Recent developments in Transverse Momentum Dependent parton densities and associated parton showers

Hannes Jung (Emeritus, II Institut f. Theoretische Physik, DESY, Hamburg)

- Why TMDs ?
- Recap of PB method for TMDs

- application of PB-TMD densities
  - Drell-Yan production at the LHC, Tevatron, low energies

The role of soft gluons in parton densities

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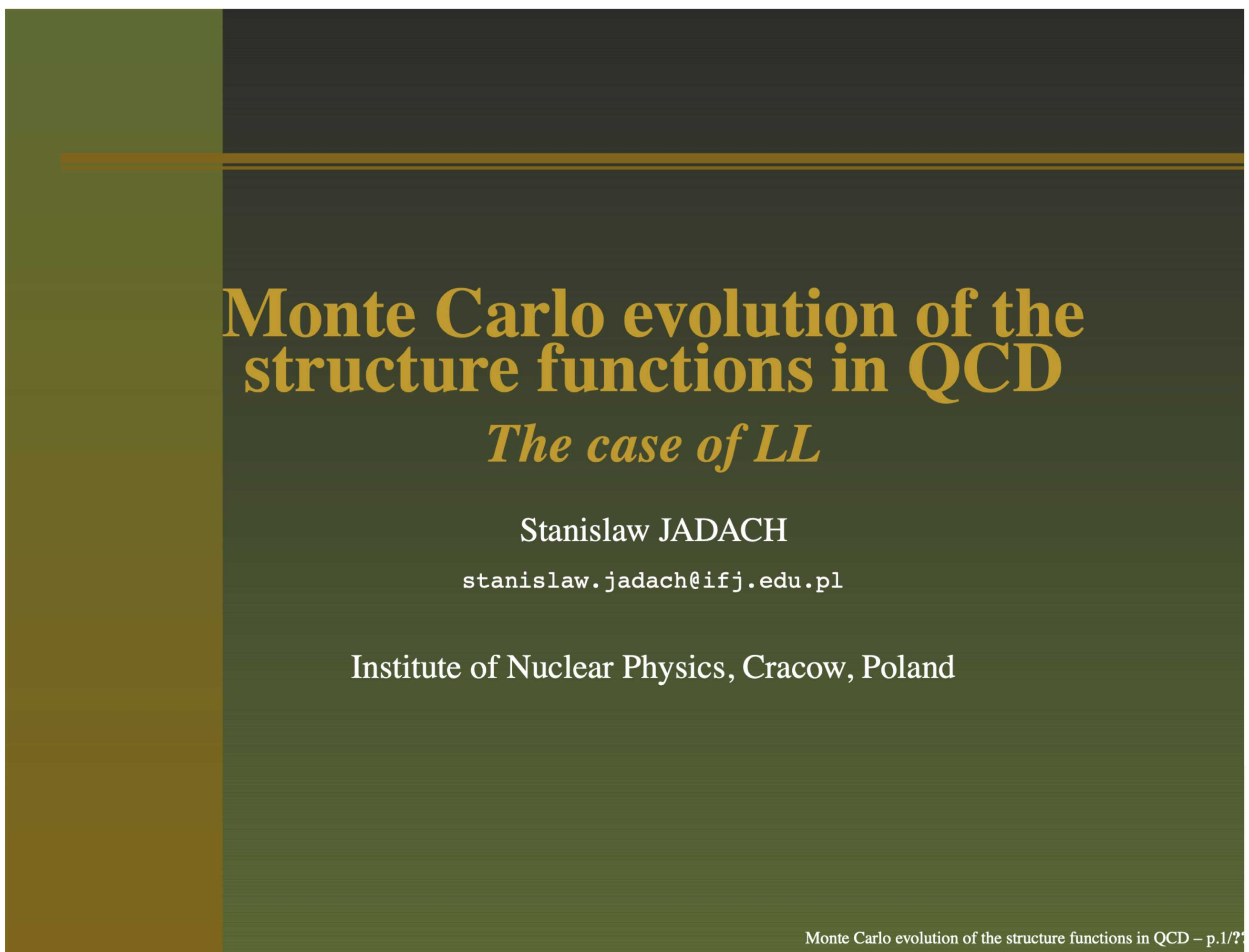
- Why TMDs ?
- Recap of PB method for TMDs

- application of PB-TMD densities
  - Drell-Yan production at the LHC, Tevatron, low energies

- The important role of soft gluons

In memory of S. Jadach

- Already back 20 years ago, my colleagues from H1, J. Turnau, L. Goerlich, G. Nowak S. Mikocki organized meetings with S. Jadach, M. Skrzypek on the evolution of un-integrated parton densities ala CCFM with a Monte Carlo approach
  - this was the beginning of a very fruitful and productive cooperation !



- ... the cooperation is still continuing, thanks a lot for this!

Preface: the ansatz

- fixed order calculations (even at higher orders) are limited in application
  - collinear and soft regions not well described
  - matrix elements with only a few partons can be calculated

- use collinear PDFs obtained from global fits using parton level NLO (NNLO) calcs.

- theoretical calculation:
  - use NLO (NNLO) ME, with soft gluon resummation to NNLL
  - applicable to only a few observables

- traditional ansatz with Parton shower Monte Carlo event generators use:
  - multi-leg matrix elements
    - parton shower (with free parameters to be tuned)
    - multiparton interaction (with even more parameters) and hadronization
  - multijet merging and matching of multi-leg ME with PS MCs

Preface: the new approach

- extend "collinear approximation"
  - determine parton densities with Parton Branching method including transverse momenta → obtain usual parton densities by integration over k_T
  - free parameters of PB Parton densities are obtained by fits to DIS data
  - PB -TMD densities automatically contain soft gluon resummation
    - at NLL identical to CSS approach, at higher orders finite terms are different

- apply PB TMD to calculations → automatically include soft gluon resummation
  - for example in DY q_T spectrum

- apply PB TMDs to TMD parton shower simulations (without additional free parameters)
  - see CASCADE3 Monte Carlo event generator (arXiv 2101.10221)

Preface: the new approach – PB

- rely on only few assumptions
  - use as few parameters as possible
    - PB pdf and PB-TMD pdf are fitted to DIS data (no pp data are included)
    - PB parton shower has no free parameters (all fixed by PB-TMD)

- Goal is NOT to fit the data but to understand the measurements
  - sometimes measurements are not (too well) described :(

Parton Branching approach - recap

DGLAP evolution – solution with parton branching method

$$f(x,\mu^2) = f(x,\mu_0^2)\Delta_s(\mu^2) + \int^{z_M} \frac{dz}{z} \int \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^{(R)}(z) f\left(\frac{x}{z}, \mu'^2\right)$$

- solve integral equation via iteration:

$$f_0(x,\mu^2) \quad = \quad f(x,\mu_0^2)\Delta(\mu^2)$$

DGLAP evolution – solution with parton branching method

$$f(x,\mu^2) = f(x,\mu_0^2)\Delta_s(\mu^2) + \int^{z_M} \frac{dz}{z} \int \frac{d\mu'^2}{\mu'^2} \cdot \frac{\Delta_s(\mu^2)}{\Delta_s(\mu'^2)} P^{(R)}(z) f\left(\frac{x}{z},\mu'^2\right)$$

- solve integral equation via iteration:

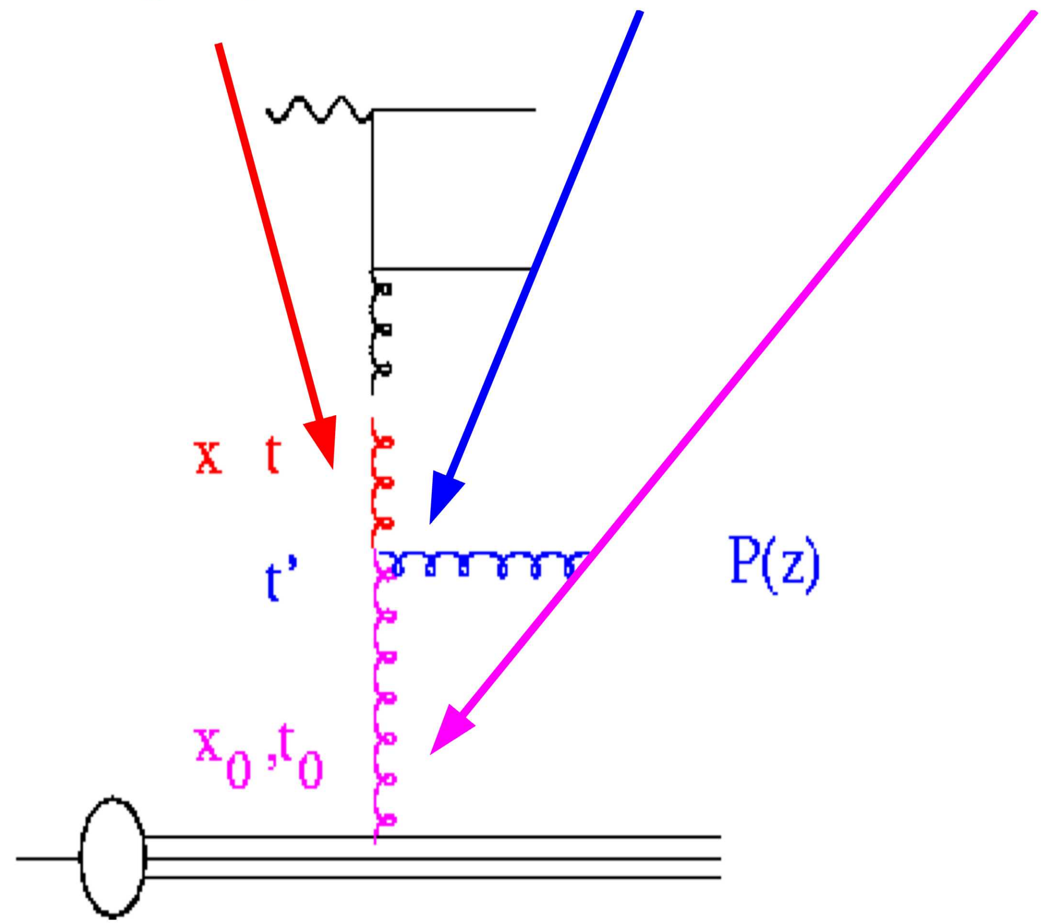
from μ' to μ w/o branching

branching at μ'

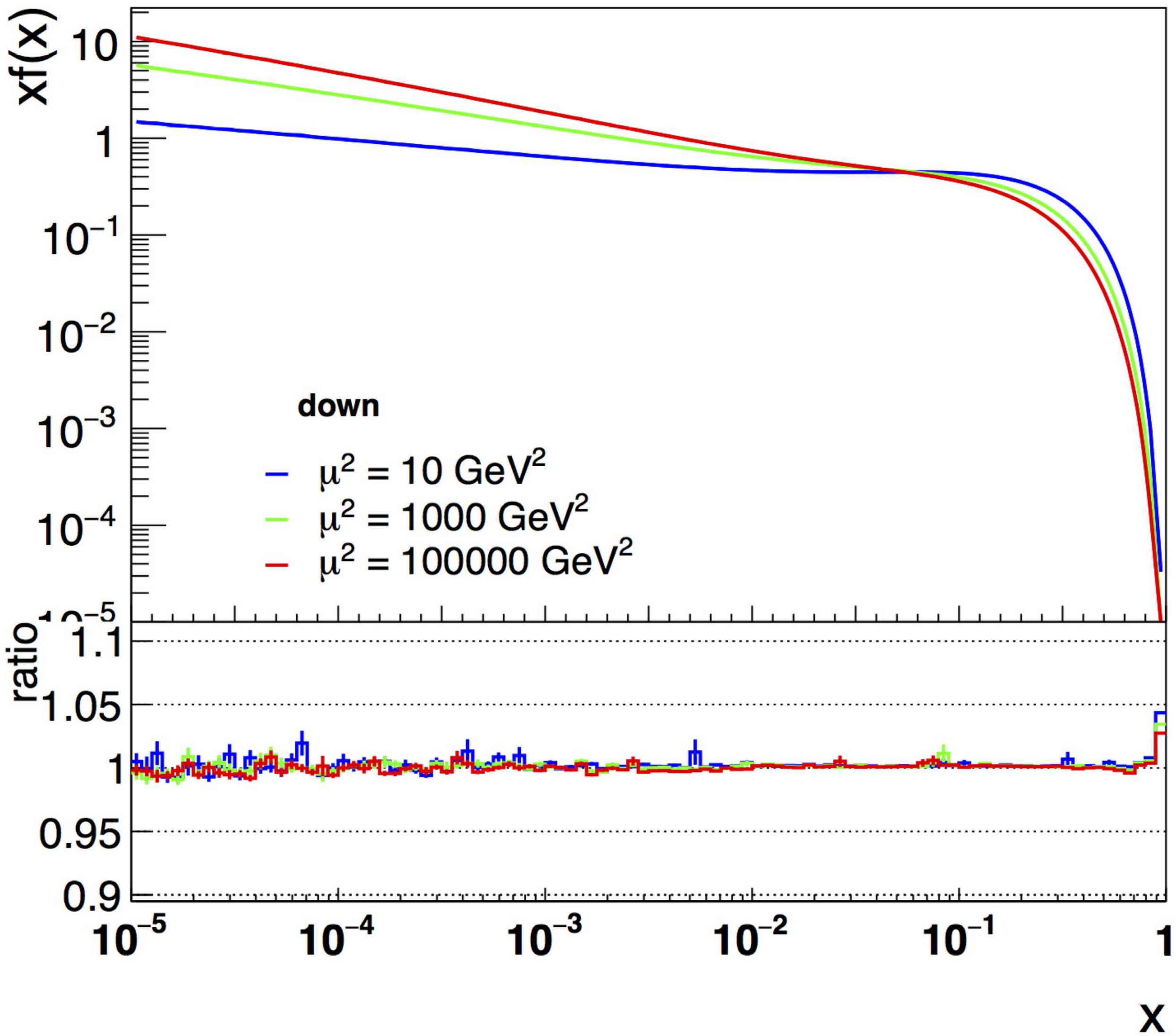
from μ to μ' w/o branching

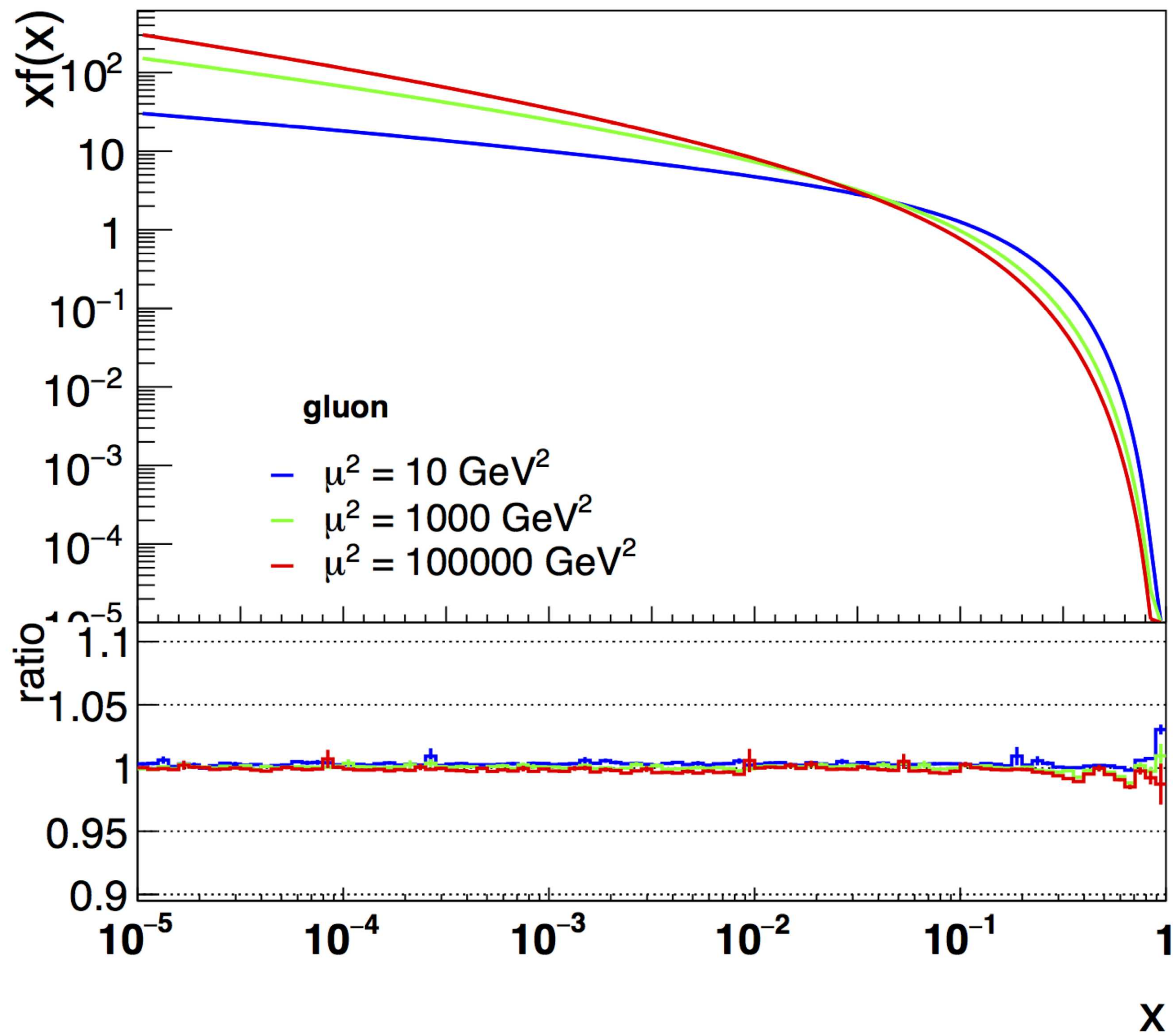
$$f_0(x,\mu^2) = f(x,\mu_0^2)\Delta(\mu^2)$$

$$f_1(x,\mu^2) = f(x,\mu_0^2)\Delta(\mu^2) + \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta(\mu^2)}{\Delta(\mu'^2)} \int^{z_M} \frac{dz}{z} P^{(R)}(z) f(x/z,\mu_0^2)\Delta(\mu'^2)$$



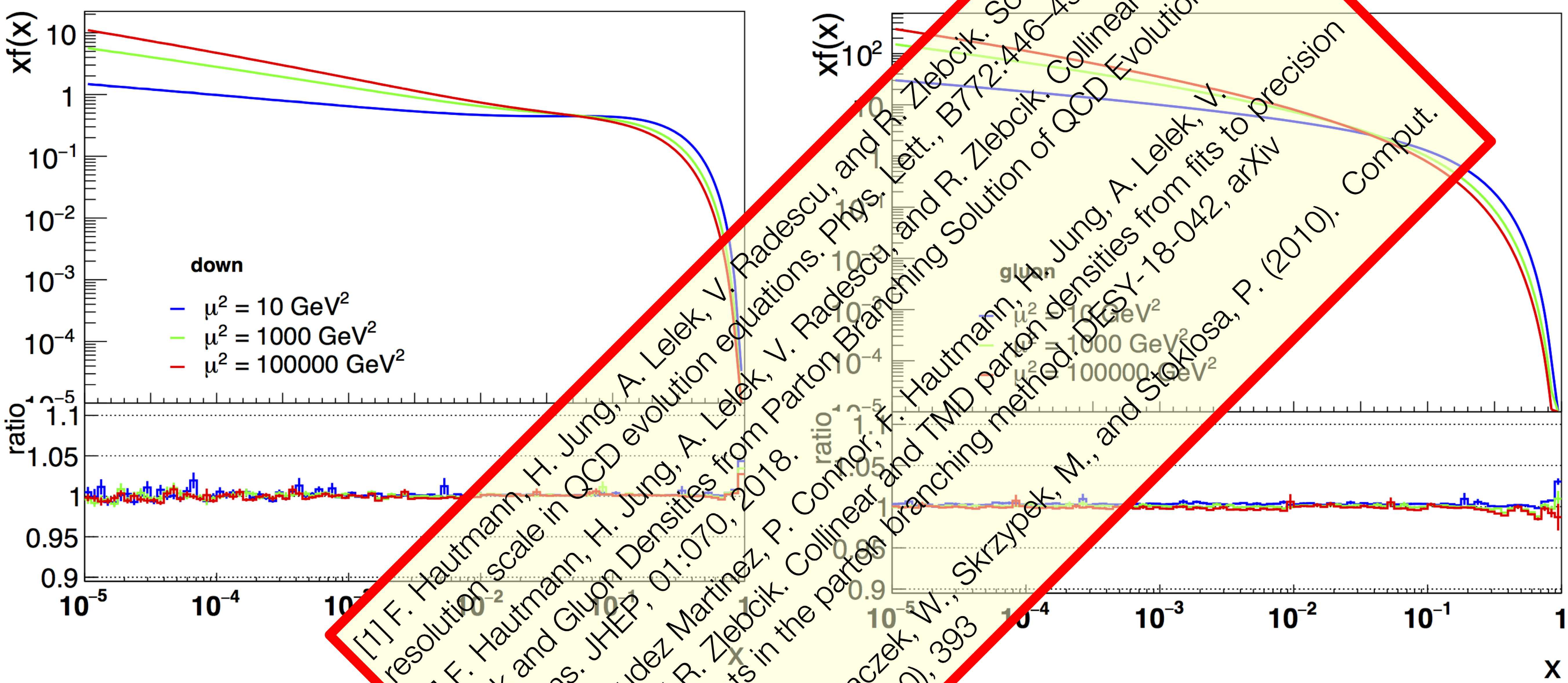
Validation of method with QCDnum at NLO





- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach works also at NNLO !

Validation of method with QCDnum at NLO



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[1] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Soft-gluon resolution scale in QCD evolution equations. Phys. Lett., B772:446–451, 2017.

[2] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD Quark and Gluon Densities from Parton Branching Solution of QCD Evolution Equations. JHEP, 01:070, 2018.

[3] A. Bermudez Martinez, P. Connor, F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD parton densities from fits to precision DIS measurements in the parton branching method. DESY-18-042, arXiv 1804.11152

see also Jadach S., Placzek W., Skrzypek M., and Stoklosa, P. (2010). Comput. Phys. Commun., 181(2010), 393

PDFs from Parton Branching method: fit to HERA data

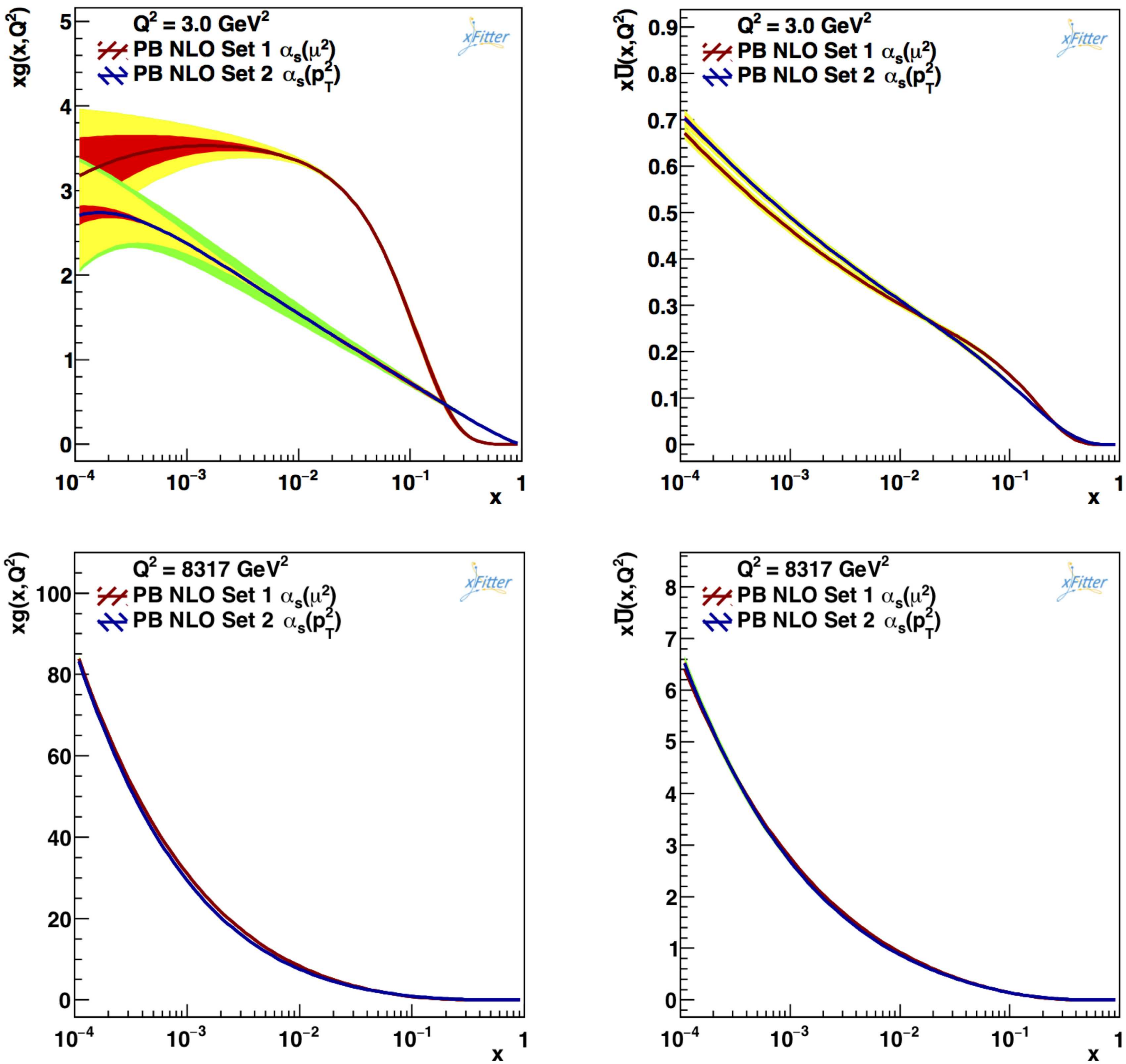
- Convolution of kernel with starting distribution

$$
\begin{aligned}
xf_a(x,\mu^2) &= x \int dx' \int dx'' \mathcal{A}_{0,b}(x') \tilde{\mathcal{A}}_a^b\left(x'',\mu^2\right) \delta(x'x''-x) \\
&= \int dx' \mathcal{A}_{0,b}(x') \cdot \frac{x}{x'}\, \tilde{\mathcal{A}}_a^b\left(\frac{x}{x'},\mu^2\right)
\end{aligned}
$$

- Fit performed using xFitter frame (with collinear Coefficient functions at NLO)
  - using full HERA I+II inclusive DIS (neutral current, charged current) data
    - in total 1145 data points
      - $3.5 \leq Q^2 \leq 50000\ \mathrm{GeV}^2$
      - $4 \cdot 10^{-5} < x < 0.65$
      - using starting distribution as in HERAPDF2.0
      - $\chi^2/ndf = 1.2$

➔ Can be easily extended to include any other measurement for fit !

Collinear parton distributions after fit

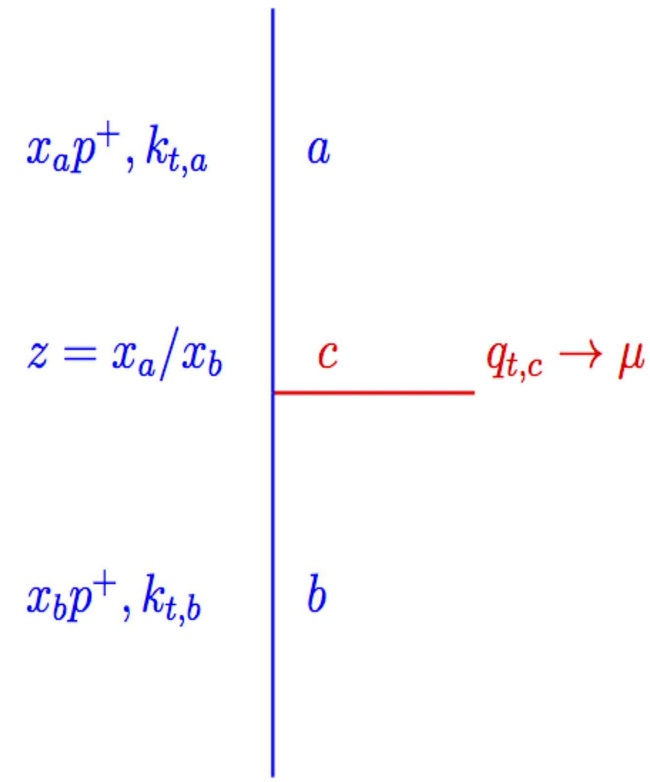


- fit 1 with $\alpha_s(q)$
  - as good as HERAPDF2.0 $\chi^2/ndf = 1.2$
- fit 2 with $\alpha_s(q(1-z))$
  - $\chi^2/ndf = 1.21$
- very different gluon distribution obtained at small Q^2

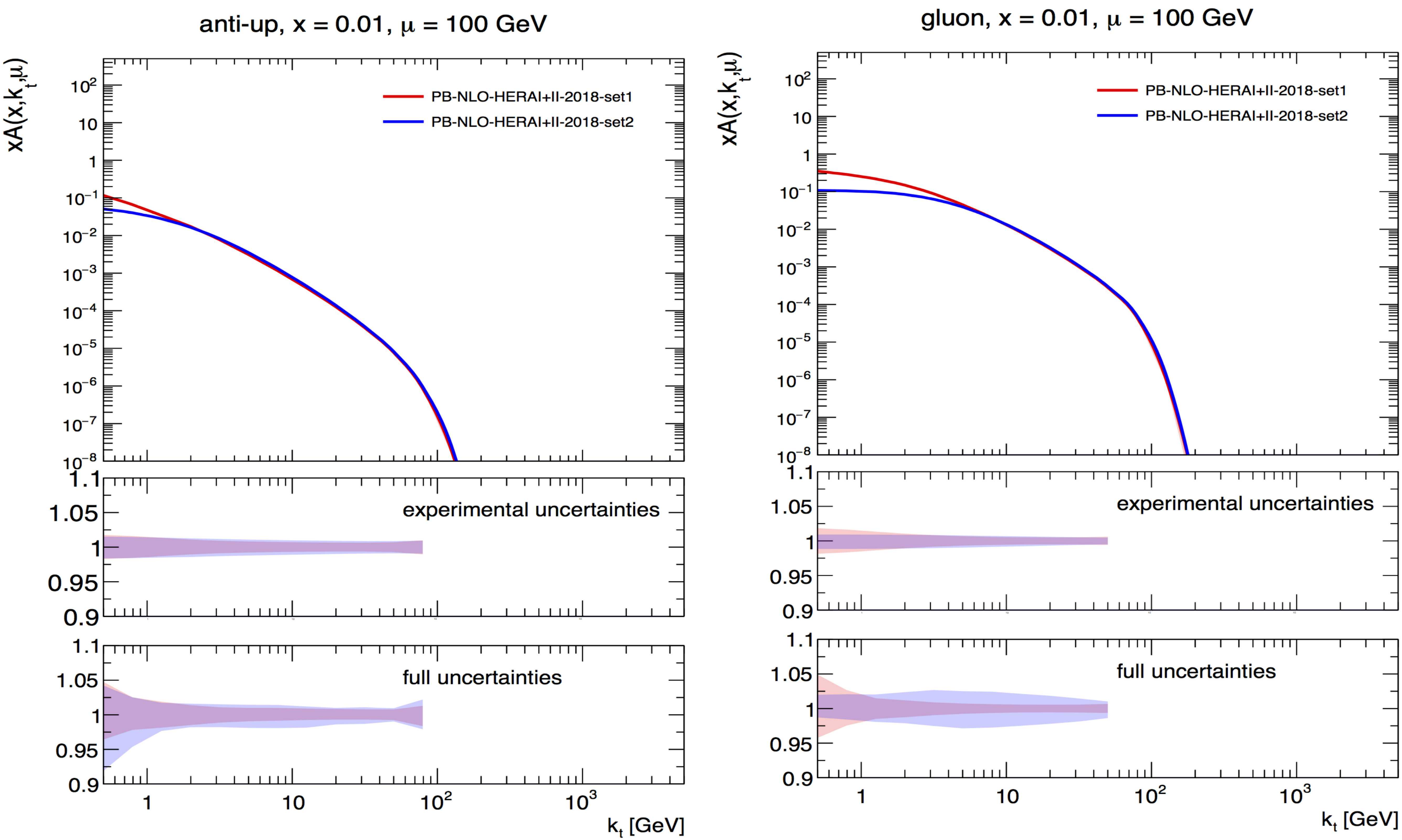
Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step
- Give physics interpretation of evolution scale:
  - angular ordering:

    $\mu = q_T/(1-z)$



TMD distributions from fit to HERA data

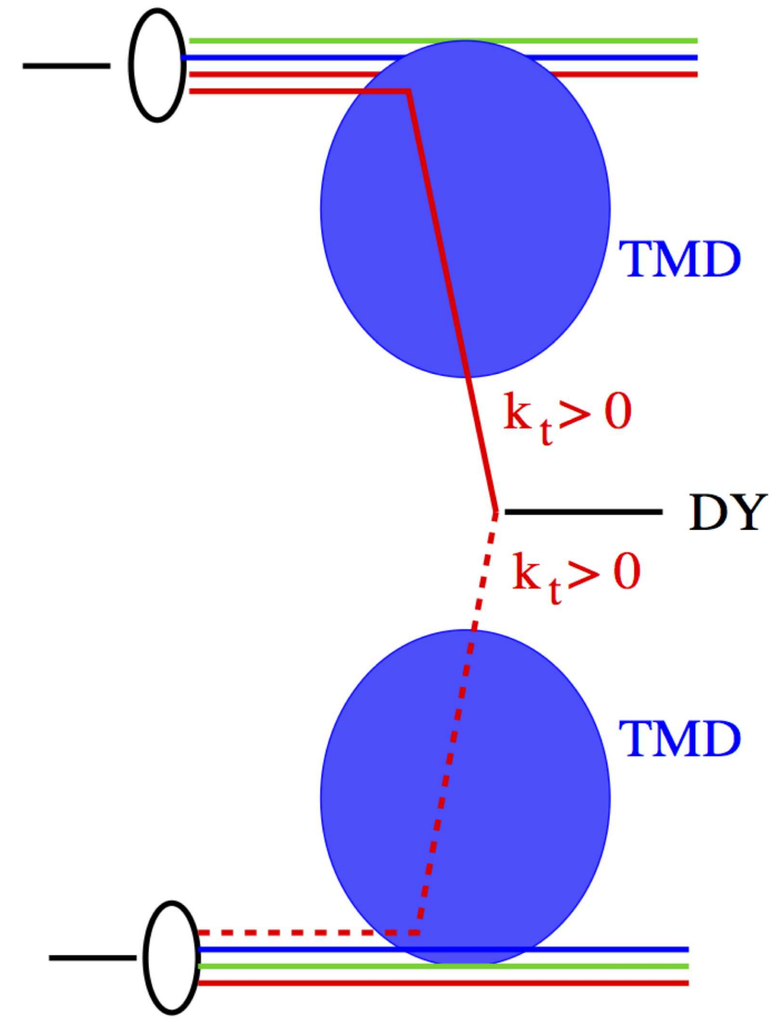


- model dependence larger than experimental uncertainties

Application of PB TMDs

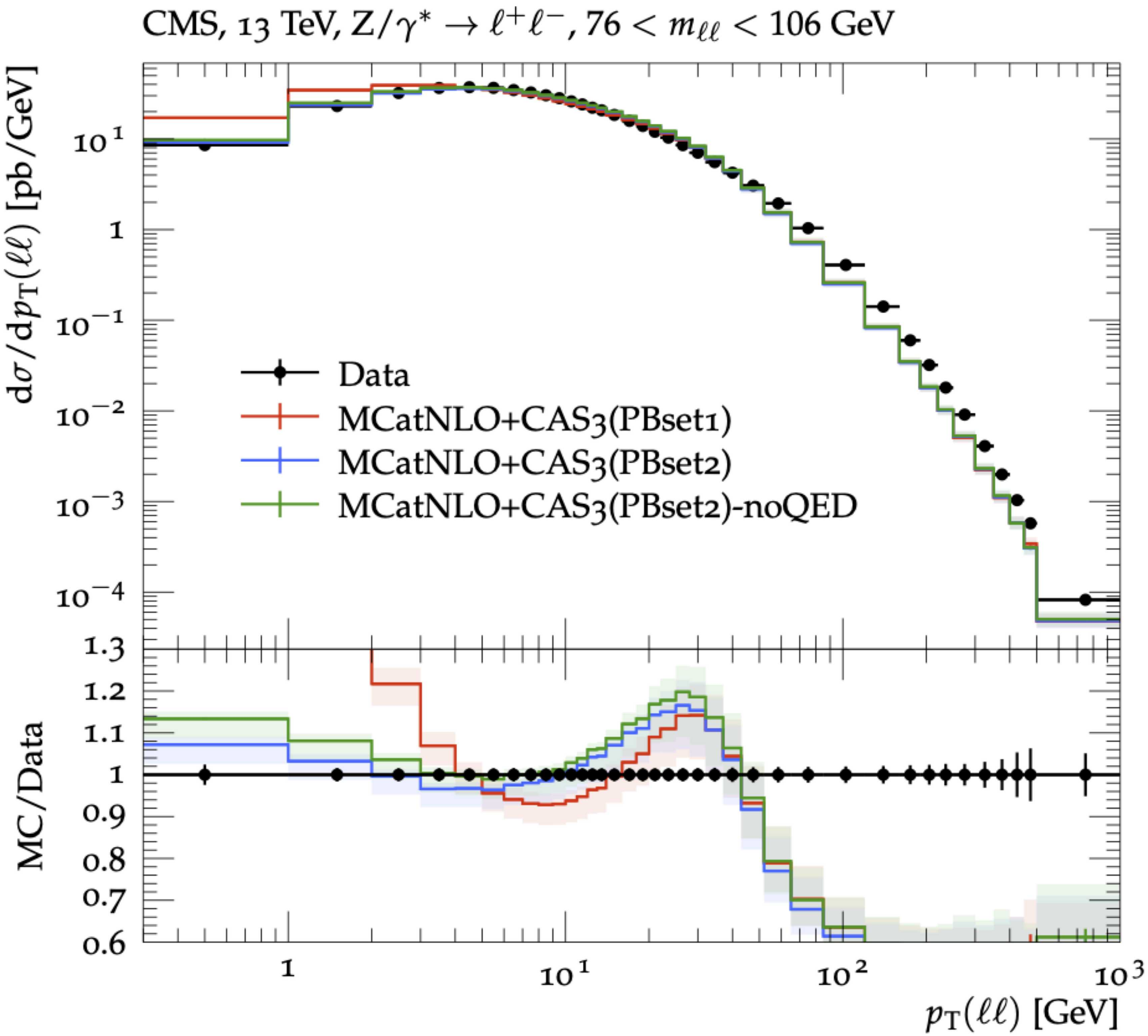
Drell-Yan production: q_T - spectrum

- DY production
  - $q\bar{q} \to Z_0$
  - use NLO calculations: MC@NLO
  - add k_t for each parton as function of x and μ according to TMD
    - keep final state mass fixed
    - preserve rapidity
      - but x_1 and x_2 (light-cone fraction) are different after adding k_t



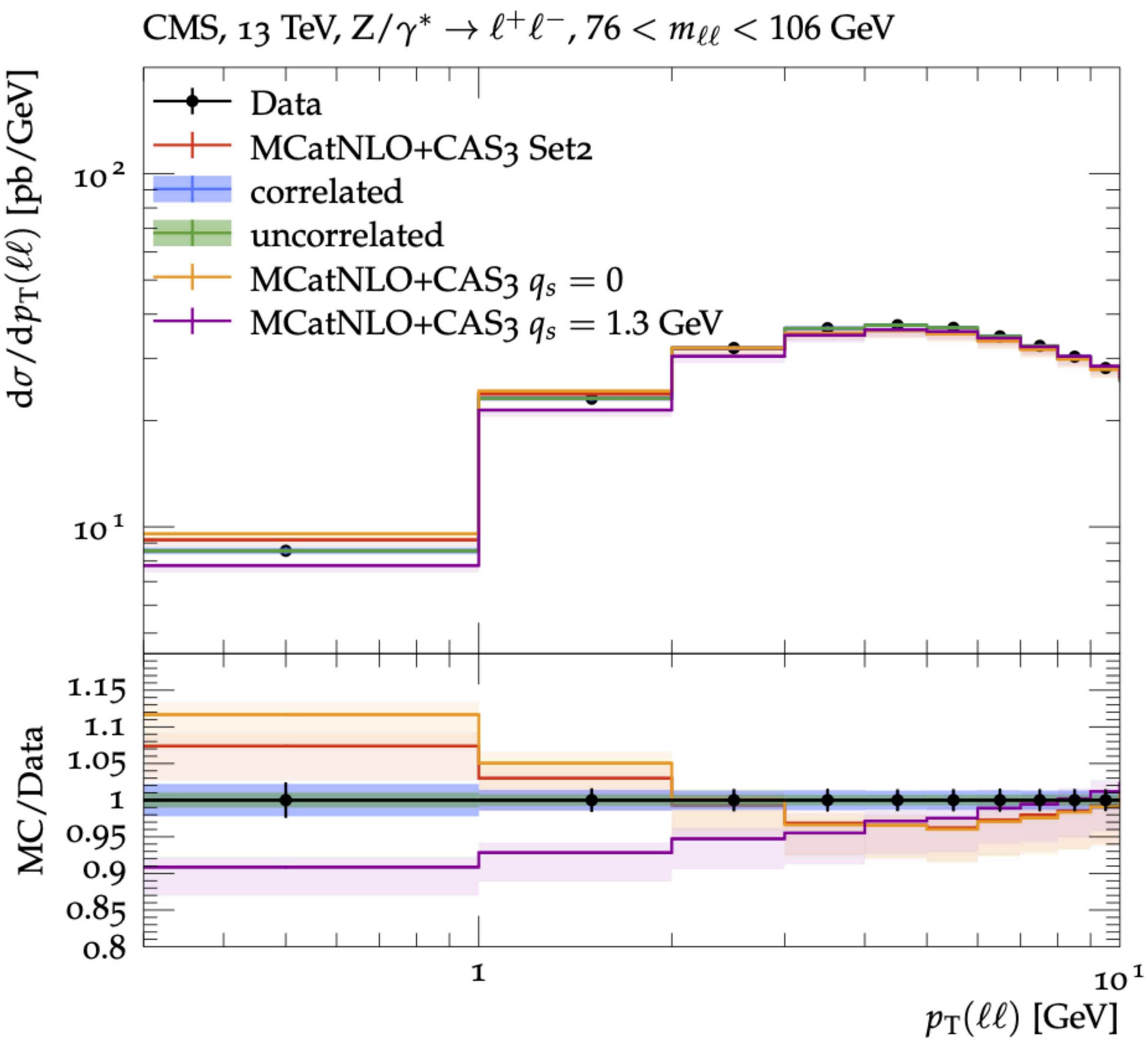
Z - production at 13 TeV (CMS)

Bubanja, I. et al, arXiv: 2312.08655



- very good description of low p_T region with PB-set 2 (with $\alpha_s(q(1-z))$)
  - at larger p_T contribution from higher order matrix elements important
- Uncertainties in PB method mainly from scale of MC@NLO matrix element

Intrinsic k_T in DY - production at 13 TeV (CMS)

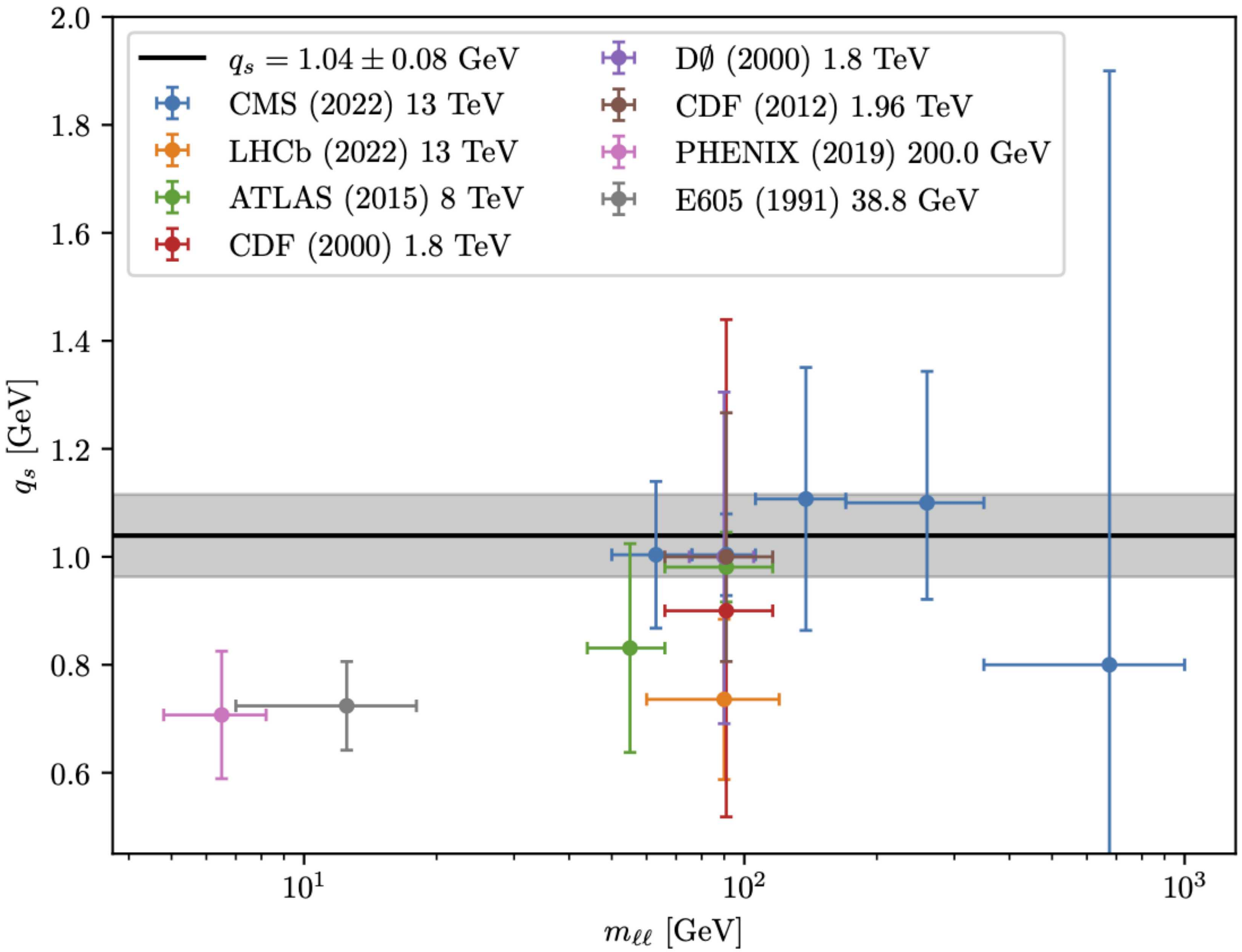


- in TMD, intrinsic k_T distribution:
  - Gauss with zero mean, width q_s

$$\sim \exp\left(-|k_T^2|/q_s^2\right)$$

- Focus on small k_T region:
  - **in lowest** p_T bin, sensitivity to intrinsic k_T
- Use DY production at different m_{DY} and $\sqrt{s}$ to determine q_s
- Is intrinsic k_T dependent on m_{DY} and $\sqrt{s}$?

Fit of Intrinsic k_T in DY – production vers m_{DY}



Bubanja, I. et al, arXiv: 2312.08655

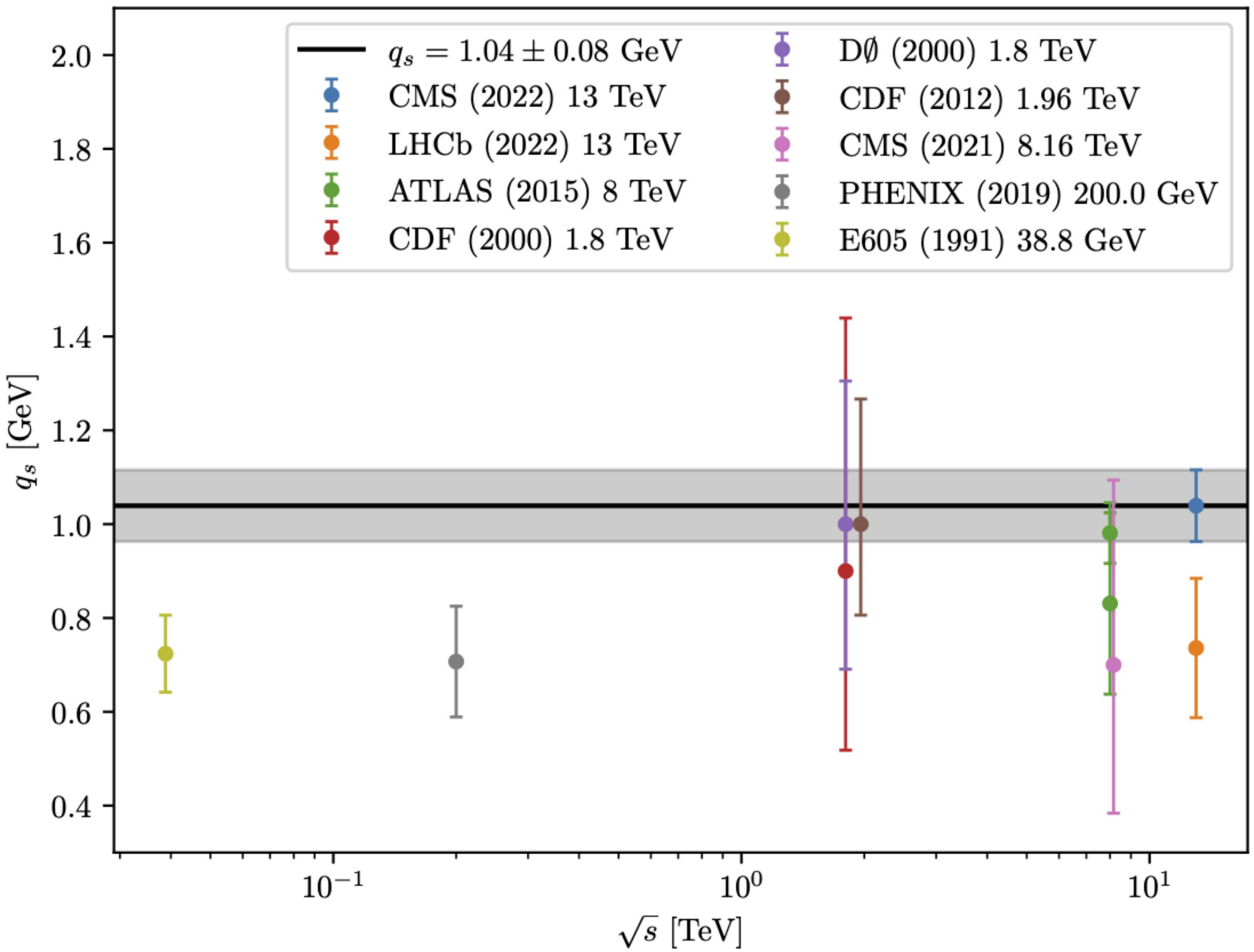
- Gauss with zero mean, width q_s

  $\sim \exp\left(-|k_T^2|/q_s^2\right)$

Fit to determine q_s of intrinsic k_T distribution from DY production as a function of m_{DY}

- obtain q_s rather independent on m_{DY}

Fit of Intrinsic k_T in DY – production vers $\sqrt{s}$



Bubanja, I. et al, arXiv: 2312.08655

- Gauss with zero mean, width q_s

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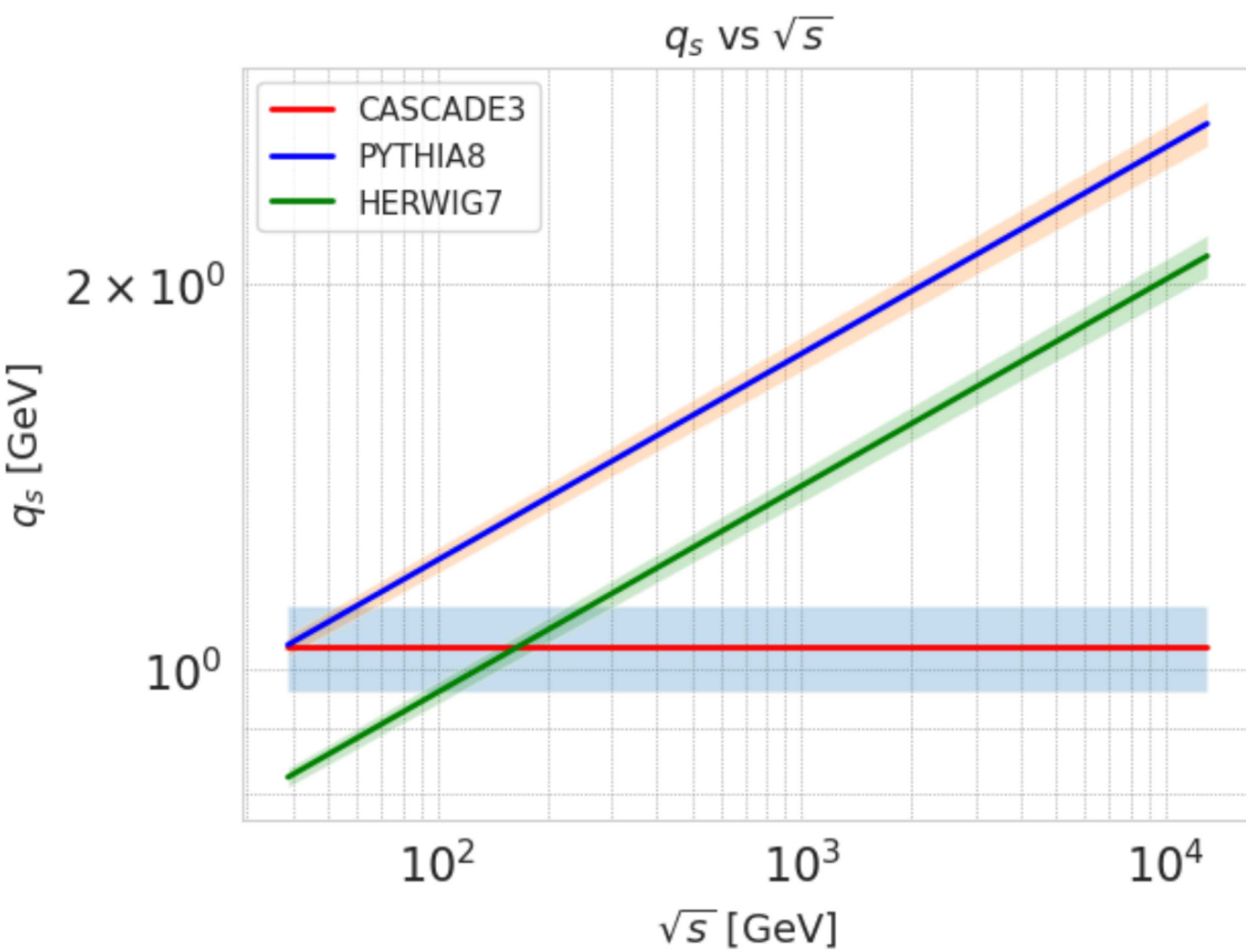
Fit to determine q_s of intrinsic k_T distribution from DY production as a function of $\sqrt{s}$

- obtain q_s rather independent on $\sqrt{s}$

Comparison to MC event generators

S. Taheri Monfared at Physics In Collision 2023

Non-perturbative effects: lessons from fixed target,Tevatron, and LHC data,
Weijie Jin, Armando Bermudez Martinez, Sara Taheri Monfared, Mikel Mendizabal Morentin, Kyle Cormier, Saptaparna Bhattacharya
(paper in preparation)



- Gauss with zero mean, width q_s

  $\sim \exp\left(-|k_T^2|/q_s^2\right)$

- MC generators need q_s dependent on $\sqrt{s}$
- PB TMDs work with constant q_s !

- Why ?

Parton Shower MC event generators

- Parton shower follows backward evolution:

$$\Pi = \exp\left[- \int_{\mu_l^2}^{\mu_h^2} \frac{d\mu'^2}{\mu'^2} \int^{z_{\rm dyn}} \frac{dz}{z} \hat{P}(z) \frac{f(x/z,\mu^2)}{f(x,\mu^2)} \right]$$

- Emitted partons should have *resolvable* energy (or p_T) with: $p_T > q_{t\,\rm cut} \sim 1 {\rm G}eV$

$$z_{\rm dyn} = 1 - \frac{q_{t\ \rm cut}}{\mu'}$$

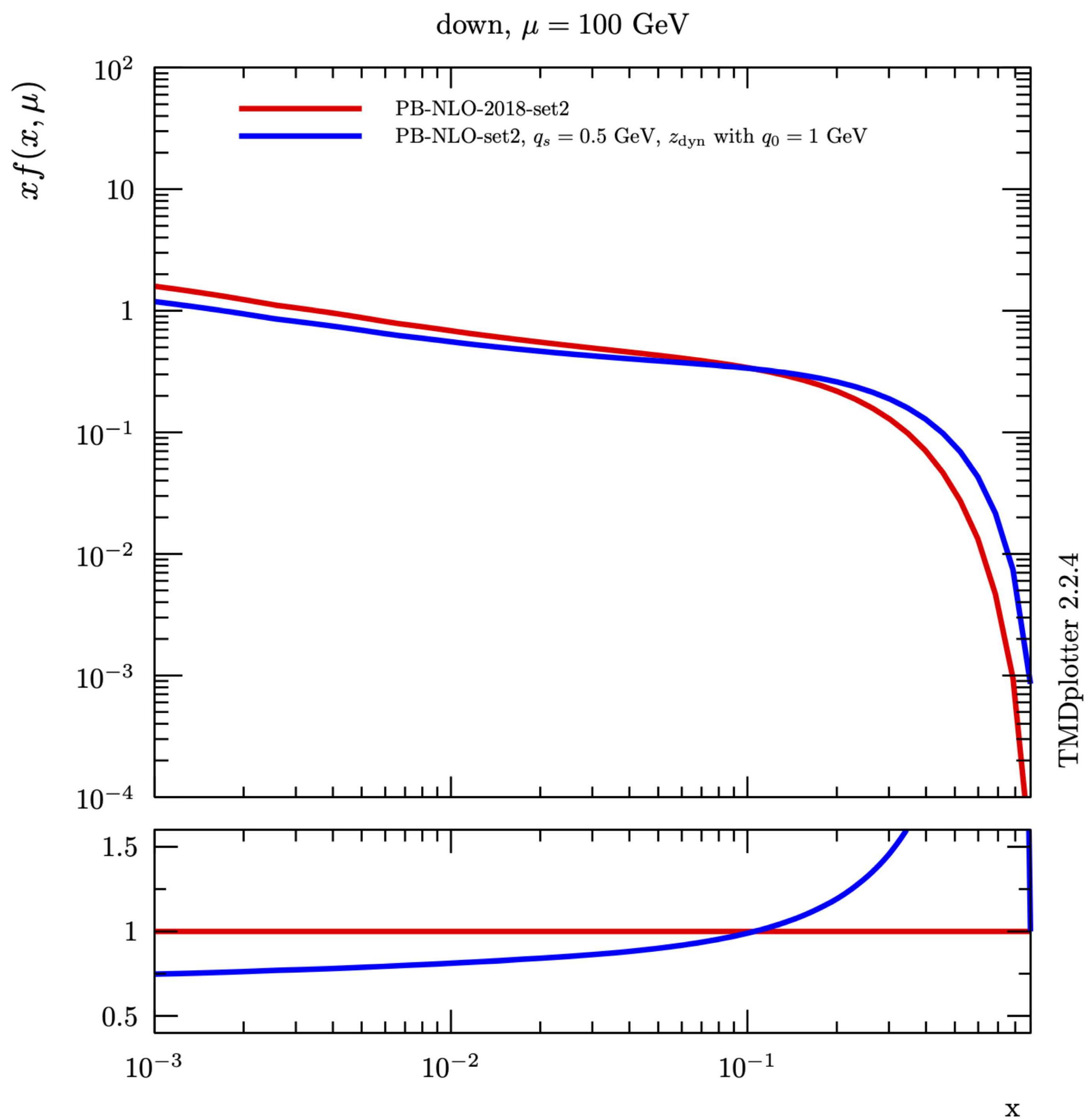
- With $z_{\rm dyn} \ll 1$ soft gluons with $p_T < 1{\rm G}eV$ are neglected.

- What is the role of these soft gluons ?

Role of soft gluons in inclusive distributions

Bubanja, I. et al, arXiv: 2312.08655

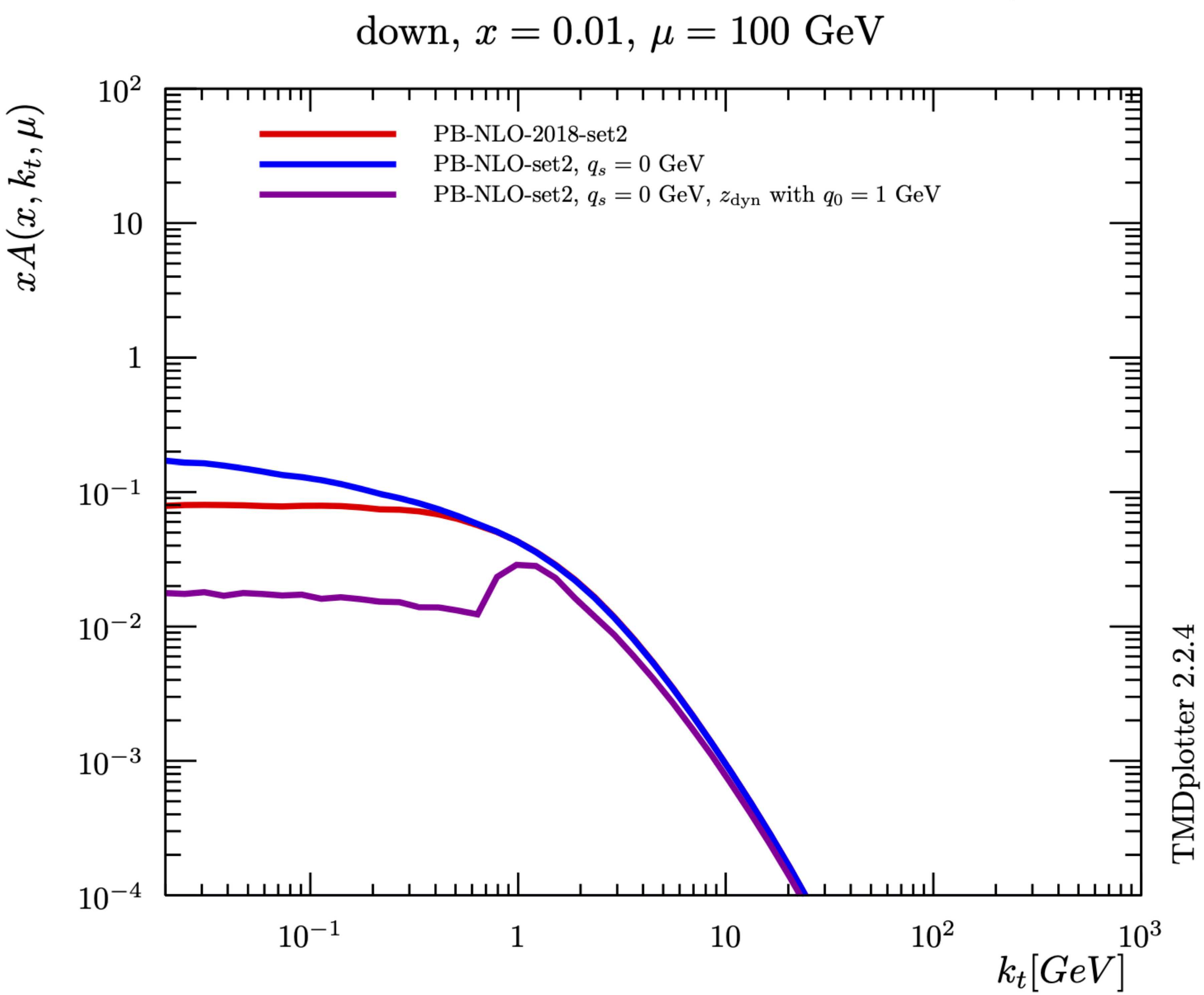
- Perform evolution with PB method with and without cut $z_{\rm dyn} = 1 - \frac{q_{t\ \rm cut}}{\mu'}$



Role of soft gluons in TMD distributions

Bubanja, I. et al, arXiv: 2312.08655

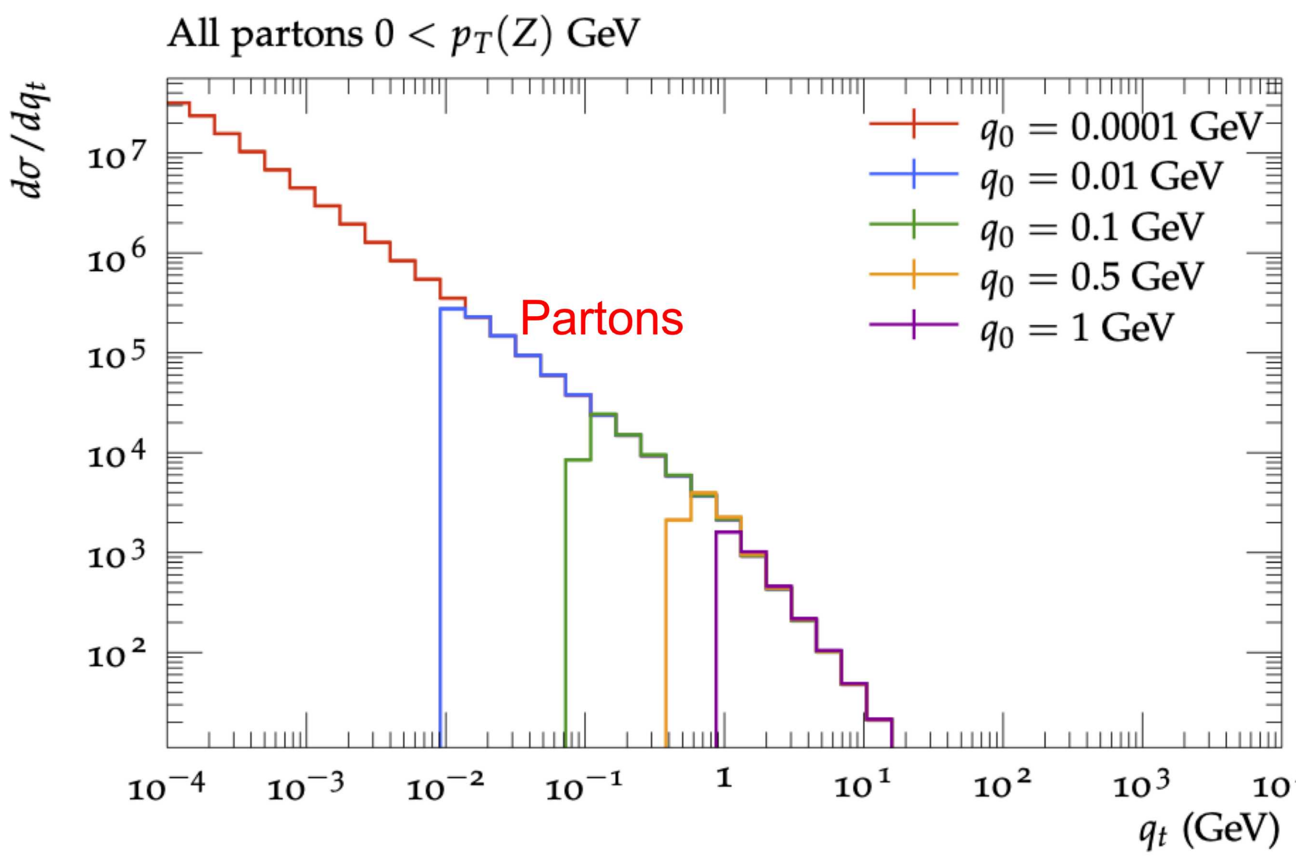
- Perform evolution with PB method with and without cut $z_{\rm dyn} = 1 - \frac{q_{t\ \rm cut}}{\mu'}$

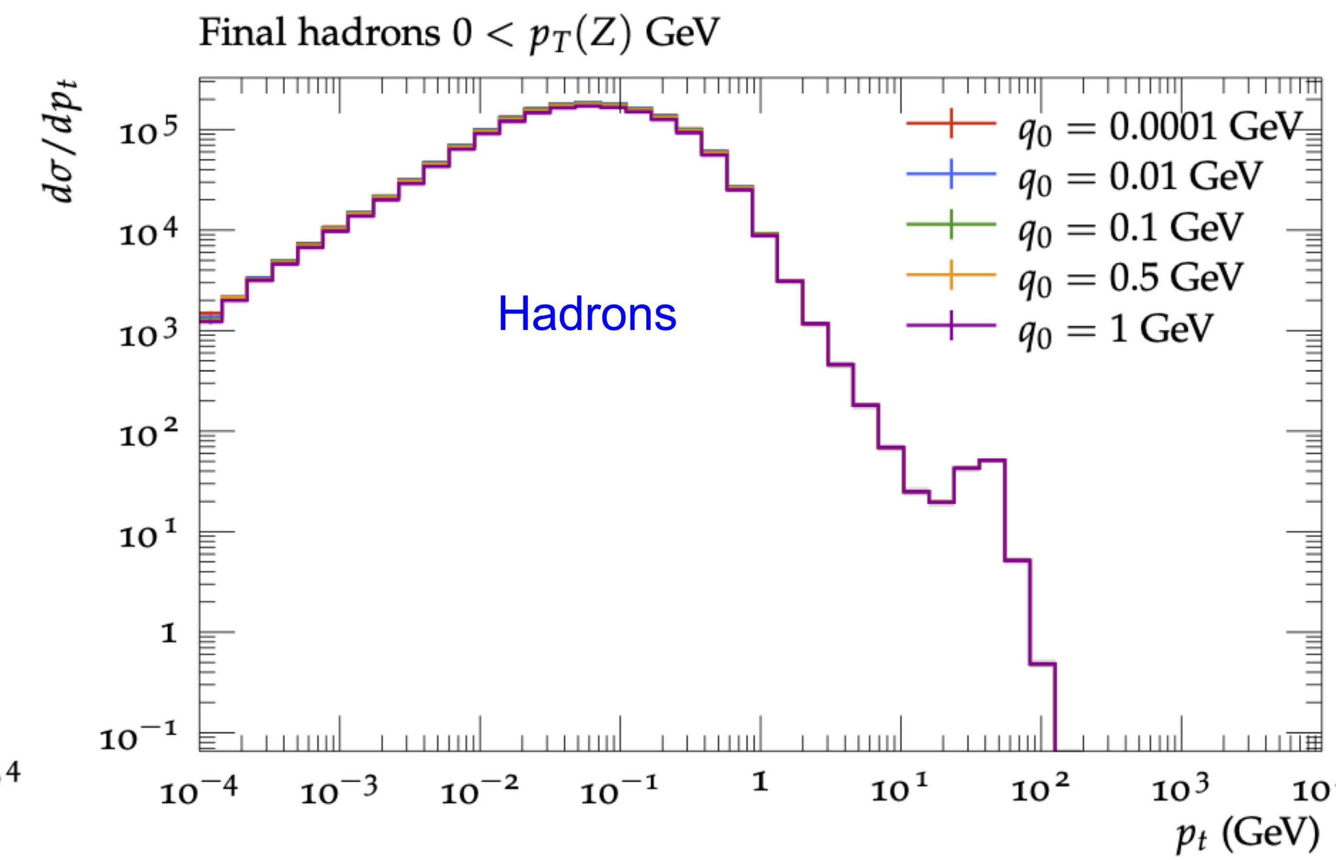


Soft gluons in Parton Shower

Mendizabal, M. et al, arXiv: 2309.11802

- With PB-TMD parton shower study effect of $z_{\rm dyn} = 1 - \frac{q_{t\ \rm cut}}{\mu'}$





- Huge effect on soft partons
  - they are important for inclusive distributions: pdfs and TMDs
  - see DY q_T spectra
- in Lund string fragmentation these soft partons do not change hadron spectra
  - no issue for hadrons or jets from parton shower !

Conclusion

- Parton Branching method to solve DGLAP equation at LO, NLO and NNLO method directly applicable to determine k_T distribution

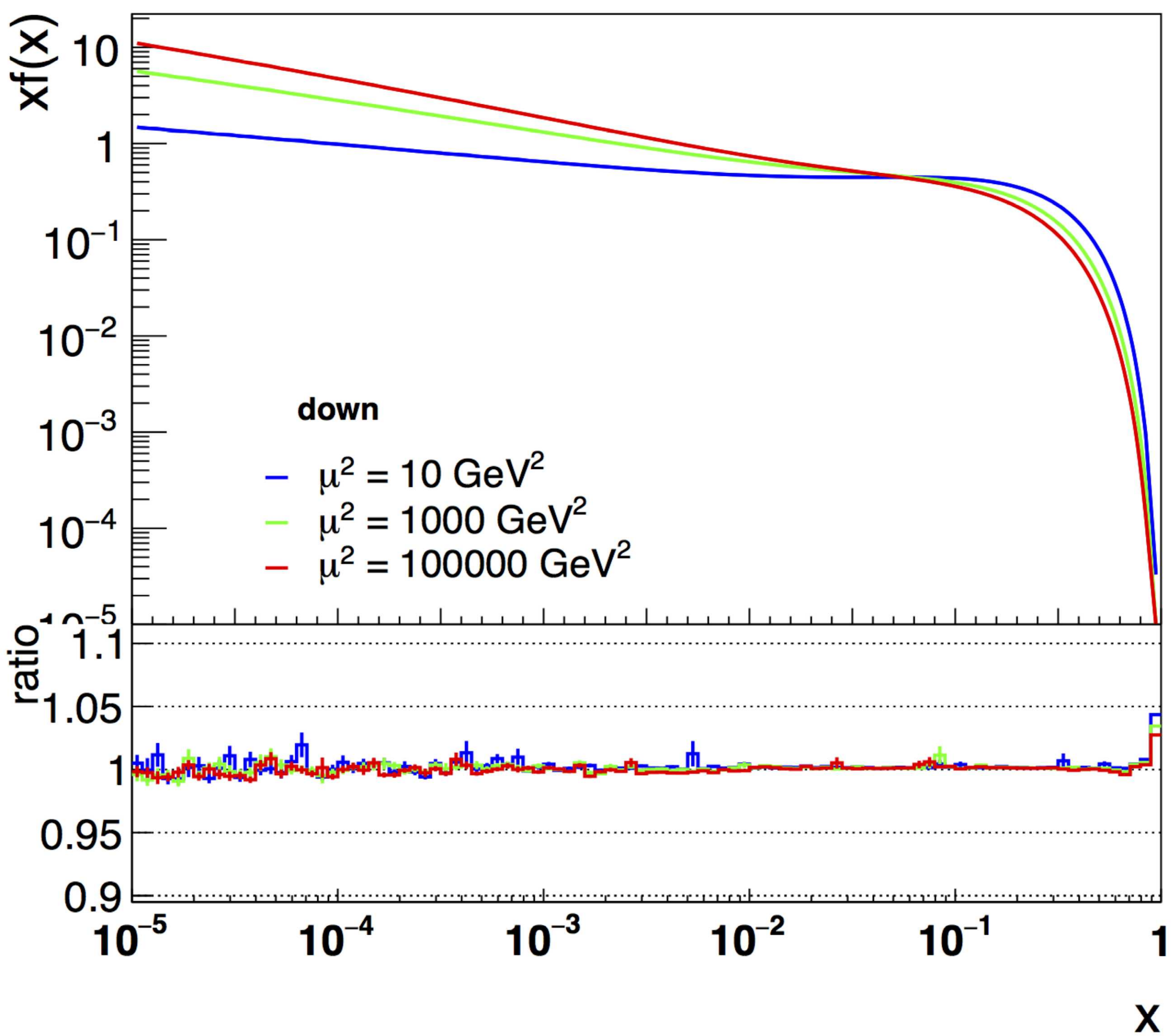
- Application to inclusive DY processes in pp at different energies and masses:
  - intrinsic k_T distribution determined over large range of m_{DY} and $\sqrt{s}$
    - no mass no $\sqrt{s}$ dependence observed, in contrast to MCEG

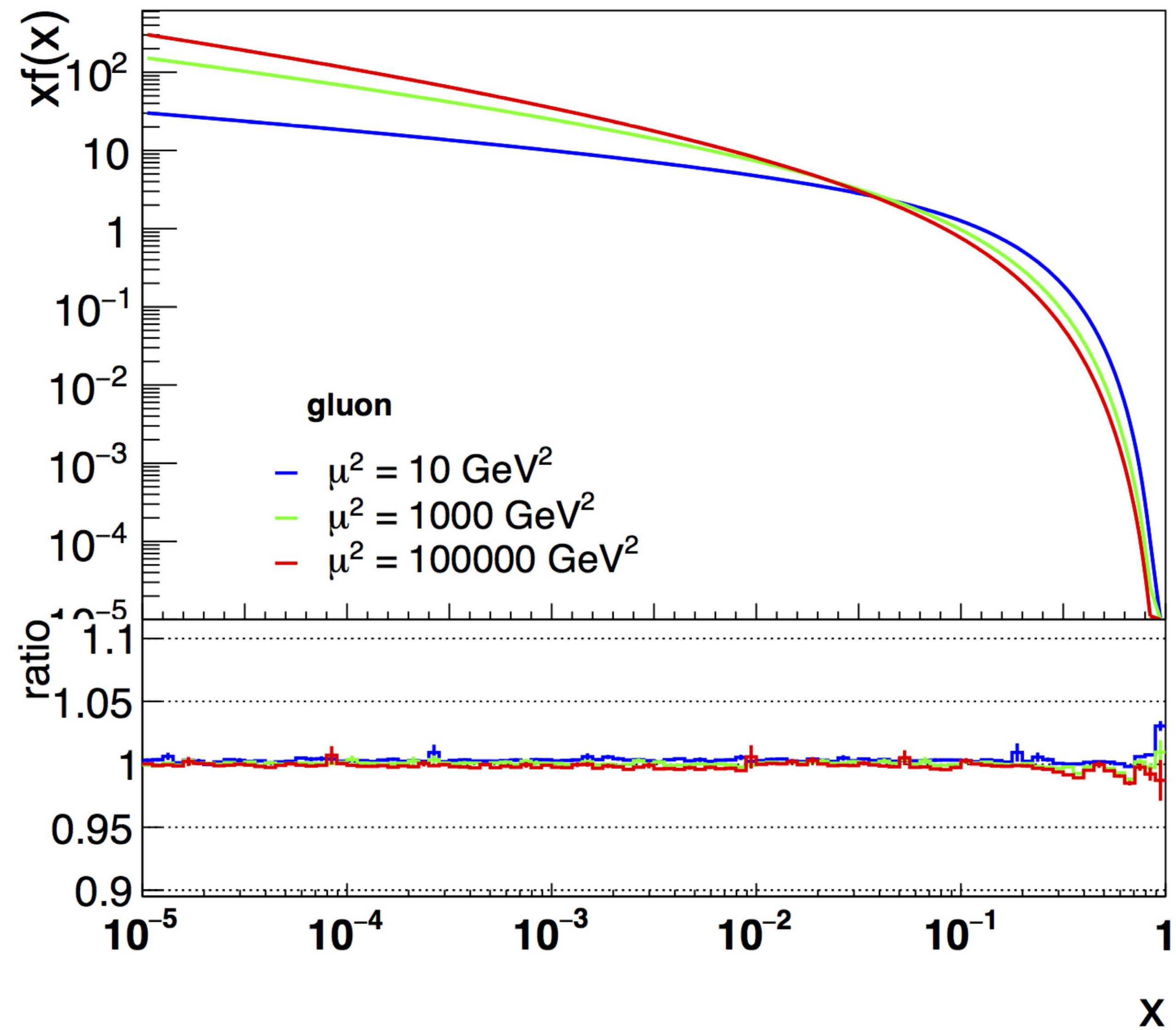
- Importance of soft gluons established:
  - essential for consistency of NLO matrix elements and pdfs !
    - otherwise new factorization scheme to be defined and all NLO ME's must be recalculated.
  - essential for inclusive parton densities (DGLAP requires $z_M \to 1$)
  - essential for inclusive TMD distributions, e.g. DY q_T spectra

- Soft gluons are not important for final state jets or hadrons from parton shower

Appendix

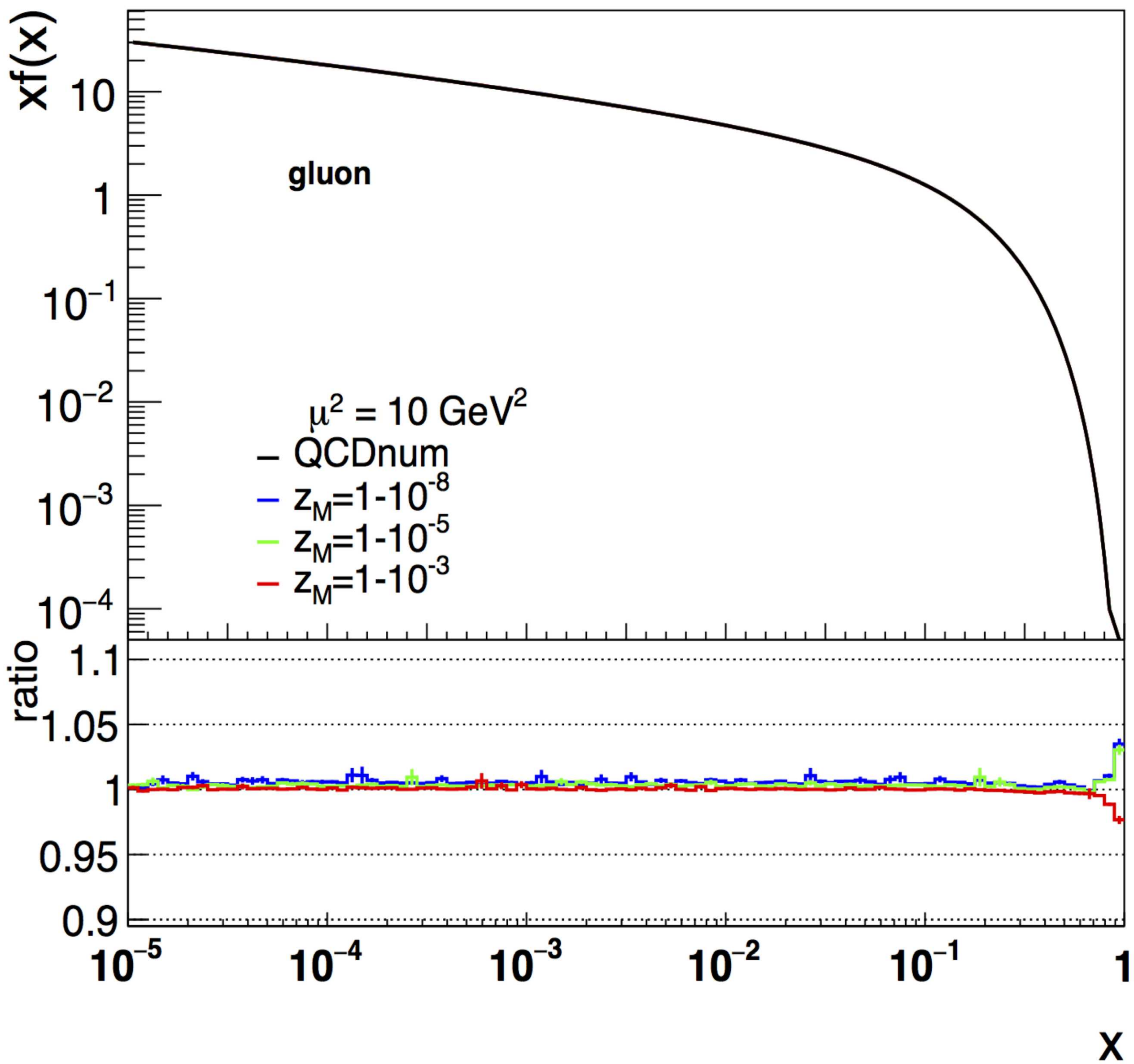
Validation of method with QCDnum at NLO

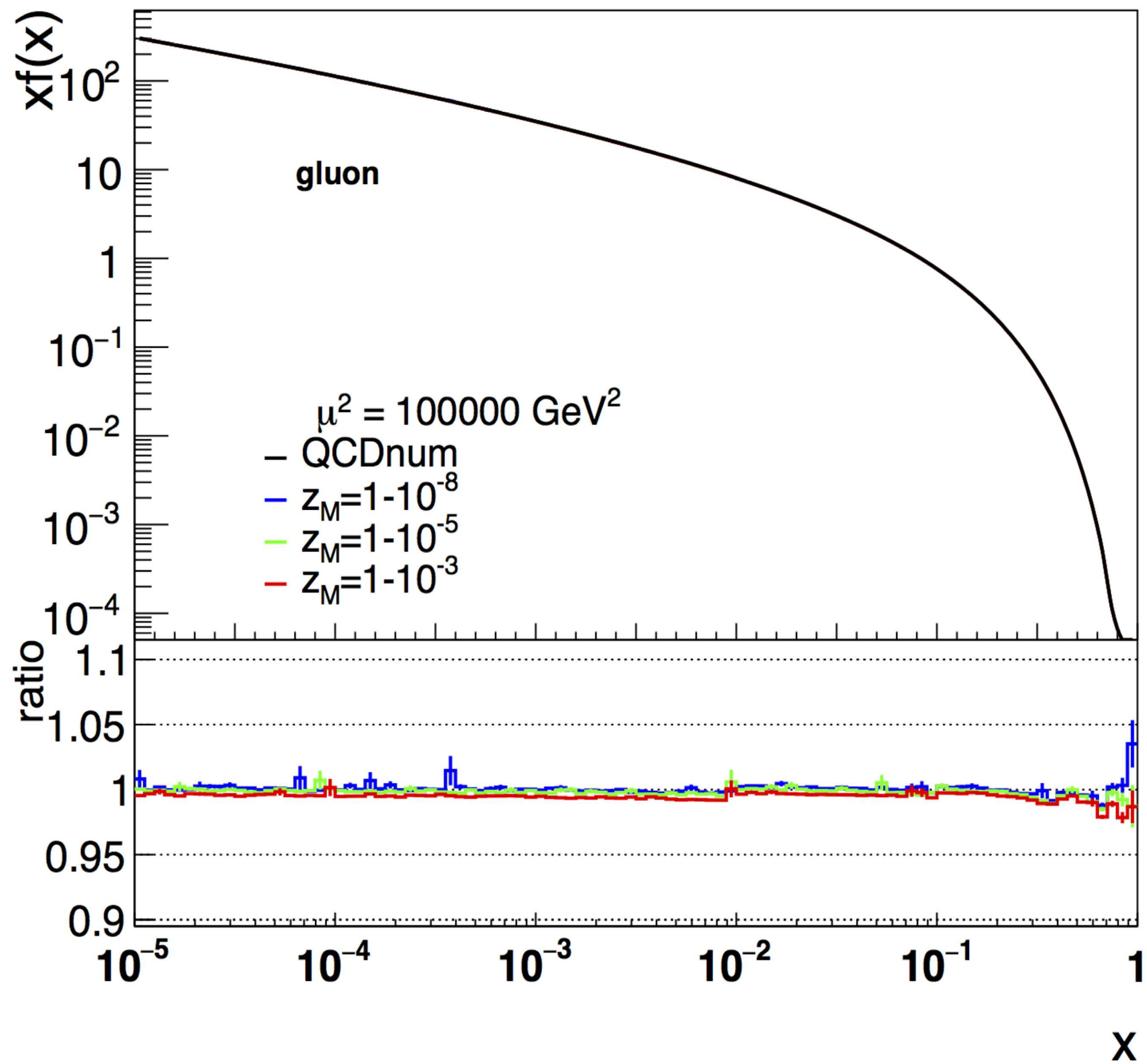




- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach works also at NNLO !

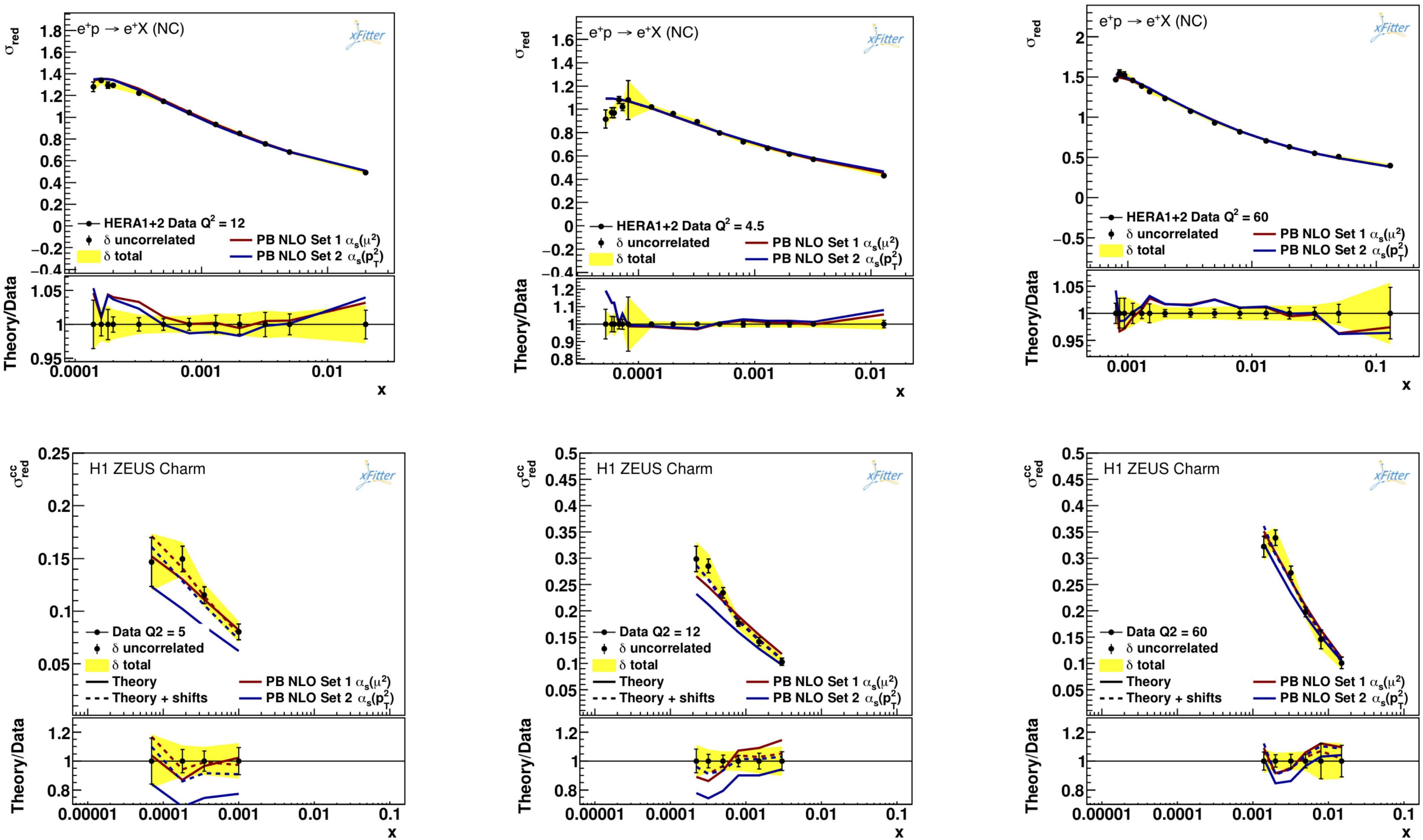
Validation of method at NLO: z_M - dependence





- No dependence on z_M if z_M is large enough:
  - approximation is of $\mathcal{O}(1 - z_M)$
- Very good agreement with NLO - QCDnum

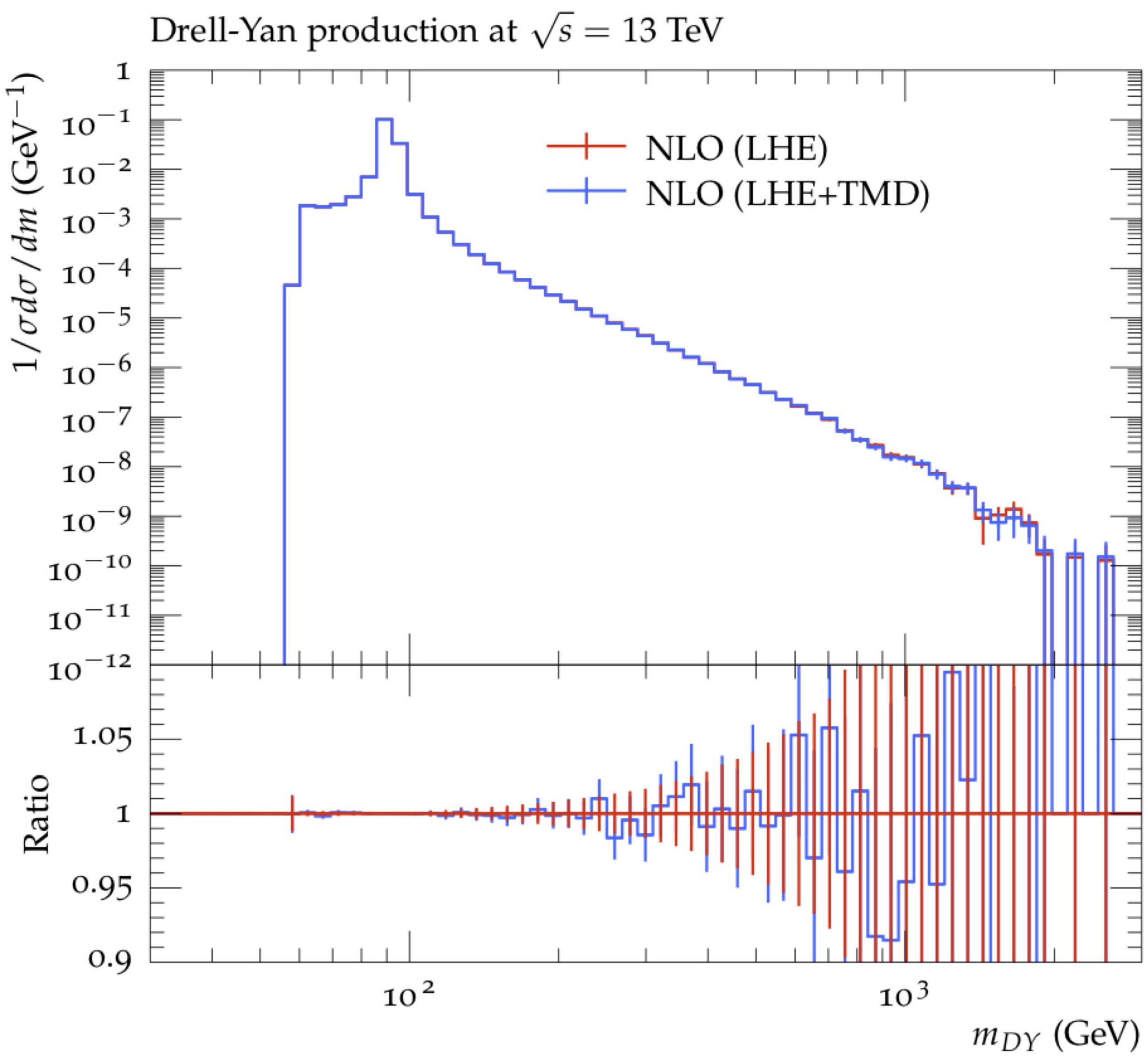
Fits to DIS x-section at NLO: F_2 and F_2^c

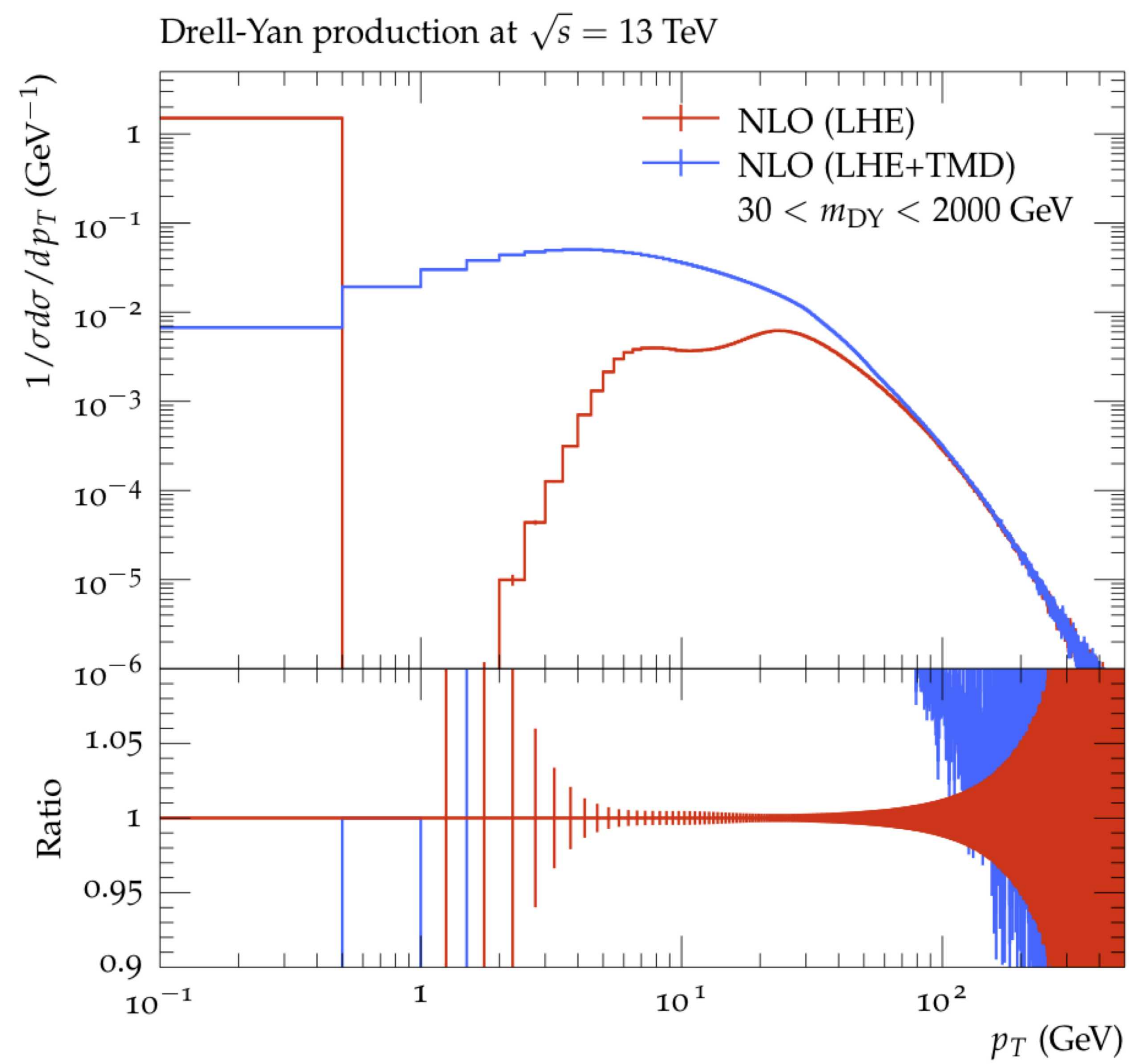


Including TMDs for DY production with MC@NLO

DY production: Bermudez Martinez, A. et al, arXiv 1906.00919, 2001.06488
CASCADE3 S. Baranov et al, arXiv 2101.10221

- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and/or parton shower)
  - MC@NLO without shower and/or TMD unphysical (here herwig6 subtraction)

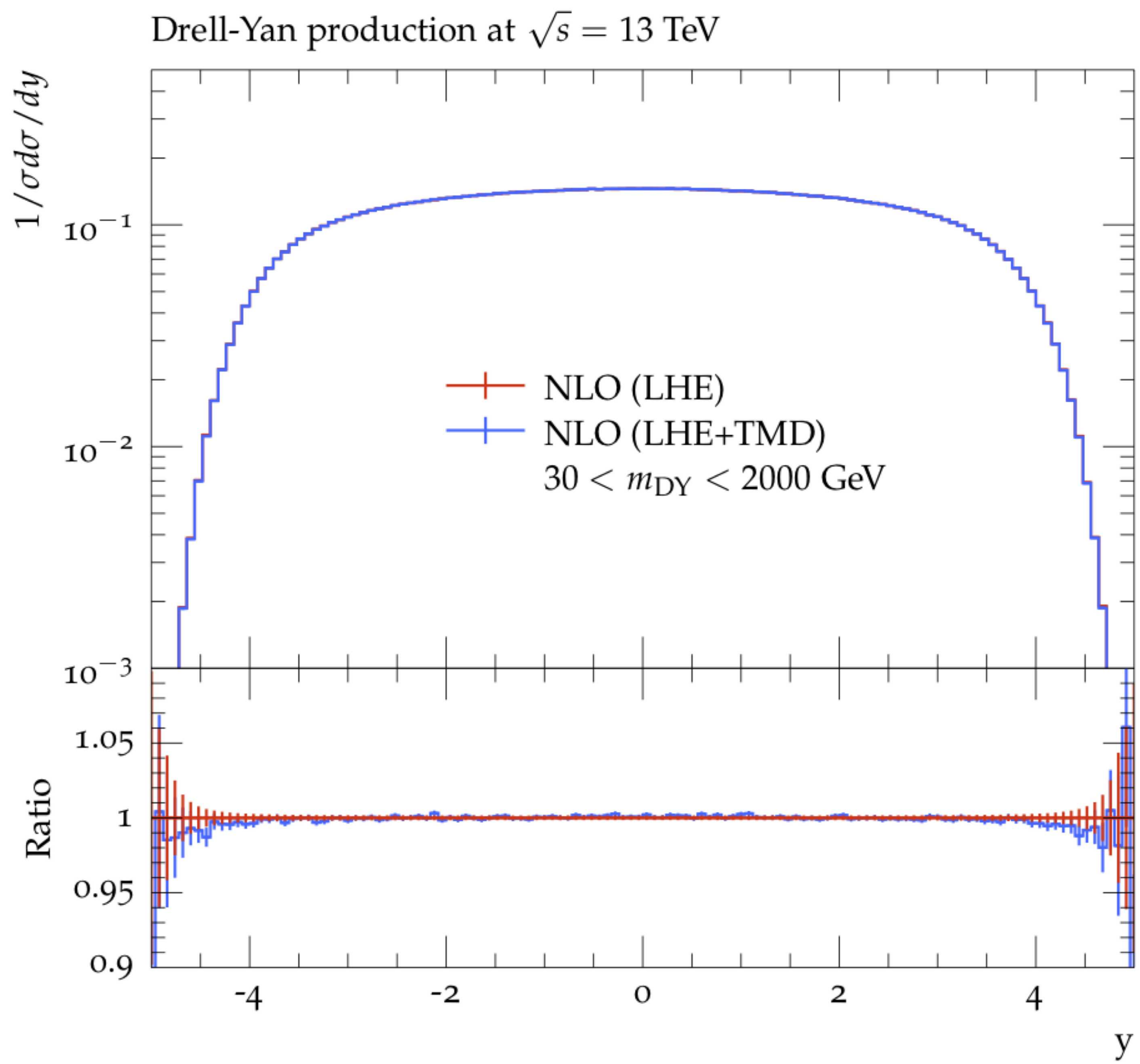




Including TMDs for Z production with MC@NLO

- Are other features of DY production preserved ?

DY production: Bermudez Martinez, A. et al, arXiv 1906.00919, 2001.06488
CASCADE3 S. Baranov et al, arXiv 2101.10221



- Rapidity of DY pair not changed … (but x_1 and x_2)

Soft gluons in calculations

- Calculations at NLO (and higher order) require (integrated) parton densities with $z_M \to 1$ (factorization scheme)
  - if $z_M \ll 1$, inconsistencies appear.

- Issue of $z_M \to 1$ was already discussed in Z. Nagy, D.Soper Phys. Rev. D102 (2020) 1

- Issue discussed in detail in M. Mendizabal, F. Guzman, H. Jung, S. Taheri Monfared arXiv 2309.11802

- S. Frixione, B Webber *arXiv 2309.15587) propose calculating NLO ME's with $z_M \ll 1$, huge enterprise, as all ME's need recalculation
  - and it is unclear, whether this can include the "non-pert Sudakov" (which is the part from z_M to 1), making intrinsic k_T distributions energy and mass independent.