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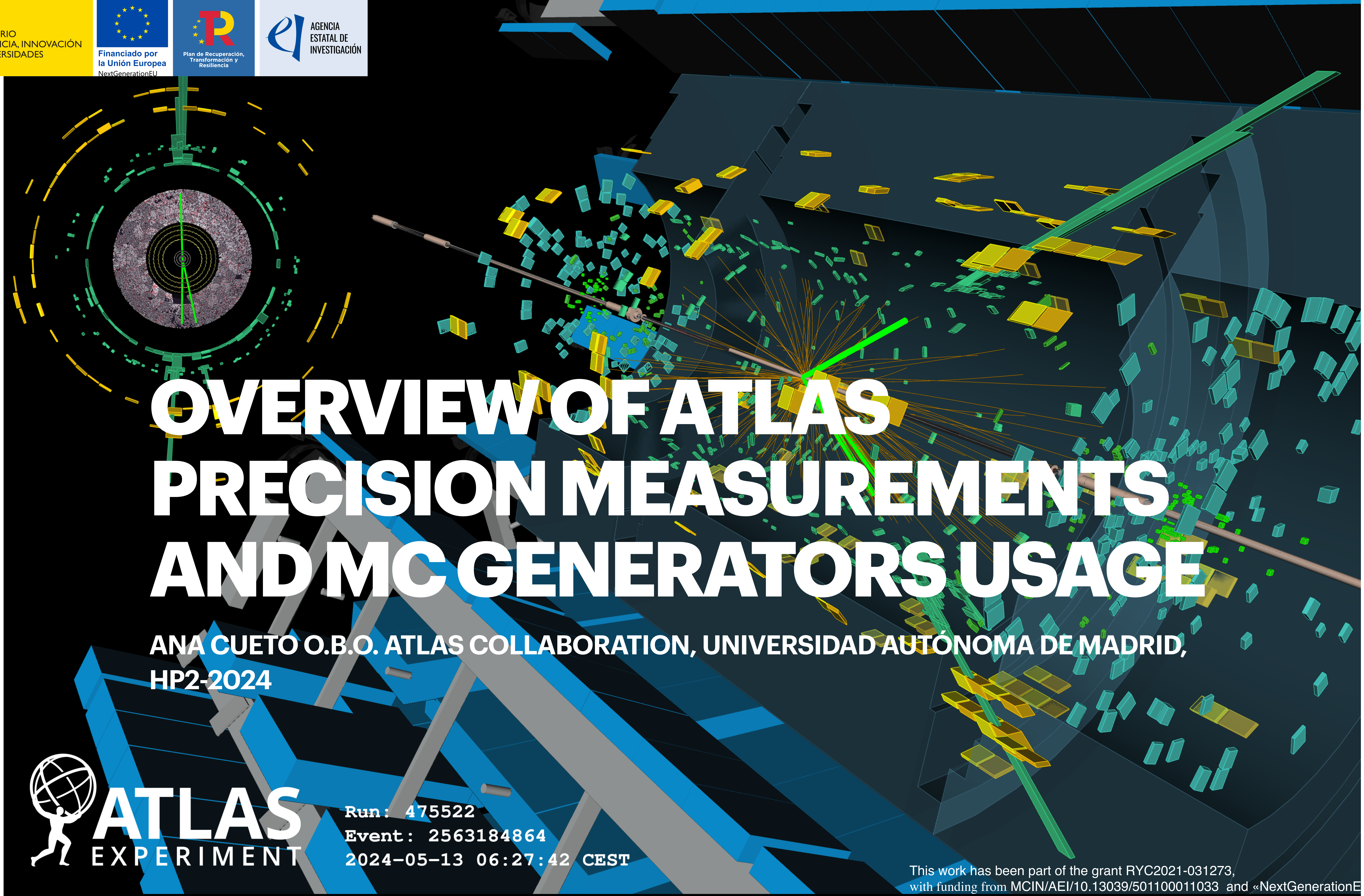


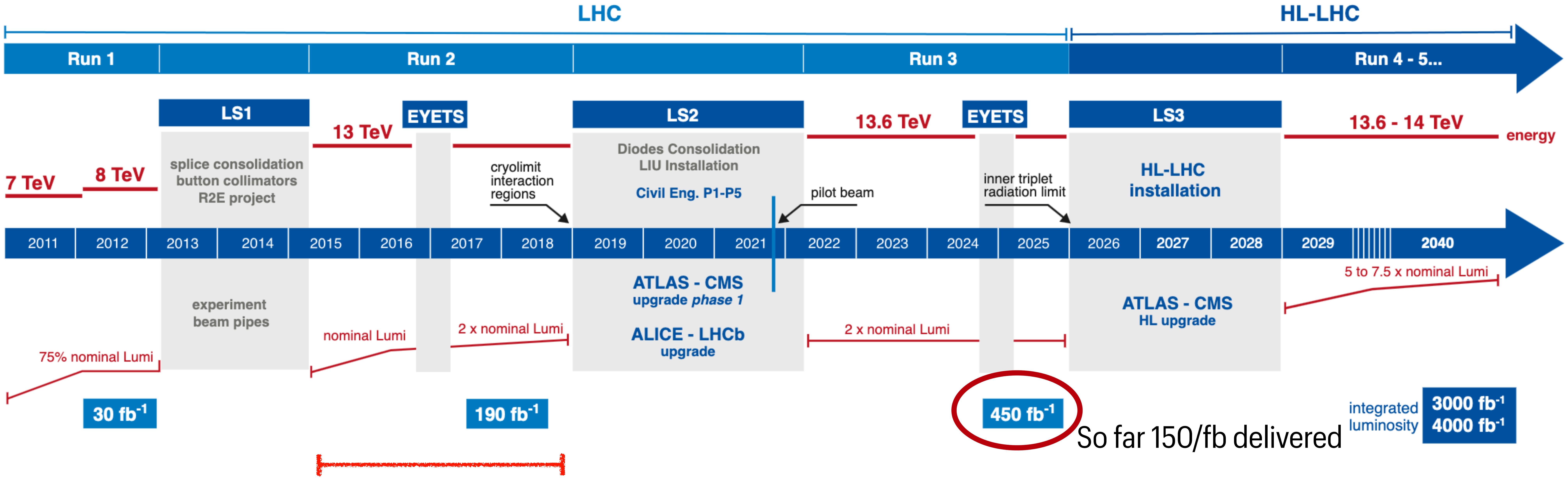
OVERVIEW OF ATLAS PRECISION MEASUREMENTS AND MC GENERATORS USAGE

ANA CUETO O.B.O. ATLAS COLLABORATION, UNIVERSIDAD AUTÓNOMA DE MADRID,
HP2-2024

ATLAS EXPERIMENT

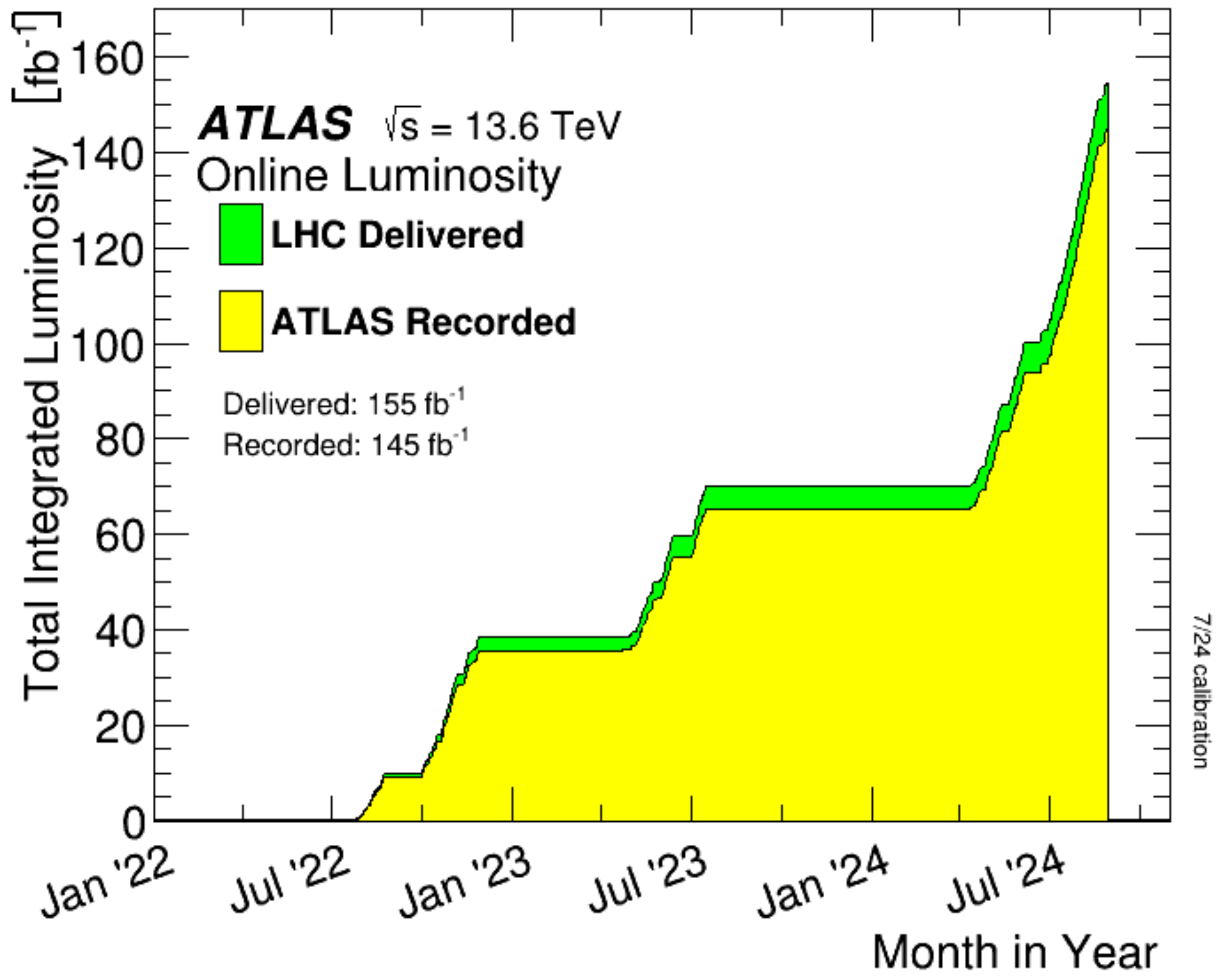
This work has been part of the grant RYC2021-031273, with funding from MCIN/AEI/10.13039/501100011033 and «NextGenerationE

LHC PLAN AND STATUS



So far 150/fb delivered

Best known data-set

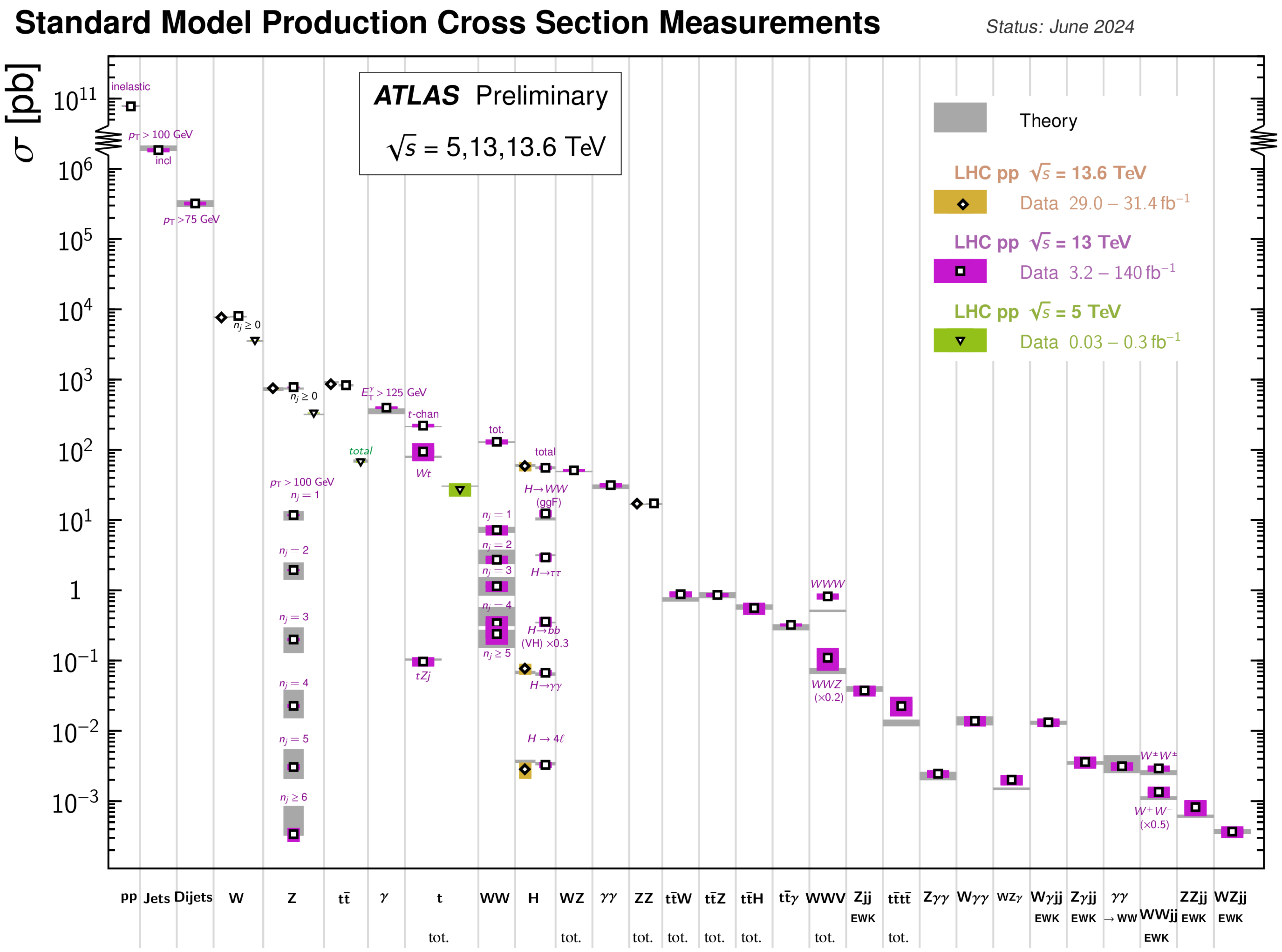


ATLAS PRECISION PHYSICS PROGRAMME

- ➡ Jets and photons
- ➡ Electroweak precision measurements
- ➡ W/Z + jets
- ➡ Top production
- ➡ Higgs
- ➡ Multi-boson measurements

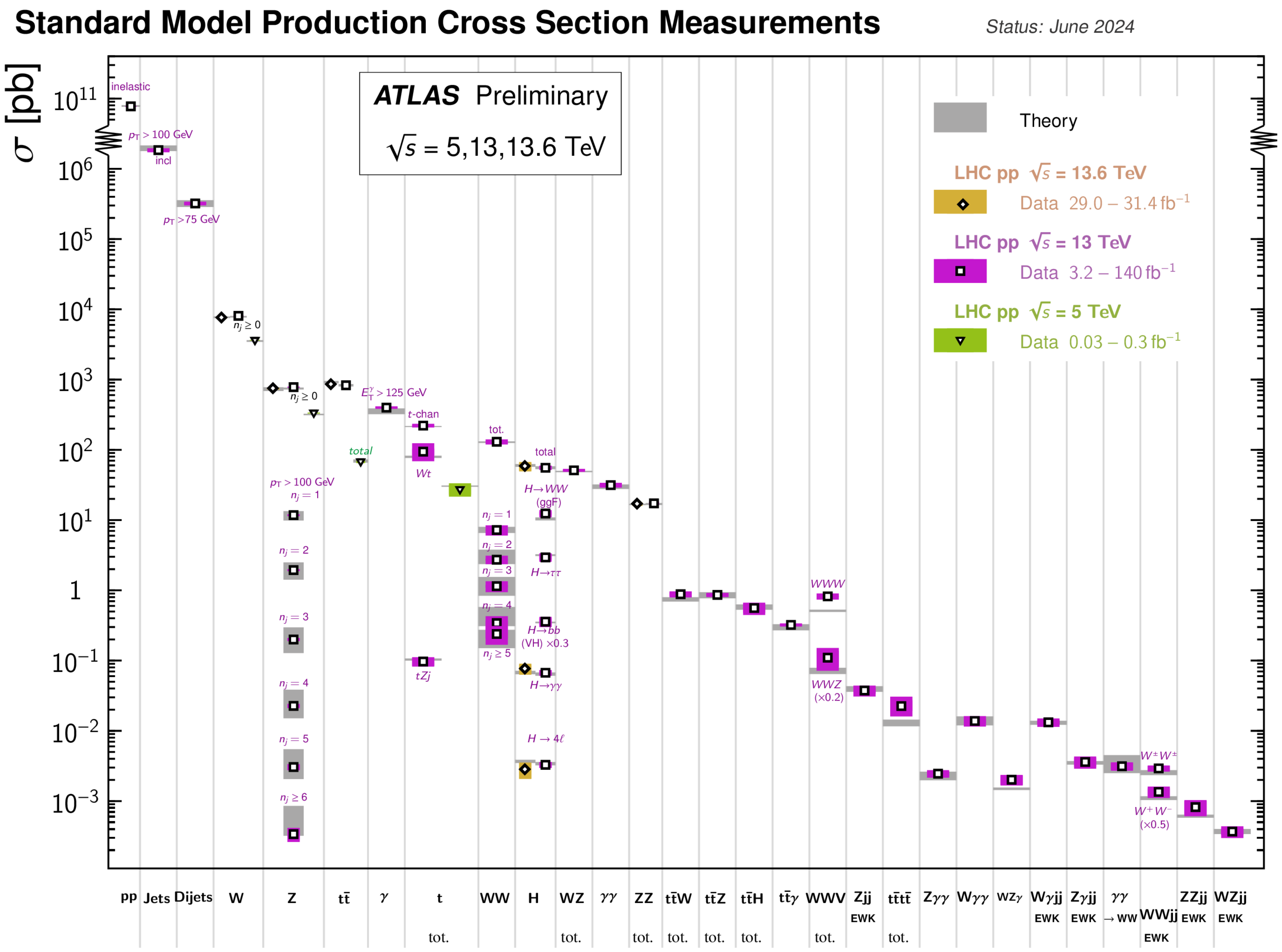
★ Caveat: Heavy ion not covered in the talk

★ Only few results shown. ATLAS results public pages: SM, Top, Higgs, diHiggs, B-Physics and light states



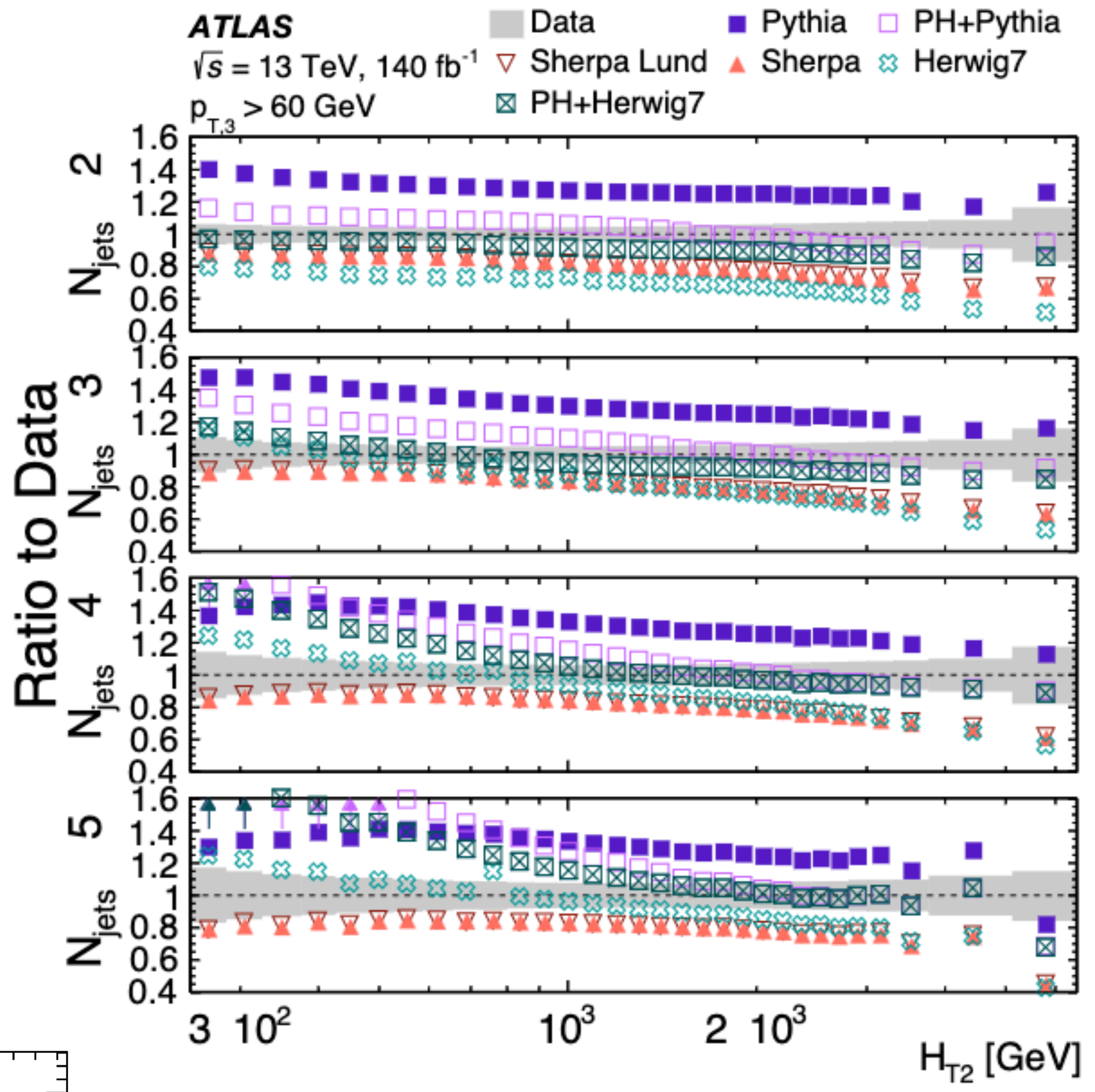
ATLAS PRECISION PHYSICS PROGRAMME

- ATLAS has a wide programme of Standard Model physics with different groups focused on different final states (SM, Top, Higgs and DiHiggs)
- Measurements of total or fiducial differential cross sections, SM parameters, but also new avenues of testing the SM (polarisation, entanglement,…) and new methodologies (e.g. unbinned cross sections)
- Large number of observation of rare SM processes during Run 2 (diboson VBS, photon induced, triboson, 4tops) and new Higgs decay channels
- Similar programme in Run 3 benefitting of the updates in the detector (e.g. New Small Wheel) and performance (e.g x4 better b-tagging background rejection)

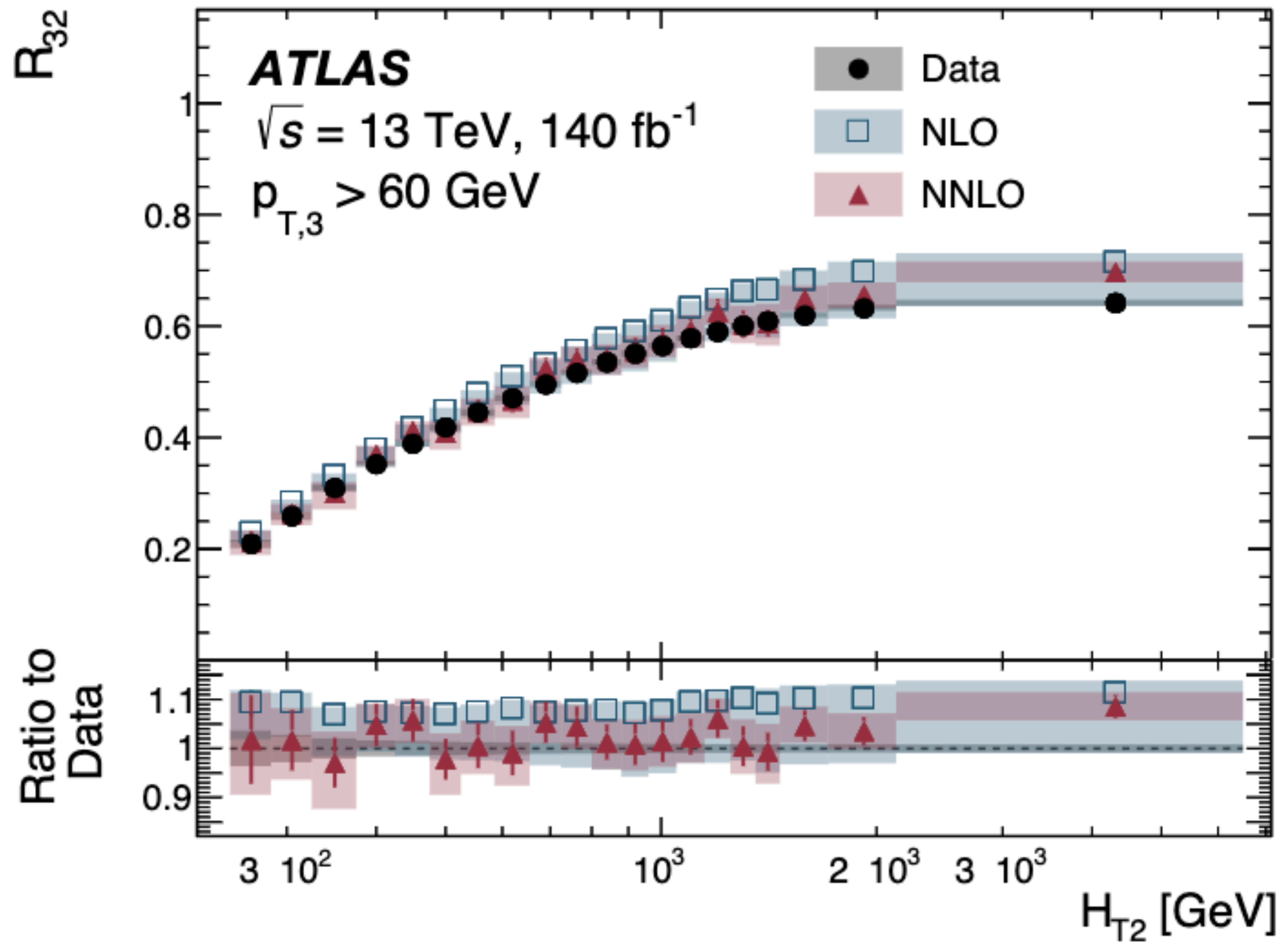


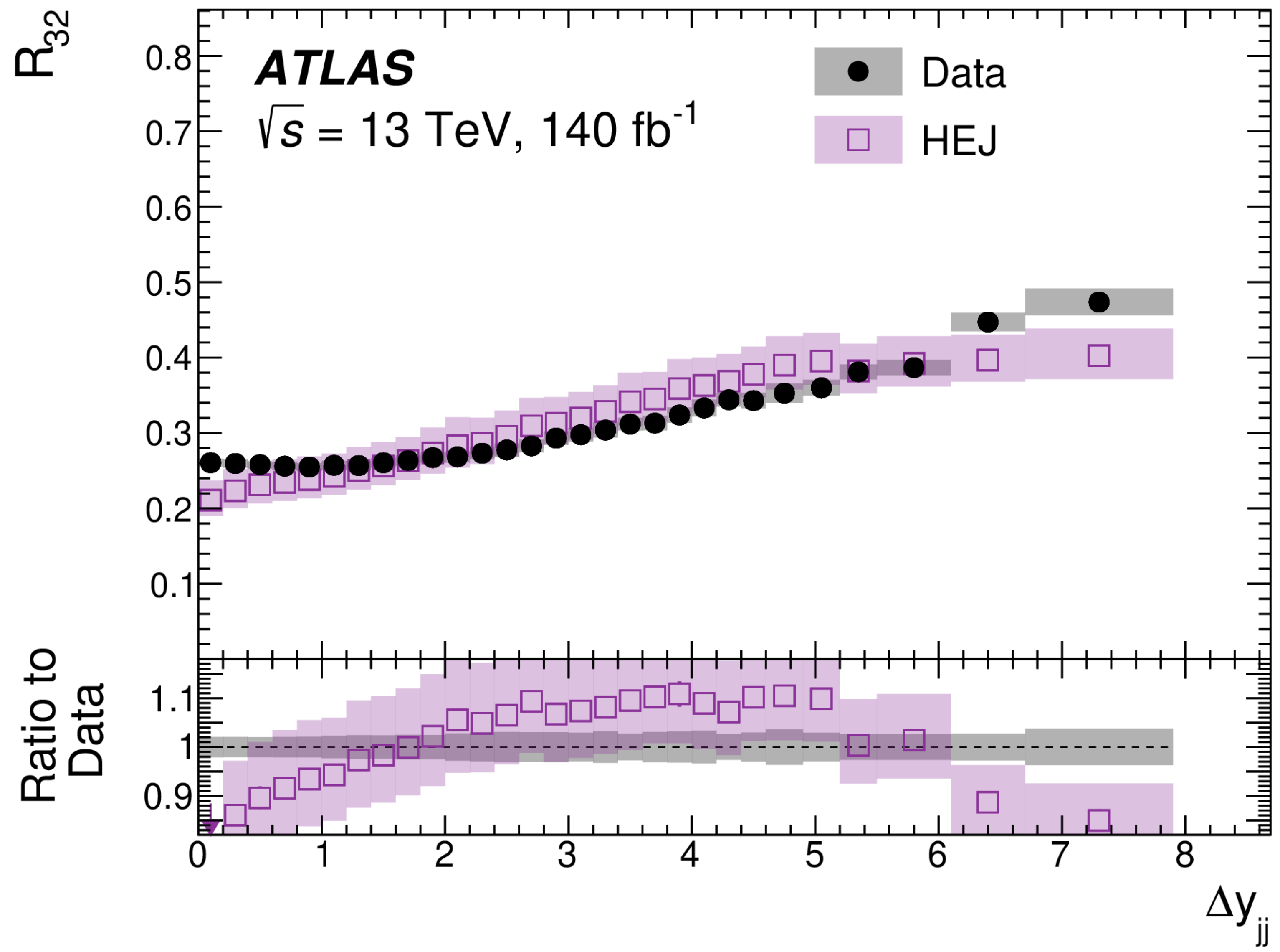
JETS PHYSICS: R3/2 RATIO

$$\frac{d\sigma_{3j}/dx}{d\sigma_{2j}/dx}$$ where x = H_{T2}, $m_{jj,max}$, $|\Delta y_{jj,max}|$, m_{jj}, $|\Delta y_{jj}|$



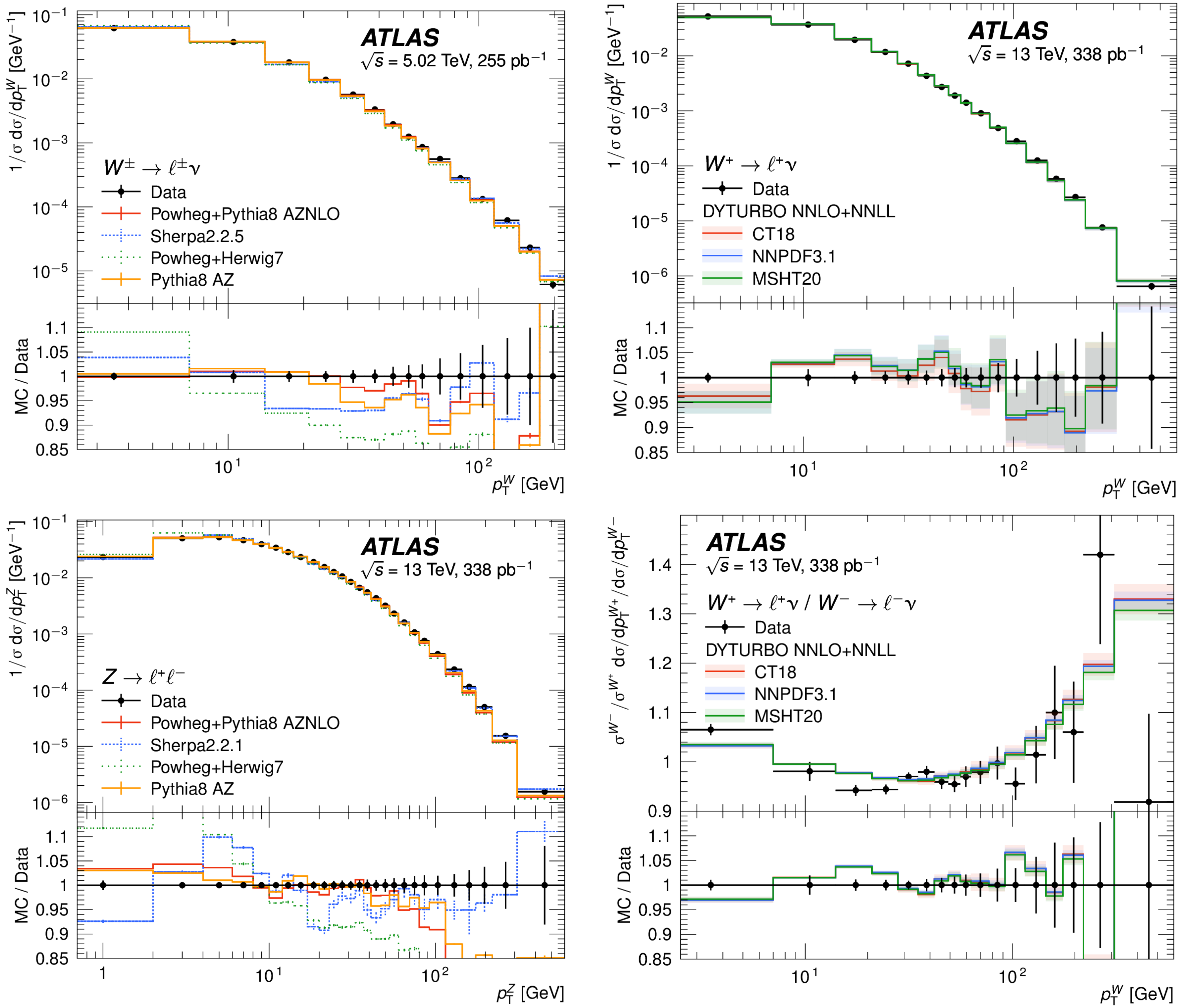
- **Differential cross sections in different jet multiplicity bins**
  - ➡**Several p_{T3} thresholds for H_{T2} measurements: explore sensitivity to resummation effects**
  - ➡ **Ratios for better sensitivity to α_s (smaller uncertainties)**
  - ➡ **NNLO needed for a good description of the data.**
  - ➡**HEJ description is better in regions with large contributions of log($p_{Tjet}/\sqrt{s}$)**





PRECISE MEASUREMENTS OF W AND Z TRANSVERSE MOMENTUM SPECTRA

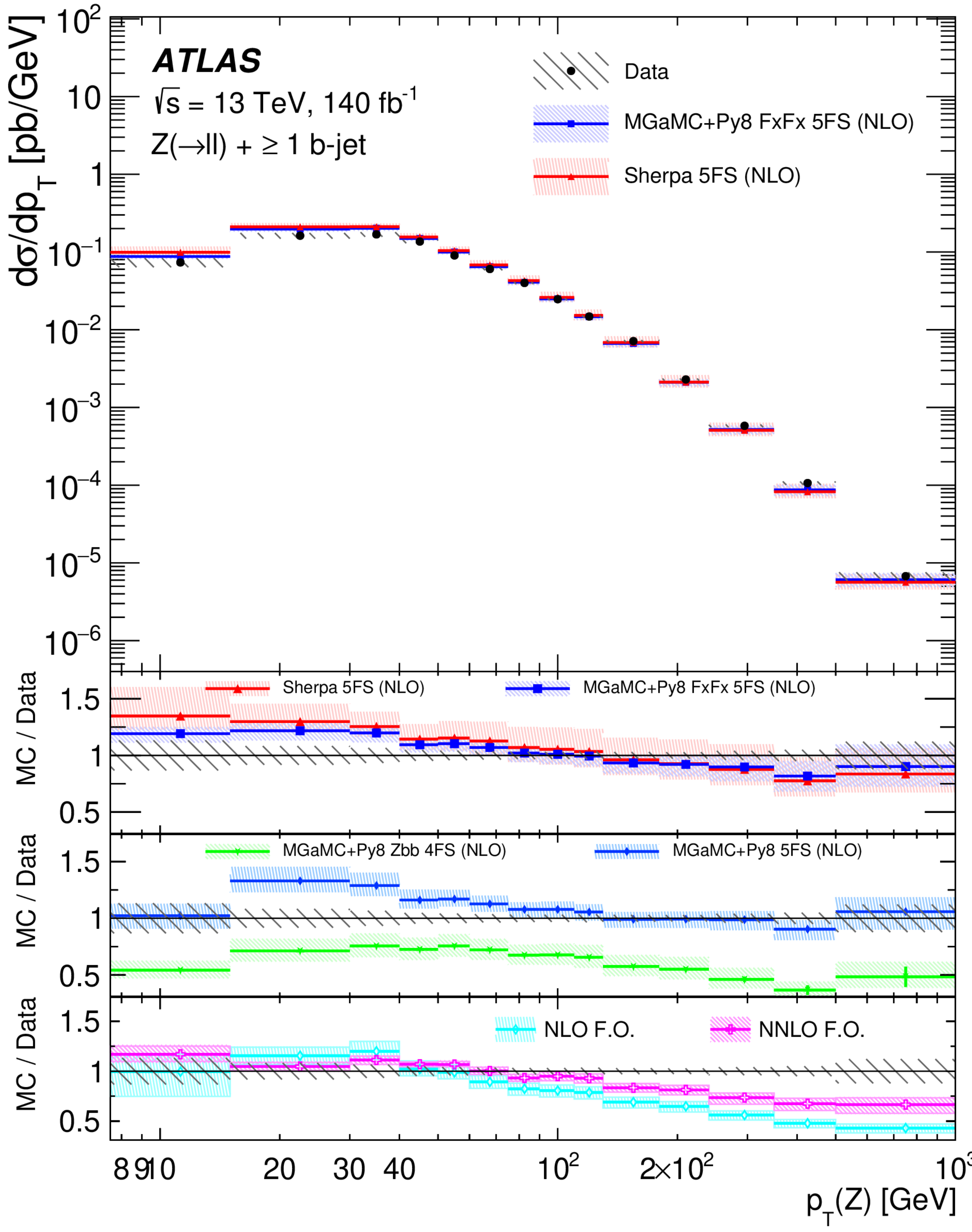
- Performed with dedicated runs of the LHC with an average of two interactions per bunch crossing at √s=5.02 and 13 TeV
  ➡Optimize the reconstruction of the hadronic recoil
  ➡ Needed for a precise measurement of m_W (m_W = 80366.5±15.9 MeV in the latest ATLAS measurement)
- Unprecedented granularity in the distributions of around 7 GeV
- Improved precision by a factor 3.5 (1.7) for the W (Z) measurement
- Several deficits in the descriptions of MC generators
  ➡Better description at 5.02 TeV with showers tuned to ATLAS 7 TeV Z data

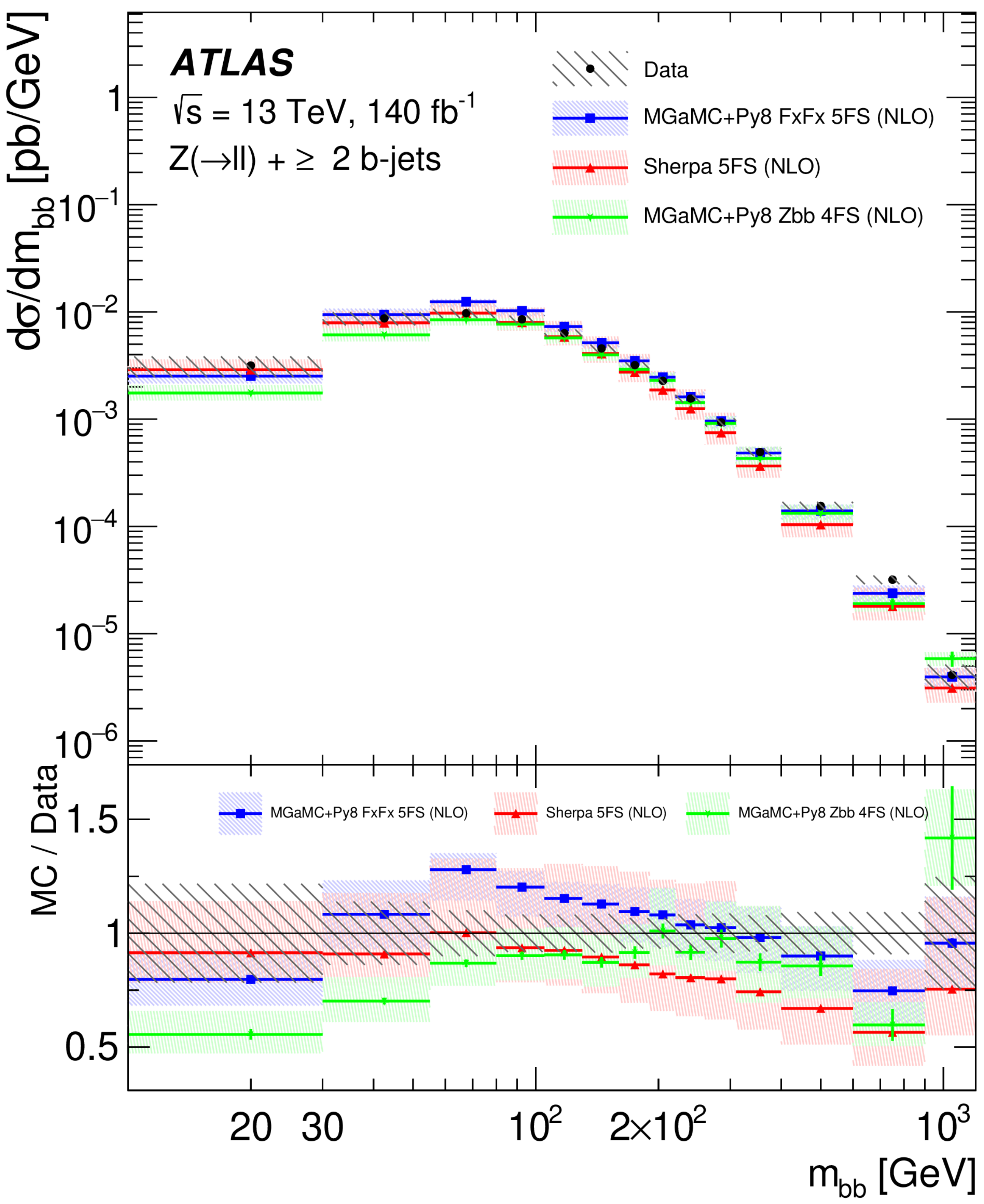


arXiv:2403.15093

Z BOSON IN ASSOCIATION WITH ONE OR TWO B- OR C-JETS

- **Modelling relevant for Z+HF production**
  - ➡ **Differences between FS**
- **Harder pT spectra by predictions in Z+1bjet**
- **Fixed-order predictions corrected for non-perturbative effects and different b-jet definition**
  - ➡ **Show discrepancies with data at high $p_T(Z)$**
- **No prediction has agreement with m_{bb} in the full spectrum**

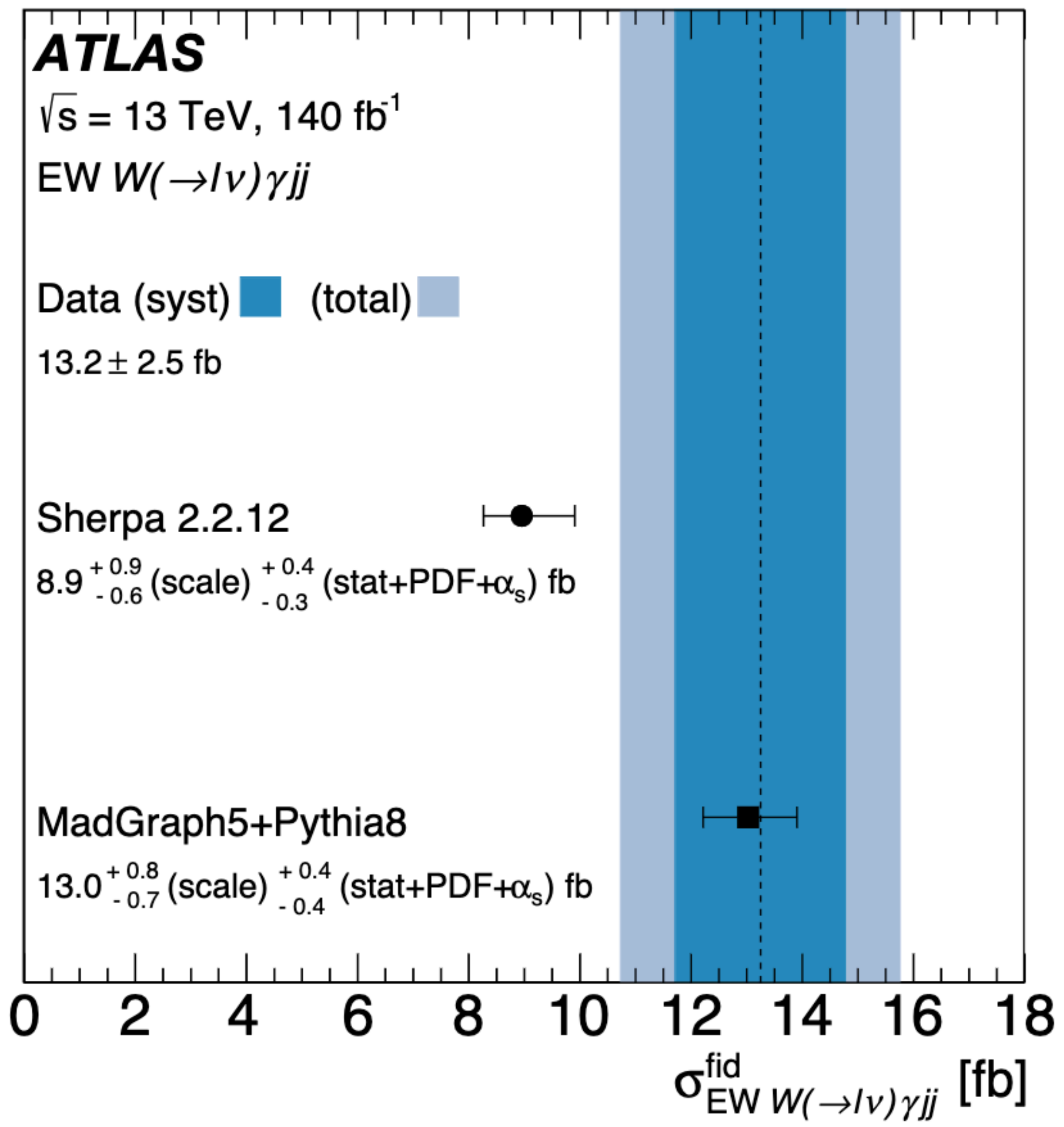


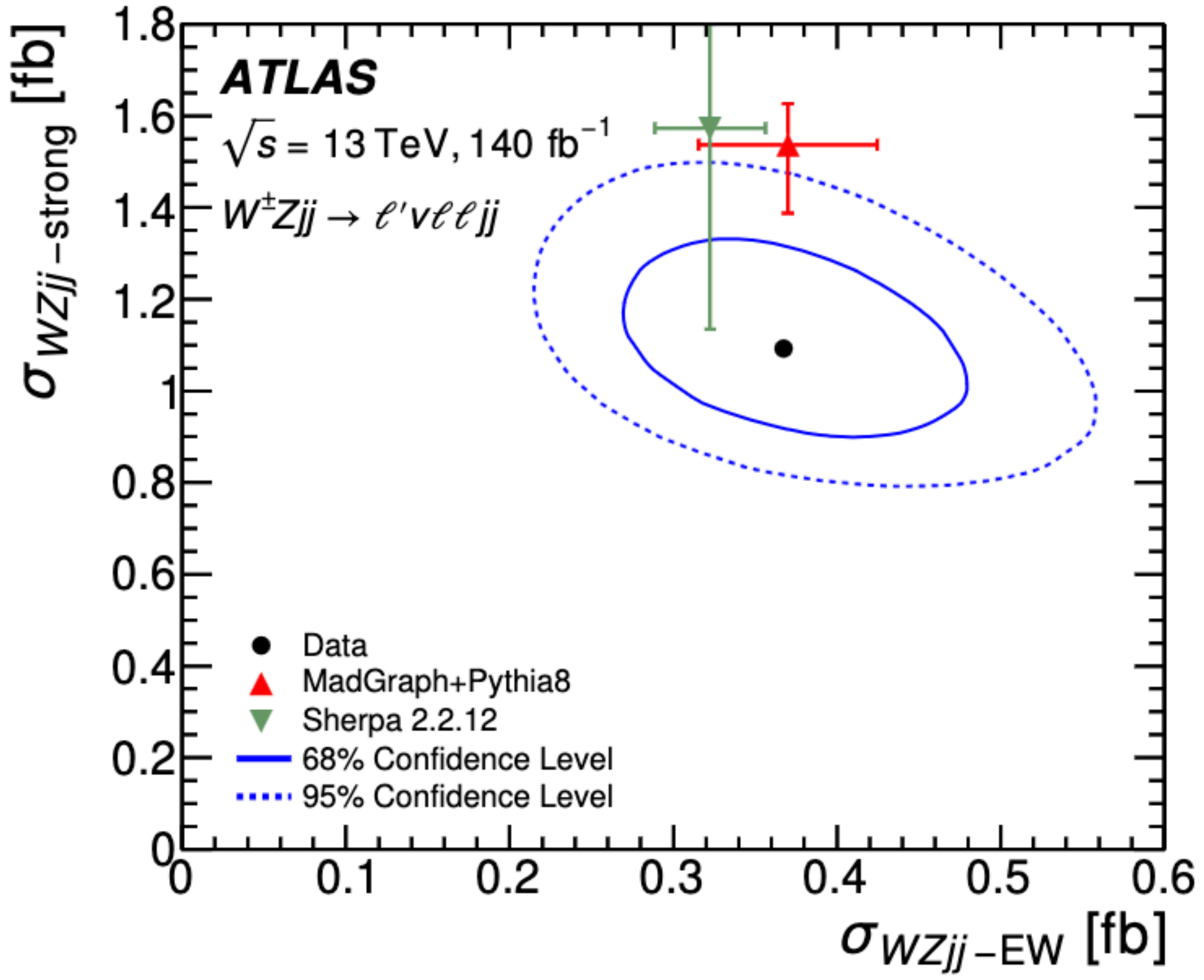


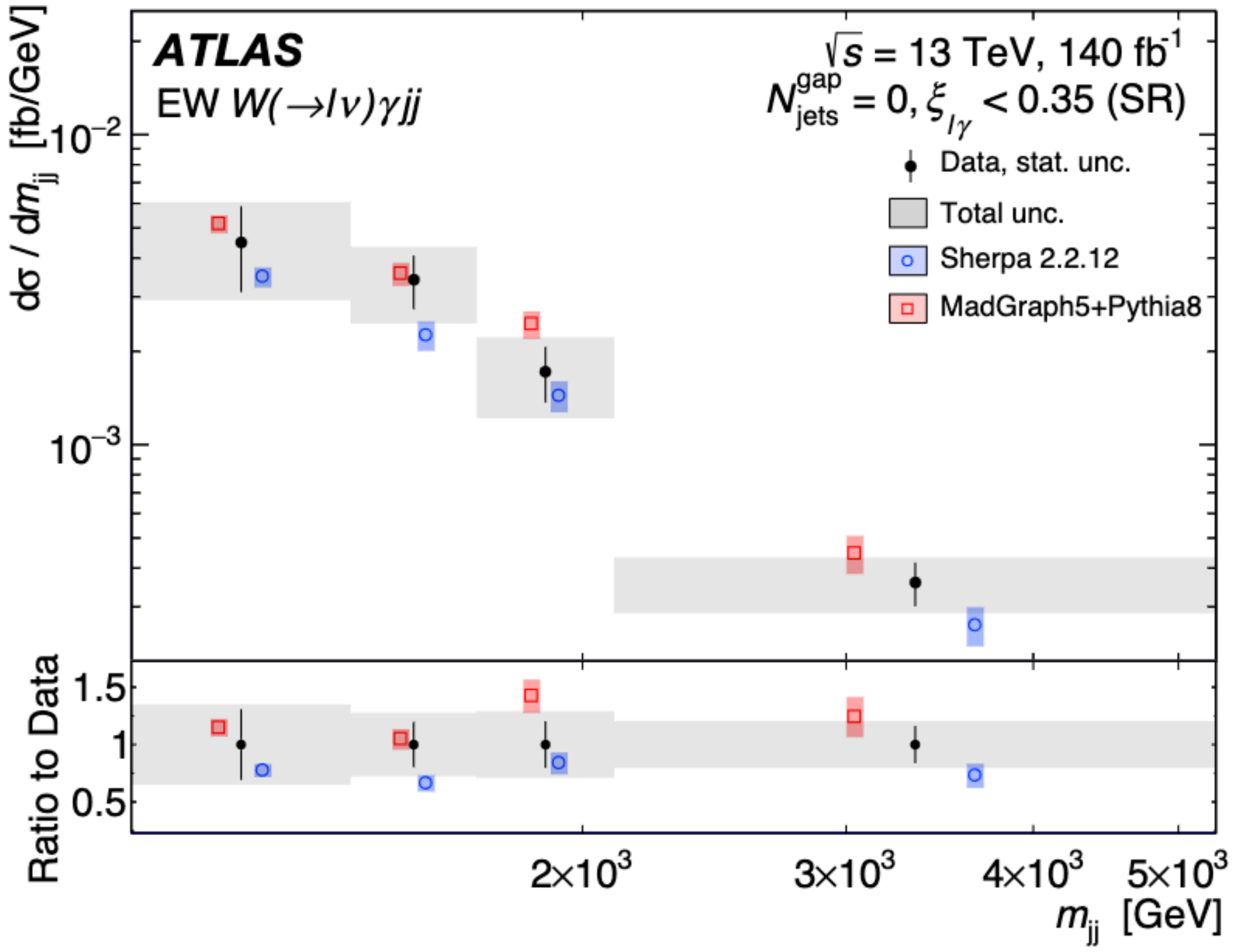
arXiv:2403.02809 arXiv:2403.15296

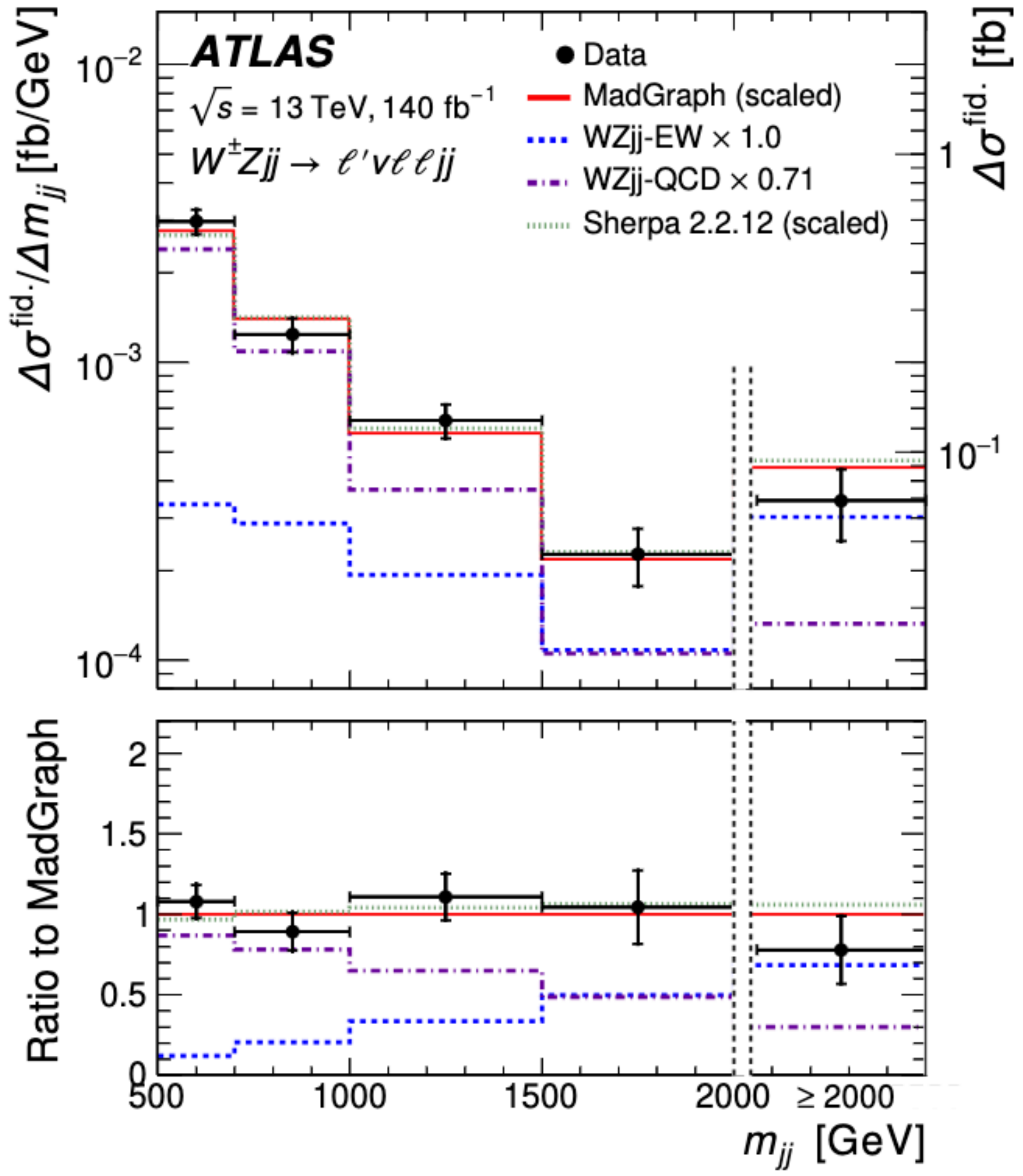
ELECTROWEAK VBS PRODUCTION OF WZ AND Wγ

- VVjj production being tested differentially
  - ➡ Helpful to test the modelling of key observables
- Multivariate techniques used to distinguish the EW production from the irreducible background
- Measurements compared to aMC@NLO and Sherpa both at LO but Sherpa includes an additional parton in the ME
- Sensitivity of the measurement to deviations of quartic gauge couplings exploited through SMEFT





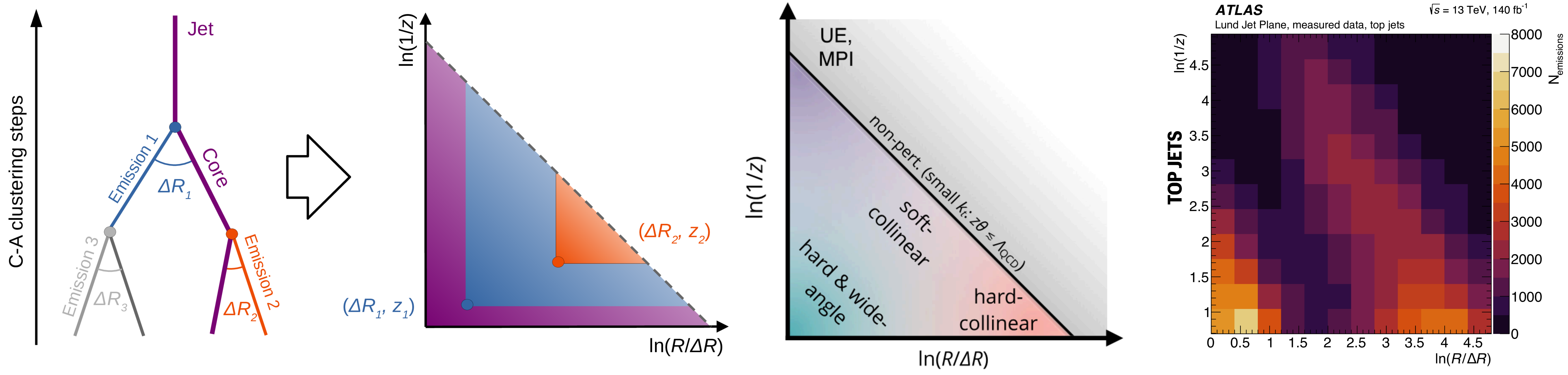




arXiv:2407.10879

LUND JET PLANE IN HADRONIC DECAYS OF TOP QUARKS AND W BOSONS

- **Lund jet plane (LJP) representation provides a significant amount of information about the jet radiation pattern**
  - ➡ **Parton shower, hadronisation and UE approximately factored in LJP**



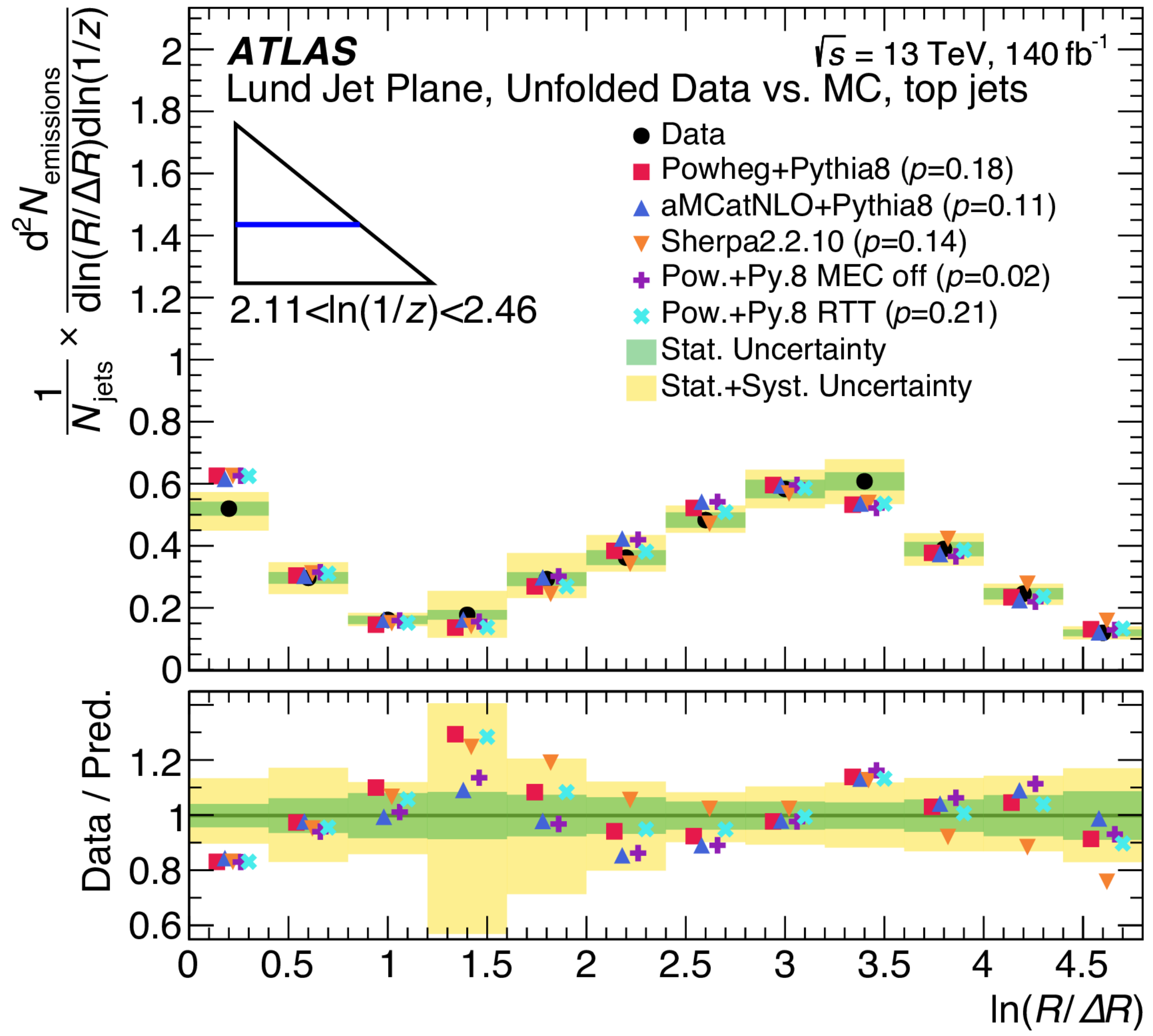
Source

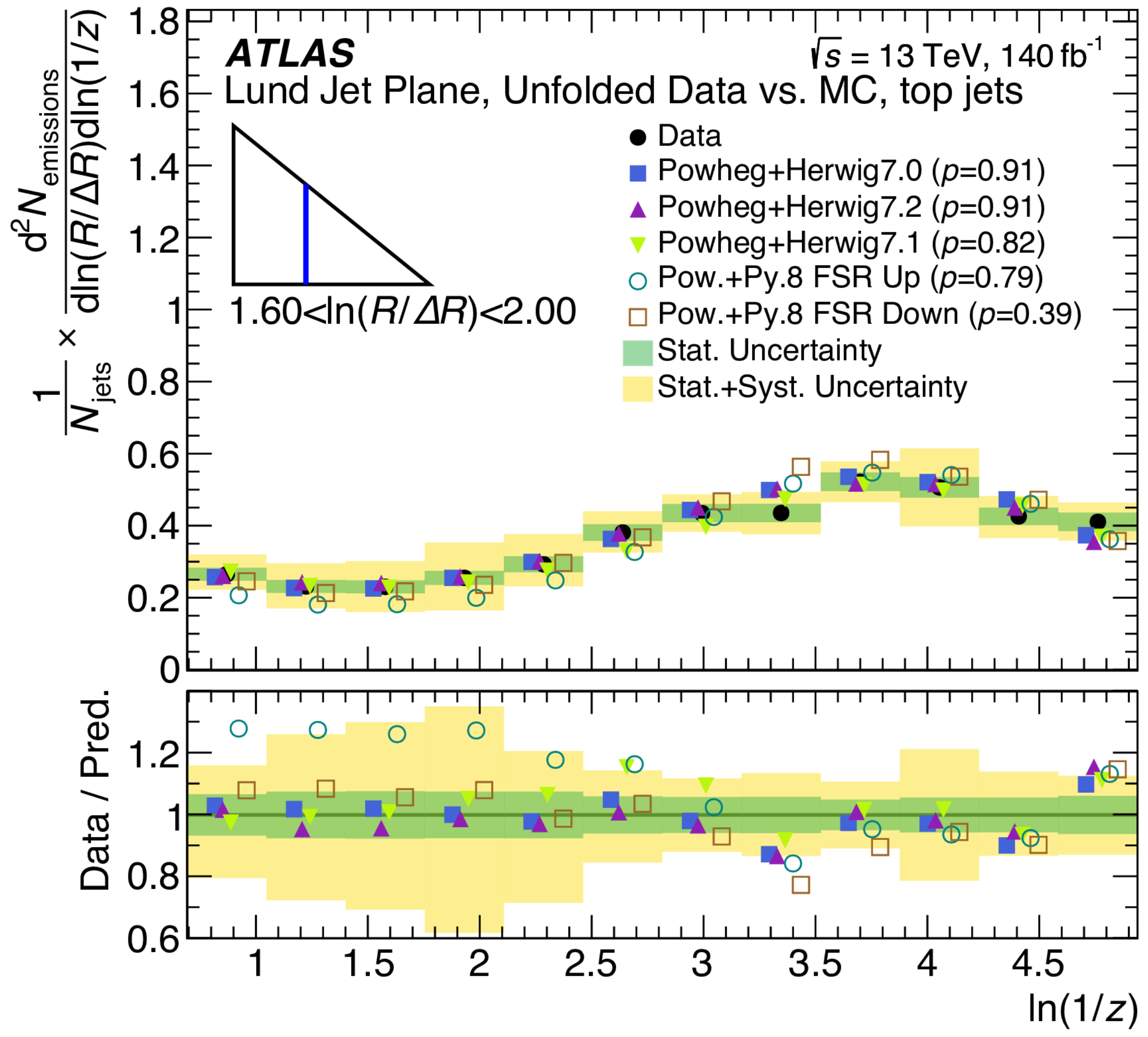
- **Measurement of W- and top-initiated anti-kt jets R=1.0 (p_T>350 GeV) using charged particles**
  - ➡ **Help to understand reconstruction and modelling of hadronic tops**
  - ➡ **Complement other jet substructure measurements and can serve as input for MC tuning**

LUND JET PLANE IN HADRONIC DECAYS OF TOP QUARKS AND W BOSONS

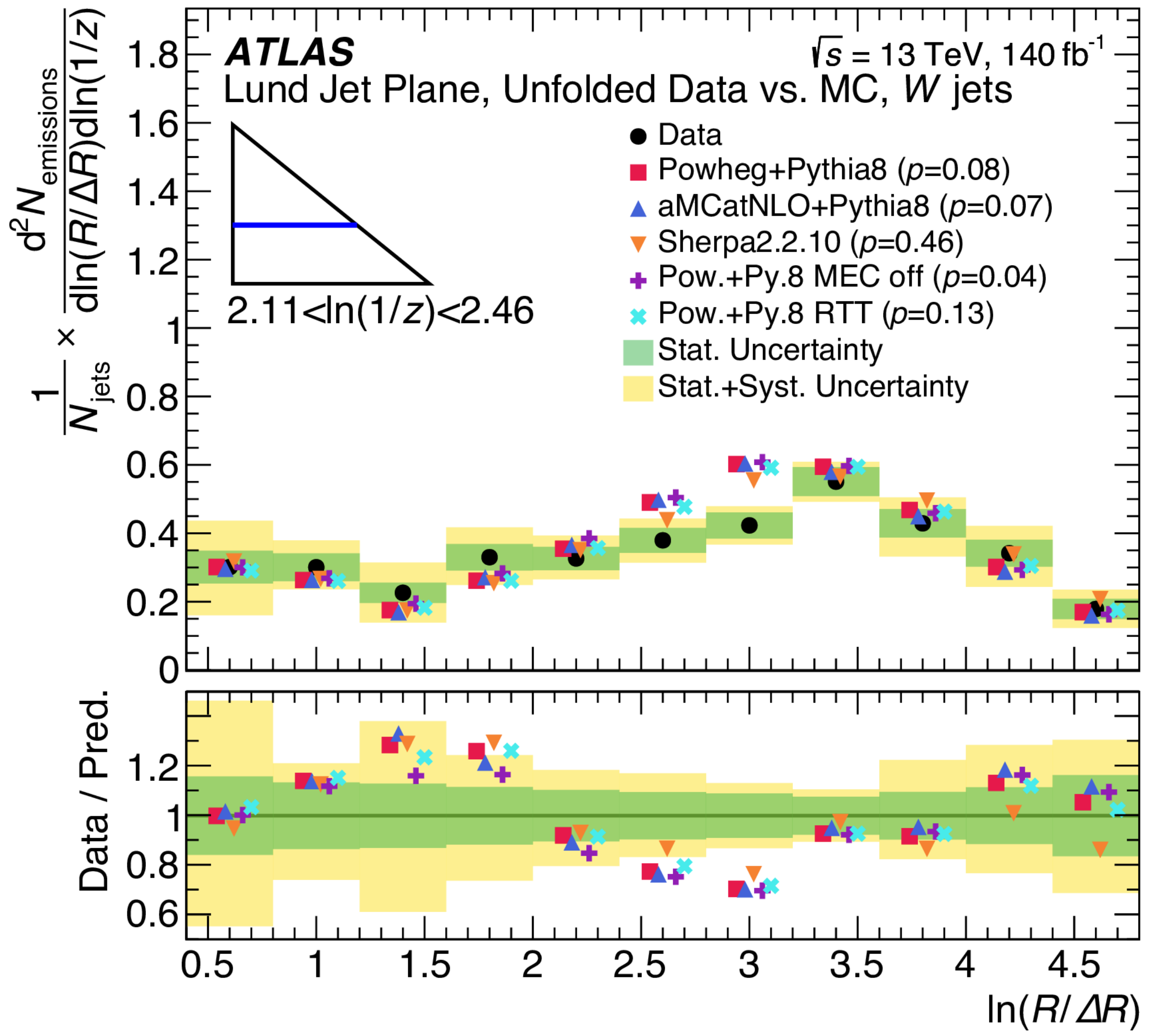
- **Agreement with predictions but regions with low p-value, specially in W-jets**
  - ➡ **Systematics dominated by the top-pair and parton shower modelling**

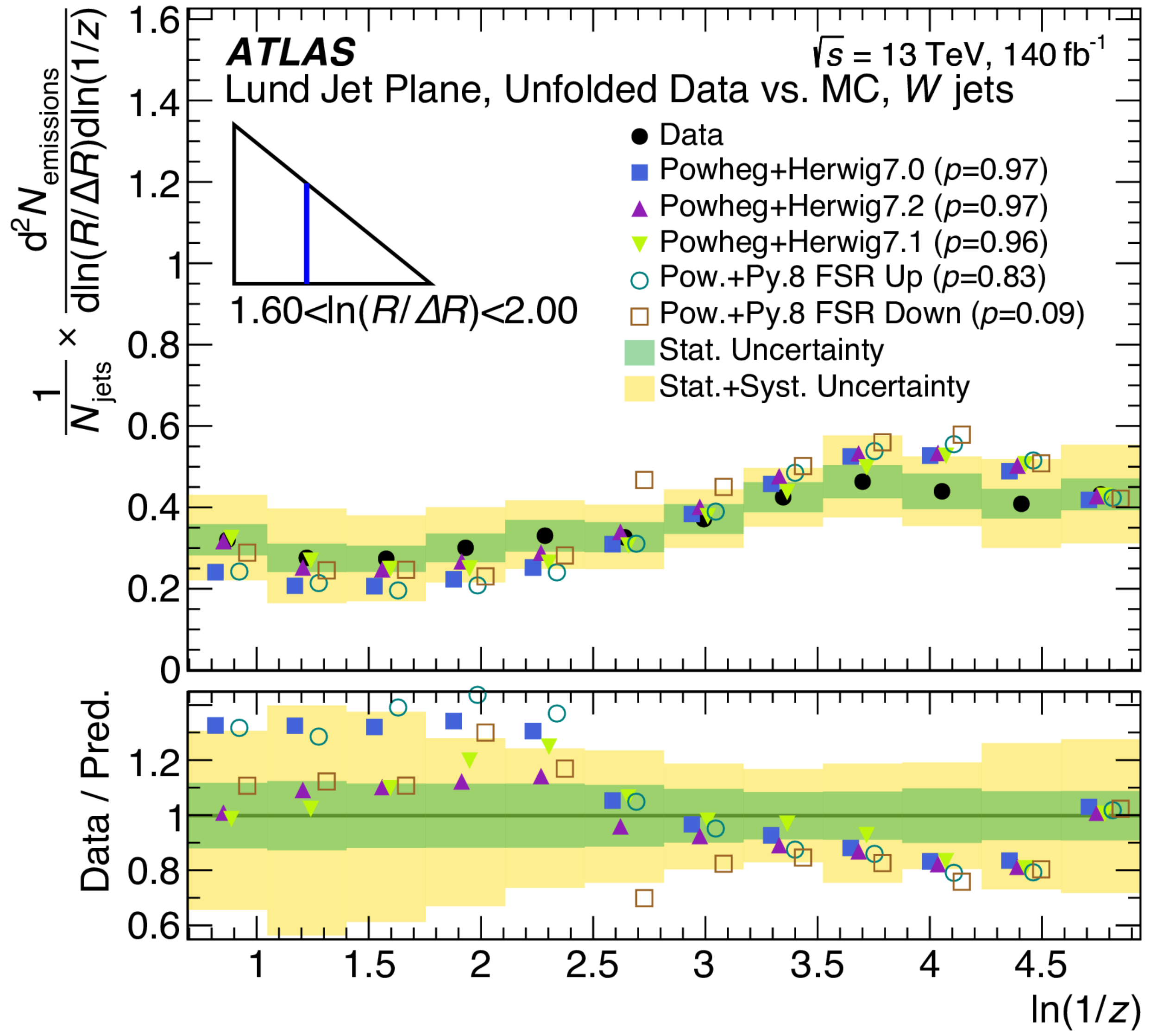
TOP JETS





W JETS





arXiv:2406.19701

DIFFERENTIAL TT AND TT+JETS CROSS SECTIONS IN L+JETS FINAL STATES

- Test of the dynamics and topology of the $t\bar{t}$ system and the hardest emissions
  - ➡ Characterisation with a wide number of observables, many of them not previously measured.

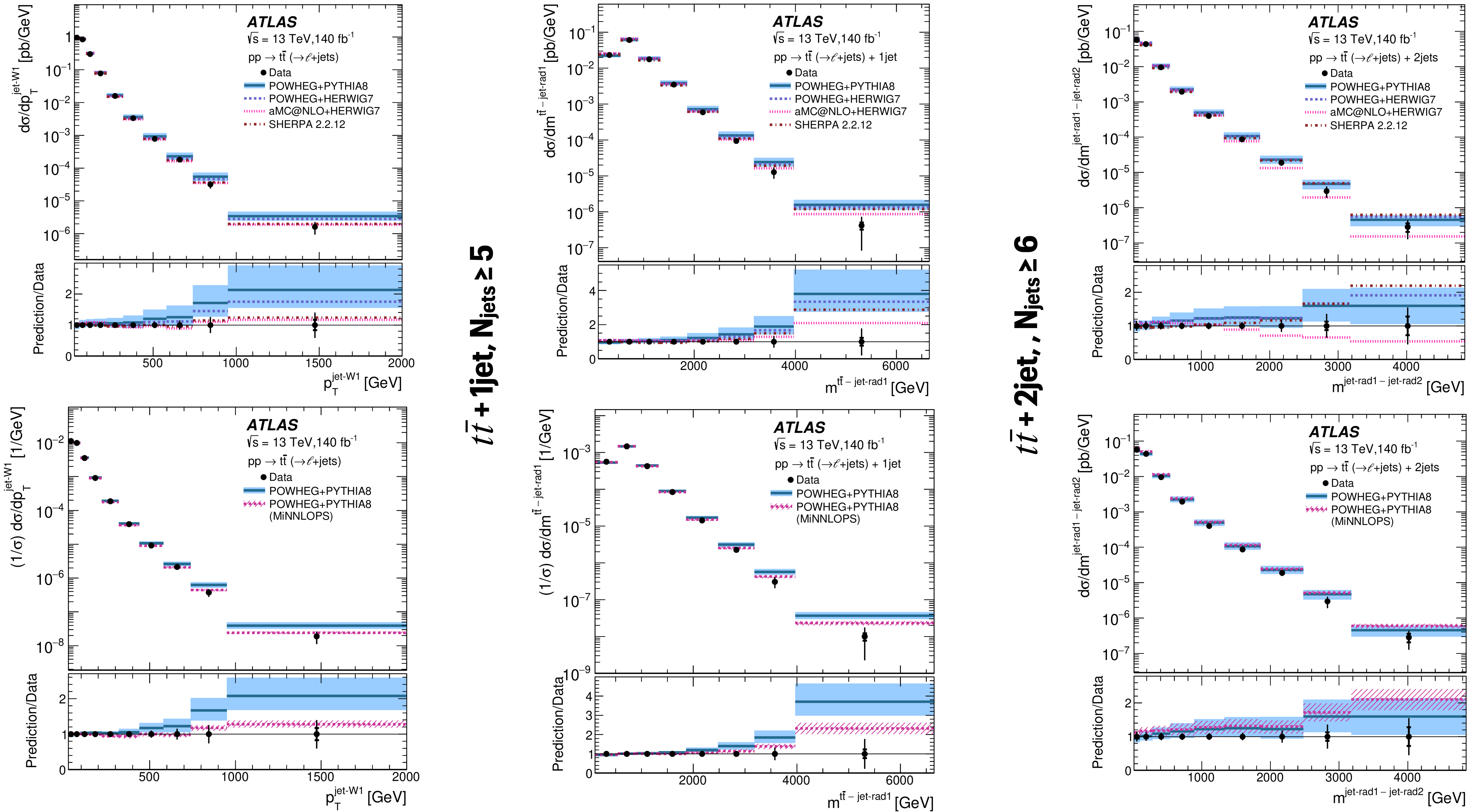
Absolute differential cross sections.

Normalised differential cross sections.

$t\bar{t}$ inclusive, $N_{jets} \geq 4$

$t\bar{t}$ + 1jet, $N_{jets} \geq 5$

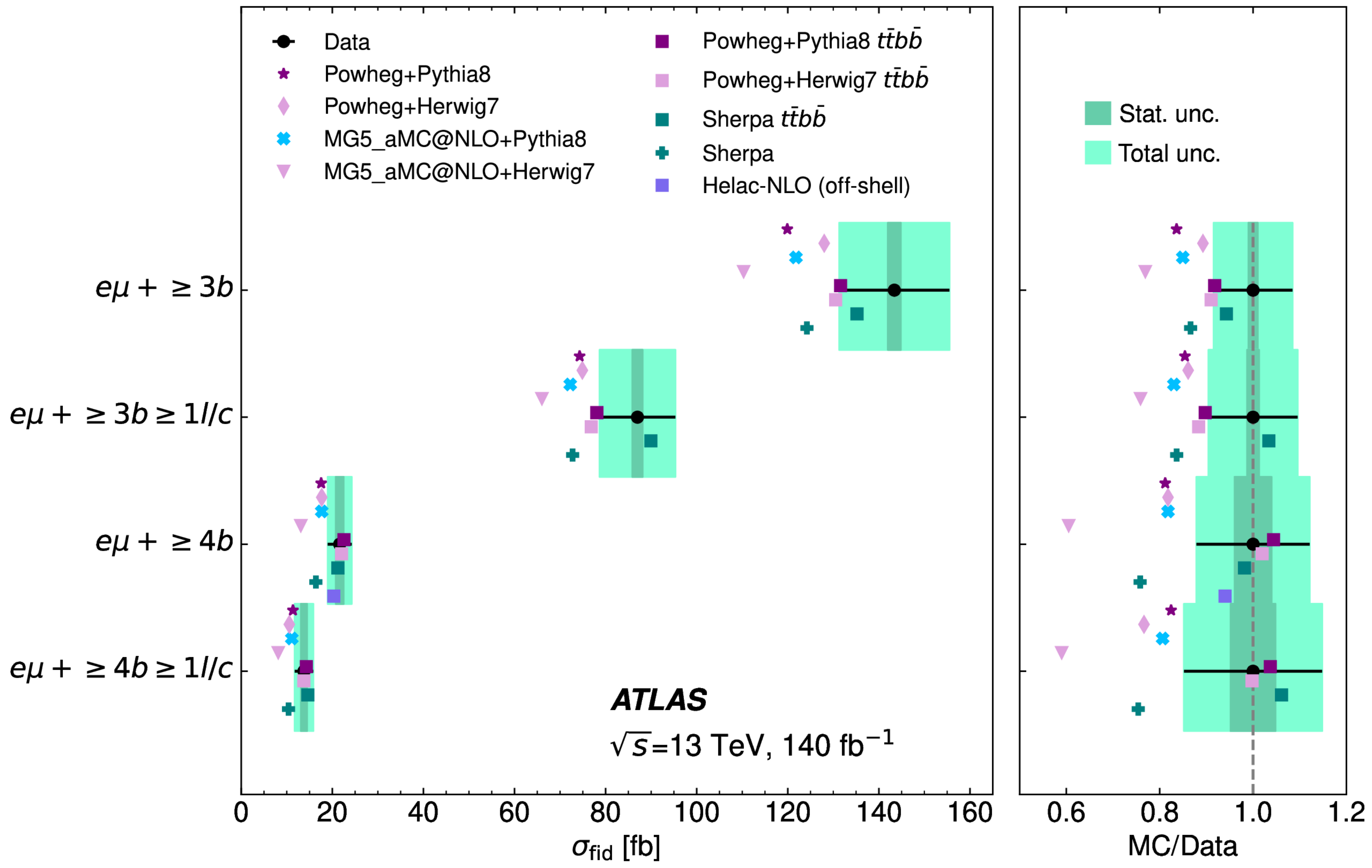
$t\bar{t}$ + 2jet, , $N_{jets} \geq 6$

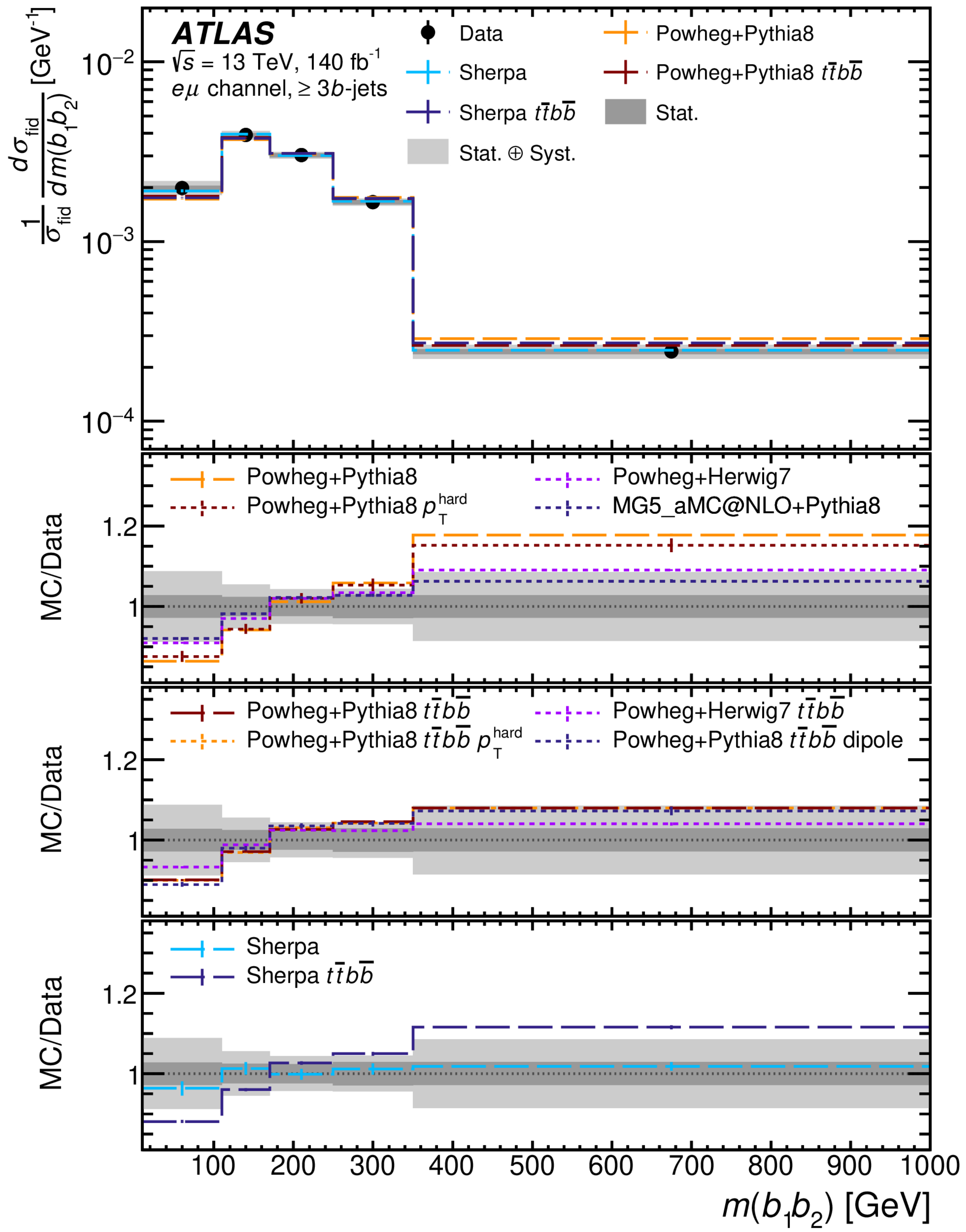


Usage of NNLO MC+PS with better agreement to data than NLO MC+PS

DIFFERENTIAL CROSS SECTIONS OF $t\bar{t}$ PLUS HEAVY FLAVOUR IN THE $e\mu$ CHANNEL

- **Important and poorly constrained background of ttH, tttt**
  - ➡ **Challenging calculations with very different scales involved ($t\bar{t}$ system and $b\bar{b}$ from gluon splitting)**
  - ➡ **MC calculations with different treatments of: b-quark mass, production of the extra b-quarks or merging of the b-quark production with the inclusive $t\bar{t}$ prediction**
- **Most observables are generally well described by the majority of MC predictions**



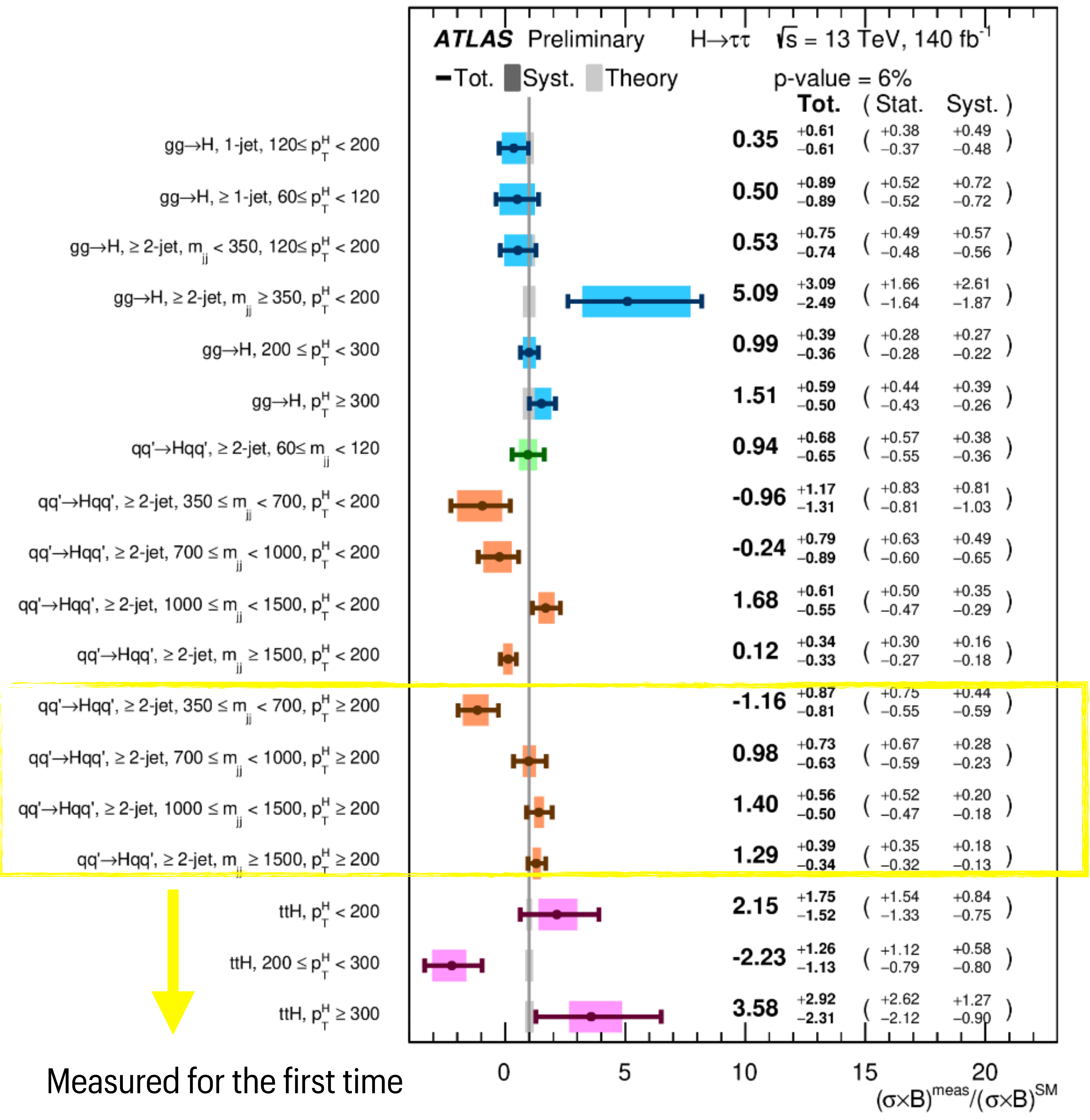


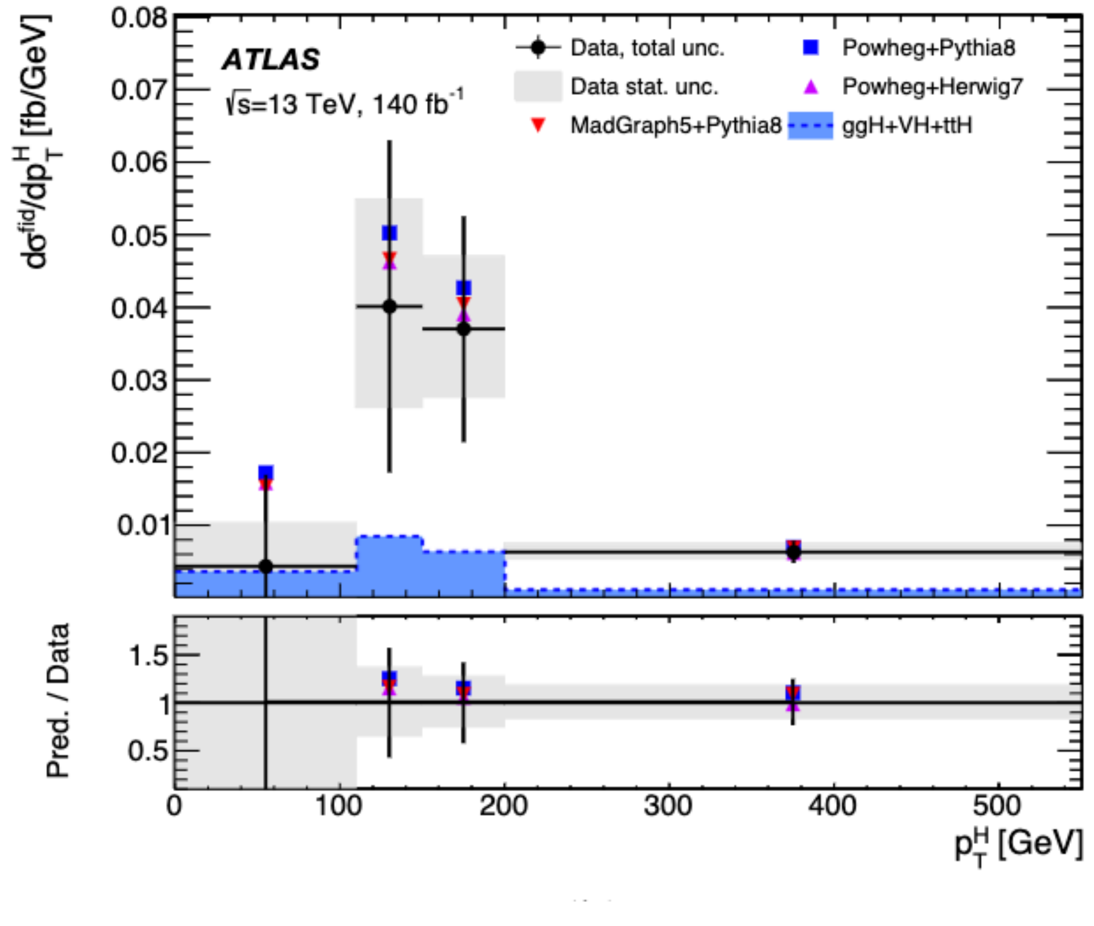
arXiv:2407.16320

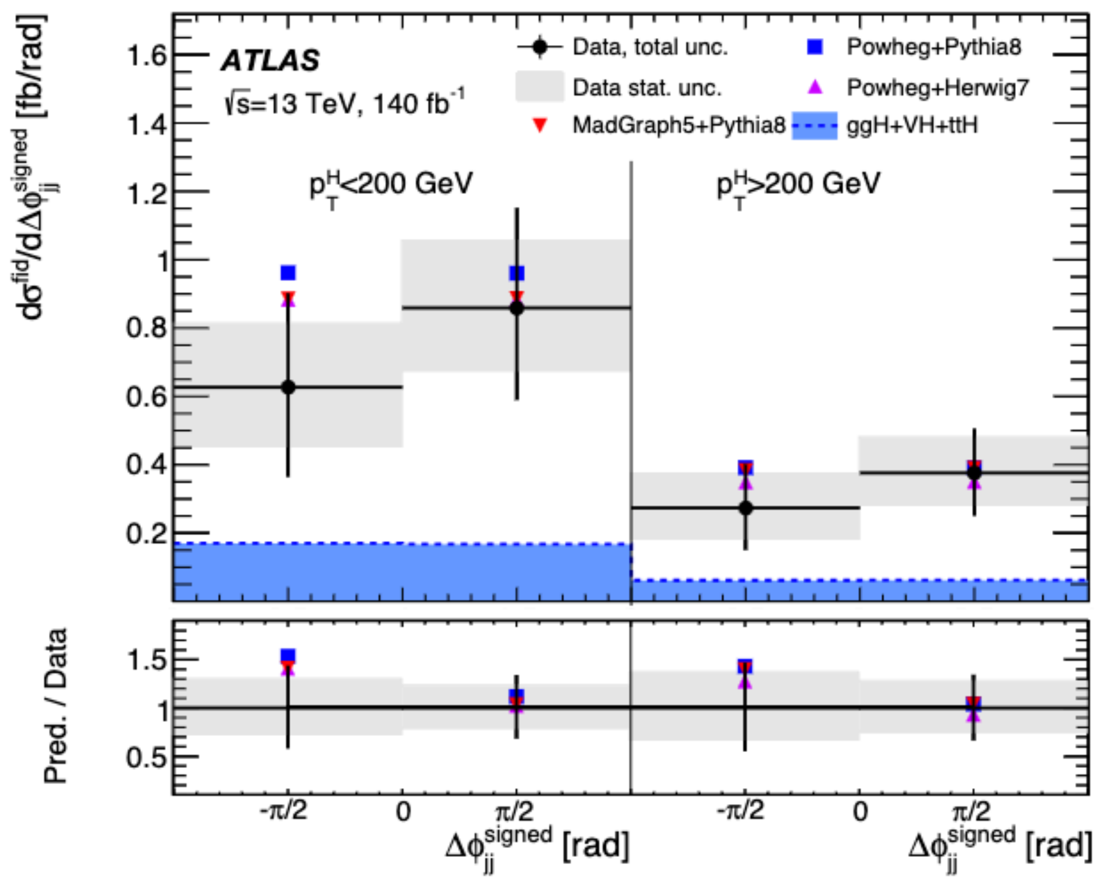
DIFFERENTIAL CROSS SECTIONS IN $H \to \tau\tau$ AND COUPLINGS MEASUREMENT

- $H \to \tau\tau$ with a BR of 6% is in a unique position of having sufficient statistics and low enough backgrounds for precise Higgs production
  ➡Reconstruction of leptonic and hadronically decaying tau leptons
- Higher granularity and improvement in the VBF and ttH measurement over previous measurements in the channel
- Theory uncertainty is dominant

Production mode	ggF	ttH	VBF	VH
Best-fit value	0.94	0.77	0.93	0.91
Total uncertainty	±0.30	±0.97	±0.16	±0.62
Samples size	±0.09	±0.32	±0.03	±0.25
Theoretical uncertainty in signal	±0.19	±0.14	±0.10	±0.13
Jet and E_T^{miss}	±0.12	±0.14	±0.03	±0.11



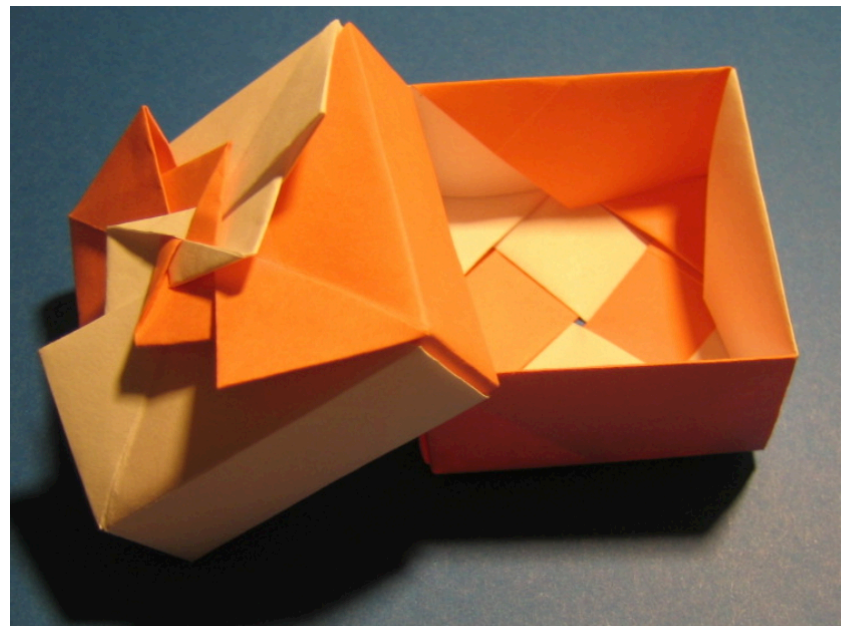




AVAILABILITY OF GENERATORS IN ATLAS

- All MC samples sets used in data analysis are centrally produced and managed in ATLAS.

- Wide range of MC event generator programs
  ➡Powheg, MadGraph, Sherpa, Pythia8 and Herwig7 most commonly used.



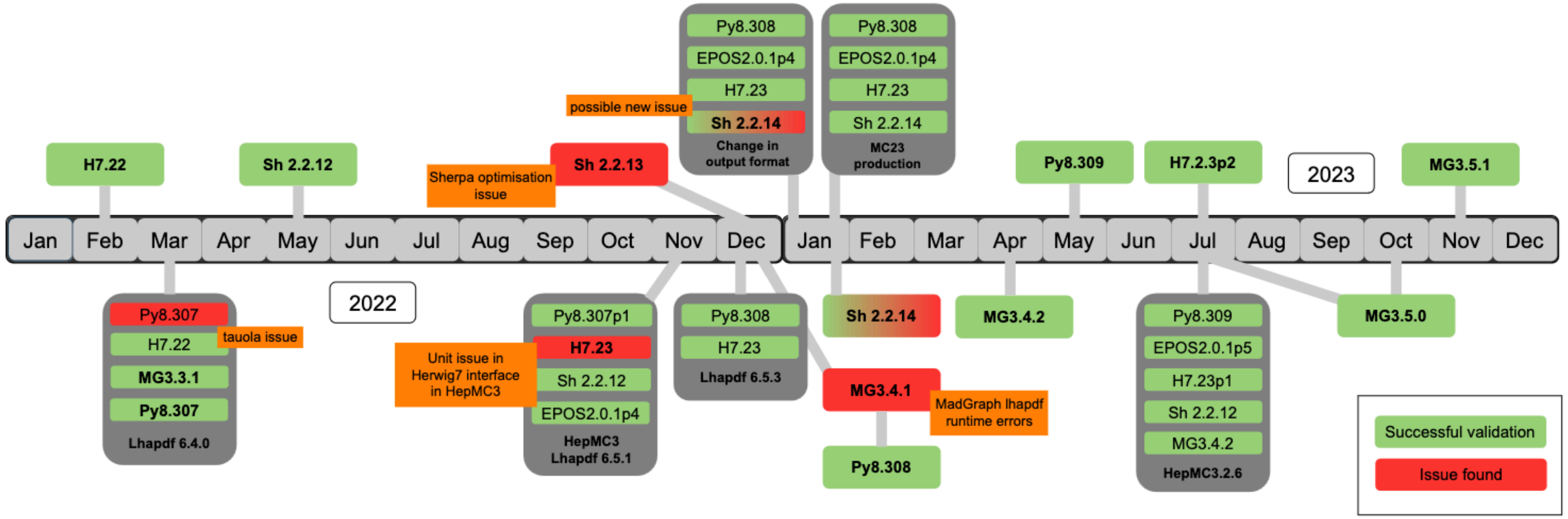
➡Afterburners run as secondary in Athena: Photos++ (refinement of FSR), Tauola++ (precise tau leptonic decays) or EvtGen (for heavy flavour hadron decays)
➡Several other limited-use generators: EPOS, Hijing, Hto4l, Pythia8B, Starlight, SuperChic, etc...

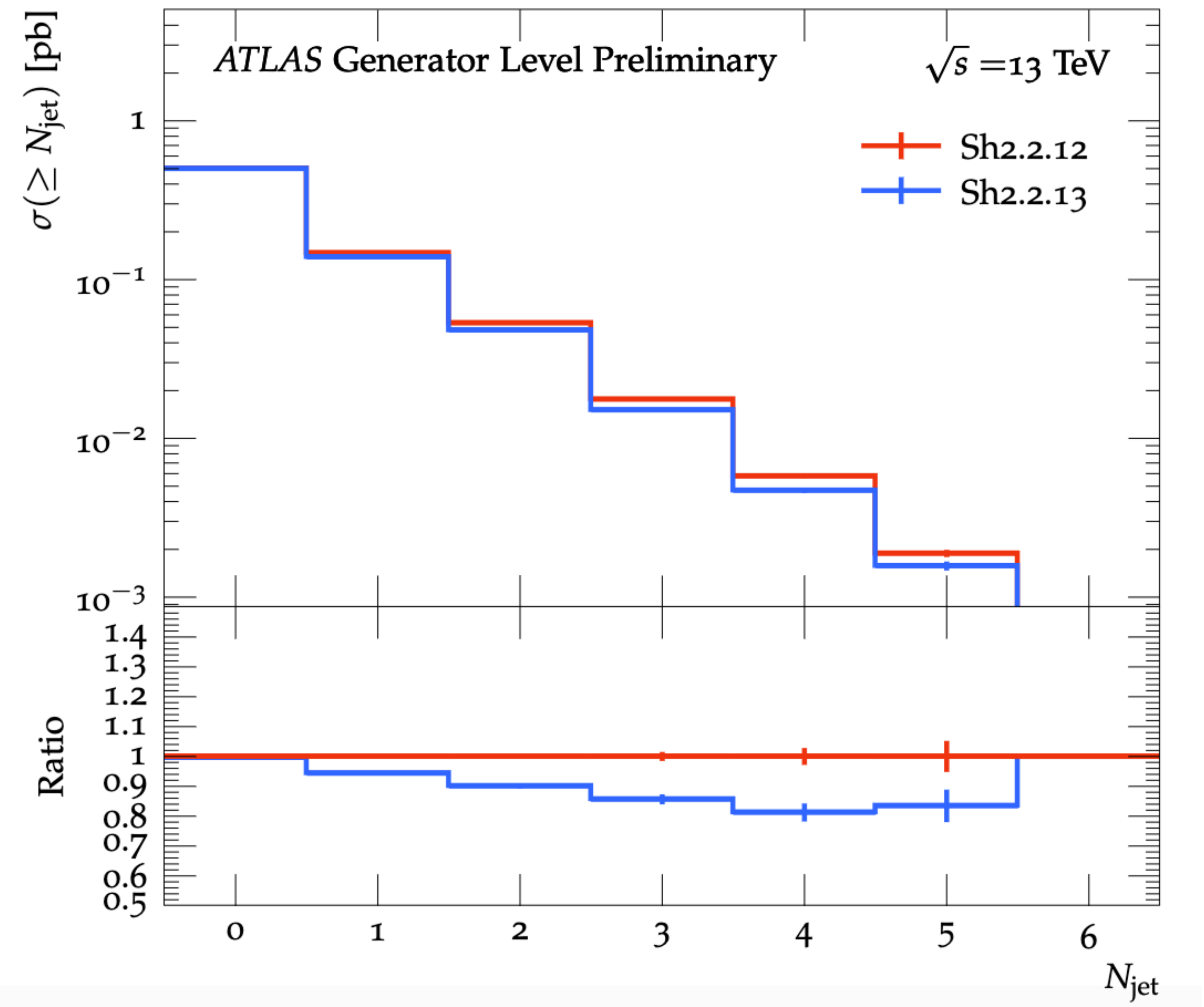
- Dedicated team outside ATLAS (CERN EP-SFT) maintain the LCG software stack that provide the MC generators installation
  ➡The GENSER (GENerator SERvices) in charge of MC programmes

- ATLAS software (Athena) publicly available in gitlab
  ➡Generator interfaces, MC default settings or MC samples steering files can be found

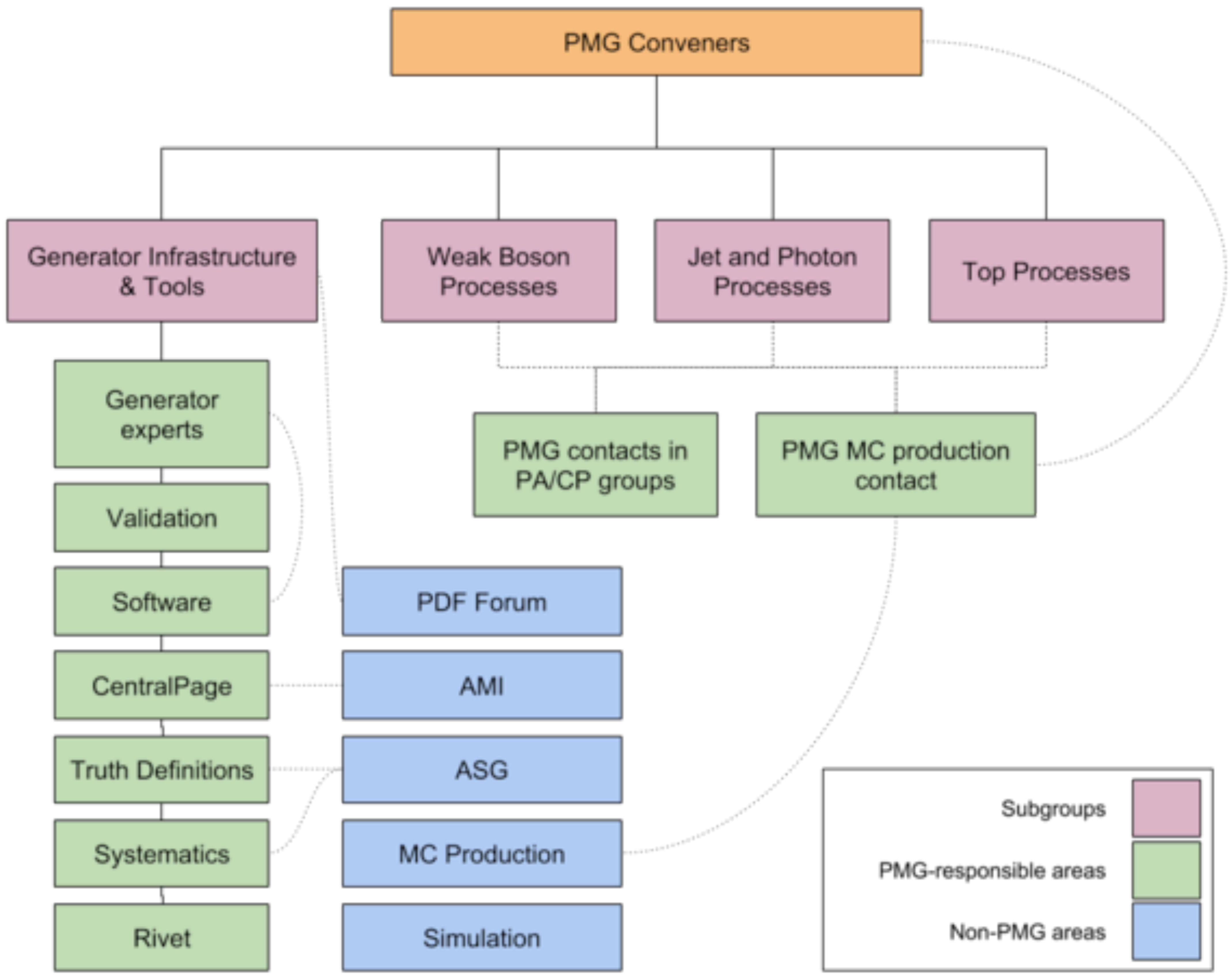
GENERATOR VALIDATION WITHIN ATLAS

- **Regular validation of event generation performed as part of the ATLAS Release Testing**
  - ➡**A small output is automatically compared to a reference output from previous test**
- **In case of change of generator version, a more thorough validation is performed based on PAVER**
  - ➡**Event samples for a variety of processes and generators are analysed with several Rivet routines and the results are compared to those of previous runs**
  - ➡**Technical parameters are also compared (cross sections, event on-the-fly weights, filter efficiencies…)**

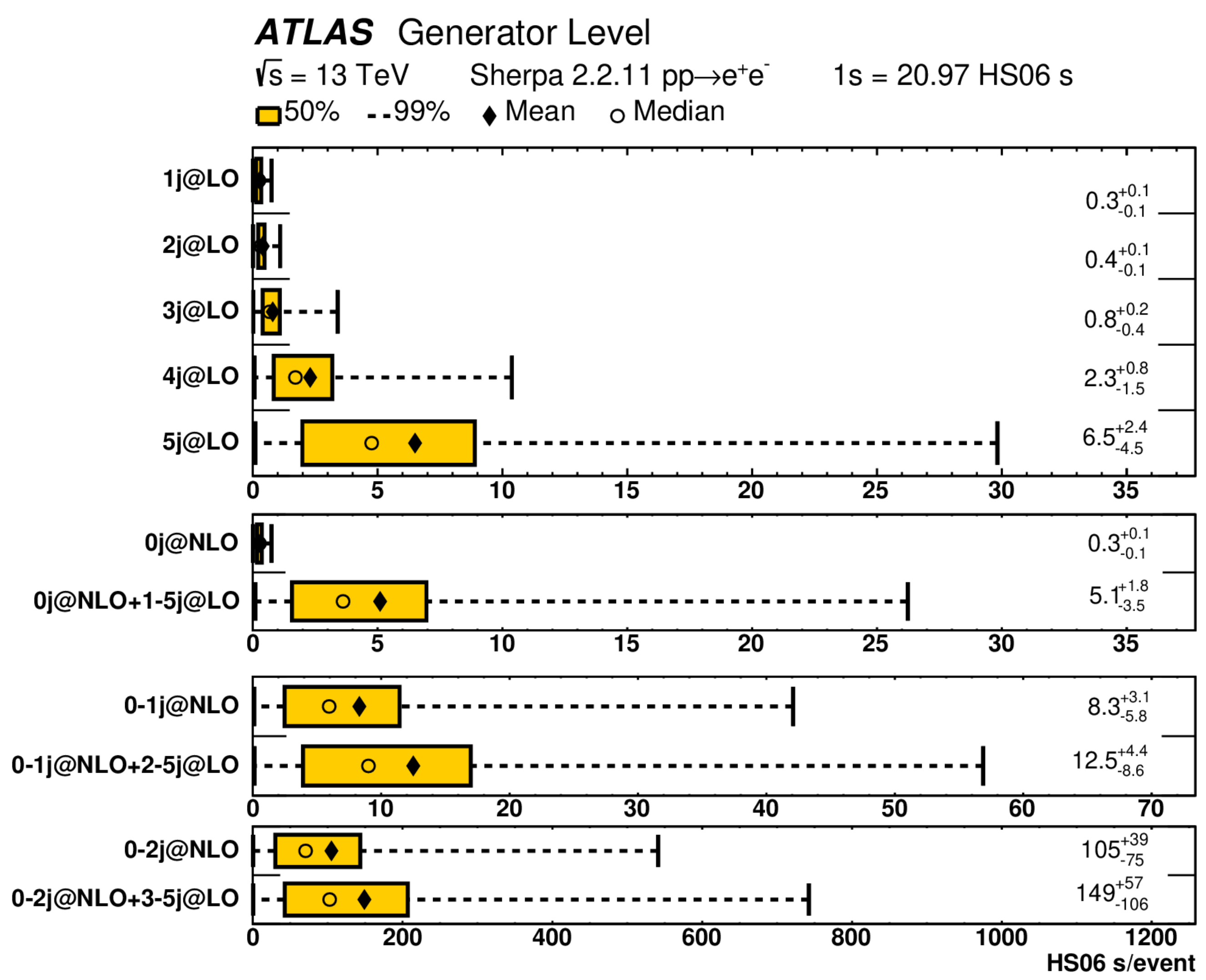




THE ATLAS PHYSICS MODELLING GROUP



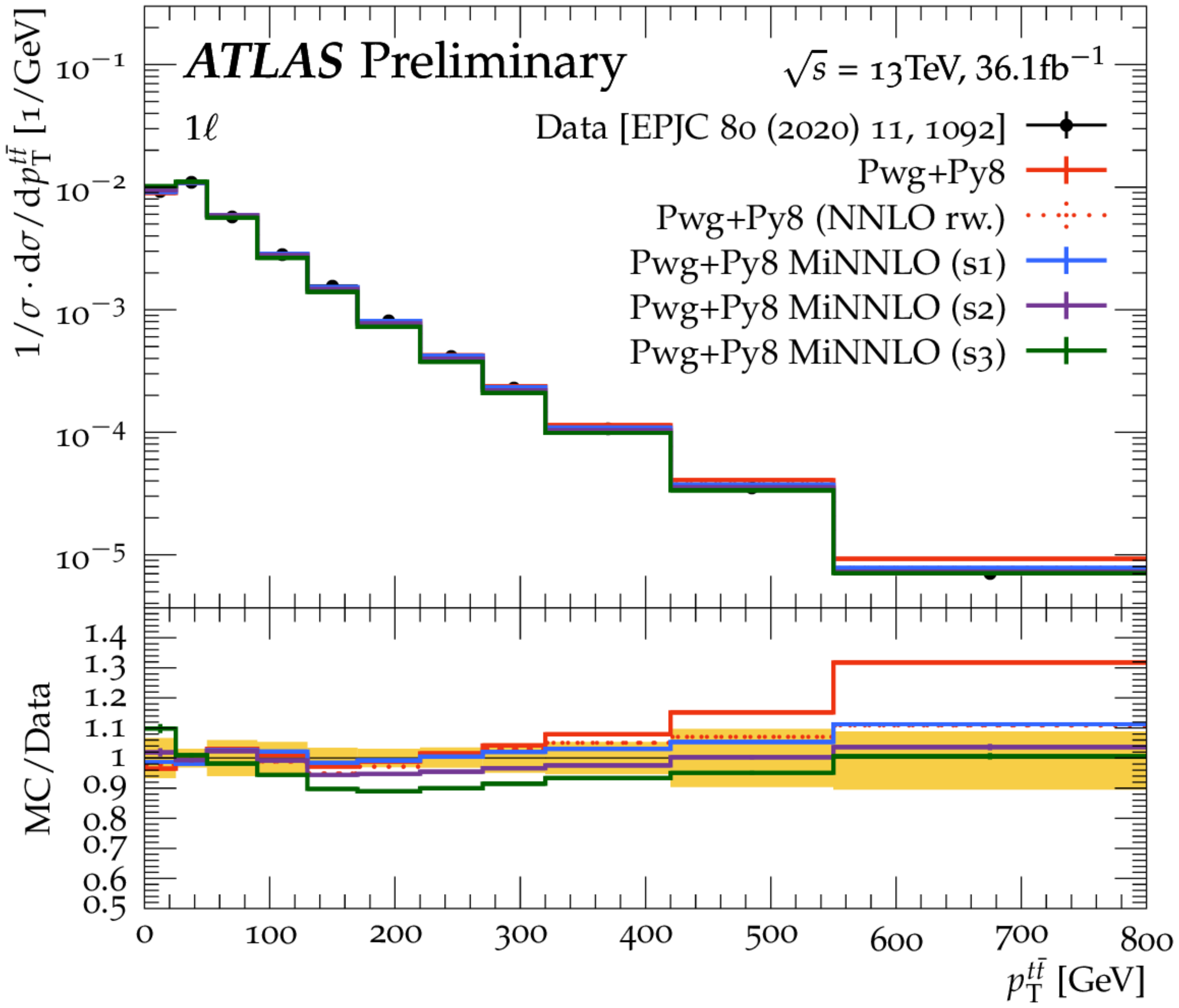
- PMG responsible for the developments and validation of MC generators and samples
  - ➡Also responsible for setting theory uncertainty recipes for the developed samples
- Central samples developments focused on bulk SM that are used across the whole collaboration
  - ➡Largest and most CPU consuming samples are V+jets
  - ➡Seek for ways to improving effective statistics and reducing CPU time without compromising much the accuracy
- Studies within the group published as PUB notes



THE ATLAS PHYSICS MODELLING GROUP

- **Slow but continuous efforts to:**
  - ➡**Update to the highest accuracy available (e.g. MiNNLO+PS)**
  - ➡**Include new features in samples (e.g EW corrections)**
  - ➡**Test additional generators (e.g Geneva)**
  - ➡ **New parton showers and their matching to matrix-element calculations (e.g Vincia)**
  - ➡**Tools to reduce the fraction of negative weights in samples (e.g cell resampler or MC@NLO-Delta matching)**
  - ➡**Usage of GPUs (e.g Madgraph GPU or Pepper)**

- **Difficulties in forming and retaining expertise in MC event generators within the collaboration**
  - ➡**Easy interaction with MC authors is key**
  - ➡ **Possibility of having an ATLAS author qualifier working with MC authors**
  - ➡**MCI figure to allow MC authors attend ATLAS meetings and ease the exchange of information**



ATL-PHYS-PUB-2023-029

(SOME) MC GENERATORS CODES WISHLIST

- Many new features and fancy generator versions take long to make production ready in ATLAS
  ➡Experienced problems with e.g bb4l, Vincia
  ➡Lack of knowledge within the collaboration that need assistance from authors

- Efficient phase-space biasing and filtering
  ➡ATLAS has gained some experience with phase-space biasing in V+jets production
  ➡ Time consuming to ensure proper working of biasing and no issues with physics results. Any regular checks that can be performed?
  ➡Heavy-flavour filtering: many events thrown away. Exploring ways of enhancing heavy flavour production and improve filter efficiency is needed

- Optimisation of parallelisation: integration of processes does not scale with CPU

- Improvement of negative weights

- Sharing of samples and common tuning with CMS

Many of these topics to be discussed in the recently formed LHC MC working group

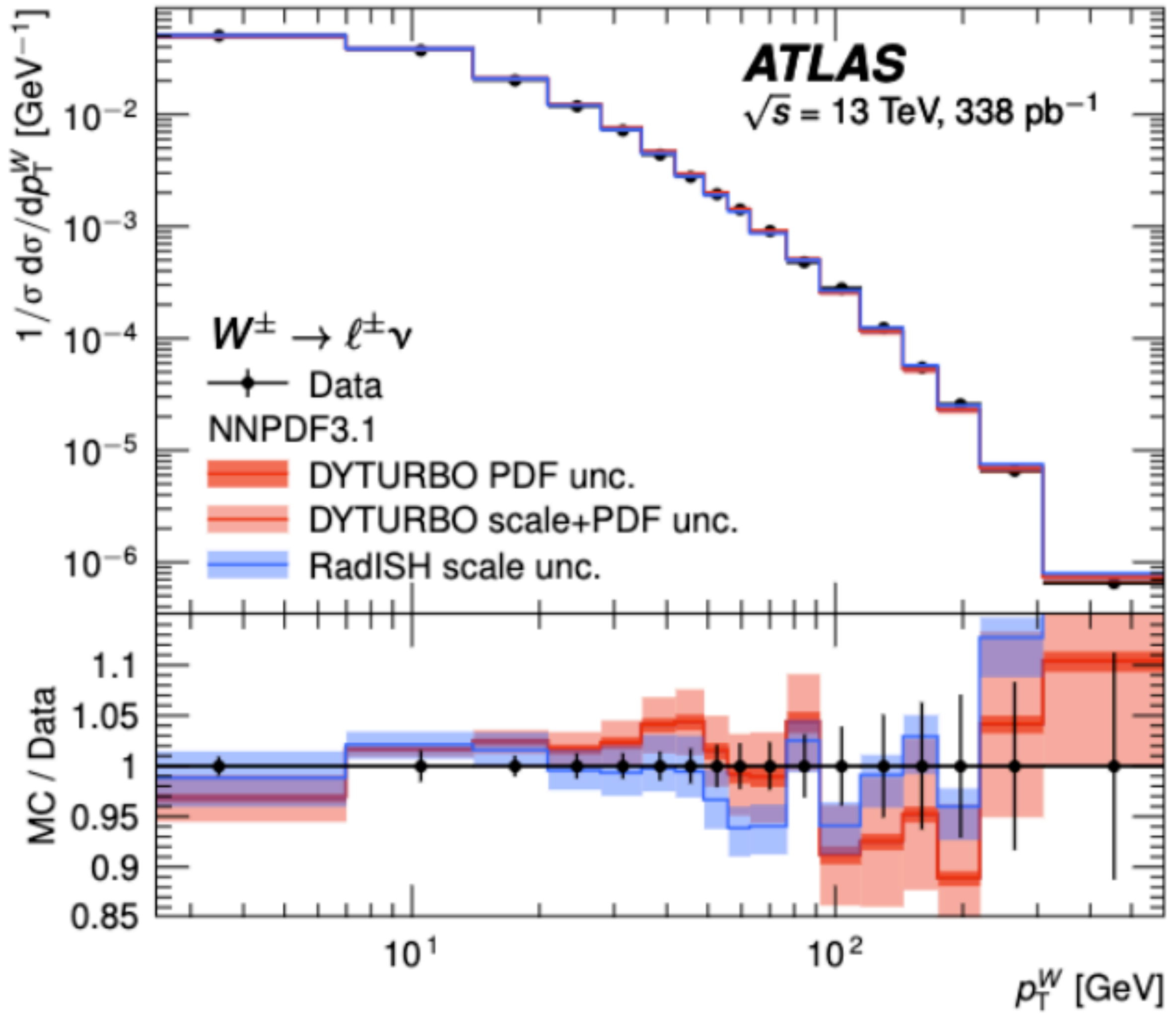
(SOME) PHYSICS MODELLING POINTS

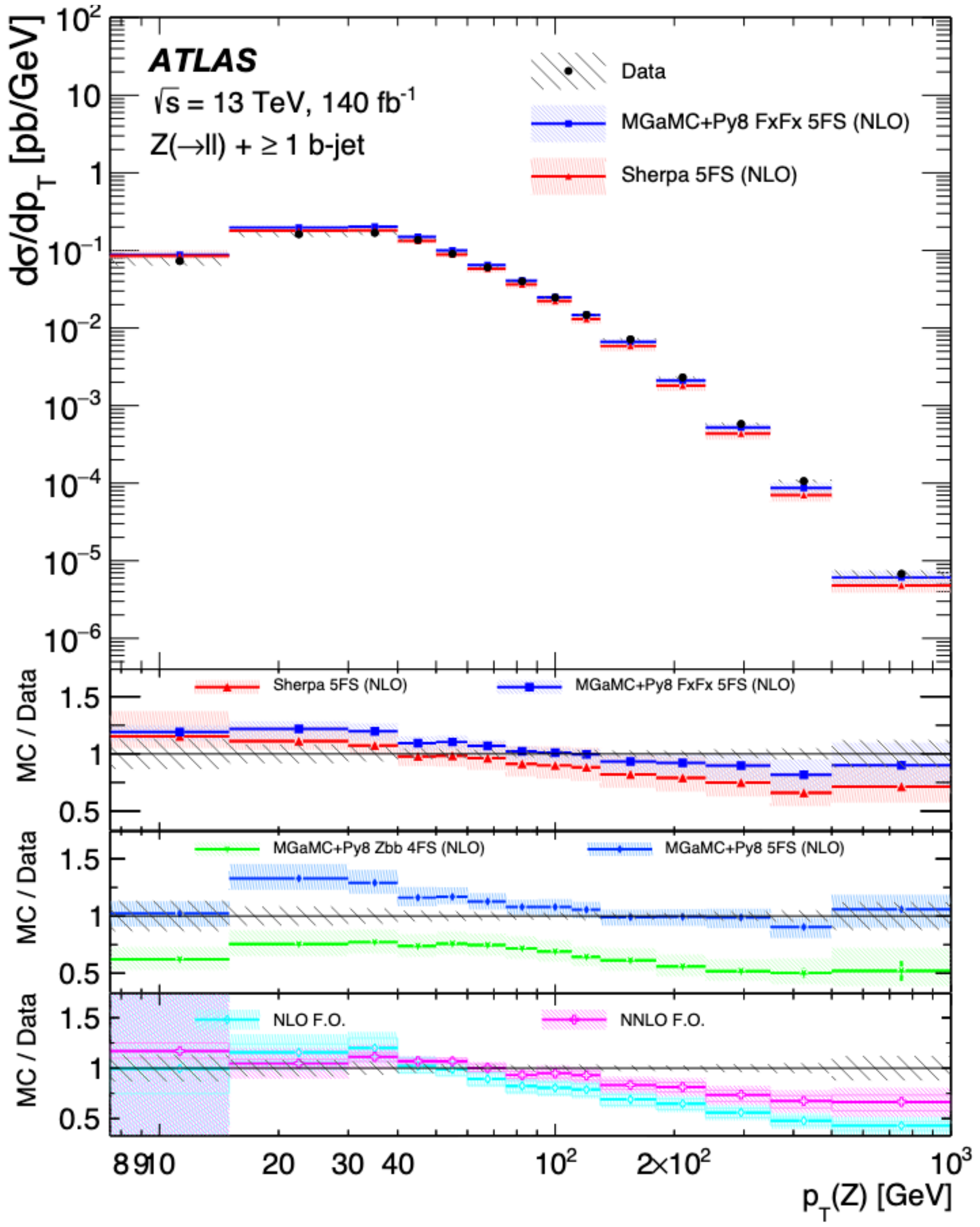
- Going beyond NNLO seems needed for some processes (e.g. DY, top)
  ➡N^3LOPS for specific processes
  ➡How far are we from NNLO QCD + NLO EW + PS ?

- Sometimes we are interested in interference effects which are intrinsically difficult to model (e.g $H\rightarrow\gamma\gamma$ and $\gamma\gamma$ QCD)

- Better accuracy/control of parton showers, mass effects and non-perturbative models

- UNCERTAINTIES!!
  ➡It is taking years to build a systematic uncertainty model for the different processes
  ➡Limiting several measurements
  ➡Theory guidance is key





SUMMARY

- ATLAS has a wide programme for precision measurements
  ➡At the same time looking for new physics and rare production never observed before

- It combine standard analysis strategies of measurement of differential cross sections or extraction of SM parameters with new methodologies

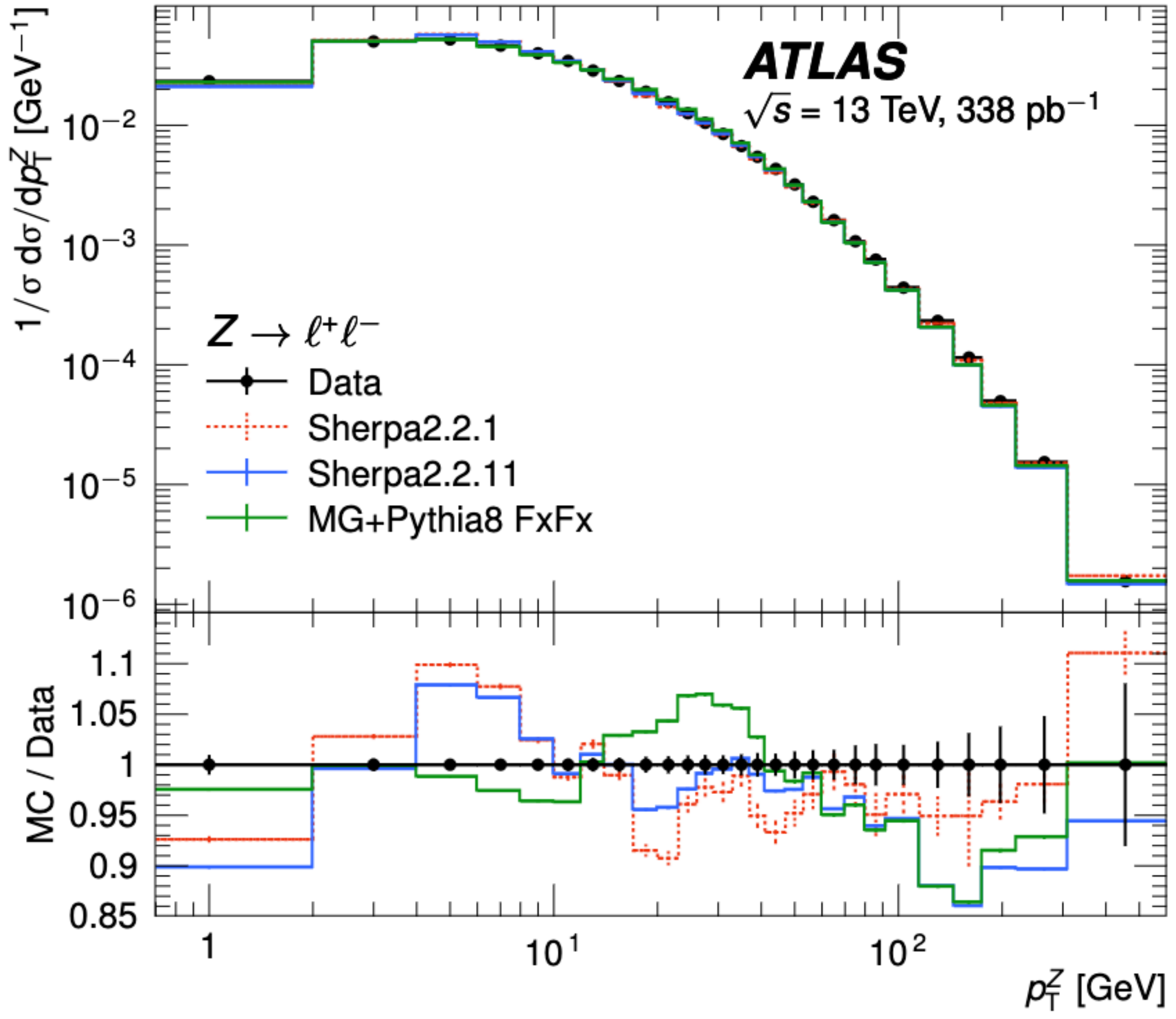
- Improving the precision of the measurements and understanding the modelling in MC generators is key to improve the sensitivity to new physics effects
  ➡A large number of measurements currently including SMEFT interpretations

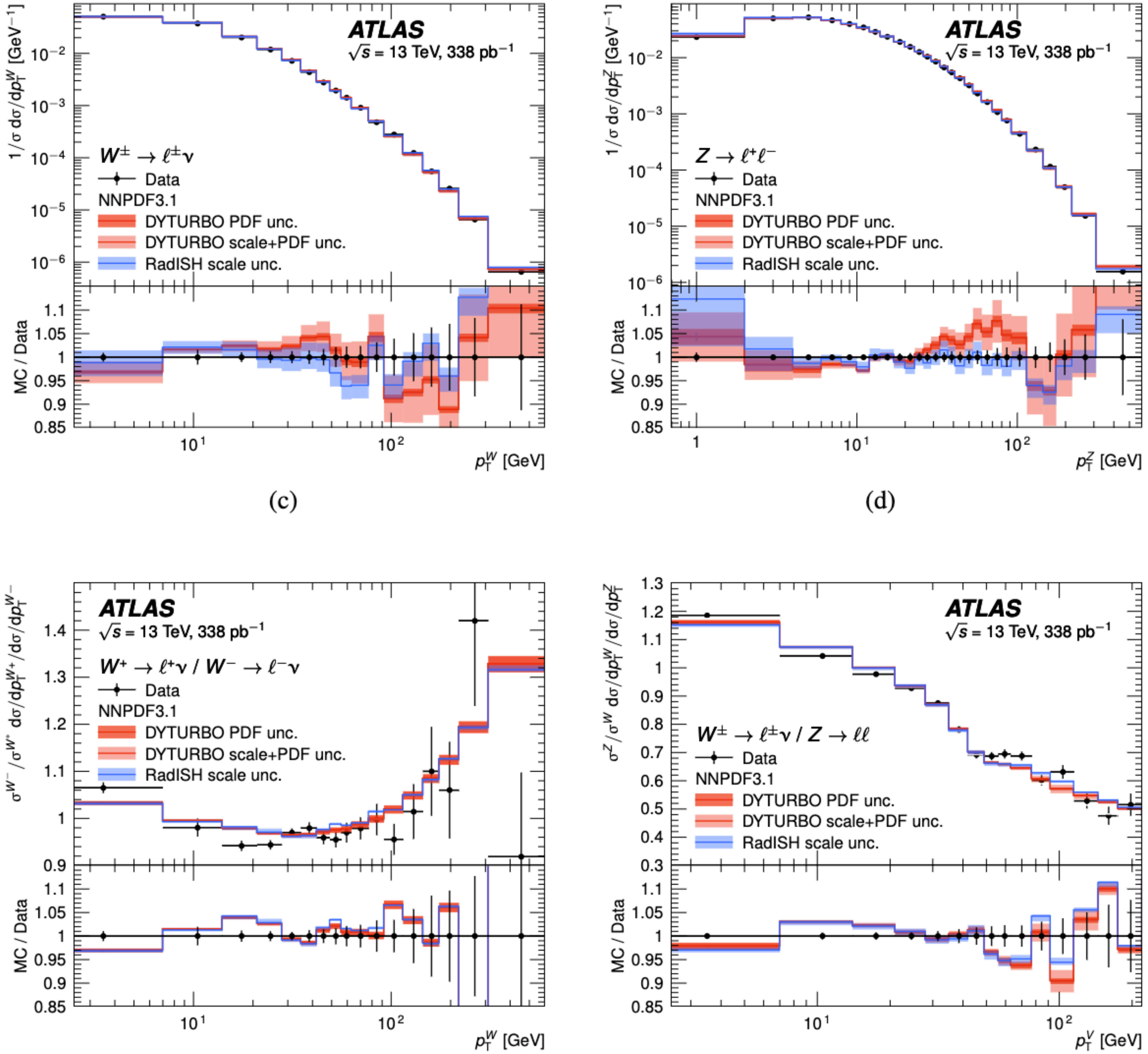
- ATLAS has a continuous effort to adapt to the newest MC versions and provide samples for the general use of the collaboration
  ➡Improvement in the knowledge exchange with MC authors is key for the success of the ATLAS SM and BSM programme
  ➡Many of the topics can be discussed in the LHC MC working group

BACK-UP

PRECISE MEASUREMENTS OF W AND Z TRANSVERSE MOMENTUM SPECTRA

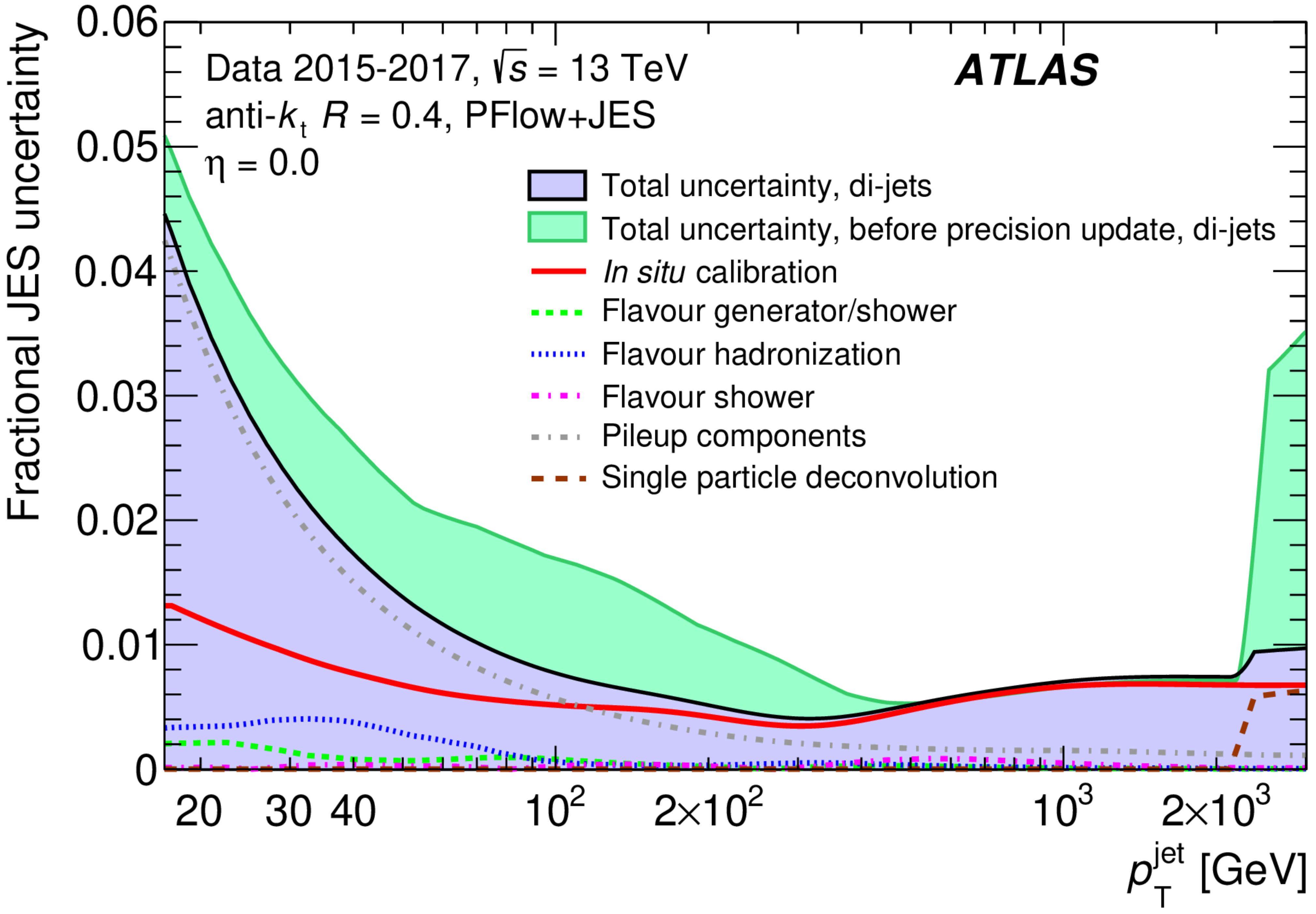
- **Comparisons to Radish at √s=13 TeV and multi-leg predictions**
  ➡**Radish is NNLO QCD + N3LL**





JETS PHYSICS: R3/2 RATIO

- **Revisited "flavour response uncertainty" of jet energy scale**
  - ➡**Flavour response depends on particle content and their pT spectrum which can have noticeable differences in different hadronisation models**
  - ➡**New factorised uncertainty targeting different regimes of the parton shower, hadronization or UE**
  - ➡ **Improvements at low and medium transverse momenta**



UNBINNED DIFFERENTIAL CROSS SECTIONS IN Z+JETS

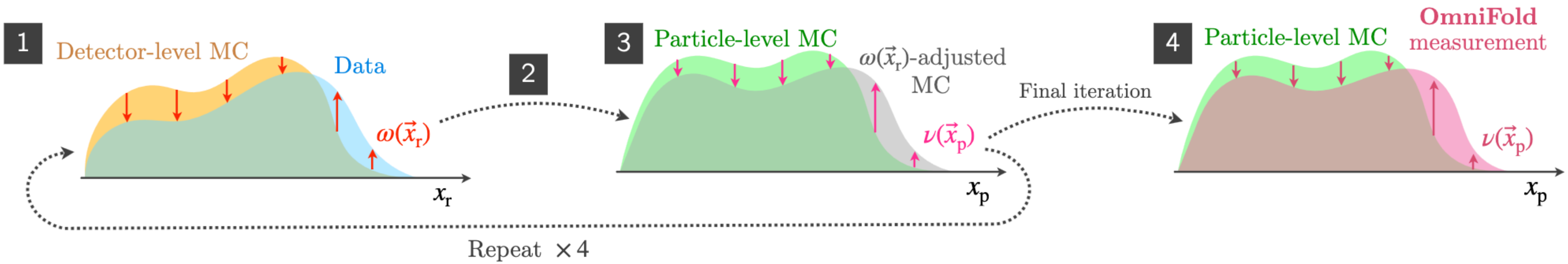
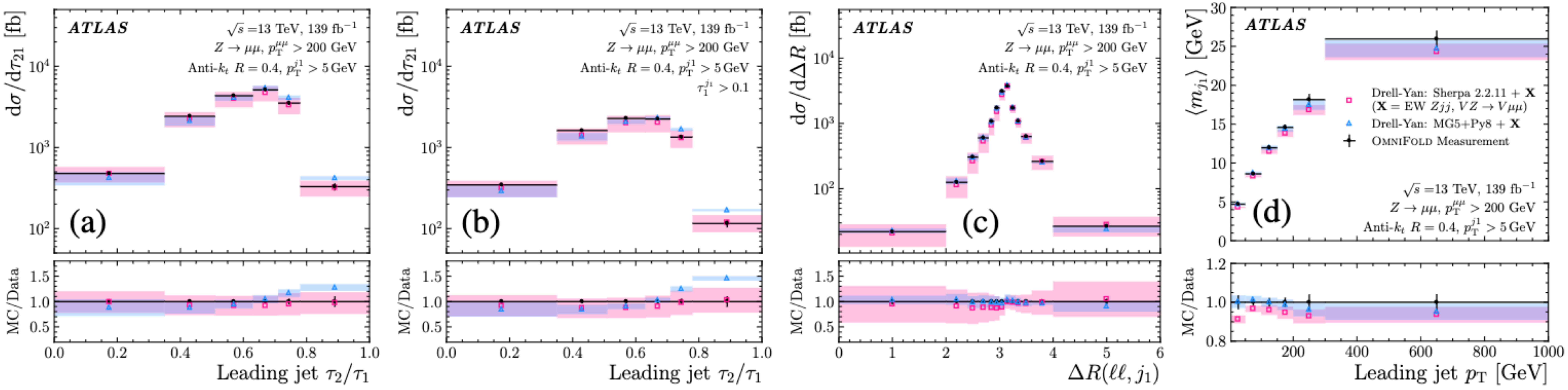


Figure 3: Illustration of the OmniFold method. First, MC is corrected to match data at the detector level. Second, particle-level MC is adjusted by propagating the learned correction through the MC using a weighting function $\omega(\vec{x}_r)$. Third, a new correction $\nu(\vec{x}_p)$ is learned based on particle-level quantities only. Finally, $\nu(\vec{x}_p)$ is propagated through the MC back to the detector level achieving an improved agreement to data. The method proceeds iteratively four more times, achieving a combined function $\nu(\vec{x}_p)$ that reweights the MC such that the event yields and kinematics match those observed in the data.

UNBINNED DIFFERENTIAL CROSS SECTIONS IN Z+JETS

Z+b and Z+bb / modelling is important 4FS and 5FS, fixed-order NLO and NNLO

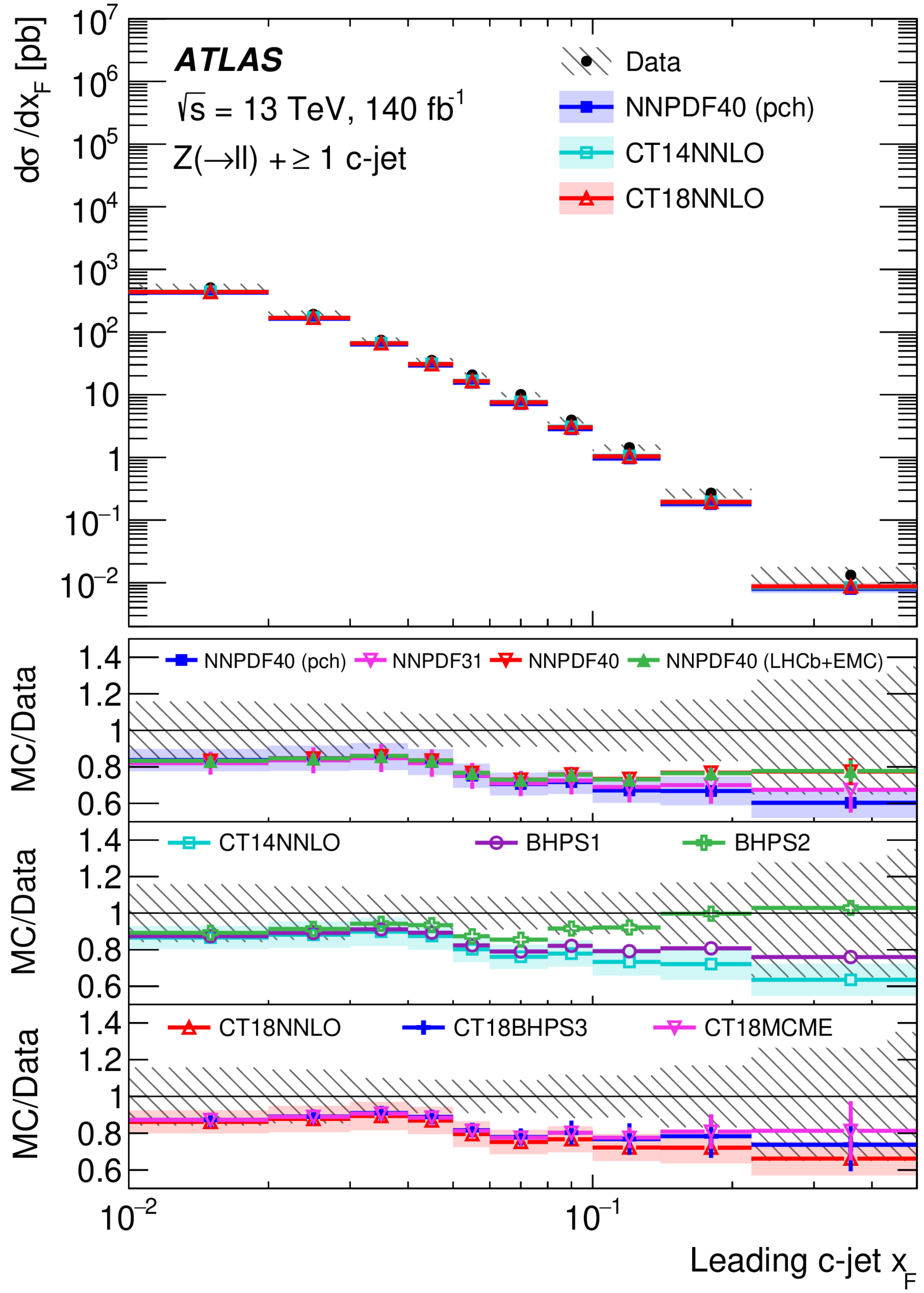
- **Z+jets cross section in 24 observables using Omnifold**
  - ➡ **Machine learning technique using discriminative NN that generalises the Iterative Bayesian Unfolding for correction for detector effects**
- **Results are presented as an unbinned dataset allowing the re-use adjusting the binning or building new observables starting from the 24 ones originally measured**
- **Recommendations on how to use the dataset formatted as Panda DataFrame also provided**



arXiv:2403.15093

Z BOSON IN ASSOCIATION WITH ONE OR TWO B- OR C-JETS

$$x_F = 2|p_z(c)|/\sqrt{s}$$



- **aMC@NLO+Pythia FxFx (5FS) compared to data with several PDF sets testing different intrinsic charm models**
  - ➡**PDFs with large IC contribution, such as CT14 BHPS2 (2.1% IC) agree at large x_F**
  - ➡**More realist PDF fits (NNPDF4.0 + LHCb + EMC) only marginal improvement at high x_F**