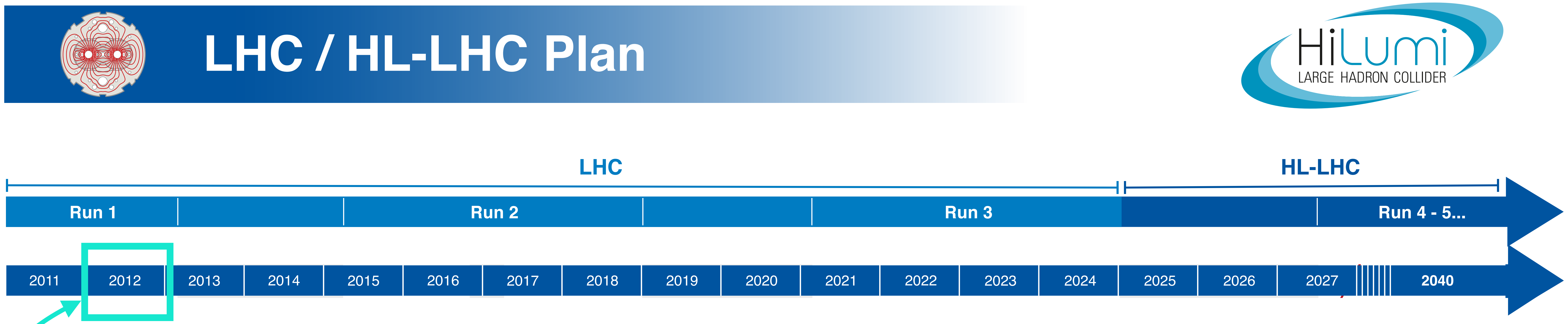
Higgs 2024
07/11/2024

Precision measurements @ LHC Cross-sections & STXS

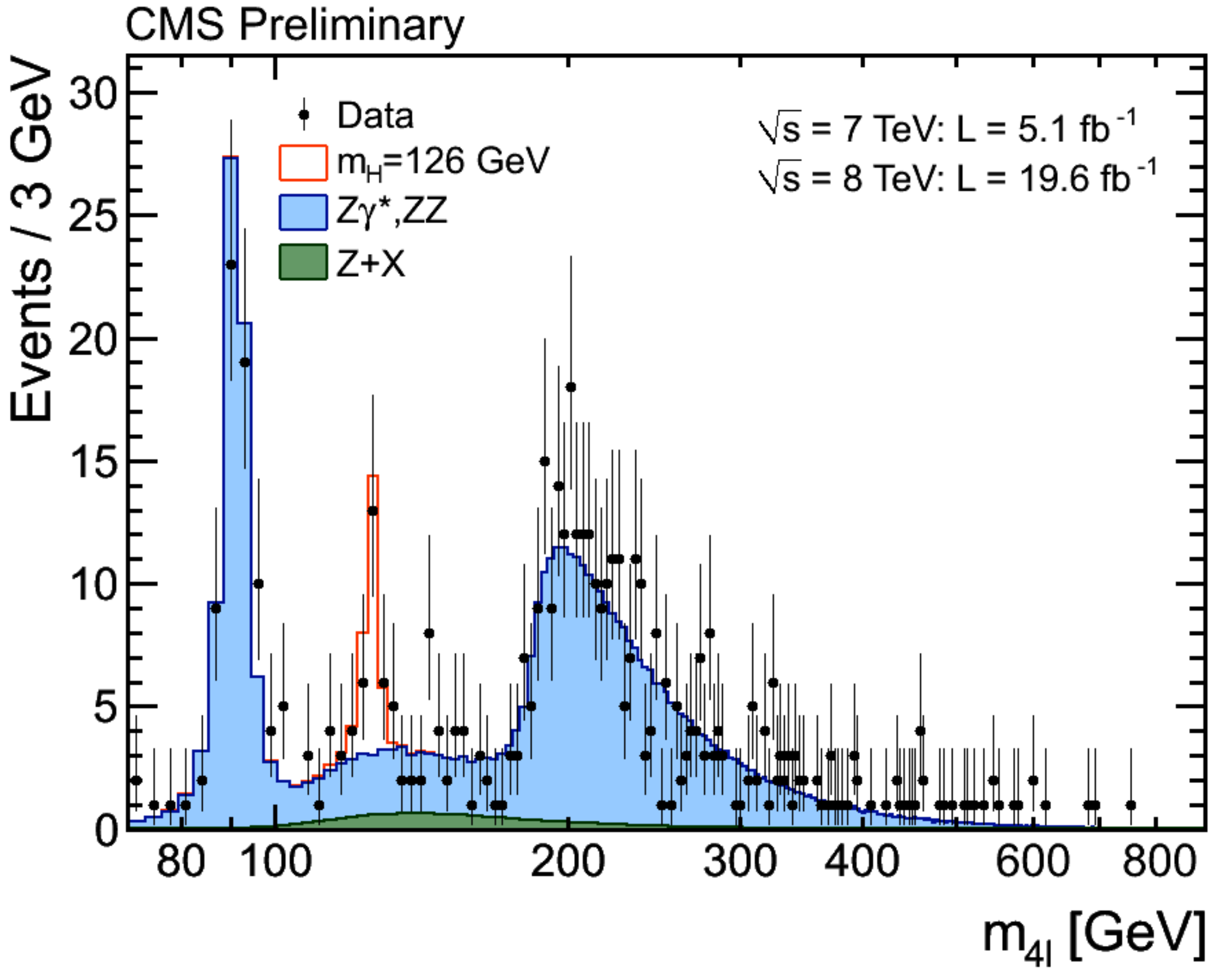
Matteo Bonanomi
(University of Hamburg)
On behalf of the ATLAS & CMS Collaborations

Cross-sections over 12 years

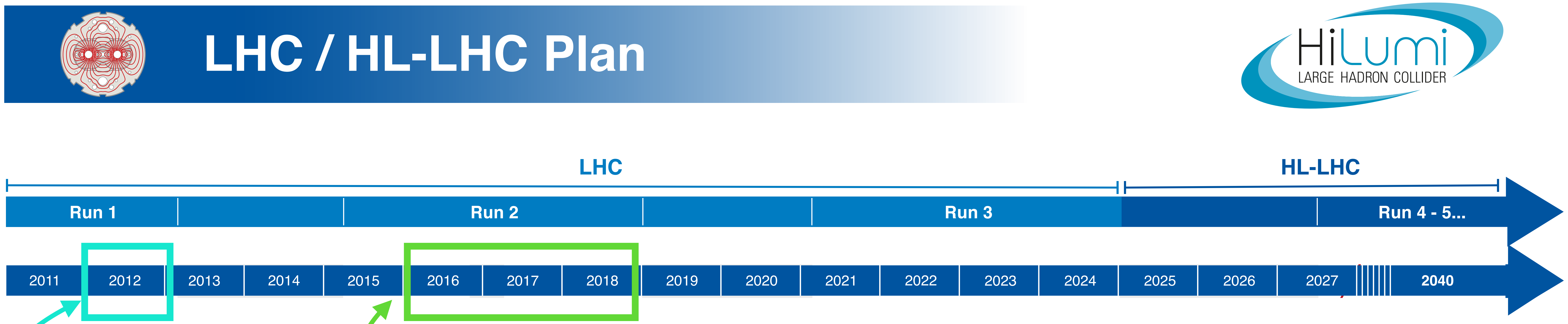


Run I

Discovery of a new particle



Cross-sections over 12 years



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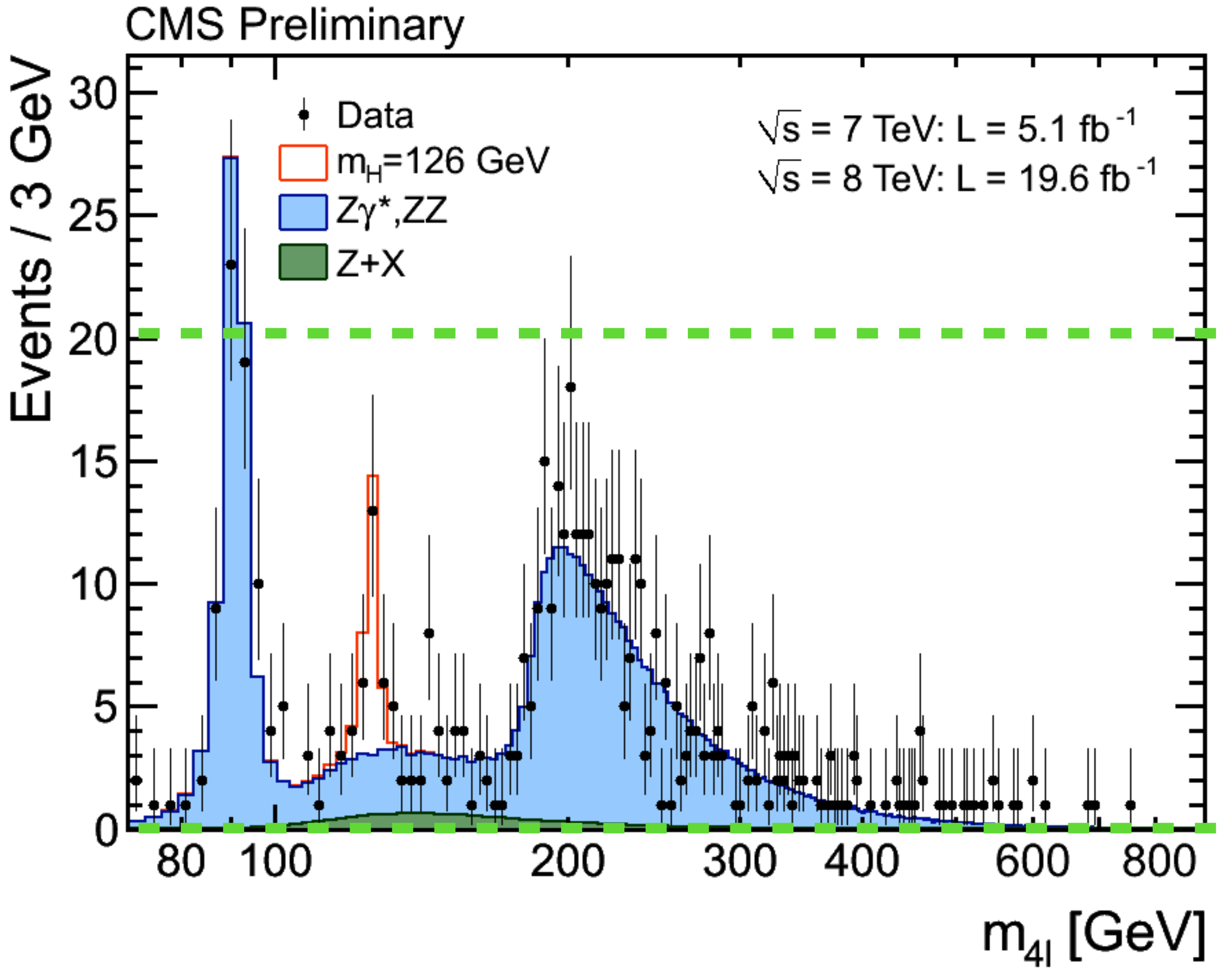
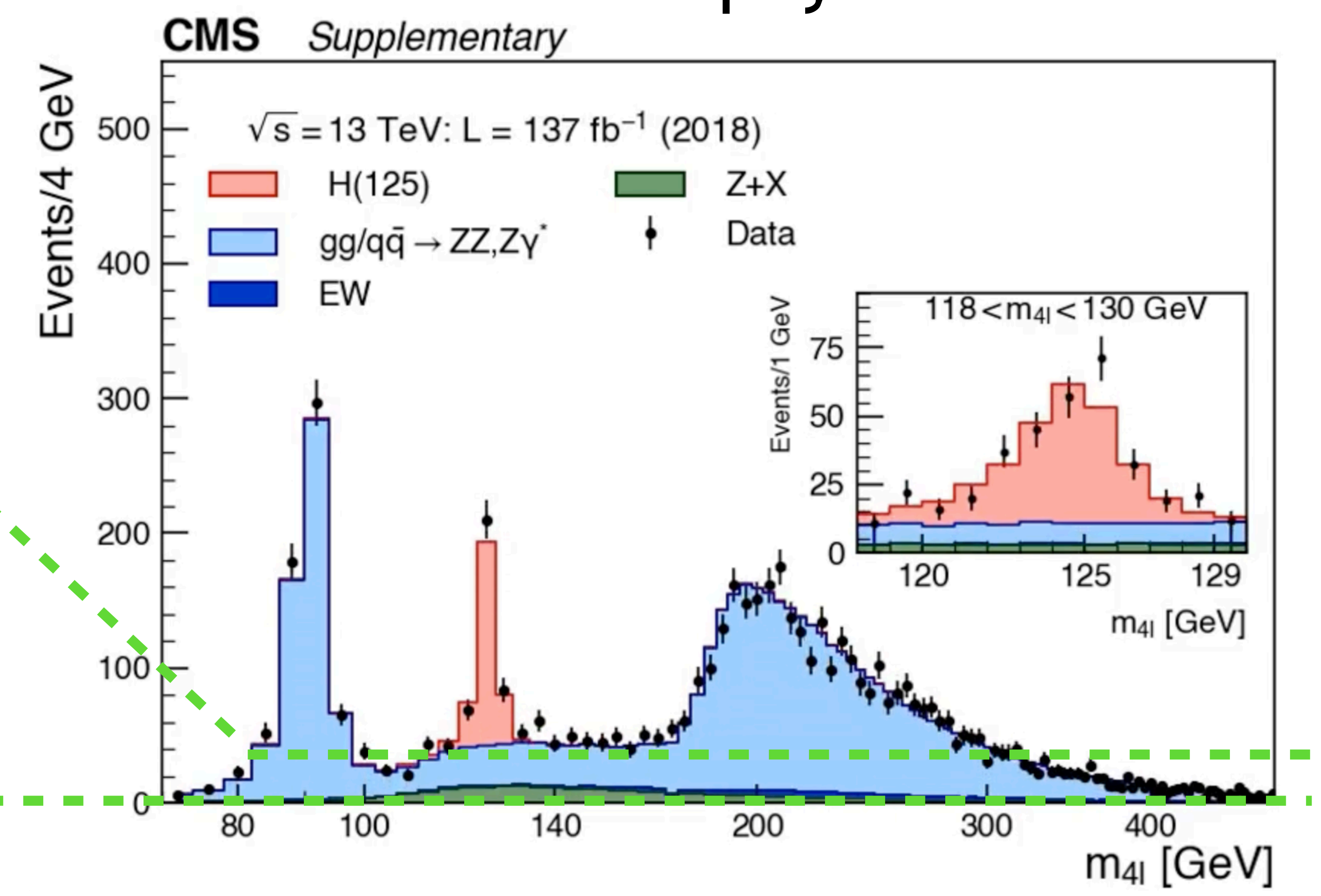
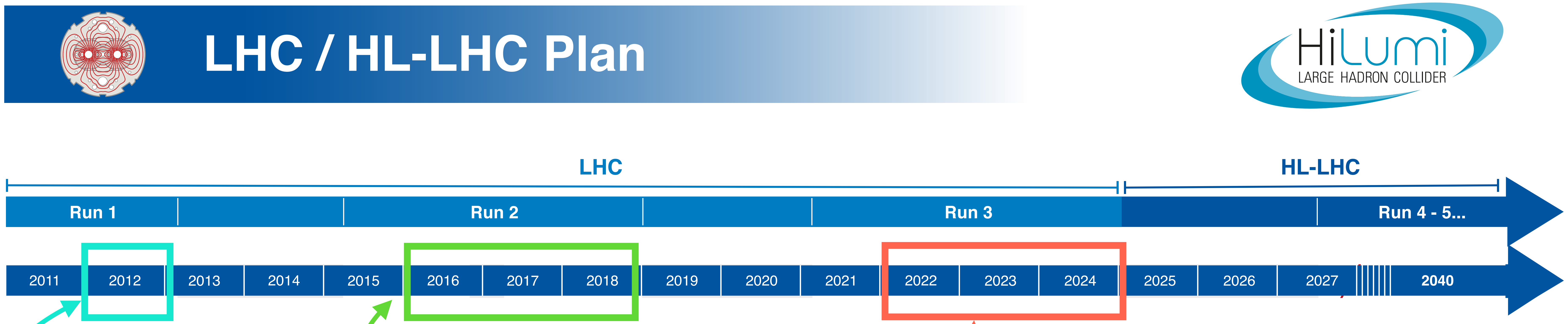


Run-II

Precision physics era

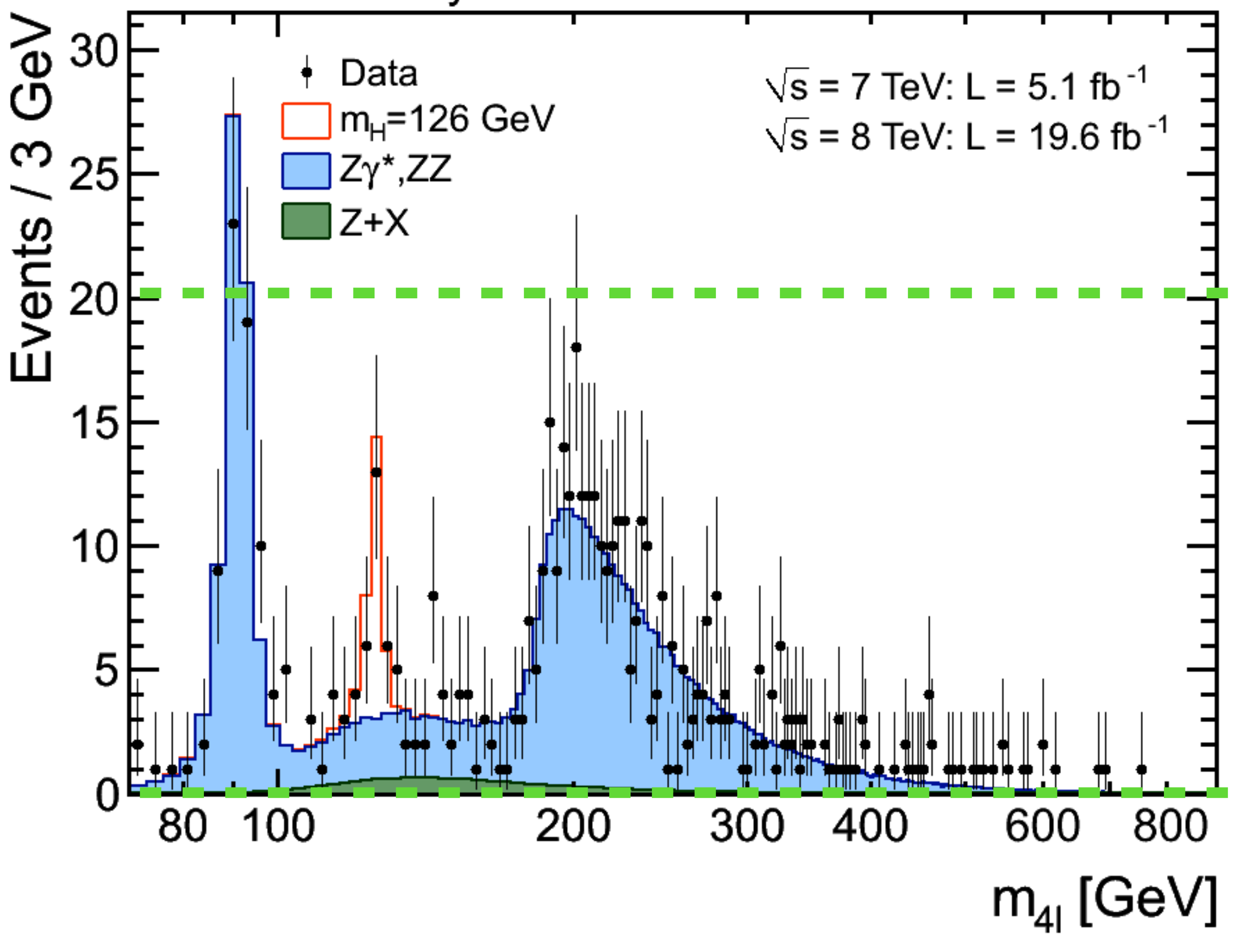


Cross-sections over 12 years



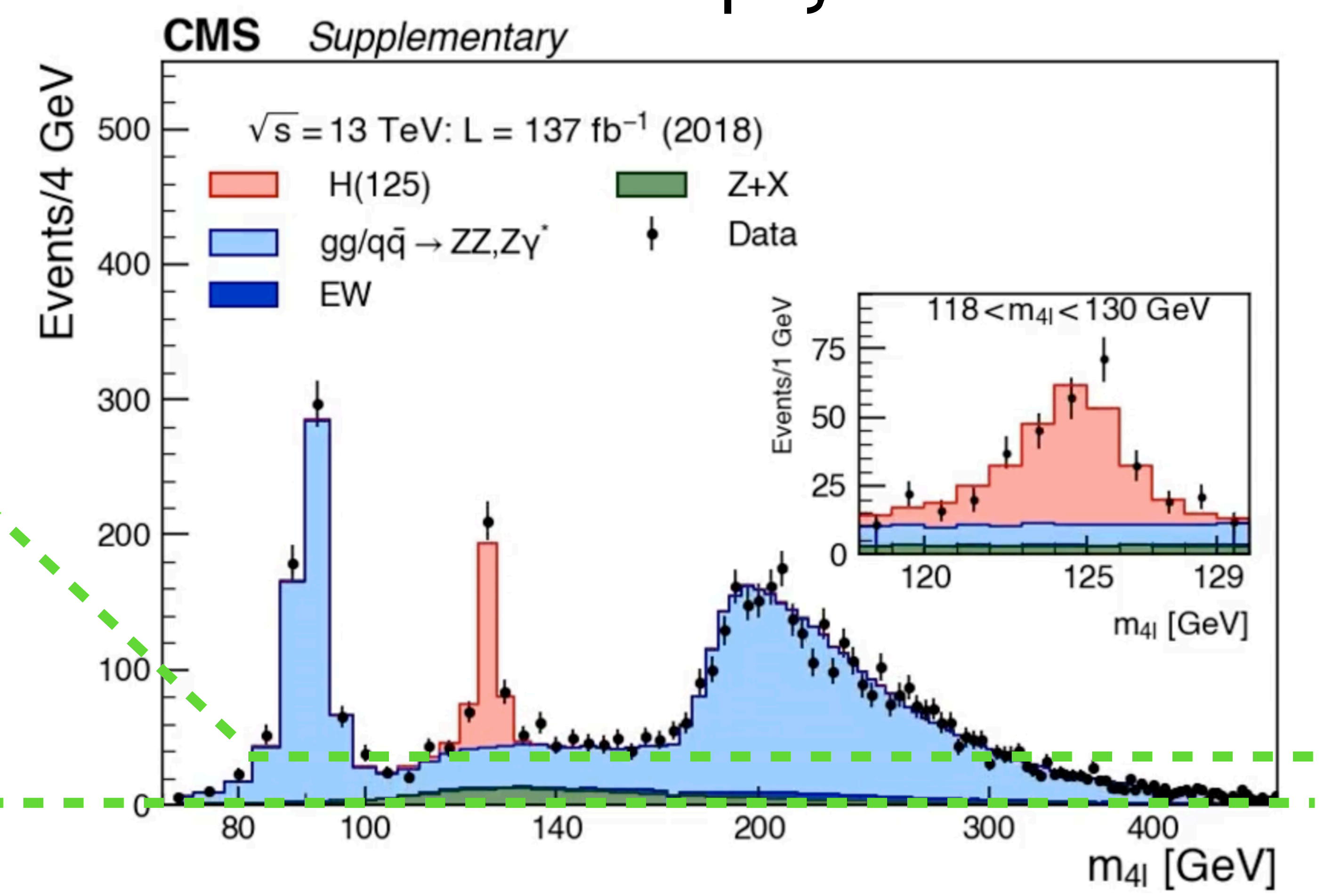
Run I

Discovery of a new particle



Run-II

Precision physics era

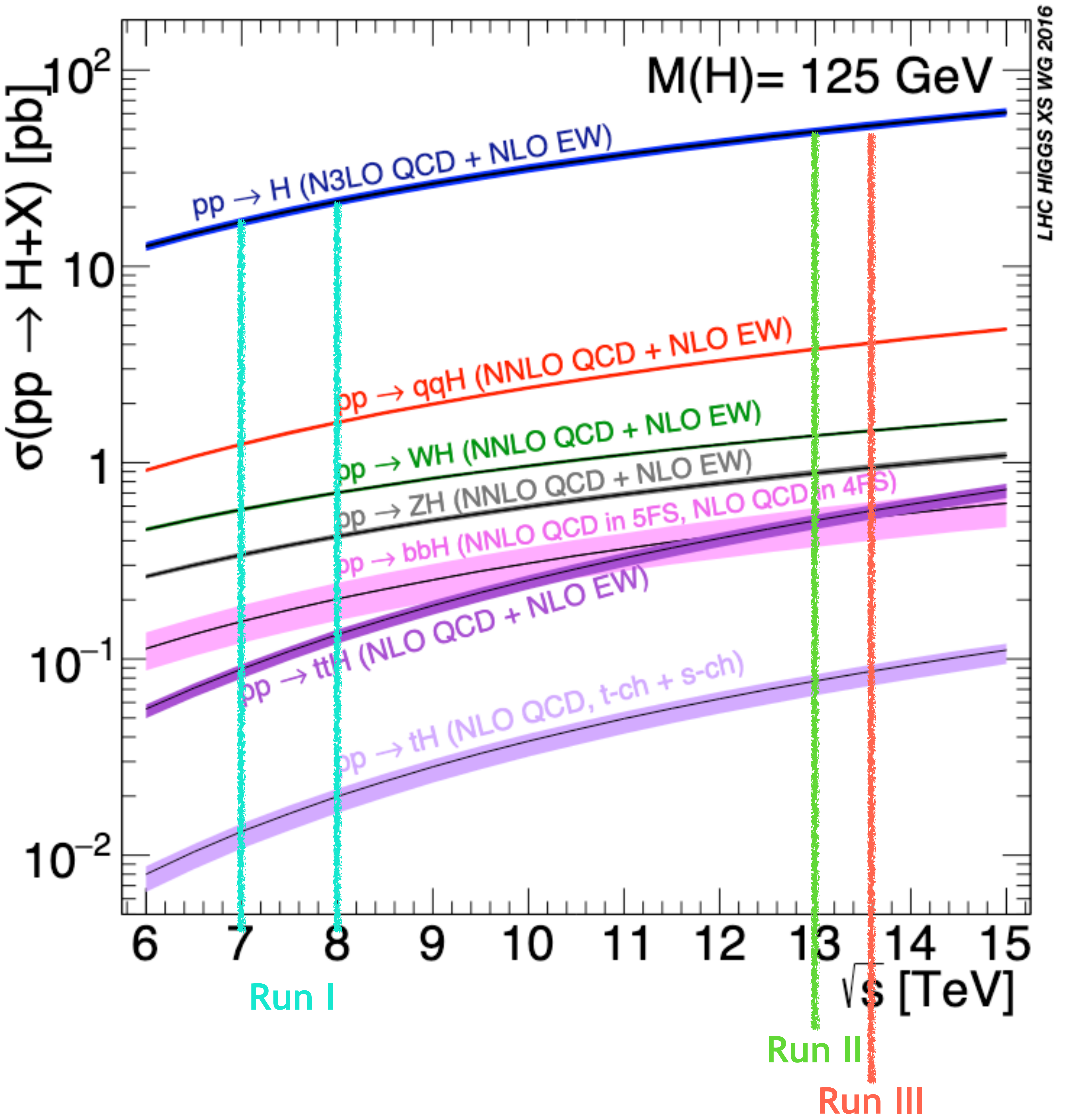


Run-III

The Higgs realm

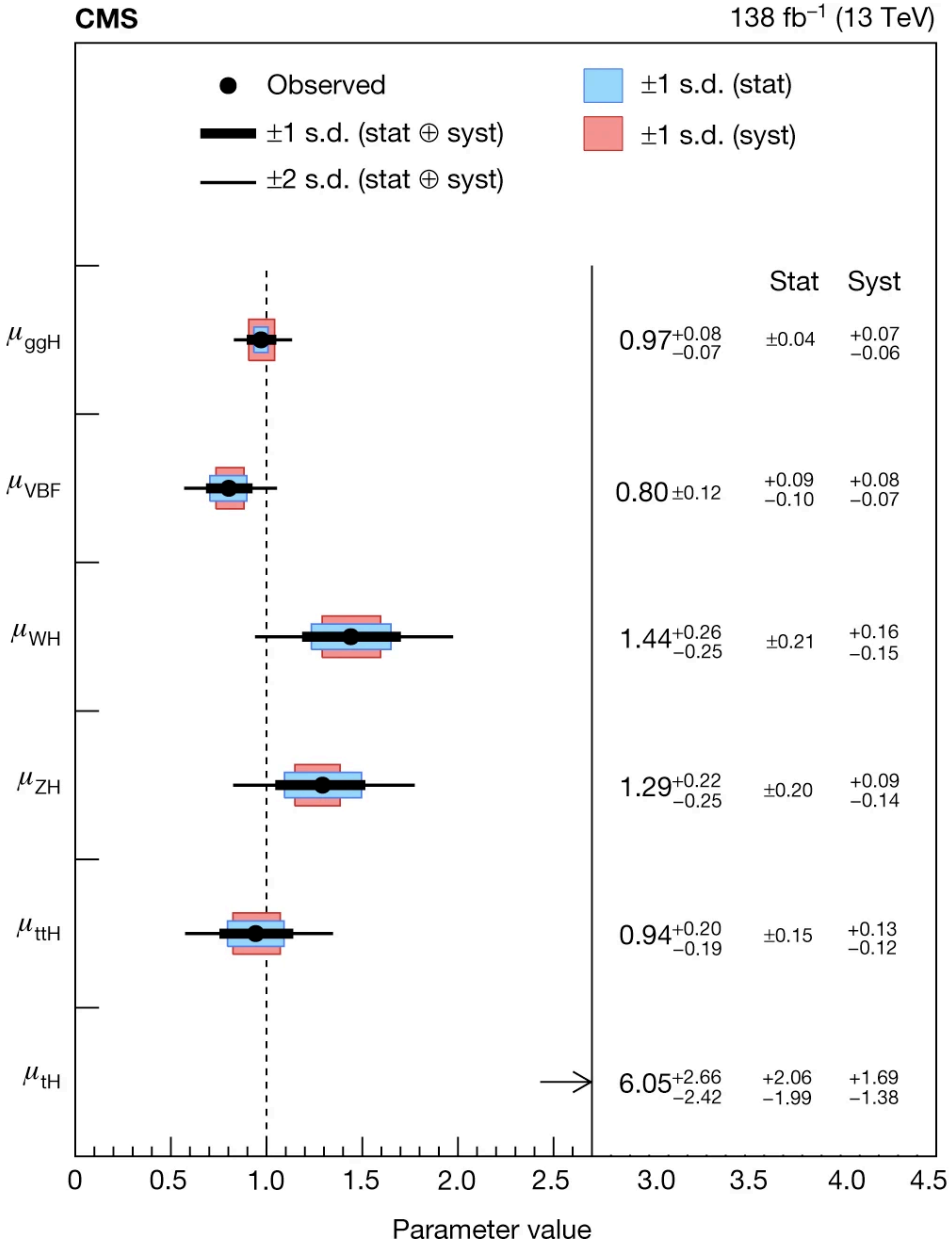
- Access to higher $\sqrt{s}$
- Improved analysis techniques
- Stress test of the SM predictions

Higgs cross sections at the LHC



A well understood particle (?)

- All the main production modes have been observed with a 5 SD significance
- Main production modes (ggH, VBF) probed at ~ 10% level
- We are entering the realm of measurements limited by systematic uncertainties (eg in ggH)
- Measuring inclusive signal strengths gives us an overall characterisation of the SM

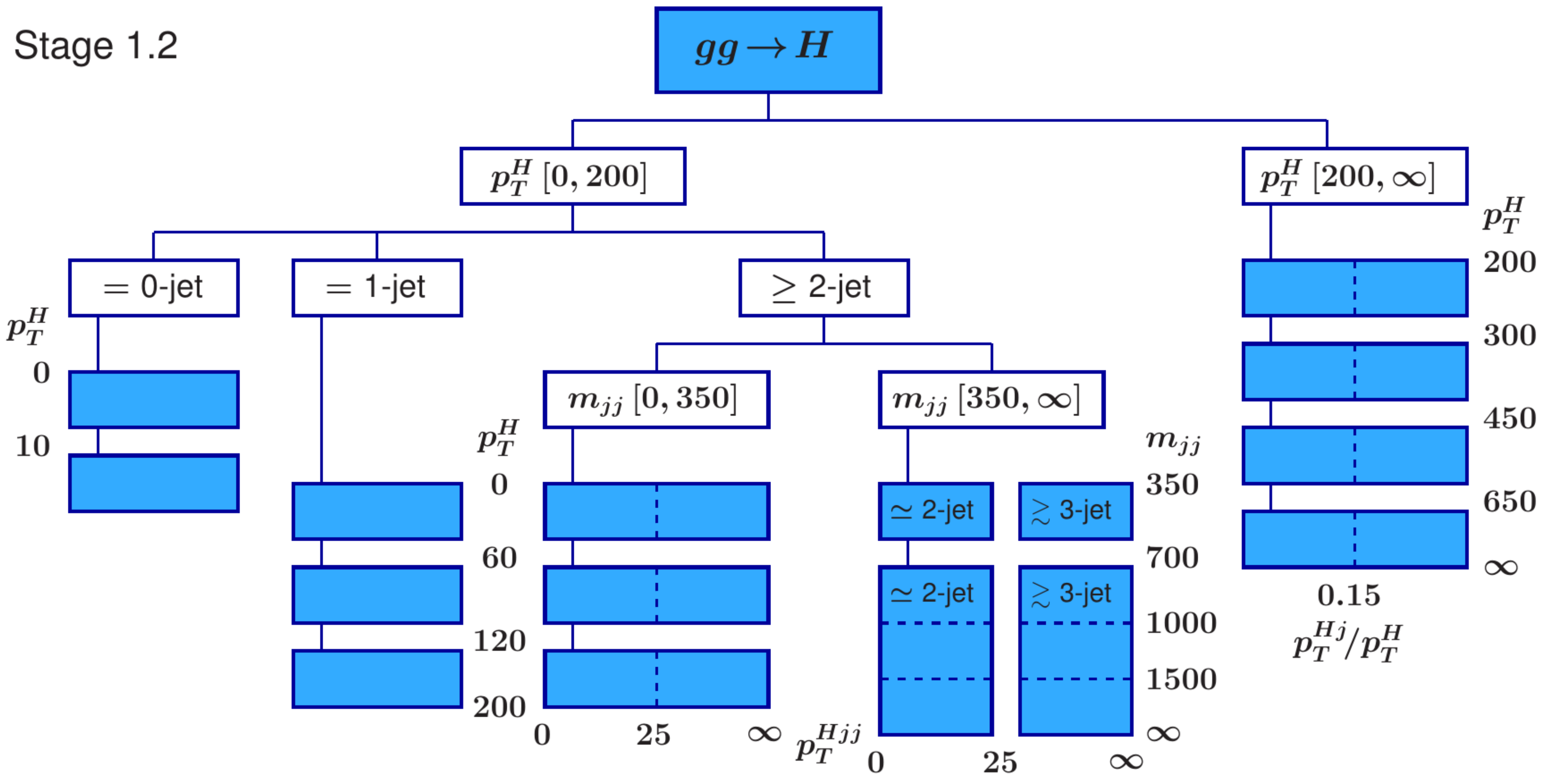


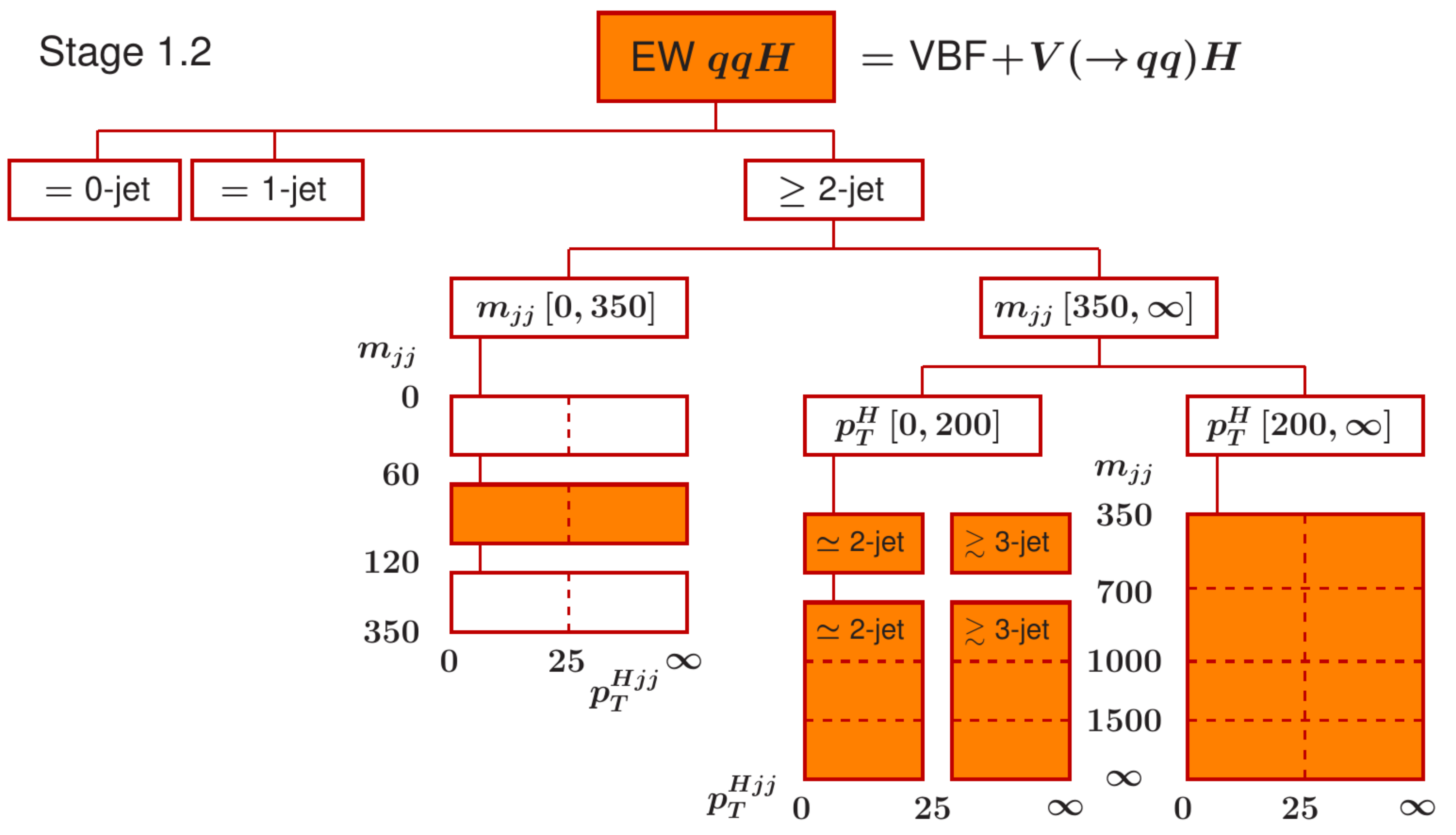
Nature 607 (2022) 60

The STXS Framework

The primary goal of STXS framework is to minimise the measurement dependence on theory predictions without losing sensitivity

Coverage of the entire phase space and **specific regions** designed **to detect BSM effects**





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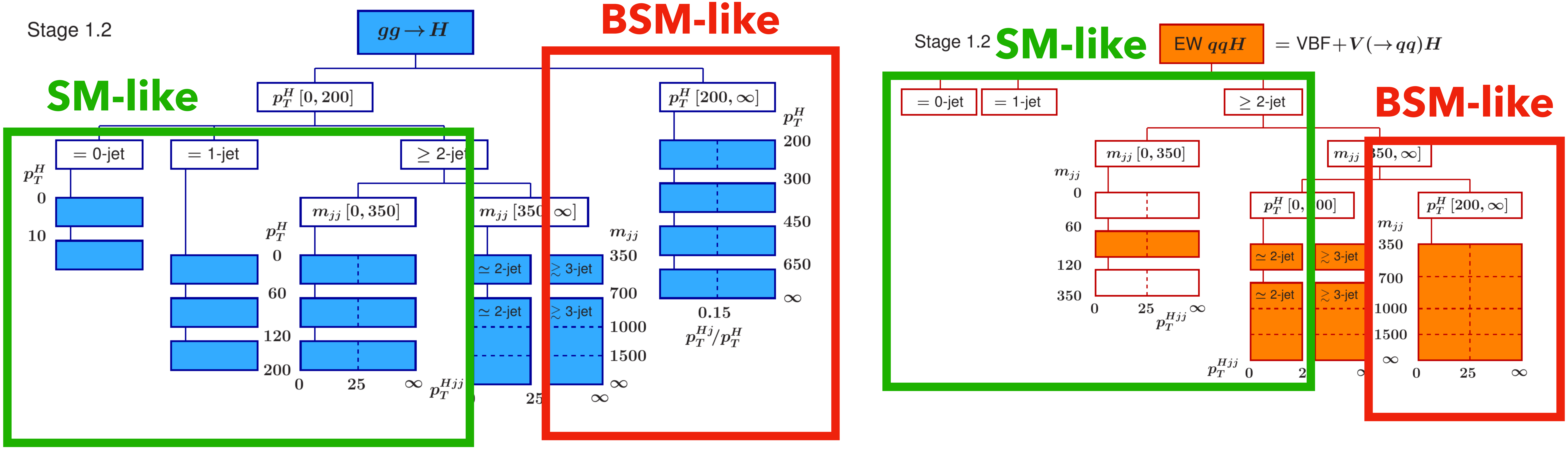
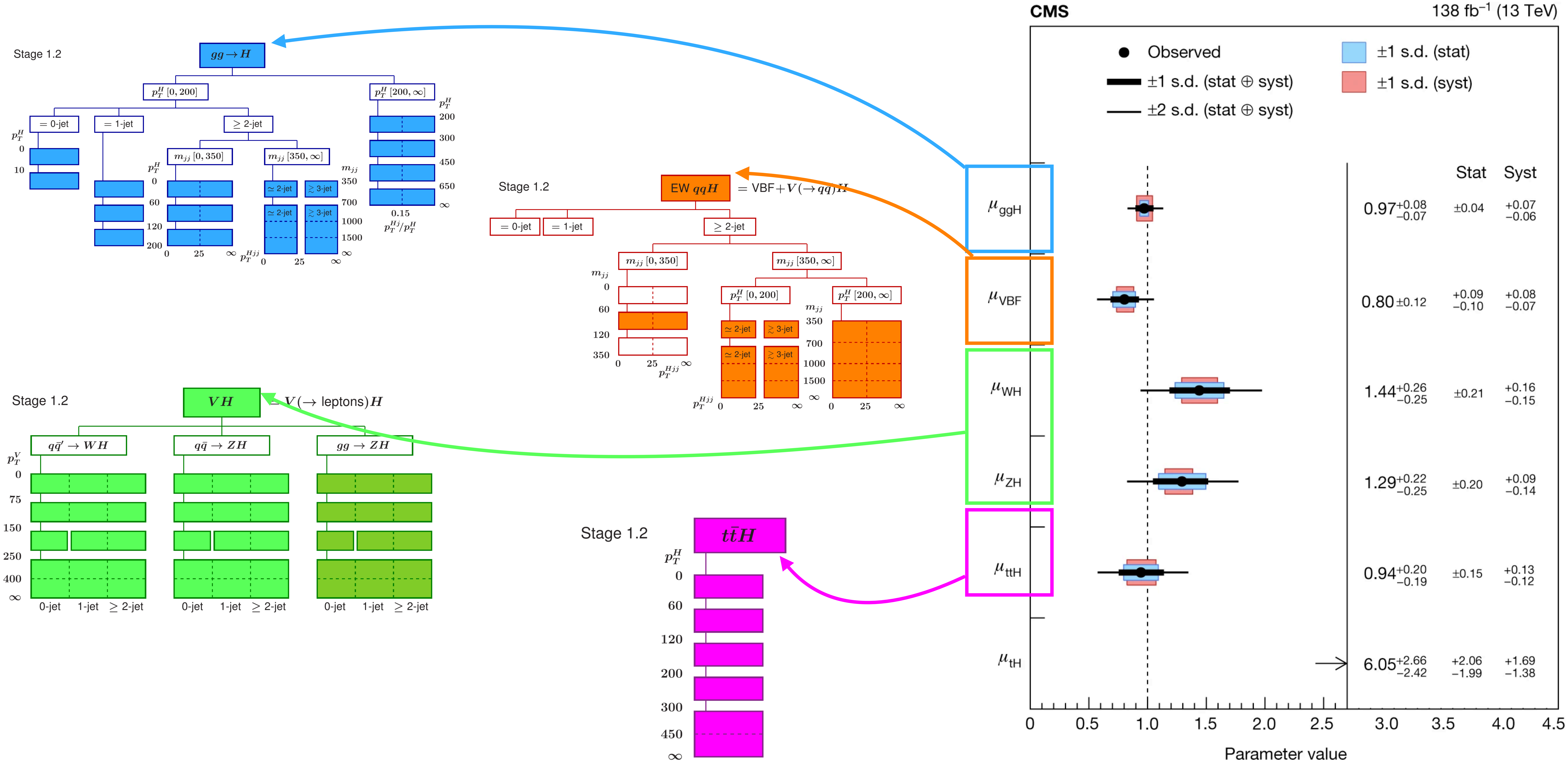


A look under the hood



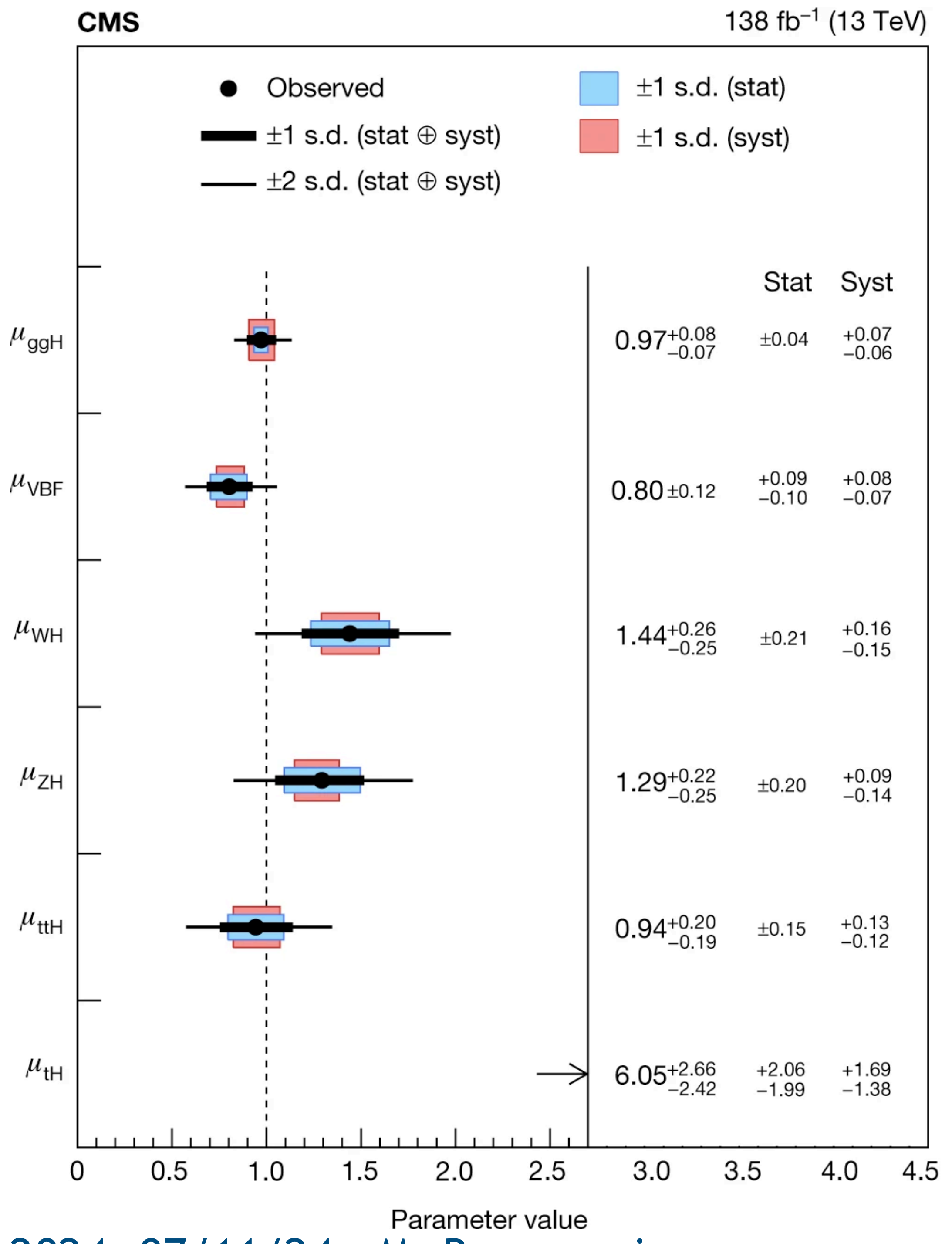
Nature 607 (2022) 60

With more data comes more responsibility

Model independence

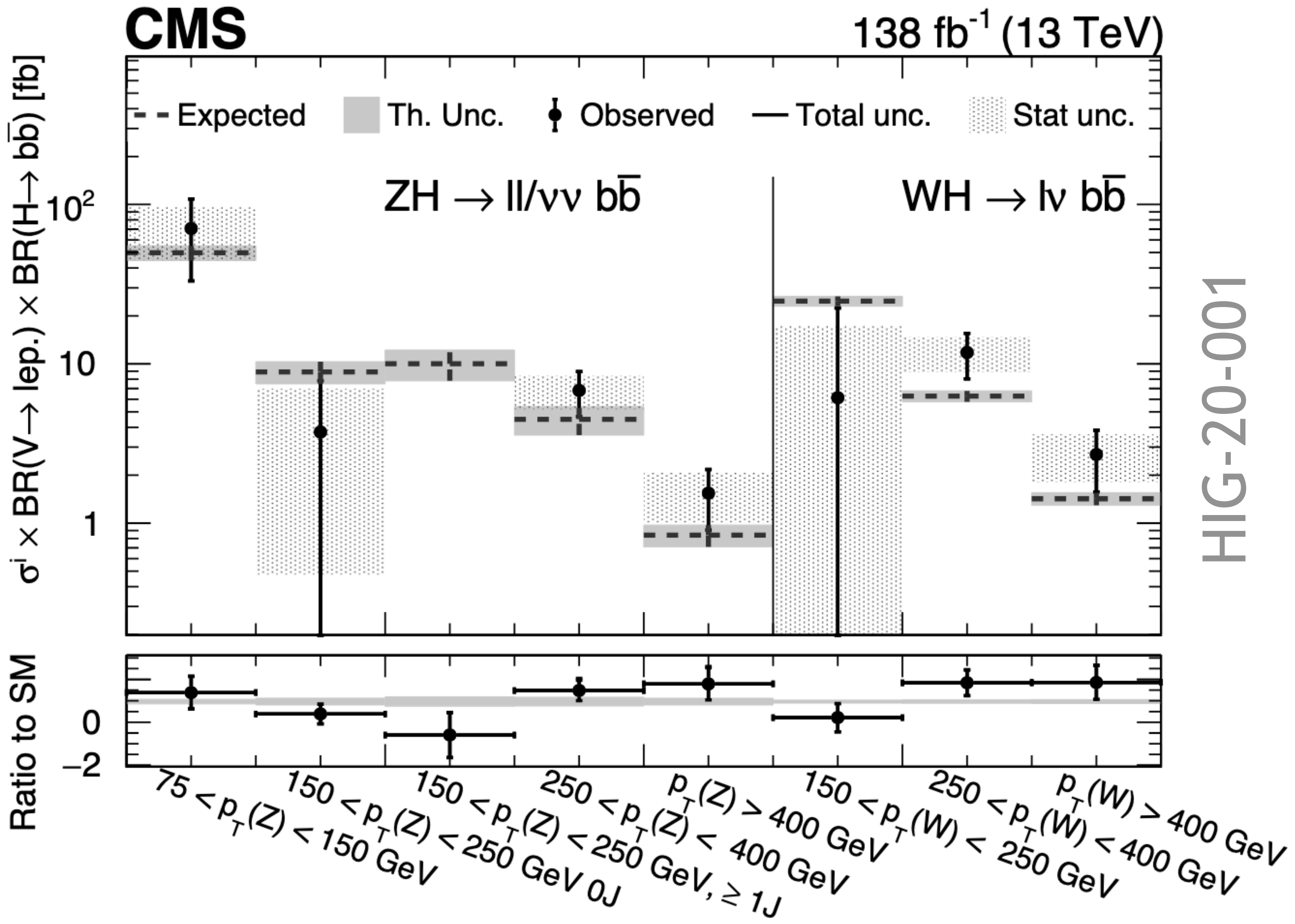
Statistically limited

Inclusive xsec
Signal strenghts



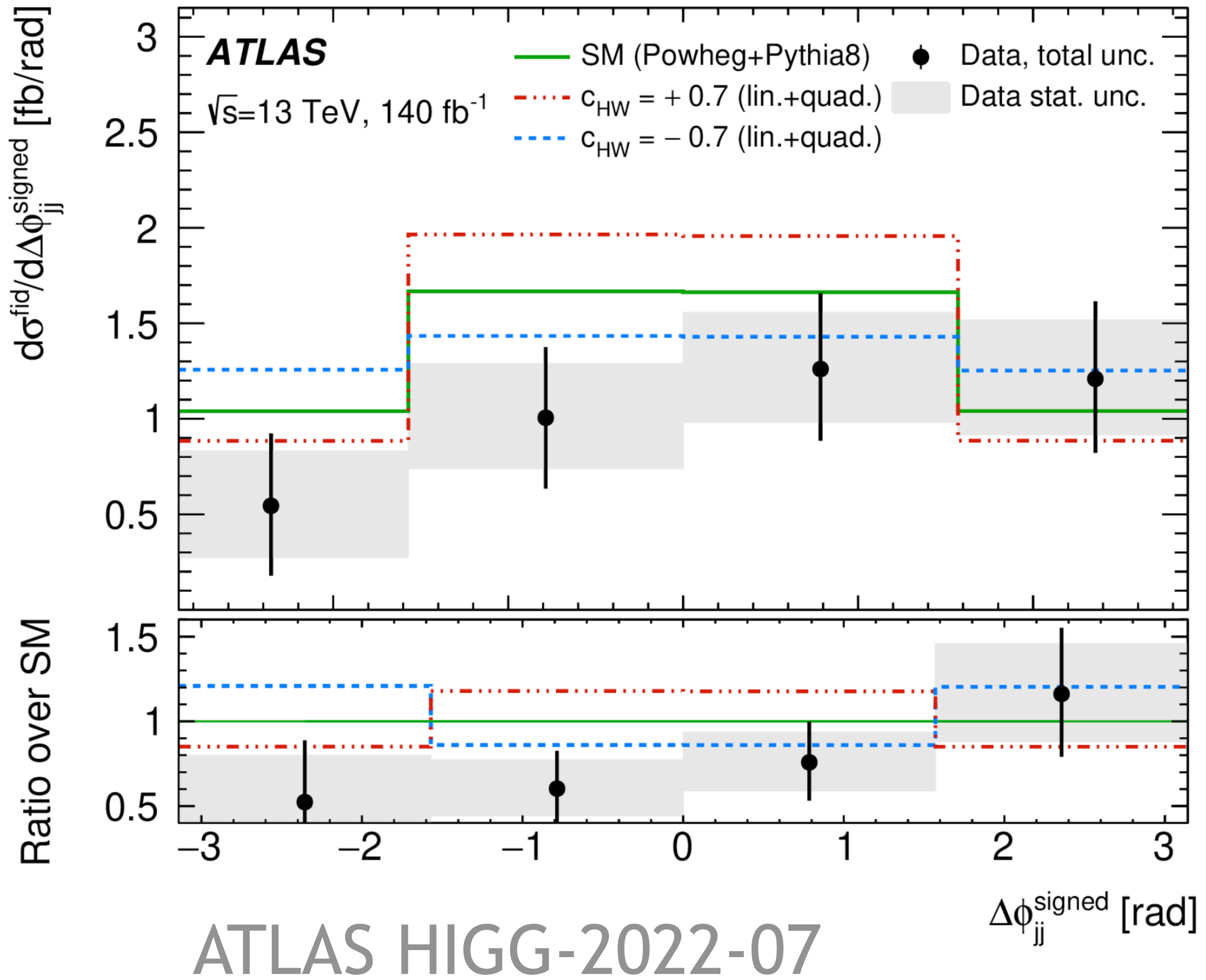
Nature 607 (2022) 60

STXS



HIG-20-001

Fiducial Cross Sections



ATLAS HIGG-2022-07

References and overview

Collaboration	Reference	Topic
CMS	Nature 607 (2022) 60	Run-II Combination
ATLAS	Nature 607 (2022) 52	Run-II Combination
ATLAS	ATLAS HIGG-2022-07	H(ττ) Run-II
ATLAS	CERN-EP-2024-194	ttH(bb) Run-II
ATLAS	HIGG-2020-20	VH(bb) Run-II
CMS	HIG-23-013	Run-II differential combination
CMS	HIG-23-015	ttH multilepton differential
CMS	HIG-23-014	H(γγ) differential Run-III
CMS	HIG-24-013	H(ZZ) differential Run-III

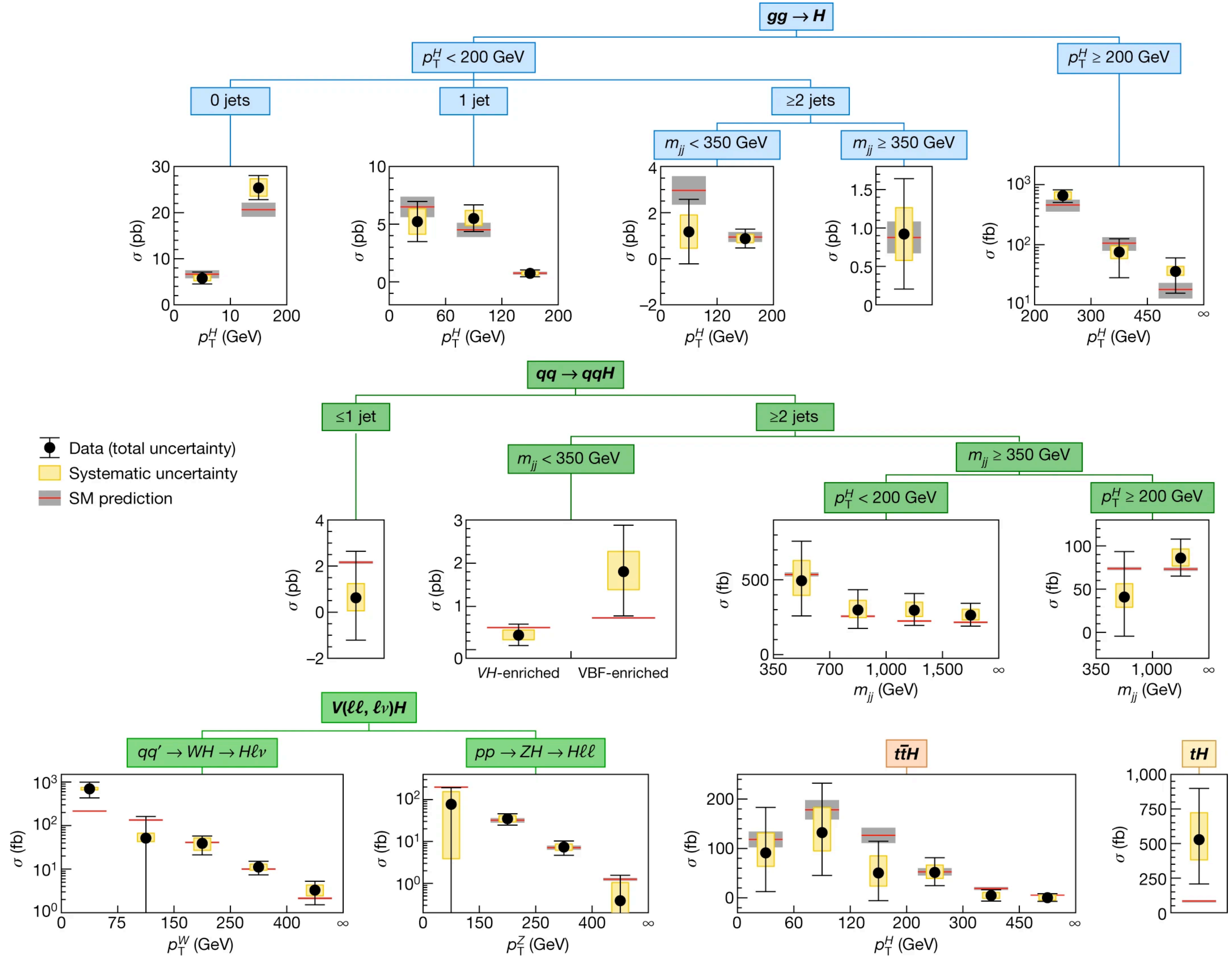
References and overview

The “negative picture” of the results shown today, from the other side of the LHC

Collaboration	Reference	Topic
CMS	HIG-19-010	H(ττ) Run-II
CMS	HIG-19-011	ttH(bb) Run-II
CMS	HIG-20-001	VH(bb) Run-II
ATLAS EXPERIMENT	JHEP 05 (2023) 028	Run-II differential combination (ZZ, γγ)
ATLAS EXPERIMENT	Eur. Phys. J. C 84 (2024) 78	H(γγ)/H(ZZ) differential Run-III
ATLAS EXPERIMENT	HIGG-2022-17	Run-II differential xsec EFT interpretation

Run-II STXS characterisation

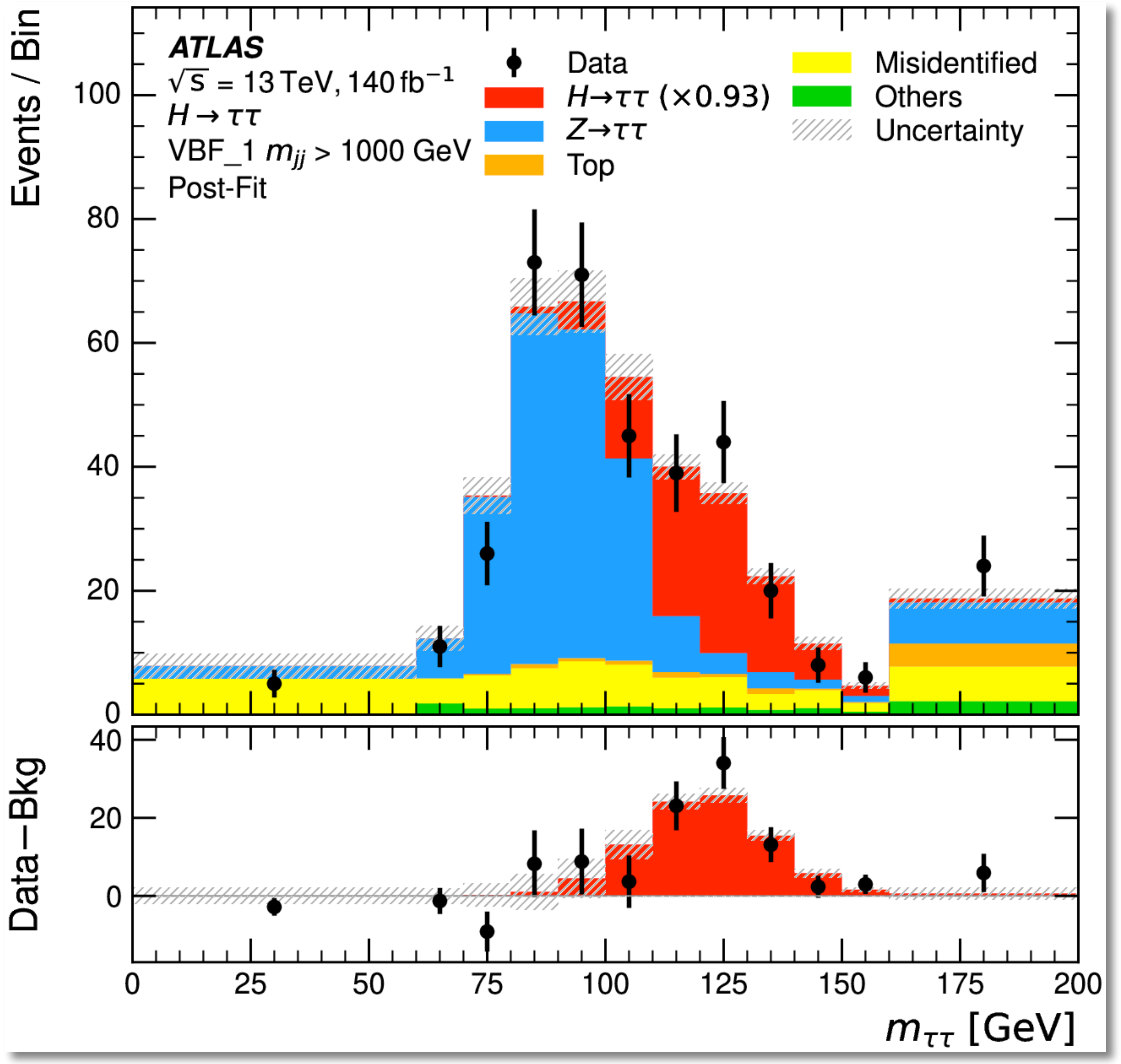
- High granularity characterisation of the Higgs boson production modes using full Run-II dataset
- In high-stat bins, experimental precision is comparable with theory precision!
- With Run-II data we can probe in detail BSM-like phase space and rarer production mechanisms!
- ATLAS & CMS keep improving their results to enhance the understanding of the Higgs sector

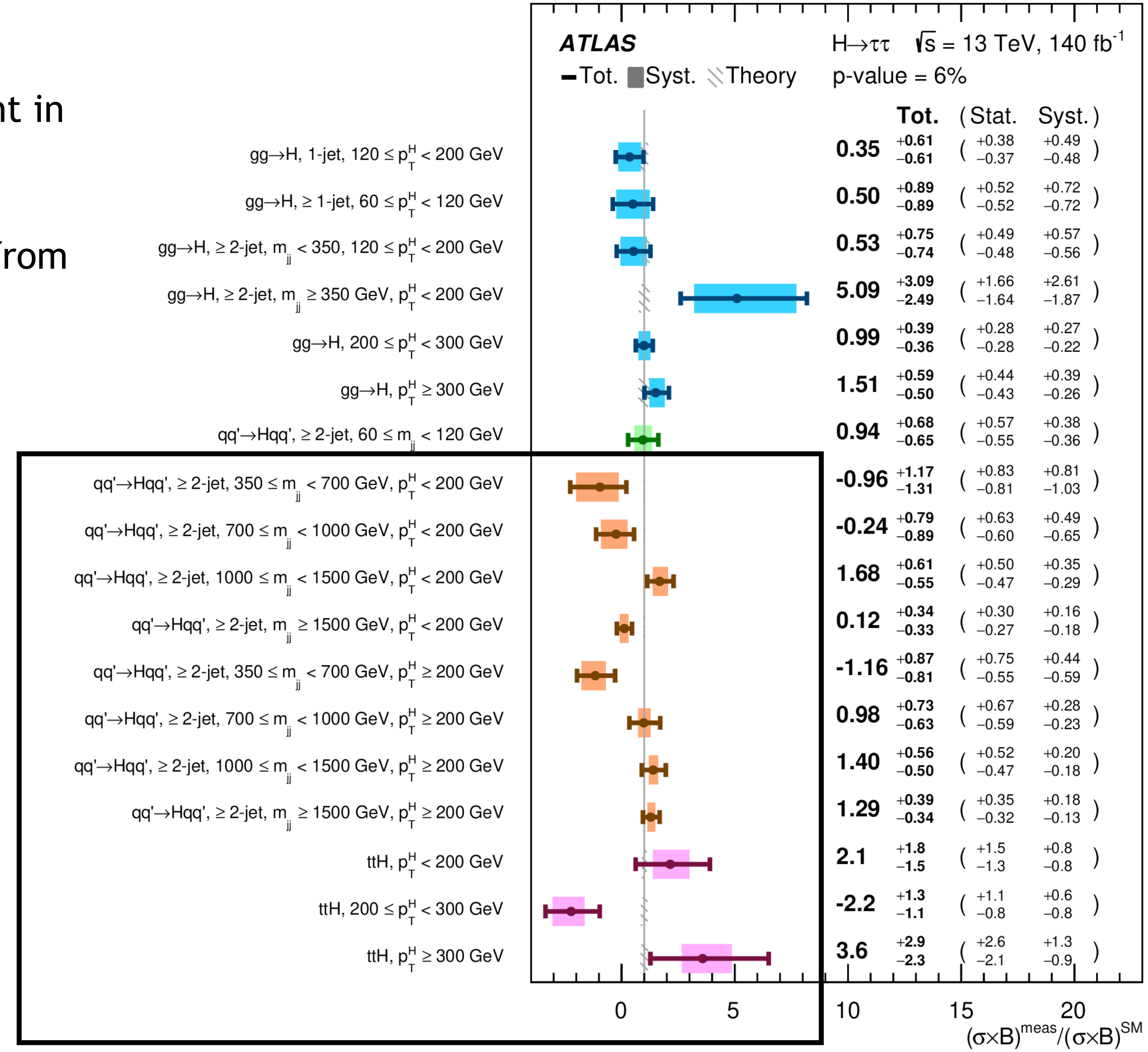


Nature 607 (2022) 52

ATLAS Run-II legacy $\mathrm{H} \to \tau\tau$

- 25% improvement in the ttH signal strength
- NN-based reconstruction of p_T^H, yielding a 50% improvement in resolution
- Multi-class BDT used to enhance separation of $t\bar{t}H$ events from backgrounds in VBF and $t\bar{t}H$ categories
- VBF categories, much higher granularity: from 1 to 8 bins



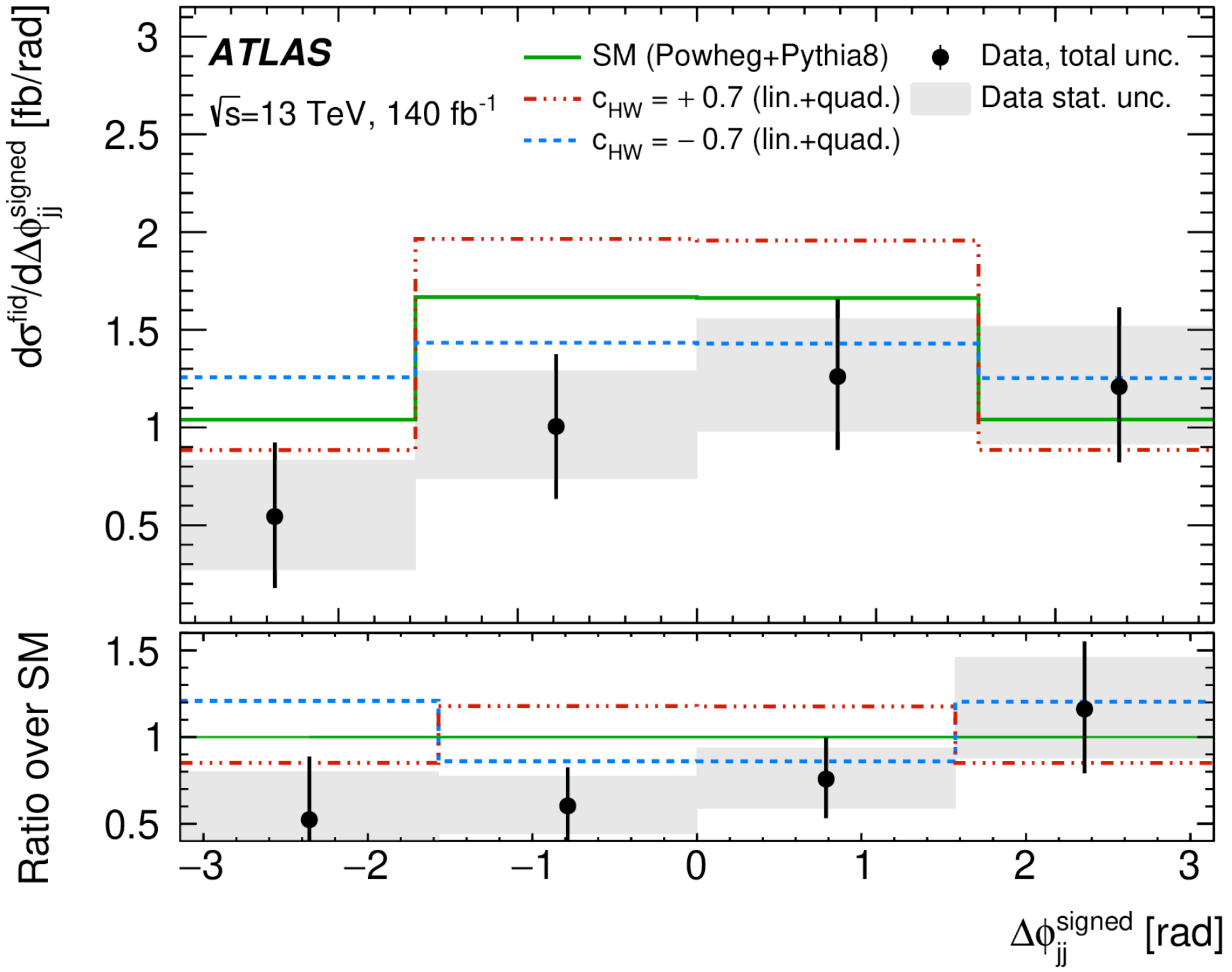


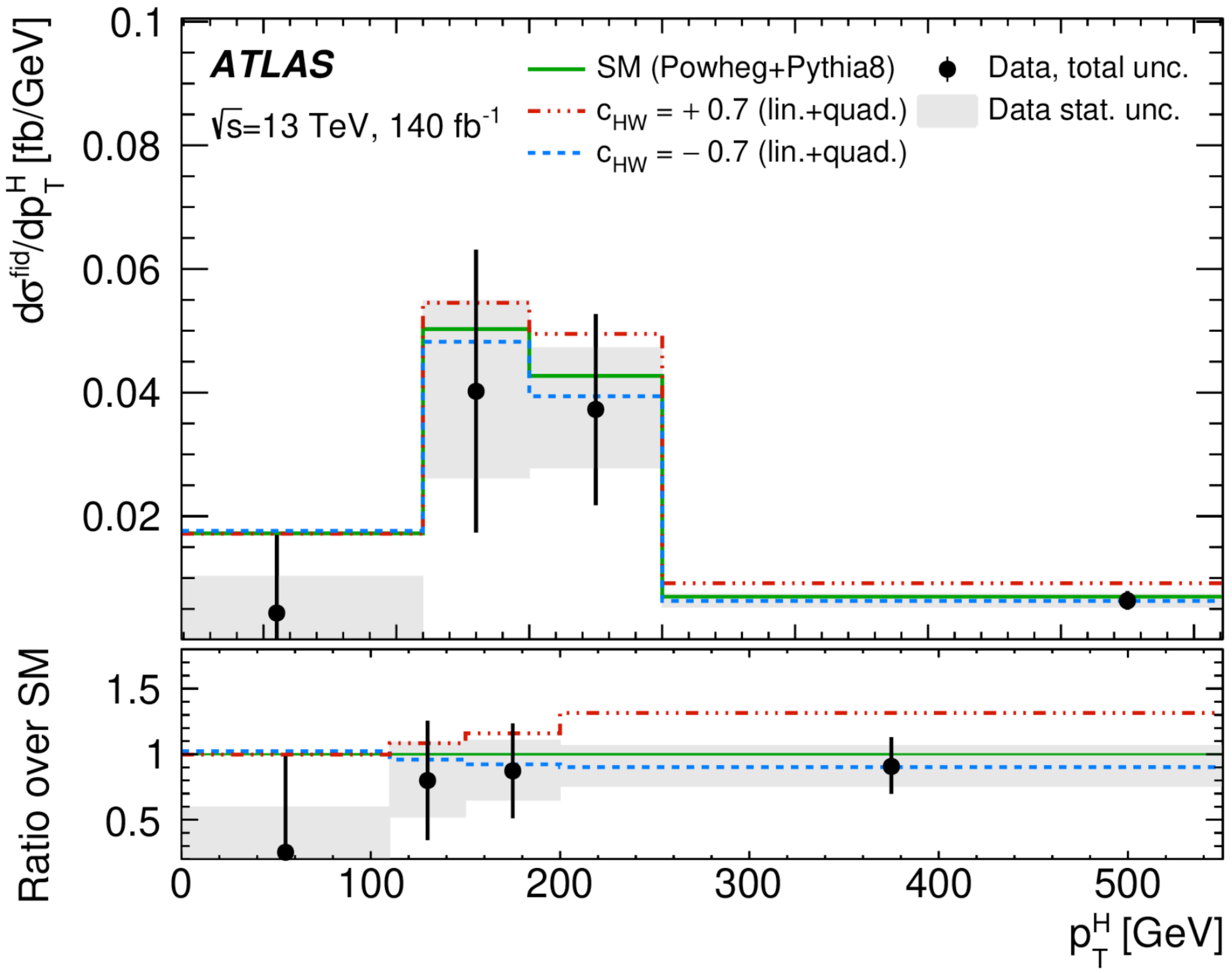
ATLAS HIGG-2022-07

ATLAS Run-II legacy $\mathrm{H} \rightarrow \tau\tau$

Measurement of cross-section in differential bins of $\Delta\phi_{jj}$ and p_T^H

Comparison with SM, but also with EFT scenarios for different Wilson Coefficients

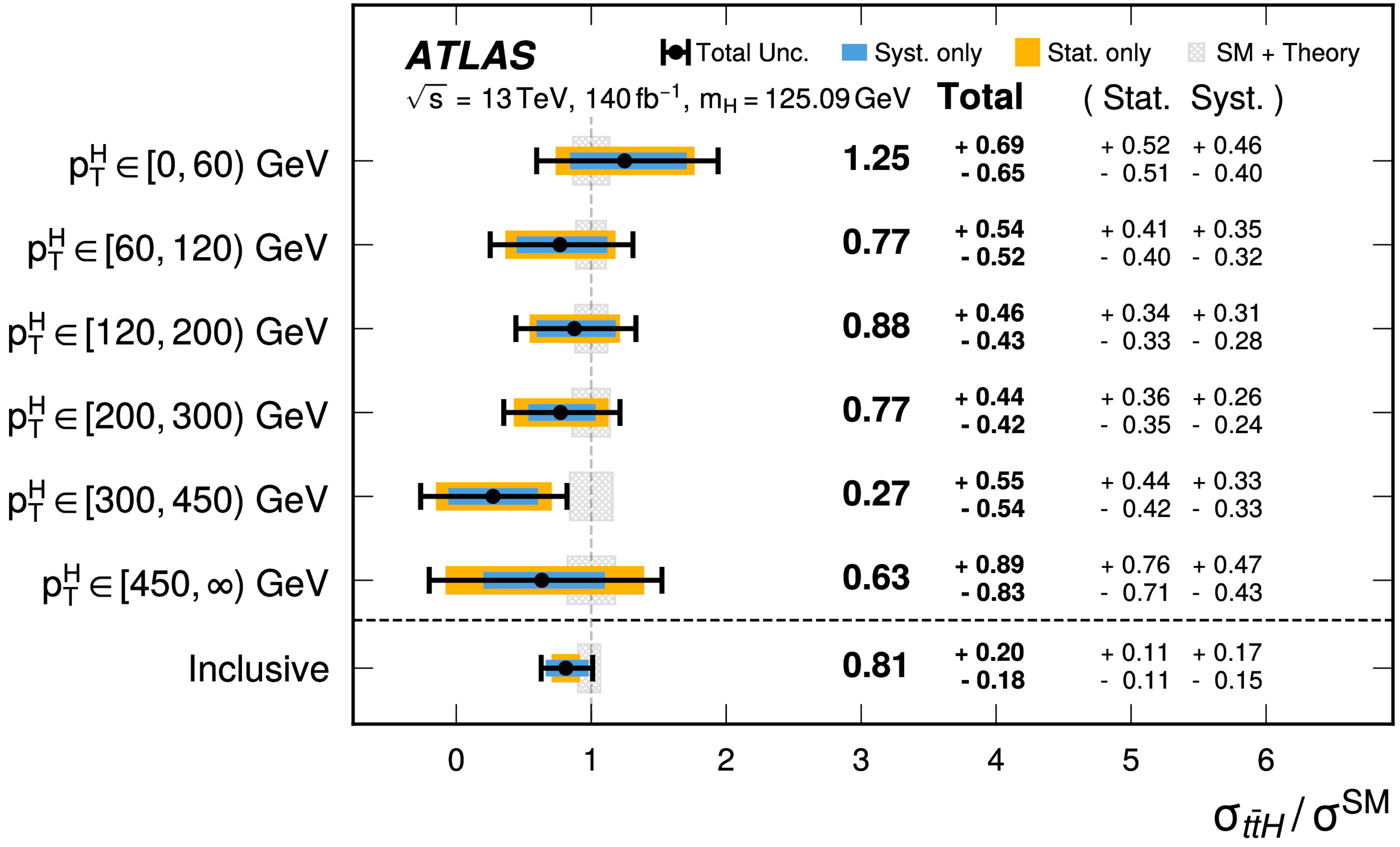




ATLAS HIGG-2022-07

ATLAS Run-II legacy $t\bar{t}H(b\bar{b})$

- Measurement of all $t\bar{t}H$ STXS bins
- NN-based classifier using transformers with attention mechanism
- Additional improvements in MC modelling
- Transformer NN to select the two Higgs candidate jets ⇒ improved categorisation into different STXS regions
- Overall uncertainty improved by factor 1.8
- 4.6 SD observed in ttH(bb) alone!



CERN-EP-2024-194

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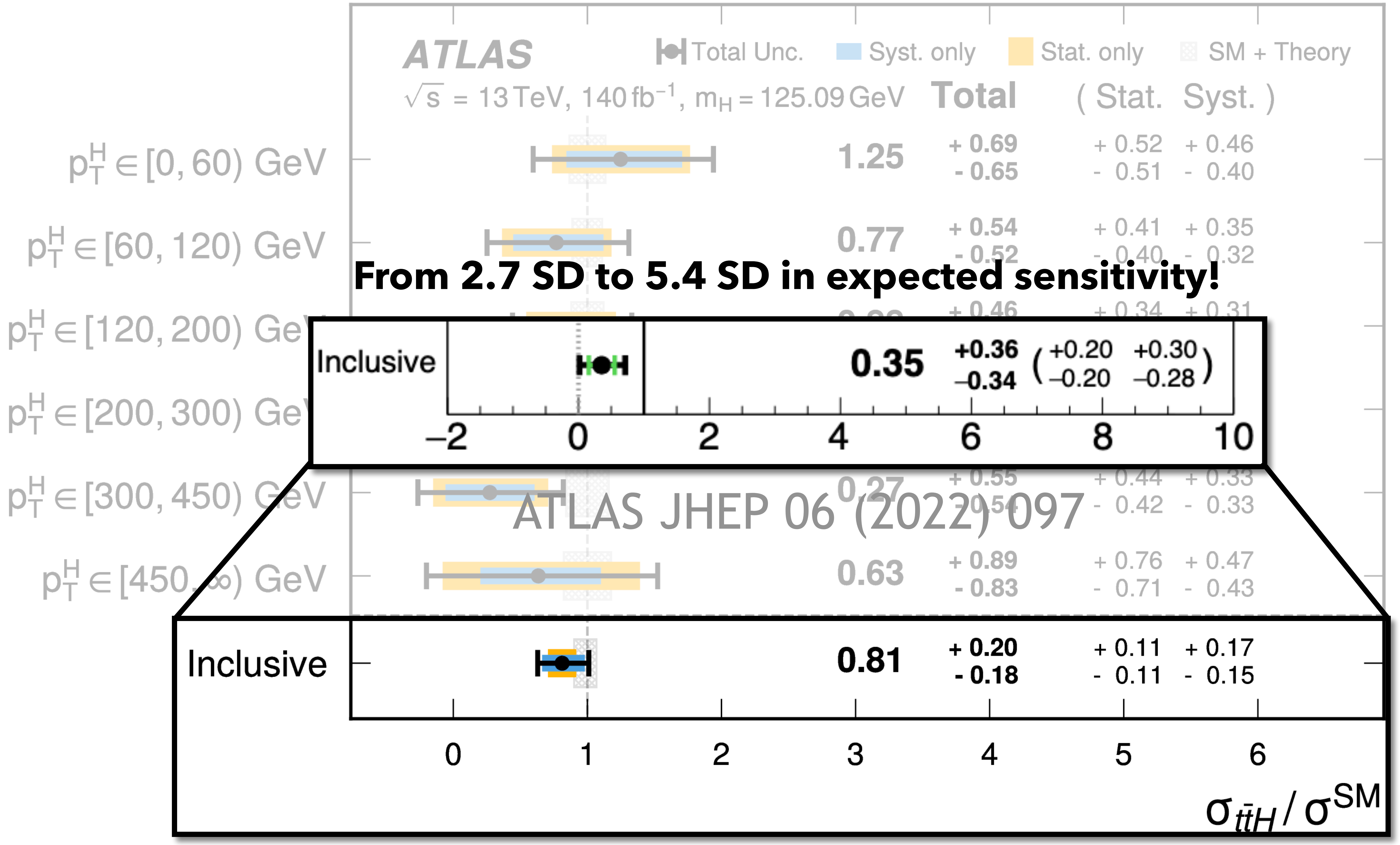
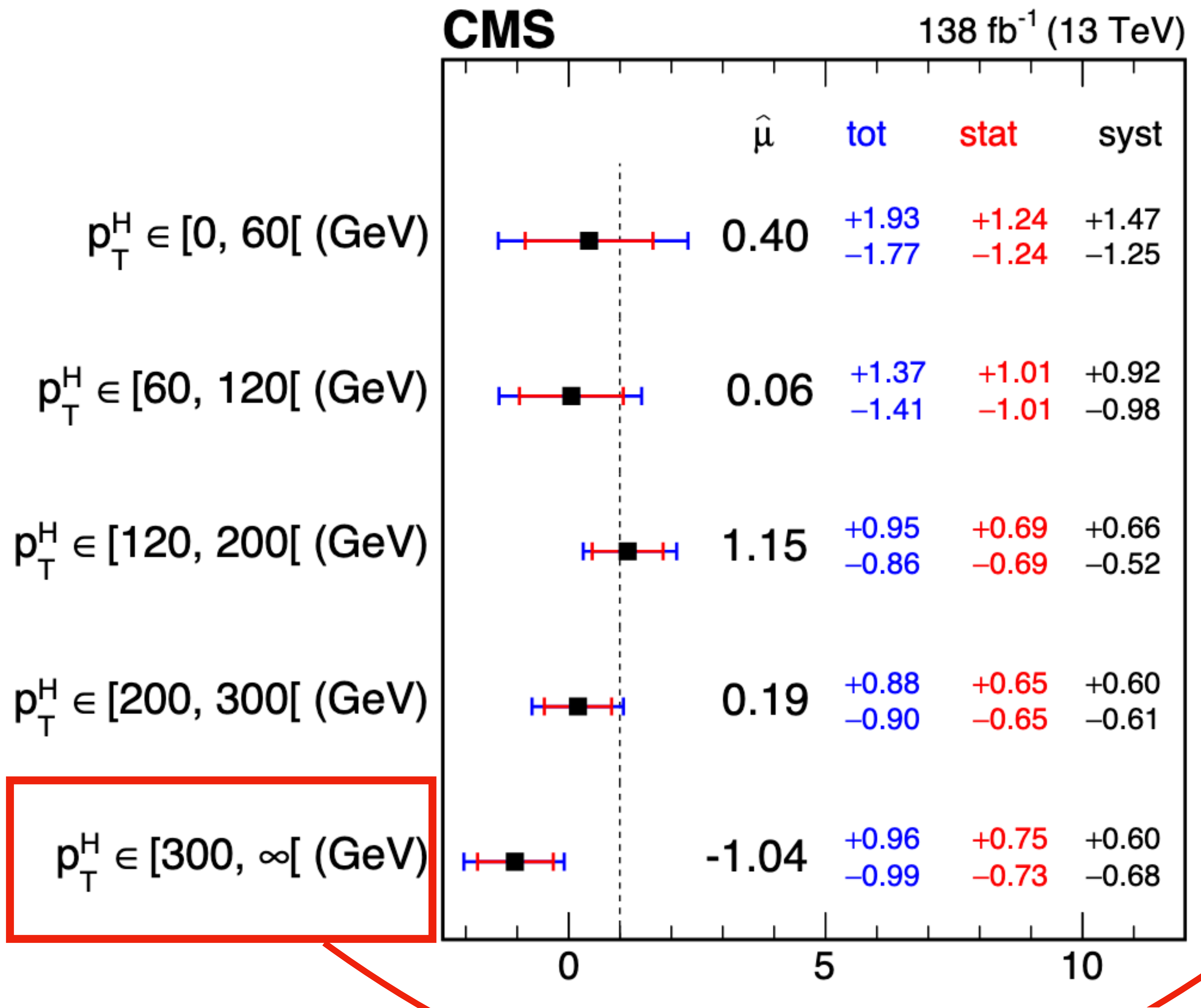


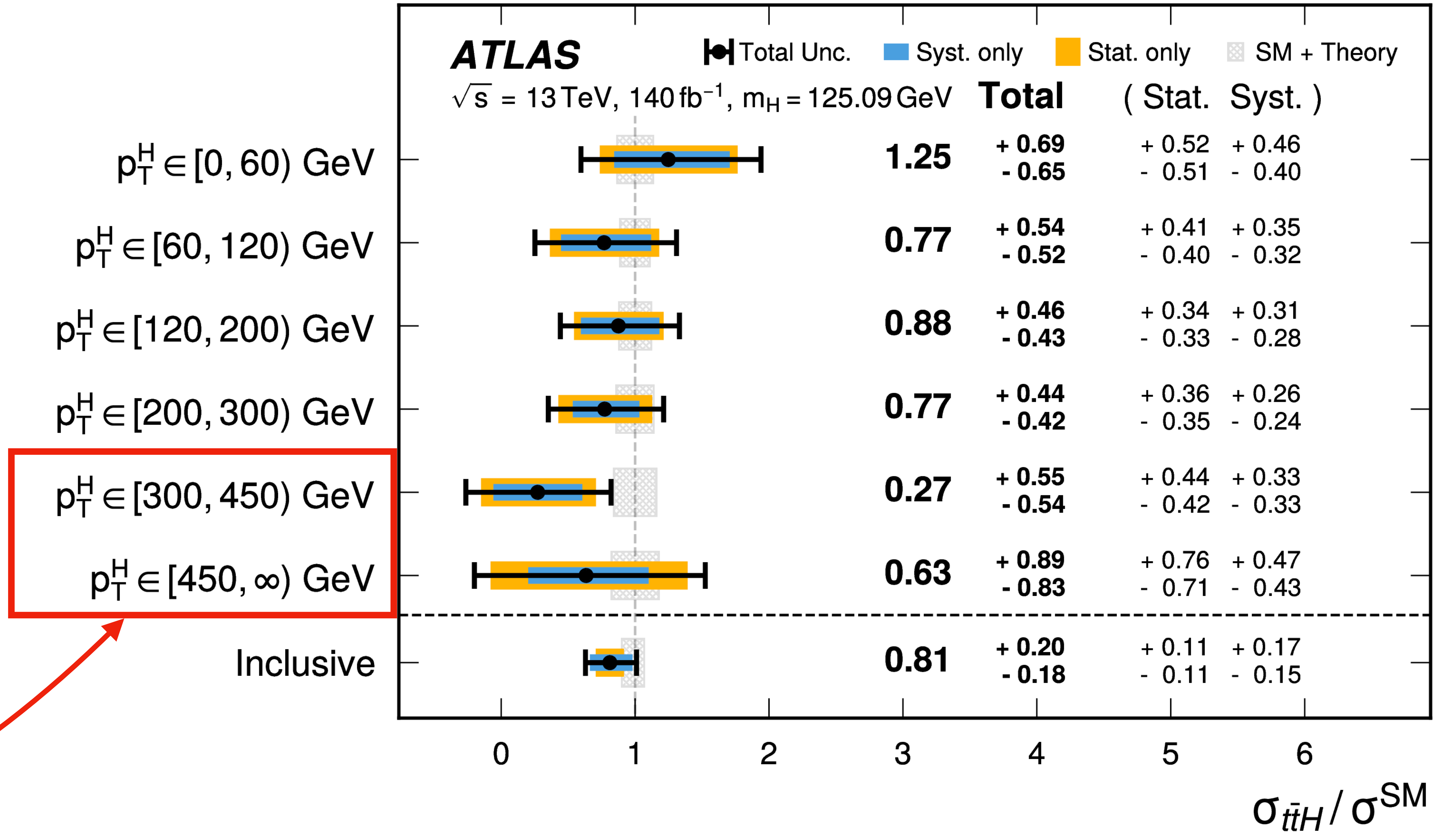
CERN-EP-2024-194

Run-II legacy $t\bar{t}H(b\bar{b})$: ATLAS & CMS



$\hat{\mu} = \hat{\sigma}/\sigma_{SM}$

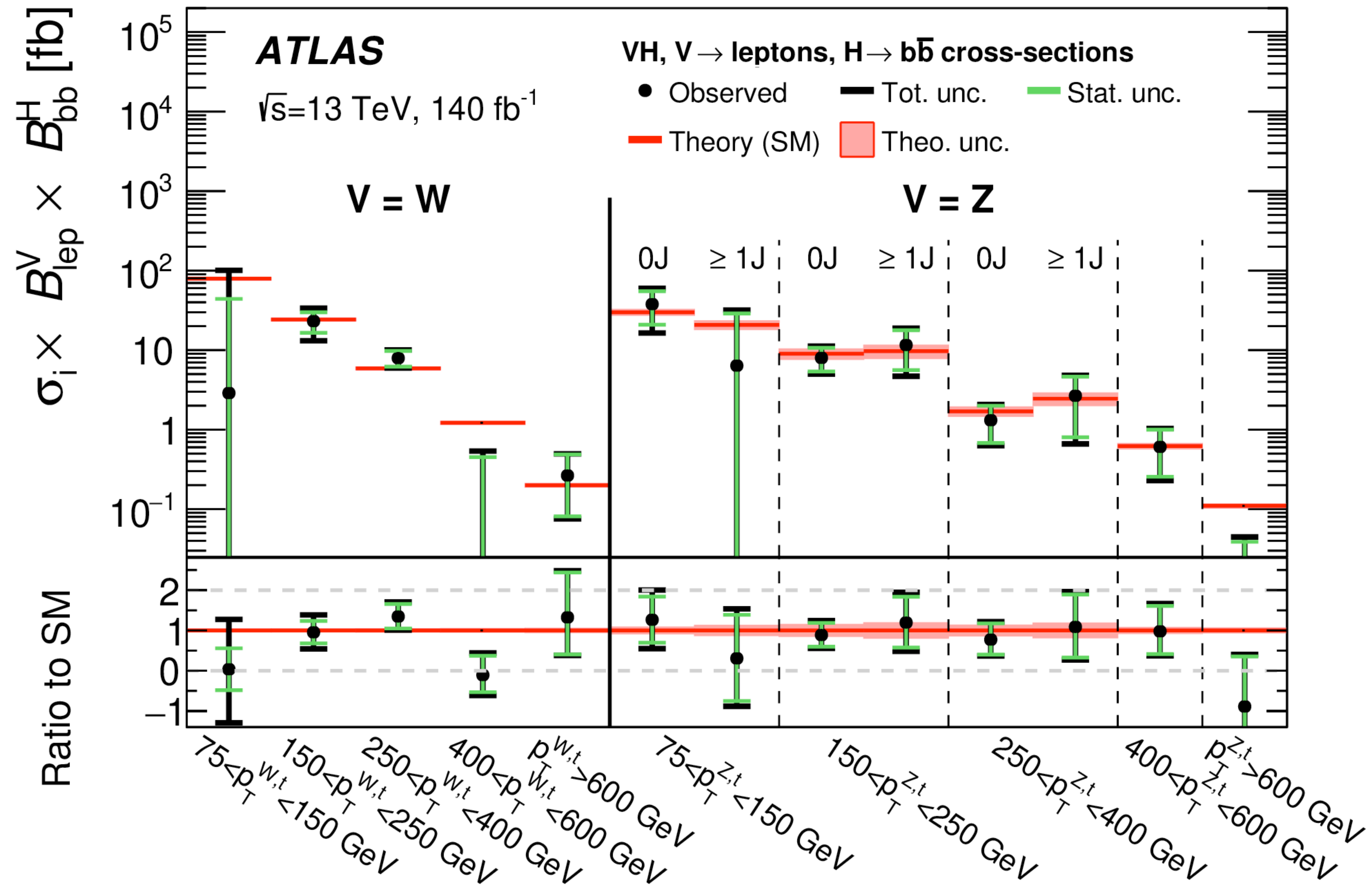
HIG-19-001



CERN-EP-2024-194

ATLAS Run-II legacy VH($b\bar{b}$)

- Combined measurement of VH(bb) and VH(cc), use flavor-based CRs to control different flavor components
- DL1r used for flavour-based jet-tagging
- Combination of resolved and boosted final states in the V-leptonic channel
- Target STXS V-lep bins & benchmarked against VZ(bb)
  - ⇒ First ATLAS result of VZ(cc) at 5 SD
- Uncertainties reduced by ~20%
- First observation of WH($b\bar{b}$) at 5.3 SD



HIGG-2020-20

Strongest (obs) limit on VH($c\bar{c}$)

- Exclusion of bottom-charm Yukawa coupling universality at ~ 3 SD

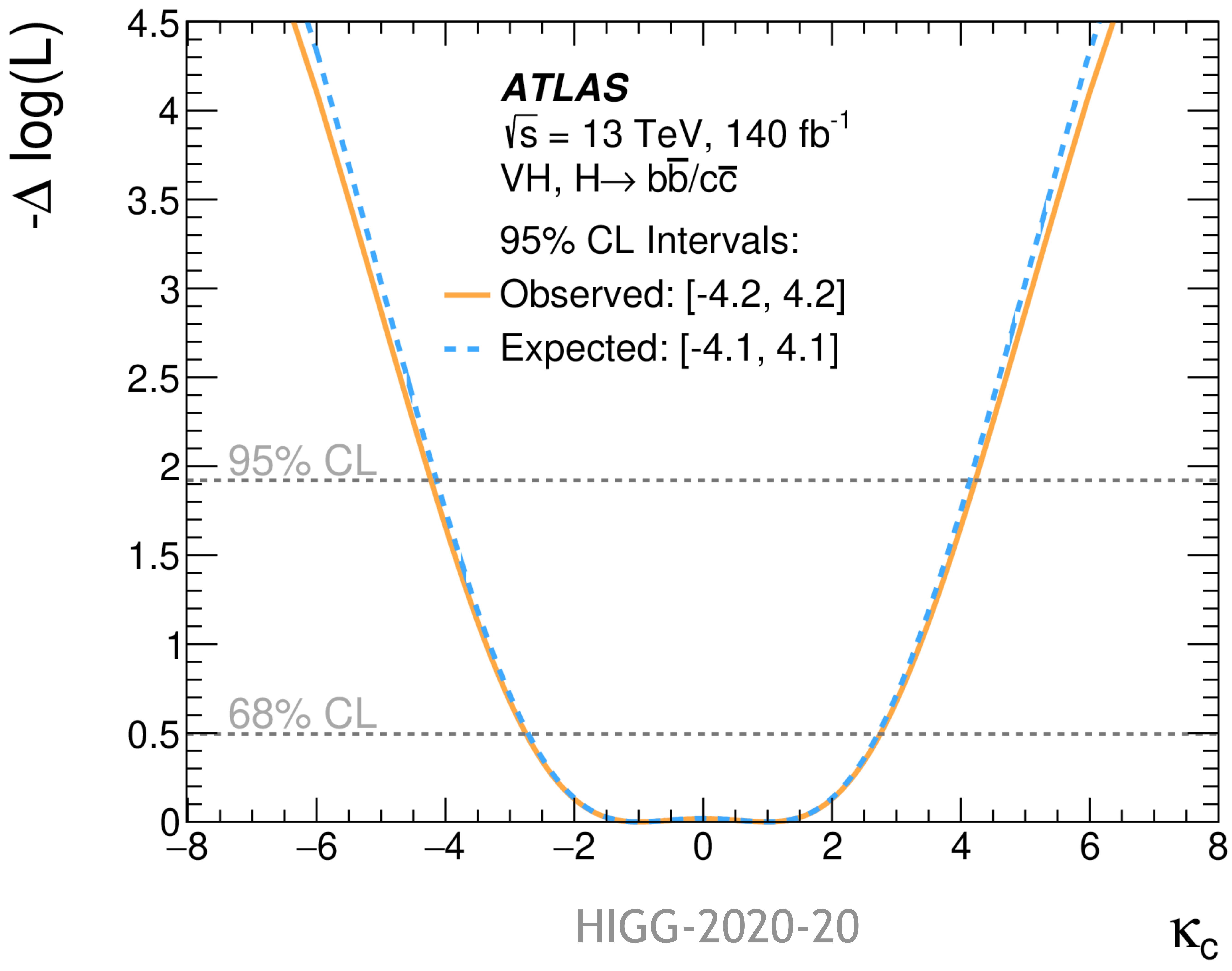
- Simultaneous extraction of VH($b\bar{b}$) and VH($c\bar{c}$), for an upper limit of

$$\mu_{VH(c\bar{c})} < 11.5 \text{ @ 95\% CL}$$

- Simultaneous extraction of VH($b\bar{b}$) and VH($c\bar{c}$) coupling modifiers

$$|\kappa_c| < 4.2 \text{ @ 95\% CL}$$

(HL-LHC projection was $|\kappa_c| < 3$)

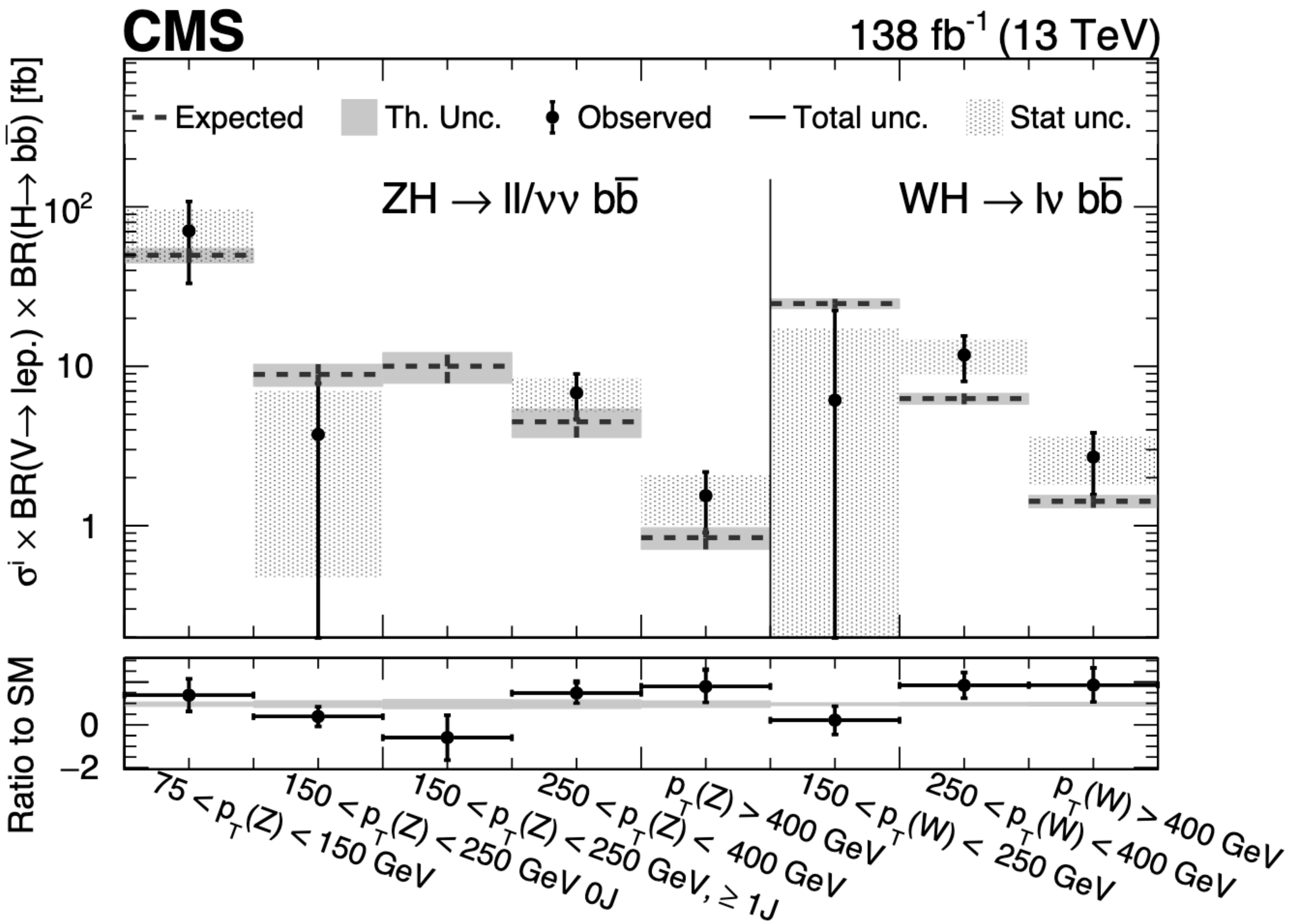


HIGG-2020-20

CMS Run-II legacy VH($b\bar{b}$)

Dedicated measurements of VH(bb) in resolved and boosted topologies

Precision of STXS measurements comparable to ATLAS results



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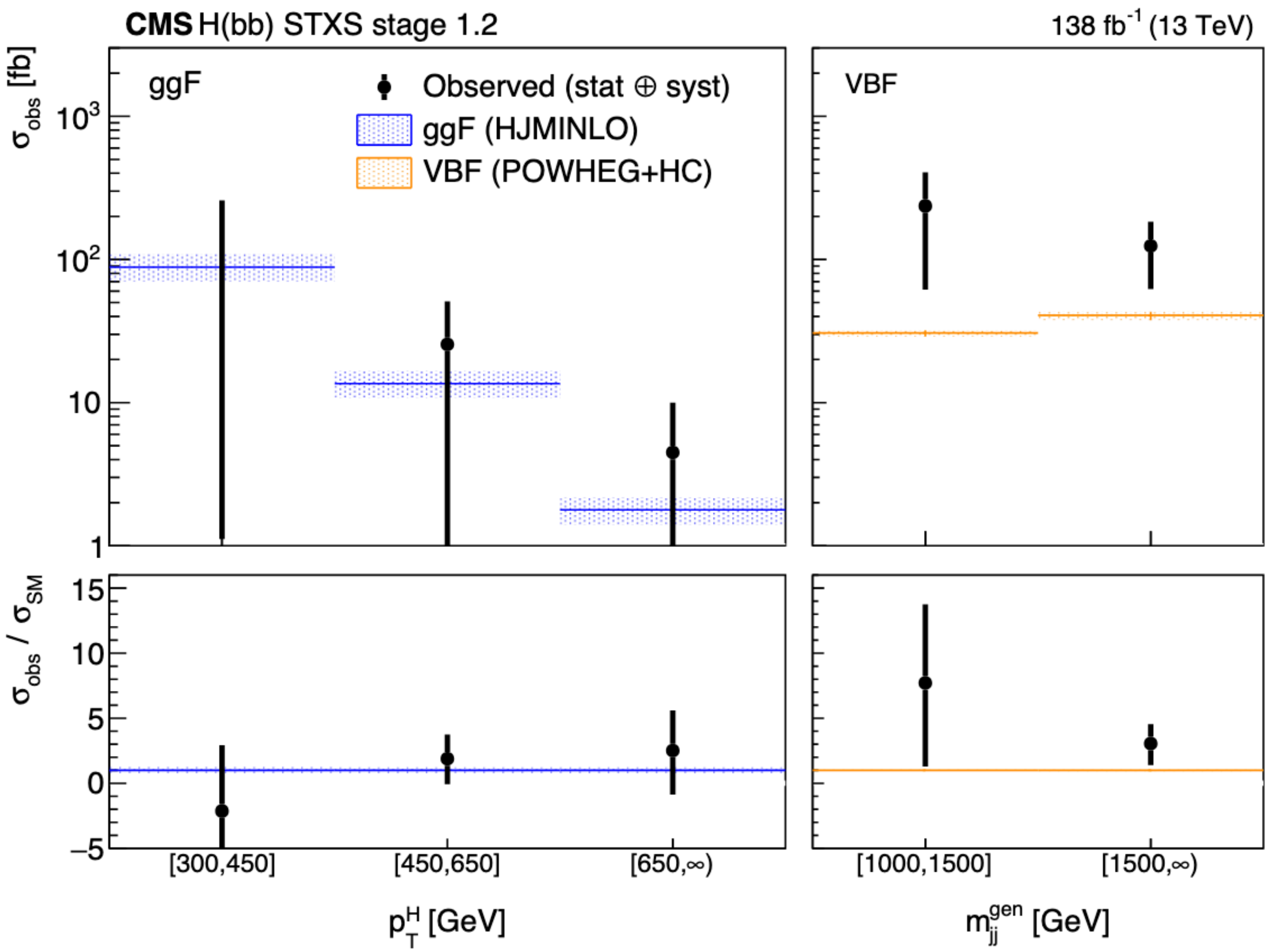
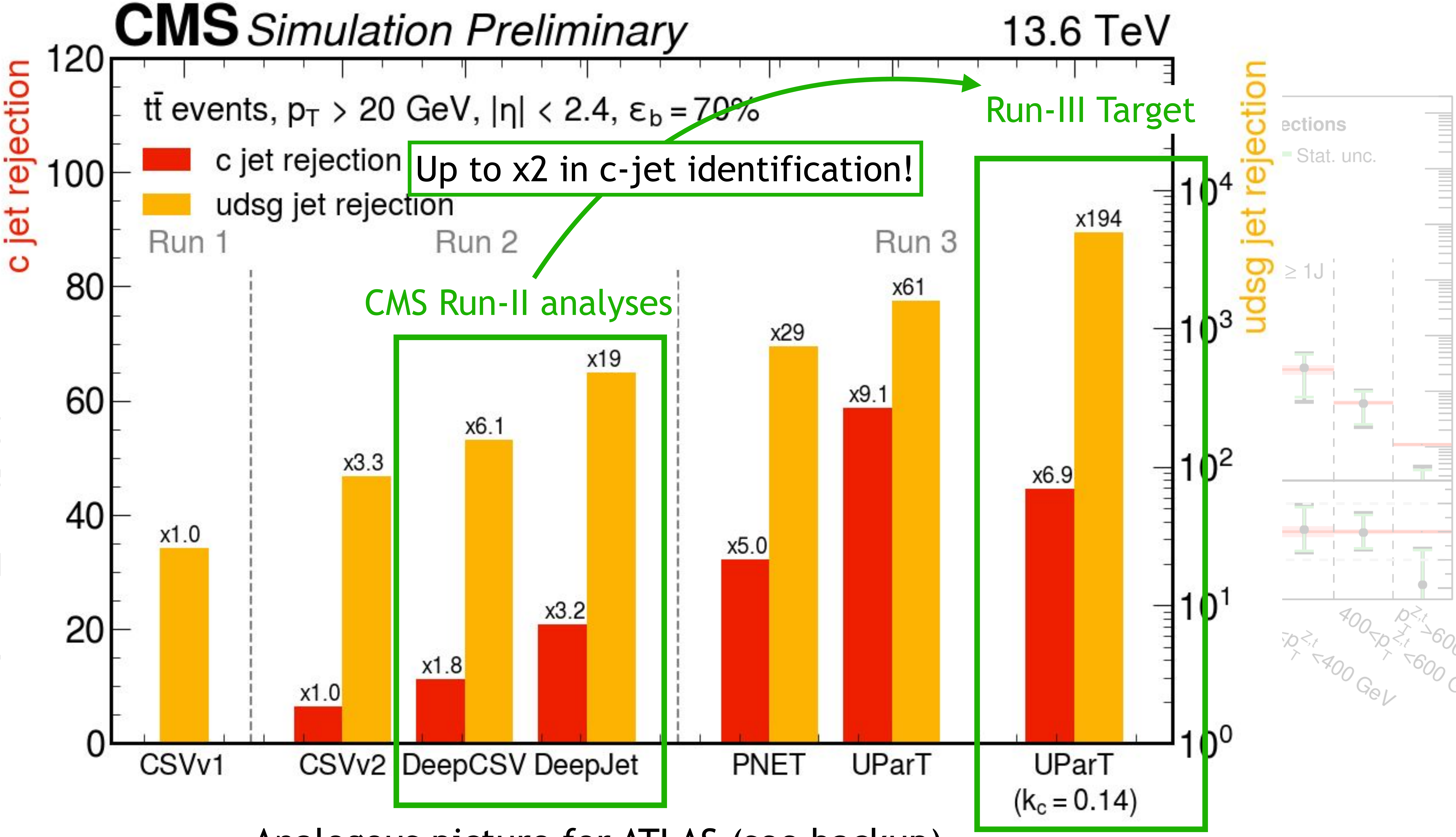


HIG-21-020

Jet-taggers from Run-II to Run-III

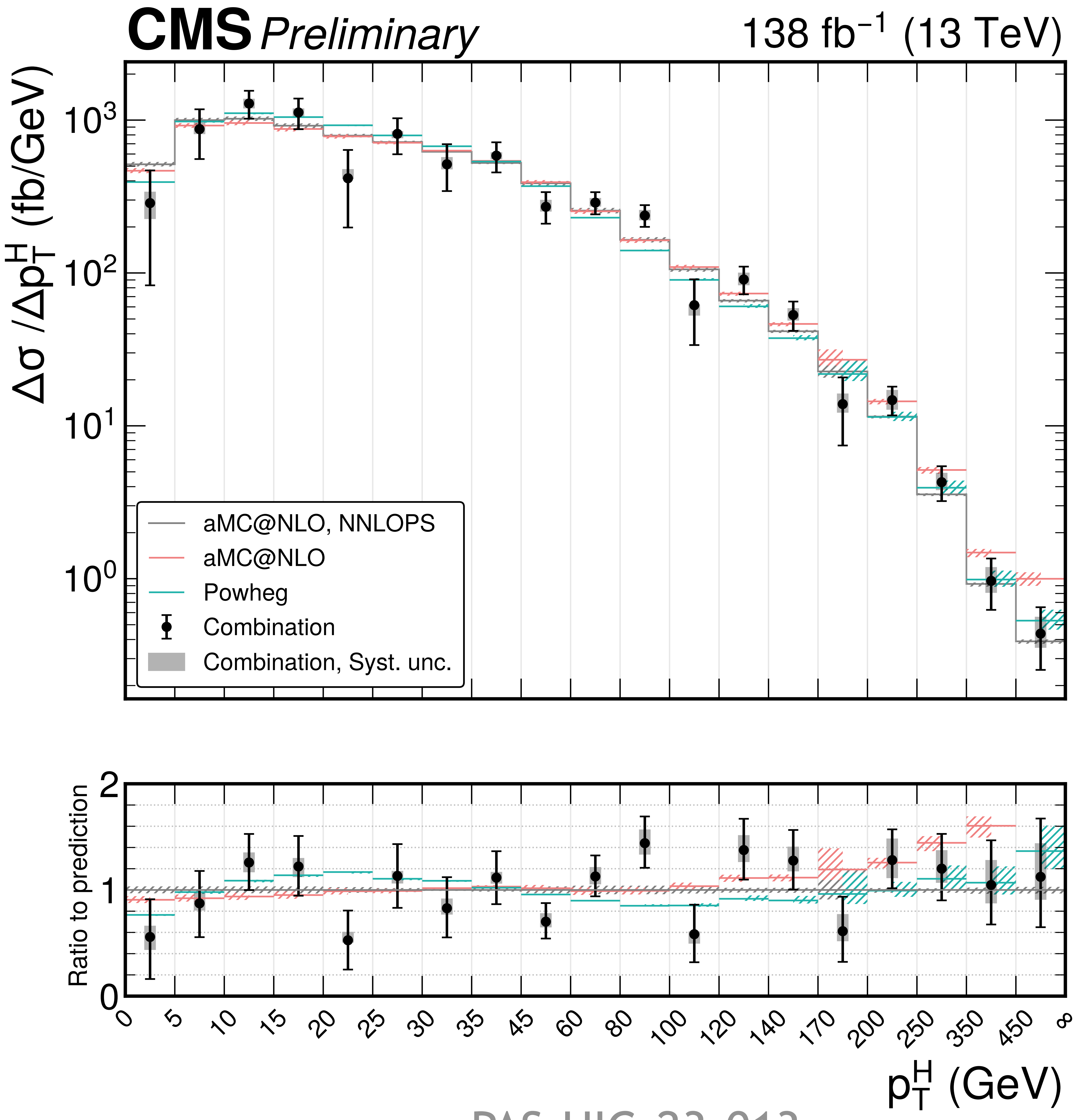
- DL1r used
- Combinati states in t
- Measure a against VZ
  ⇒ First /
- Uncertaint
- WH->bb 5.



Analogous picture for ATLAS (see backup)

CMS Run-II combination

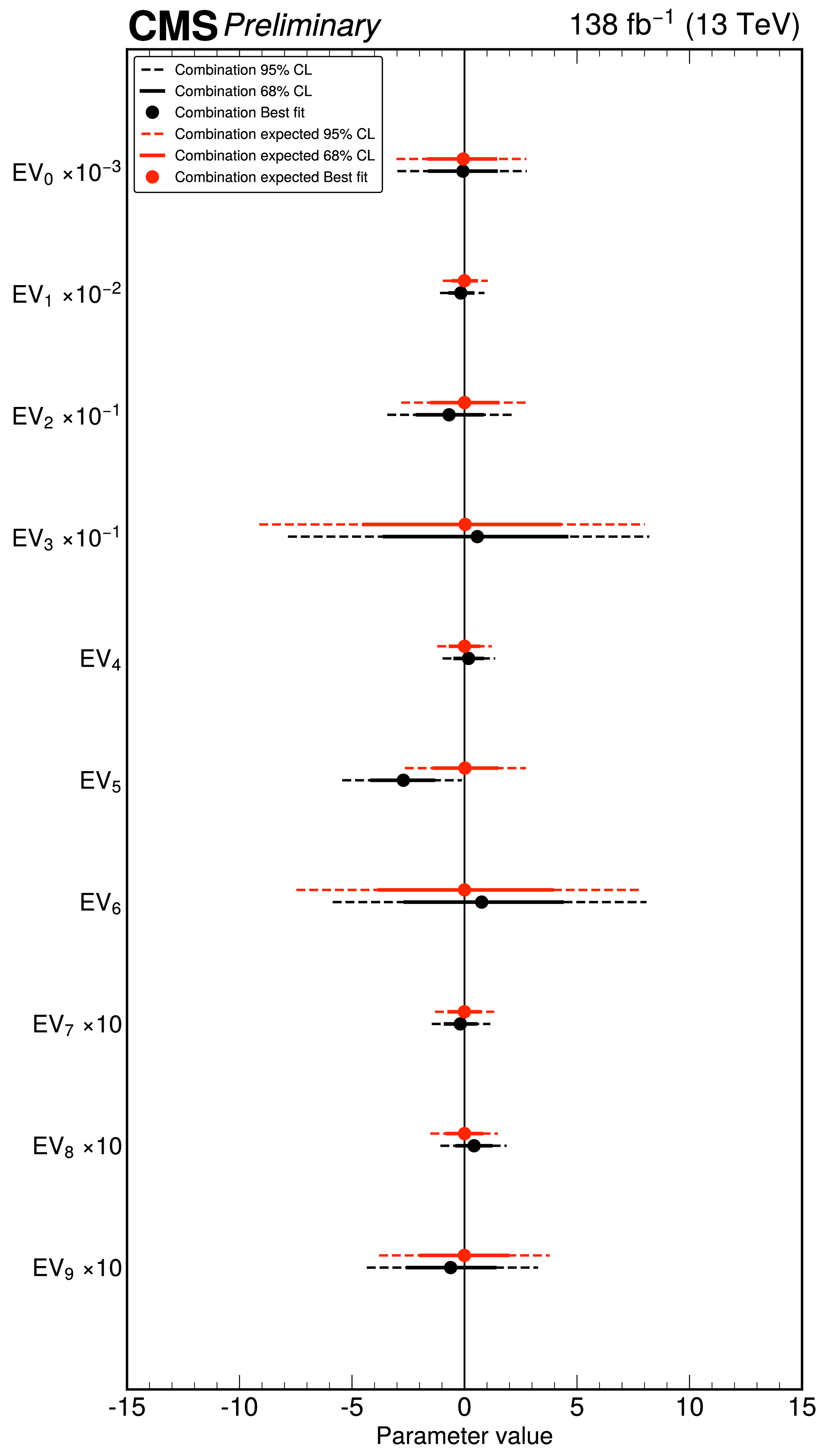
- Characterisation of Higgs boson kinematics to the highest level of precision possible, combining all the main decay channels
- Run-II legacy result, probing kinematics of the Higgs boson and its couplings with respect to the SM hypothesis
- Re-interpretation of differential measurements in κ-framework, extending previous results
- First CMS interpretation of differential measurements in SMEFT, using PCA decomposition of EFT operators

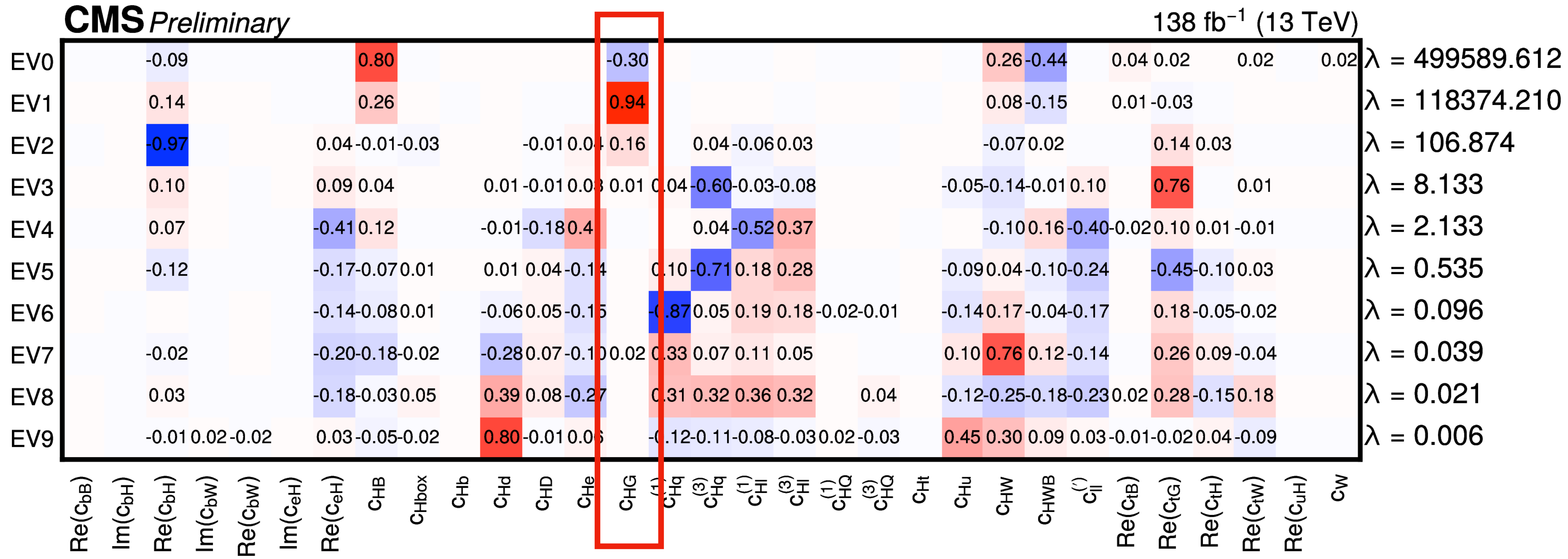


PAS-HIG-23-013

CMS Run-II combination

PAS-HIG-23-013

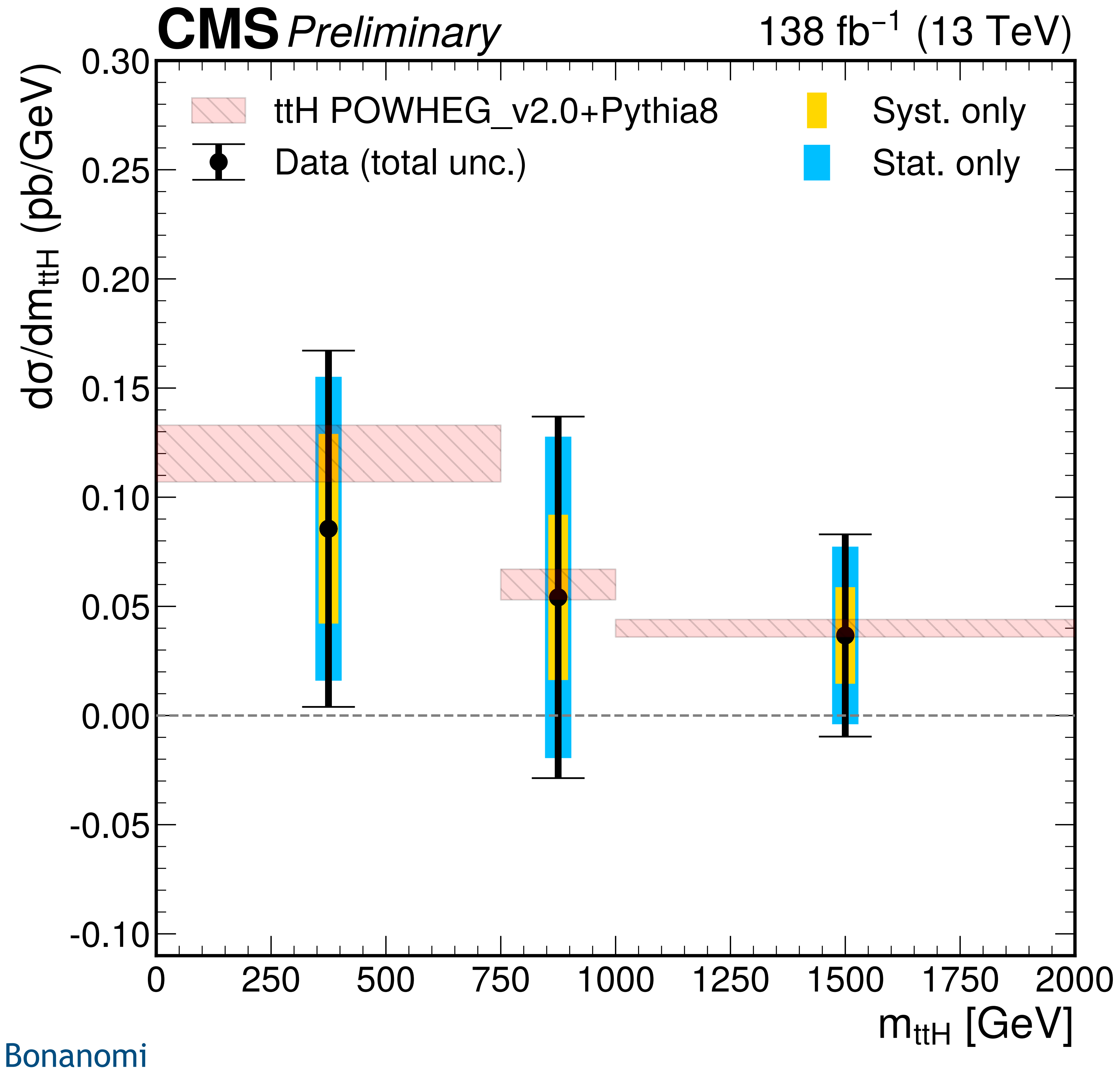


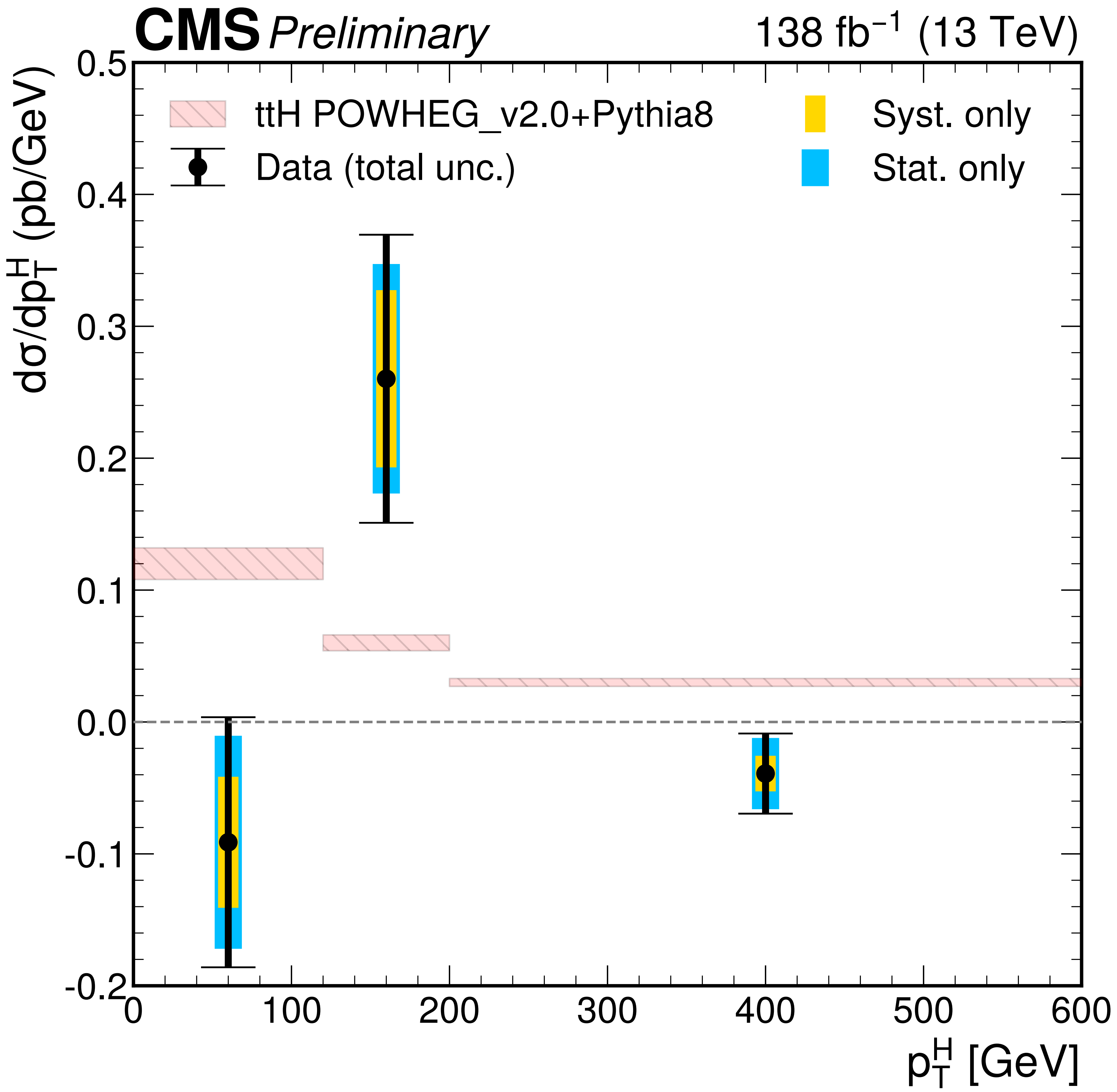


- Eigenvector decomposition of the Fisher information matrix
- Eigenvalues with highest constraining power left floating in the (simultaneous) fit
- Sensitivity of decay channels dominated by c_{HG}
- $H\gamma\gamma$ introduces sensitivity to c_{HB}, c_{HW}, and c_{HBW}
- Similar result from ATLAS in HIGG-2022-17

CMS ttH multilepton differential

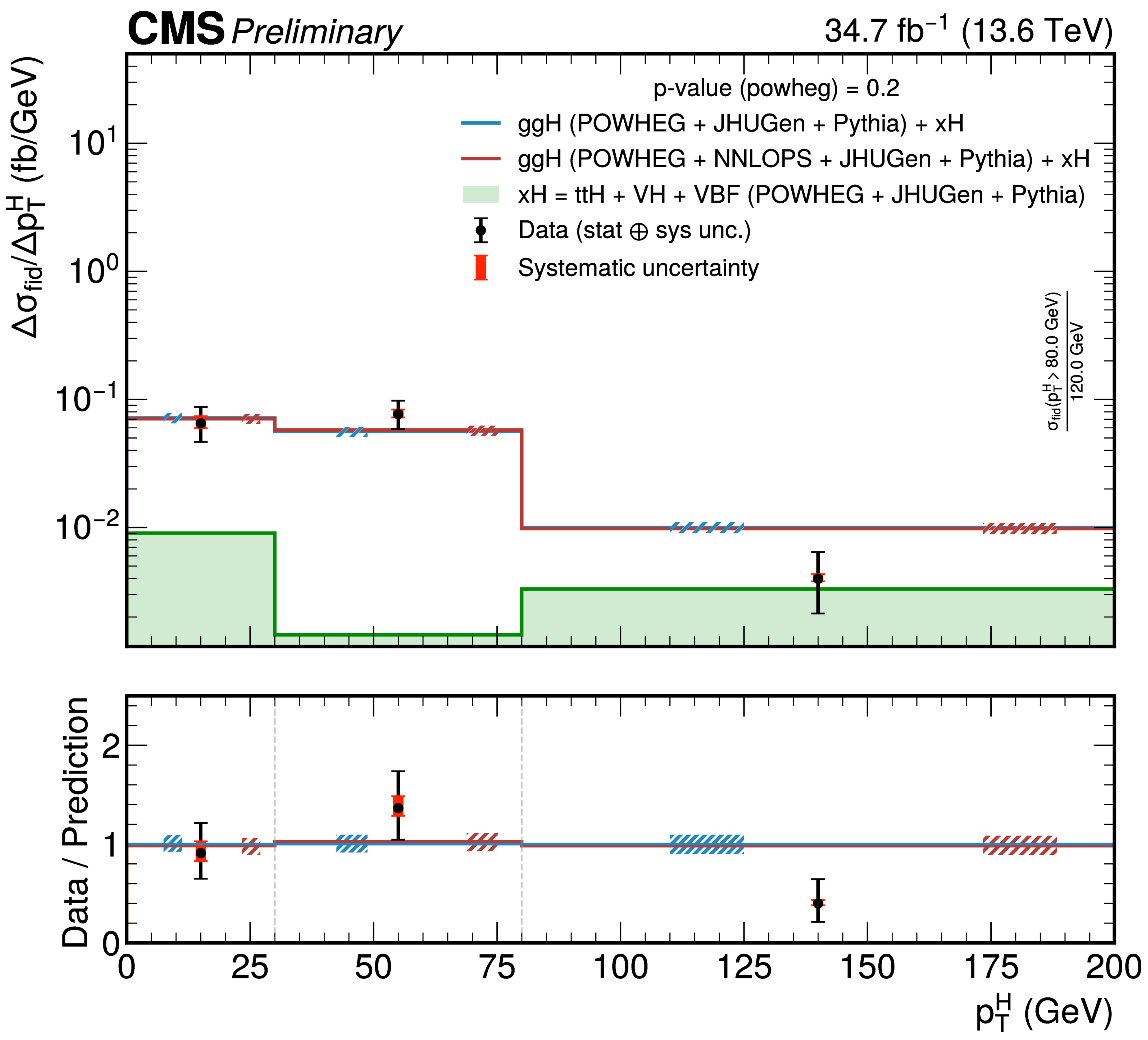
- Target the three most sensitive final states: 2lss + $0\tau_h$, 3l + $0\tau_h$, 2lss + $1\tau_h$
- DNNs to categorise events and regress p_T^H, using custom loss function $L = \frac{1}{N}\sum_N ((y_t - y_p)^2 \times | \sigma_t^2 - \sigma_p^2 |)$
- Measurement of differential xsec in (adapted) STXS and $m_{t\bar{t}H}$ bins





Run-III differential xsec

- Cross sections measured at $\sqrt{s} = 13.6$ TeV in $\mathrm{H} \rightarrow \mathrm{ZZ}$ and $\mathrm{H} \rightarrow \gamma\gamma$
- Results limited by statistics at the current stage, with only 34.7 fb^{-1} analysed



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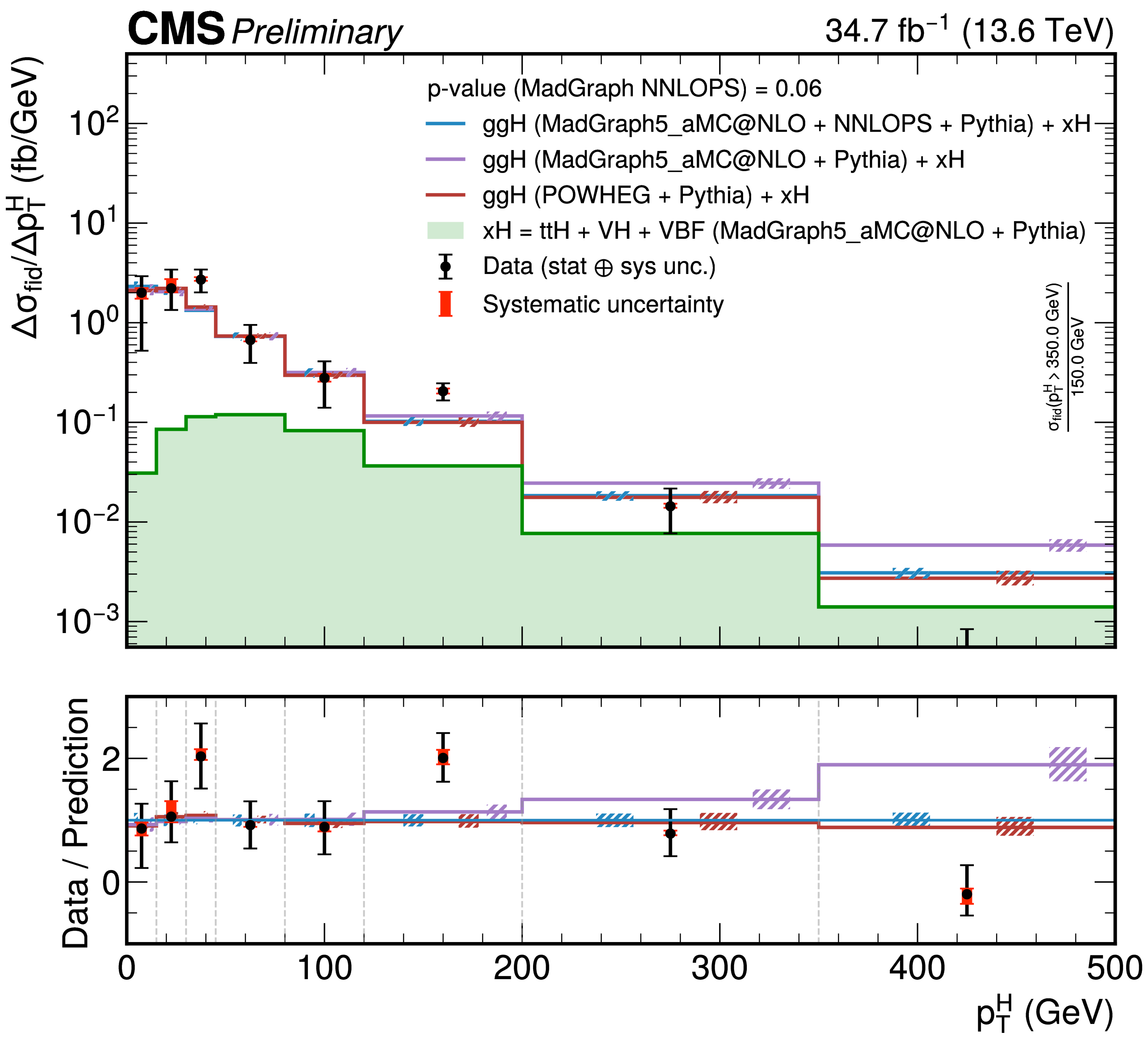
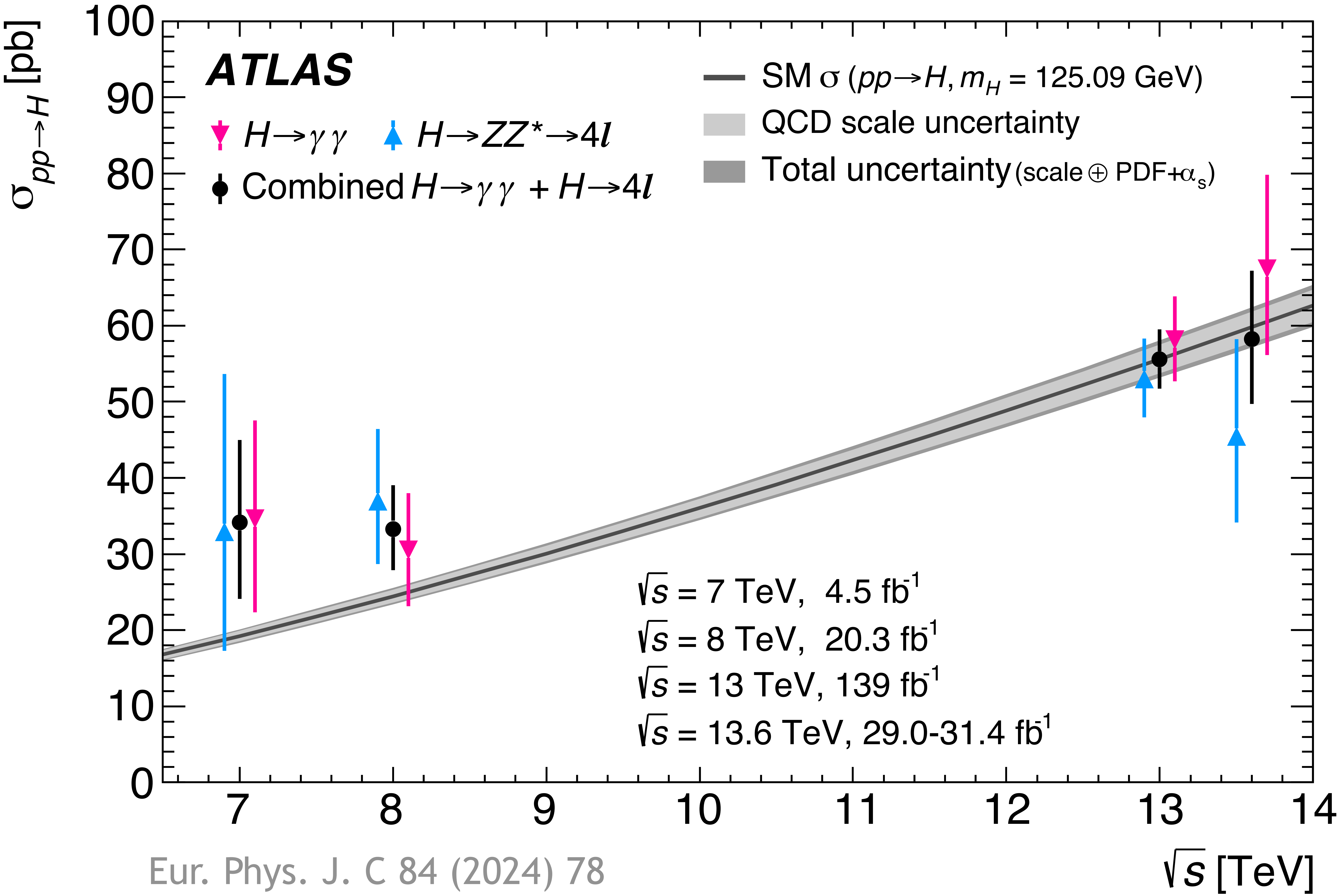


PAS-HIG-23-014

Extrapolation to full phase space

- Cross sectic
- Results limi



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Conclusion

After 12 years, we have achieved a substantial understanding of the Higgs boson properties at the LHC

- Cross sections of the main production modes have been measured with O(10%) precision
- STXS gives access to a high-granularity description of the Higgs production, enhancing sensitivity to new physics
- ATLAS and CMS released Run-II legacy results in all production modes, over exceeding the expectations we had at the beginning of Run-II (e.g. $|\kappa_c| < 4.2$ @ 95% CL, comparable with HL-LHC projections)
- Run-III data-taking will end next year, giving access to more data and better characterisations!

To expand on today's talk

10:00 **STXS and differential cross section measurements at CMS, bosonic channels** 20m

We will discuss the latest differential measurements of Higgs boson cross sections with the CMS detector in bosonic decay channels. Both fiducial differential cross section measurements and measurements in the simplified template cross section framework will be presented. The data collected during Run 2 of the LHC by the CMS experiment are used. We also present interpretations of these measurements as constraints on constraints of Wilson coefficients of beyond Standard Model operators in the framework of Effective Field Theories.

Speaker: Caio Cesar Daumann (Rheinisch Westfaelische Tech. Hoch. (DE))

11:10 **Higgs combined measurements at CMS** 20m

The newest Higgs combined measurements at CMS are presented in this talk.

Speaker: Massimiliano Galli (ETH Zurich (CH))

11:30 **Combined Higgs boson measurements and their interpretations with the ATLAS experiment** 20m

Very detailed measurements of Higgs boson coupling and kinematical properties can be performed using the data collected with the ATLAS experiment, exploiting a variety of final states and production modes, and probing different regions of the phase space with increasing precision. These measurements can then be combined to exploit the specific strength of each channel, thus providing the most stringent global measurement of the Higgs properties. This talk presents the latest combination of Higgs boson measurements by the ATLAS experiment, with results presented in terms of production modes, branching fractions, Simplified Template Cross Sections and coupling modifiers. These combined measurements are interpreted in various ways: specific scenarios of physics beyond the Standard Model are tested, as well as a generic extension in the framework of the Standard Model Effective Field Theory. The results are based on pp collision data collected at 13 during Run 2 of the LHC.

Speaker: Oliver Rieger (Nikhef National institute for subatomic physics (NL))

10:20 **Searches for rare Higgs boson production processes with the CMS detector** 20m

The full set of data collected by CMS experiment at a centre of mass energy of 13 TeV allows searches for rare production modes of the Higgs boson, subdominant with respect the ones already observed at the LHC, by using a variety of decay modes profiting of the ones with largest expected branching fractions. They include associate production of the Higgs with two b-quarks, with a c-quark, or vector boson scattering production with two associated Ws. While the expected rate is still limited with the collected data, these modes become enhanced in several BSM theories and can be used to constrain such models.

Speaker: Mr Tiziano Bevilacqua (University of Zürich (CH))

12:10 **Measurements of Higgs boson production with top quarks with the ATLAS detector** 20m

The study of Higgs boson production in association with one or two top quarks provides a key window into the properties of the two heaviest fundamental particles in the Standard Model, and in particular into their couplings. This talk presents property measurement of Higgs boson, in particular cross section and CP nature, with tH and ttH production in pp collisions collected at 13 TeV with the ATLAS detector using the full Run 2 dataset of the LHC.

Speaker: Nihal Brahimi (CNRS/IN2P3 LAPP)

09:00 **Measurements of Higgs boson coupling properties to bottom and charm with the ATLAS detector** 20m

Testing the Yukawa couplings of the Higgs boson with fermions is essential to understanding the origin of fermion masses. Higgs boson decays to quark pairs are an important probe of these couplings, and of properties of the Higgs boson more generally. This talk presents various measurements of Higgs boson decays into two bottom quarks as well as searches for Higgs boson decays into two charm quarks by the ATLAS experiment, using the full Run 2 dataset of pp collisions collected at 13 TeV at the LHC, as well as their combination and interpretation. The results of the search for Higgs boson production associated with a charm quark is also reported.

Speaker: Marion Missio (Nikhef National institute for subatomic physics (NL))

09:20 **STXS and differential cross section measurements at CMS, fermionic channels** 20m

e will discuss the latest differential measurements of Higgs boson cross sections with the CMS detector in fermionic decay channels and ttH production. Both fiducial differential cross section measurements and measurements in the simplified template cross section framework will be presented. The data collected during Run 2 of the LHC by the CMS experiment are used. We also present interpretations of these measurements as constraints on constraints of Wilson coefficients of beyond Standard Model operators in the framework of Effective Field Theories.

Speaker: Simone Gennai (Universita & INFN, Milano-Bicocca (IT))

09:40 **Constraints on Higgs-charm couplings** 20m

The discovery of the Higgs boson ten years ago and successful measurement of the Higgs boson couplings to third generation fermions by ATLAS and CMS mark great milestones for HEP. The much weaker coupling to the second generation quarks predicted by the SM makes the measurement of the Higgs-charm coupling much more challenging. With the full run-2 data collected by the CMS experiment, a lot of progress has been made to constrain this coupling. In this talk, we present the latest results of direct and indirect measurements of the HIggs-charm coupling by the CMS experiment. Prospects for future improvements are also given.

Speaker: Sebastian Wuchterl (CERN)

11:50 **EFT interpretations in the Higgs sector at CMS** 20m

Effective Field Theories provide an interesting way to parameterize indirect BSM physics, when its characteristic scale is larger than the one directly accessible at the LHC, for a large class of models. Even if the Higgs boson is SM-like, BSM effects can manifest itself through higher-dimension effective interactions between SM fields, providing indirect sensitivity through distortions of kinematic distributions. Constraints on such effects derived by measurements of several production and decay modes of the Higgs boson and their combination on the data set collected by the CMS experiment a centre of mass energy of 13 TeV will be presented.

Speaker: Vasilije Perovic (ETH Zurich (CH))

11:30 **Measurements of Higgs boson coupling properties to leptons with the ATLAS detector** 20m

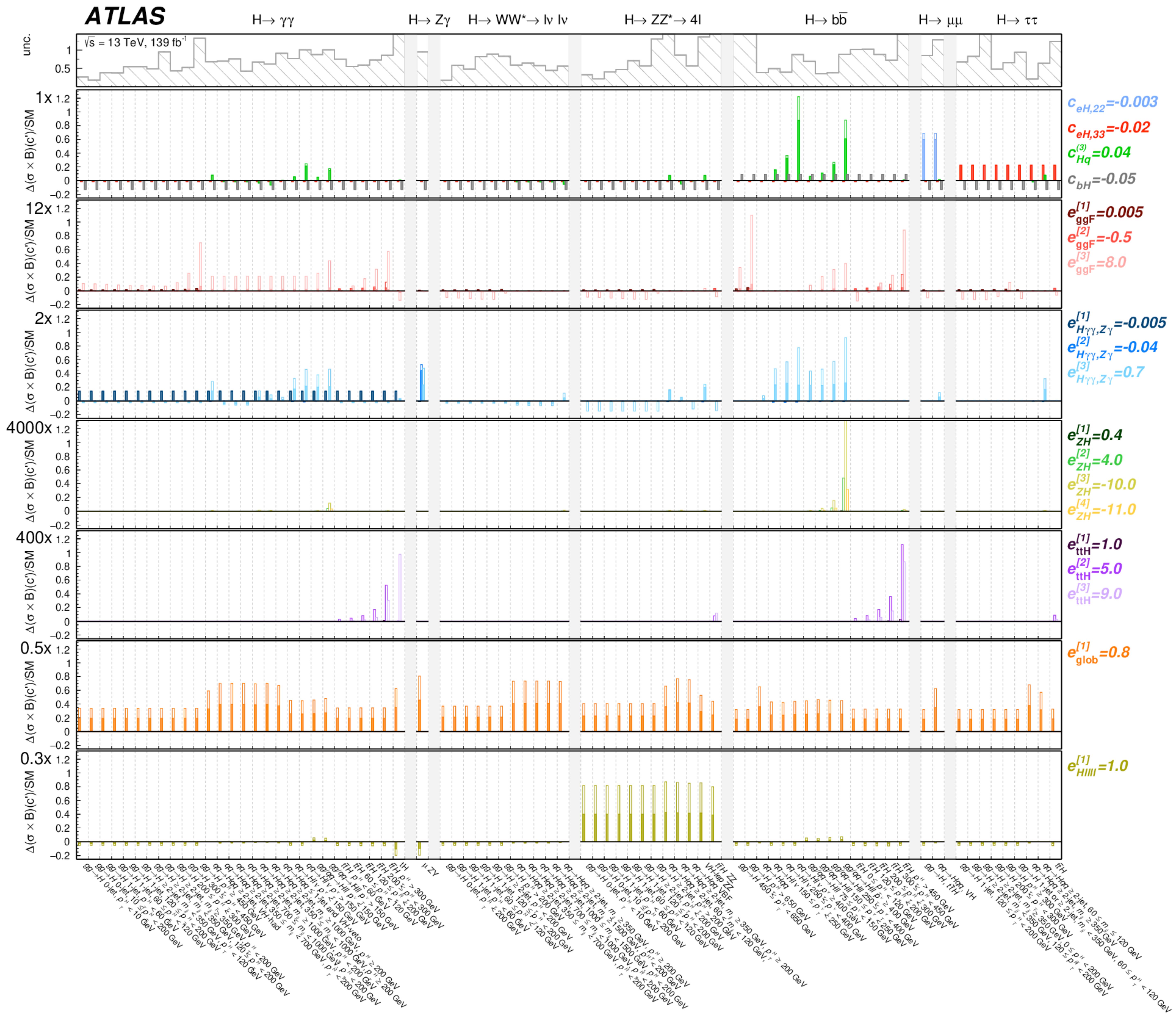
Detailed measurements of Higgs boson properties can be performed using its decays into fermions, providing in particular a key window into the nature of the Yukawa interactions. This talk presents the latest measurements by the ATLAS experiment of Higgs boson properties in its delays into pairs of leptons, using the full Run 2 pp collision dataset collected at 13 TeV.

Speaker: Enrique Valiente Moreno (Univ. of Valencia and CSIC (ES))

\+ A. Nigamova (EFT), D. Valsecchi (Taggers/ML), P. Bokan (Higgs properties), and all other plenary talks!

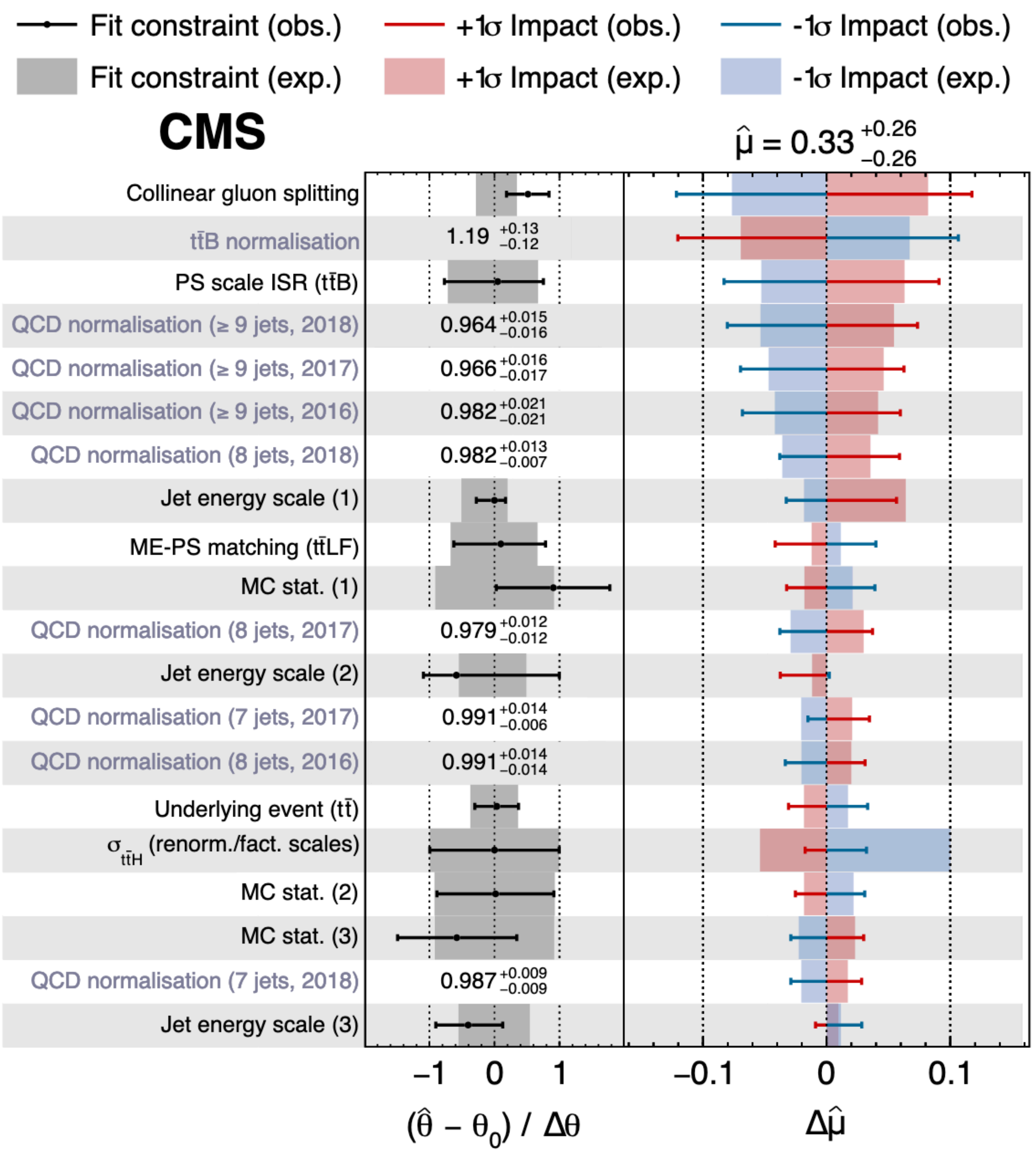
BACKUP SLIDES

EFT Sensitivity in STXS

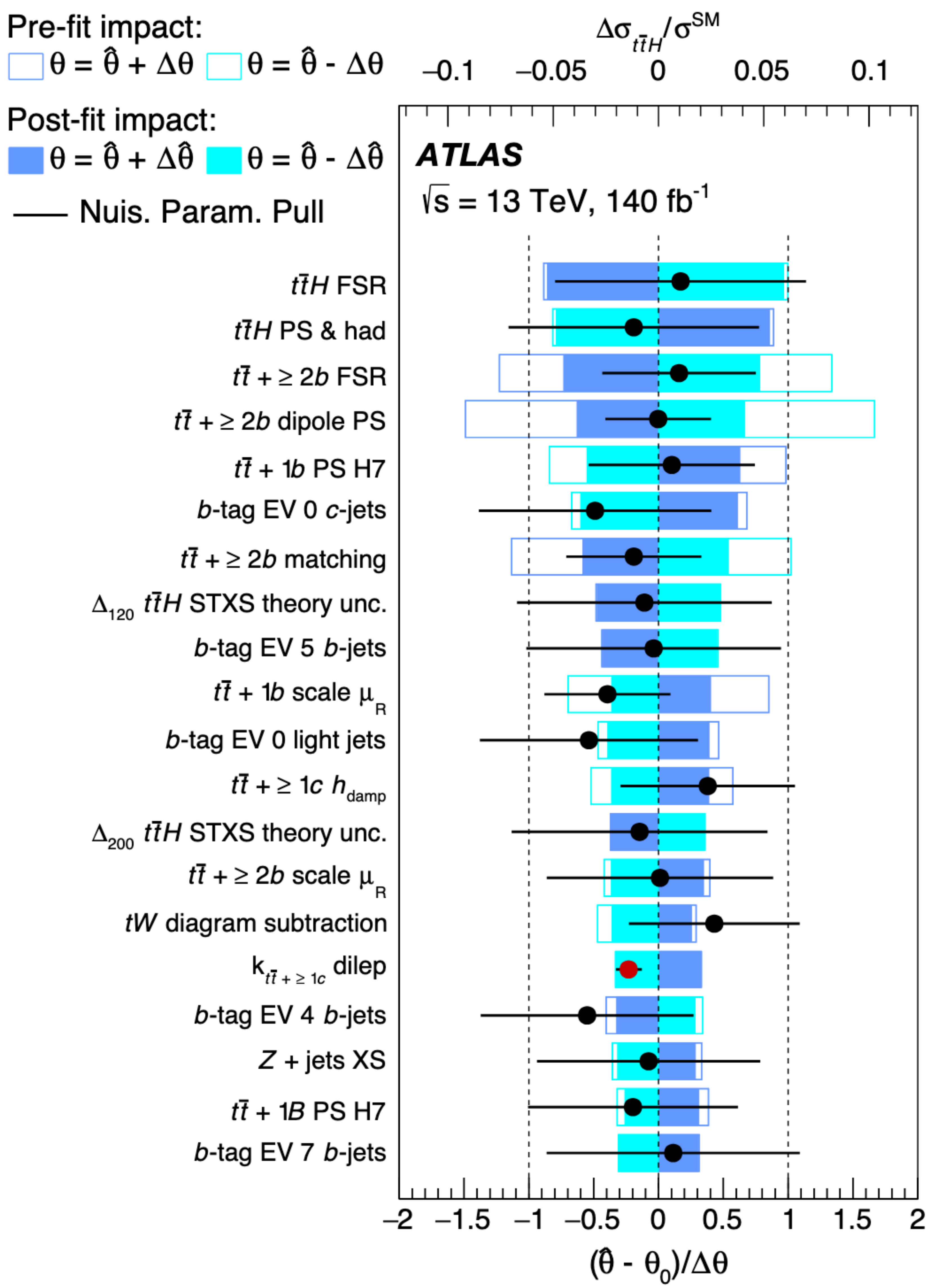


HIGG-2022-17

Impacts on Run-II legacy $t\bar{t}H(b\bar{b})$

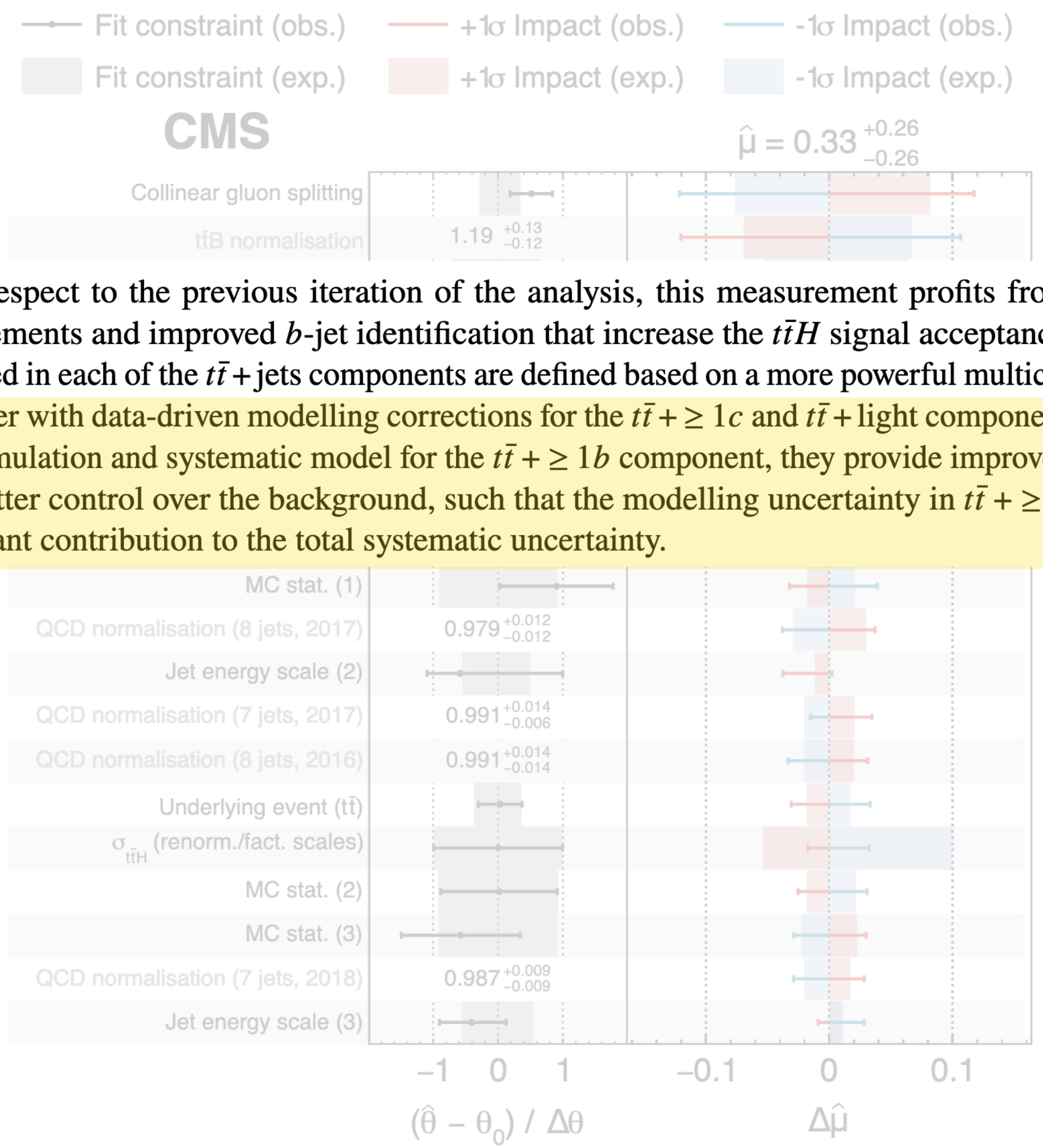


HIG-19-011



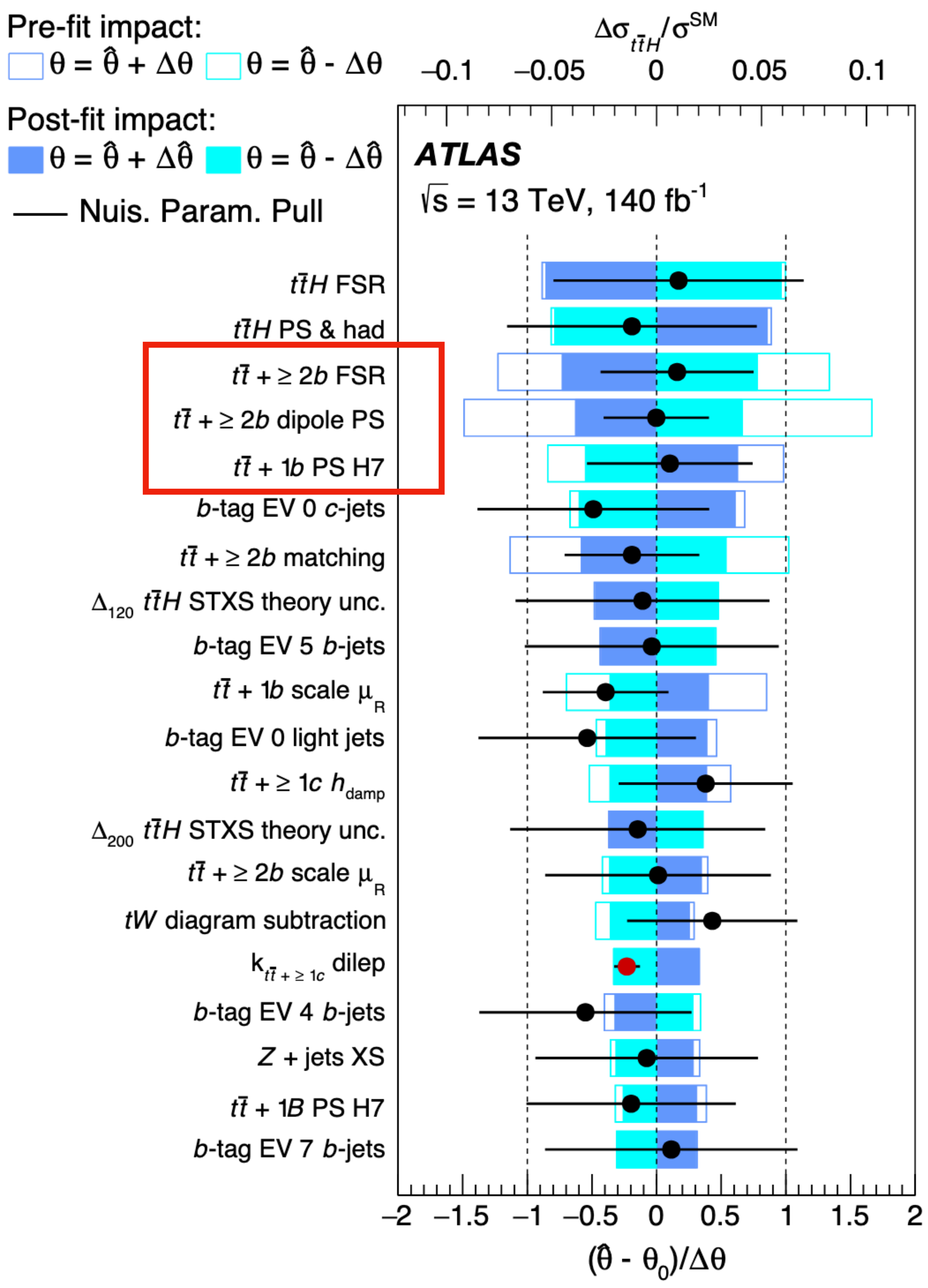
CERN-EP-2024-194

Impacts on Run-II legacy $t\bar{t}H(b\bar{b})$



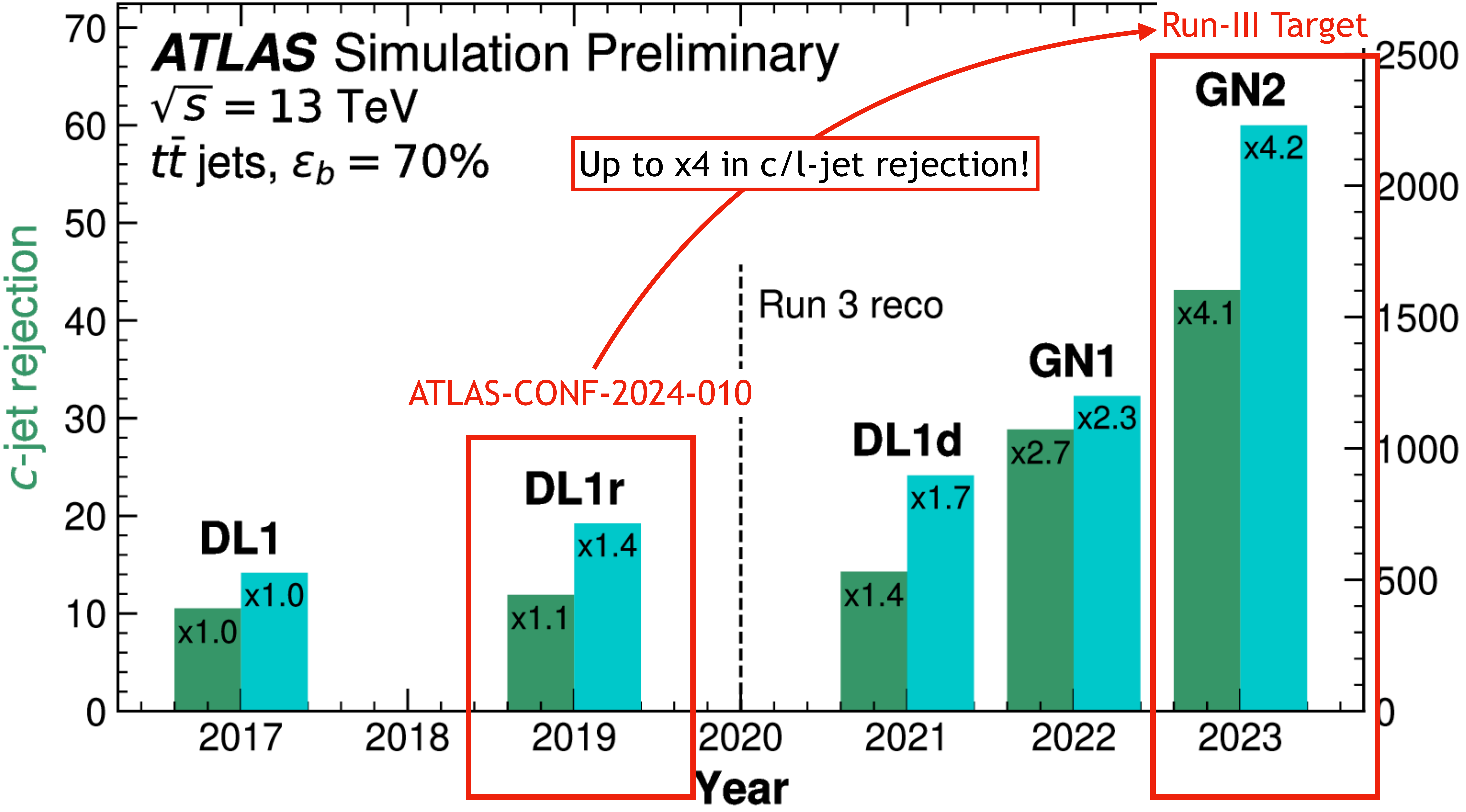
With respect to the previous iteration of the analysis, this measurement profits from looser selection requirements and improved b-jet identification that increase the $t\bar{t}H$ signal acceptance. Control regions enriched in each of the $t\bar{t}$+jets components are defined based on a more powerful multiclass neural network. Together with data-driven modelling corrections for the $t\bar{t}+\geq 1c$ and $t\bar{t}$+light components, and a dedicated MC simulation and systematic model for the $t\bar{t}+\geq 1b$ component, they provide improved signal sensitivity and better control over the background, such that the modelling uncertainty in $t\bar{t}+\geq 1b$ is no longer the dominant contribution to the total systematic uncertainty.

HIG-19-011



CERN-EP-2024-194

Jet-taggers from Run-II to Run-III



Extrapolation to full phase space