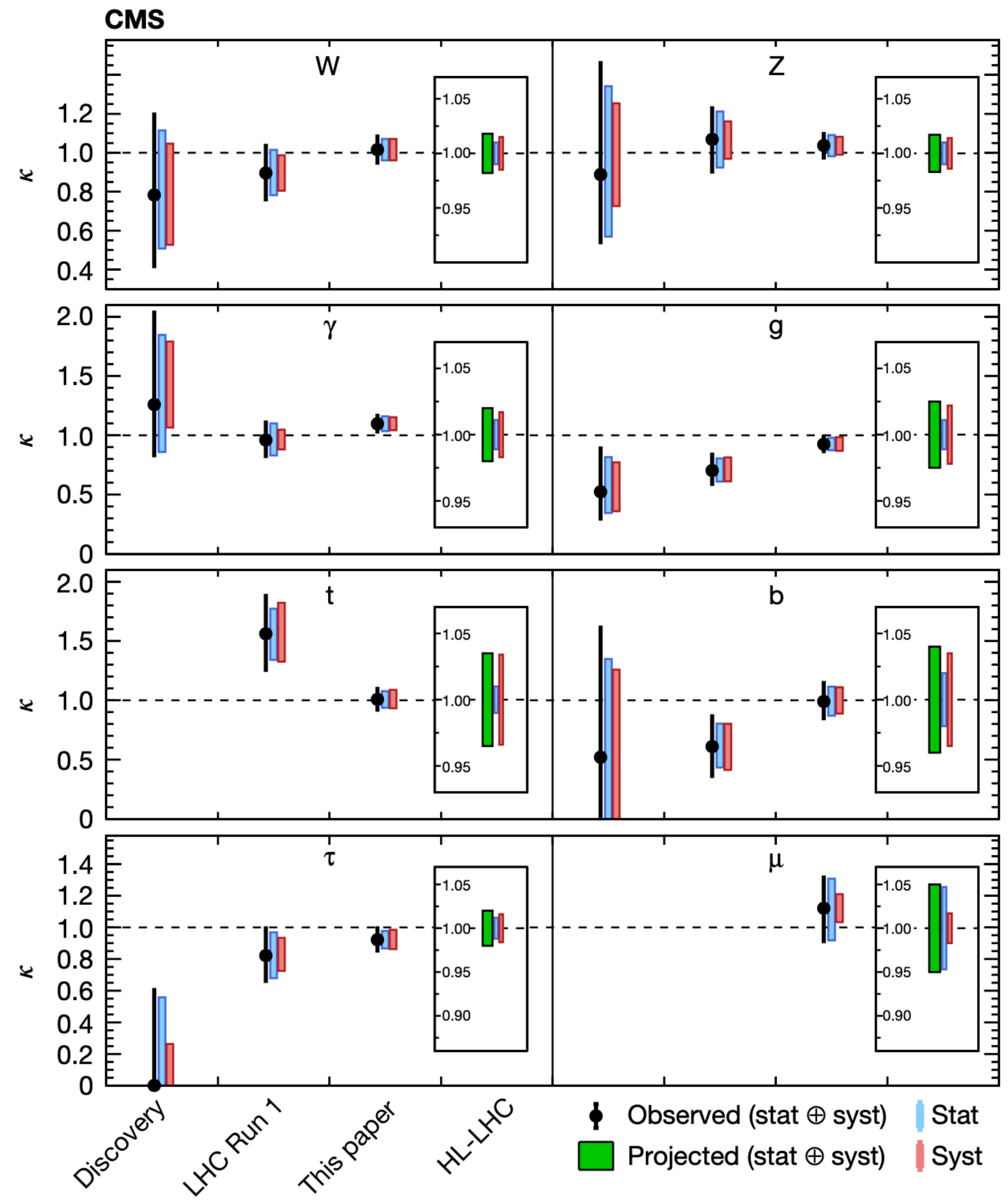
See parallel talks for more details!
T1P1 on Tuesday afternoon

Higgs mass and width measurements at ATLAS	Laura Nasella
Rare (SM) Higgs boson decays and rare Higgs production modes at CMS	Jae-Bak Kim
Higgs self-coupling at CMS (including di-Higgs resonant searches)	Oguz Guzel

Conclusion & Outlook

Yet more precision and data needed to…

- observe the Higgs coupling to muons (3.0σ significance)
- observe H → Zγ (3.4σ significance ATLAS+CMS)
- improve the limits on c-Yukawa ($1.1 < |\kappa_c| < 5.5$)
- have evidence to strange, down, up quarks, electrons couplings
- have evidence for tH and bbH production modes
- have evidence for the Higgs self-coupling ($-1.4<\kappa_\lambda<6.1$)



Thanks for the interesting conference in this beautiful place!