Current status, scope and future developments for

STXS and differential Higgs measurements

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On behalf of the ATLAS and CMS Collaborations

SM@LHC, May 2024

The Why

- differential cross sections allow to probe Higgs production and decay
  - confront measurements with SM and BSM predictions
- cross sections rather than event counts for easier interpretability
  - examples in many Higgs talks during this conference!
- avoid extrapolations as much as possible => improved model independence

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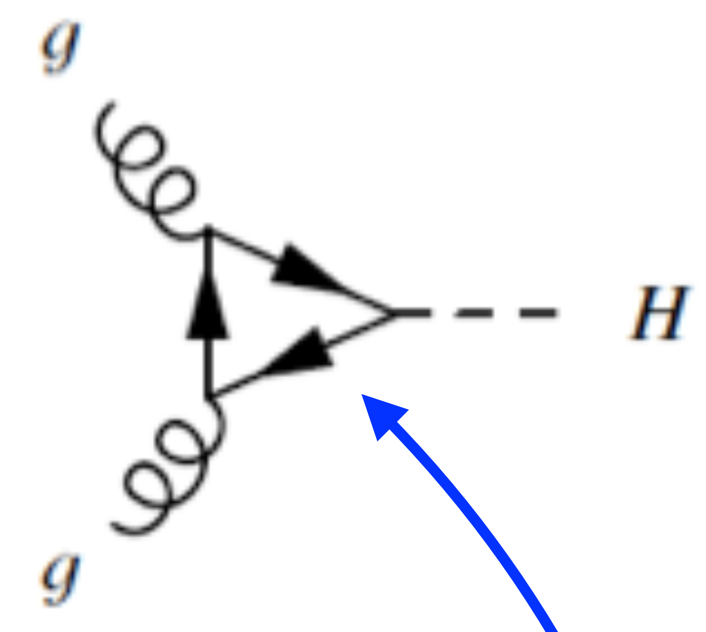
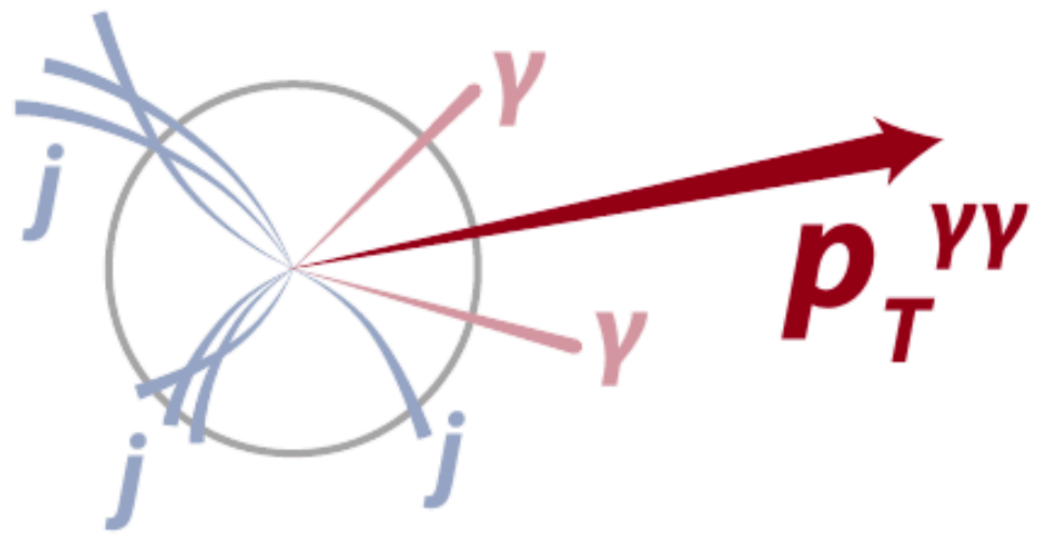
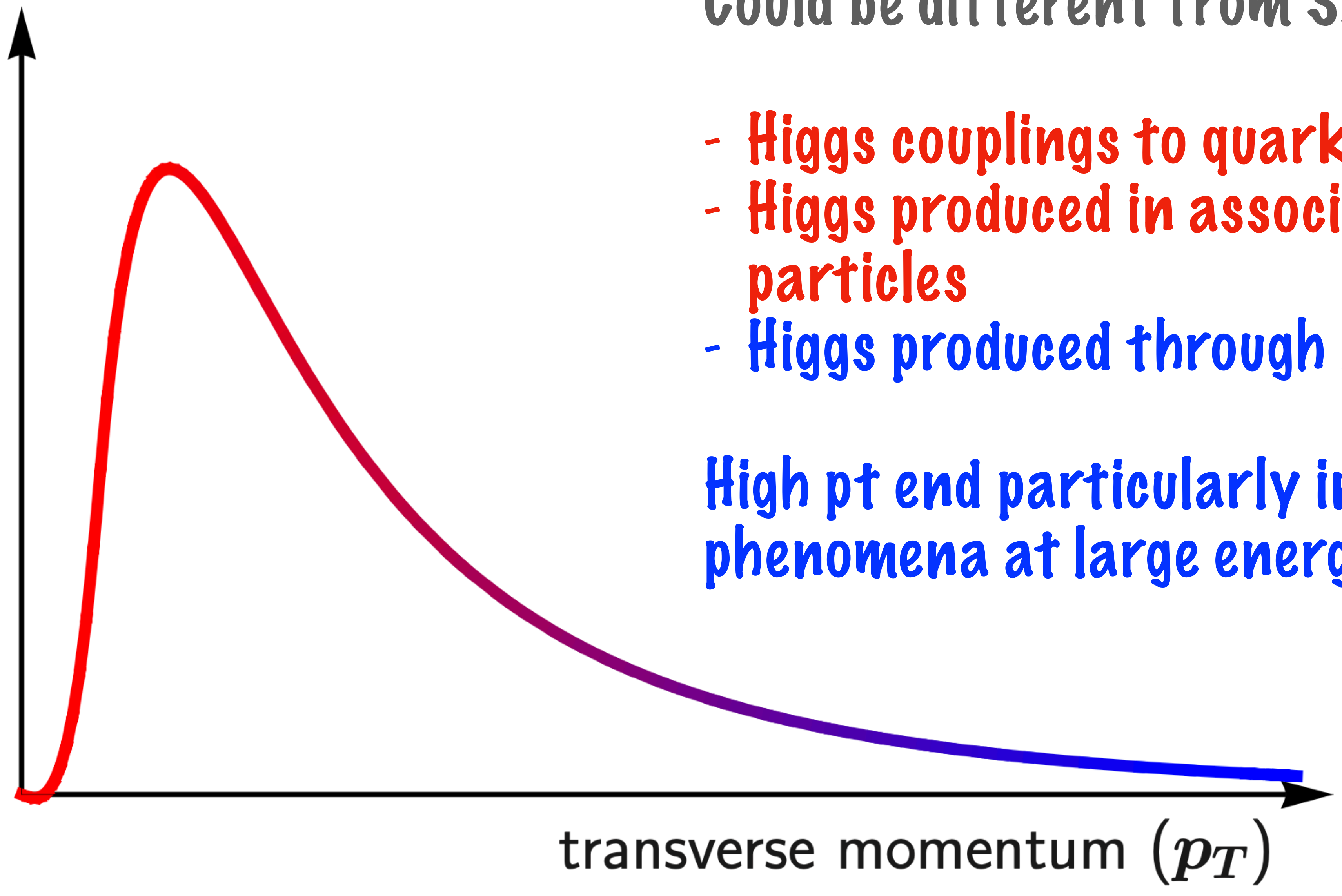
  - examples in many Higgs talks during this conference!
- avoid extrapolations as much as possible => improved model independence
- **most prominent example: Higgs transverse momentum**







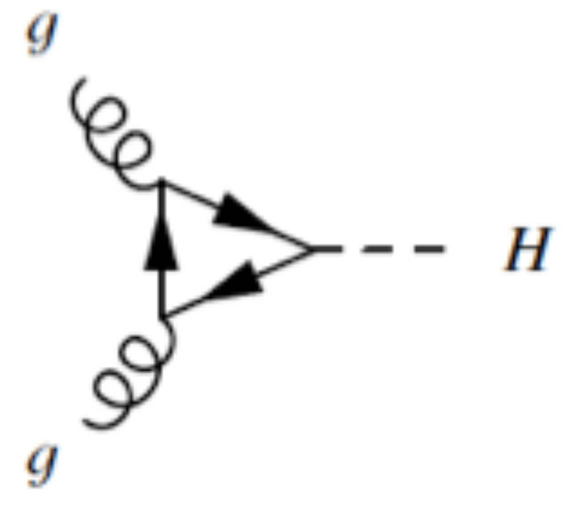
Could be different from SM expectations, if

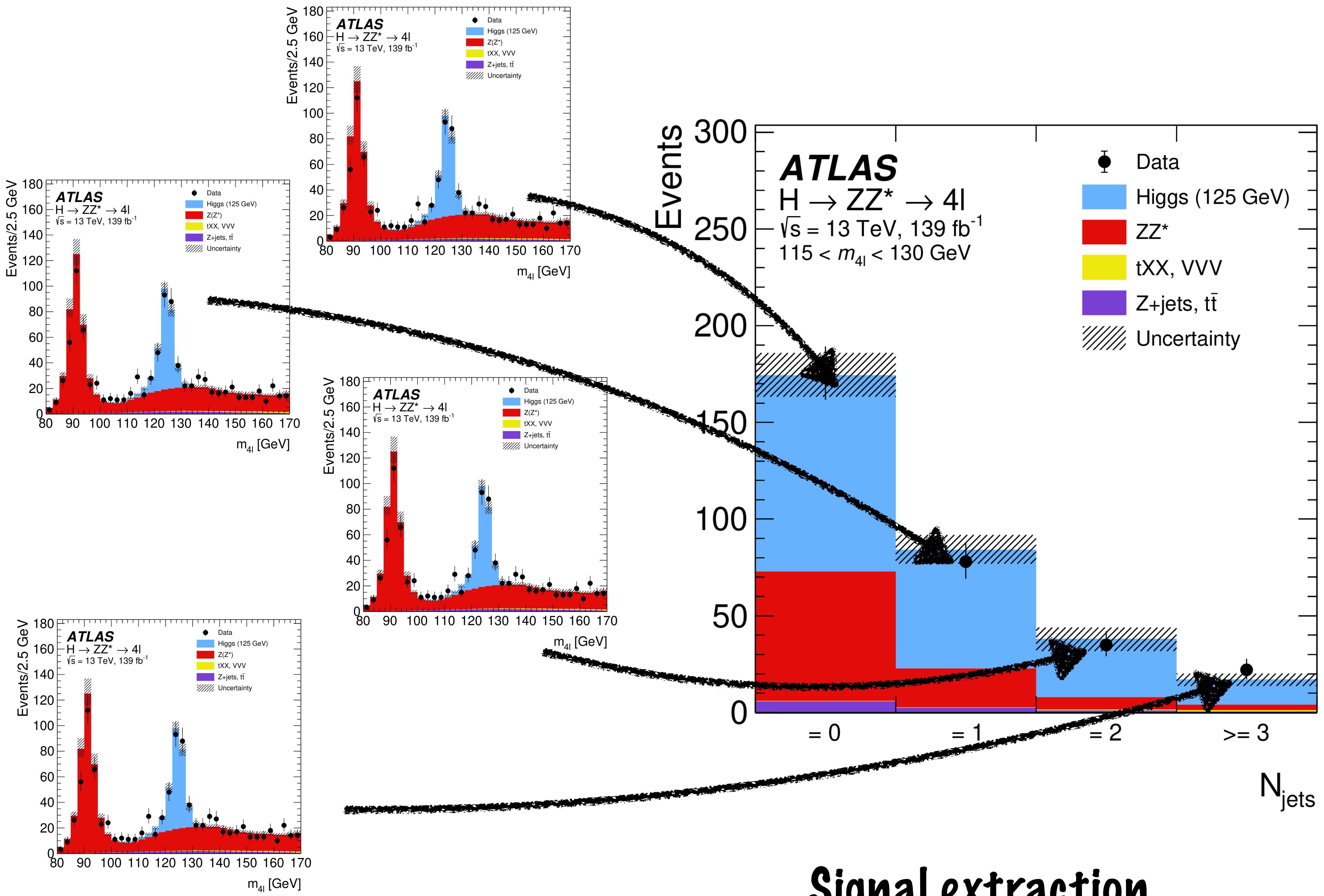
- Higgs couplings to quarks are modified
- Higgs produced in association with different particles
- Higgs produced through loops with heavy particles

High pt end particularly interesting for exotic phenomena at large energy scales

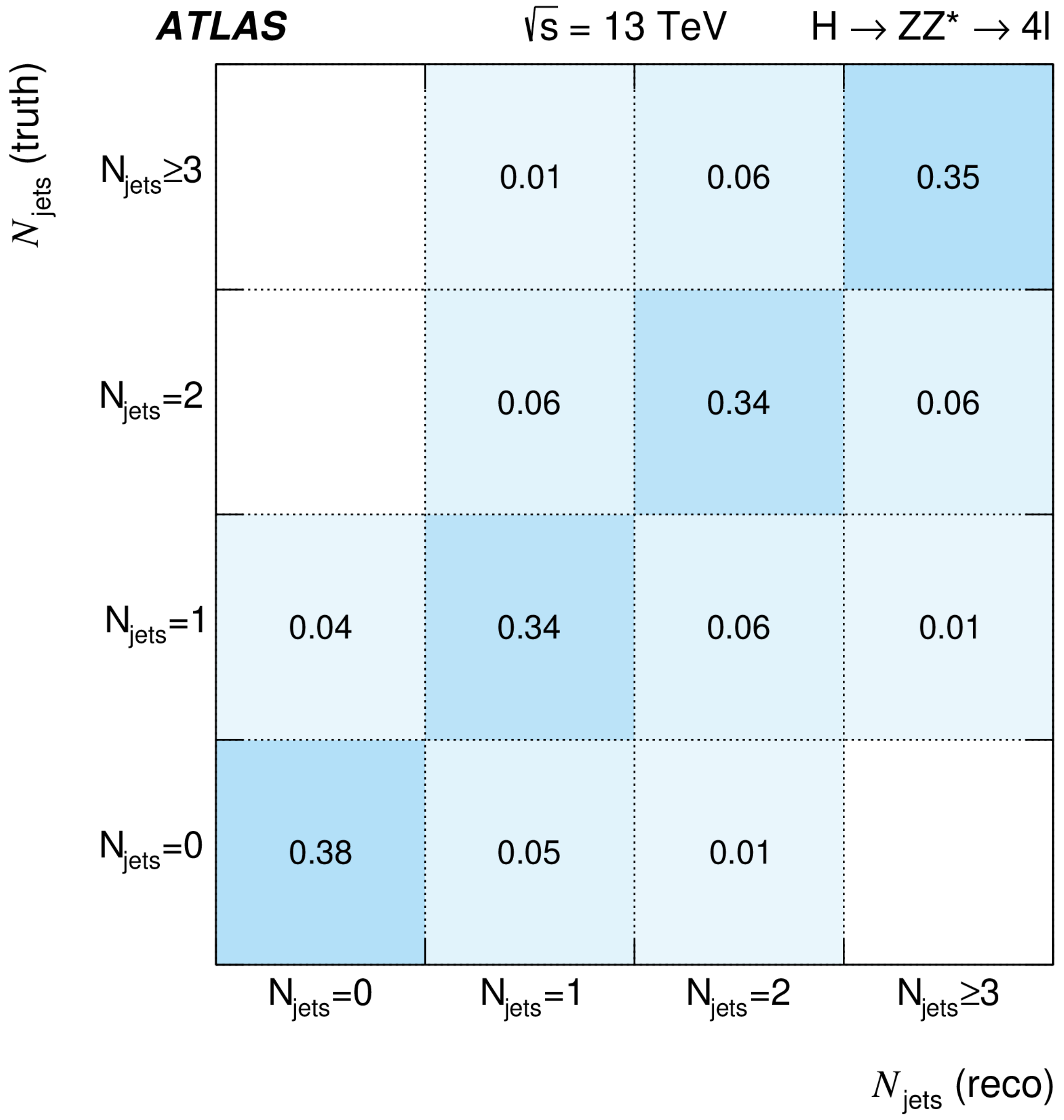
The How (1): Differential (fiducial) cross sections

- usually inclusive in production mode (dominated by ggF)
- traditionally performed with high-resolution, high S/B channels
- fiducial volume to avoid extrapolations, includes branching ratio
- unfolding with regularization if needed

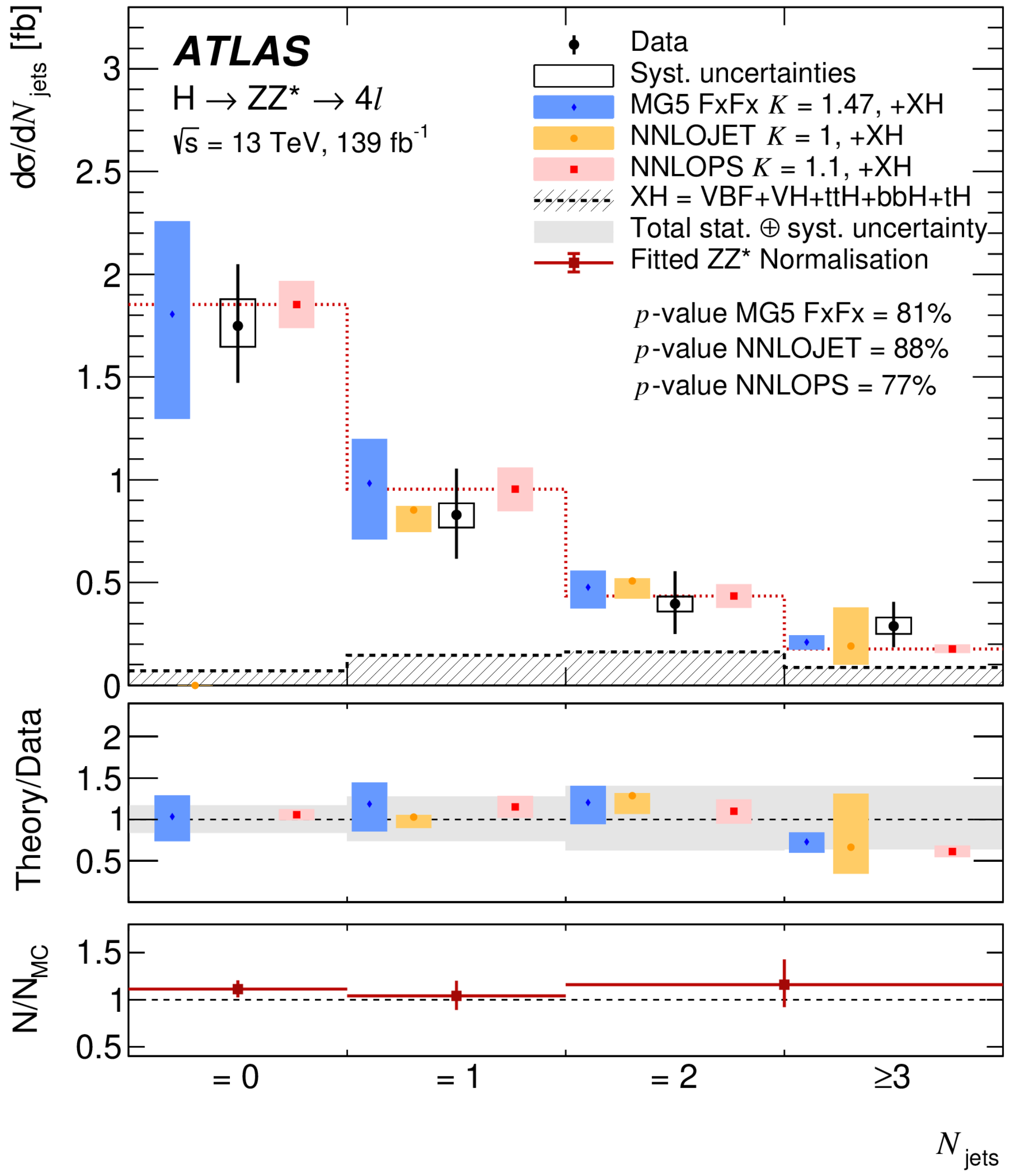




Signal extraction



Unfolding

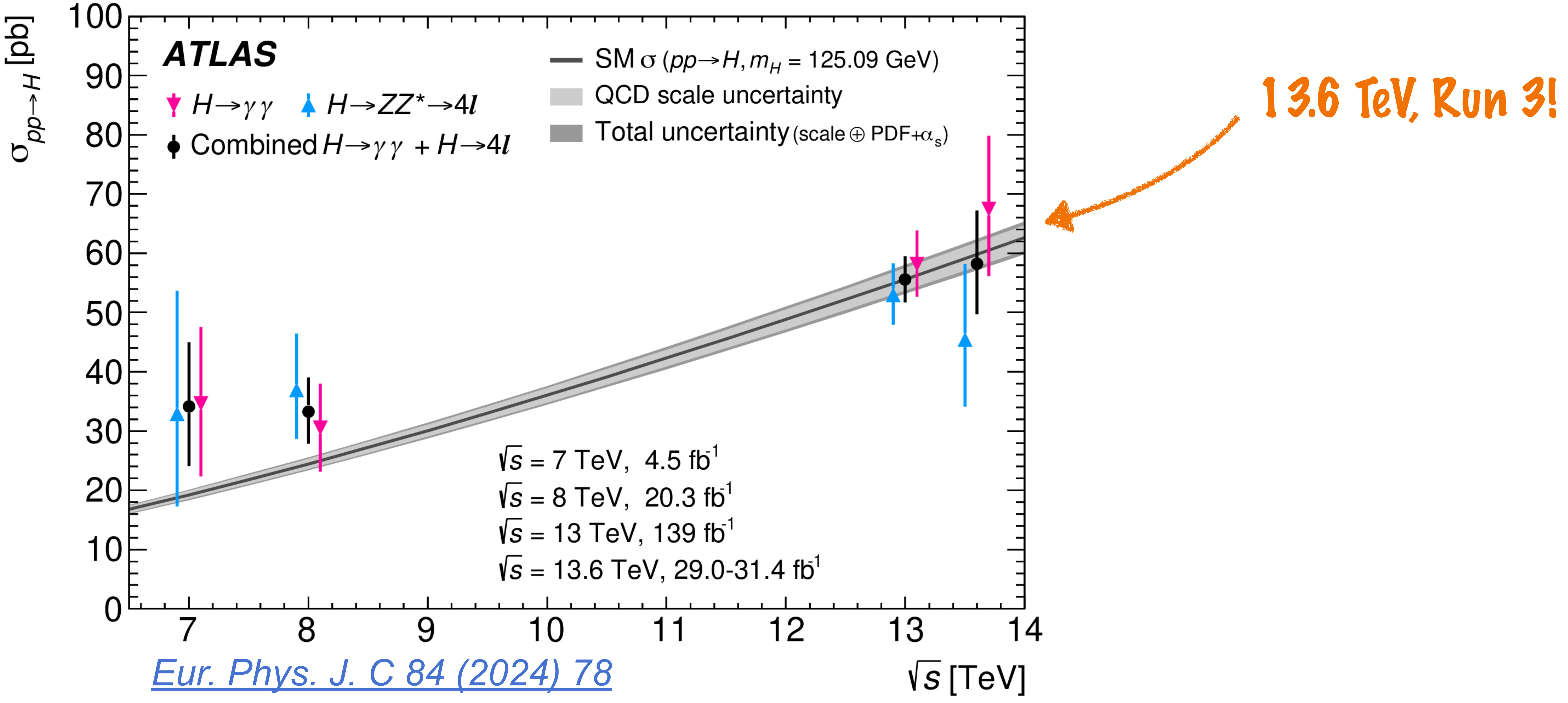


Cross sections

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

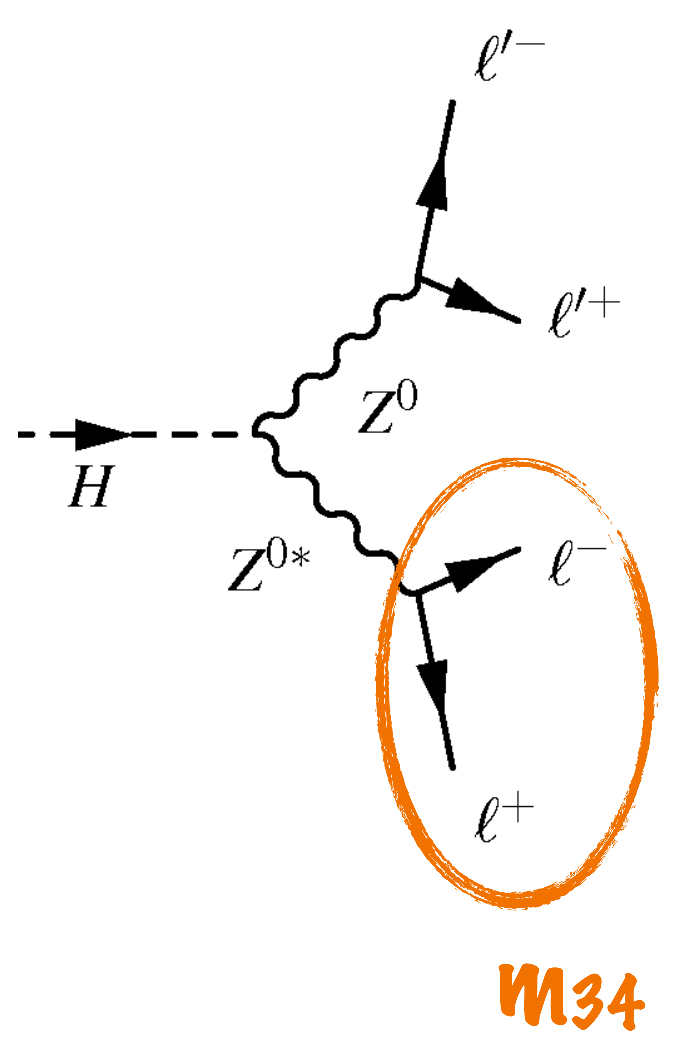
Diff and total XS - the classics: 4l, $\gamma\gamma$

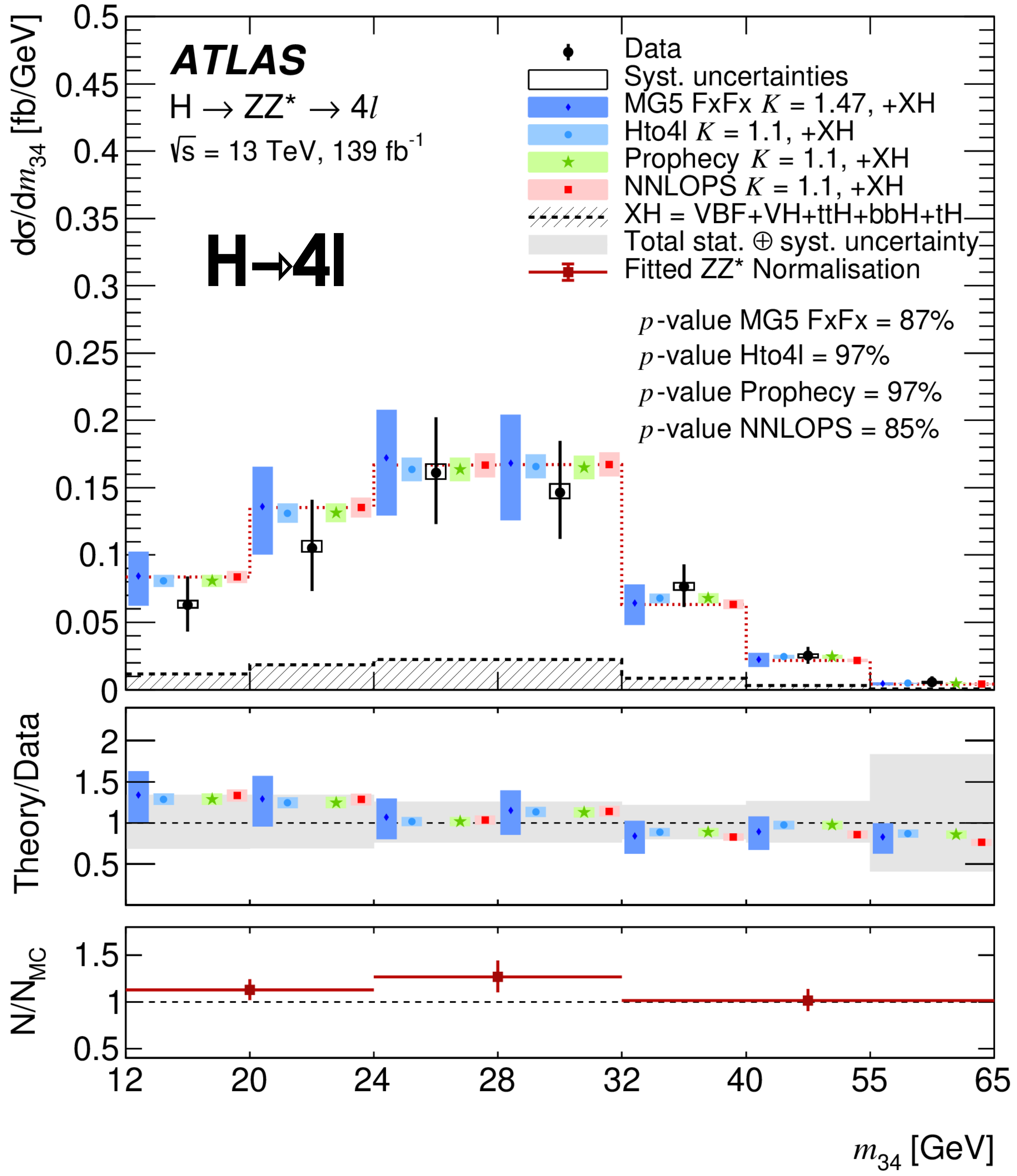
- "Golden channels": excellent signal resolution and S/B, but suffer from low event counts
- Combination of 4l and $\gamma\gamma$ channels effectively doubles the dataset
  - necessary extrapolation to total phase space introduces model dependence



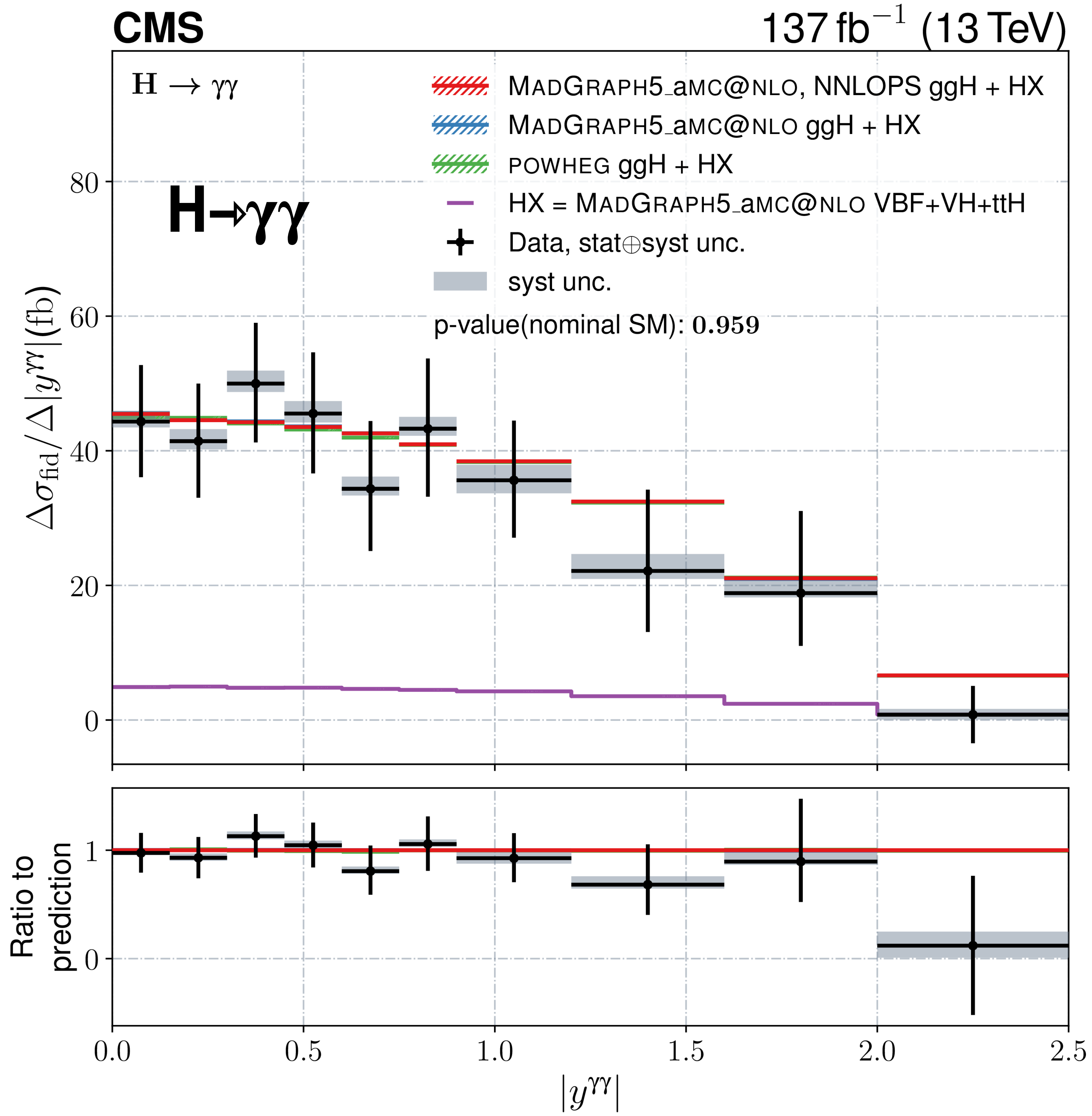
Eur. Phys. J. C 84 (2024) 78

Diff XS - the classics: 4l, γγ



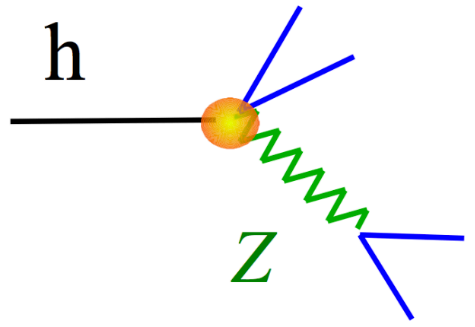


Eur. Phys. J. C 80 (2020) 942



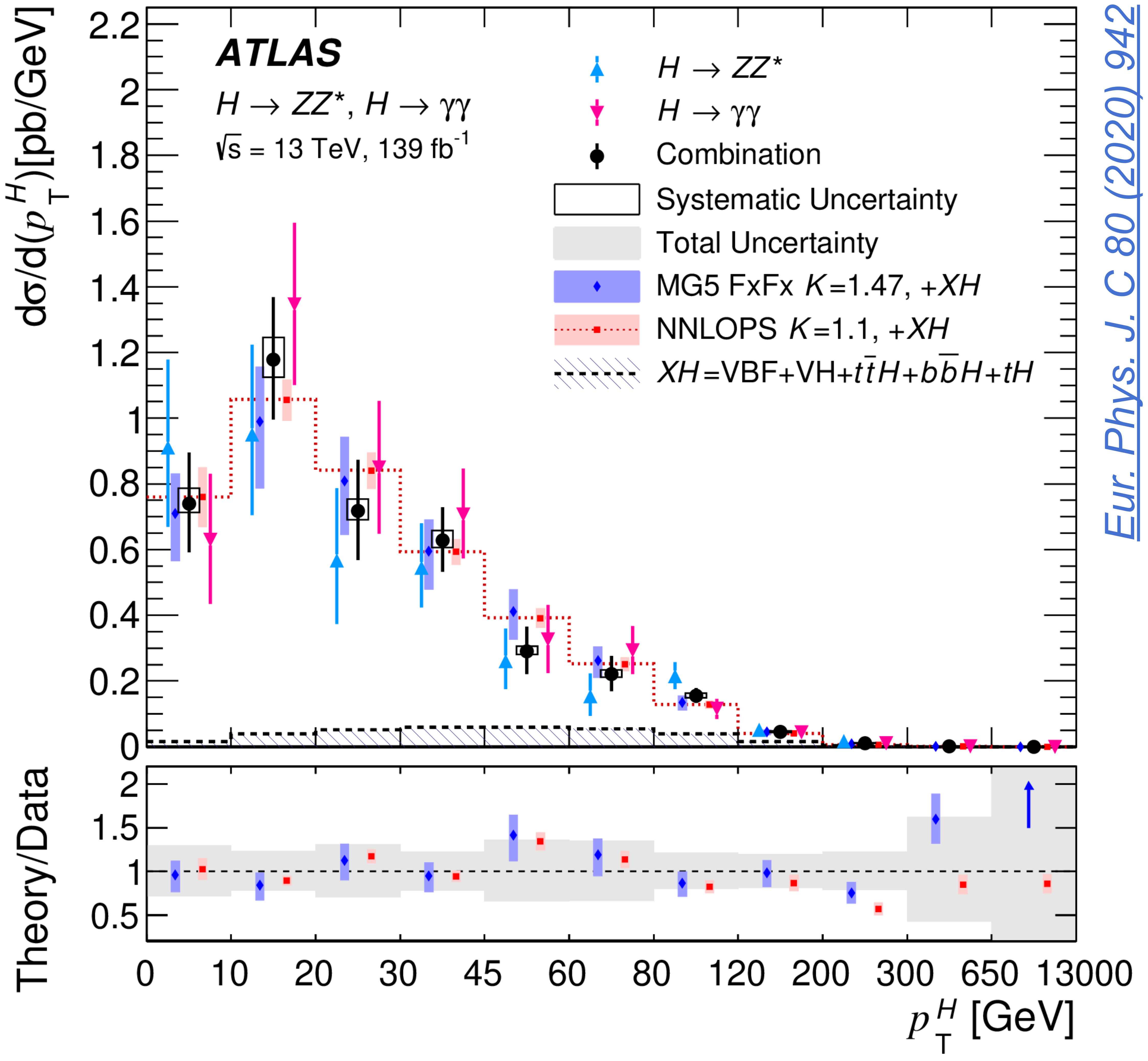
JHEP 07 (2023) 091

- mass of the off-shell Z boson
  - sensitive to dark Z bosons, contact interaction



- Higgs rapidity
  - probes PDF, QCD radiative corrections

Diff XS - Higgs transverse momentum



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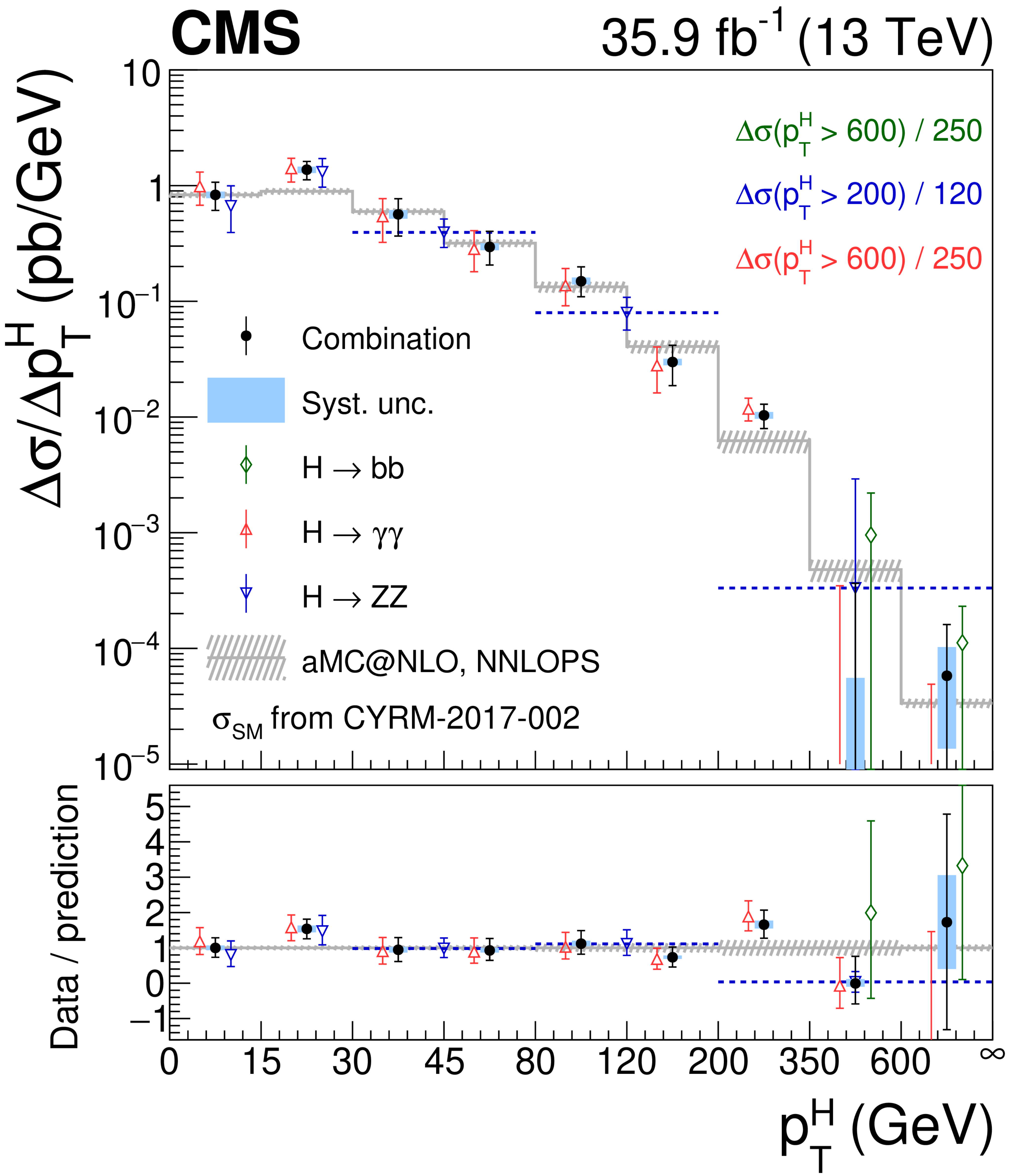
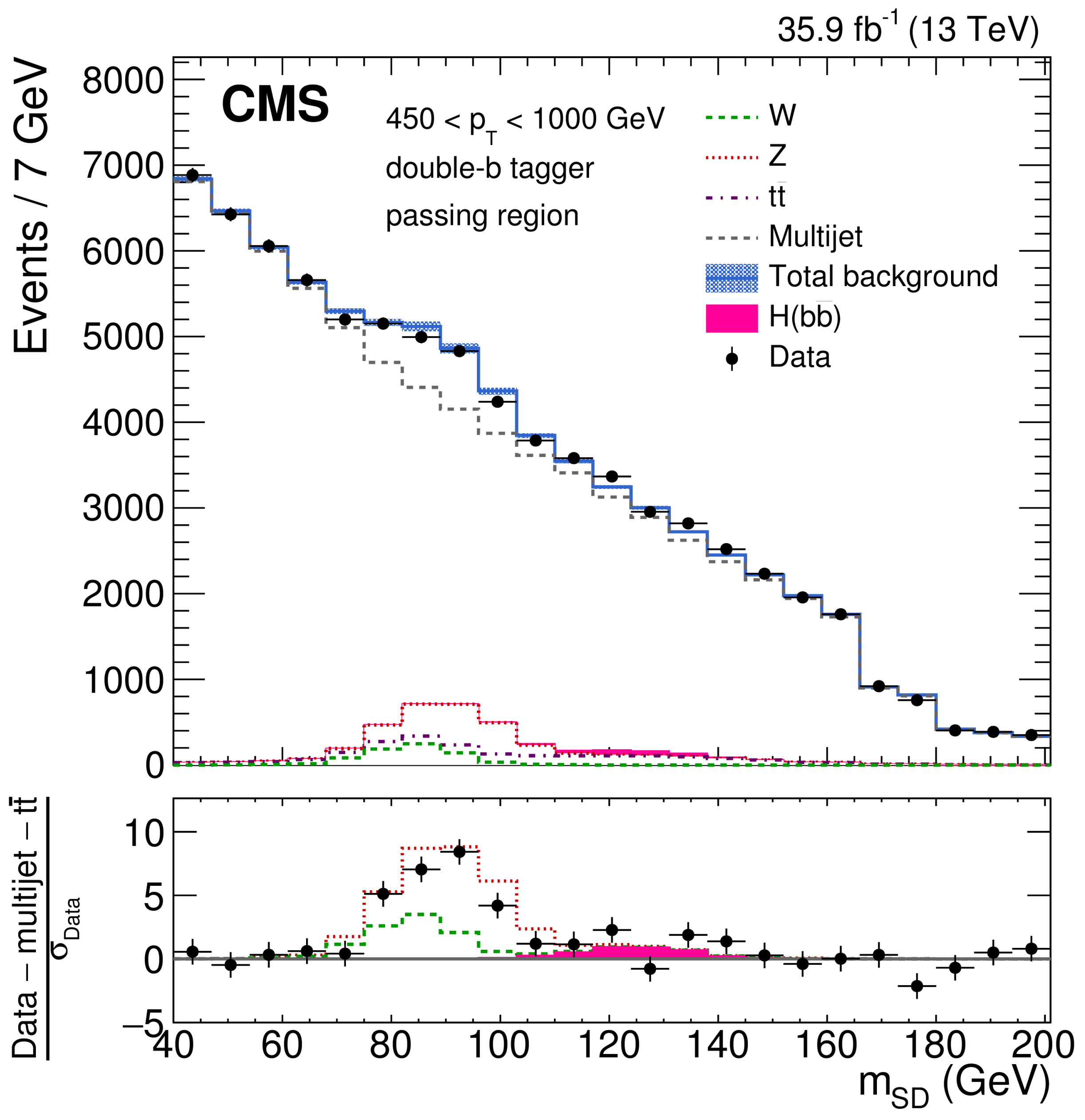


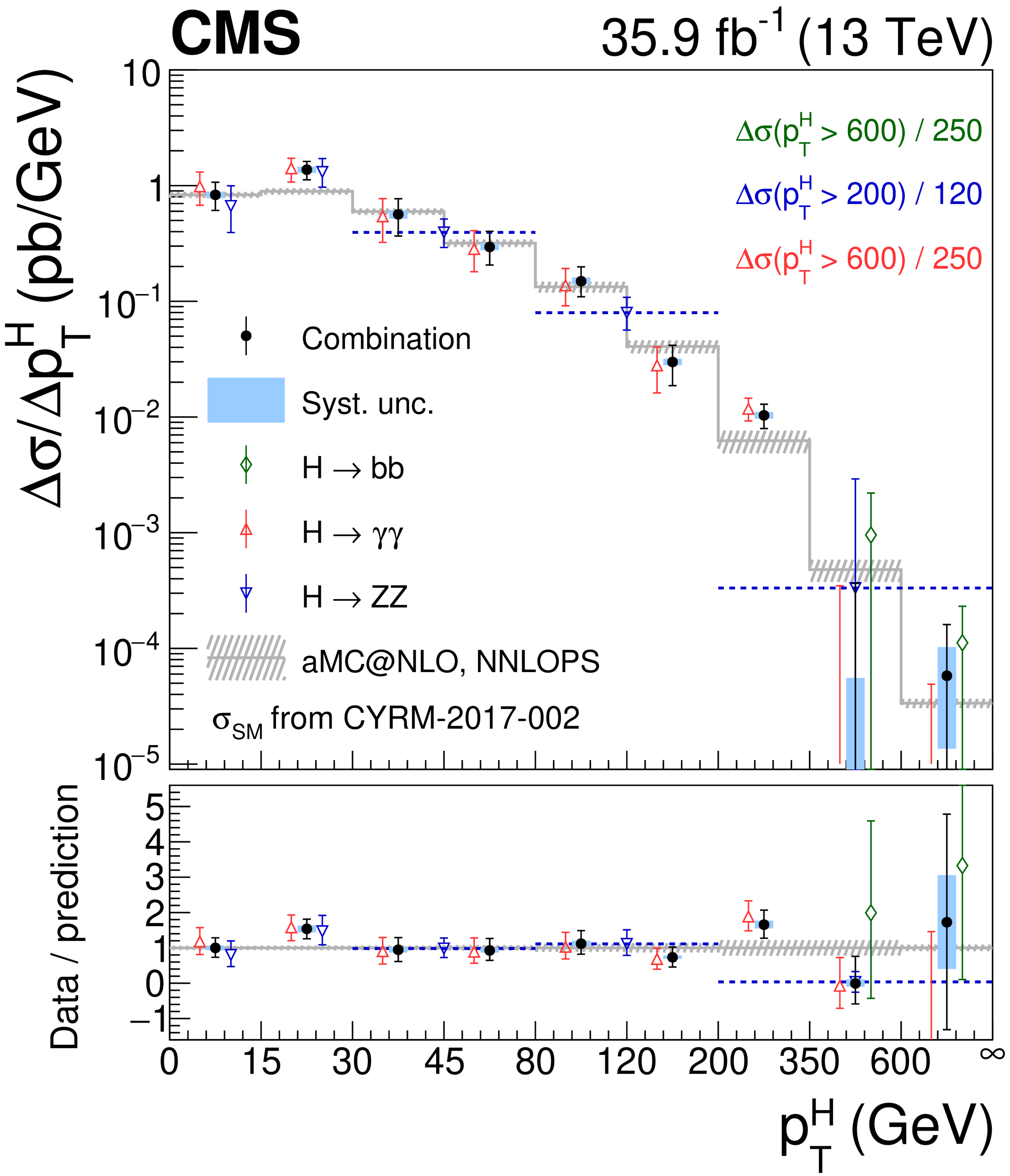
Phys. Lett. B 792 (2019) 369

Diff XS - Higgs transverse momentum

- H→bb adds at high Higgs transverse momenta
  - collimated: one large-R jet, substructure to find H→bb
  - not unfolded to fiducial phase space



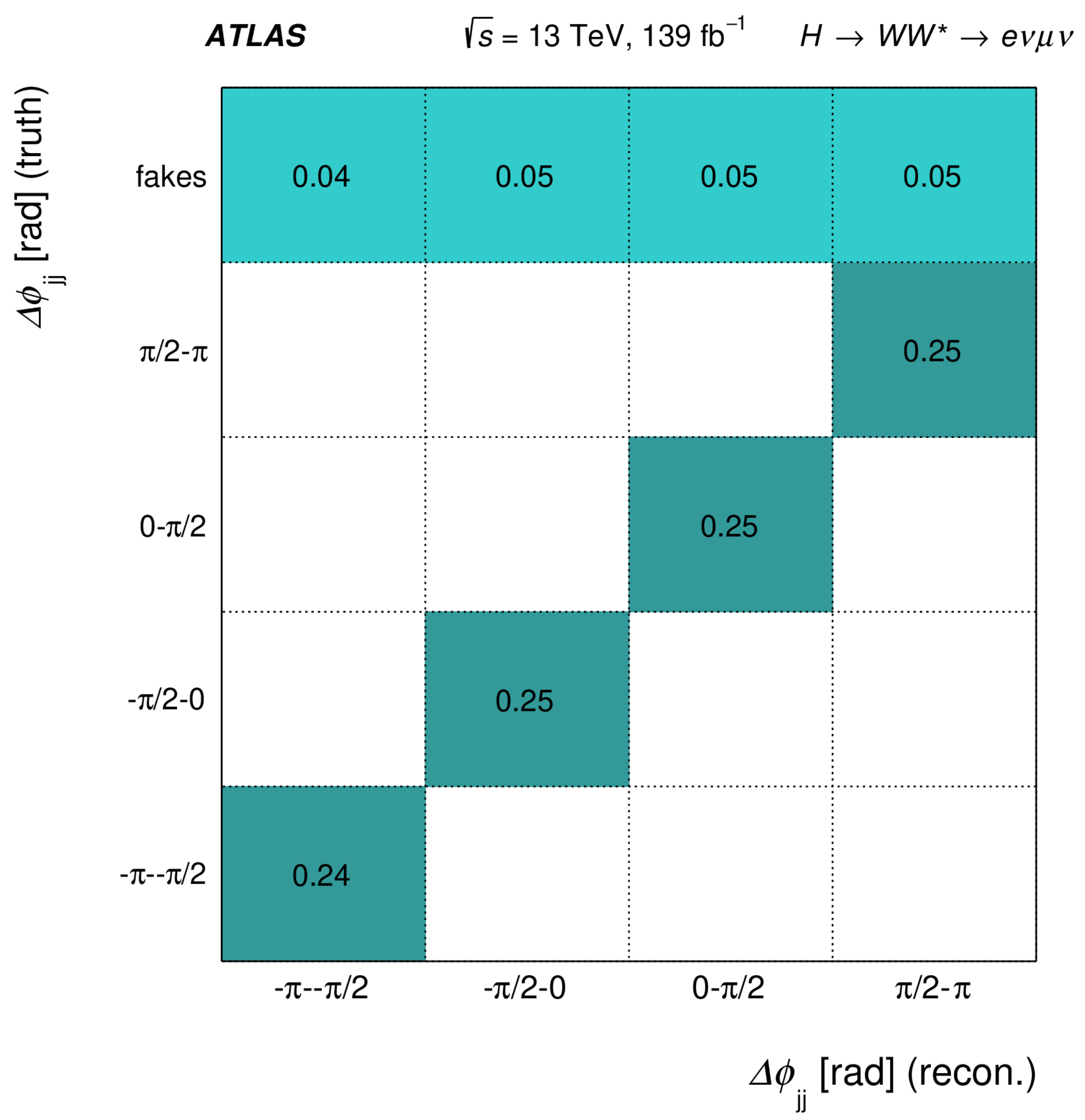
Phys. Rev. Lett. 120 (2018) 071802

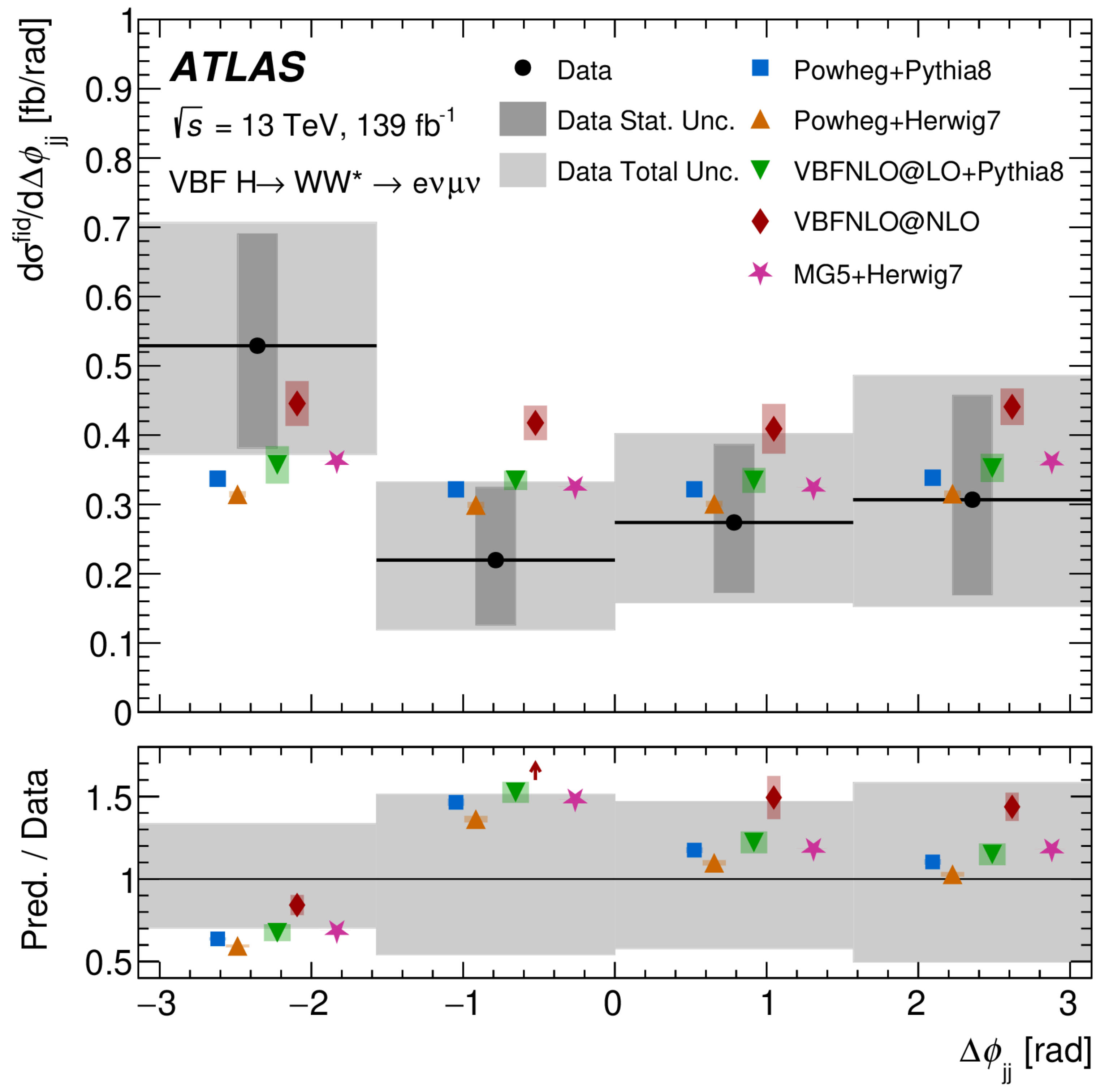


Phys. Lett. B 792 (2019) 369

Diff XS - the special one: H→WW→eνμν

- large branching ratio
- but: poor resolution (neutrinos!), and large backgrounds
- ATLAS: split into ggF and VBF, CMS: inclusive
- ATLAS VBF measurement
  - BDT discriminants for signal extraction (no cuts)
  - Response matrices quite diagonal!
  - no regularization necessary



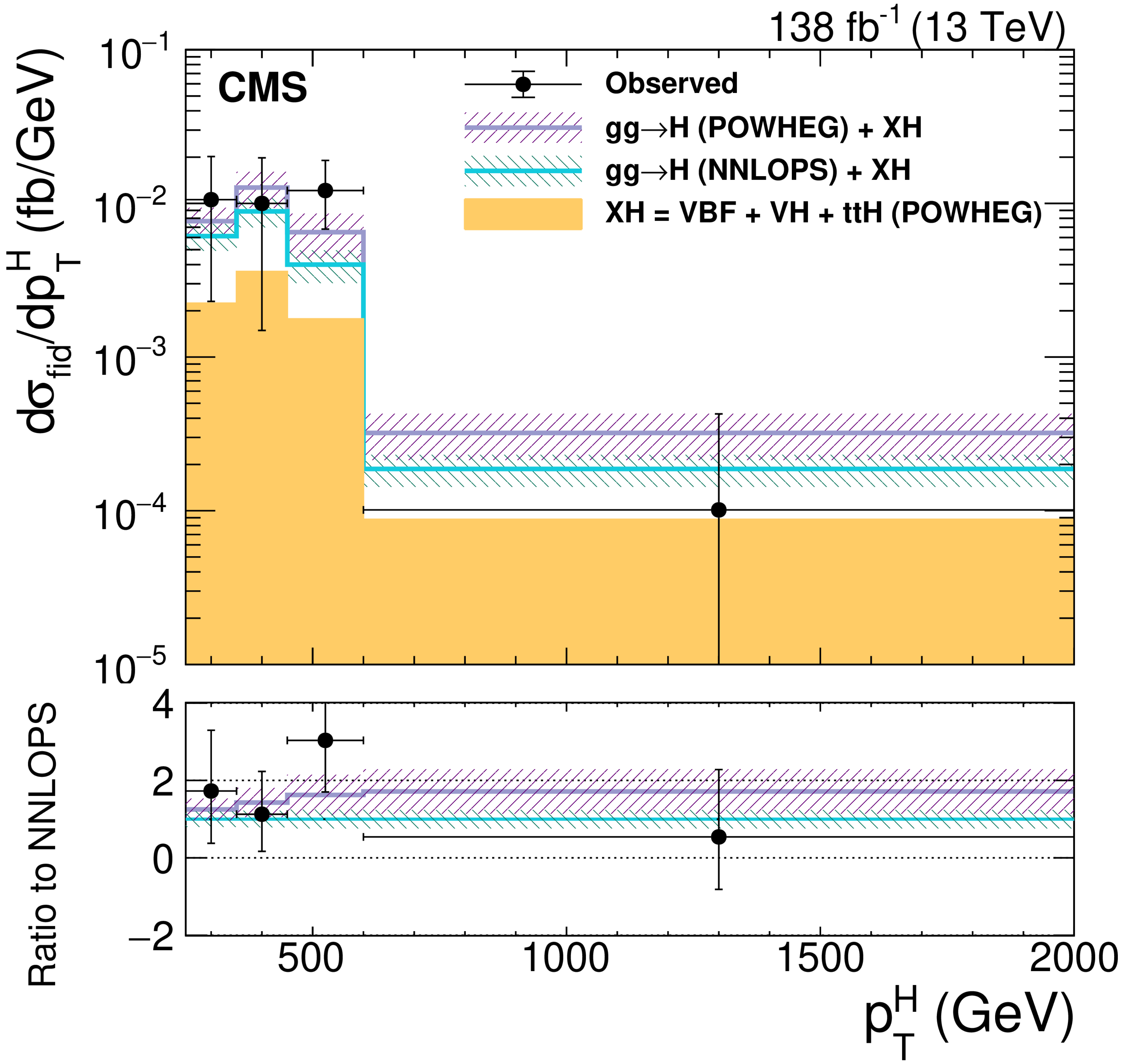


Phys. Rev. D 108 (2023) 072003

- in VBF phase space
- angle between the two jets
- CP sensitive

Diff XS - the newcomer: H→ττ

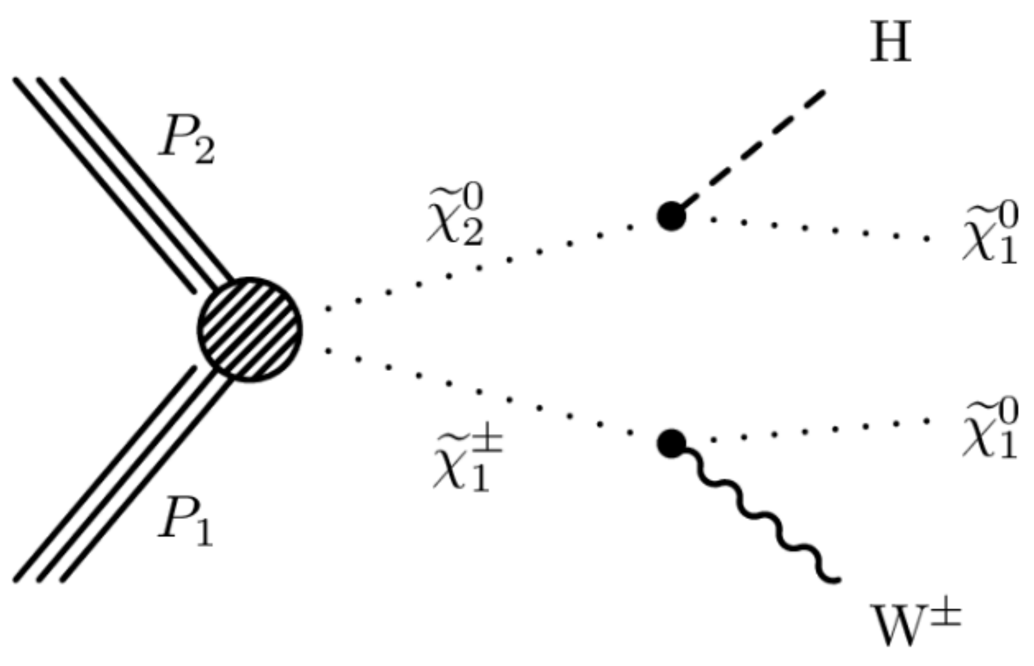
- large branching fraction, poor mass resolution
- resolved and boosted analysis
- boosted $\Delta R(\tau\tau) < 0.8$
  - dedicated algorithm to reconstruct close-by taus
  - multiclass NN for signal/background separation
- Probing high transverse momenta!

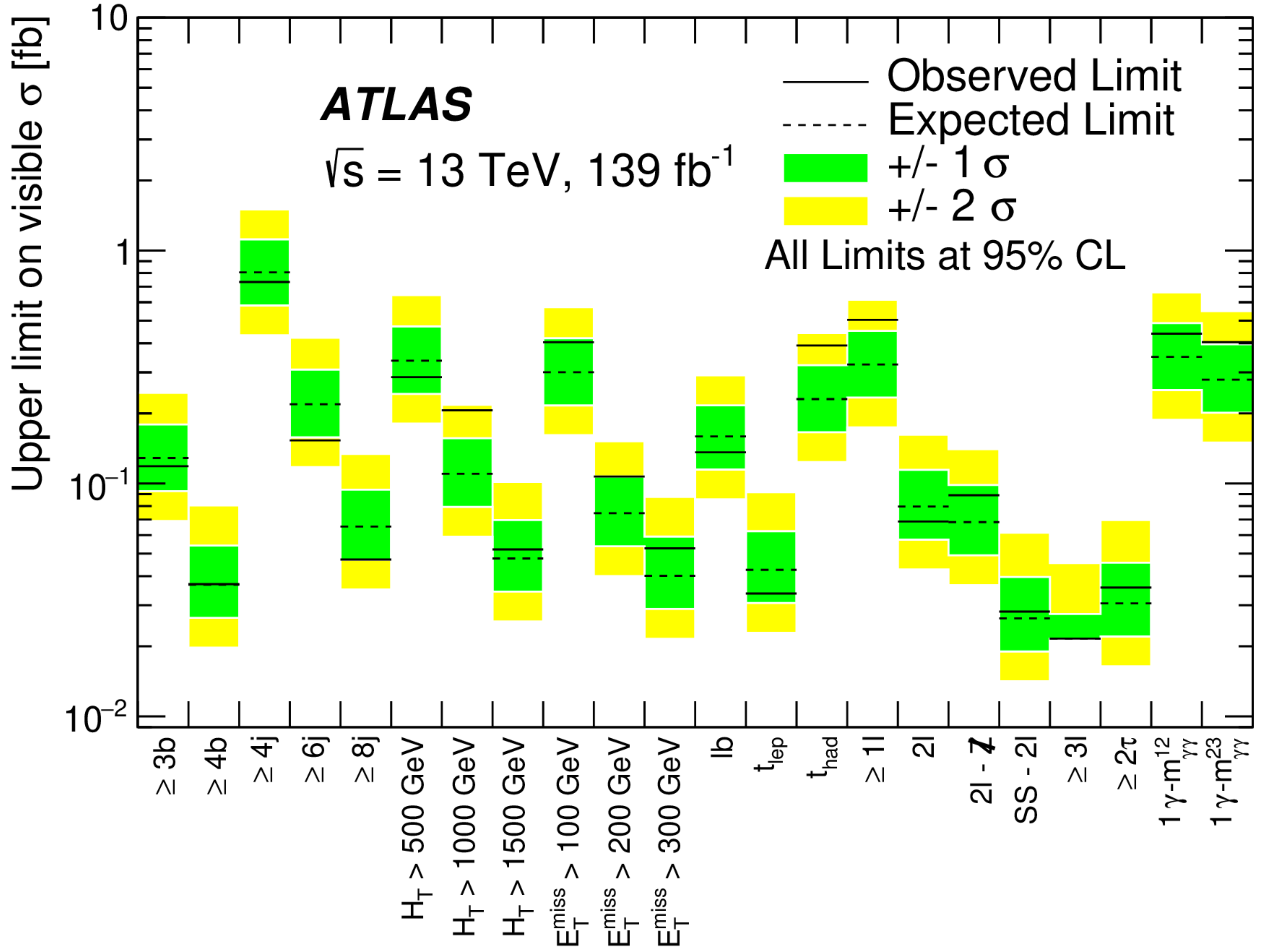


Submitted to Phys. Lett. B

Fiducial XS - the exotic one: γγ + X

- model independent search for H(→ **γγ**) + X
- sensitivity to exotics Higgs boson production
- models in which the Higgs is produced together with other particles
    - SUSY decays
    - exotic top quark decays (FCNC), top partners
    - hidden sectors

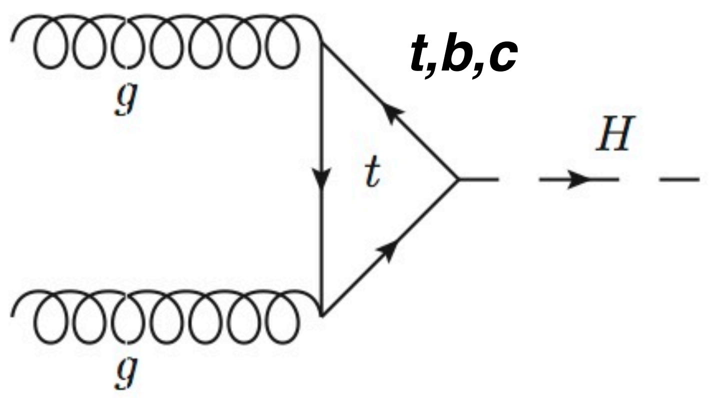


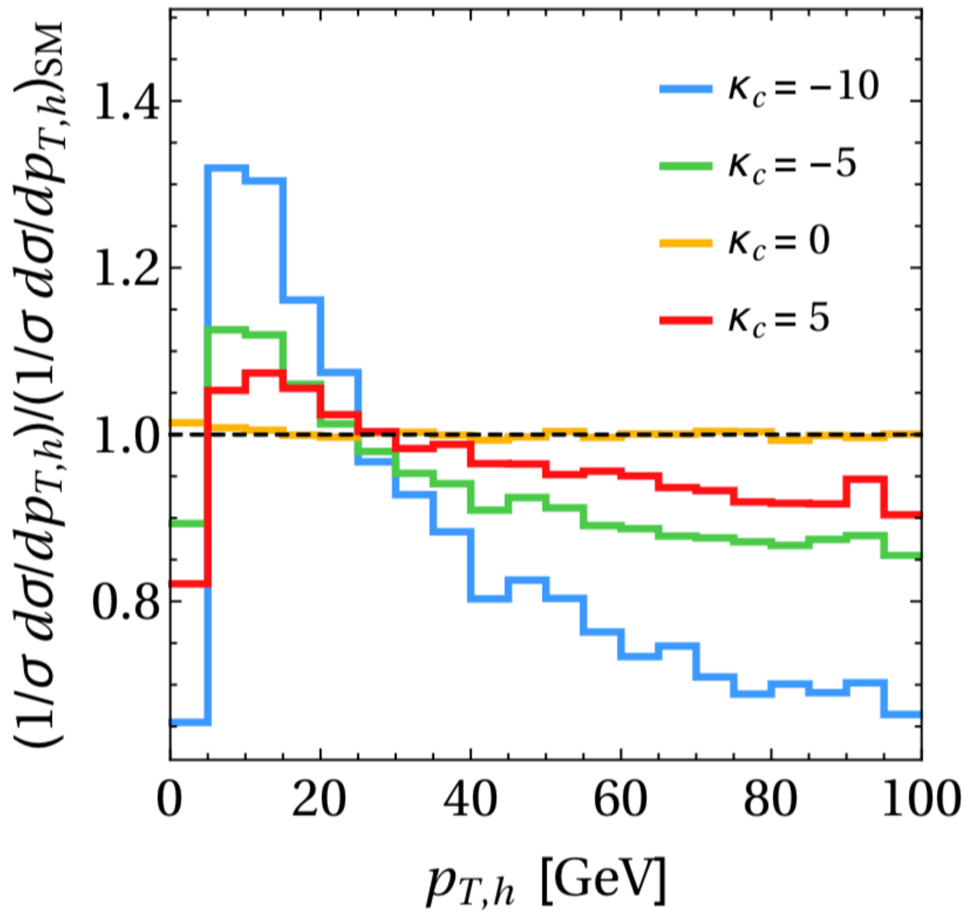


JHEP 07 (2023) 176

Diff XS - selected interpretations

PRL 118, 121801 (2017)

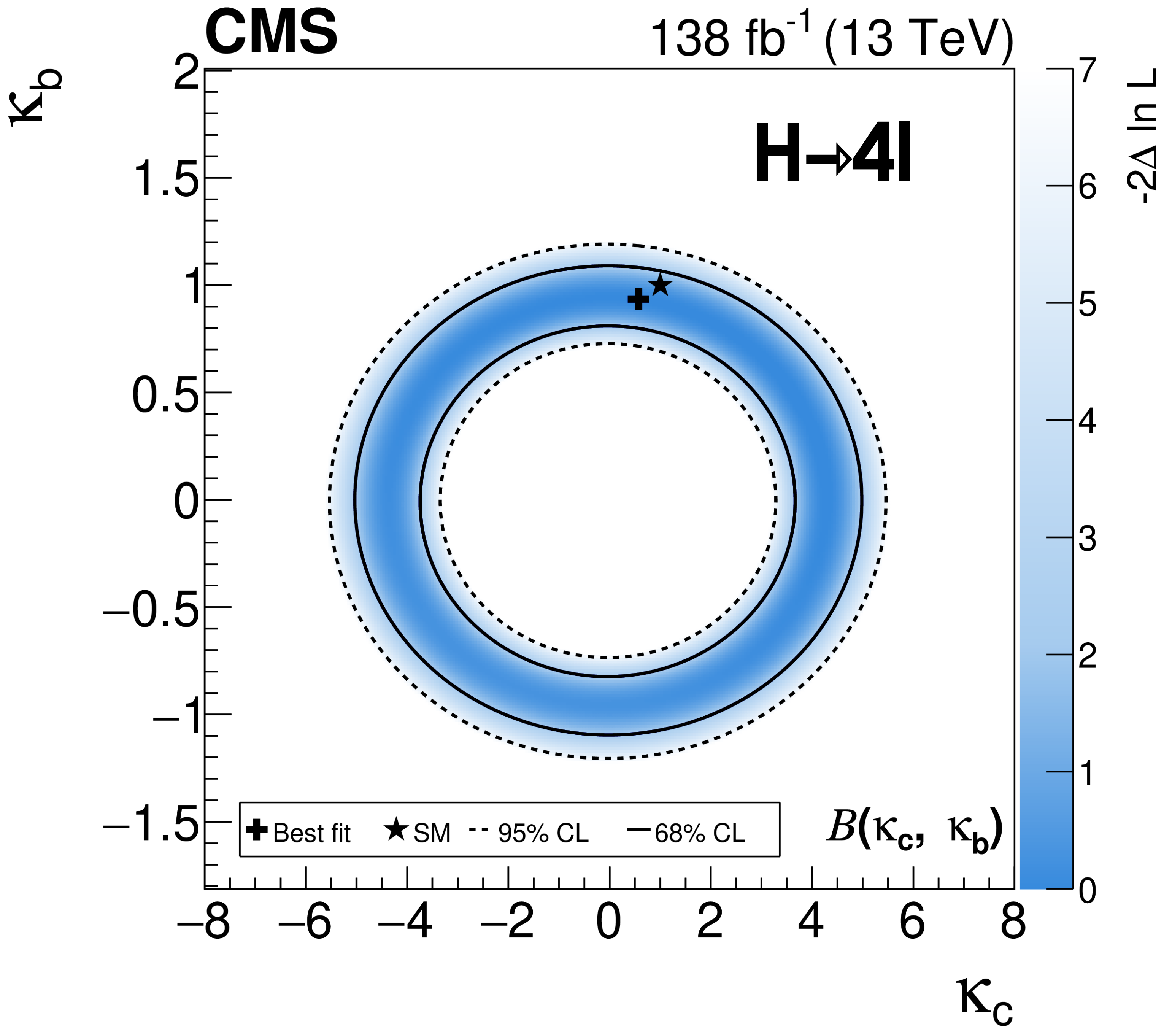




Covered in topical talks!

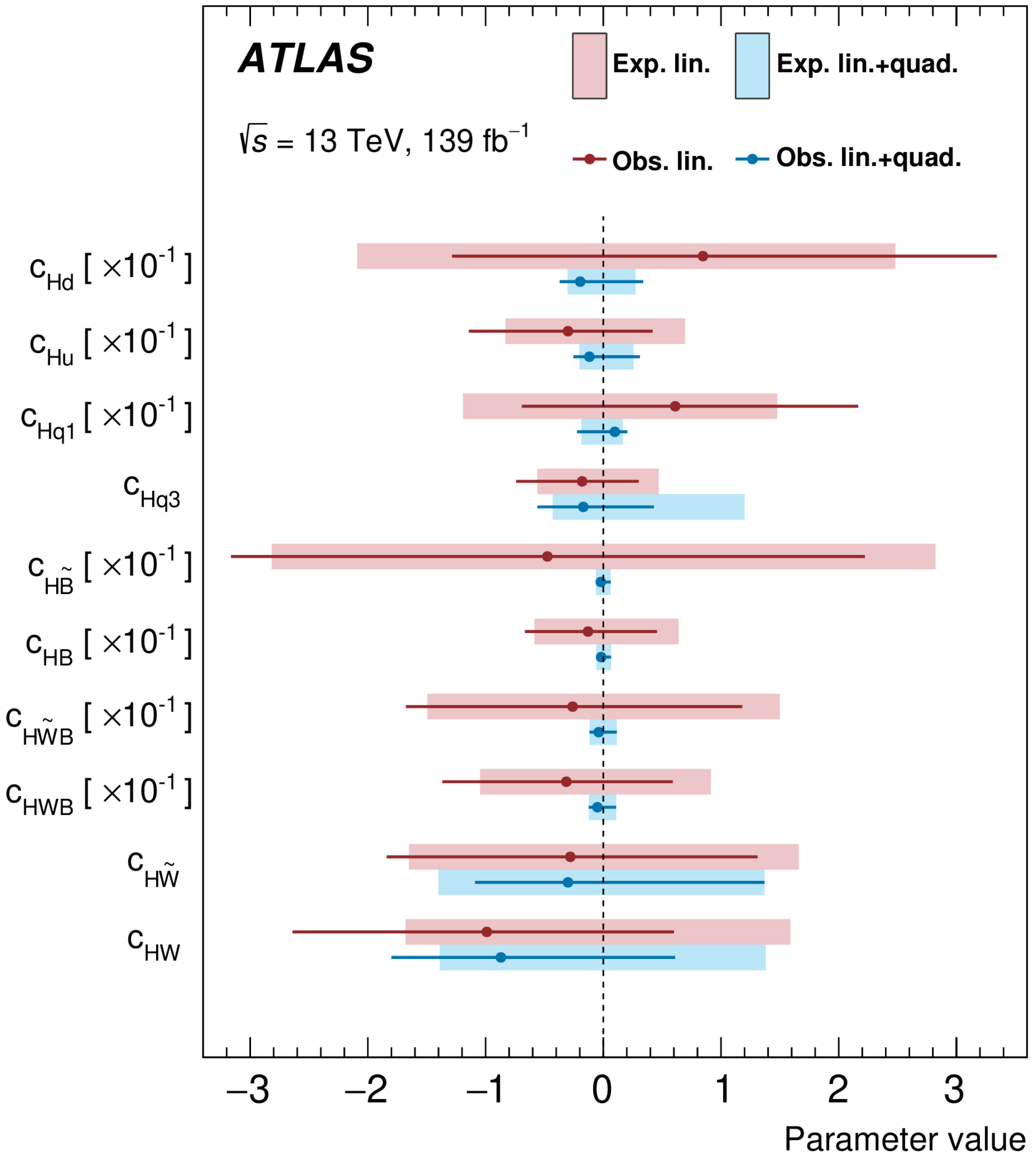
Just a few examples from the experiments

- Yukawa couplings
- trilinear self-coupling
- effective field theory & CP studies



JHEP 08 (2023) 040

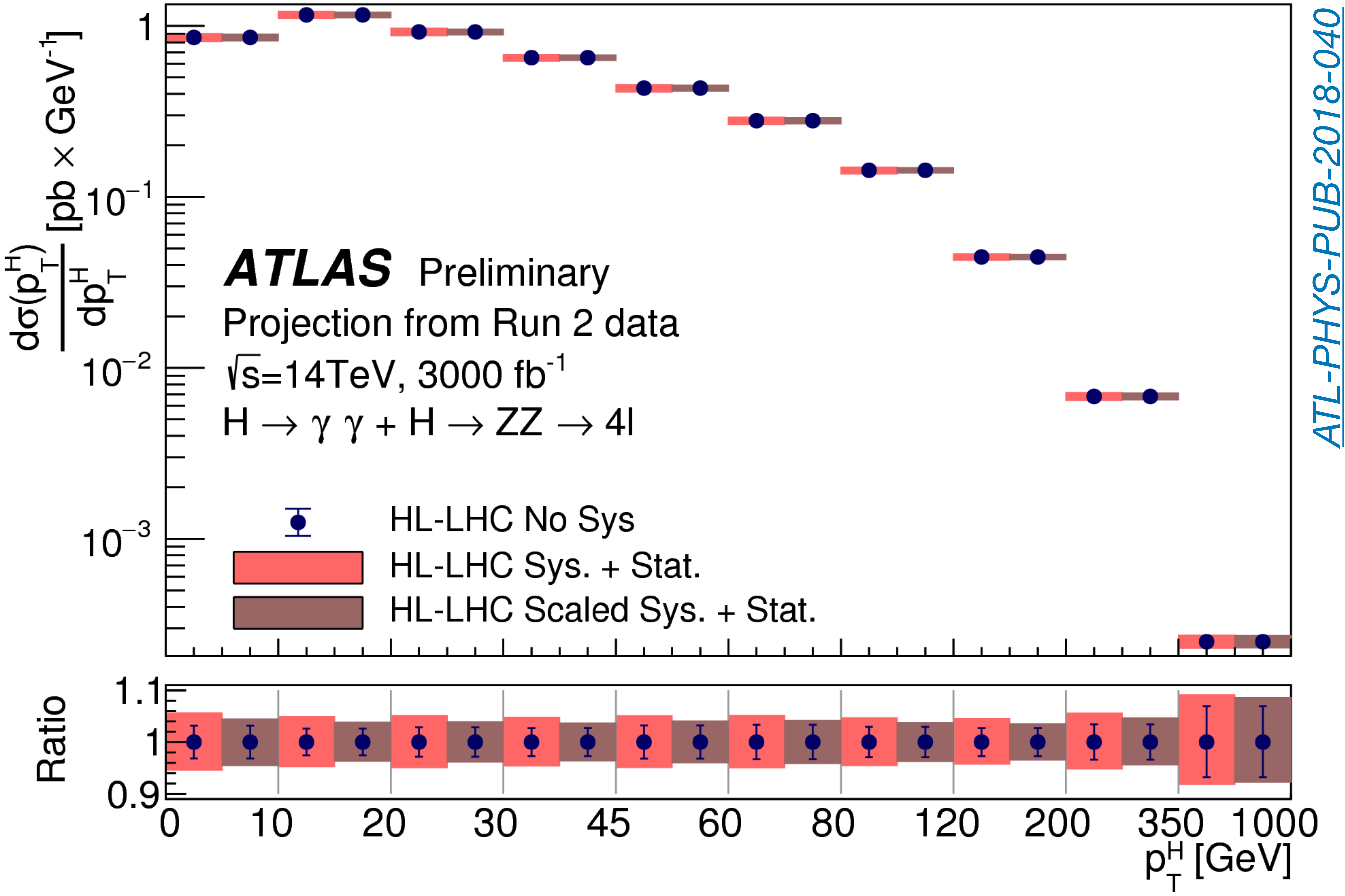
H→WW



Phys. Rev. D 108 (2023) 072003

Diff XS - future

- more data
  - more variables, finer binning, higher dimensionalities
  - additional decay channels (llγ?)
- also for STXS, discussed next:
  - Feedback welcome on what is needed to make the measurements as useful as possible
  - (besides likelihoods - see last talk)

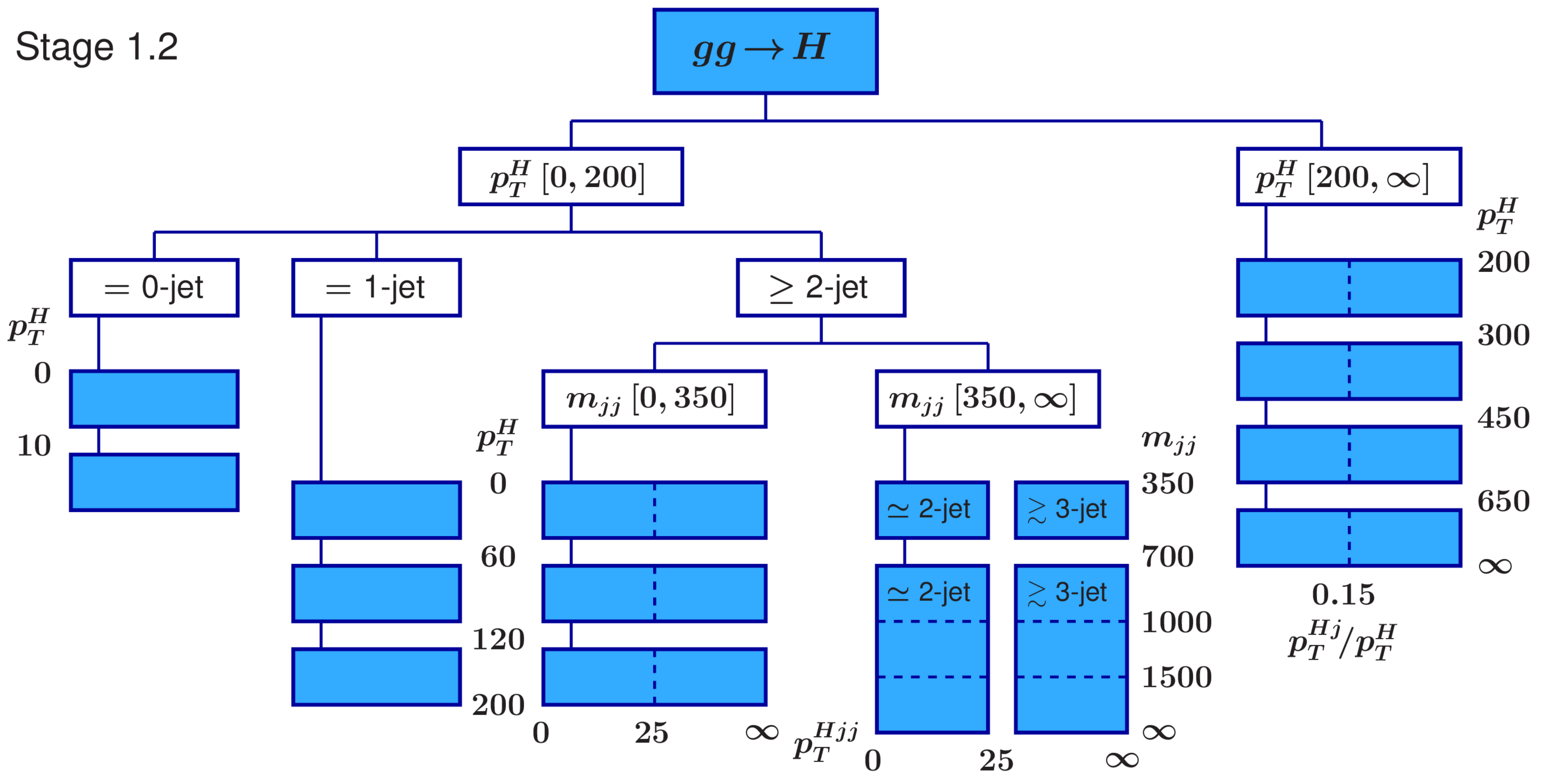


ATL-PHYS-PUB-2018-040

The How (2): Simplified template cross sections (STXS)

- divided into production modes and kinematic/jet properties
- centralized binning definition (through LHC Higgs WG), current version: STXS 1.2
  - binning compromise between maximizing BSM sensitivity and minimizing theory uncertainties
- performed in all available channels
- cross sections given without decay BR

Example ggF



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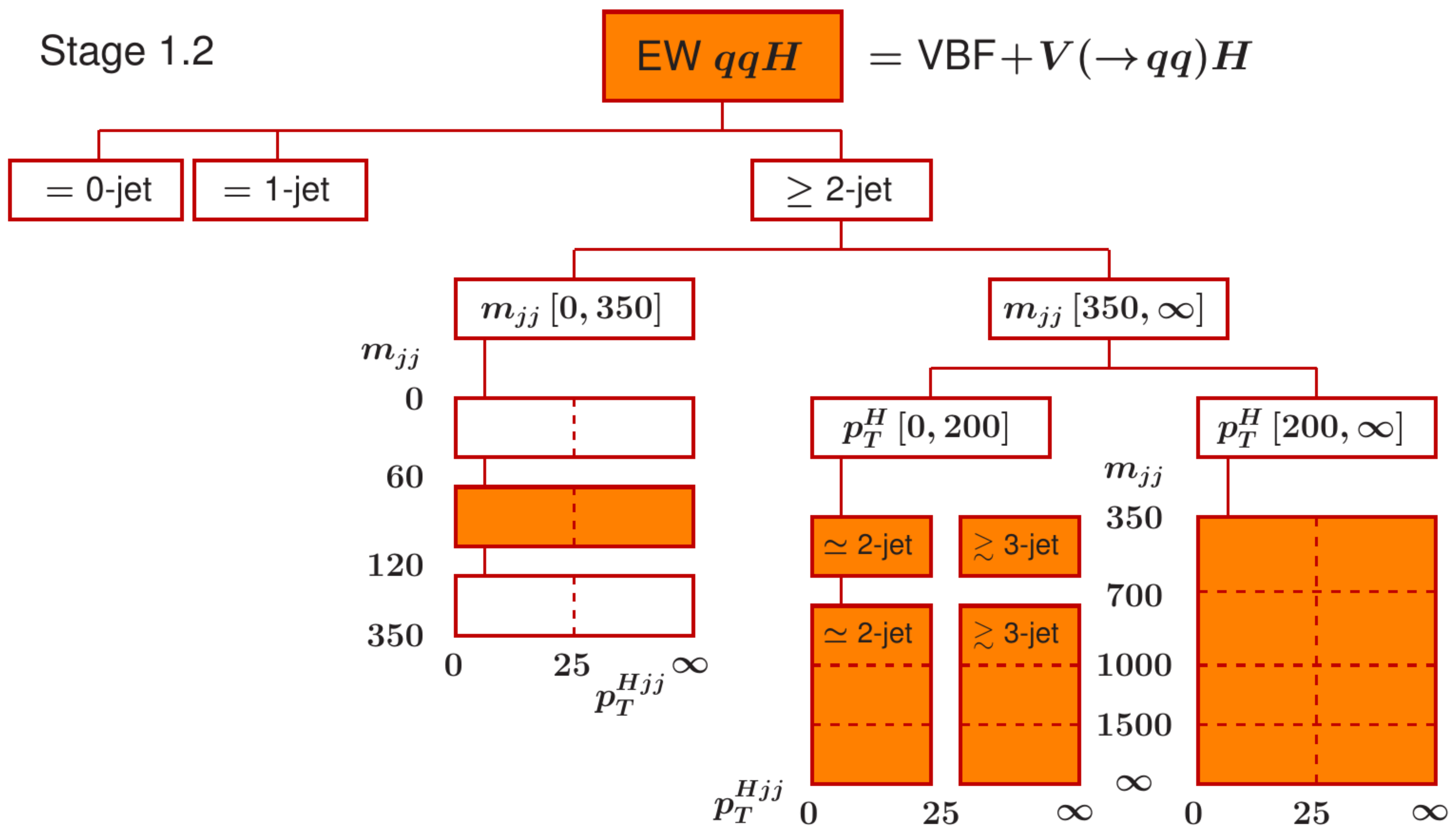
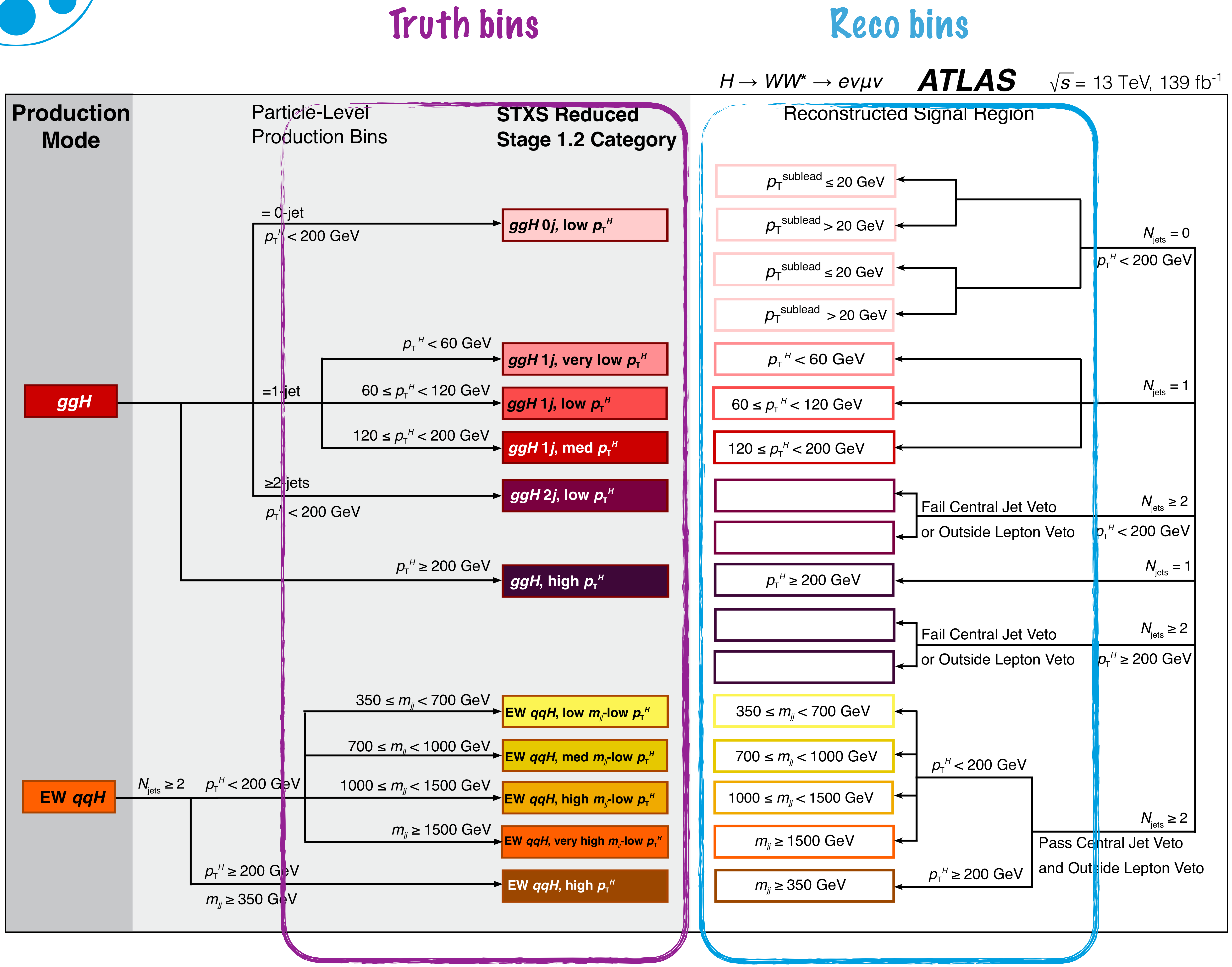
Example qqHqq

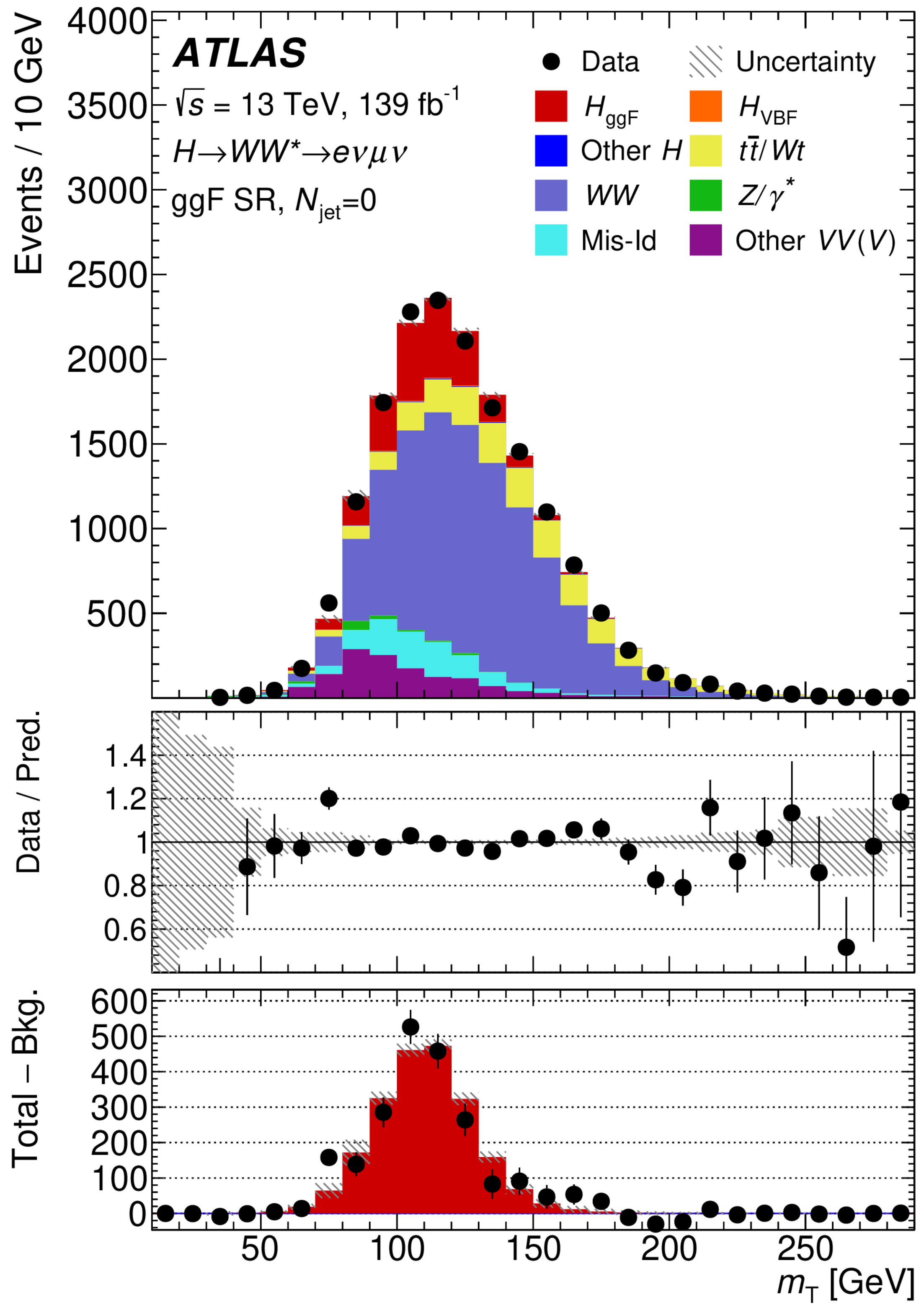


- “Unfolding” with a likelihood fit to reco-level categories that **try to match the truth categories to avoid extrapolations**
- The harmonized categories are extremely useful for combinations and the base for further interpretations
  - also for consistent calculation of theory uncertainties

STXS - example H→WW



- simultaneous fit to signal and control regions
- observables: transverse mass (ggF), DNN (VBF)
- POIs: XS in STXS categories

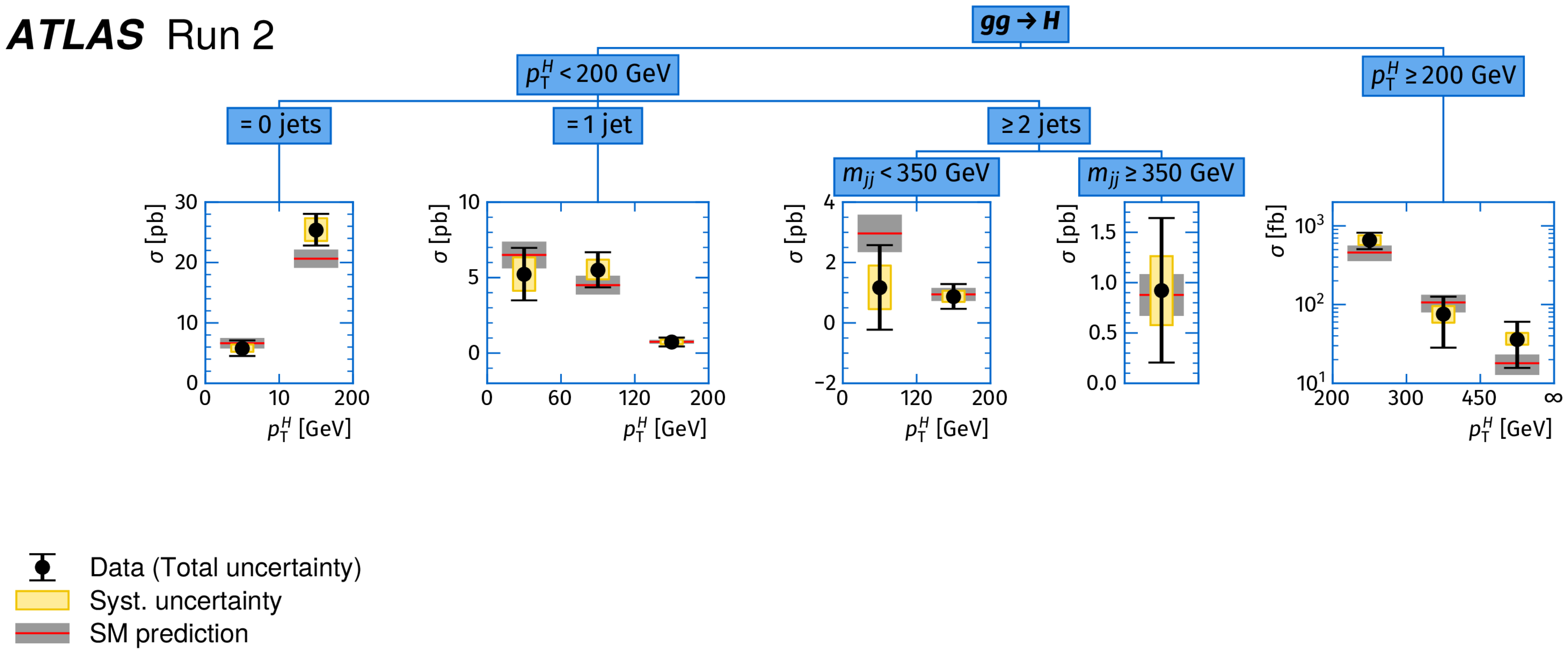


Phys. Rev. D 108 (2023) 032005

STXS - Combination of decay channels

Example ATLAS Nature paper (2022)

(CMS: Nature 607 (2022) 60)



Nature 607, 52 (2022)

Input channels:

H->γγ

H->ZZ(4l)

H->WW(eνμν)

H->ττ

H->bb

Correlation matrix in appendix

STXS - Combination of decay channels

Example ATLAS Nature paper (2022)

(CMS: Nature 607 (2022) 60)

Input channels:

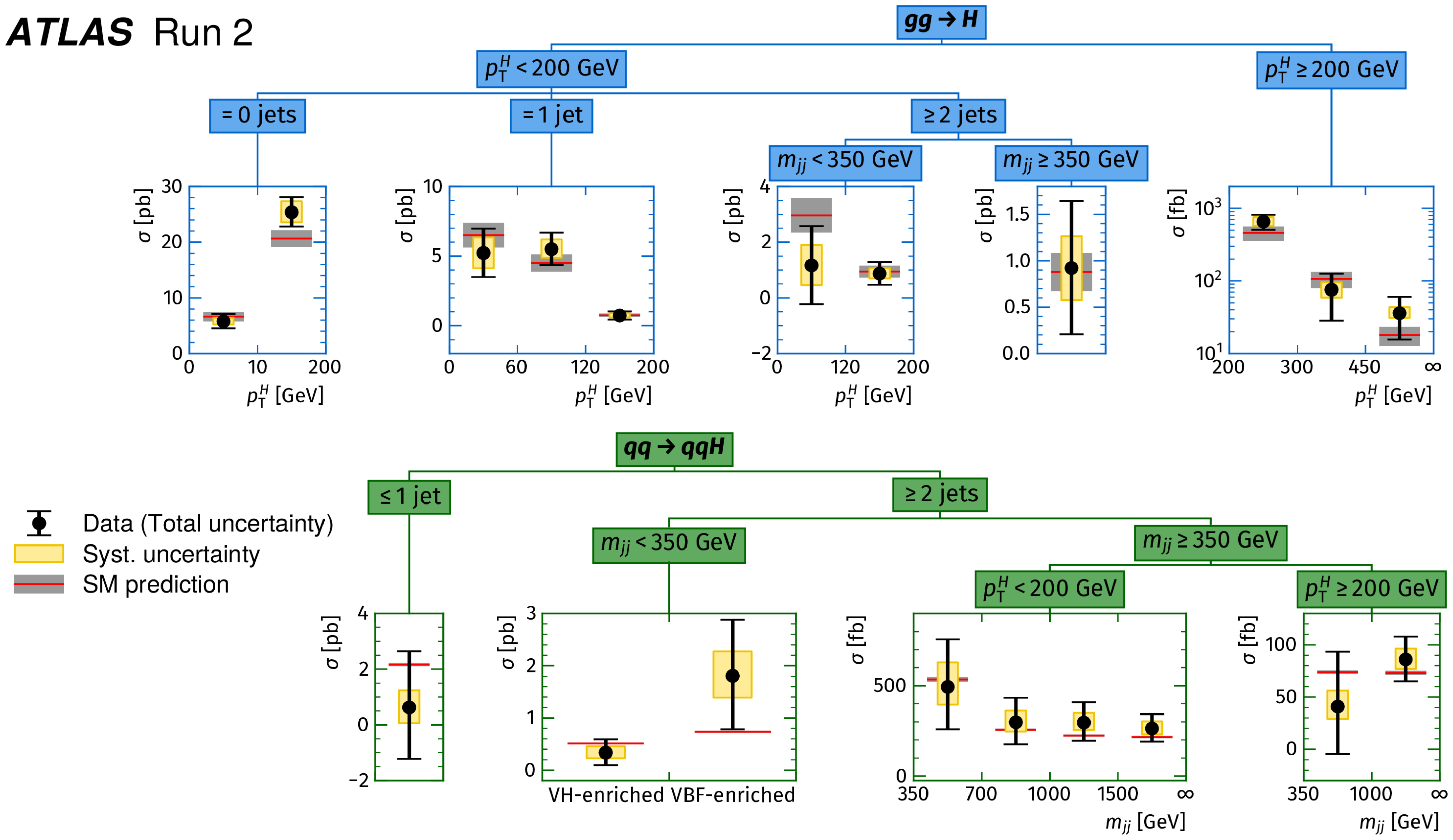
$H \to \gamma\gamma$

$H \to ZZ(4l)$

$H \to WW(e\nu\mu\nu)$

$H \to \tau\tau$

$H \to bb$



Nature 607, 52 (2022)

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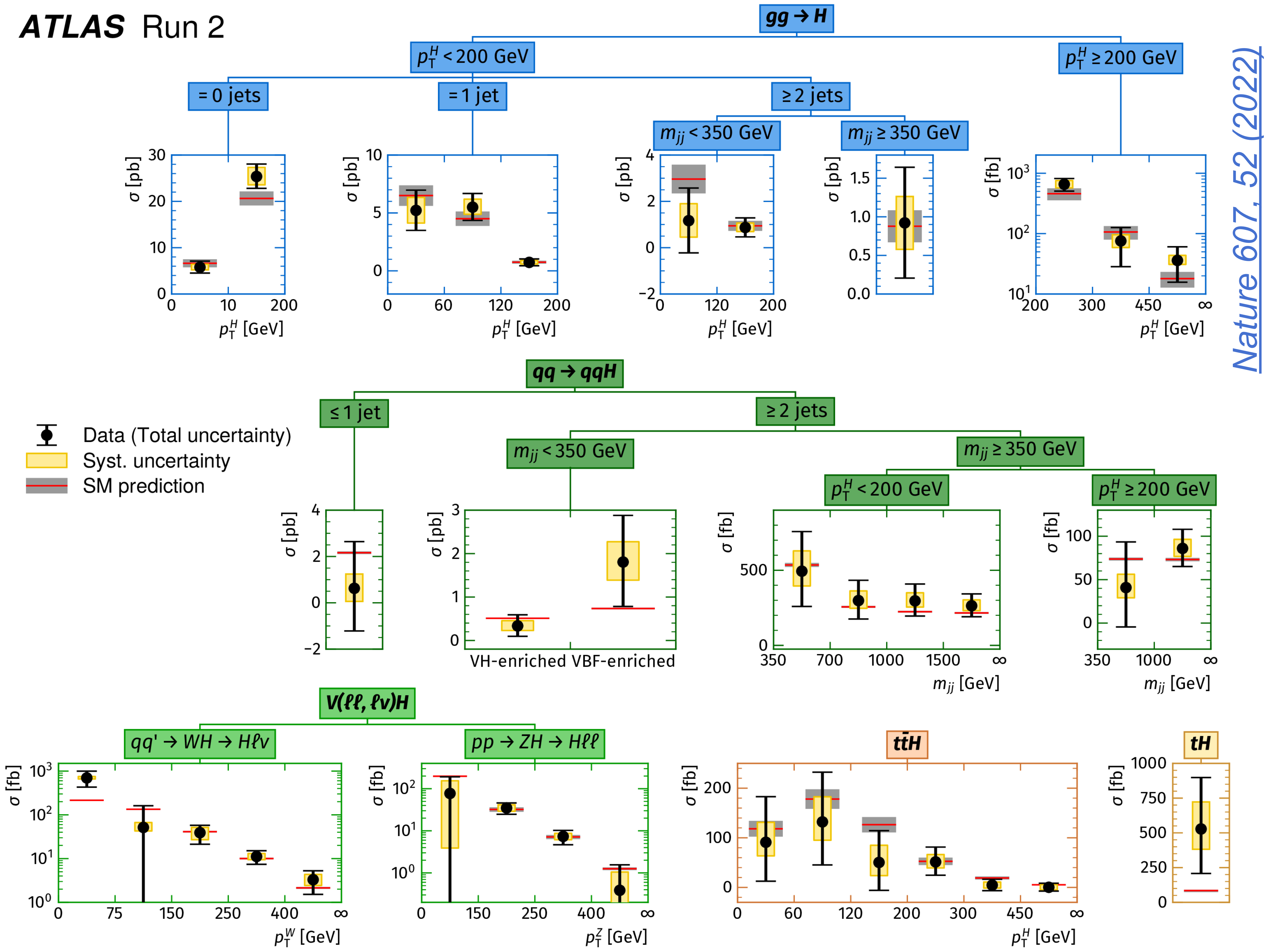


Nature 607, 52 (2022)

Input channels:

H->γγ

H->ZZ(4l)

H->WW(eνμν)

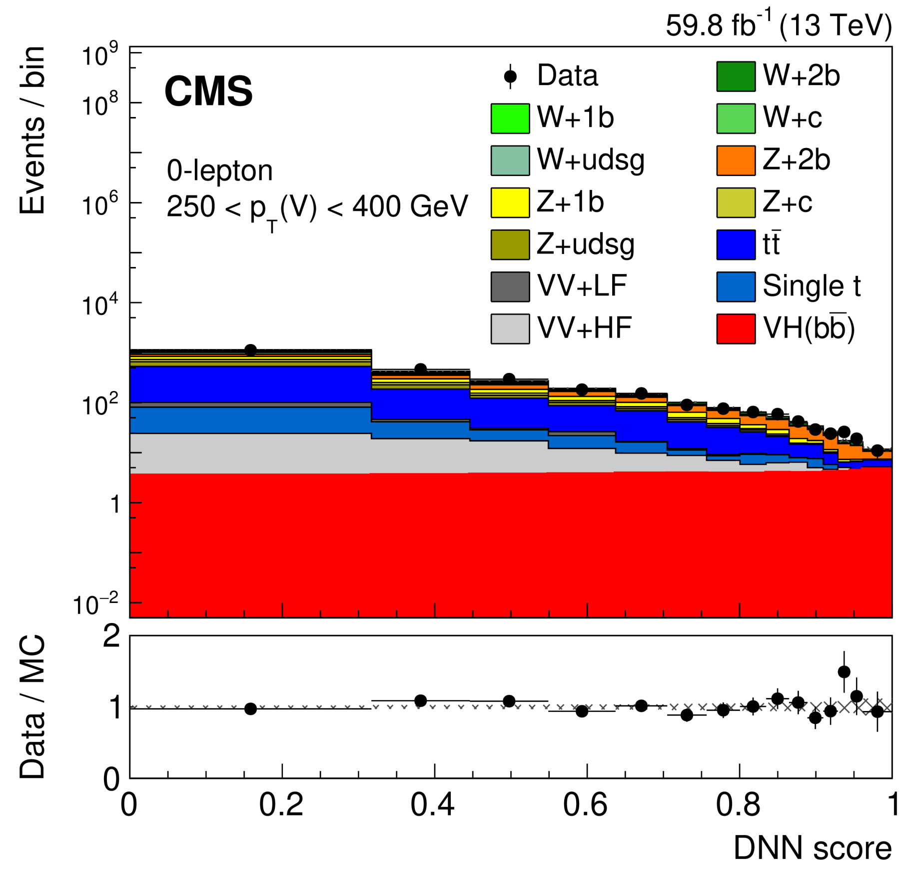
H->ττ

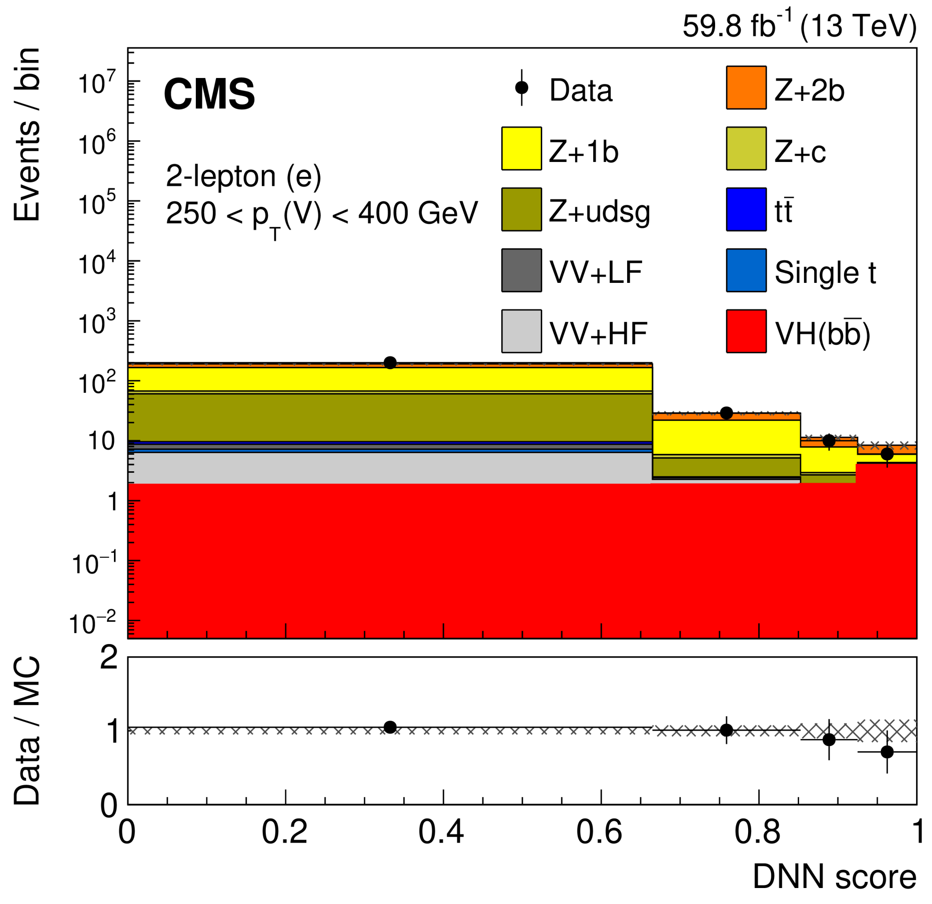
H->bb

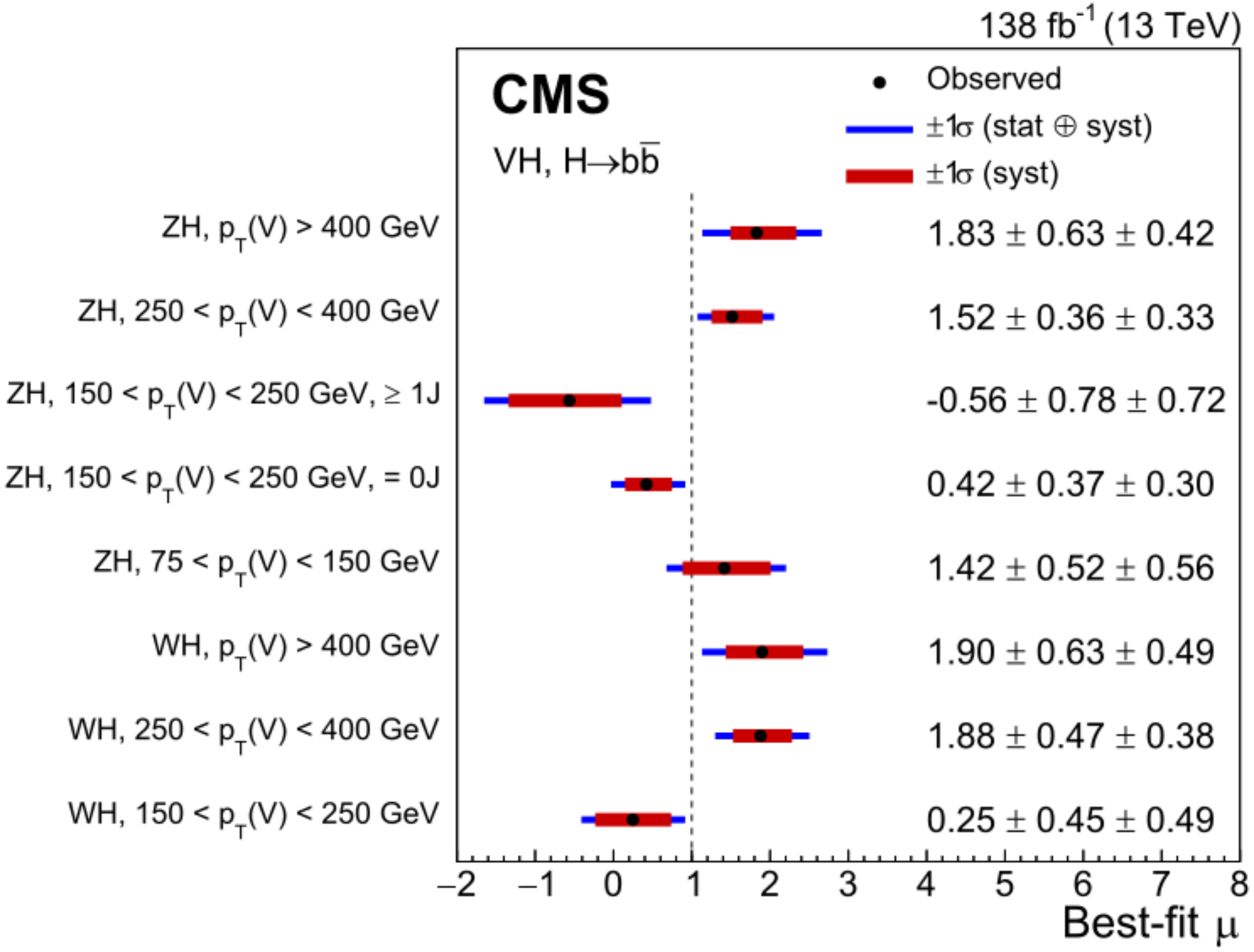
Correlation matrix in appendix

STXS - beyond the Nature papers

- since the Nature combinations, updated measurements, in particular in the fermion channels
- example CMS H→bb
  - V(lep)H, resolved and boosted
  - fit to DNN discriminants







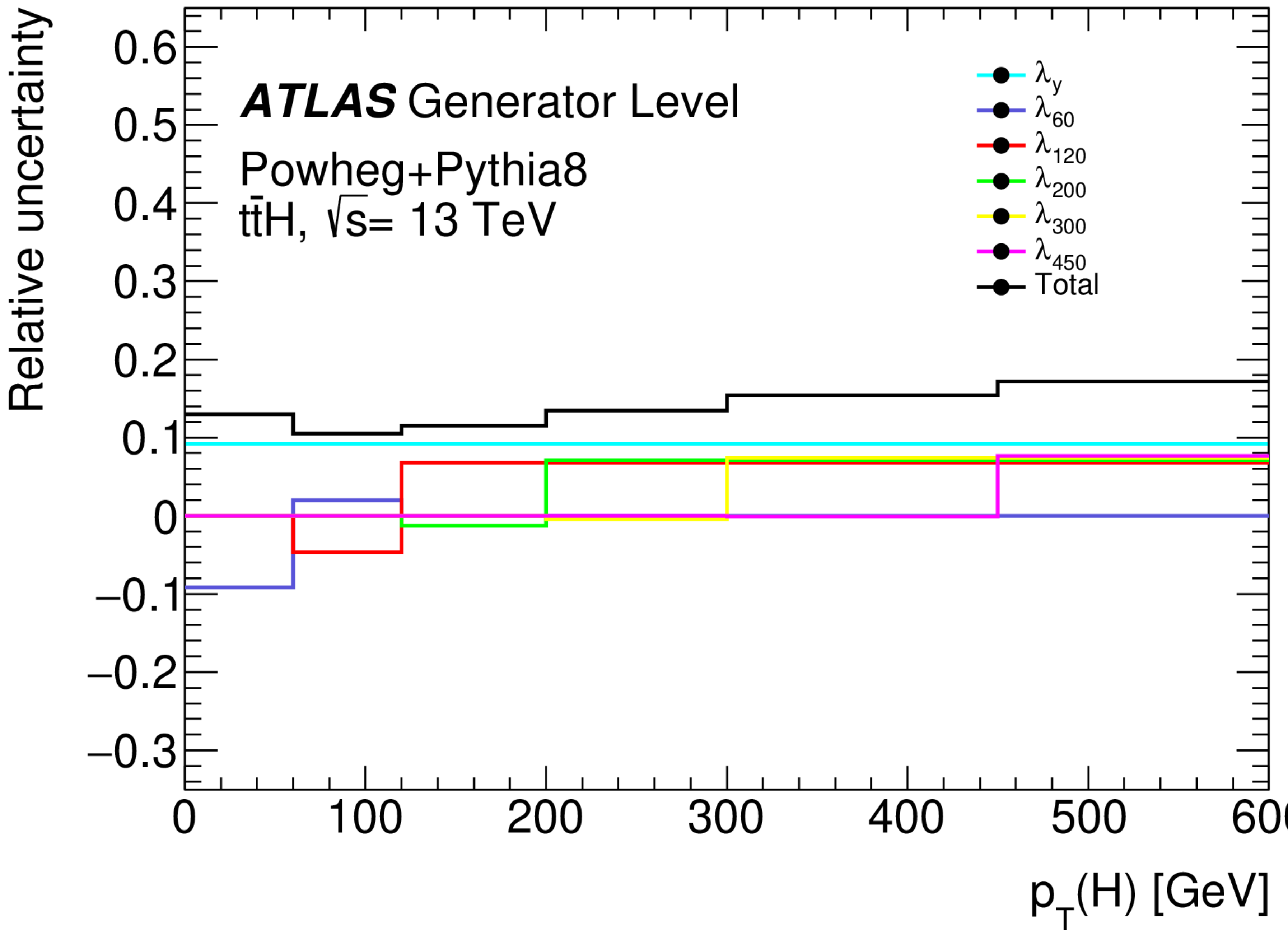
Accepted in Phys. Rev. D

- expect updated combinations

STXS - a word about scale uncertainties

Phys.Rev.D 85 (2012) 03401

- uncertainties derived for STXS 1.2 binning with long-range Stewart-Tackmann method
- idea Stewart-Tackmann: $\Delta(1\text{jet}) = \sqrt{\Delta(\geq 1\text{jet})^2 + \Delta(\geq 2\text{jet})^2}$
    - avoids cancellation effects in usual fixed order scale variations
- long-range: assign uncertainty to inclusive cross sections and to migrations at bin boundaries
    - uncorrelated uncertainties: nuisance parameters in fits, which can be correlated between measurements
    - also used in many other Higgs measurements
    - very useful for combinations, also between experiments!

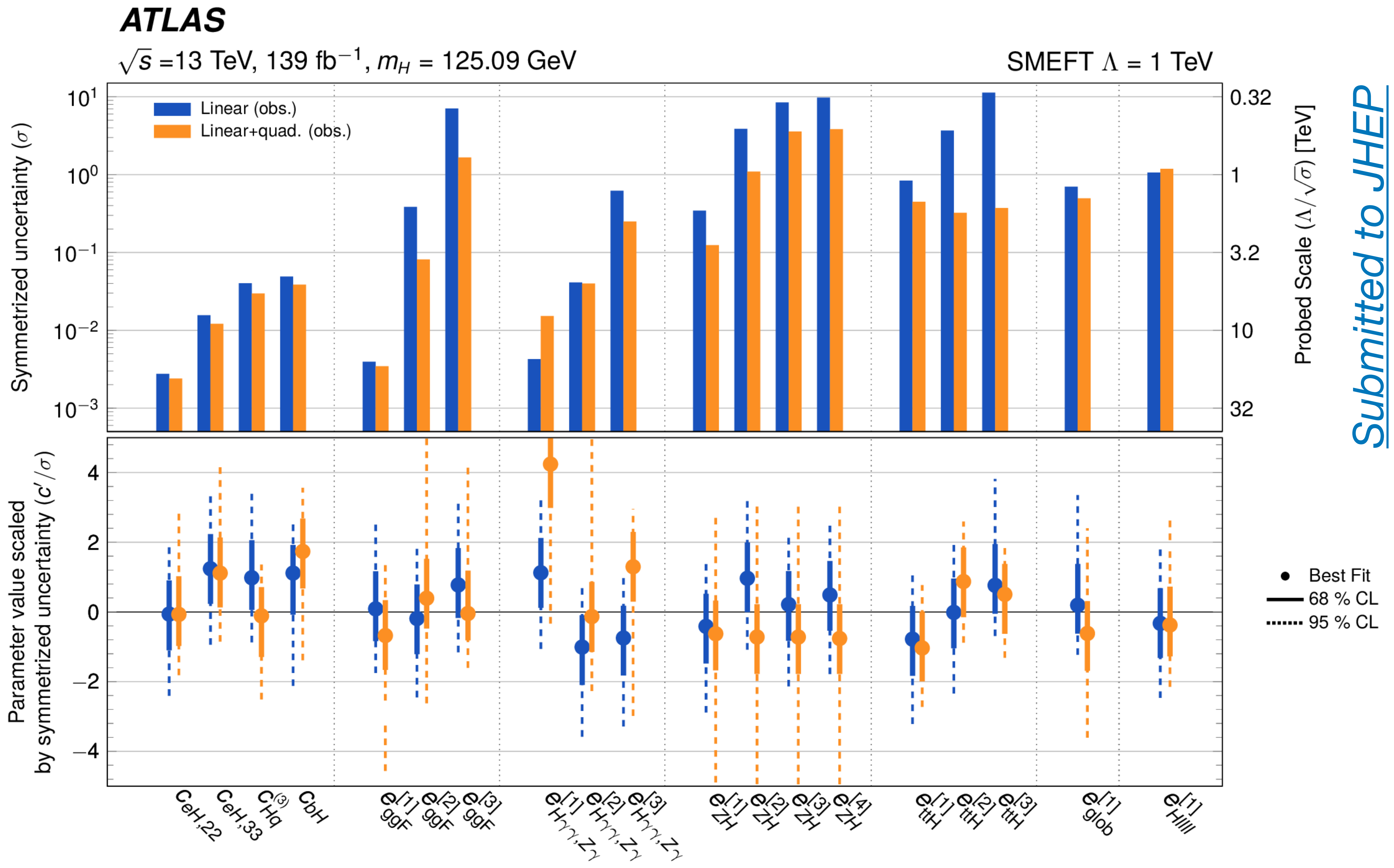


ATL-PHYS-PUB-2023-031 for ggF/ttH, paper planned for all

STXS - selected interpretations

- on the experimental side, usually reparametrization of the STXS likelihoods
  - effective field theory
  - 2HDM, MSSM

- Examples from outside the experiments
  - Lilith to constrain new physics from Higgs measurements (eg [2012.11408](2012.11408))
  - HiggsSignals to compare the predictions of BSM Higgs sectors with the existing measurements (eg Eur.Phys.J.C 81 (2021) 2, 145)
  - SMEFT fits (eg [2111.05876](2111.05876))



Submitted to JHEP

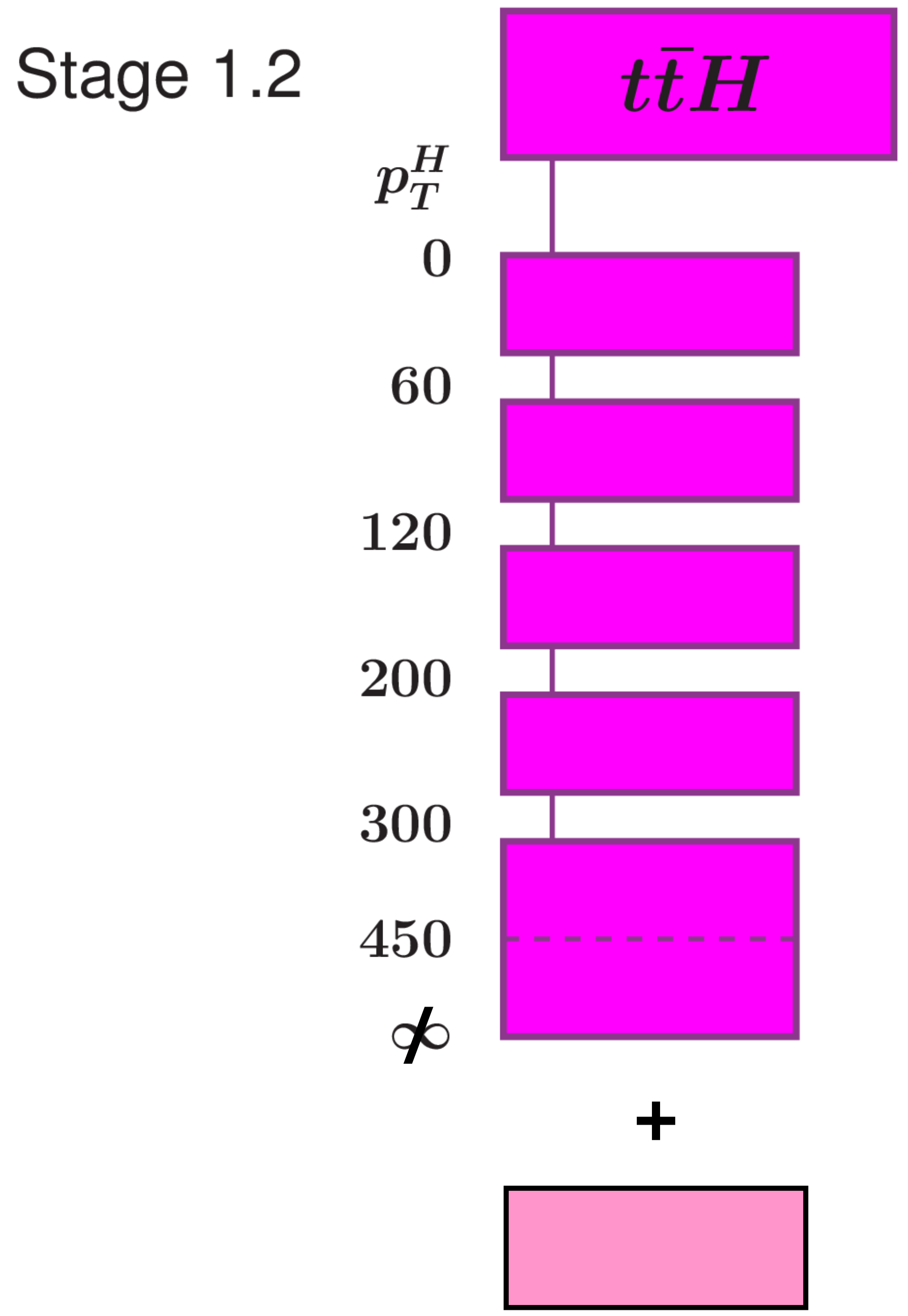
STXS for the future

LHC Higgs WG working on STXS 1.3 for Run 3 (iterations with community ongoing)

- add higher transverse momentum bins in almost all production channels
- add CP sensitive $\Delta\varphi_{jj}$ bins to VBF and possibly to ggF
- try to improve match of VH categories for boosted hadronic analyses with merged jets

Longer time-scale: STXS 2.0 for HL-LHC (~1 ab^{-1})

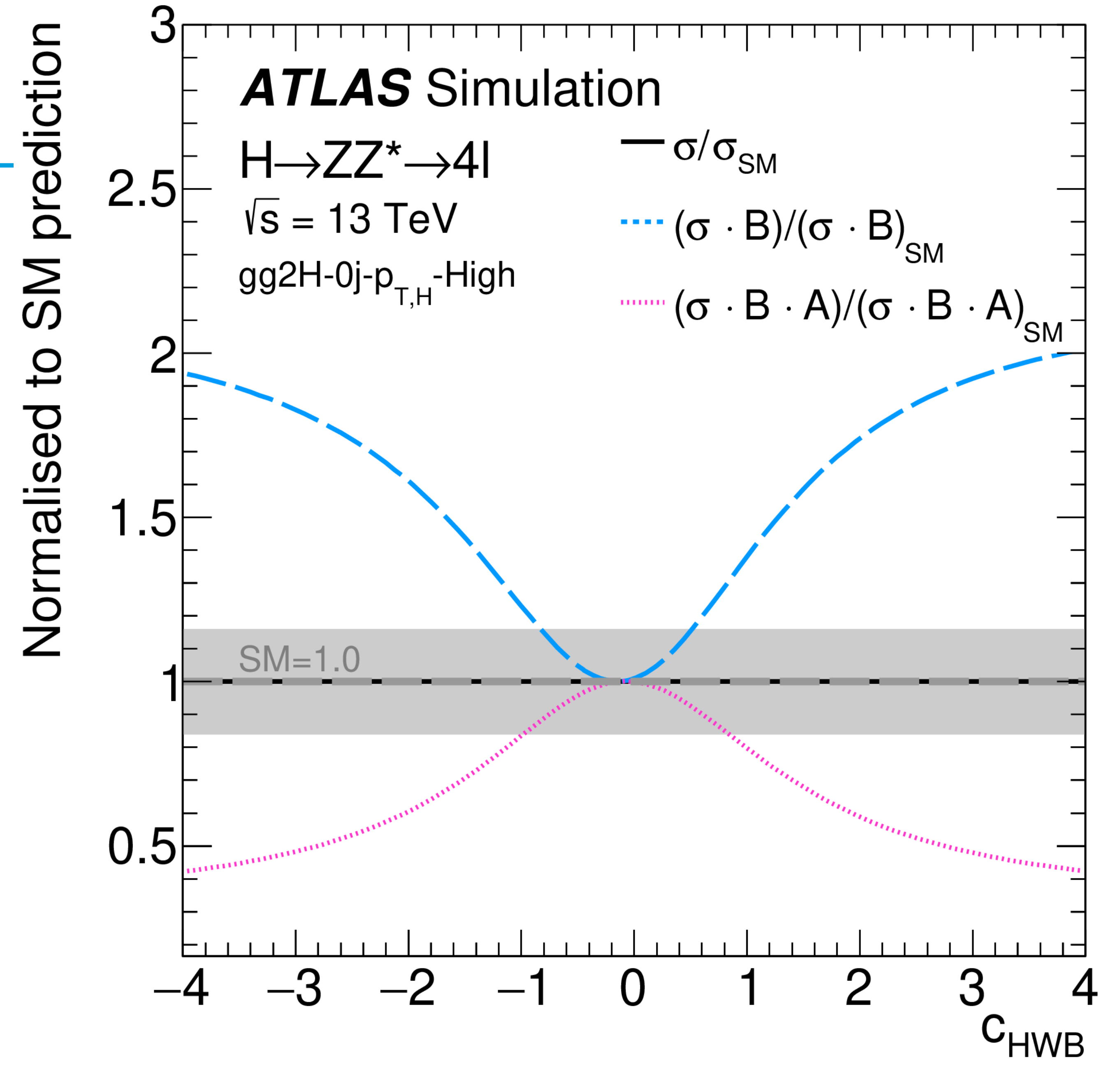
- changes that do not make it into 1.3
- VBF+γ?
- CP-sensitive observable for ttH

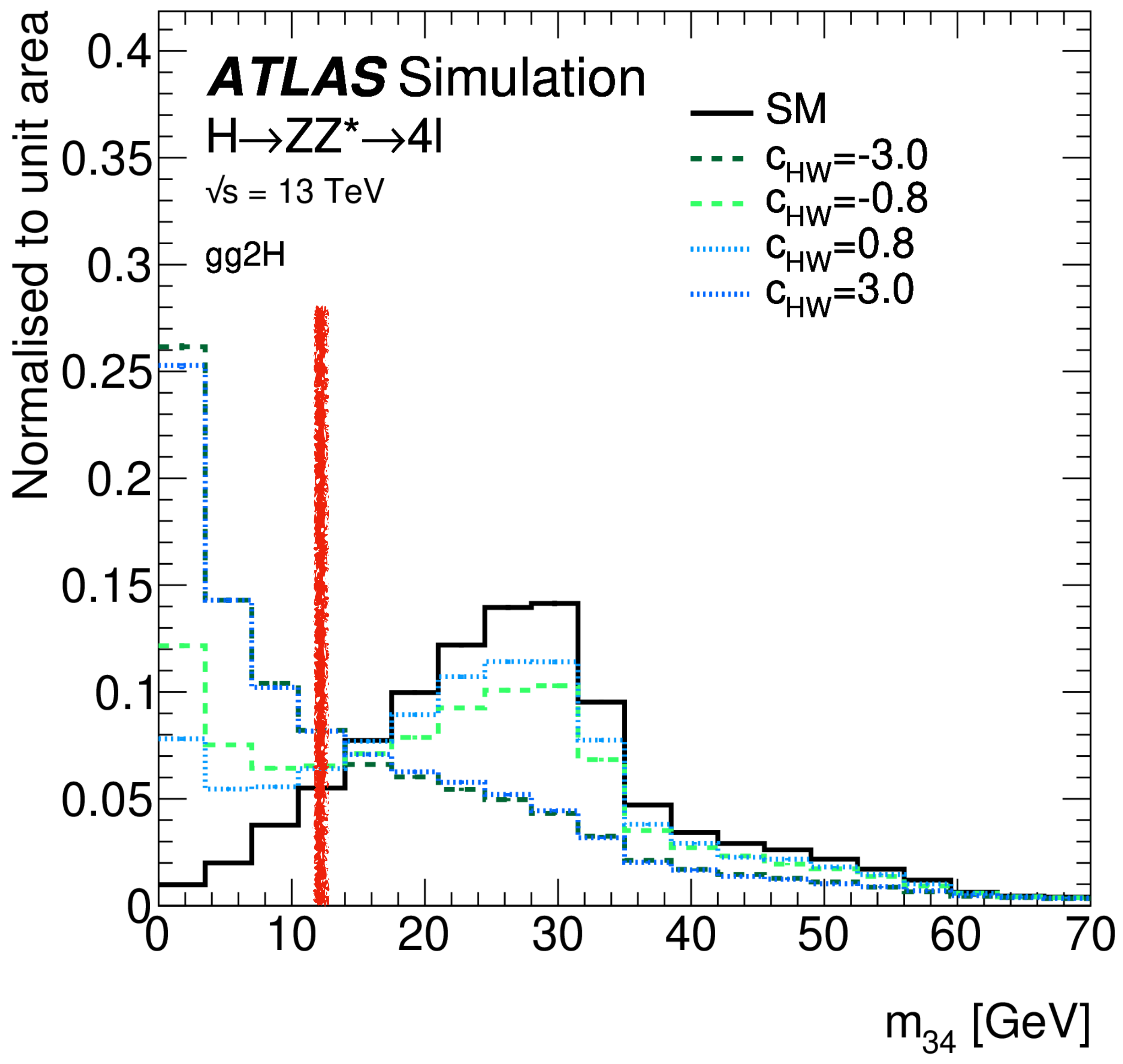


STXS and decays

Note by M. Dührssen et al

- **Example problem:** Acceptance of the ATLAS H→4l STXS measurement depends on EFT parameters
- **Solution:**
  - Lorentz invariant fiducial selection per decay mode
  - Higgs scalar: production and decay decouple
  - two-body decays: No kinematic information
  - the others (H→llγ, H→WW*→lνlν, H→ZZ*→4l) need more work





Eur. Phys. J. C 80 (2020) 957

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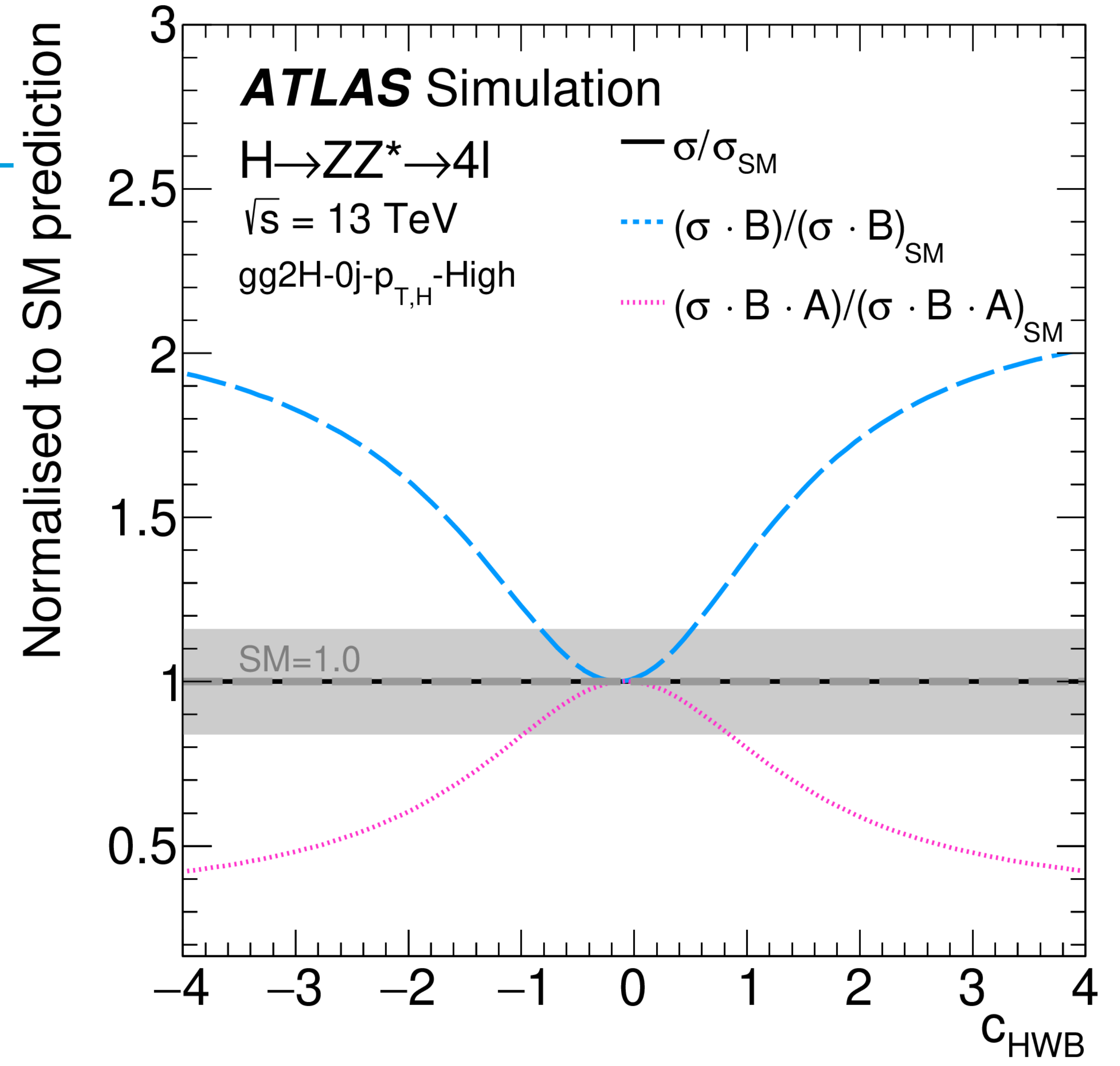
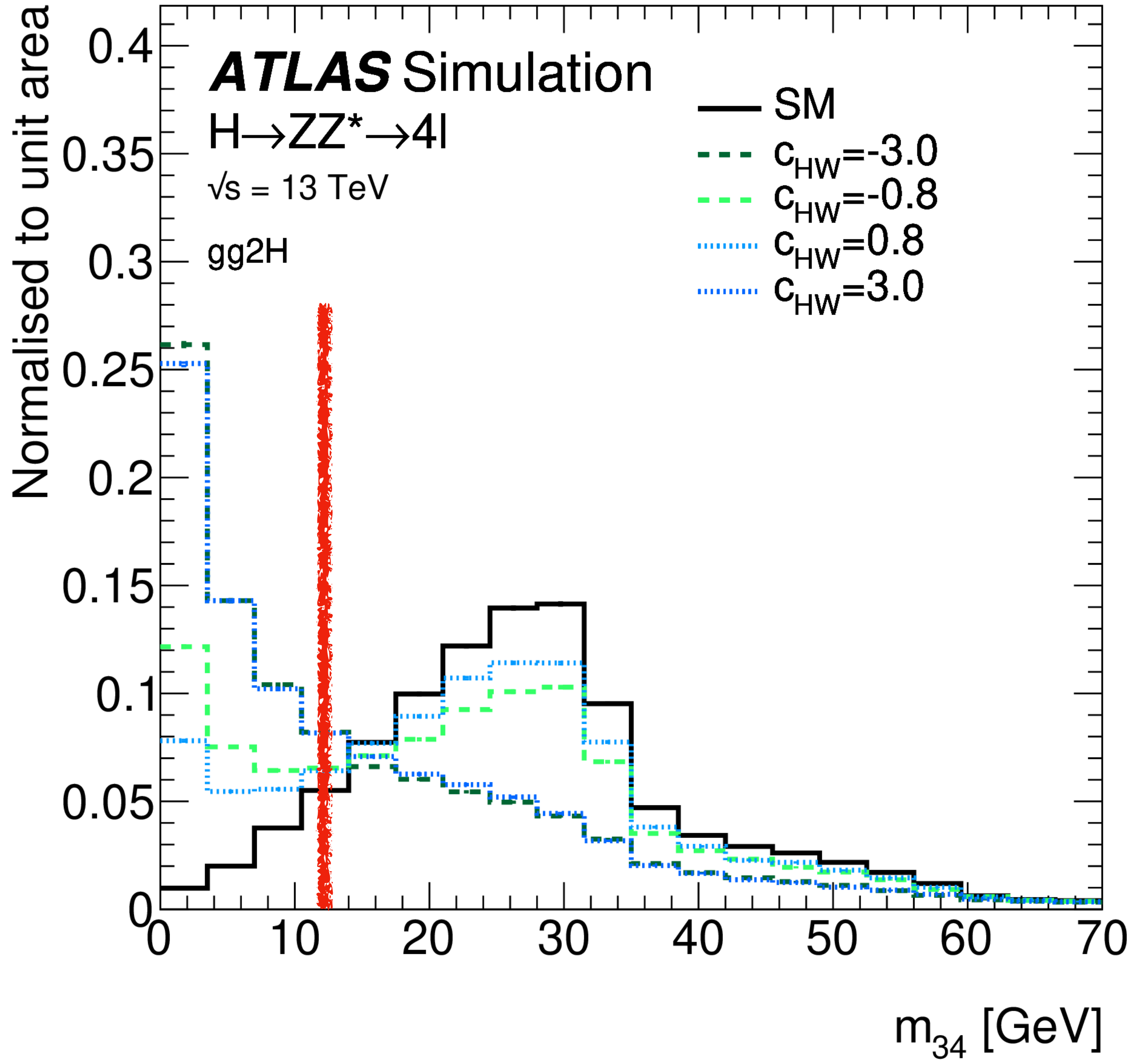
  - the others (H→llγ, H→WW*→lνlν, H→ZZ*→4l) need more work
- **Status**
  - H→4l compromise selection for ATLAS and CMS
    - cuts on lepton pt in Higgs rest frame, invariant mass cuts
  - implementation in LHC H XS WG STXS Rivet ongoing
  - further future: Stage 1, binning in decay variable (e.g. m34)





Eur. Phys. J. C 80 (2020) 957

Conclusions and outlook

Wealth of differential measurements to characterize Higgs boson production and decays

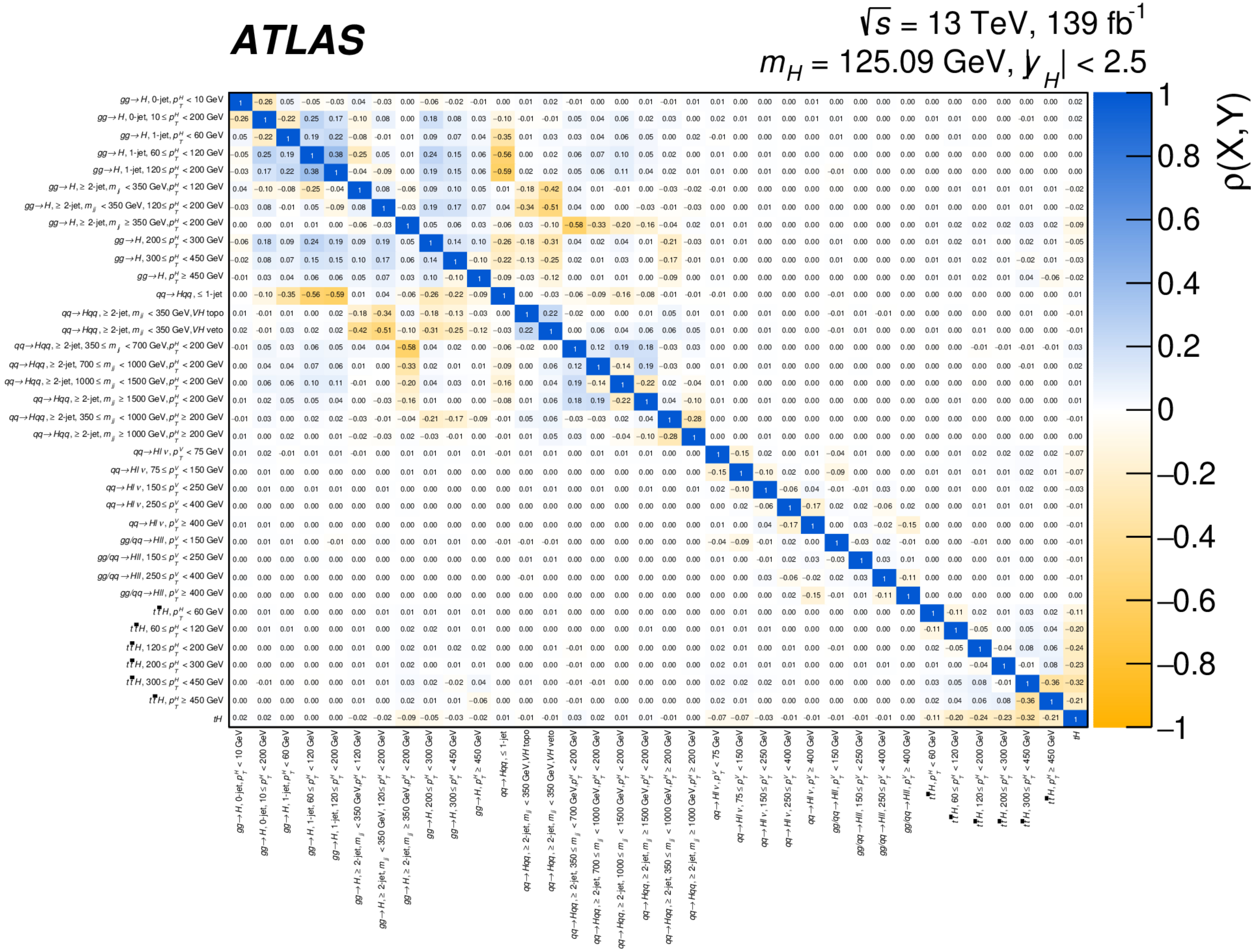
- traditional differential cross sections
- simplified template cross sections

Measurements can be used as base for various interpretations: EFT, MSSM, Yukawa couplings, …

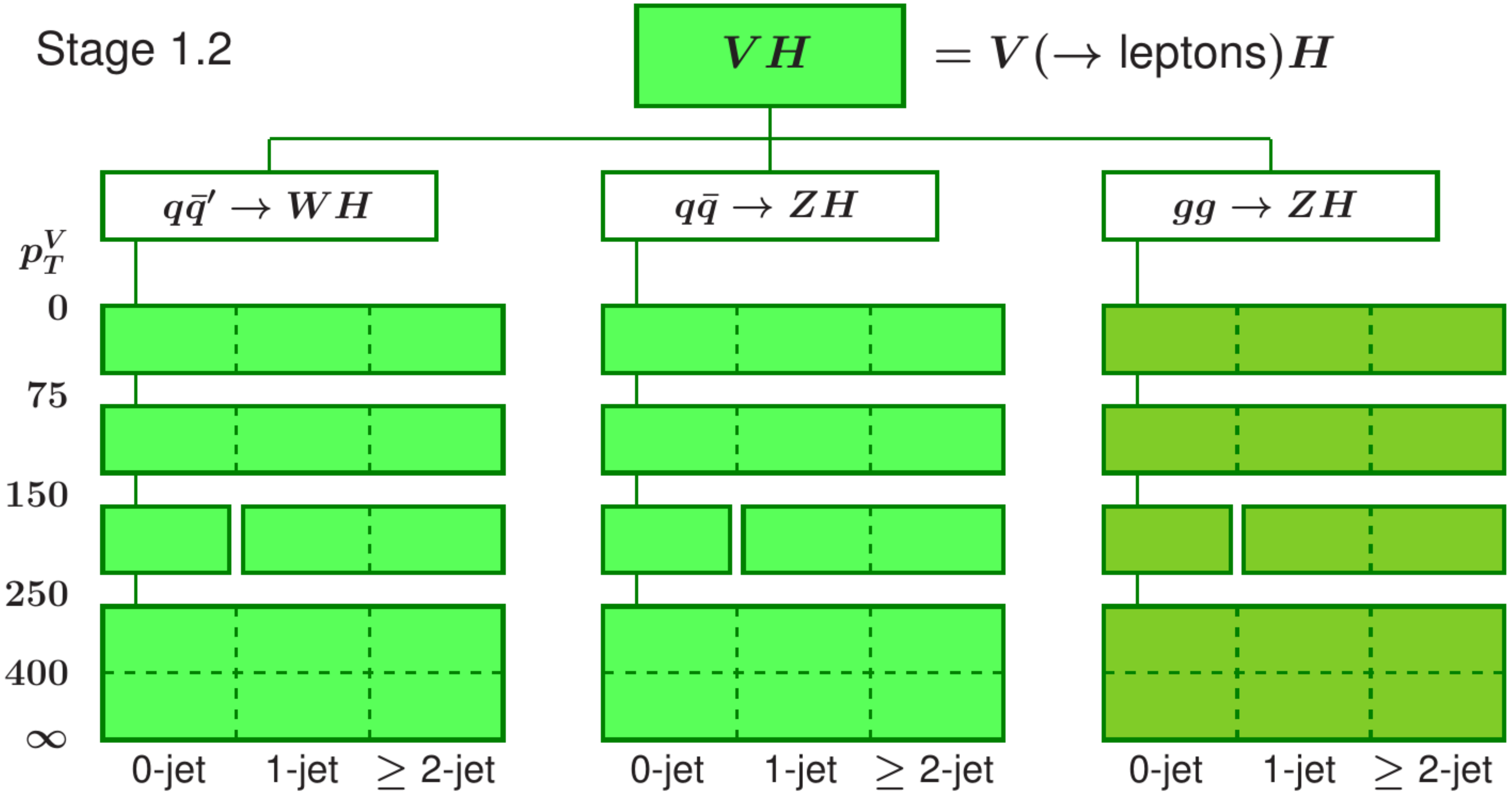
Interplay/communication between experiment and theory important to make the measurements as useful as possible!

Backup

Correlation matrix ATLAS STXS



STXS V(lep)H


Stage 1.2
VH
$= V(\to \text{leptons})H$
$q\bar{q}' \to WH$
$q\bar{q} \to ZH$
$gg \to ZH$
p_T^V
0
75
150
250
400
∞
0-jet
1-jet
$\geq$ 2-jet
0-jet
1-jet
$\geq$ 2-jet
0-jet
1-jet
$\geq$ 2-jet

Likelihood for H4l STXS

$$\mathcal{L}(\vec{\sigma}, \vec{\theta}) = \prod_{j}^{N_{\text{categories}}} \prod_{i}^{N_{\text{bins}}} P\left(N_{i,j} \mid L \cdot \vec{\sigma} \cdot \mathcal{B} \cdot \vec{A}_{i,j}(\vec{\theta}) + B_{i,j}(\vec{\theta})\right) \times \prod_{m}^{N_{\text{nuisance}}} \mathcal{C}_m(\vec{\theta})$$

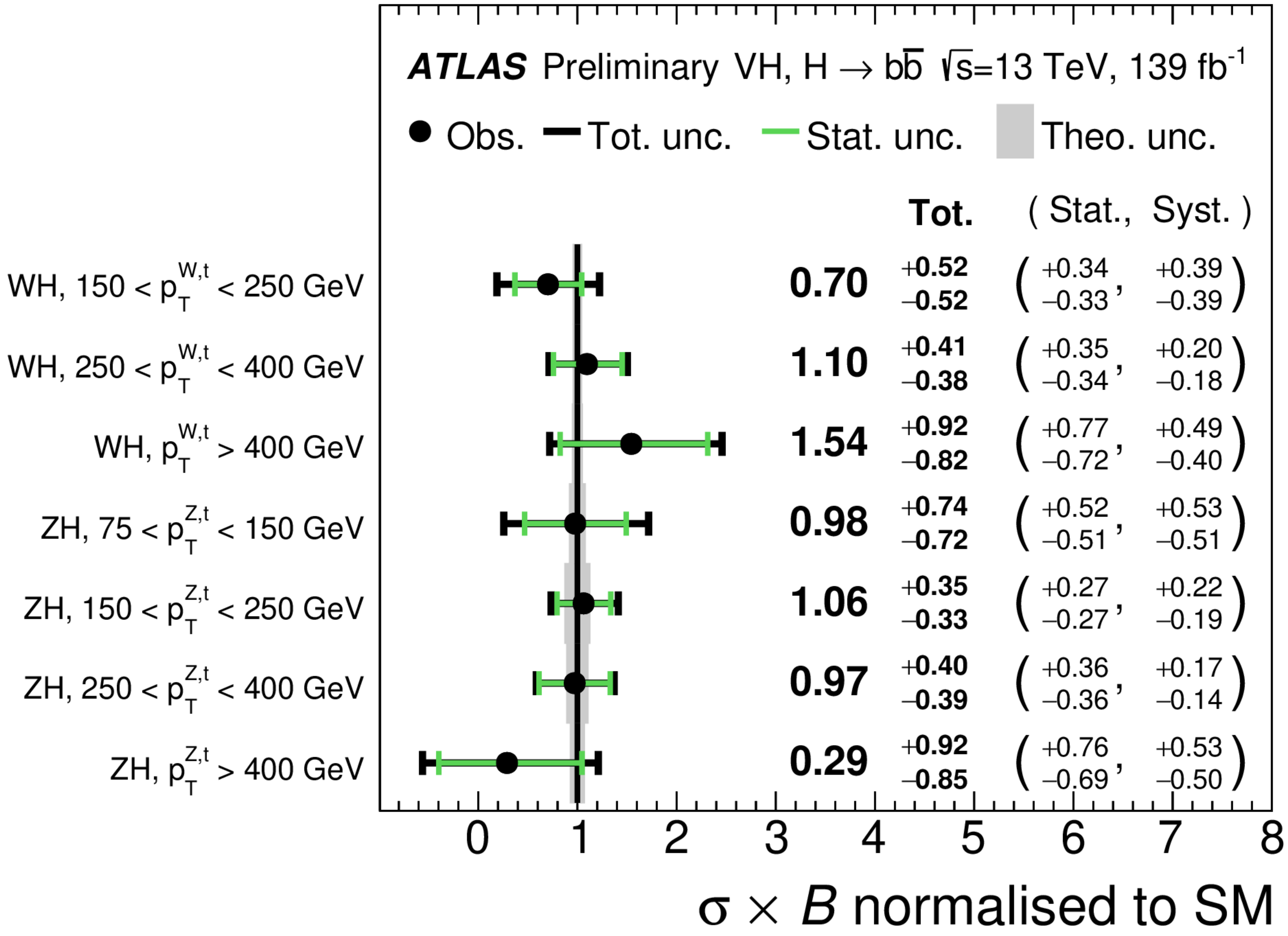
Regularization

Matrix inversion: creates large negative off-diagonals → statistical fluctuations of the data are amplified

Regularization can be applied (encourage smooth-ness)

Bayesian unfolding with limited number of iterations: some level of regularization (update the MC prior with data)

H->bb ATLAS



ATLAS Preliminary VH, H → bb̄ √s=13 TeV, 139 fb-1
Obs.
Tot. unc.
Stat. unc.
Theo. unc.
Tot. (Stat., Syst.)
WH, 150 < pT W,t < 250 GeV
0.70 +0.52 −0.52 (+0.34 −0.33 , +0.39 −0.39)
WH, 250 < pT W,t < 400 GeV
1.10 +0.41 −0.38 (+0.35 −0.34 , +0.20 −0.18)
WH, pT W,t > 400 GeV
1.54 +0.92 −0.82 (+0.77 −0.72 , +0.49 −0.40)
ZH, 75 < pT Z,t < 150 GeV
0.98 +0.74 −0.72 (+0.52 −0.51 , +0.53 −0.51)
ZH, 150 < pT Z,t < 250 GeV
1.06 +0.35 −0.33 (+0.27 −0.27 , +0.22 −0.19)
ZH, 250 < pT Z,t < 400 GeV
0.97 +0.40 −0.39 (+0.36 −0.36 , +0.17 −0.14)
ZH, pT Z,t > 400 GeV
0.29 +0.92 −0.85 (+0.76 −0.69 , +0.53 −0.50)
0 1 2 3 4 5 6 7 8
σ × B normalised to SM