Caltech

Precise Higgs measurements at the LHC

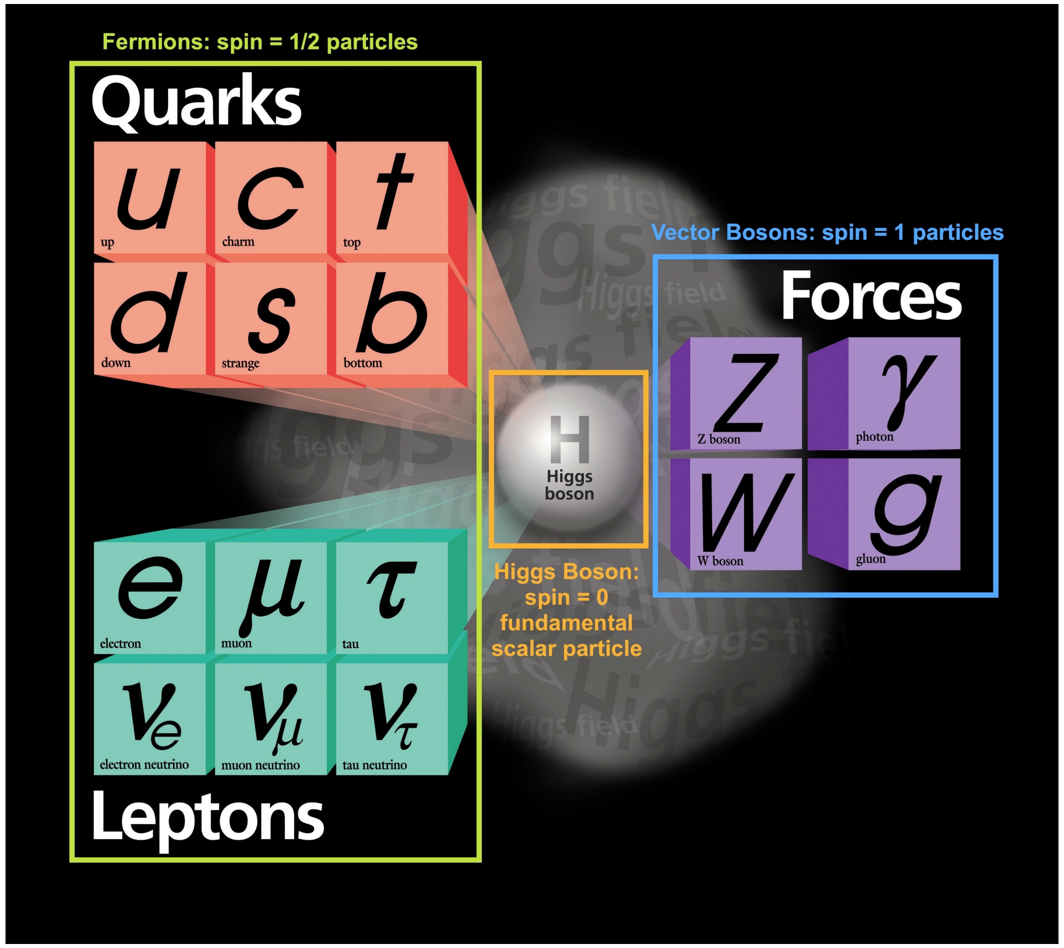
Nan Lu

California Institute of Technology

Higgs potential and BSM opportunity Workshop

August 28, 2021

The Standard Model Higgs Boson



- Quarks, charged leptons, W/Z bosons acquire mass through the Brout-Englert-Higgs (BEH) mechanism in the Standard Model

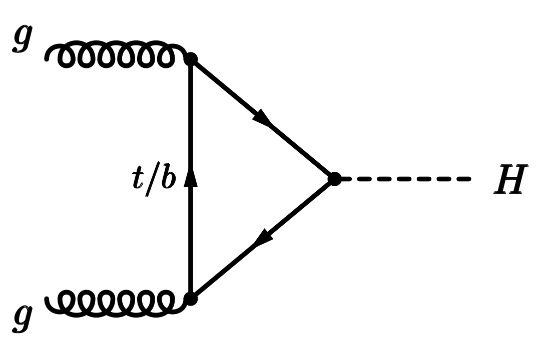
- Higgs boson physics is one of the most important goals of LHC physics program and the next generation collider experiments

ATLAS Recent Higgs Results

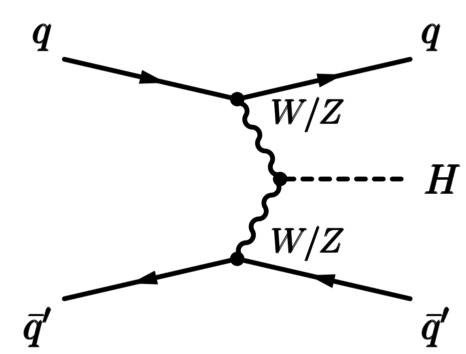
CMS Recent Higgs Results

Standard Model Higgs production at LHC

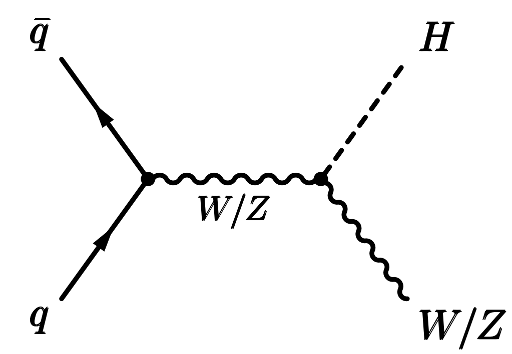
Gluon-fusion ggF (~87%) 48.5 pb



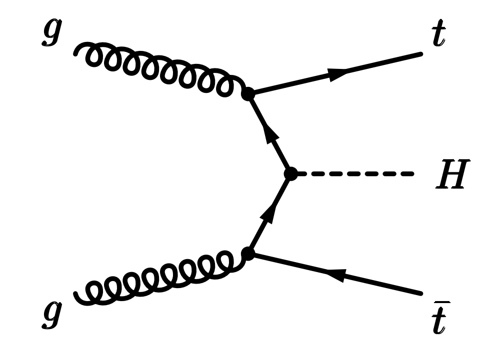
Vector boson fusion VBF (~7%): 3.78 pb



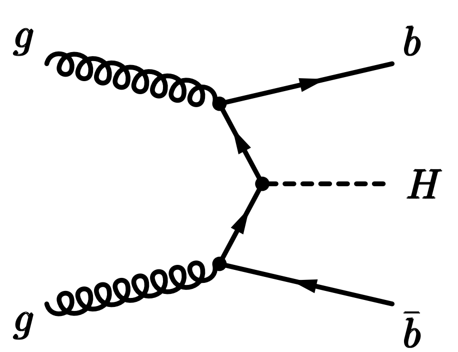
VH (~4%) ZH: 0.88 pb WH: 1.37 pb



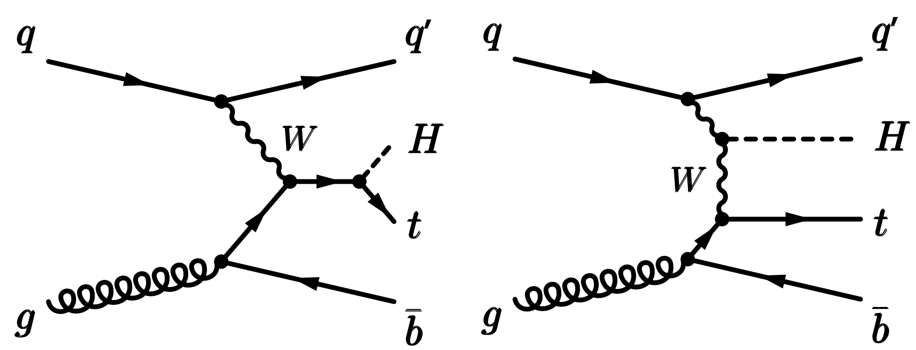
ttH (~1%), 0.51 pb



bbH (~1%), 0.49 pb



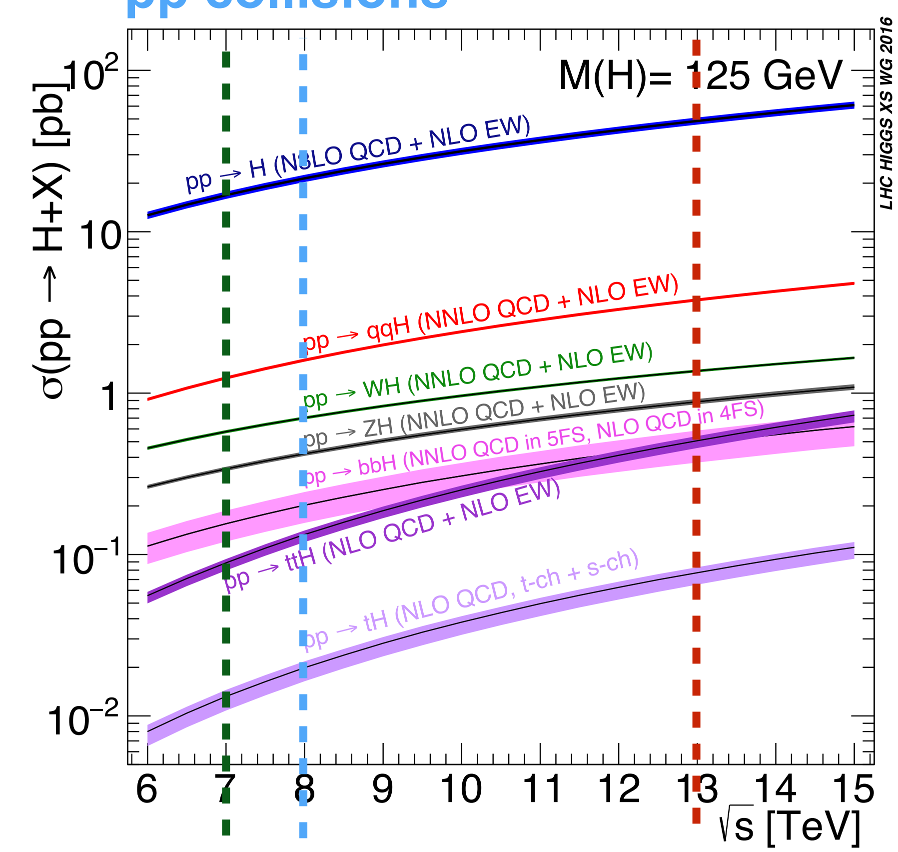
single top tH (~0.1%), 0.09 pb



* Cross-sections @ $\sqrt{s} = 13$ TeV

Run 1: 7-8 TeV pp collisions

Run 2: 13 TeV



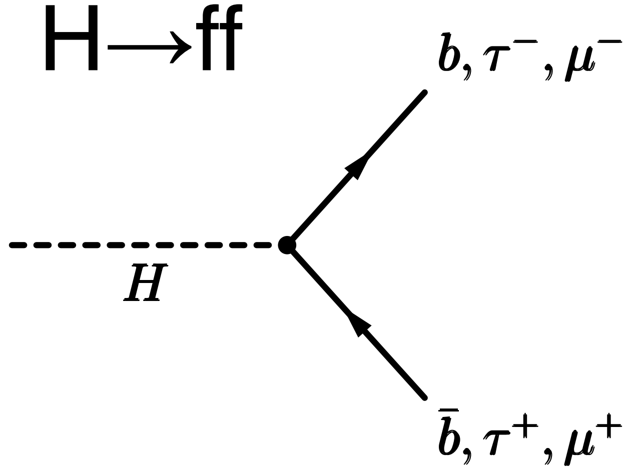
Yellow Report 4

- Distinct topology in each production mode
- Rare production modes difficult to probe, important for beyond the SM scenarios

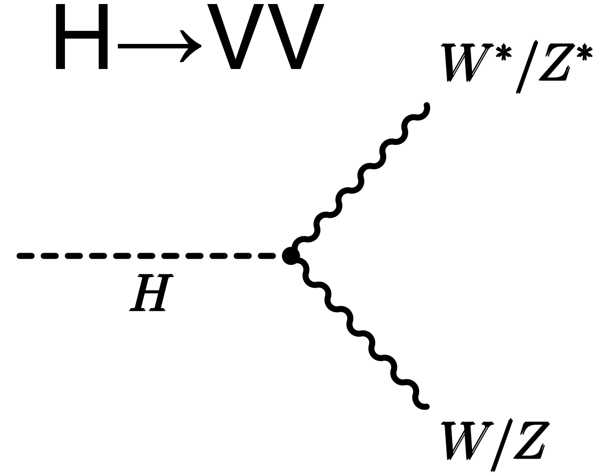
Higgs boson decays

- **“Big five”**: **γγ**, **ZZ**, **WW**, **ττ**, **bb**
  - γγ and ZZ→4l: high resolution and S/B: precise mass and differential measurement
  - WW: high BR, low S/B, low resolution due to neutrinos
  - **ττ**, **bb:** high BR, low S/B, **directly probe Higgs couplings to fermions**
- **Rare decay channels to be observed: μμ, Zγ, cc, …**

H→ff

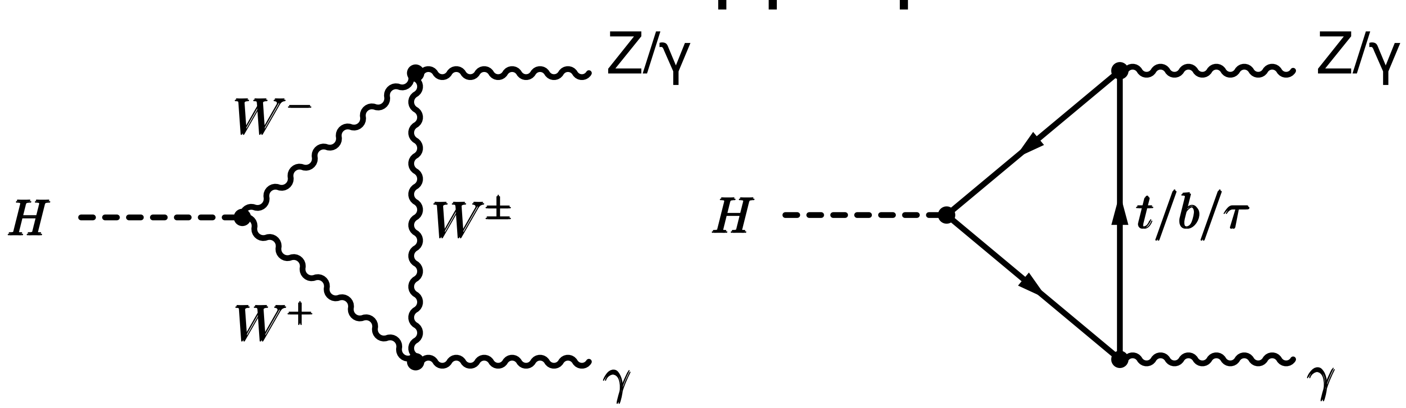


H→VV



H→γγ/Zγ

Yellow Report 4



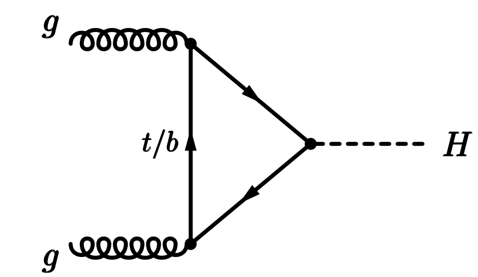
Decay channel	SM BR [%] with m_H=125.09 GeV
H→bb	58.1
H→WW	21.5
H→ττ	6.26
H→ZZ	2.64
H→γγ	0.23
H→μμ	0.022
H→Zγ	0.154
H→cc	2.88
H→gg	8.18

Precision Higgs measurements

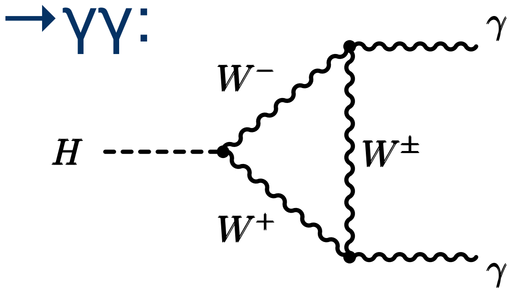
We are entering an era of precision measurements of Higgs boson properties: a test bench for the SM and a portal to look for possible new physics

- Mass and width
- Production and decay rates
  - e.g. loop-induced **ggF** and **H→γγ** processes sensitive to new physics
- Differential distributions and simplified template cross sections
- Quantum numbers (spin and CP)
- Off-shell couplings and indirect constraint of width

ggF:

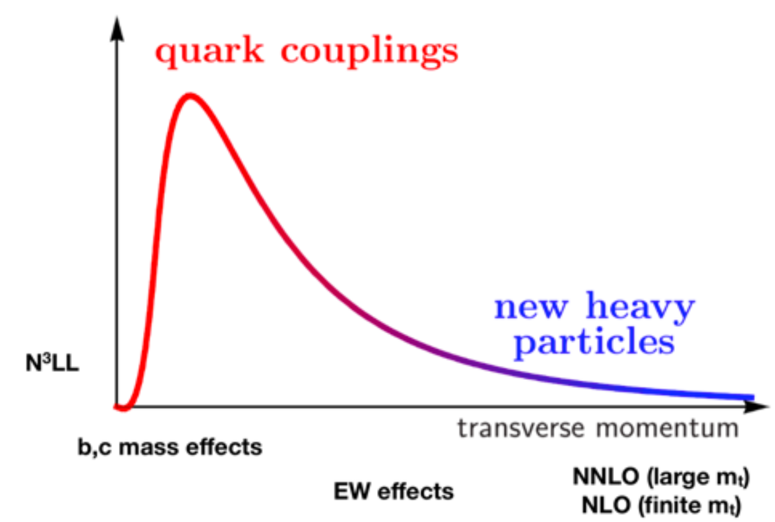


H→γγ:

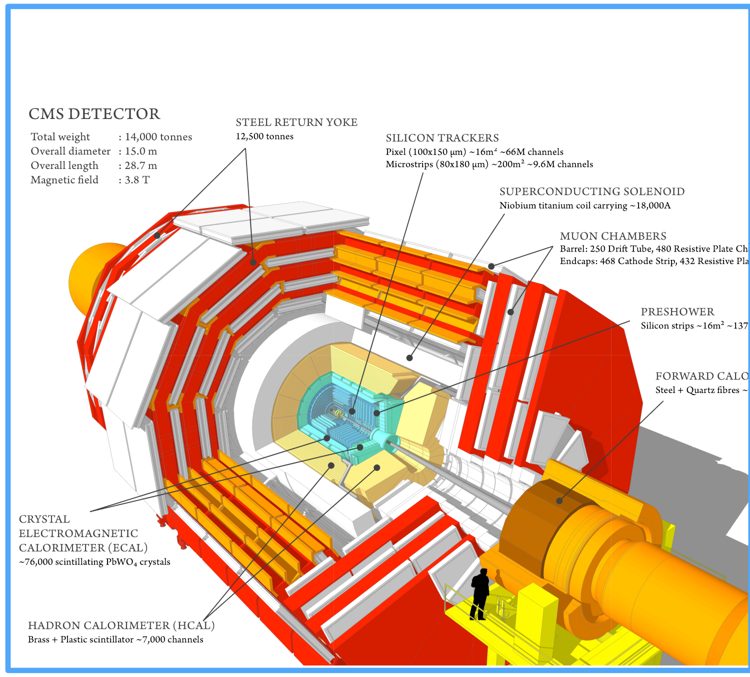


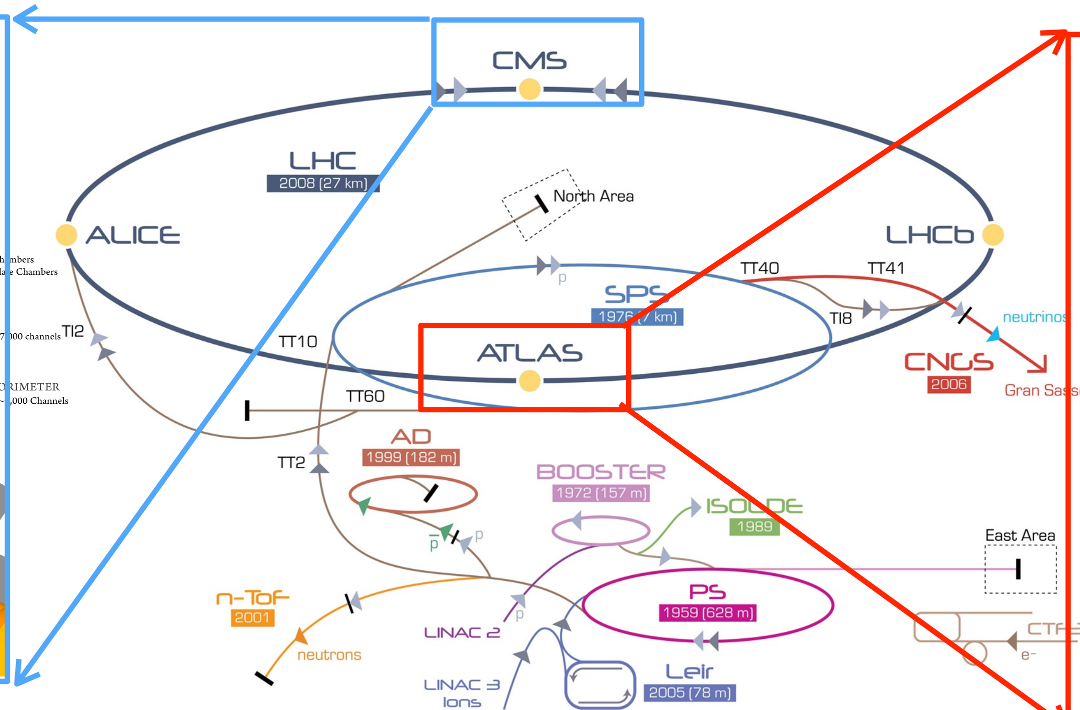
Higgs pT

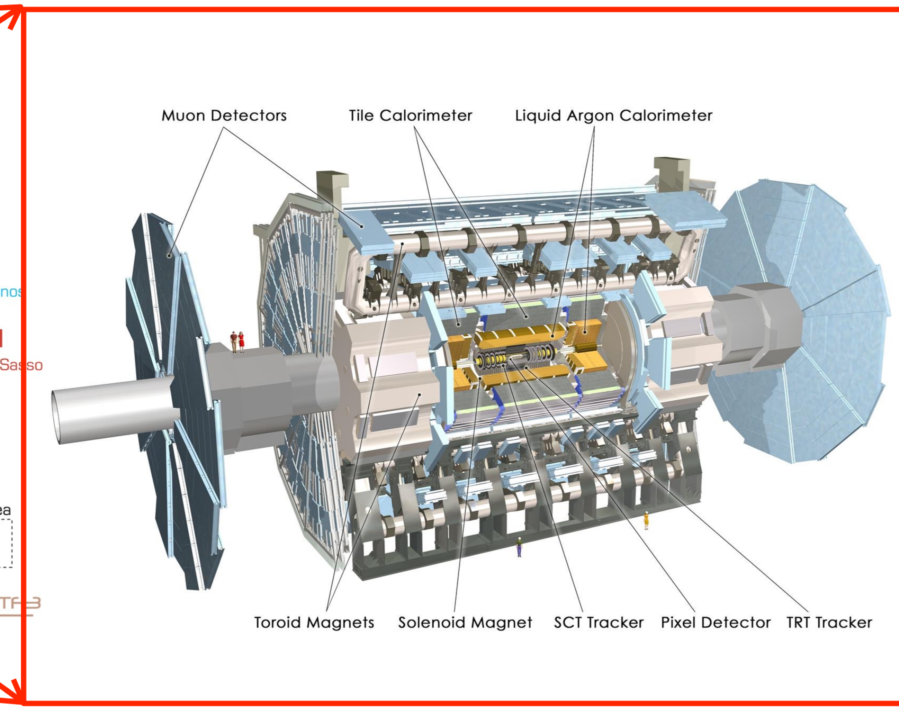
From G. Zanderighi HH2019

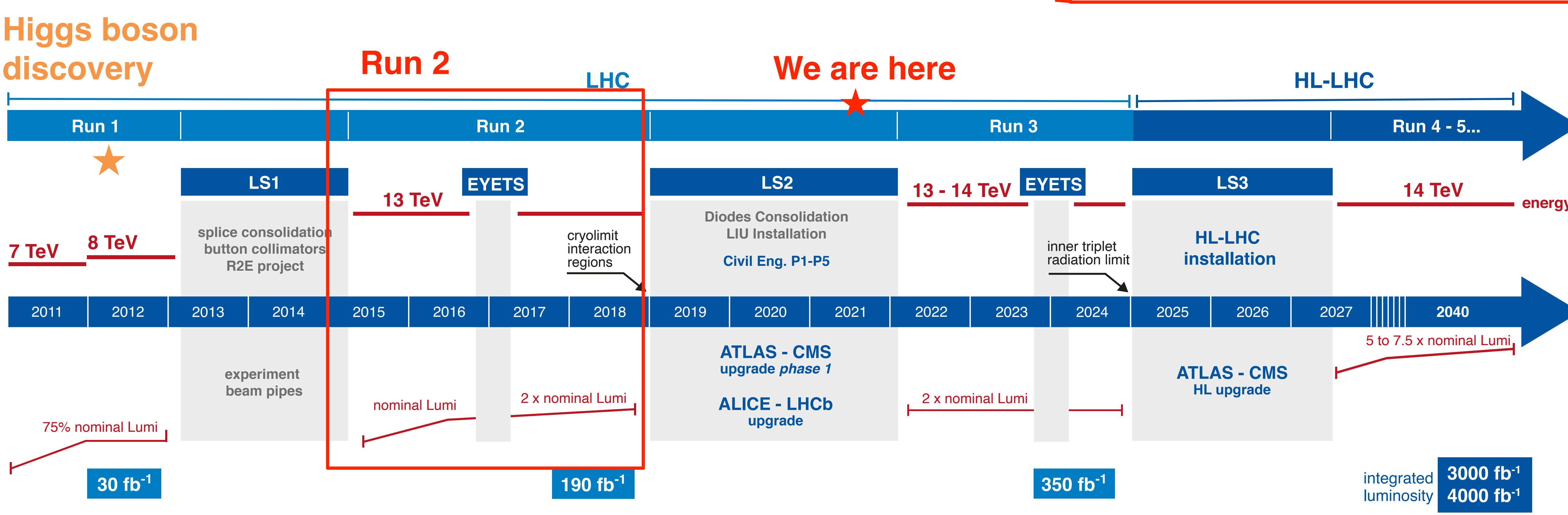


LHC, CMS and ATLAS detector

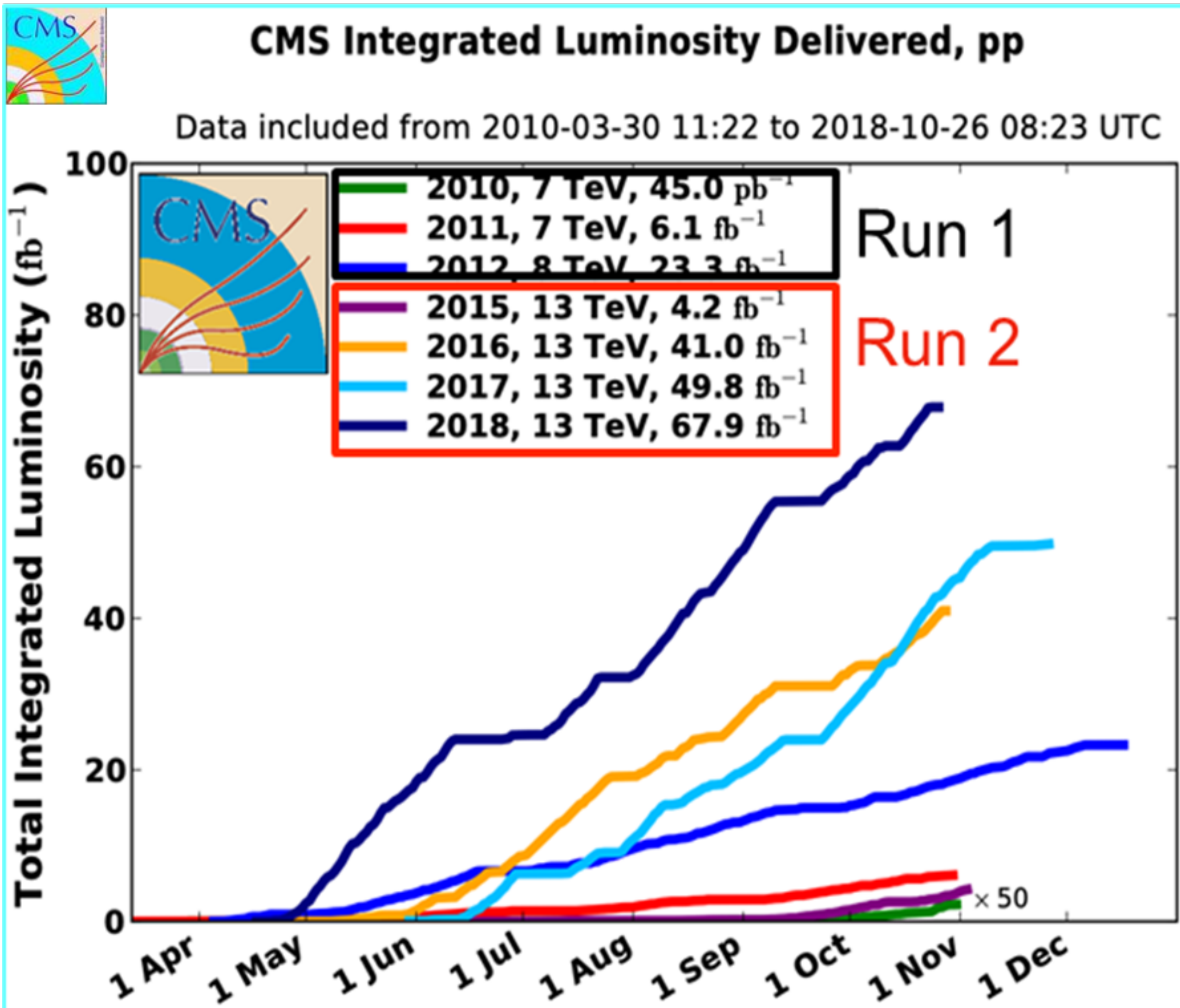


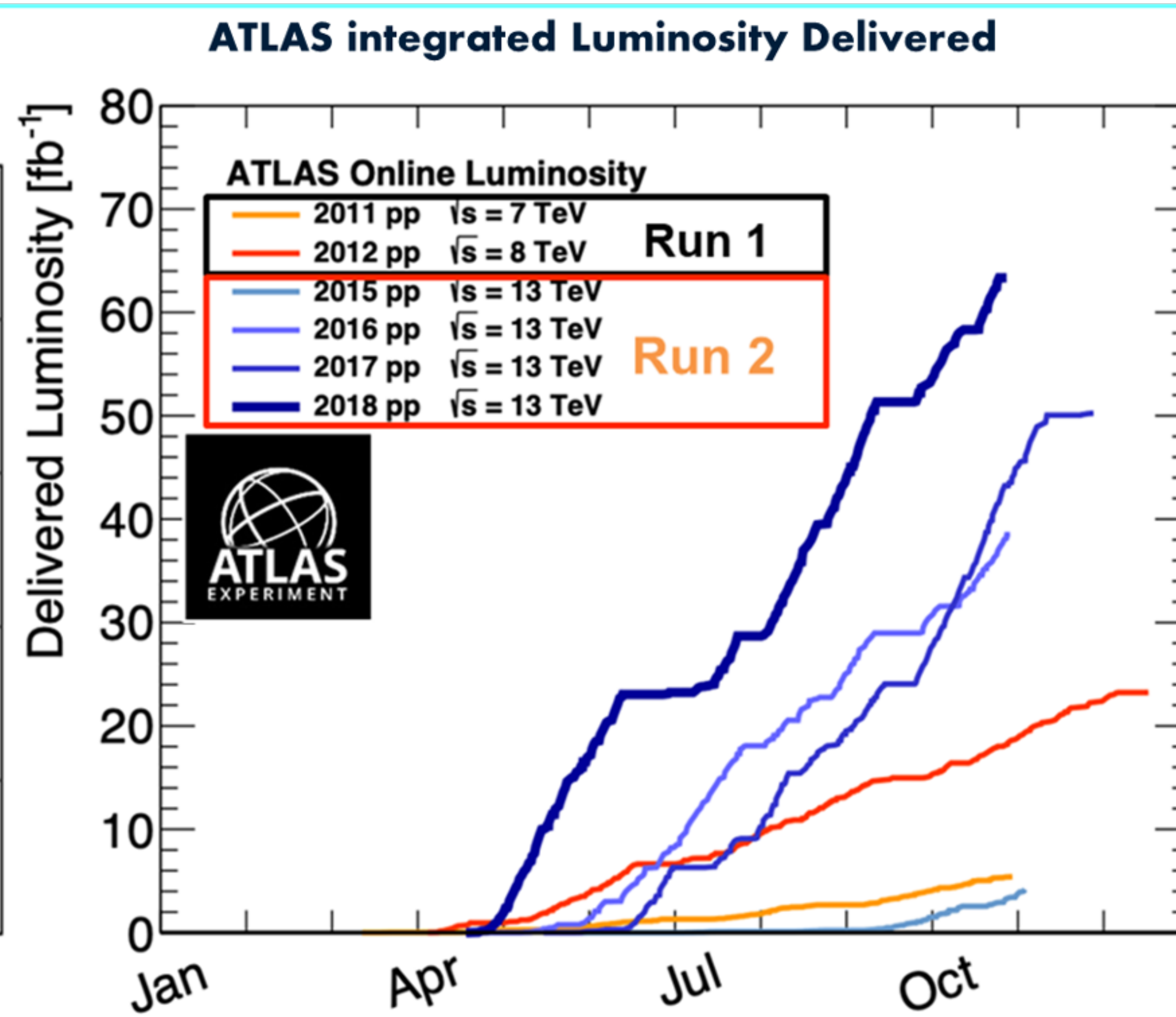






LHC Run 2 data taking



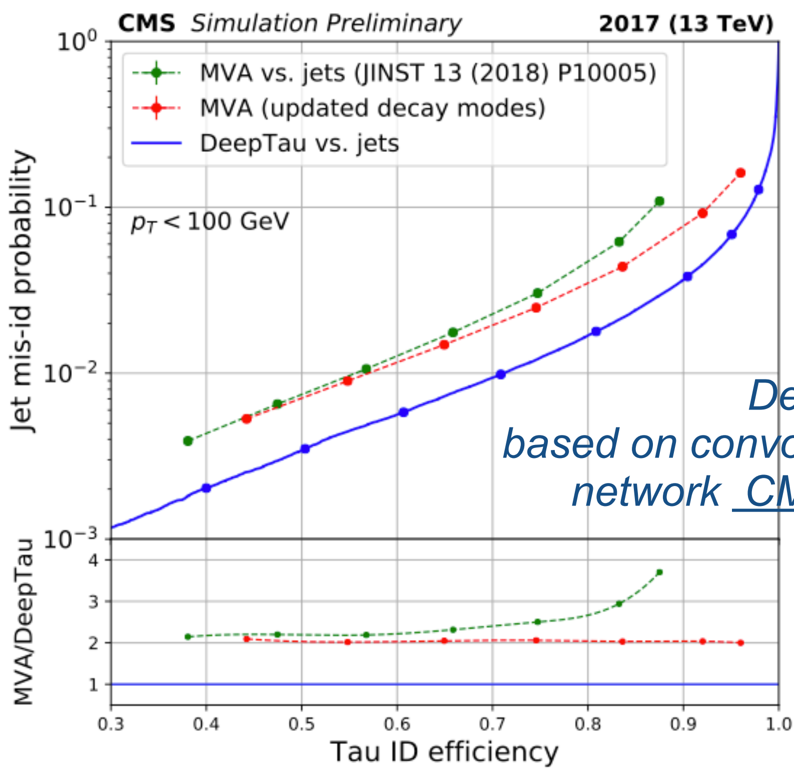


ATLAS and CMS detectors collected 139 and 137 fb^{-1} pp collision data at 13 TeV

Thanks to the excellent performance of the LHC and efficient operation of the two detectors

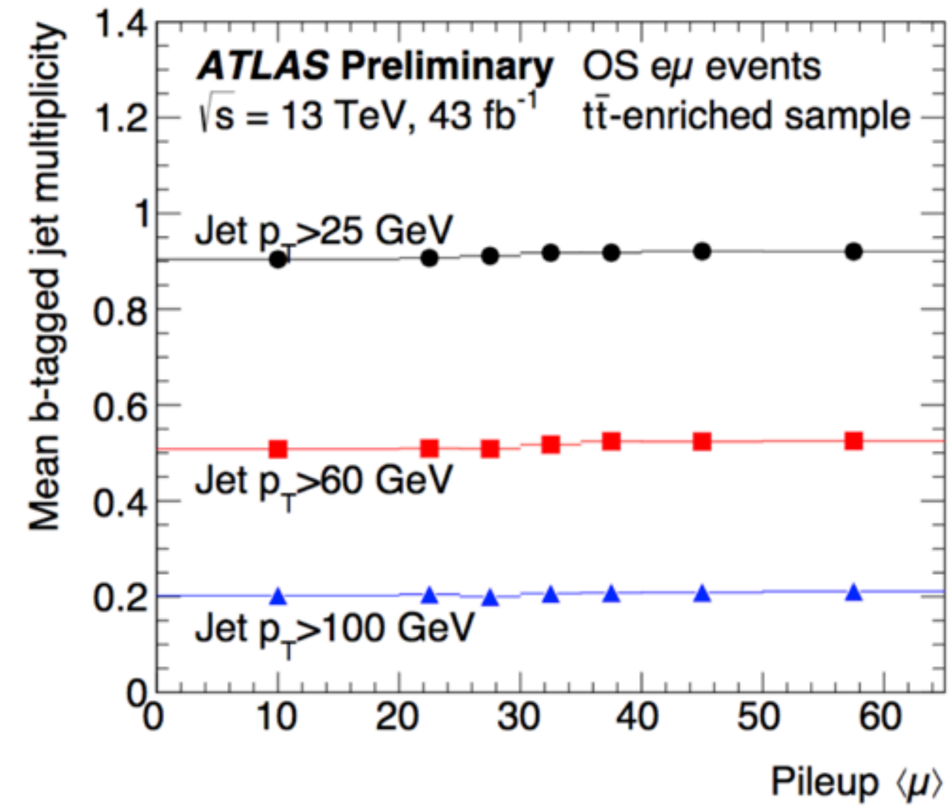
Physics object performance achievements

Deep learning techniques bring significant improvement to the physics object identification

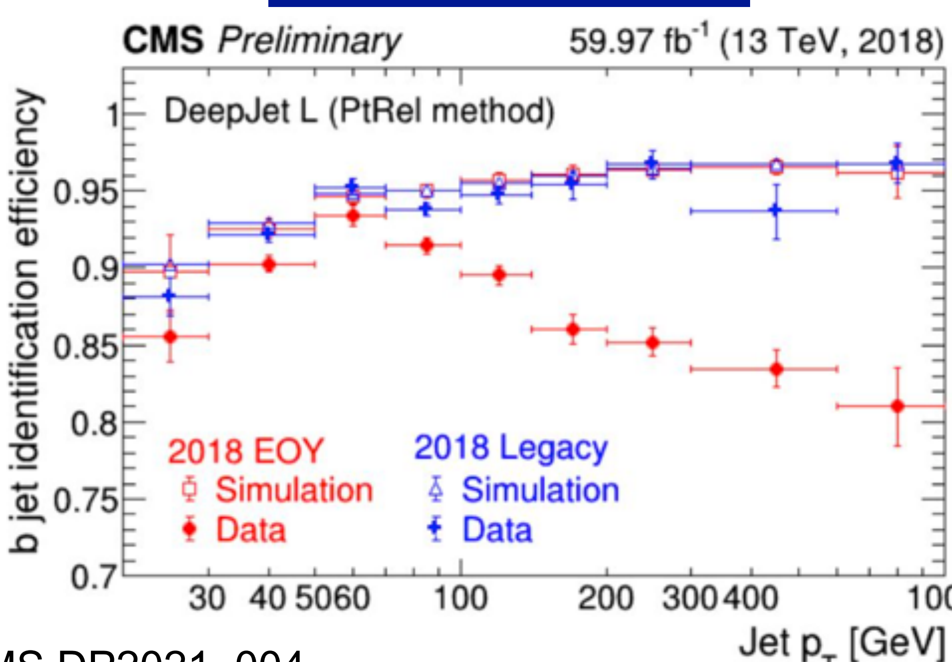


DeepTau:
based on convolutional deep neural network [CMS-DP-2019-033]

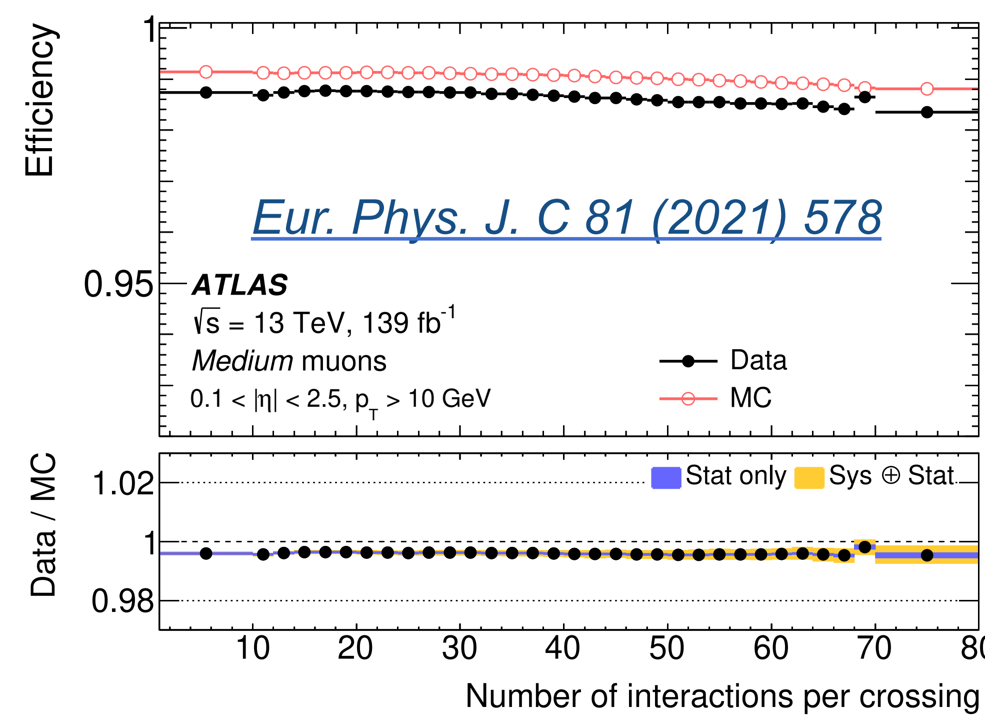
Reconstruction performance robust to pileup



In-situ calibration



CMS DP2021_004
Improved efficiency observed for data in 2018 Legacy w.r.t EOY



[Eur. Phys. J. C 81 (2021) 578]

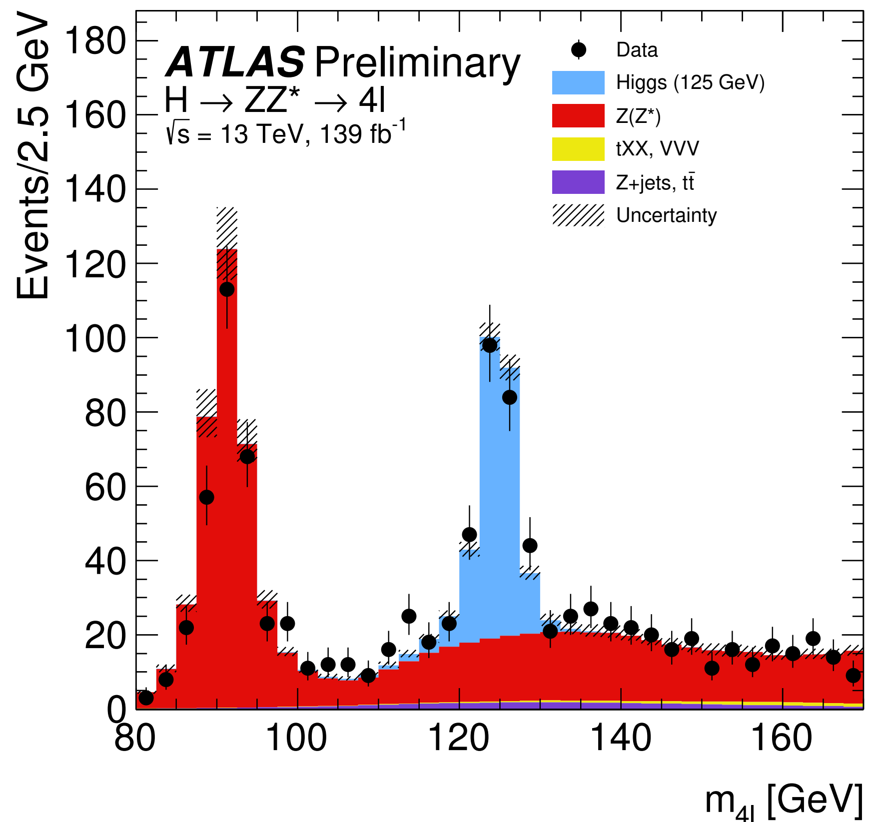
Higgs boson mass

ATLAS-CONF-2020-005

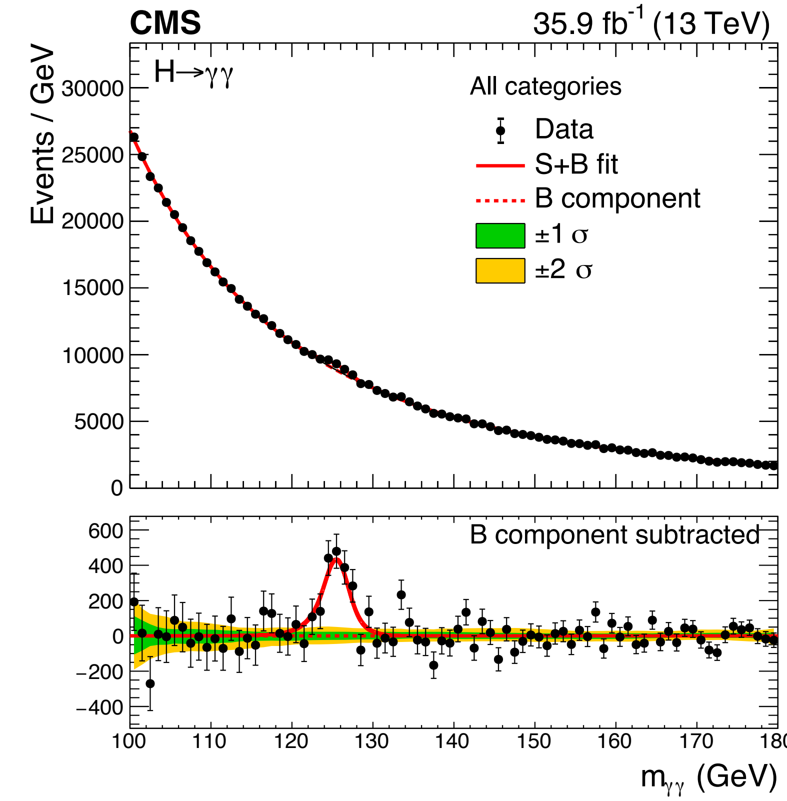
Phys. Lett. B 805 (2020) 135425

- m_H is a free parameter in the Standard Model: once known, all Higgs boson couplings to SM particles are fixed
- H→ZZ*→4l and H→γγ are most sensitive channels: fully reconstructed with high resolution

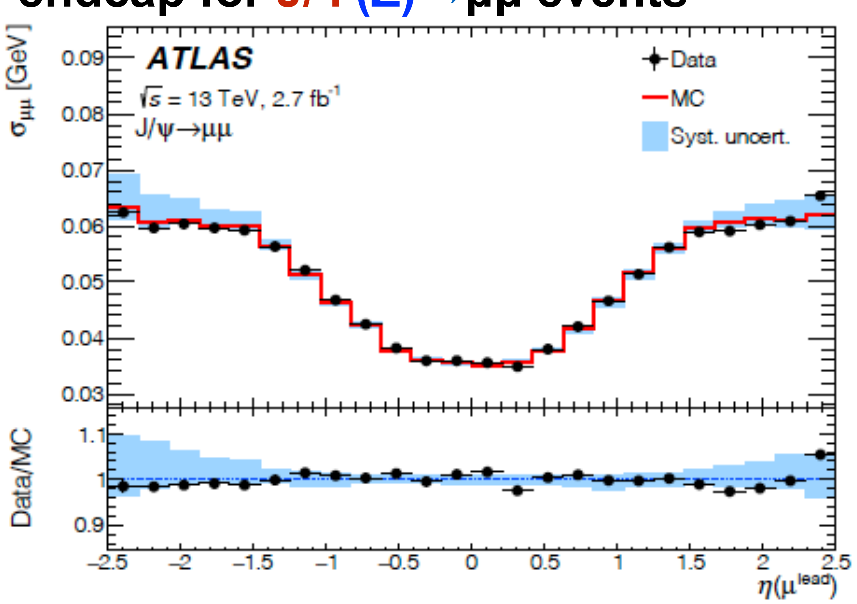
H→ZZ*→4l mass distribution



H→γγ mass distribution

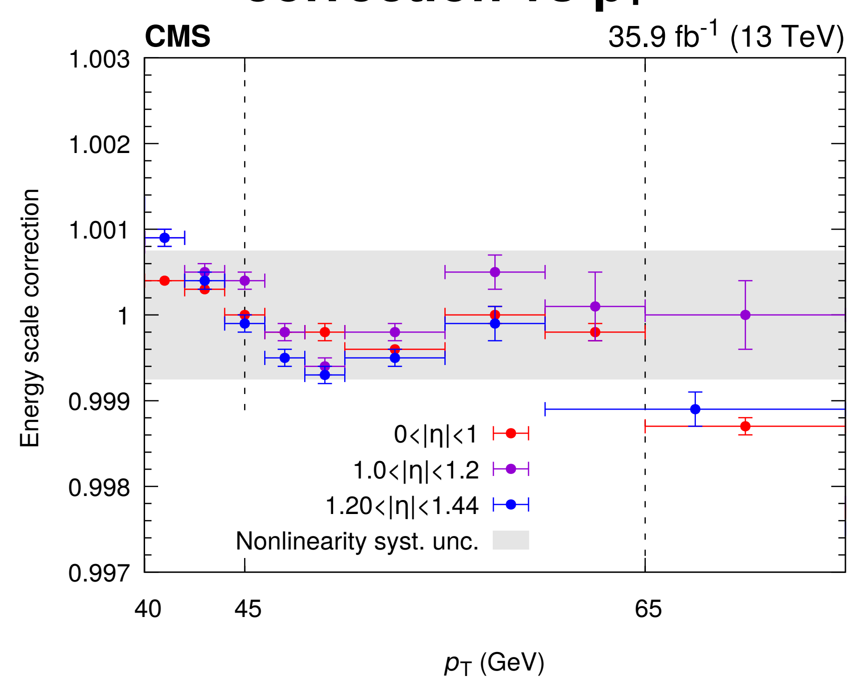


Muon Momentum Calibration:
$\sigma(m_{\mu\mu})/m_{\mu\mu}$=1.2%(1.6%) barrel 1.6%(1.9%) endcap for J/Ψ(Z)→μμ events

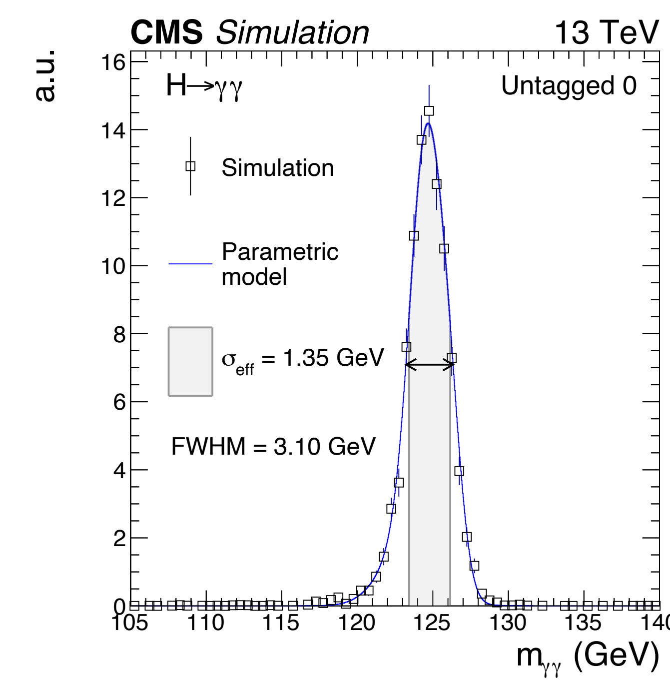


Eur. Phys. J. C76 (2016) 292

Photon Energy Scale correction vs p_T



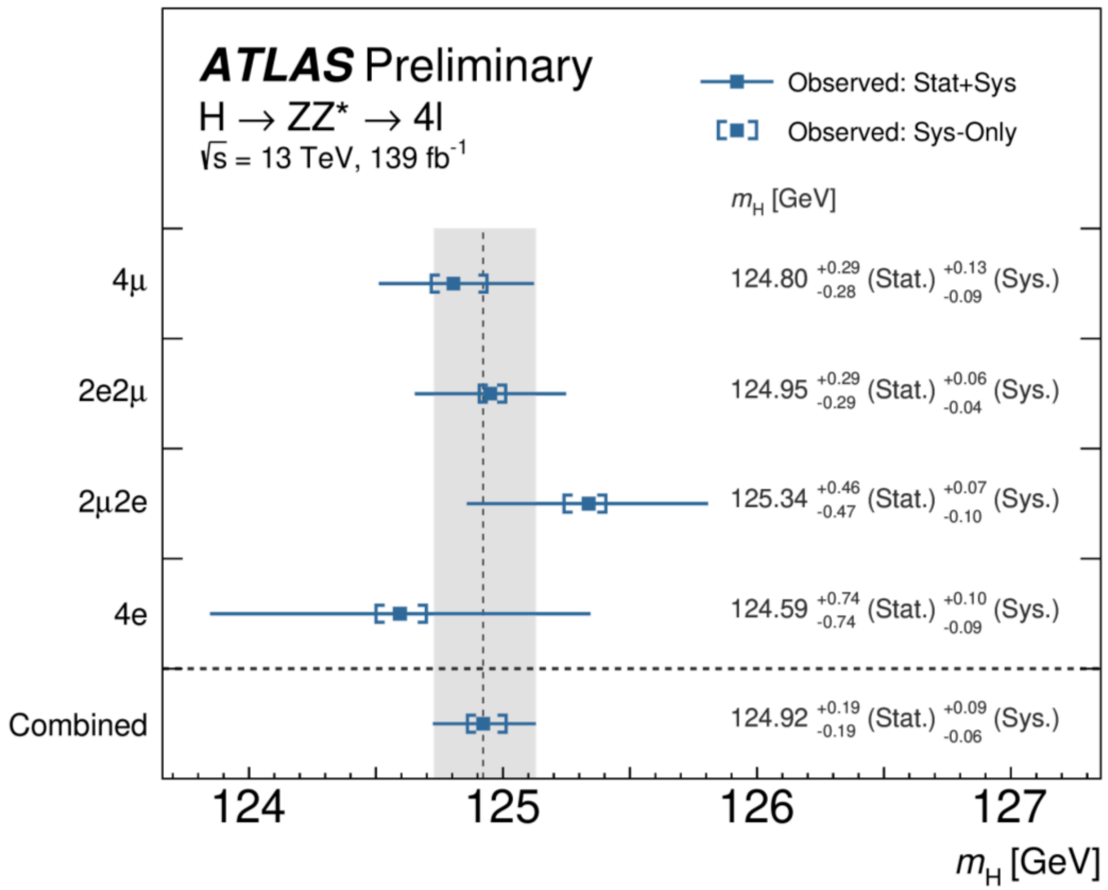
$m_{\gamma\gamma}$ in highest resolution category

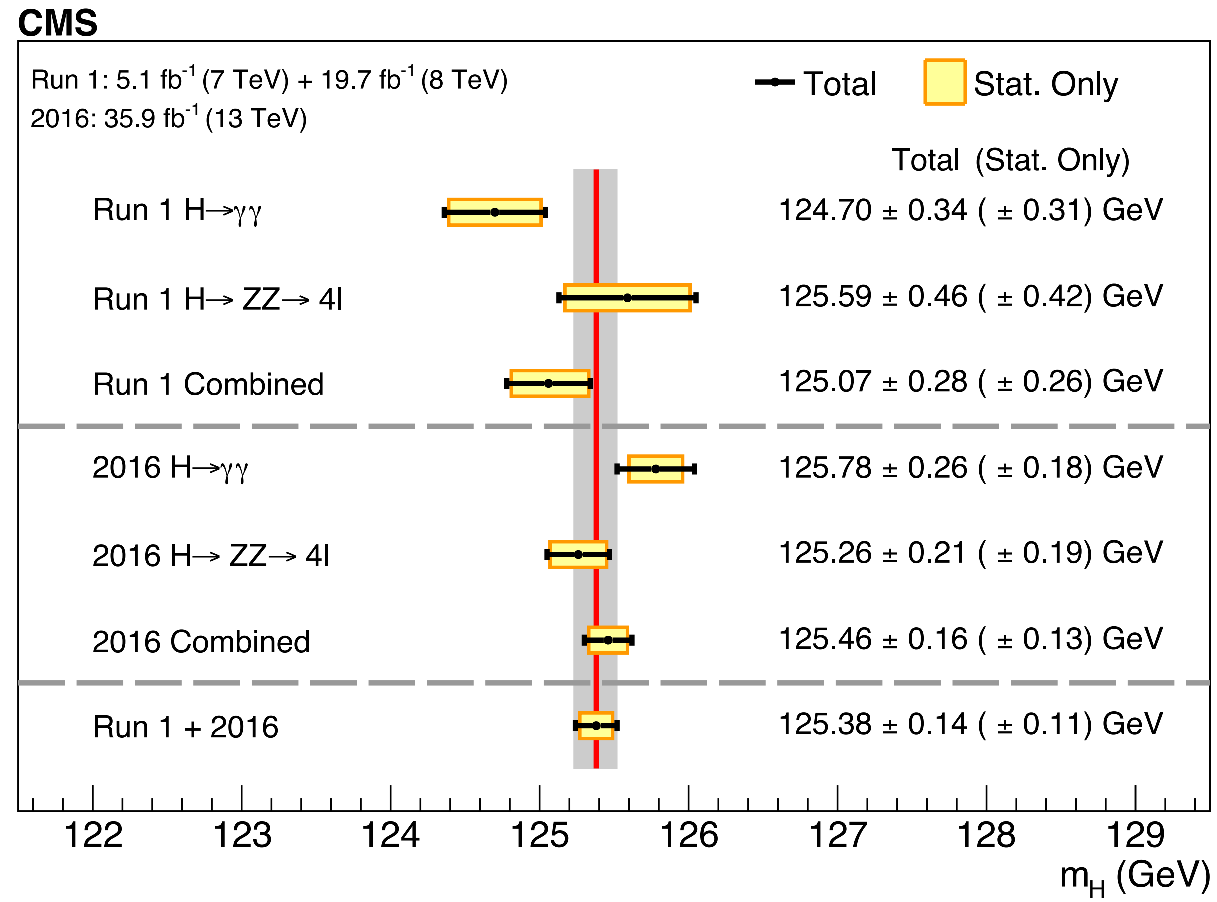


Higgs boson mass

ATLAS-CONF-2020-005

Phys. Lett. B 805 (2020) 135425



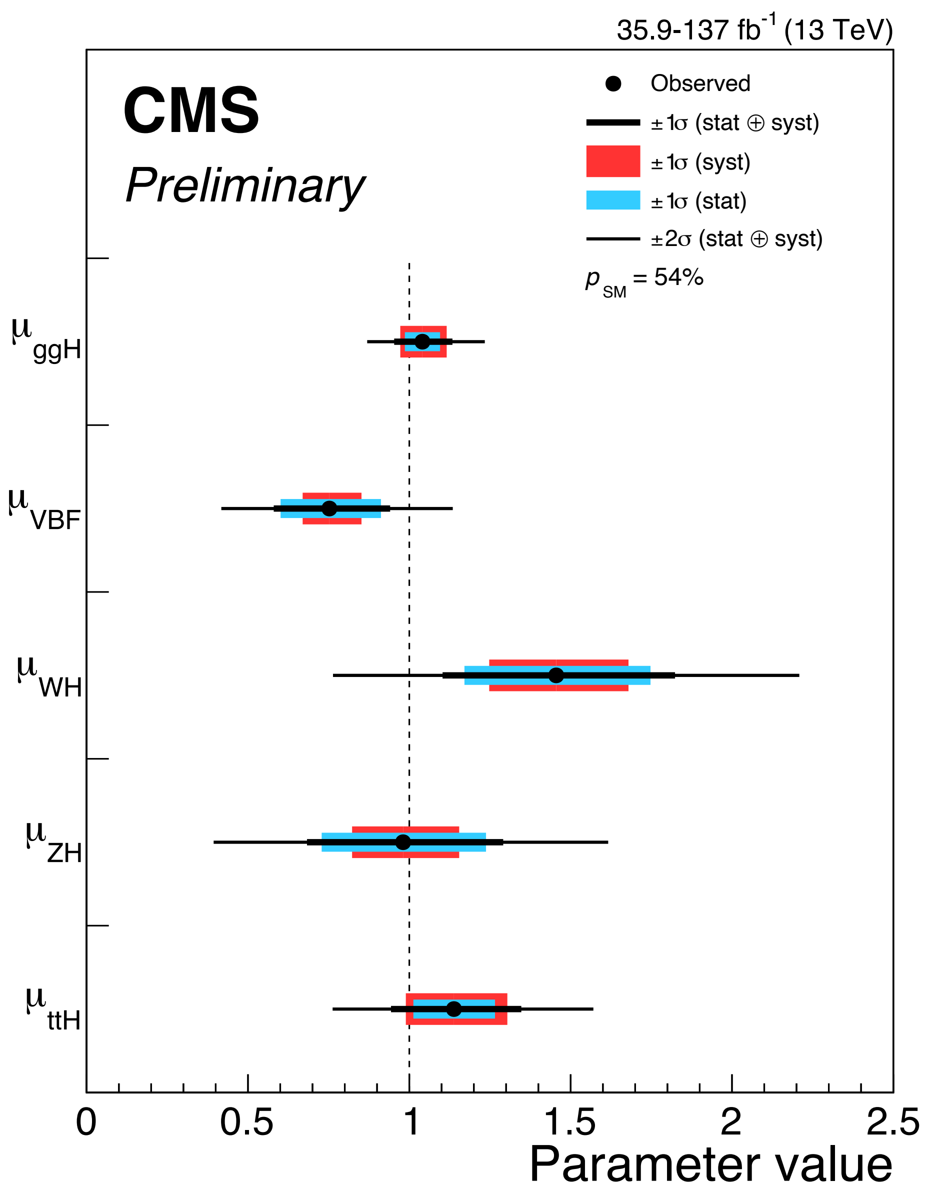


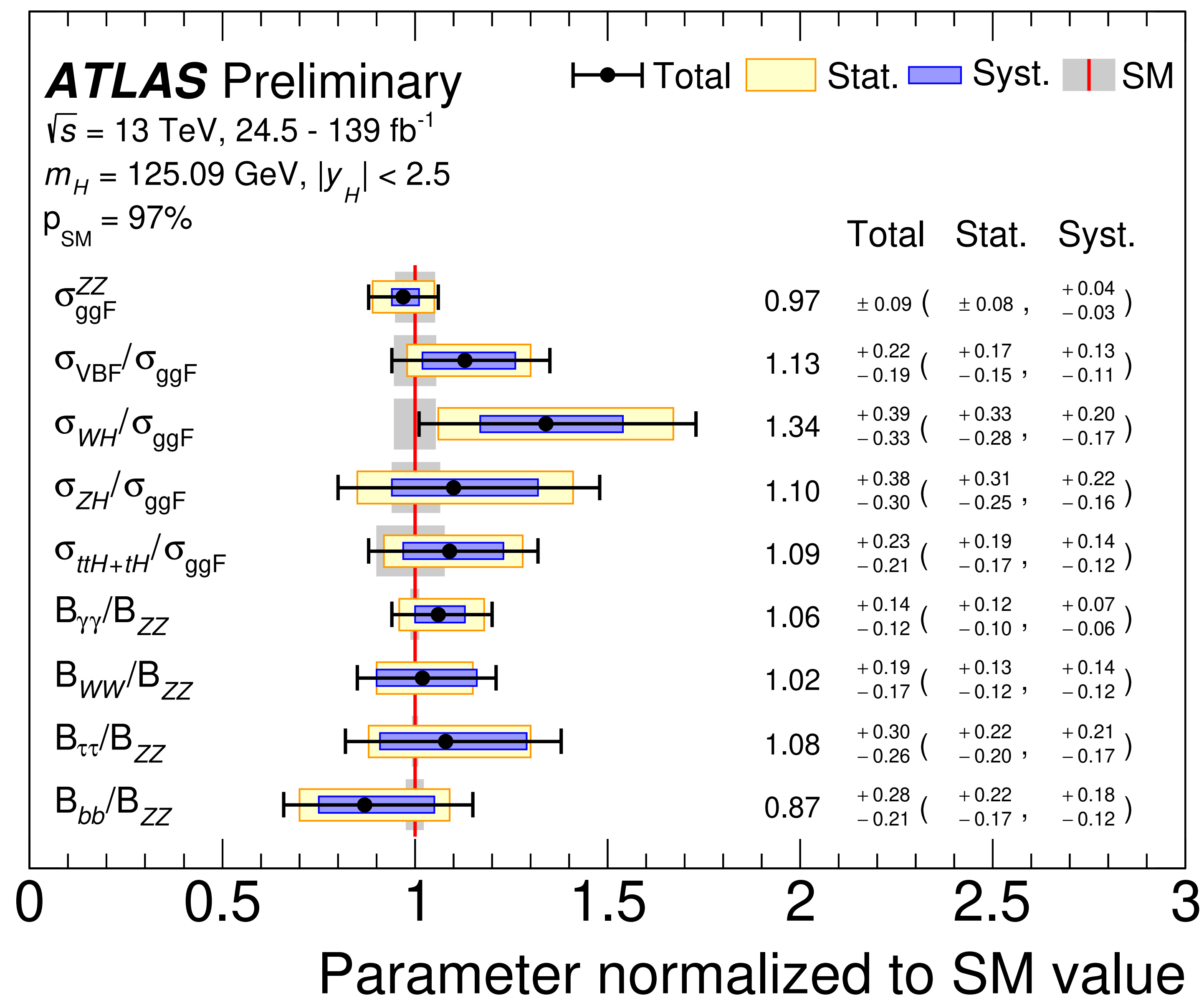
- One of the most precise electroweak measurements: reaching **0.1%** precision
  - CMS+ATLAS Run1 combination: **m_H = 125.09 ± 0.24 GeV**
  - ATLAS H→ZZ*→4l full Run 2 data: $m_H = 124.92 \pm 0.19(Stats.)^{+0.09}_{-0.06}(Sys.)$ **GeV**
  - CMS: H→γγ & H→ZZ*→4l Run1 + 2016: **m_H = 125.38 ± 0.14 (±0.11 Stat. only) GeV**
- Measurement still dominated by statistical uncertainty:
  - more precise measurements expected with full Run 1+2 dataset
  - expected to reach 10-20 MeV precision at HL-LHC

Higgs boson production and decay rates

[ATLAS-CONF-2020-027, JHEP 07 (2021) 027, CMS HIG-19-005]

- ggF, VBF, VH and ttH observed with significance > 5σ
- Good compatibility among decay channels and with the SM





Higgs boson couplings: kappa framework

- Leading order framework to characterize possible deviations from the SM: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_Z, κ_t…) and total width (κ_H)
- Assumptions: single resonance, zero width, SM tensor structure $J^P = 0^+$
- Coupling Compatibility Tests using κ and their ratios

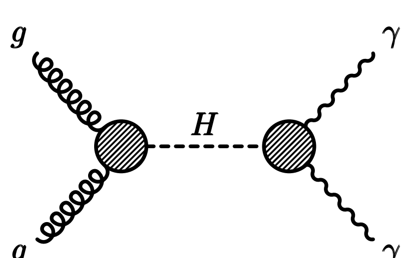
Cross section for production and decay i→H→f parametrized as SM cross sections and widths scaled by coupling modifiers

$$\sigma \cdot B(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H} = \frac{\sigma_i^{SM} \cdot \Gamma_f^{SM}}{\Gamma_H^{SM}} \cdot \left(\frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\right)$$

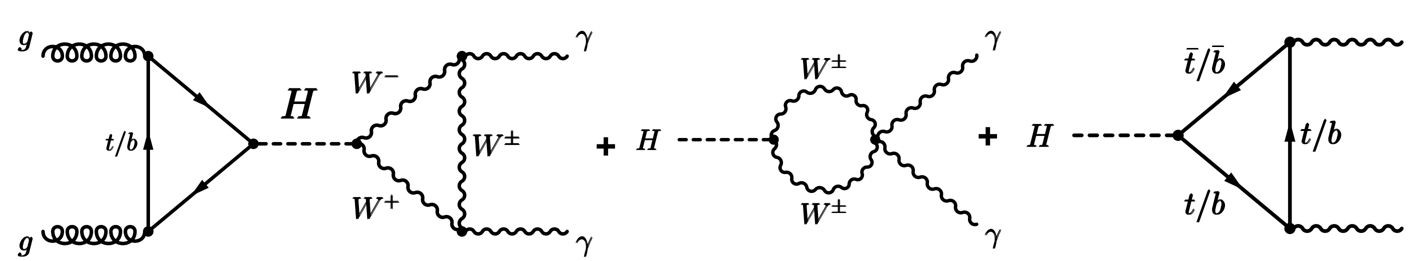
coupling modifiers: $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$ Production; $\kappa_f^2 = \frac{\Gamma_f}{\Gamma_f^{SM}}$ Decay; $\kappa_H^2 = \frac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$ Total width

Yellow Report 3

Example: $gg \to H \to \gamma\gamma$



Assume only SM particles contribute

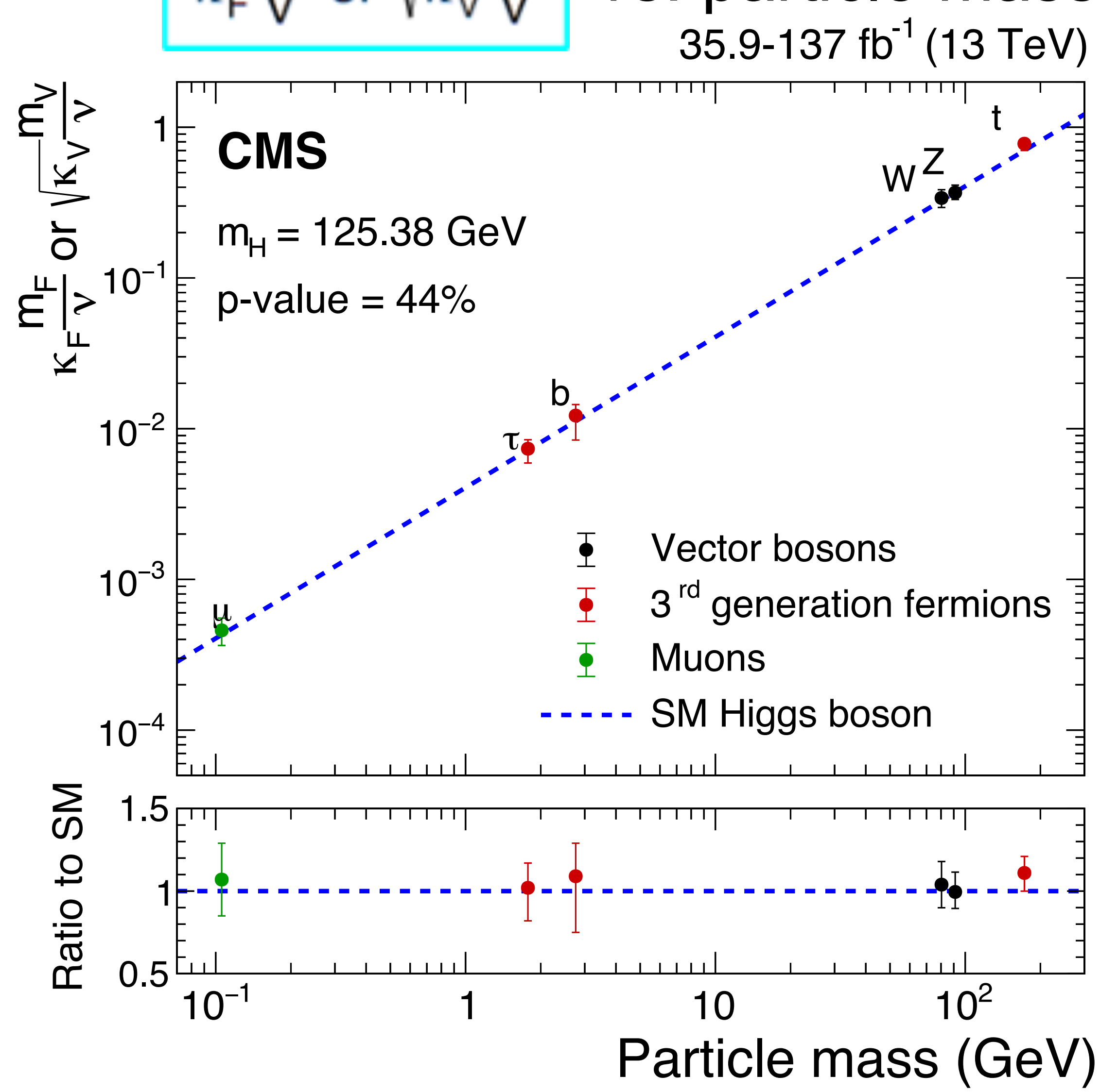


$$\frac{\sigma \times BR(gg \to H \to \gamma\gamma)}{\sigma \times BR(gg \to H \to \gamma\gamma)_{SM}} = \kappa_g^2 \frac{\kappa_\gamma^2}{\kappa_H^2} = (1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b) \frac{1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.67\kappa_W\kappa_t}{\kappa_H^2(\kappa_b, \kappa_W, \kappa_\tau, \ldots)}$$

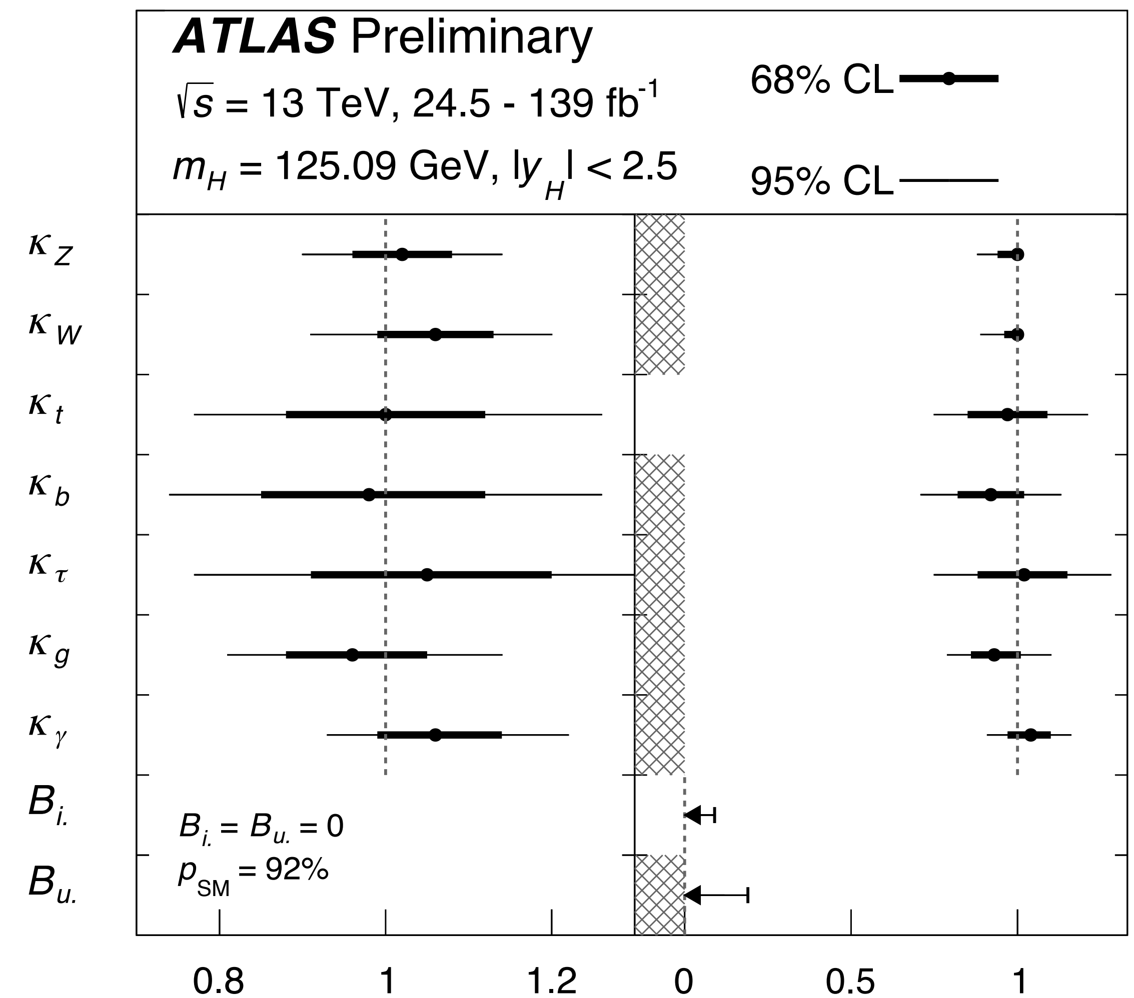
Higgs Boson coupling results

- typical precision of κ: 6~20% (partial Run 2 data)
- full Run 2 combination to come

$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$ vs. particle mass



Generic model [ATLAS-CONF-2020-027]



JHEP 01 (2021) 148

full Run 2 H→μμ + 2016 data H → γγ, H→ZZ, H→WW, H→ττ, H→bb

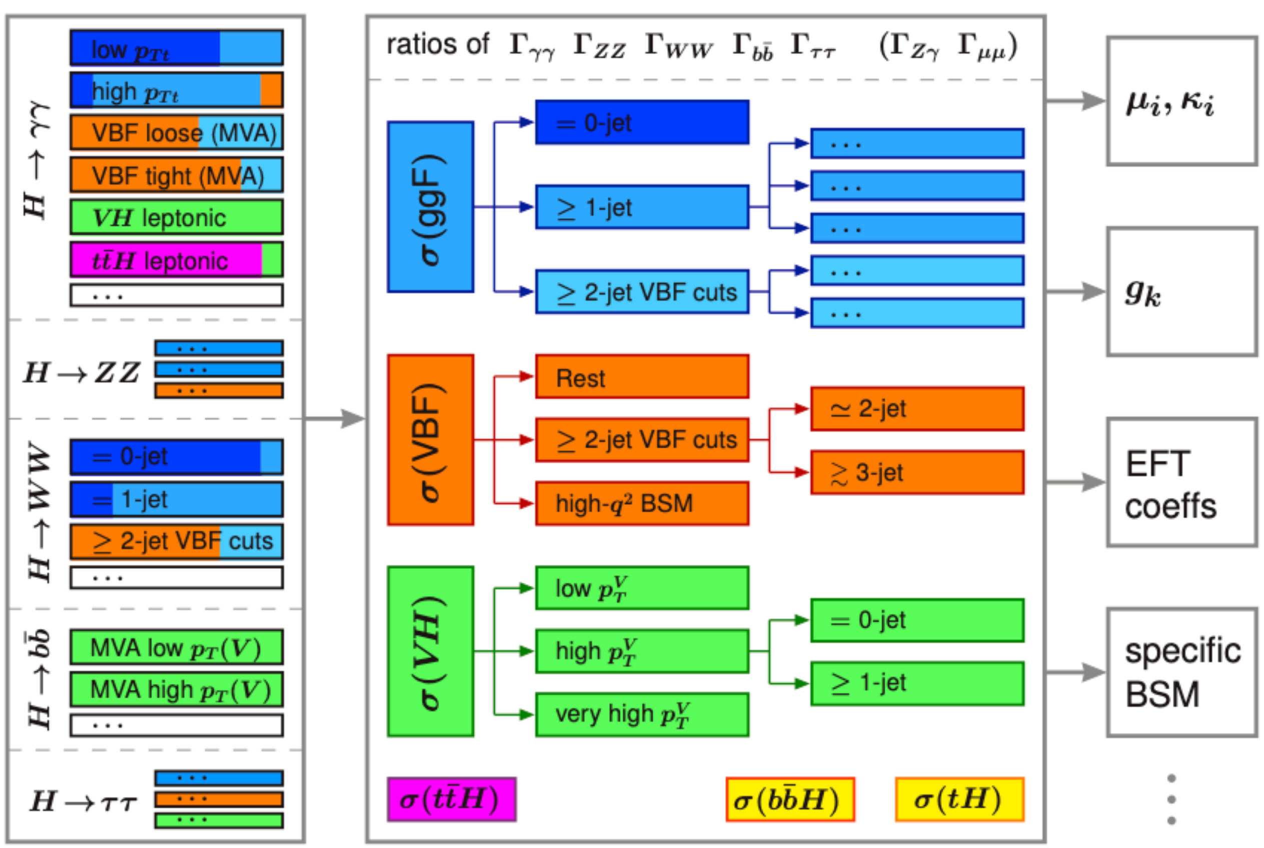
- **$B_{inv.}$ < 9%** @95% CL, mainly constrained by H→inv.
- **$B_{undet.}$ < 19%** @95% CL, constrained by inclusive rate + assuming **$|\kappa_V| \leq 1$**

Simplified Template Cross Sections (STXS)

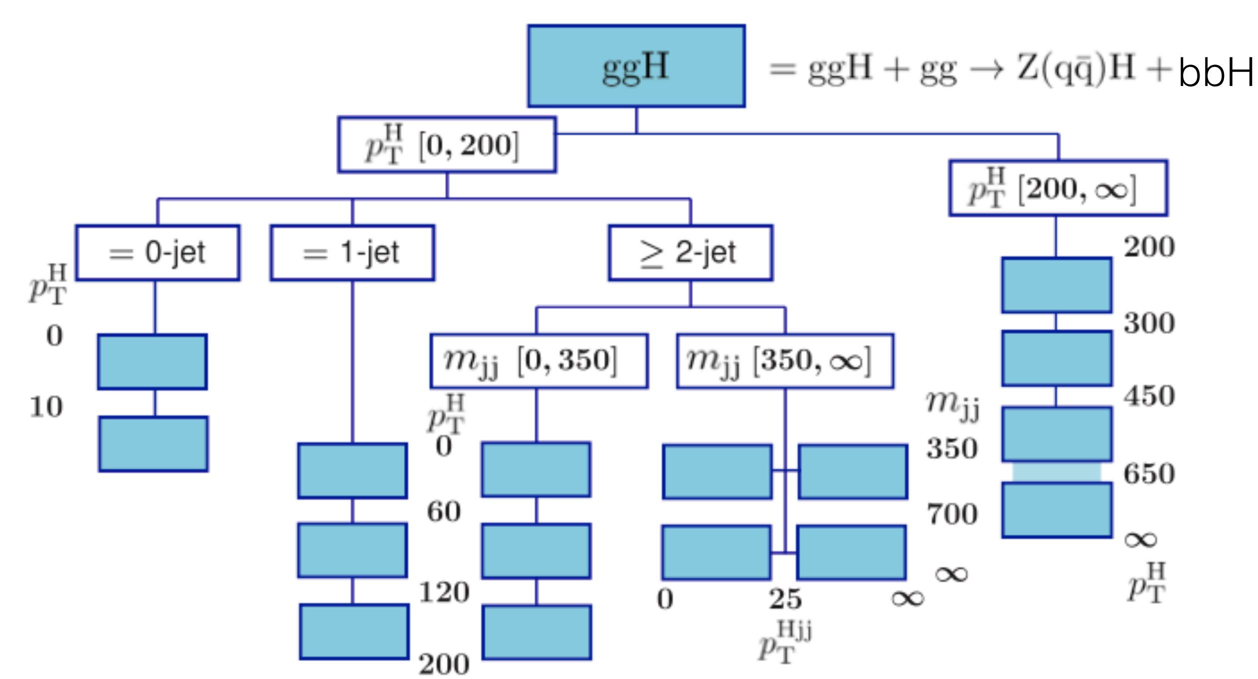
STXS: a natural evolution from Run 1 signal strength measurements

- Measure **production mode cross sections** in **exclusive phase space regions**
  - reduce theory dependence comparing to signal strength measurements
  - provide more finely-grained measurements
  - isolate BSM sensitive phase space
- Benefitting from **global combination**
  - Significant progress from ATLAS and CMS across accessible Higgs decays

Development initiated at Les Houches 2015



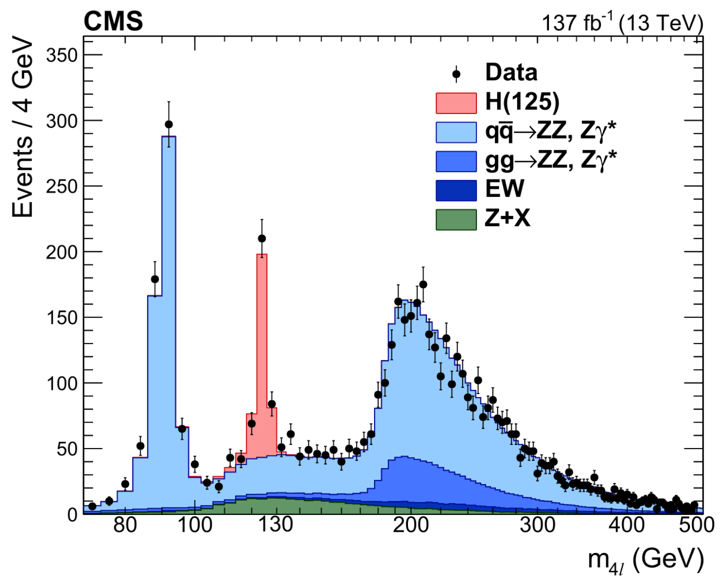
STXS stage 1.2 ggH production mode bins



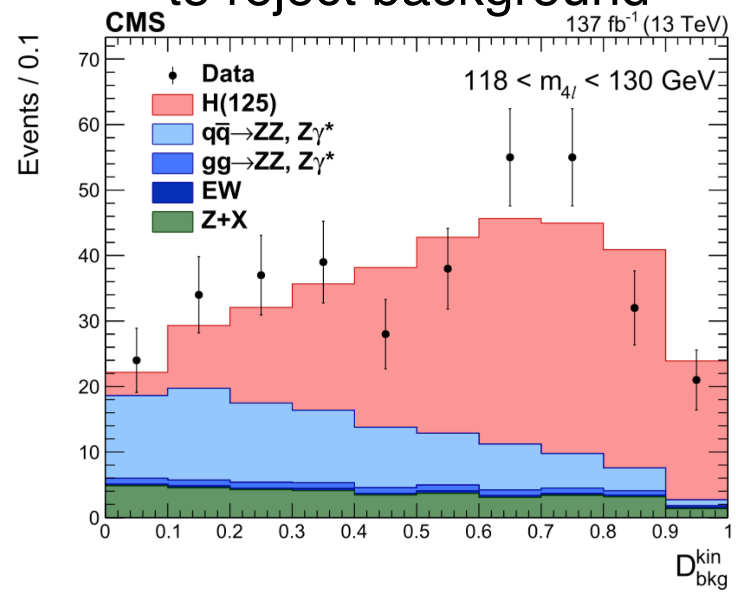
H→ZZ*→4l channel STXS

[Eur. Phys. J. C 81(2021) 488]

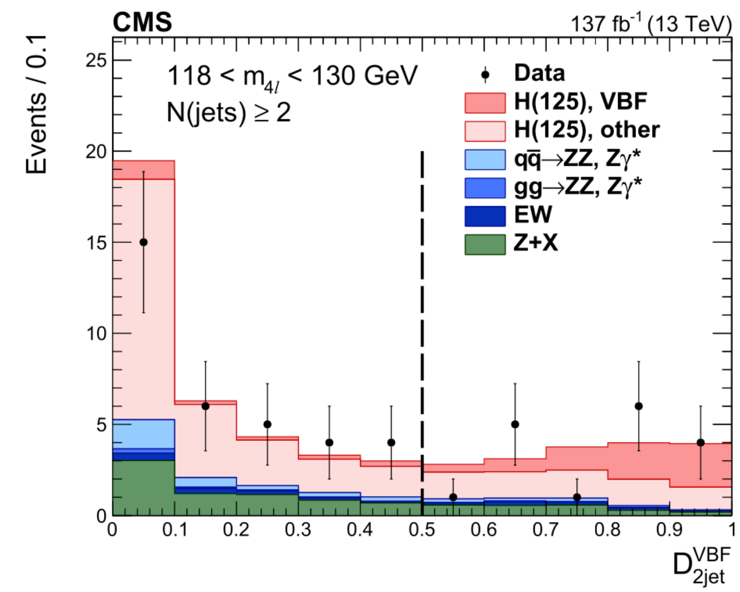
H→ZZ*→4l Mass distribution



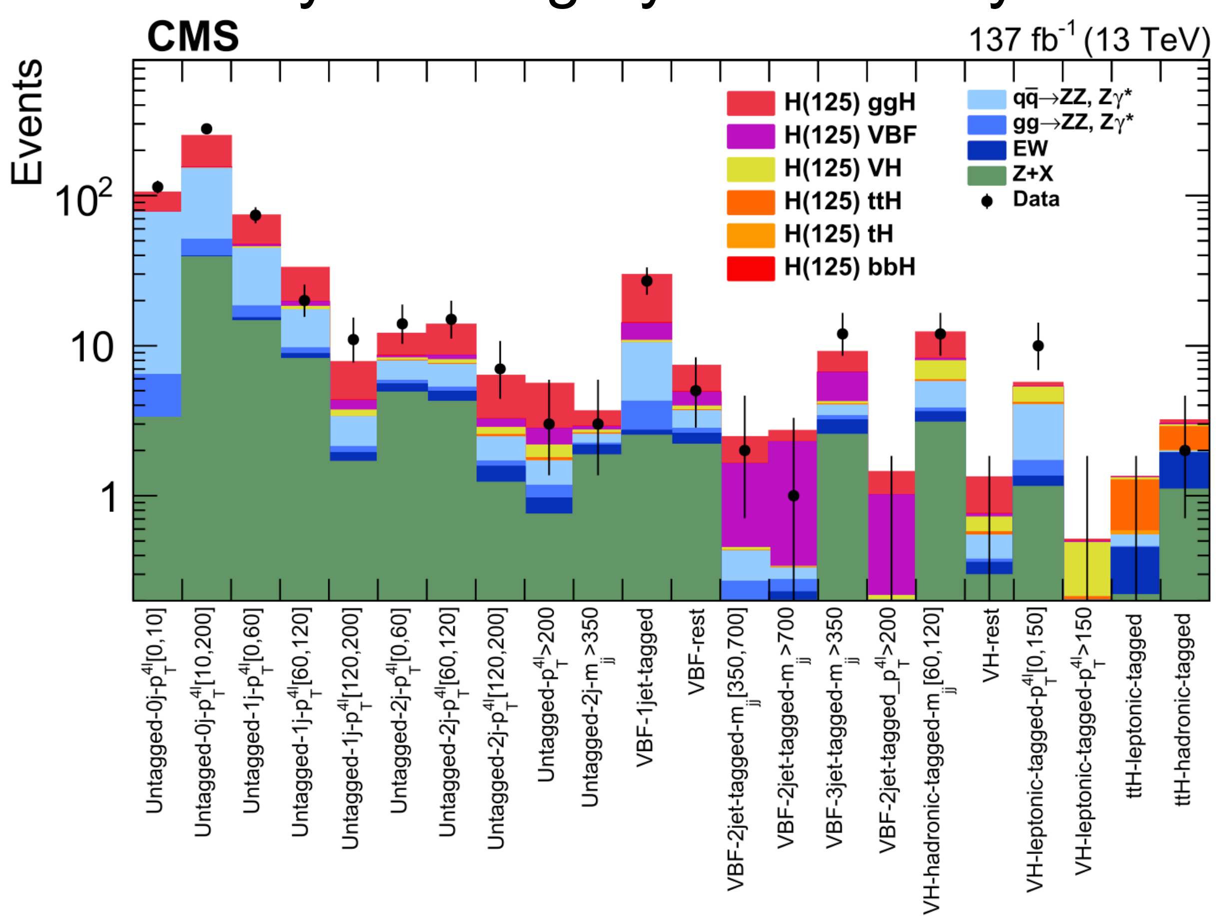
kinematic discriminants to reject background



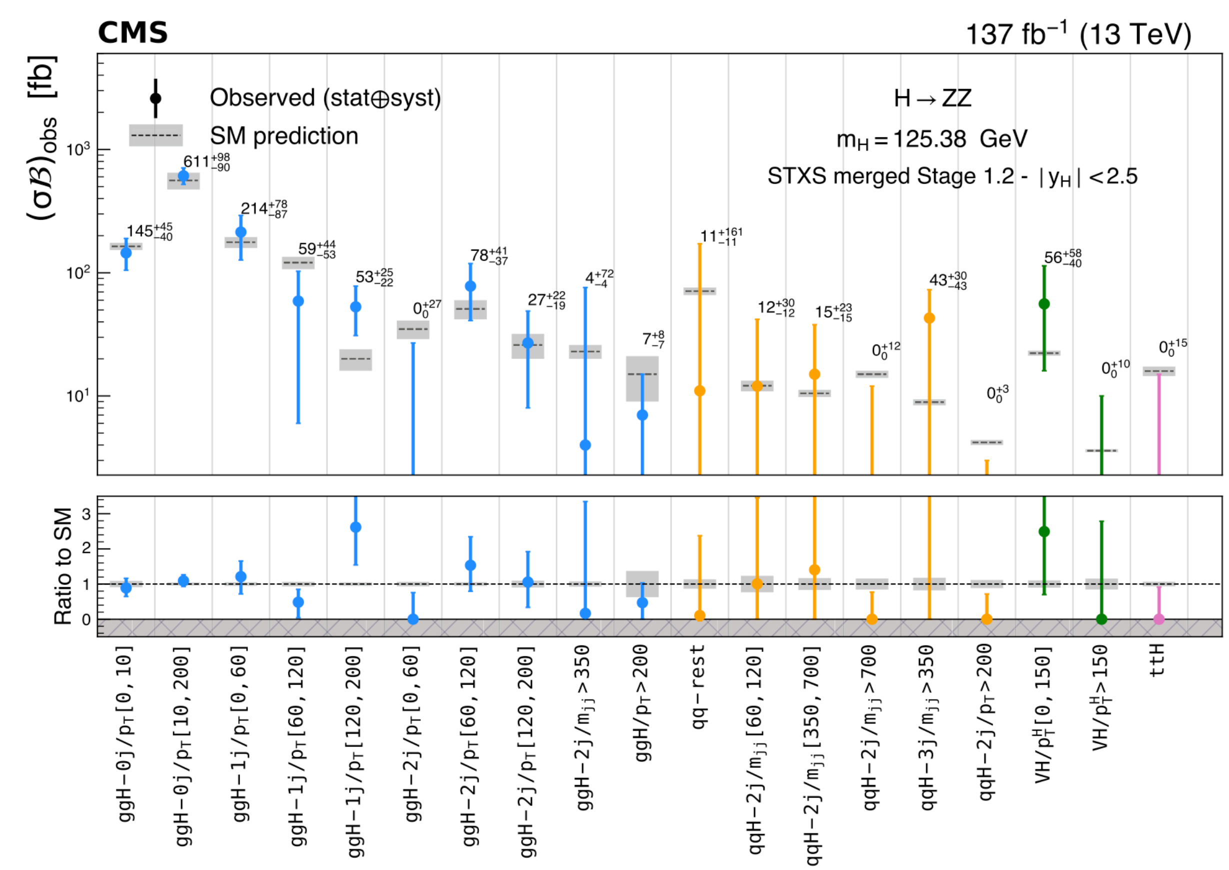
categorization discriminants



Analysis category and event yields



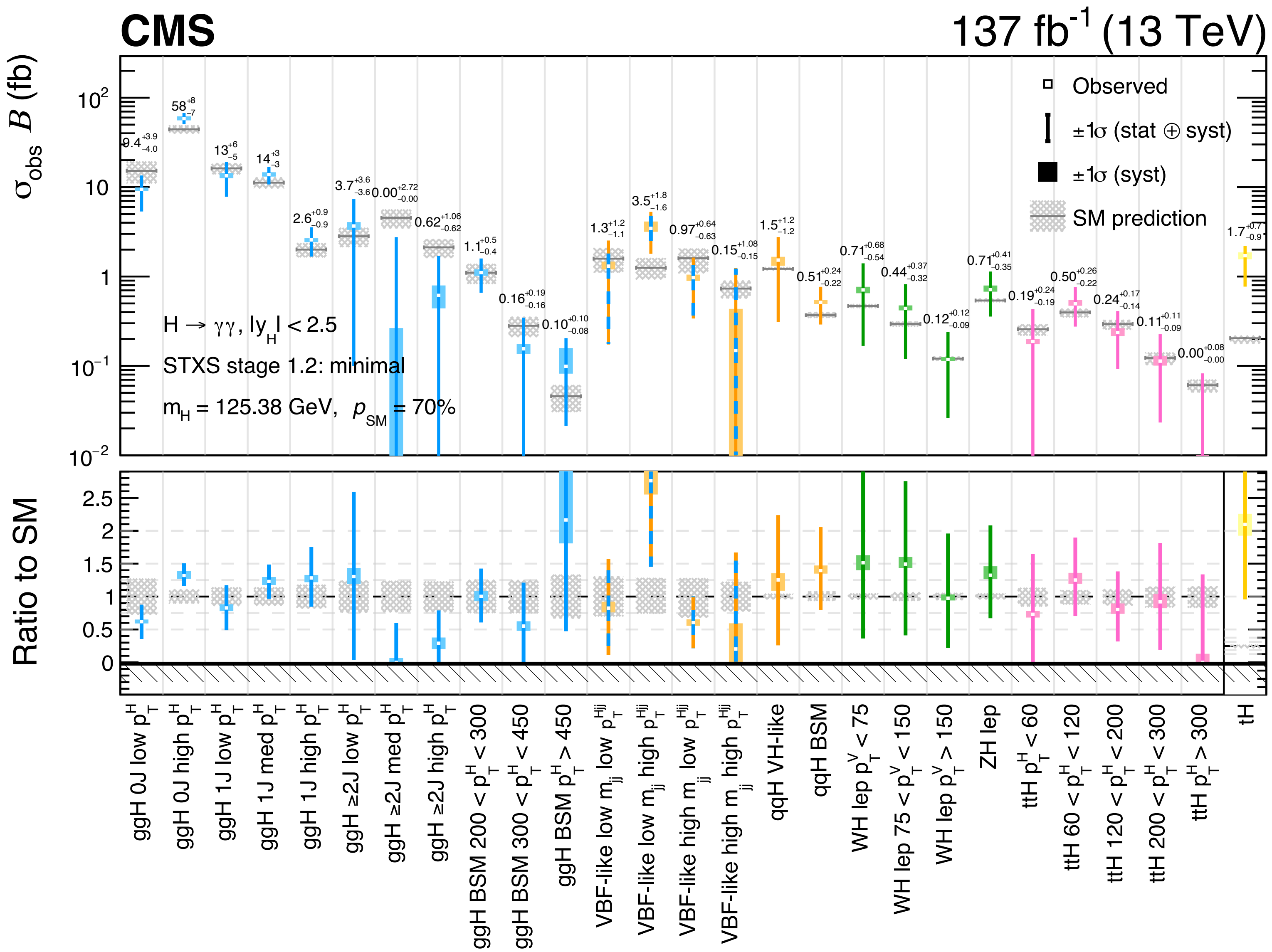
Measurements in merged Stage 1.2 STXS bins



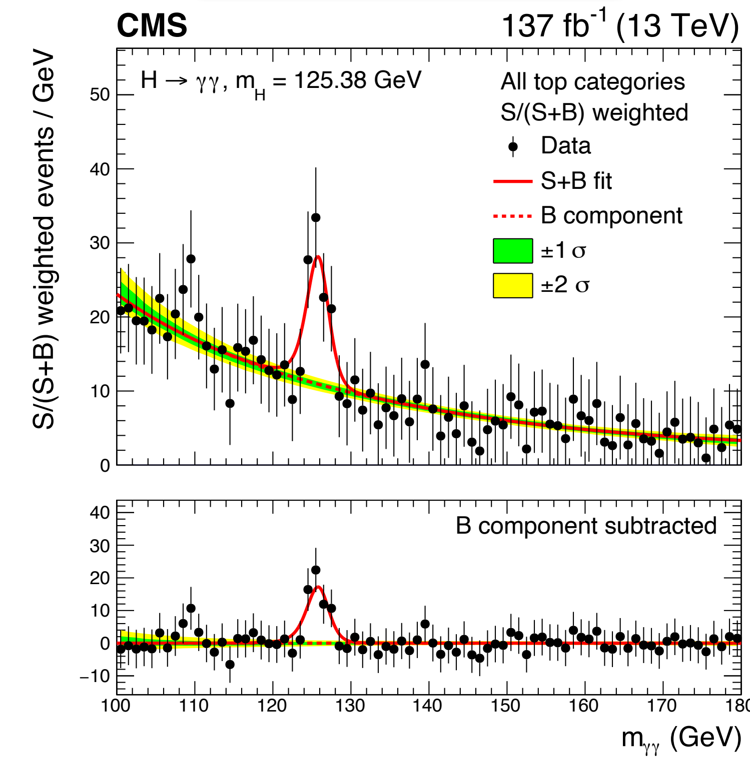
[JHEP 07 (2021) 027, ATLAS-CONF-2020-026]

$H \rightarrow \gamma\gamma$ decay channel STXS

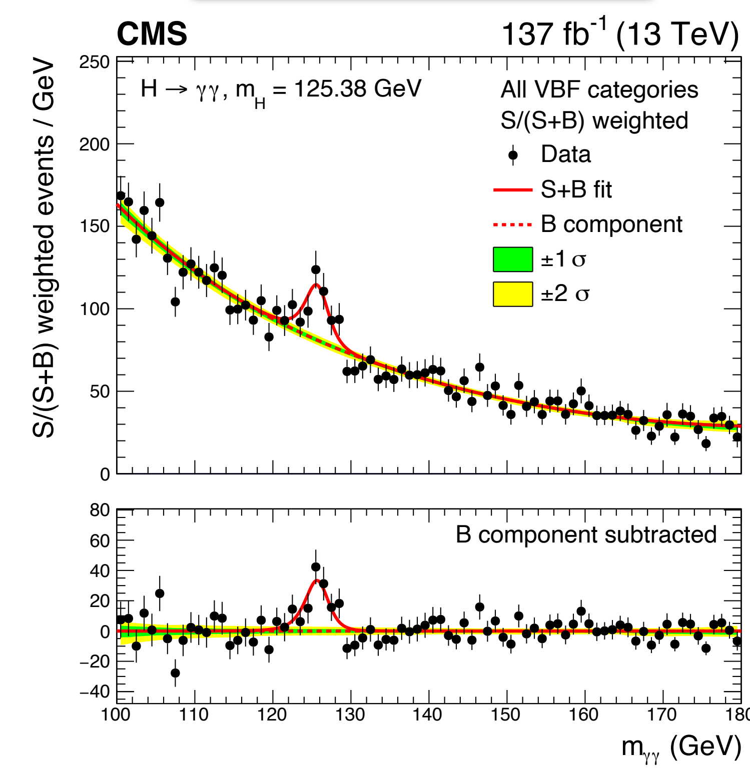
- Measurements of various kinematic regions in ggH, VBF, VH, ttH production modes and tH



ttH categories



VBF categories

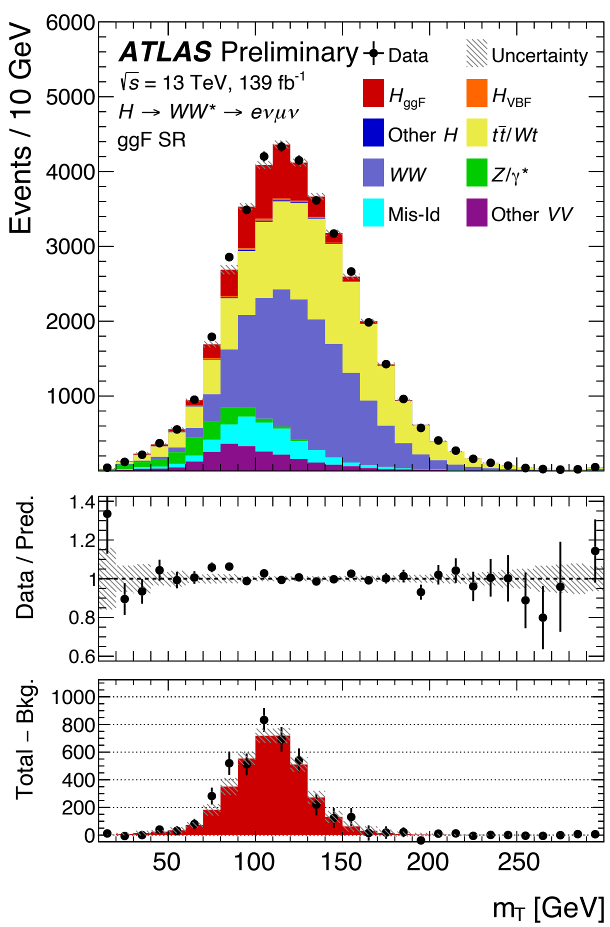


H→WW*→eνμν STXS

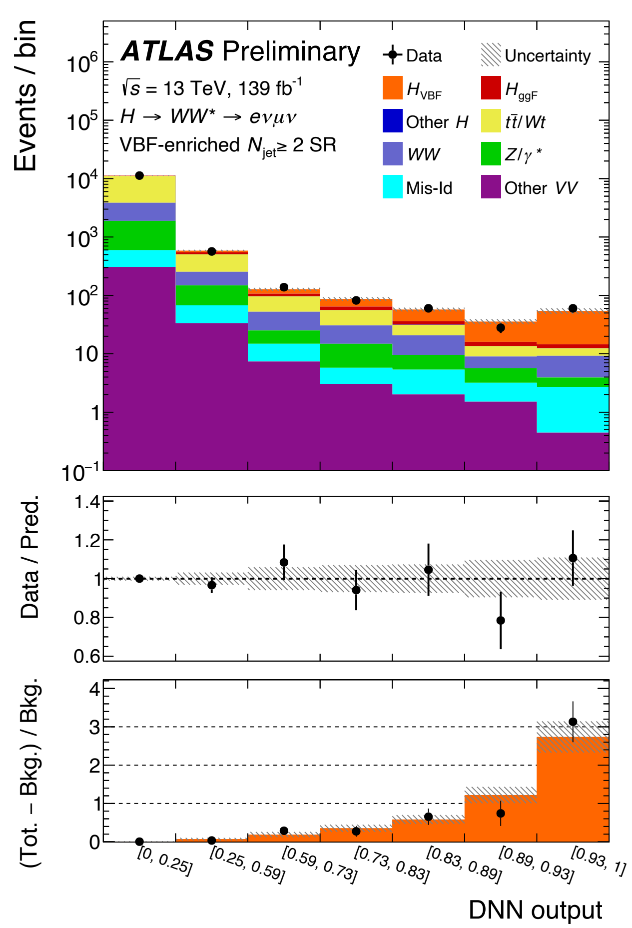
[ATLAS-CONF-2021-014, Phys. Lett. B 798 (2019) 134949
CMS-PAS-HIG-19-017, PLB 791 (2019) 96]

- Select events with an oppositely charged lepton pair, large missing transverse momentum
- Mass resolution worsened by neutrinos
- Large event rate and backgrounds: main backgrounds WW, tt, Z+jets measured in control regions

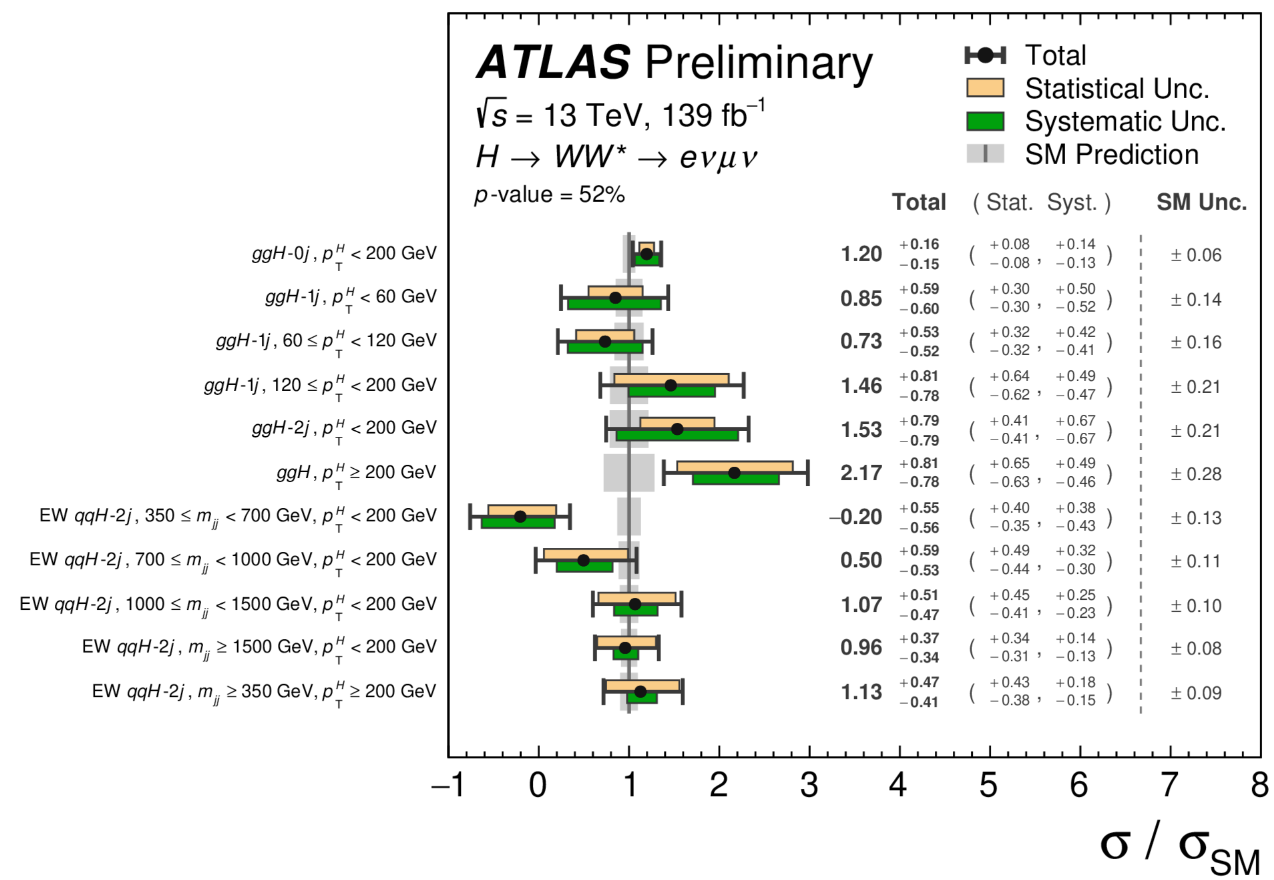
dilepton transverse mass



DNN in VBF categories



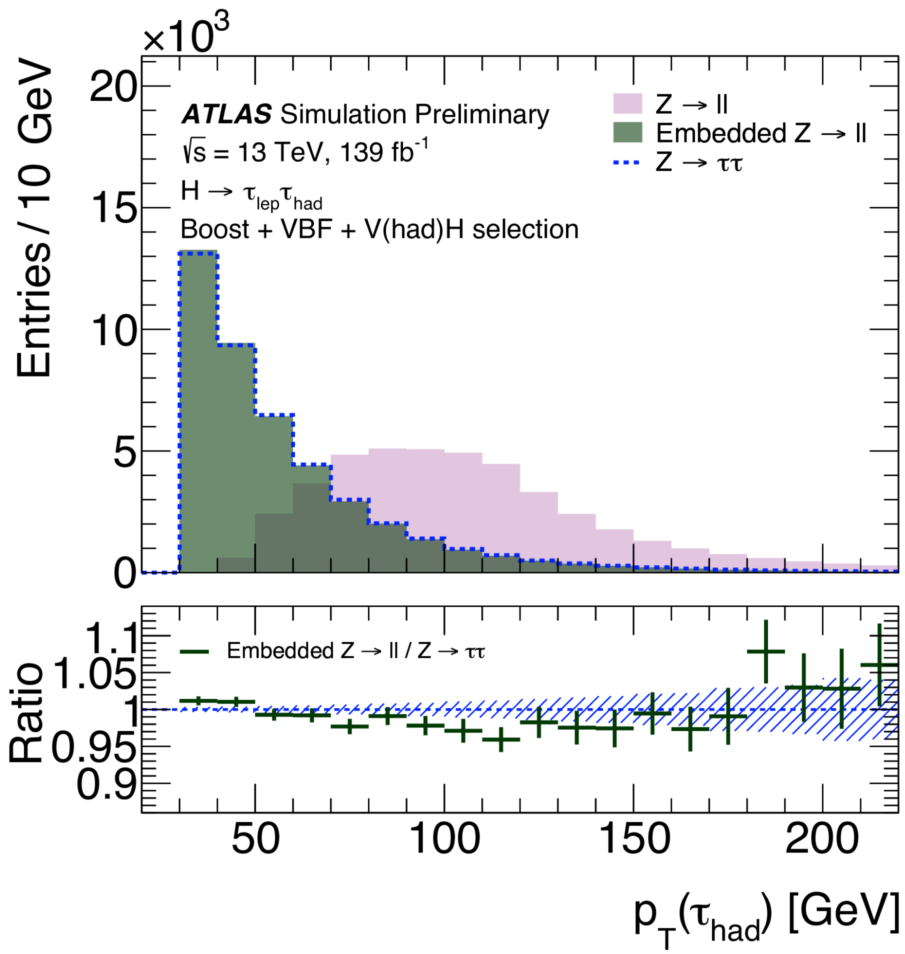
Measurements in kinematic regions for ggH and VBF production modes

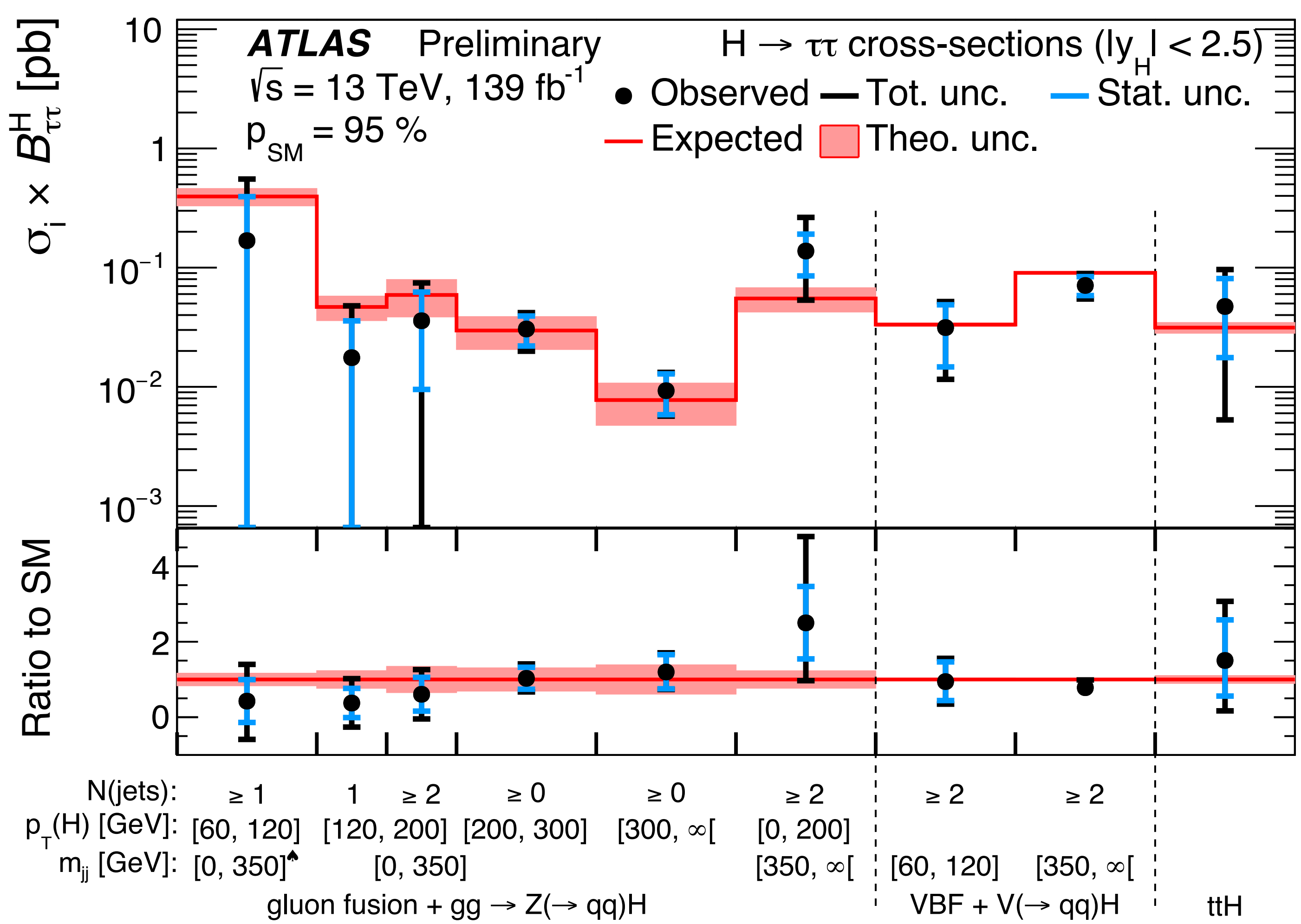


$H\rightarrow\tau\tau$ channel STXS

[ATLAS-CONF-2021-044]
[CMS: CMS-PAS-HIG-19-010]

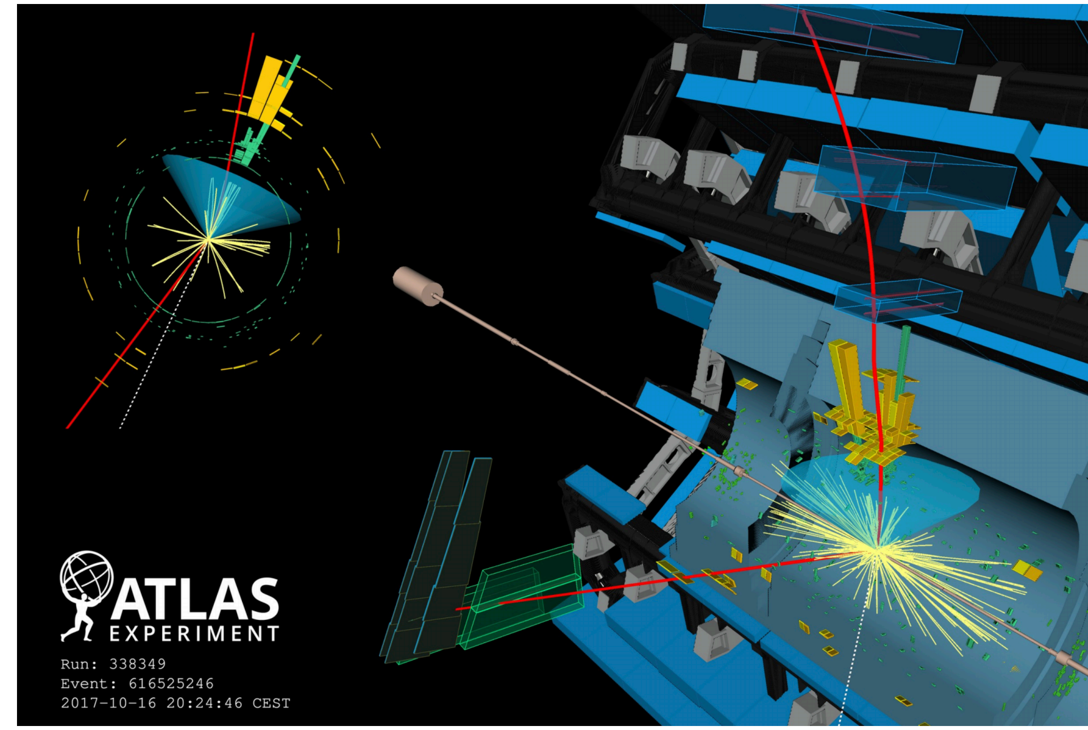
- New background estimation method: MC $Z\rightarrow\tau\tau$ background estimation validated with $Z\rightarrow ll$ data with simulation-based corrections to kinematics (four vectors) and efficiencies
- Uncertainty improved by factor of 2-2.5 wrt 2016 data analysis [Phys. Rev. D 99, 072001 (2019)]
- Production modes: ggF 3.9σ obs. (4.6σ exp.); VBF 5.3σ obs. (6.2σ exp.)





VH→bb STXS

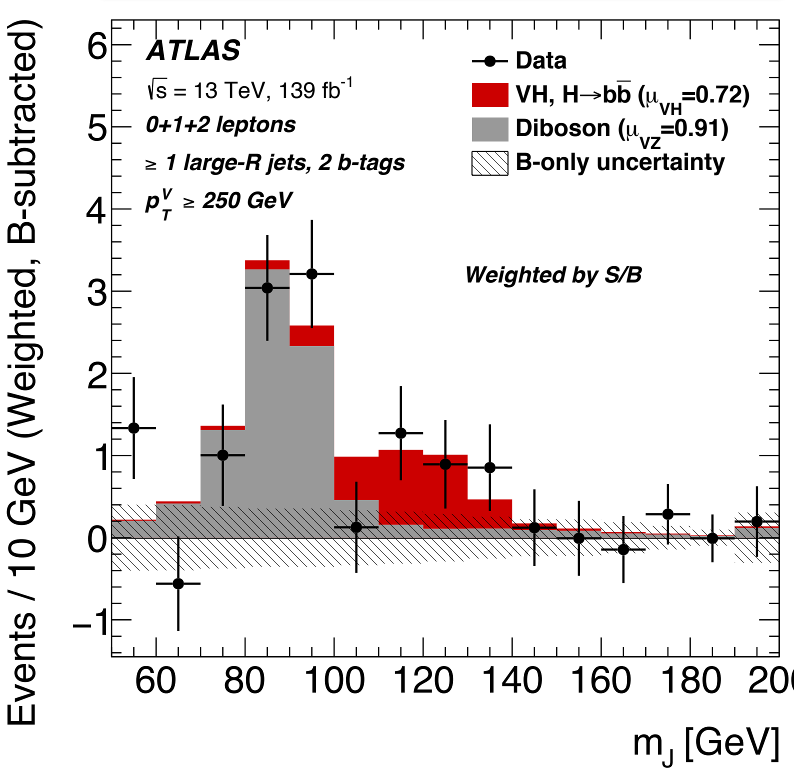
Boosted analysis: Phys. Lett. B 816 (2021) 136204
small-R jets analysis: Eur. Phys. J. C 81 (2021) 178



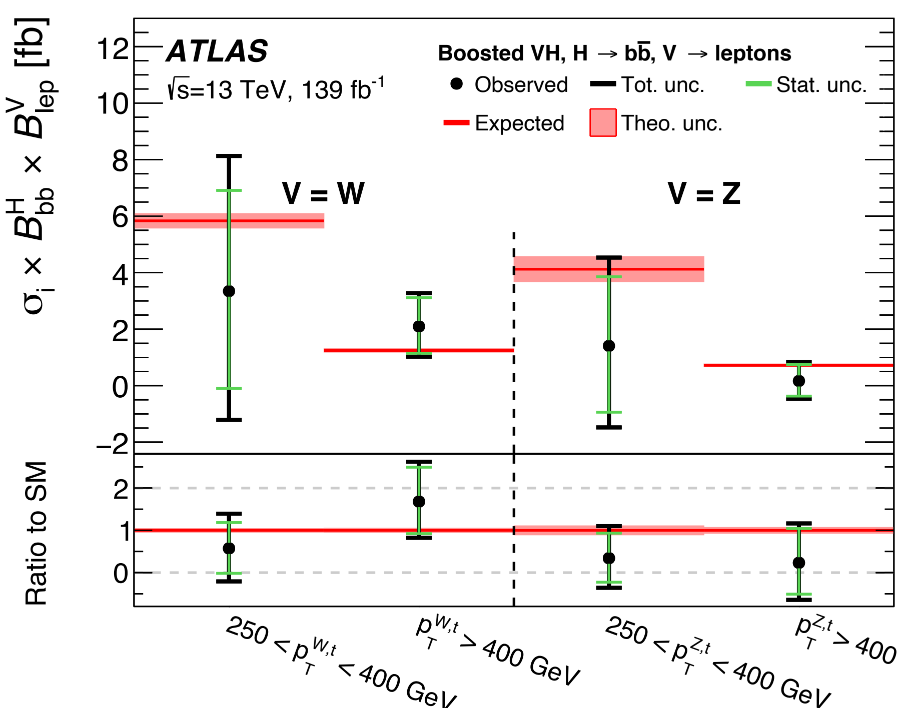
Complementary analyses using small-R jets and boosted Higgs physics objects:

- Strong evidence 4.0σ for WH; observation 5.3σ of ZH [small-R jets analysis]
- Boosted Higgs analysis: 2.1σ of VH

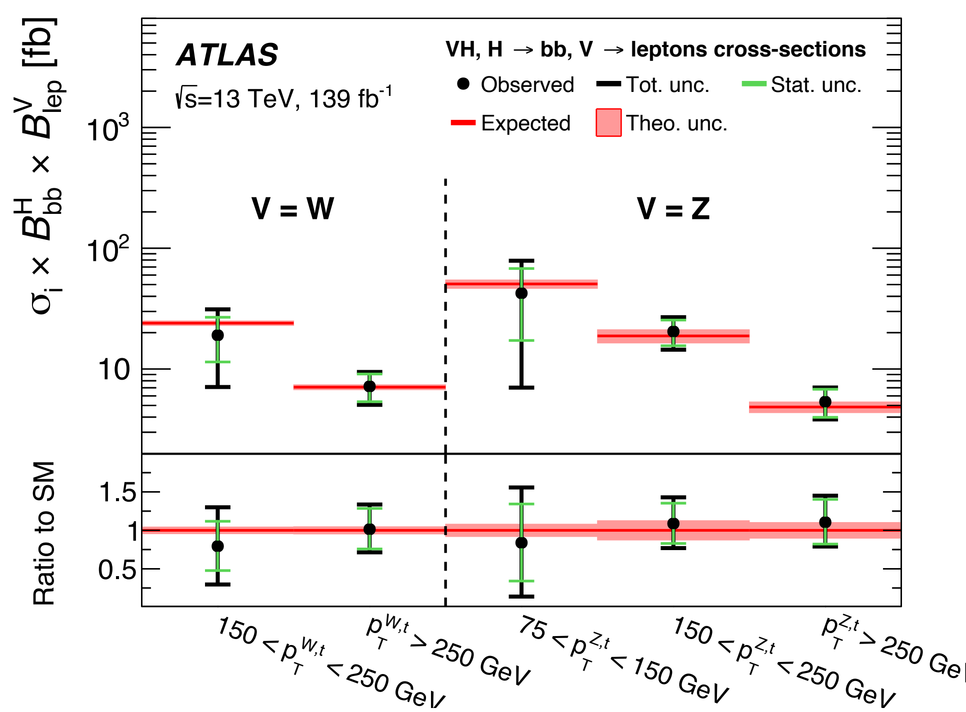
boosted Higgs analysis



boosted Higgs analysis



small-R jets analysis

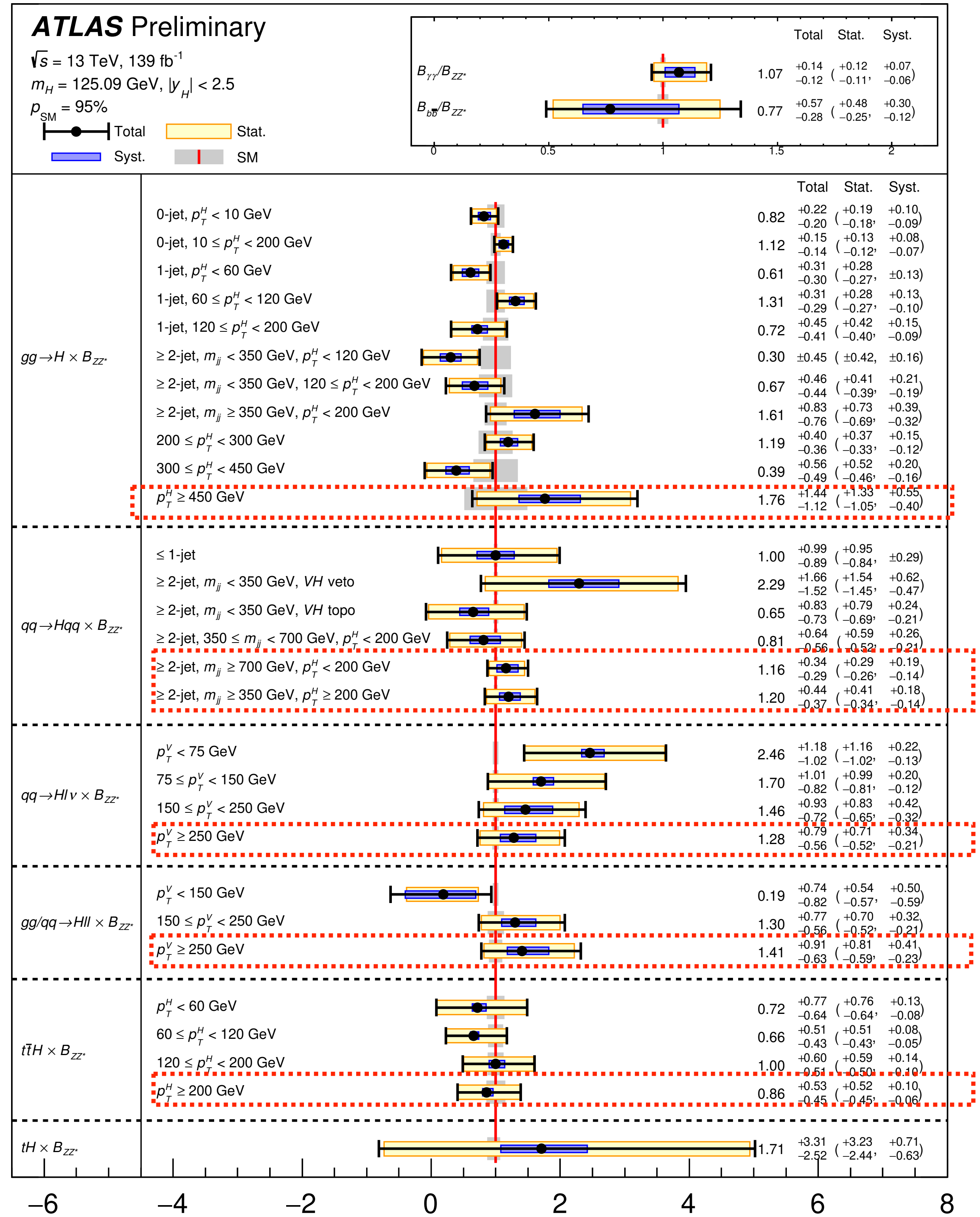


STXS Combination

- Combination of STXS measurements in H→γγ, H→ZZ*→4l and VH,H→bb
- Overall good compatibility with SM

Most precise measurements and interpretations obtained from statistical combination of production modes and decay channels:

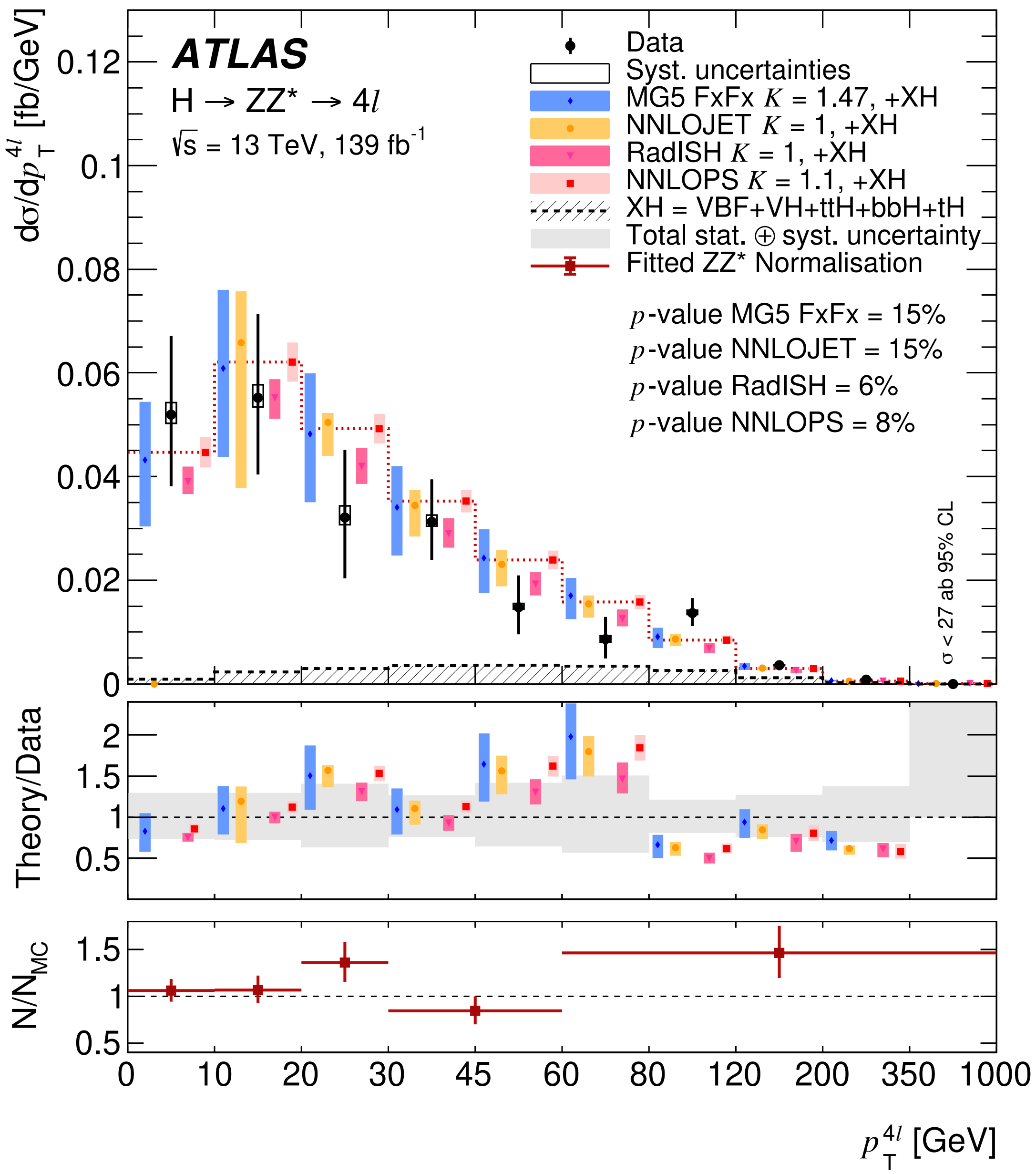
- Statistical precision, in particular in most BSM-sensitive regions is still limited: more data will help!
- Provide an indirect constraint of the Higgs boson self-coupling through NLO EW corrections [ATLAS-CONF-2019-049, CMS HIG-19-005]
- Measurements interpreted using EFT framework and BSM models: [ATLAS-CONF-2020-053, CMS HIG-19-005]



ATLAS-CONF-2020-027

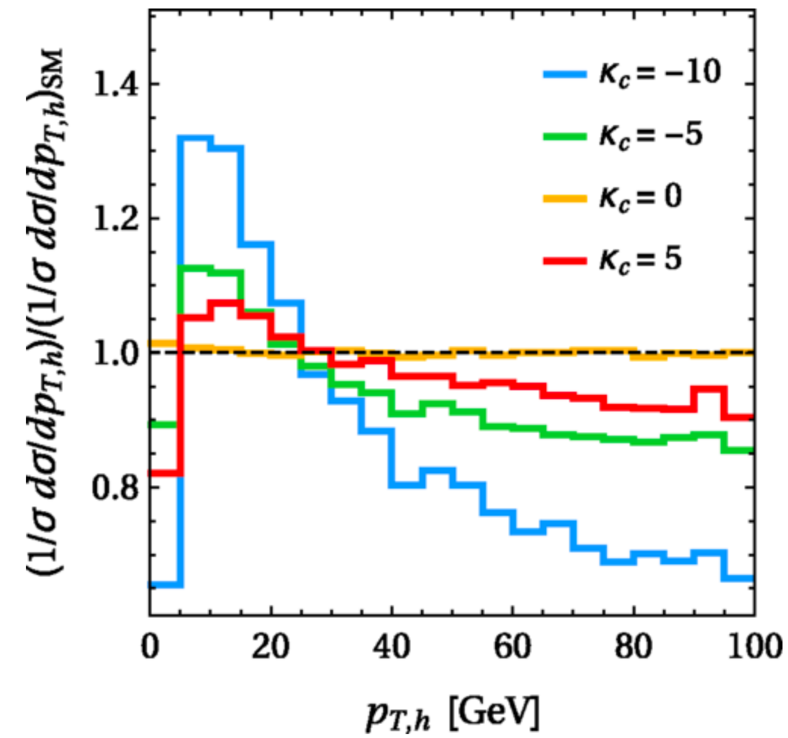
Higgs boson differential measurements

Higgs p_T sensitive to many BSM effects: physics in the ggF loops, perturbative QCD calculations, Higgs couplings to charm and bottom quarks, …



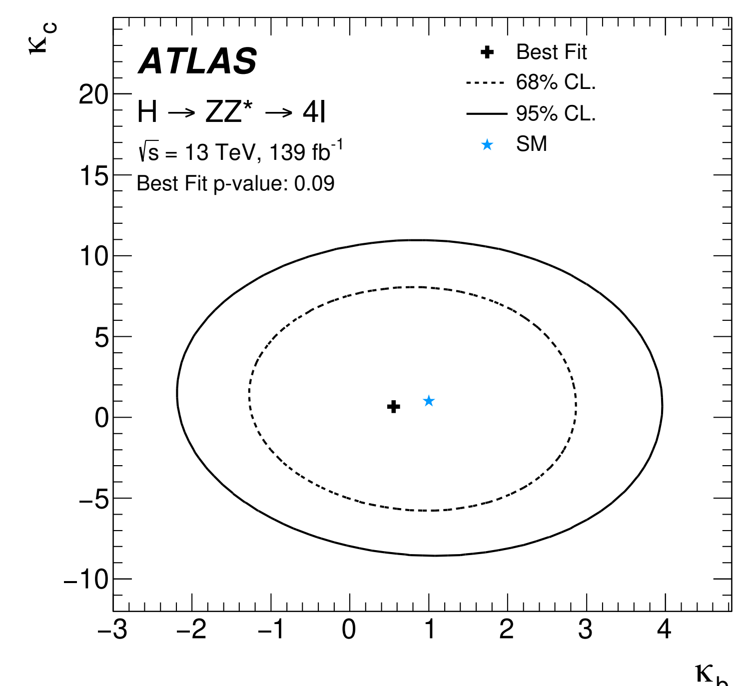
[ATLAS: Eur. Phys. J. C 80 (2020) 942
CMS: Eur. Phys. J. C 81(2021) 488]

Variations in p_T(H) with κ_c



Phys. Rev. Lett. 118 (2017) 121801

κ_c vs κ_b constraint from p_T(H) shape



$H \rightarrow \tau\tau$ differential measurements

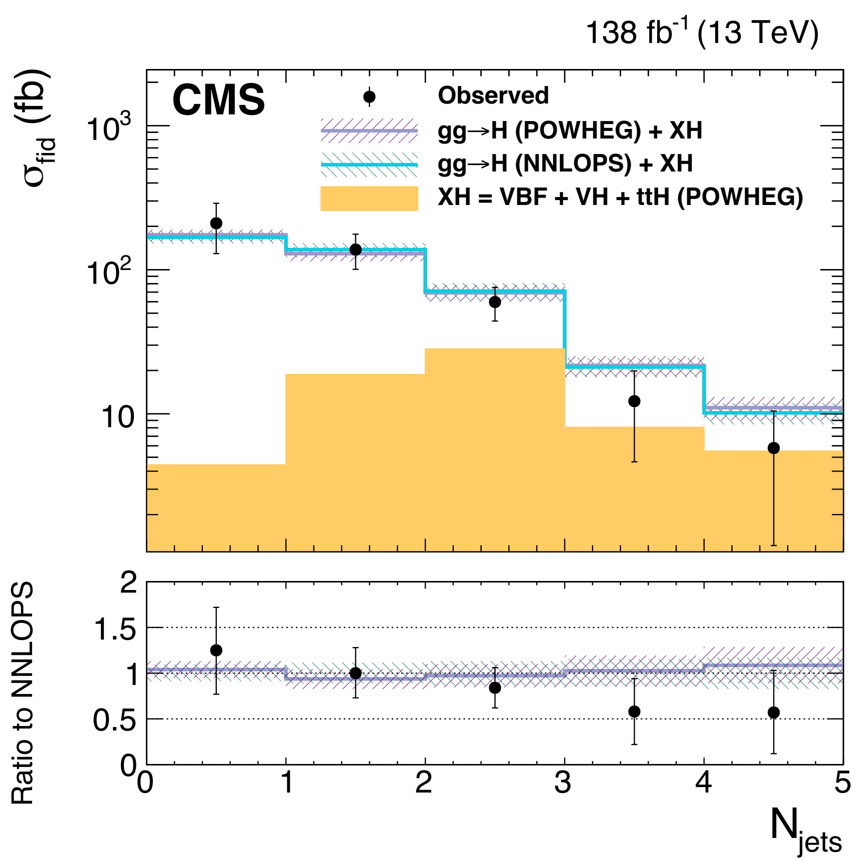
Comparing to other final state (4l, $\gamma\gamma$) measurements, brings significant improvements: exploring the phase space of large jet multiplicities and/or Lorentz-boosted Higgs bosons

[$\tau\tau$: CMS Submitted to Phys. Rev. Lett.

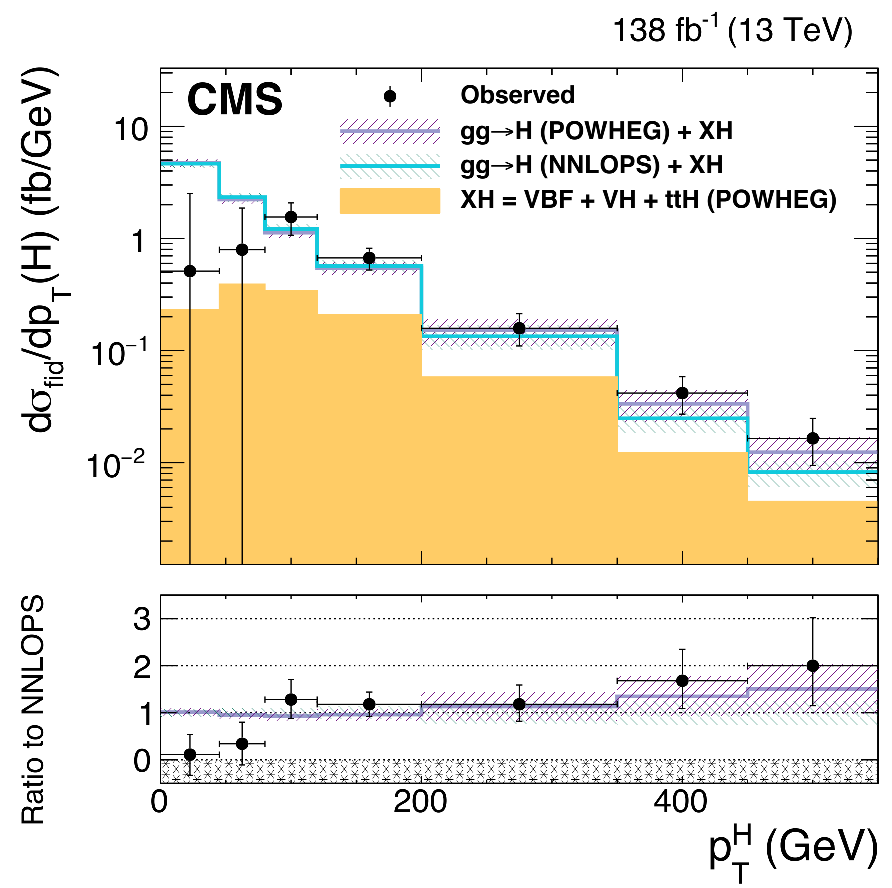
[$\gamma\gamma$: CMS JHEP 07 (2021) 027, ATLAS-CONF-2020-026]

[4l: CMS Eur. Phys. J. C 81(2021) 488, ATLAS Eur. Phys. J. C 80 (2020) 942]

$H \rightarrow \tau\tau$ ggF H and XH $d\sigma/N_{jets}$
XH = VBF + VH + ttH



$H \rightarrow \tau\tau$ ggF H and XH $d\sigma/dp_T$



[JHEP 12 (2020) 085]

High pT Higgs production with H→bb

Highly Lorentz-boosted Higgs as a tool to access very high-p_T regime, sensitive to BSM physics. CMS full Run 2:

- Observed (exp) Significance: 2.5σ (0.7σ)
- Signal strength

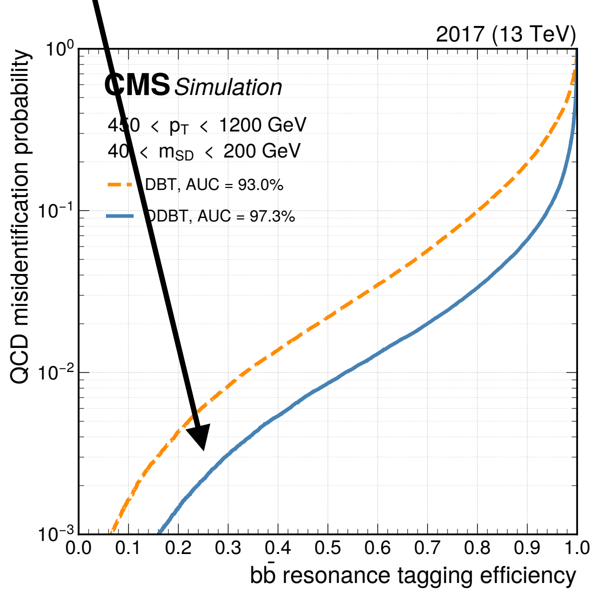
$$\mu_H = 3.7 \pm 0.12(Stats.)^{+0.8}_{-0.7}(Sys.)^{+0.8}_{-0.5}(Theo.)$$

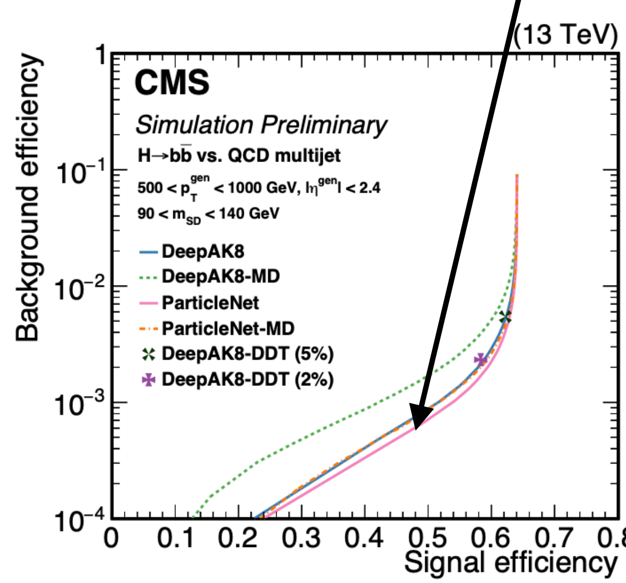
validation with Z→bb $1.01 \pm 0.05\,(\mathrm{stat})^{+0.20}_{-0.15}\,(\mathrm{syst})^{+0.13}_{-0.09}\,(\mathrm{theo})$

- Local significance with respect to SM: 1.9σ

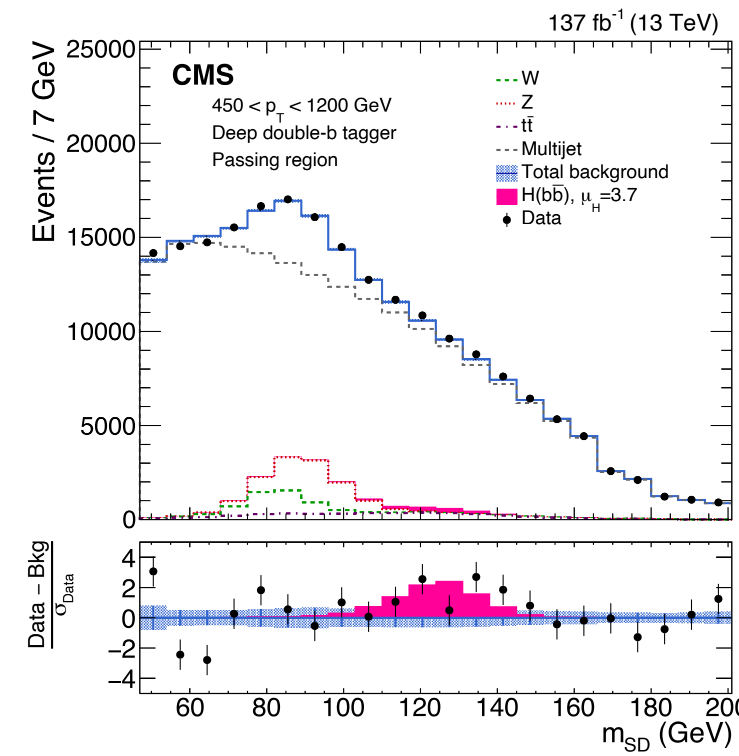
Machine-learning methods based on signature of two b quarks inside a large-radius (distance parameter R = 0.8)

- DDBT tagger improves efficiency by a factor of 1.6 at same QCD misidentification rate;
- New possibilities brought by a new algorithm based on ParticleNet graph neural network [CMS-DP-2020-002]

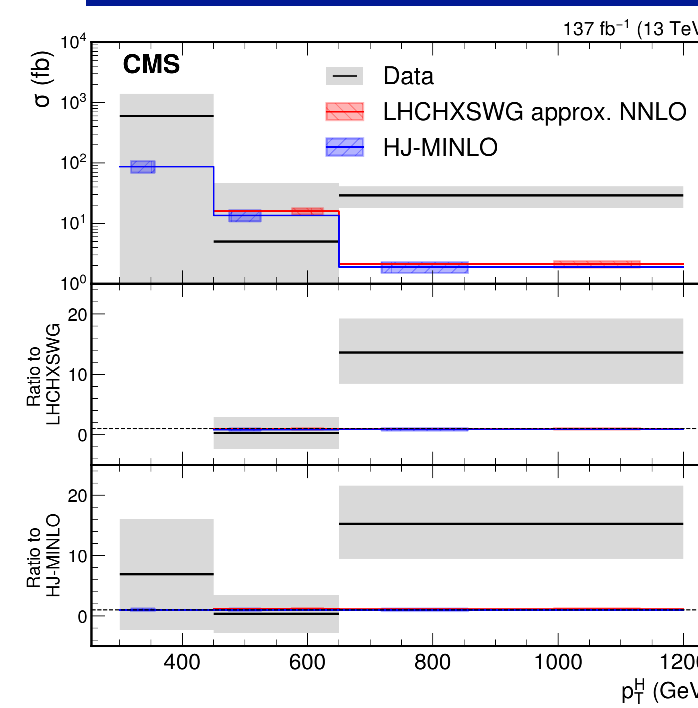




Soft-drop mass m_{SD}(bb) in signal region



Unfolded differential cross section in pT(H)



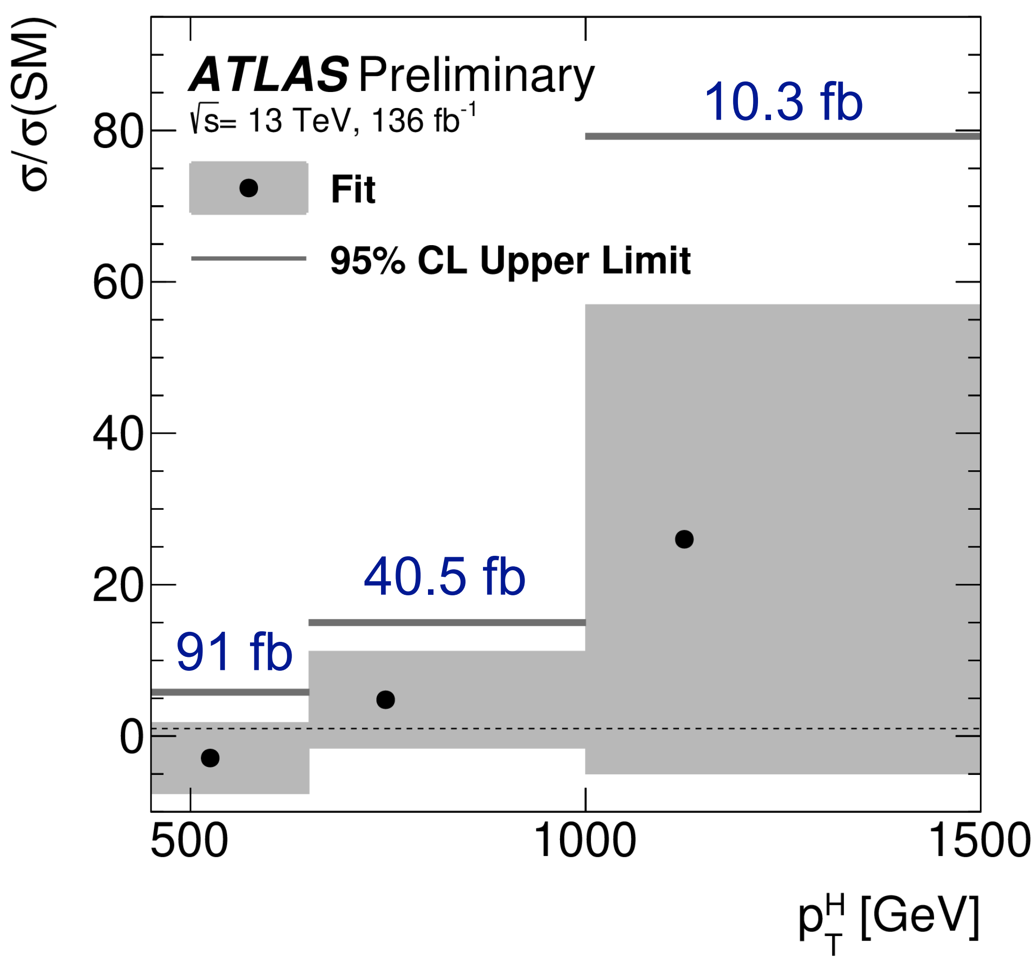
High pT Higgs production with H→bb

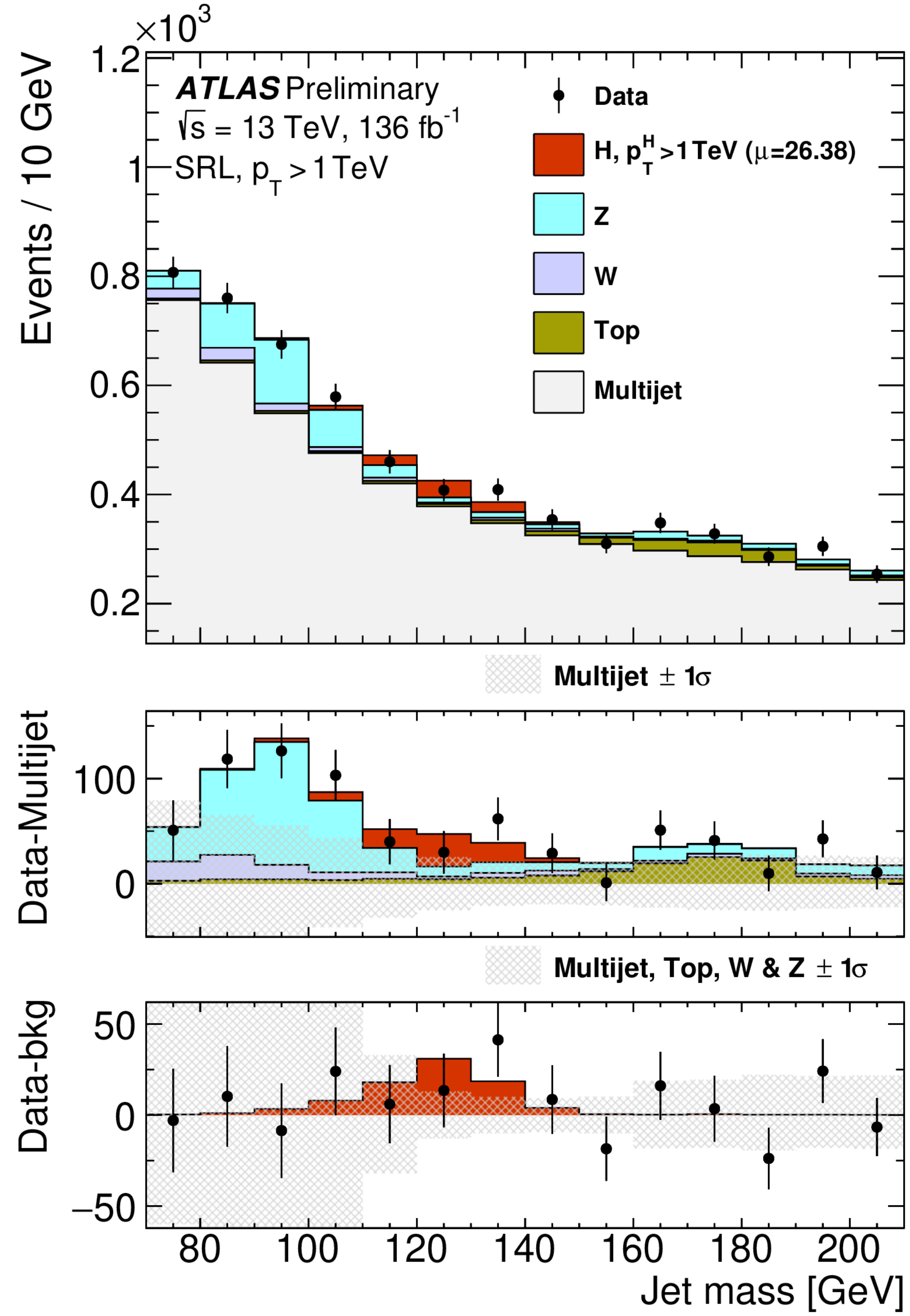
[ATLAS-CONF-2021-010]

ATLAS full Run 2

- b-tagging applied to contained track jets in large-radius (R = 1.0) jets
- Large backgrounds: multijet and V+jets studied using validation region, tt from control region
- Analysis method validated with Z→bb

Measured cross section σ/σ_{SM} and 95% CL upper limits in three pT(H) bins





Higgs boson CP studies

- SM Higgs boson quantum number $J^{CP} = 0^{++}$
- Run 1: spin-0 nature established, CP structure explored in Higgs-boson couplings in H→ZZ*→4l and H→WW*→eνμν decays
- Run 2:
  - first study of CP structure in Higgs-fermion couplings in ttH, tH(H→γγ)
    [ATLAS: Phys. Rev. Lett. 125 (2020) 061802
    CMS: Phys. Rev. Lett. 125 (2020) 061801]
  - CP structure of Higgs-τ Yukawa coupling using H→$\tau\tau$ decay channel
    [CMS-PAS-HIG-20-006]
  - CP and anomalous couplings measured using H→ZZ*→4l decay channel
    [arXiv:2104.12152, Submitted to Phys. Rev. D
    Eur. Phys. J. C 80 (2020) 957]
  - CP structure in Hgg coupling using H→WW*→eνμν+jj [ATLAS-CONF-2020-055]

Parametrize Higgs Fermion Couplings in the mass eigenstate basis

$$A(\mathrm{Hff}) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + i\tilde{\kappa}_f\gamma_5\right)\psi_f$$

Define mixing angle (α or in next slide $\varphi_{\tau\tau}$):

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau \text{ CP-odd coupling}}{\kappa_\tau \text{ CP-even coupling}}$$

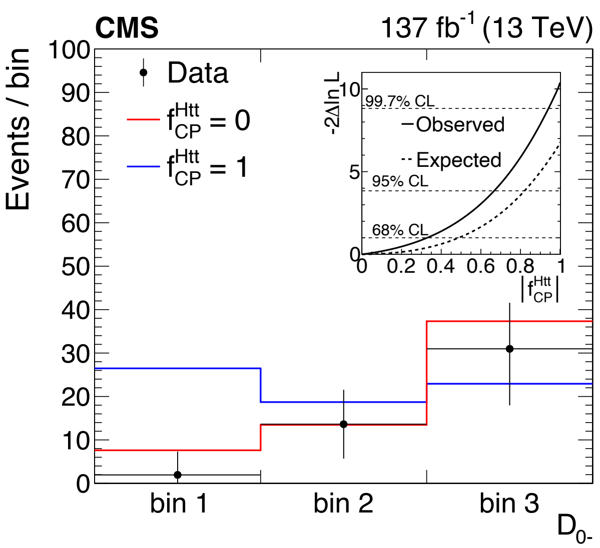
SM **SM Pure CP-even state:** $\alpha = 0^o$

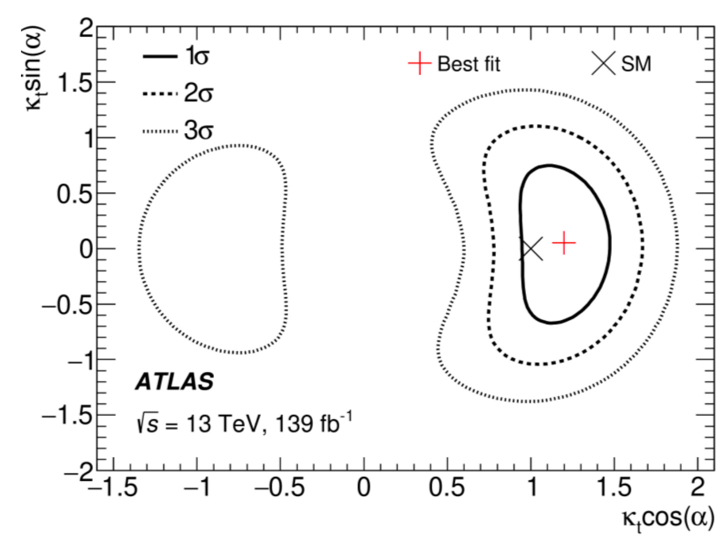
Pure CP-odd state: $\alpha = 90^o$

Define: CP-odd contribution:

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

Study CP structure in Higgs-top coupling





CMS: $|f_{CP}^{Htt}| < 0.67$ @95 % CL, pure CP-odd excluded at 3.2σ

CP-mixing angle $|\alpha| < 43°$ @95% CL
pure CP-odd excluded at 3.9σ

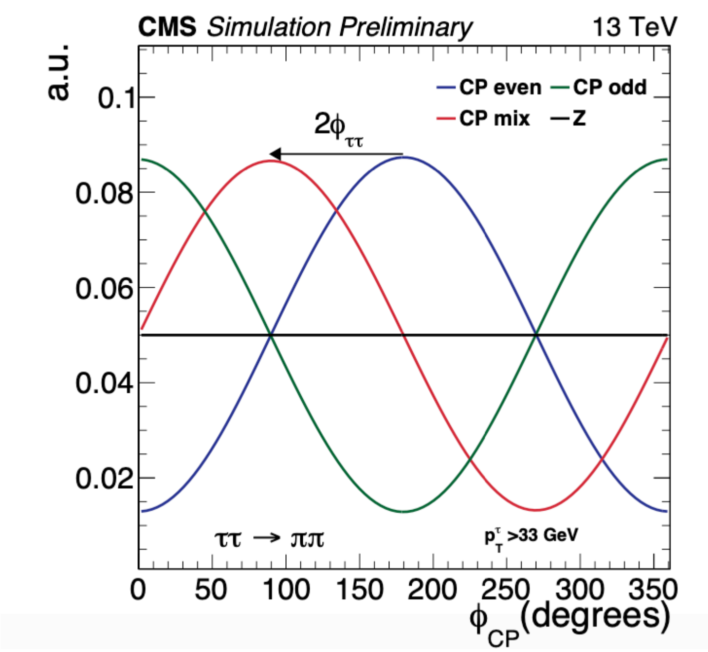
CP structure of Higgs-τ Yukawa coupling using H→$\tau\tau$ decay channel

[CMS-PAS-HIG-20-006]

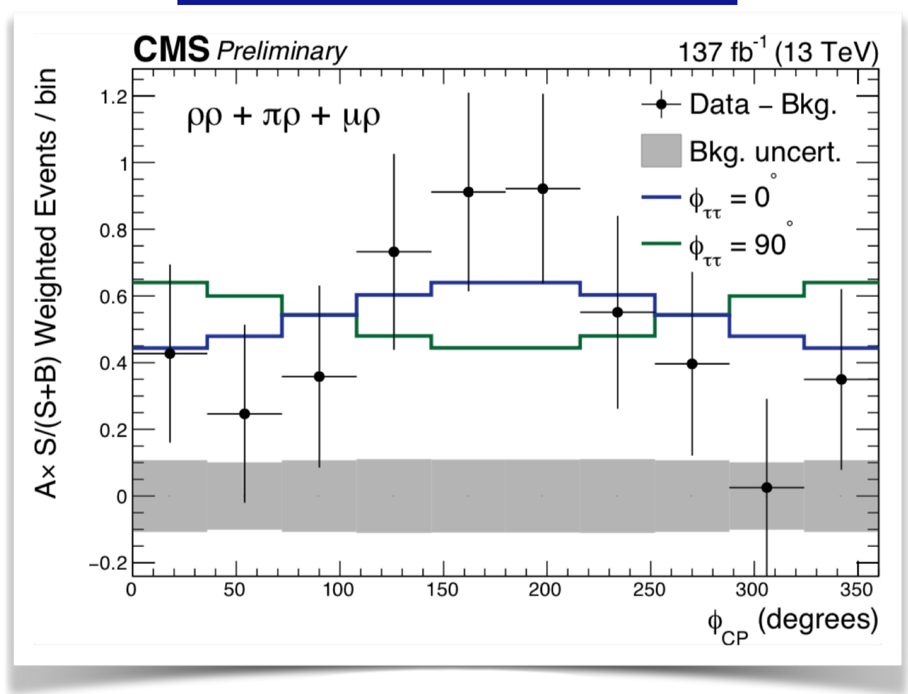
CP-mixing angle $\phi_{\tau\tau}$ = (4 ± 17)° @68% CL
pure CP-odd excluded at 3.2σ

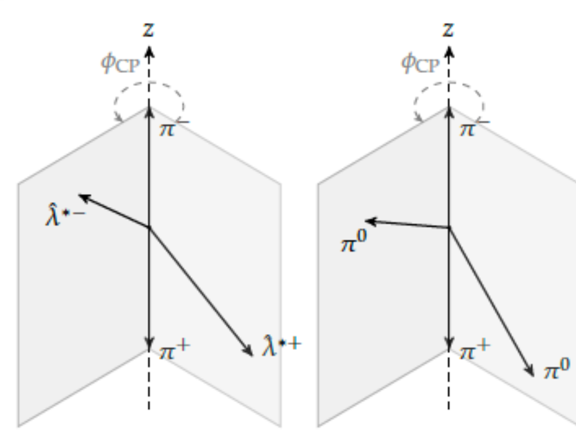
- discriminating variable: angle between the τ decay planes ϕ_{CP} $$\frac{d\Gamma}{d\phi_{CP}} \propto \cos(\phi_{CP} - 2\phi_{\tau\tau})$$

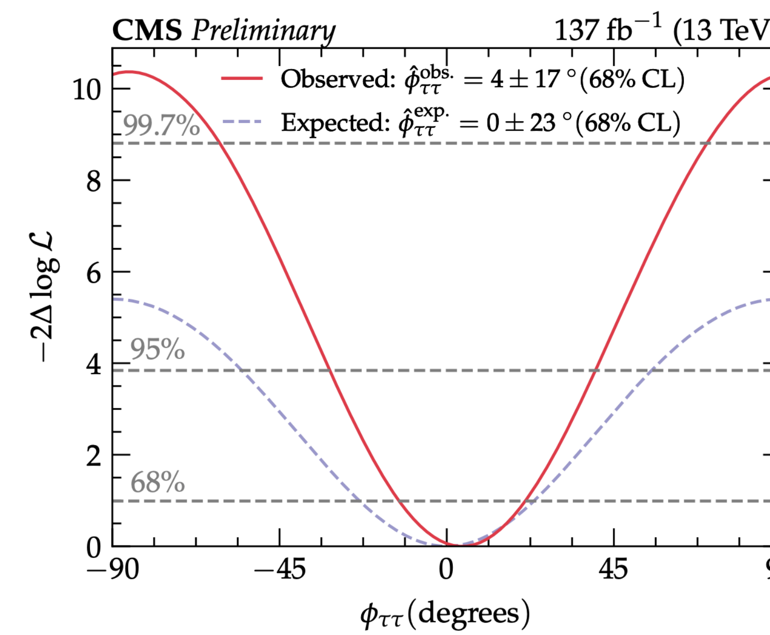
gen level ϕ_{CP}

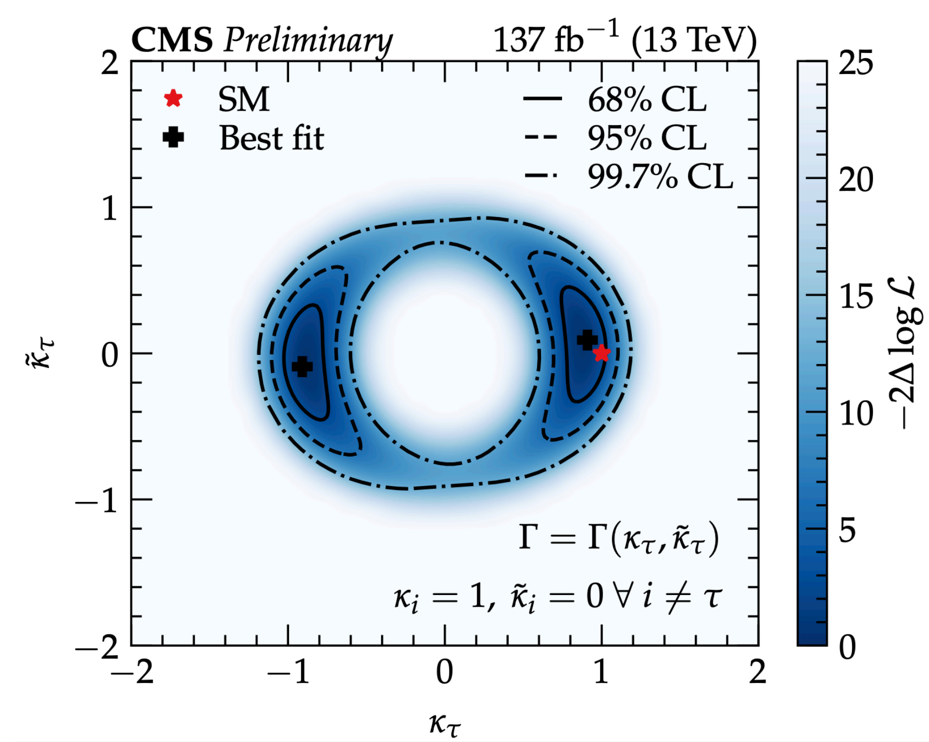


reconstructed ϕ_{CP}









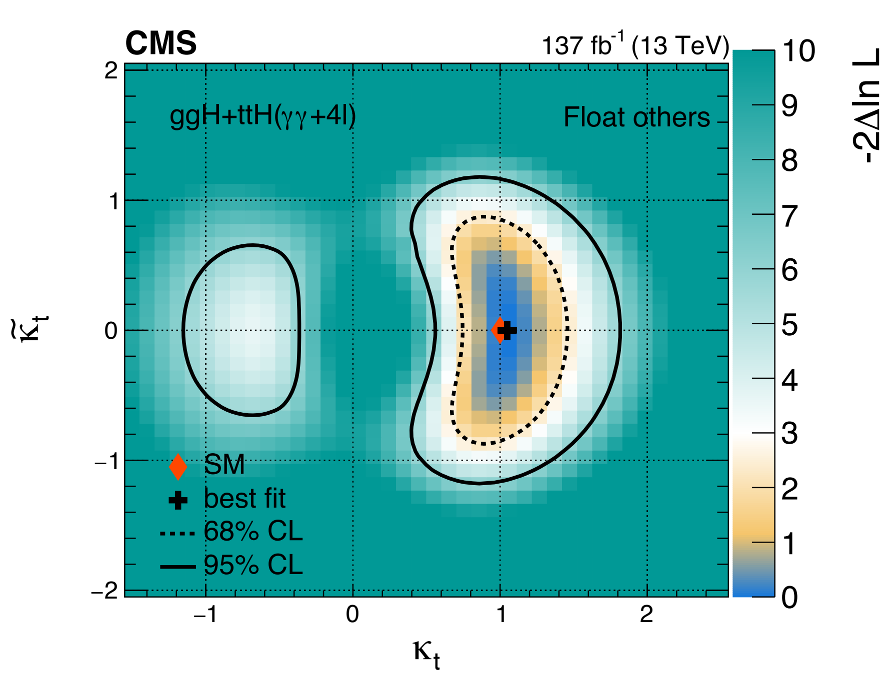
ϕ_{CP}: reconstructed by the impact parameter and charged particle or π^0 vectors in the Higgs rest frame

CP and anomalous couplings in H→ZZ*→4l

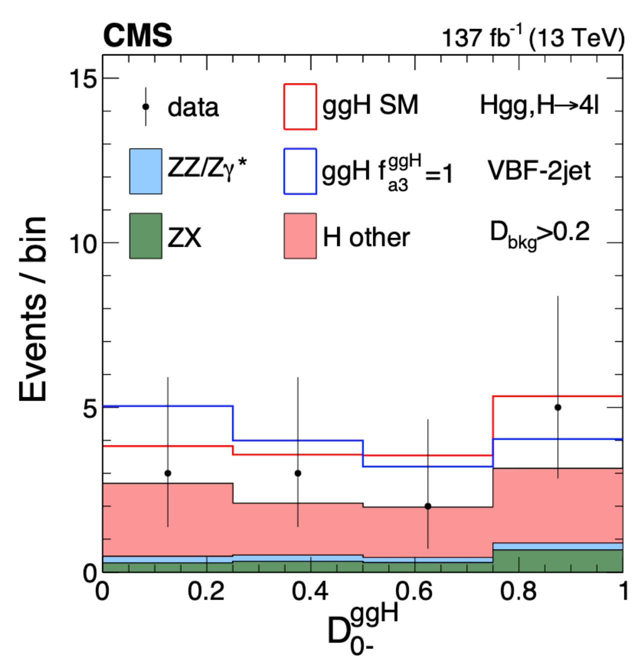
[CMS: arXiv:2104.12152, Submitted to Phys. Rev. D
ATLAS: Eur. Phys. J. C 80 (2020) 957]

- Using ggH+2j, VBF, VH, ttH and H→4l decay
- Matrix element techniques
- Two categorization schemes employed to study:
  - effects in HVV vertices: joint analysis of four anomalous couplings
  - effects in Htt and effective Hgg vertices: CP even and CP odd couplings, combine with recent analysis of ttH(H→γγ) [Phys. Rev. Lett. 125 (2020) 061801]

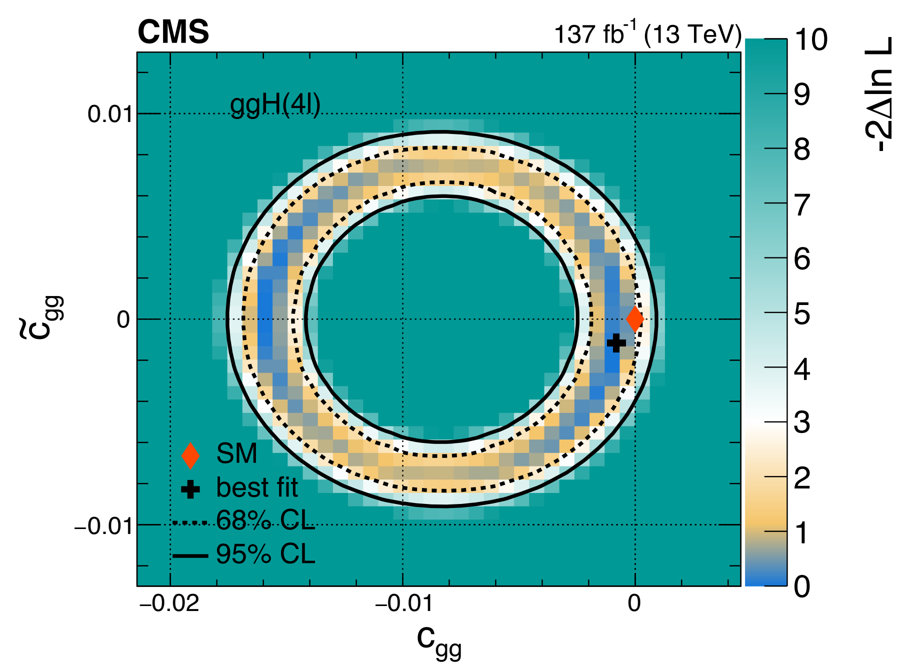
CP structure in Higgs couplings to top quarks combining ggH and ttH(γγ,H→4l)



Matrix element based CP-sensitive discriminant



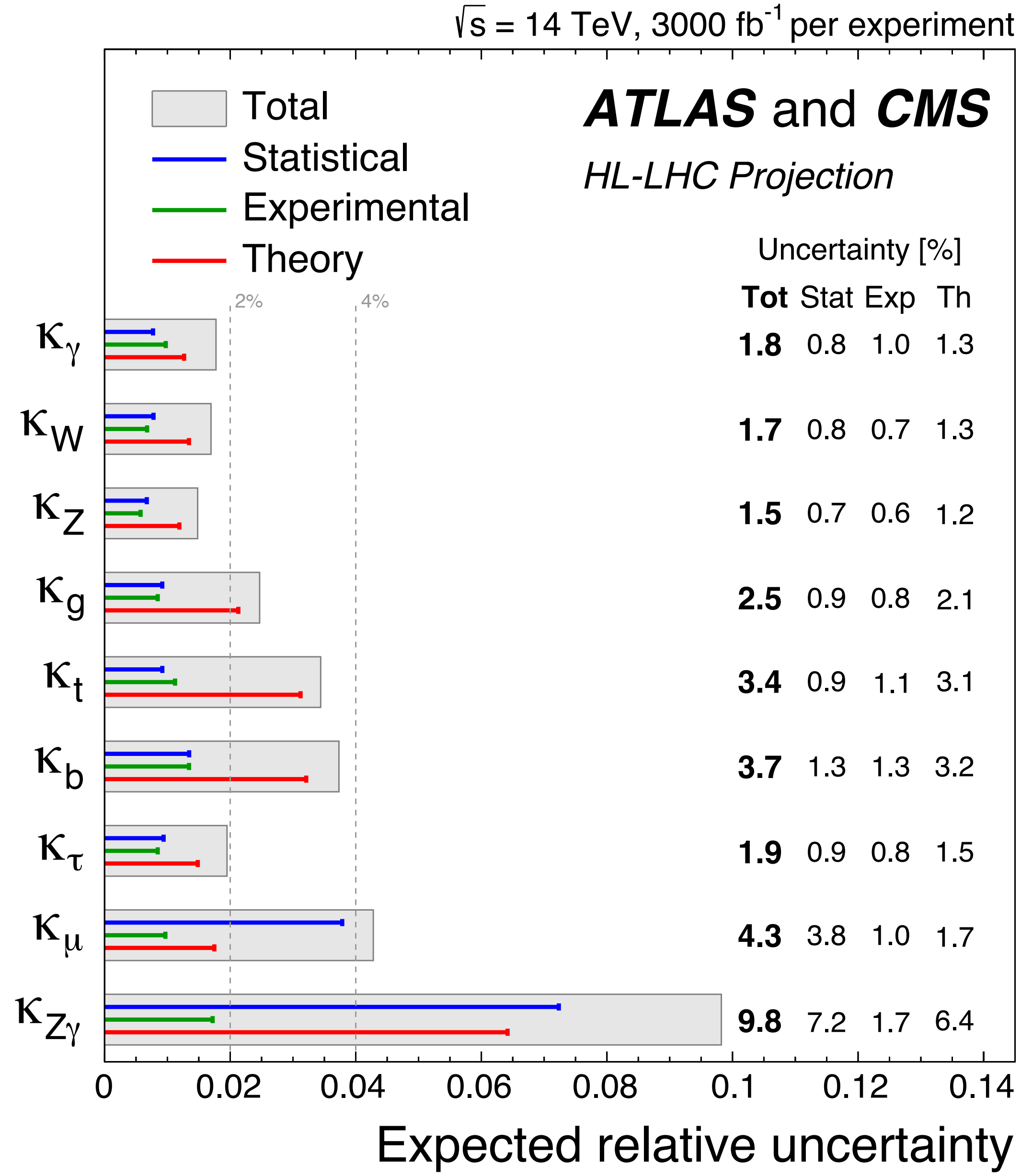
CP structure in ggH coupling



Conclusion and outlook

- Precision measurements of Higgs boson properties so far agree with SM, hints for new physics could be unravelled as data accumulates and analysis advance
  - Higgs boson mass reaching 0.1% precision
  - Significant progress in fiducial/differential and STXS measurements
  - Higgs boson coupling CP-structure studied in both Higgs-fermion and Higgs-boson couplings, no sign of CP-mixing so far
- The Discovery of the Higgs boson and the study of its properties have expanded our vision of particle physics
- Looking forward to LHC Run 3 and beyond

Projection for HL-LHC: arXiv:1902.00134



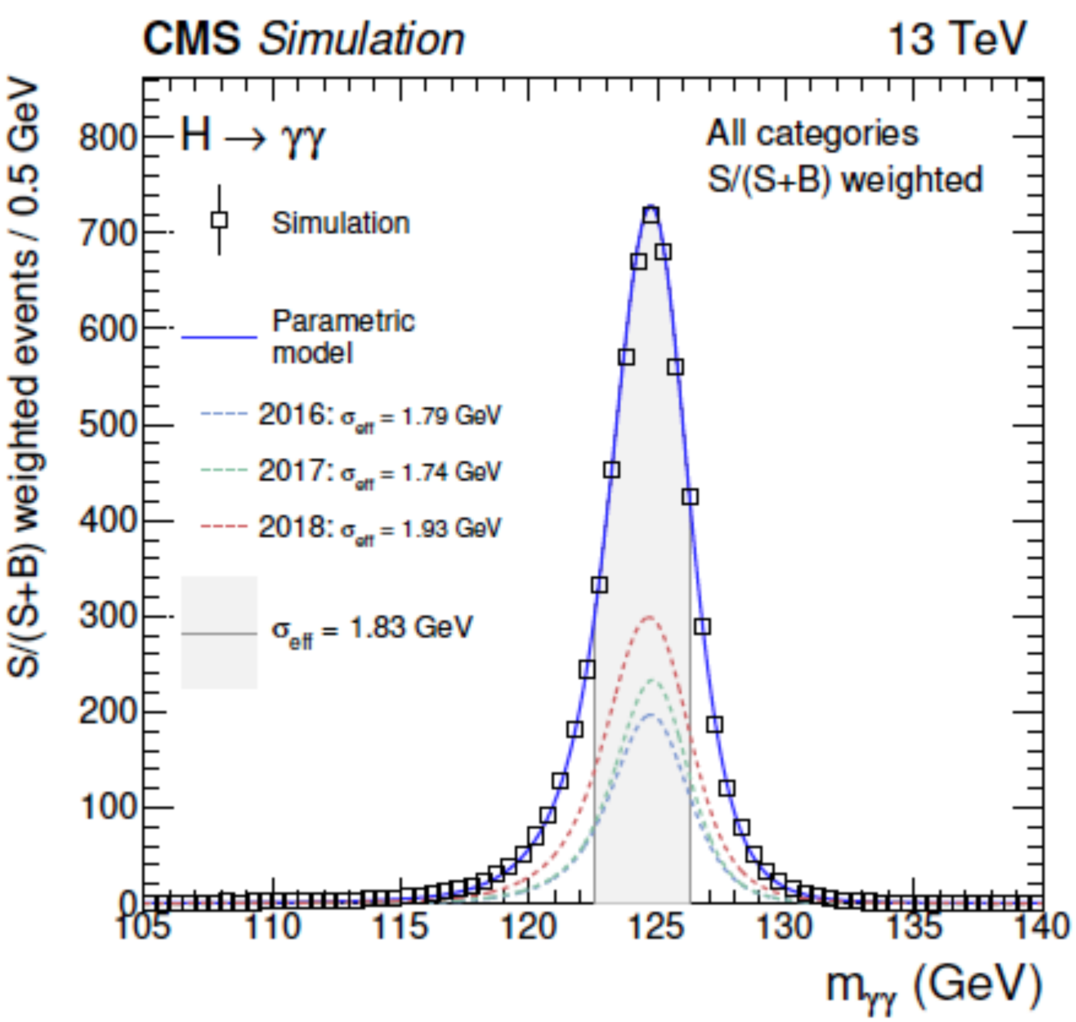
- **The expected LHC + HL LHC dataset is 20X the current dataset: percent precision of Higgs couplings**
- **Prospects for sub-percent precision at next generation colliders**

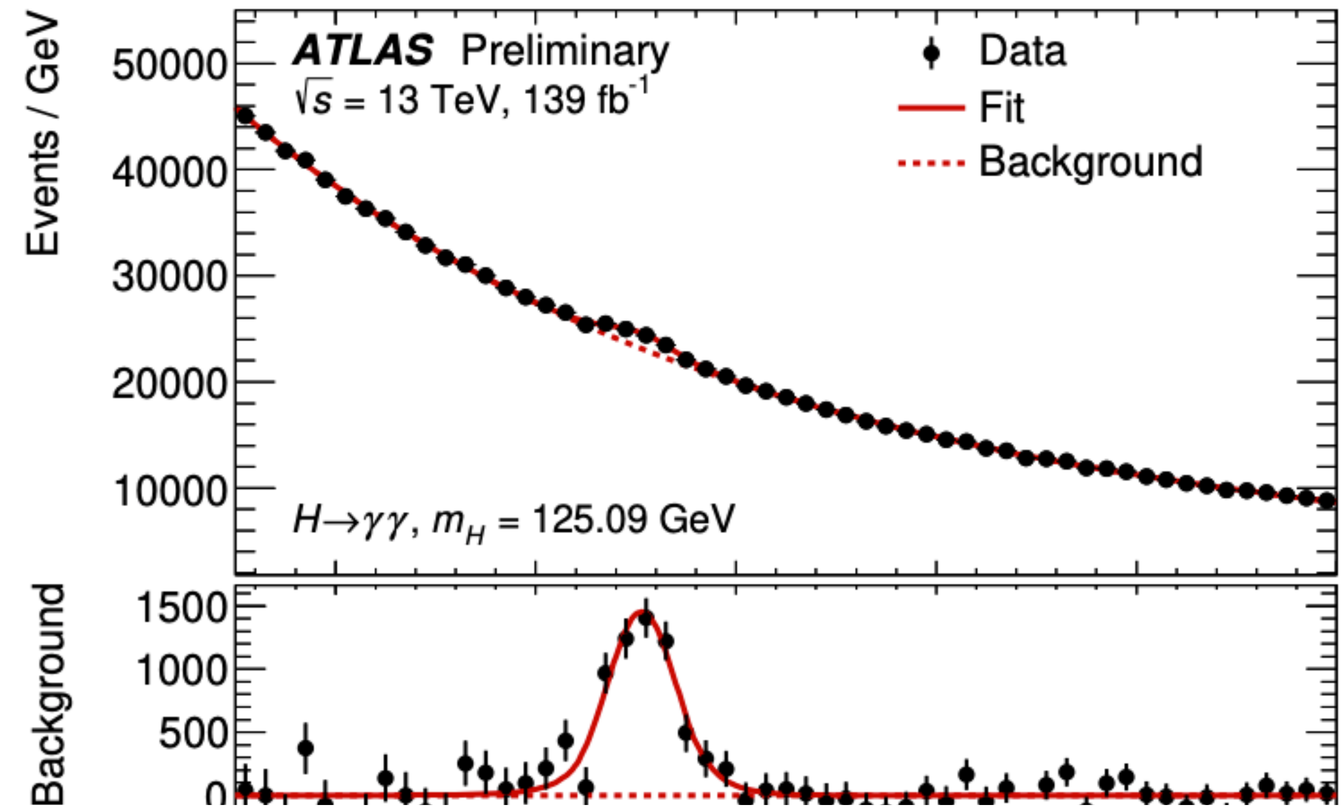
Apologies for all I could not cover

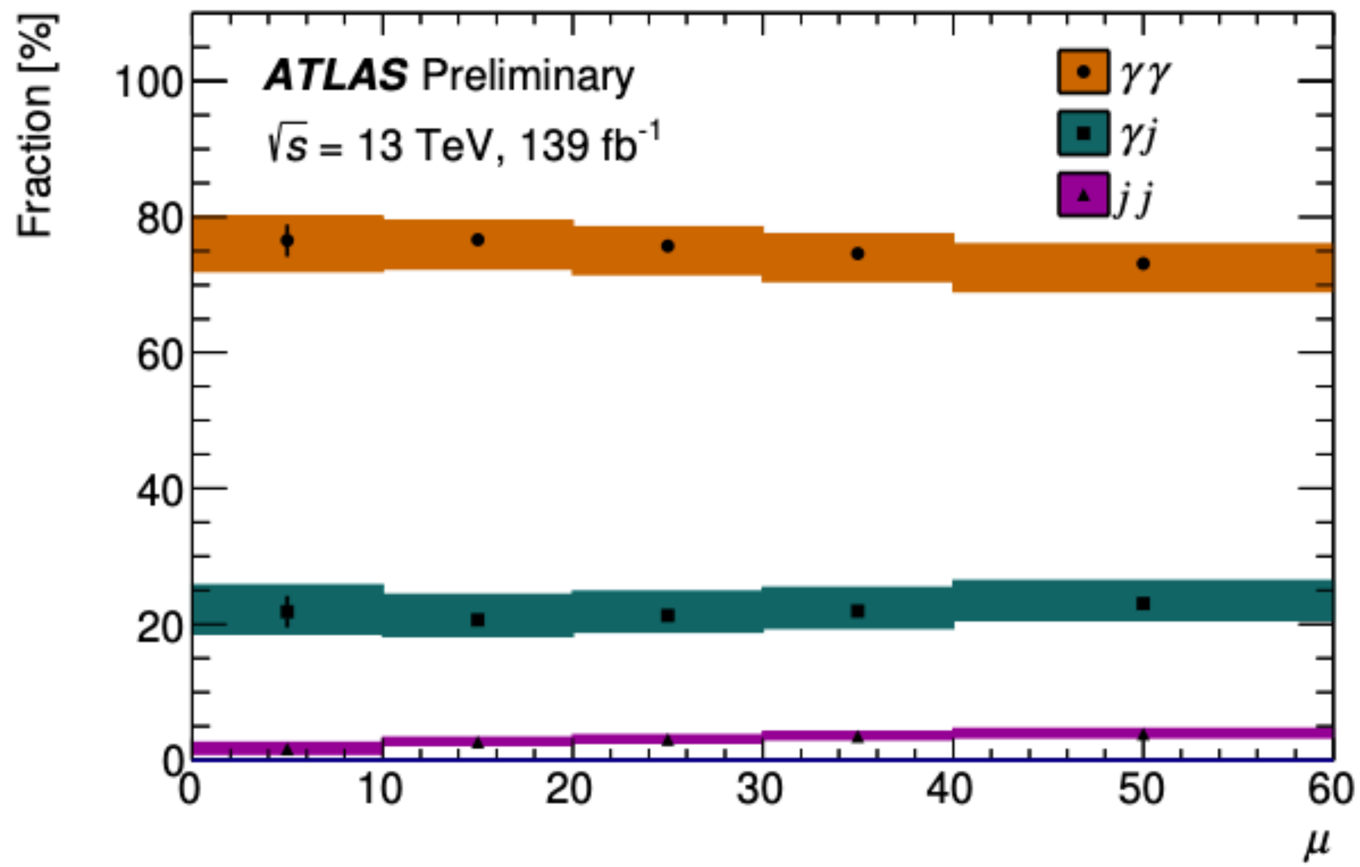
Thank you!

backup slides

H→$\gamma\gamma$



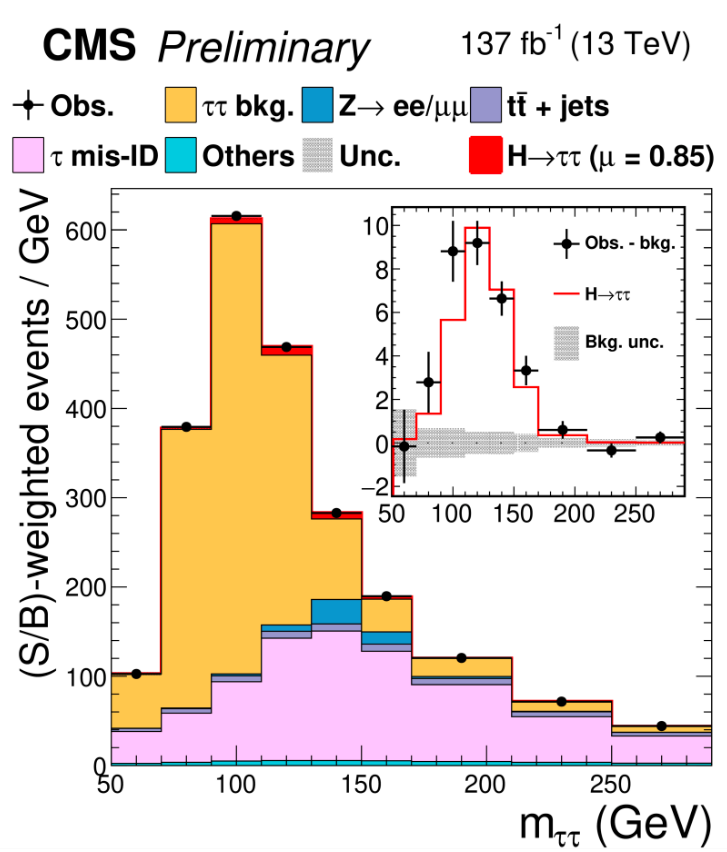




H→$\tau\tau$ channel STXS

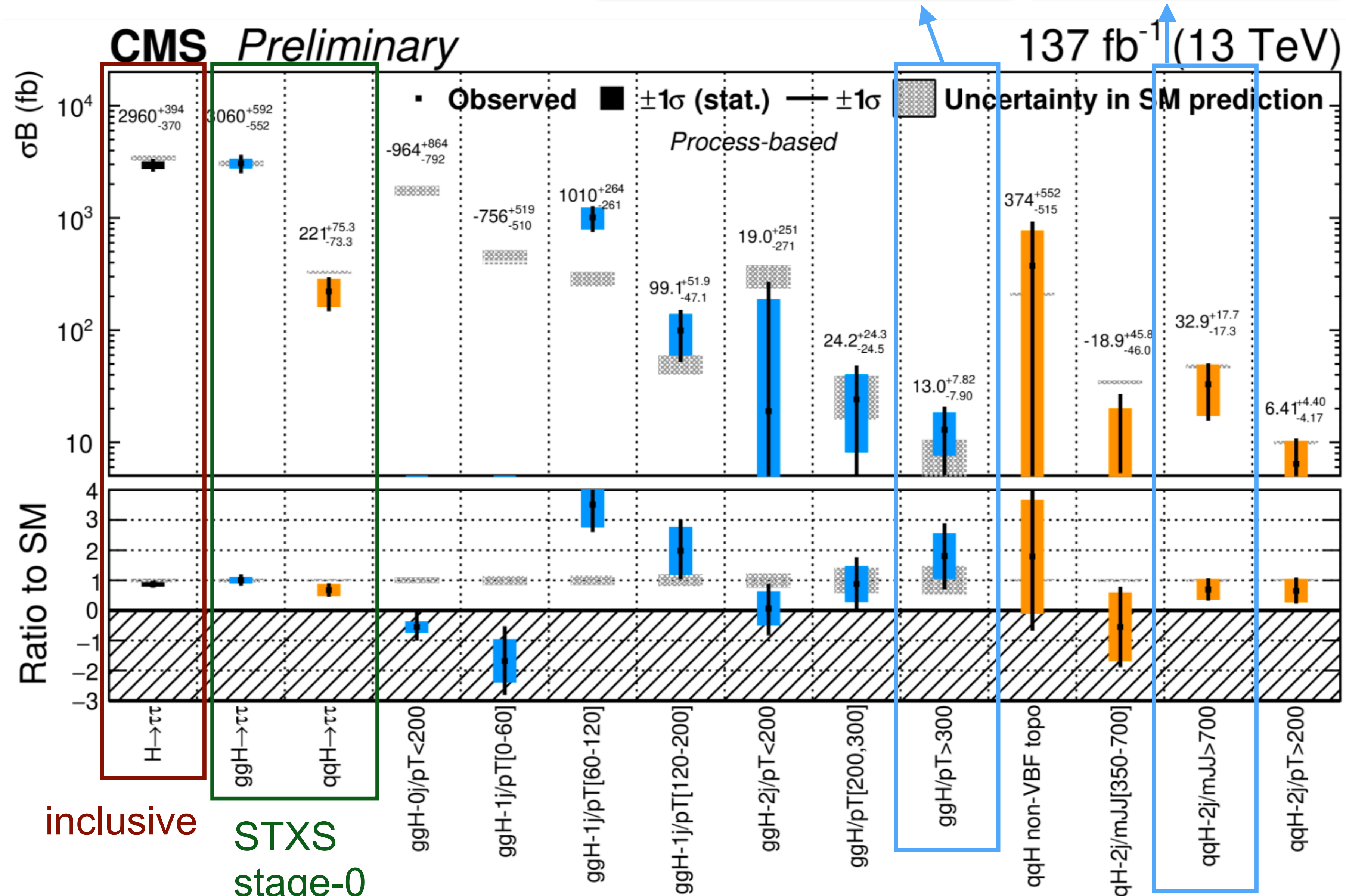
CMS-PAS-HIG-19-010
ATLAS-CONF-2021-044

- Probe Higgs coupling to third-generation fermions
- Sensitive to the gluon fusion process with relatively high Higgs boson p_T and sensitive to the VBF topology



ggH pT > 300 GeV

m_{jj} > 700 GeV



- Main backgrounds:

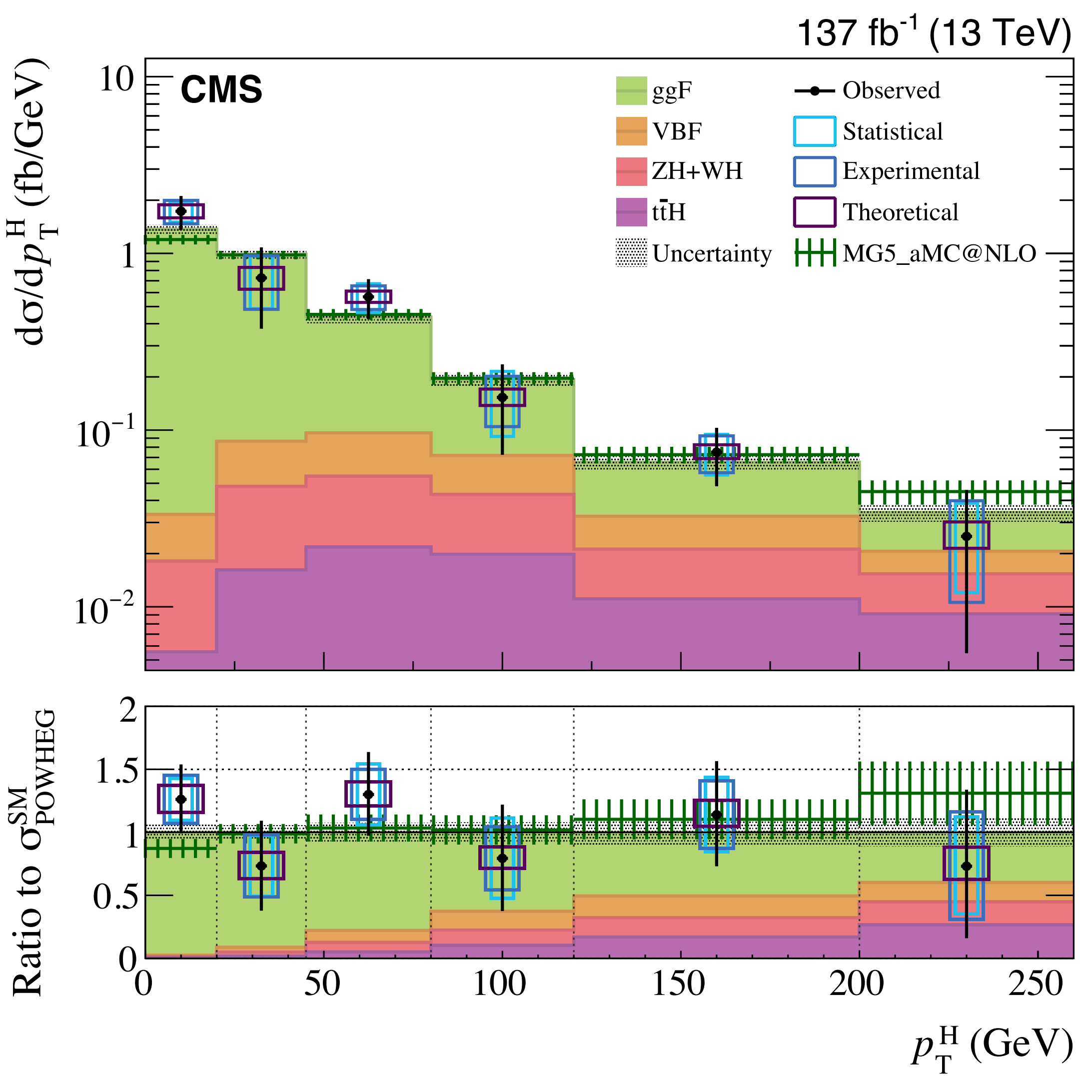
Z→$\tau\tau$, fake

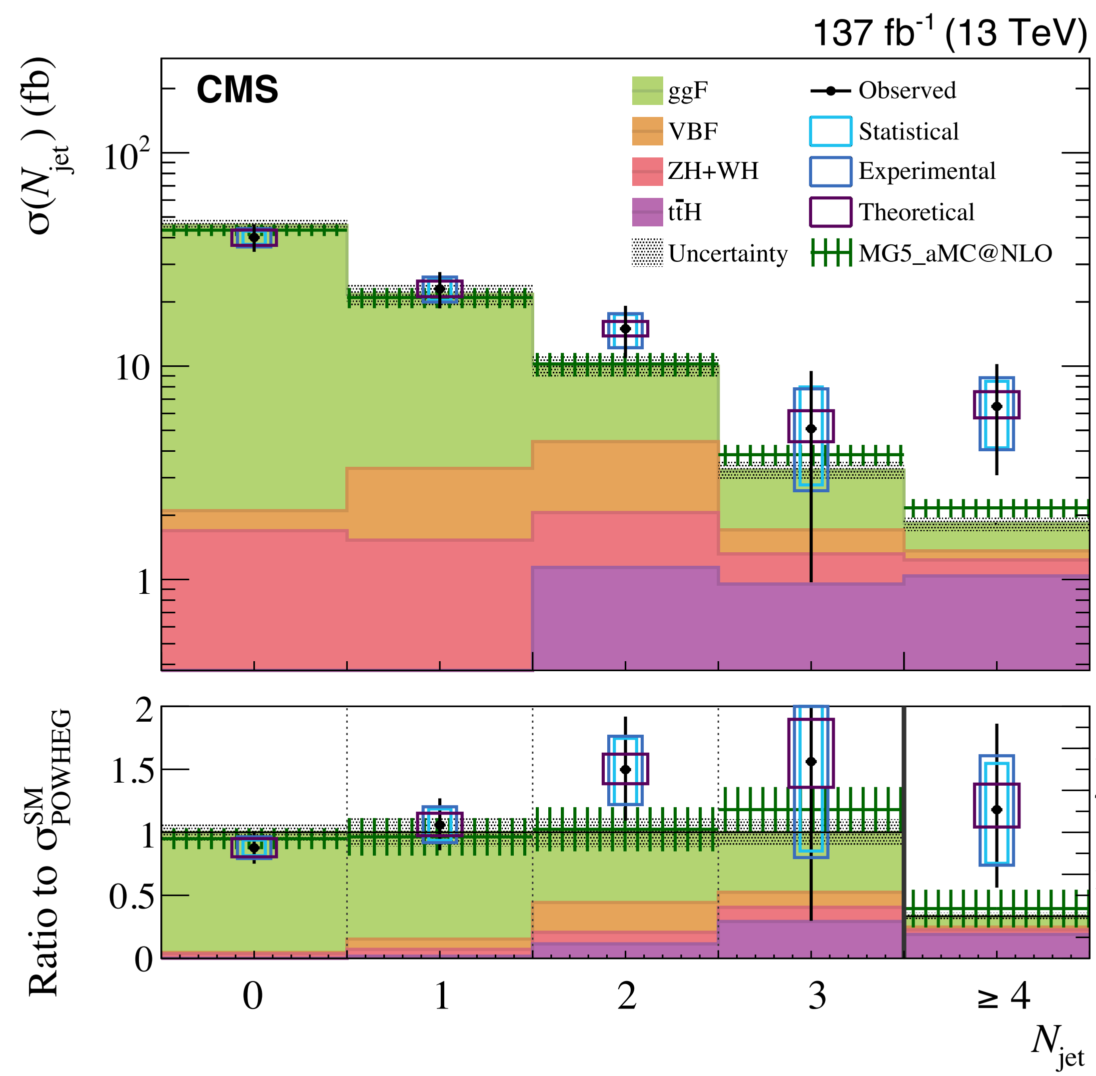
Higgs boson differential measurements

JHEP 03 (2021) 003

Measurements in WW→μeνν decay channel using full Run 2 data

- large branching ratio makes this channel competitive with H→γγ and H→ZZ*→4l channels

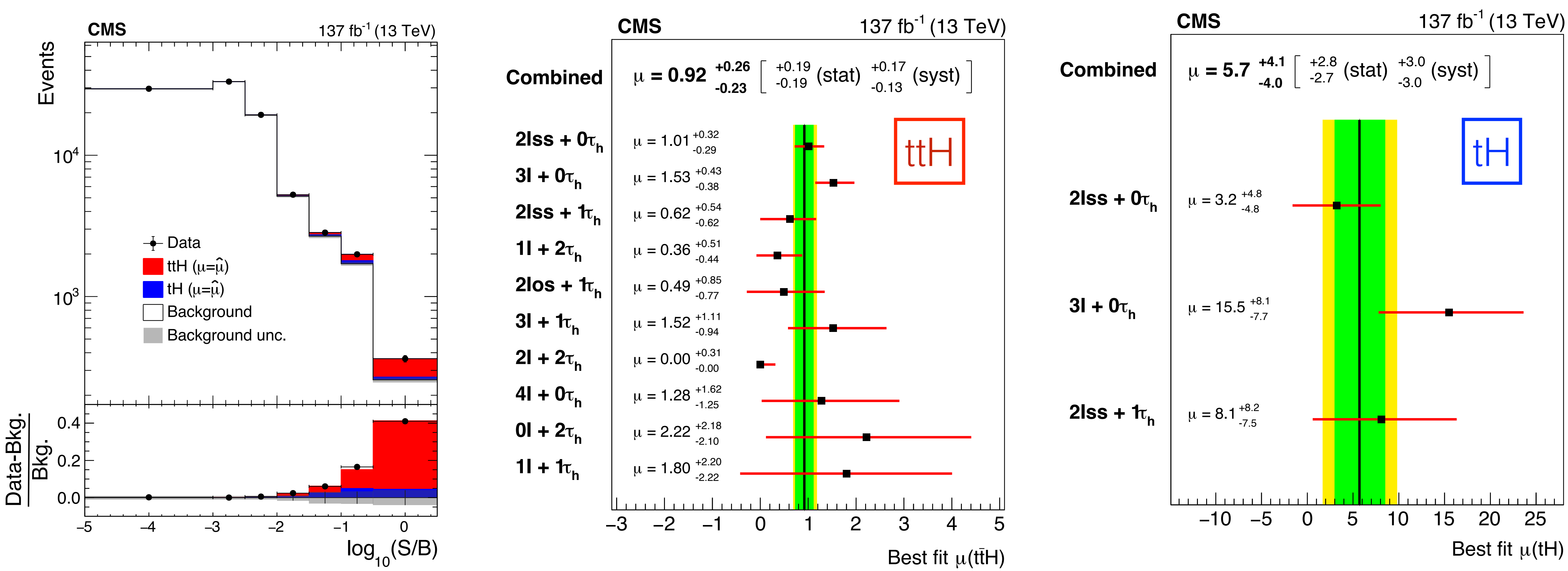




ttH and tH production: final state with electron, muon and hadronically decaying τ leptons

Eur. Phys. J. C 81 (2021) 378

- Target events in ttH and tH production modes (top quark decays either to lepton+jets or all-jet channels) and H→WW, H→ττ, or H→ZZ decays channels
- Significance ttH: 4.7(5.2)σ, tH: 1.4(0.3)σ obs(exp)
- Higgs coupling to top quark: $-0.9 < \kappa_t < -0.7$ or $0.7 < \kappa_t < 1.1$ @95% CL



ttH multilepton and STXS in ttH,H→bb

- ttH Significance: 1.3(3.0)σ, obs(exp) ATLAS-CONF-2020-058
- Simplified template cross section (STXS) measurements in five bins of pT(H), boosted selection targeting $p_T(H) > 300$ GeV