The spectrum of weak gauge bosons: accurate predictions and theory uncertainties

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Introduction

- The transverse momentum spectrum of EW bosons can be precisely determined at the LHC
  - often reconstructed from decay products (Z case) —> no underlying event contamination
  - sensitive to QCD through kinematic recoil —> small hadronisation
  - **Great experimental precision (sub-% level) challenges current theory predictions**
    - see previous talk by Lorenzo Bianchini
- Data can be exploited for different aspects of particle phenomenology:
  - fit of parton densities (collinear or transverse-momentum-dependent PDFs)
  - extraction of strong coupling constant and W boson mass
  - calibration of multi-purpose tools & generators
- **This talk will focus on the intermediate/small transverse momentum regime**

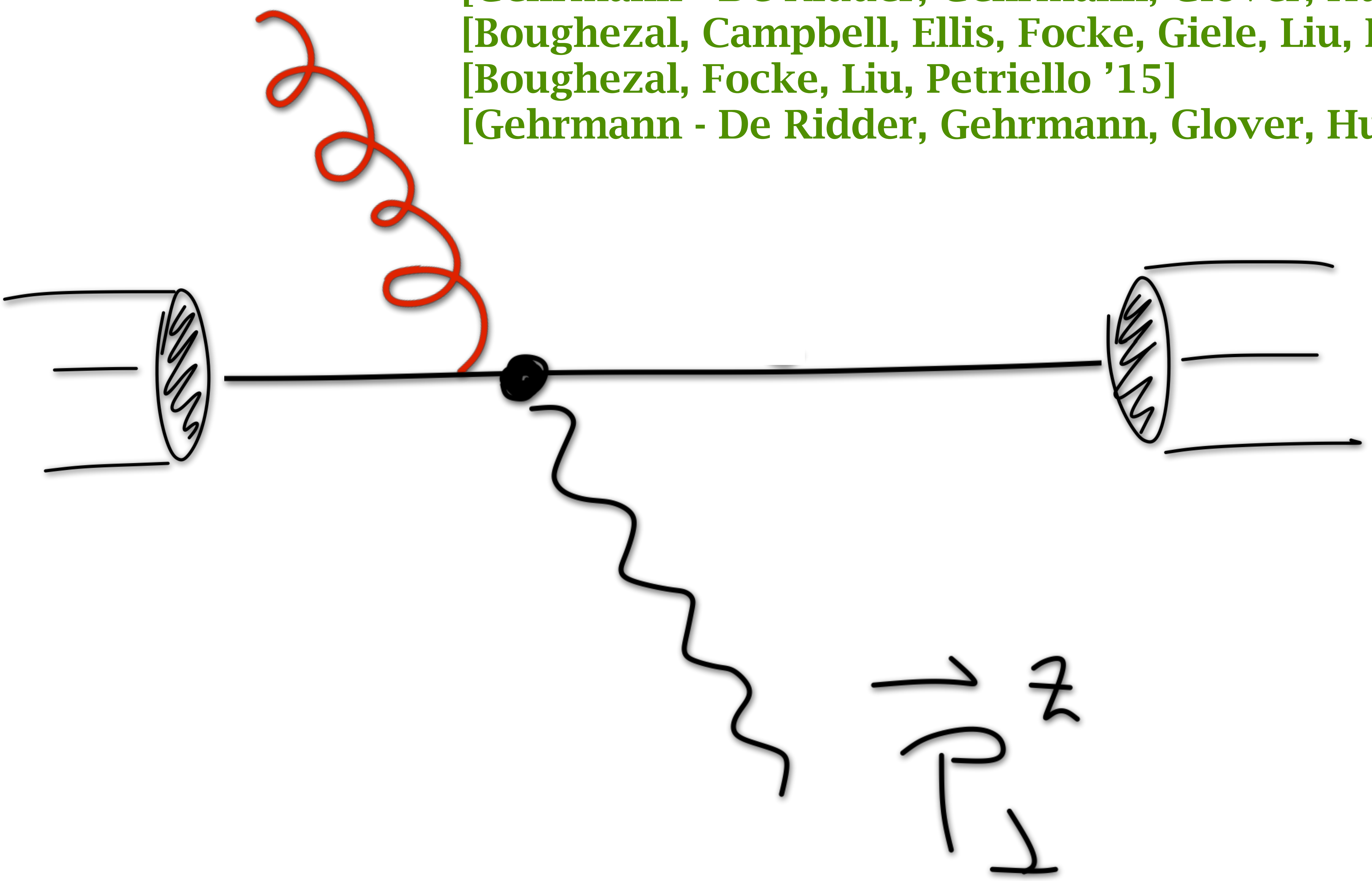
W/Z spectrum in QCD

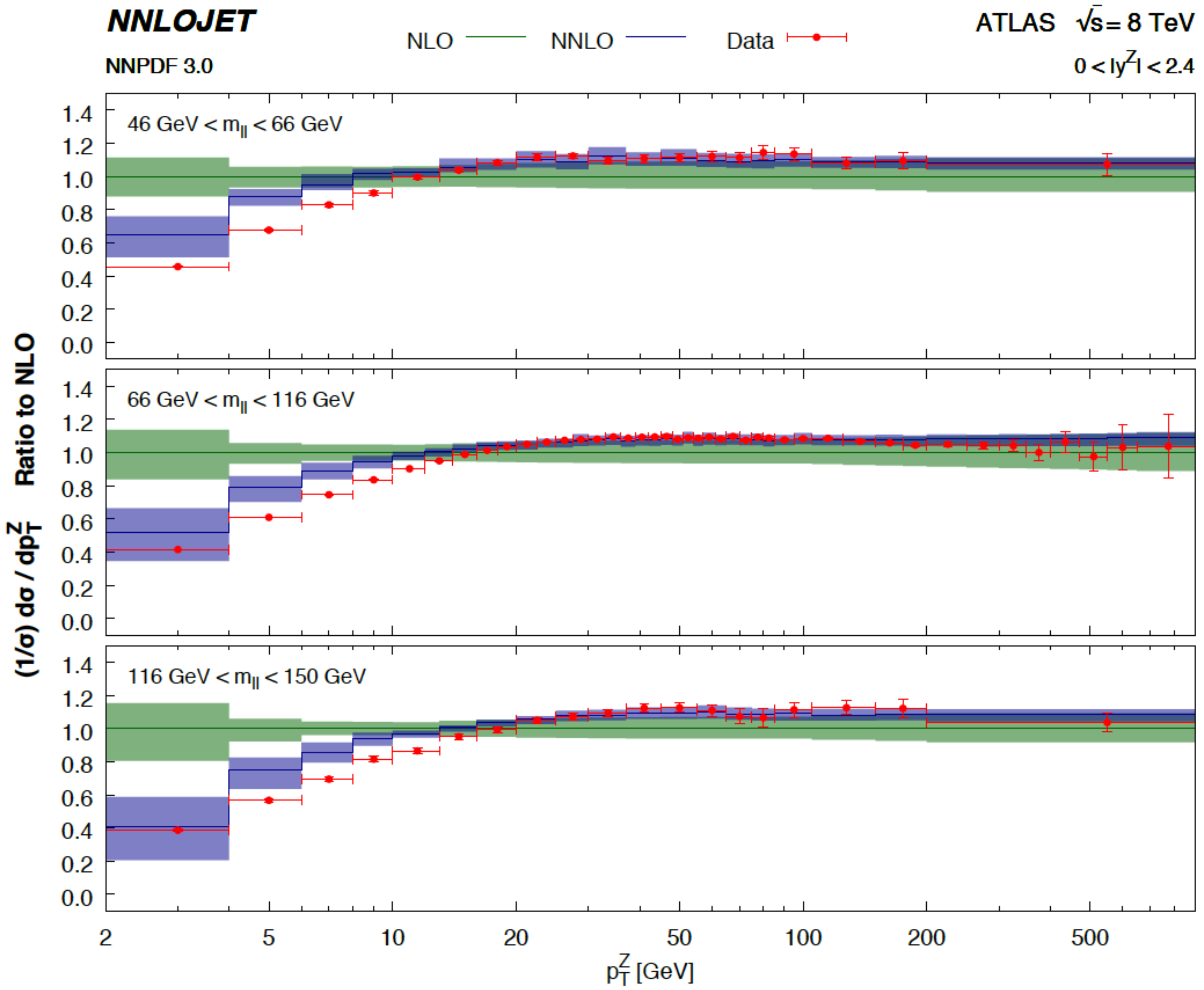
- NNLO total cross section known for many years

[Hamberg, van Neerven, Matsuura ’91] [van Neerven, Zijlstra ’92]
[Anastasiou, Dixon, Melnikov, Petriello ’03]
[Melnikov, Petriello ’06]
[Catani, Cieri, Ferrera, de Florian, Grazzini ’09]
[Catani, Ferrera, Grazzini ’10]
[Gavin, Li, Petriello, Quackenbush ’10]

- **State of the art for fixed order p_T spectrum is NNLO**: Z recoiling against at least one hard radiation

[Gehrmann - De Ridder, Gehrmann, Glover, Huss, Morgan ’15-’16]
[Boughezal, Campbell, Ellis, Focke, Giele, Liu, Petriello ’15]
[Boughezal, Focke, Liu, Petriello ’15]
[Gehrmann - De Ridder, Gehrmann, Glover, Huss, Walker ’17]





W/Z spectrum in QCD

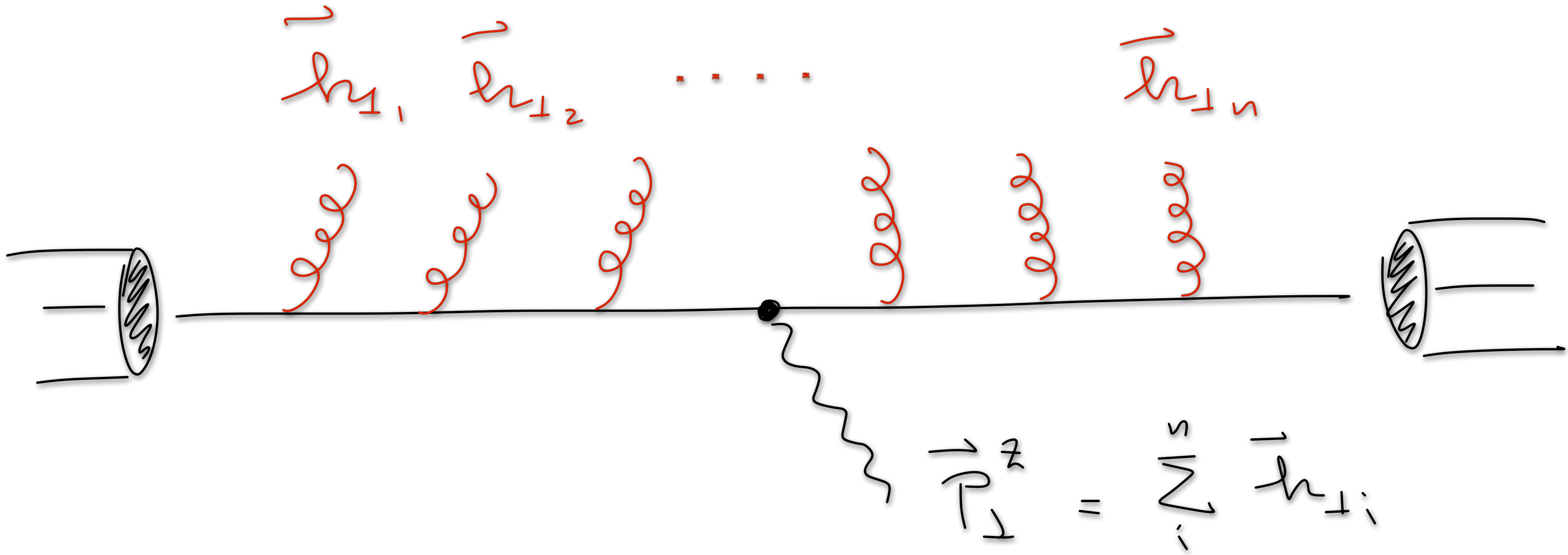
- Physics at p_T —> 0 governed by multi scale dynamics [$p_T << M$ —> large $L = \ln(M/p_T)$]
  - All order logarithmic structure of DY studied from different angles in the literature

[Collins, Soper, Sterman ’85]
[Bozzi, Catani, Ferrera, de Florian, Grazzini ’10][Becher, Neubert ’10][Echevarria, Idilbi, Scimemi ’11]
[Bizon, Chen, Gehrmann-De Ridder, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli ’18]

- spectrum at small p_T dominated by a *cascade* of soft radiation off the initial state quarks

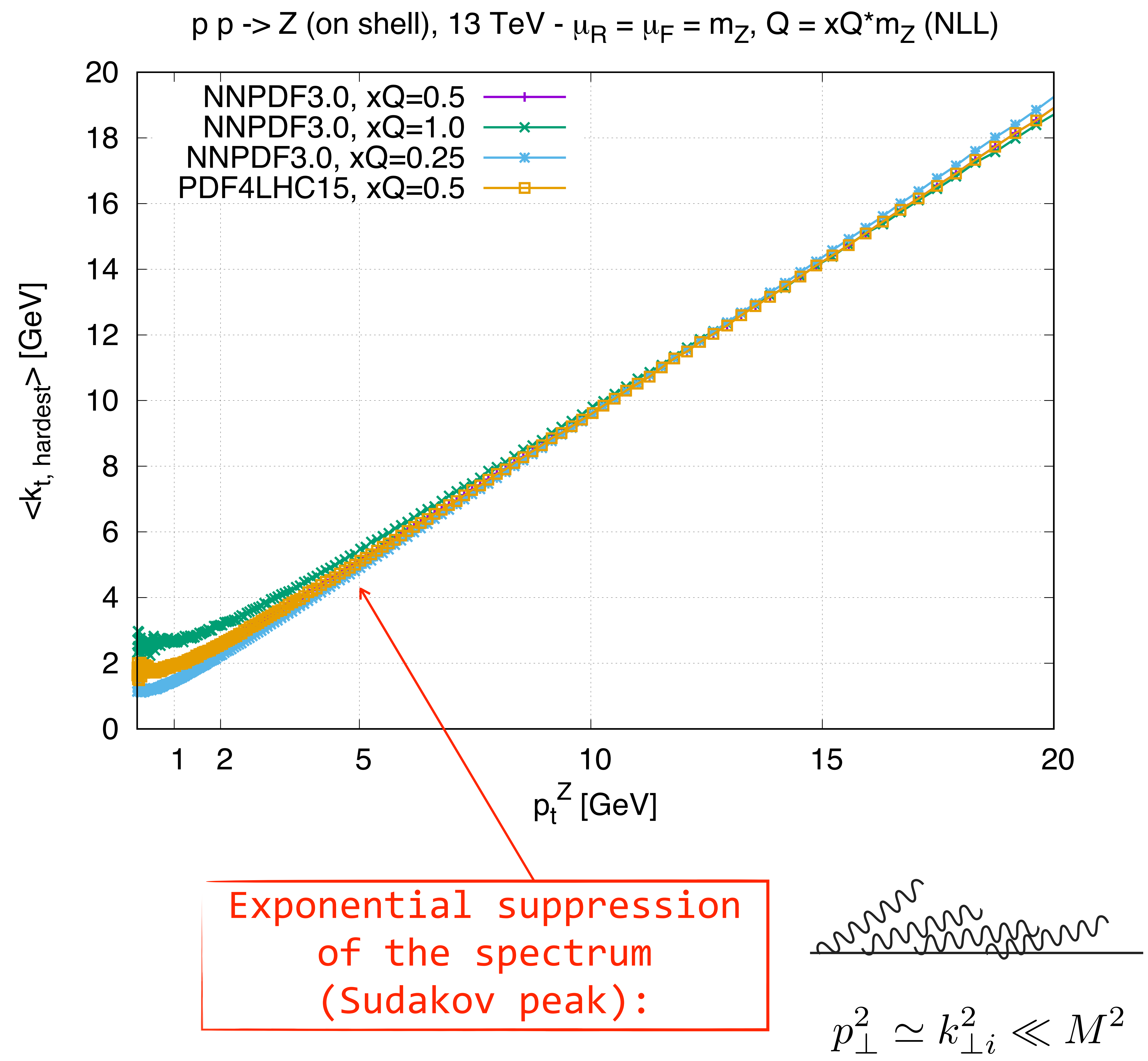
$$\ln\left(\Sigma(p_\perp)\right) \equiv \ln\left(\int_0^{p_\perp} dp'_\perp \frac{d\Sigma(p'_\perp)}{dp'_\perp}\right) = \sum_n \left\{\mathcal{O}\left(\alpha_s^n L^{n+1}\right) + \mathcal{O}\left(\alpha_s^n L^n\right) + \ldots\right\}$$

LL NLL



- Subleading logarithmic corrections captured by including **radiative corrections & less singular limits of QCD amplitudes**

- Two concurring mechanisms drive the $p_T \to 0$ limit of the system **[both improvable in pert. theory]**:



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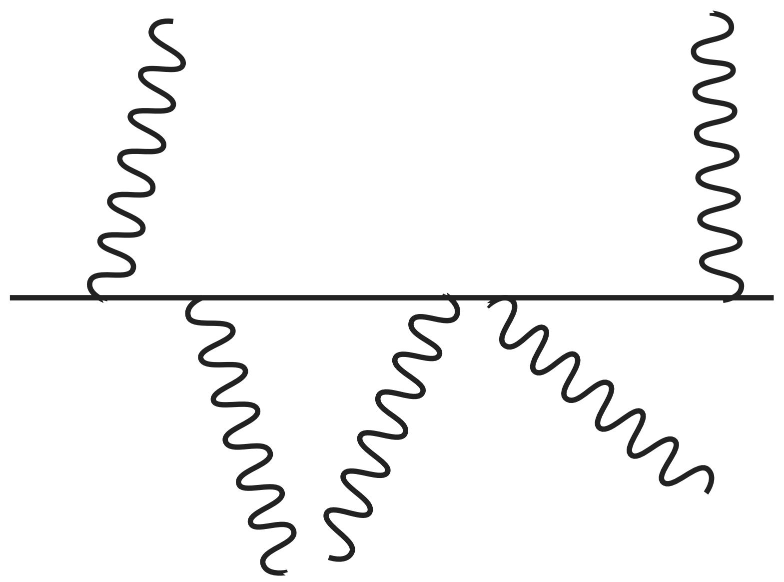
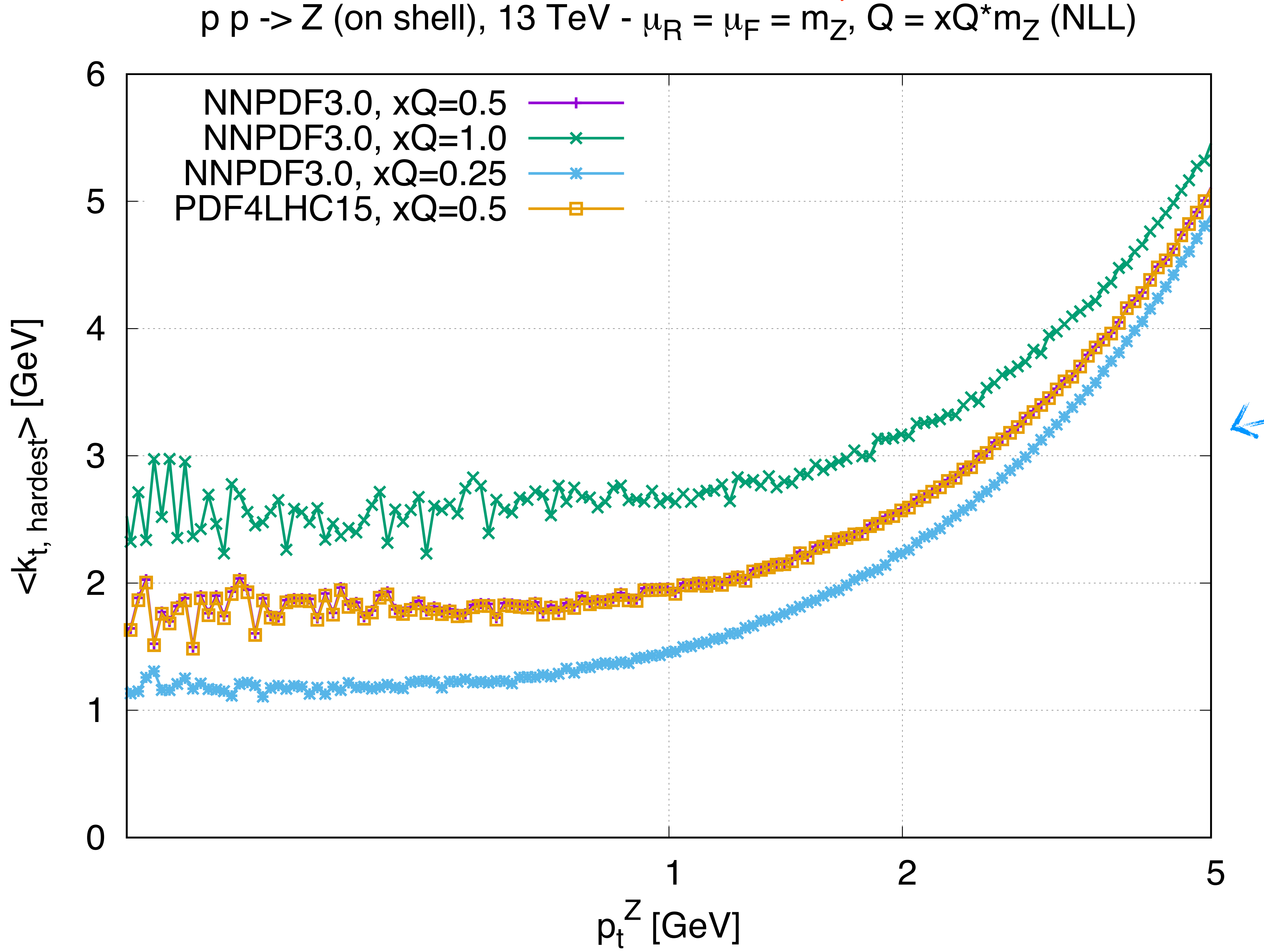
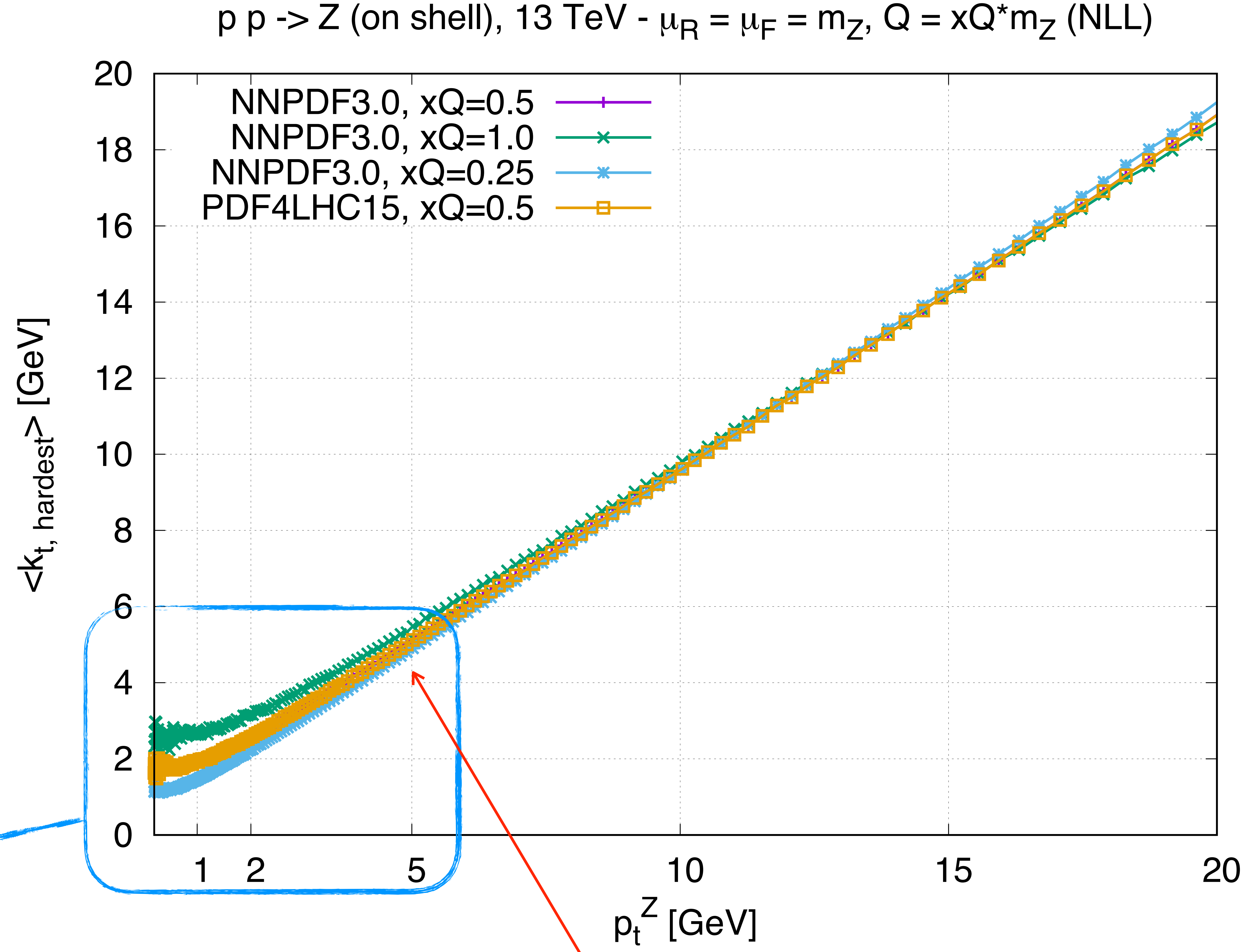


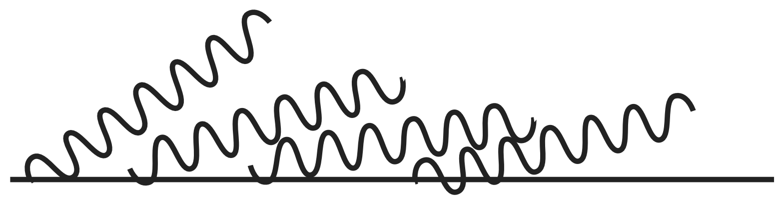
$$\sum_i \vec{k}_{\perp i} \simeq 0, \quad p_\perp^2 \ll k_{\perp i}^2 \ll M^2$$

O(p_T) suppression of the spectrum (dominant for p_T -> 0) [absent at fixed order]





Exponential suppression of the spectrum (Sudakov peak):



$$p_\perp^2 \simeq k_{\perp i}^2 \ll M^2$$

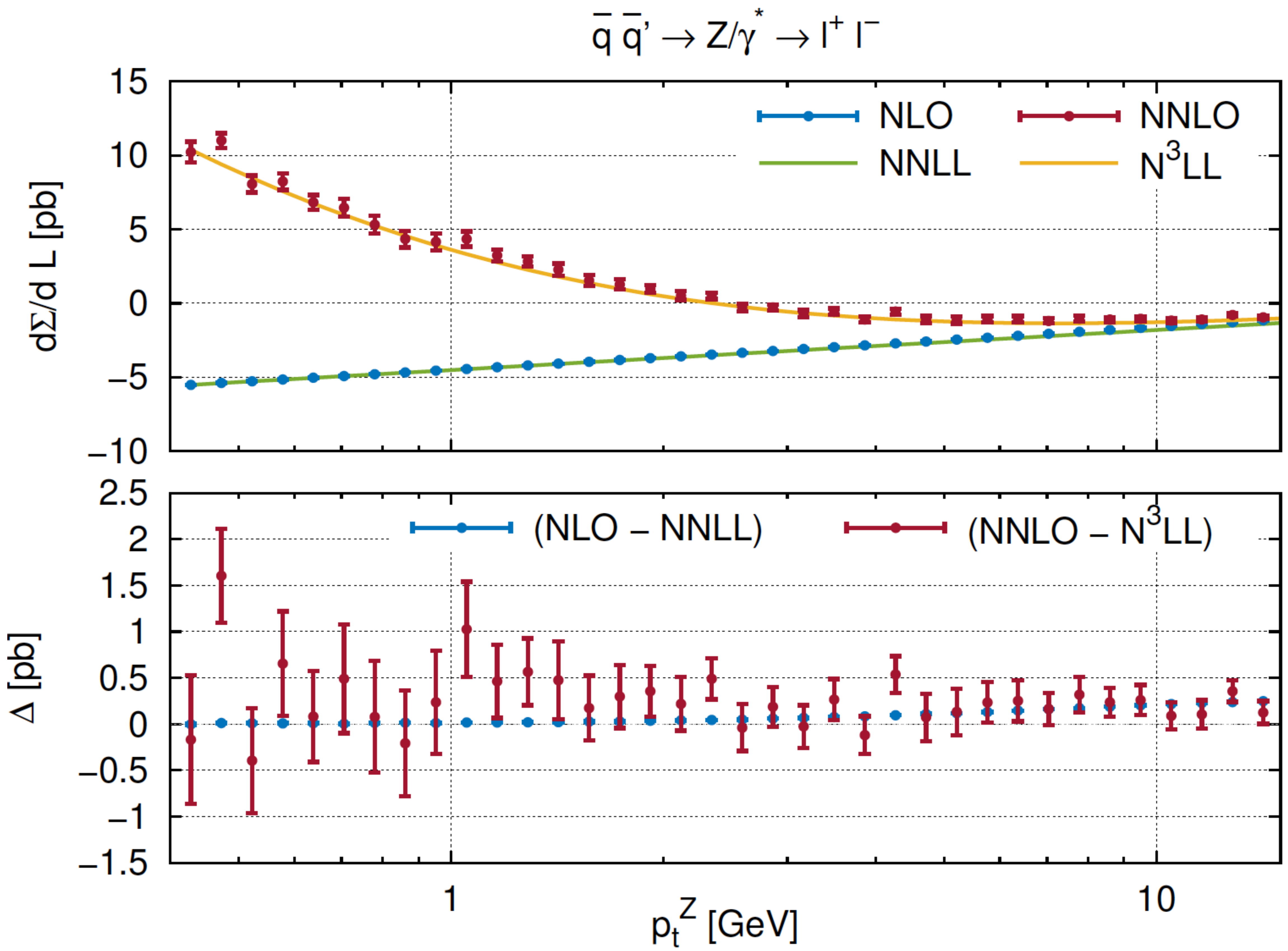
Matching of fixed order and resummed calculations

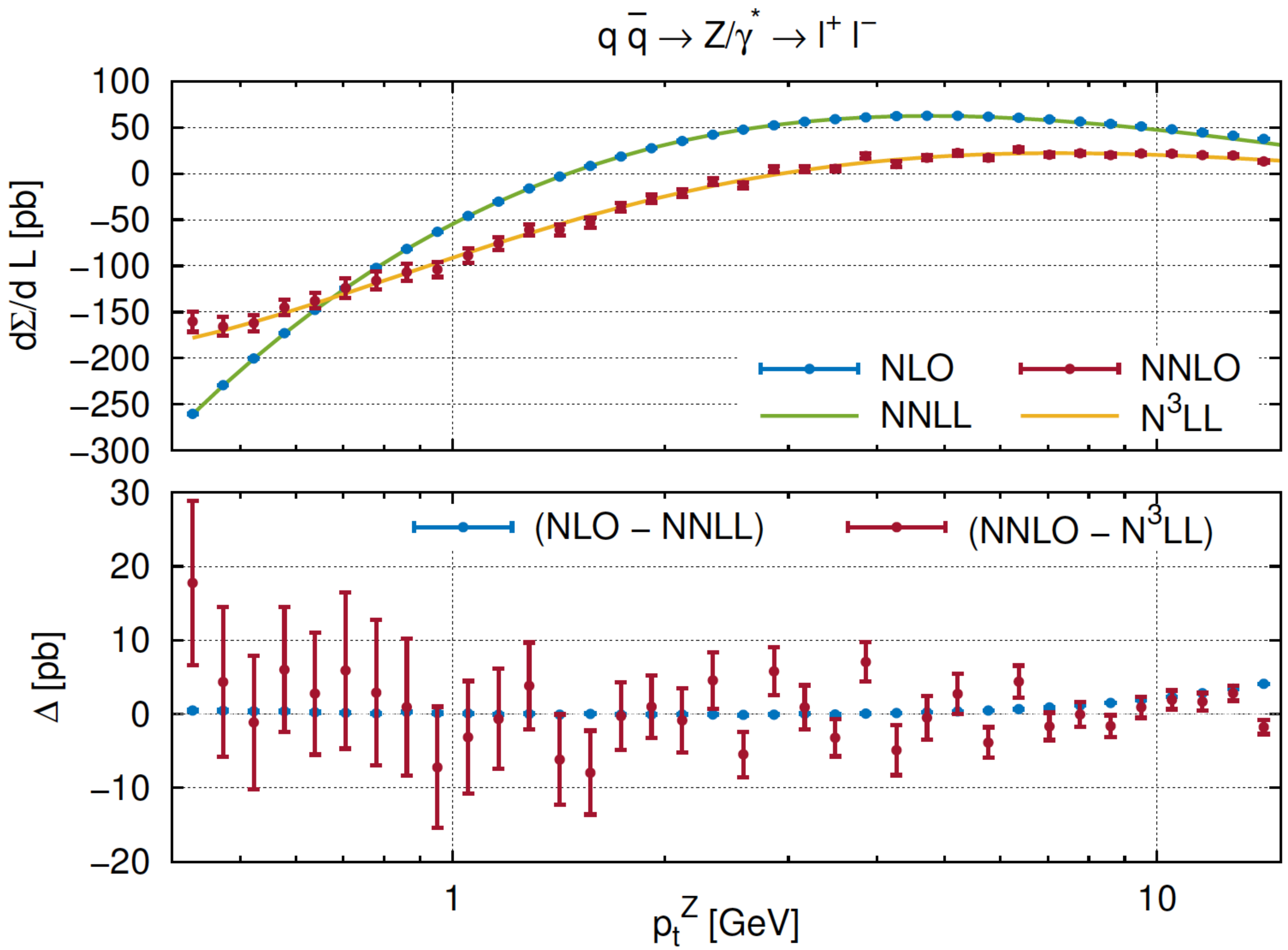
- State of the art N^3LL **resummation of $\ln(M/p_T)$ is matched to NNLO calculations** for the differential spectrum

  [Bizon, Chen, Gehrmann - De Ridder, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli '18]

  - **subtract all logarithms from NNLO calculation and replace them with their all-order summation**

- Subtraction numerically challenging (few-% level cancellations)





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- Combine the two predictions according to a matching scheme
  - e.g. multiplicative

$$\Sigma^{\mathrm{N^3LL+N^3LO}} = \int_0^{p_T} \frac{d\sigma}{dp_\perp} dp_\perp \sim \Sigma^{\mathrm{N^3LL}} \underbrace{\left[\frac{\Sigma^{\mathrm{N^3LO}}}{\Sigma^{\mathrm{N^3LL}}_{\mathrm{expanded}}} \right]_{\mathrm{expanded}}}_{\text{finite for } \mathrm{p_T} \to 0}$$

$$\Sigma^{\mathrm{N^3LO}} = \sigma^{\mathrm{N^3LO}}_{\mathrm{total}} - \int_{p_T}^{\infty} \frac{d\sigma^{\mathrm{NNLO}}}{dp_\perp} dp_\perp$$

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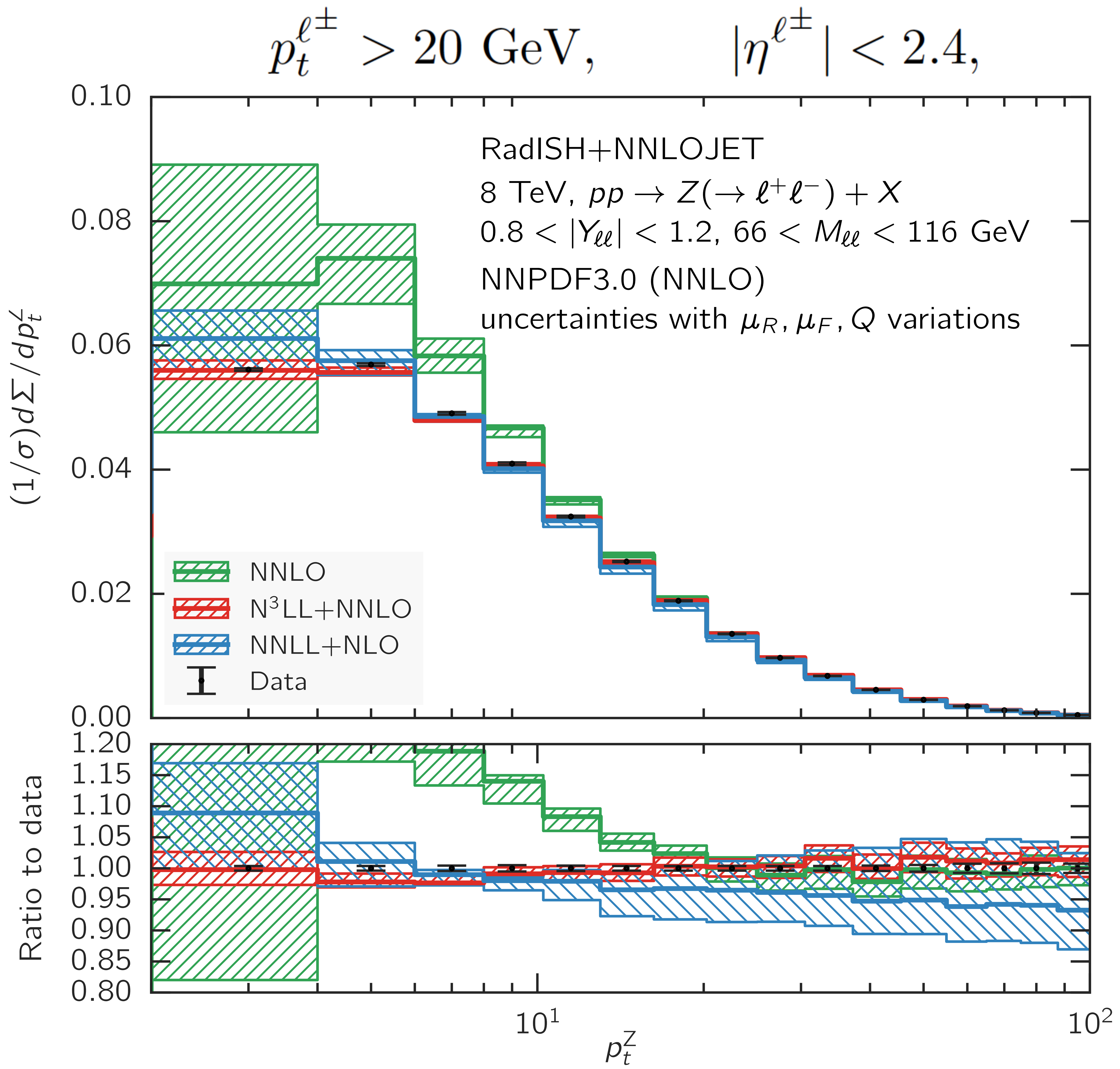
Effect of N^3LO total cross section subleading (N^4LL) in the differential spectrum !

$$\Sigma^{\mathrm{N^3LO}} = \cancel{\sigma^{\mathrm{N^3LO}}_{\mathrm{total}}}\ \sigma^{\mathrm{NNLO}}_{\mathrm{total}} - \int_{p_T}^{\infty} \frac{d\sigma^{\mathrm{NNLO}}}{dp_\perp} dp_\perp$$

← NNLOJet

Predictions at LHC8 (Z)

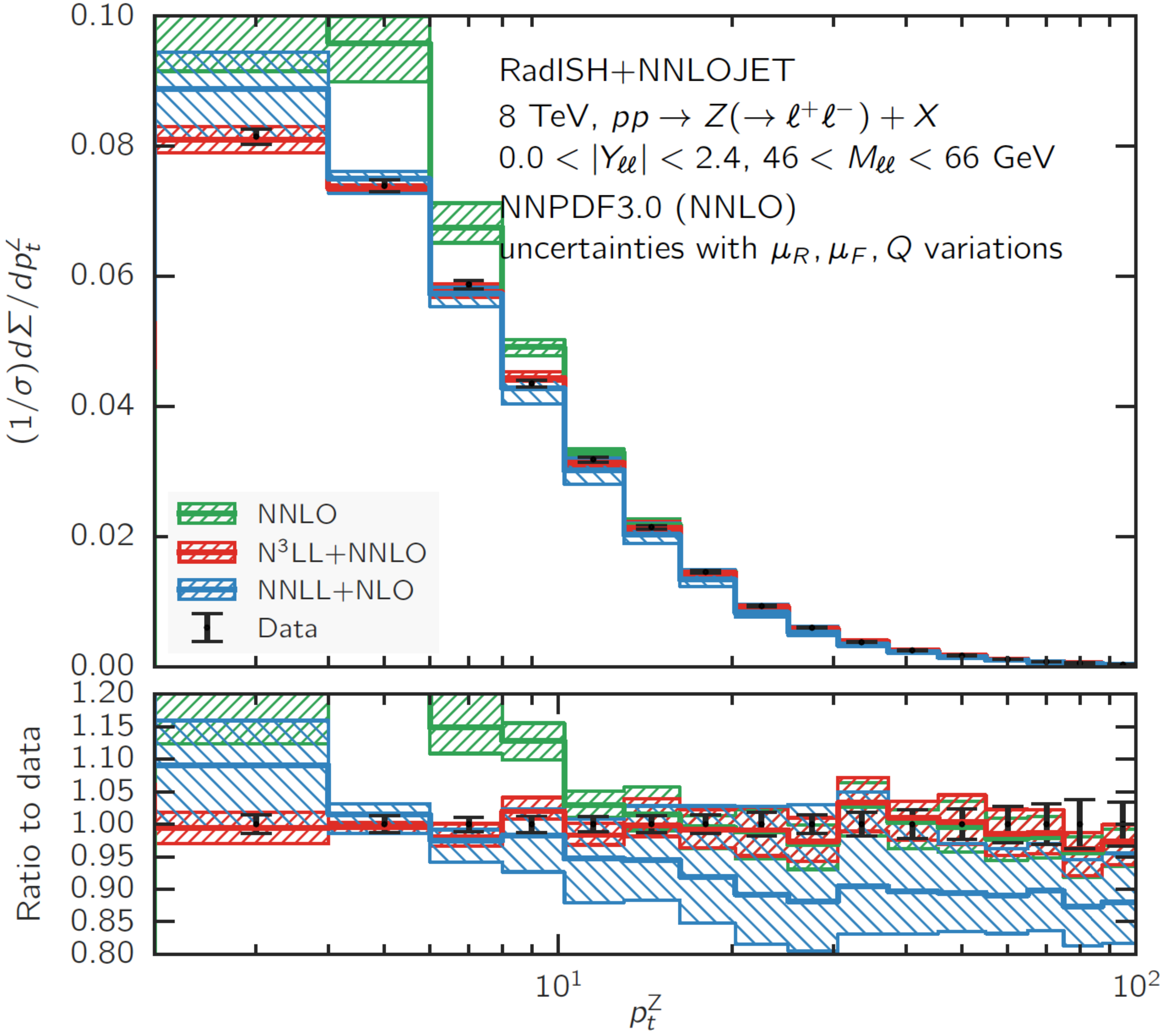
- Data and fiducial cuts from **[ATLAS 1512.02192]**
- **~7%-10% corrections w.r.t. NNLL+NLO**
- **Scale uncertainties below the 5% level**
  - Similar findings for the phi* angular observable [backup]

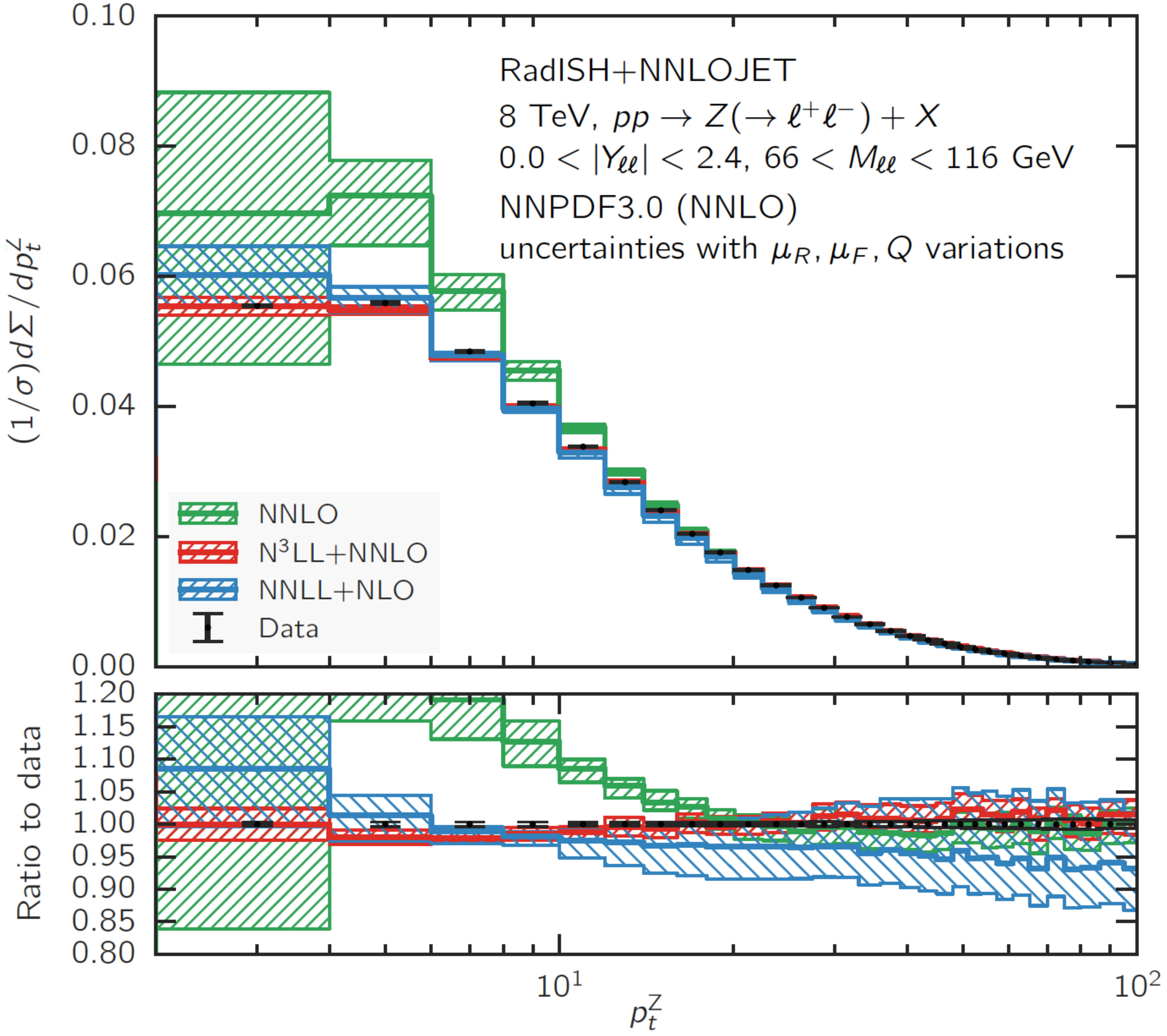


[Bizon, Chen, Gehrmann - De Ridder, Gehrmann, Glover, Huss, PM, Re, Rottoli, Torrielli ’18]

Predictions at LHC8 (Z)

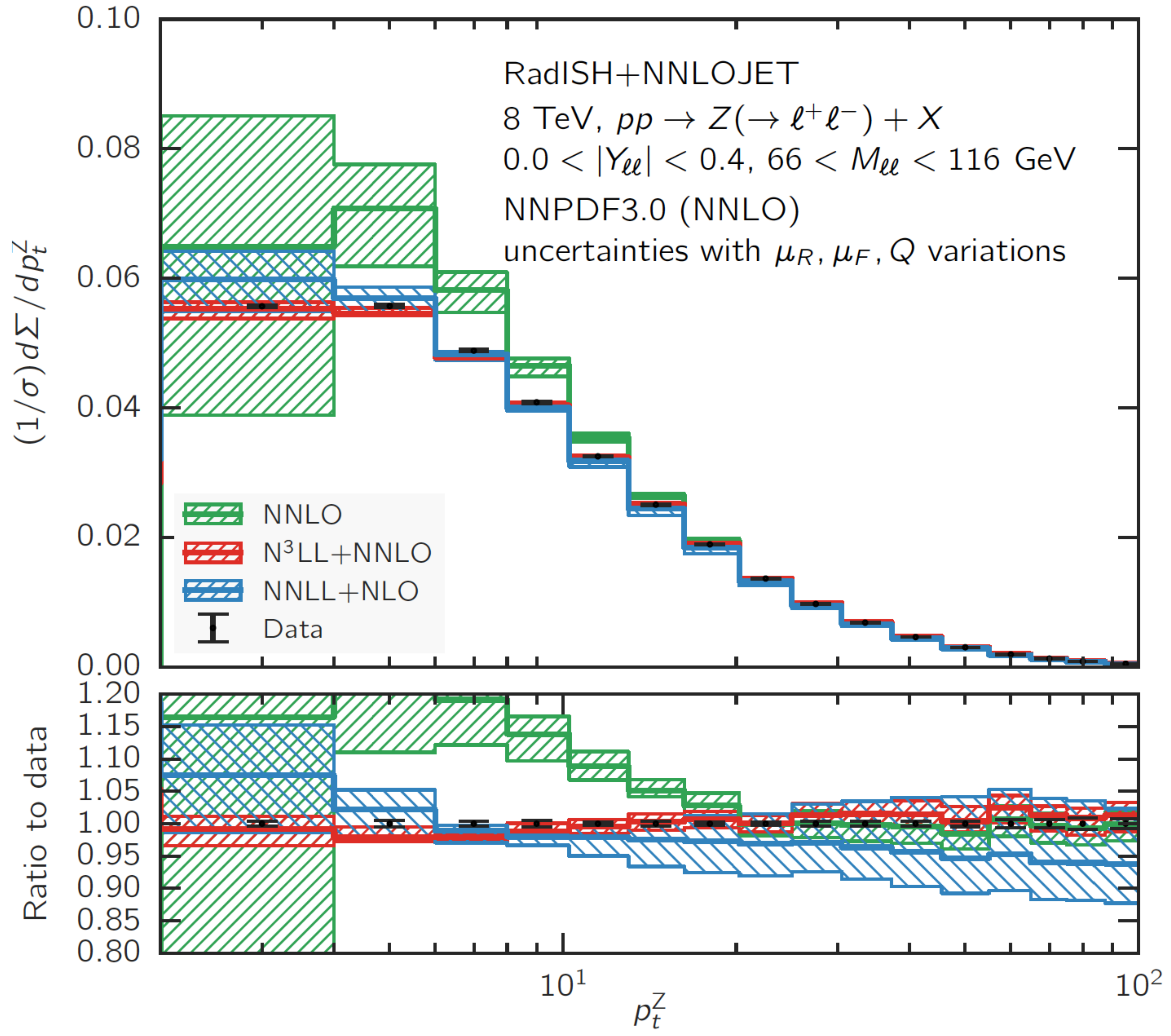
- Good agreement with measurement in different **invariant mass** bins

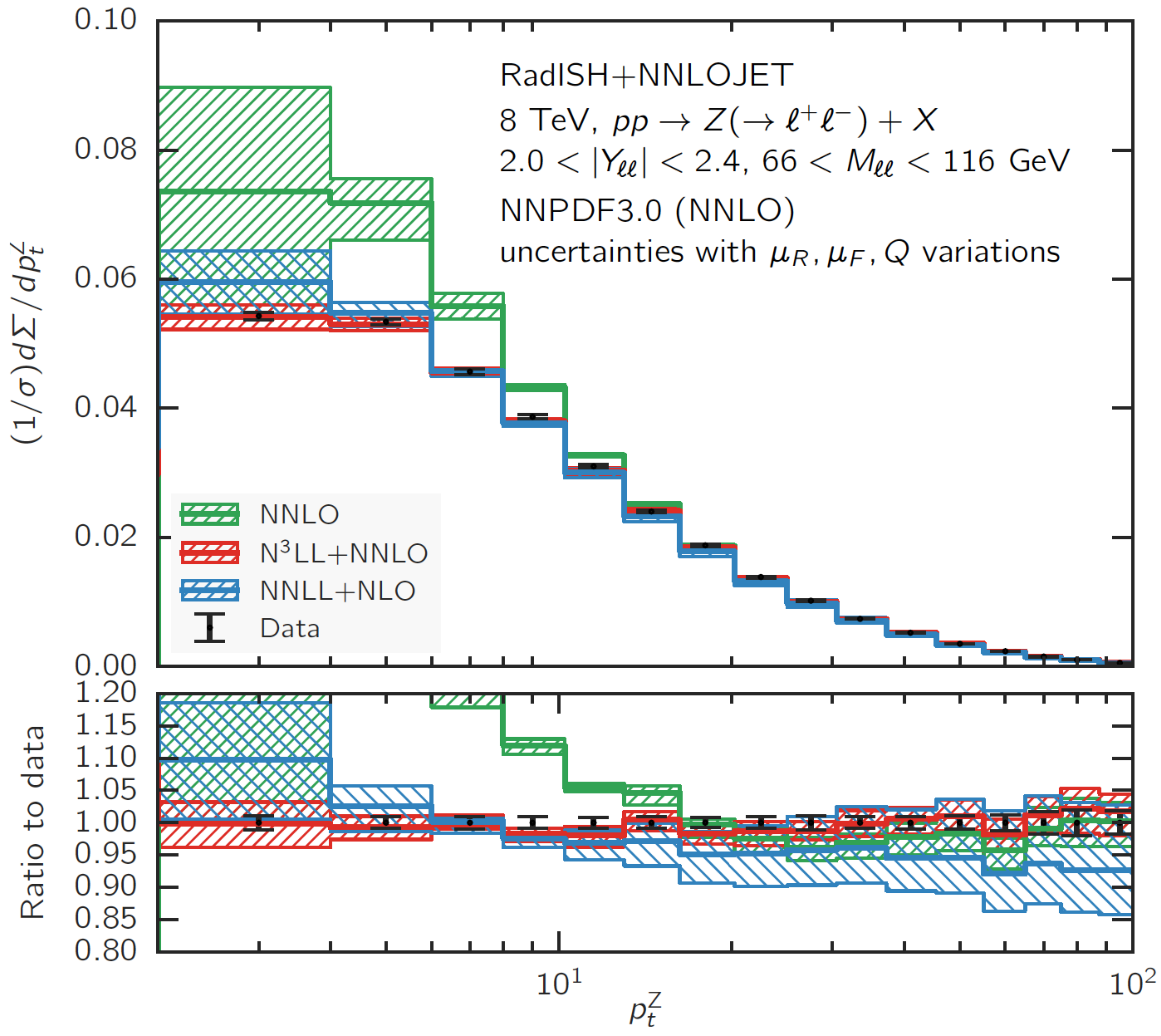




Predictions at LHC8 (Z)

- Good agreement with measurement in different **rapidity** bins



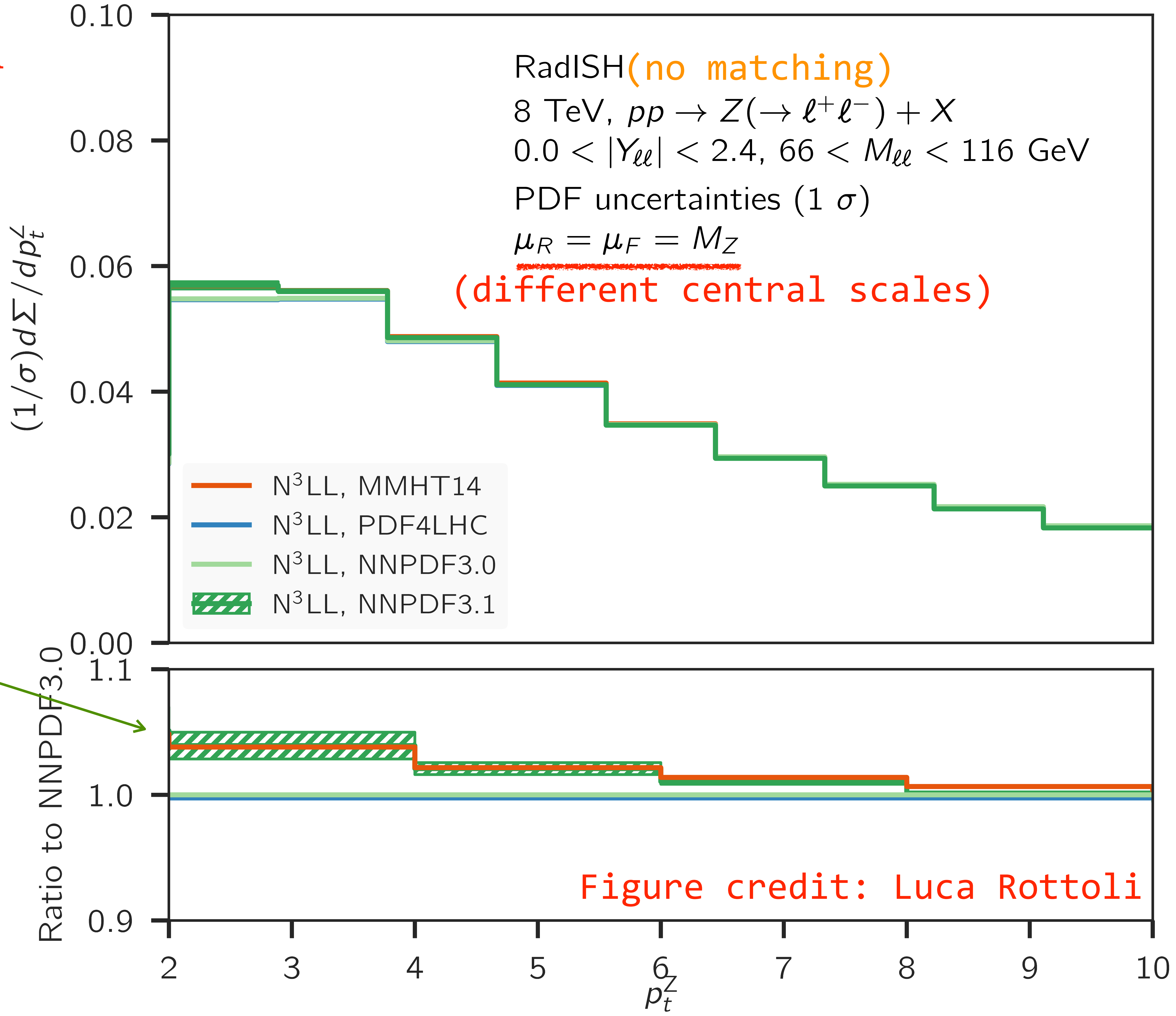


PDF uncertainty (Z @ LHC8)

- Data and fiducial cuts from [**ATLAS 1512.02192**]
- **PDF errors at the 1% level, but difference between sets can be as large as 3.5%**
  - Spectrum slightly harder with latest sets
  - Theory uncertainties in PDFs become relevant
    - see also Juan Rojo's talk (this morning)

Envelope of NNPDF3.1 sets

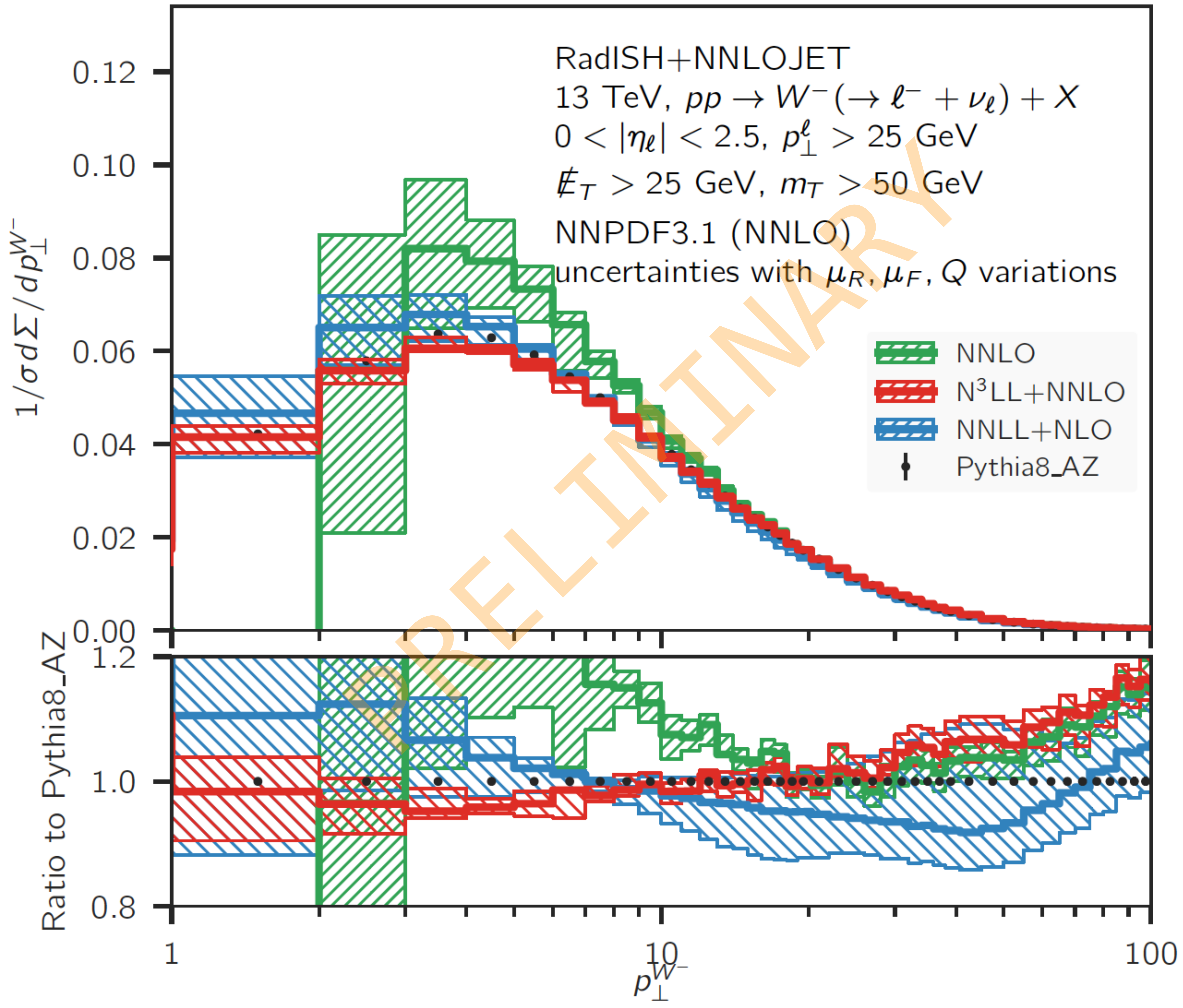
$p_t^{\ell^\pm} > 20$ GeV, $|\eta^{\ell^\pm}| < 2.4$,

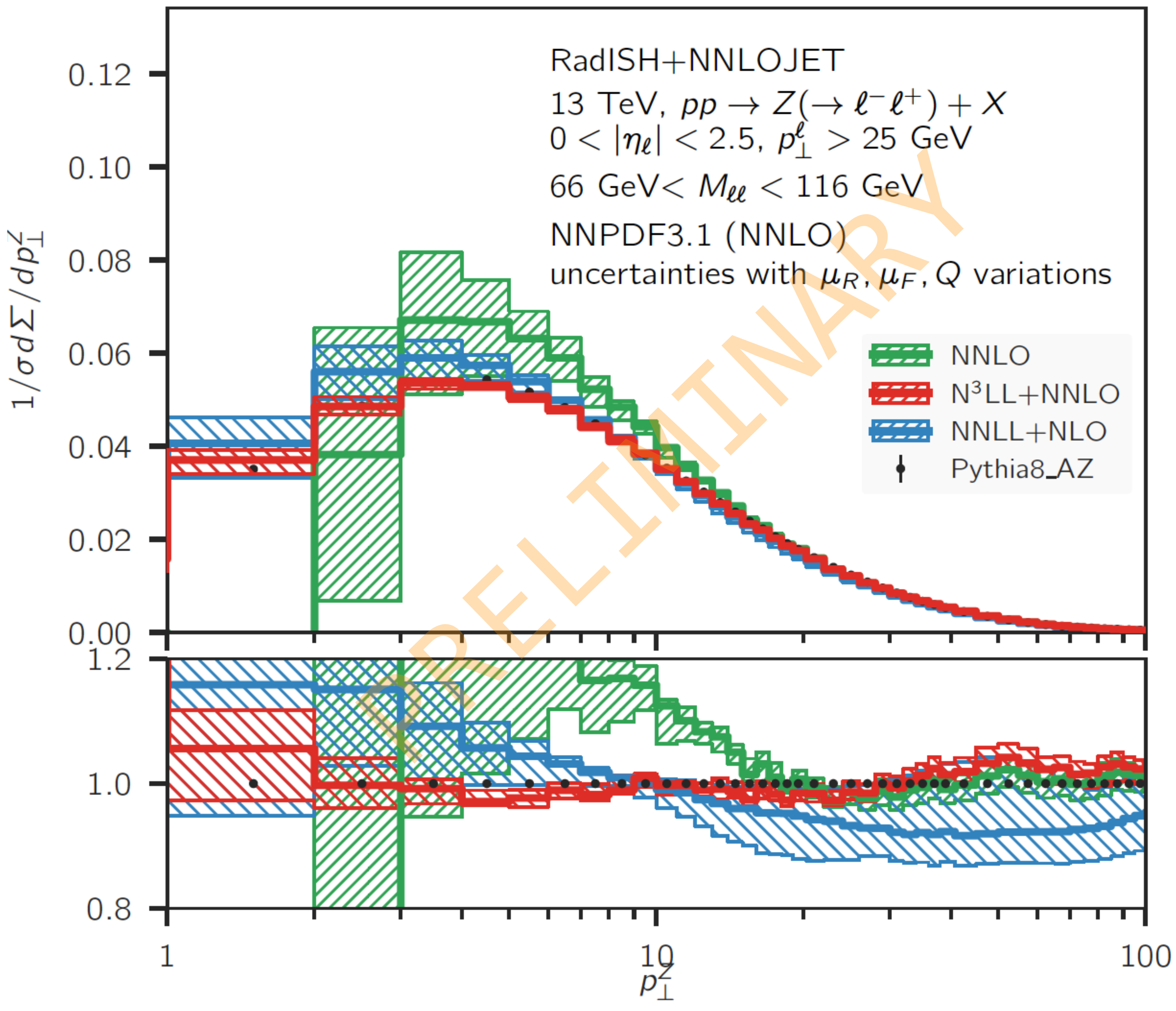


Pythia8 simulation in the ATLAS setup kindly provided by Jan Kretzschmar

Predictions at LHC13 (Z & W)

- Some discrepancies with Pythia8 [**AZ tune = tuned to p_T^Z at 7 TeV**]: **is this tune reliable at 13 TeV ?**





[Gehrmann - De Ridder, Gehrmann, Glover, Huss, PM, Re, Rottoli, Walker in preparation]

Ratios of differential distributions

- Important to understand correlation between Z & W distributions to exploit data driven predictions

$$\frac{1}{\sigma^{\mathrm{W}}}\frac{d\sigma^{\mathrm{W}}}{dp_\perp} \simeq \frac{1}{\sigma^{\mathrm{Z}}_{\mathrm{data}}}\frac{d\sigma^{\mathrm{Z}}_{\mathrm{data}}}{dp_\perp}\,\frac{\frac{1}{\sigma^{\mathrm{W}}_{\mathrm{theory}}}\frac{d\sigma^{\mathrm{W}}_{\mathrm{theory}}}{dp_\perp}}{\frac{1}{\sigma^{\mathrm{Z}}_{\mathrm{theory}}}\frac{d\sigma^{\mathrm{Z}}_{\mathrm{theory}}}{dp_\perp}}$$

- **Z and W production share a similar pattern of QCD radiative corrections**

- Several plausible procedures to estimate uncertainties in the ratio, e.g.

1. **Correlate resummation and renormalisation scale variations. Vary factorisation scale in an uncorrelated manner [different initial state flavour structure, quark thresholds]** while keeping

$$\frac{1}{2} \leq \frac{\mu_F^{\mathrm{num.}}}{\mu_F^{\mathrm{den.}}} \leq 2$$

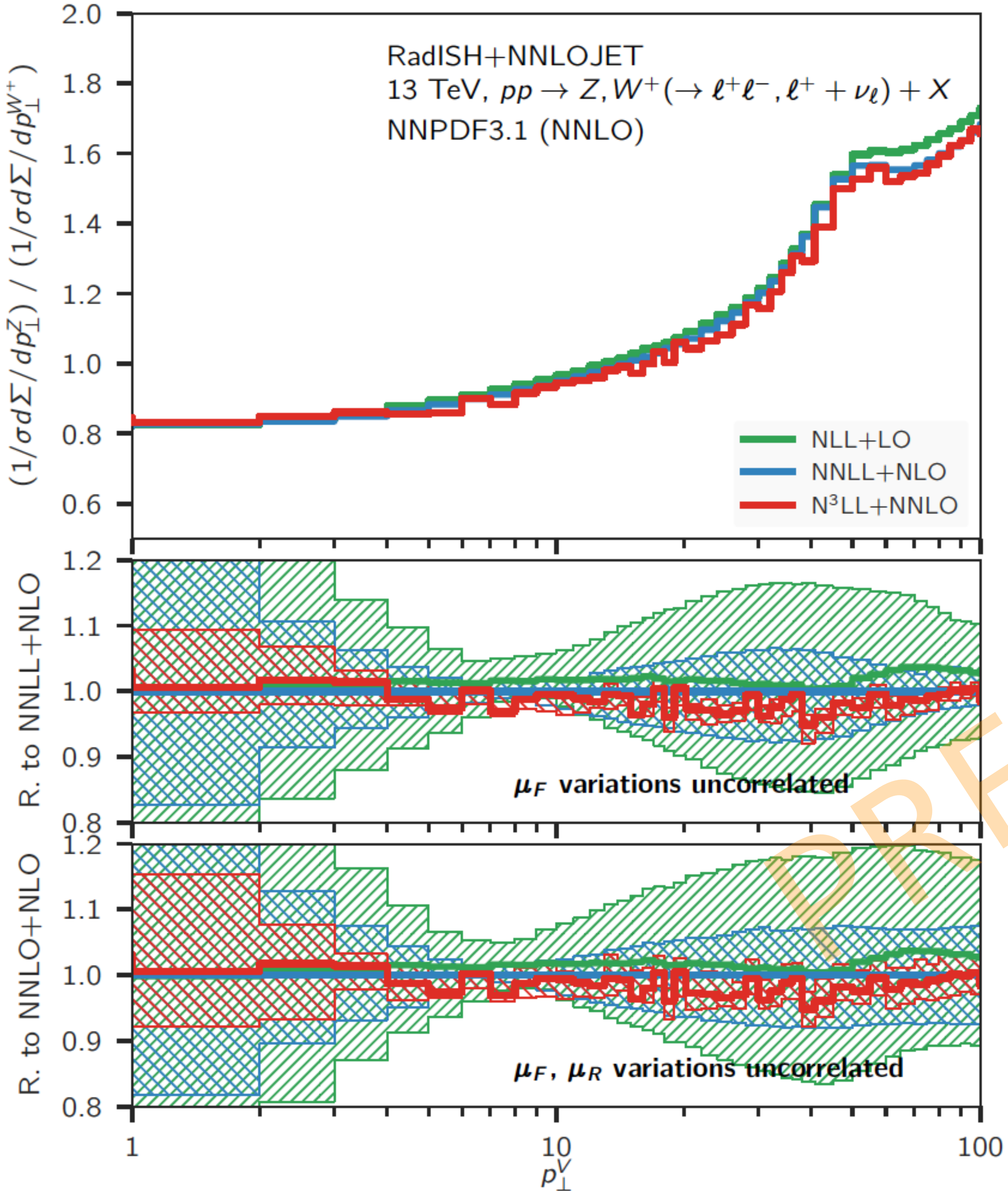
2. Vary **both renormalisation and factorisation scales in an uncorrelated way** with

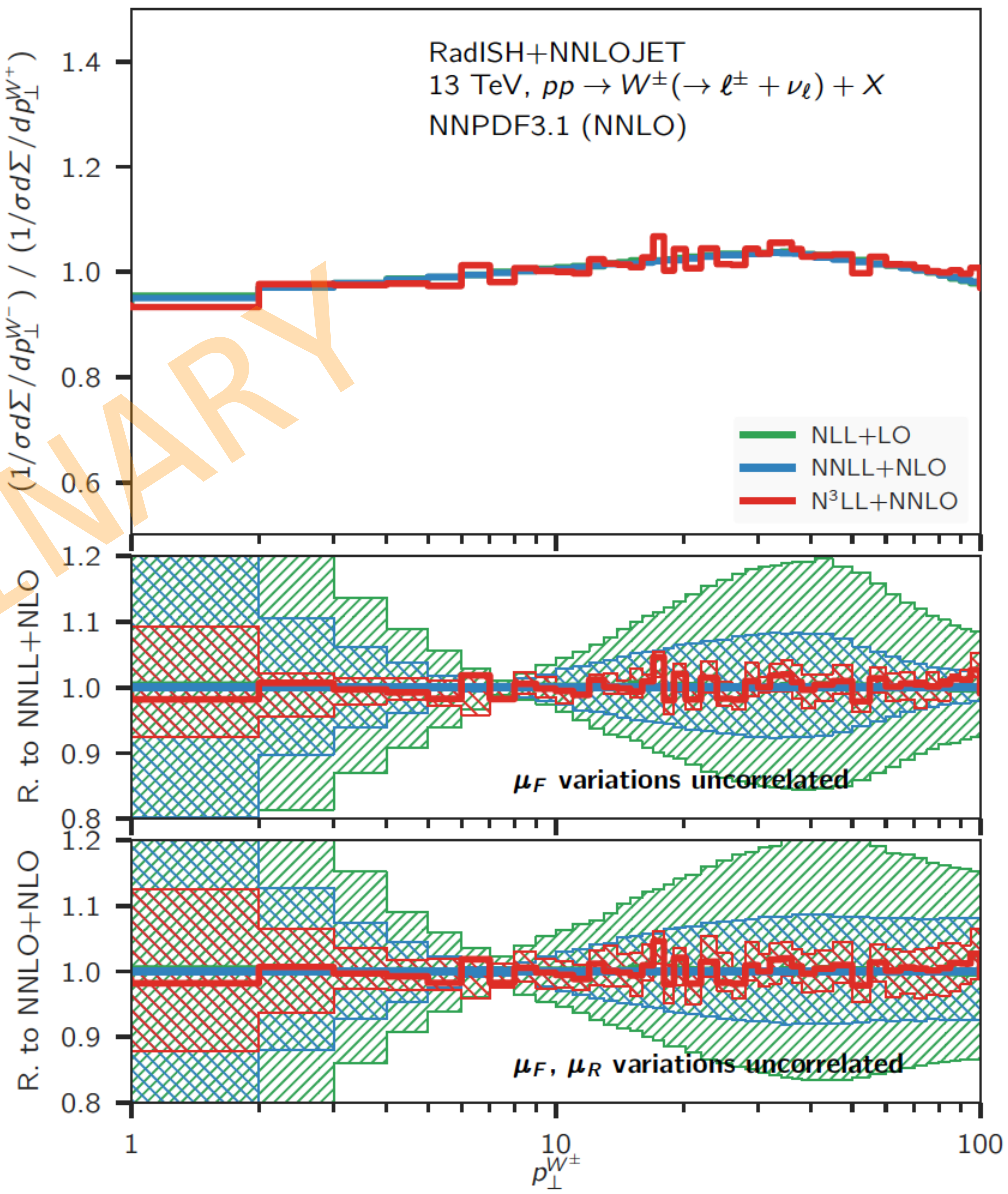
$$\frac{1}{2} \leq \frac{\mu^{\mathrm{num.}}}{\mu^{\mathrm{den.}}} \leq 2$$

Ratios of differential distributions

Less conservative prescription is justified

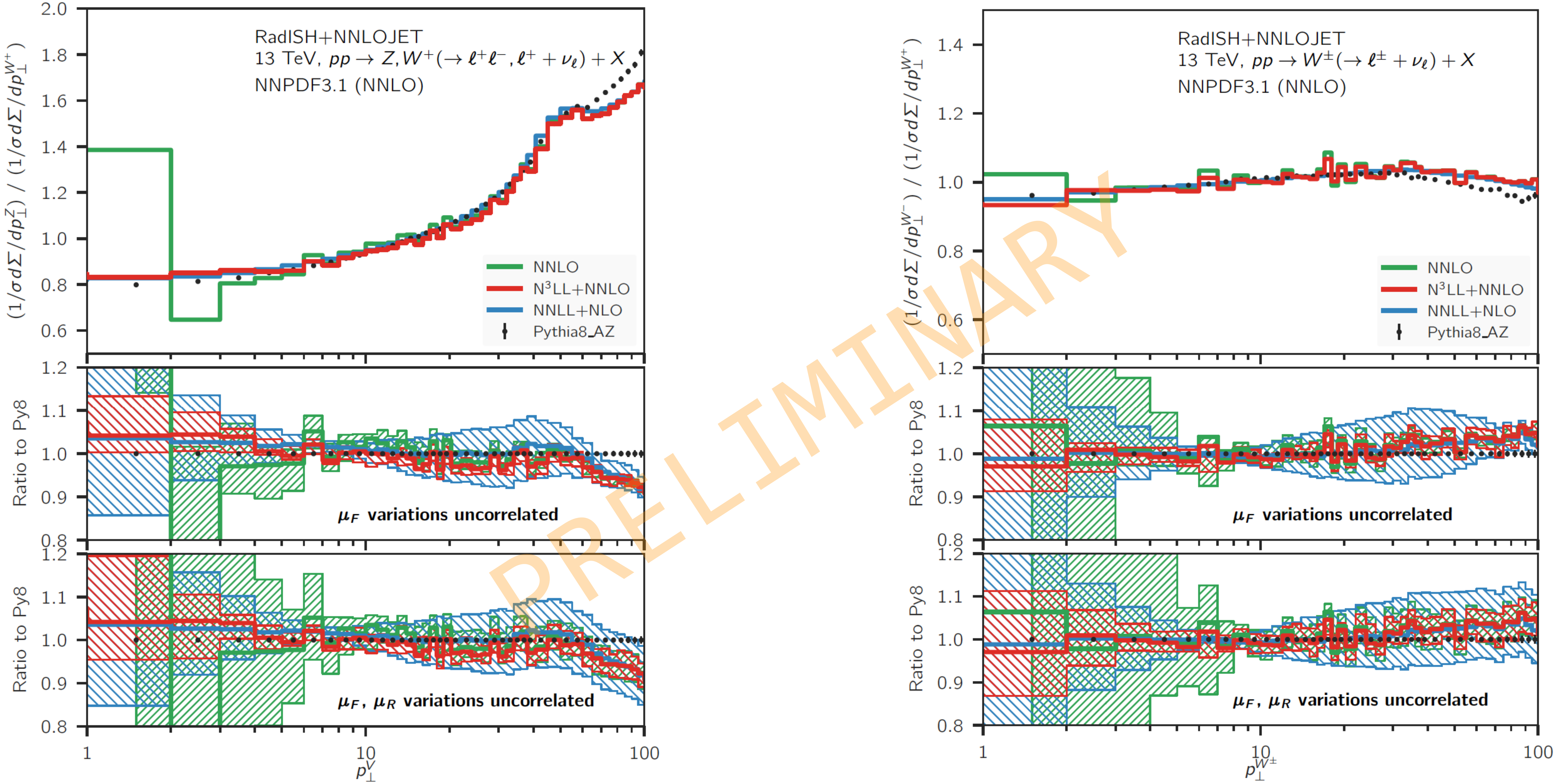
- Validate by studying the convergence of the perturbative predictions





Ratios of differential distributions

- Reasonable agreement with Pythia8 at small p_T, significant differences at large p_T



Non perturbative corrections

- Above calculation has a cutoff when the radiation approaches the Landau singularity, i.e.

$$\alpha_s(\mu_R)\beta_0 \ln \frac{Q}{k_{t1}} = \frac{1}{2} \longrightarrow k_{t1} \simeq 0.09\,\mathrm{GeV}\ (\mathrm{for}\ \mu_\mathrm{R} = \mathrm{Q} = \mathrm{M_Z})$$

- Parton densities freeze at higher scales (~ 1 GeV)

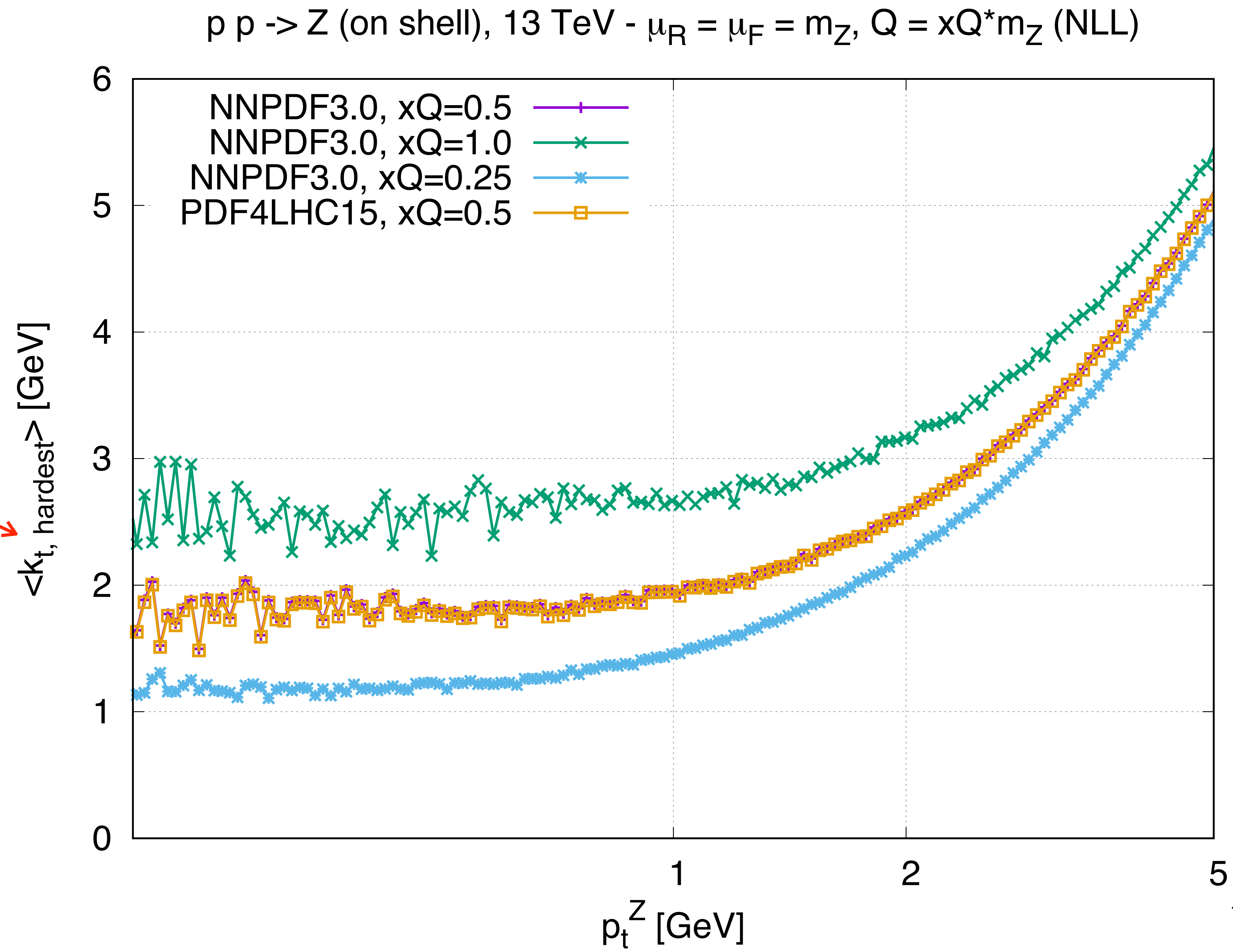
- However, NP corrections **expected to be suppressed** at $M \sim M_Z$ for $p_T \longrightarrow 0$ (within pert. uncertainty):

  - **radiation (on average) *lives* at perturbative scales**

  - situation changes at small invariant mass: hadronisation & intrinsic p_T become relevant

    - **constrain models from DY data**: first attempts to extract TMD parton densities very recently

[Bertone, Scimemi, Vladimirov '19]



Impact of quark masses

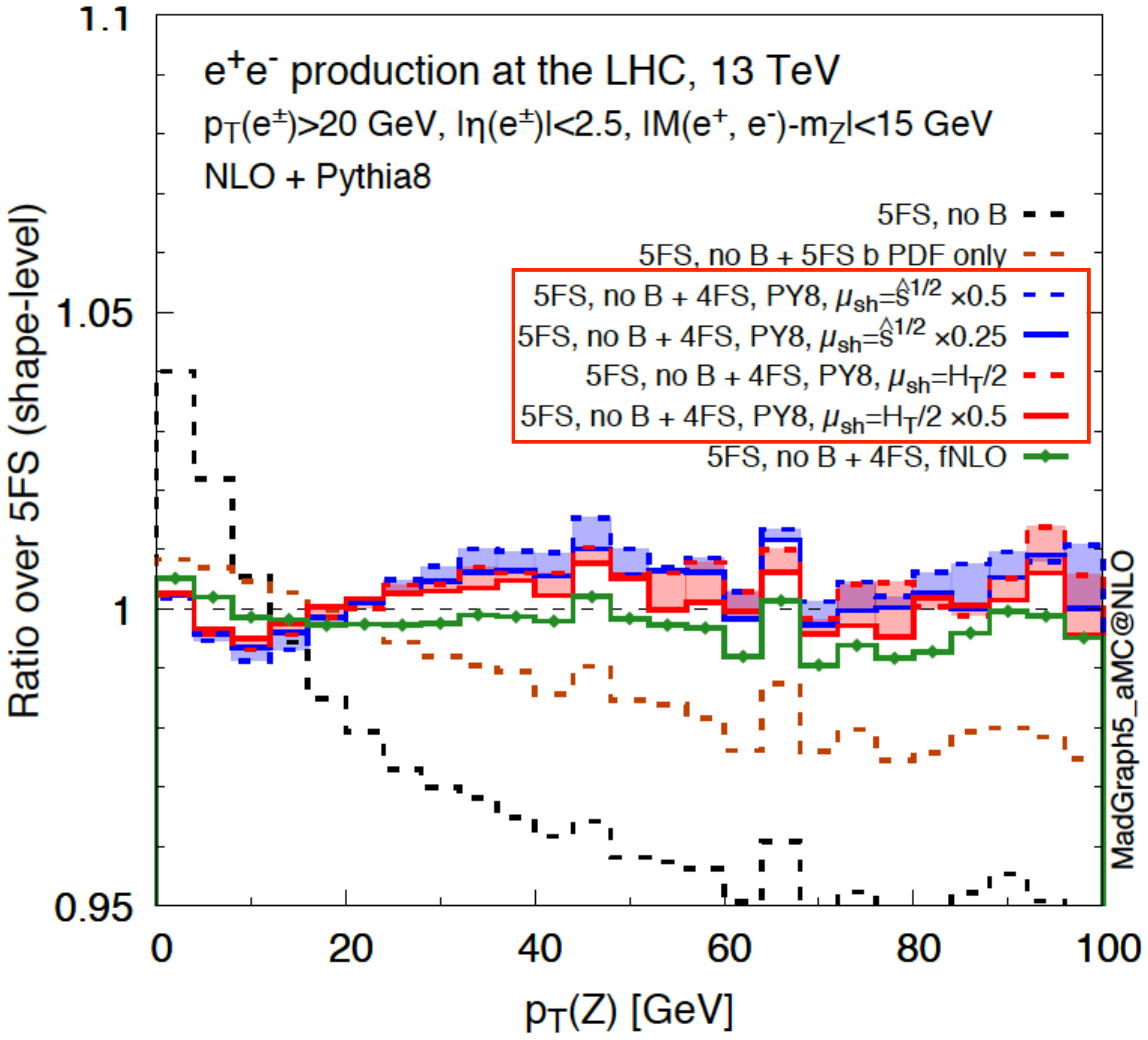
- Bottom quarks in the initial state yield ~4% of the total Z cross section (CKM suppressed for W)
  - Collinear logarithmic contributions encoded in DGLAP evolution in the 5FS (—> **predictions above**)
- Accounting for their mass can be important at scales **$p_T \sim m_b \sim$ peak region**
- Existing studies indicate **very small corrections ~ 1%**

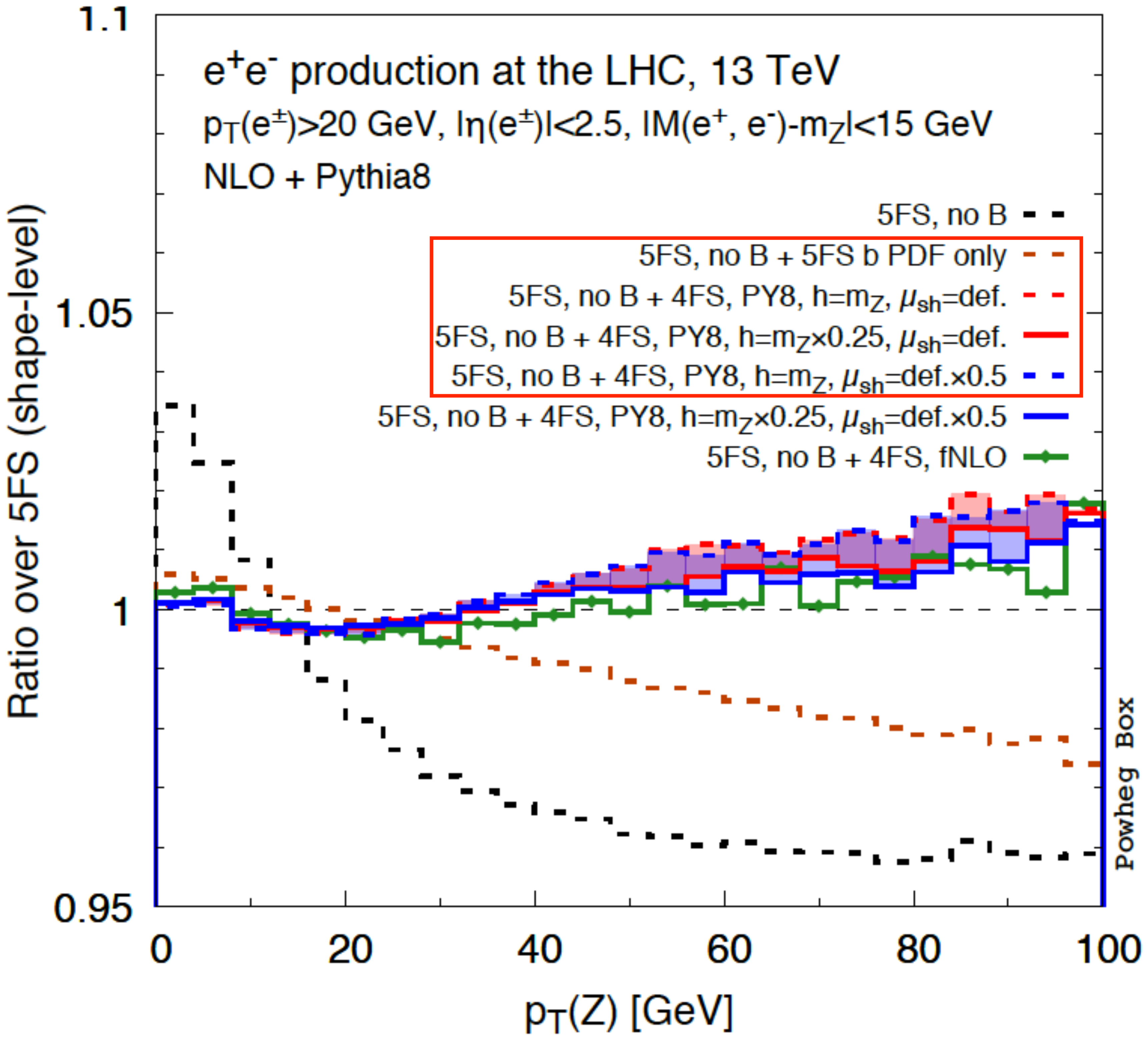
e.g. @ NLO & NLO+PS

$$\frac{d\sigma^{\text{mass}}}{dp_\perp^{\ell^+\ell^-}} = \frac{d\sigma^{\text{5FS}-\text{Bveto}}}{dp_\perp^{\ell^+\ell^-}} + \frac{d\sigma^{\text{4FS}}}{dp_\perp^{\ell^+\ell^-}}$$

[Bagnaschi, Maltoni, Vicini, Zaro '18]

See also:
[Krauss, Napoletano '17]
[Hoeche, Krause, Siegert '19]





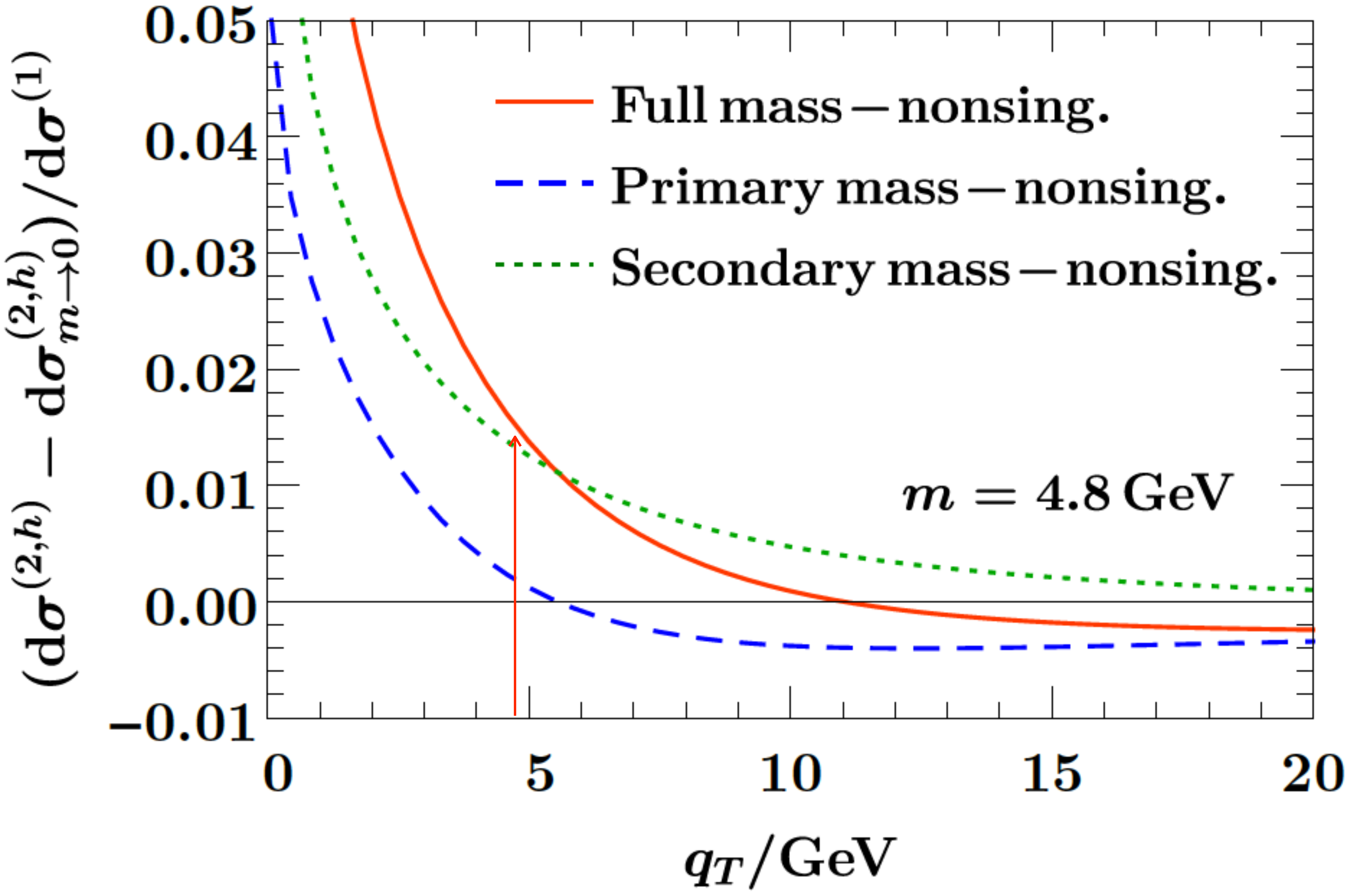
Impact of quark masses

- **Exact shape details remain an open question:** fully consistent treatment in resummations useful for %-level precision

  [Aivazis, Collins, Olness, Tung '93]
  [Nadolsky, Kidonakis, Olness, Yuan '02]
  [Berge, Nadolsky, Olness '05]
  [Pietrulewicz, Samitz, Spiering, Tackmann '17]

- Full calculation still unavailable, but partial results indicate a **percent effect at $p_T \sim m_b$**

  e.g. O(as^2) expansion [resummation necessary at these p_T scales]



Plot from [Pietrulewicz, Samitz, Spiering, Tackmann '17]

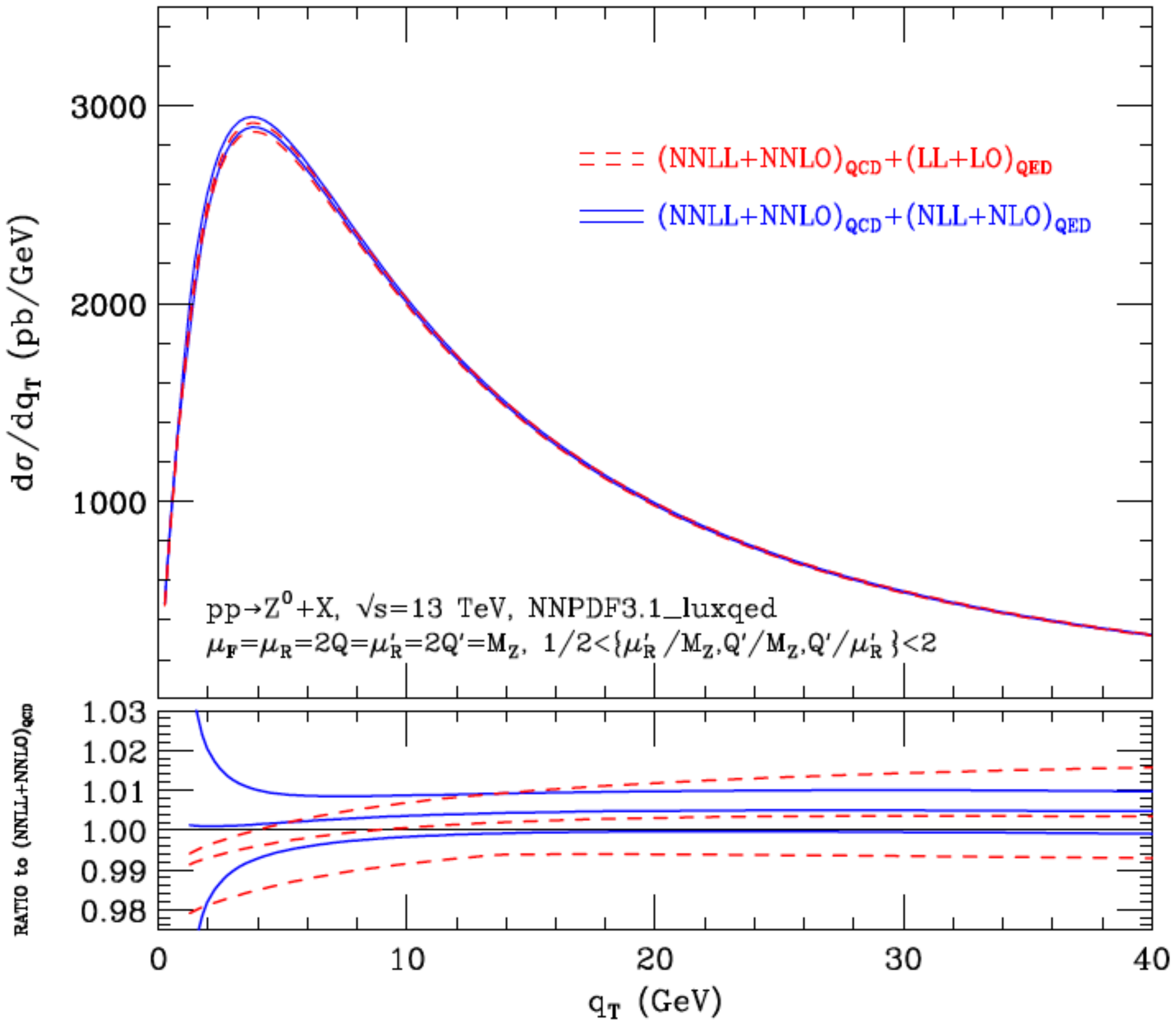
QED effects

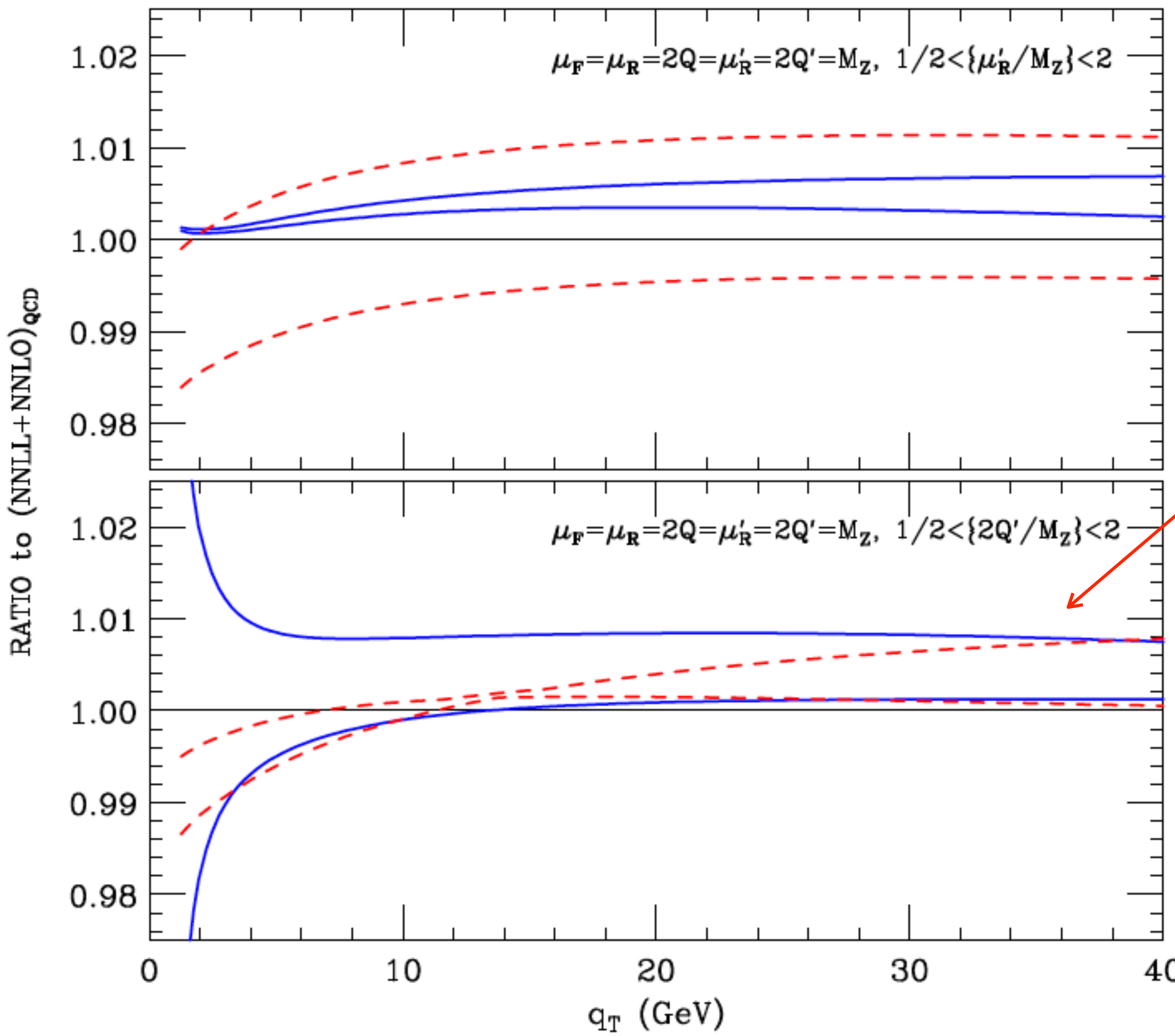
- QED $\mathcal{O}(\alpha^2)$ and mixed $\mathcal{O}(\alpha_s\alpha)$ QED/QCD corrections contribute at the permille level to the total cross section

[de Florian, Der, Fabre '18]

- QED effects lead to a 1-2% correction to the differential distribution

[Cieri, Ferrera, Sborlini '18]





Error dominated by resummation uncertainties

Summary

- Measurements of gauge boson p_T at the LHC require us to push theory predictions to the limits of perturbation theory and beyond
- Pattern of QCD (massless, except for thresholds in PDFs) corrections well understood, with residual **errors at the 3-5% level** across most of the spectrum
- Beyond this point, several effects become relevant:
  - **higher order QCD corrections** to the differential spectrum (i.e. N^4LL+N^3LO)
  - **PDF errors at the 1-3% level**: How to combine with the remaining perturbative error ? Are differences between sets really understood ? Theory uncertainties in PDFs ?
  - **NP corrections expected to be as large as 1-2%**, small-mass Drell-Yan could be exploited to constrain these in a data driven manner (high TH+EXP precision required, challenging for TMD PDFs)
  - **QED corrections at the ~1-2% level**, uncertainties can be potentially reduced
  - **bottom-quark mass corrections at the ~1-2% level**, calculation at small p_T feasible
  - parametric uncertainties, e.g. **strong coupling at the ~1% level**, currently hard to improve further

Summary

- Within the above accuracy, large correlations are observed between **W^+, W^-, and Z** production in massless QCD

- Little is known about the degree of correlation between all of the remaining sources of corrections

  - Still room for improvement in some directions, but a solid control requires **many of the above issues to be well understood**

  - This also needs some deep insight on **how we should estimate scale uncertainties** in QFT (e.g. PDFs) with this level of accuracy

- Data can surely help constrain some of the above points. **However, Monte Carlo tunes for sub-percent precision must be handled with care.** Very careful study of what parameters are actually being tuned is necessary to avoid unphysical correlations

Thank you for listening

More predictions at LHC8 (phi*)