New parton densities with Parton Branching method

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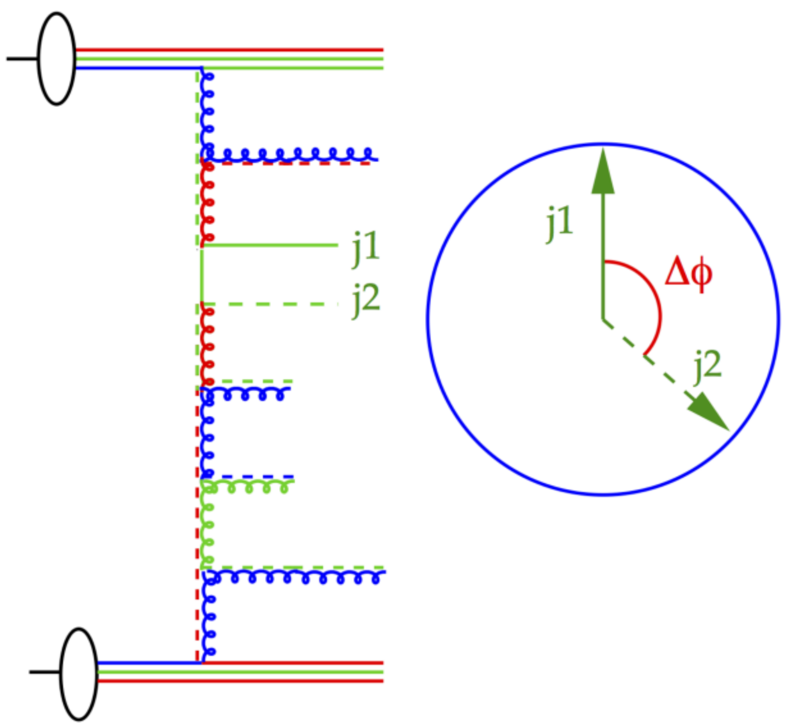
- Why TMDs are needed
  - TMDs for hadron-hadron collisions
- New developments
  - parton branching algorithm to solve evolution equations
    - benchmark tests
    - advantages for integrated PDFs
  - determination of TMD densities at NLO with xFitter
- Application to DY production and high p_T dijets

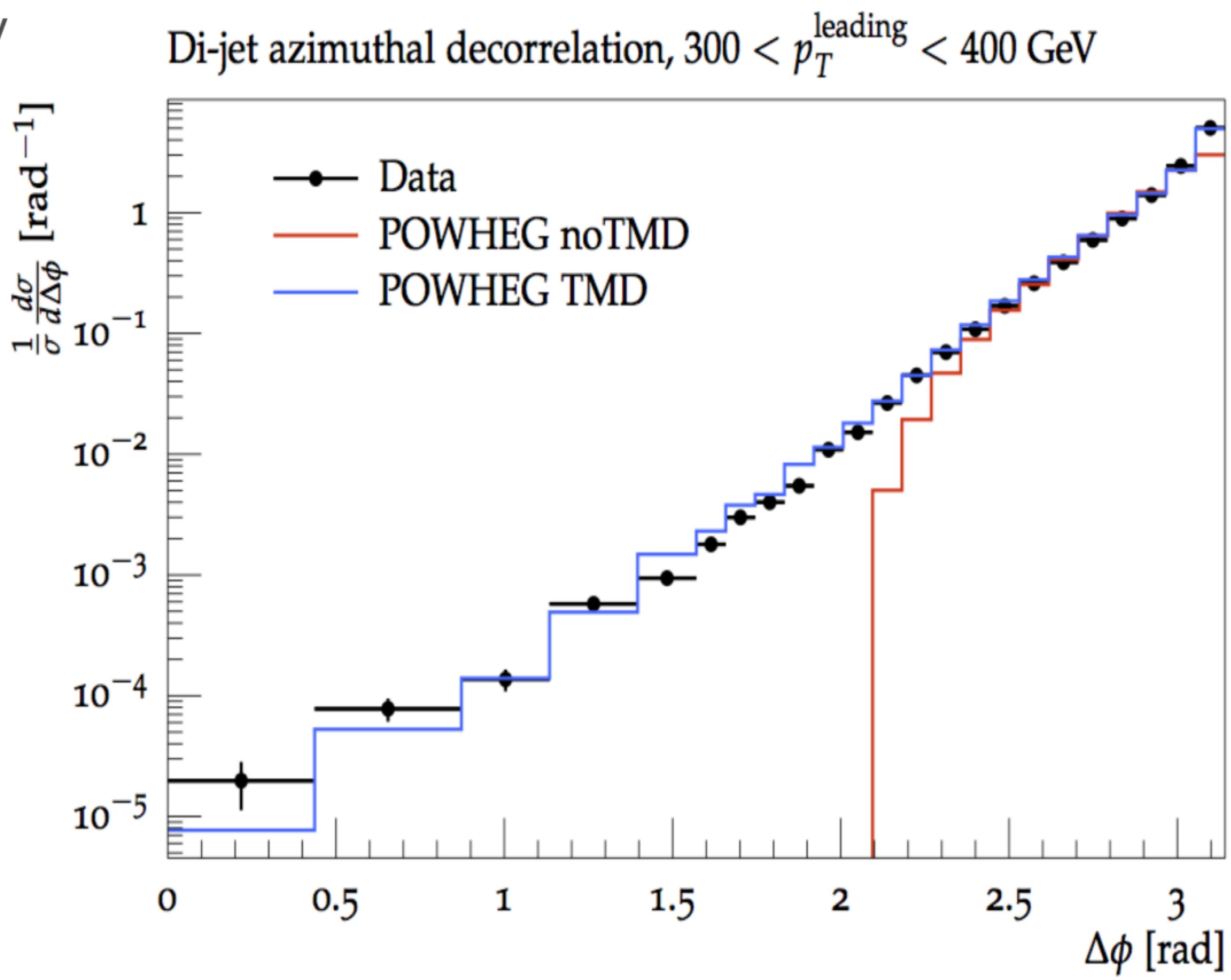
TMDs – what is it ?

- TMDs (Transverse Momentum Dependent parton distribution)
  - at very small transverse momenta
    - typically for small q_t in DY production, or semi-inclusive DIS
  - at very small x – un-integrated PDFs
    - essentially only gluon densities (CCFM, BFKL etc)
  - new approach to cover all transverse momenta from small k_t to large k_t as well as to cover all x and all μ^2
    - parton branching method (described here)

Why TMDs ?

- Measurements with $p_T > 200$ GeV
  - at least 2 jets





- NLO-dijet (Powheg) w/o PS cannot describe small $\Delta\,\phi$
- NLO-dijet (Powheg) with TMDs describes spectrum at small and large $\Delta\,\phi$
- Region of higher order emissions described by TMDs

TMDs – how to determine ?

- Transverse momentum effects are naturally coming from intrinsic k_t and parton showers
- TMD effects can be significant in all distributions, even for inclusive (or semi-inclusive) distributions at large pt

- New: parton branching method
  - perform evolution using a parton branching method
  - determine integrated PDF from parton branching solution of evolution eq.
    - check consistency with standard evolution on integrated PDFs
      - at LO, NLO and NNLO
  - determine TMD:
    - since each branching is generated explicitly, energy-momentum conservation is fulfilled and transverse momentum distributions can be obtained

How to obtain TMDs – the evolution equation

[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 determined from fits to HERA DIS measurements, DESY-18-042

DGLAP evolution – solution with parton branching method

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

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

- differential form using f/Δ_s with

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

- 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 – solution with parton branching method

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

- solve integral equation via iteration:

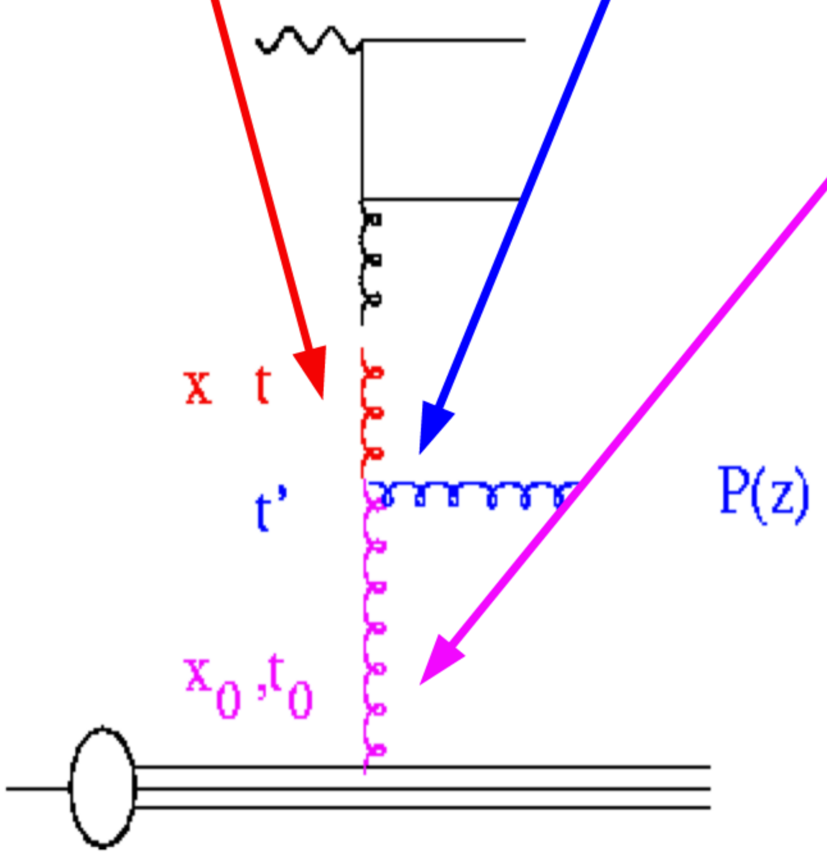
from t' to t w/o branching

branching at t'

from t_0 to t' w/o branching

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

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



Evolution equation and parton branching method

- use momentum weighted PDFs: $xf(x,t)$

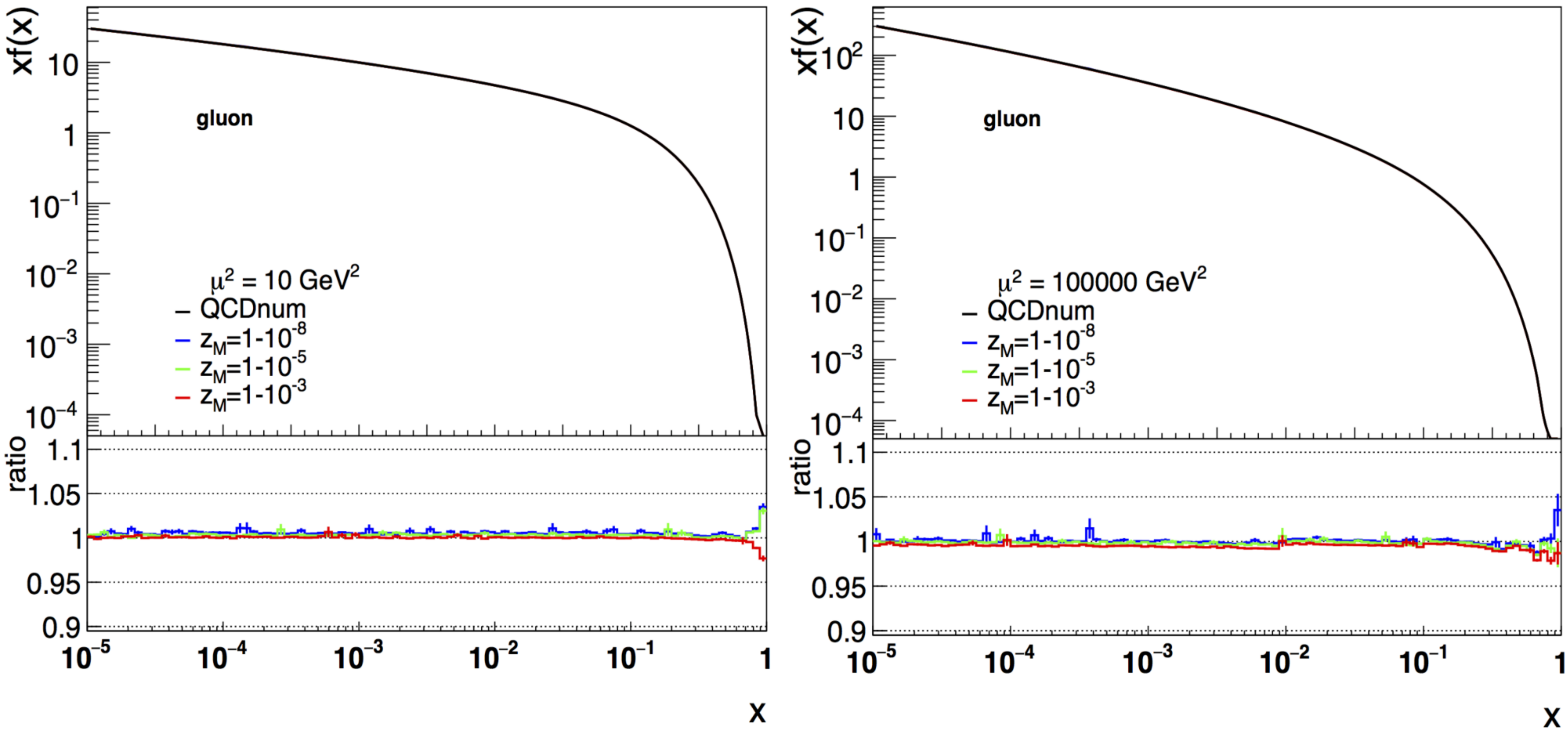
$$xf_a(x,\mu^2) = \Delta_a(\mu^2)\, xf_a(x,\mu_0^2) + \sum_b \int_{\mu_0}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s, z)\, \frac{x}{z} f_b\left(\frac{x}{z}, \mu'^2\right)$$

- with $P_{ab}{}^{(R)}(\alpha_s(t'),z)$ 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 to treat non-resolvable and virtual corrections

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

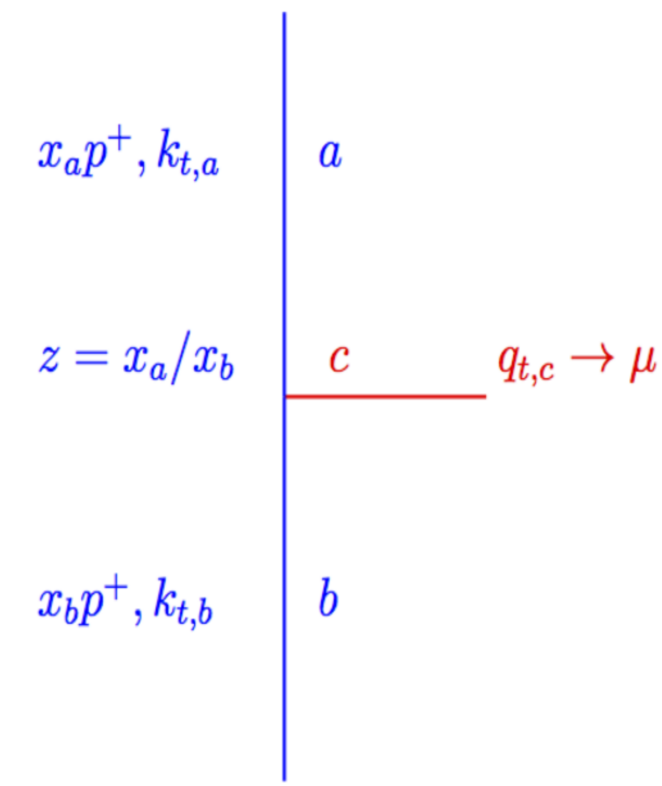
Validation of method with QCDnum at NLO



- Very good agreement with NLO - QCDnum if z_M is large enough:
  - approximation is of $\mathcal{O}(1 - z_M)$

Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step



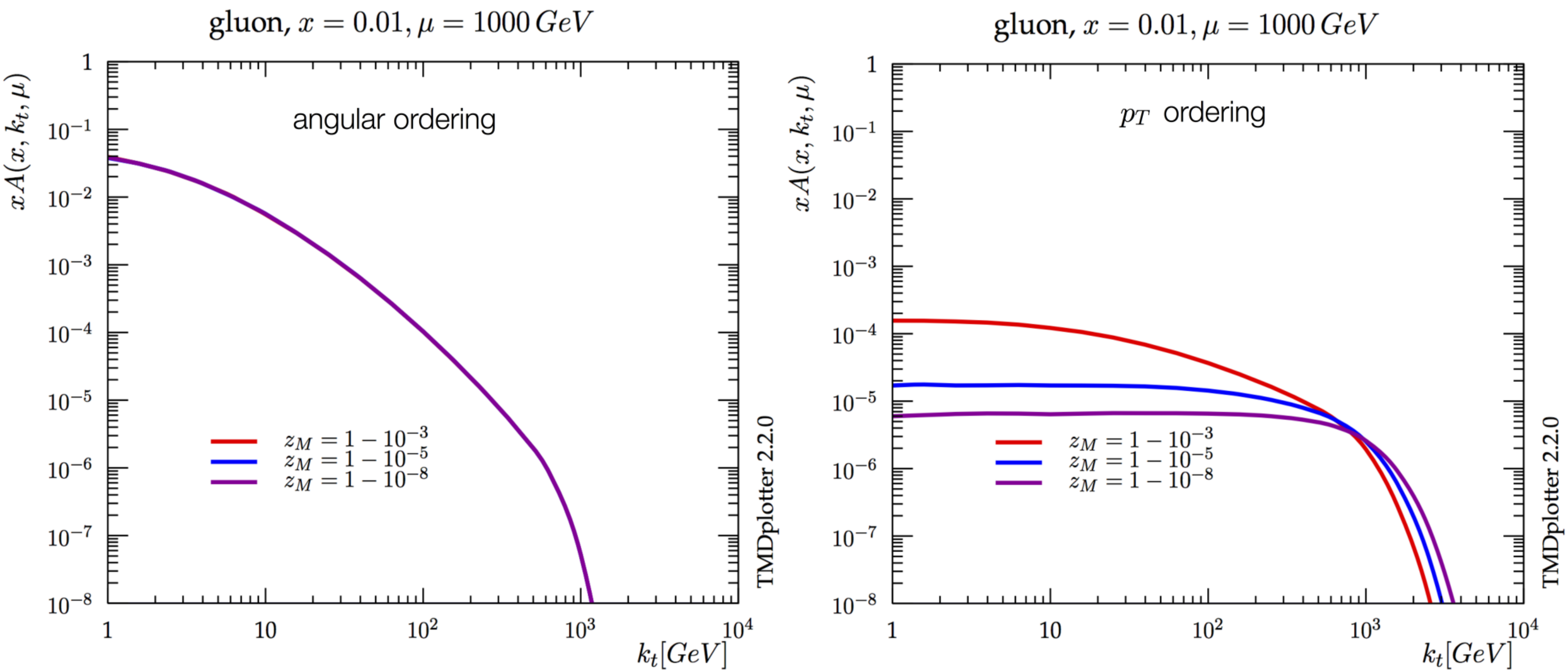
- Give physics interpretation of evolution scale:
  - in high energy limit: p_T -ordering:

    $\mu = q_T$

  - angular ordering:

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

Transverse Momentum: dependence on z_M



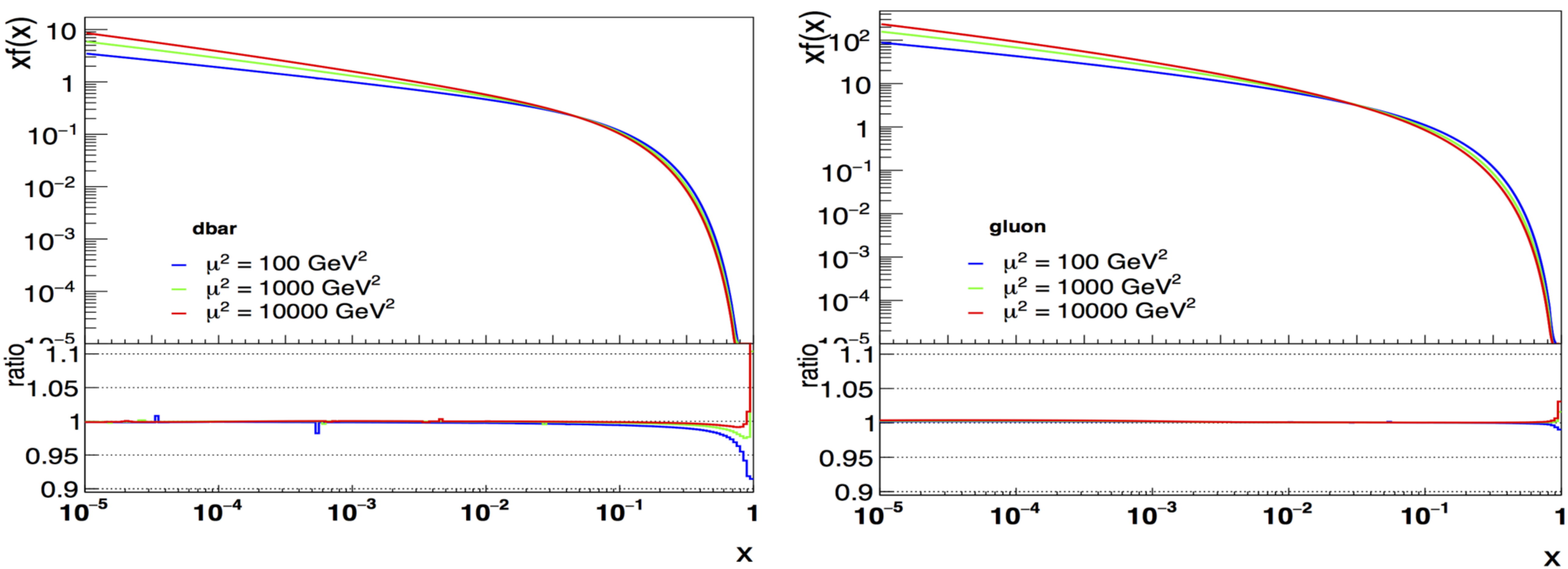
- p_T – ordering ($\mu = q_T$) shows significant dependence on z_M: unstable result because of soft gluon contribution
- angular ordering ($\mu = q_T/(1-z)$) is independent of z_M: stable results since soft gluons are suppressed (angular ordering)

Parton branching method in xFitter

- Convolution of kernel with starting distribution

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

  - kernel defined on grid (for integrated and TMD distribution)
  - validation of method:



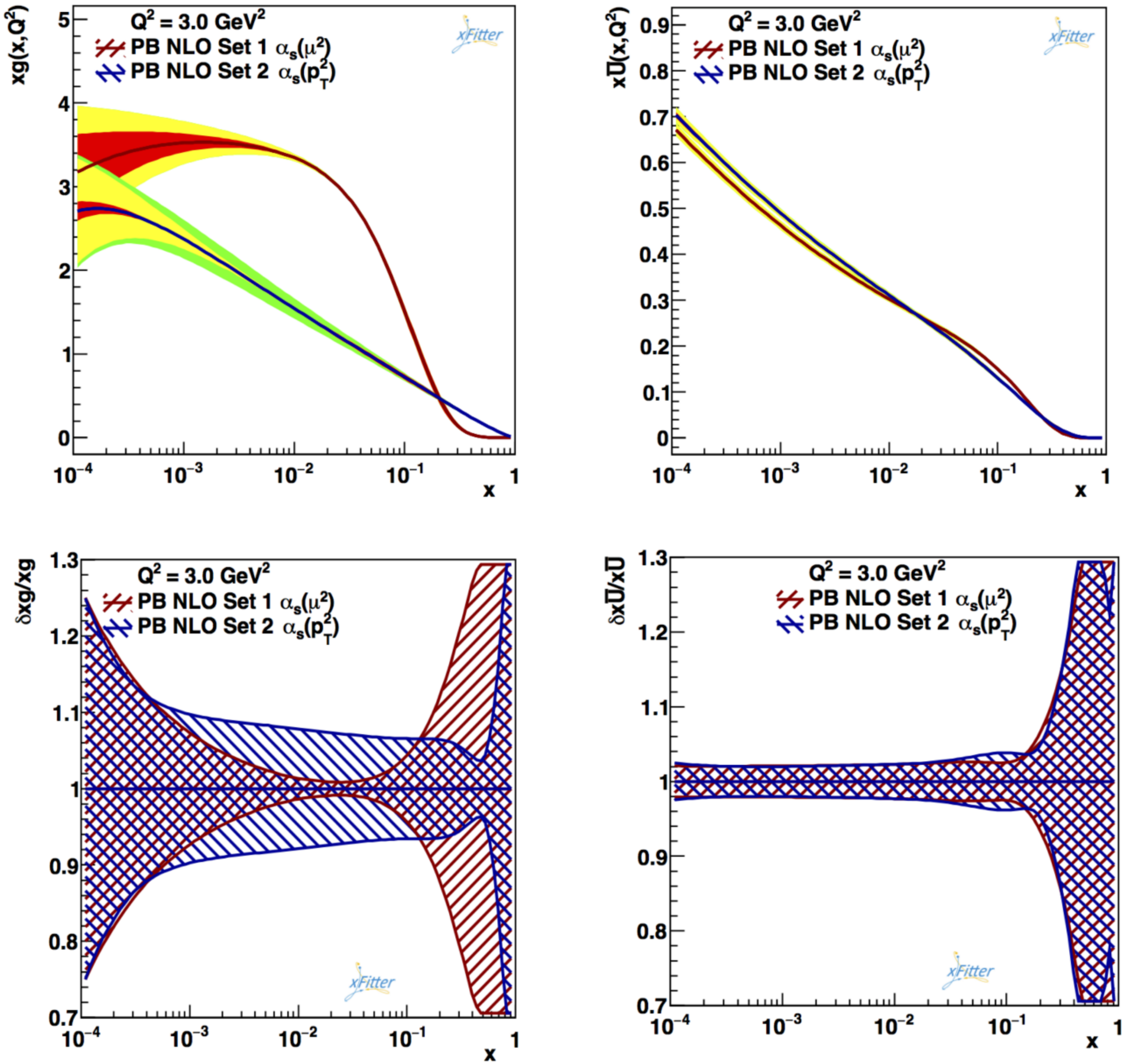
Advantages of parton branching method

- DGLAP equation:

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

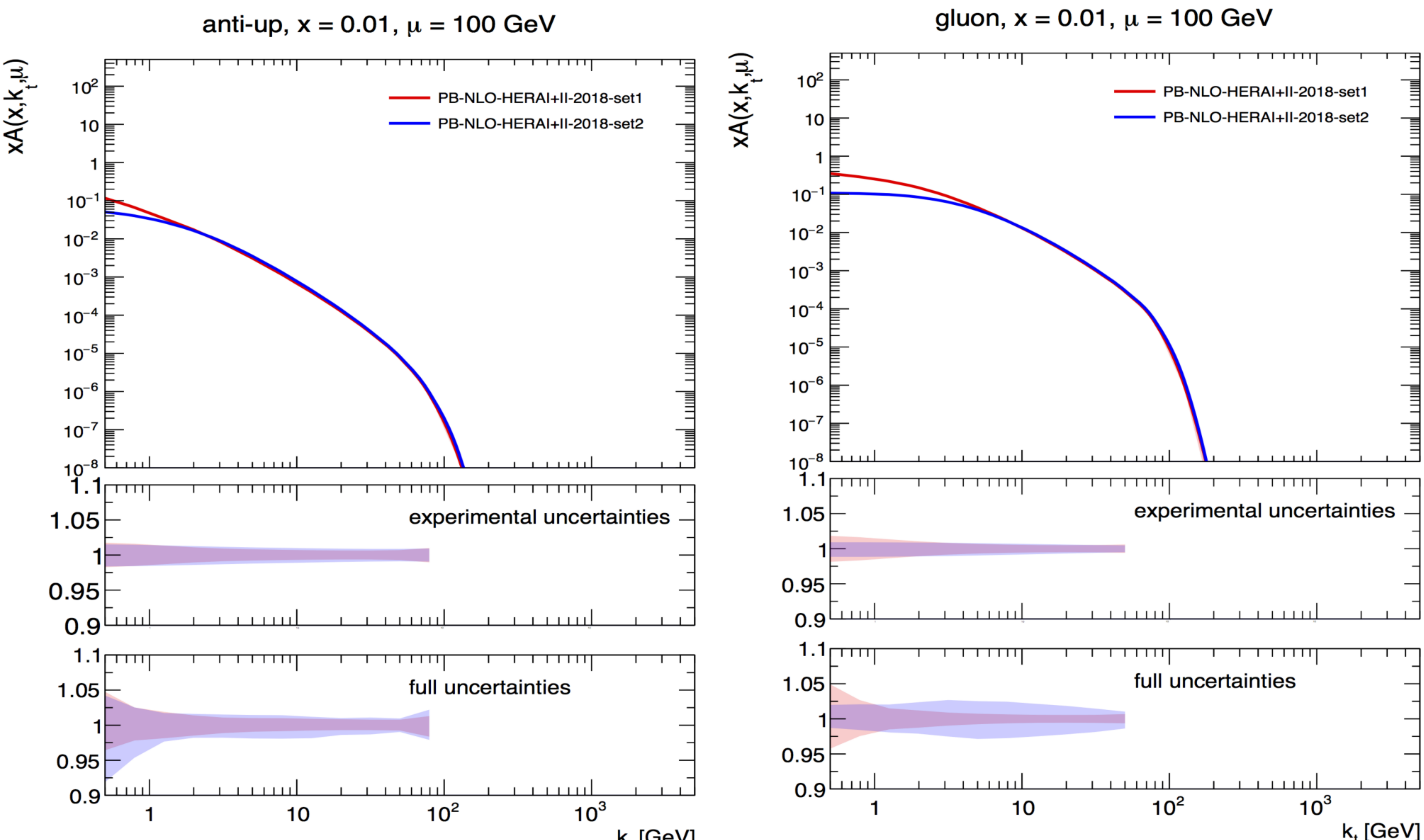
- Advantages of parton branching method for collinear PDFs:
  - access to all kinematic variables and combinations between them
    - full freedom of choosing:
      - renormalisation scale: $\alpha_s(\mu_r)$
      - evolution scale: μ_f
  - studies of different ordering conditions possible for the first time
    - angular ordering with $\alpha_s(q)$
    - but angular ordering suggests that renormalization scale is p_T and not angle
      - angular ordering with $\alpha_s(p_T) \rightarrow \alpha_s(q(1-z))$
      - repeat fits with changed renormalisation scale in pdf (but not yet in coefficient fct)

Fit with changed $\alpha_s(p_T)$: at small Q^2



- 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

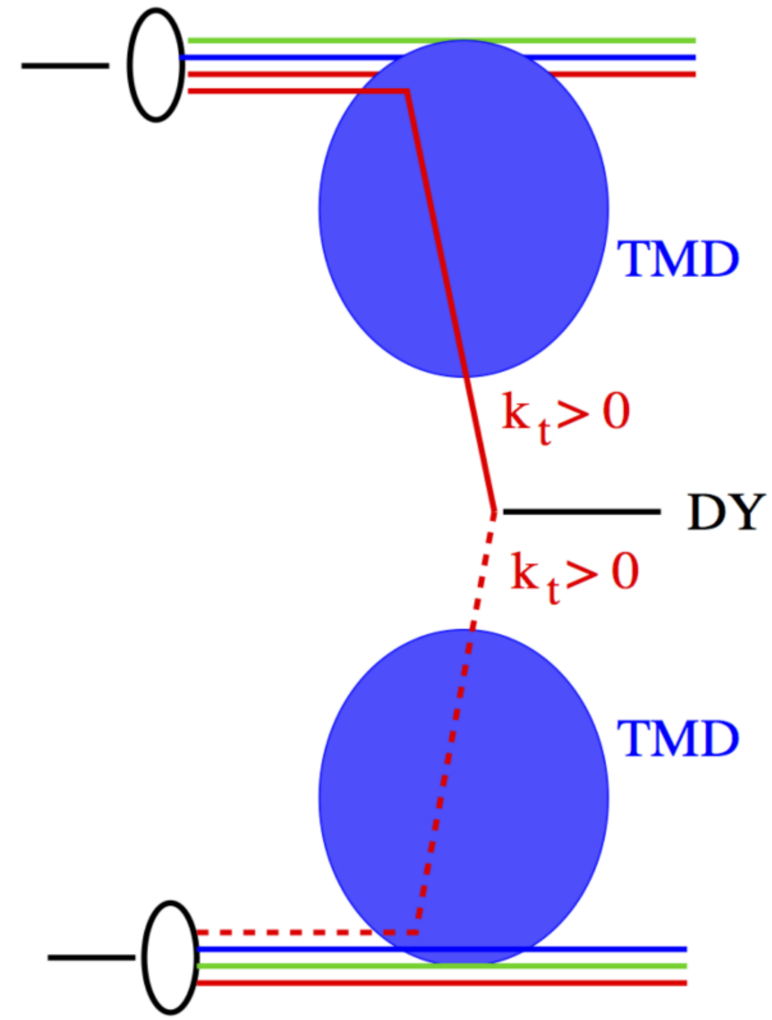
TMD distributions



- model dependence larger than experimental uncertainties

Application to DY q_T - spectrum

- Use LO 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



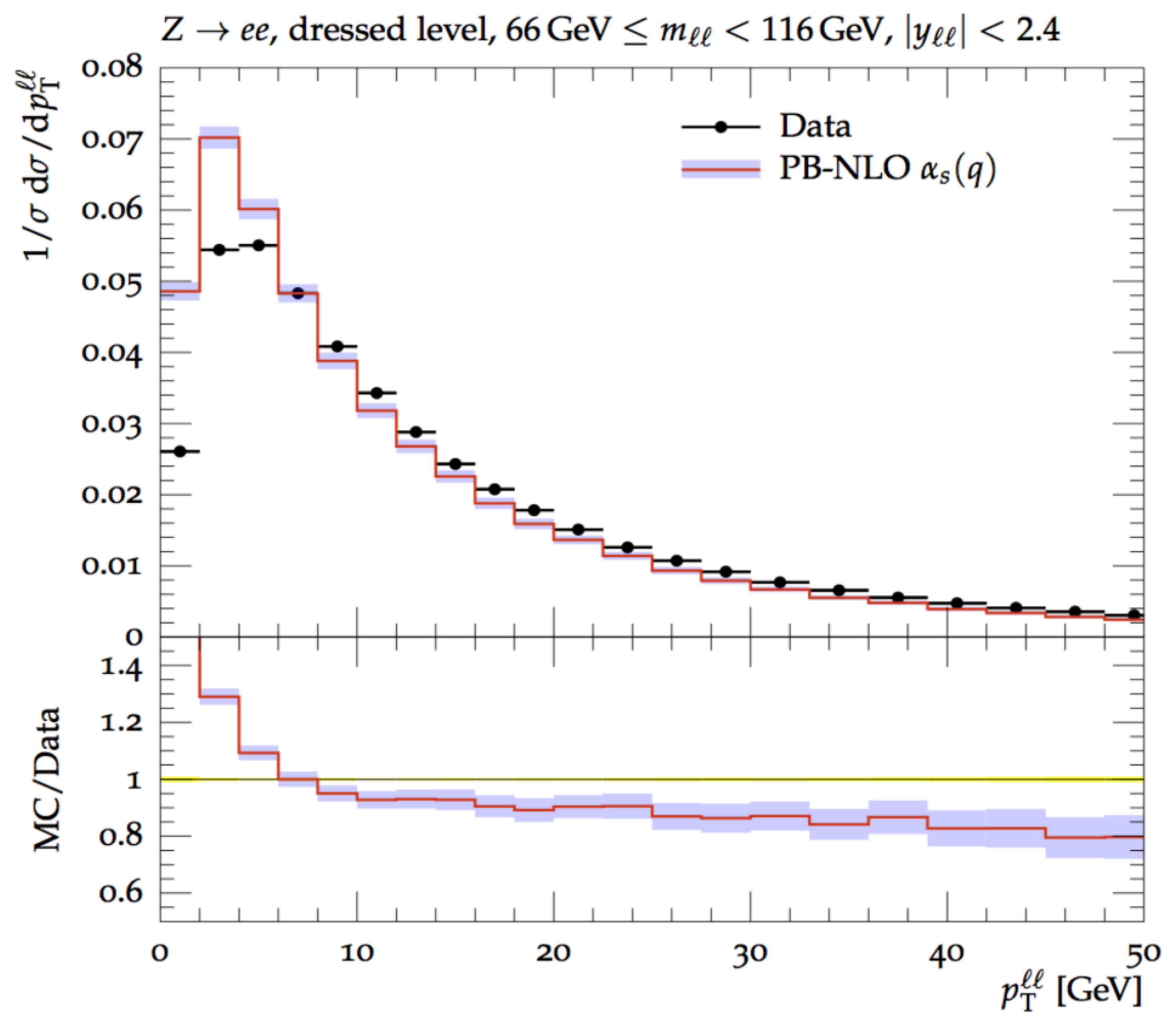
Application to DY q_T - spectrum

- Use LO DY production

$$q\bar{q} \to Z_0$$

- TMD with angular ordering including $\alpha_s(q)$

ATLAS Collaboration Eur. Phys. J. C76 (2016), 291 [arXiv:1512.02192



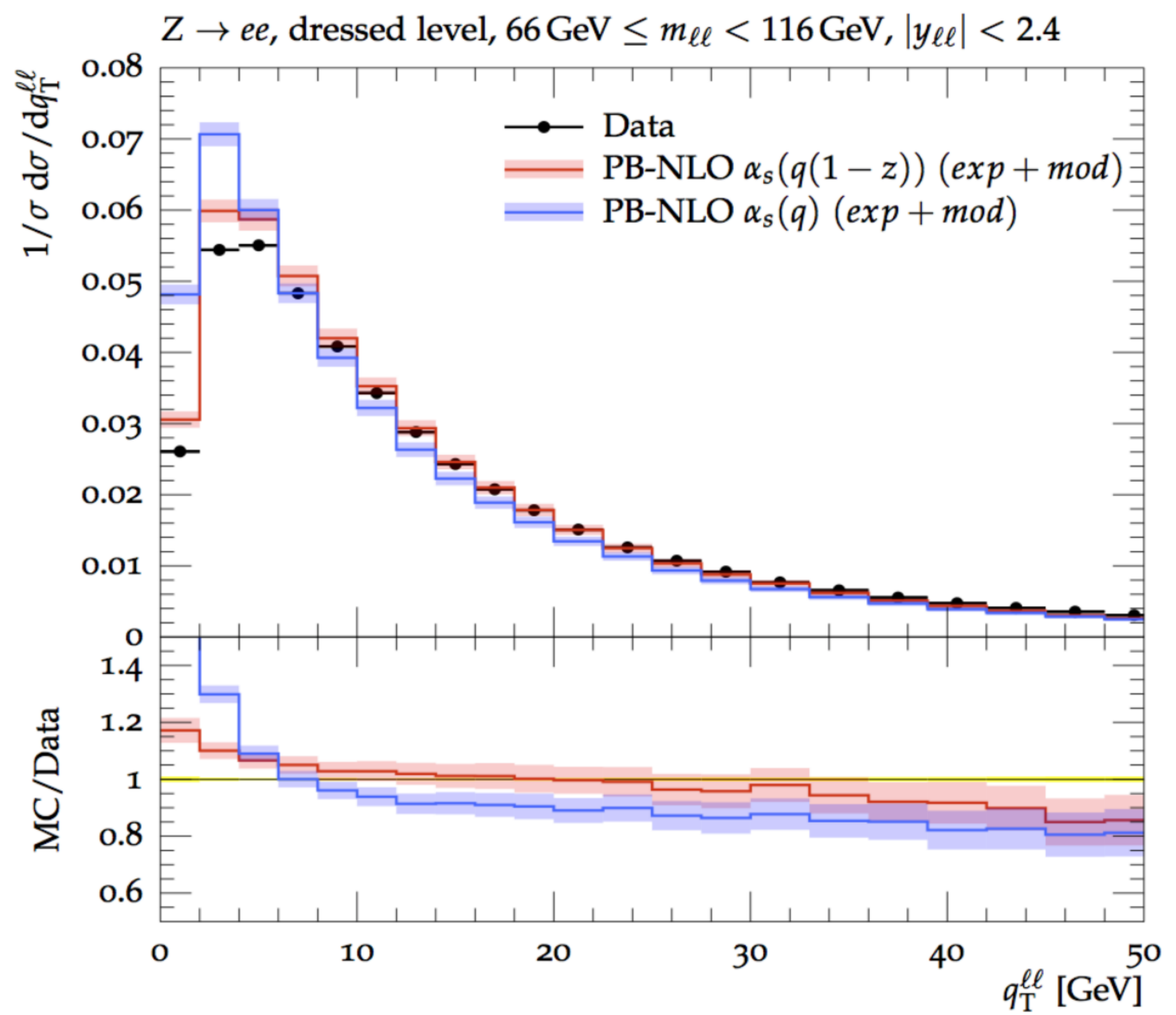
Application to DY q_T - spectrum

- Use LO DY production

$$q\bar{q} \to Z_0$$

- TMD with angular ordering including $\alpha_s(q)$
- TMD with angular ordering including $\alpha_s(p_T)$
  - in low p_T much better !

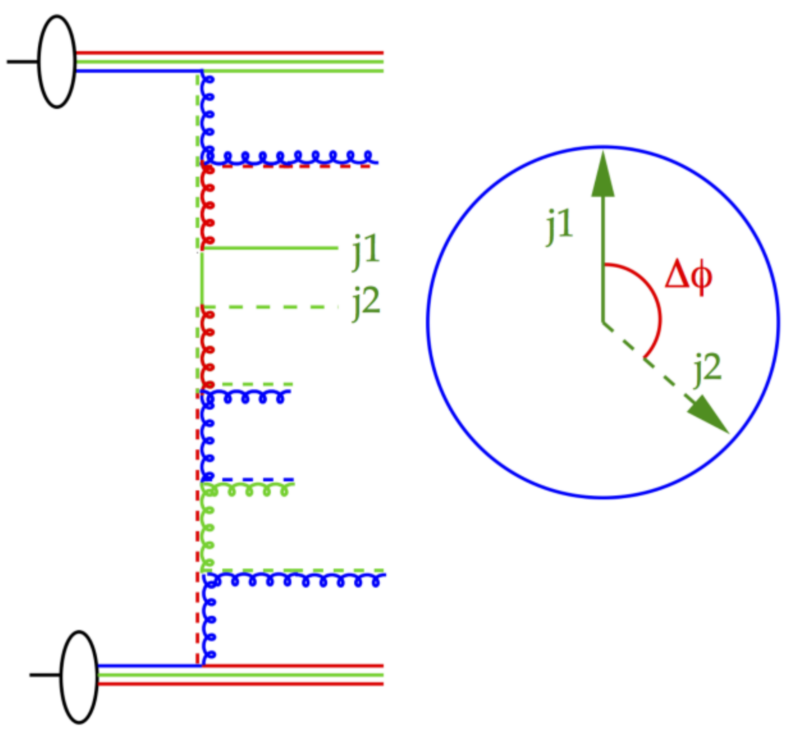
ATLAS Collaboration Eur. Phys. J. C76 (2016), 291 [arXiv:1512.02192]

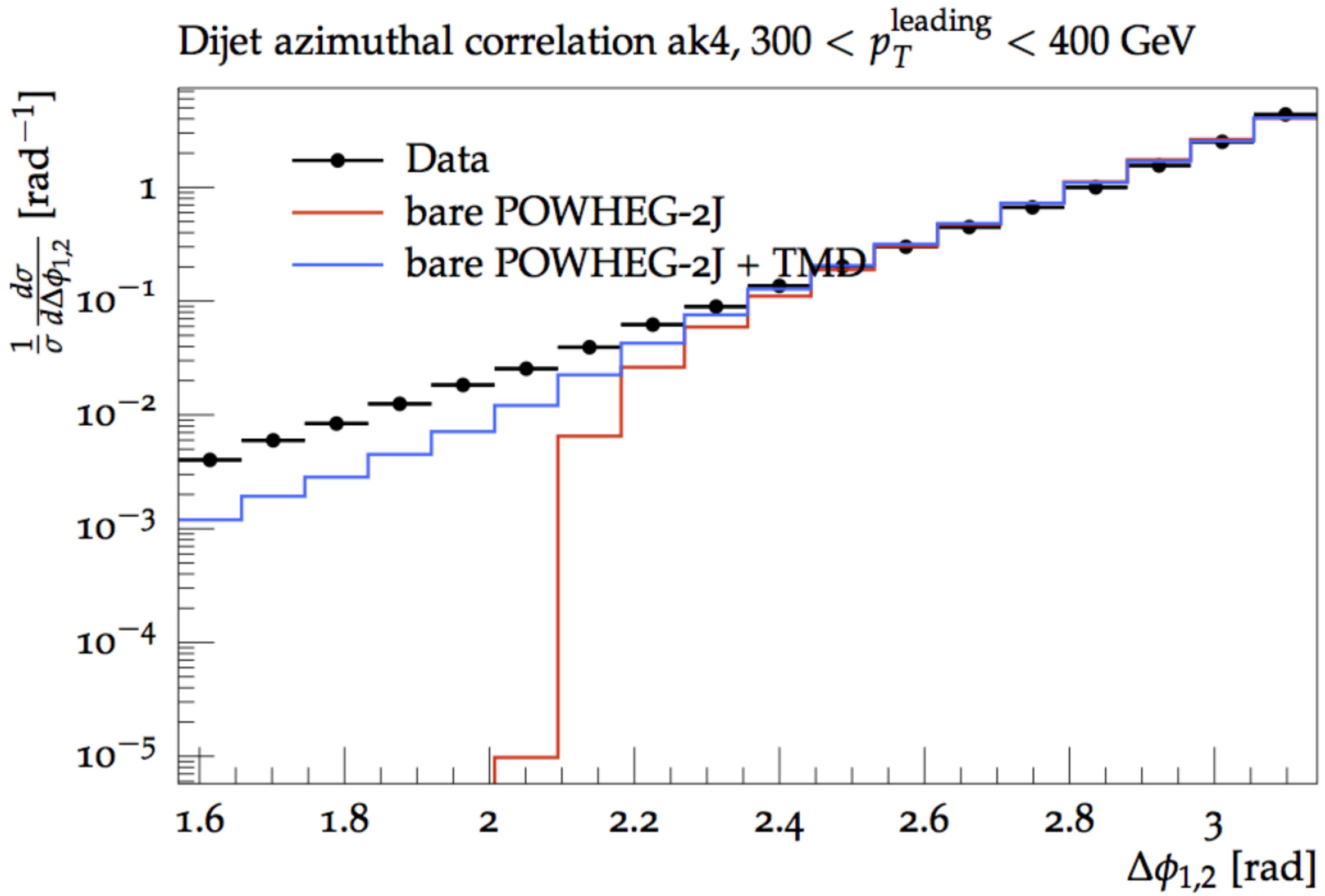


- Additional issues:
  - resolvable branching
  - freeze α_s
  - intrinsic k_T

Application to high p_T dijets in pp

- Dijet production at in pp, a test for TMDs and PS :

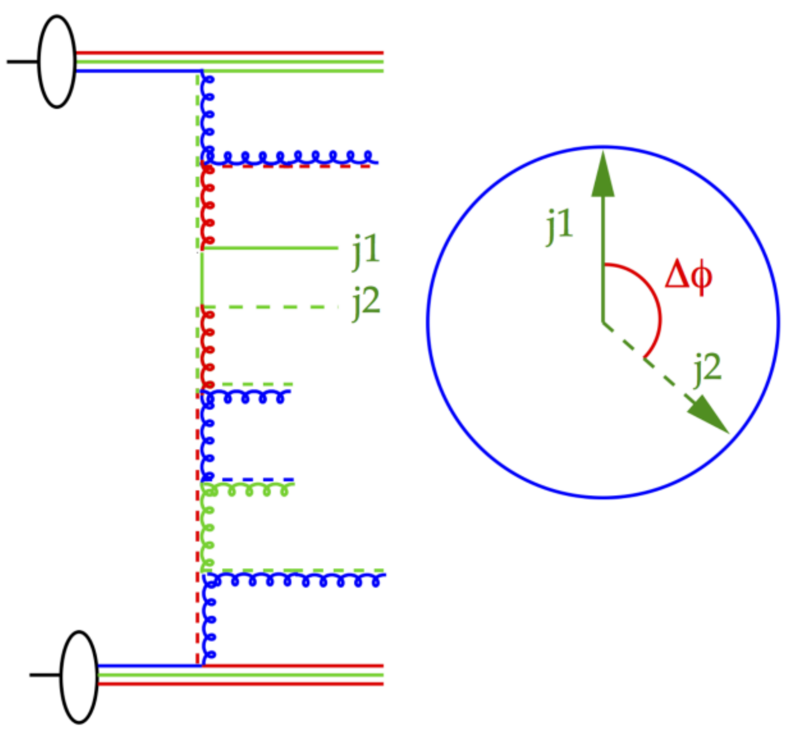


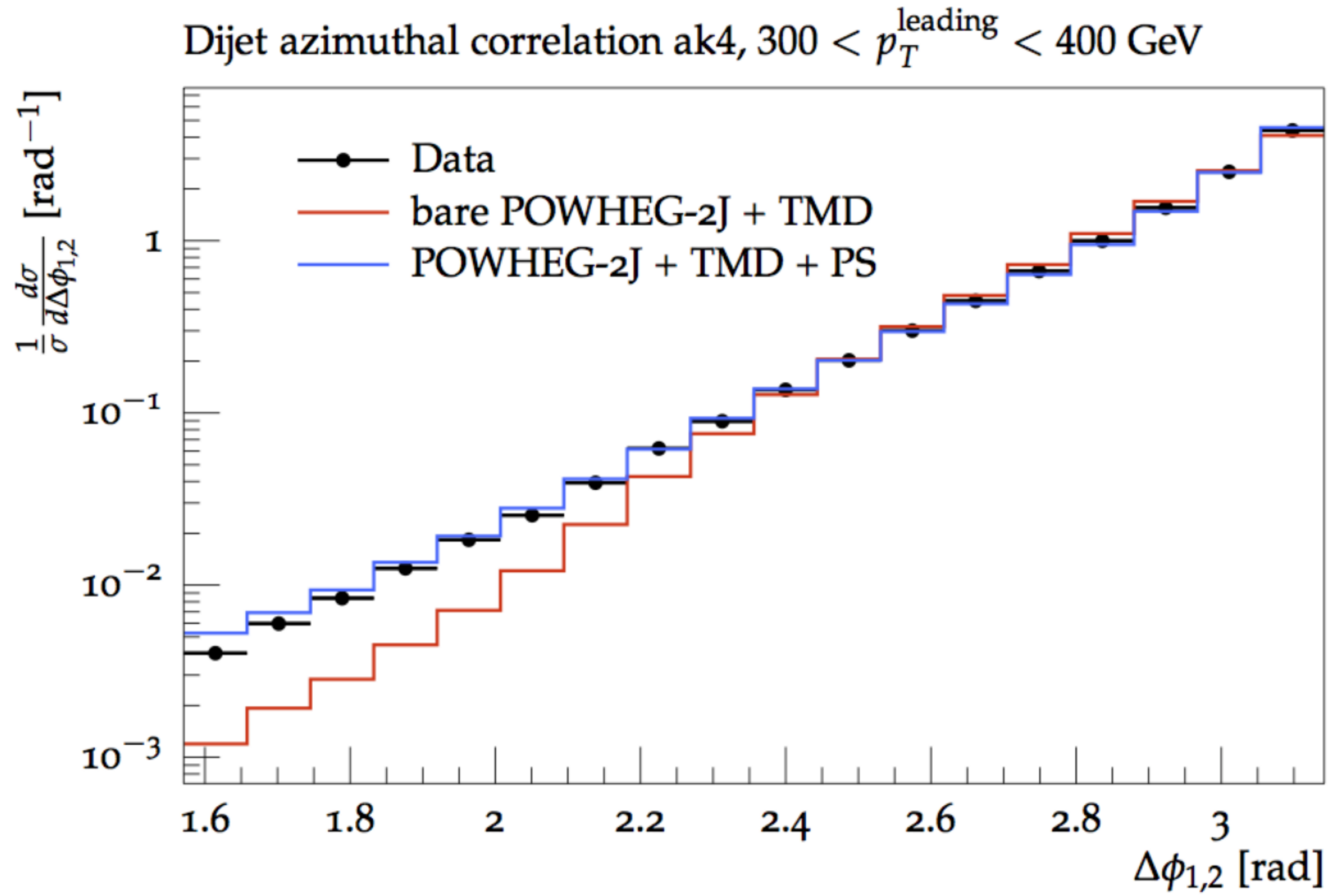


- TMDs with NLO dijets get closer to data !

Application to high p_T dijets in pp

- Dijet production at in pp, a test for TMDs and PS :

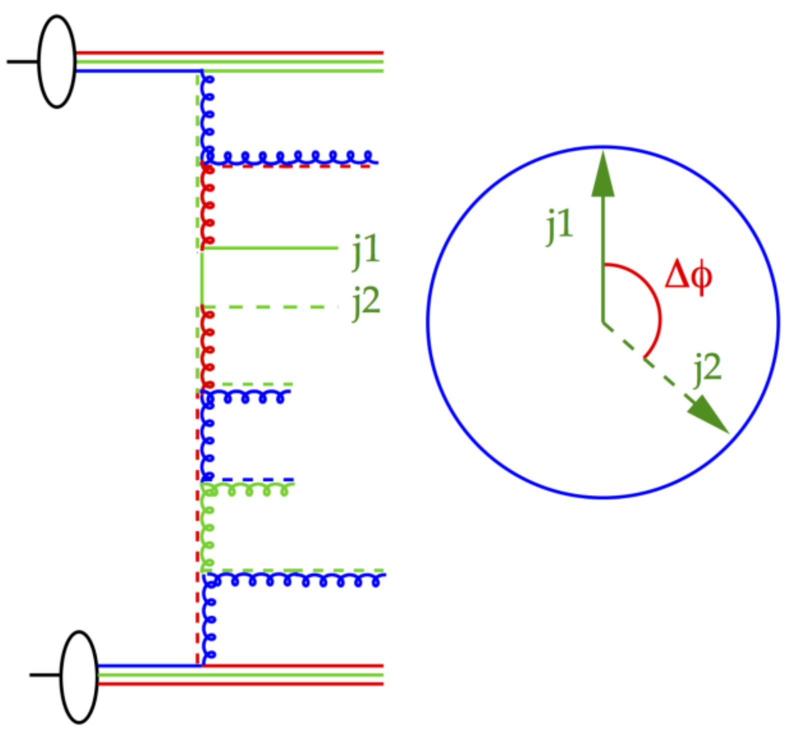


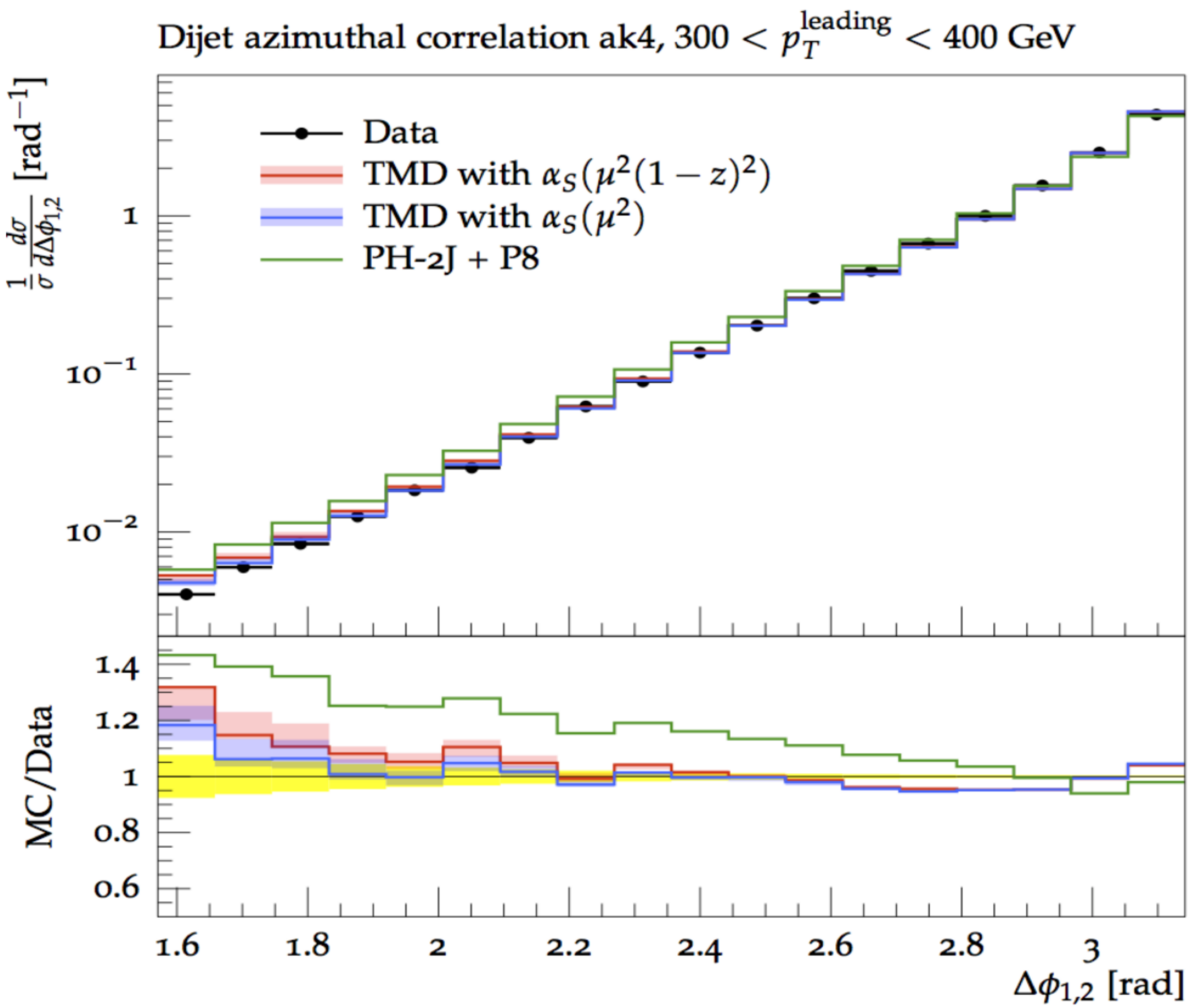


- TMDs with NLO dijets + parton shower (following TMD) describes data!

Application to high p_T dijets in pp

- Dijet production at in pp, a test for TMDs and PS :





- TMDs with NLO dijets + parton shower (following TMD) describes data!
  - different TMD sets are very similar
- TMD + NLO dijets + PS → better than conventional treatment !

Conclusion

- Parton Branching method to solve DGLAP equation at LO, NLO and NNLO
  - ➔ consistence for collinear (integrated) PDFs shown
  - ➔ advantages of Parton Branching method !

- method directly applicable to determine k_t distribution (as would be done in PS)
  - ➔ TMD distributions for all flavors determined at LO and NLO, without free parameters
  - ➔ TMD evolution implemented in xFitter – fits to DIS processes at the moment

- Application for pp, ep processes, like DY, jets:
  - ➔ DY q_T - spectrum without new parameters
  - ➔ TMD initial parton shower:
    - ➔ backward evolution following exactly the TMD density
    - ➔ dijet $\Delta\,\phi$ very well described with NLO dijets + TMD + TMD shower

Appendix

Where to find TMDs ? TMDlib and TMDplotter

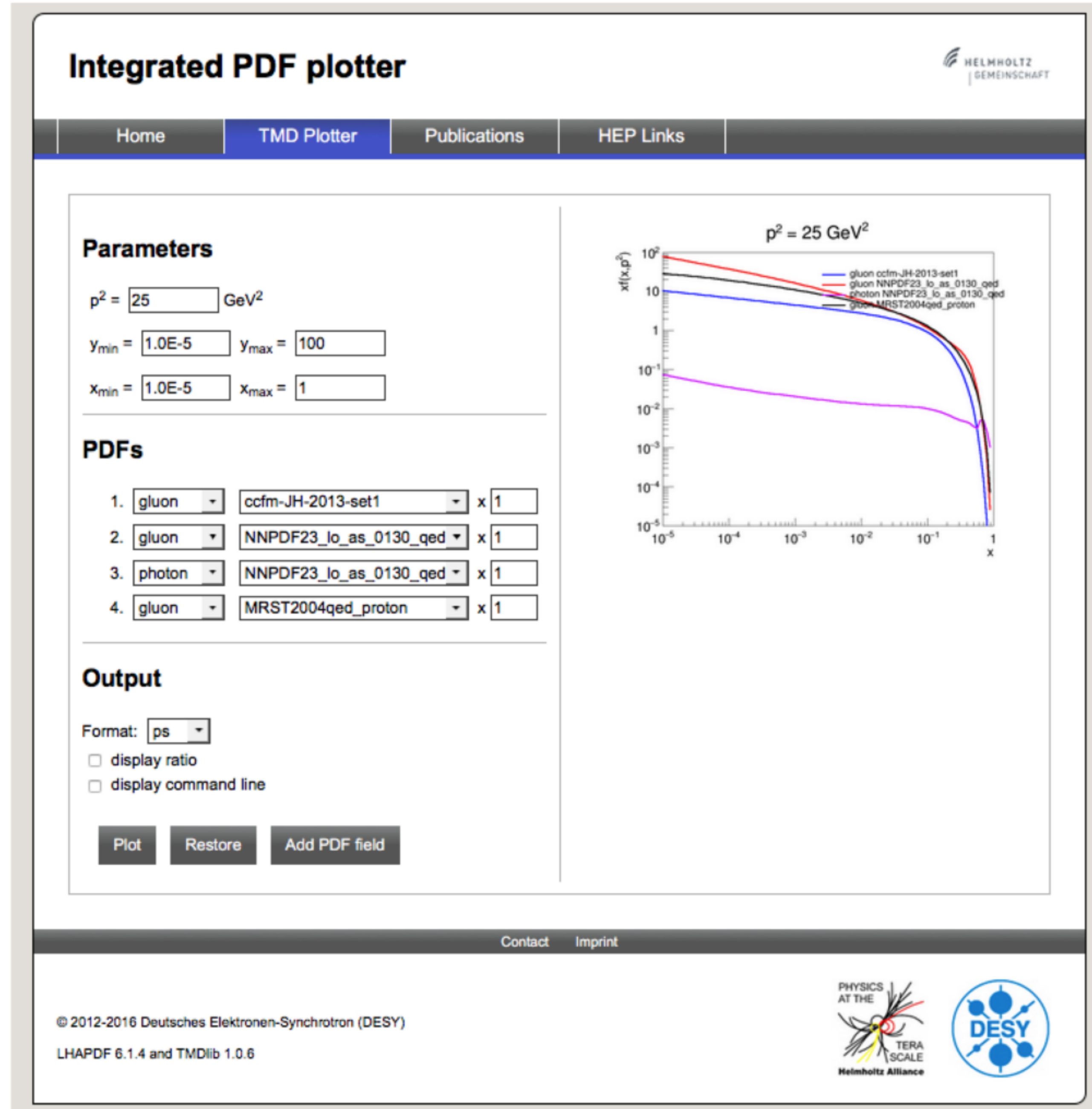
- TMDlib proposed in 2014 as part of REF workshop and developed since
- combine and collect different ansaetze and approaches:

  http://tmd.hepforge.org/ and
  http://tmdplotter.desy.de

→ TMDlib: a library of parametrization of different TMDs and uPDFs (similar to LHApdf)

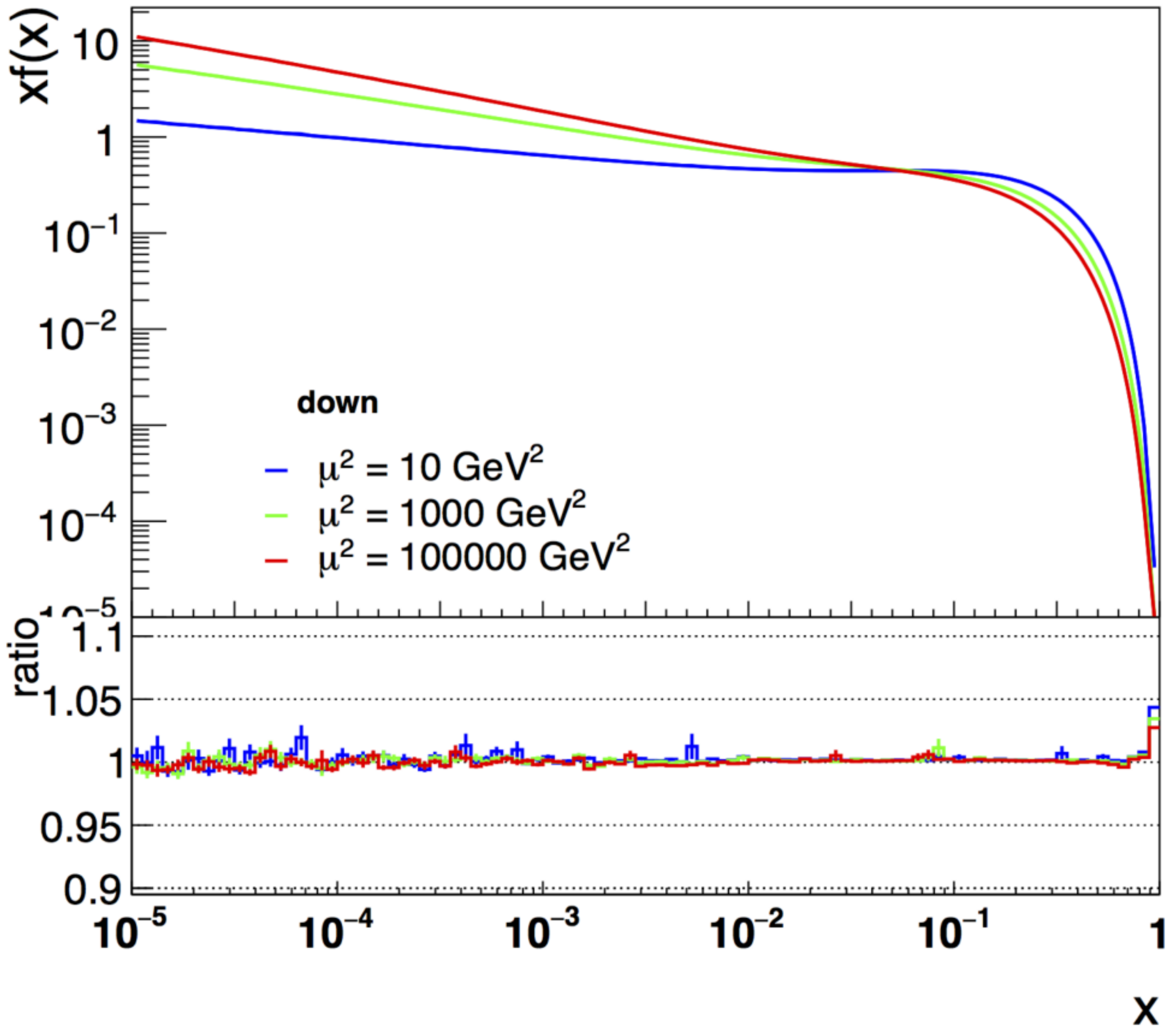
TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions, *F. Hautmann et al.* arXiv 1408.3015, **Eur. Phys. J., C 74(12):3220, 2014.**

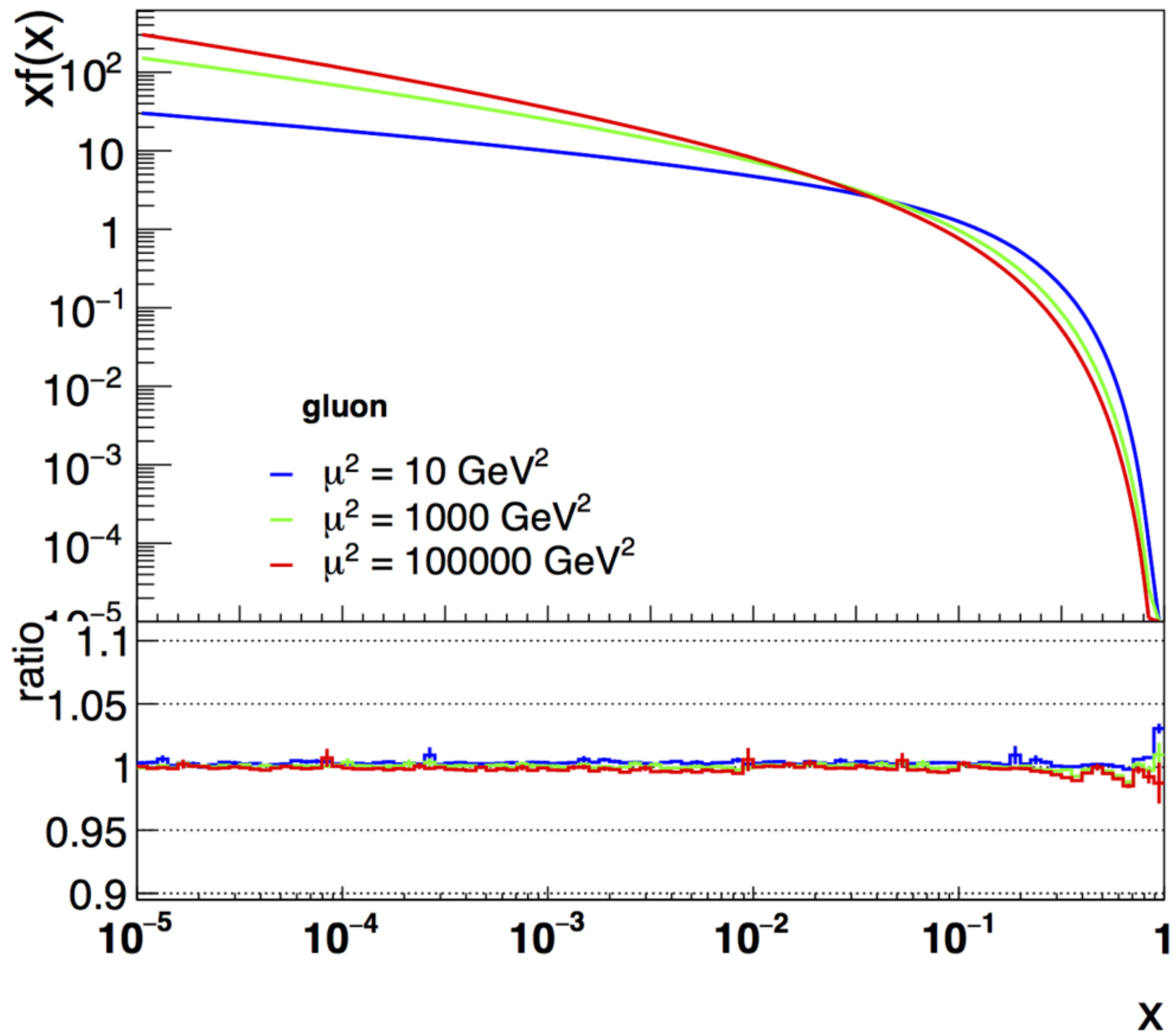
→ Also integrated pdfs (including photon pdf are available via LHAPDF)



- Feedback and comments from community is needed – just use it !

Validation of method with QCDnum at NLO

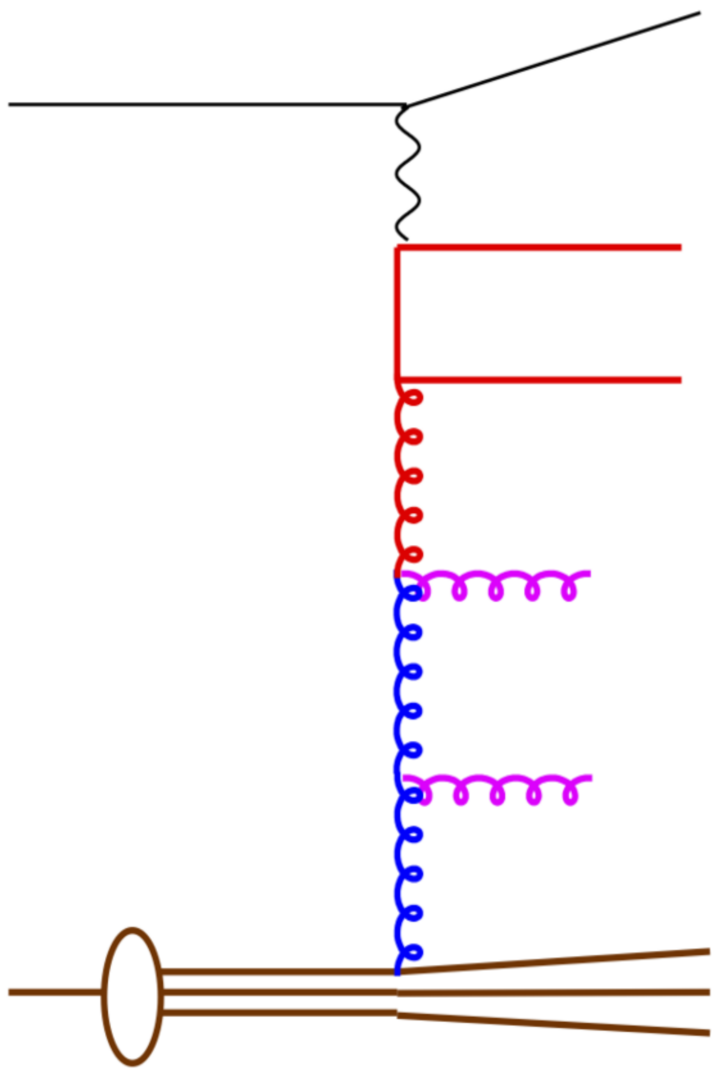




- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach work also at NNLO !

MCEG: TMDs, parton shower

- basic elements are:
  - Matrix Elements:
    - ➔ on shell/off shell
  - PDFs
    - ➔ TMDs
  - Parton Shower
    - ➔ following TMDs for initial state !
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA



- Parton shower with TMDs follows exactly the evolution of the TMD
  - no (!) free parameter in shower
  - resolvable branchings and calculation of k_T defined in TMD
  - no adjustment of kinematics during/after shower