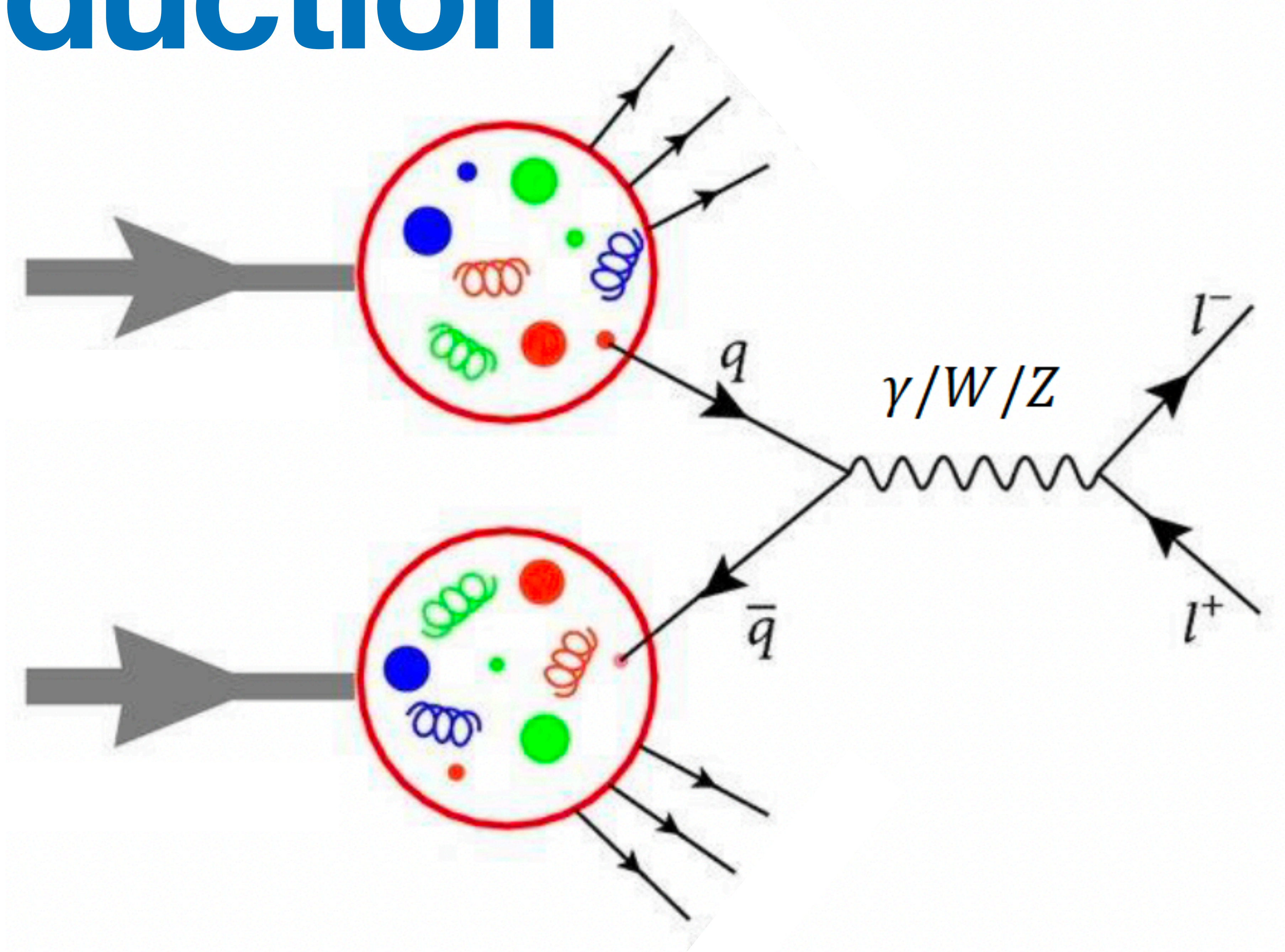
Precision measurements of Drell-Yan processes in ATLAS

Daniel Lewis 27/08/2025
Lepton Photon 2025, Madison, WI, USA

Funded by the European Union
European Research Council
Established by the European Commission
DITTO - GA 101089007

Drell-Yan production



High cross-section and clean final states allow for precise and expansive differential measurements

Ability to constrain fundamental SM parameters

Precision probes of state-of-the-art pQCD calculations

Provide constraining power to non-perturbative PDFs

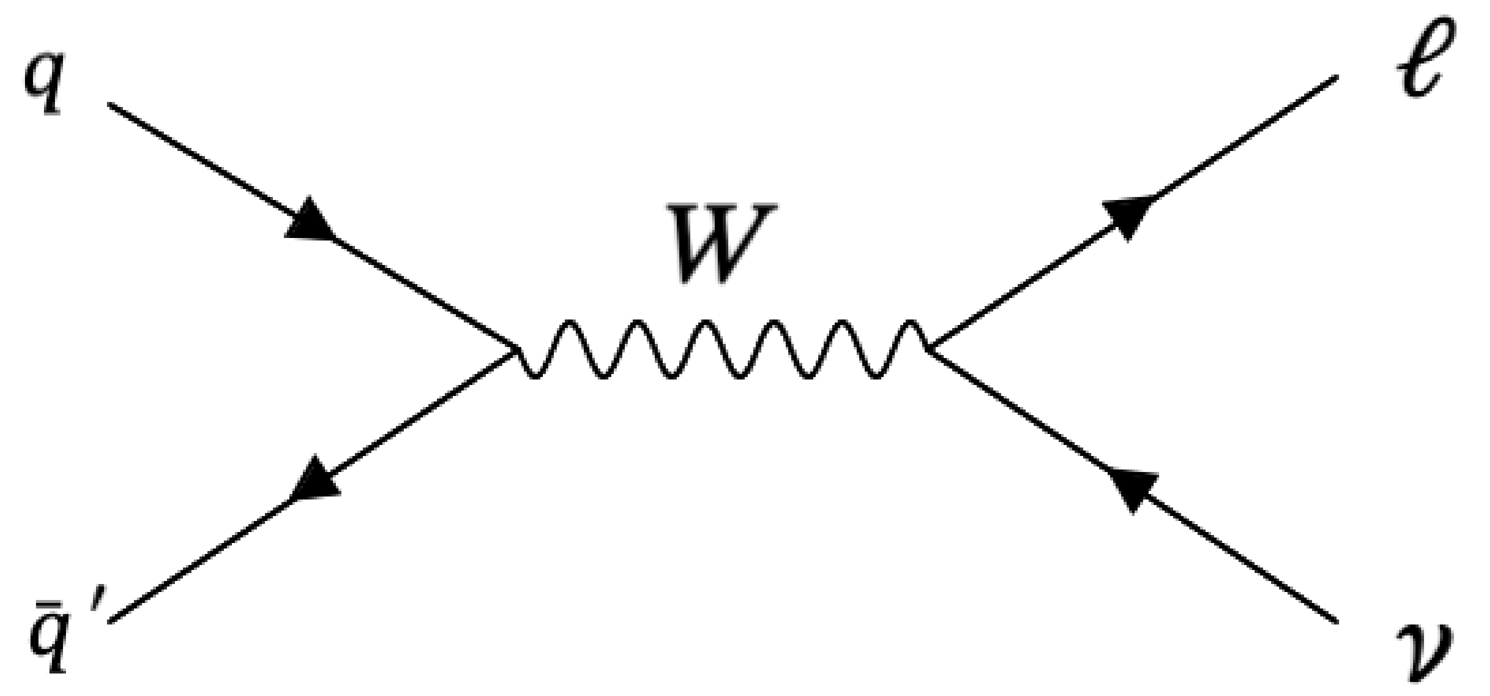
Useful for tuning MC generators

High-precision measurements are also powerful tests of new physics

Measurements of W cross-sections with low pile-up

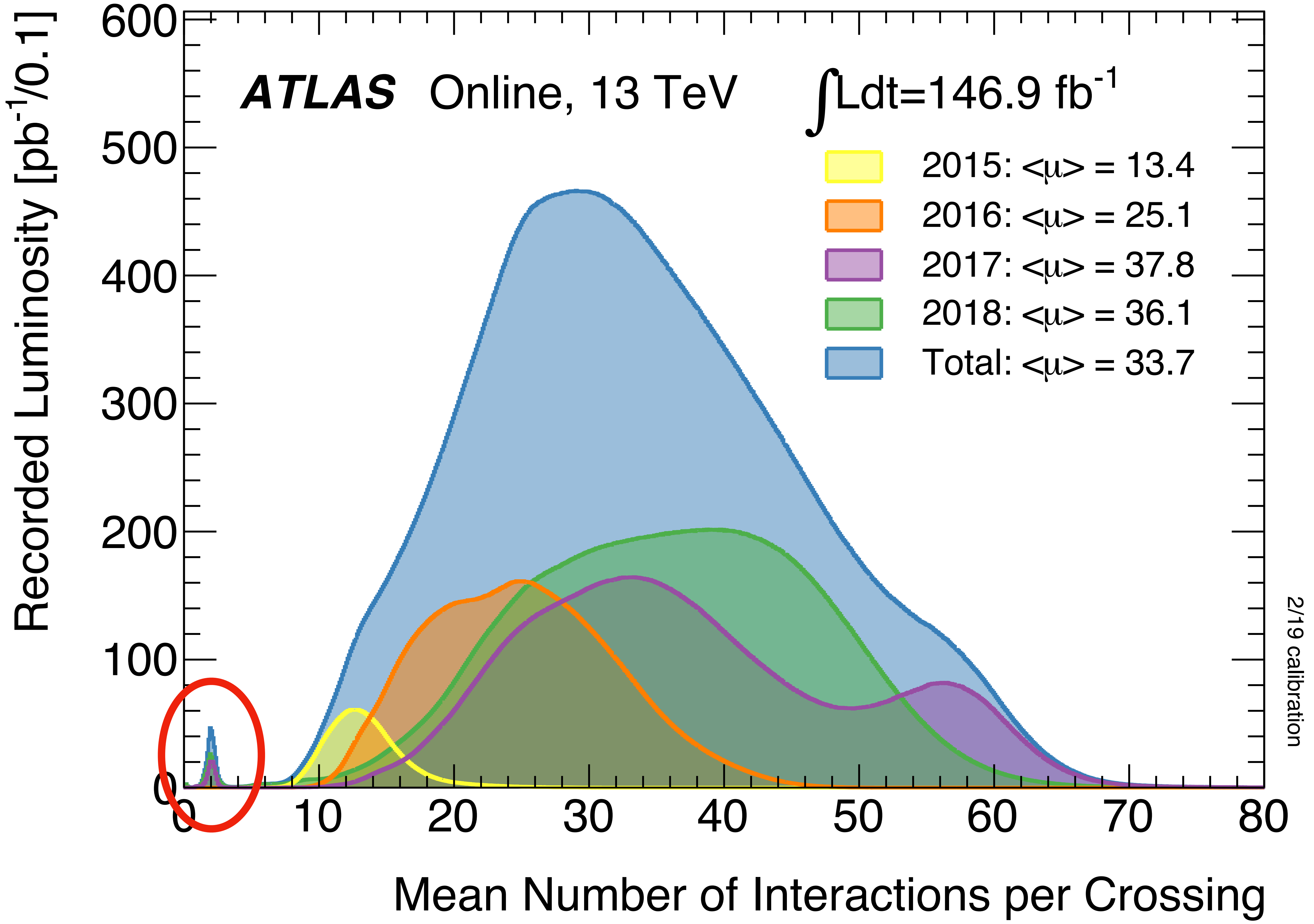
W cross-section measurements

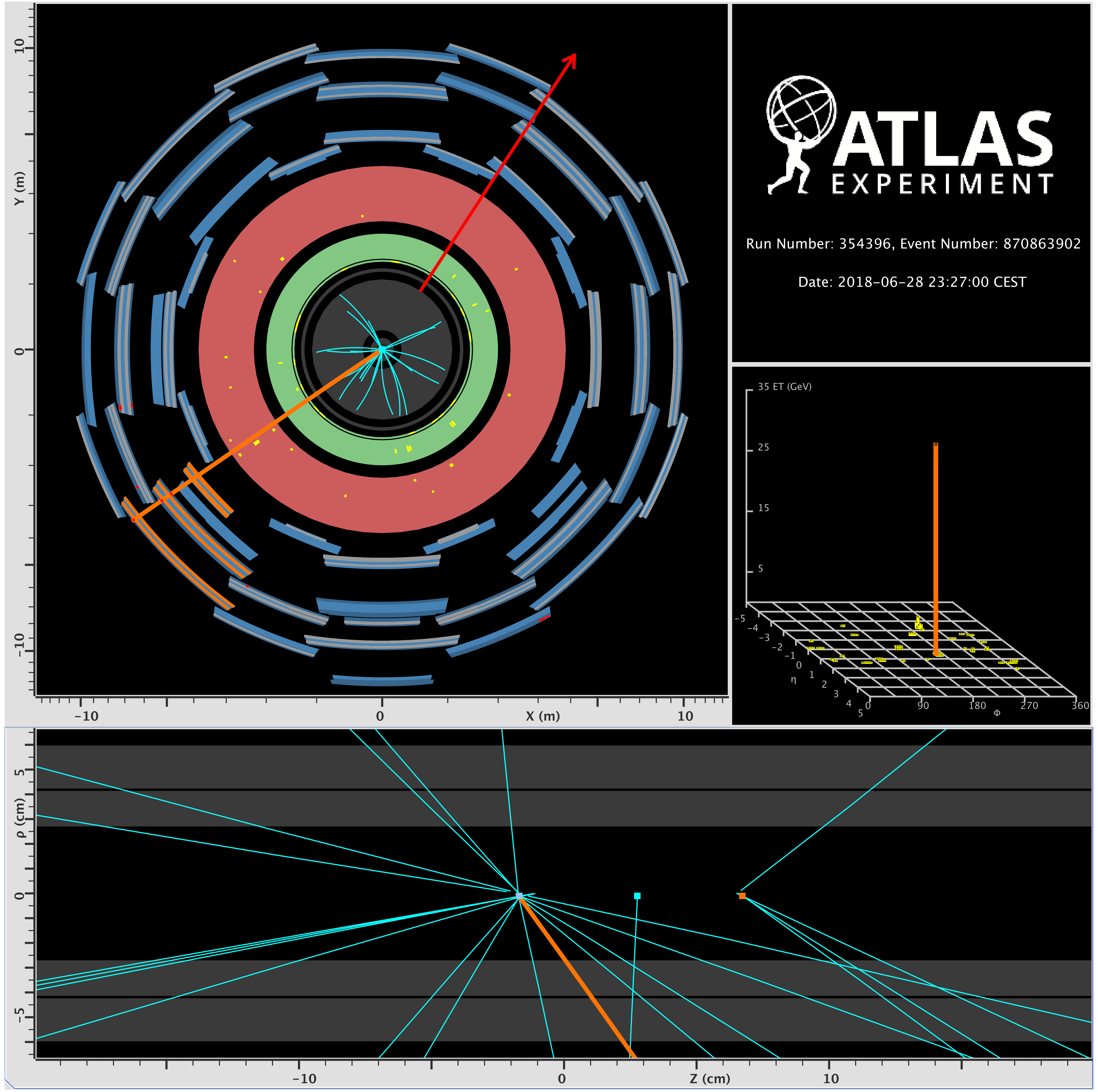
- Probe of QCD & discrimination of different PDF sets - W-boson rapidity correlated with Bjorken-x
  - Also a probe of valence quark makeup of the proton via charge asymmetry
- Cross-sections measured as a function of lepton p_T and η
- Electron and muon channels studied $\rightarrow$ high precision and low backgrounds
- Resolution of E_T^{miss} greatly improved using low pile-up data



Eur. Phys. J. C 85 (2025) 729

Low pile-up data





245.9 ± 2.6 pb^{-1} @ $\sqrt{s} = 5.02$ TeV

338.1 ± 3.1 pb^{-1} @ $\sqrt{s} = 13$ TeV

Eur. Phys. J. C 85 (2025) 729

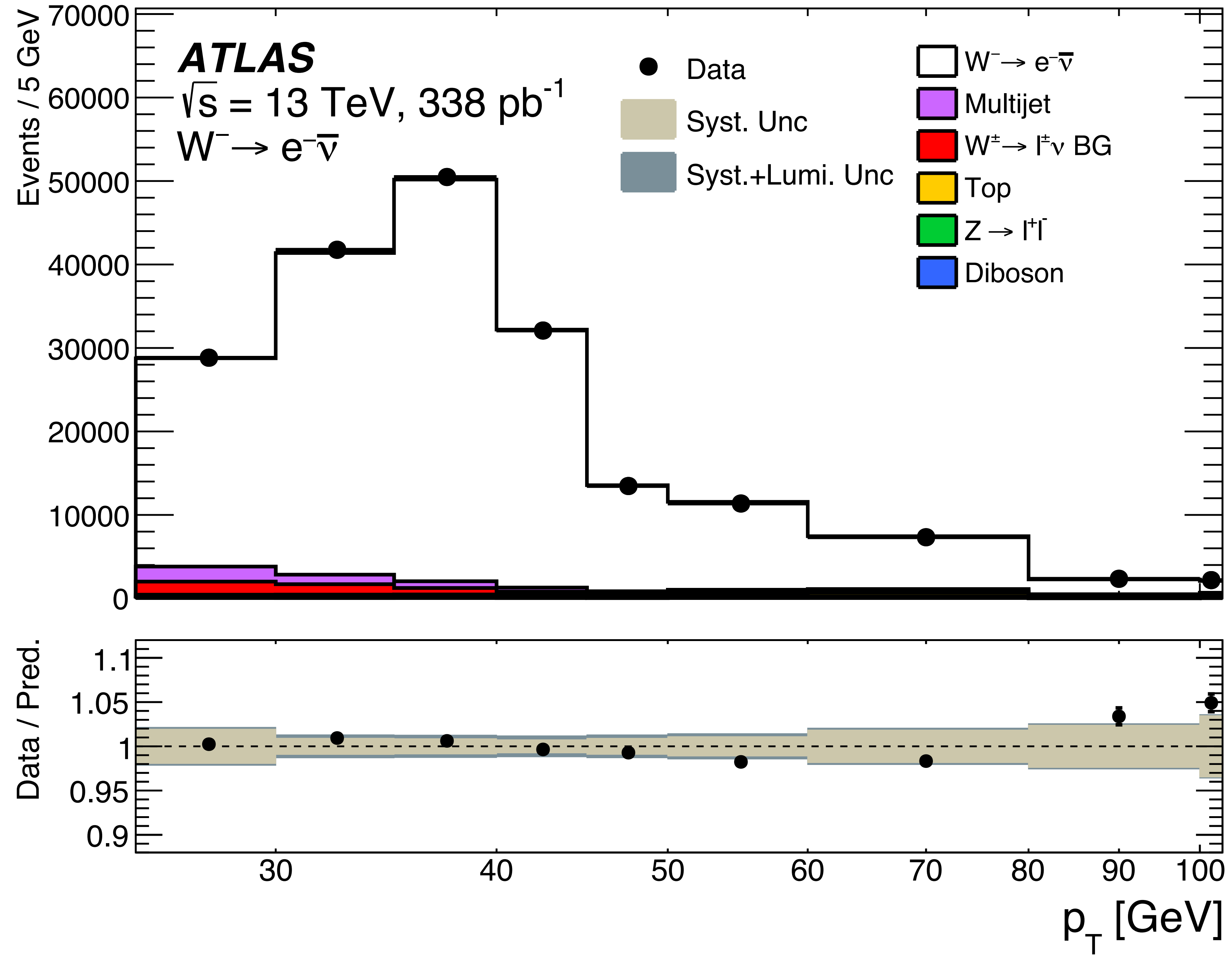
Methodology

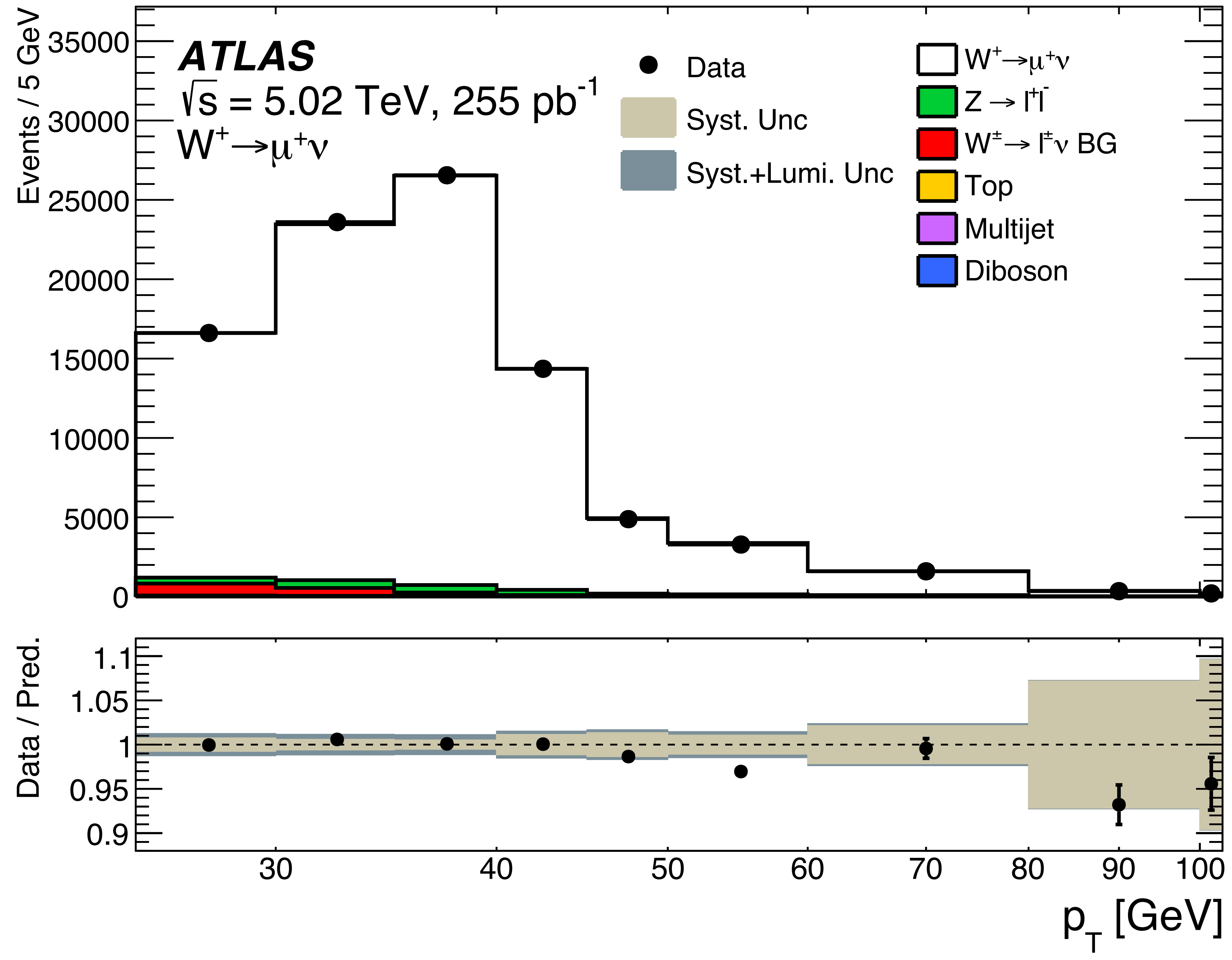
- Data-driven multi-jet background
- Remaining backgrounds from simulation (Z, $t\bar{t}$, $W \to \tau\nu$, VV)
- Fiducial phase space definition:

$$p_T^{\ell} > 25 \text{ GeV}, \ |\eta^{\ell}| < 2.5$$

$$m_T^{W} > 50 \text{ GeV}, \ p_T^{\nu} > 25 \text{ GeV}$$

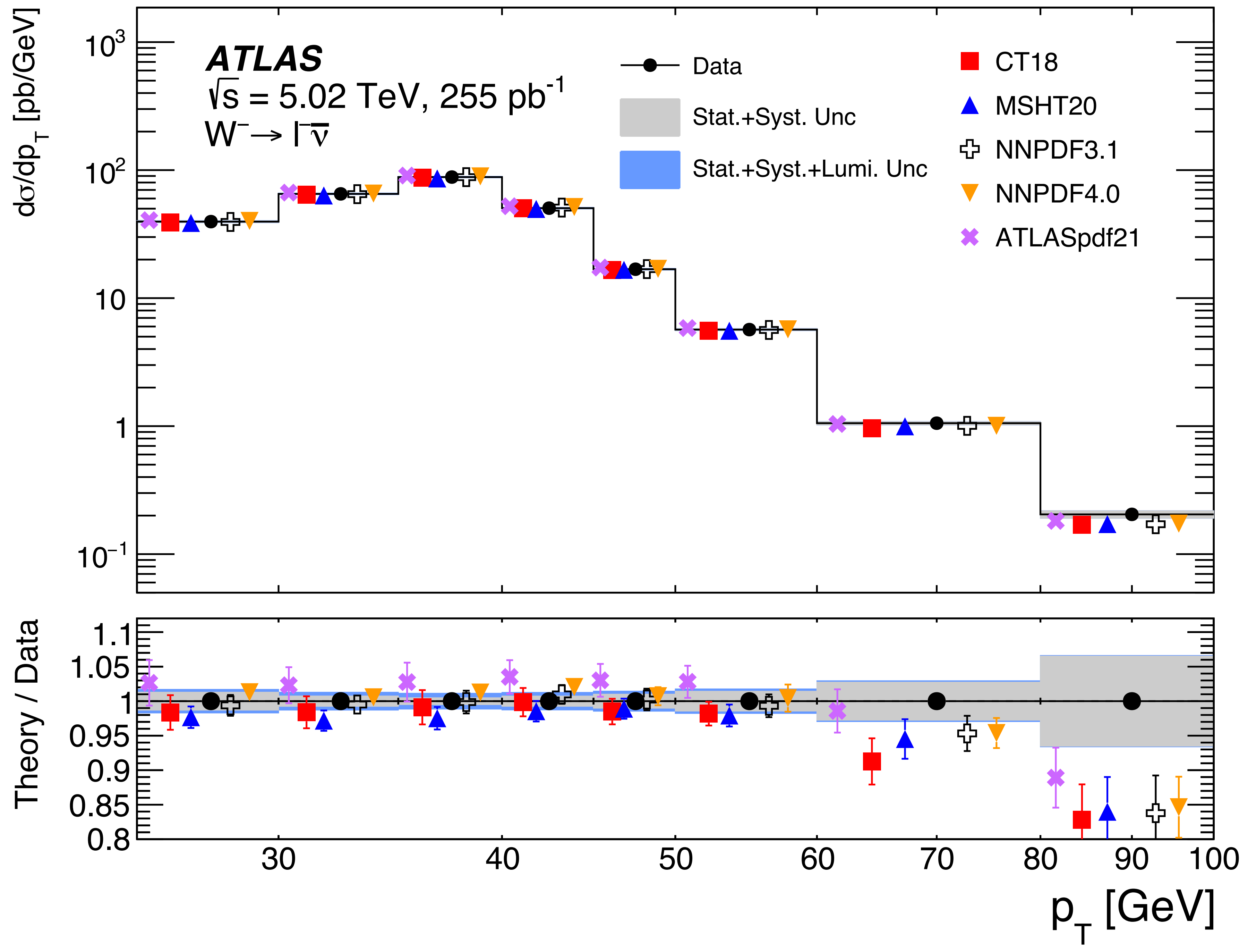
- Unfolding to this born-level phase space performed with iterative Bayesian technique
- Dominant uncertainties from luminosity (~1% globally) and generator choice (up to 5% at high-p_T)

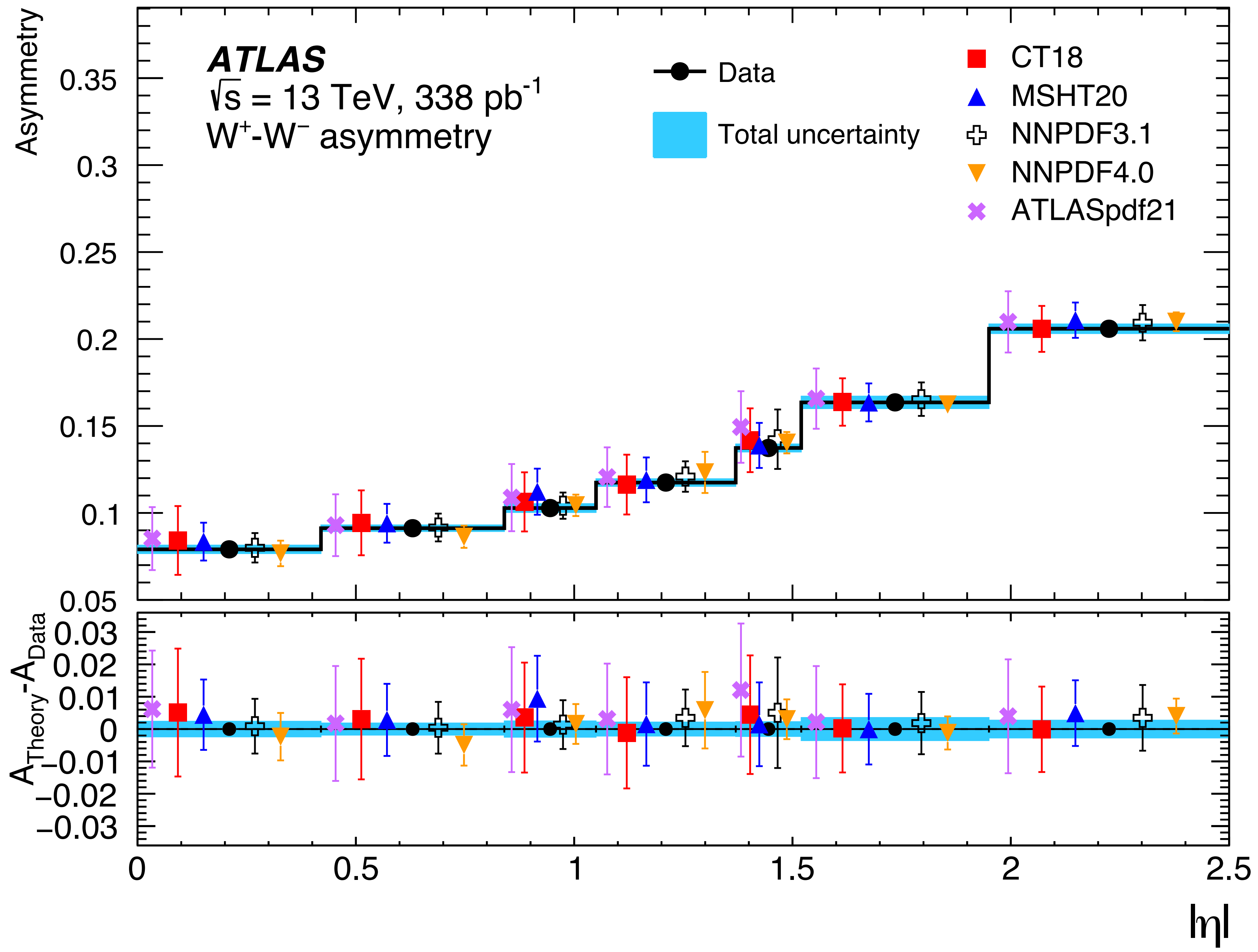




Eur. Phys. J. C 85 (2025) 729

Results

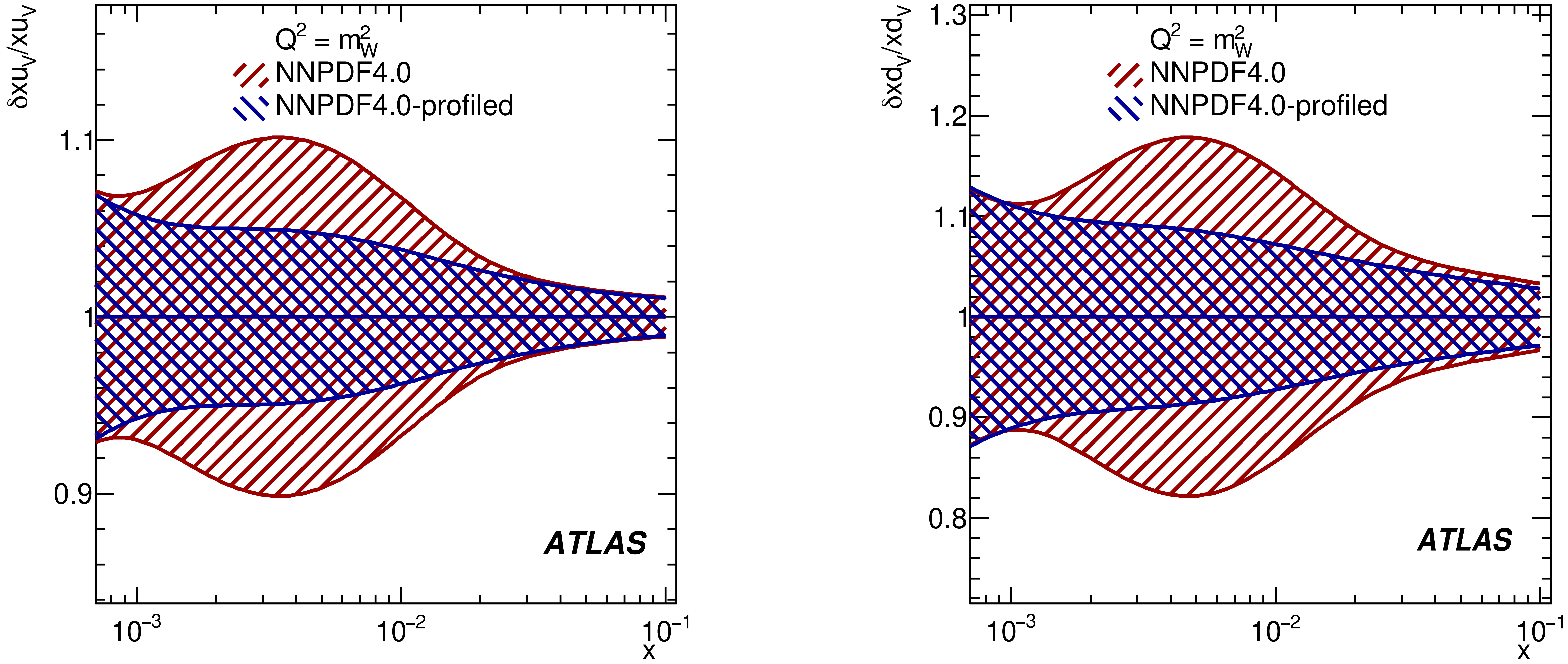




- Cross-sections reported for both CoM energies and both W charge as a function of p_T, η and $p_T \times \eta$
- Predictions from DYTurbo (NNLO QCD + NNLL) tested with various PDF sets
- Description generally good except at high-p_T, overall a slight preference to NNPDF3.1 & NNPDF4.0

- Charge asymmetry measured as a function of η
- Good agreement seen with all predictions
- Measurement much more precise than predictions, indicating potential of constraining PDFs

PDF profiling



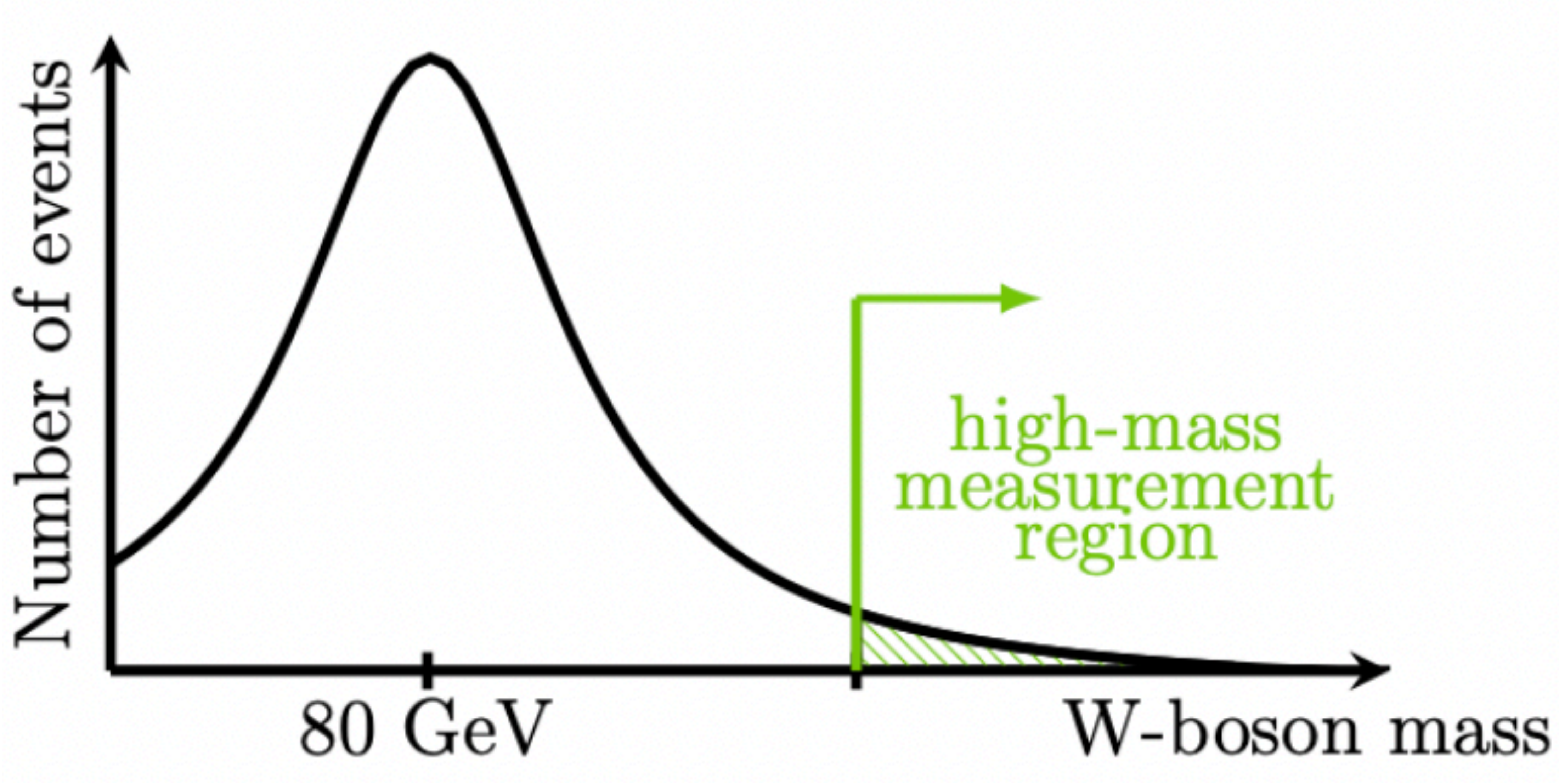
- $\frac{d\sigma}{d\eta}$ distribution used to asses constraining power of the measurements on PDFs
- Done by treating the correlated uncertainties as nuisance parameters in χ^2 minimisation
- Factor 2 improvement of xu_v and xd_v around x ~ 0.004

Eur. Phys. J. C 85 (2025) 729

High transverse mass spectrum at 13 TeV

Charged-current high-mass DY

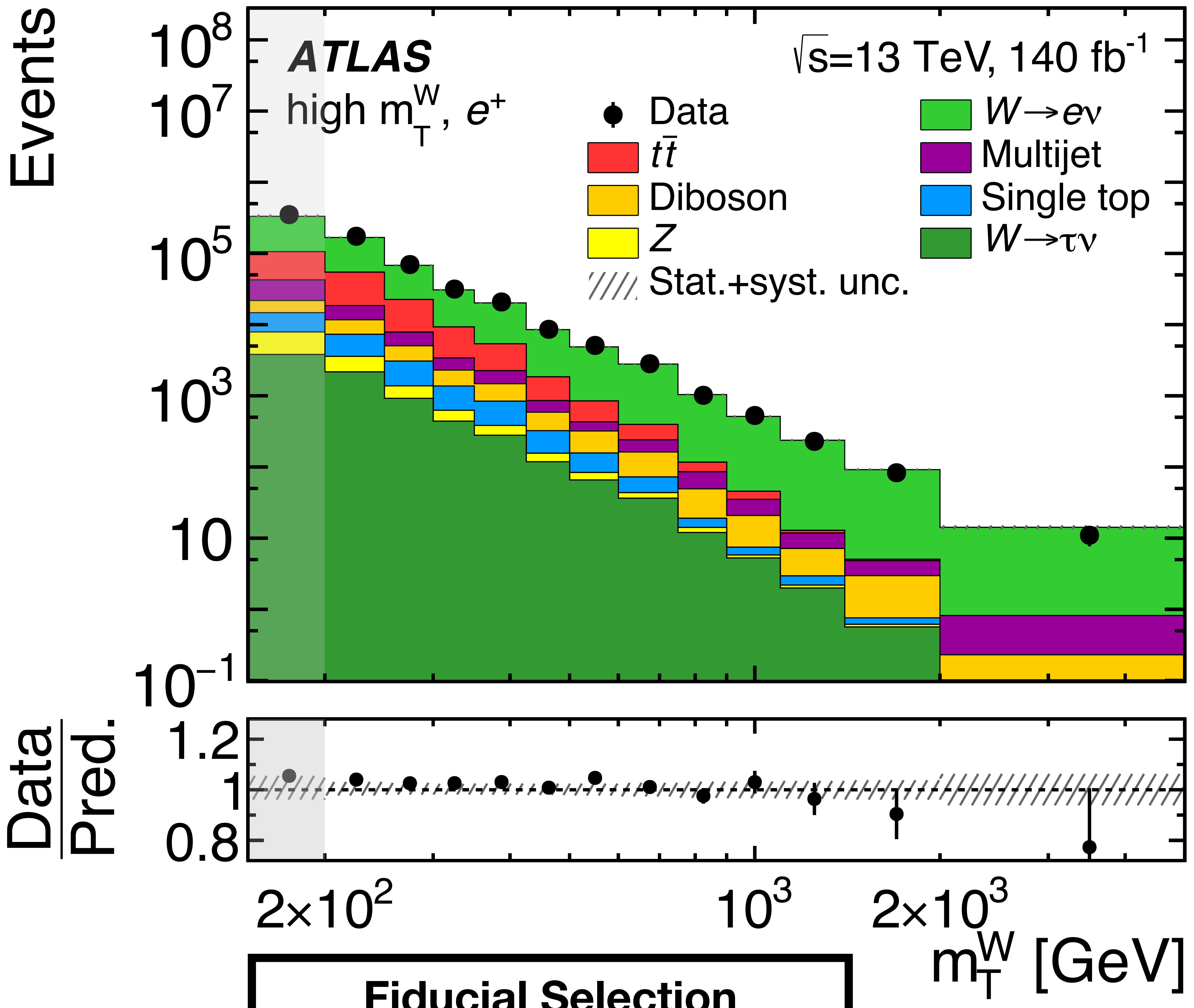
- Variable of interest: $m_{\mathrm{T}}^{\mathrm{W}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\nu}(1-\cos\Delta\phi(\ell,\nu))}.$
- First measurement in the high-mass regime ($m_T^W > 200$ GeV)
  - Using full Run-2 dataset of 140fb^{-1} @ 13 TeV
- Sensitivity to constrain high-x region of PDFs and sensitive to BSM physics



JHEP 07 (2025) 026

Methodology

- Largest background from top processes (~20%)
- Data-driven multi-jet background significant in electron channel (4%)
- Iterative Bayesian unfolding, with shadow bin to account for in-smearing
- Dominant systematics: electron channel - multi-jet background and electron energy scale, muon channel - muon scale calibration
    - Total uncertainty up to 7% in electron channel, up to 20% in muon channel



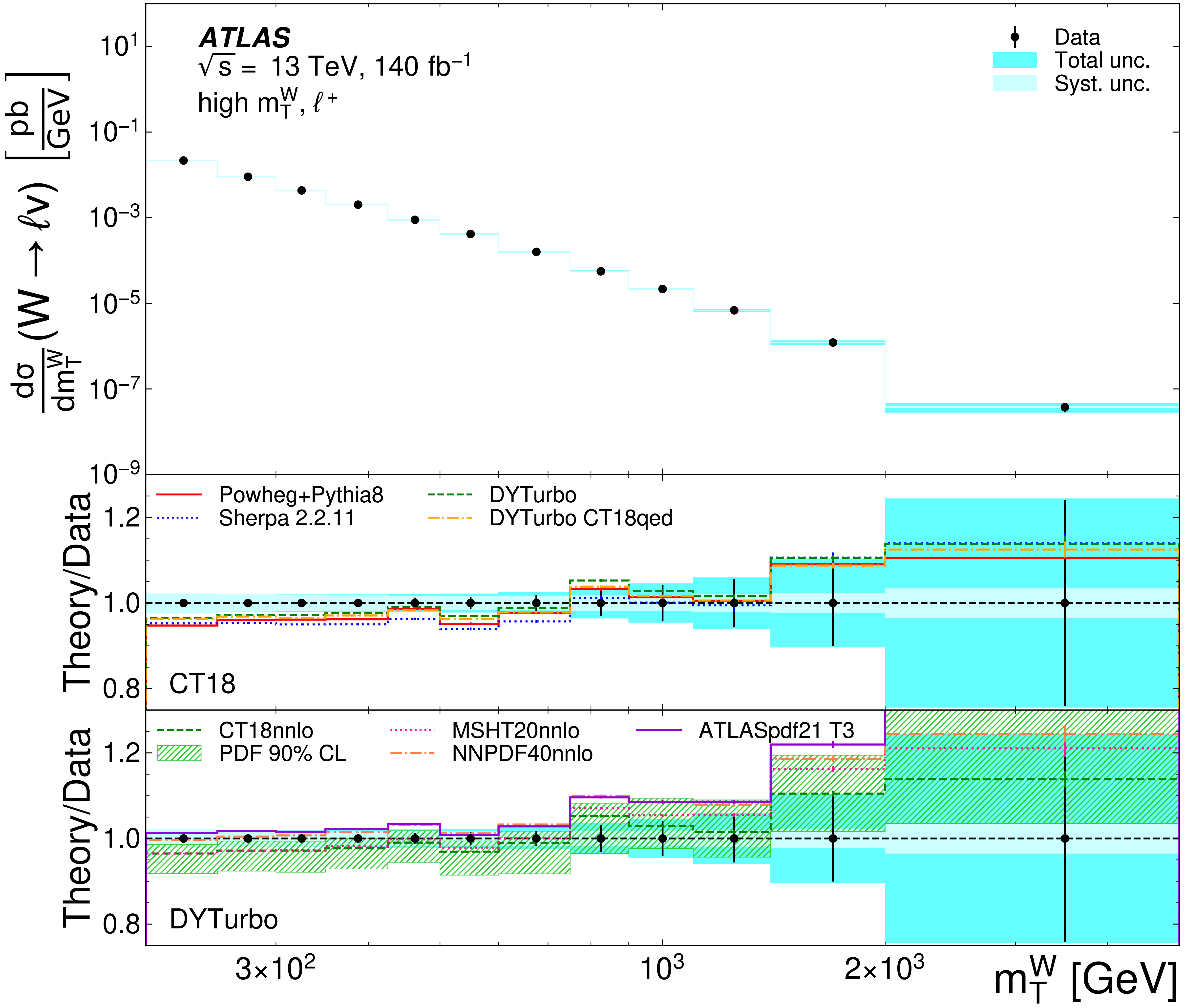
Fiducial Selection

- Born-level lepton
- $p_T^\ell > 65$ GeV
- $|\eta^\ell| < 2.4$
- $p_T^\nu > 85$ GeV
- $m_T^W > 200$ GeV

Paper on arXiv

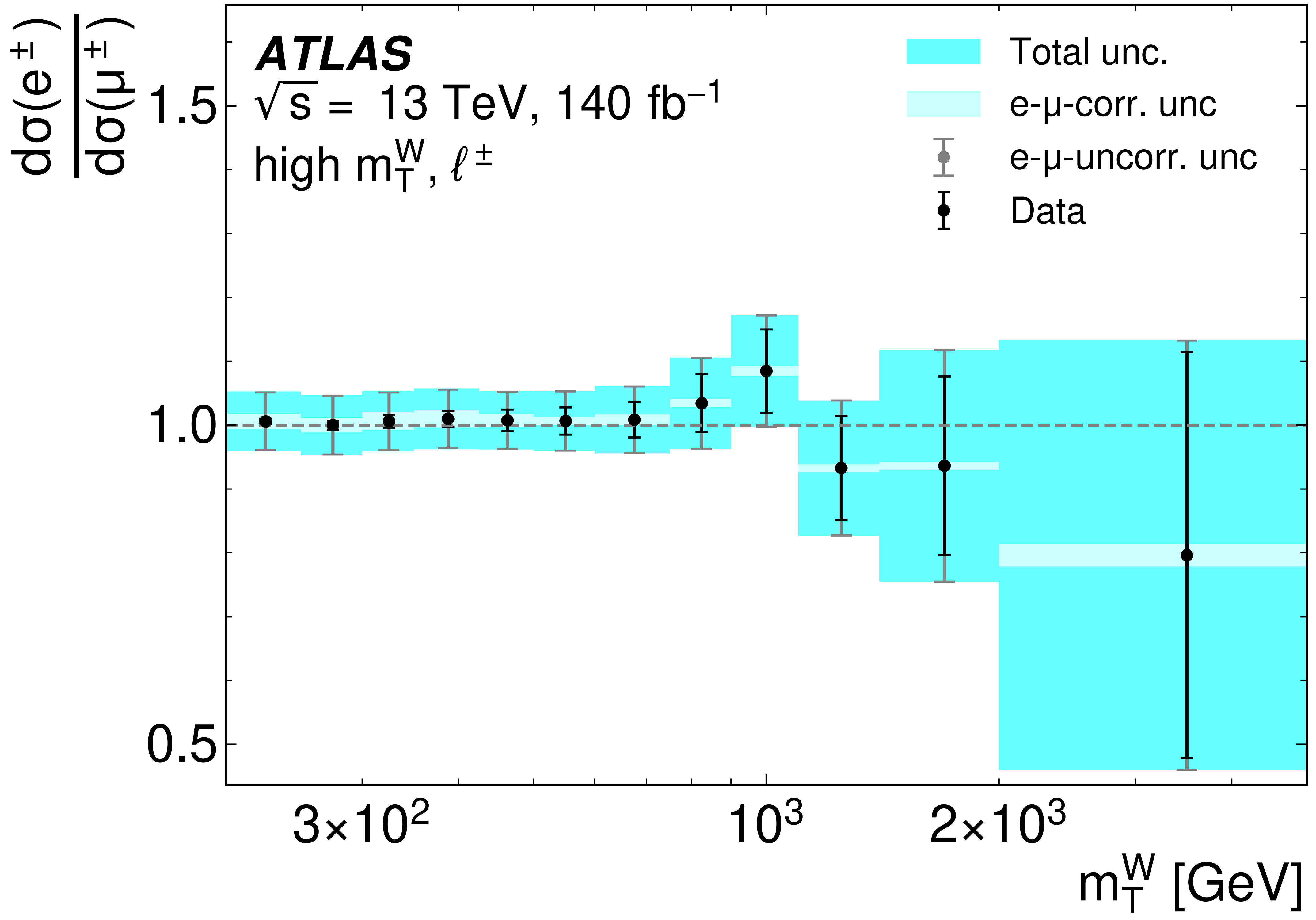
Results - measurements

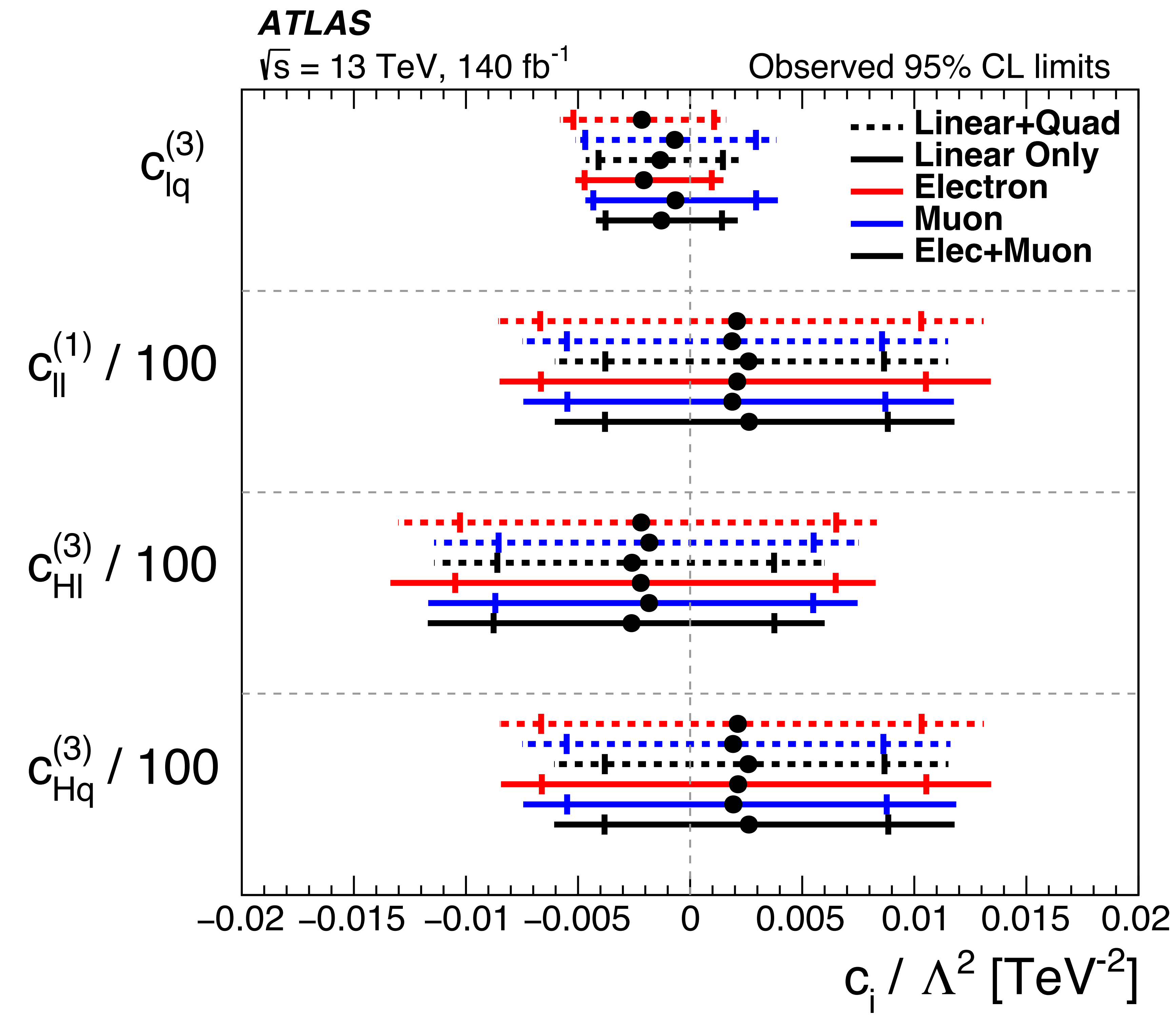
- m_T^W and $m_T^W \times \eta$ presented for e^-, e^+, $\mu^-$and μ^+ as well as charge-integrated
  - Charge asymmetry also measured
- Combination of both channels, including correlations
- Comparison to state-of-the-art calculation from DYTurbo (NNLO + NNLL)
  - Typically well described and experimental uncertainty smaller than PDF uncertainty on prediction (for masses below 1 TeV)



Paper on arXiv

Results - new physics probes





- $e^\pm/\mu^\pm$ ratio also presented but consistent within uncertainties with SM value of 1
- EFT interpretation produces most stringent constraints on $c_{lq}^{(3)}$, operator describing four-fermion interactions

Paper on arXiv

Measurements and searches in high-mass $\tau\tau$ production

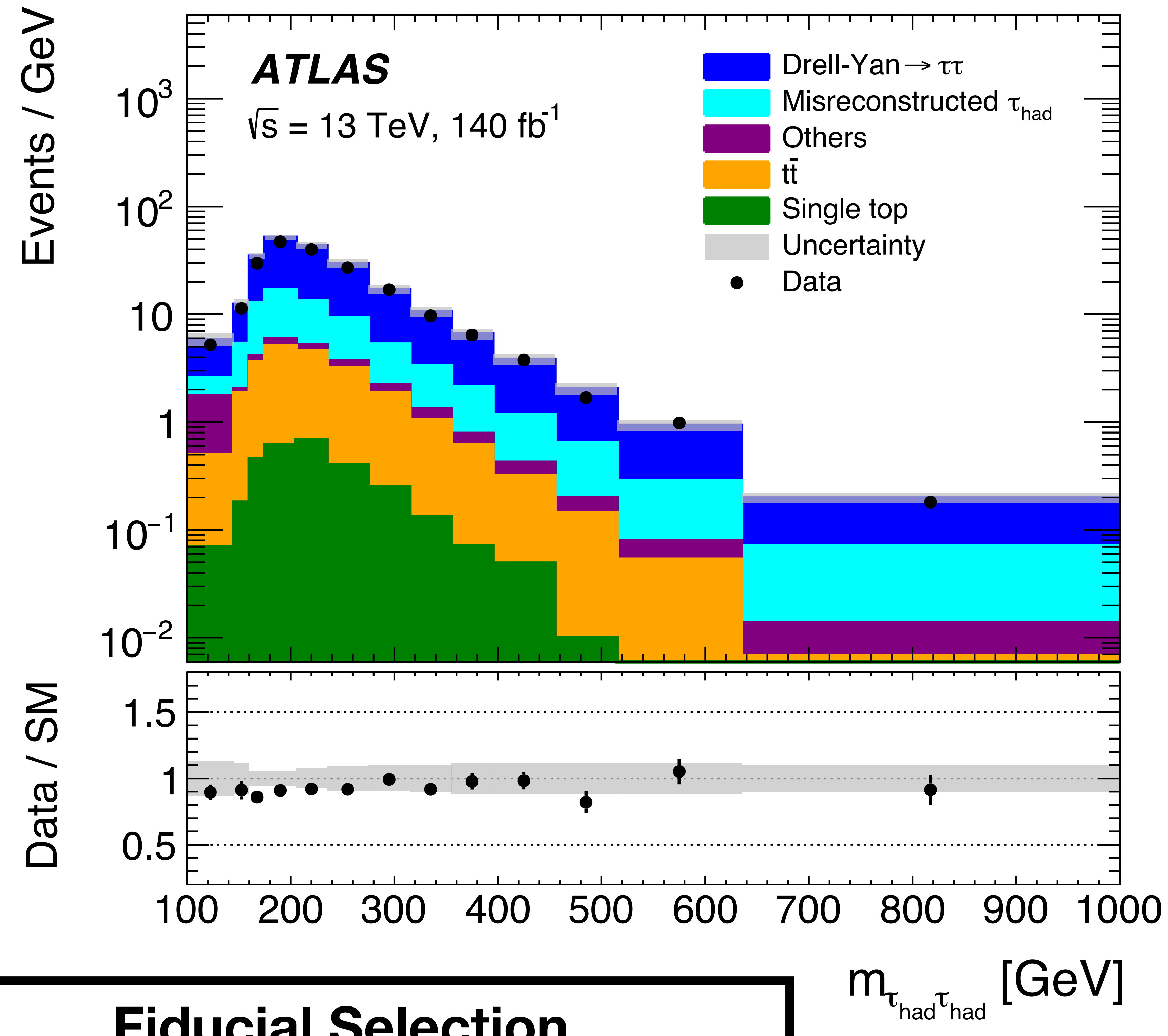
High-mass DY $\tau\tau$

- Neutral current with final state of $\tau\tau$, where both taus decay to hadrons
  - DY purity in lepton-hadron and lepton-lepton channels too low
- More challenging final state than light leptons but stronger probe of new physics if preferential coupling to 3rd generation
- First measurement of this final state in high-mass regime, using full Run-2 dataset
- Searches also performed as a function of b-jet multiplicity to further probe 3rd generation couplings
- Variable of interest: $m_{\tau\tau}^{vis}$
  - Detector level: all visible decay products
  - Truth level: all decay particles excluding neutrinos
  - High-mass region: $m_{\tau\tau}^{vis} > 100$ GeV

arXiv:2503.19836 [hep-ex]

Methodology

- Challenging background from mis-reconstructed taus using data-driven fake factor method
  - Different fake factor for quark- and gluon-initiated jets
  - Validated in a same-sign CR
  - Only process not considered in fiducial definition
- Signal definition for measurement is process-agnostic → all hadronic taus are considered part of signal (i.e. including $t\bar{t}$, multi-boson etc.)
- Unfolding via iterative bayesian method



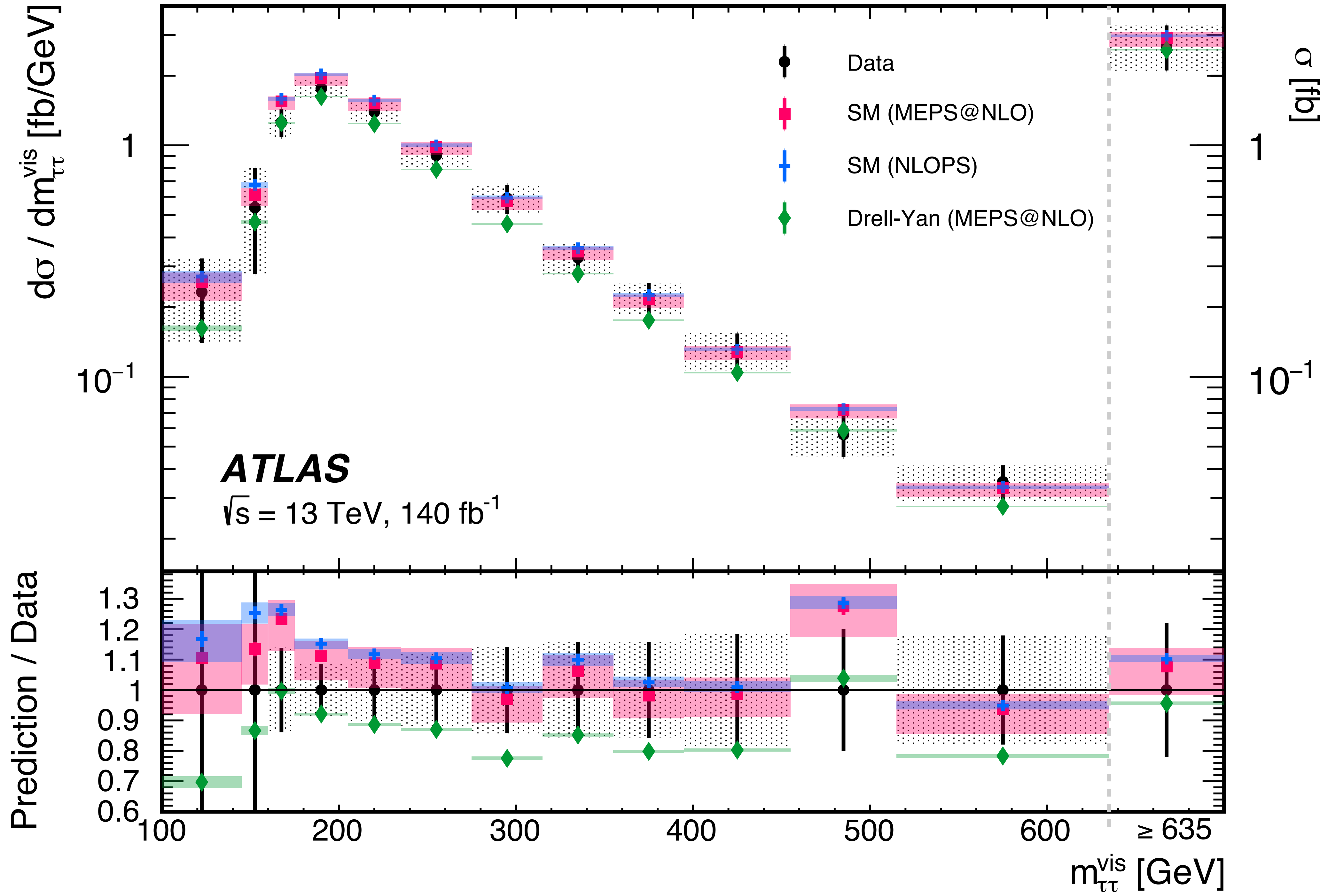
Fiducial Selection

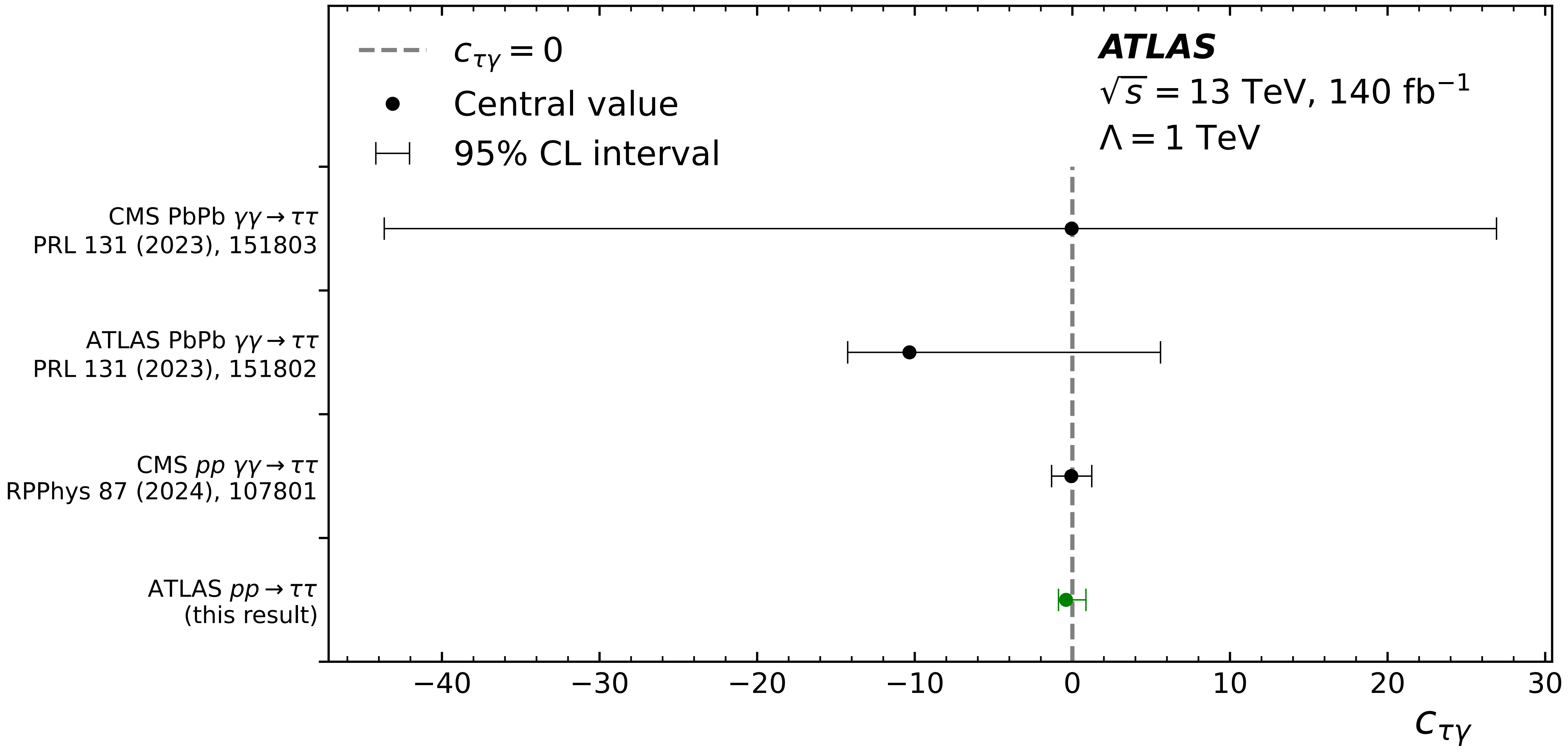
- Particle-level τ built from visible decay products
- $p_T^{\tau,vis} > 90, 60$ GeV
- $|\eta^{\tau,vis}| < 2.47$ excl. 1.37-1.52
- $m_{\tau\tau}^{vis} > 100$ GeV

arXiv:2503.19836 [hep-ex]

Results

- Cross-section measured as a function of $m_{\tau\tau}^{vis}$ with precision up to 15% at high-mass
  - First differential cross-section measurement of this final state
  - Dominant uncertainties: modelling and Tau ID
- After splitting detector-level distribution in to bins of N_{bjets}, three interpretations presented:
  - EFT: 15 parameters constrained including $c_{\tau\gamma}$ which translates to very competitive limits on the τ anomalous magnetic moment
  - Z’: Limits set on couplings to third-gen quark states as a function of Z’ boson mass
  - Leptoquarks: improvements of limits, exclusion of CMS local excess and removal of small region preferred by B-hadron measurements

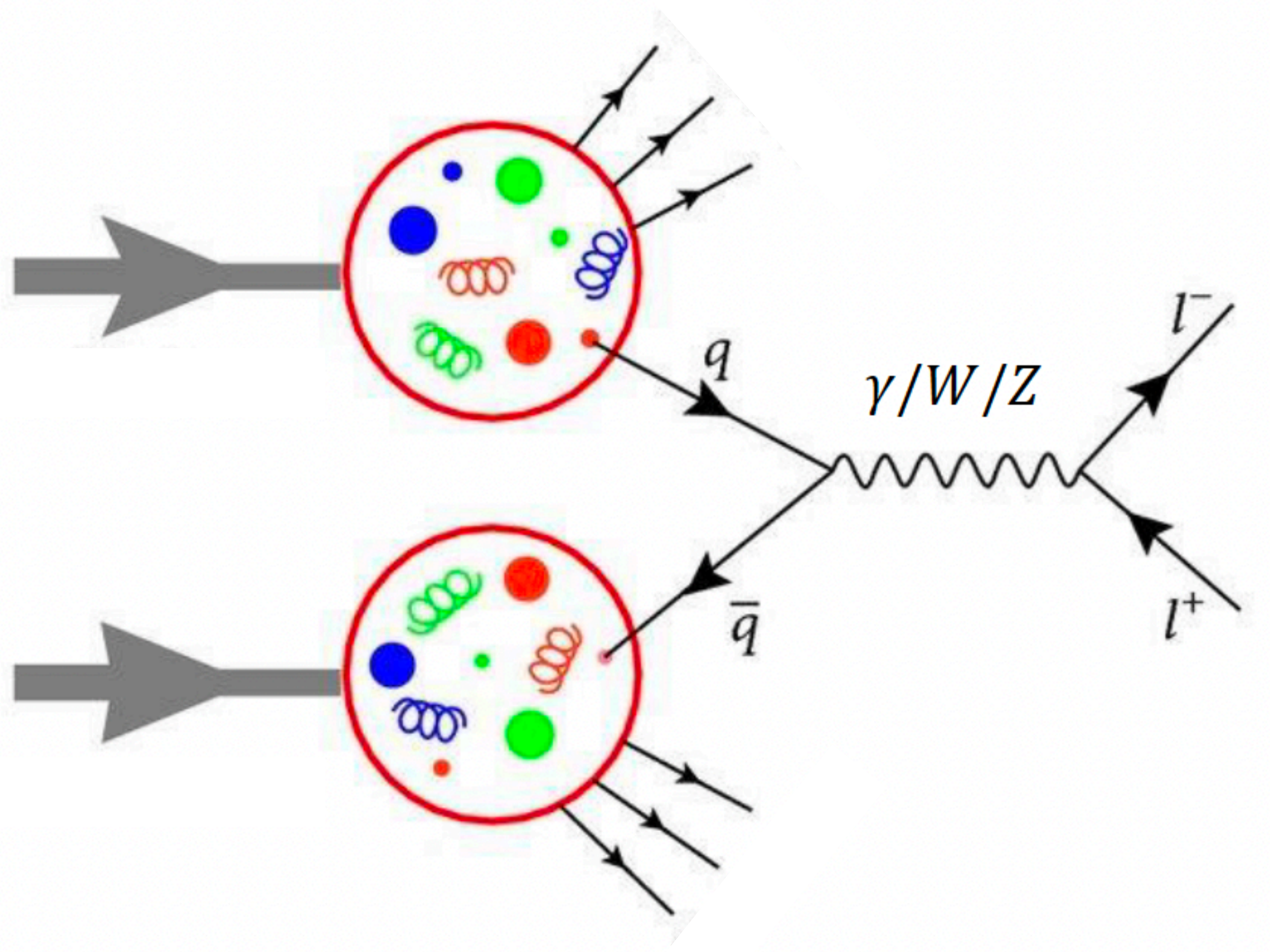




arXiv:2503.19836 [hep-ex]

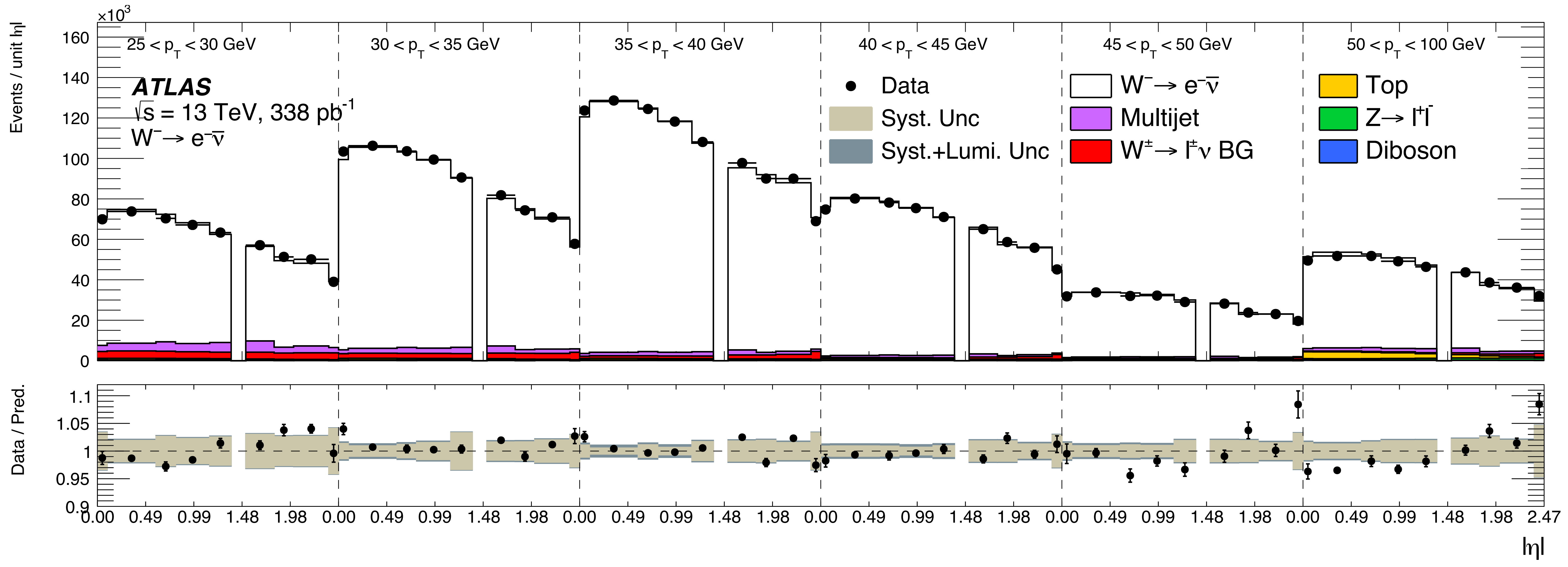
Summary

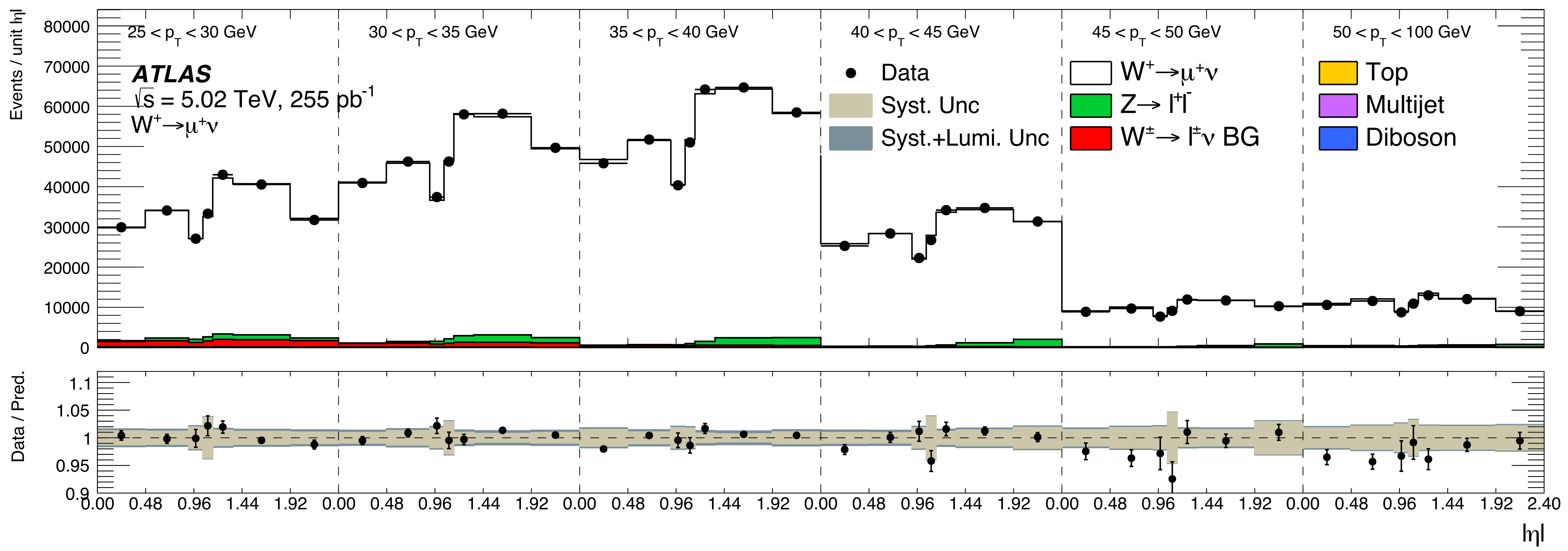
- Drell-Yan measurements are both high-precision tests of SM and probes of new physics
- Measurements of W cross-sections in low pile-up data are very precise and ability to constrain PDFs has been demonstrated
- Measurements of the high-m_T^W spectra performed for the first time and provide very strong constraints on EFT operators
- High-mass neutral current $\tau\tau$ measured for the first time and used to investigate multiple new physics scenarios



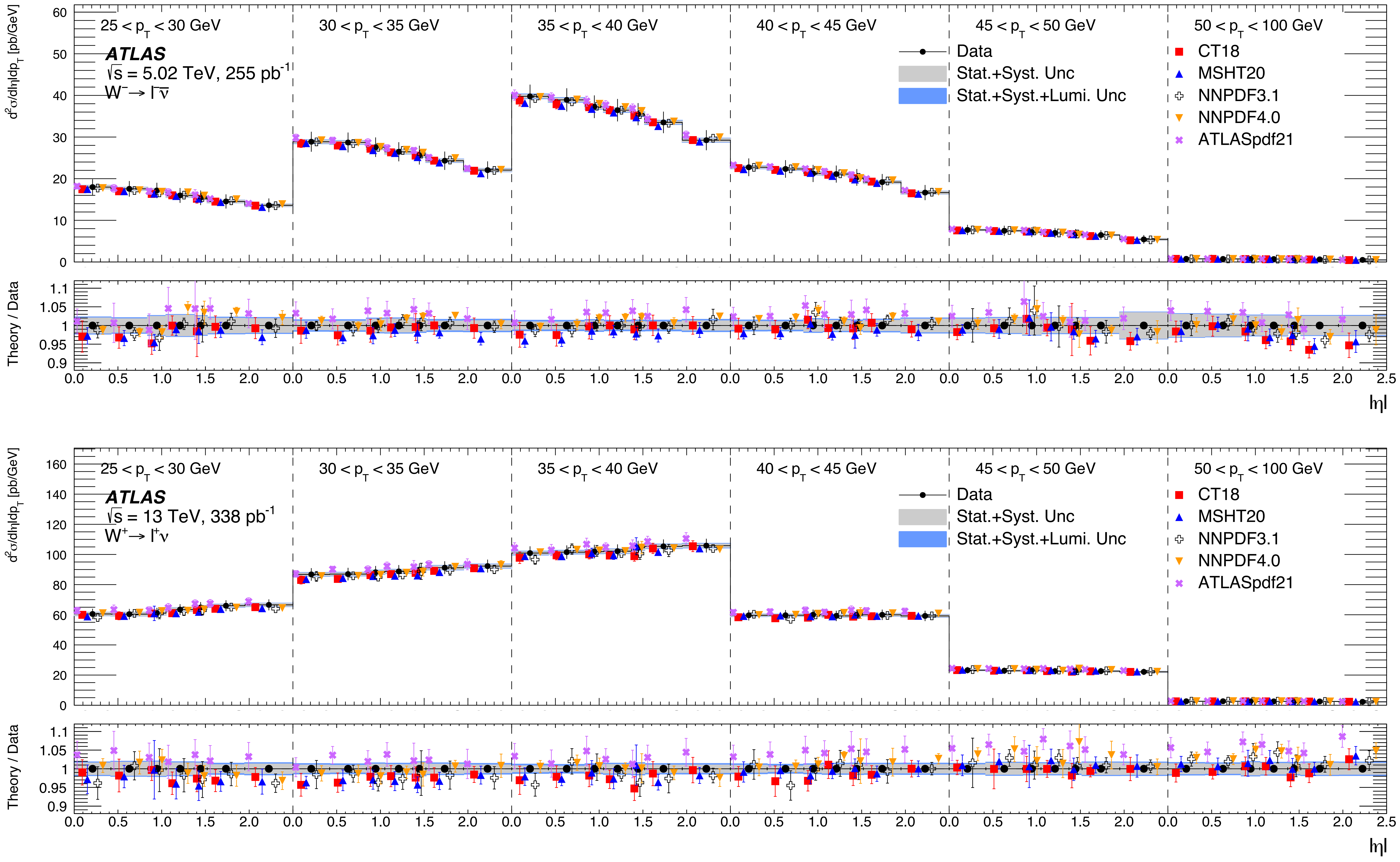
Backup

CC DY in low pile-up data

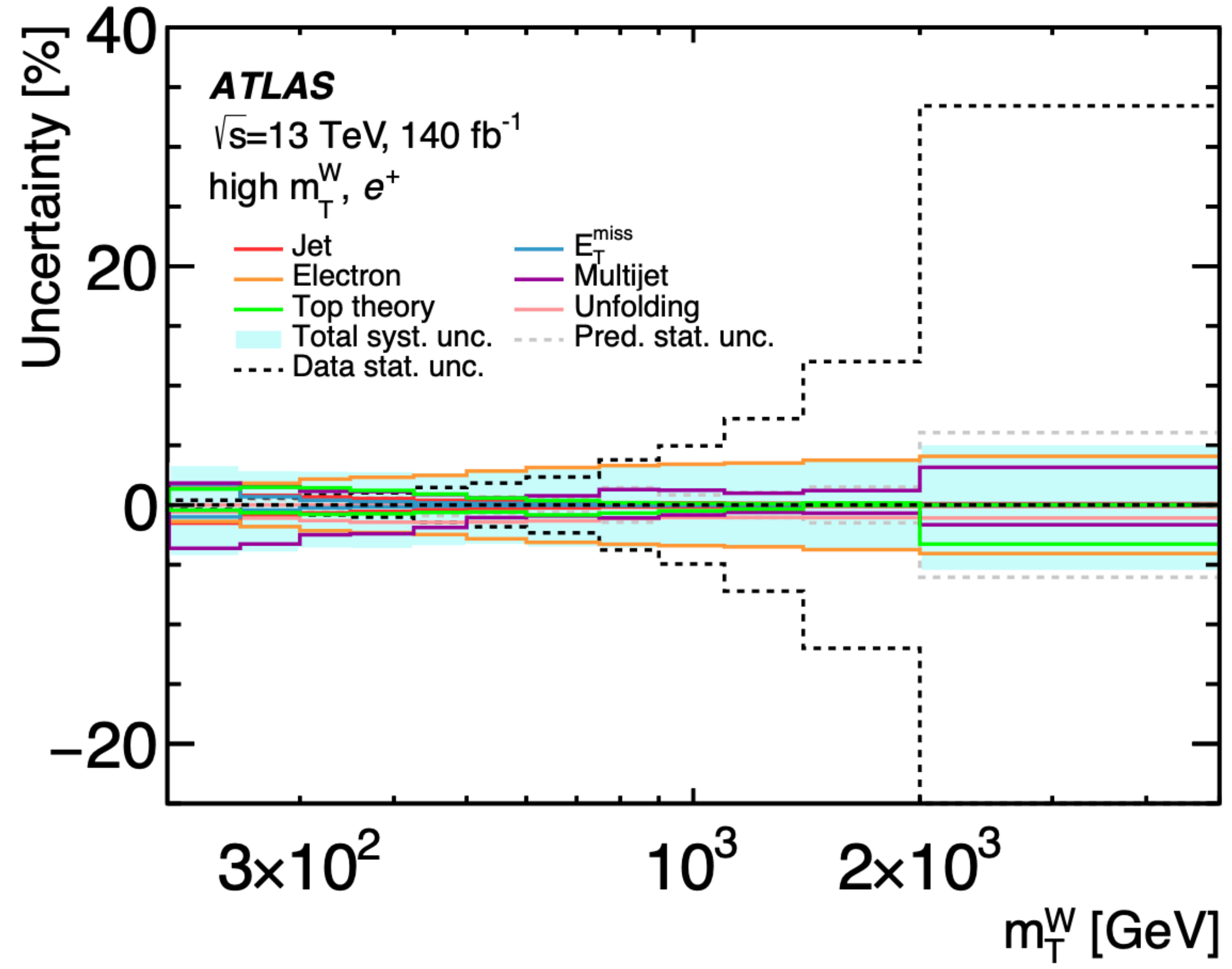


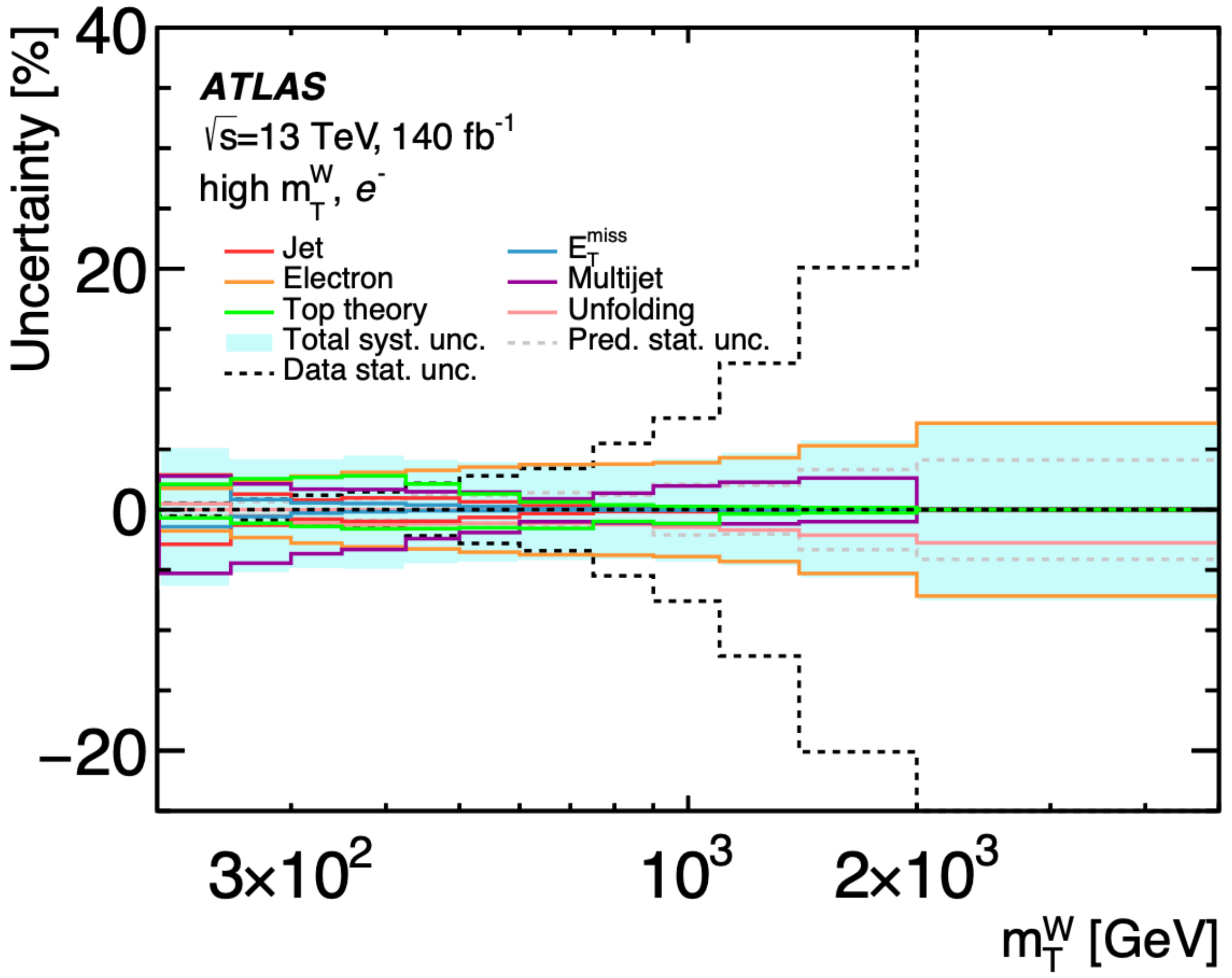


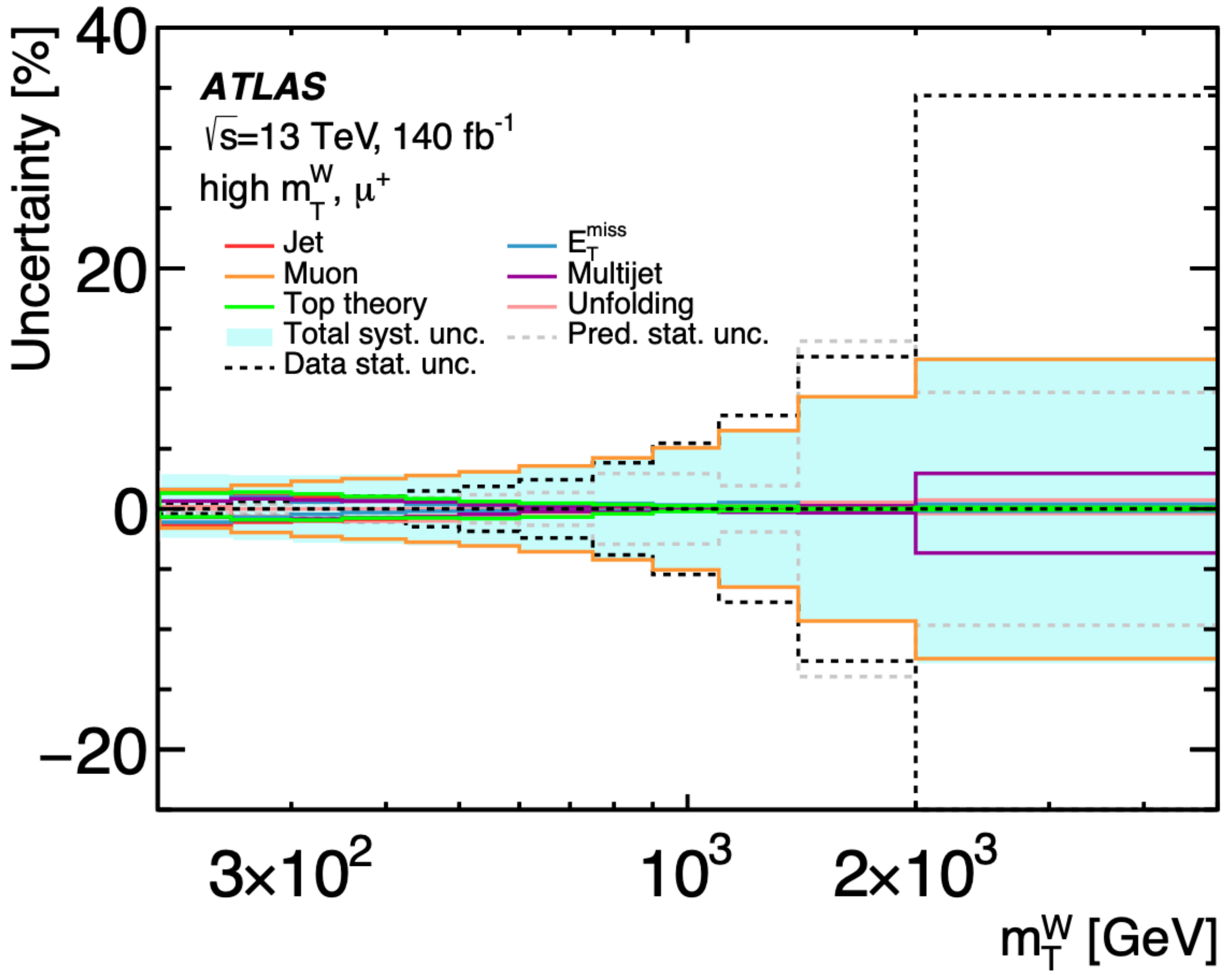
CC DY in low pile-up data

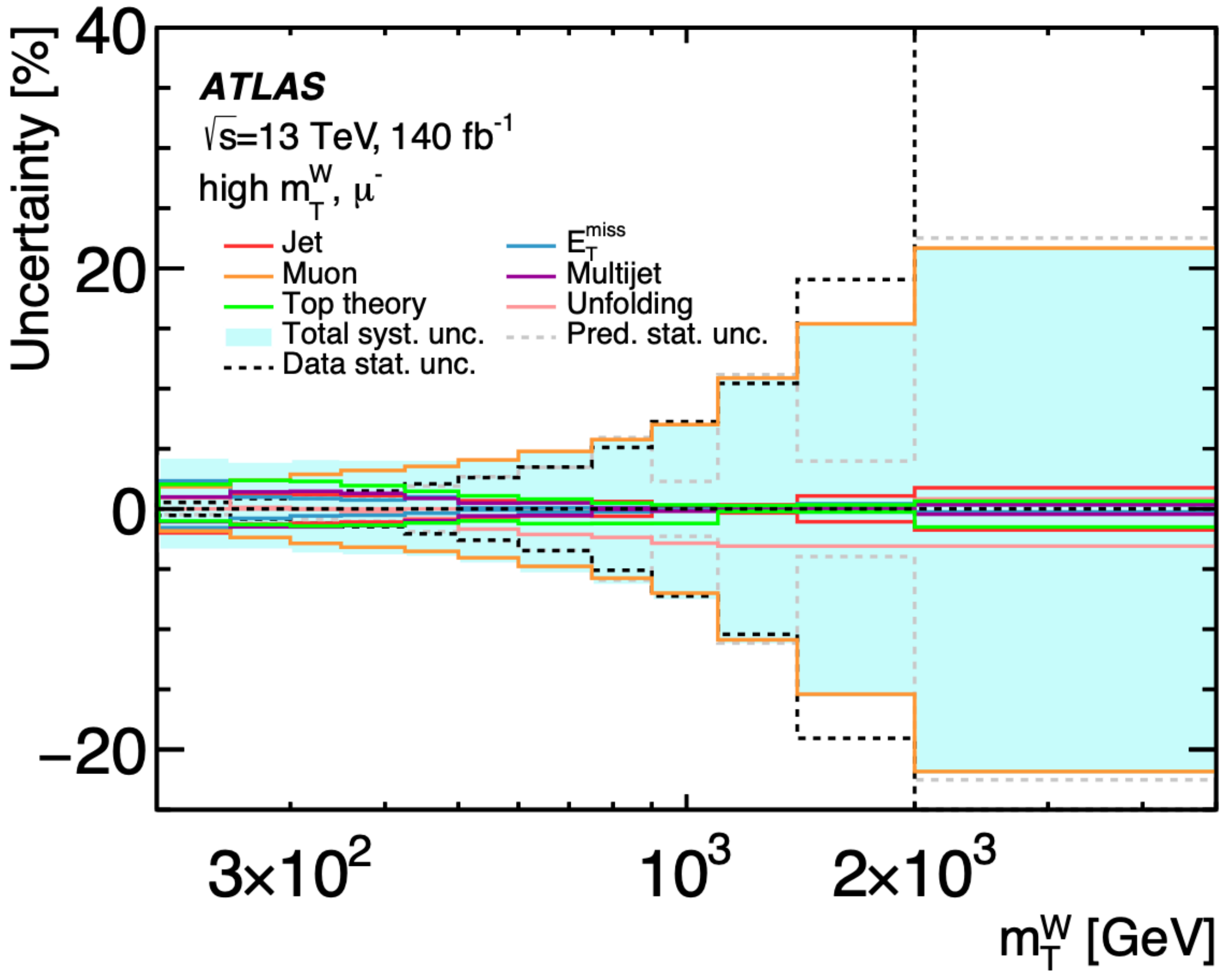


Charged-current HMDY

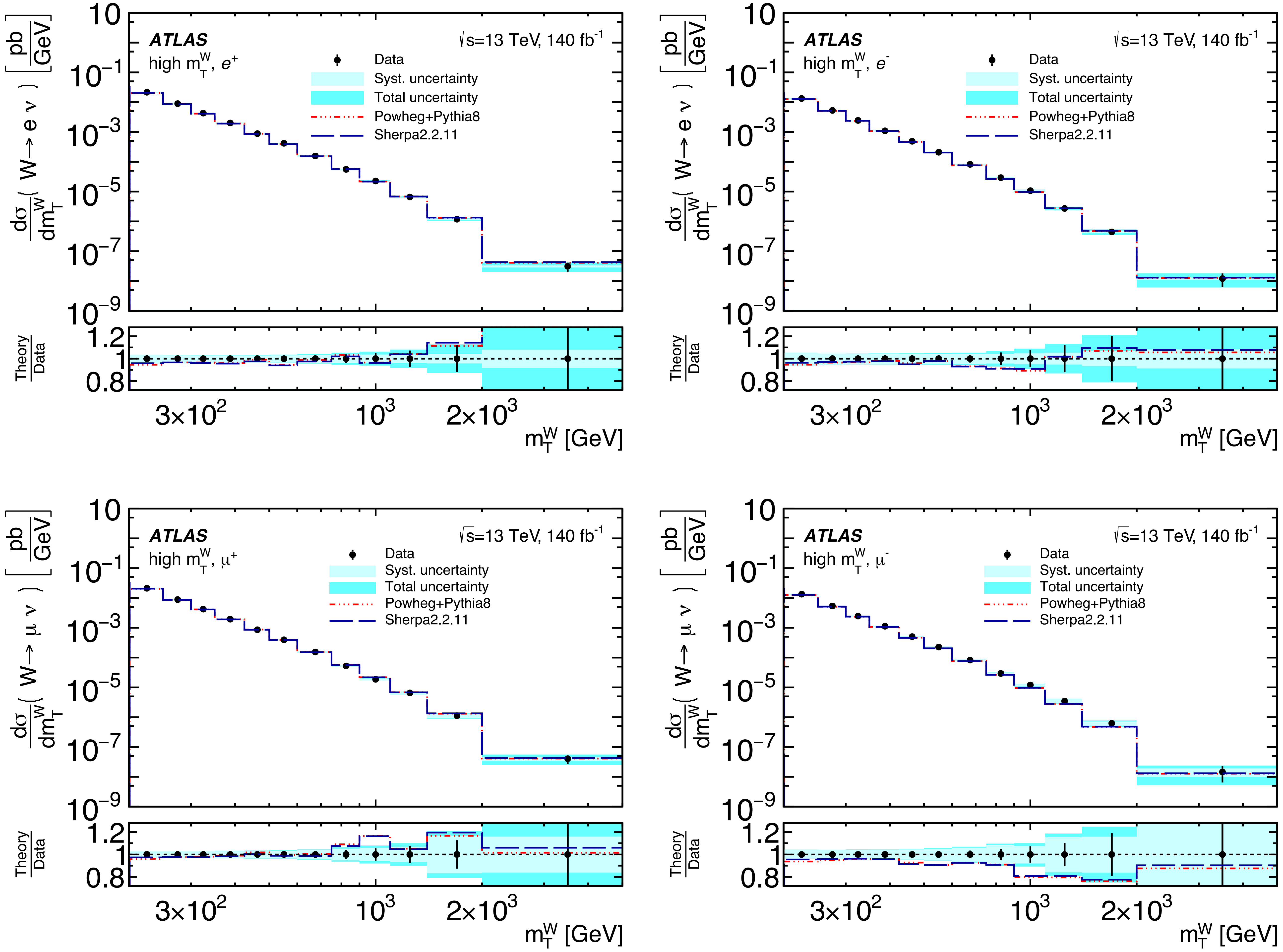






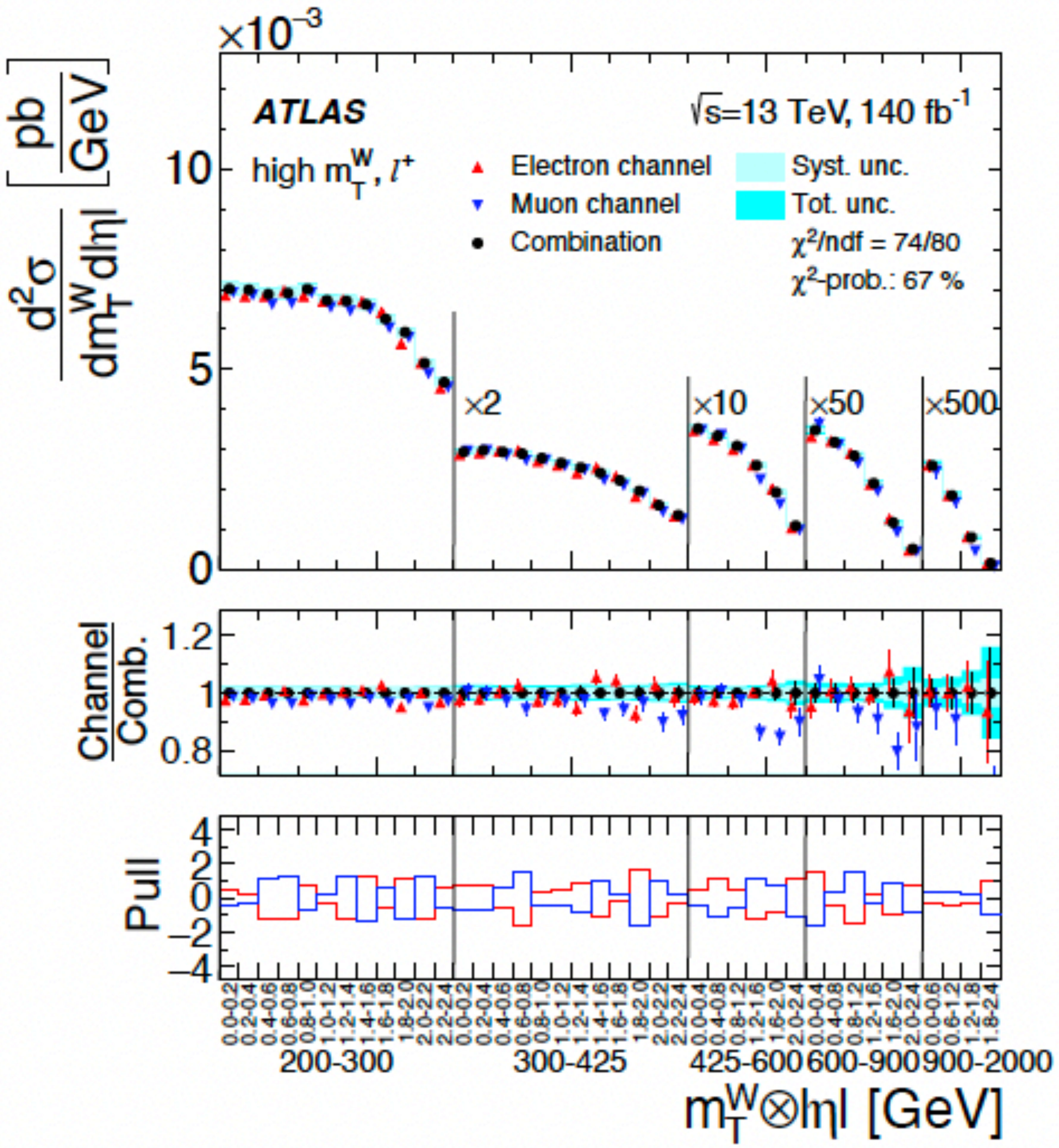


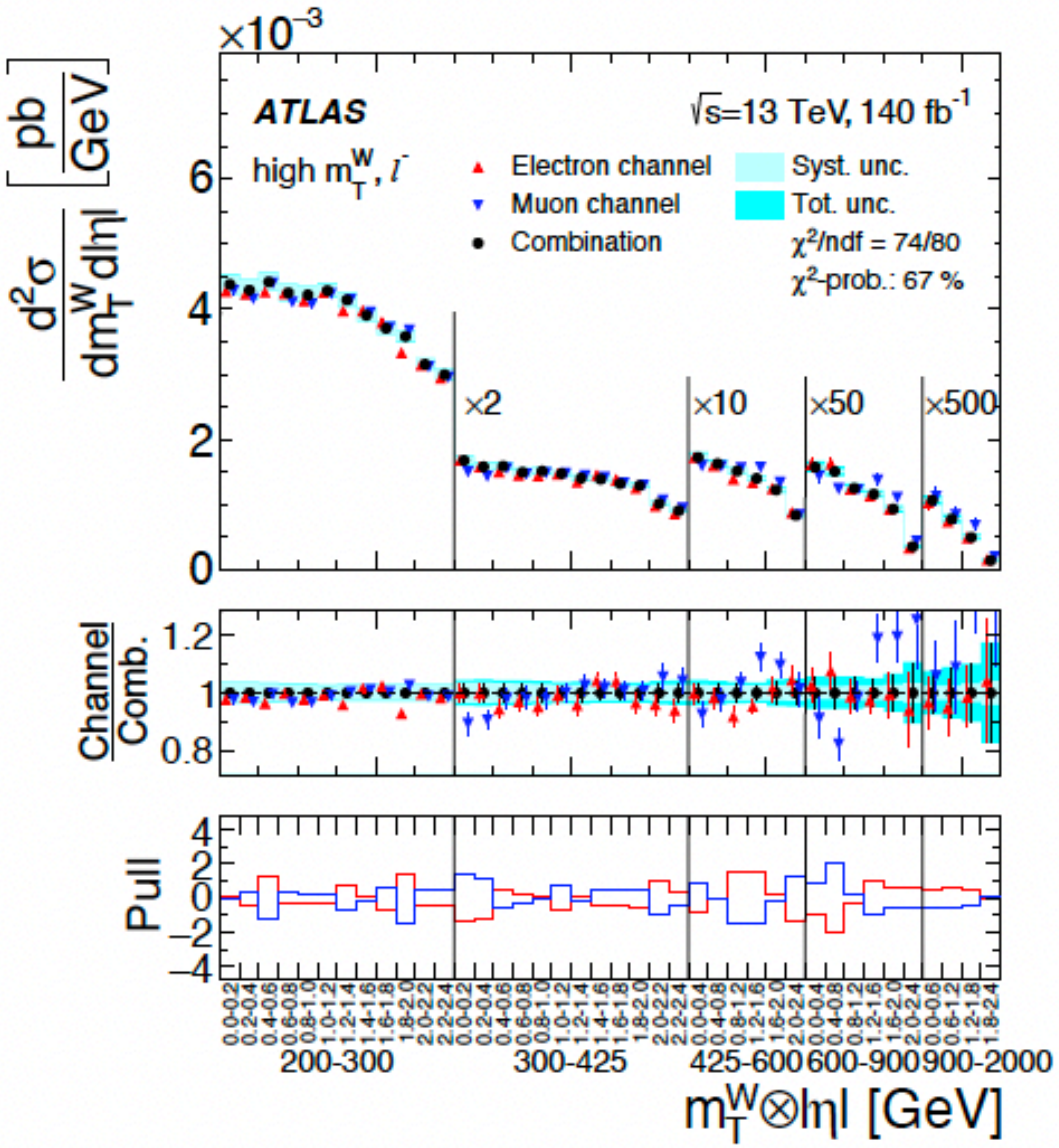
Charged-current HMDY



Paper on arXiv

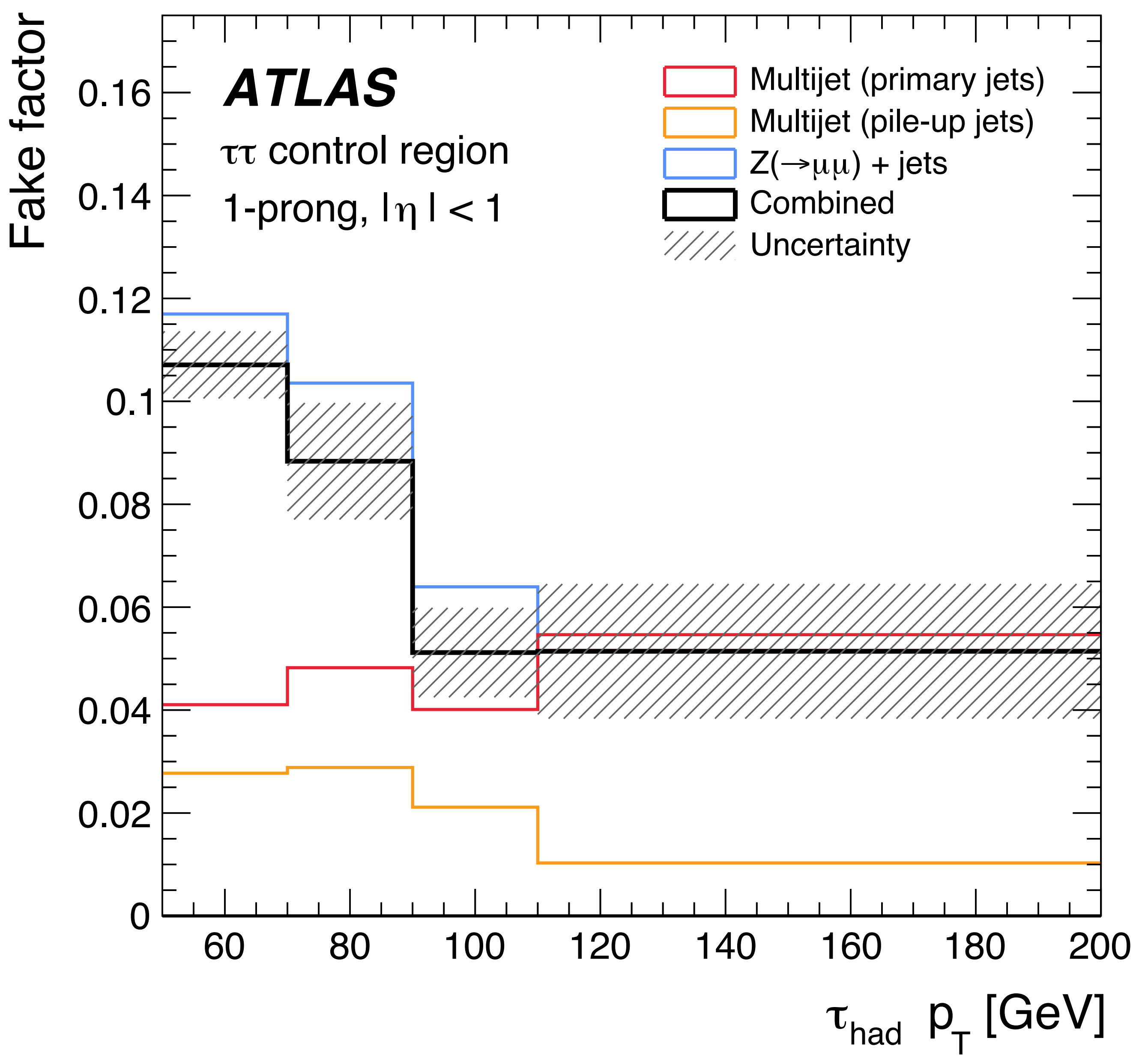
Charged-current HMDY

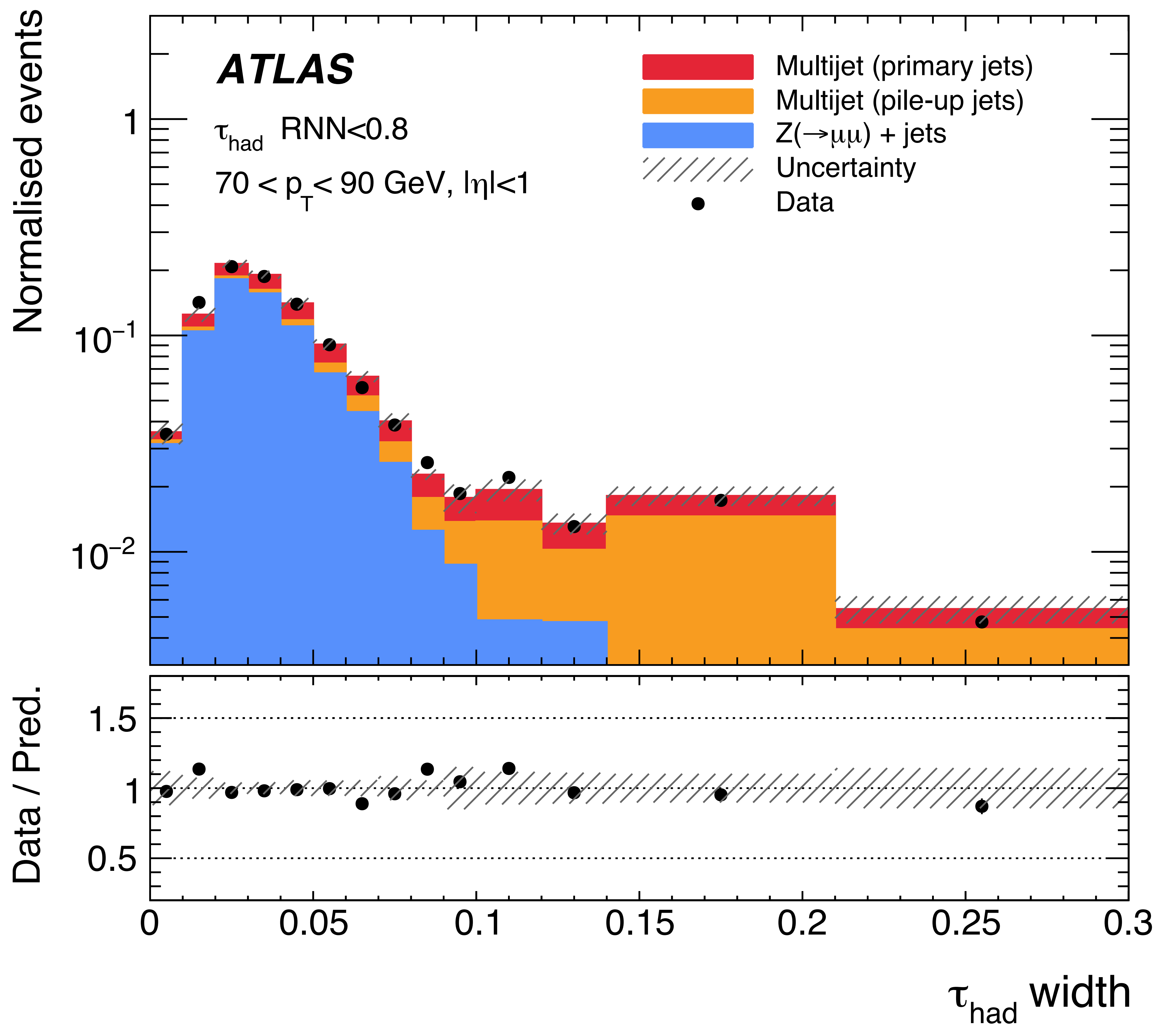




HMDY $\tau\tau$ fake factor method

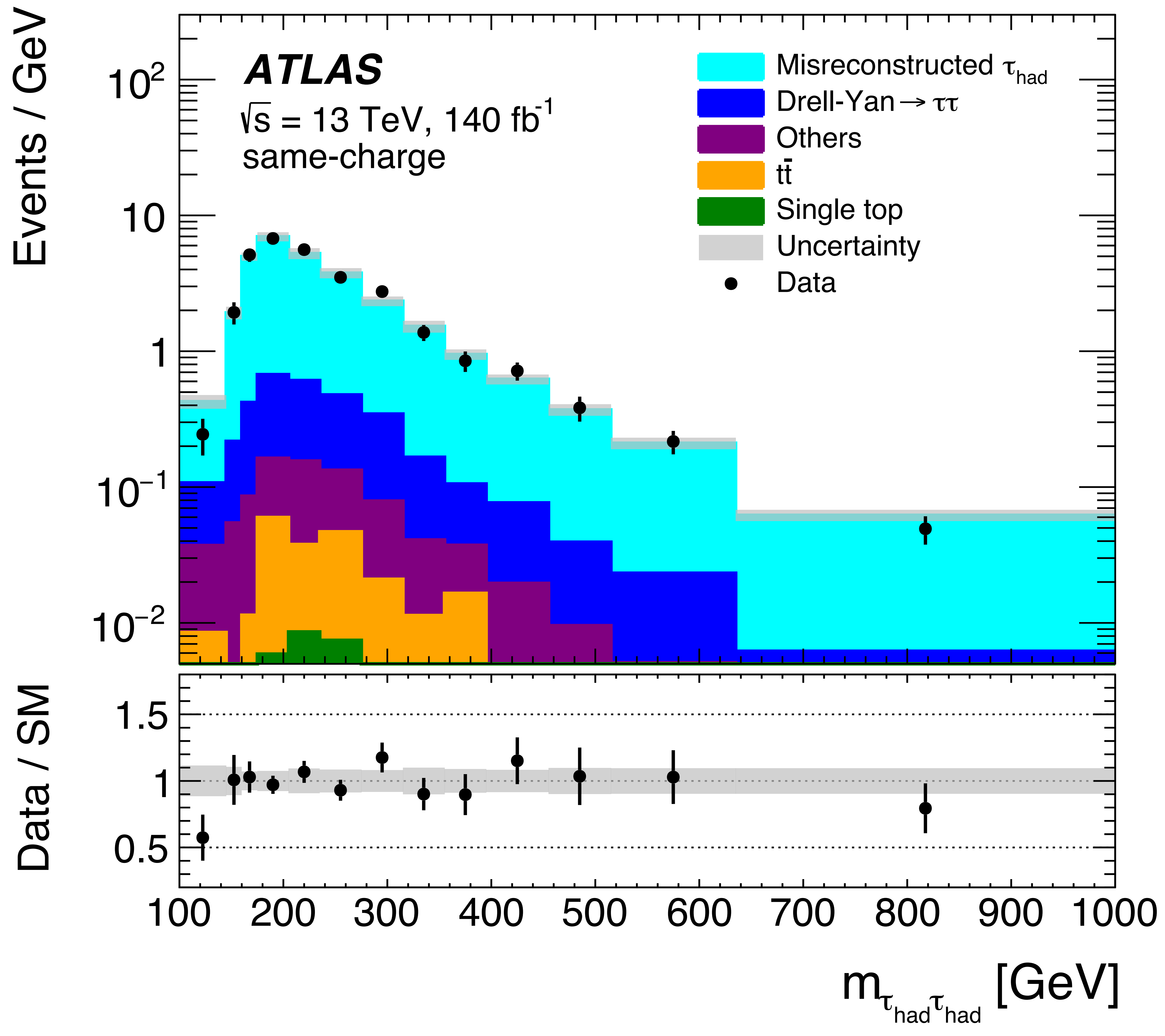
- Fake factors used to extrapolate fake tau yields in a fake-enriched CR to the signal region
- Tau RNN score used as CR/SR separation variable
- Tau width used as a separation variable for quark- initiated and gluon-initiated jet-faking-taus
- Fake factor ~3 times larger for quark-initiated jets

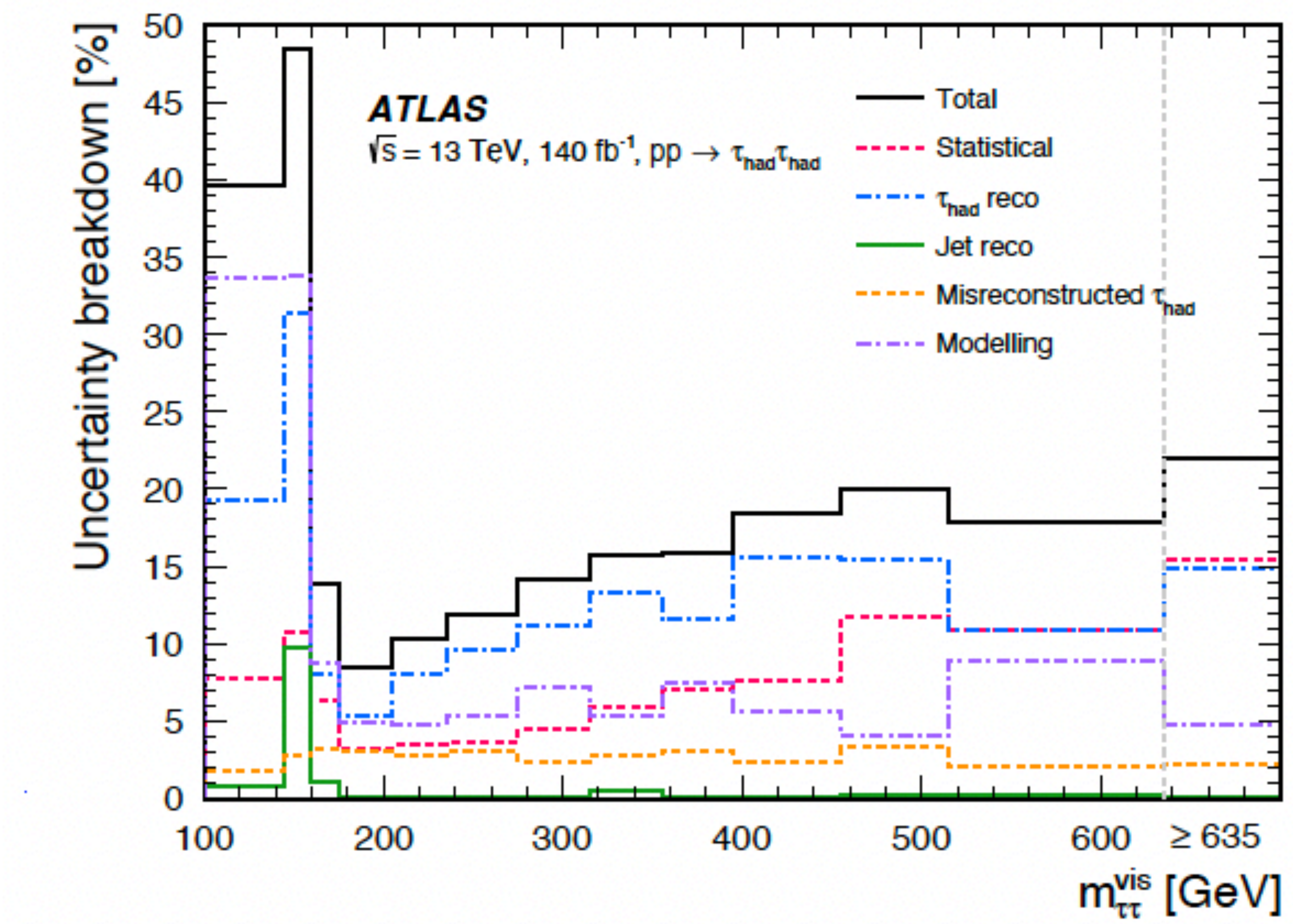




Paper on arXiv

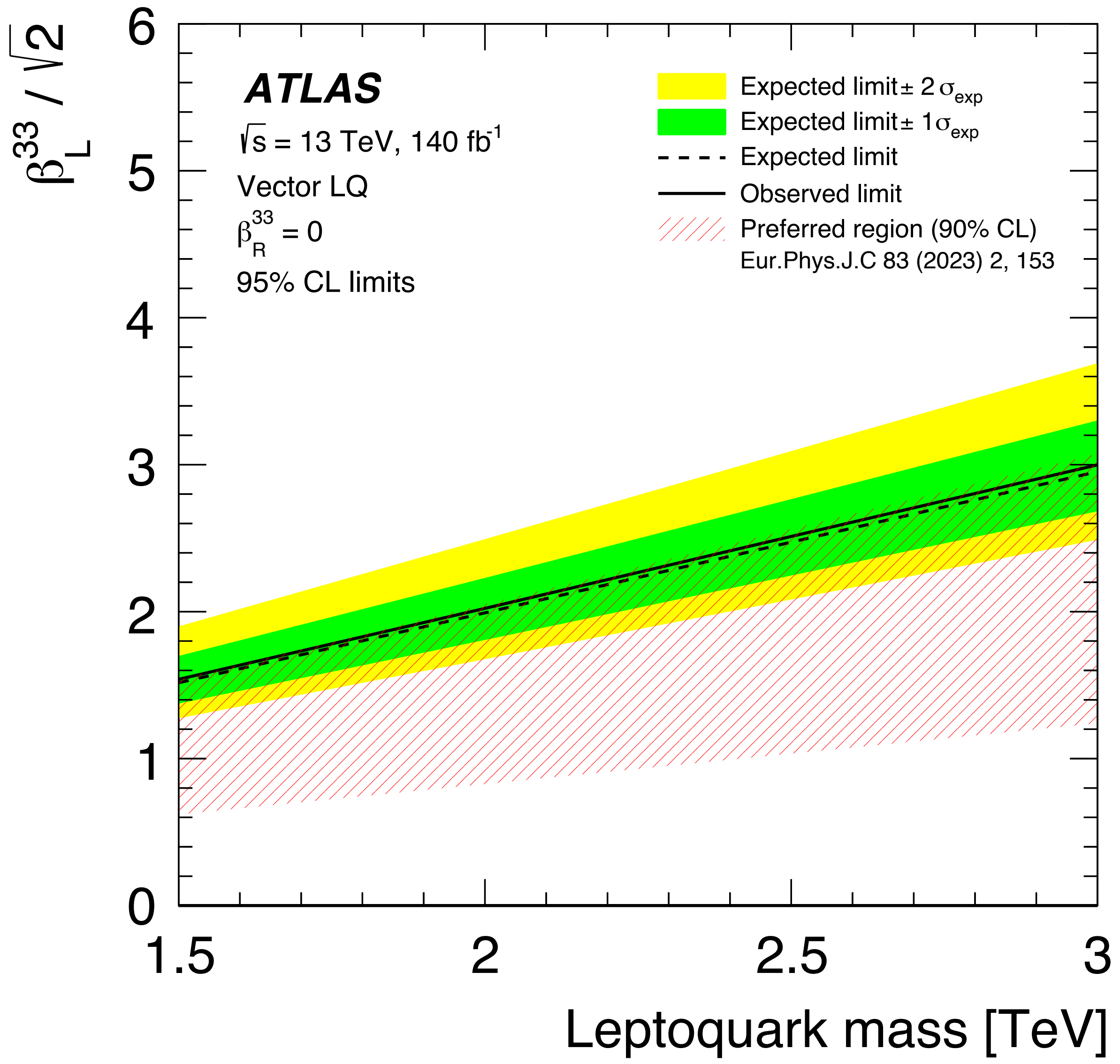
HMDY $\tau\tau$

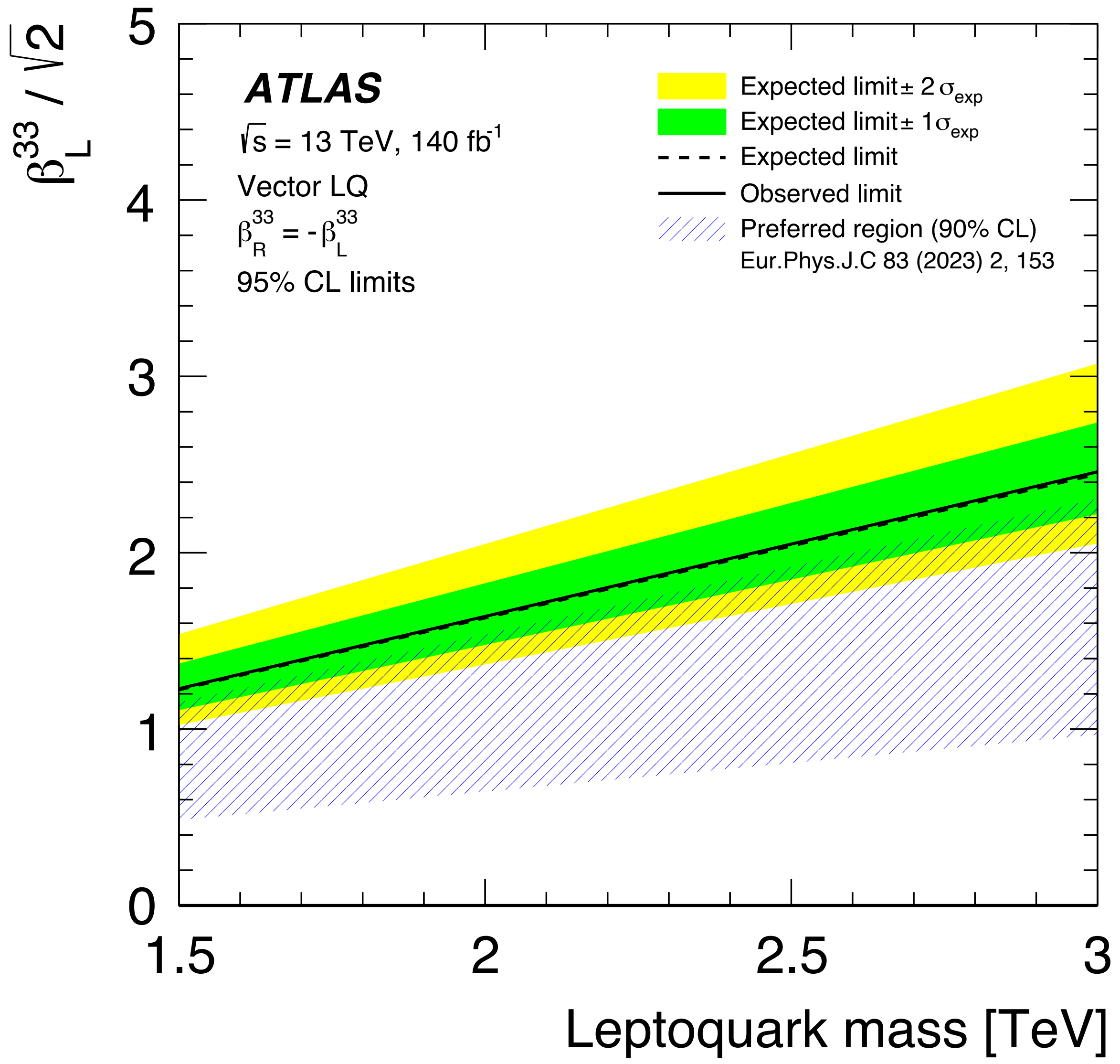


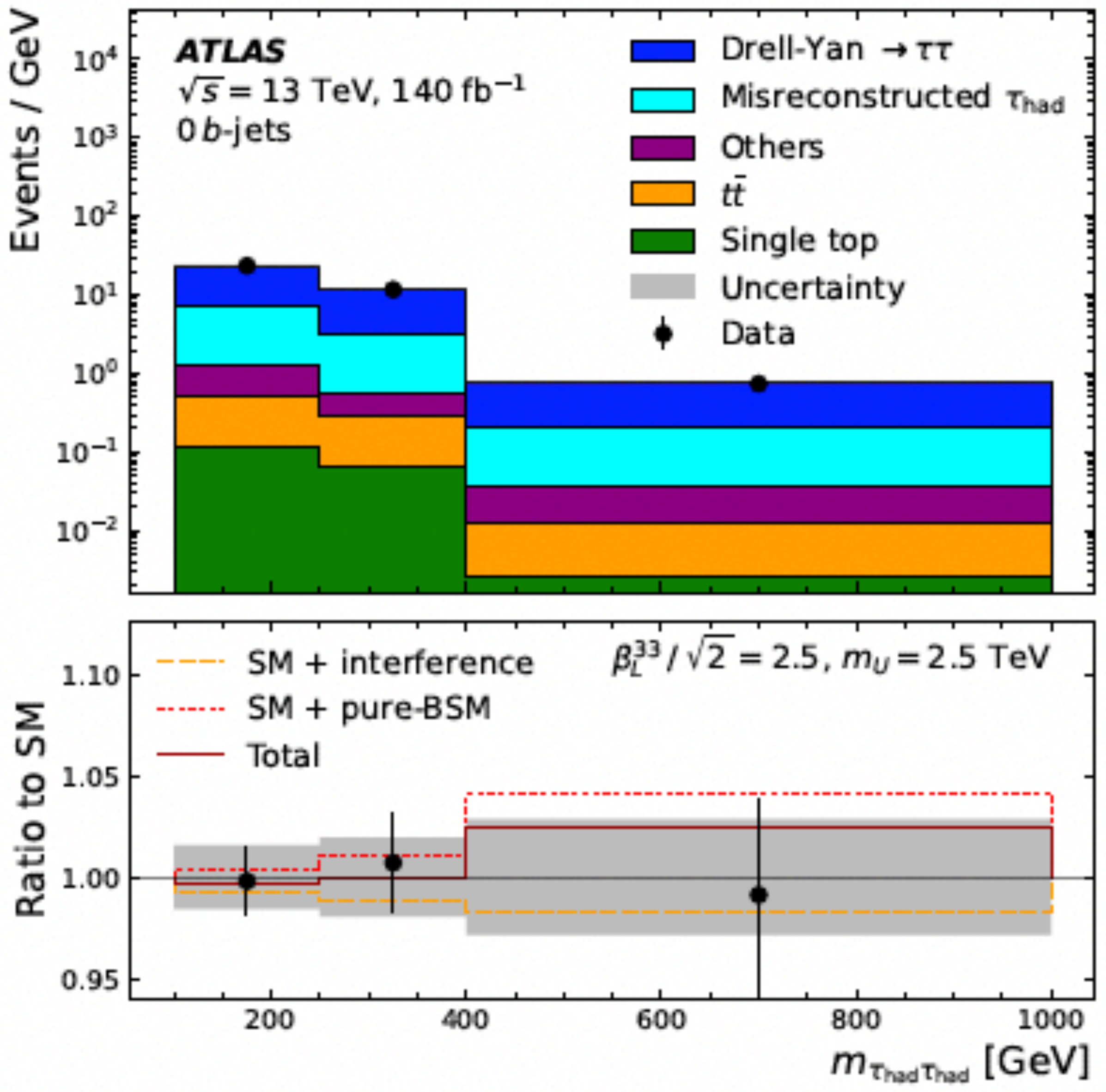


Paper on arXiv

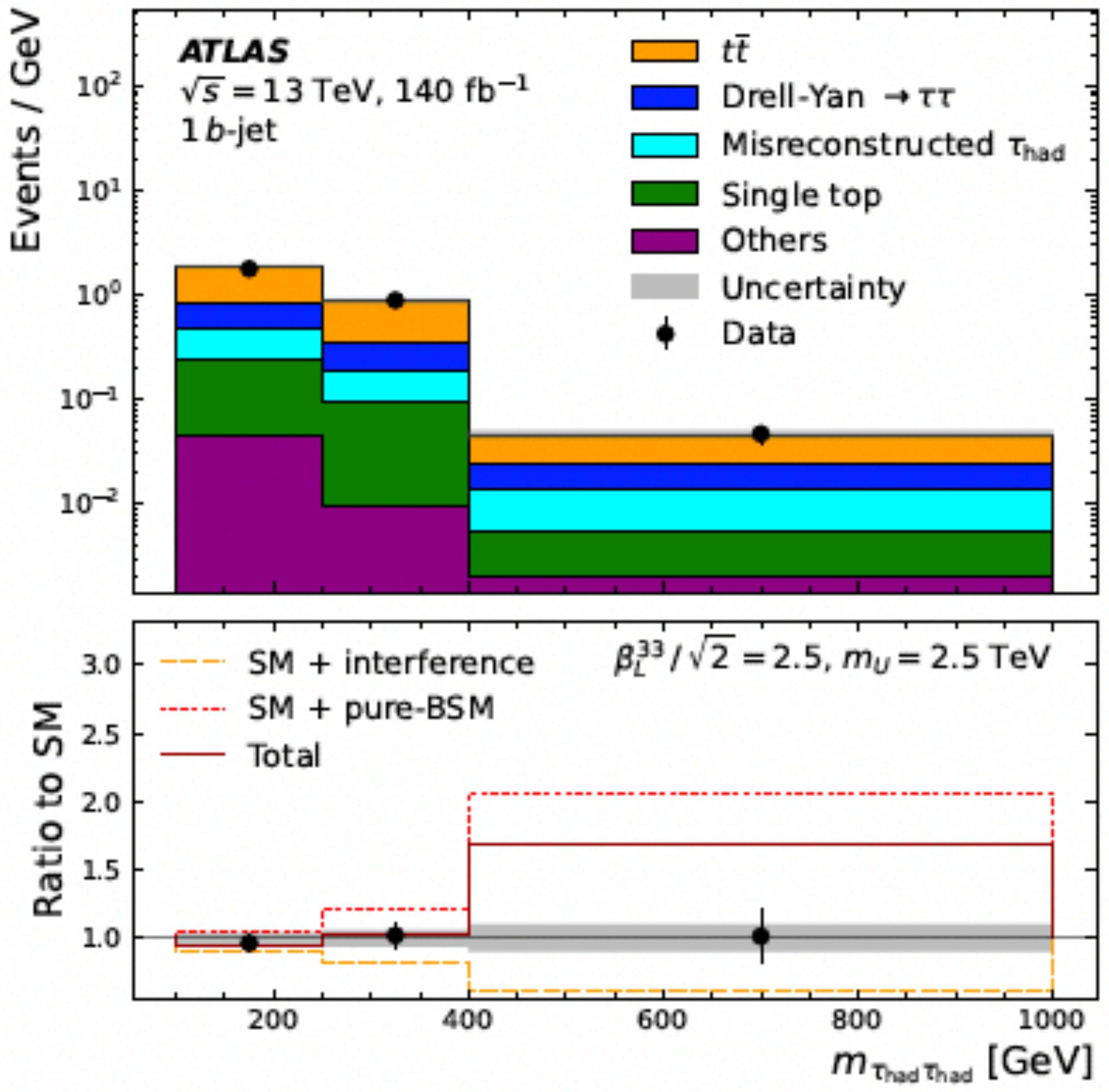
HMDY $\tau\tau$



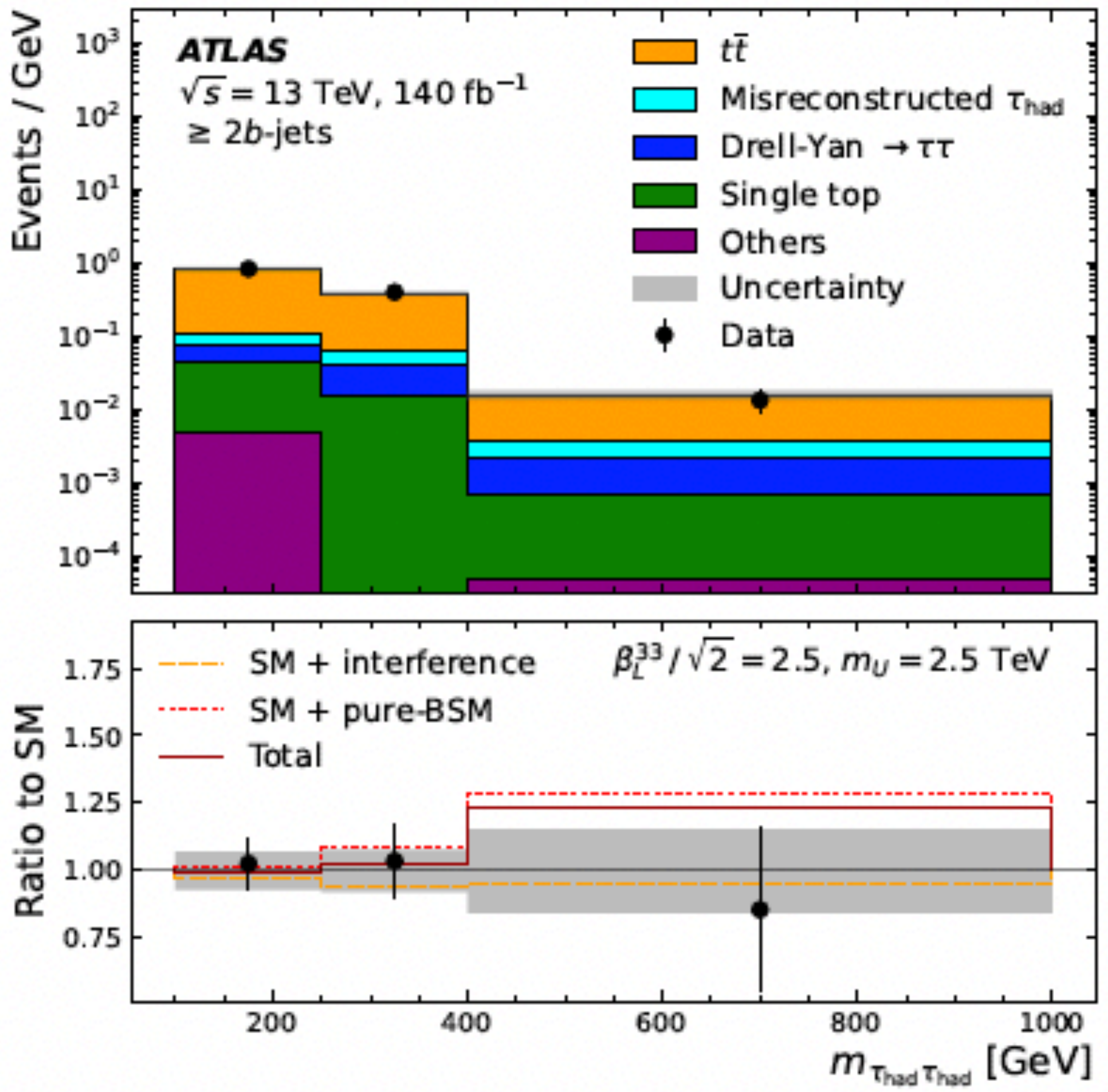




(a)



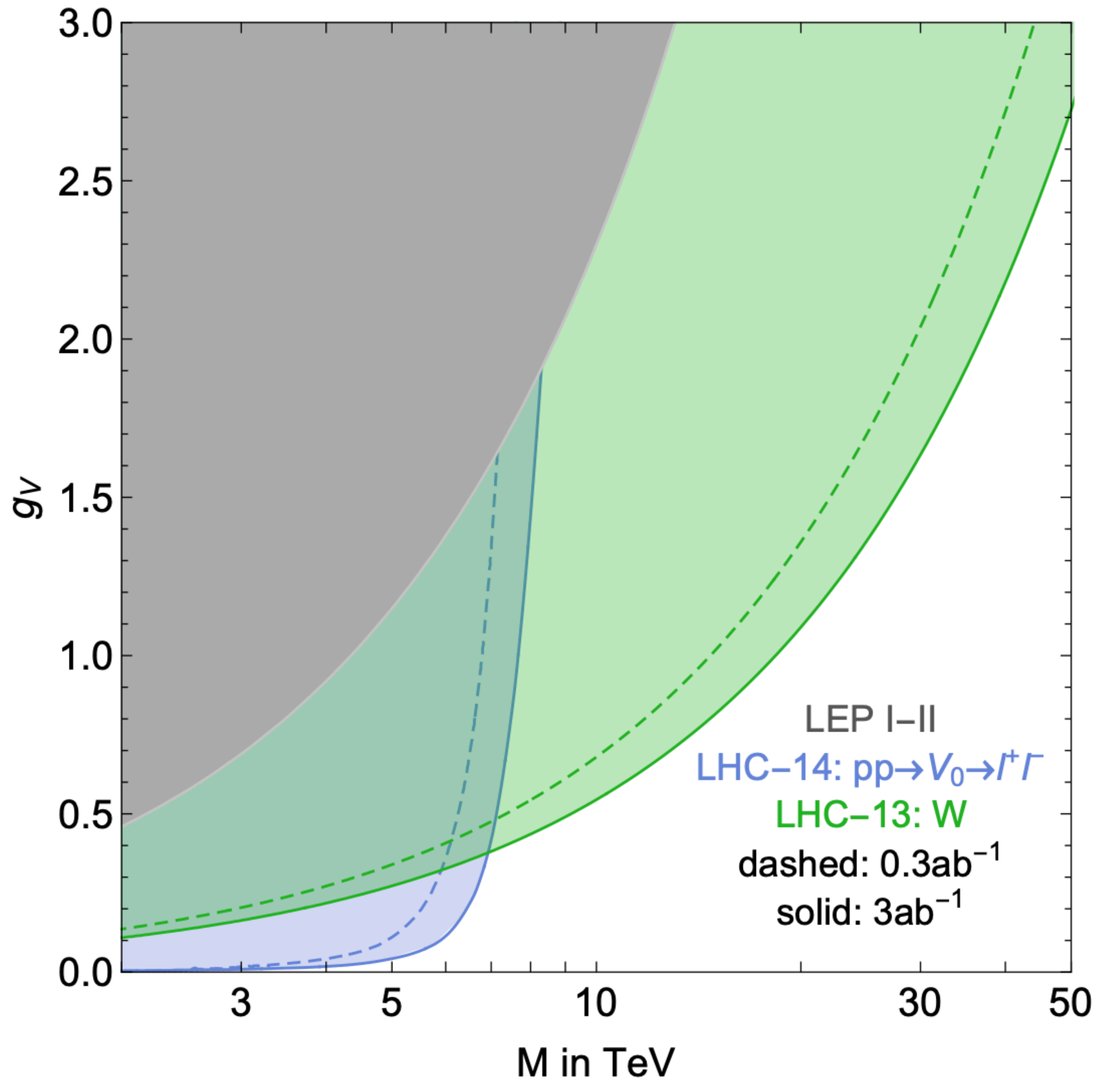
(b)



Paper on arXiv

Why measurements?

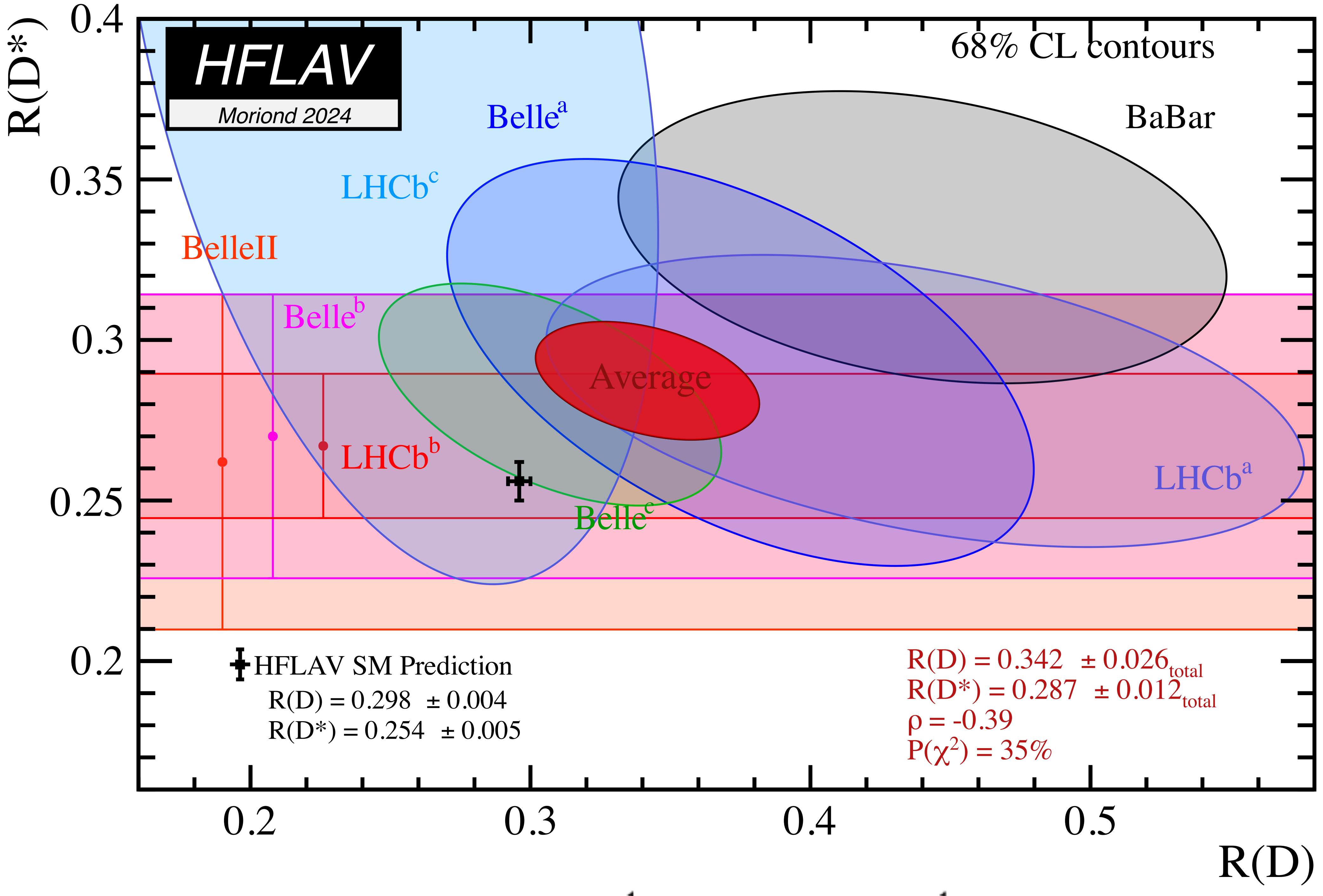
- Measurements are “unfolded” to truth level based on simulation particles
    - Correct for detector inefficiency, resolution and geometry
    - Easier comparison to theory predictions and other experiments
- Powerful tests of the Standard Model - probing up to N^{3}LO QCD
- Measurements used as inputs to EFT interpretations
    - Model independent probes of new physics
    - Can extend reach beyond direct searches



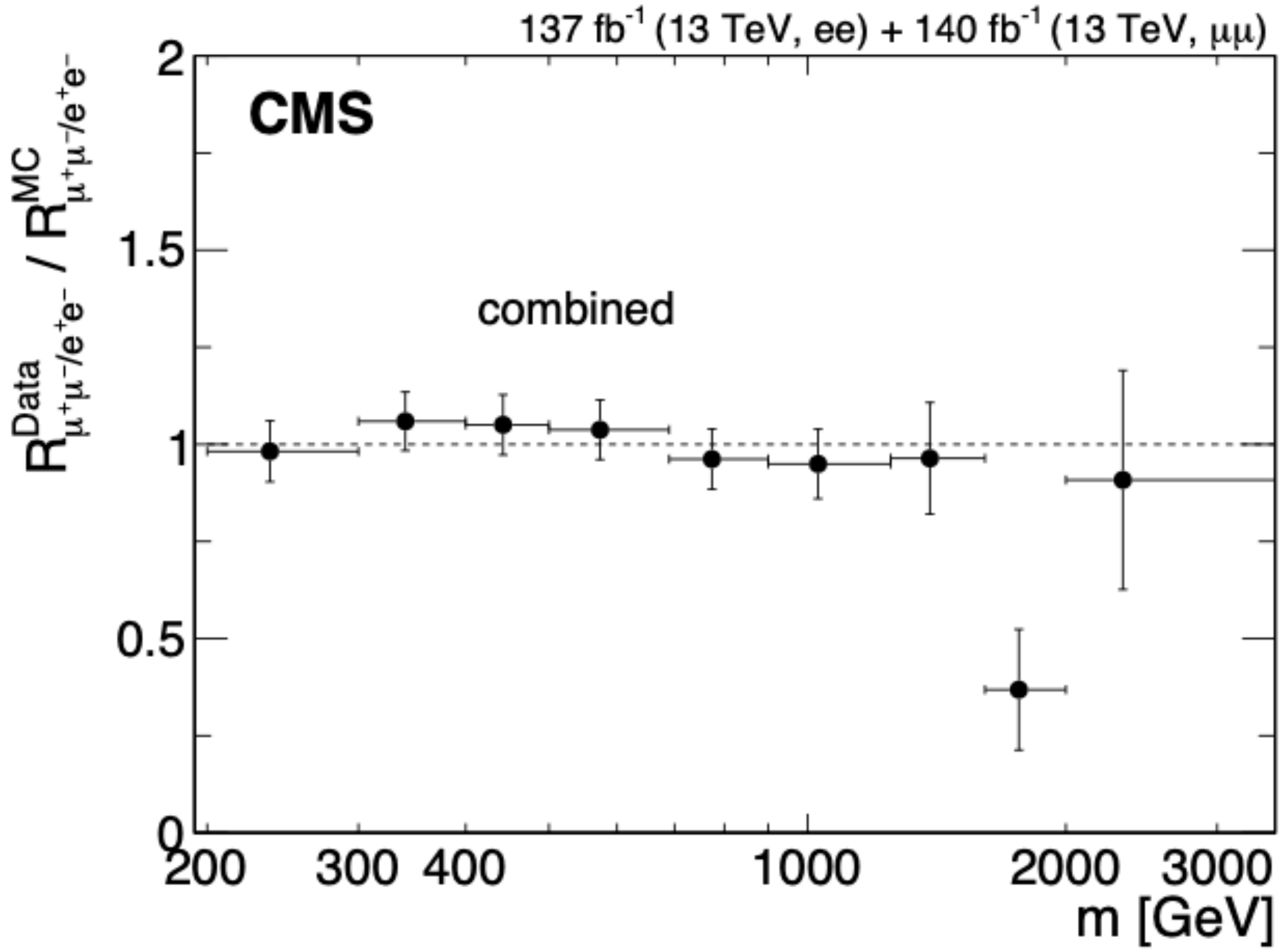
arXiv [hep-ph] 1609.08157

Flavour anomalies

- Tensions with the SM have been observed in vertices involving quarks and leptons ($q \to q'\ell\ell'$)
- Measurements of Drell-Yan probe the same vertices ($qq' \to \ell\ell'$)
  - CMS even sees a small tension in these measurements
- Performing measurements in association with b-hadron-tagged jets can further probe specifically the "B-anomalies" (i.e. $bs\ell\ell/bc\tau\nu$ vertices)



HFLAV



JHEP 07 (2021) 208