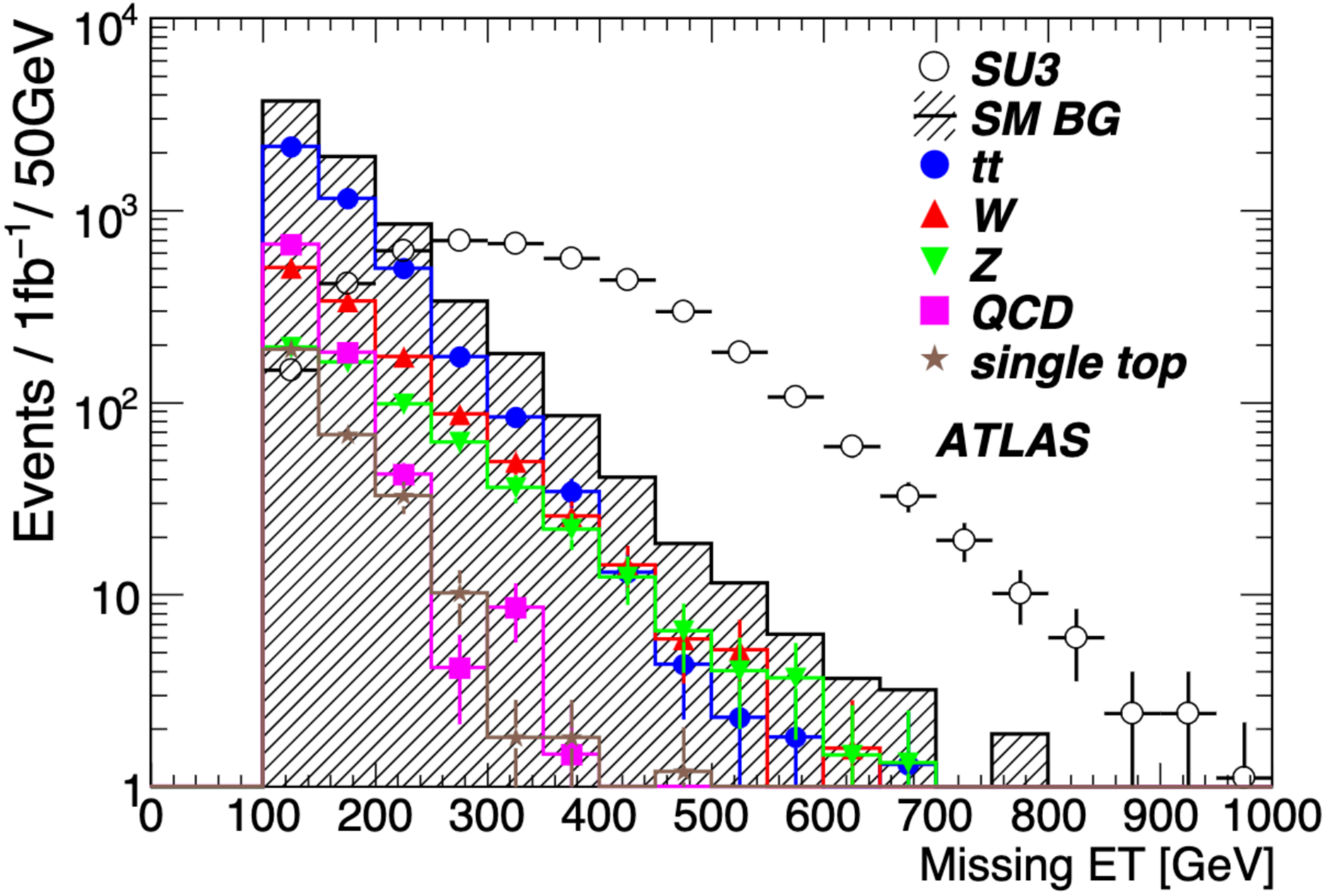
Experimental overview on MC event generators (and a bit of resummation)

Parton Showers and resummation 2023

Oct. 6th, 2022

Simone Amoroso (DESY)

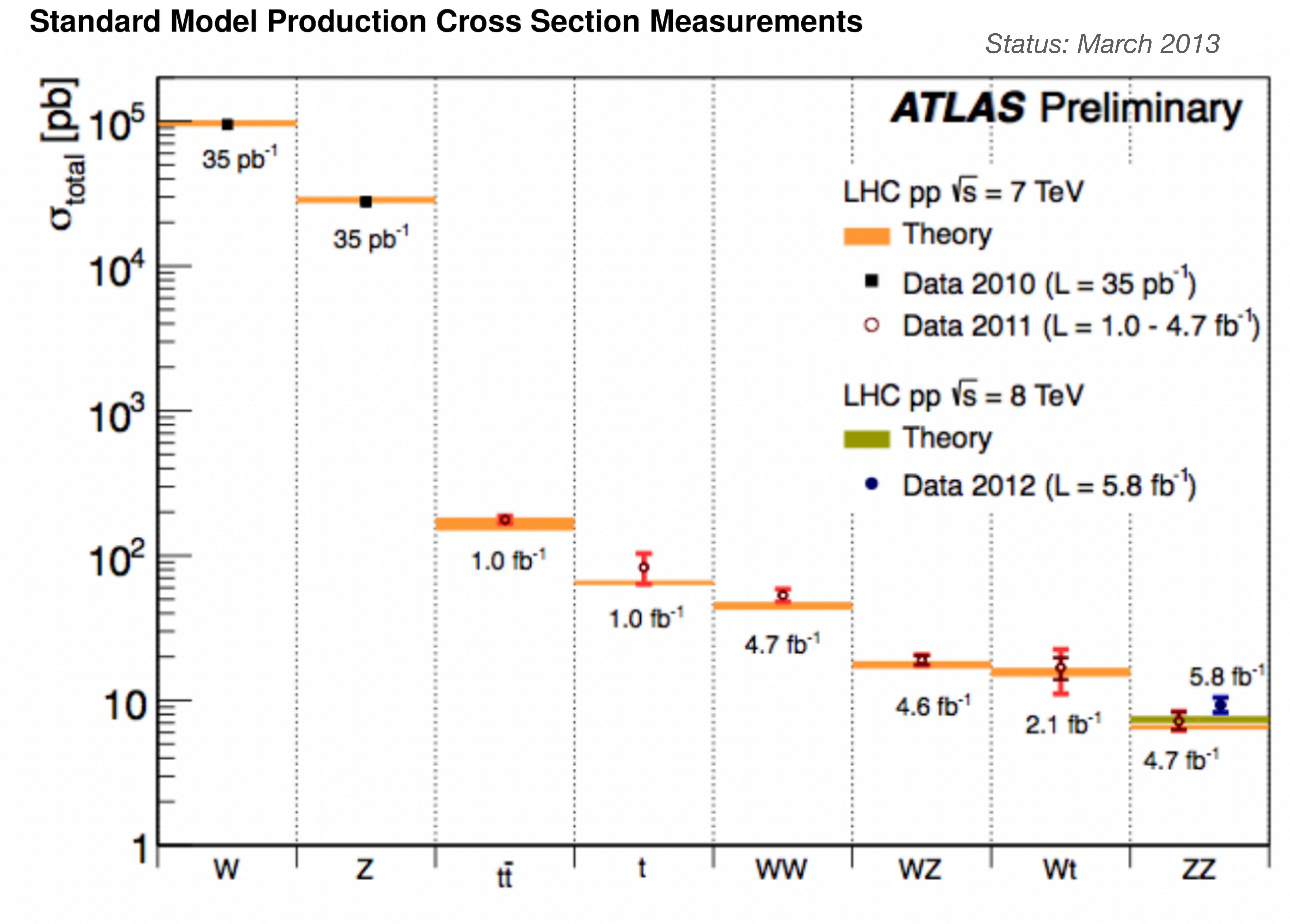
Monte Carlos before the LHC



ATLAS CSC studies (2008)

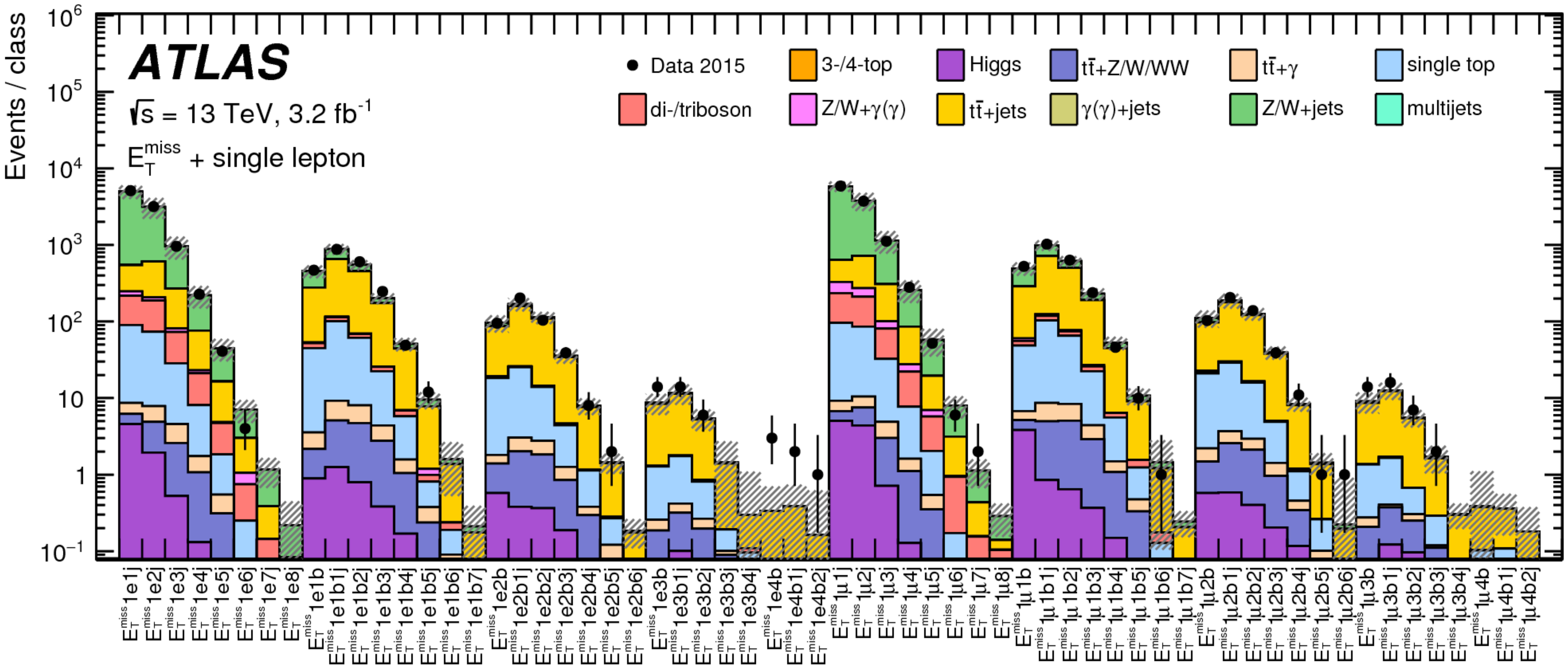
- LO+PS State-of-the-art: Alpgen/Madgraph +Pythia/Herwig
- NLO+PS only appearing in those years
- Can we even use MC?
- Strong push for data-driven methods for backgrounds

Standard Model at the LHC: then



- 10% precision for top, Higgs, dibosons
- %-level precision for DY
- Thanks to established LO/NLO automation and NLO-merging techniques

How well do MC generator works ?



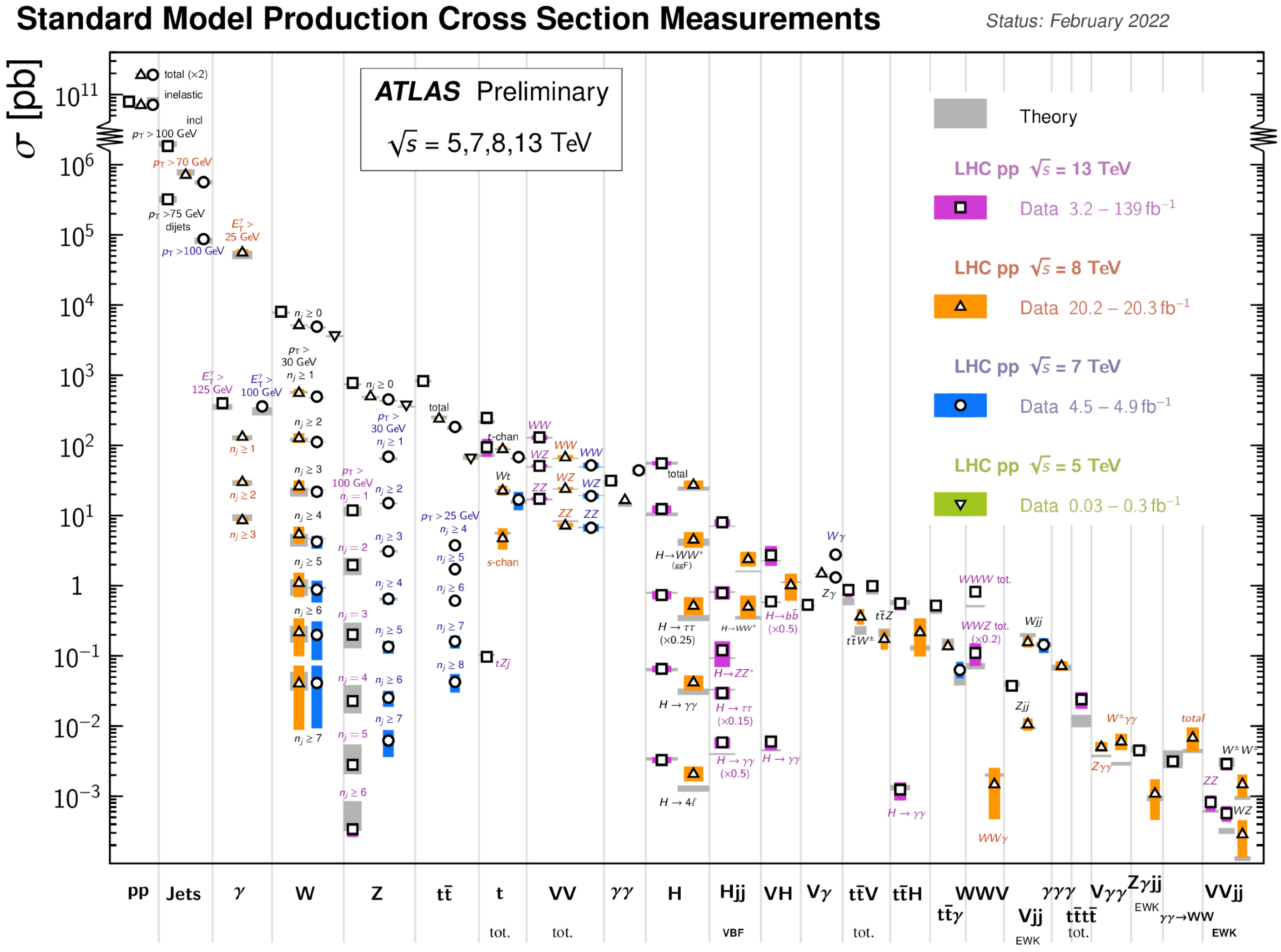
EXOT-2016-38

THE LHC: THE "EVERYTHING FACTORY"

Particle	Produced in 139 fb^{-1} at $\sqrt{s}$ = 13 TeV	
Higgs boson	7.7 millions	
Top quark	275 millions	
Single top quark	50 millions	
Z boson	2.8 billions	290 millions leptonic
W boson	12 billions	3.7 billions leptonic
Bottom quark	~40 trillions	

From [A. Hoecker @ EPS 2019]

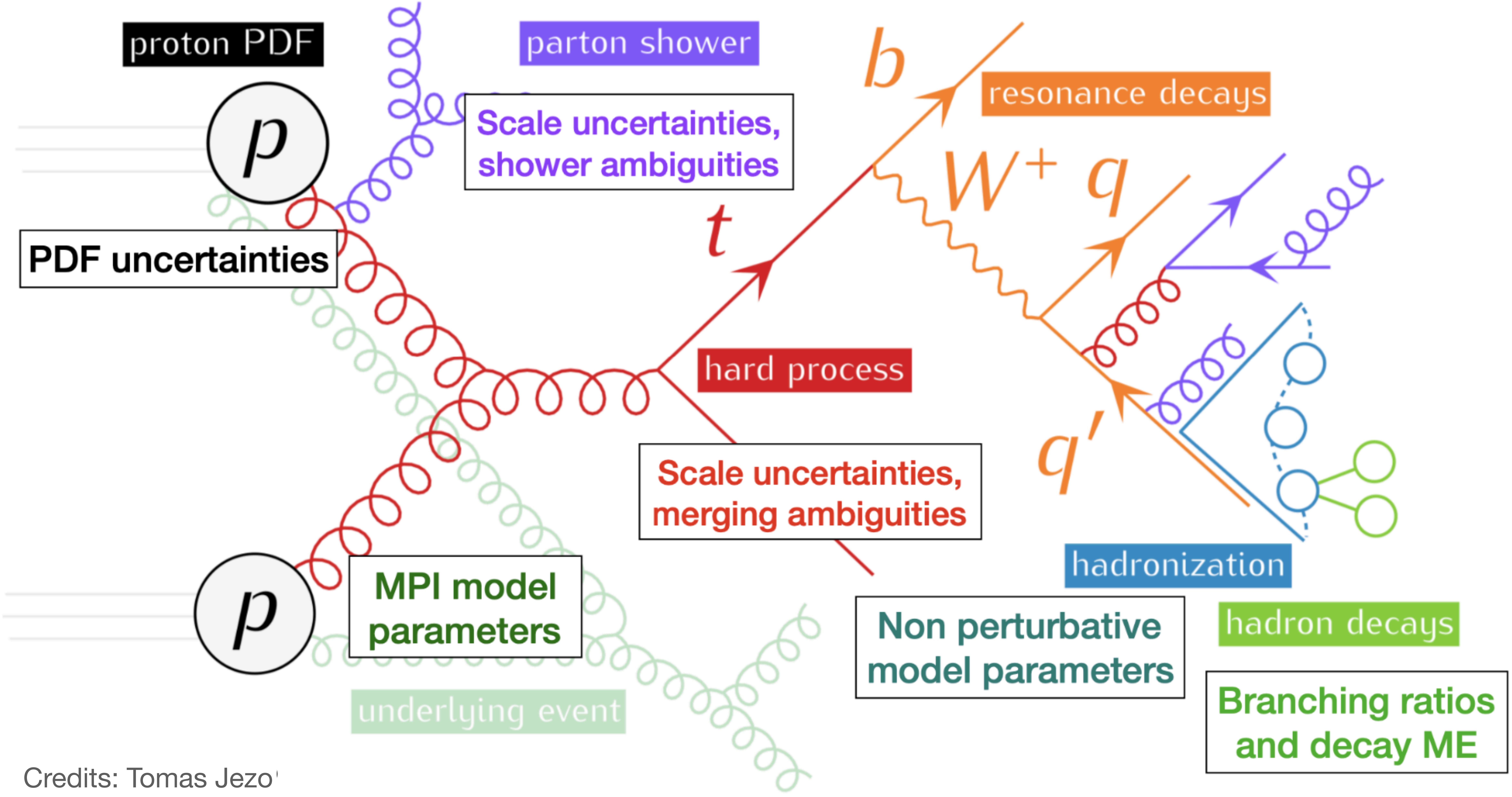
Standard Model at the LHC: now



- %-level measurements of Higgs, VV, top and %% precision on W, Z
- Many first measurements of high-multiplicity processes
- Refined NLOPS and first NNLOPS simulations
- *Precision* is the new LHC buzzword

https://atlas.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2022-009/

Bits and pieces of an event generator

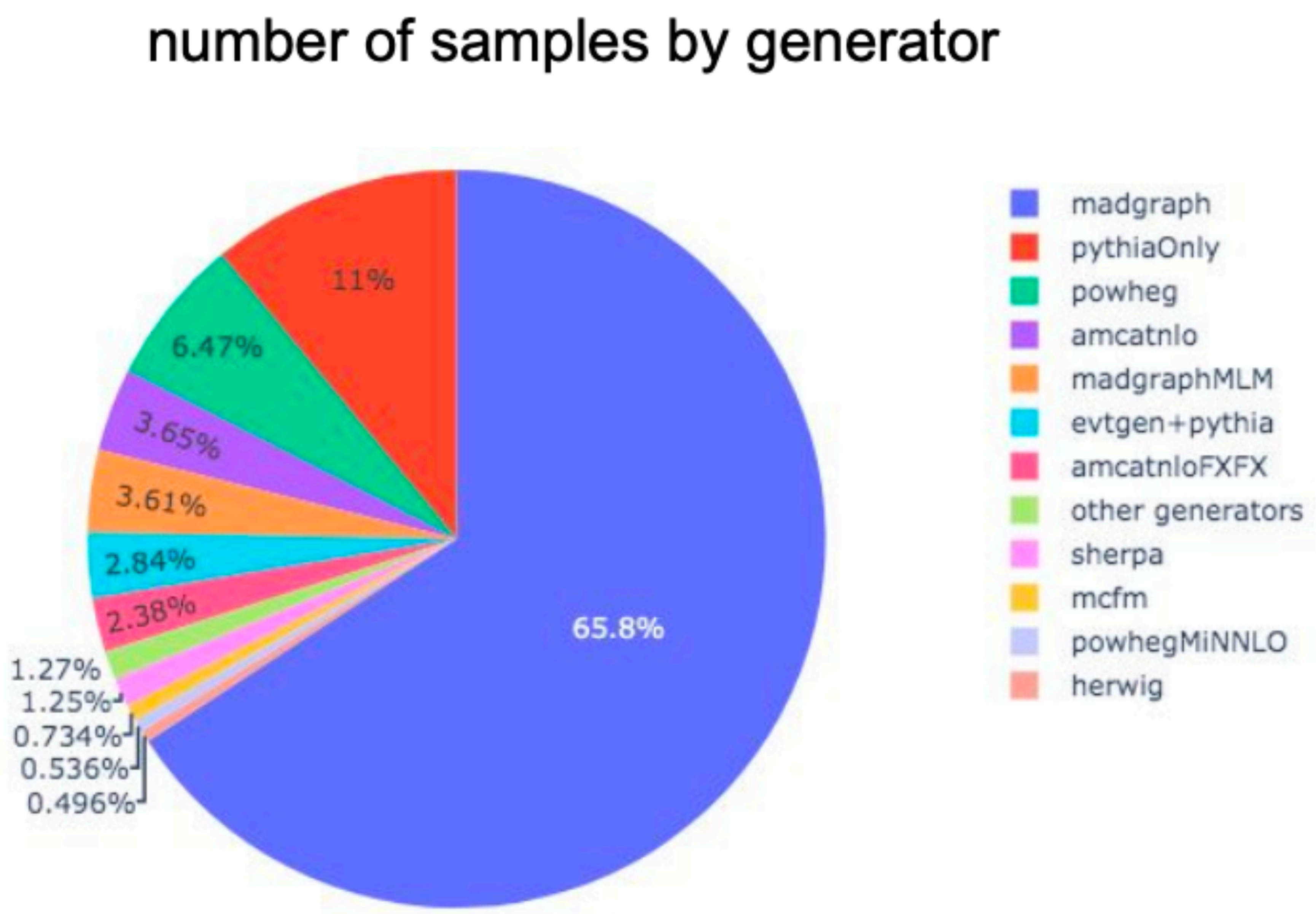


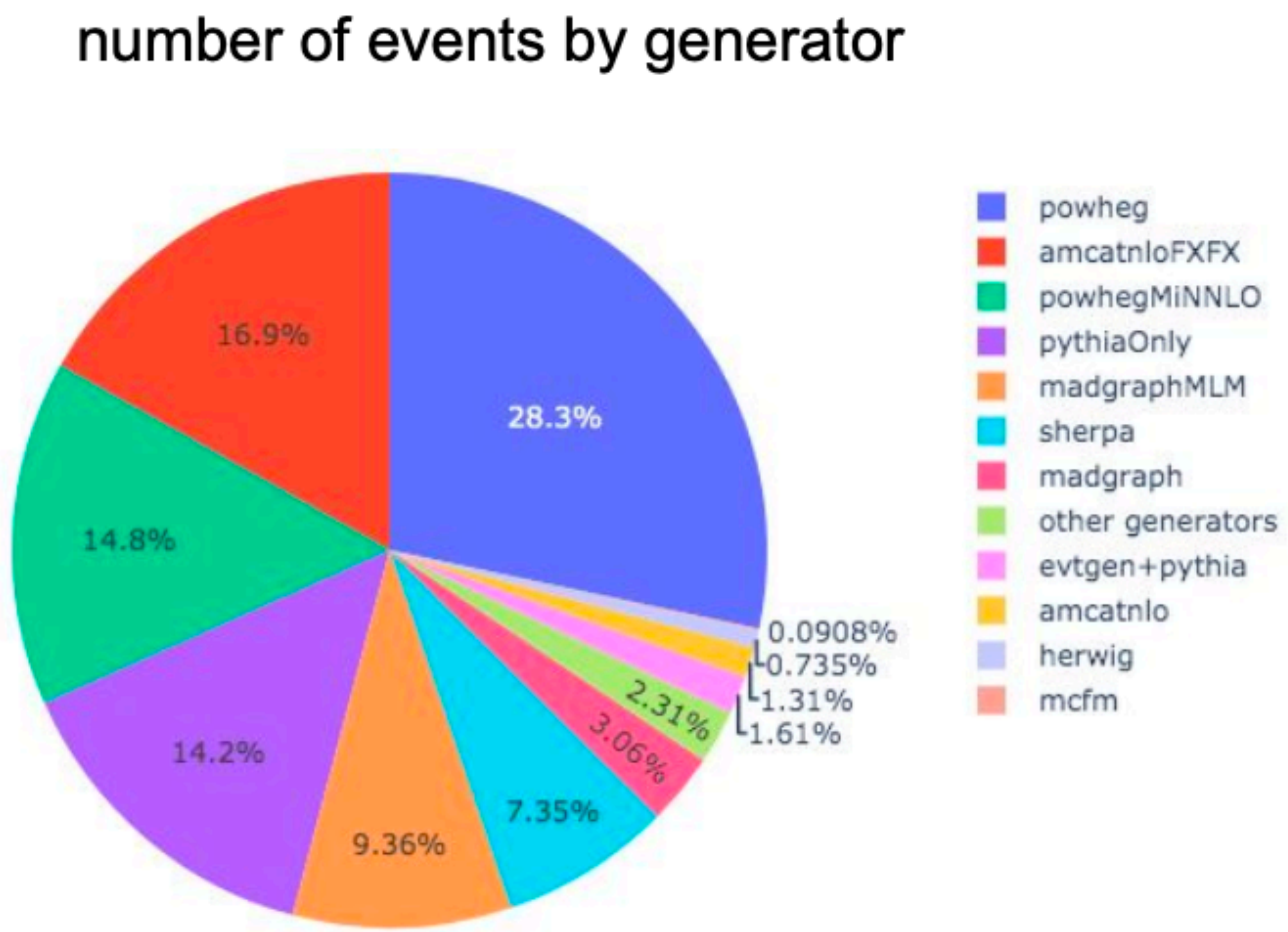
Credits: Tomas Jezo

Generators usage in ATLAS/CMS - 2015/16

based on Run-2 MC campaign for 2016 data

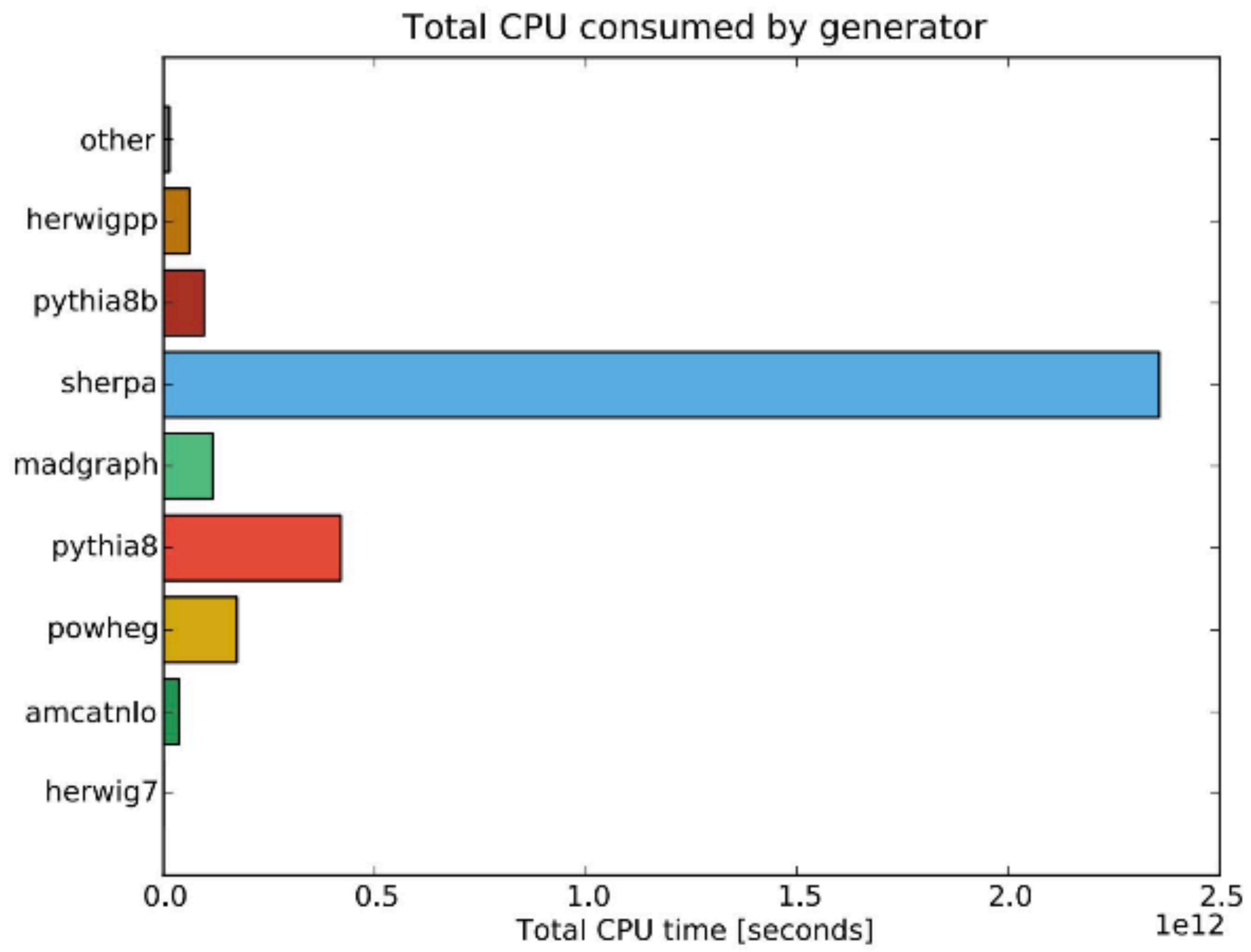
CMS

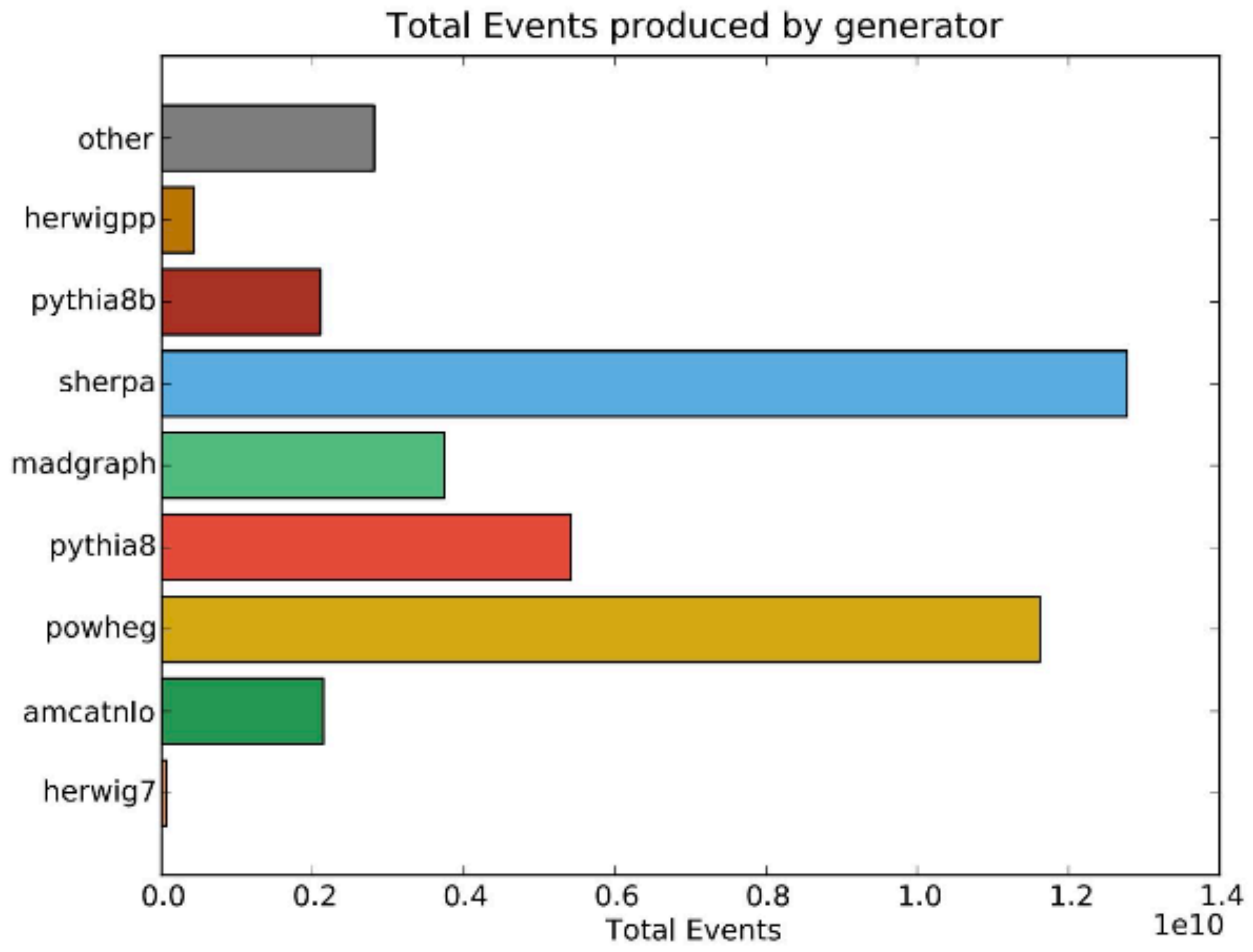




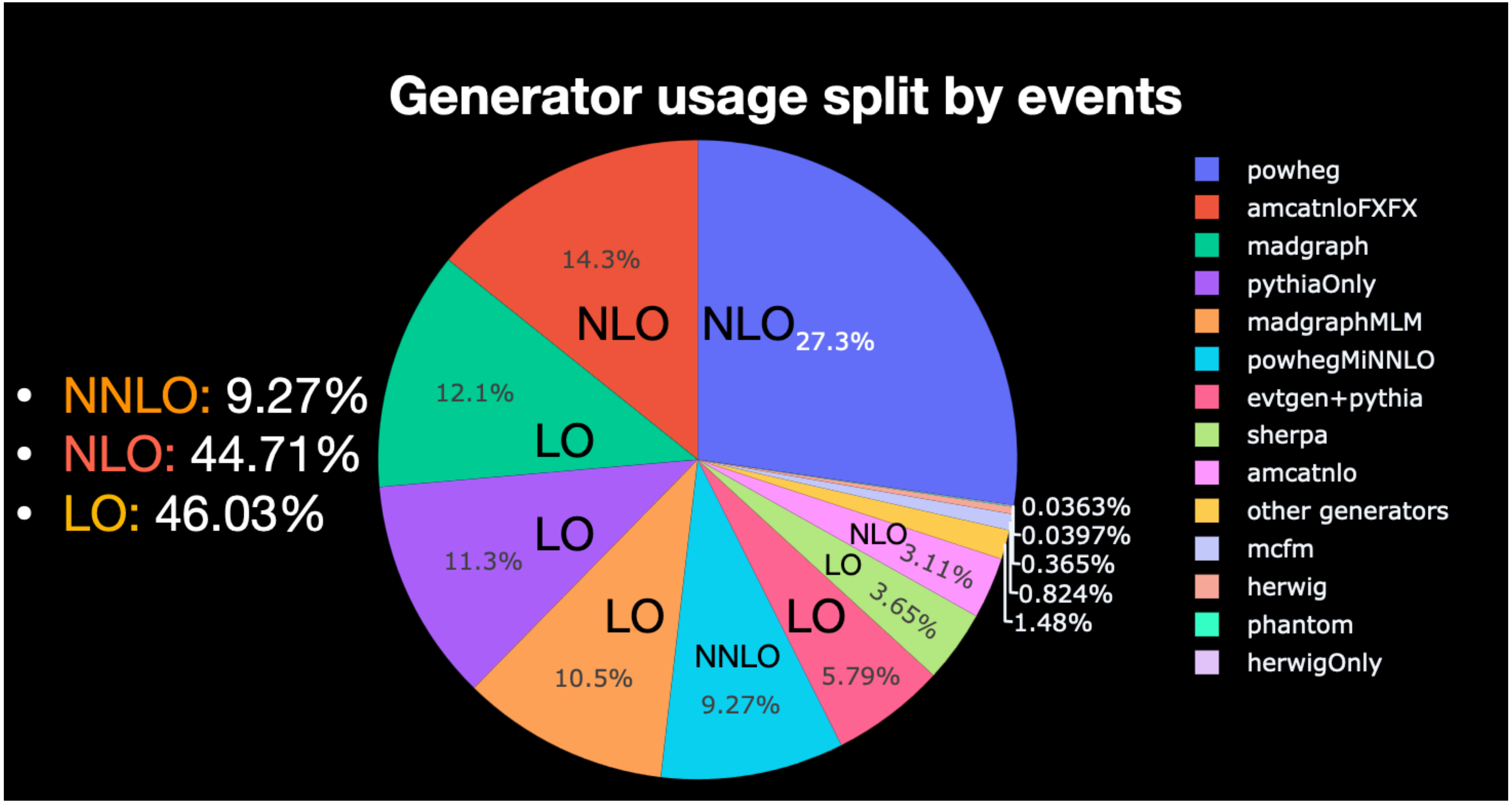
based on Run-2 MC campaign for 2015 data

ATLAS



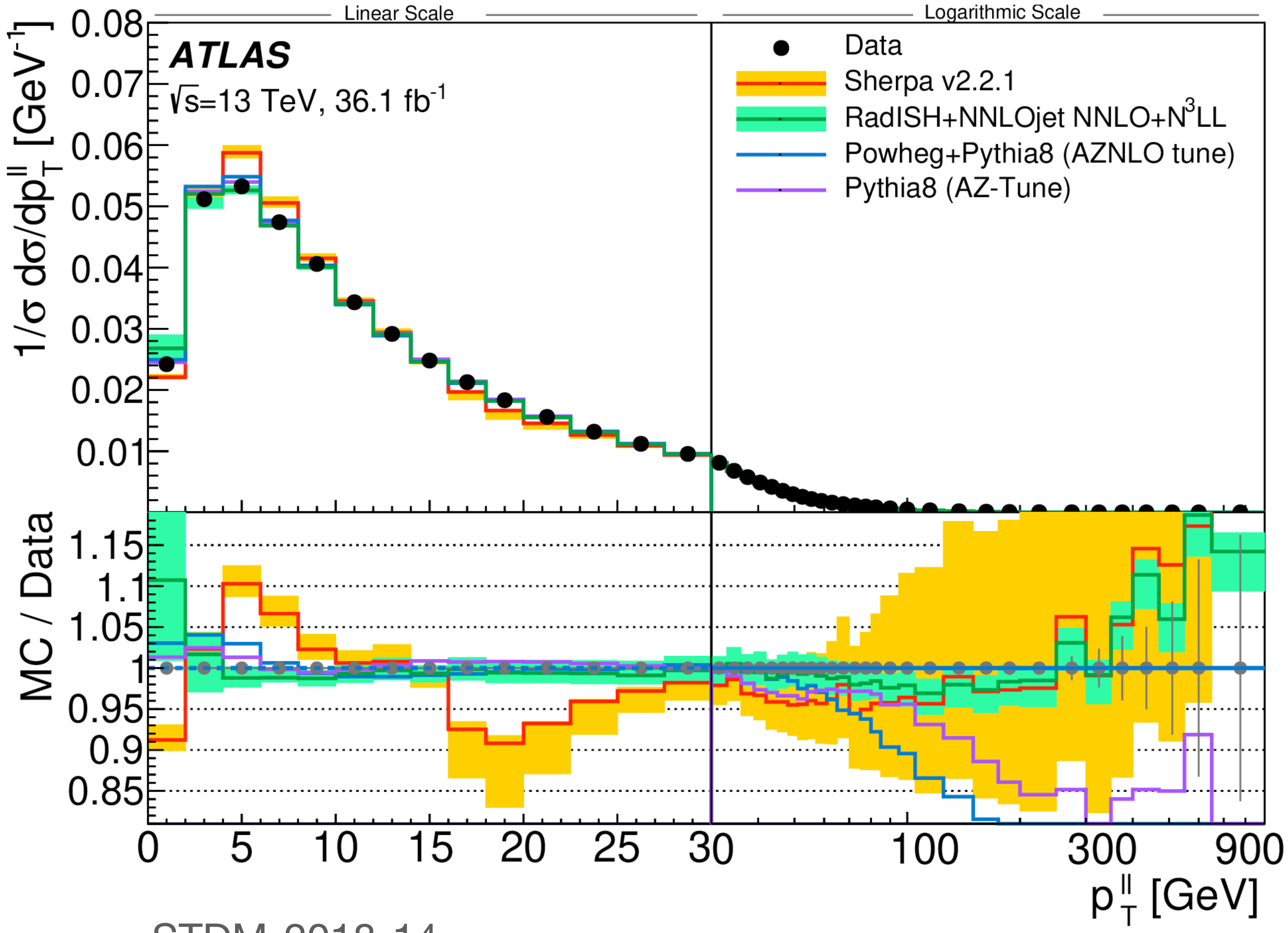


Generators usage in CMS - 2023



The Z-boson transverse momentum

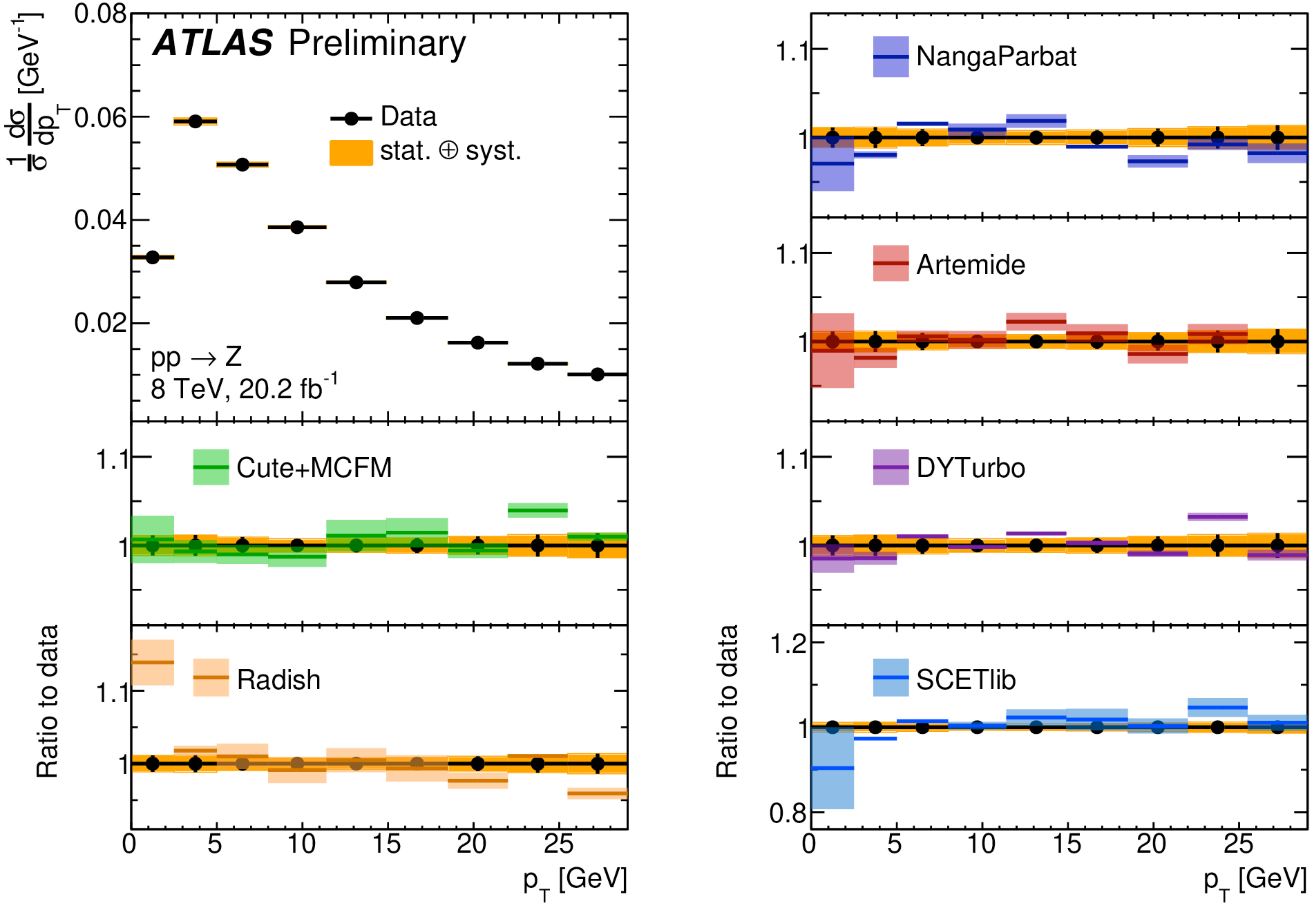
- The Z boson transverse momentum is a special observable for LHC physics



STDM-2018-14

- Purely leptonic quantity, can be measured with the highest accuracy
- No QCD radiation from the final state
- Ideal benchmark and testing ground for highest accuracy calculations

ATLAS full phase-space Z p_T at 8 TeV



- Angular coefficients decomposition to avoid lepton fiducial cuts
- %-level precision on normalized cross-section
- Well described by (many) analytic resummations of $\log(q_T/m)$

ATLAS-CONF-2023-013

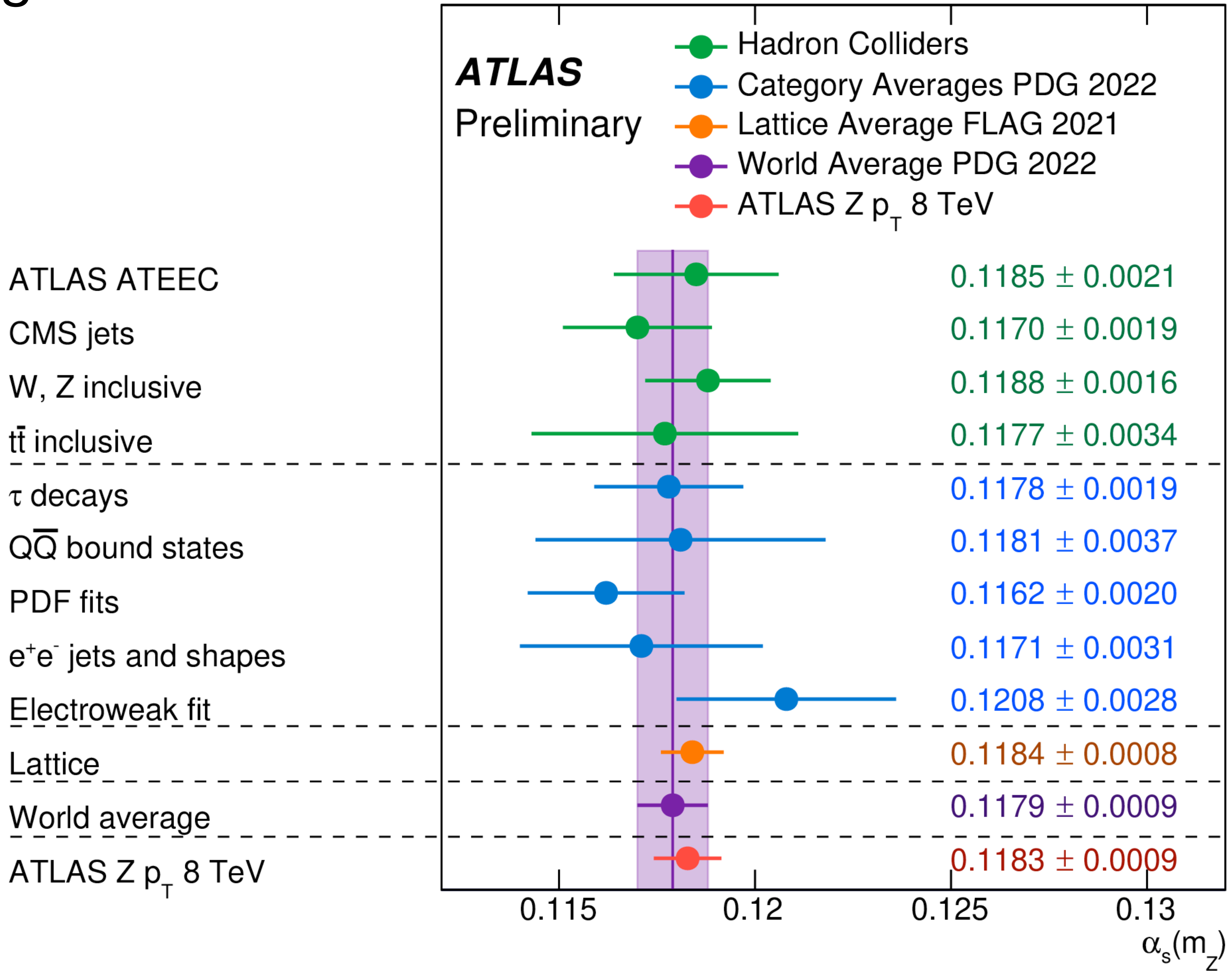
Z p_T and strong coupling extraction

- The position of the Sudakov peak can be used for a precision extraction of the strong coupling

$$\alpha_s(m_Z) = 0.11828^{+0.00084}_{-0.00088}$$

- DYTURBO N4LL matched to MCFM $o(\alpha_S^3)$
- Largest uncertainties from PDFs and MHO

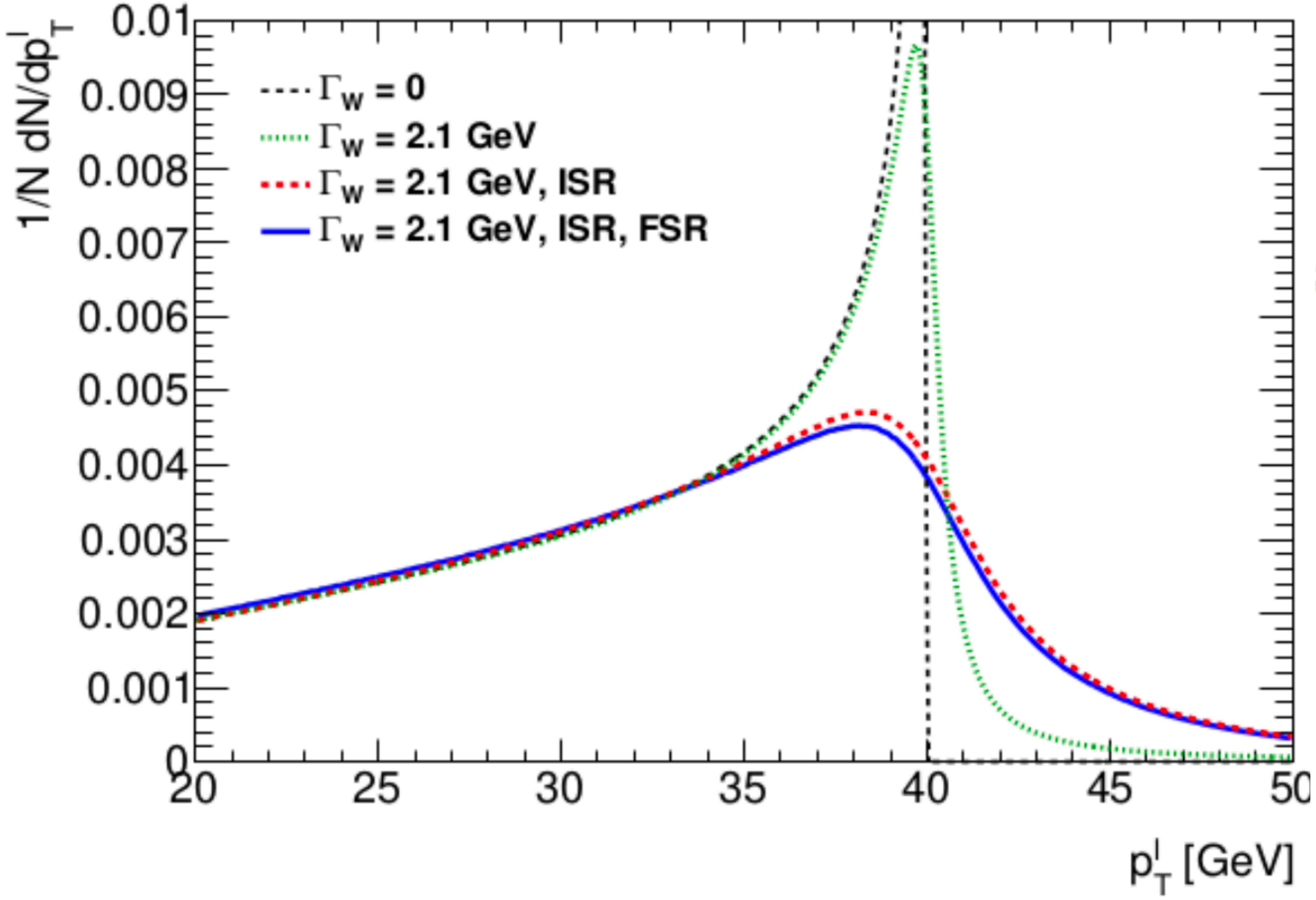
Experimental uncertainty	+0.00044	-0.00044
PDF uncertainty	+0.00051	-0.00051
Scale variations uncertainties	+0.00042	-0.00042
Matching to fixed order	0	-0.00008
Non-perturbative model	+0.00012	-0.00020
Flavour model	+0.00021	-0.00029
QED ISR	+0.00014	-0.00014
N4LL approximation	+0.00004	-0.00004
Total	+0.00084	-0.00088

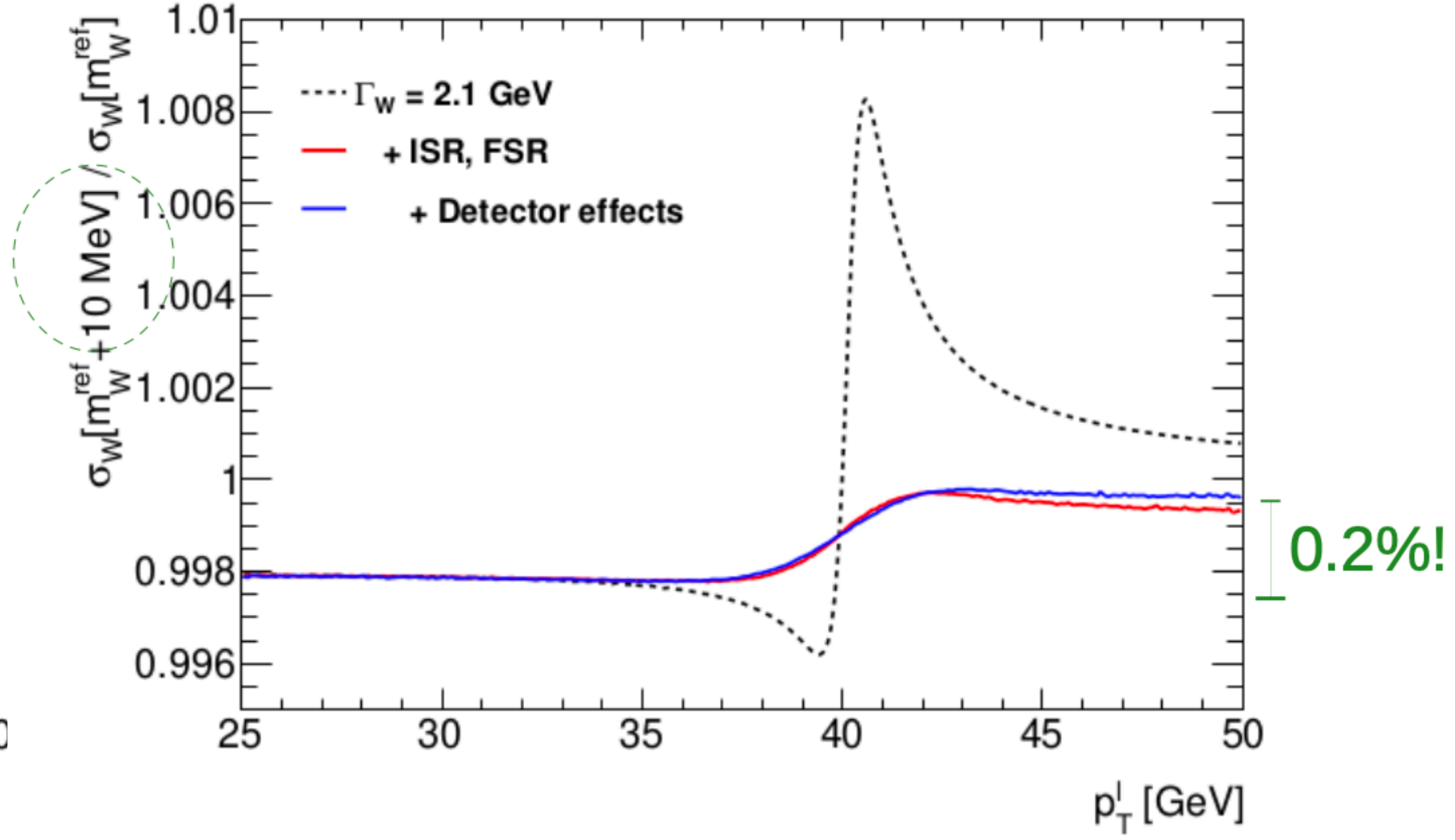


ATLAS-CONF-2023-015

W boson p_T and the W-mass

- W-mass measurement at LHC sensitive to the description of the W boson p_T
- 2 permill shift in lepton p_T corresponds to ~10 MeV in m_W

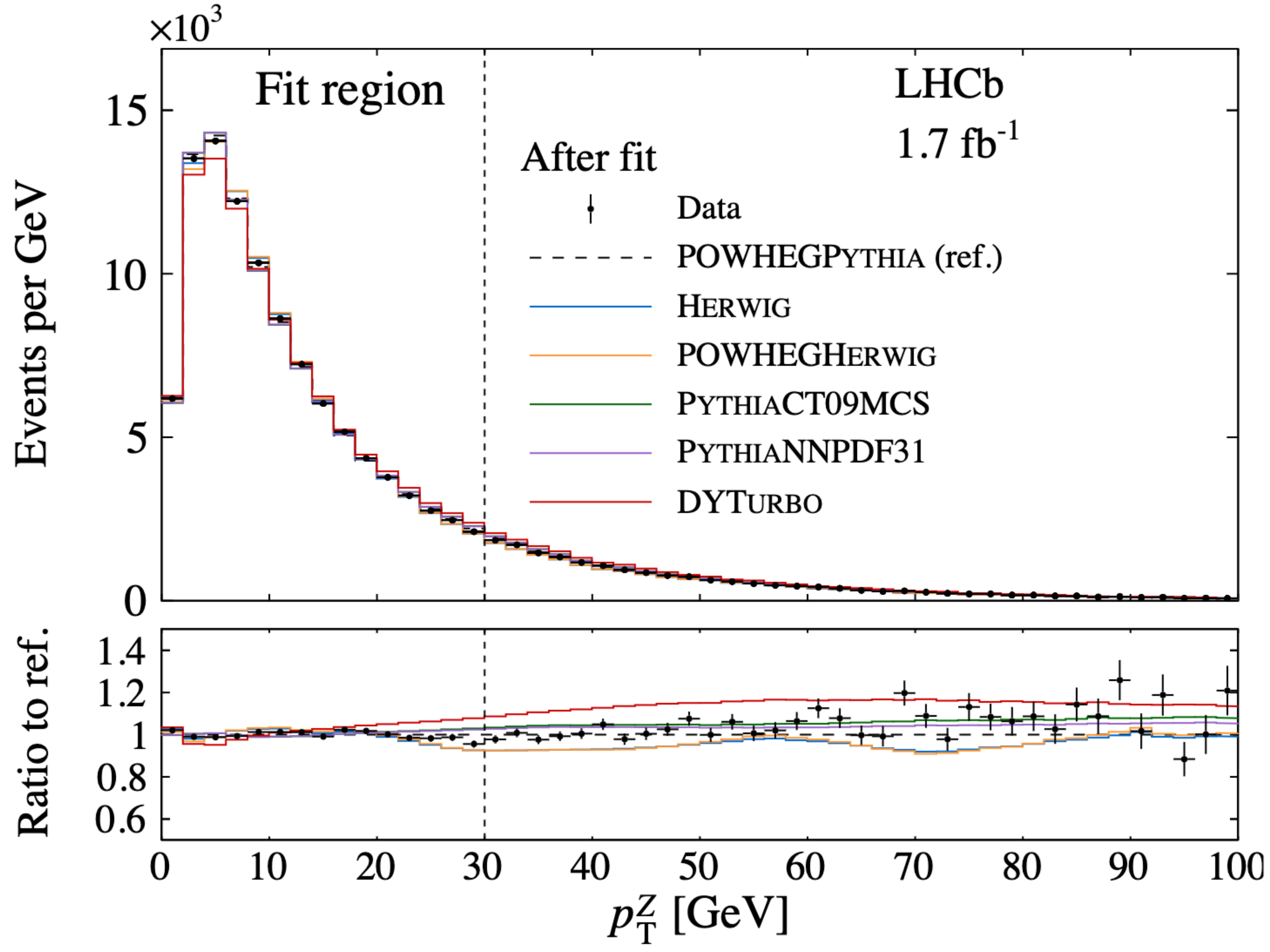




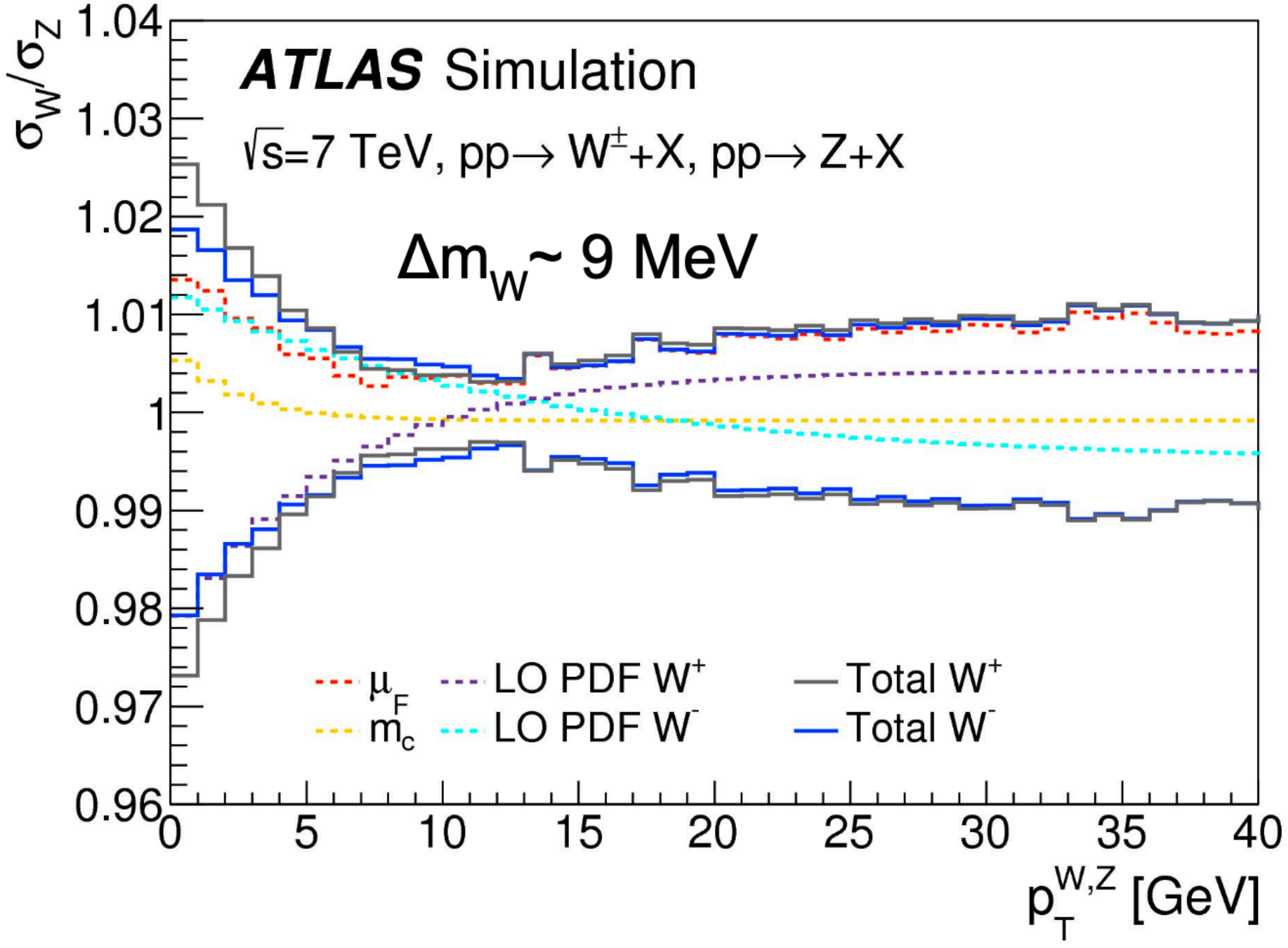
Extrapolating p_T from Z to W

- Exploit the well measured Z p_T to get the best possible description of W p_T

$$p_T^W = R_{W/Z} \cdot p_T^Z$$



LHCb-PAPER-2021-024

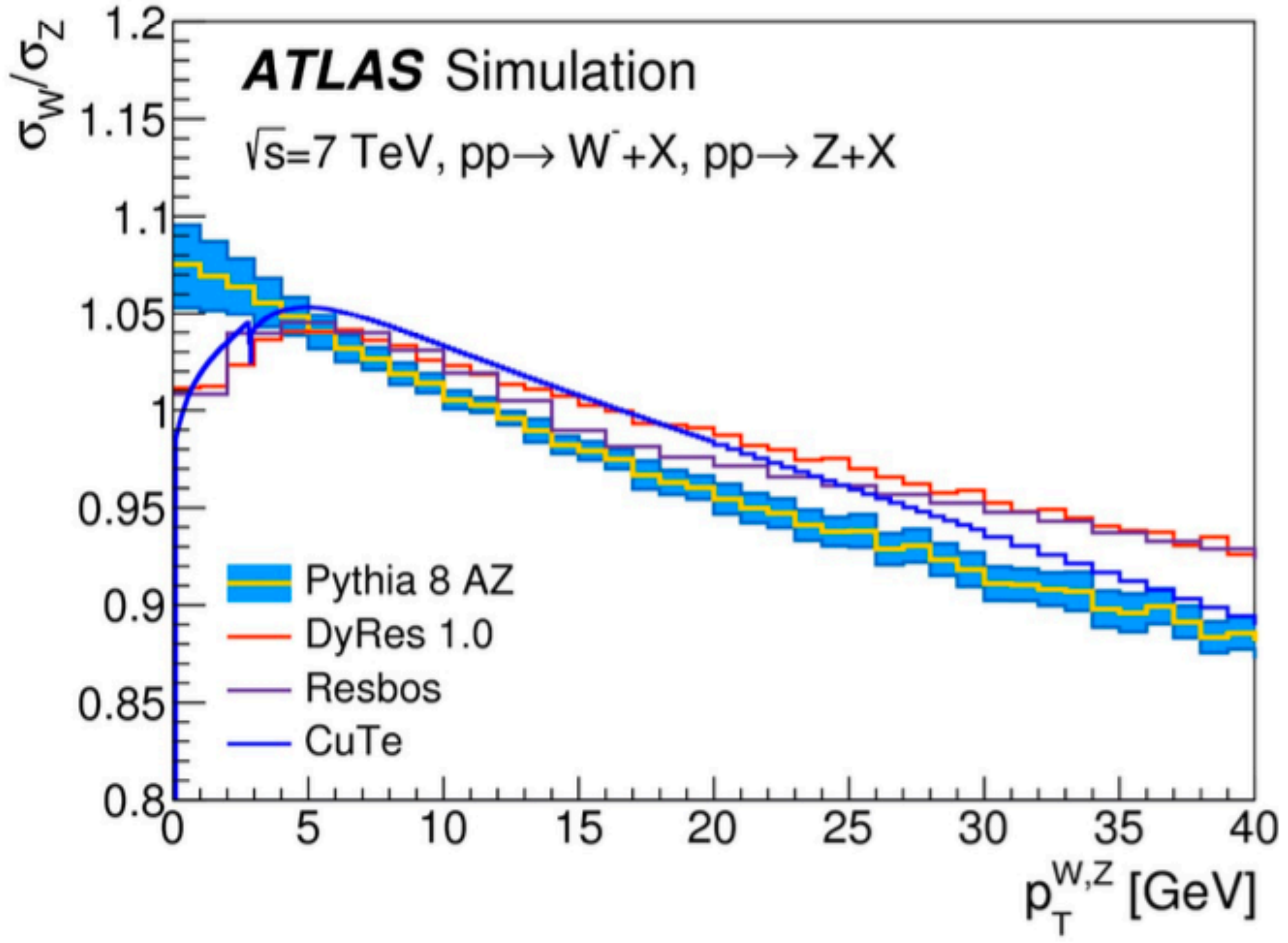


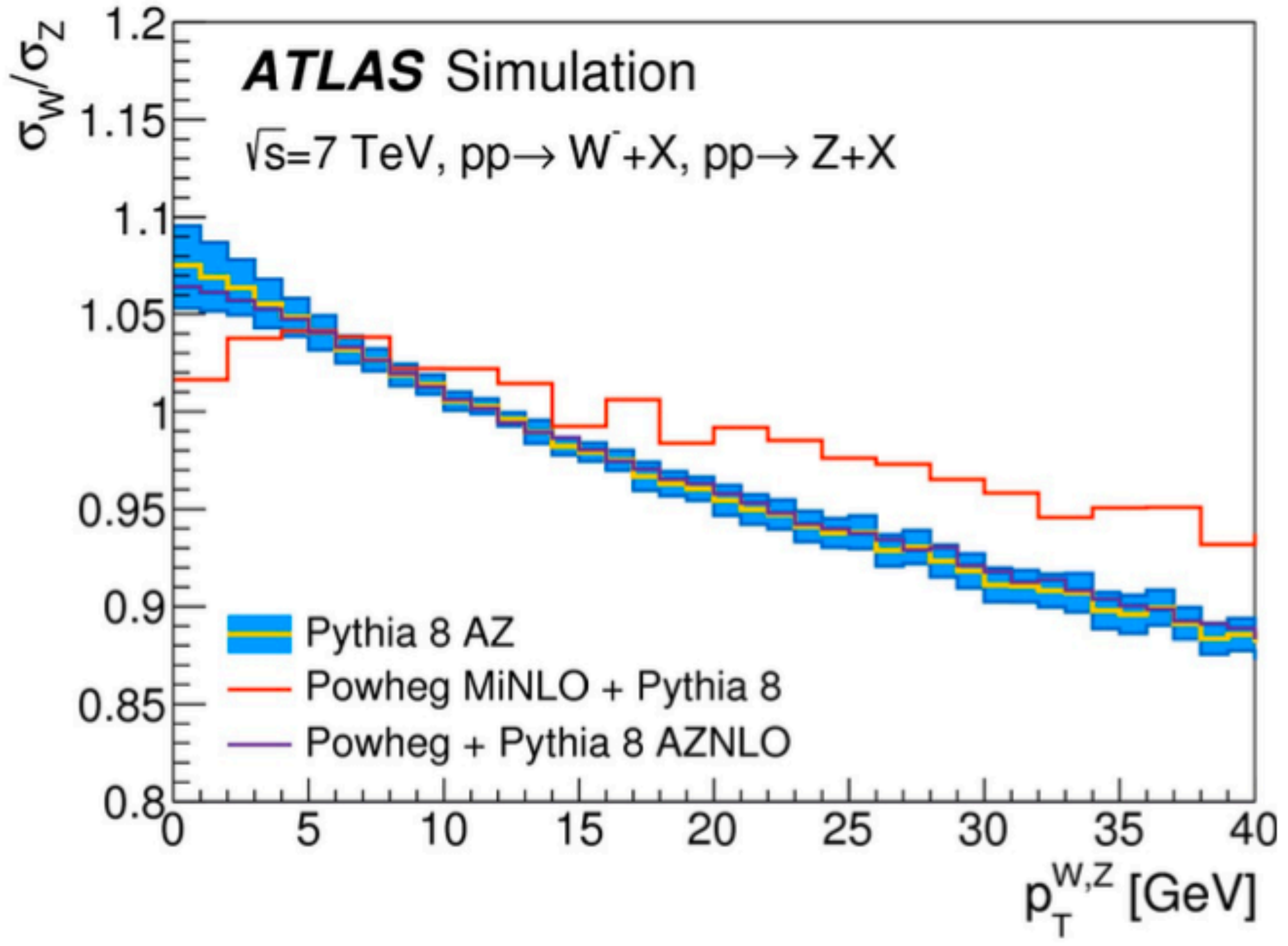
STDM-2014-18

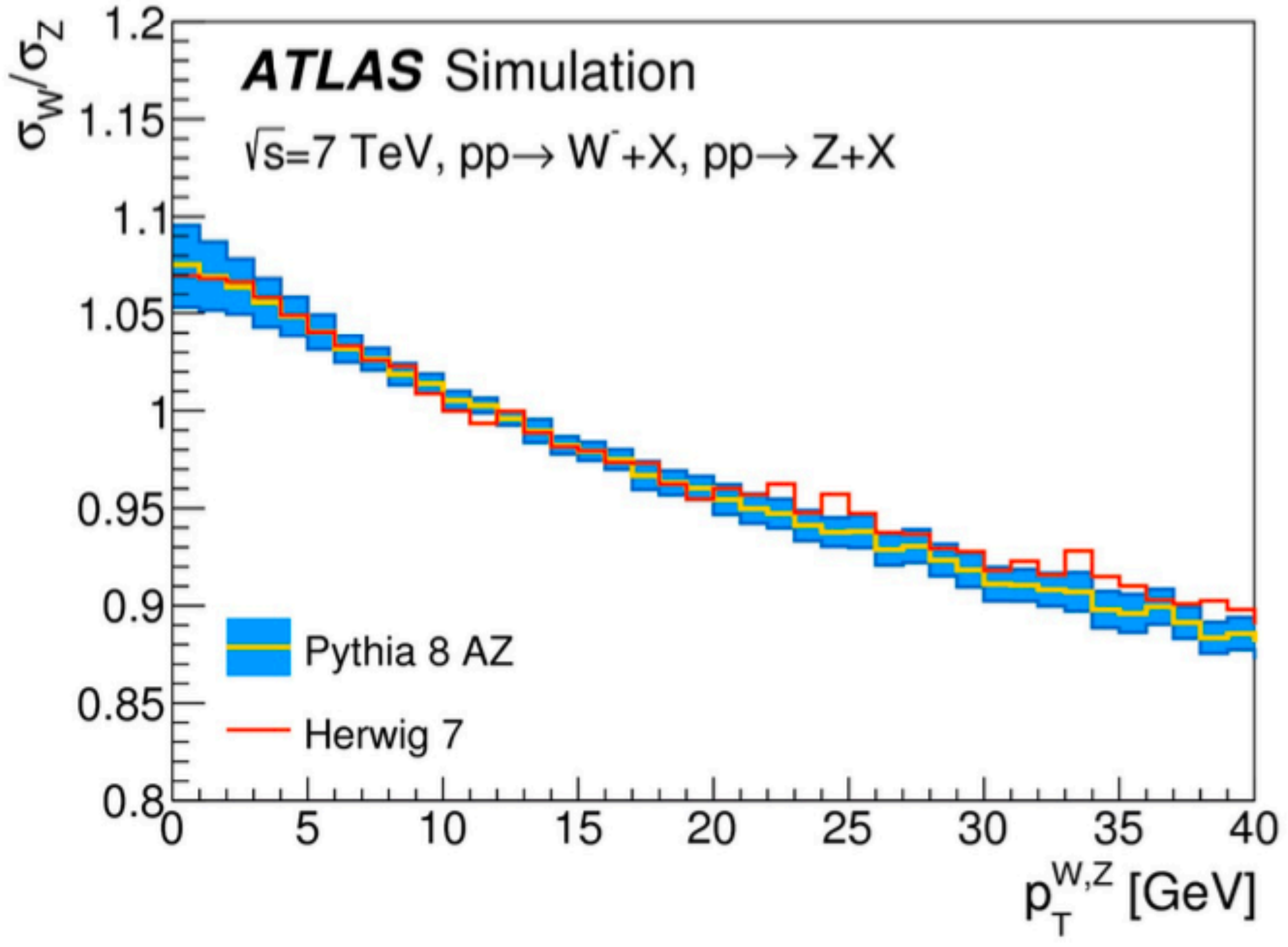
- Model for Z p_T from fitting a flexible MC prediction (Pythia8, Resbos, …) to data
- Crucial to estimate residual effects which decorrelate between W and Z

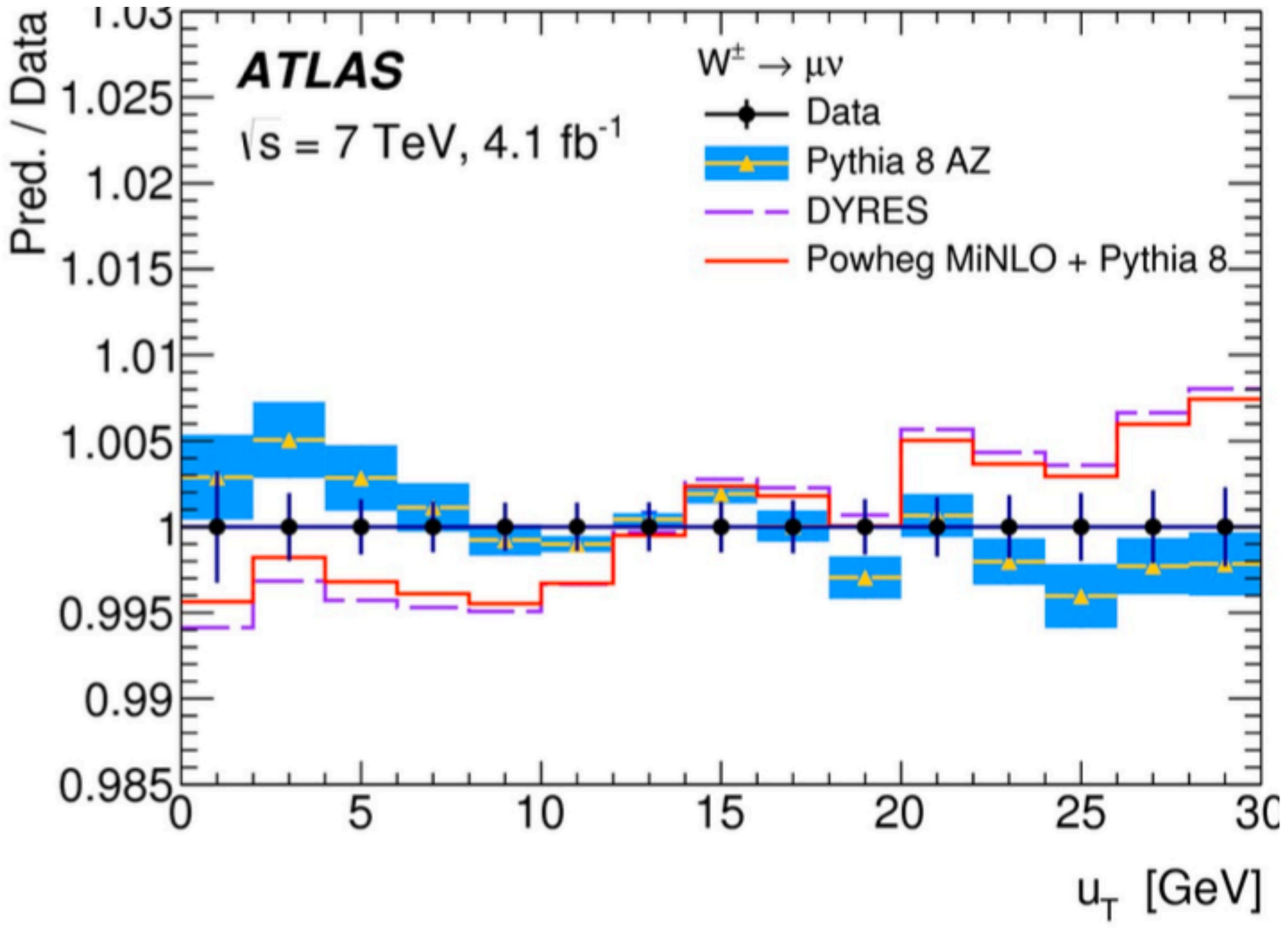
Higher order models

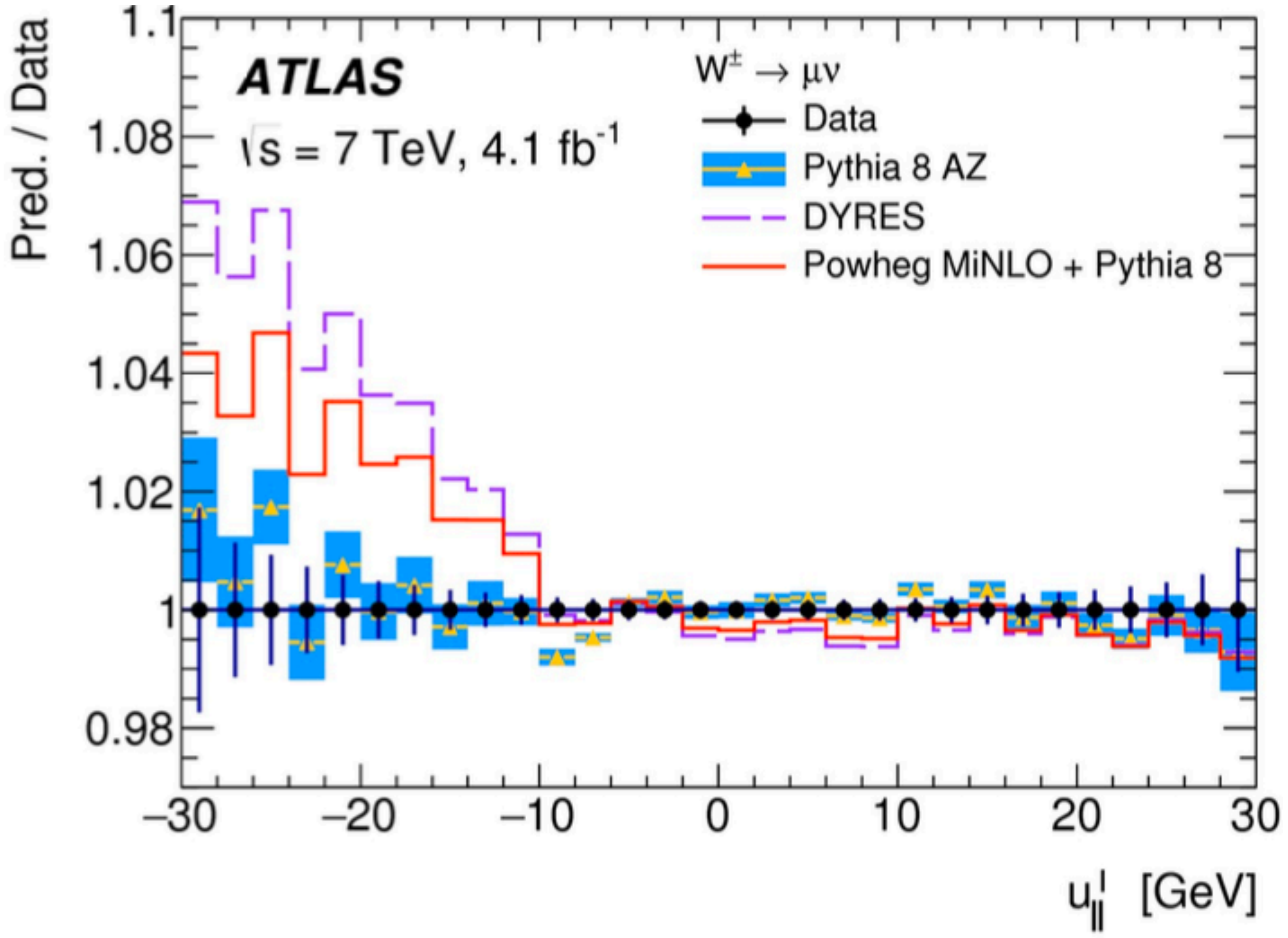
- Only Pythia, Herwig and Powheg gave a W/Z p_T ratio in agreement with data







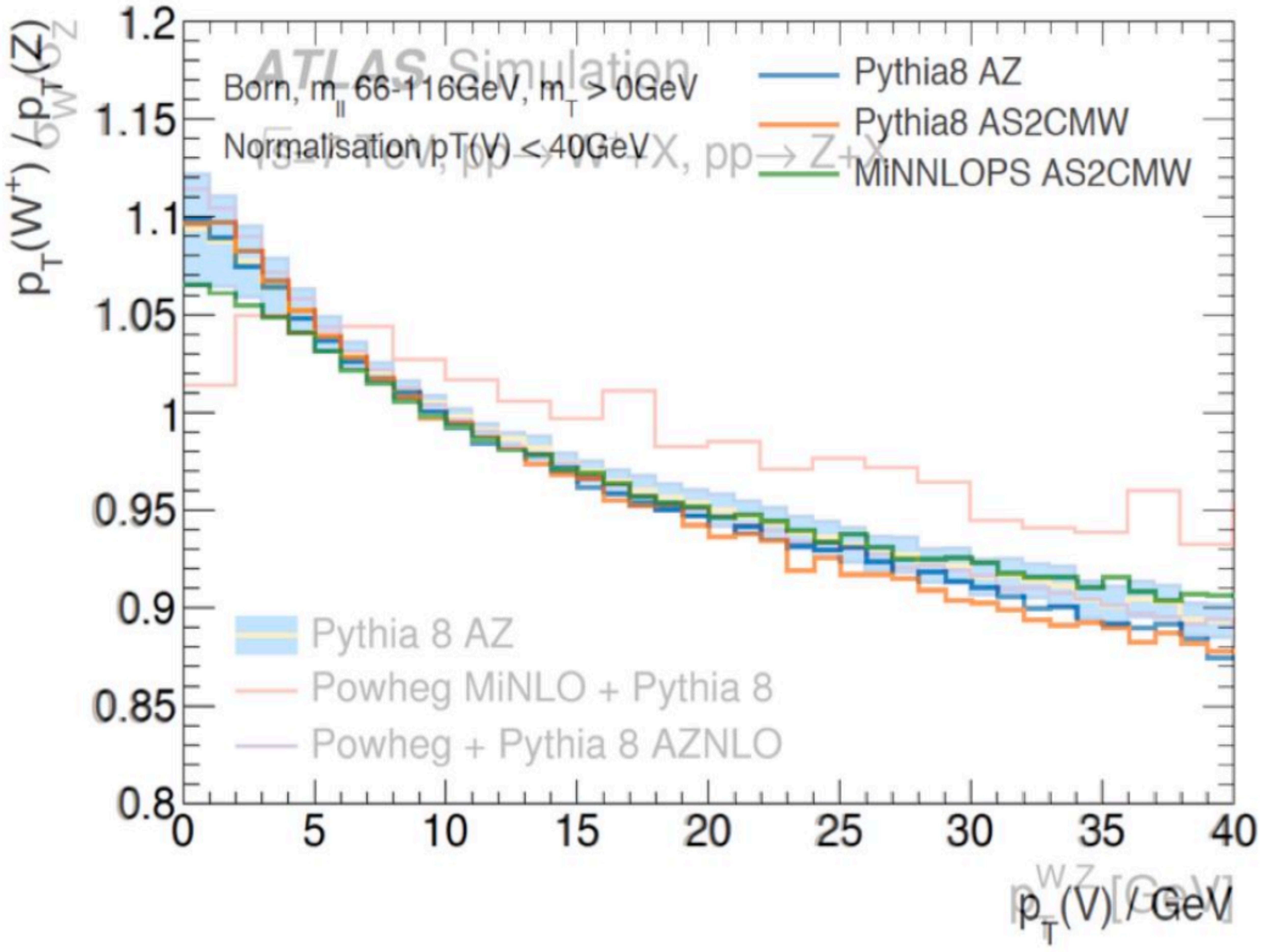


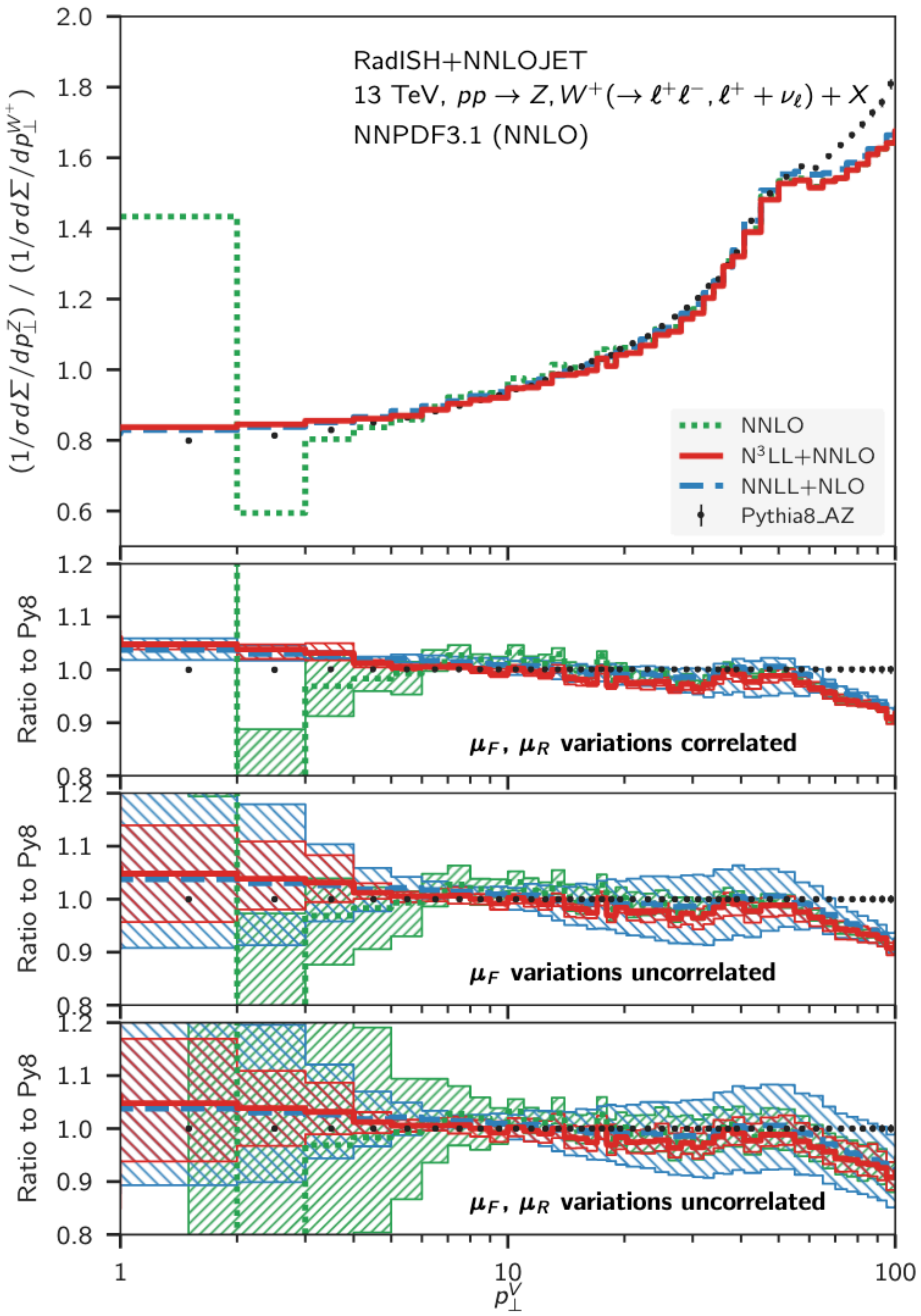


- Hadronic recoil in data strongly disfavored MiNLO and analytic resummation predictions

Higher order models

- Modern predictions in agreement with Pythia AZ
- Are they also in agreement with data ?





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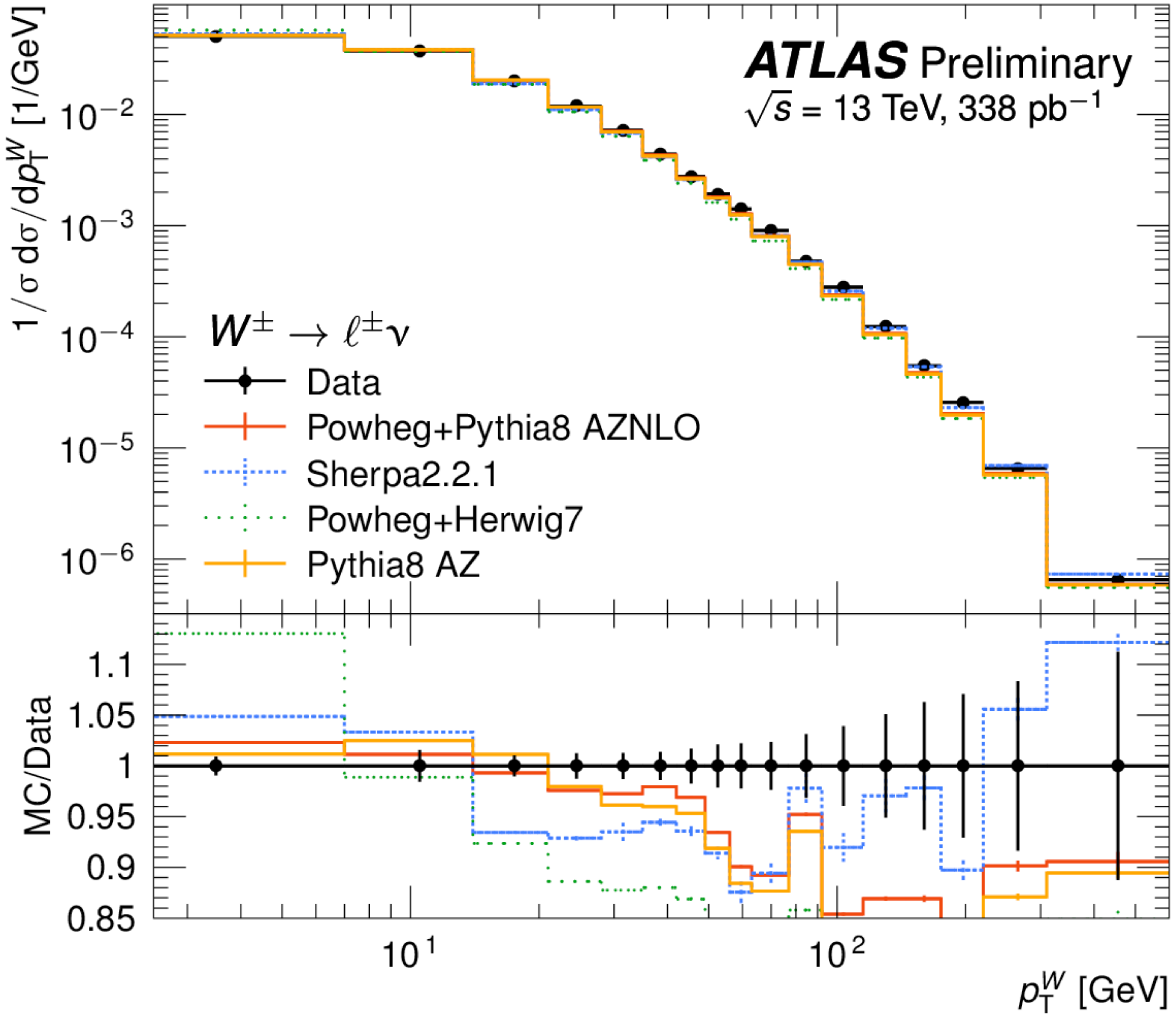
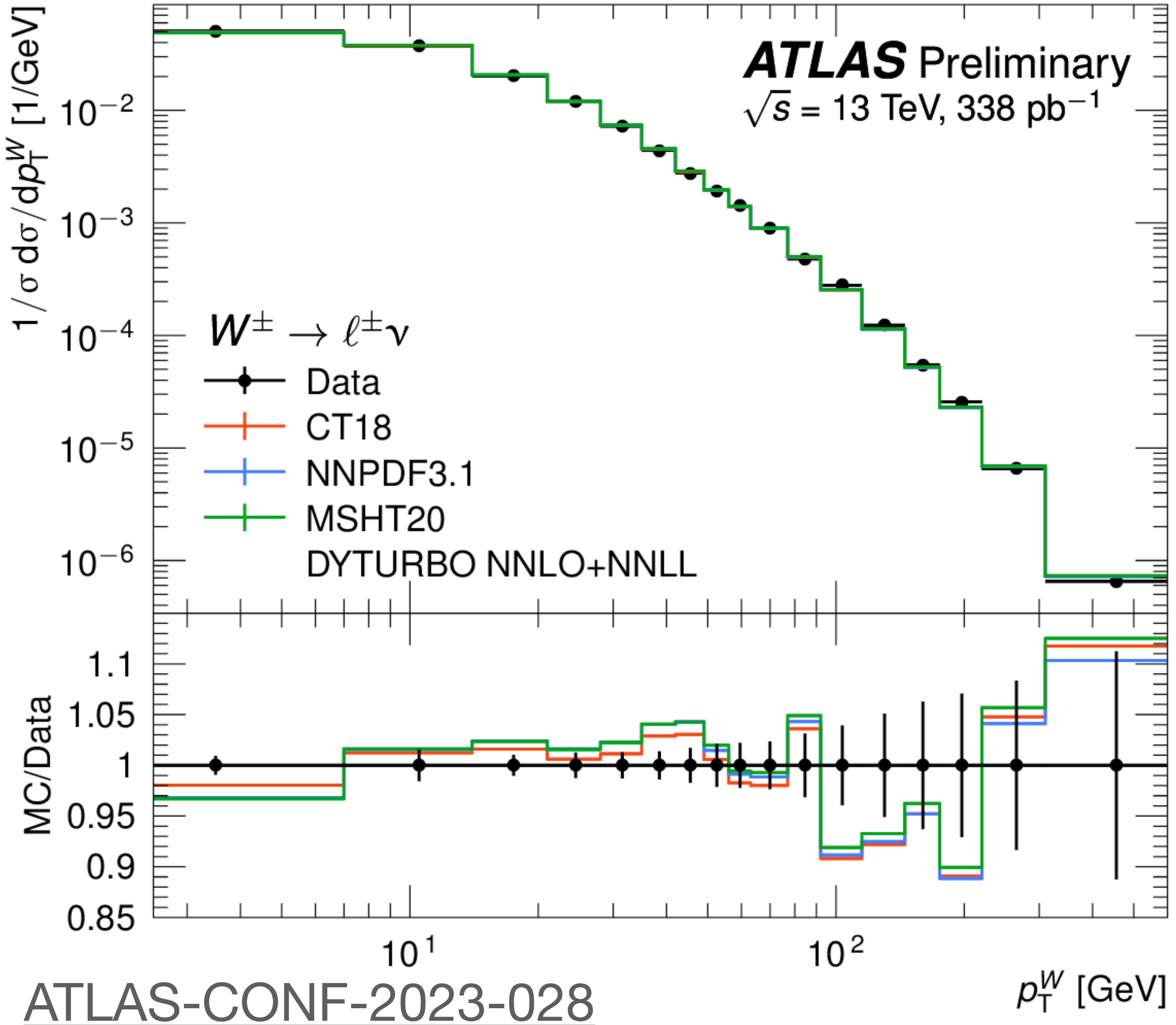
ATLAS 5/13 TeV W (and Z) p_T with low pile-up data

- 1-2% experimental precision in 7 GeV bins
- None of the considered prediction describes all distributions
- Essential to validate future p_T models for W-boson mass

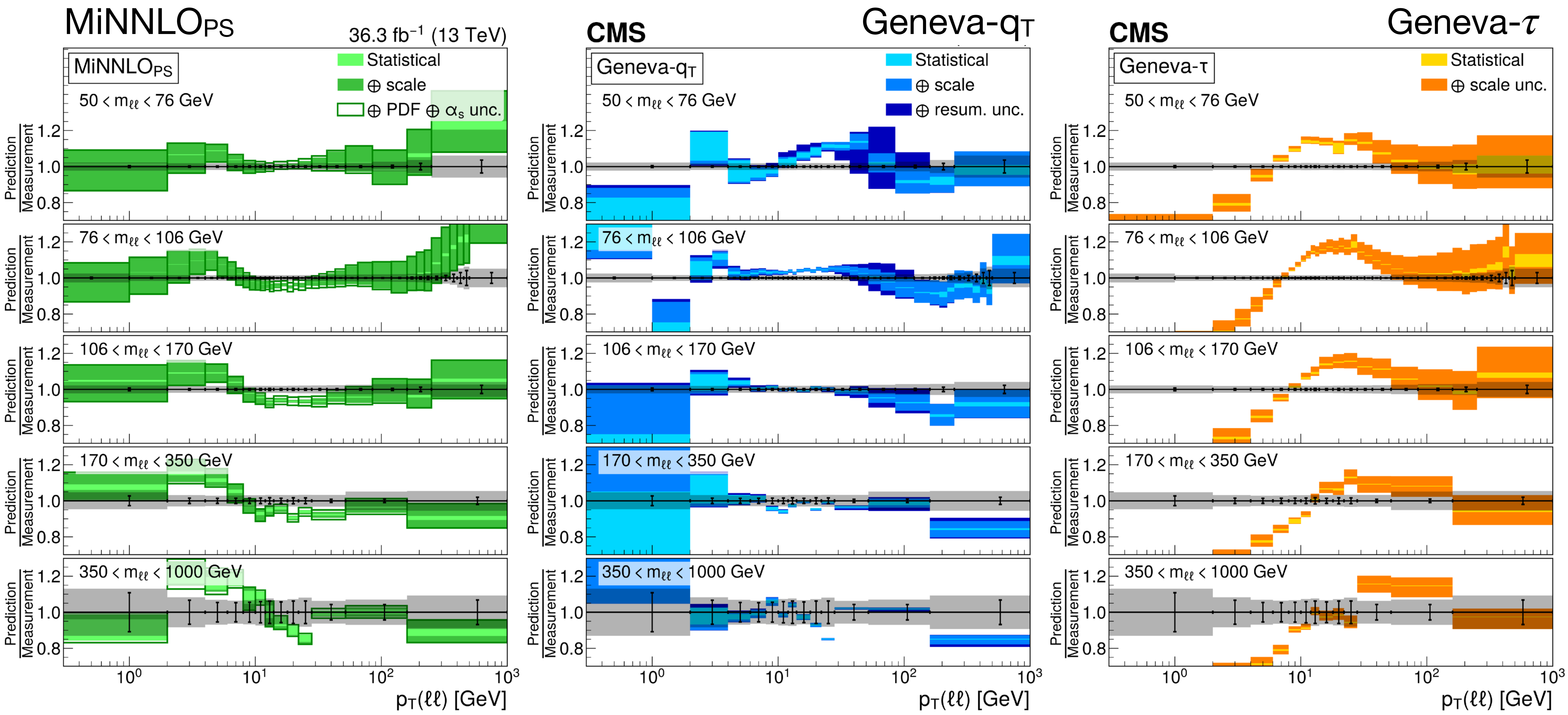




ATLAS-CONF-2023-028

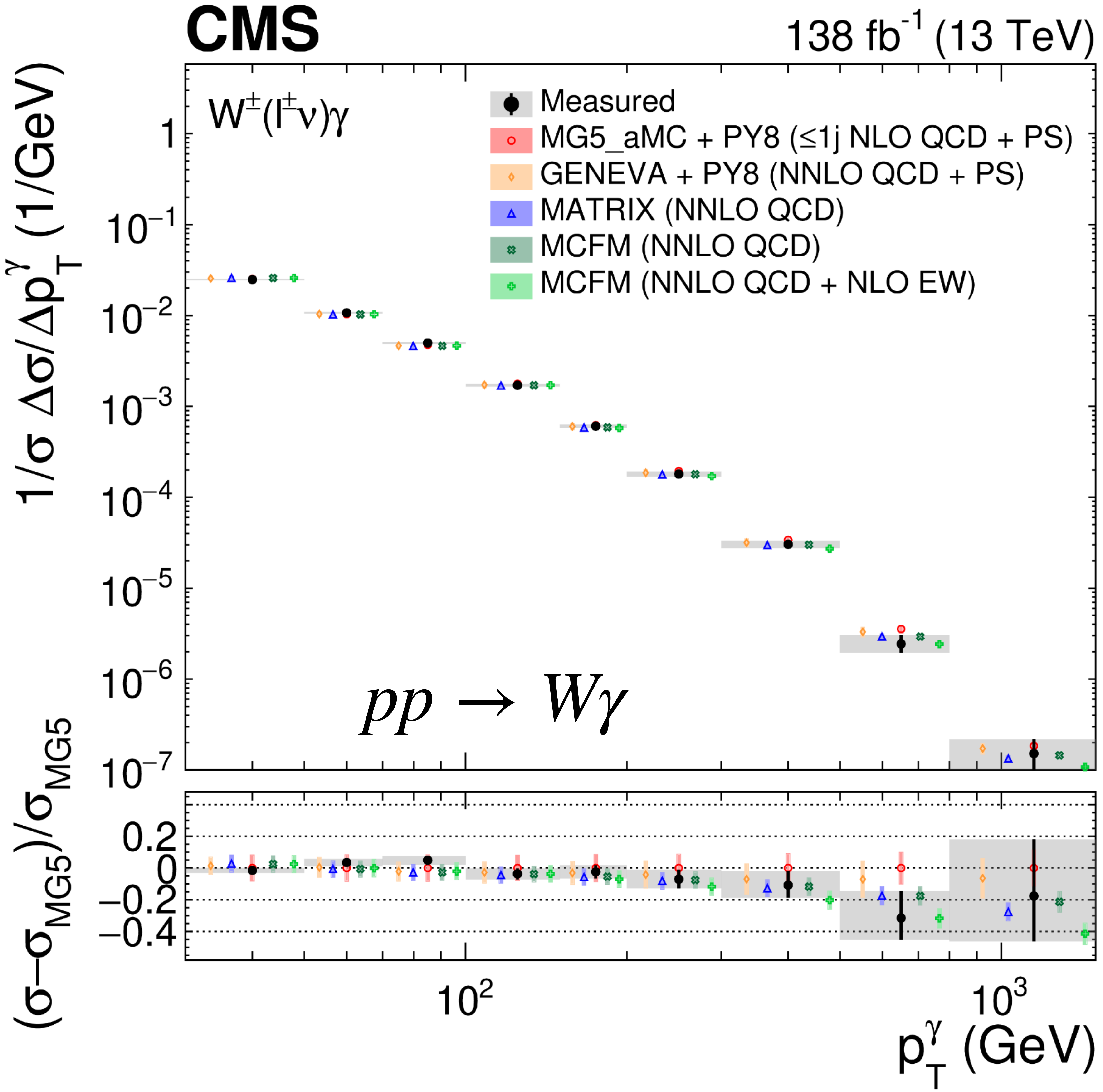
THE Z p_T AT NNLOPS

- Test of new NNLOPS simulations and of $\log(q_T/m)$ behavior



SMP-20-003

NNLOPS for DIBOSONS



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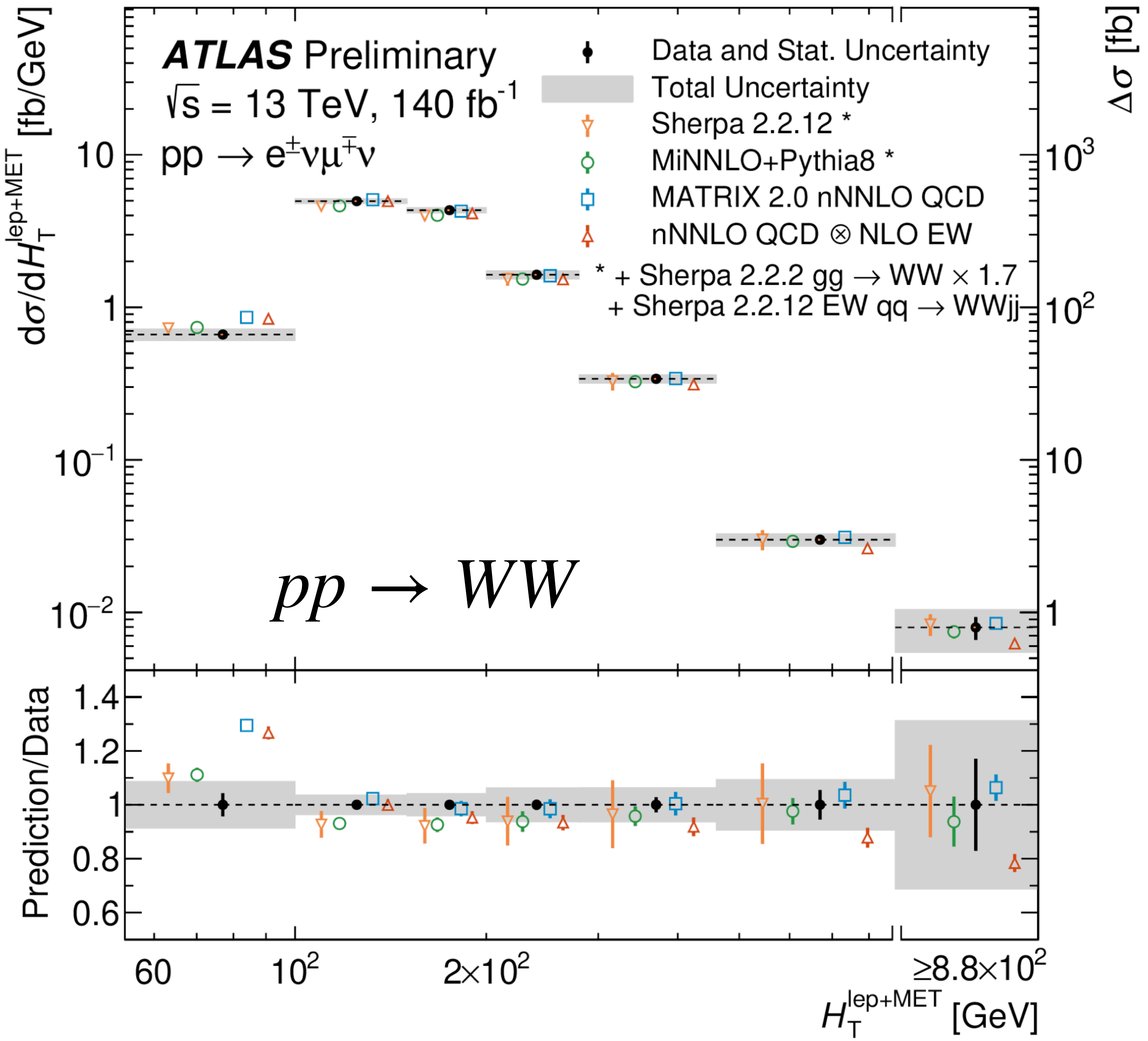
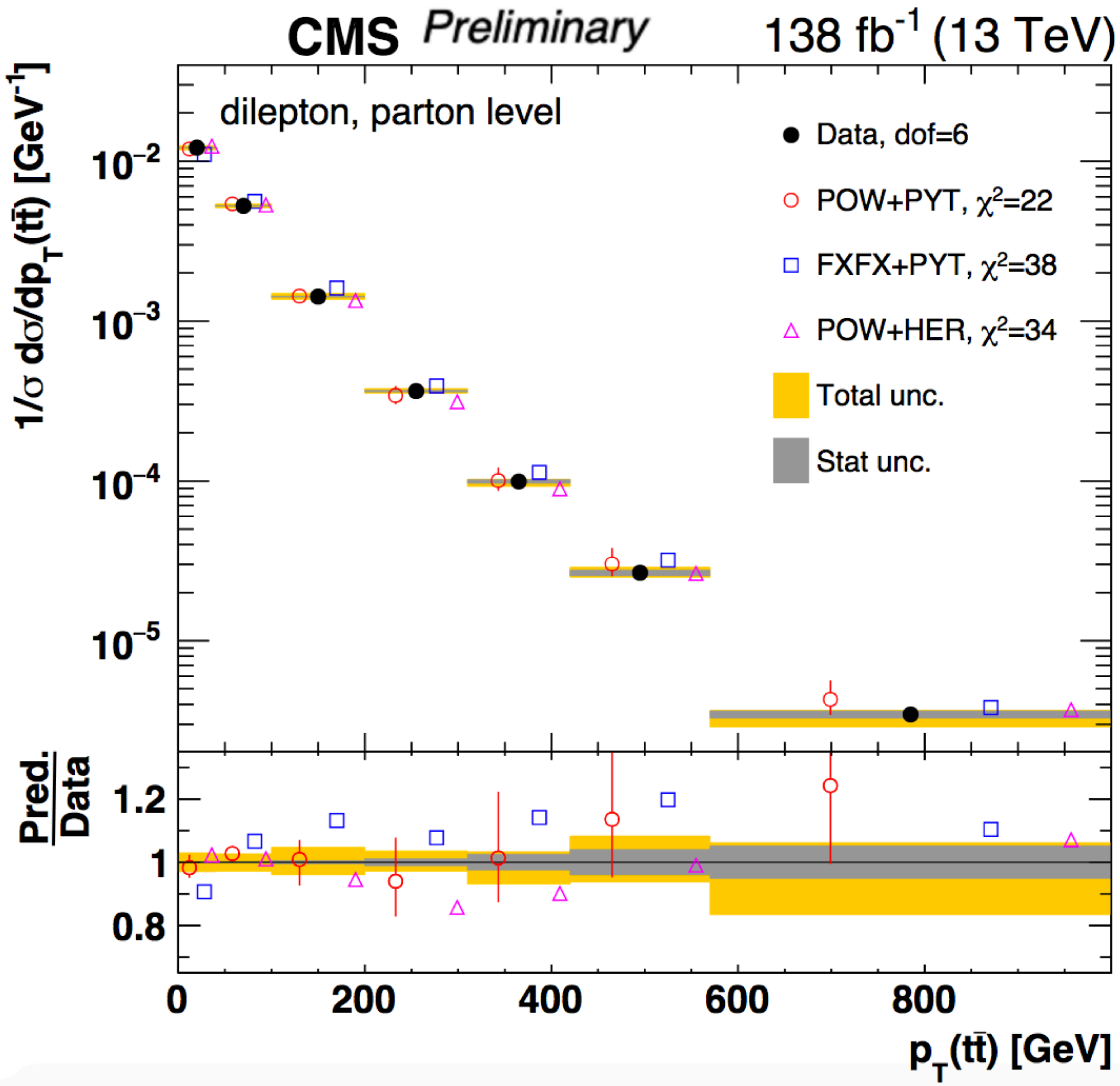
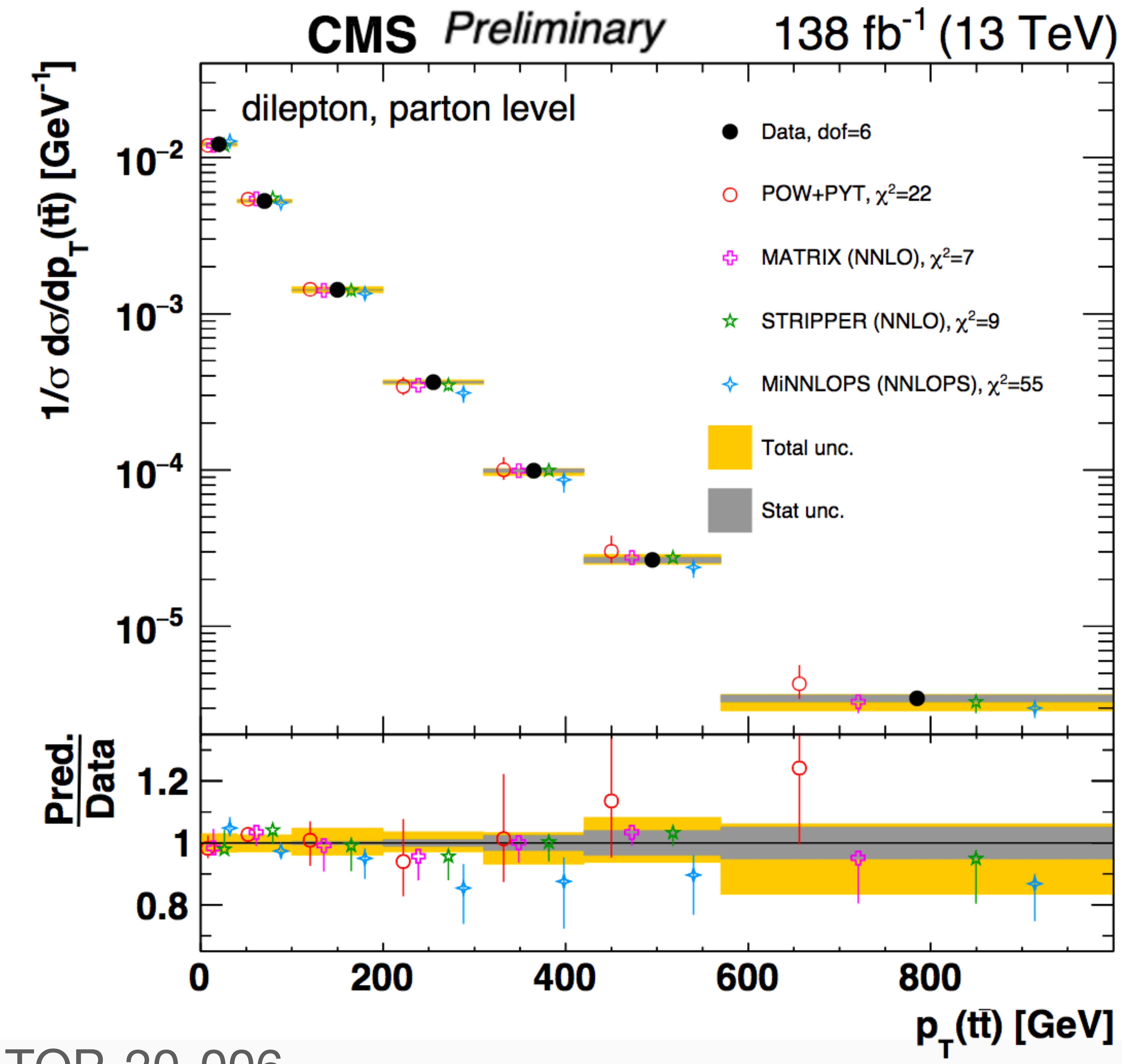


ATLAS-CONF-2023-012

NNLOPS FOR HEAVY QUARKS

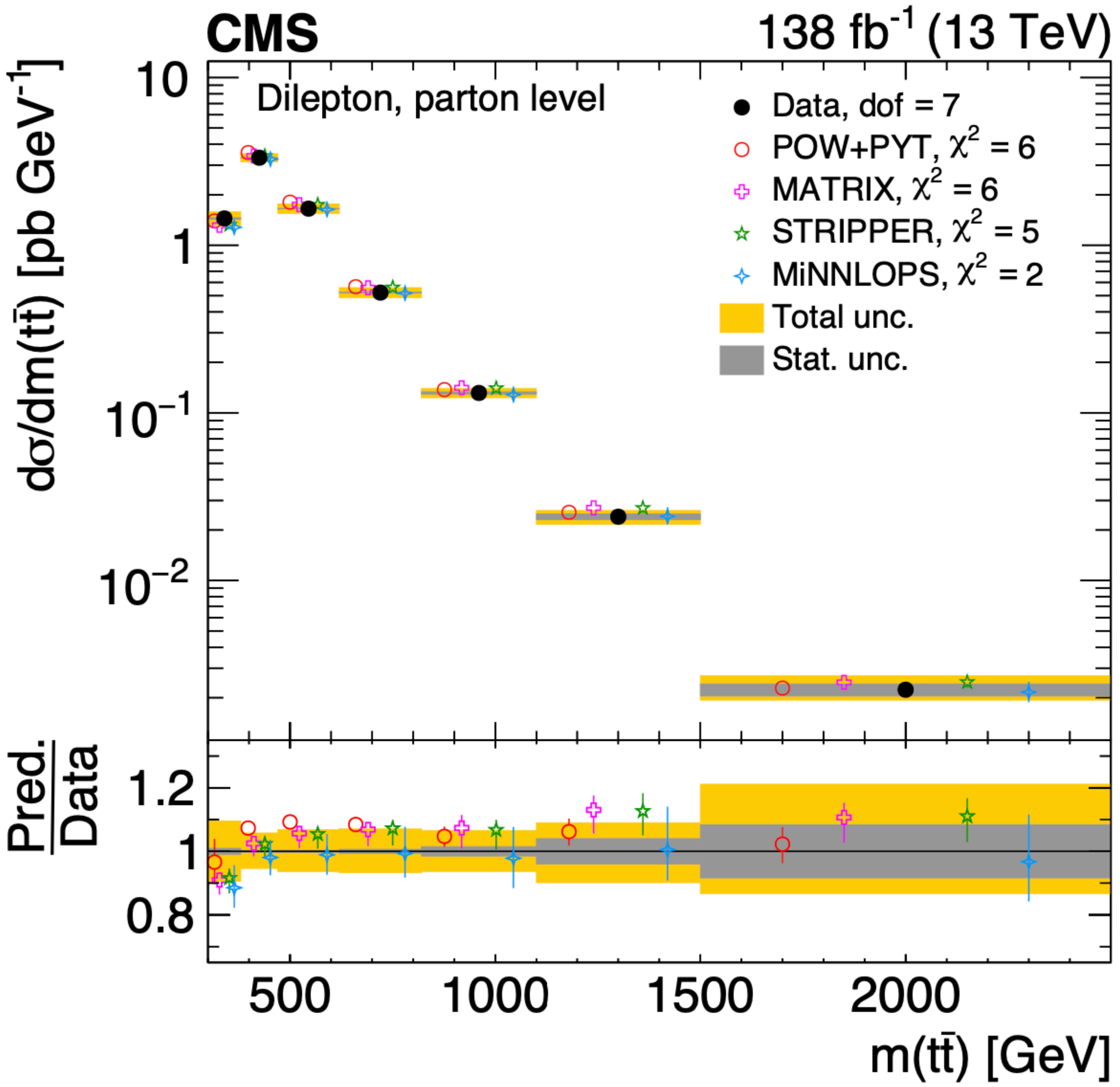
- Finally fixing the (mis)modeling of the top quark p_T at NLOPS

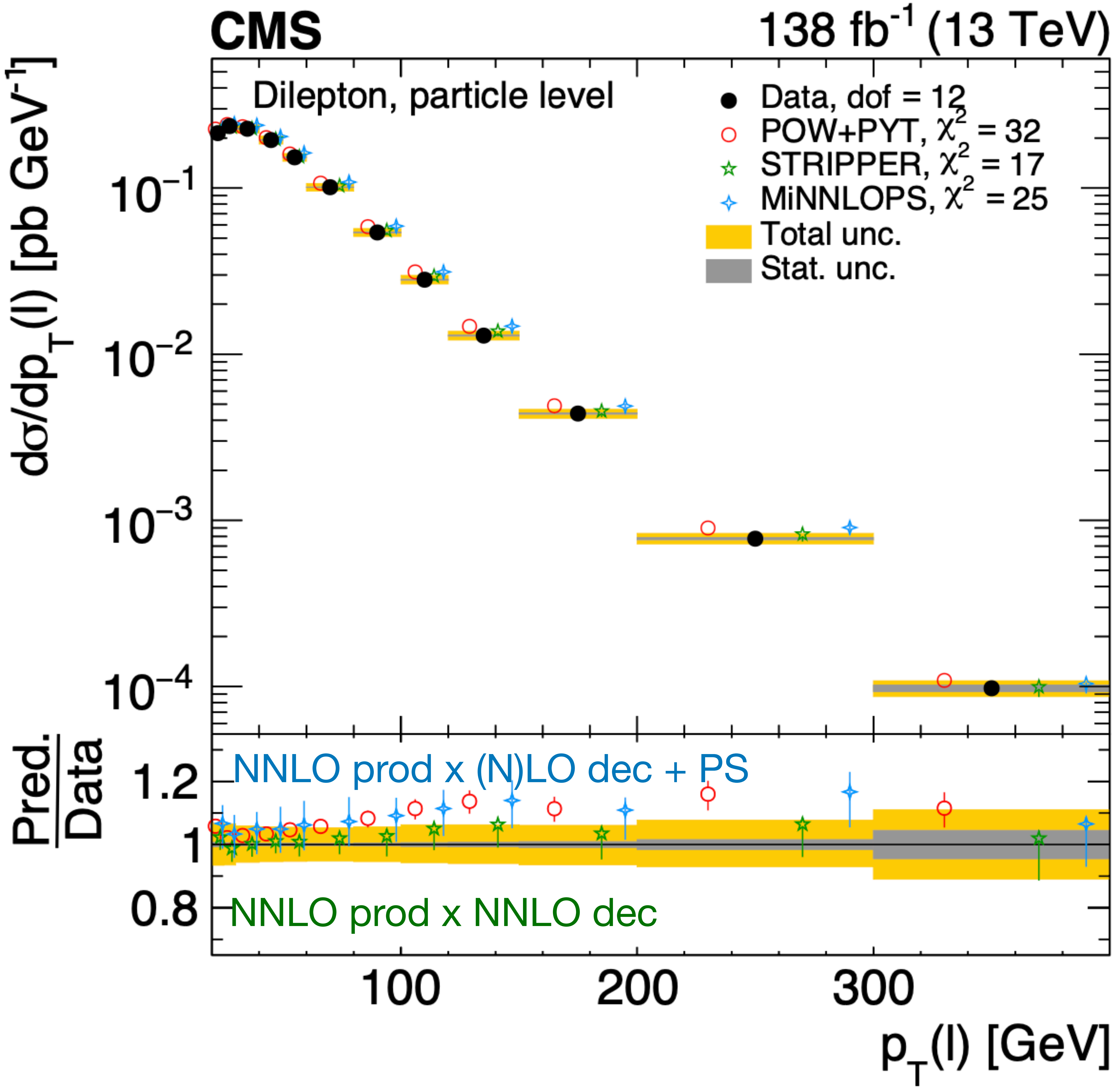




TOP-20-006

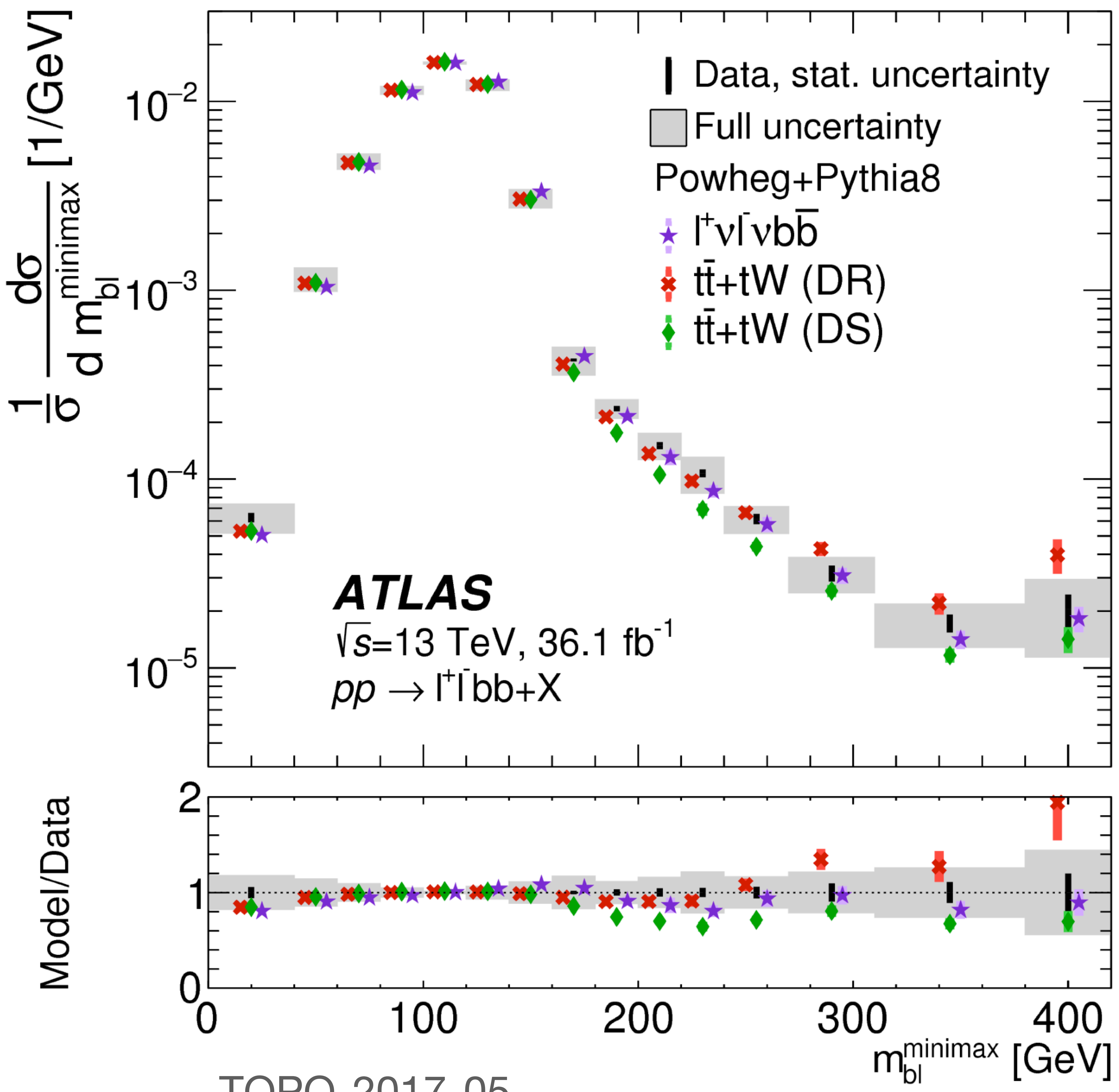
NNLOPS FOR HEAVY QUARKS



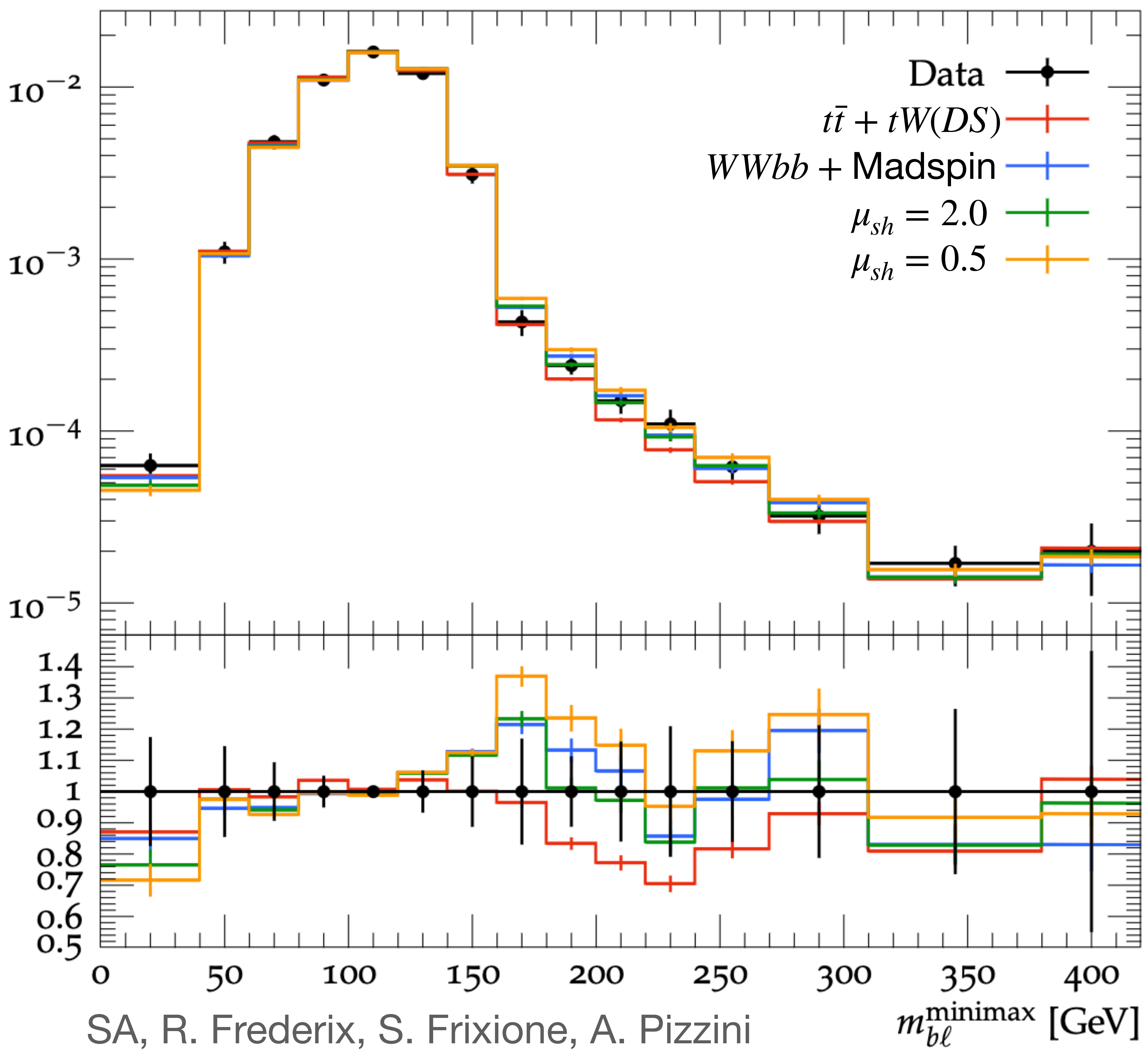


How narrow a width is enough?

- Fully off-shell matched calculations being benchmarked by experiments



TOPQ-2017-05



SA, R. Frederix, S. Frixione, A. Pizzini

Matching at NLO QCD + EW

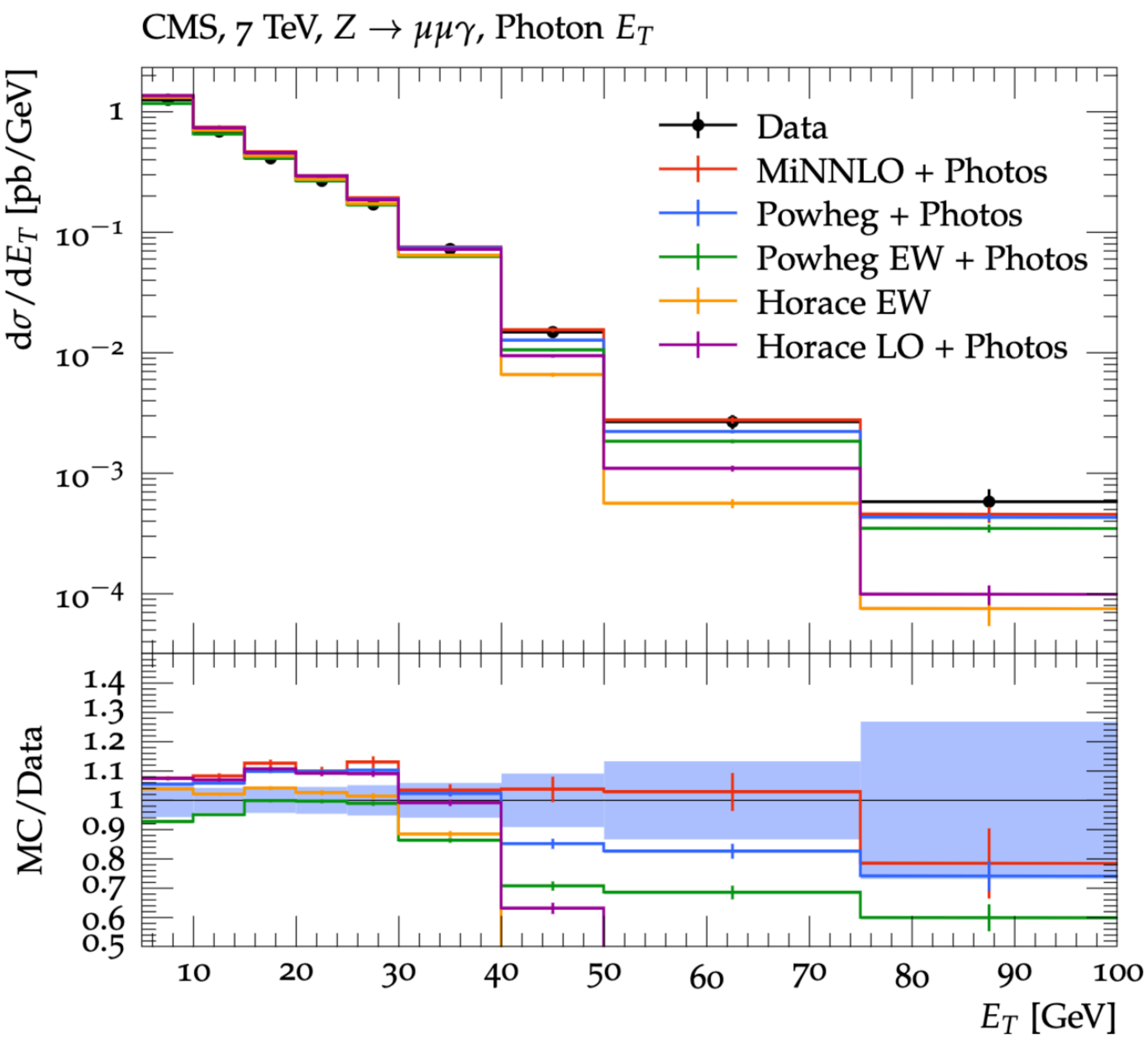
- At the level at which we start worrying about NNLO QCD effects,
  we also cannot ignore NLO EW

- QED initial and final-state radiation already included with showers/Photos (sufficient?)

- NLO QCD+EW matching to showers available in Powheg for selected processes

  Possibly still needs optimizations, alternative codes would be welcome

- How far are we from
  NNLO QCD + NLO EW + PS ?



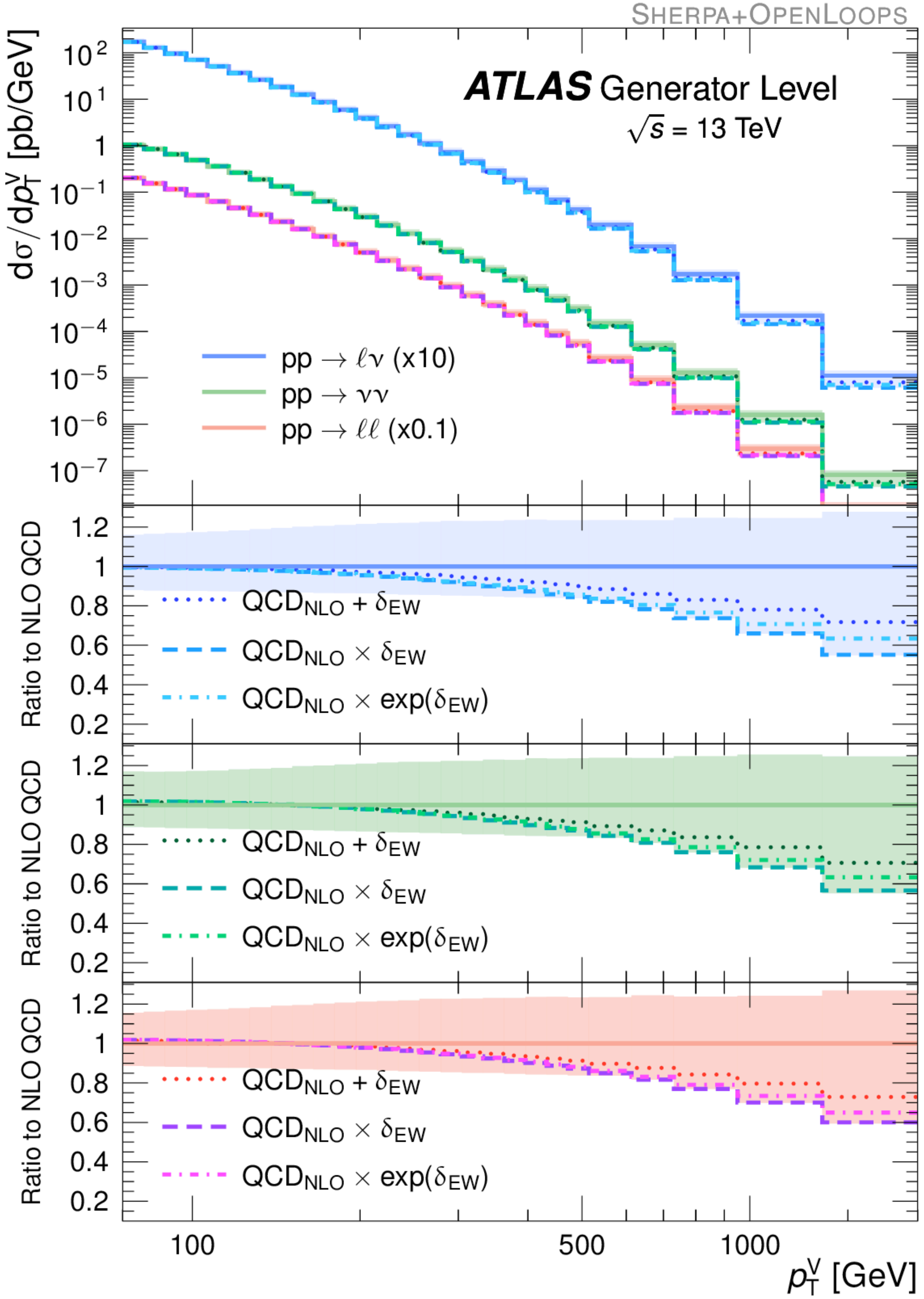
EW Sudakov corrections

- Electroweak Sudakovs important at high energy (reach negative tens of percent)

- Sherpa allows for them to be included in an approximated approach within its MEPS@NLO QCD merging

- Additive, multiplicative or exponentiated prescription to evaluate uncertainties

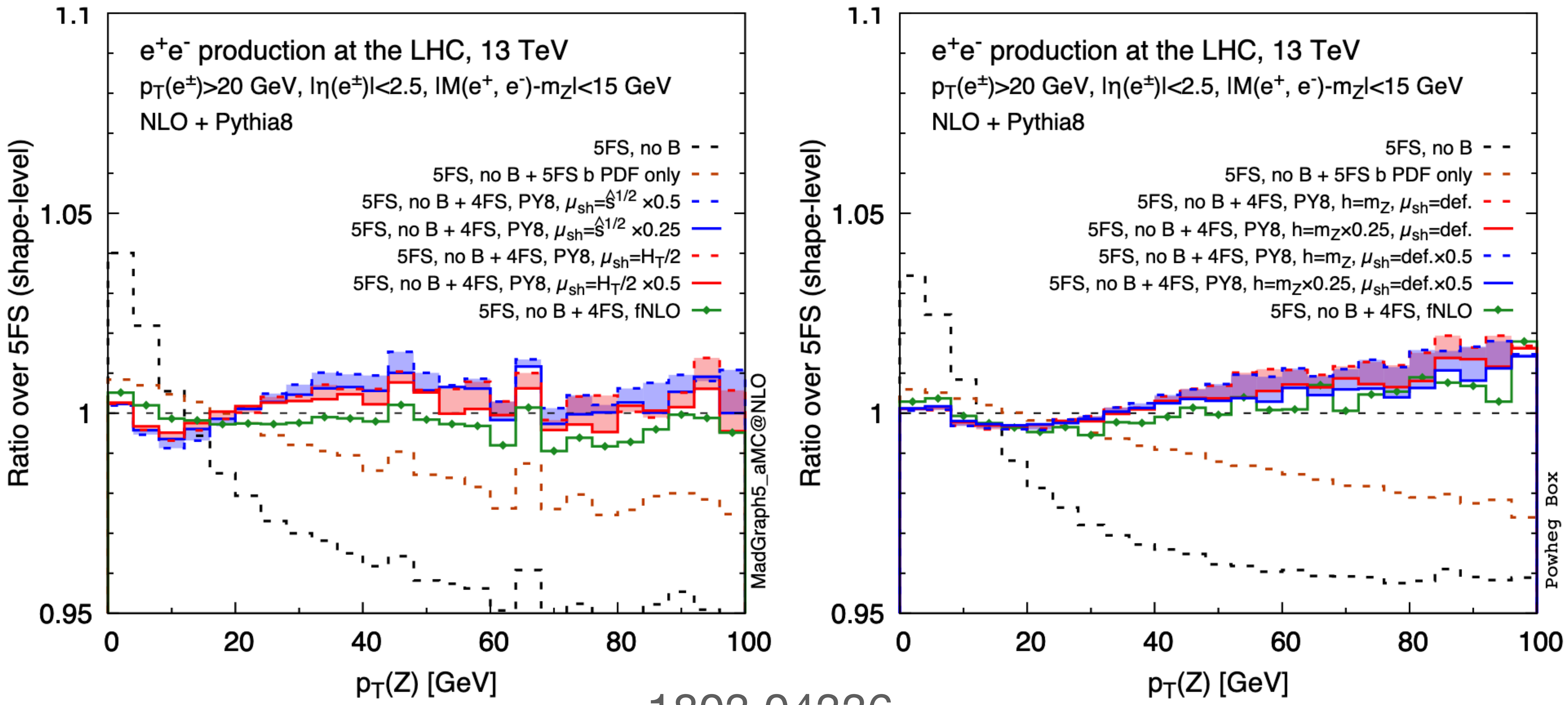
- Conveniently available as weights on top of the QCD-merged prediction



PMGR-2021-01

Are mass effects under control?

- Heavy Flavors important contribution to DY,H p_T and background to i.e. $h \to b\bar{b}$
- Modelled with MC with massless quarks, as shower contribution not small
- Sherpa FONLL-like merging of 4FS/5FS ME used in new ATLAS samples of DY/$t\bar{t}$



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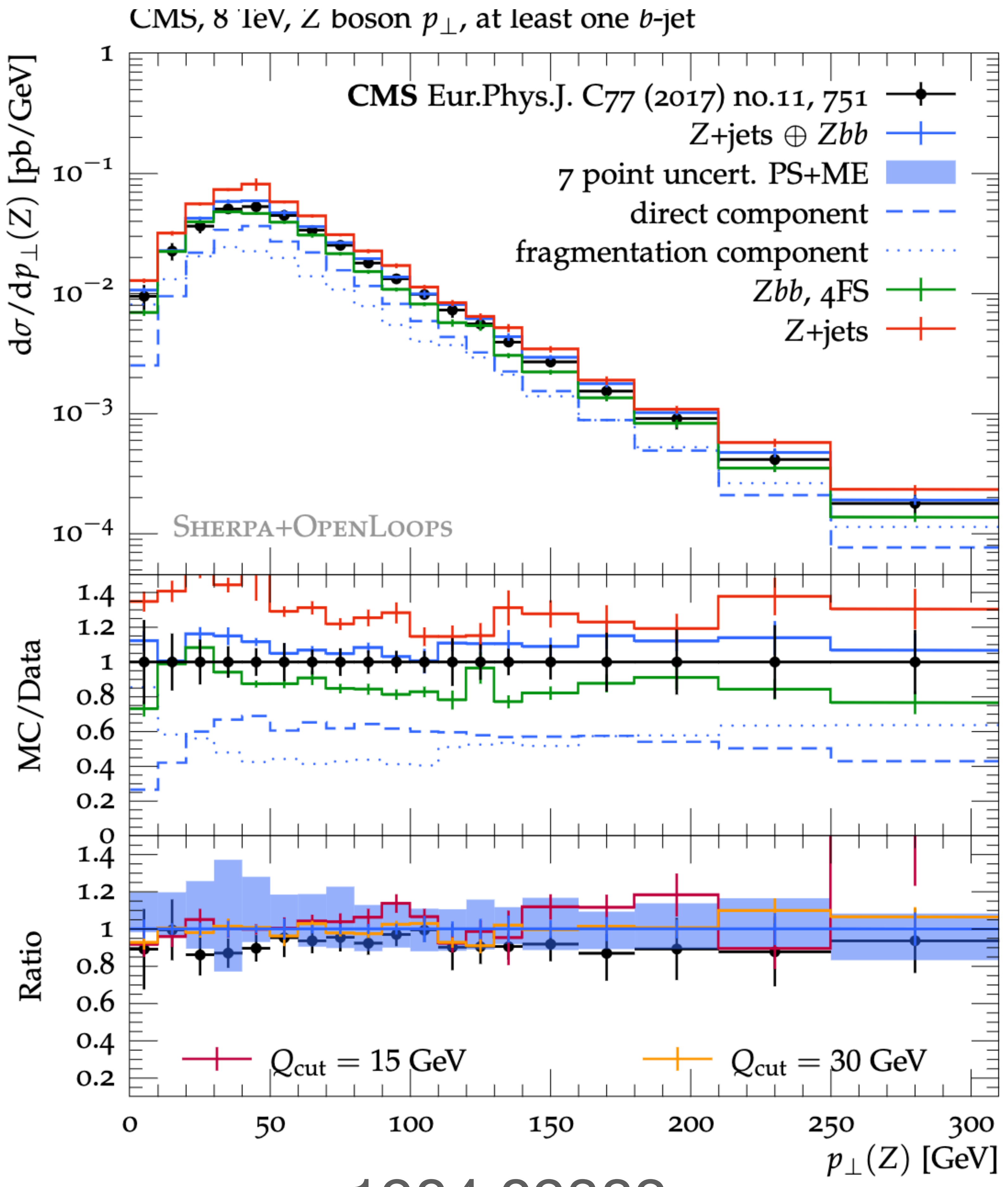
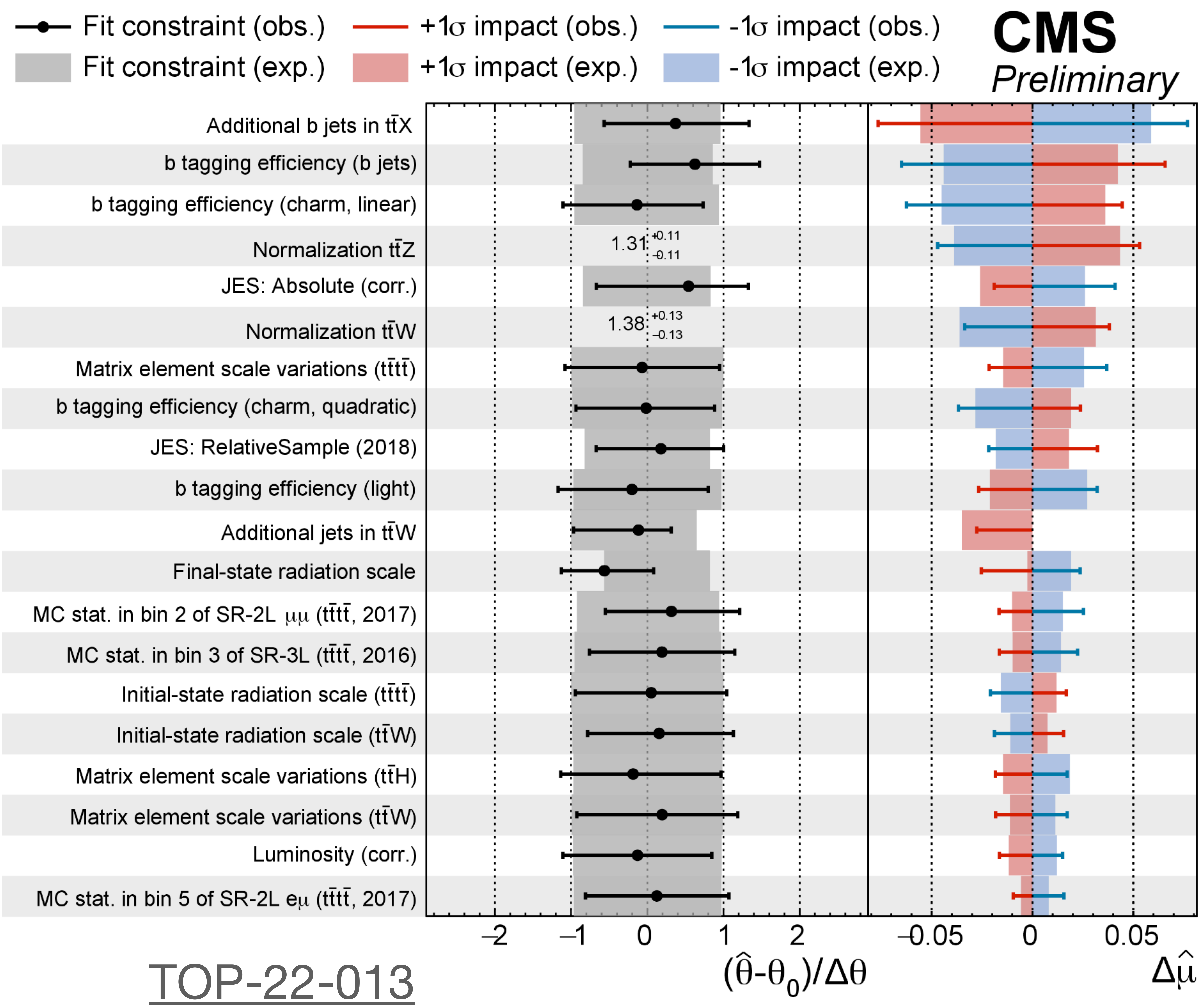


1904.09382

Uncertainties

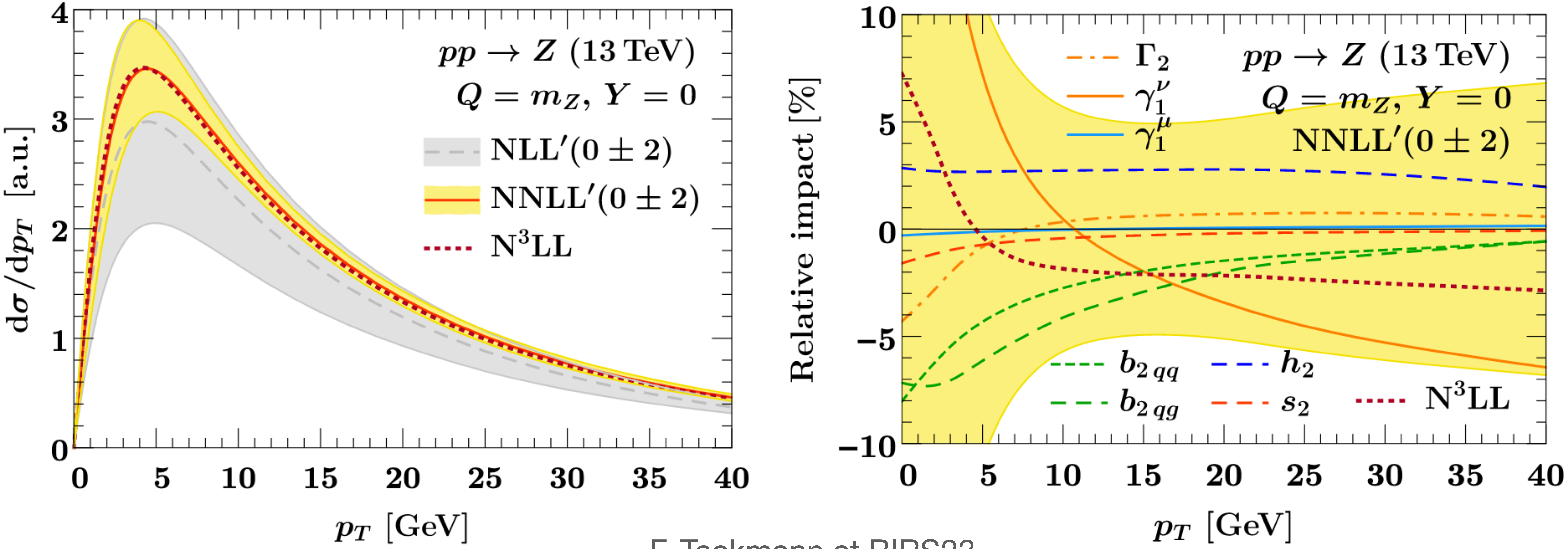
- A prediction is only as good as its uncertainty
- Most LHC analyses nowadays use Likelihood fits to extract maximal information from data

- Need to incorporate uncertainties on theoretical predictions in the likelihood
- Often just propagate (and fit) scales as if they were physical parameters
- Can lead to very wrong results
- No clear solution, but any progress would be welcome



TOP-22-013

MHO Uncertainties - resummation



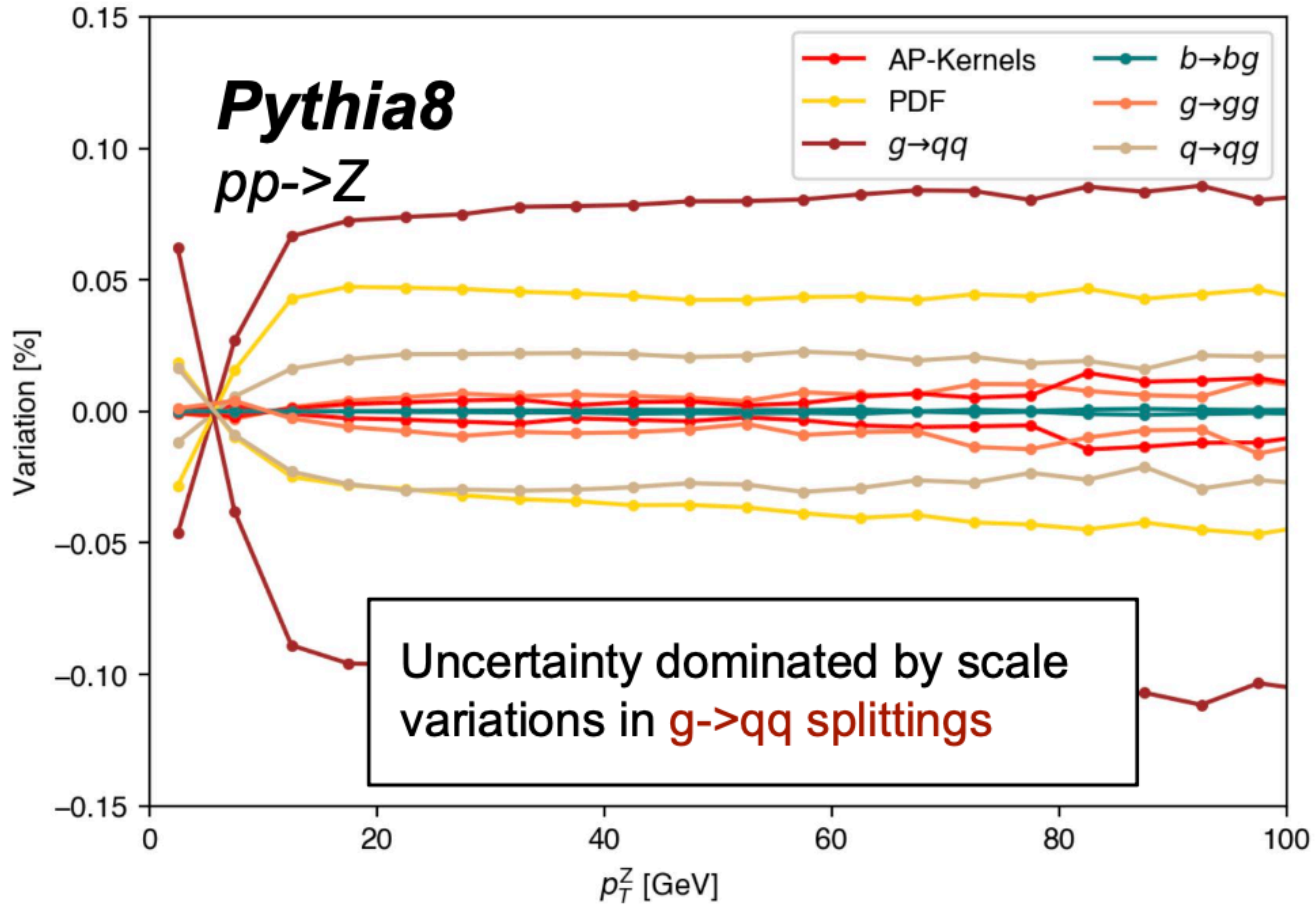
F. Tackmann at BIRS23

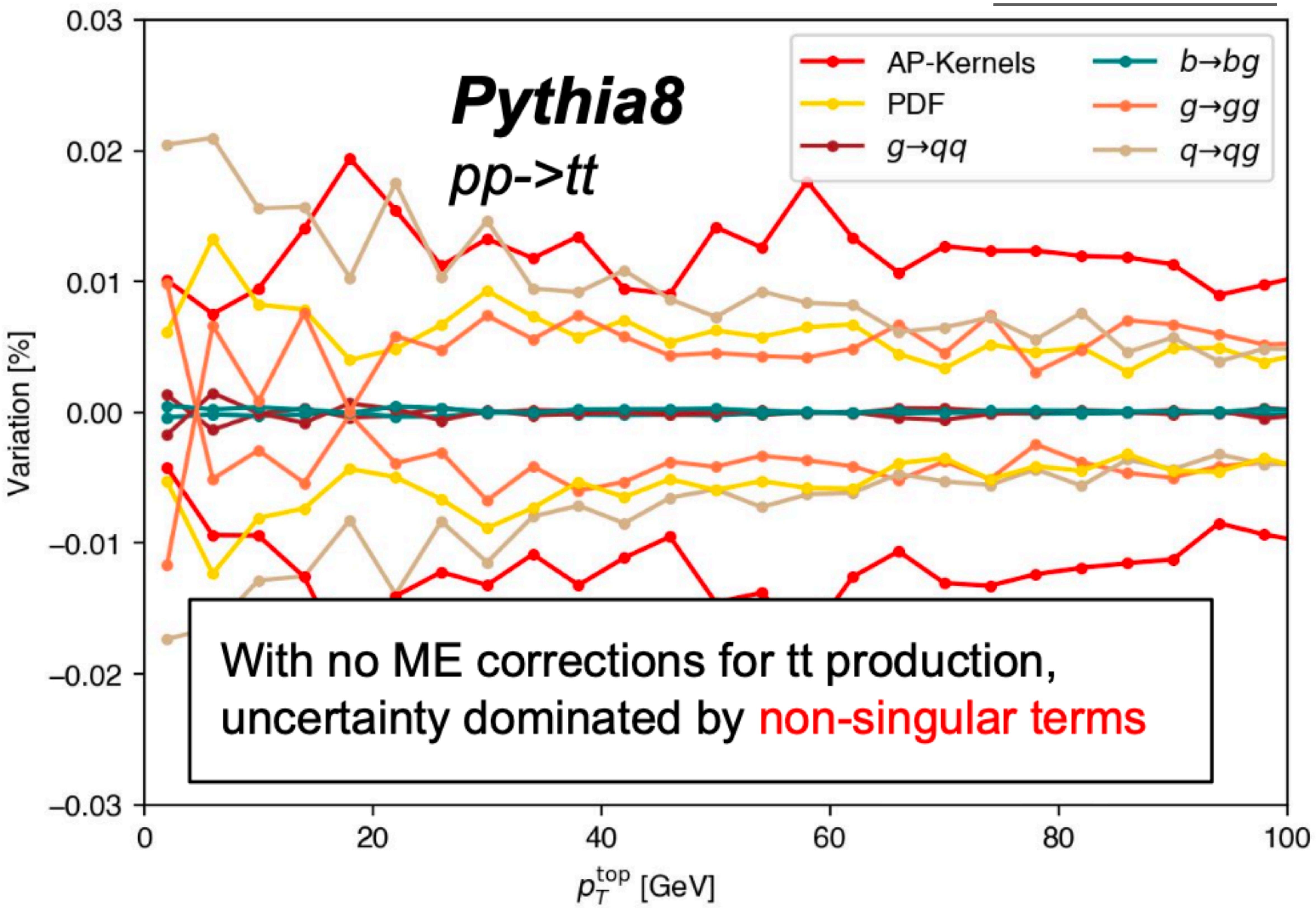
- Use known structure of resummation at higher orders to parametrise it in terms of nuisance parameters giving rise to a pattern of correlations
- Size of these nuisance parameters ambiguous, but not important if they are constrained by data

MHO Uncertainties - Parton shower

- Pythia8 allows for a similar decomposition into nuisance parameters by varying independently the each DGLAP splitting as well as non-singular terms
- CMS now propagates these weights in all Pythia MC samples such that they can provide a more realistic correlation model in likelihood analysis

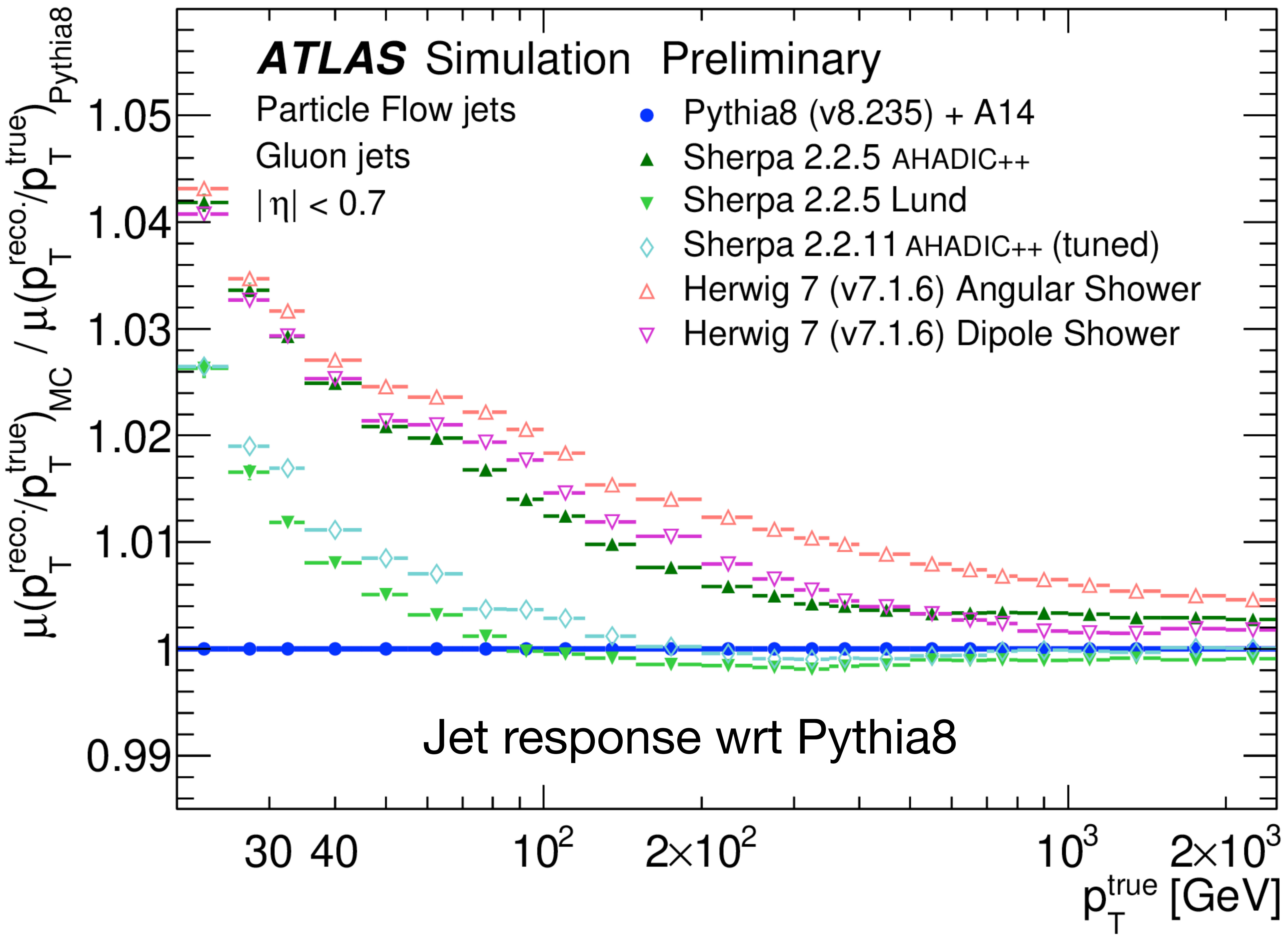
1605.08352





Hadronisation in jet measurements

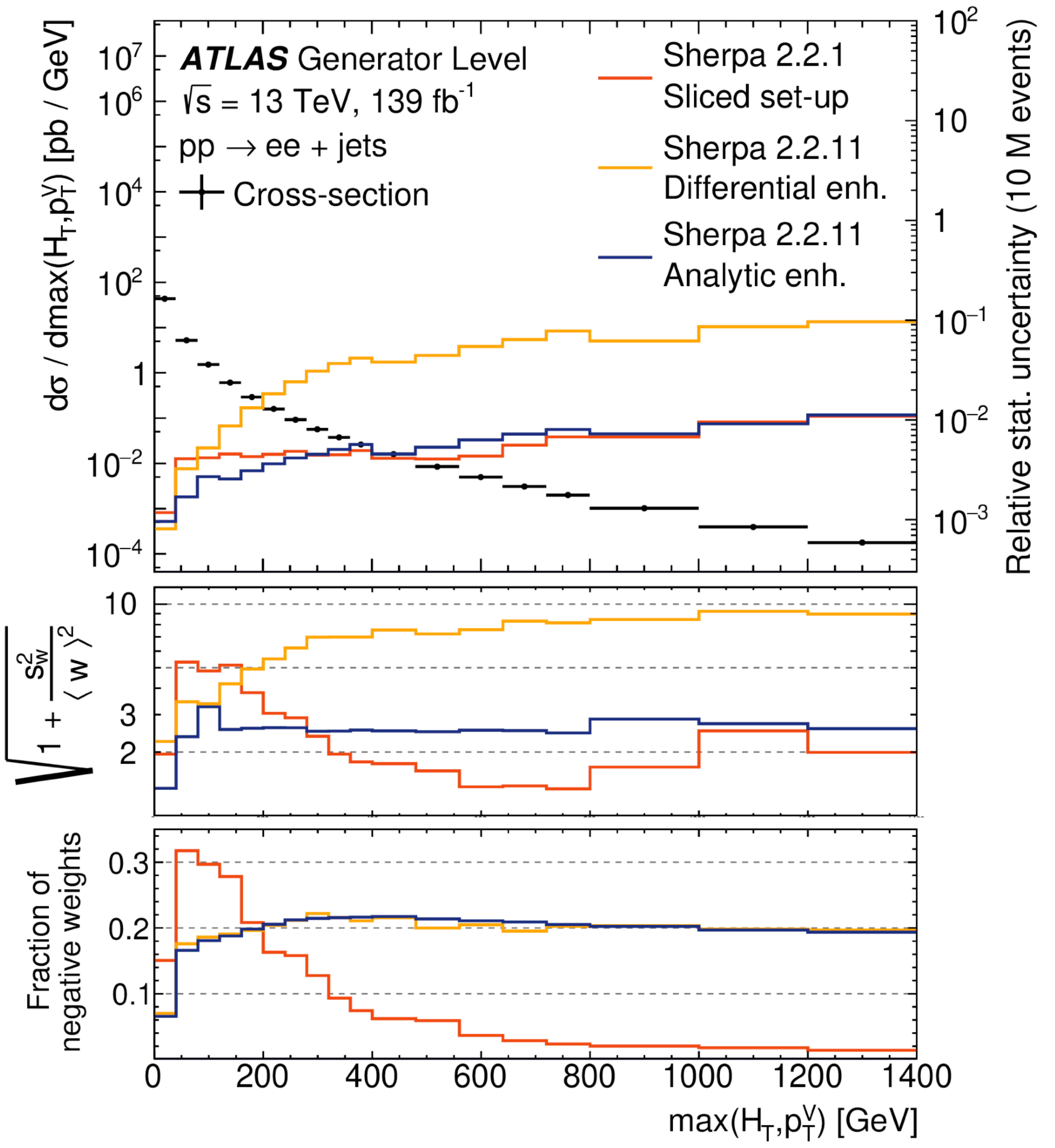
- Jet energy measurements depend on the simulated hadron content of jets
- 1-2% differences depending on the hadronisation model
- Differences mostly from Kaon and Baryon fractions



- One of the largest sources of jet energy uncertainties, unclear if can be reduced by further tuning

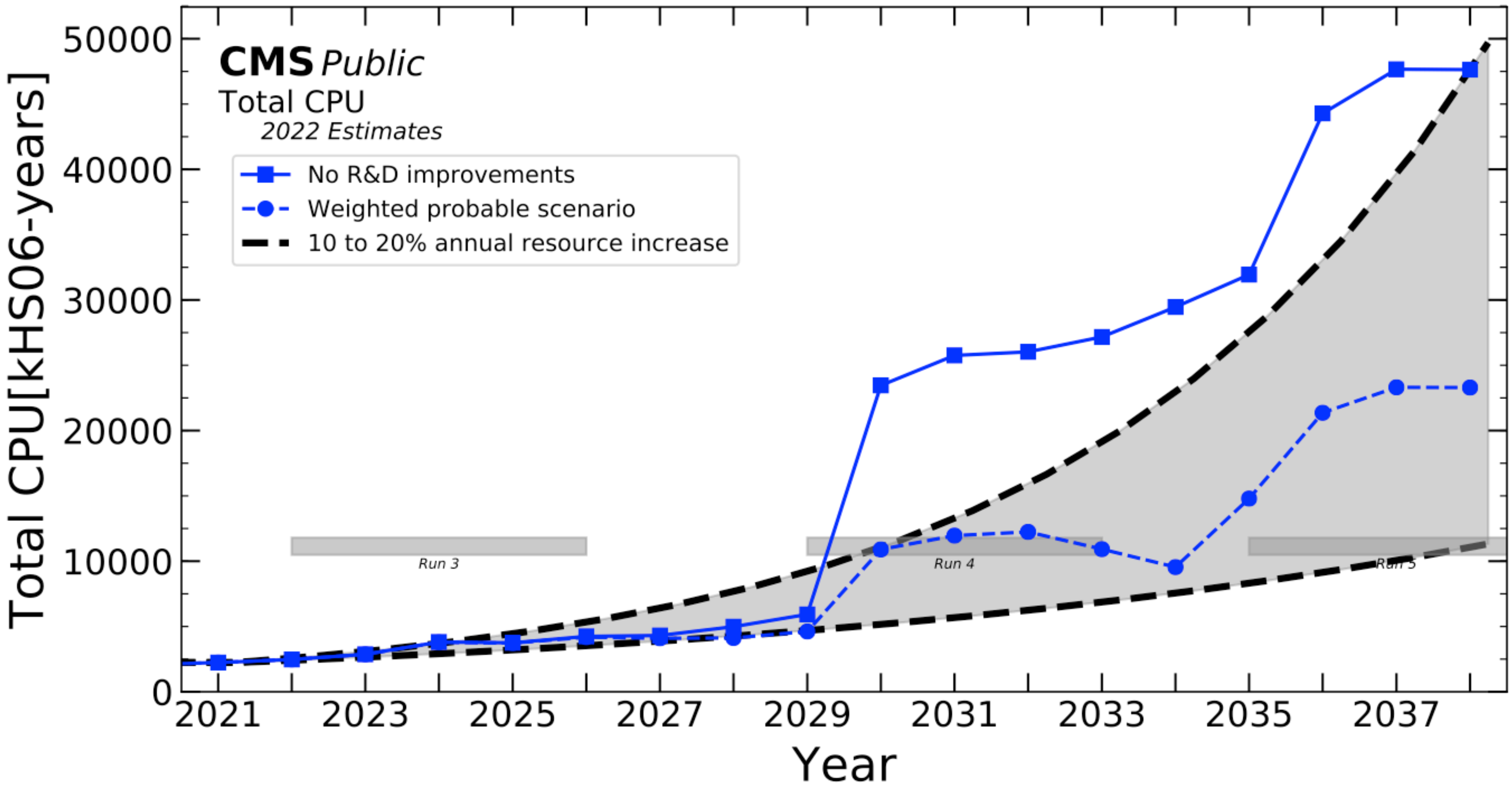
Computing aspects

- We don't just need better generators, we also need to run them at scale
- Public, fast, scalable
- Small fraction of negative weighted events
- Fast and efficient reweighting at least for scale and PDF variations
- Simple and efficient biasing in phase space (to populate tails)
- Support for heterogeneous computing (?)



PMGR-2021-01

HL-LHC Computational Challenges



https://twiki.cern.ch/twiki/bin/view/CMSPublic/CMSOfflineComputingResults

Summary

- Last 15 years have seen huge progress in Monte Carlo event generators
  - From LOPS to NLOPS (including off-shell and EW matching) and now NNLOPS
- These developments have been/are essential for the LHC physics program
  - And many still need to propagate to the experiments
- Enormous progress on the hard process calculations,
  for the future we will need to match it for the remaining bits
  - N3LOPS for selected processes: Drell-Yan, Higgs, top(?)
  - Better shower accuracy/control, mass effects treatment, non-perturbative models
  - Uncertainties, uncertainties, uncertainties, …