Drell Yan production at NLO with the PB method

Hannes Jung (DESY)
together with
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J. Lidrych, A. Lelek, M. Schmitz, S. Taheri Monfared, H. Yang, Q. Wang

- Recap of PB method
- Application of PB TMDs to
  - Z_0 production at the LHC
    (based on Phys Rev D.100.074027 (2019))
  - low mass DY at low energies
    (based on arXiv 2001.06488)

Recap of Parton Branching method

DGLAP evolution – solution with parton branching method

- differential form: $$\mu^2 \frac{\partial}{\partial \mu^2} f(x, \mu^2) = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P_+(z) \, f\left(\frac{x}{z}, \mu^2\right)$$

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$$\Delta_s(\mu^2) = \exp\left(- \int^{z_M} dz \int_{\mu_0^2}^{\mu^2} \frac{\alpha_s}{2\pi} \frac{d\mu'^2}{\mu'^2} P^{(R)}(z) \right)$$

- differential form using f/Δ_s with

$$\mu^2 \frac{\partial}{\partial \mu^2} \frac{f(x,\mu^2)}{\Delta_s(\mu^2)} = \int \frac{dz}{z} \frac{\alpha_s}{2\pi} \frac{P^{(R)}(z)}{\Delta_s(\mu^2)} f\left(\frac{x}{z},\mu^2\right)$$

DGLAP evolution – solution with parton branching method

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- integral form

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

no – branching probability from $\mu^2{}_0$ to μ^2

DGLAP evolution – solution with parton branching method

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- solve integral equation via iteration:

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- solve integral equation via iteration:

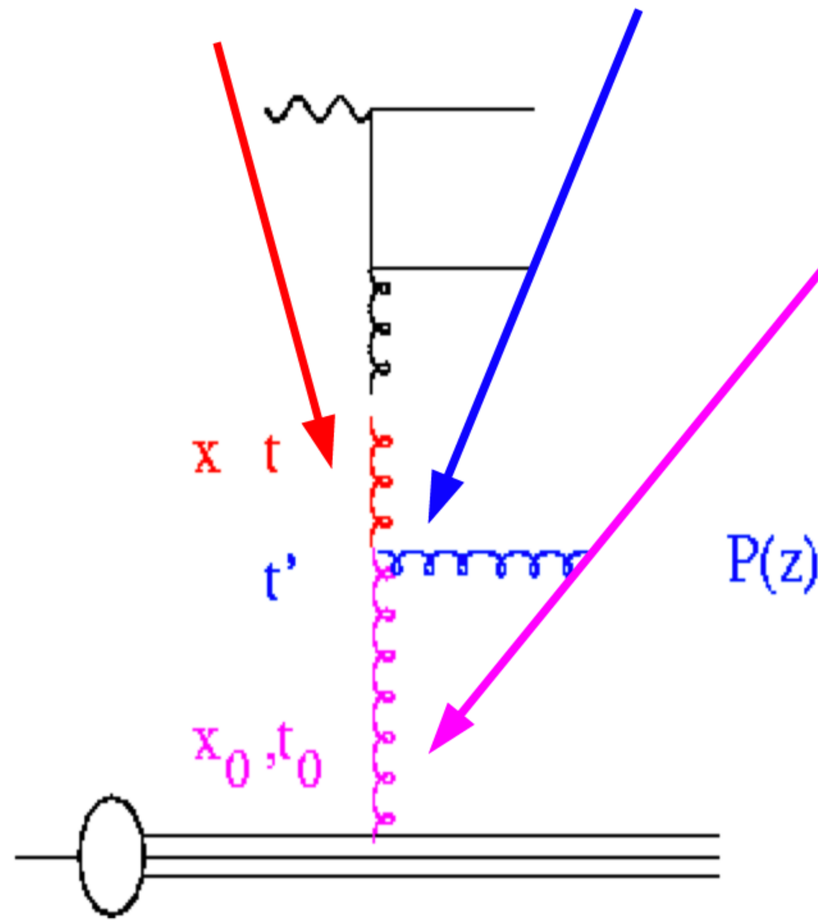
from t' to t w/o branching

branching at t'

from t_0 to t' w/o branching

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

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



DGLAP evolution – solution with parton branching method

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

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- with $P_{ab}{}^{(R)}(z)$ real emission probability (without virtual terms)
  - z_M introduced to separate real from virtual and non-emission probability
  - reproduces DGLAP up to $\mathcal{O}(1-z_M)$

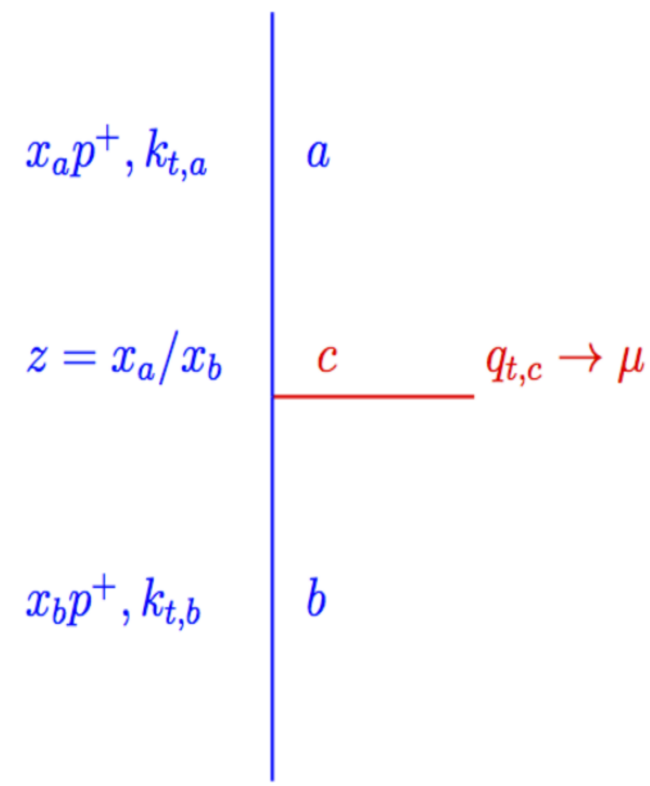
- make use of momentum sum rule to treat virtual corrections
  - use Sudakov form factor for non-resolvable and virtual corrections

$$\Delta_a(z_M,\mu^2,\mu_0^2) = \exp\left(-\sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\; z\; P_{ba}^{(R)}(\alpha_s), z)\right)$$

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:

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



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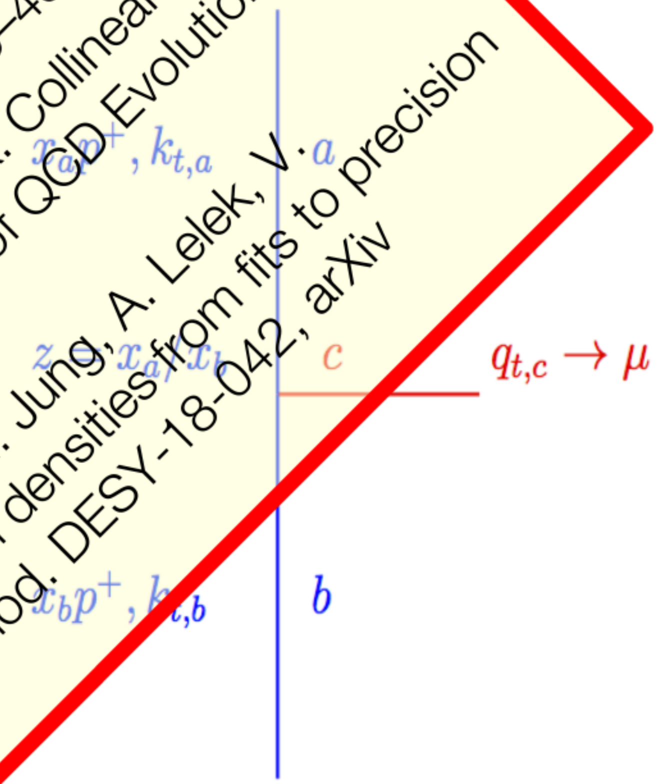


[1] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Soft-gluon resolution scale in QCD evolution equations. Phys. Lett., B772:446–451, 2017.
[2] F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD Quark and Gluon Densities from Parton Branching Solution of QCD Evolution 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

similar concept investigated previously:

Placzek, W., Golec-Biernat, K. J., Jadach, S., and Skrzypek, M. (2007) Acta Phys. Polon., B38(), 2357
Golec-Biernat, K. J., Jadach, S., Placzek, W., and Skrzypek, M. (2006) Acta Phys. Polon., B37(), 1785-1832
Jadach, S. and Skrzypek, M. (2004). Acta Phys. Polon., B35(), 745

PDFs from Parton Branching method: fit to HERA data

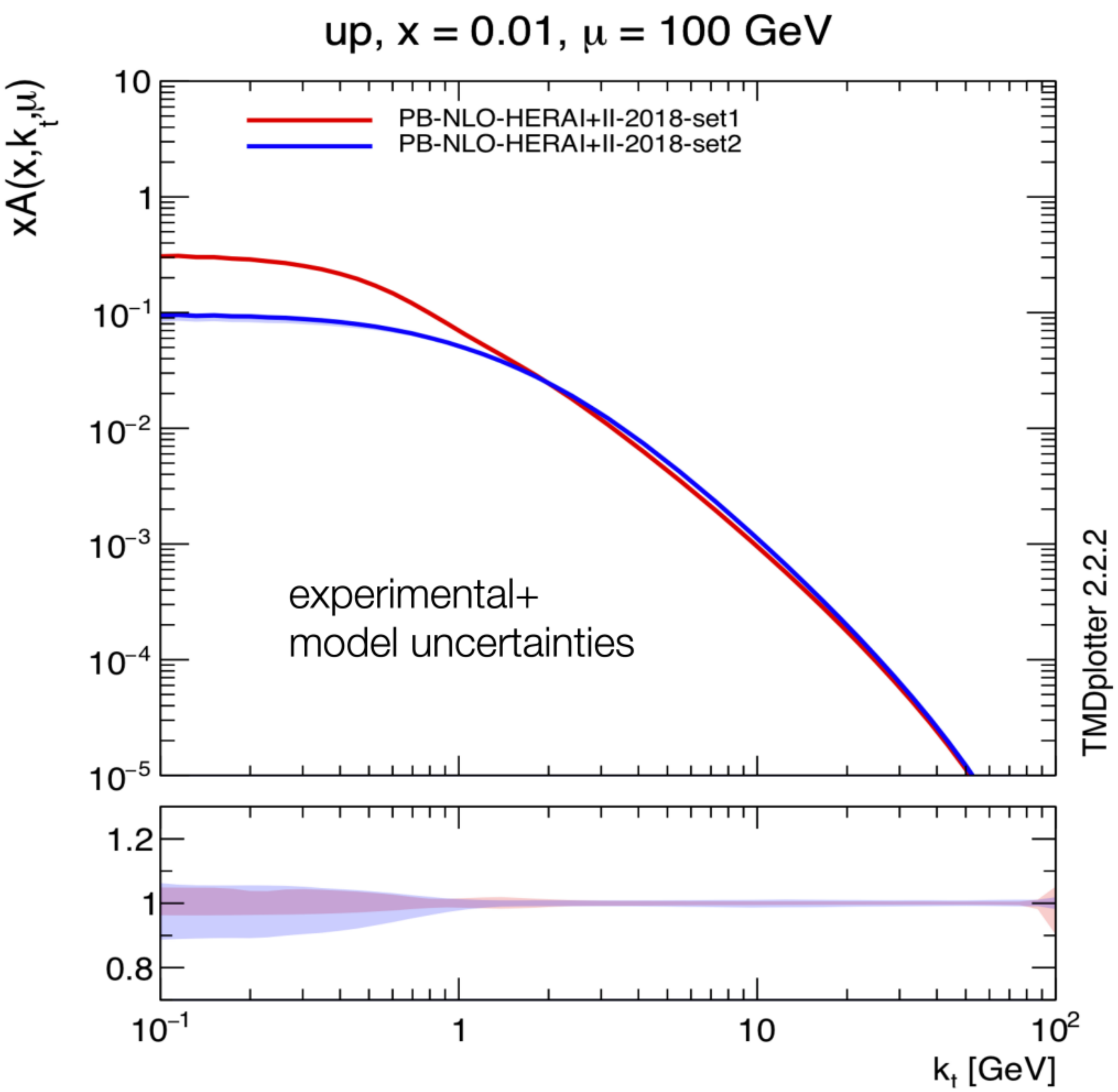
- Convolution of kernel with starting distribution

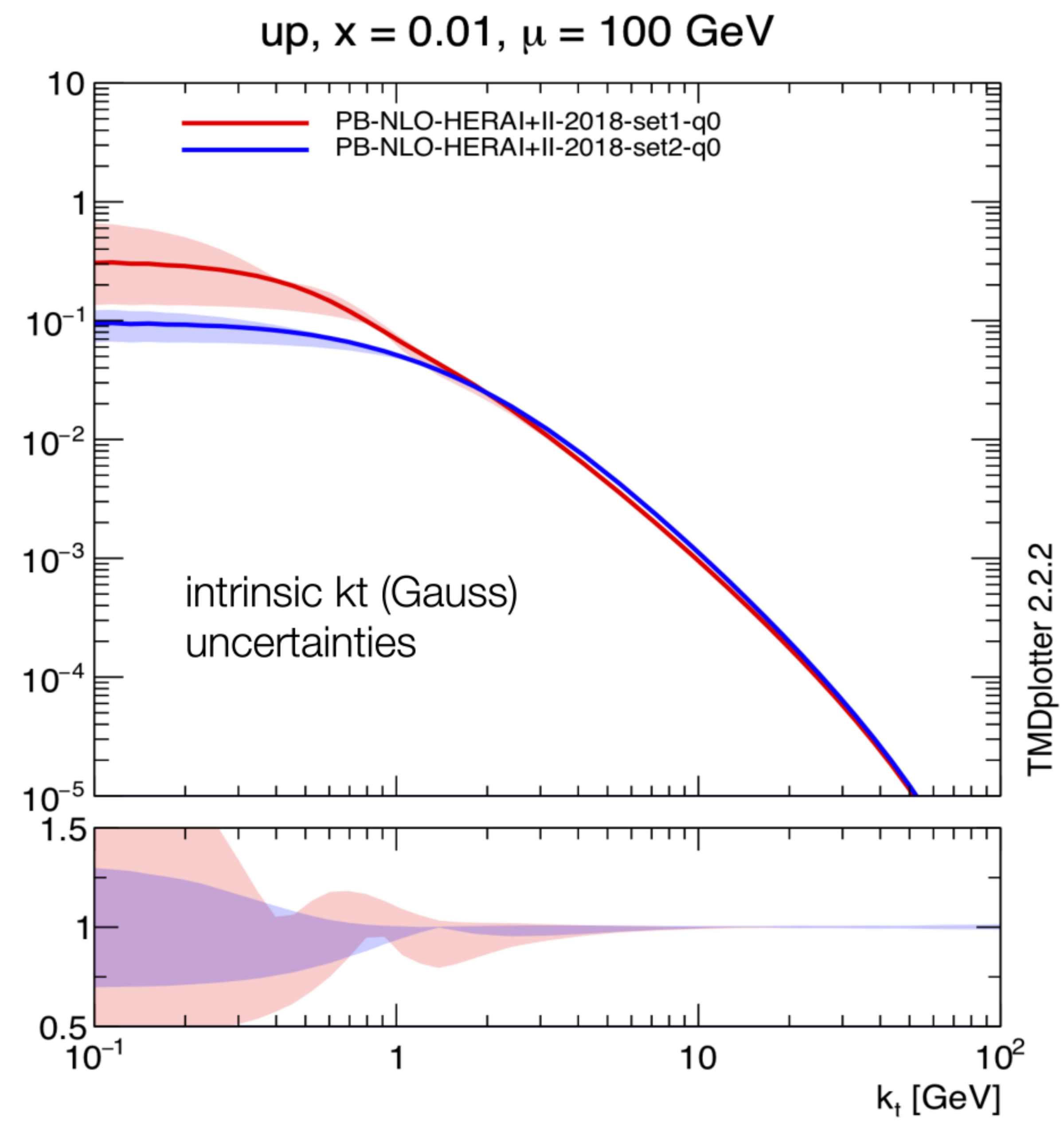
$$
\begin{aligned}
x f_a(x, \mu^2) &= x \int dx' \int dx'' \mathcal{A}_{0,b}(x') \tilde{\mathcal{A}}_a^b \left(x'', \mu^2\right) \delta(x' x'' - x) \\
&= \int dx' \mathcal{A}_{0,b}(x') \cdot \frac{x}{x'} \, \tilde{\mathcal{A}}_a^b \left(\frac{x}{x'}, \mu^2\right)
\end{aligned}
$$

- Fit performed using xFitter frame (with collinear Coefficient functions at NLO)
  - using full HERA 1+2 inclusive DIS (neutral current, charged current) data
    - in total 1145 data points
      - $3.5 < Q^2 < 50000 \text{ GeV}^2$
      - $4 \cdot 10^{-5} < x < 0.65$
      - using starting distribution as in HERAPDF2.0
      - $\chi^2/ndf = 1.2$

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

TMD distributions





Differences essentially in low k_T region

- experimental+model uncertainties small
- at very low k_T, uncertainties from intrinsic k_T sizable

Application to Drell – Yan production

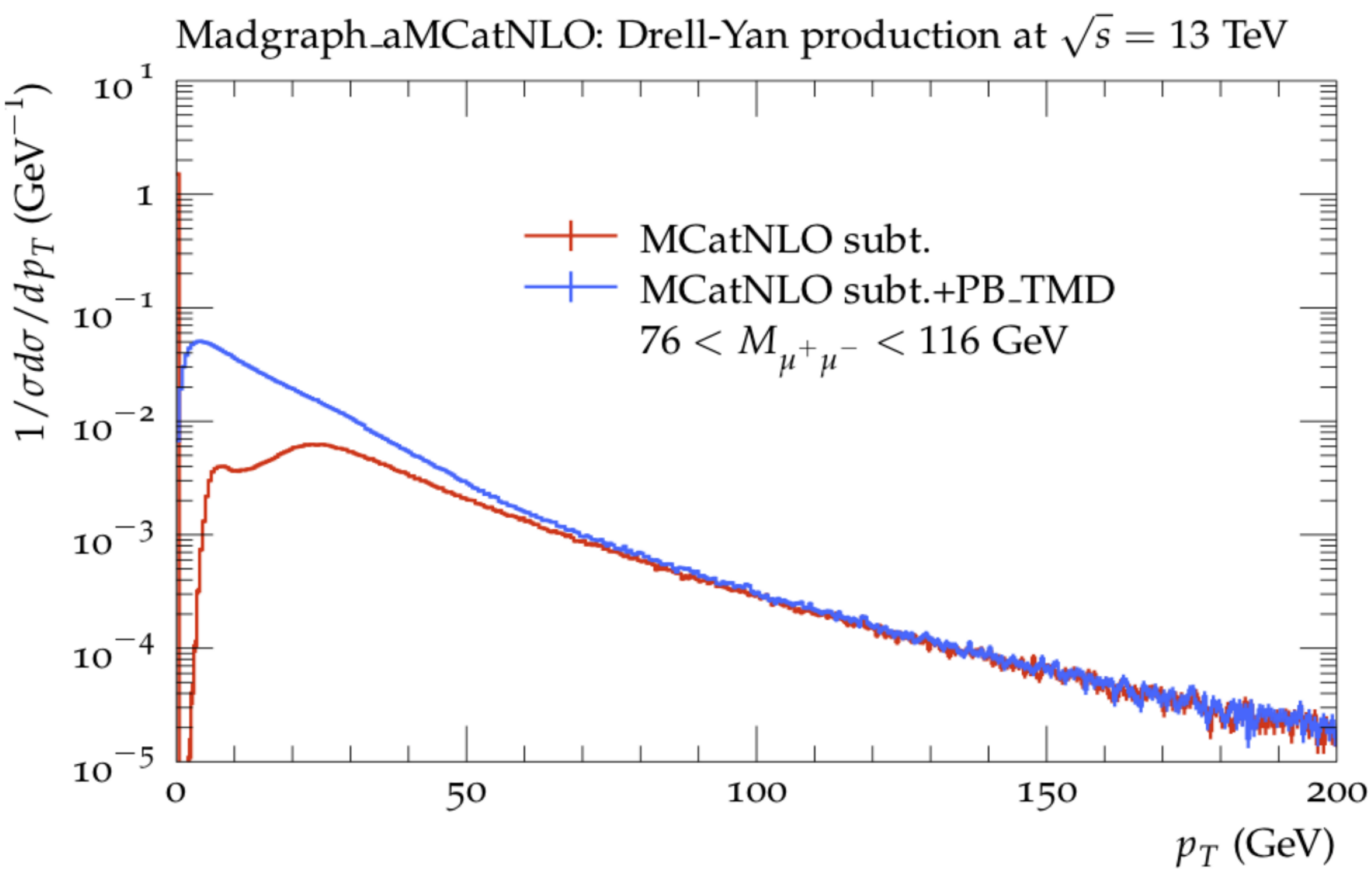
Drell -Yan production: q_T - spectrum

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

Matching to hard process: MC@NLO method

The transverse momentum spectrum of low mass Drell-Yan production at next-to-leading order in the parton branching method
Bermudez Martinez, A. et al, arXiv 2001.06488

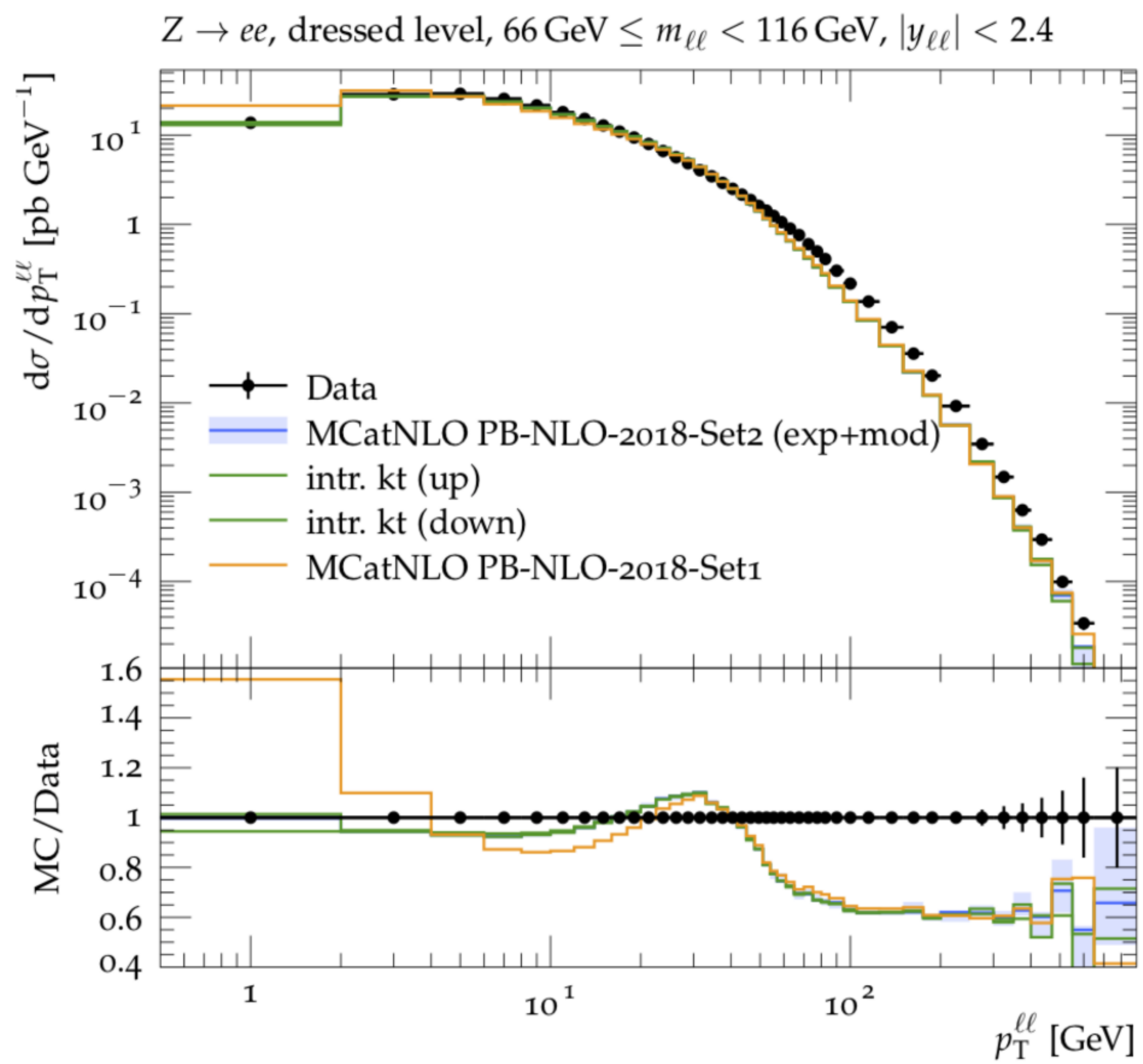
- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and/or parton shower)
  - MC@NLO without shower unphysical
    - use herwig6 subtraction terms



Matching to hard process: MC@NLO method

- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and shower)
- low q_T region affected by subtraction of soft & collinear parts
  - filled by TMD (+ PS)
- DY production very well described by TMD with MC@NLO
  - TMD fills low q_T part
    - angular ordering with $\alpha_s(q(1-z))$ is best
    - intrinsic Gauss plays little role

DY with PB TMDs: Bermudez Martinez, A. et al, arXiv 1906.00919, PhysRevD.100.074027



ATLAS (2016). DY at 8 TeV, EPJC76, 291, 1512.02192

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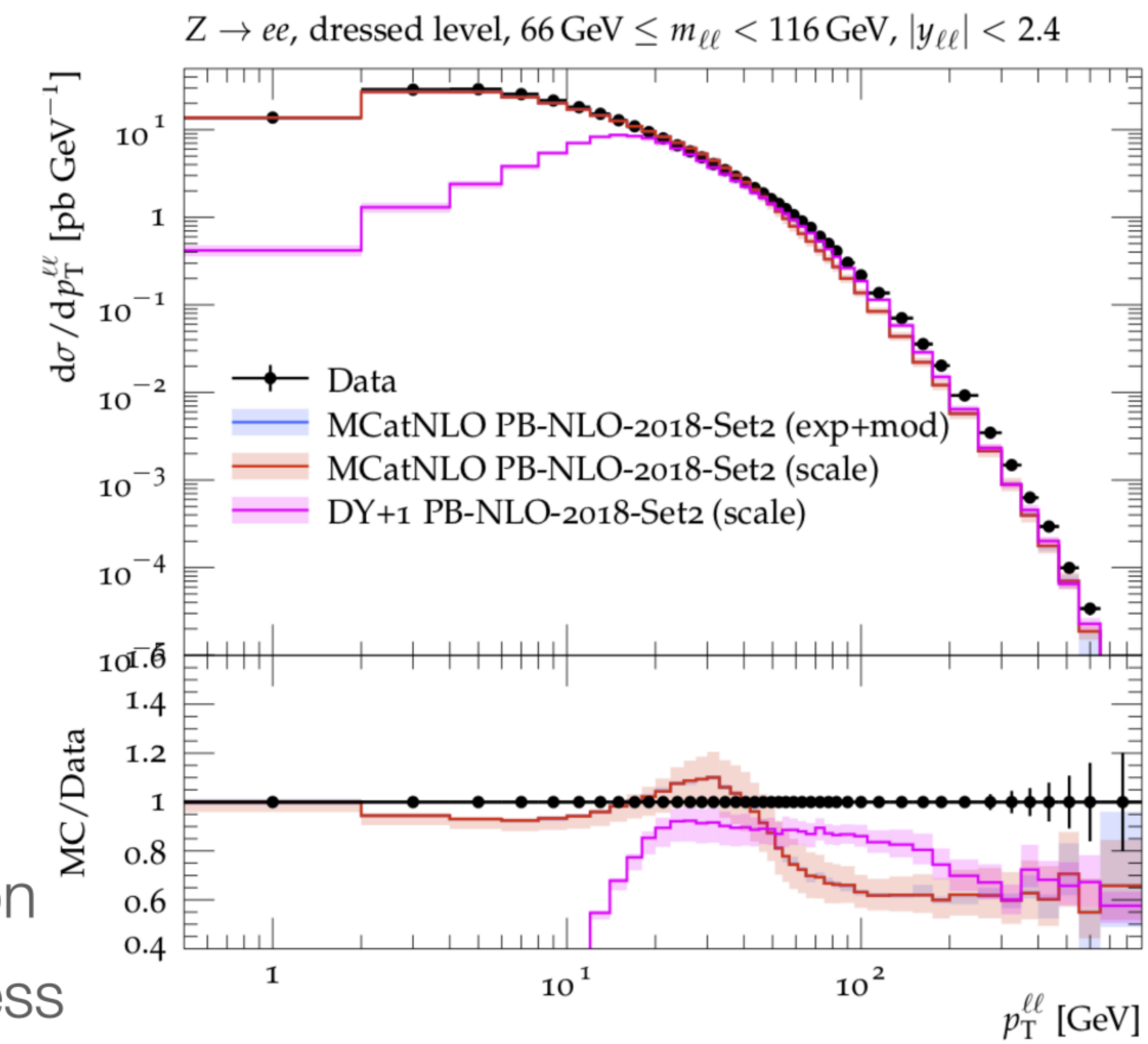
- MC@NLO subtracts soft & collinear parts from NLO (added back by TMD and shower)
- low q_T region affected by subtraction of soft & collinear parts
  - filled by TMD (+ PS)
- DY production very well described by TMD with MC@NLO
  - TMD fills low q_T part
    - small uncertainties in small p_t region
    - scale uncertainties from hard process sizable !
  - at large q_T contribution from DY+1 jet significant

DY with PB TMDs: Bermudez Martinez, A. et al, arXiv 1906.00919, PhysRevD.100.074027

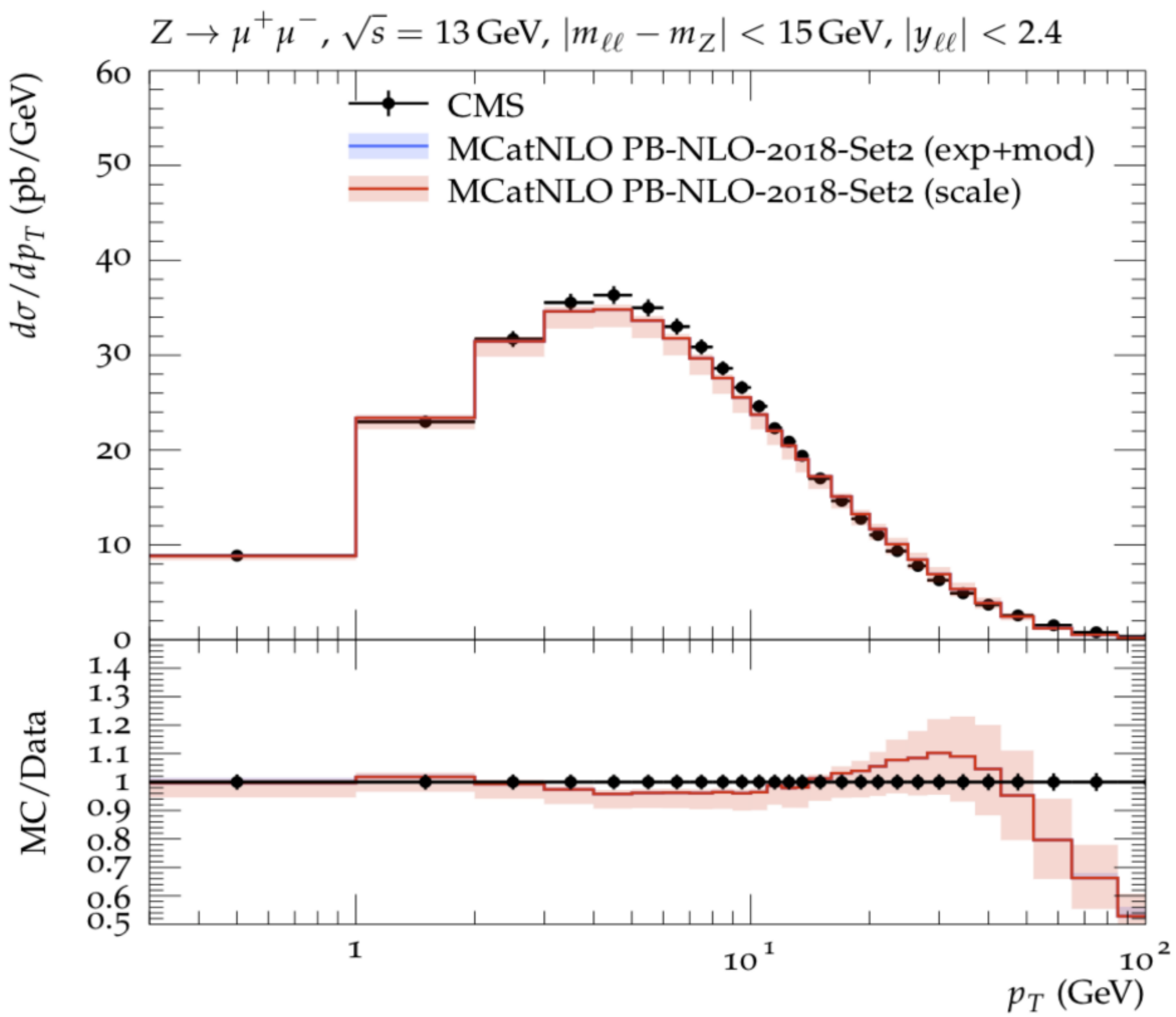


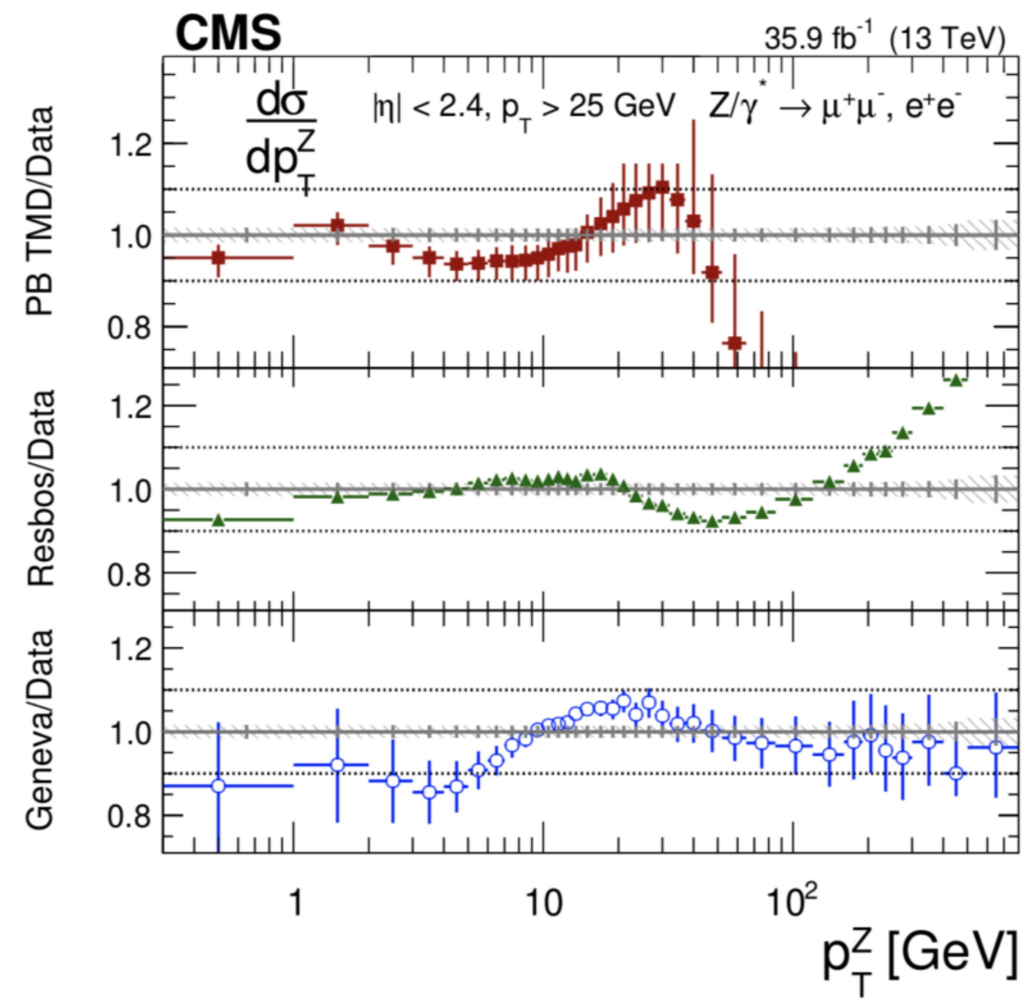
ATLAS (2016). DY at 8 TeV, EPJC76, 291, 1512.02192

Z production at 13 TeV (CMS)

Bermudez Martinez, A. et al, arXiv 2001.06488

SMP-17-010, JHEP12 (2019) 061



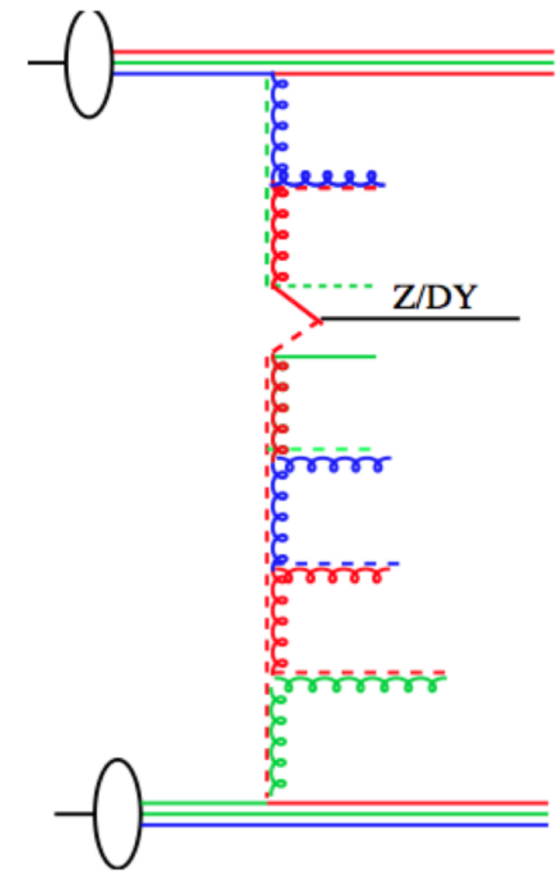


- very good description of low p_T region
  - at larger p_T contribution from higher order matrix elements important
- Uncertainties in PB method mainly from scale of MC@NLO matrix element

What happens at small m_{DY} and small $\sqrt{s}$?

What happens at small m_{DY} and small $\sqrt{s}$?

- at low mass
  - p_T of DY is dominated by **intrinsic $\boldsymbol{k_T}$** and by **soft gluons**, which need to be resummed :)
    - latest measurement: PHENIX (PhysRevD.99.072003) at $\sqrt{s} = 200$ GeV for $4.6 \leq m_{DY} \leq 8.2$ GeV
    - other measurements (older)
      - R209 (1982) PhysRevLett.48.302 at $\sqrt{s} = 62$ GeV (data read from plot in paper)
      - NUSEA (2003) hep-ex/0301031 at $\sqrt{s} = 38$ GeV (unpublished)



- Can PB method with MCatNLO + PB be applied to measurements at small $\sqrt{s}$ and small m_{DY} ?
- Is there a small p_T crisis ?

The difficulties at small q_T and small $\sqrt{s}$

PHYSICAL REVIEW D **100,** 014018 (2019)

Difficulties in the description of Drell-Yan processes at moderate invariant mass and high transverse momentum

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Both regimes, $q_T \ll Q$ and $q_T \sim Q$, as well as their matching, must be under theoretical control in order to have a proper understanding of the physics of the Drell-Yan process. In the present work, we study the process at fixed-target energies for moderate values of the invariant mass Q and in the region $q_T \lesssim Q$. We focus on the predictions based on collinear factorization and examine their ability to describe the experimental data in this regime. We find, in fact, that the predicted cross sections fall significantly short of the available data even at the highest accessible values of q_T. We investigate possible sources of uncertainty in the predictions based on collinear factorization, and two extensions of the collinear framework: the resummation of high-q_T threshold logarithms, and transverse-momentum smearing. None of these appear to lead to a satisfactory agreement with the data. We argue that these findings also imply that the Drell-Yan cross section in the "matching regime" $q_T \lesssim Q$ is presently not fully understood at fixed-target energies.

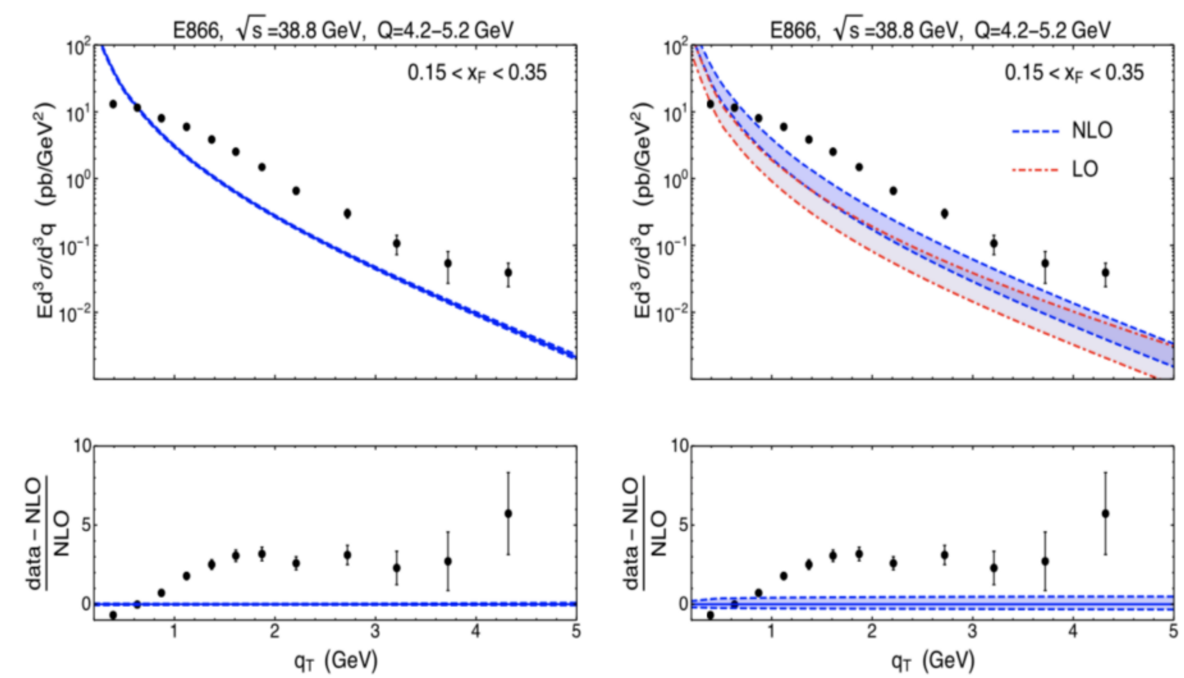
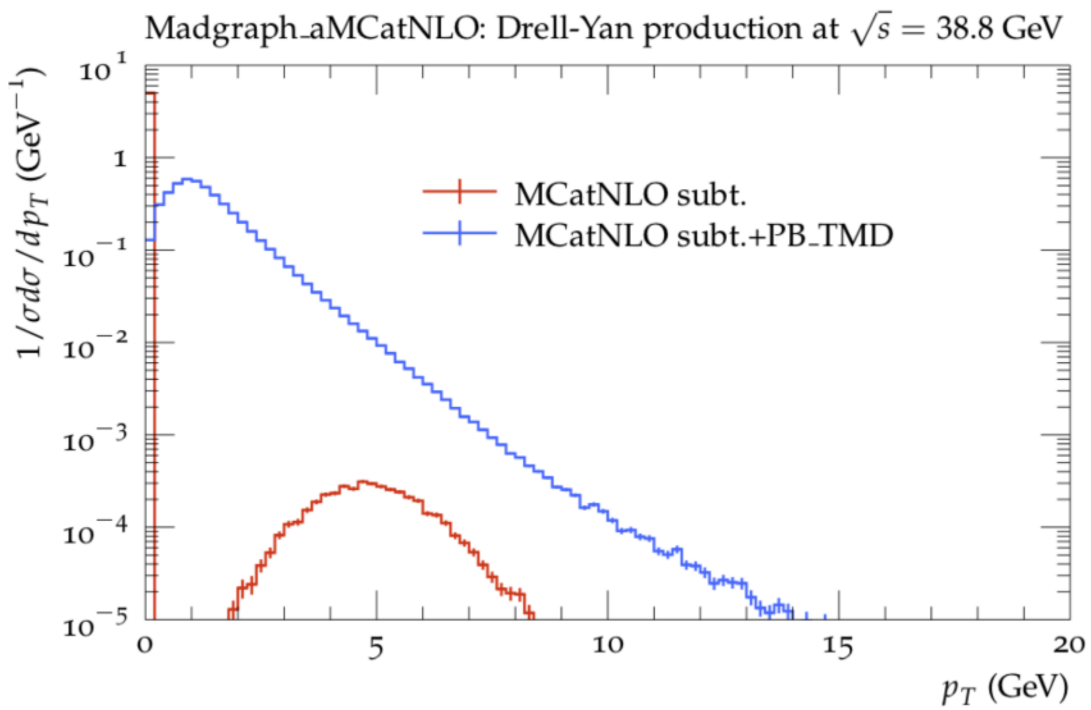
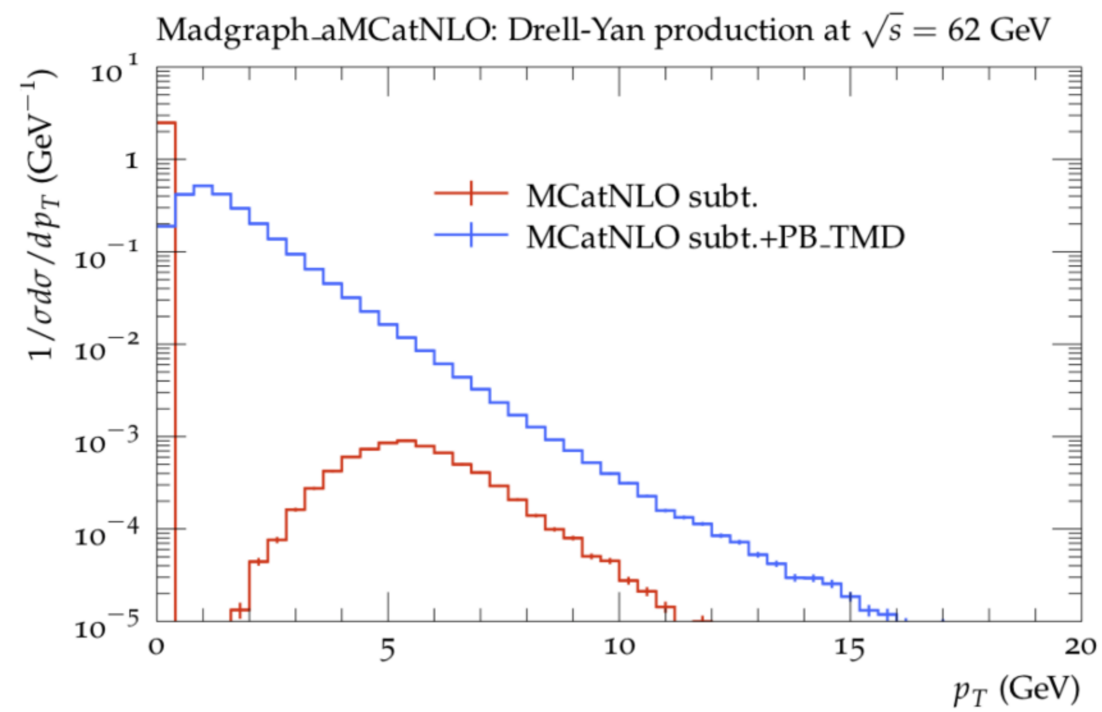


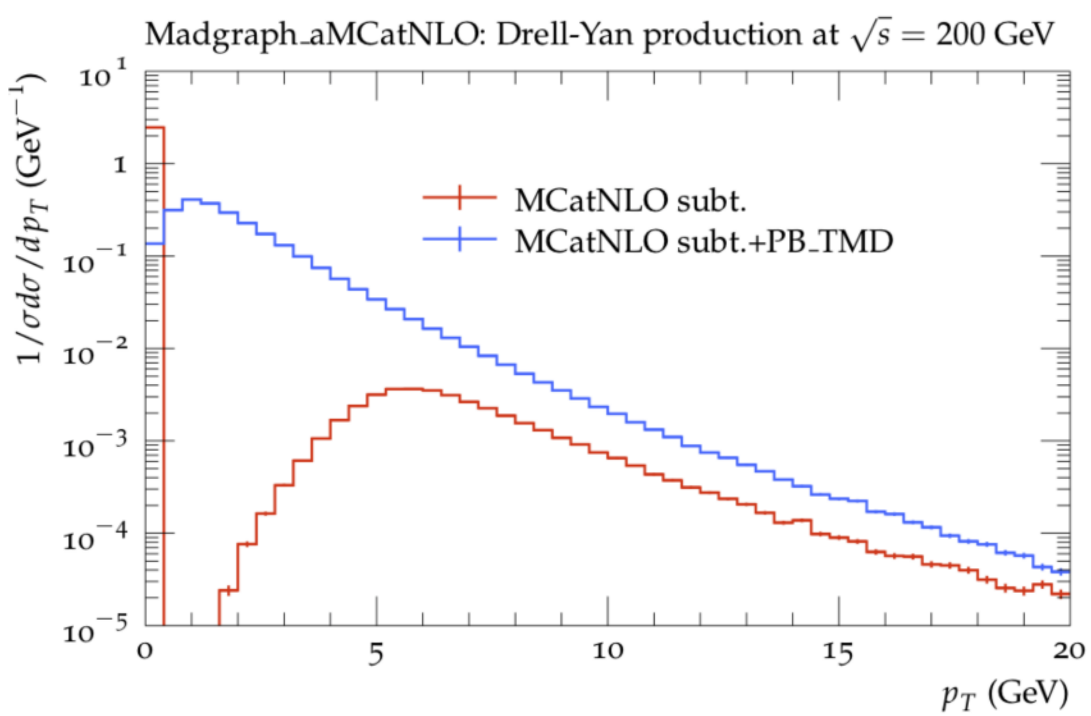
FIG. 2. Transverse-momentum distribution of Drell-Yan dimuon pairs at $\sqrt{s} = 38.8$ GeV in a selected invariant mass range and Feynman-x range: experimental data from Fermilab E866 (hydrogen target) [41] compared to LO QCD and NLO QCD results. (Left panels) NLO QCD $[\mathcal{O}(\alpha_s^2)]$ calculation with central values of the scales $\mu_R = \mu_F = Q = 4.7$ GeV, including a 90% confidence interval from the CT14 PDF set [39]. (Right panels) LO QCD and NLO QCD theoretical uncertainty bands obtained by varying the renormalization and factorization scales independently in the range $Q/2 < \mu_R, \mu_F < 2Q$.

MCatNLO for small m_{DY} and small $\sqrt{s}$

Bermudez Martinez, A. et al, arXiv 2001.06488



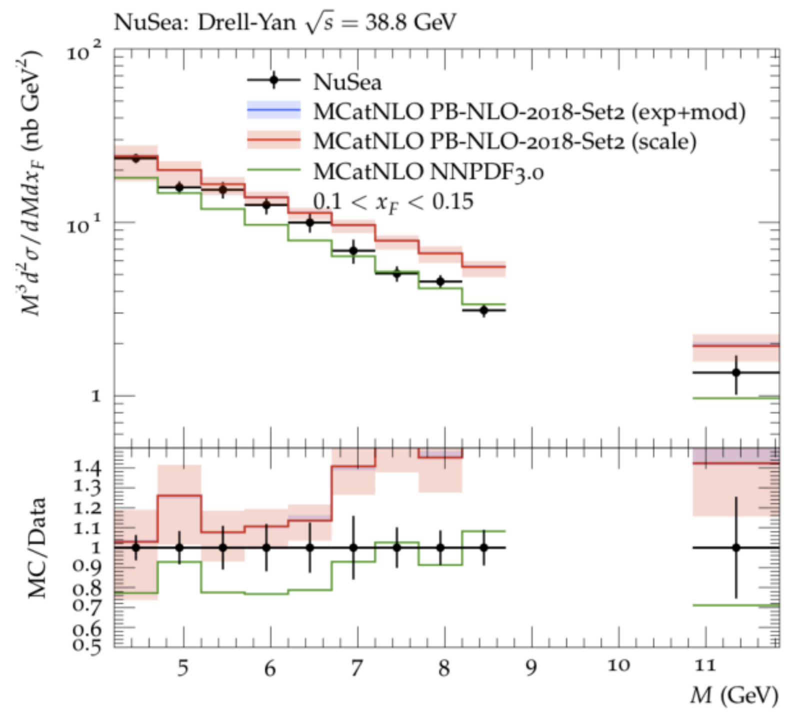


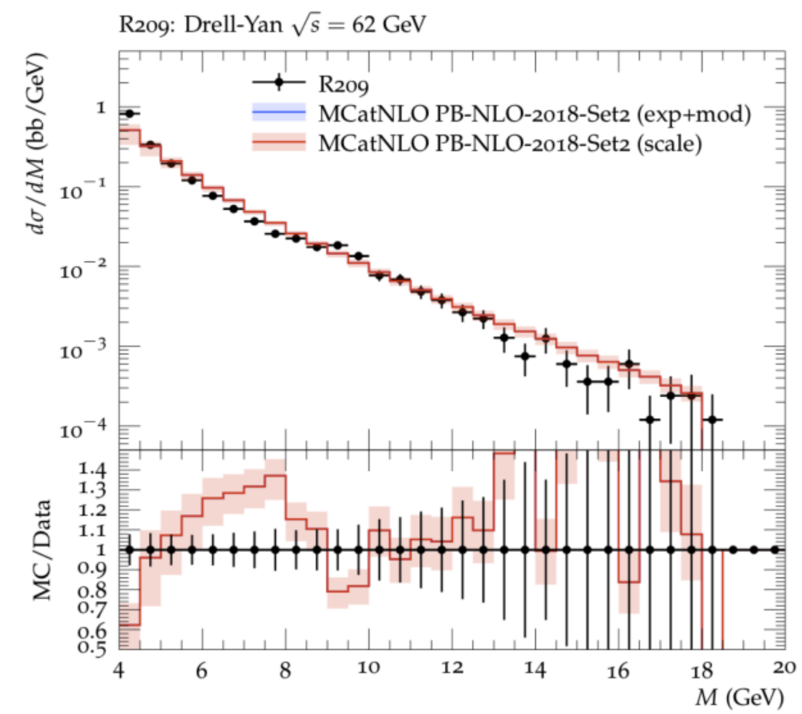


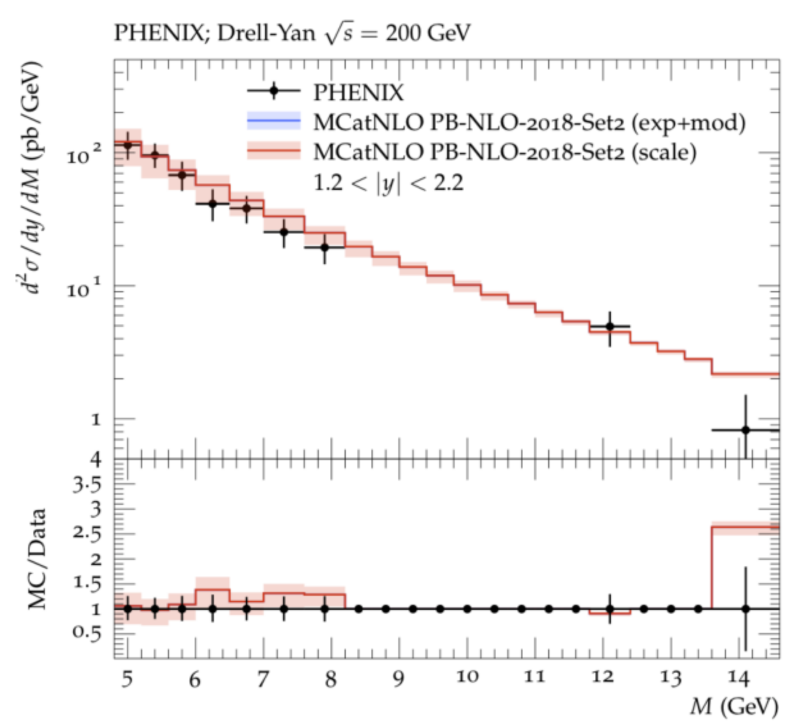
- Contribution of real 1 parton emission increases with $\sqrt{s}$
- NLO corrections are large at small m_{DY} (factor of 2 or more) because scale (m_{DY}) is small and $\alpha_s(m_{DY})$ is large !

Comparison with measurements

Bermudez Martinez, A. et al, arXiv 2001.06488



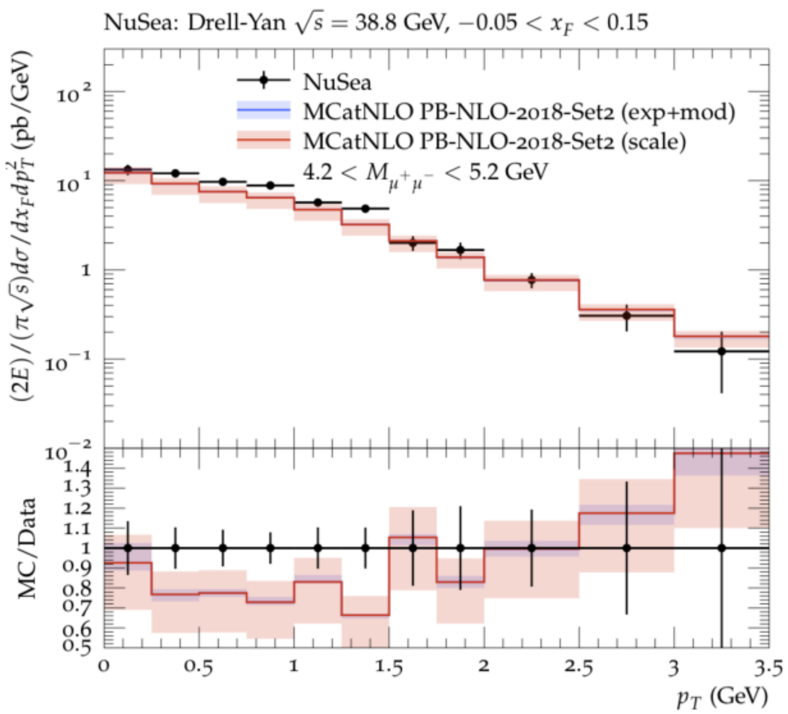


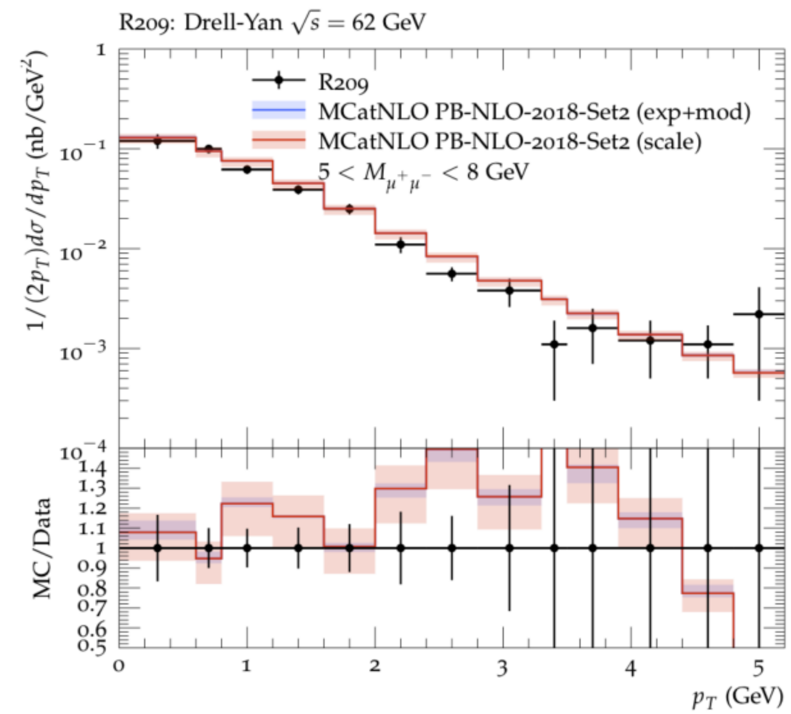


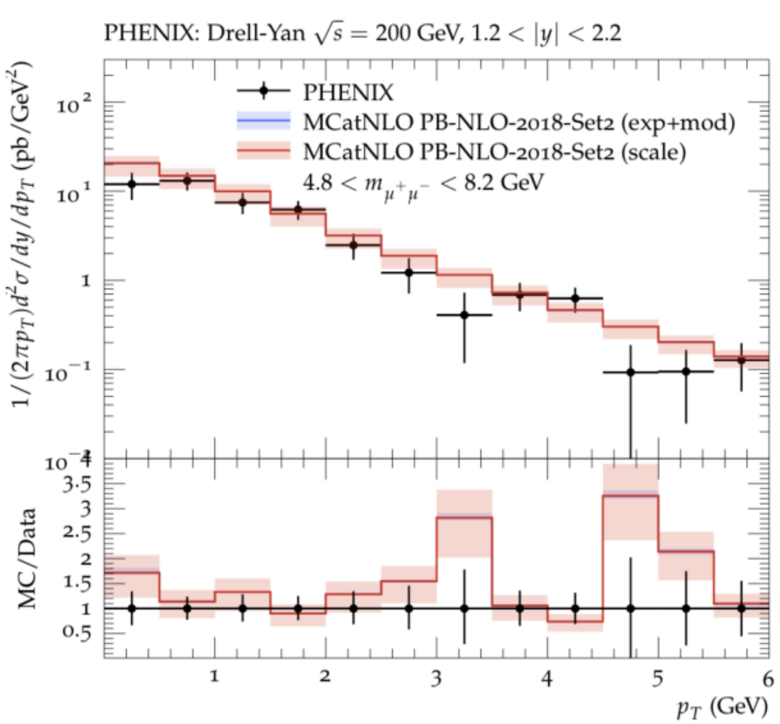
- Mass distribution well described with McatNLO + PB pdfs
  - sensitive only to collinear pdf
    - at smallest $\sqrt{s}$, large x probed
    - pdfs are fitted to HERA data and not well constrained at large x

The DY p_T - spectrum

Bermudez Martinez, A. et al, arXiv 2001.06488







- DY p_T -spectrum well described with MC@NLO+PB-TMDs
  - good agreement within uncertainties:

	NuSea	R209	PHENIX
χ^2/ndf	1.08	1.27	1.04

  - no hint for p_T crisis !

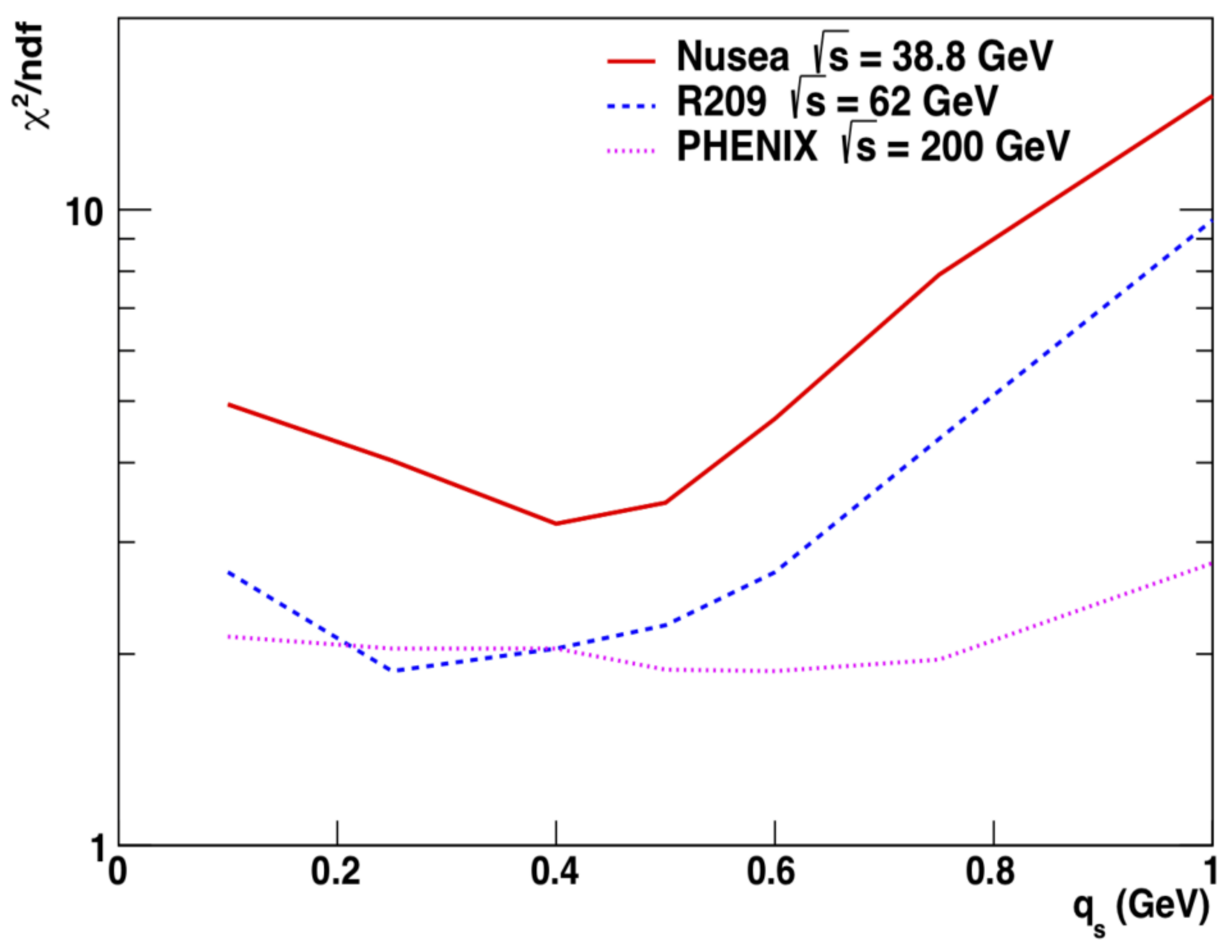
Constraints on intrinsic k_T

Bermudez Martinez, A. et al, arXiv 2001.06488

- Intrinsic k_T is included in starting distribution, for simplicity Gauss is assumed

$$\mathcal{A}_{0,b}(x, k_T^2, \mu_0^2) = f_{0,b}(x, \mu_0^2) \cdot \exp\left(-|k_T^2|/2\sigma^2\right)/(2\pi\sigma^2)$$

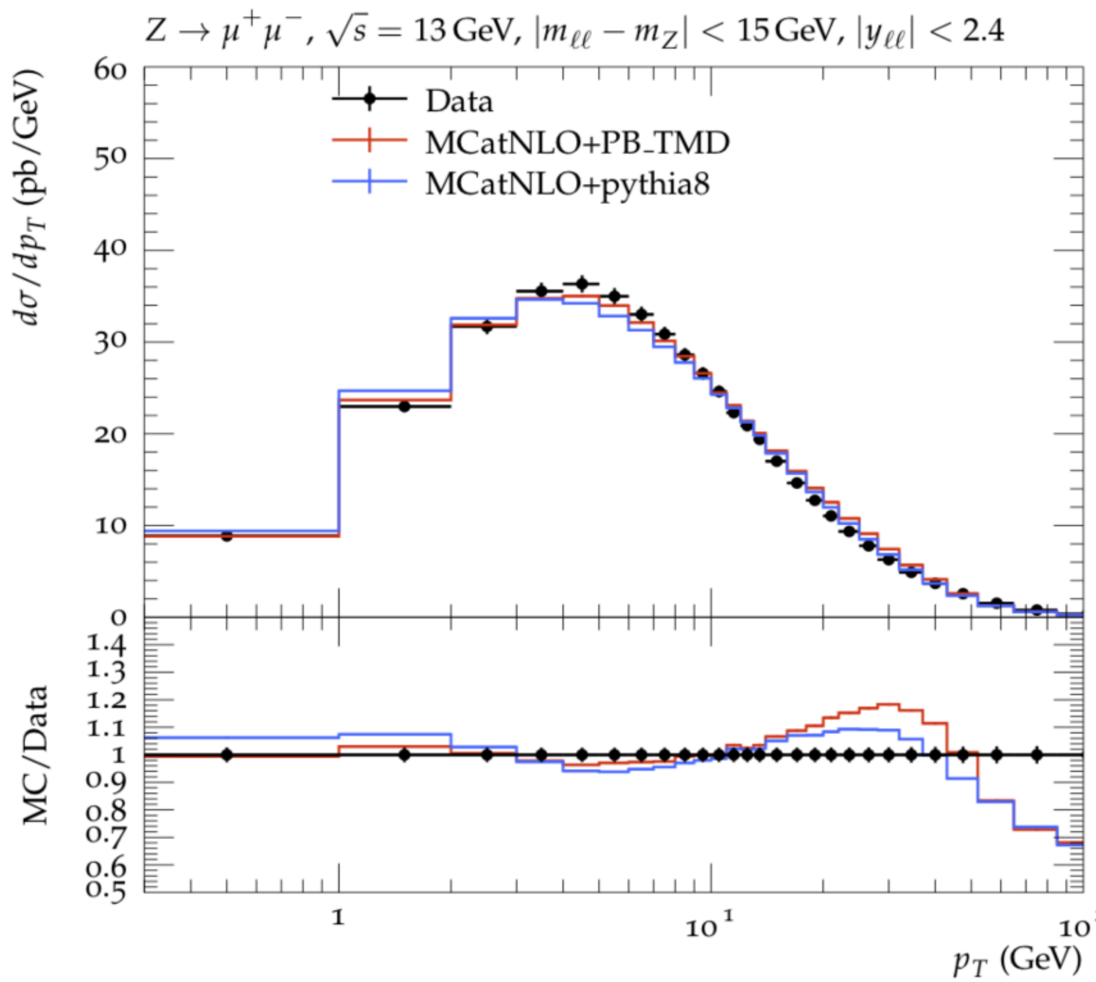
- constrain width $\sigma^2 = q^2{}_s/2$ of Gauss distribution (default $q_s = 0.5\,GeV$)

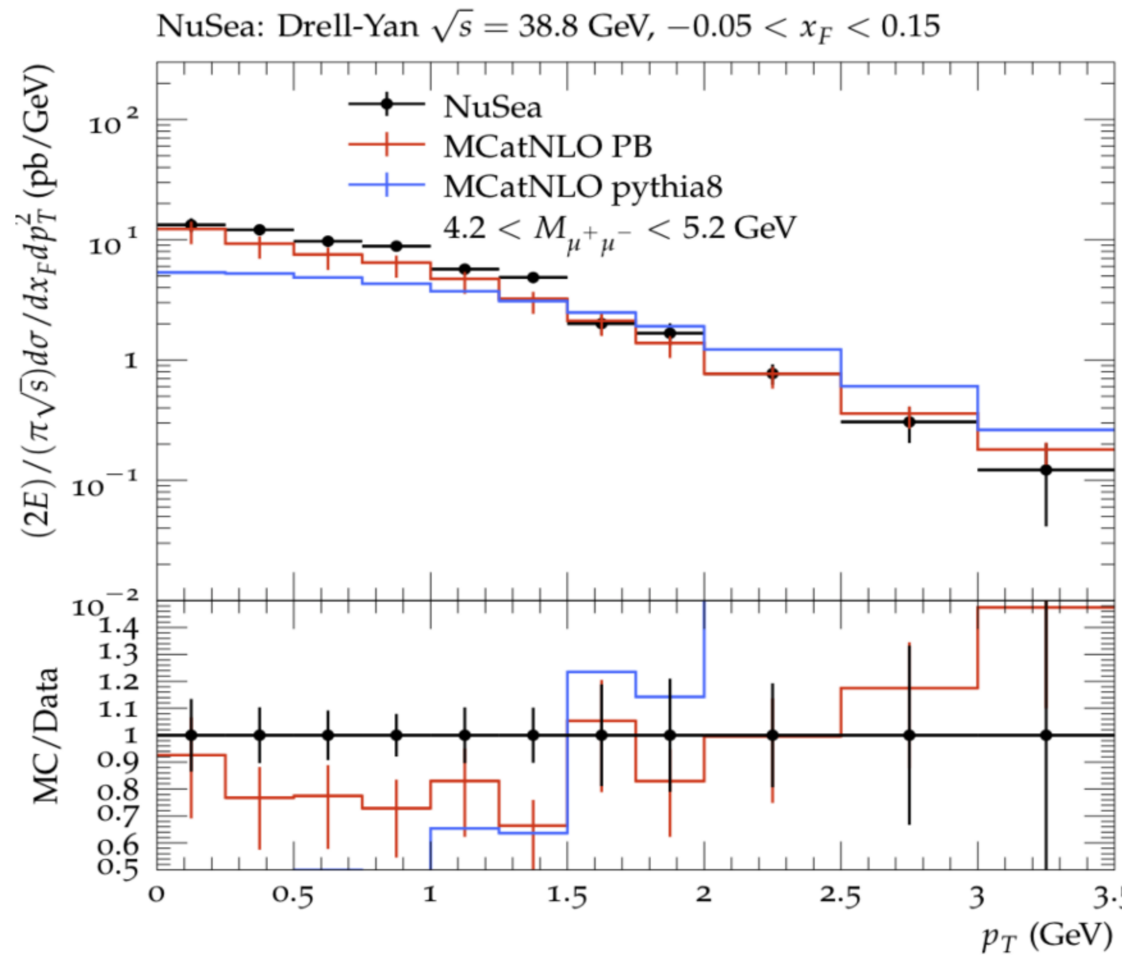


- Only at low energies, sensitivity to intrinsic Gauss observed....

How do other approaches perform ?

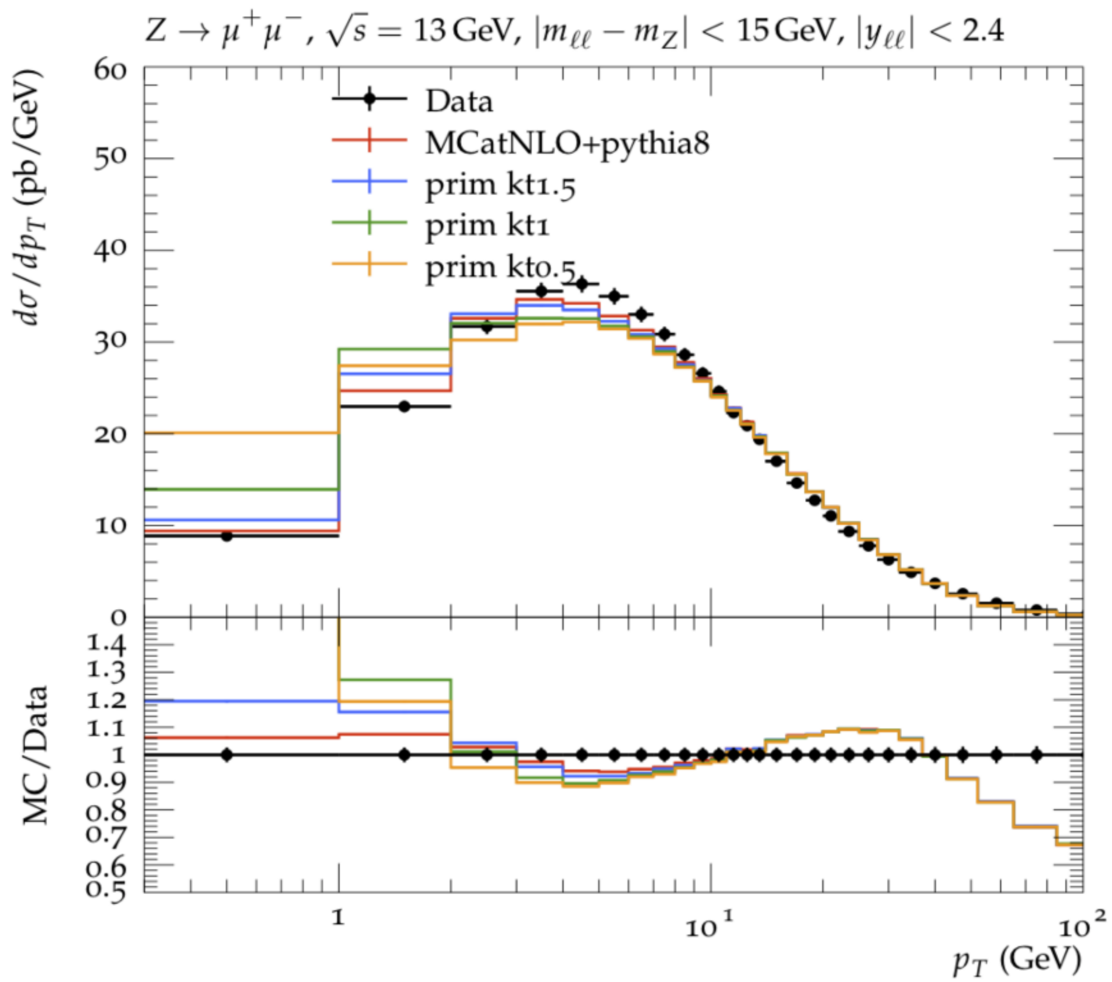
Predictions from MCatNLO+PYTHIA8

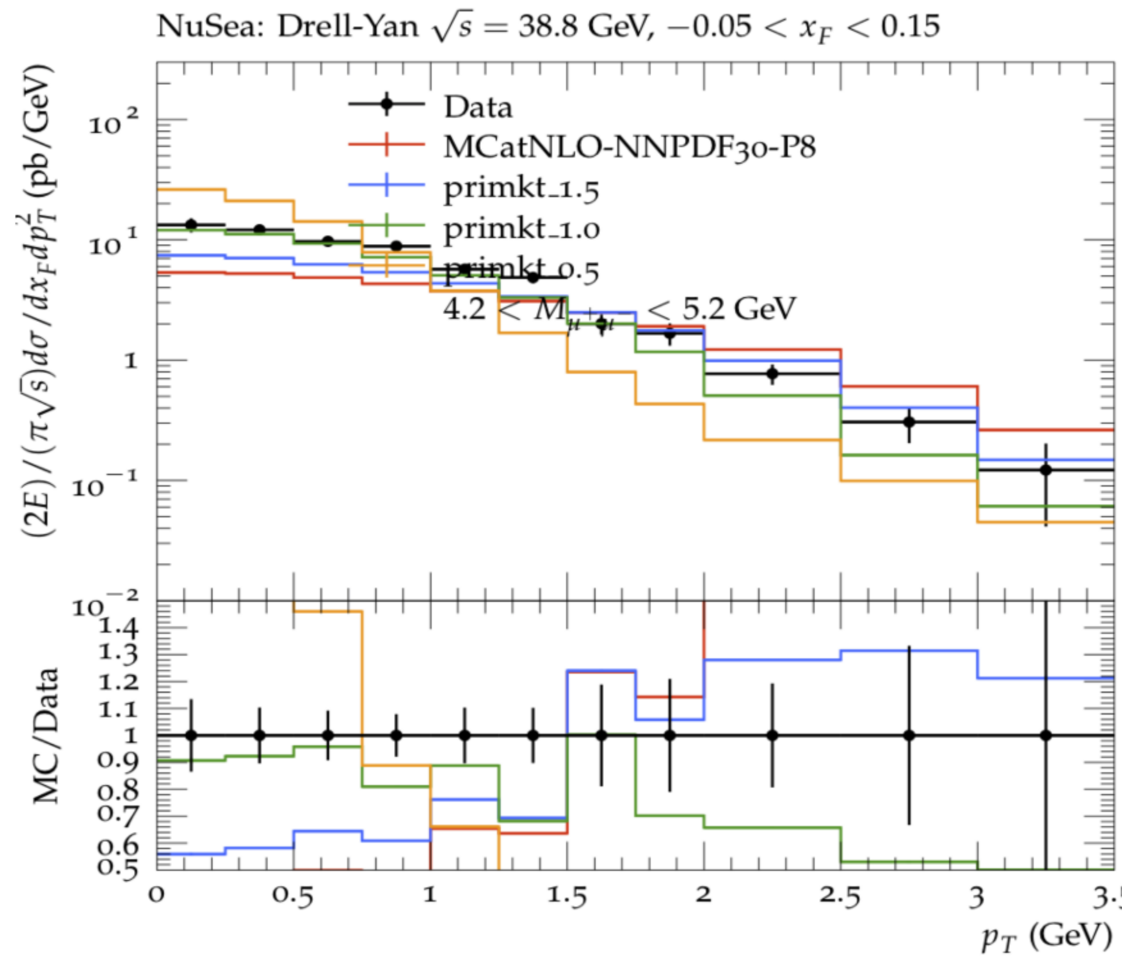




- differences observed with McatNLO using Monash tune in P8
  - too high at high energy
  - too low at low energy
    - can it be tuned ?

Predictions from MCatNLO+PYTHIA8





- differences observed with McatNLO using Monash tune in P8
  - intrinsic k_T in P8 cannot be simply tuned to describe both high and low energy data

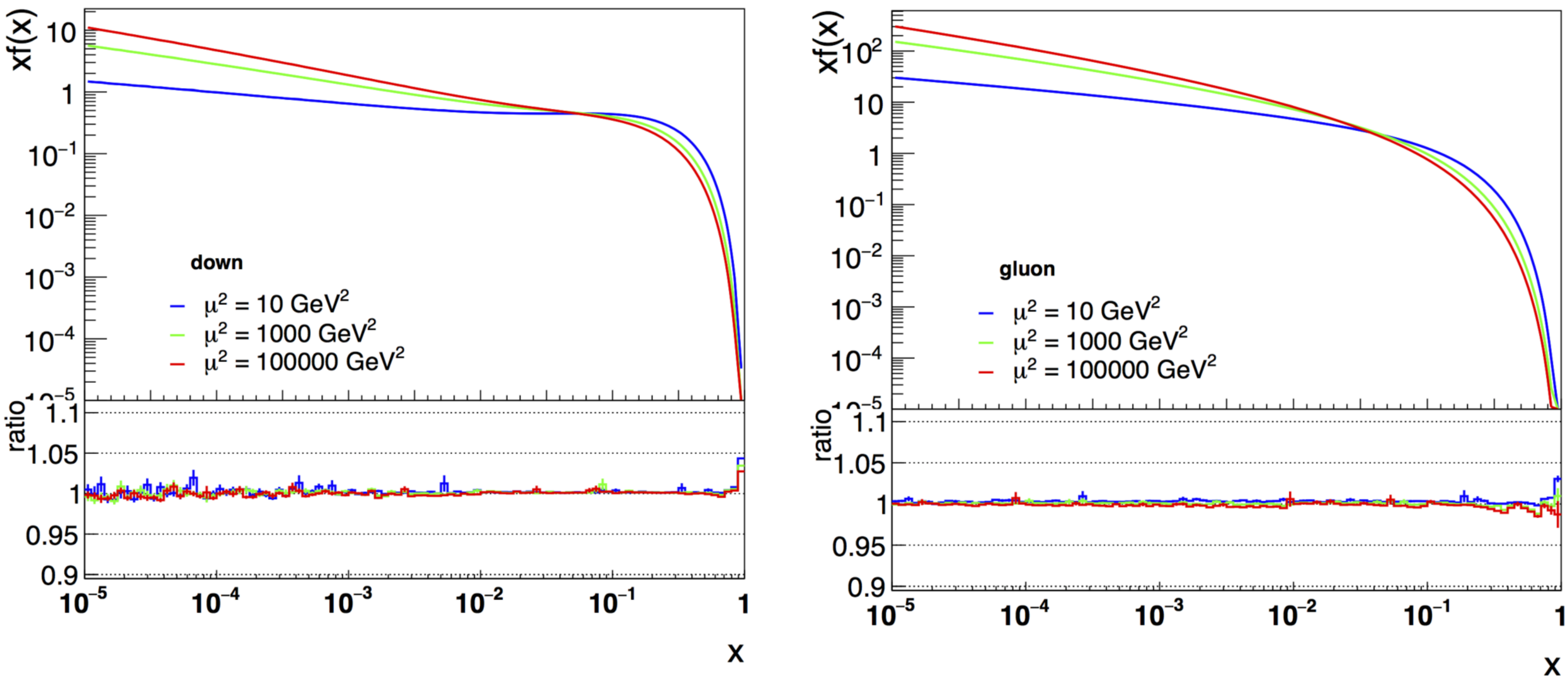
Conclusion

- Parton Branching method to solve DGLAP equation at LO, NLO and NNLO
  - method directly applicable to determine k_t distribution (as would be done in PS)
  - ➔ TMD distributions for all flavors determined at LO and NLO
  - ➔ TMD evolution implemented in xFitter – fits to DIS processes at the moment

- Application to DY processes in pp:
  - ➔ DY q_T - spectrum without new parameters for Z and low mass DY
    - ➔ matching TMD with MC@NLO
  - DY q_T - spectrum at low mass and low energies well described
    - in contrast to prediction using pythia
  - Success of PB TMDs with McatNLO:
    - describe DY production over wide range
    - proper prediction of low p_T spectrum – needed for m_W determination

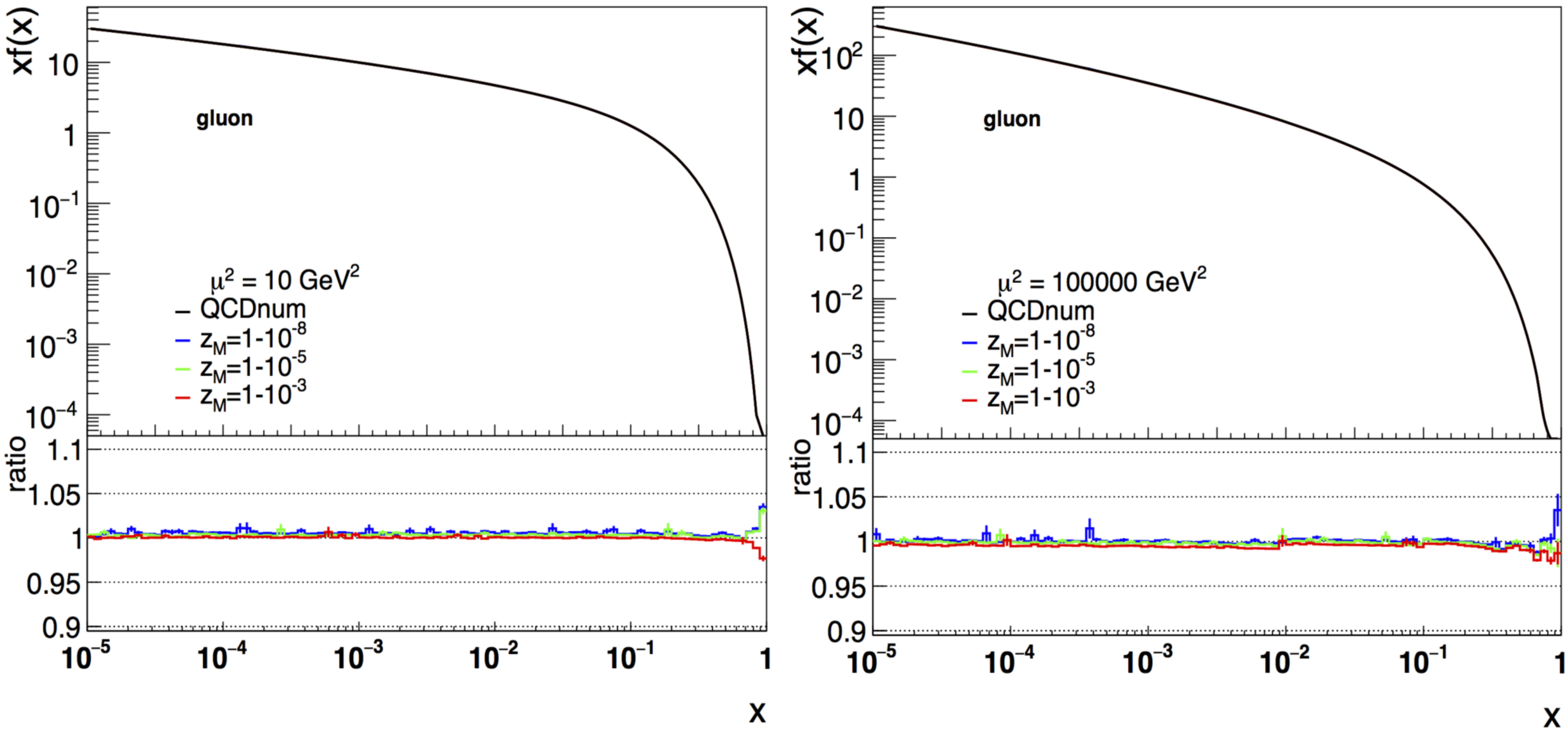
Appendix

Validation of method with QCDnum at NLO



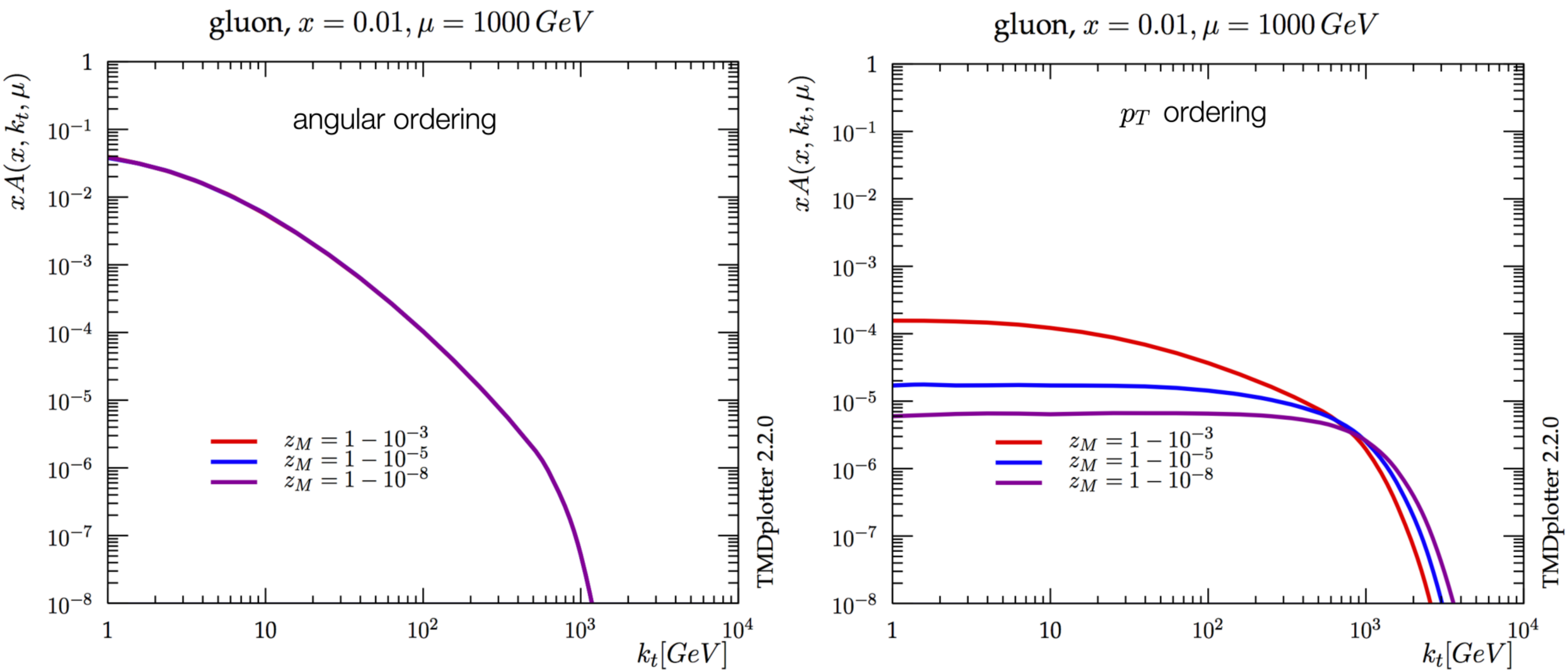
- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach works also at NNLO !

Validation of method at NLO: z_M - dependence



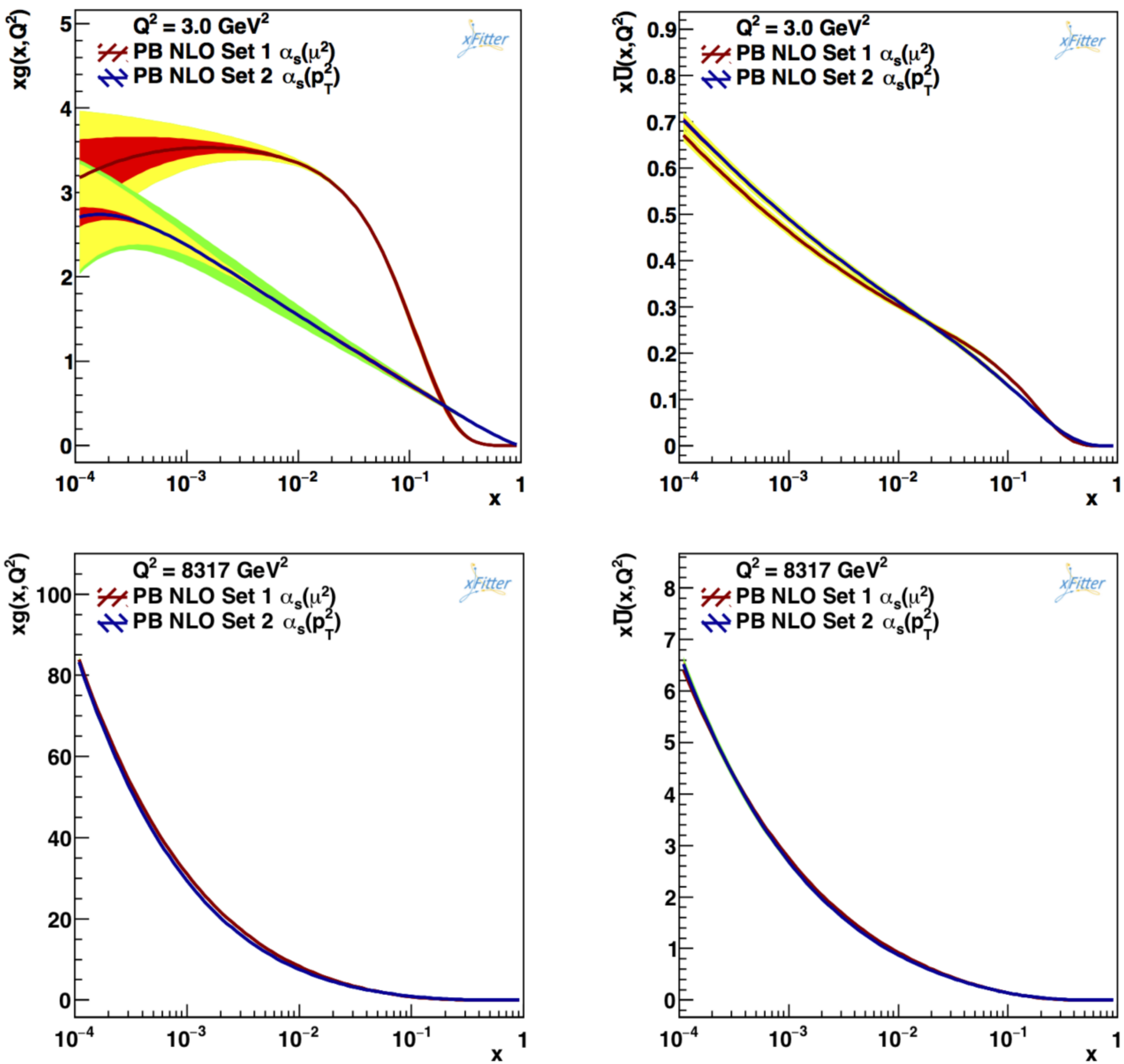
- No dependence on z_M if z_M is large enough:
  - approximation is of $\mathcal{O}(1 - z_M)$
- Very good agreement with NLO - QCDnum

Transverse Momentum: z_M - dependence



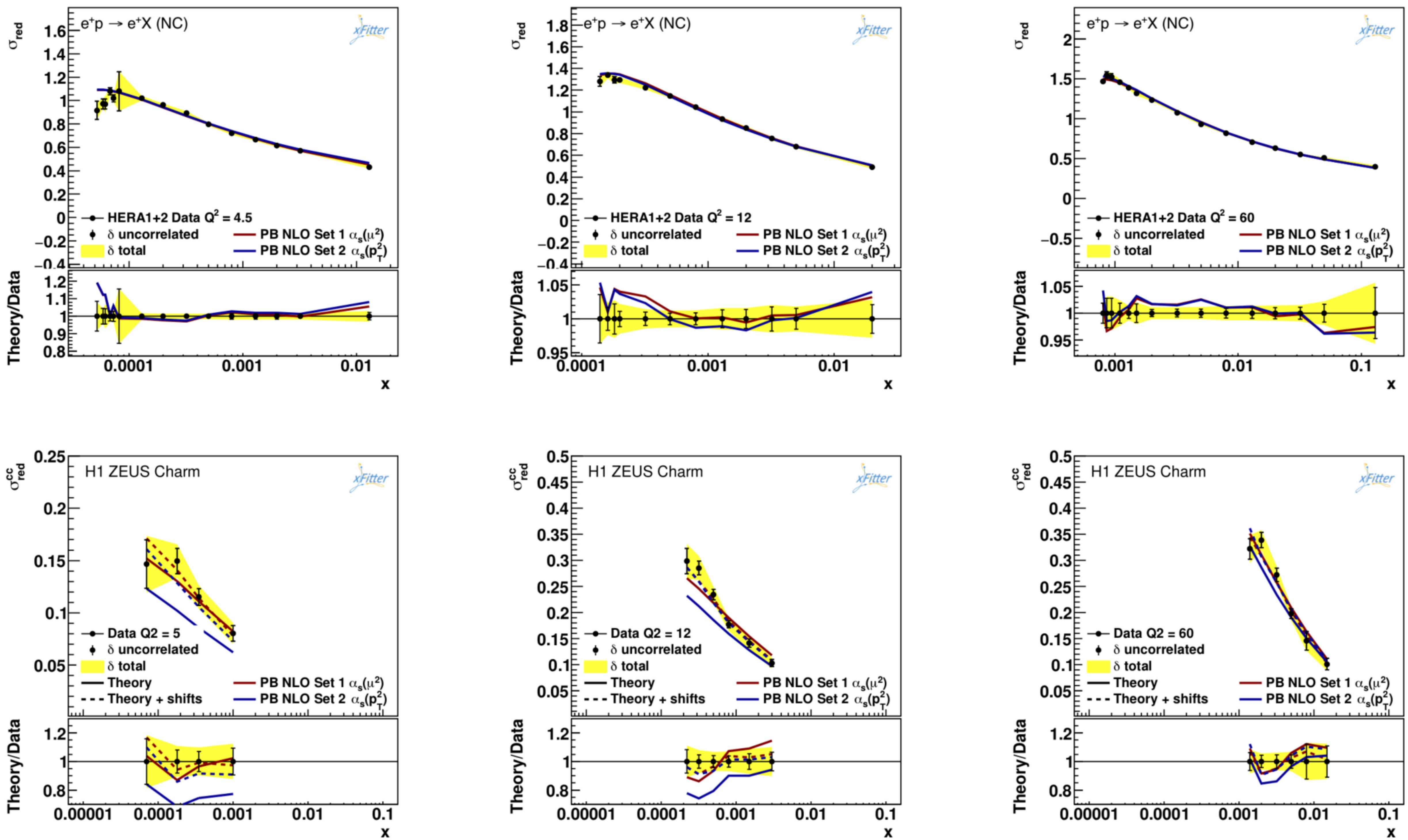
- p_T ordering ($\mu = q_T$) shows significant dependence on z_M: unstable result because of soft gluon contribution
- angular ordering ($\mu = q_T/(1-z)$) is independent of z_M: stable results since soft gluons are suppressed

Fit with different scale in α_s

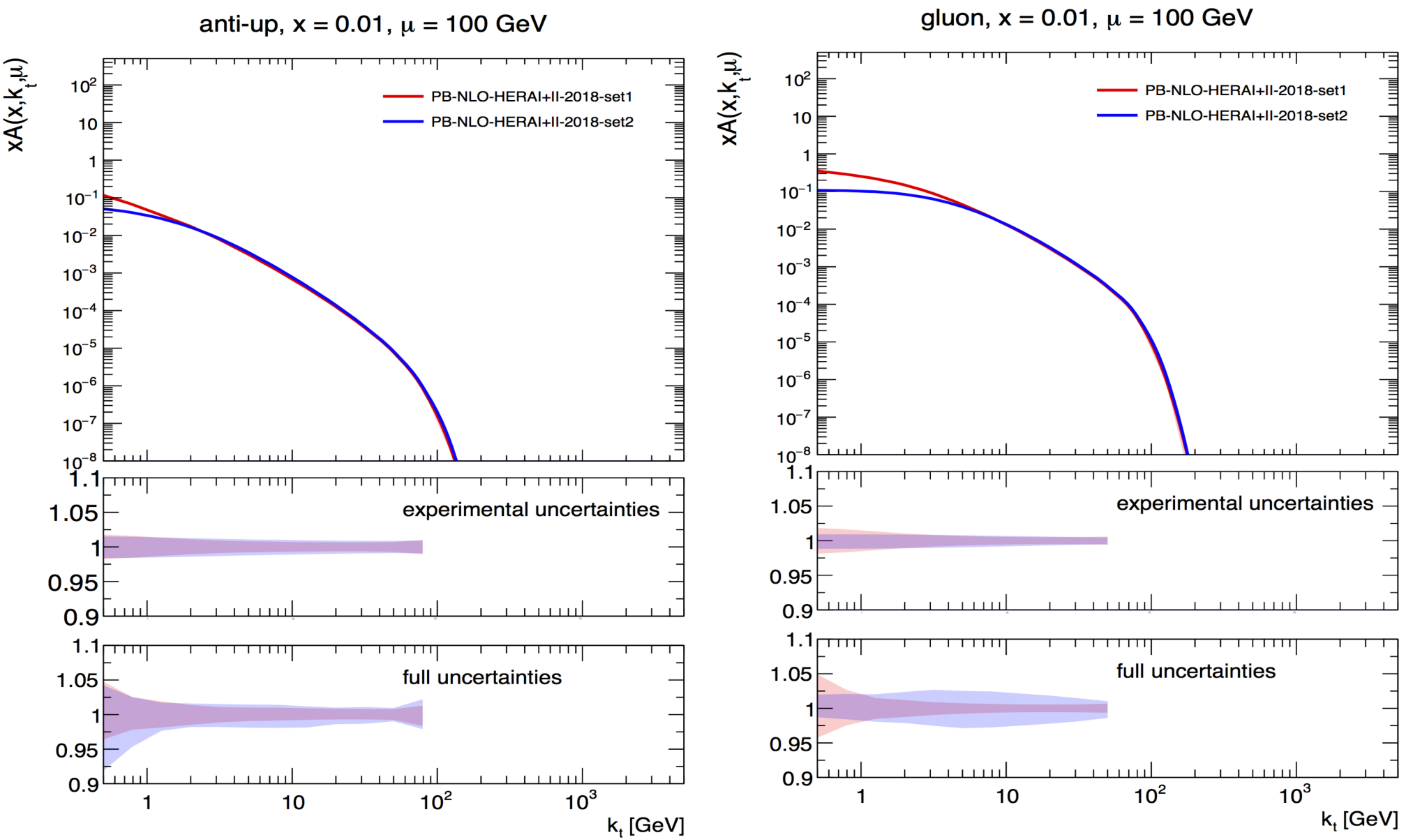


- fit 1 with $\alpha_s(q)$
  - as good as HERAPDF2.0 $\chi^2/ndf = 1.2$
- fit 2 with $\alpha_s(q(1-z))$
  - $\chi^2/ndf = 1.21$
- very different gluon distribution obtained at small Q^2

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



TMD distributions from fit to HERA data



- model dependence larger than experimental uncertainties