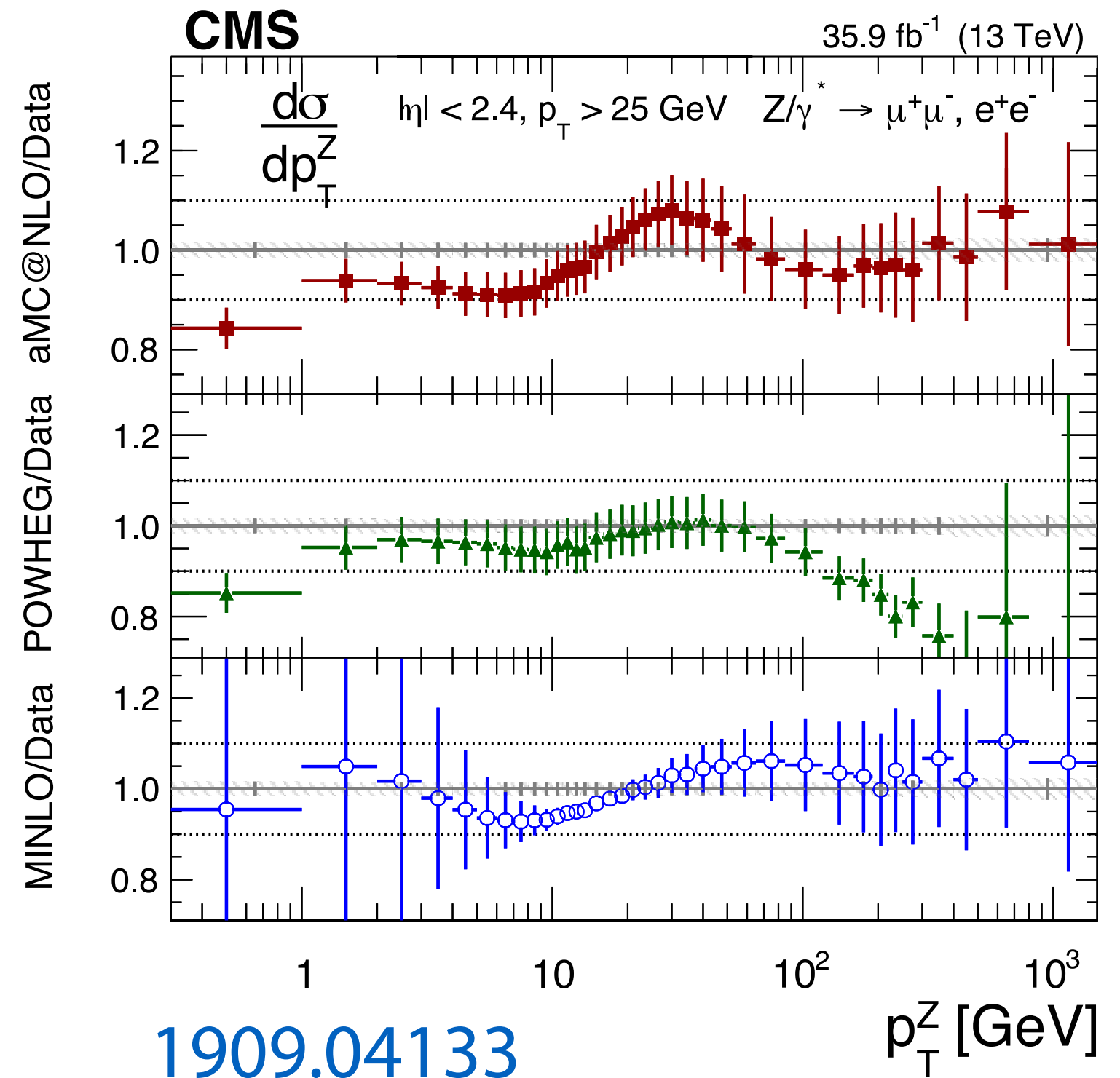
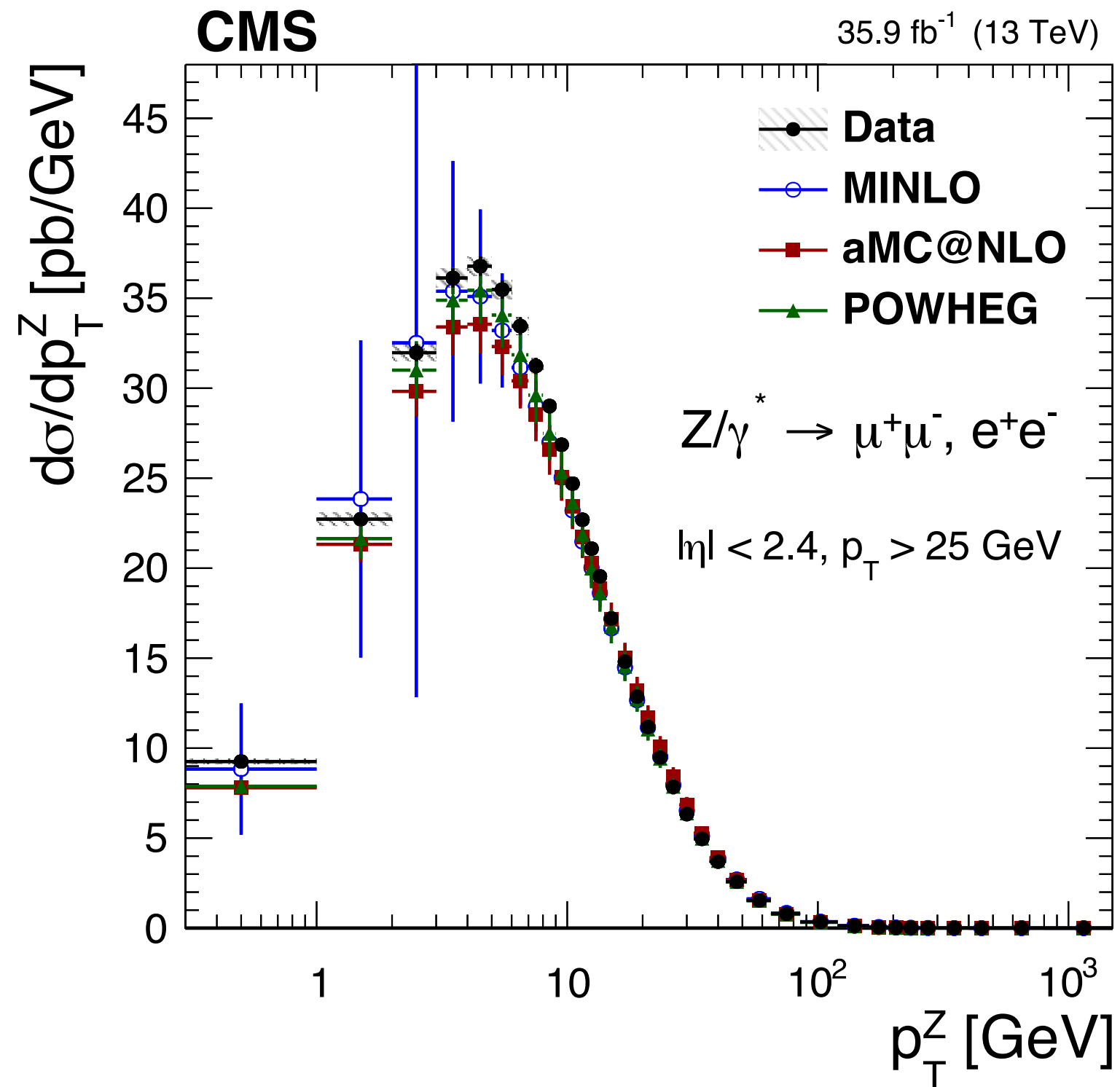


# Vector boson modeling for precision physics

**Tobias Neumann, Brookhaven National Lab**

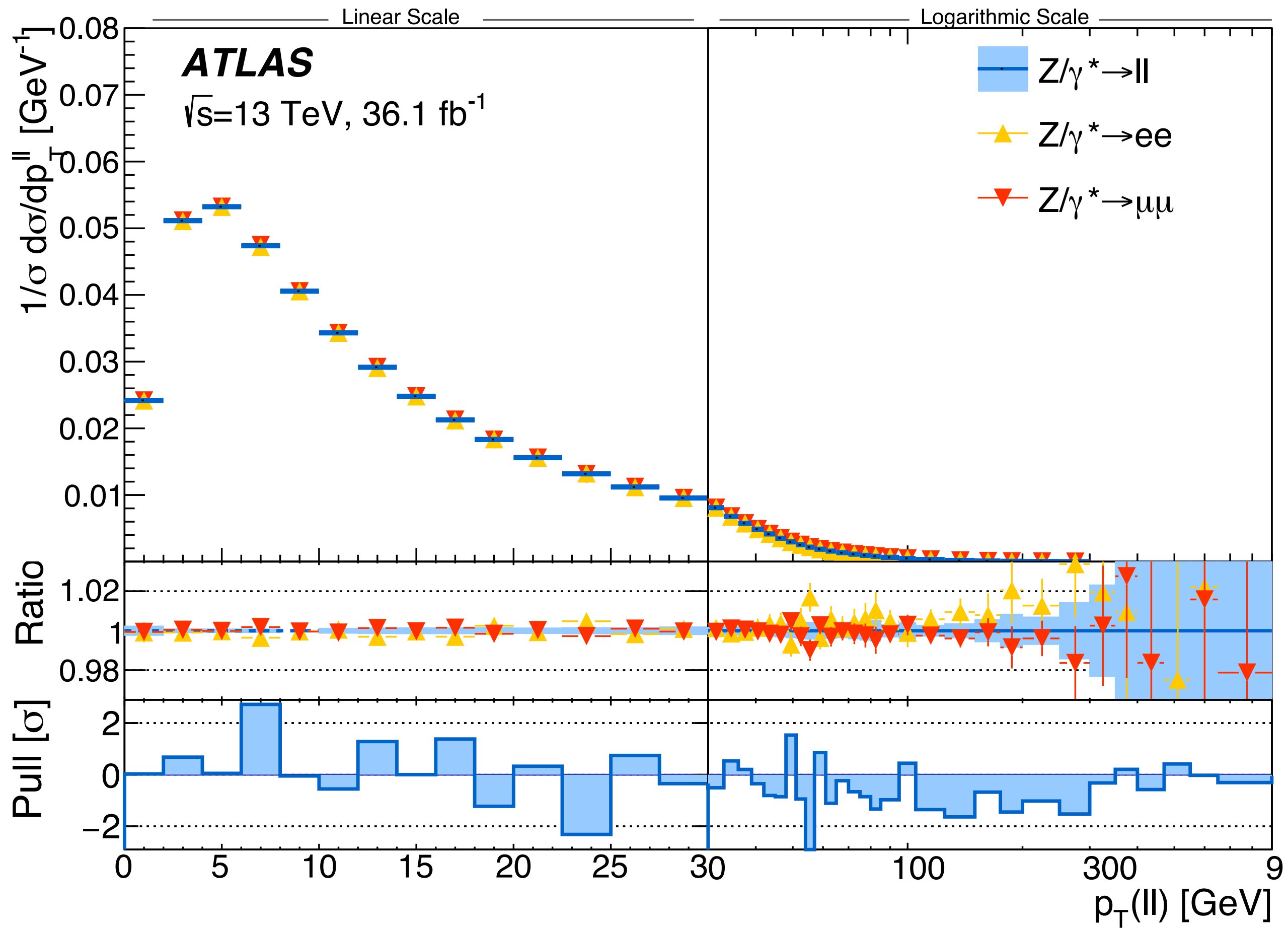
# Precision limited by luminosity uncertainty!

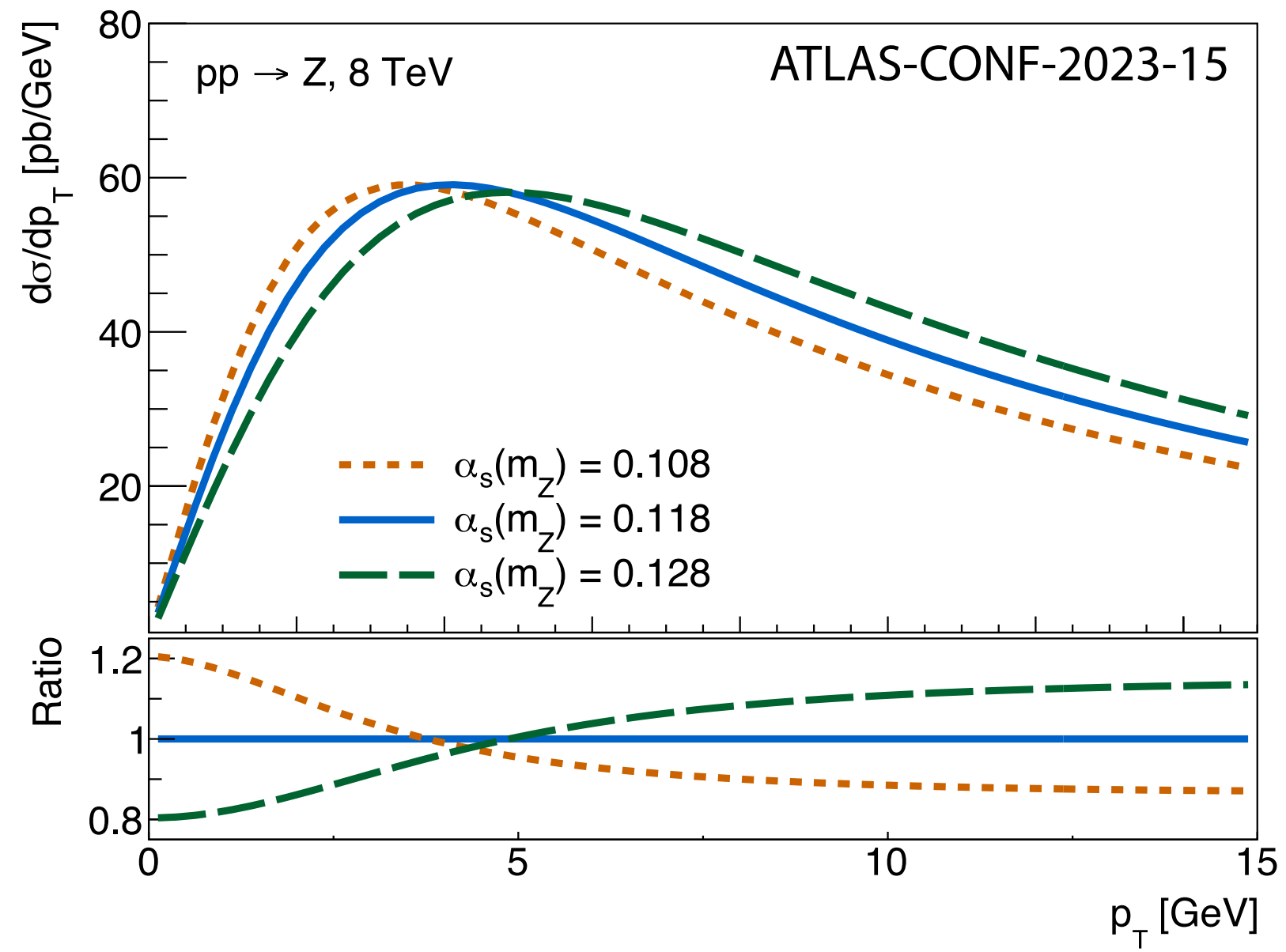


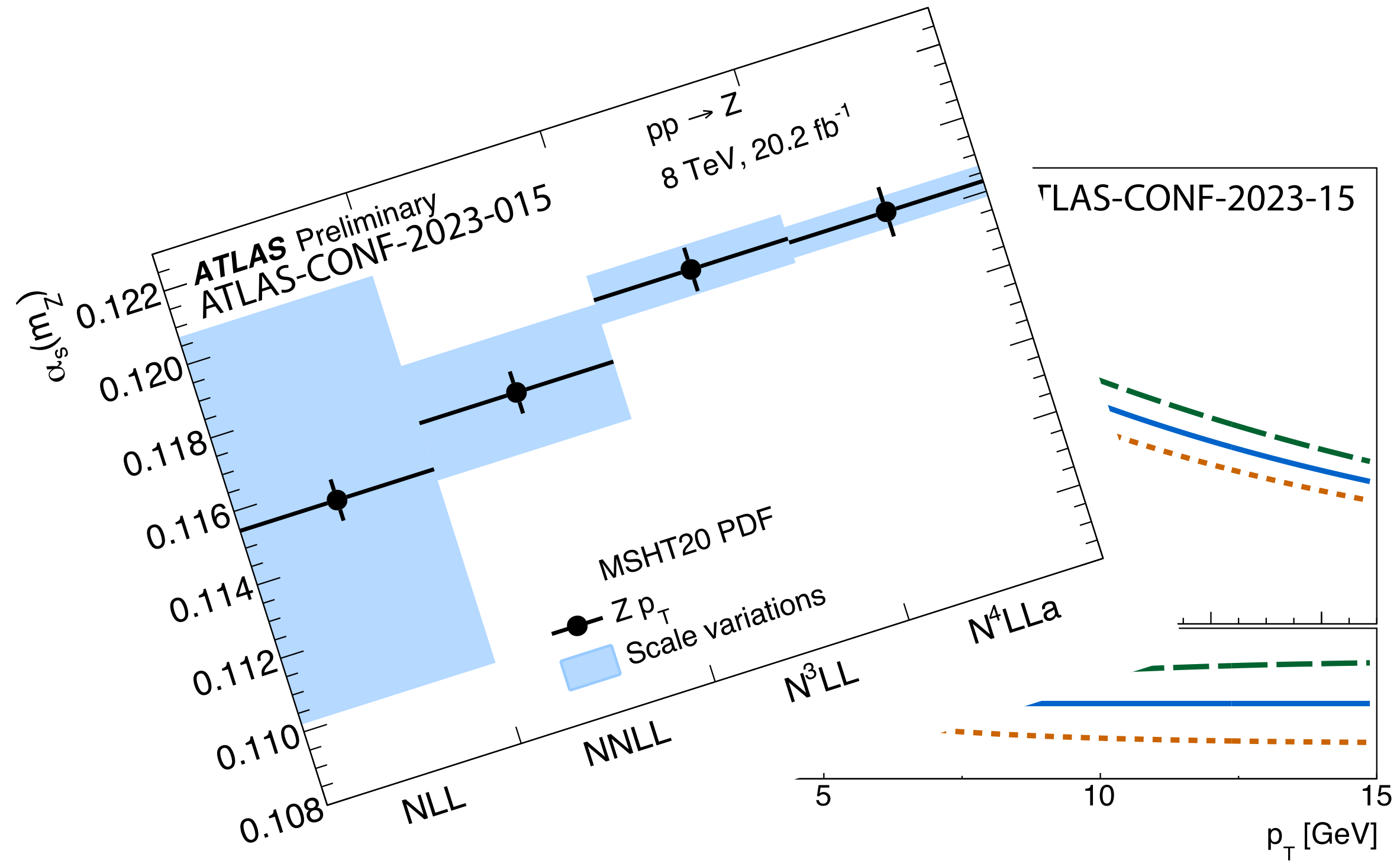
**Precision luminosity measurement in proton-proton collisions at  $\sqrt{s} = 13$  TeV in 2015 and 2016 at CMS**

**Luminosity determination in pp collisions at  $\sqrt{s}=13$  TeV using the ATLAS detector at the LHC**

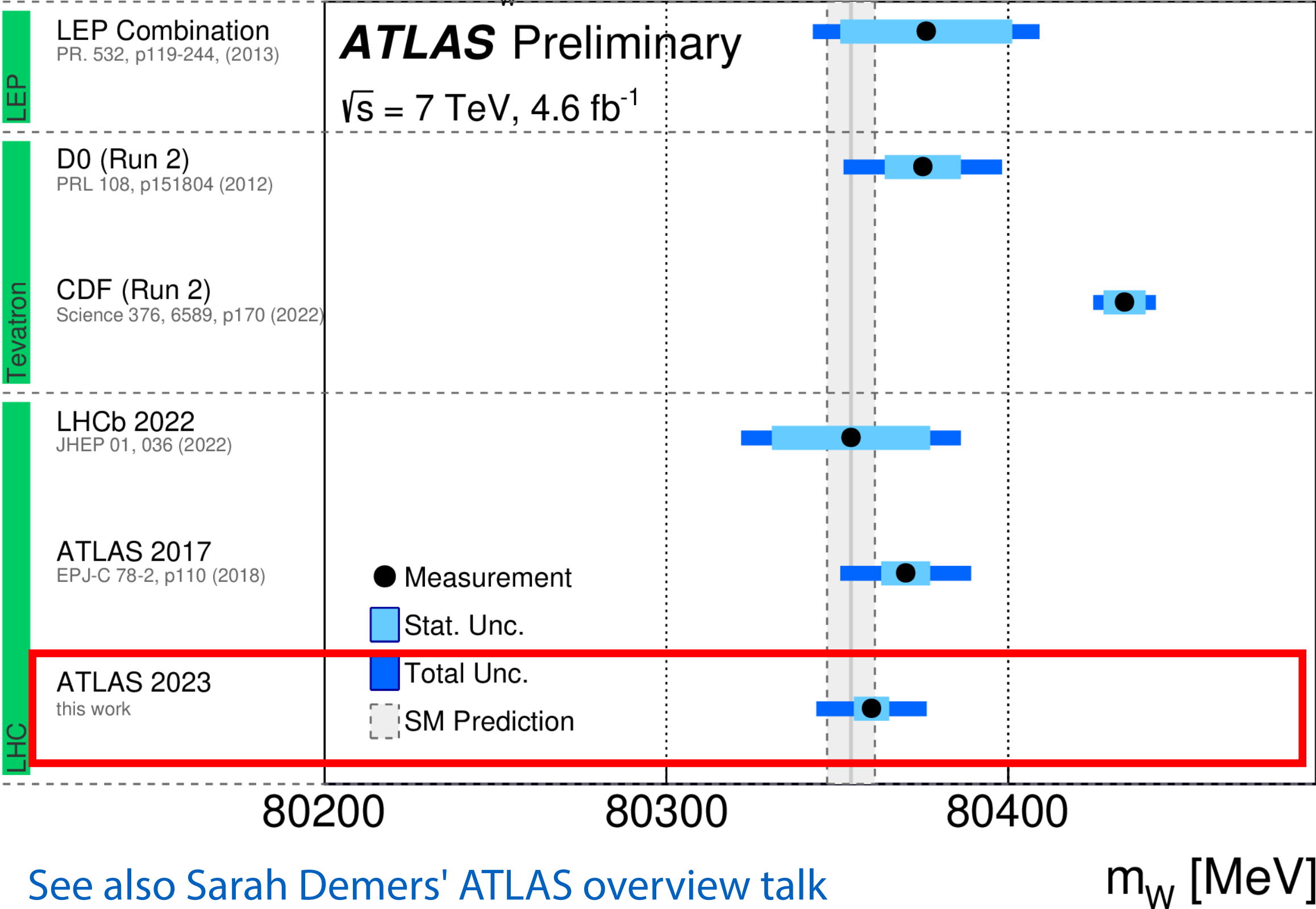
**1% luminosity measurements**







Overview of  $m_W$  Measurements



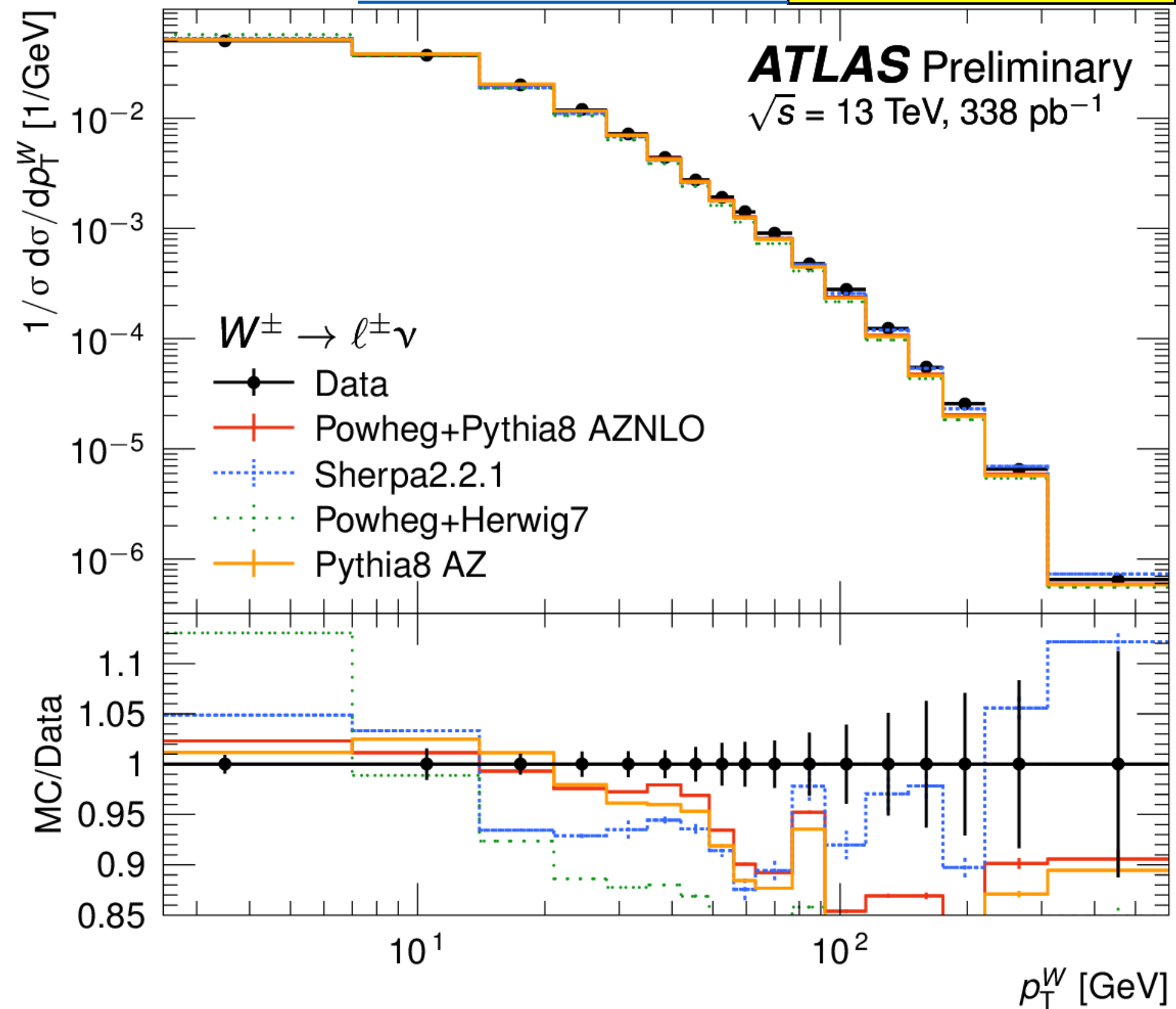
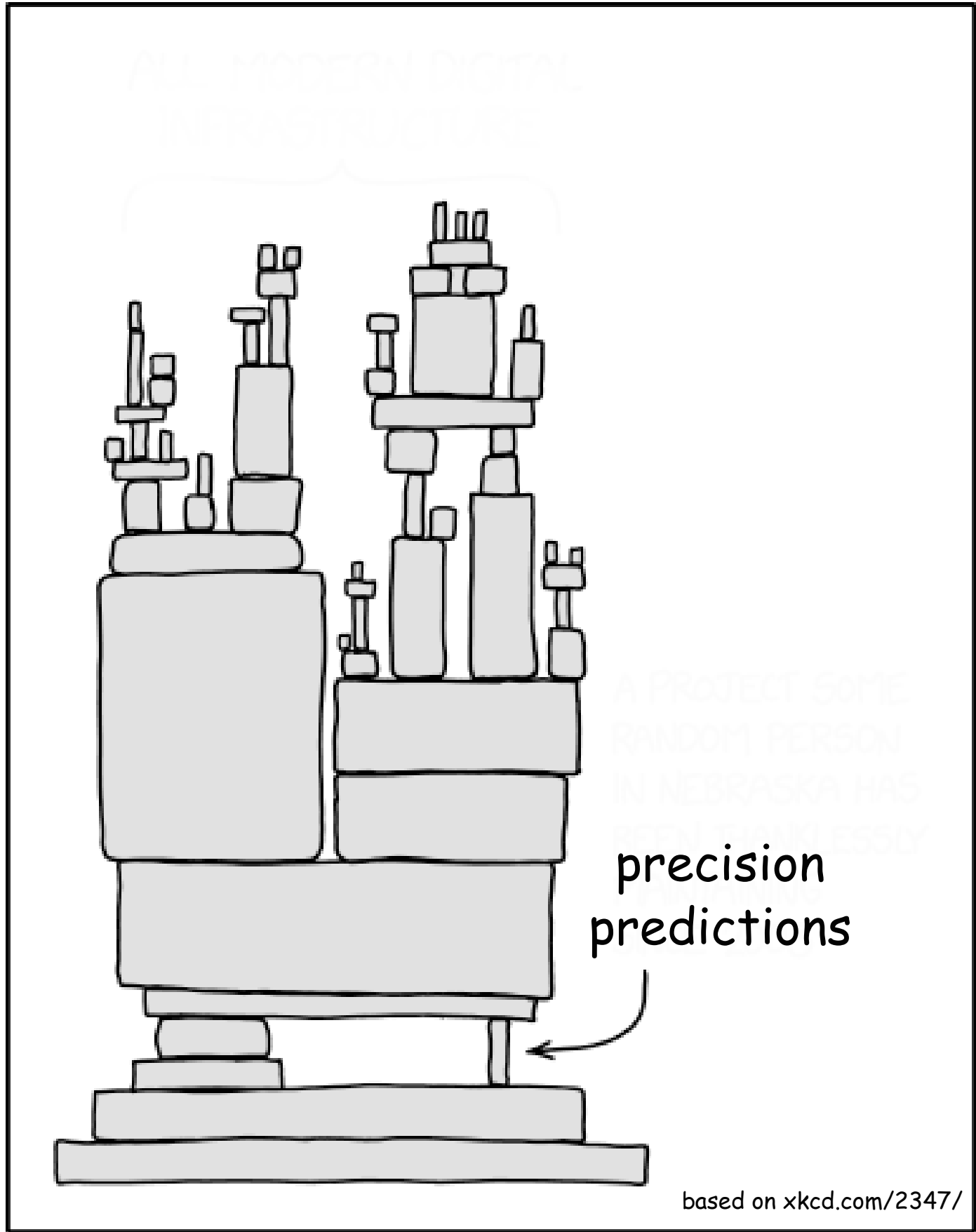






Illustration: Gaia Fontana



# **LHC as discovery machine**

... transitioning to...

## **LHC as EW precision machine?**

**Precision is discovery.**

# Theory uncertainties

- Fixed-order expansions in QCD and QED, EW
- Higher-order resummation
- Parton shower event generators
- Non-perturbative effects, PDFs, TMDs, ..
- Higher power/twist terms in factorization
- Understanding universality of tuning
- Numerical precision
- ...

# Theory uncertainties

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# Recent workshops on DY

- Regular meetings of the LHC EW WG
- November 2022, "Precision calculations for Drell-Yan processes" in Milano
- February 2023, "W mass workshop" in Orsay
- April 2023, "MWDays23" at CERN

# LHC EW precision sub-group DY resummation benchmark

artemide

NangaParbat

ResBos2

DYTurbo

reSolve

CuTe-MCFM

SCETlib

RadISH



# QCD for DY at $\alpha_s^3$

- via small- $q_T$  factorization

$$d\sigma_{ij} \sim \int d\xi_1 d\xi_2 d\sigma_{ij}^0 \cdot H(\xi_1 p_1, \xi_2 p_2, \mu).$$

$$\cdot \int d^2 x_\perp e^{-iq_\perp x_\perp} (x_T^2 Q^2)^{-F(x_\perp, \mu)} \cdot B_i(\xi_1, x_\perp, \mu) \cdot B_j(\xi_2, x_\perp, \mu) + \mathcal{O}(q_T/m_Z)$$

- three-loop beam functions

*M.-x. Luo, T.-Z. Yang, H. X. Zhu, Y. J. Zhu '19, '20; Ebert, Mistlberger, Vita '20*

- Z+jet NNLO calculation

*Boughezal, Focke, Liu, Petriello; Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello '15  
Gehrmann-De Ridder, Gehrmann, Glover, Huss, Morgan '15*

- towards  $N^4$  LL  $q_T$  resummation: Four loop rapidity anomalous dimension

*Duhr, Mistlberger, Vita '22; Moul, H.X. Zhu, Y. J. Zhu '22*

- e.g. Four-loop collinear anomalous dimension

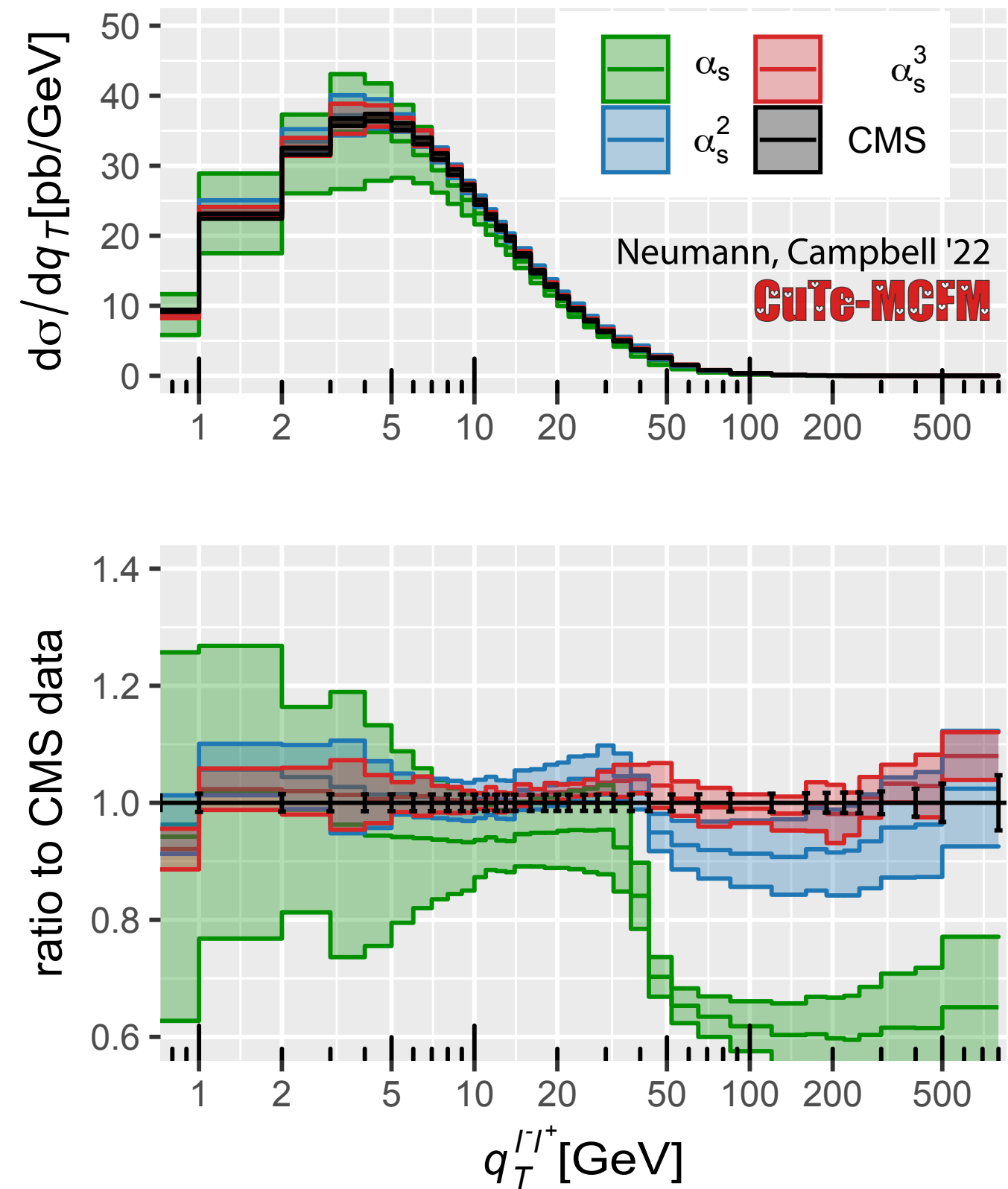
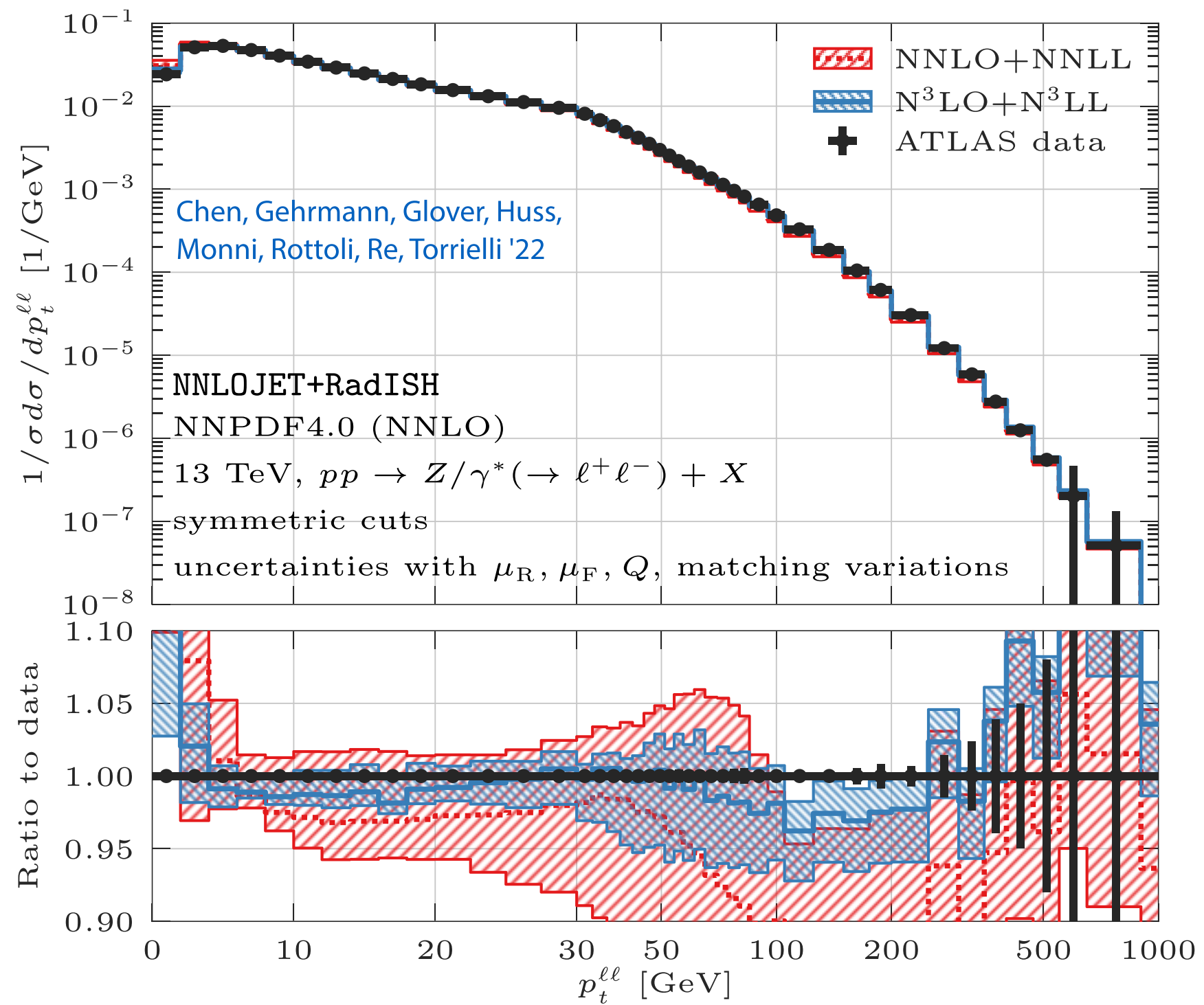
*Agarwal, von Manteuffel, Panzer, Schabinger '21*

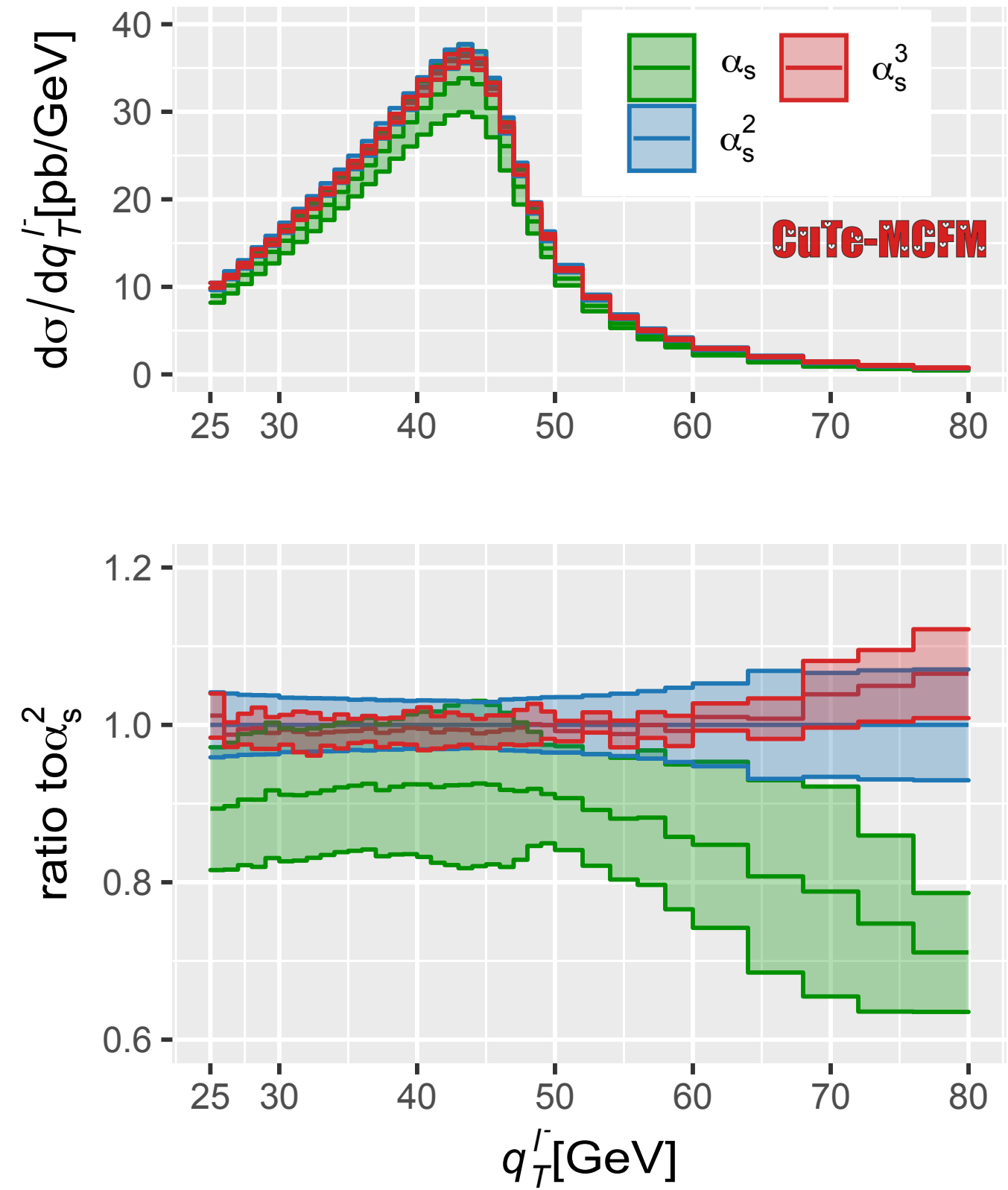
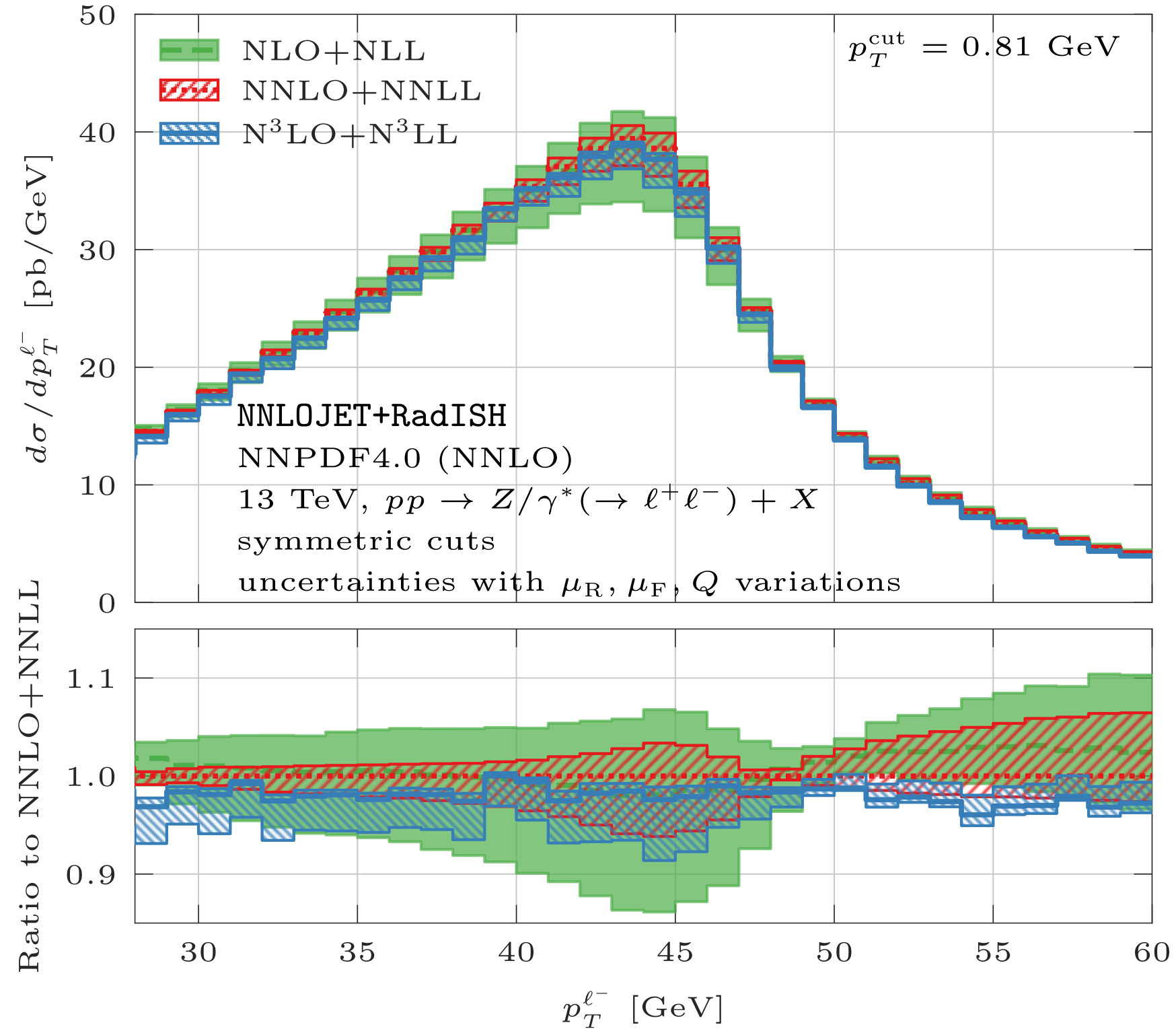
- Massive two/three-loop axial singlet contributions

*Chen, Czakon, Niggetiedt '22; Gehrmann, Peraro, Tancredi '23*

are some

ingredients







*“If a theoretical calculation is done, but it can not be used by any experimentalist, does it make a sound?”*

*— Joey Huston*

*“If a theoretical calculation is done, but it can not be used by any experimentalist, does it make a sound?”*

*— Joey Huston*

*“It's just a push to GitHub!”*

*— Josh Bendavid*

## RadISH+MATRIX

$N^3$  LL+NNLO ( $\alpha_s^2$ ) *Kallweit, Re, Rottoli, Wiesemann '20*

## DYTurbo

$N^3$  LL+NNLO ( $\alpha_s^2$ ) but can use external  $\alpha_s^3$  fixed-order for  $N^3$  LL' *Camarda, Cieri, Ferrera '21*

## CuTe-MCFM

$N^4$  LL +  $N^3$  LO ( $\alpha_s^3$ ) *Neumann, Campbell '22; Becher, Neumann '20* NLO EW *Campbell, Wackerroth, Zhou '15*  
allows for NNLO  $Z$  +jet calculation to be used by other codes (DYTurbo)

## MiNNLO-PS+POWHEG

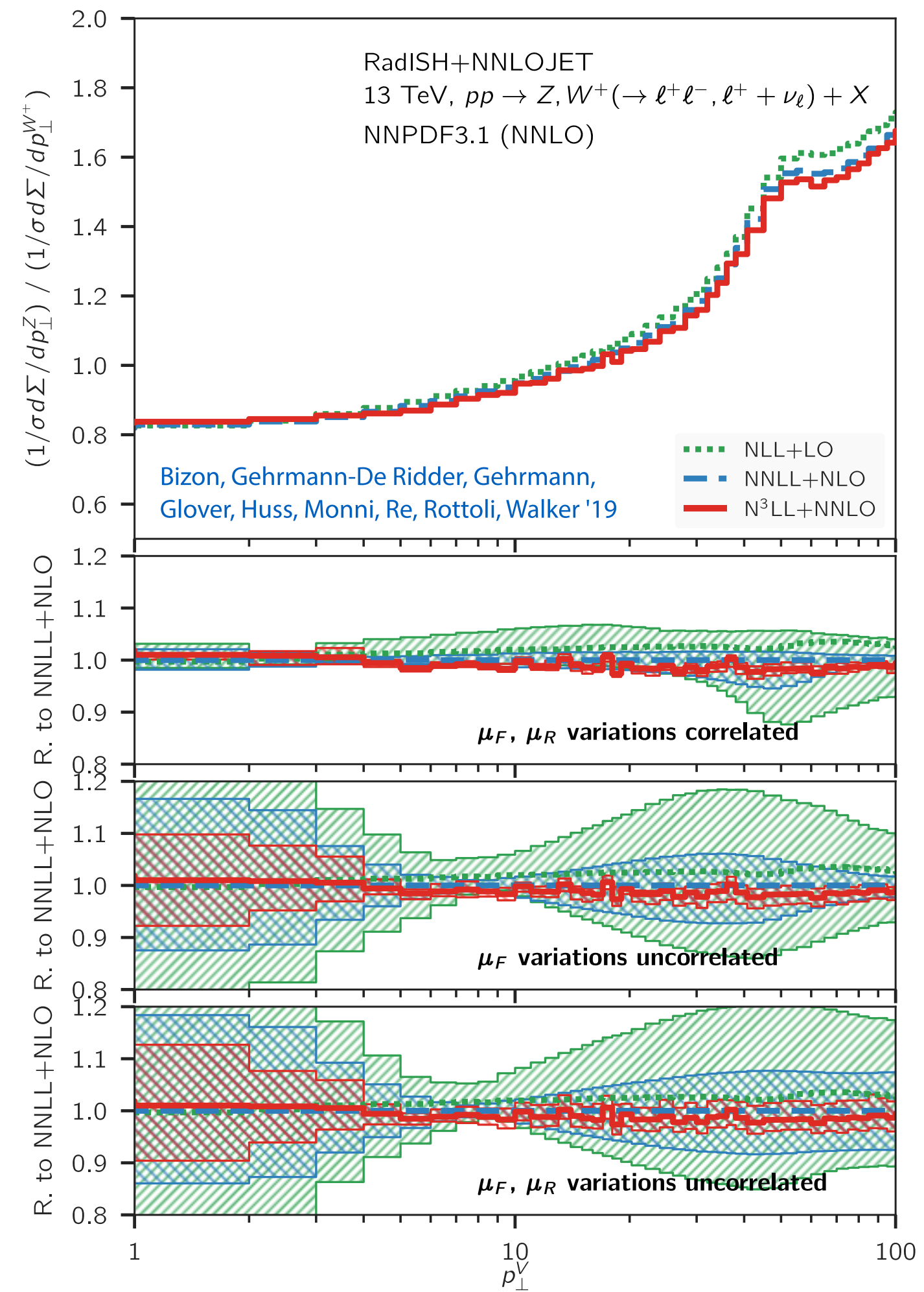
Parton shower + NNLO *Monni, Nason, Re, Wiesemann, Zanderighi '20*

## artemide and Nanga Parbat (TMD fitting)

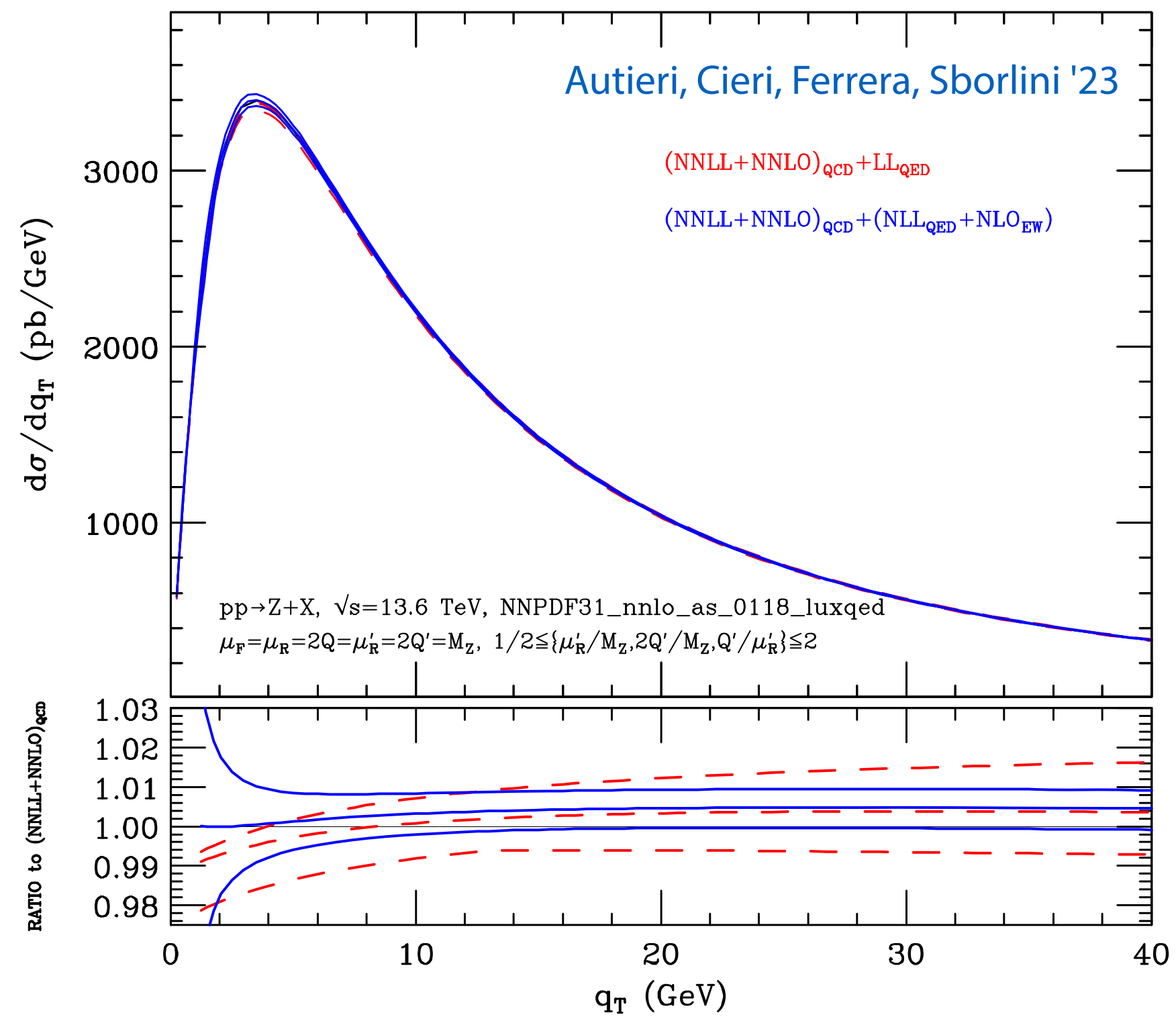
*Scimeni, Vladimirov '18; Bacchetta, Bertone, Bissolotti, Bozzi, Delcarro, Piacenza, Radici '20*

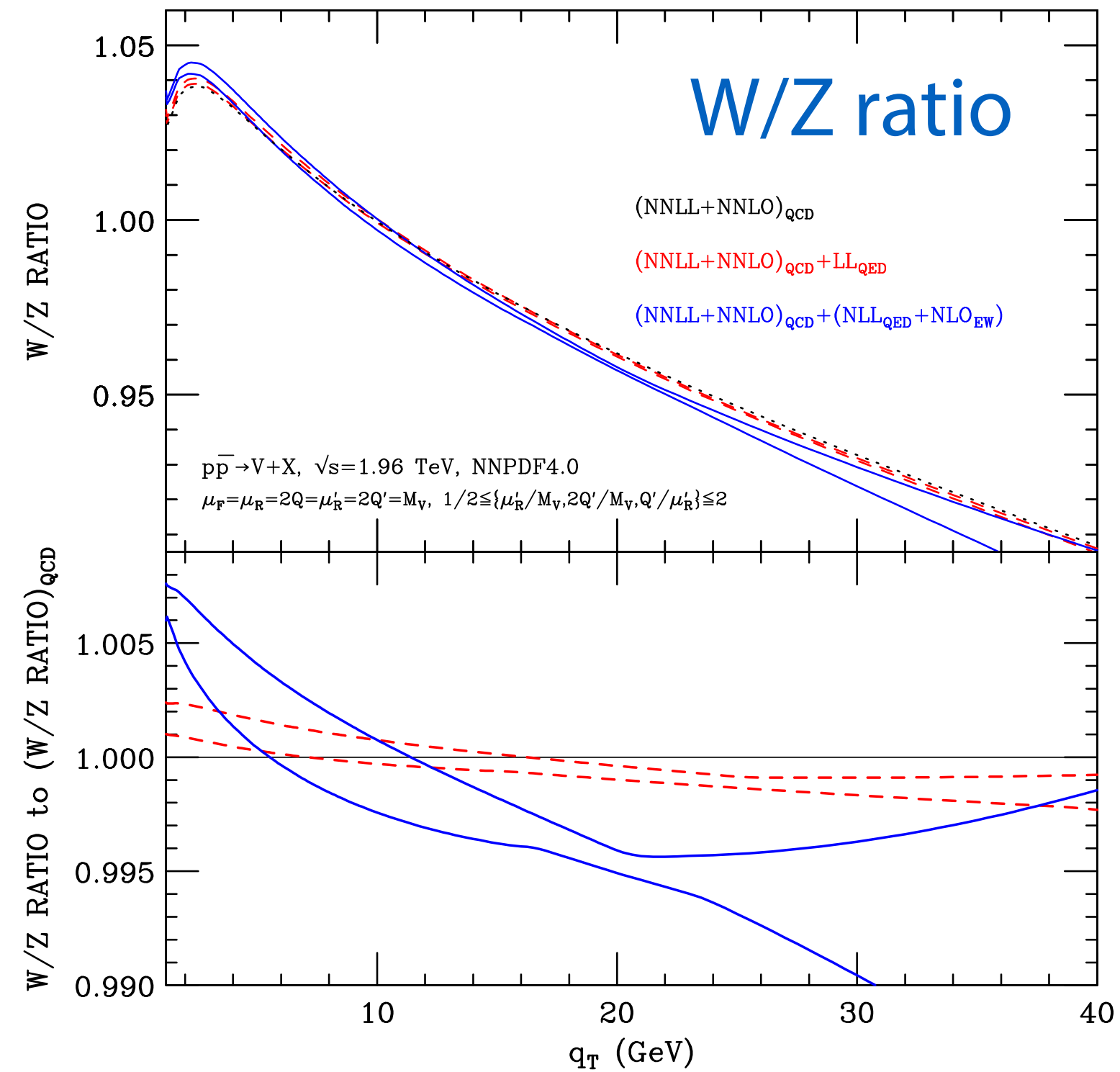
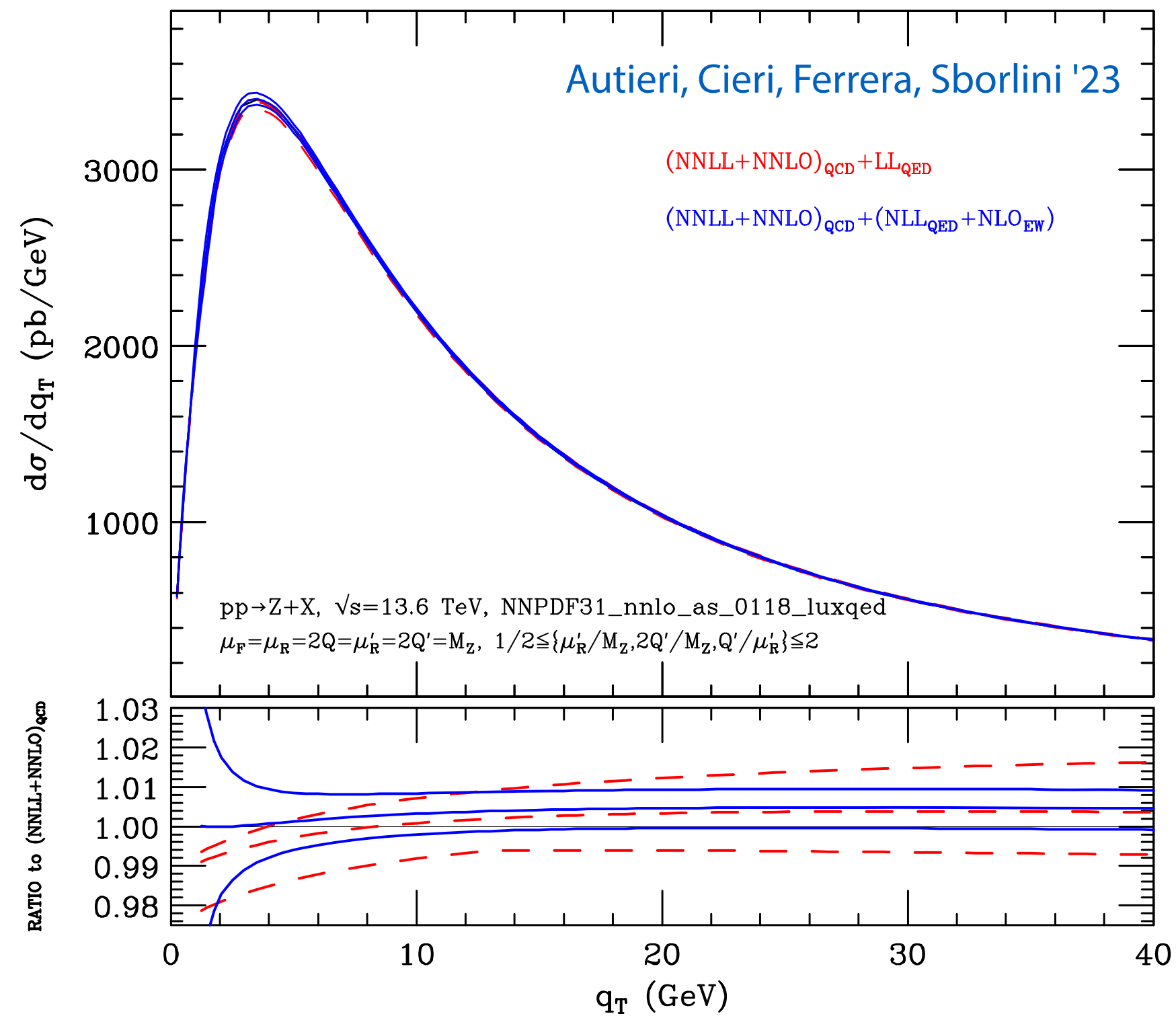
## FEWZ

NNLO+NLO EW *Gavin, Li, Petriello, Quackenbush '10, '12*

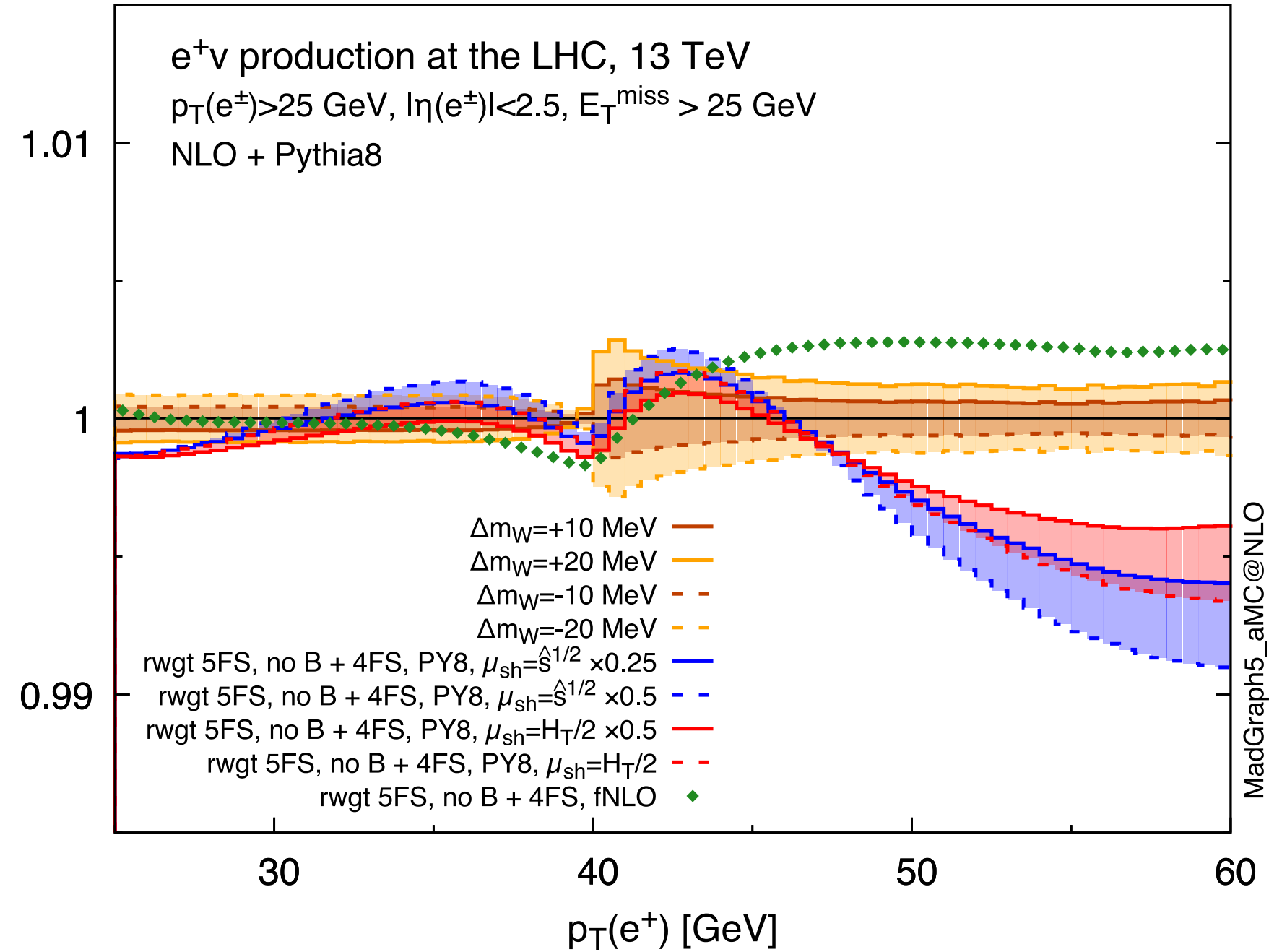








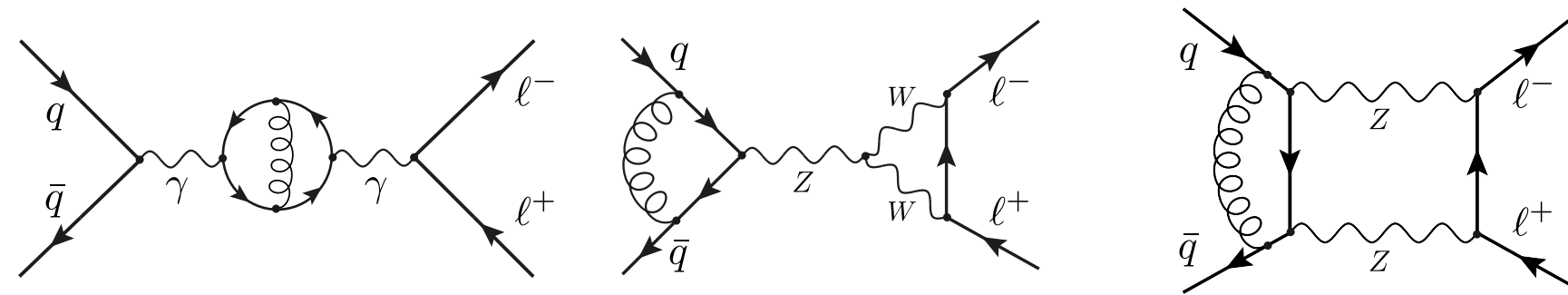
# Impact of improved five-flavor four-flavor scheme matched predictions in $Z + \bar{b}b$



Bagnaschi, Maltoni, Vicini, Zaro '18

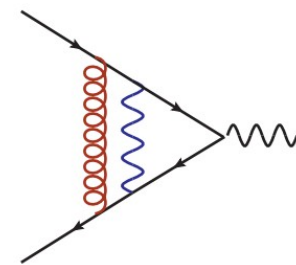
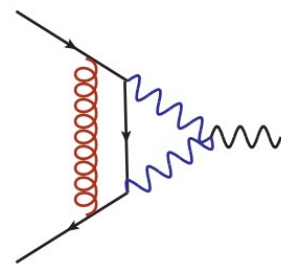
(Impact on  $m_W$  estimated to be smaller than 5 MeV)

# Mixed QCDxEW corrections to $Z$ and $W$ production



Heller, von Manteuffel, Schabinger '19; Heller, von Manteuffel, Schabinger, Spiesberger '20  
 Buccioni, Caola, Chawdhry, Devoto, Heller, von Manteuffel, Melnikov, Röntsch, Signorile-Signorile '22, ...

Armadillo, Bonciani, Devoto, Rana, Vicini '22; Bonciani, Buccioni, Rana, Vicini '21;  
 Bonciani, Buonocore, Grazzini, Kallweit, Rana, Tramontano, Vicini '22; Bonciani, Buccioni, Rana, Vicini '20; Bonciani, Buccioni, Rana, Vicini '19; Dittmaier, Schmidt, Schwarz '20, ...



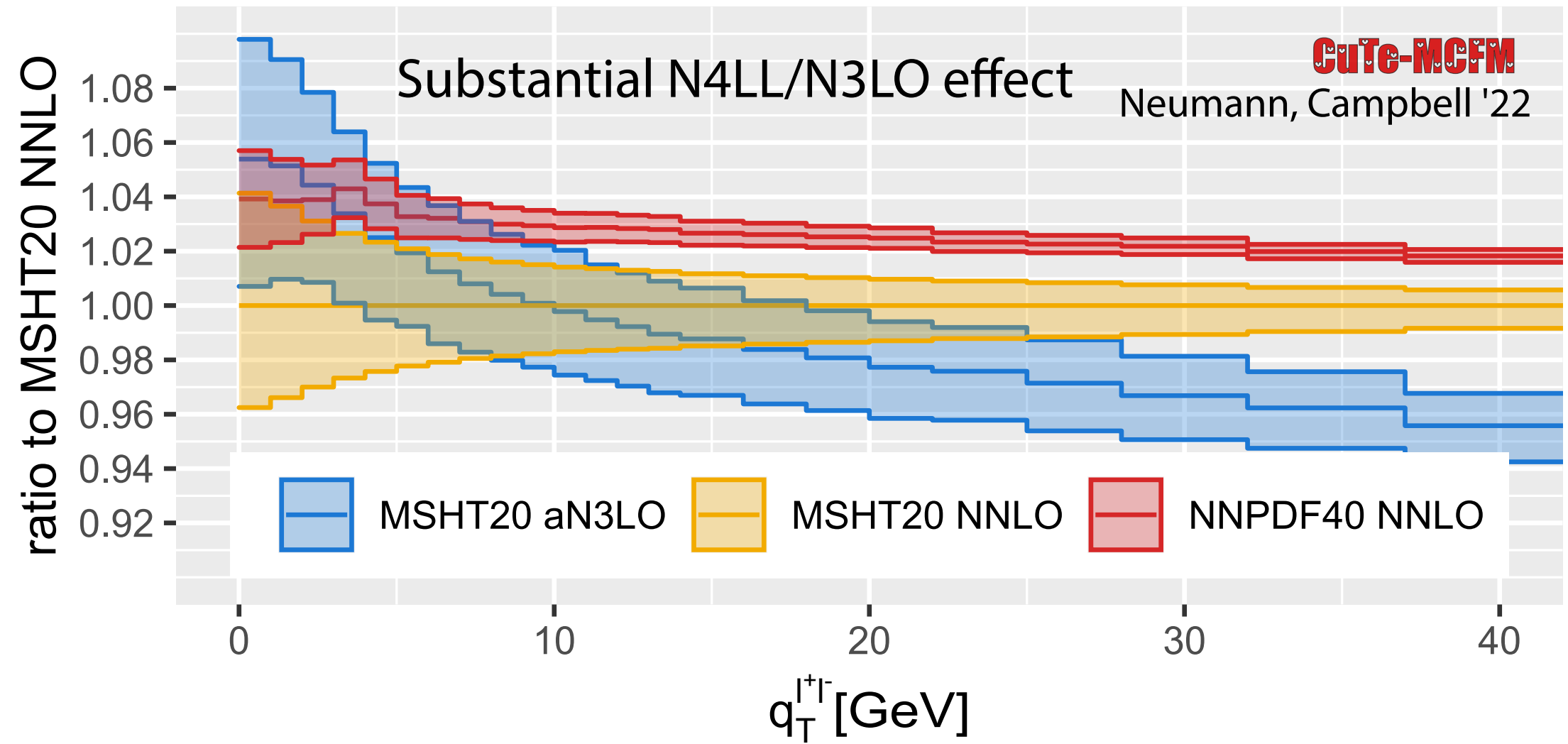
Shifts in W-mass, inclusive:

- NLO EW:  $\Delta m_W = 1 \text{ MeV}$
- QCD-EW:  $\Delta m_W = -7 \text{ MeV}$

Shifts in W-mass: fiducial setup

- Inclusive setup:  $\Delta m_W = -7 \text{ MeV}$
- "ATLAS" cuts:  $\Delta m_W = -17 \text{ MeV}$
- Cuts can have **dramatic impact**

Behring, Buccioni, Caola, Delto, Jaquier '20  
 Behring, Buccioni, Caola, Delto, Jaquier, Melnikov, Röntsch '21



### MSHT20 aN3LO: Approximate N<sup>3</sup> LO PDFs with MHO

*McGowan, Cridge, Harland-Lang, Thorne '22*

# Vector-boson production: A preview of precision at the LHC

## Precision is discovery!

- Theory and experiment are interdependent
- Without precision theory we cannot interpret precision data
- Theory at the level of 1% is incredibly challenging:
  - Fixed-order expansions in QCD and EW & higher-order resummation
  - Higher power/twist terms in factorization
  - Parton shower event generators
  - Understanding universality of tuning
  - Non-perturbative effects, PDFs, TMDs, ..
  - Numerical precision
  - ...
- Public codes & results are crucial for efficient progress  
Both on the experimental side, and on the theory side

