Higgs measurements at CMS

Highlights and prospects

KRUGER 2022
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On behalf of the CMS collaboration

KRUGER2022, Mpumalanga
South Africa
5-11 December 2022

HIGGS MEASUREMENTS @CMS

- The knowledge produced on the SM Higgs sector every year is remarkable showing it an extremely active and interesting topic
  - **More than a dozen public results on measurements in 2022!**
- This talk includes **only a selection of highlights**
- Full list of results available in the experiments dedicated webpages (CMS)

HIGGS MEASUREMENTS @CMS

- Higgs measurements are typically of two types
  - **Property measurement** (quantum numbers using dedicated analysis)
    - input to the theoretical model
  - **Coupling measurements** (number of events in various topology and phase space)
    - compared to model expectation

HIGGS PROPERTIES

What we know so far

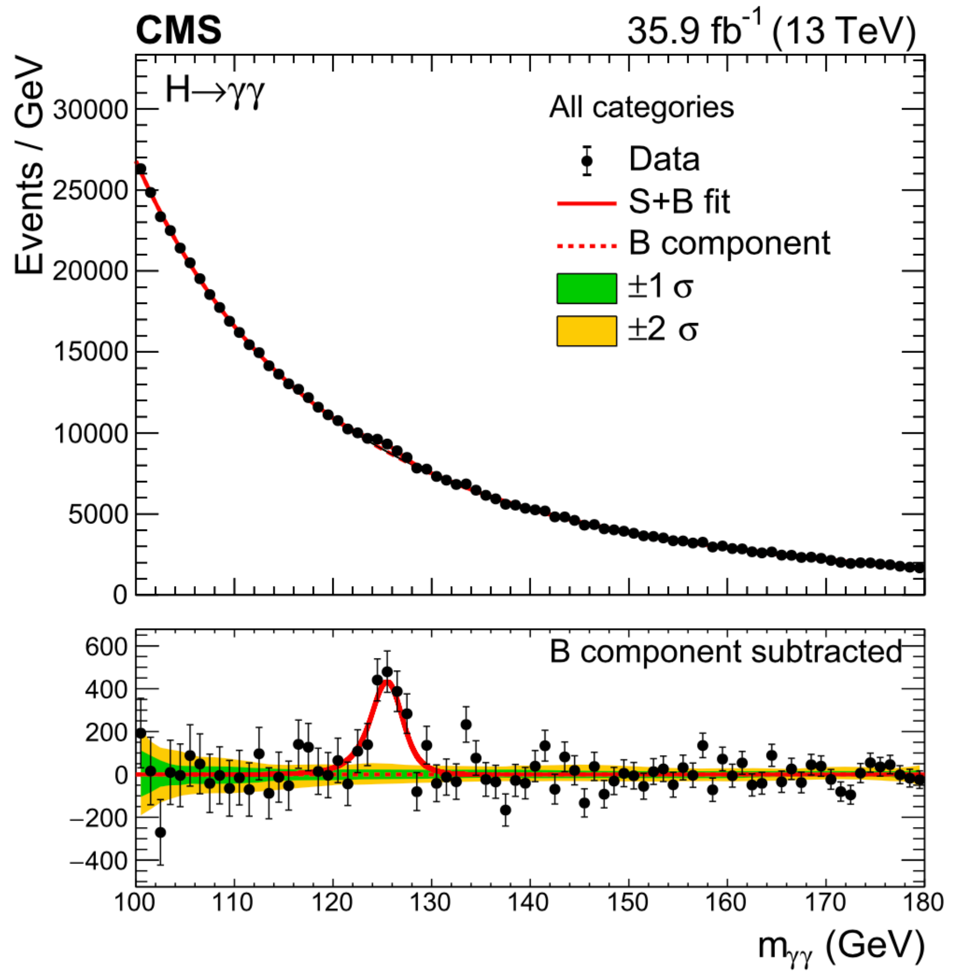
H^0

$J = 0$

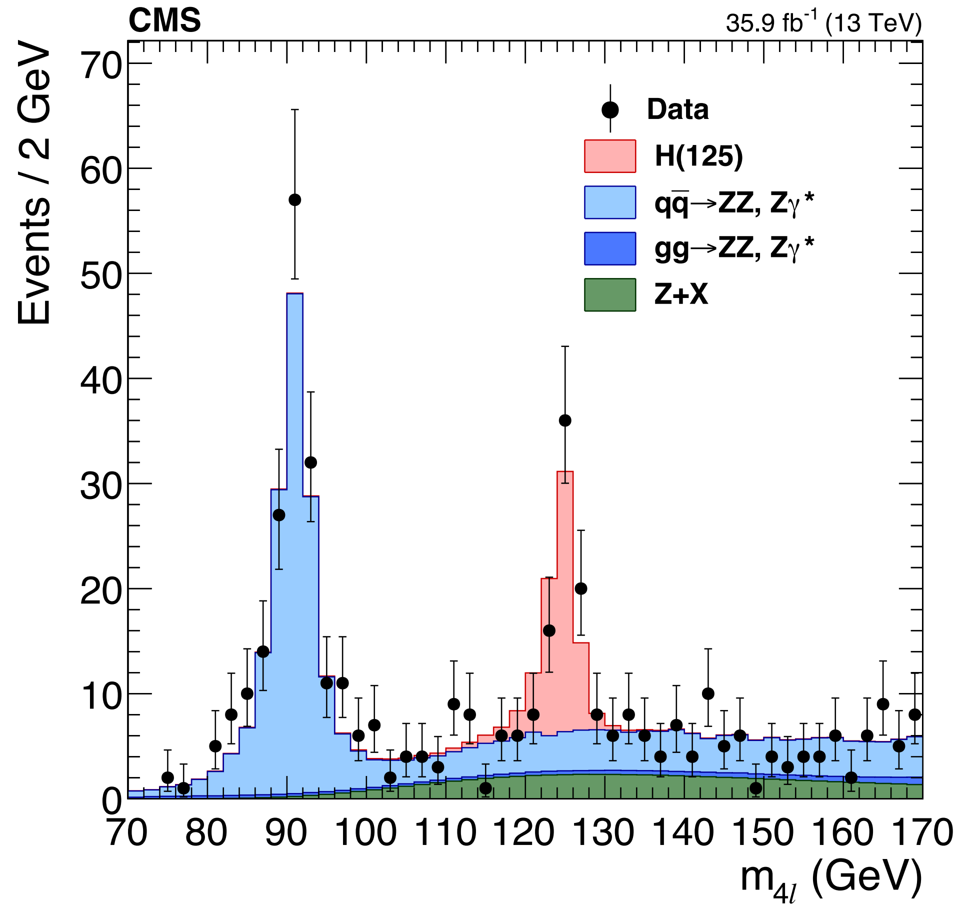
Mass $m = 125.10 \pm 0.14$ GeV
Full width $\Gamma < 0.013$ GeV, CL = 95% (assumes equal on-shell and off-shell effective couplings)

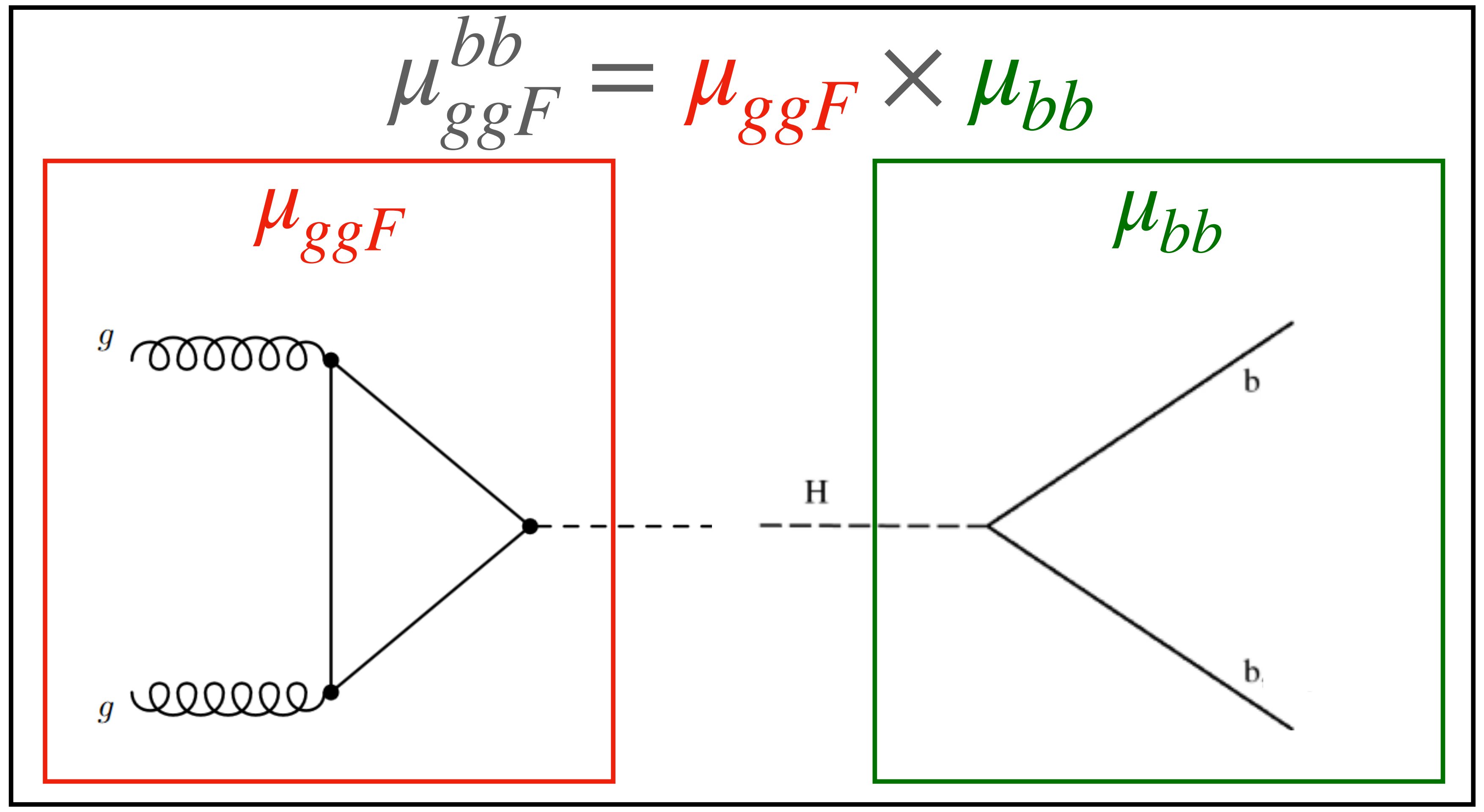
- Charge: Neutral
  - Evident from decay products ($\gamma\gamma$)
- Mass: 125.38 ± 0.14 GeV (CMS only)
  - Measured directly with high resolution channels H→ $\gamma\gamma$, H→ ZZ→ 4l
- Spin and parity: 0^+
  - sensitive variables distributions are compared to different models

Phys. Lett. B 805, 135425 (2020)



J. High Energy Phys. 11 (2017) 047

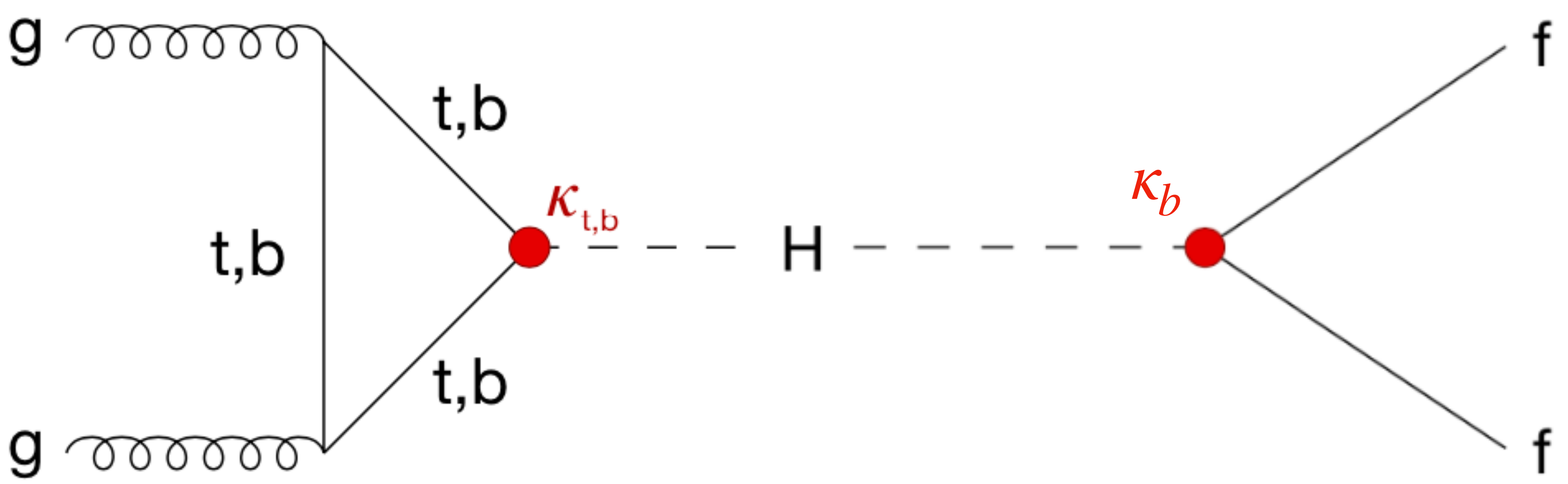




HIGGS COUPLINGS

A reminder

- **Signal strength** μ
  - measure events yield for different production and decay modes
  - can be exclusive for production (decay) modes when the decay (production) is fixed to SM expectation
  - $\mu_i = \dfrac{\sigma_i}{(\sigma_i)_{SM}}$ and $\mu_f = \dfrac{BR_f}{(BR_f)_{SM}}$



$$\sigma_{ggF} = (1.06\kappa_t^2 + 0.01k_b^2 - 0.07\kappa_b\kappa_t)\, \sigma_{ggF}(SM) \qquad \Gamma_{bb} = \kappa_b^2\, \Gamma_{bb}(SM)$$

- **Kappa framework** - coupling modifier κ
  - attempt to be closer to model parameters
  - kappas correspond to tree-level couplings to different particles
  - $\kappa_i^2 = \dfrac{\sigma_i}{\sigma_i^{SM}}$, $\kappa_f^2 = \dfrac{\Gamma_i}{\Gamma_i^{SM}}$, $\kappa_H^2 = \dfrac{\sum \Gamma_f}{\sum \Gamma_f^{SM}}$, so that

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

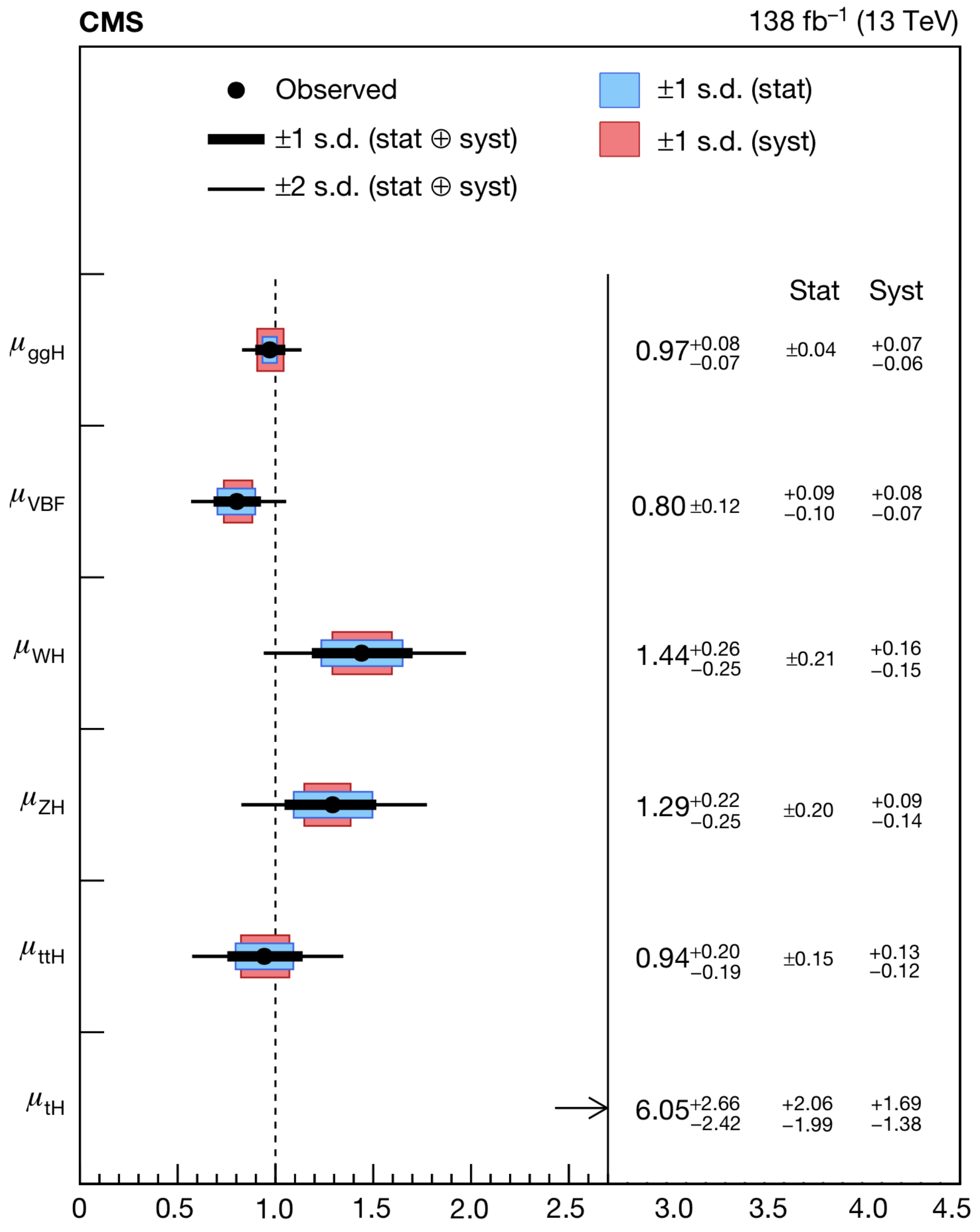
HIGGS COUPLINGS

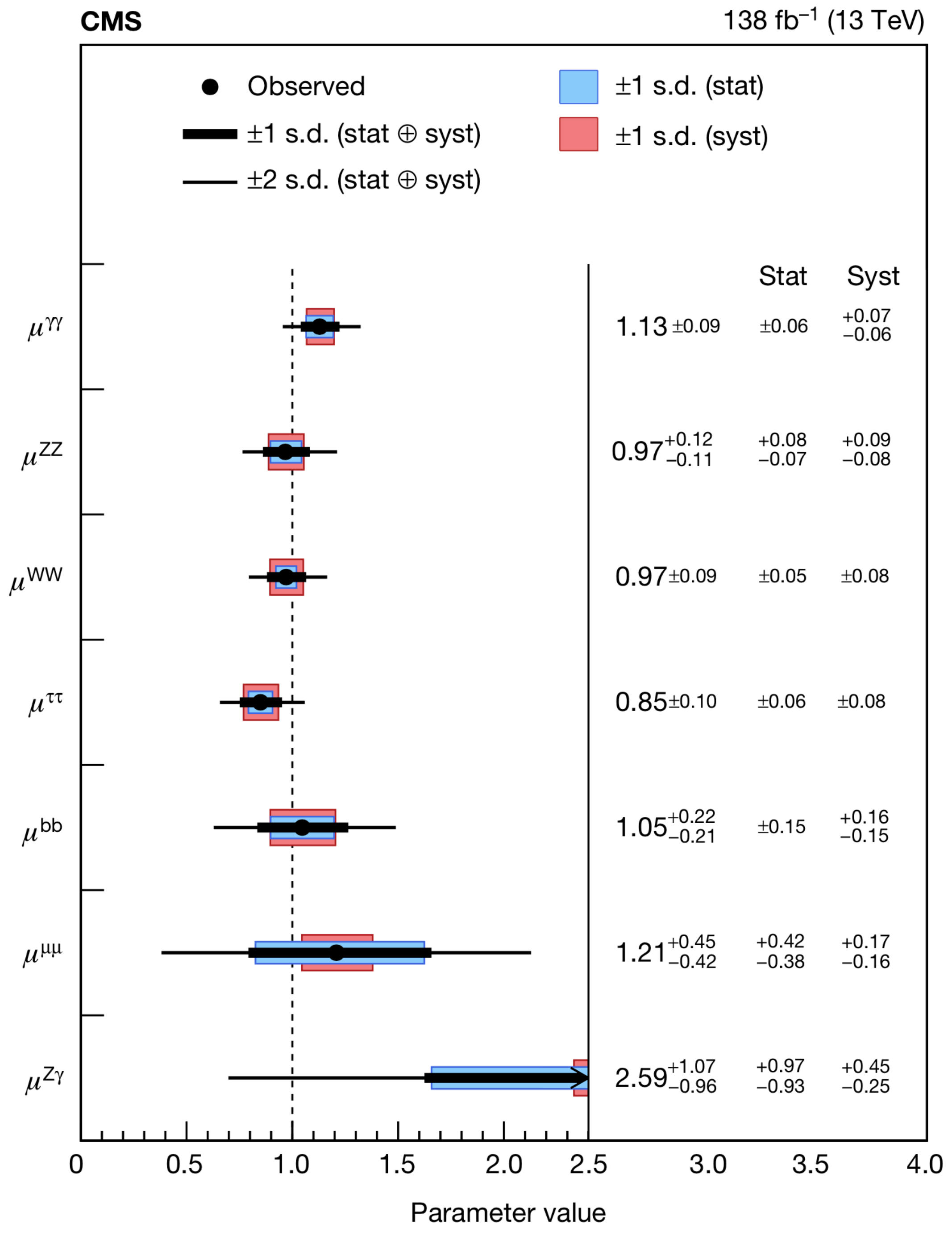
What we know so far

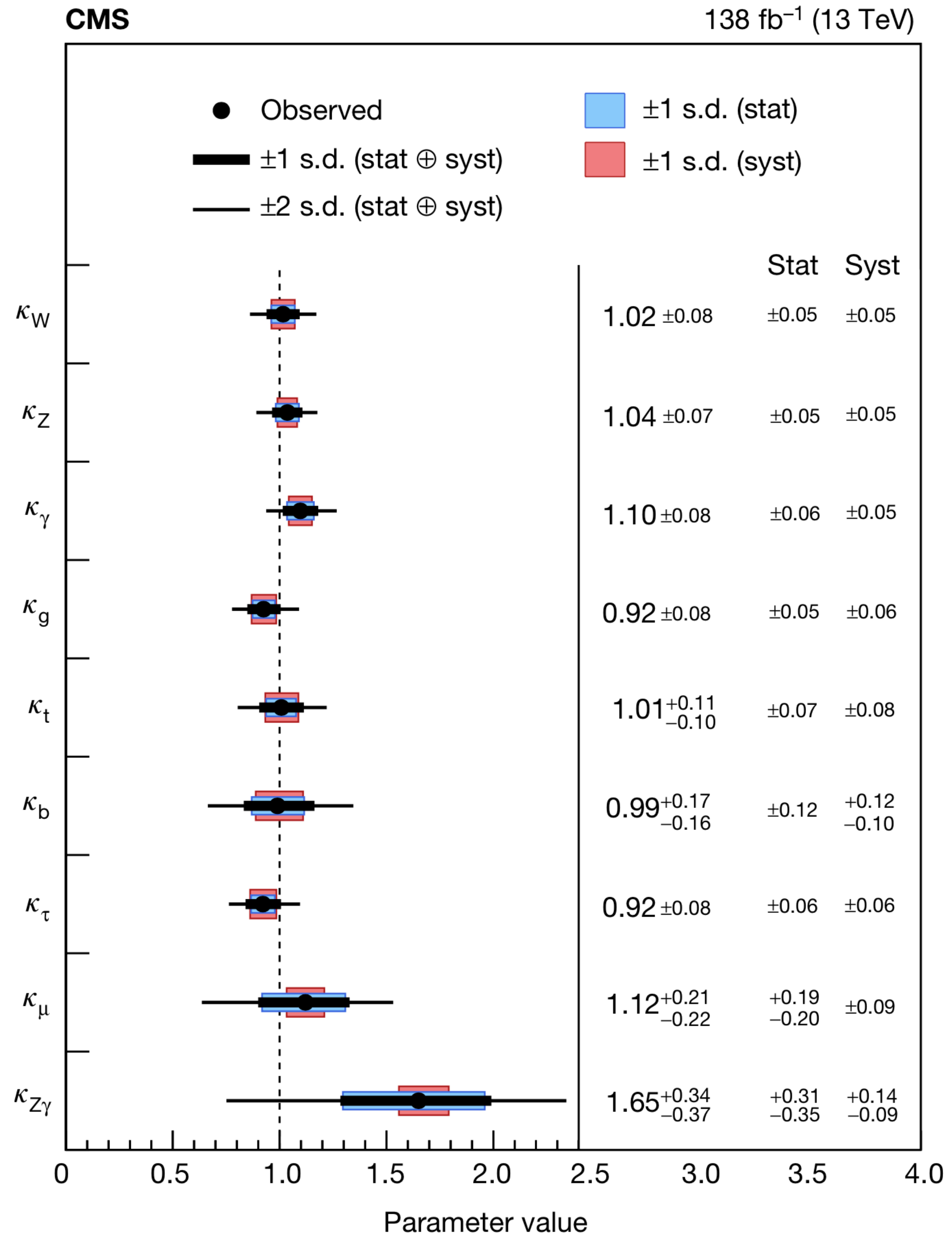
- Signal strengths compatible with SM expectations
- Observation of ggH, VBF, WH, ZH, ttH each > 5σ
- κ_V , κ_F = 0 excluded at > 5σ (only 3rd generation)
    - two different coupling structure (gauge, Yukawa)
- This paper doesn't include latest results on Hcc

Nature 607, p60–68 (2022)

Nature 607, p60–68 (2022)







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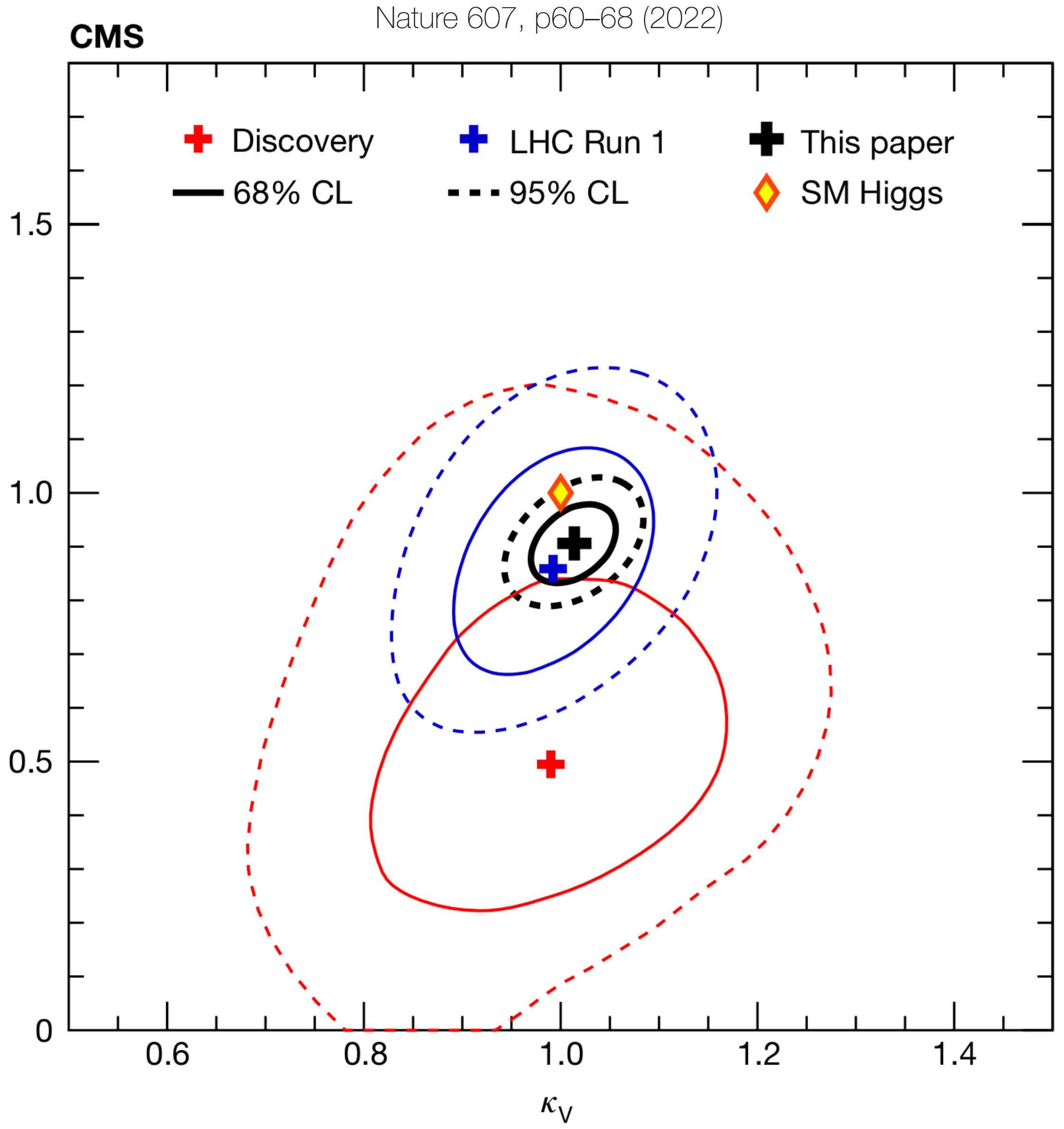
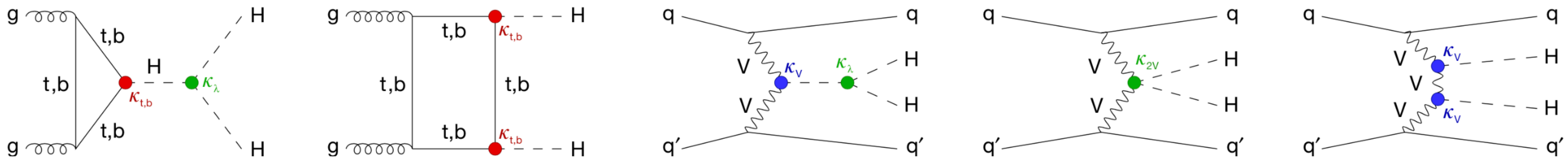
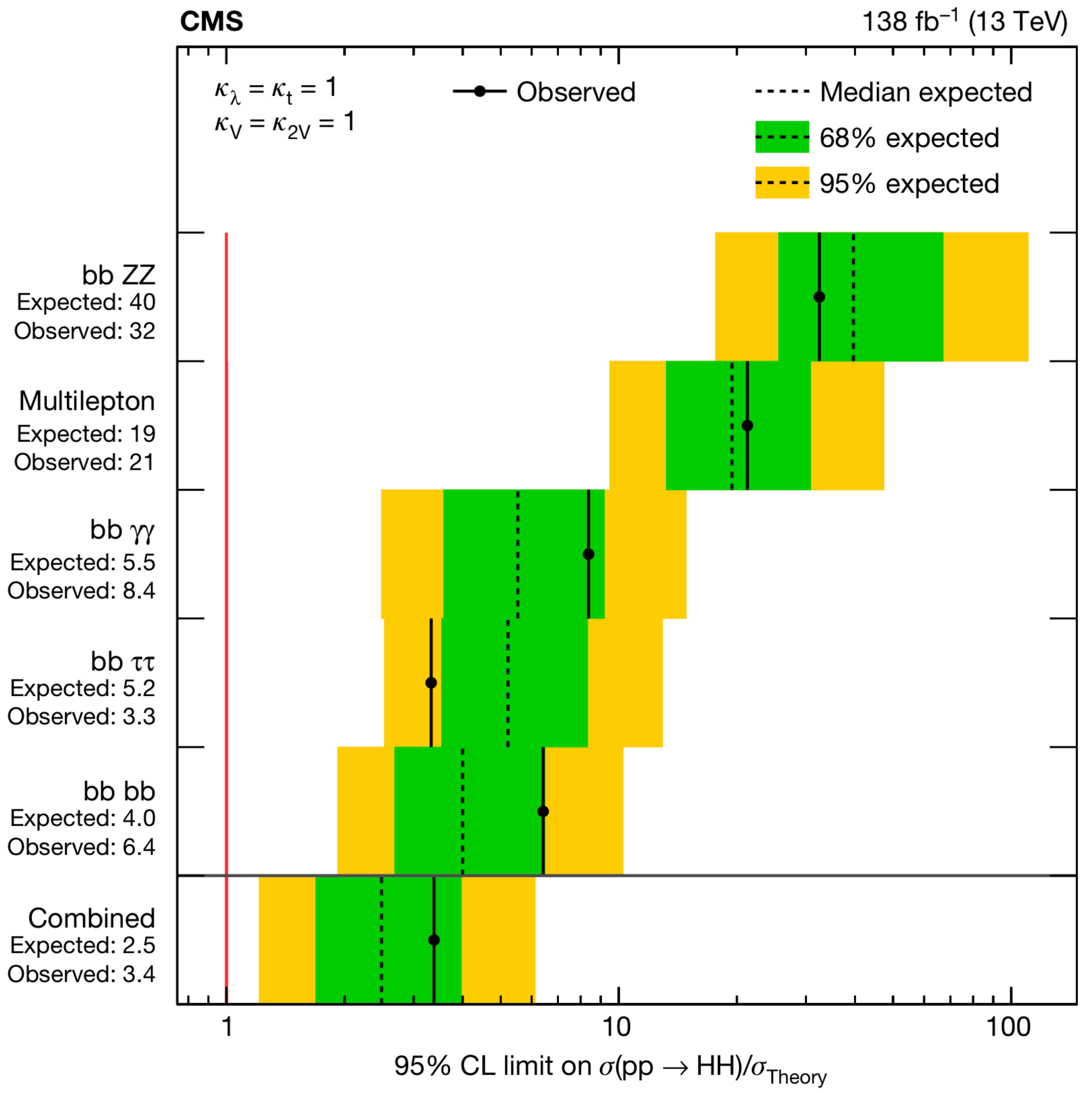


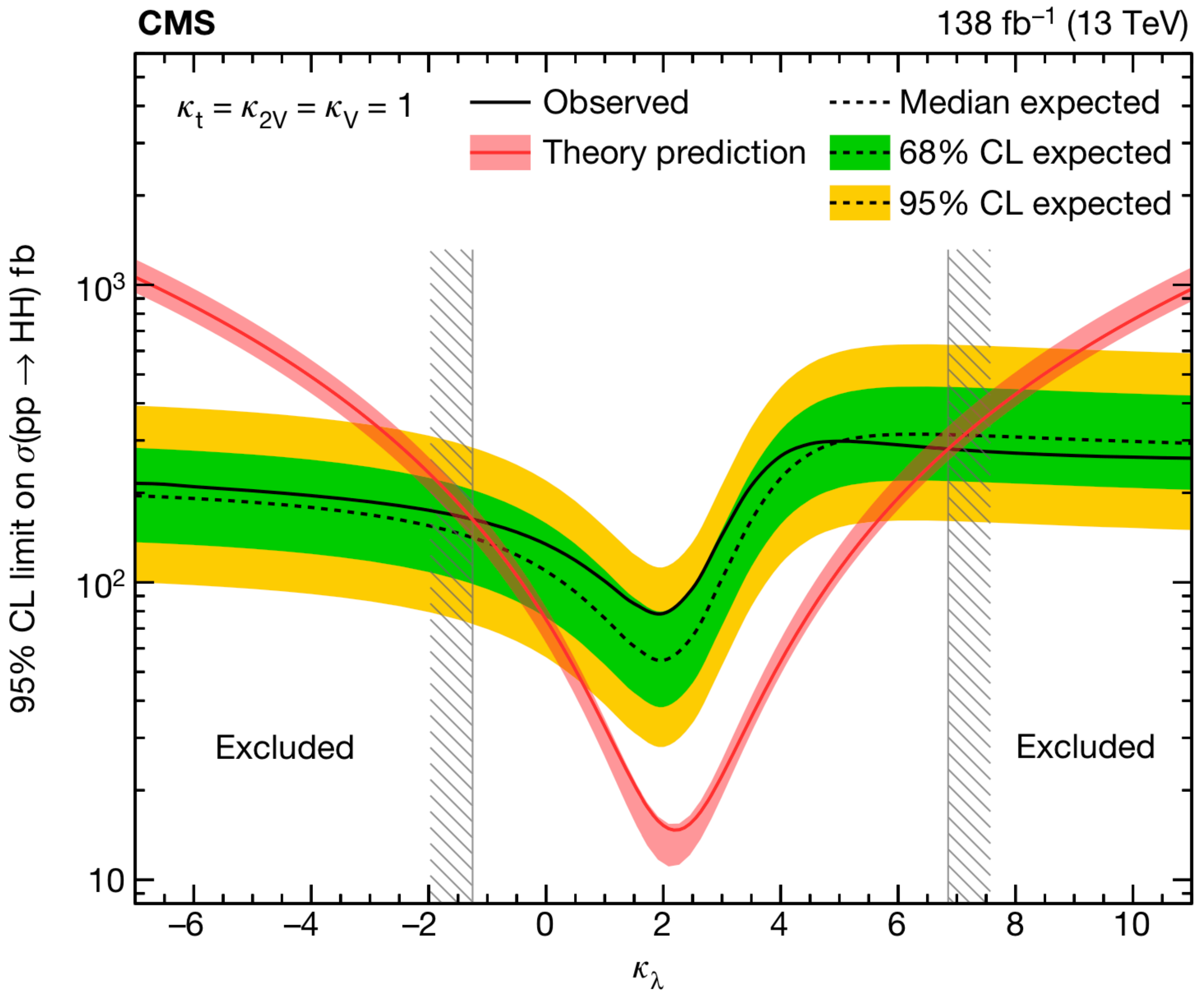
HIGGS SELF-COUPLINGS

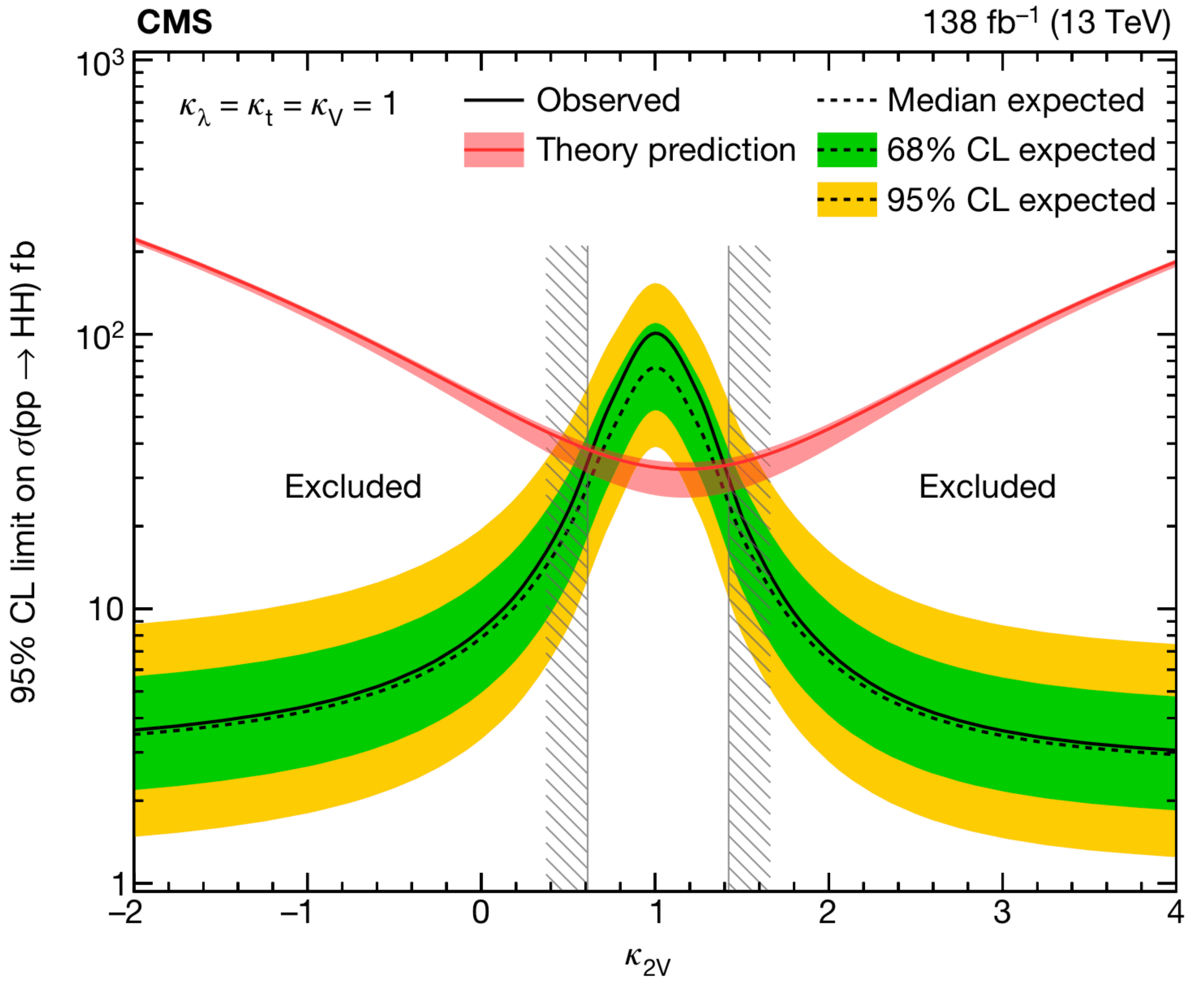
What we know so far





- Combining all channels the cross section of HH is < 3.4 x SM
- Limits on $\kappa_{\lambda,2V}$ show strong dependence on assumed value of $\kappa_{\lambda,2V}$
  - $-1.24 < \kappa_\lambda < 6.49$
  - $0.67 < \kappa_{2V} < 1.38$
  - $k_{2V} = 0$ excluded with 6.6 σ
  - we know there is a quartic HHVV coupling!





Nature 607, p60–68 (2022)

Highlights

…what came after the previous combination…

$$\mathcal{T}_{\mathrm{C}}^{\max} = \max_{j} \left(\frac{\sqrt{E_j^2 - p_{z,j}^2}}{2\cosh\left(y_j - y_{\mathrm{H}}\right)} \right),$$

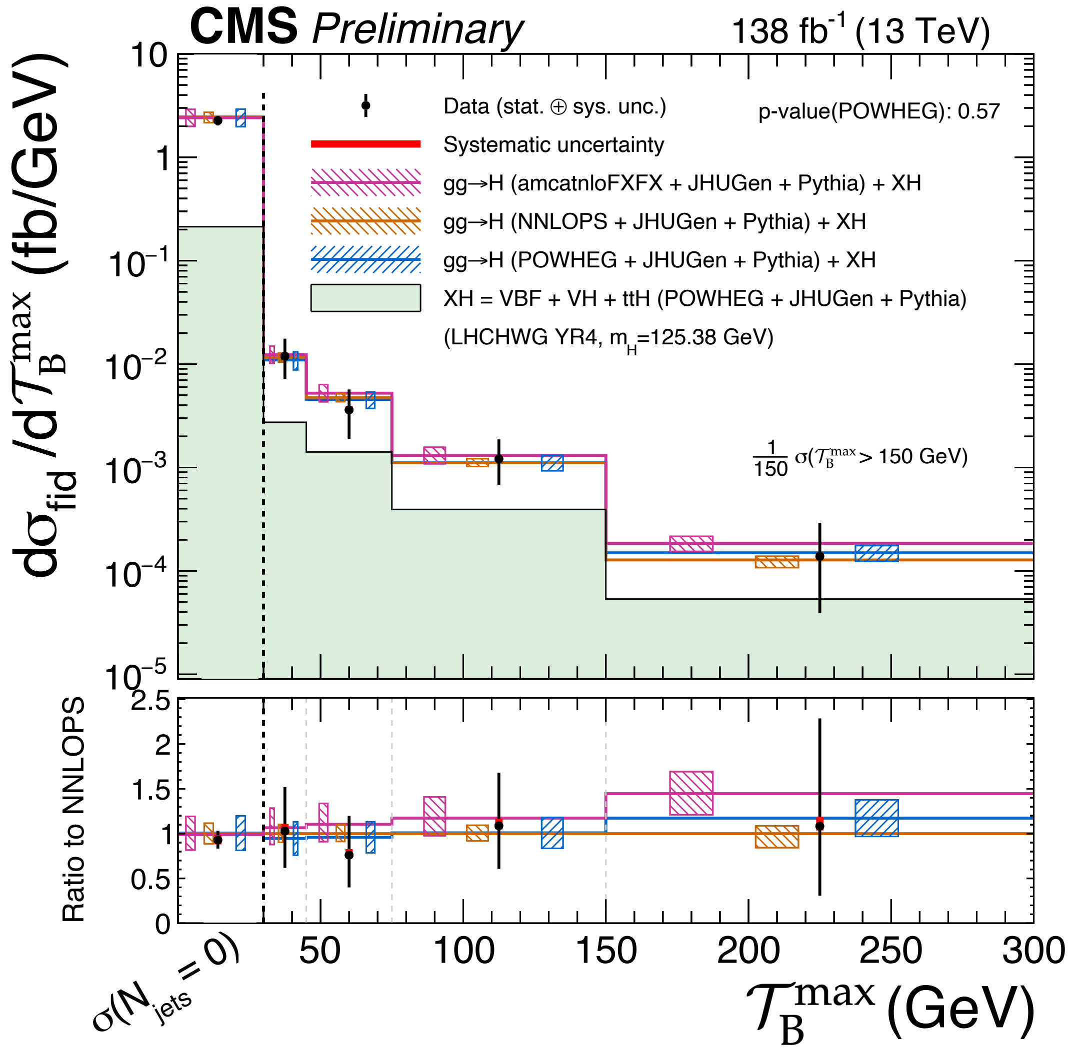
$$\mathcal{T}_{\mathrm{B}}^{\max} = \max_{j} \left(m_{\mathrm{T}}^{j} e^{-|y_j - y_{\mathrm{H}}|} \right),$$

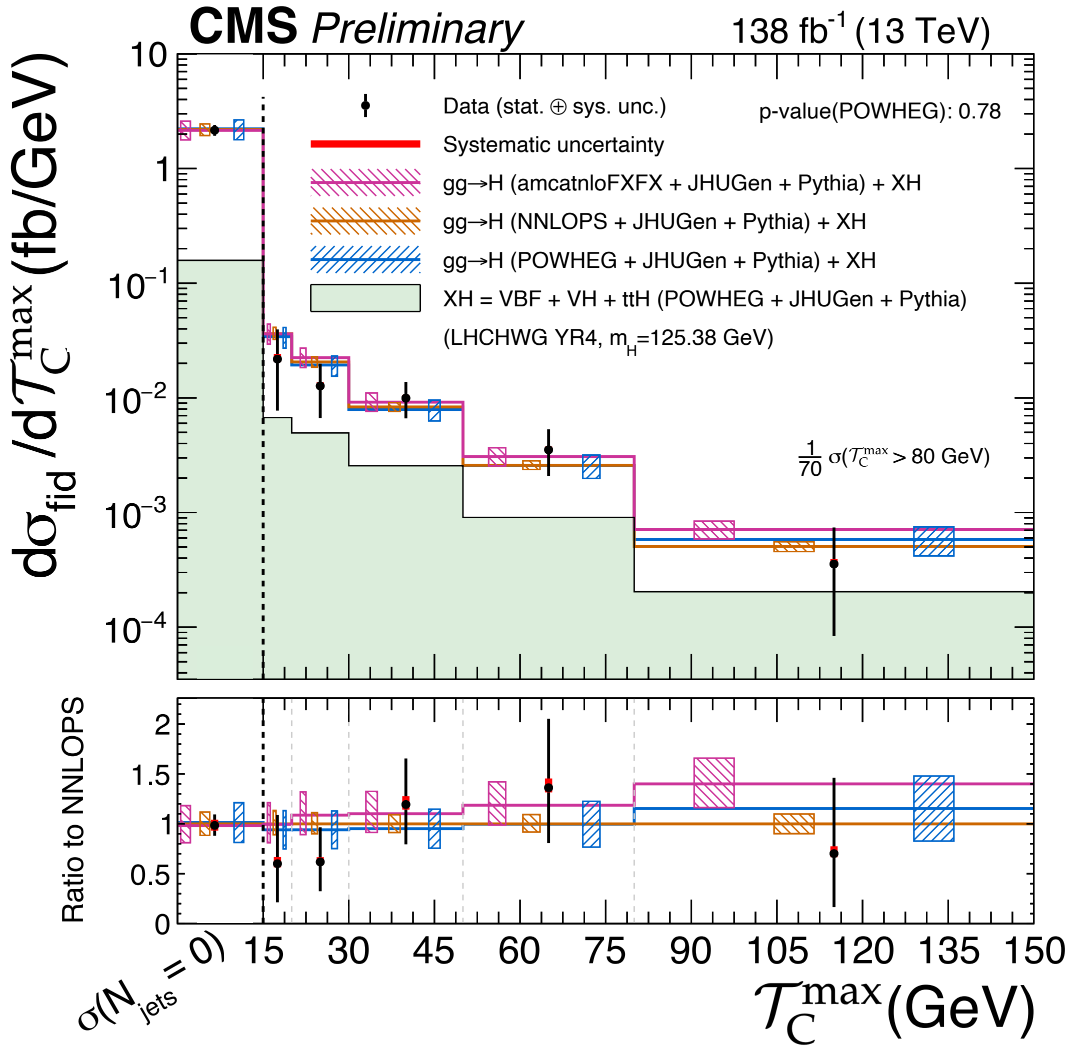
H→ ZZ→ 4l

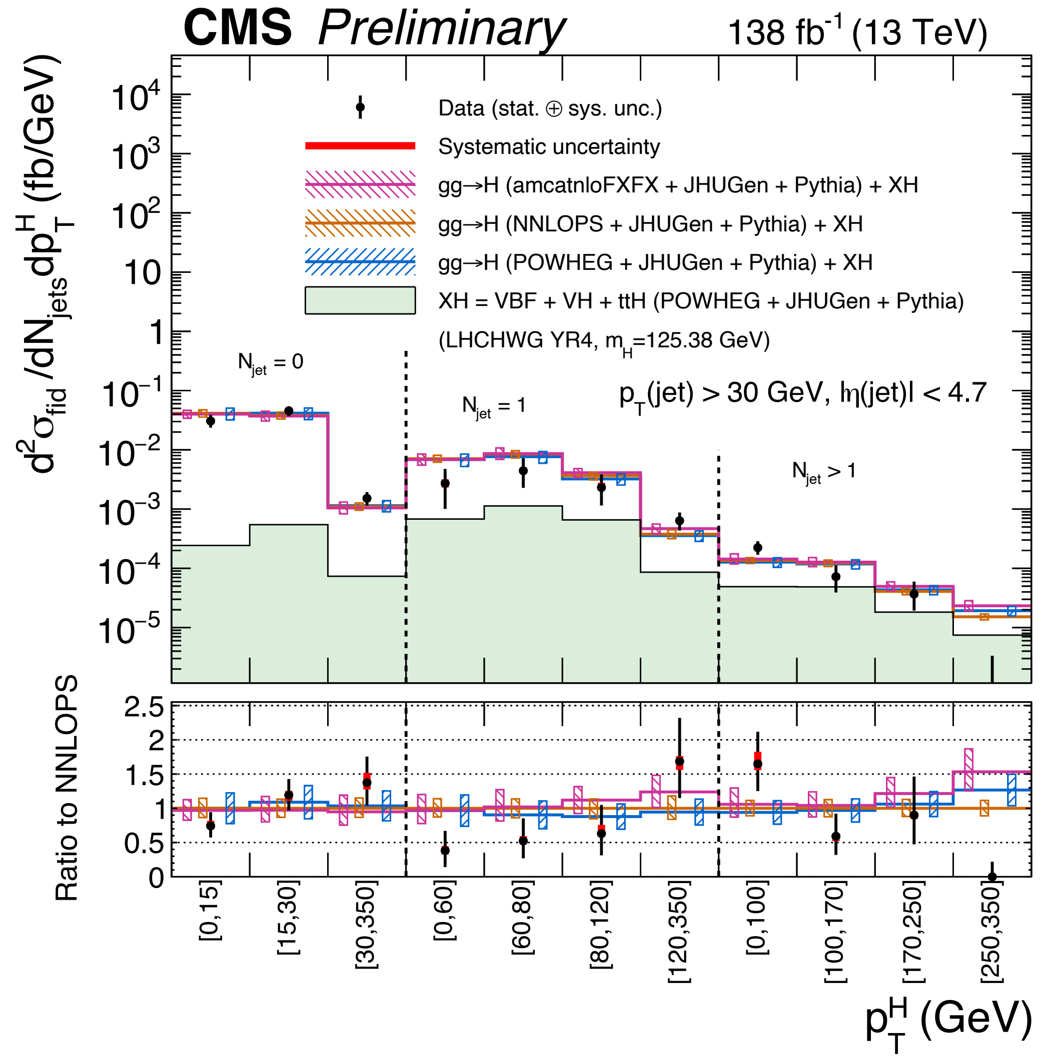
Differential cross sections

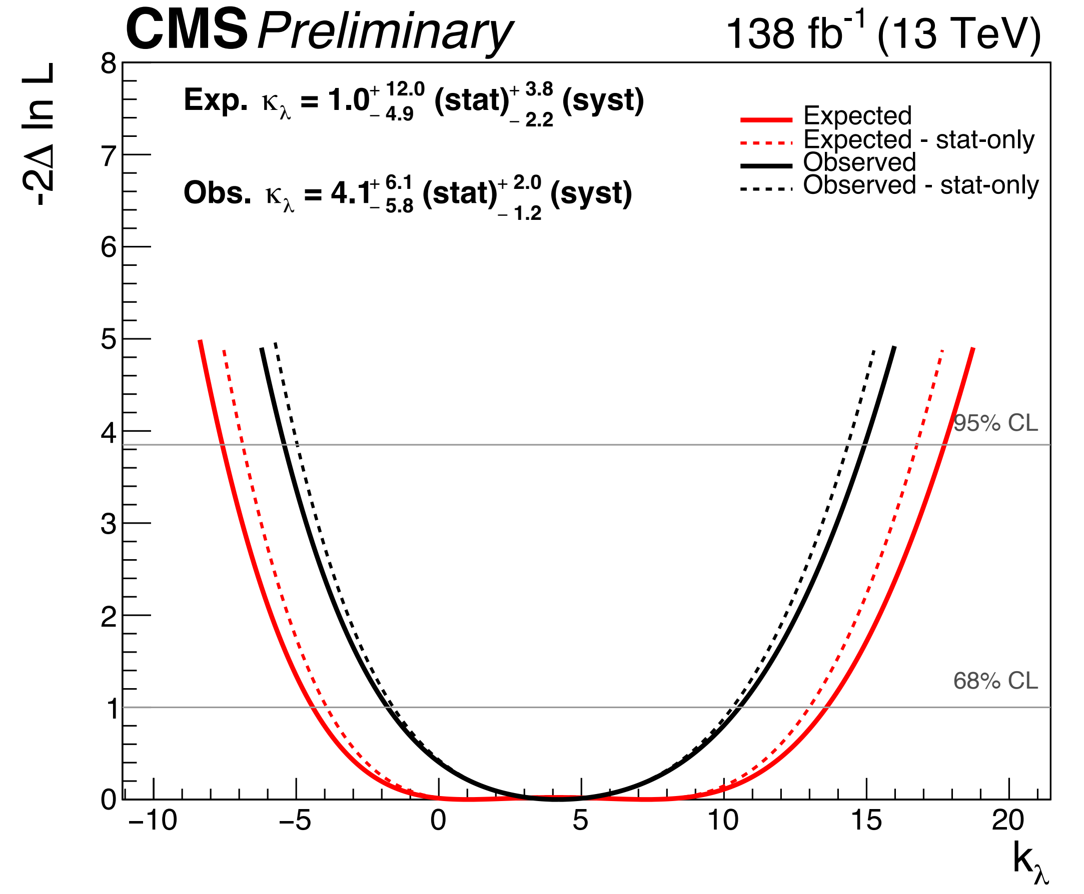
HIG-21-009

- This analysis feature improved reconstruction algorithms and 40% reduced systematics compared to its precedent
- Fiducial cross sections are measured in bins of the seven kinematic observables that define the four-lepton decay
- As a novelty, cross section measurements are done as a function of jet weighed veto variables $\mathcal{T}_{\mathrm{B}}^{\max}$ and $\mathcal{T}_{\mathrm{C}}^{\max}$, providing sensitivity to dynamical evolution of QCD scales and resummation effects
- The measurement of fiducial cross section in differential bins of the H pT is used to set constraints on κ_λ , κ_b and κ_c competitive with direct limits
  - -5.5 (-7.7) < κ_λ < 15.1 (17.9)
  - -1.1 (-1.3) < κ_b < 1.1 (1.2)
  - -5.3 (-5.7) < κ_c < 5.2 (5.7)









H→ ZZ→ 4l

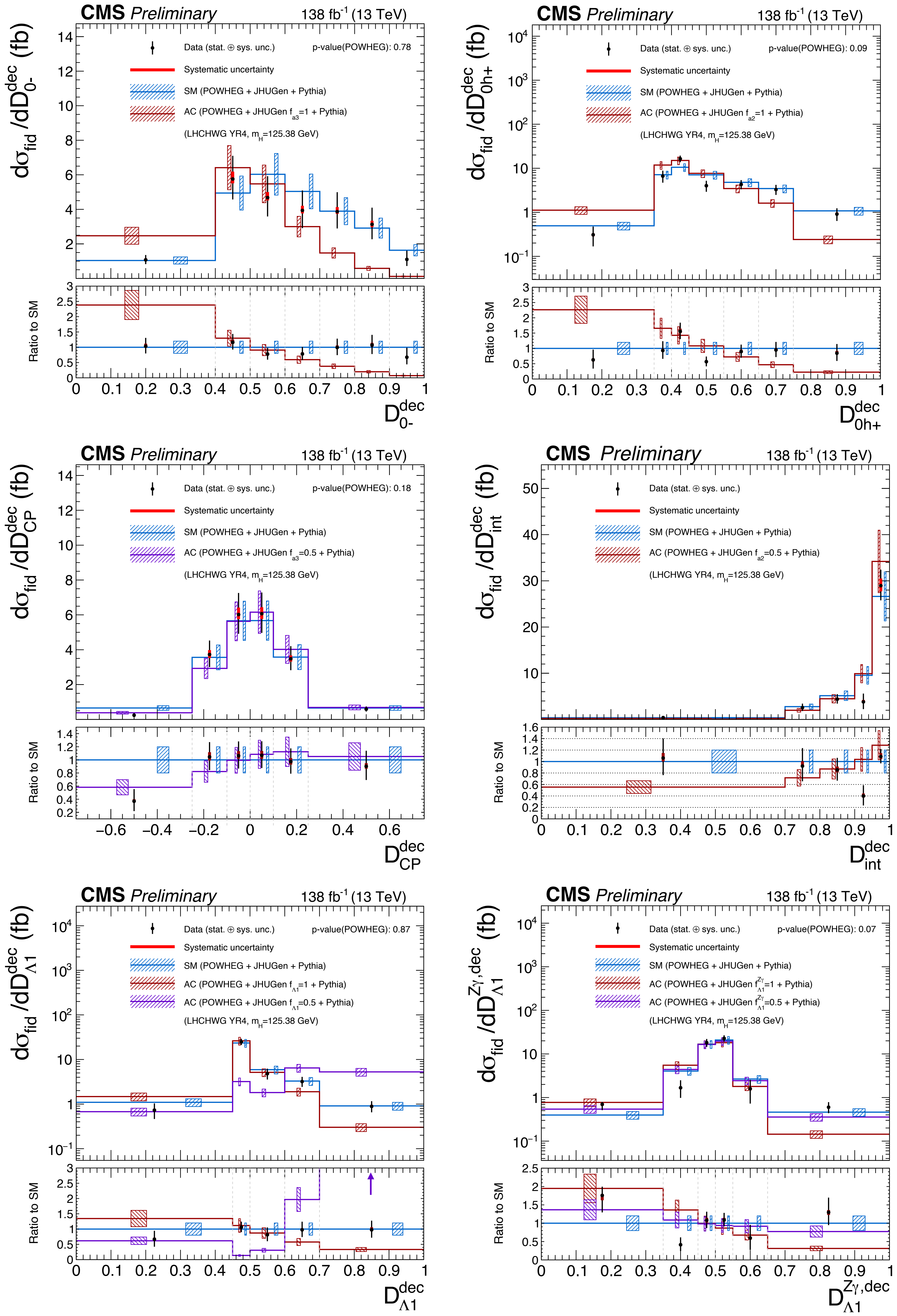
Matrix Element Discriminants

- Another novelty is the measurement of cross sections in bins of the six ME discriminants sensitive to various anomalous couplings of the H boson to vector bosons

- An extensive set of double-differential measurements is presented, providing a complete coverage of the phase space under study

- All results are consistent with the SM predictions

HIG-21-009

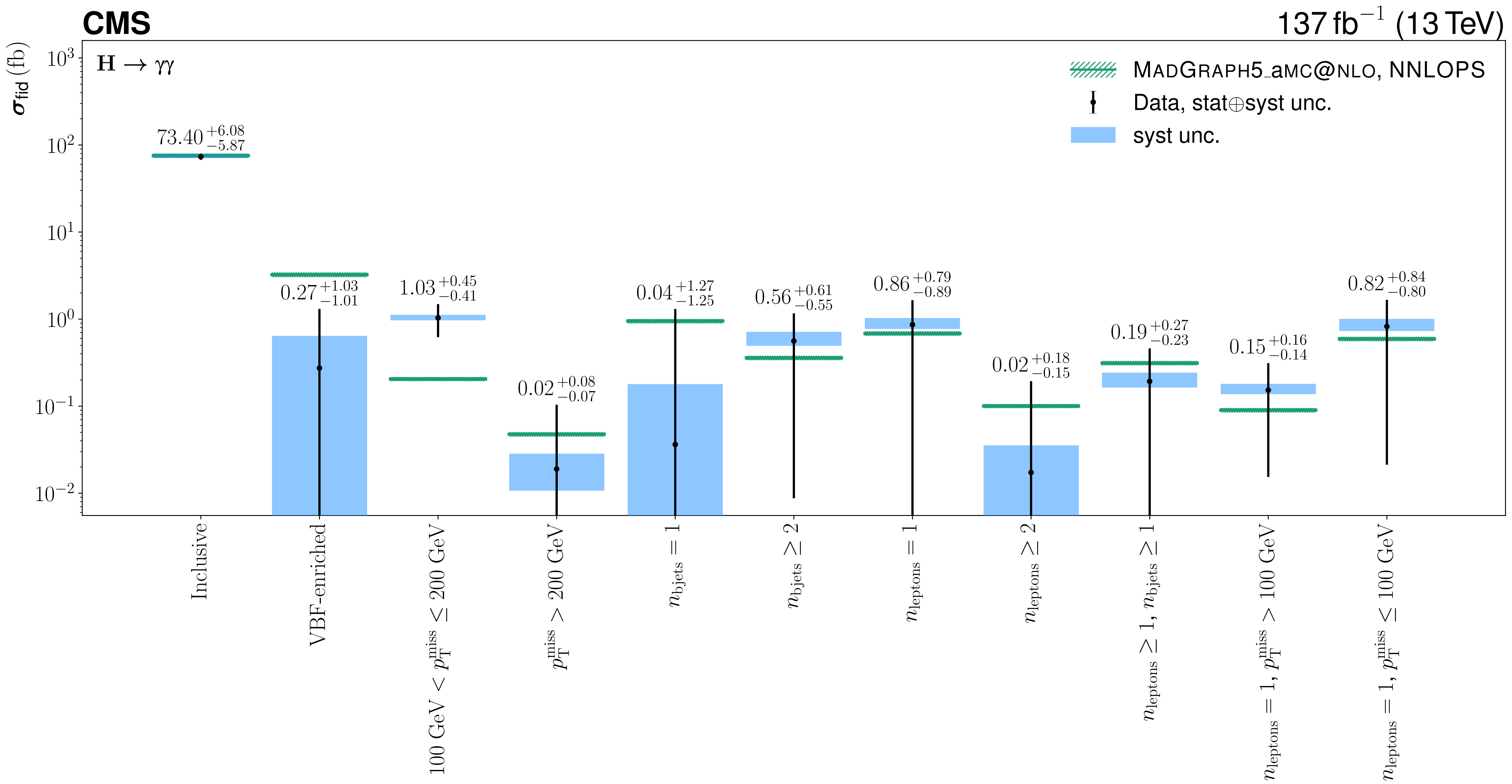


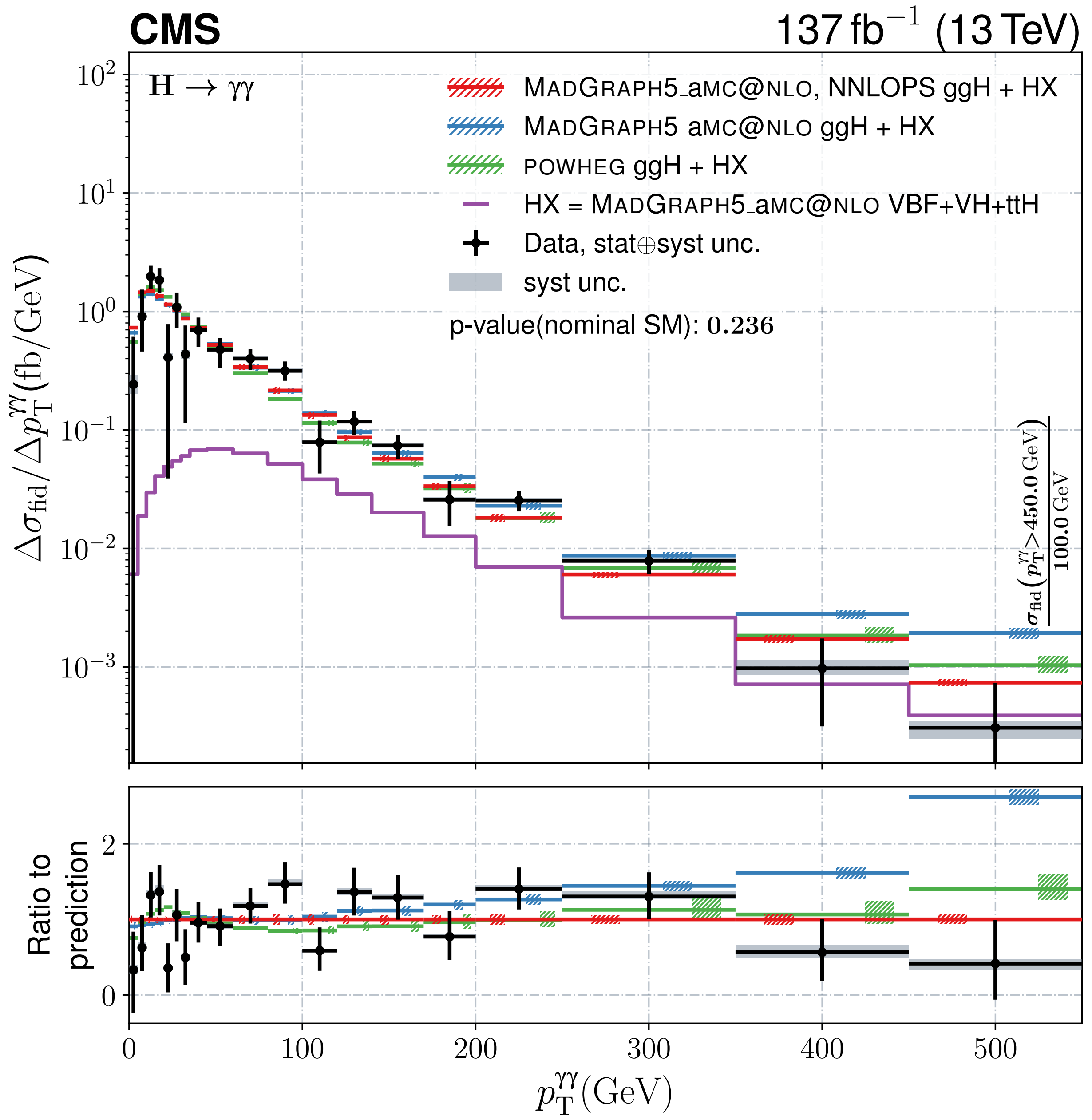
H $\rightarrow \gamma\gamma$

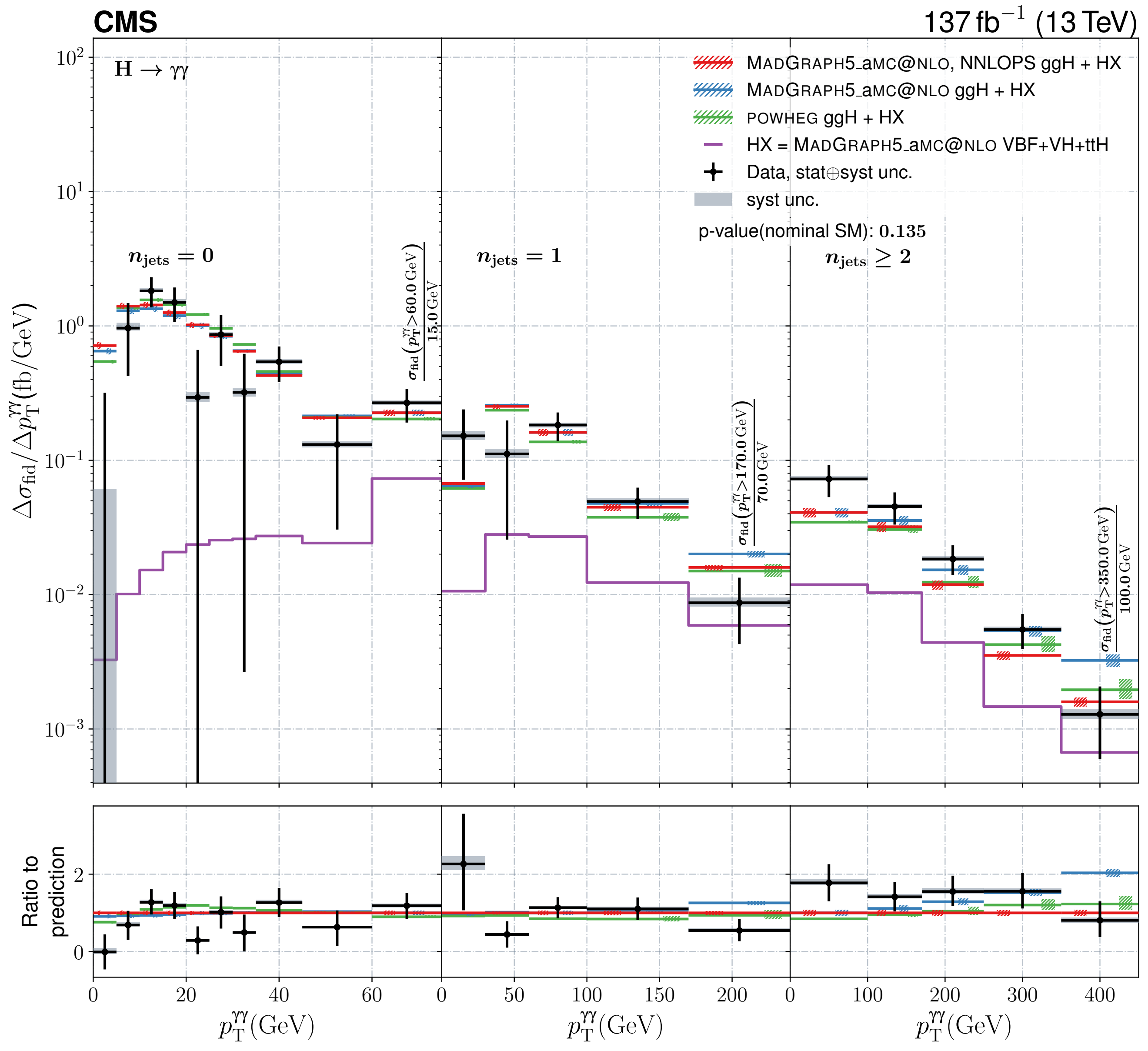
Differential cross sections

HIG-19-016 arXiv:2208.12279v1

- Cross section has been measured as a function of observables of the diphoton system, as well as several others involving properties of the leading and subleading jet
- Observables corresponding to the number of jets, leptons, and b-tagged jets are included as well
- For the first time the cross section has been measured as a function of the rapidity weighted jet pT (τ_C^j) using up to six additional jets in the event, and as a function of a measure for the deviation from "back-to-backness" $|\phi_\eta^*|$
- Two double-differential cross section measurements have been performed (pT, n_j) and (pT, τ_C^j)





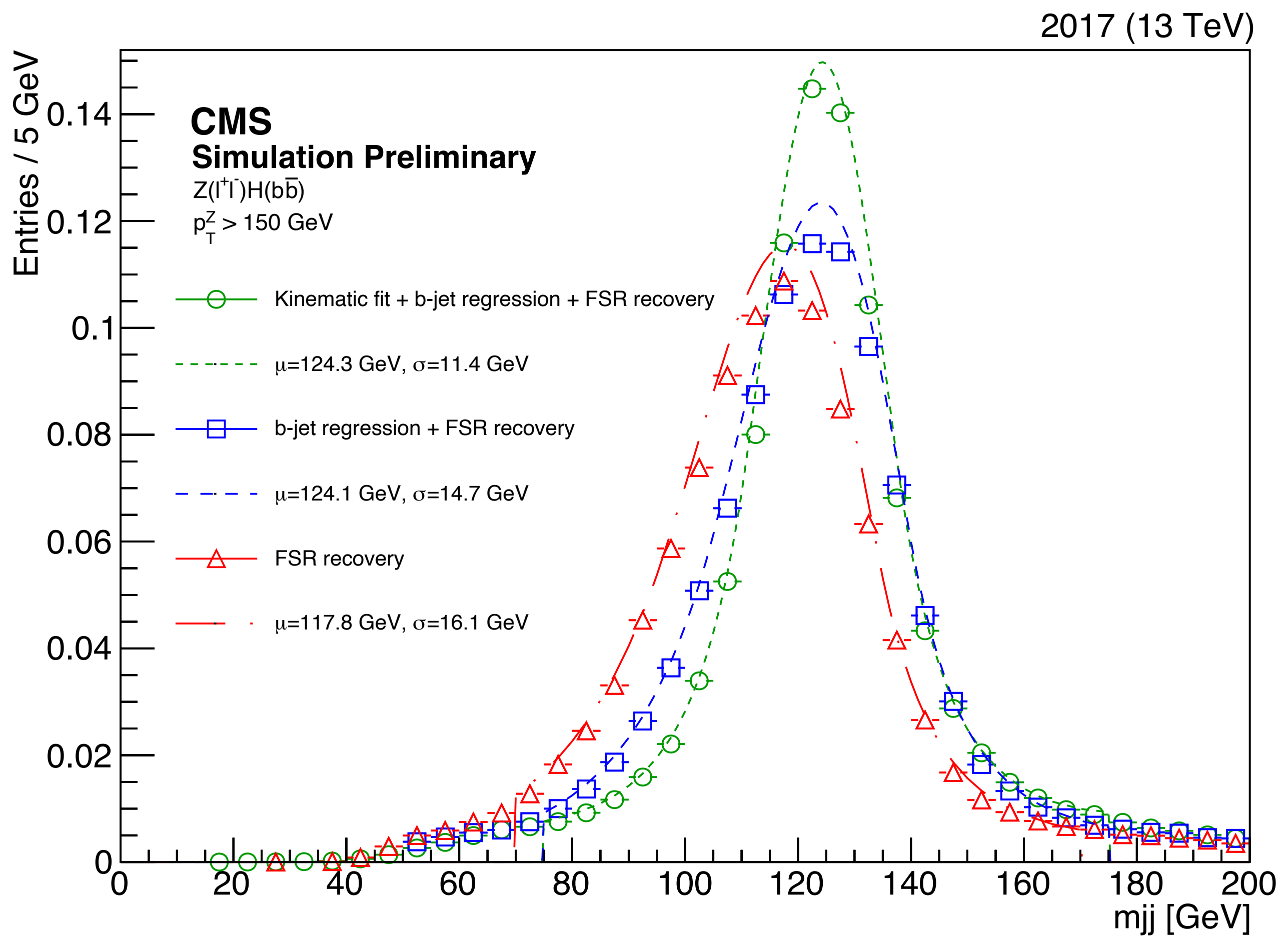


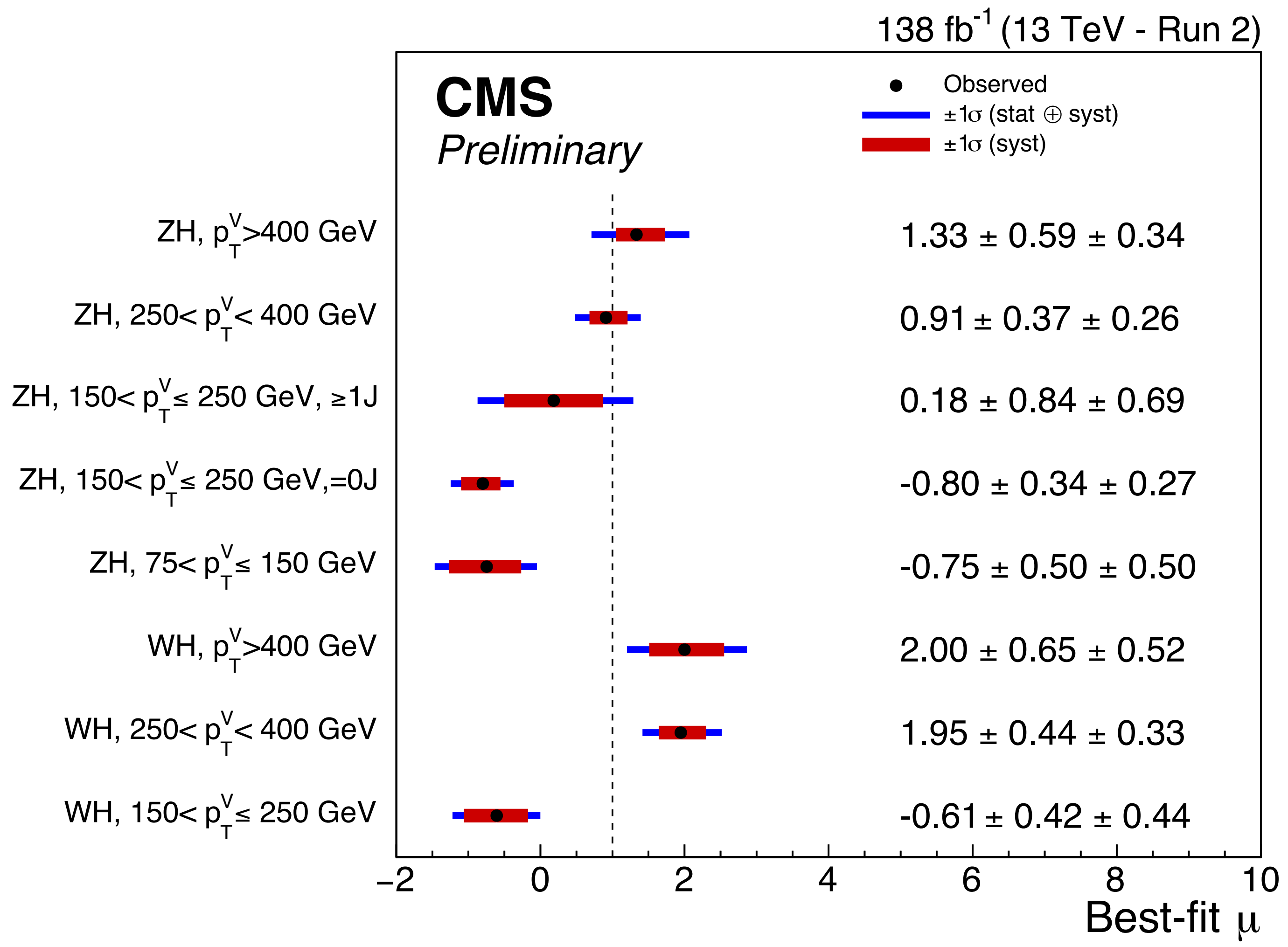
VHbb

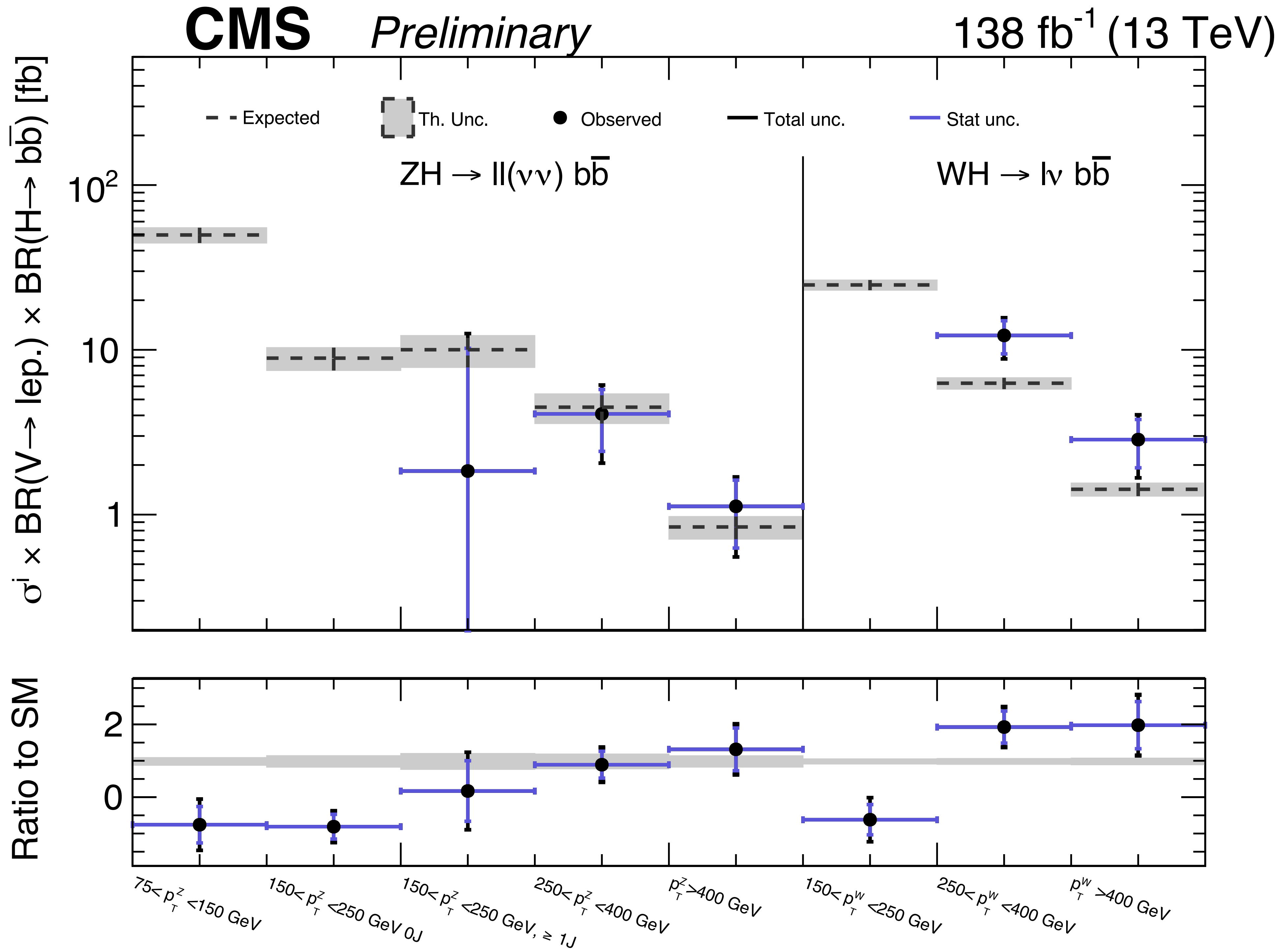
Differential in STXS

HIG-20-001

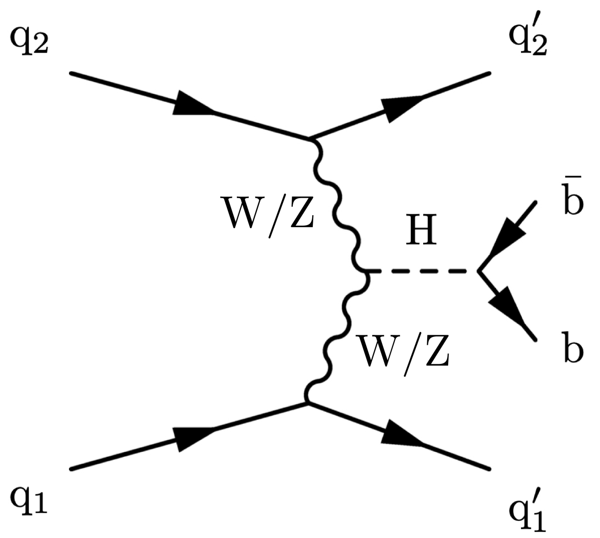
- Five decay modes have been analysed, and for each mode both a resolved and merged jet topologies are exploited
- Improving mass resolution with kinematic fit, b-jet energy regression and FSR recovery of soft jets in the proximity
- An additional subcategorization in the transverse momentum of the vector boson and the number of additional jets in the event is applied to maximize the sensitivity to the different simplified template cross section bins
- Results are presented in STXS bins

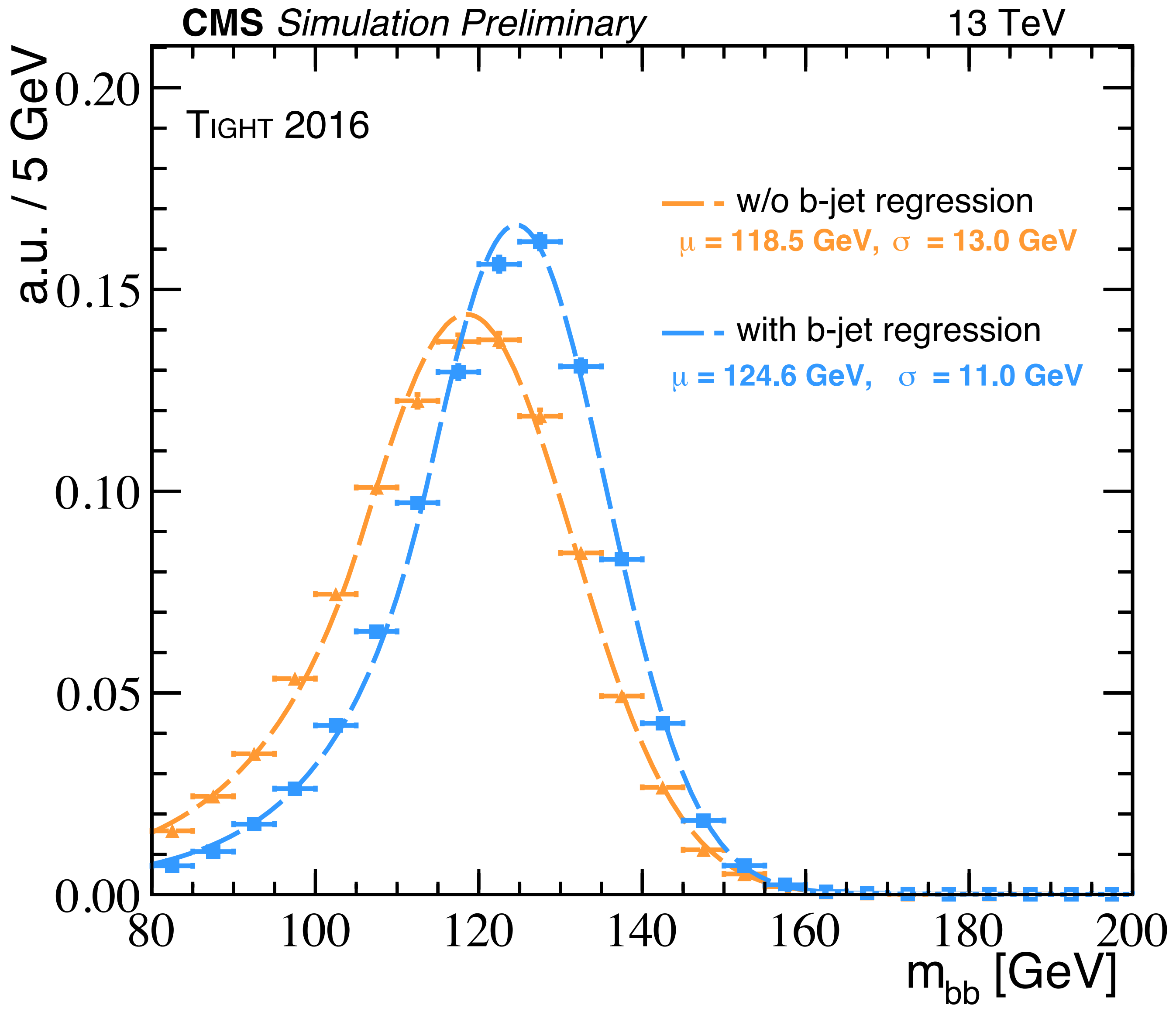






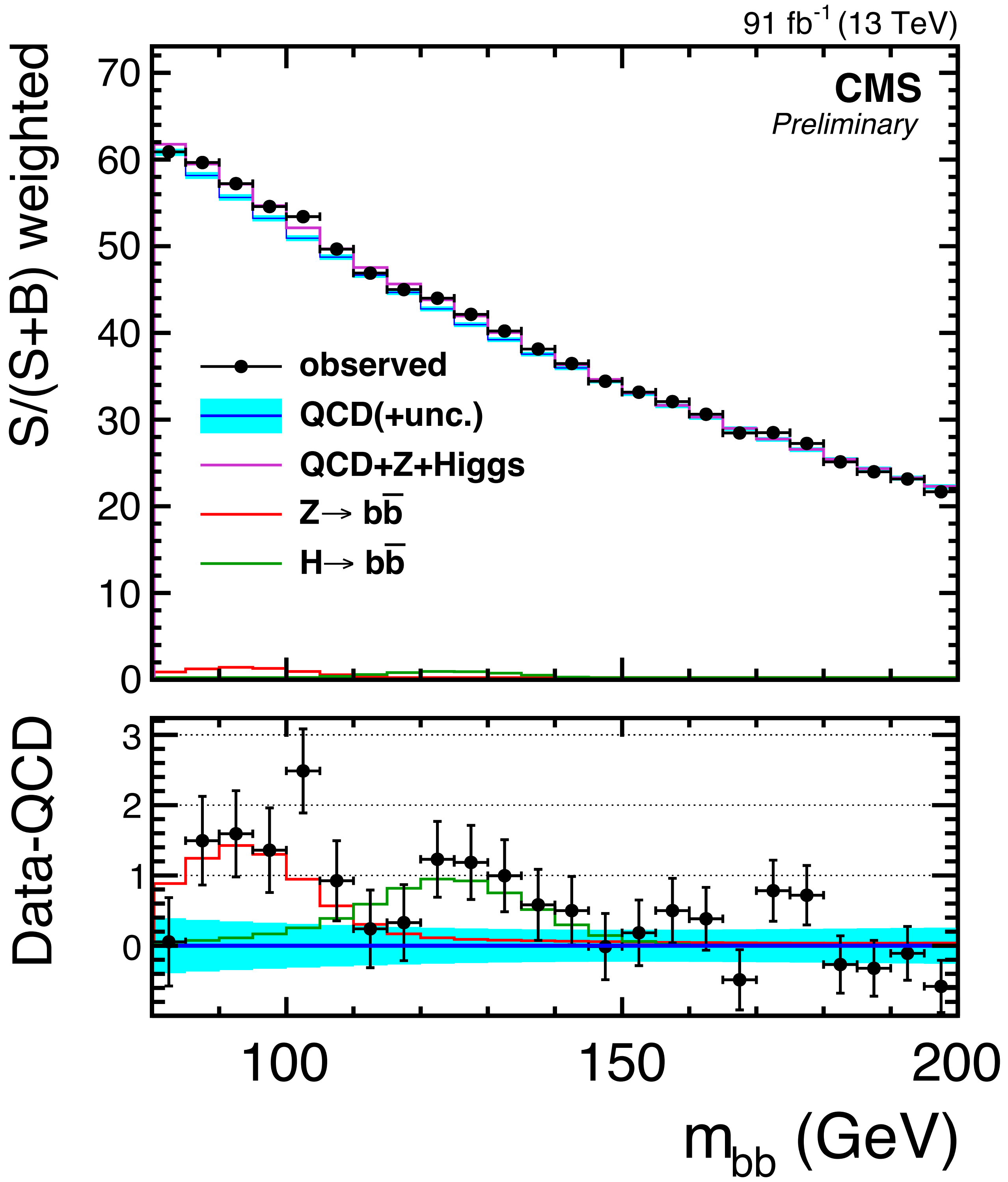
VBF Hbb





HIG-22-009

- Really challenging analysis for the large multijet-QCD background and b-jet identification
- The analysis employs boosted decision trees (BDT) to discriminate signal against major background
- Based on the BDT response, multiple event categories are introduced, targeting VBF, ggH and Z(bb) + jets processes to achieve maximum sensitivity for the signal
- Introduction of ggF category enhanced the sensitivity to the inclusive production of the Higgs boson in association with two jets
- Signal has been observed with a significance of 2.4σ (2.7 expected)
- Signal strength is also measured for qqH and Hbb
  - $\mu_{qqH} = 0.97^{+0.35}_{-0.35}(stat)^{+0.39}_{0.28}(syst)$
  - $\mu_{Hbb} = 0.92^{+0.32}_{-0.32}(stat)^{+0.31}_{0.22}(syst)$

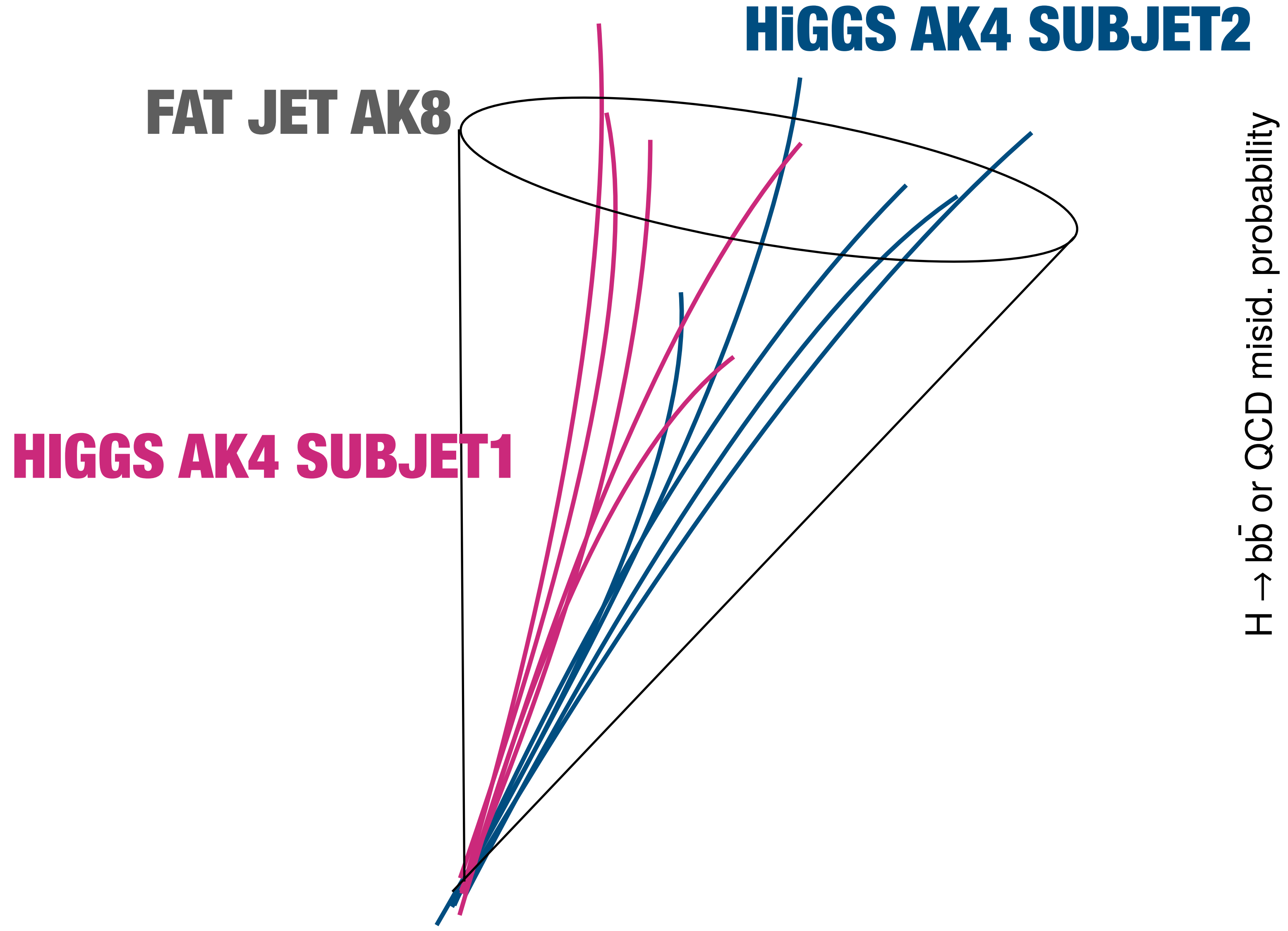


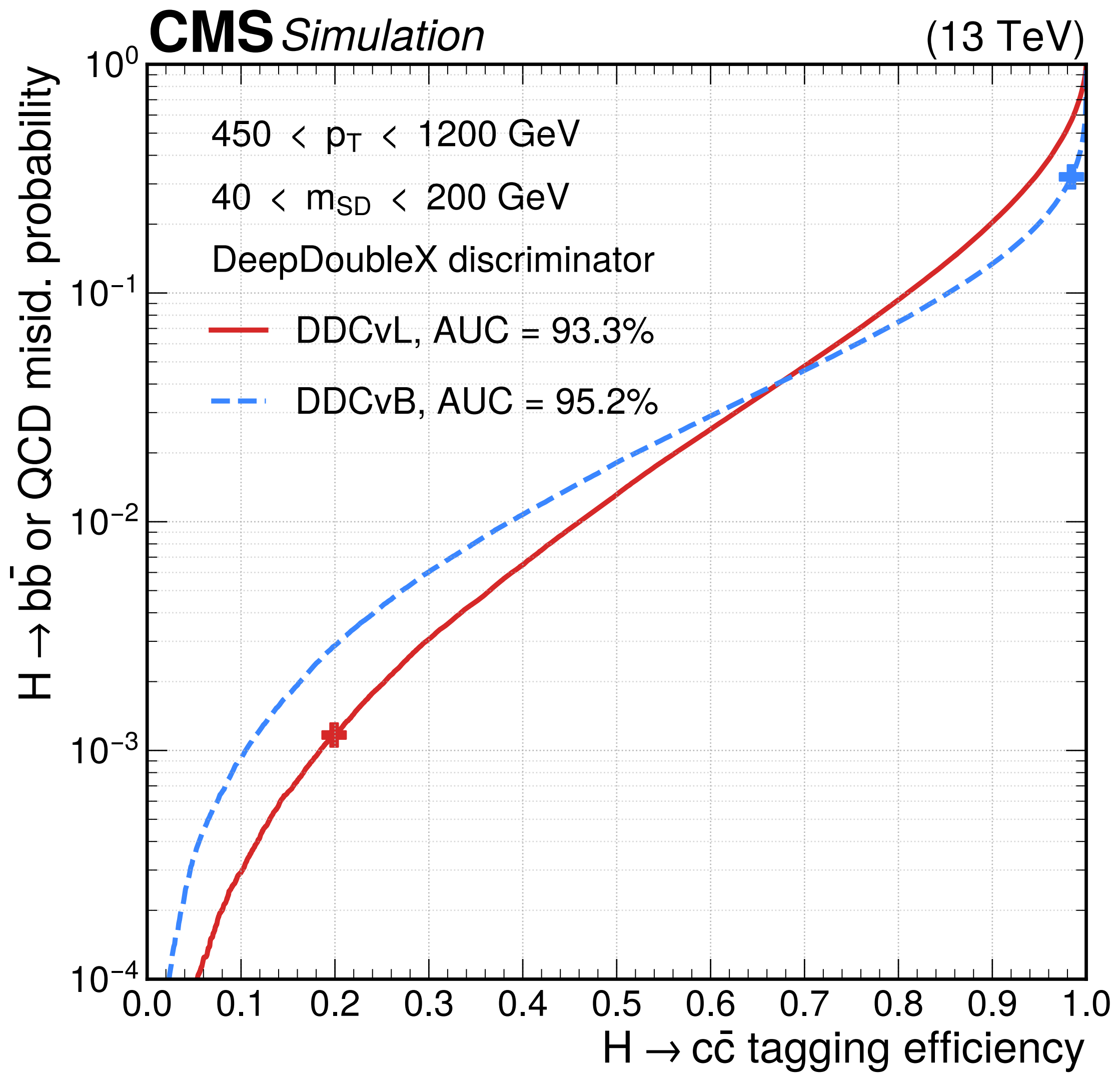
ggHcc

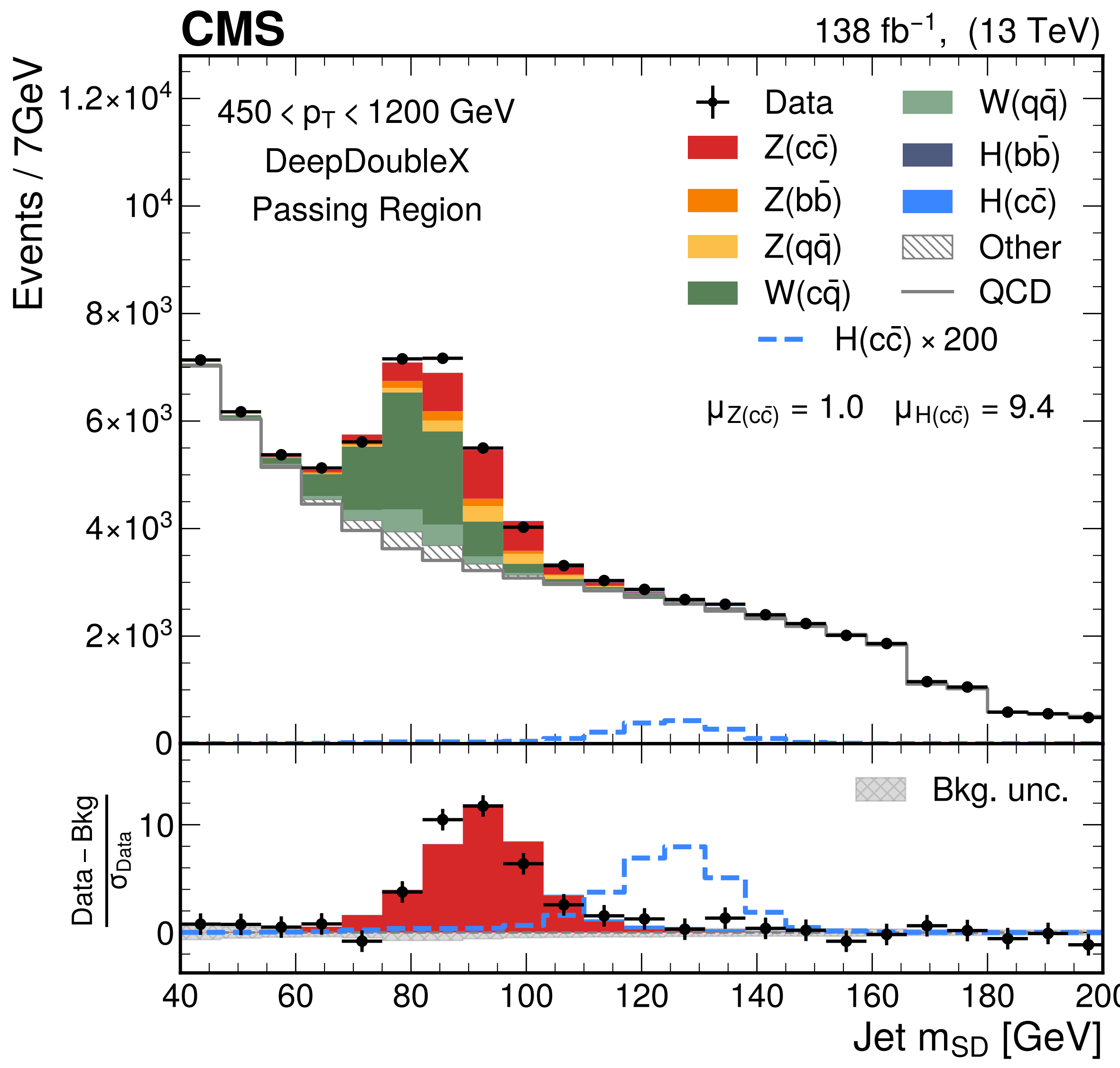
A very challenging analysis

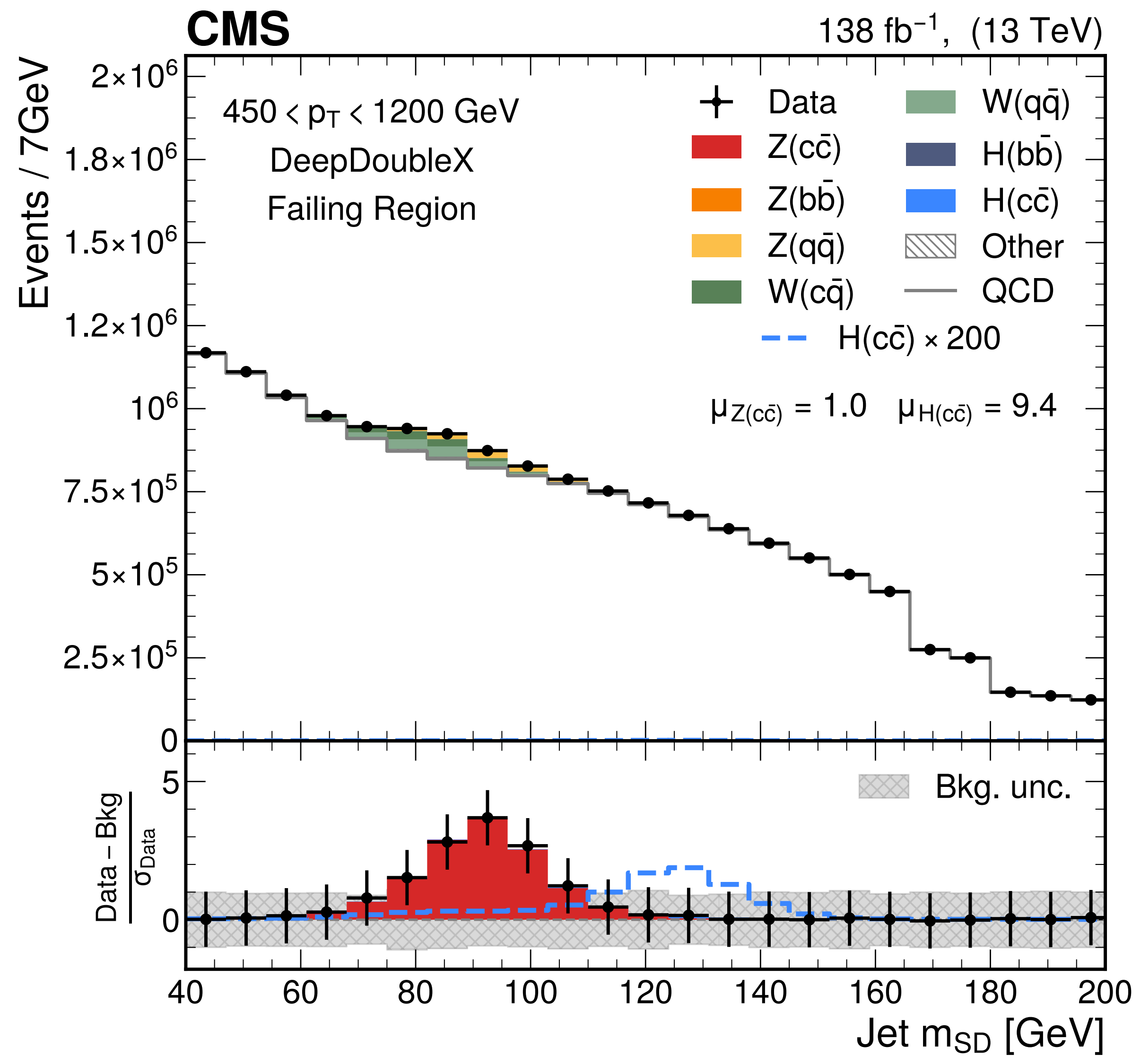
HIG-21-012

- Higgs bosons produced with transverse momenta greater than 450 GeV
  - Two charmed jets merged into a fat-jet
- New algorithms based on deep neural networks treating jets like images have been developed to identify jets originating from charm quark pairs
- The Z->cc process is observed in association with jets at a hadron collider for the first time with a signal strength of $1.00^{+0.19}_{-0.17}$
- An upper limit of Hcc is set to 47 (39 expected) times the SM expectation





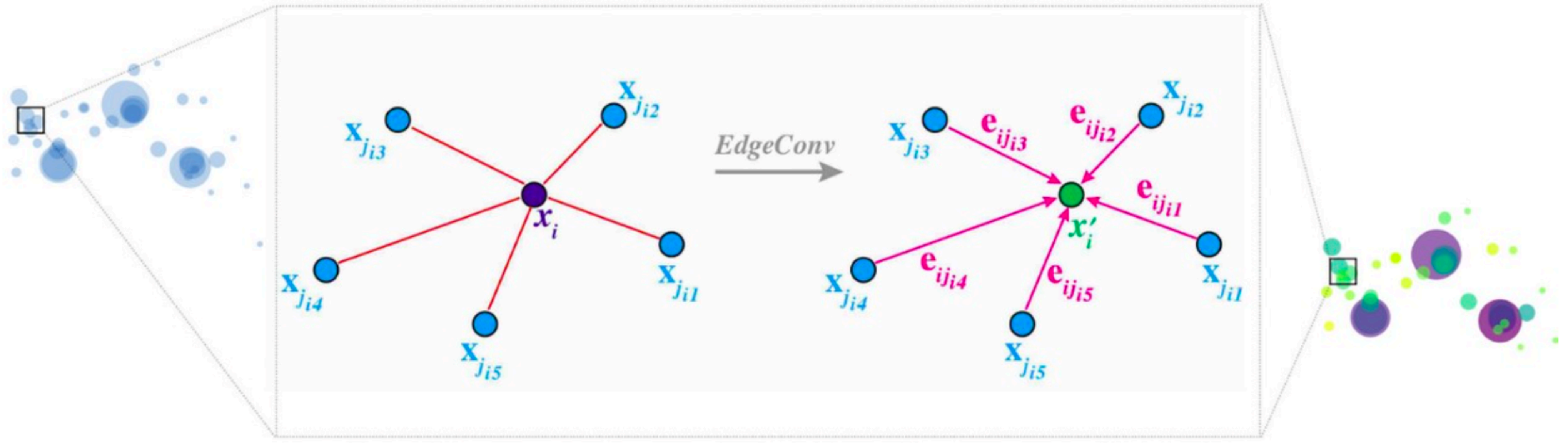


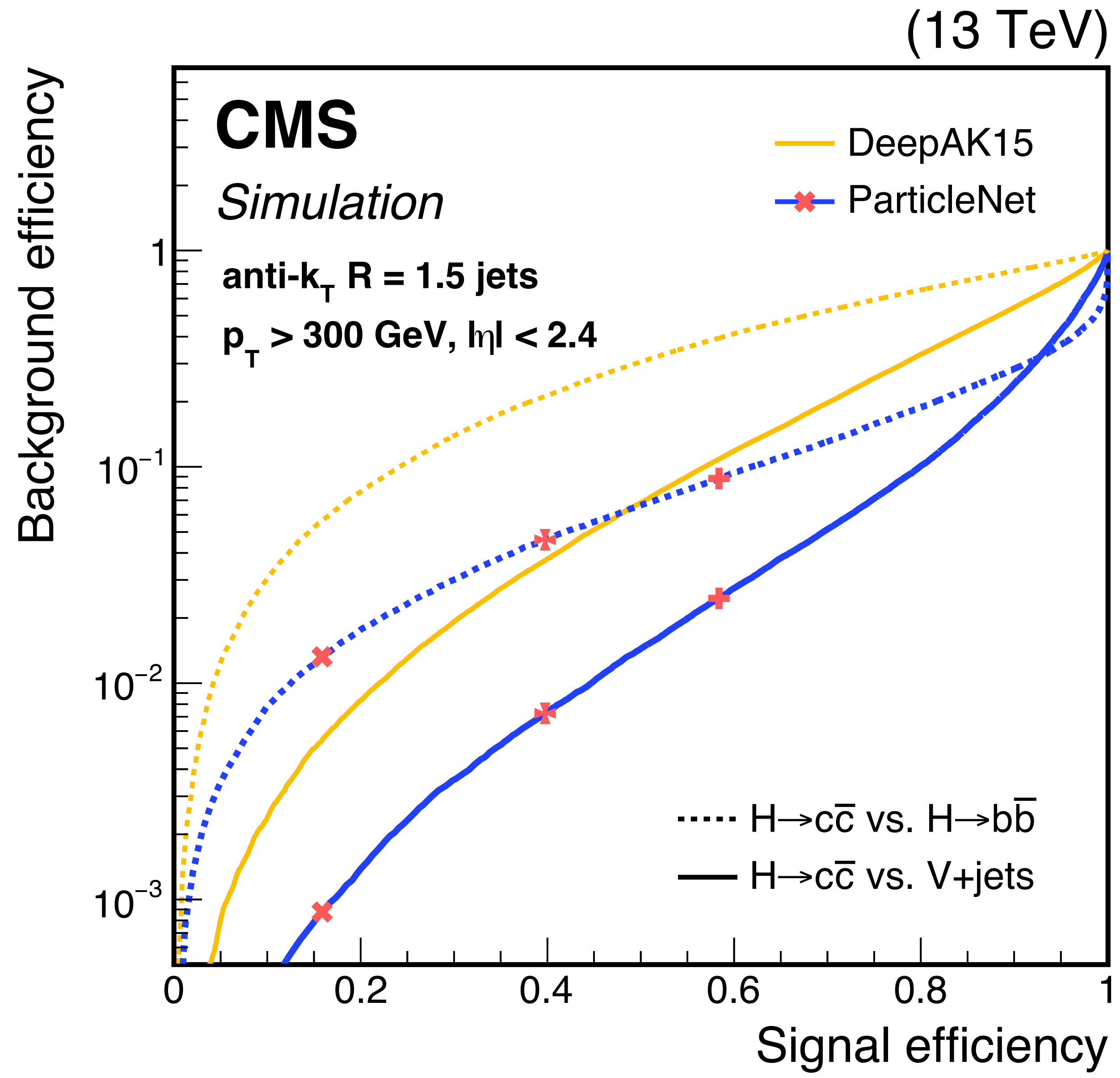


HIG-21-008

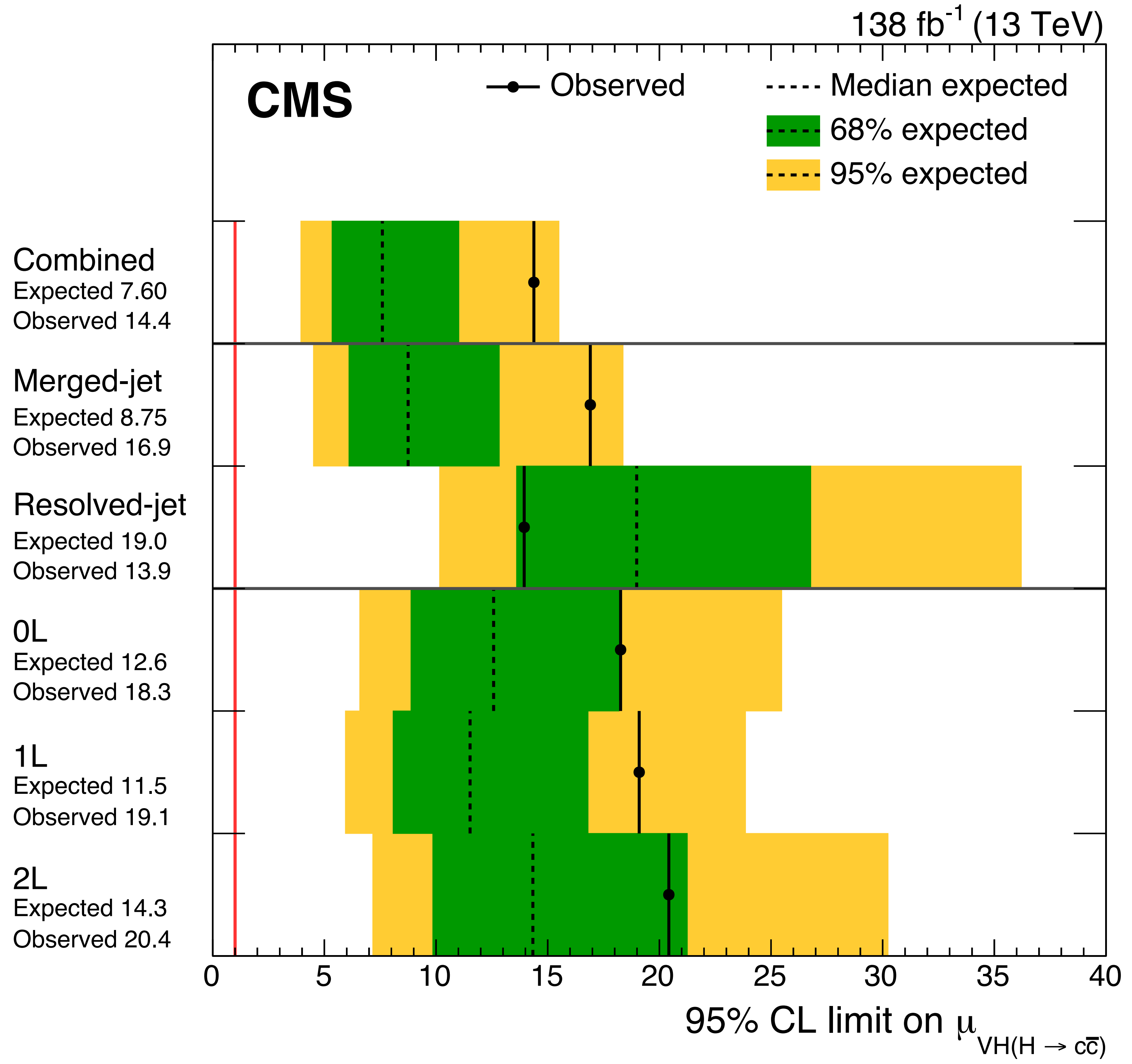
VHcc

ParticleNet
Phys. Rev. D 101, 056019





- Novel jet reconstruction and identification tools, and analysis techniques are developed for this analysis
  - Validated by measuring the VZcc process with 5.7 (5.9) s.d.
  - This is the first observation of Zcc at hadron colliders
- Set the most stringent constraints on $|\kappa_c|$: $1.1 < |\kappa_c| < 5.5\ (< 3.4)$

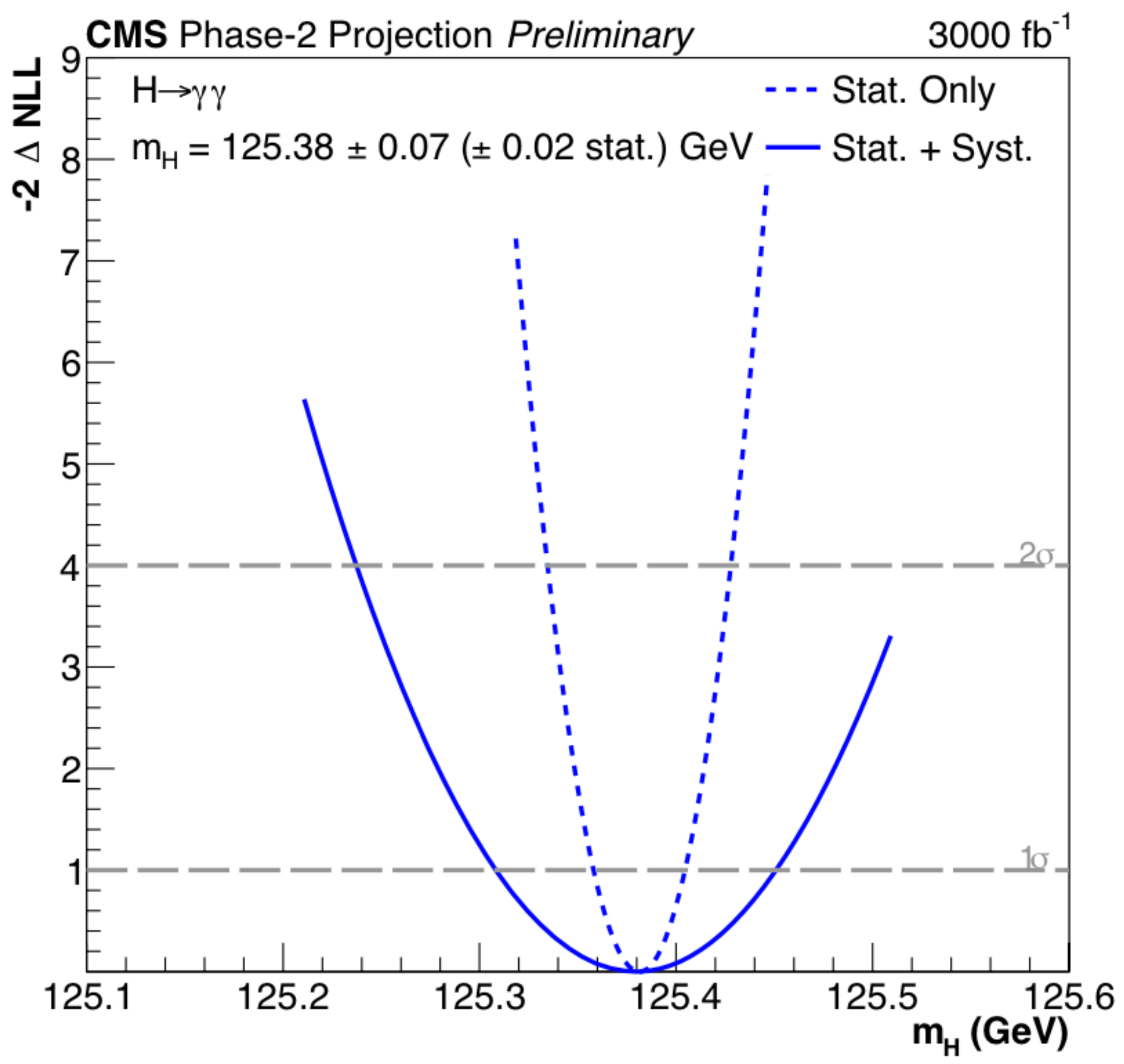


Prospects

…what will come…

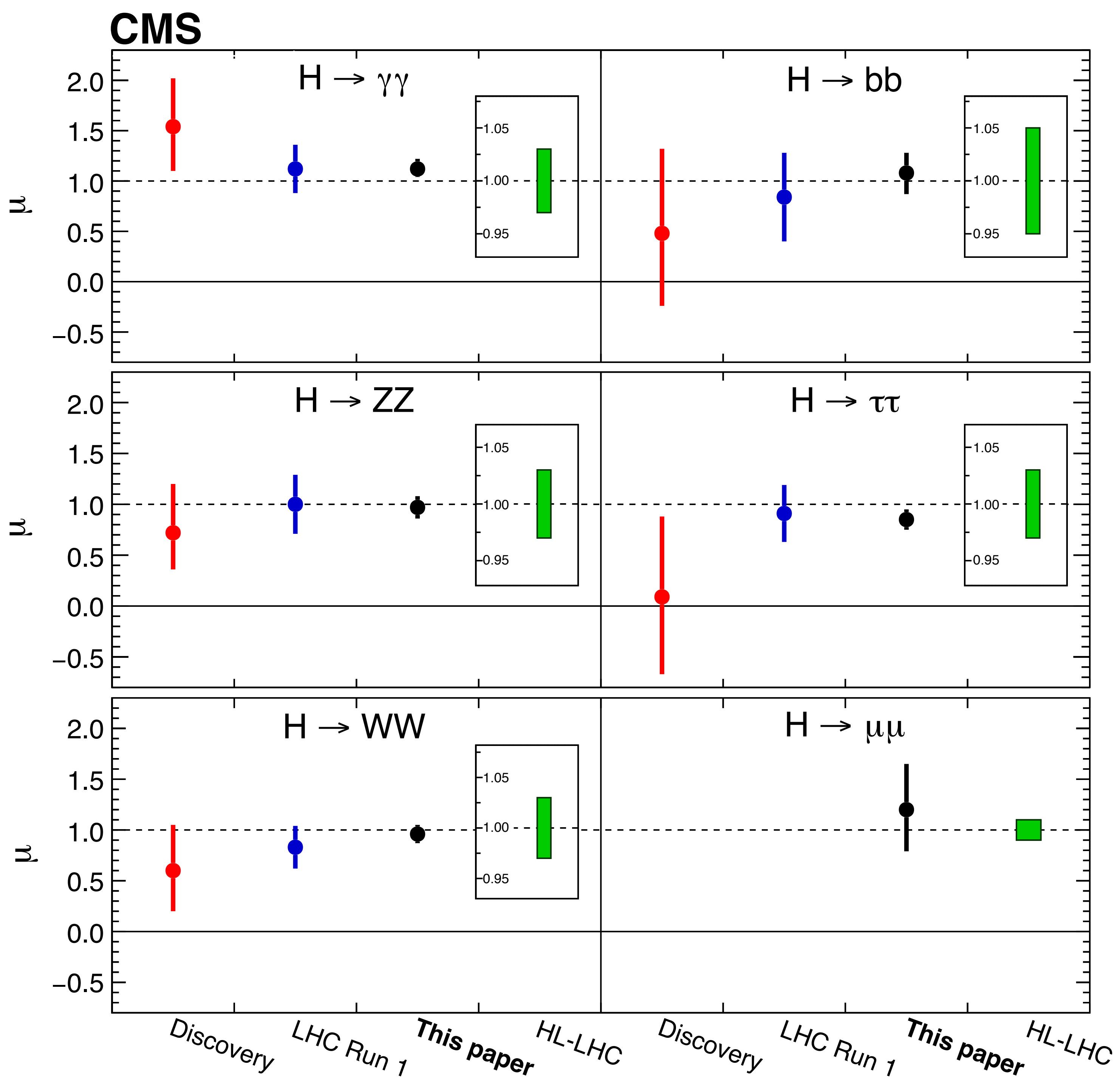
PROSPECTS

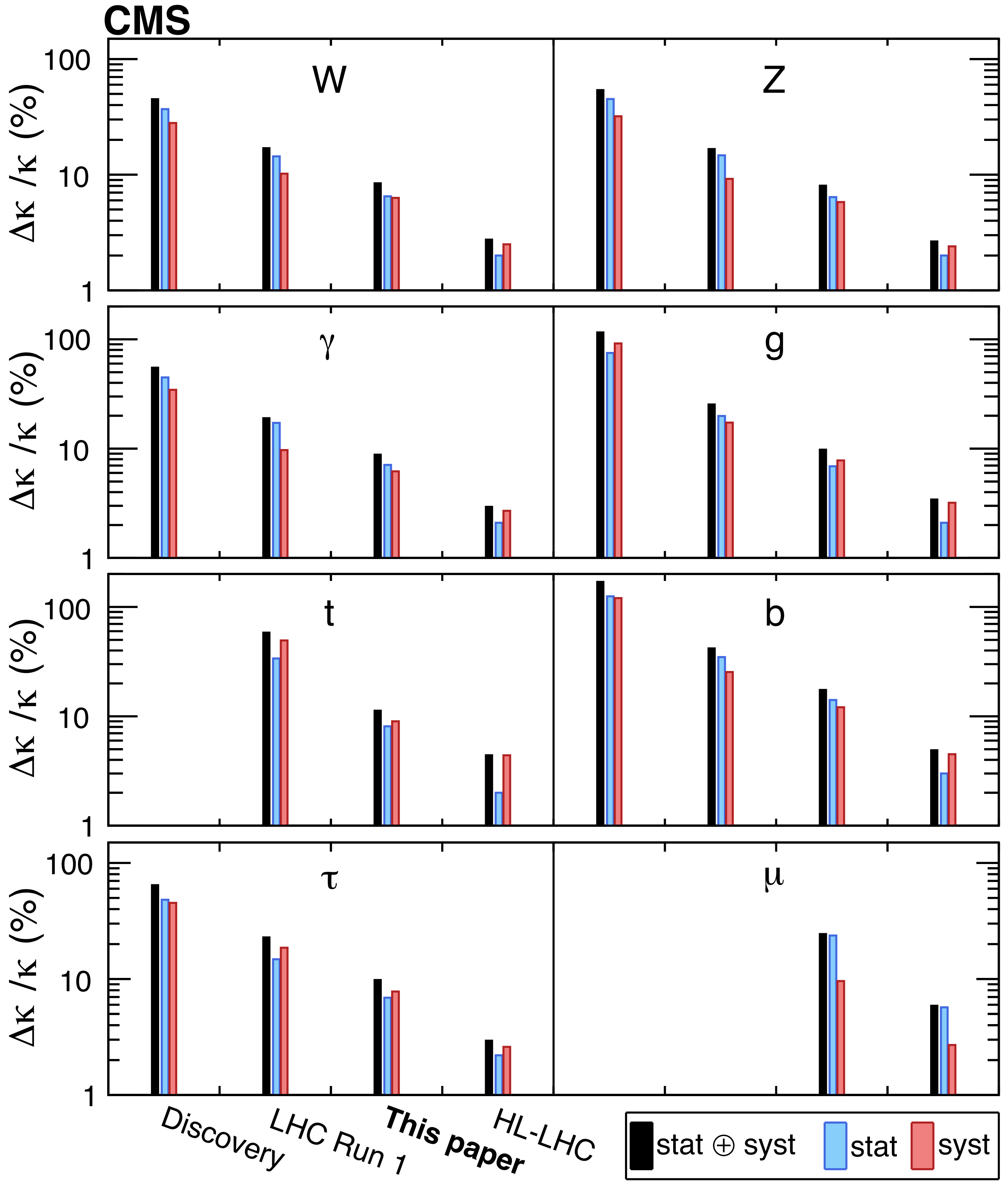
Time evolution of measurements



- Operation with the high-luminosity LHC is expected during the next decade and should yield ten times more data (3000 fb^{-1})
- Should allow to establish
  - Mass measurement at 30 MeV for HZZ and 0.5 per mill in H$\gamma\gamma$
  - Width limit at 4.1 MeV (ATLAS and CMS combined)
  - Signal strengths and kappas for main decay channels, bosons, and most fermions at percent level

Nature 607, p60–68 (2022)
FTR-22-001





PROSPECTS

Time evolution of measurements

- Should allow to establish
  - Higgs boson coupling to charm $\sigma_{\mu(cc)}/\mu(cc) \simeq 0.8$
  - 12% uncertainty on ttH (similar to κ_t)
  - the SM Higgs boson pair production with a significance of 4 s.d.
- Improvements in experimental techniques and theoretical calculations are also anticipated to continue

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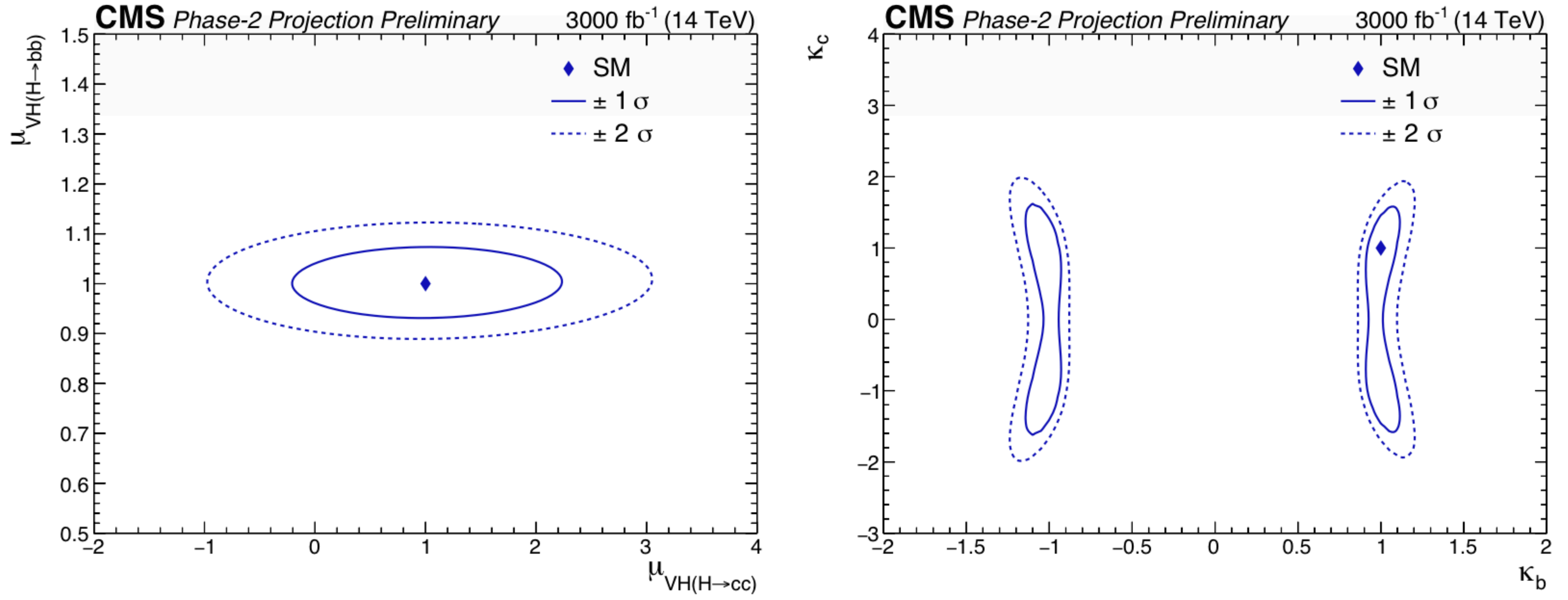

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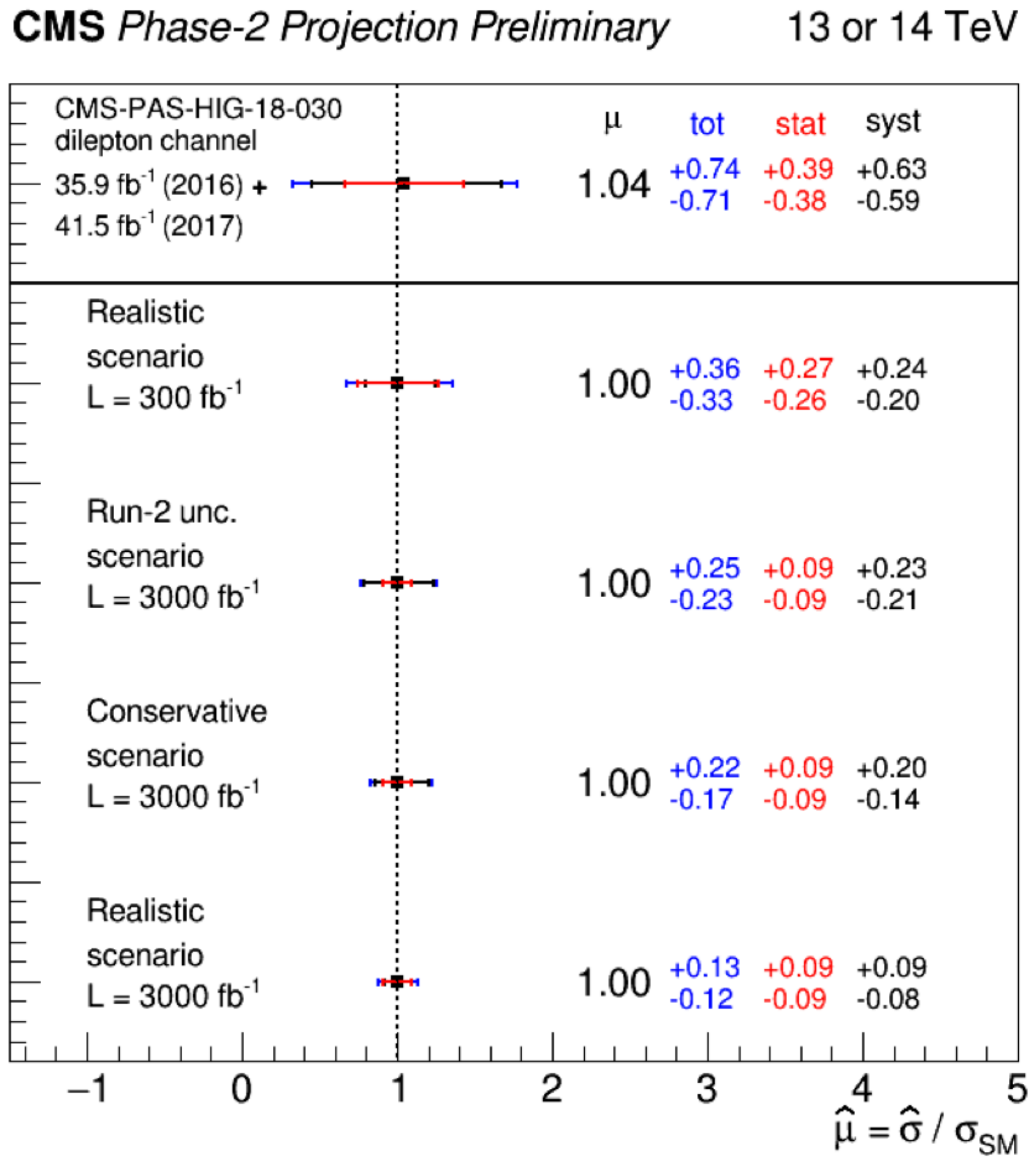

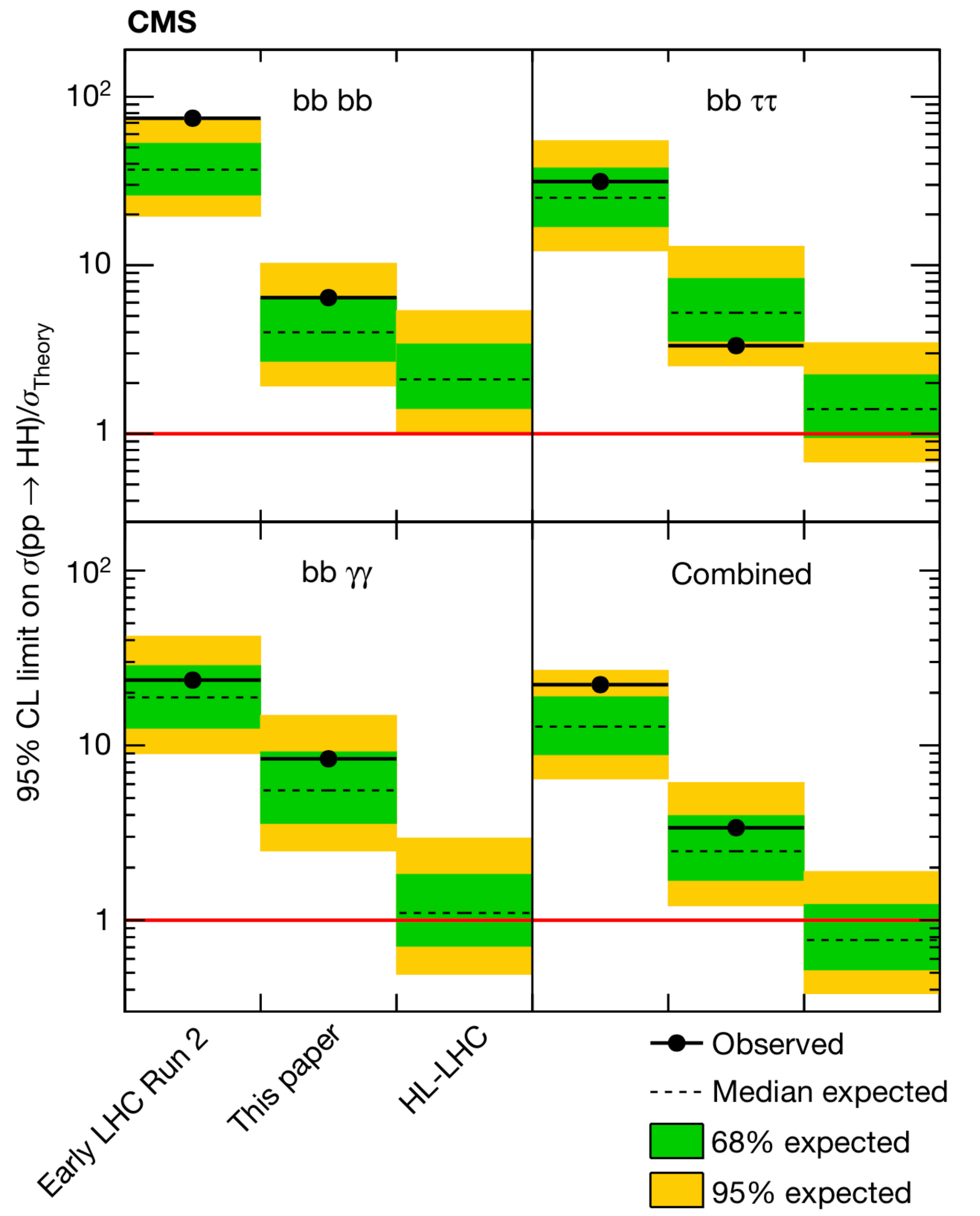

CONCLUSIONS

- The Higgs sector is a very active and productive research area
- Since the discovery 10 years ago the Higgs profile knowledge has been constantly improved and parameters measured with better precision
- All measurements are in agreement with the SM expectations
- HL-LHC in the next decade will give us the opportunity of the observation of the Higgs rare decays, and the evidence of its self coupling, and percent level measurement of most of Higgs coupling
  - Higher precision measurements lead to higher probability to encounter BSM effects
- CMS is running a Higgs precision physics program at a hadron collider