TMD parton densities from Parton Branching method and applications

Hannes Jung (DESY)
in collaboration with
A. Bermudez-Martinez, P. Connor, F. Hautmann, A. Lelek, V. Radescu, R. Zlebcik

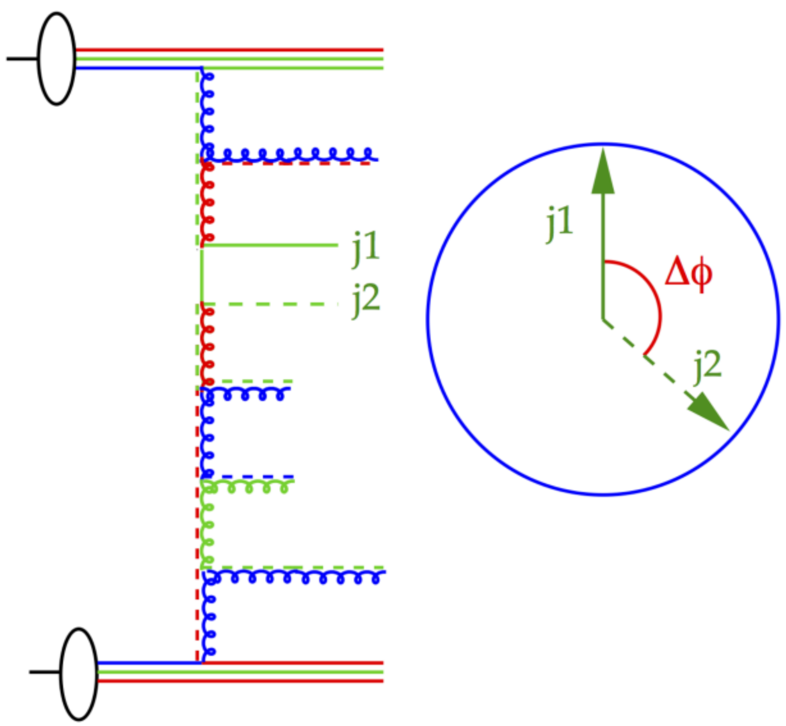
- Why TMDs are needed
  - TMDs for hadron-hadron collisions
- New developments
  - parton branching algorithm to solve evolution equations
    - benchmark tests
    - advantages for integrated PDFs
  - determination of TMD densities at NLO from HERA DIS data
- Application to DY production and high p_T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

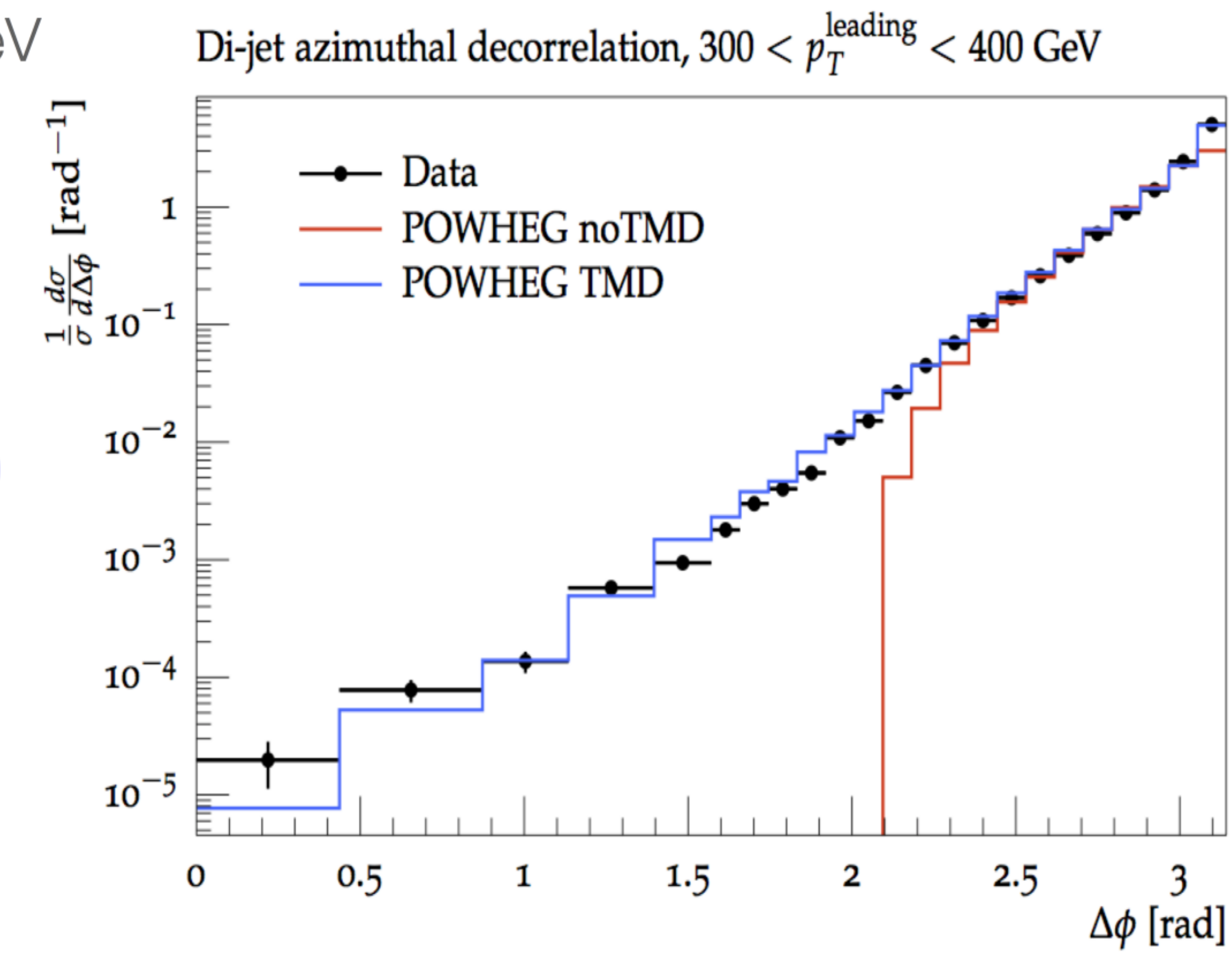
TMD – what is it ?

- 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 – unintegrated PDFs
    - essentially only gluon densities (CCFM, BFKL etc)
  - new approach: Parton Branching Method
    - cover all transverse momenta from small k_t to large k_t as well a large range in x and μ^2

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

- New: 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
      - advantages of Parton Branching Method

  - determine TMD:
    - since each branching is generated explicitly, energy-momentum conservation is fulfilled and transverse momentum distributions can be obtained

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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

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 re-sums leading logs...

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

- solve integral equation via iteration:

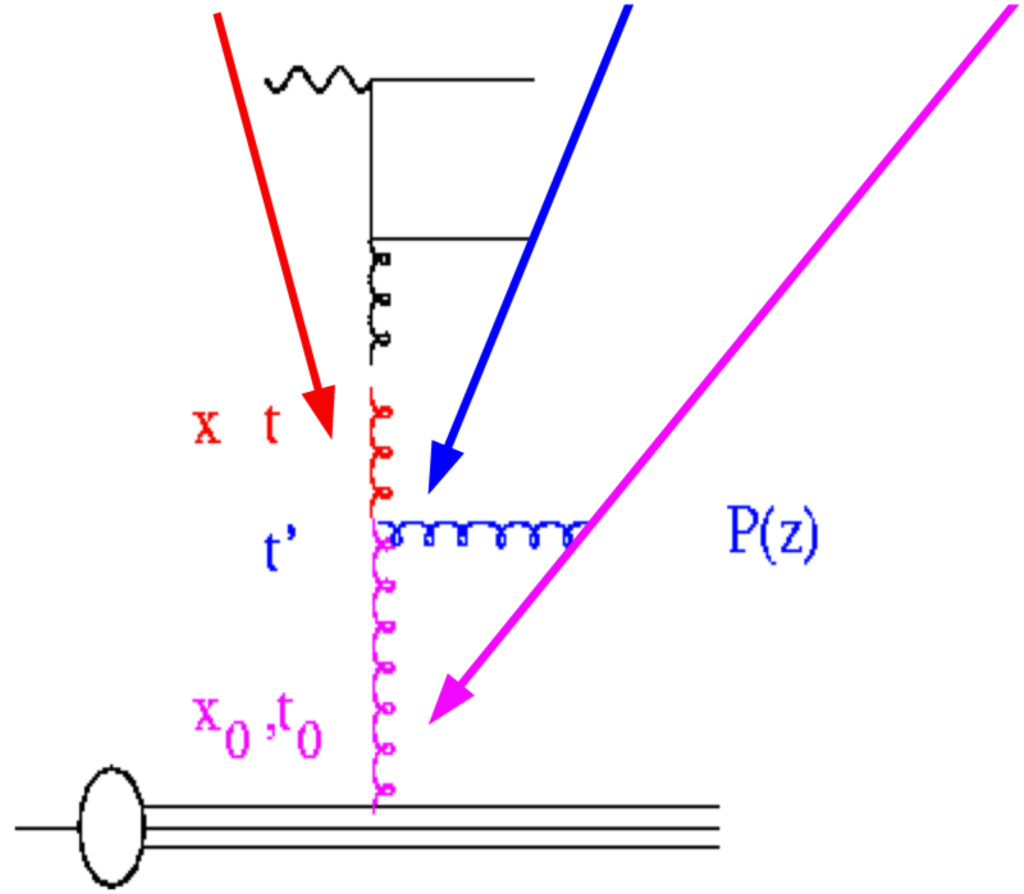
from t' to t w/o branching

branching at t'

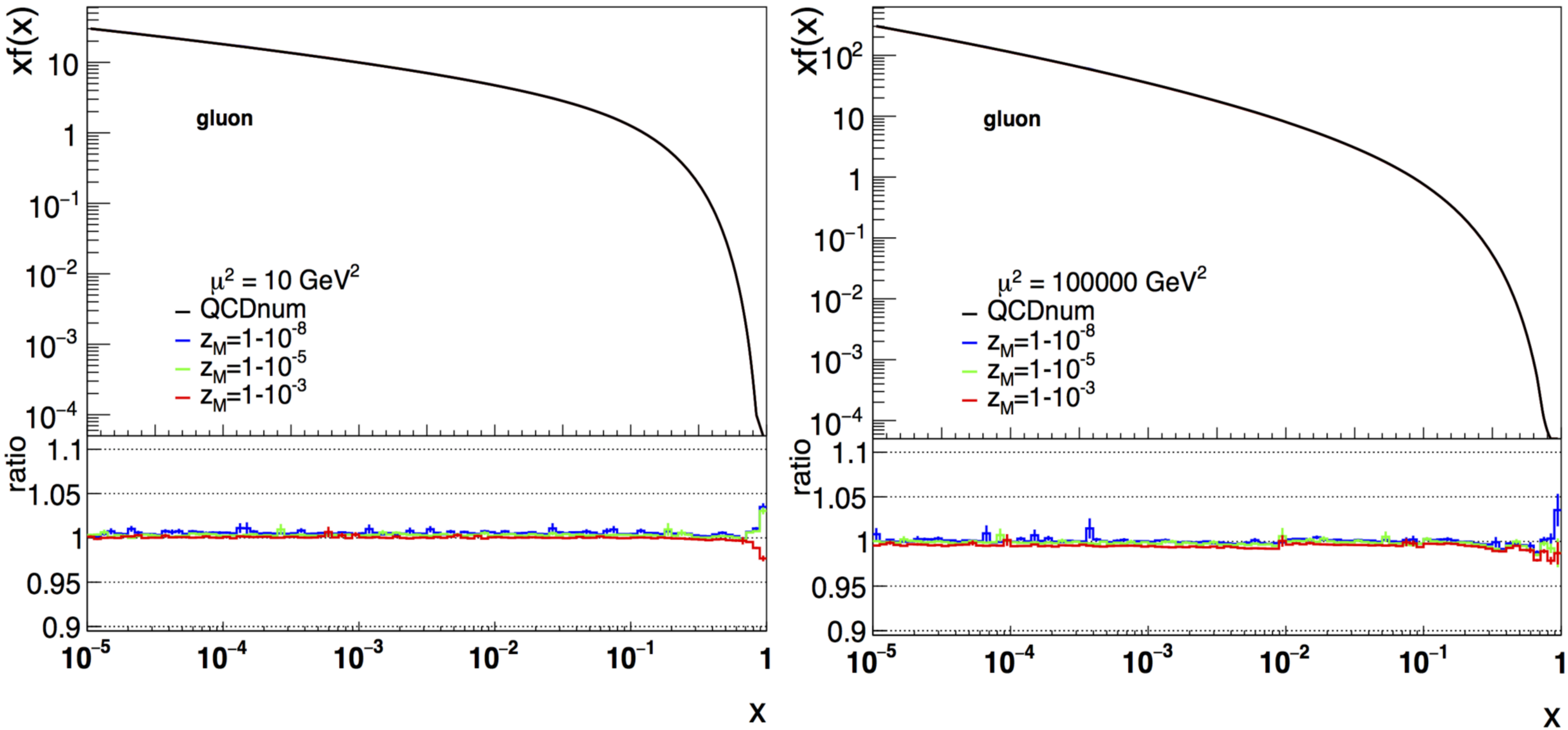
from t_0 to t' w/o branching

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

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



Validation of method at NLO: z_M - dependence



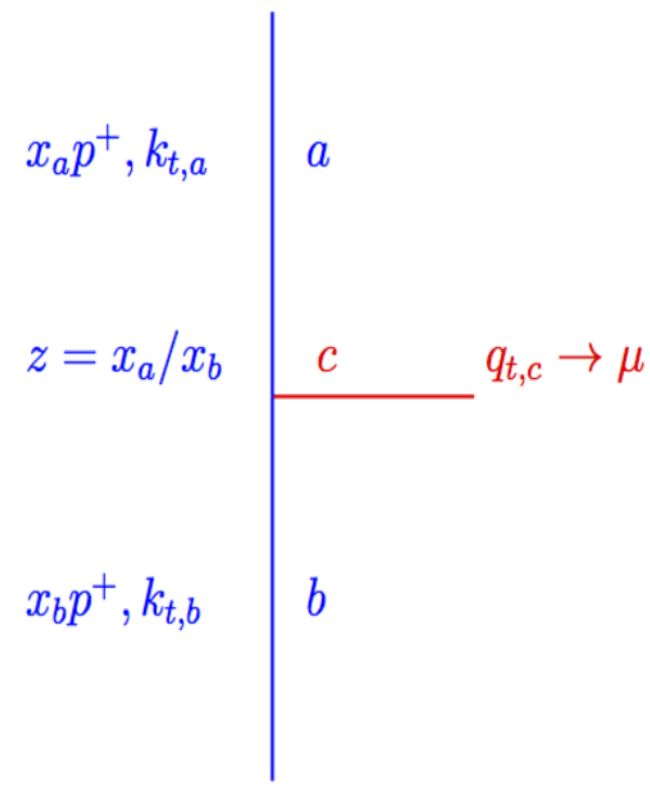
- No dependence on z_M if z_M is large enough:
  - approximation is of $\mathcal{O}(1 - z_M)$
- Very good agreement with NLO - QCDnum

Transverse Momentum Dependence

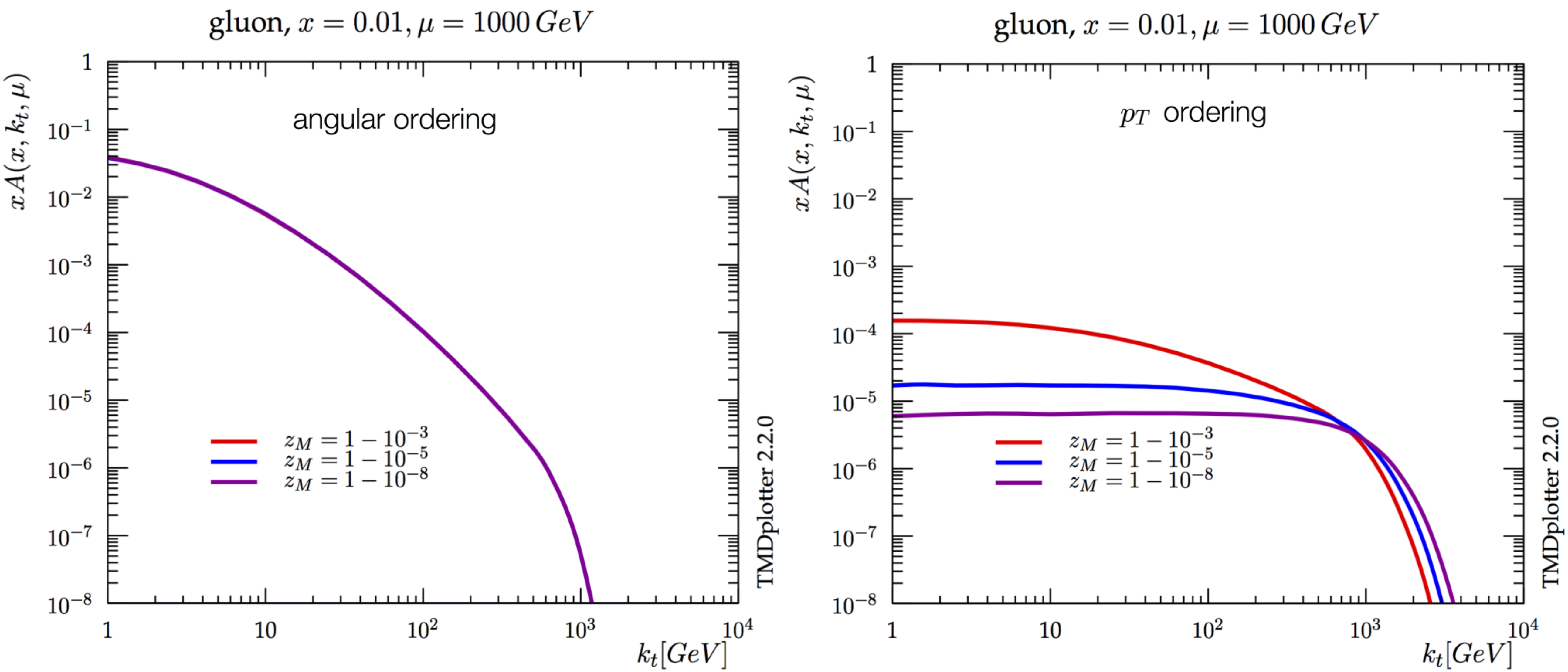
- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step
- Give physics interpretation of evolution scale:
  - in high energy limit: p_T -ordering:

    $\mu = q_T$
  - angular ordering:

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



Transverse Momentum: 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 (angular ordering)

PDFs from Parton Branching method: fit to HERA data

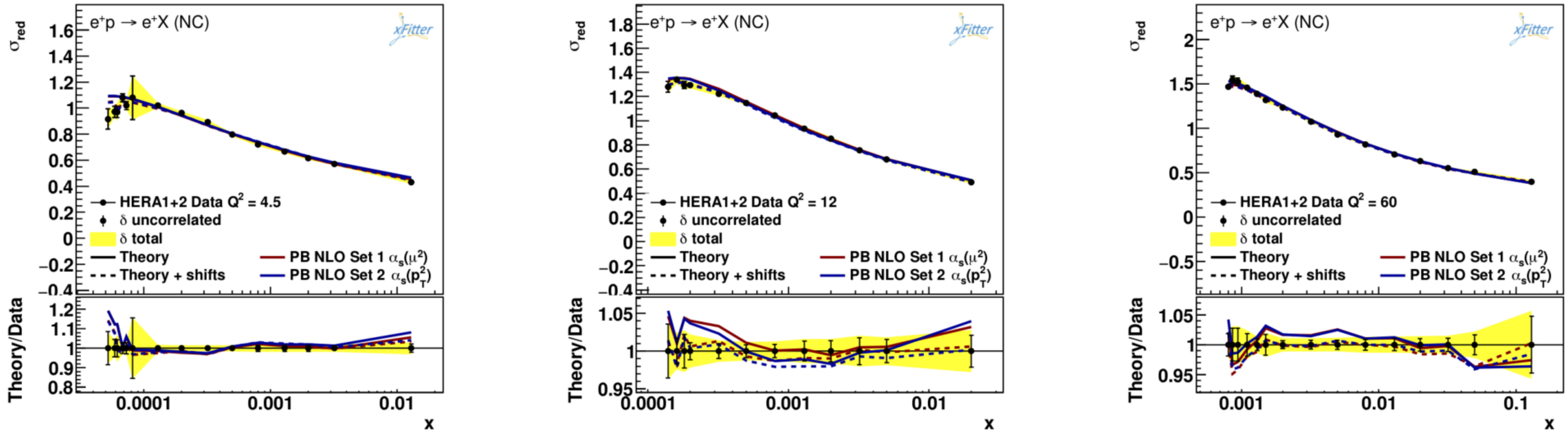
- Convolution of kernel with starting distribution

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

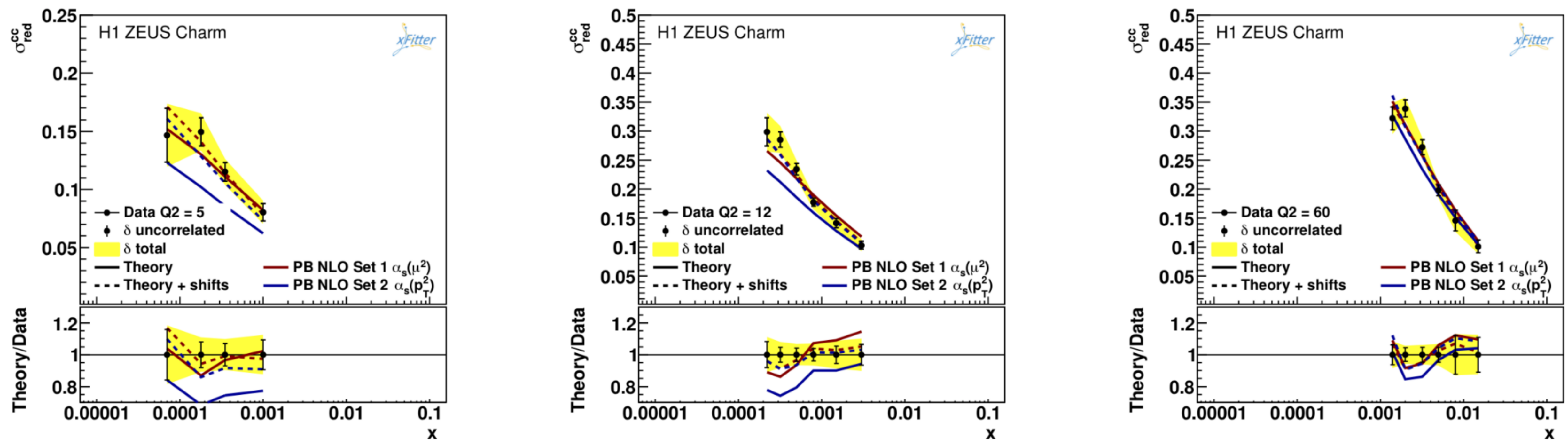
- NLO fit to combined HERA 1+2 inclusive DIS (neutral current, charged current) data
  - with in total 1145 data points
    - $3.5 < Q^2 < 50000 \text{ GeV}^2$
    - $4 \cdot 10^{-5} < x < 0.65$
    - using starting distribution as in HERAPDF2.0
    - $\chi^2/ndf = 1.2$
    - using `xFitter` frame
    - ➔ collinear PDFs and TMDs from PB method with full experimental and model dependent systematic uncertainties

Fit to DIS structure functions: F_2 and F_2^c

Inclusive DIS

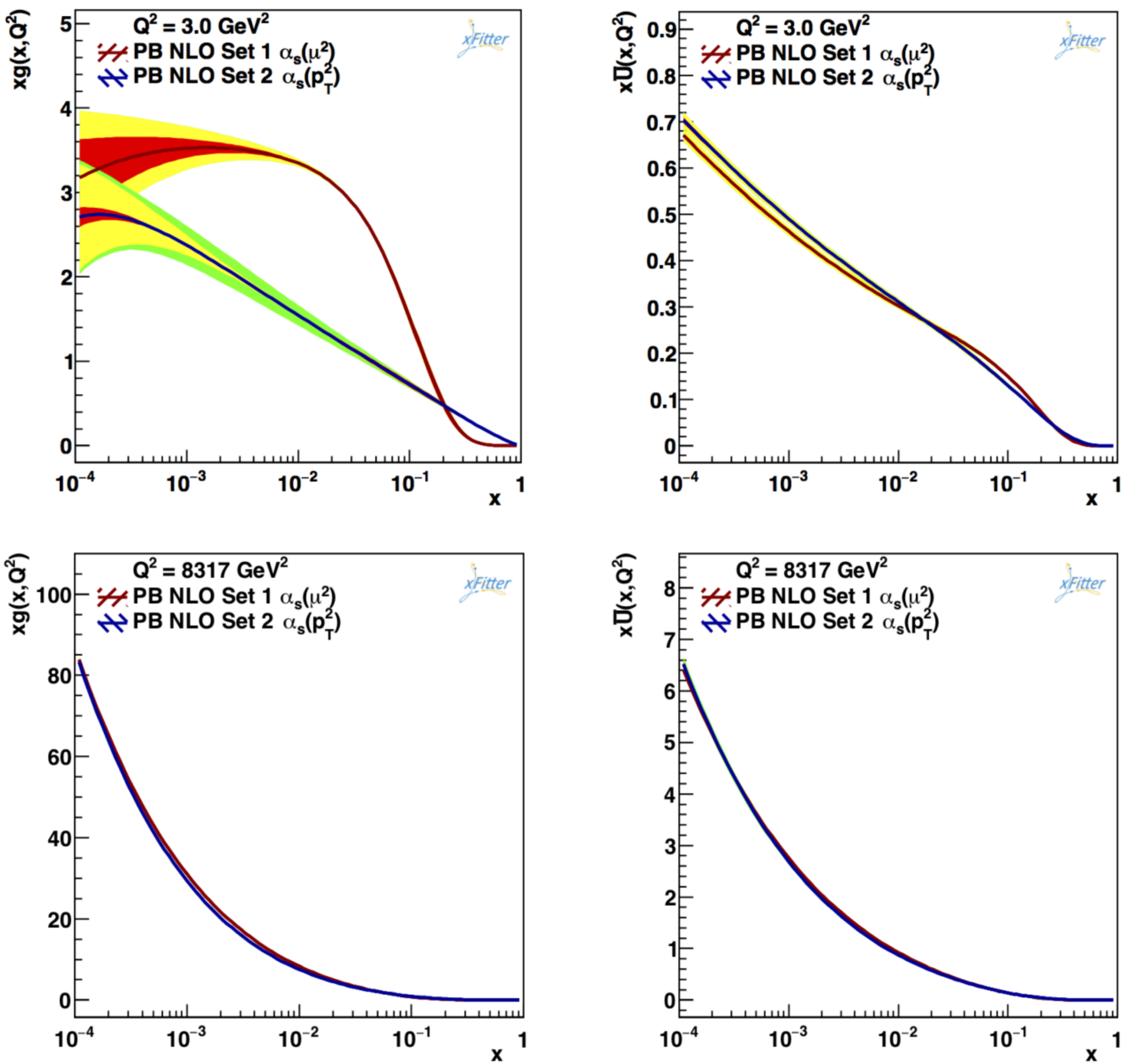


Inclusive Charm DIS



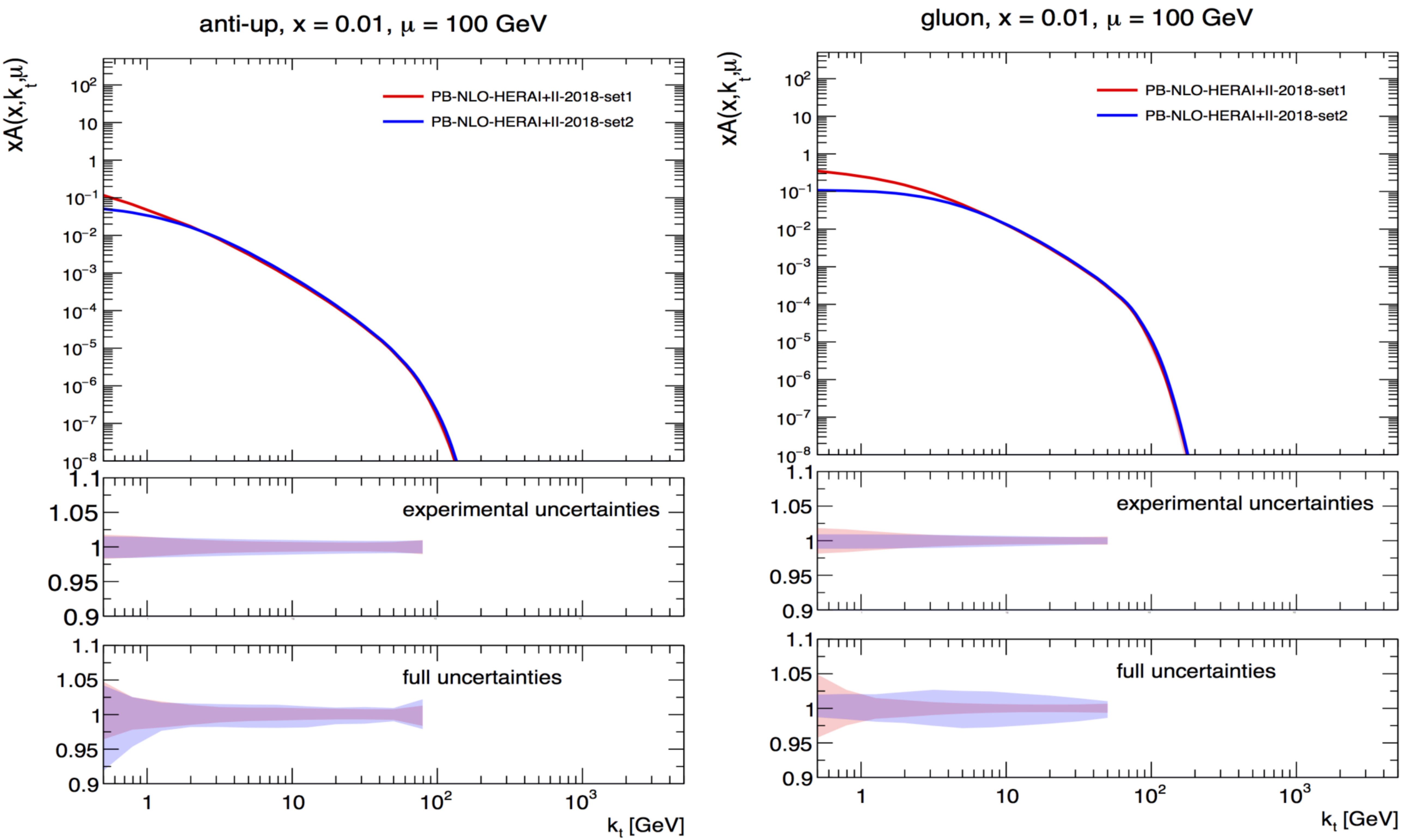
1145 inclusive DIS data points fitted with $\chi^2/ndf = 1.2$

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 $\alpha_s(q(1-z))$
  - $\chi^2/ndf = 1.21$
- uncertainties:
  - experimental
  - starting scale
  - heavy quark masses
- gluon distribution at small Q^2 depend on scale choice in α_s

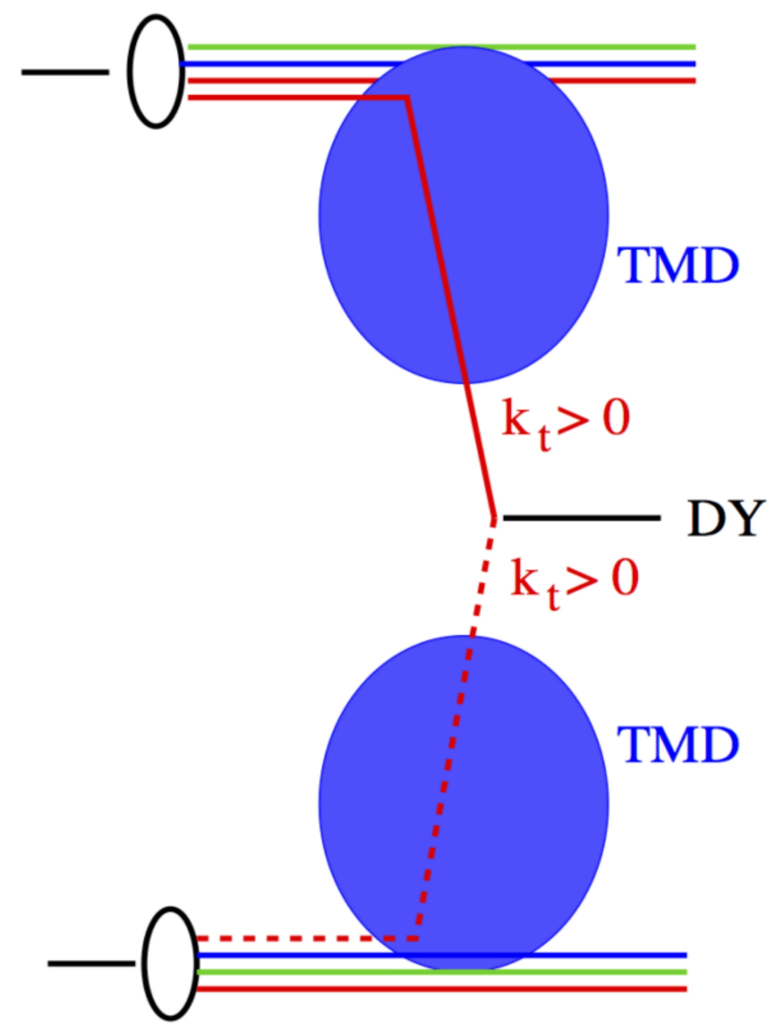
TMD distributions from fit to HERA data



- 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



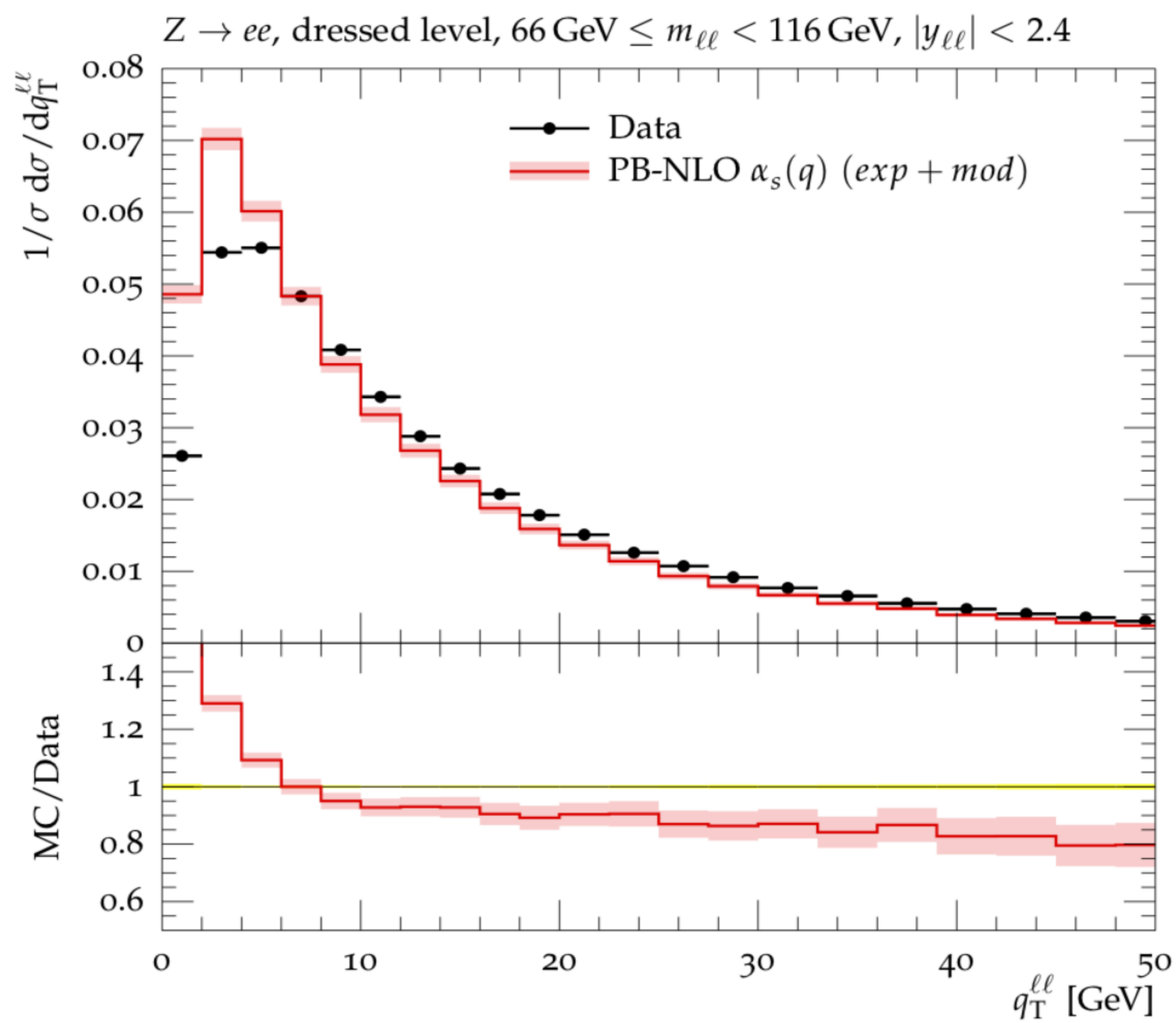
Application to DY q_T - spectrum

- Use LO DY production

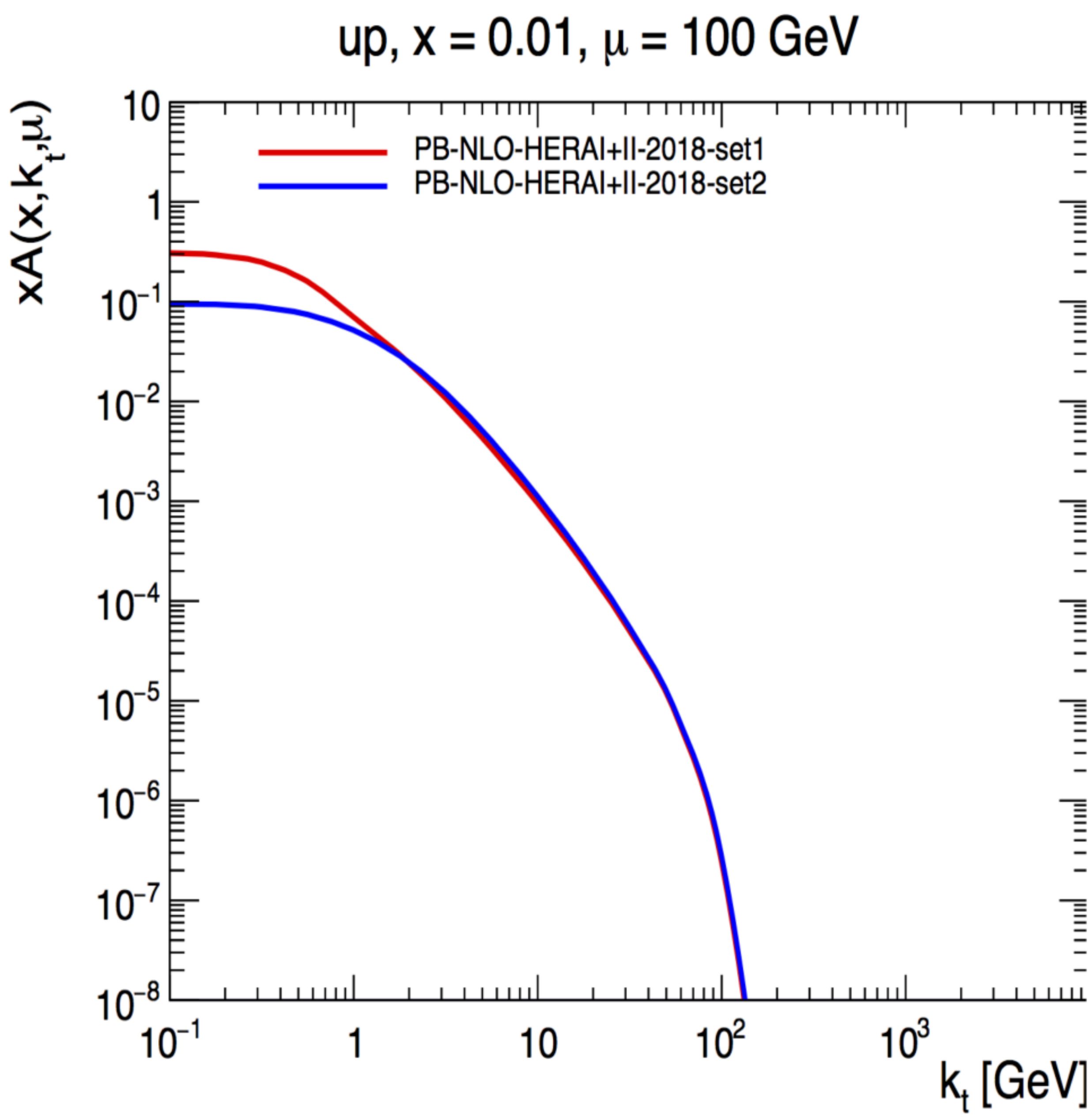
  $q\bar{q} \rightarrow Z_0$

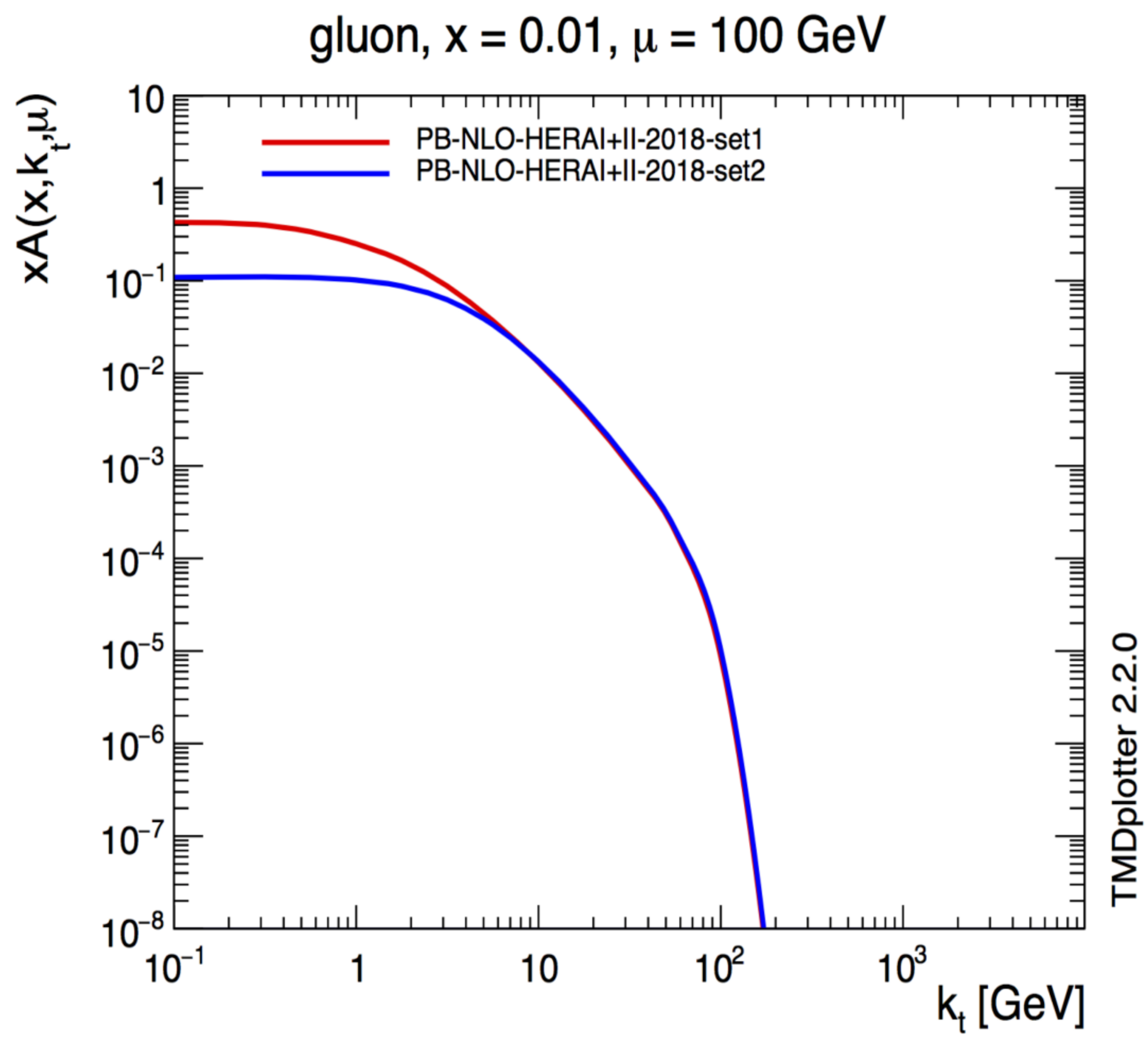
- TMD with angular ordering including $\alpha_s(q)$

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



TMD distributions





- Differences essentially in low k_T region
  - introducing q_T instead of q, suppresses further soft gluons at low k_T !

Application to DY q_T - spectrum

- Use LO DY production

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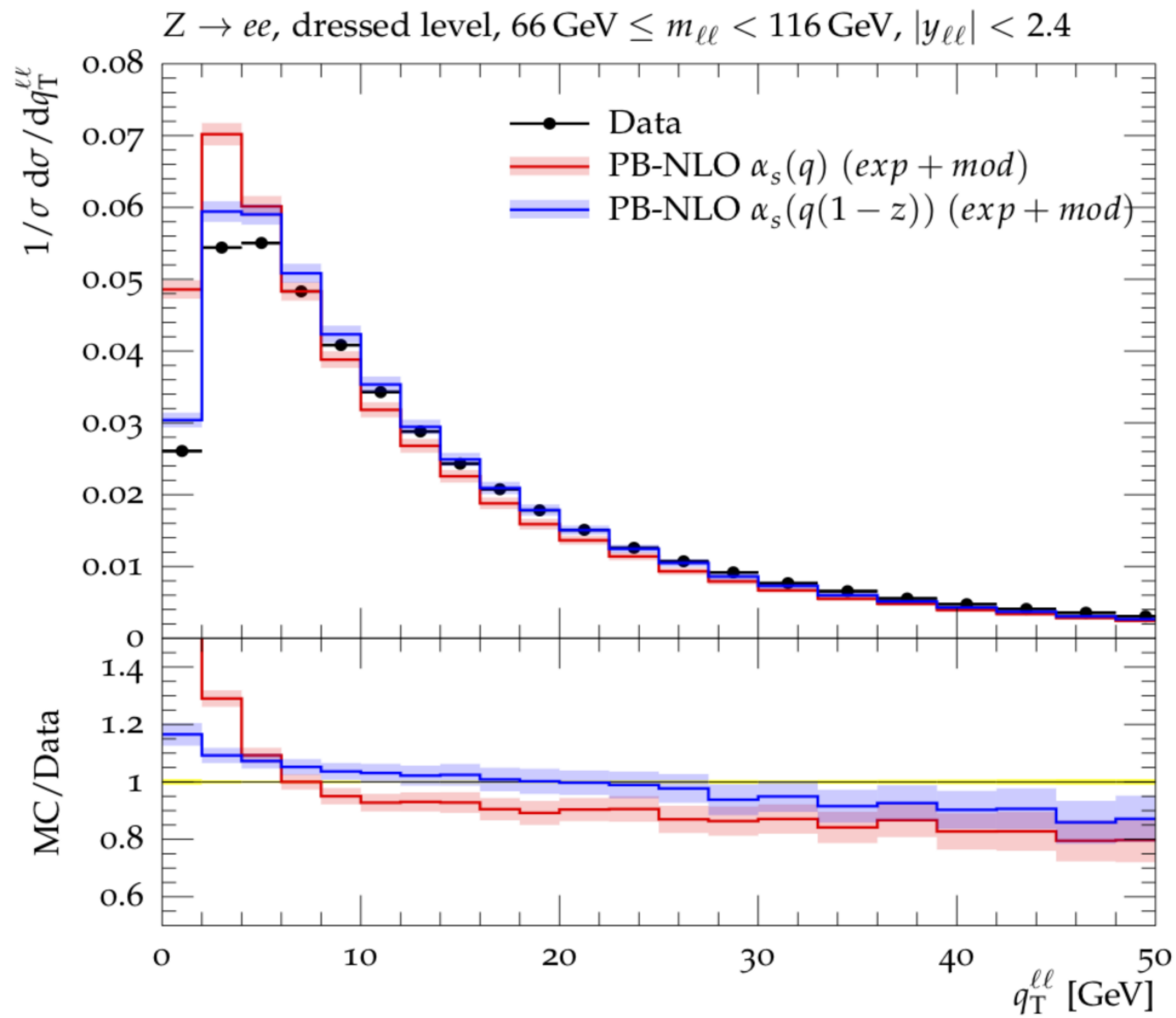


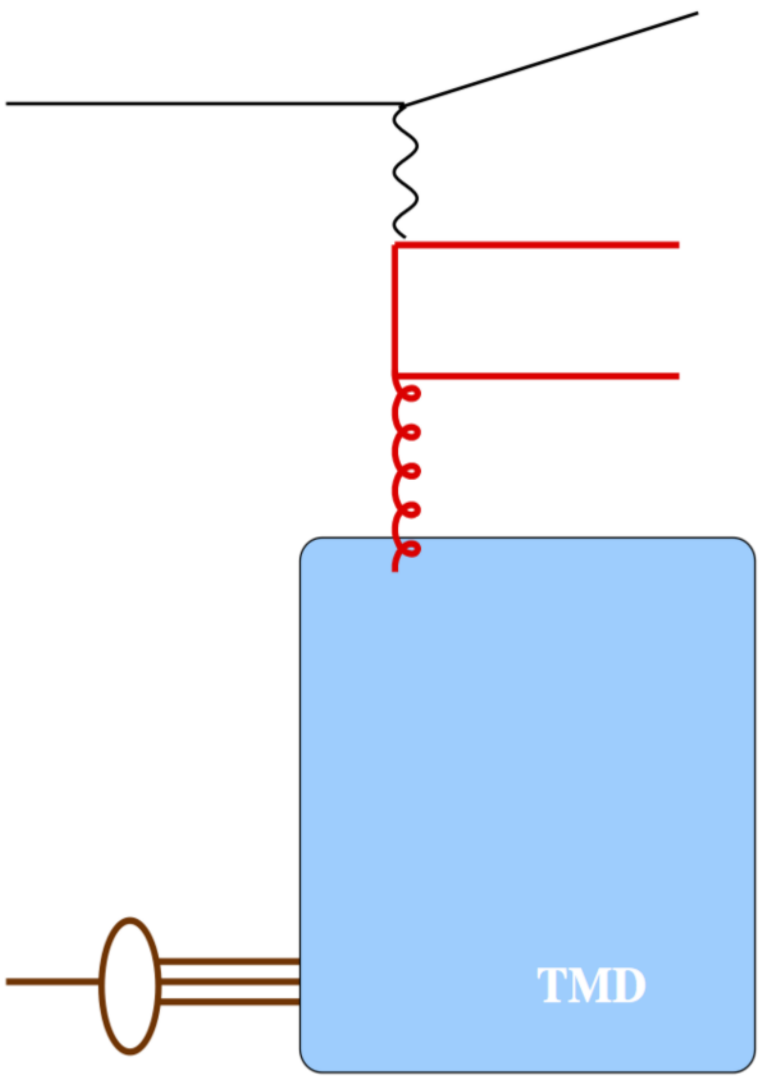
- TMD with angular ordering including $\alpha_s(q)$

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

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

MCEG: TMDs and parton shower

- basic elements are:
  - Matrix Elements:
    - ➔ on shell/off shell
  - PDFs
    - ➔ TMDs



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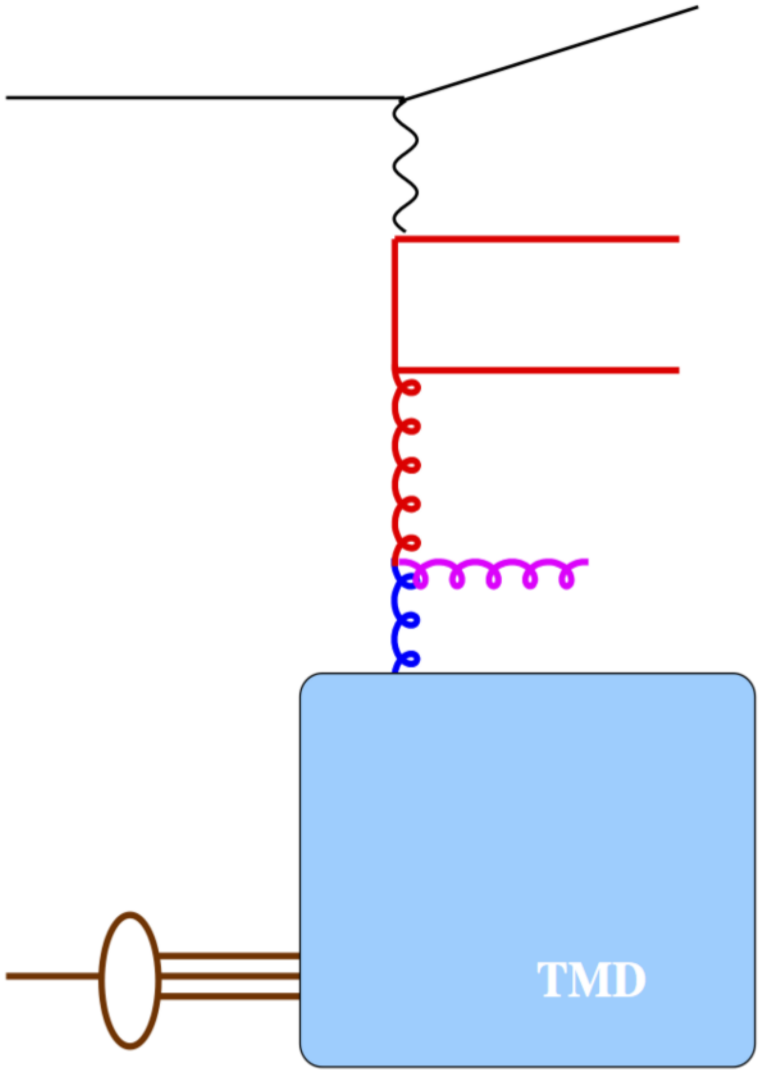
    - ➔ following TMDs for initial state !



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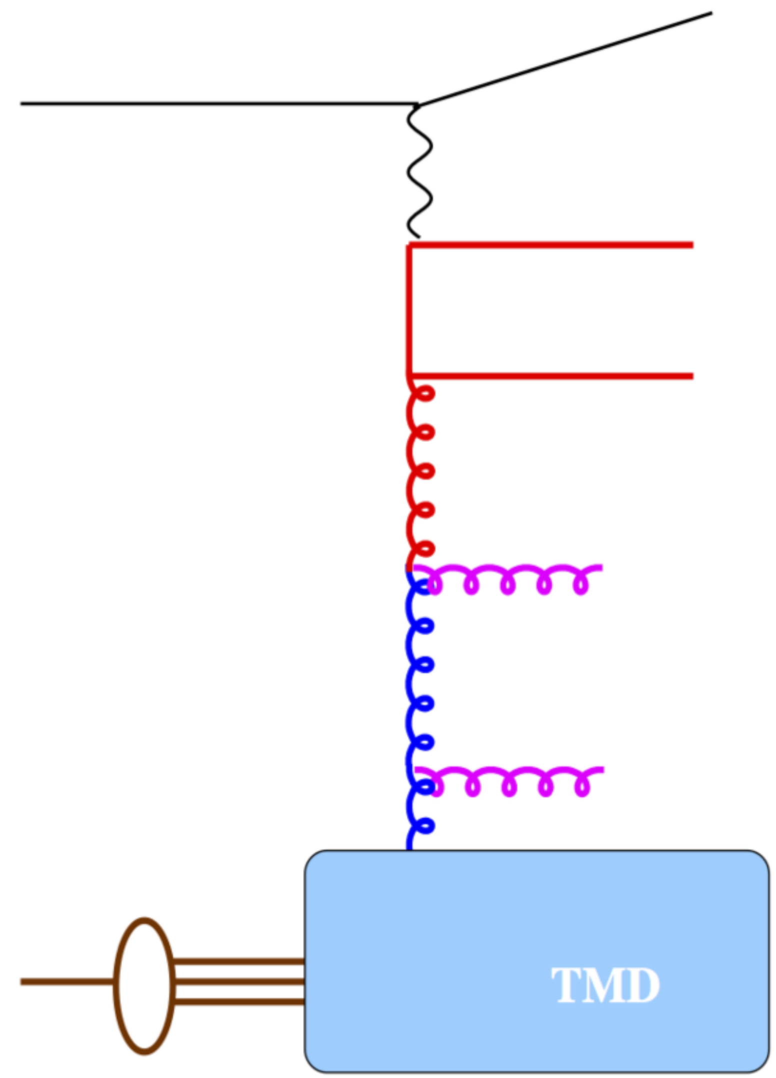

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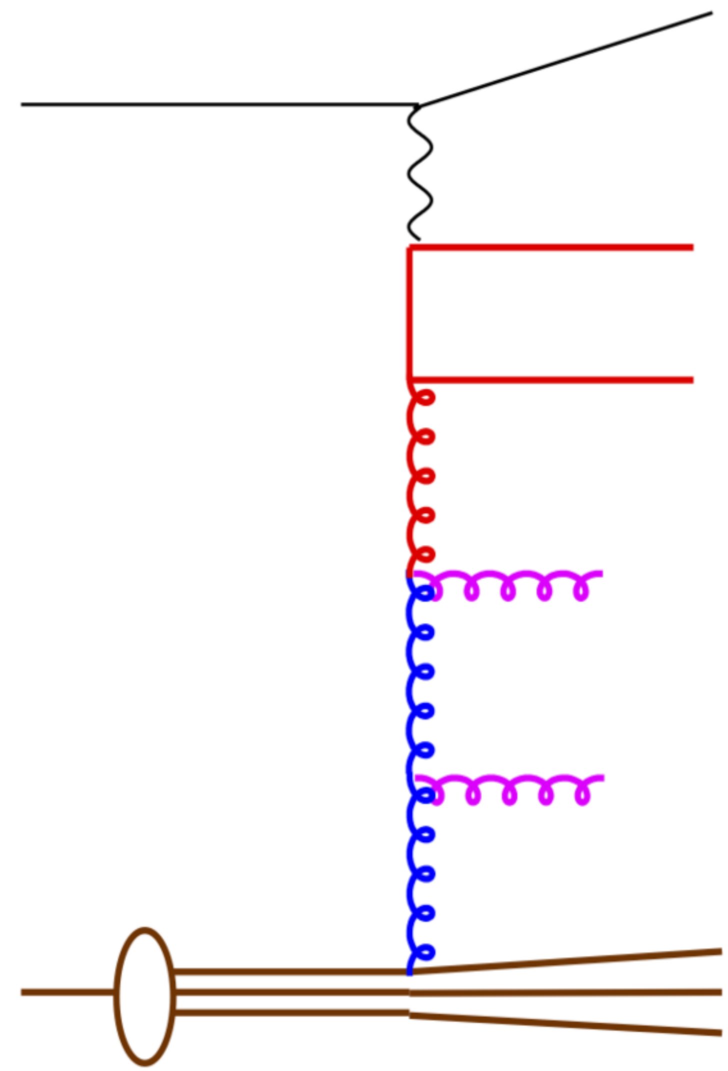
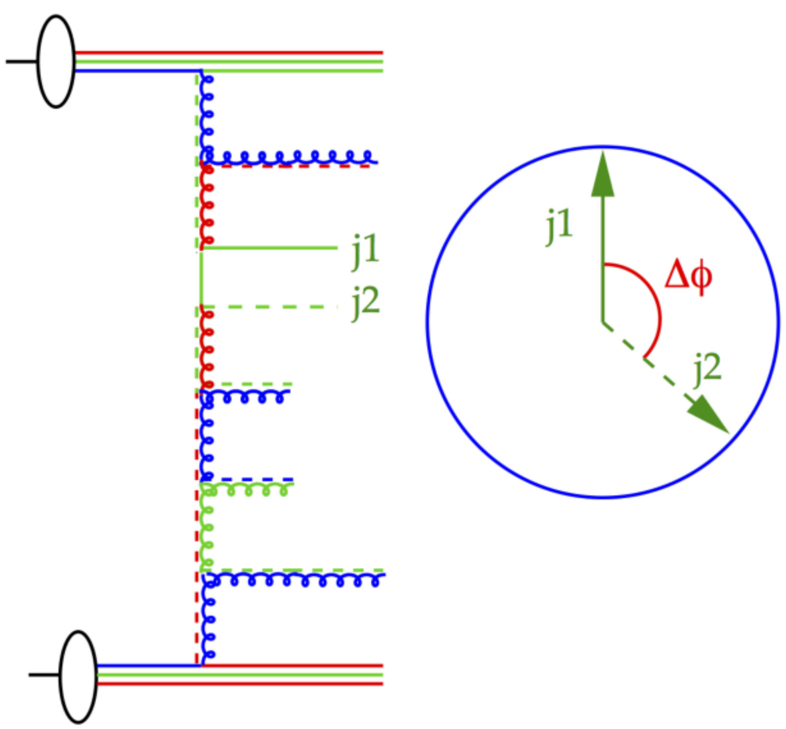
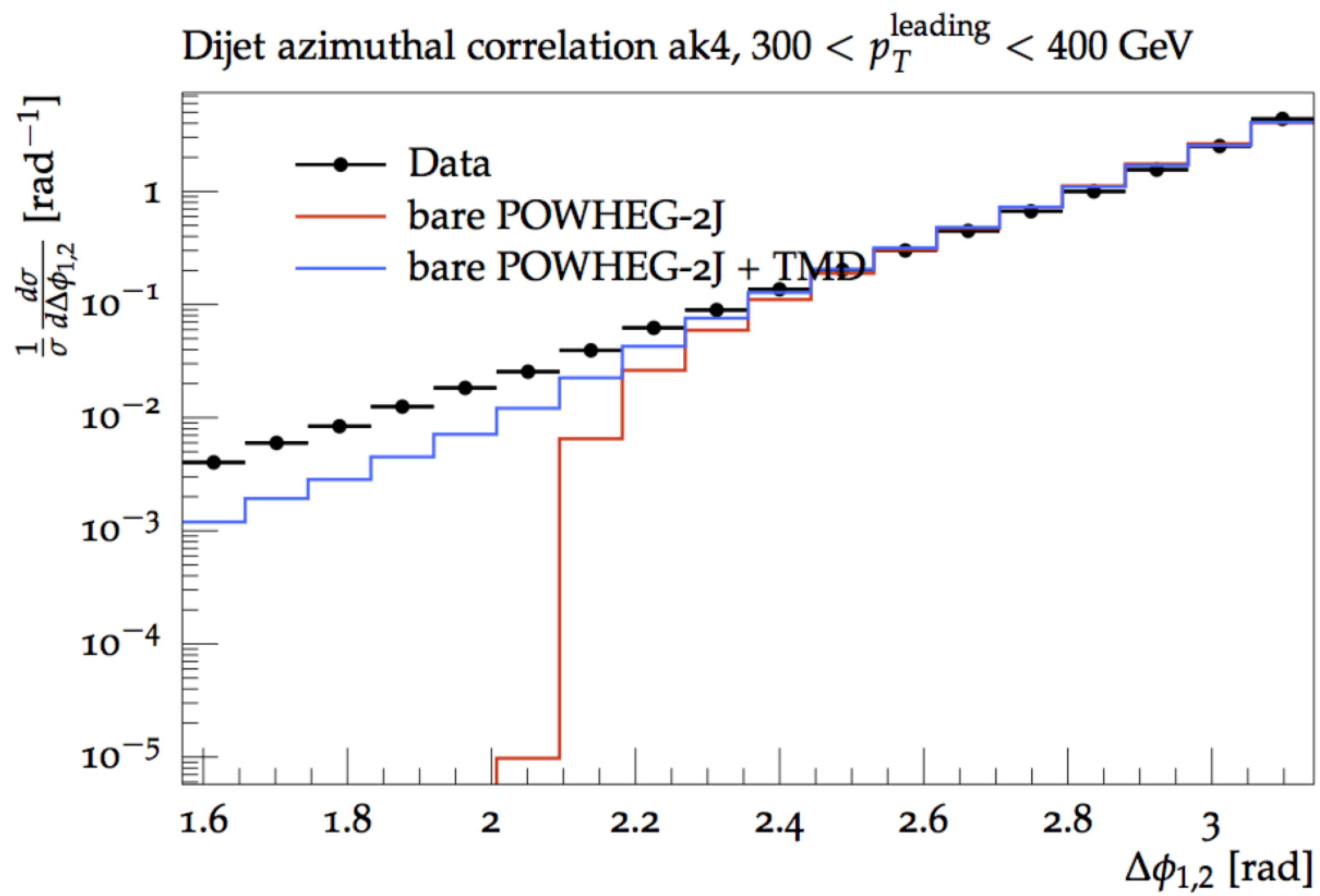
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA



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

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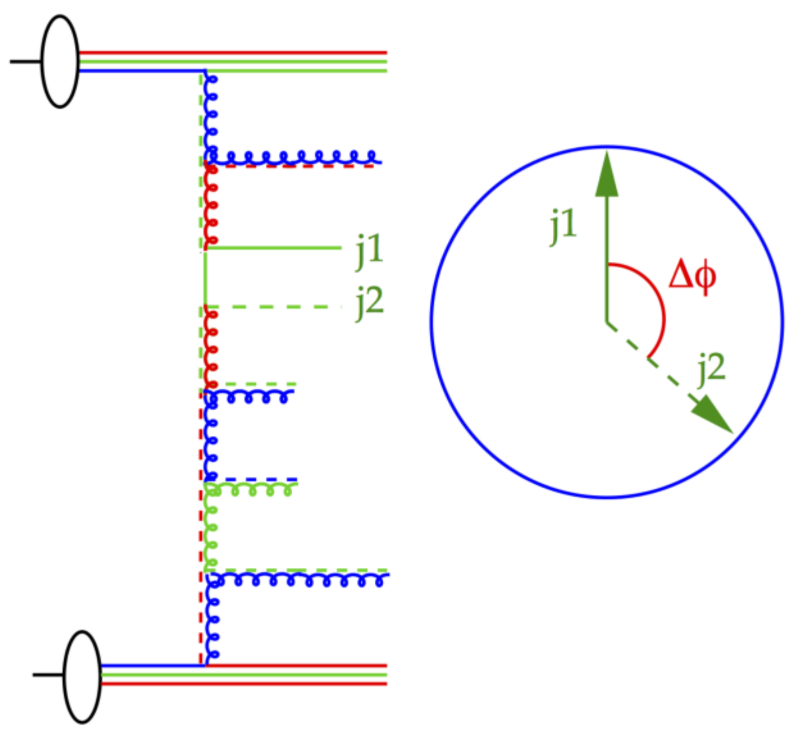

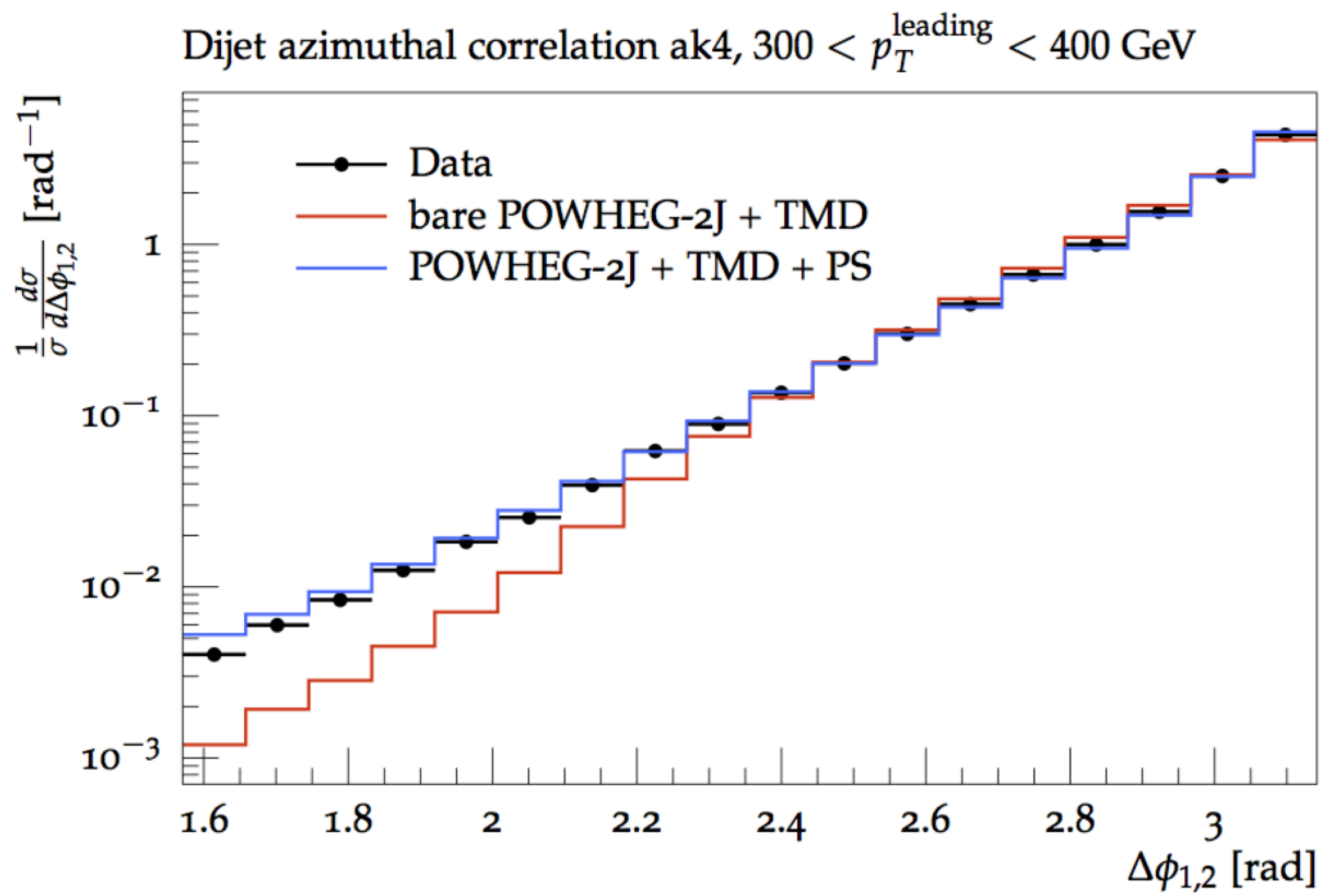

- TMDs with NLO dijets + parton shower (following TMD) describes data!

Application to high p_T dijets in pp

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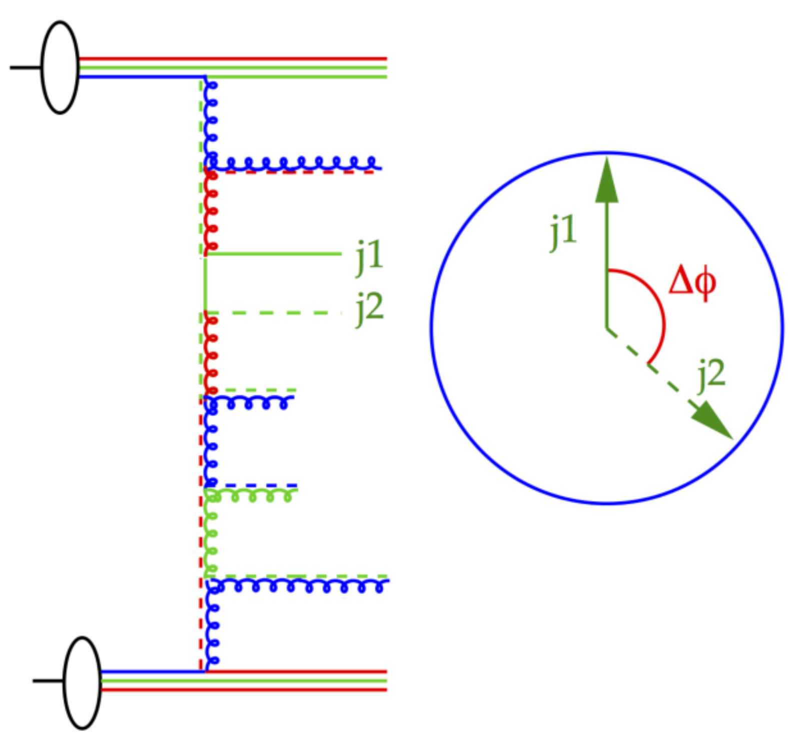
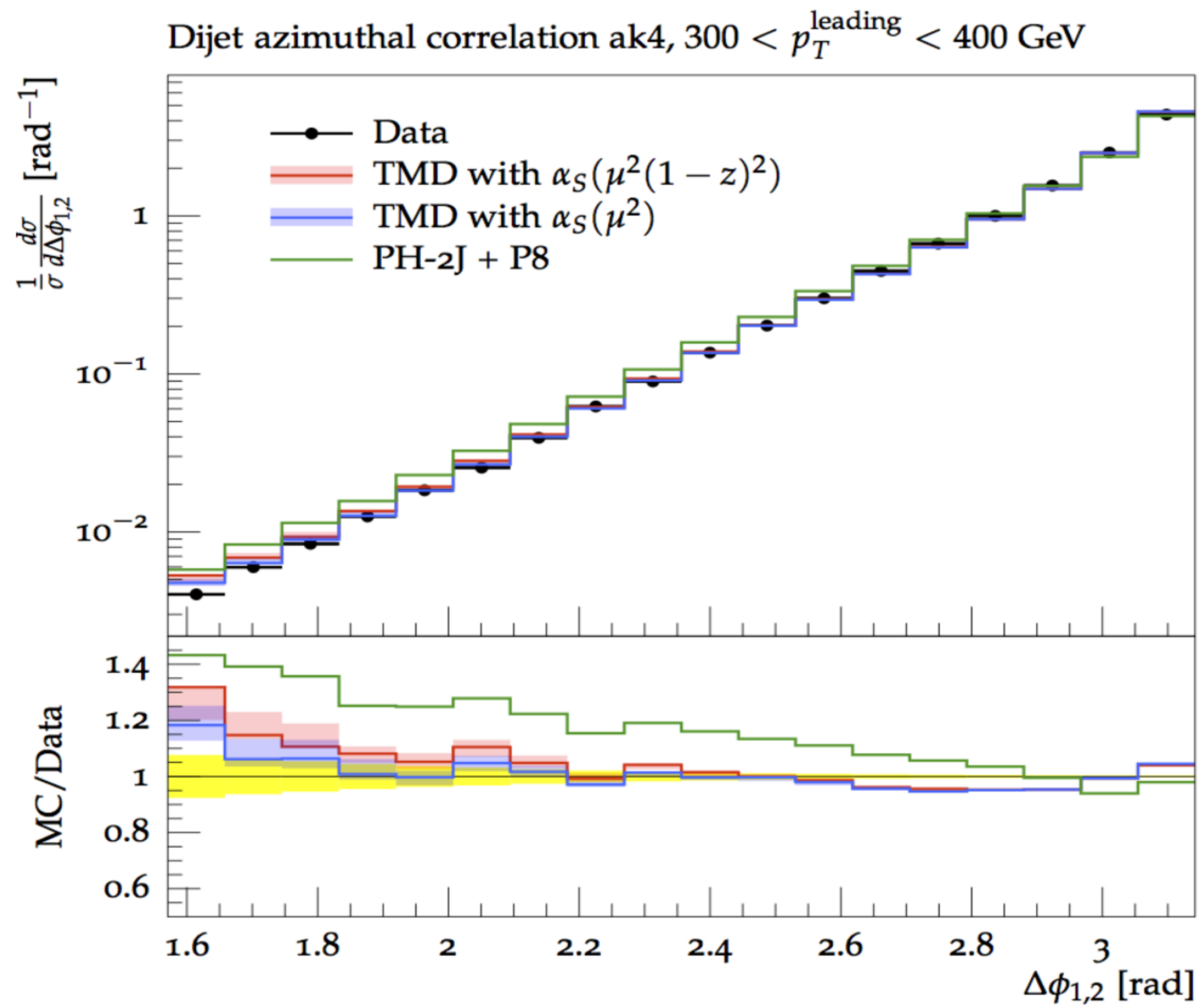




- TMDs with NLO dijets + parton shower (following TMD) describes data!
  - different TMD sets are very similar

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 to pp processes: 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

Evolution equation and parton branching method

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

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

  - 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 for non-resolvable and virtual corrections

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

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)

The limit z_M

- Investigating the large z part:

$$\sum_b \int_x^1 dz\, K_{ab}(\alpha_s)\, \frac{1}{(1-z)_+}\, \widetilde{f}_b(x/z,\mu^2)$$

$$= \sum_b \int_x^1 dz\, K_{ab}(\alpha_s)\, \frac{1}{1-z}\, \widetilde{f}_b(x/z,\mu^2) - \sum_b \int_0^1 dz\, K_{ab}(\alpha_s)\, \frac{1}{1-z}\, \widetilde{f}_b(x,\mu^2)$$

- in the region $1 > z > z_M$ expand:

$$\widetilde{f}_b(x/z,\mu^2) = \widetilde{f}_b(x,\mu^2) + (1-z)\frac{\partial \widetilde{f}_b}{\partial \ln x}(x,\mu^2) + \mathcal{O}(1-z)^2$$

- up to $\mathcal{O}(1-z_M)$:

$$\sum_b \int_x^1 dz\, K_{ab}(\alpha_s)\, \frac{1}{(1-z)_+}\, \widetilde{f}_b(x/z,\mu^2)$$

$$= \sum_b \int_x^{z_M} dz\, K_{ab}(\alpha_s)\, \frac{1}{1-z}\, \widetilde{f}_b(x/z,\mu^2) - \sum_b \int_0^{z_M} dz\, K_{ab}(\alpha_s)\, \frac{1}{1-z}\, \widetilde{f}_b(x,\mu^2)$$

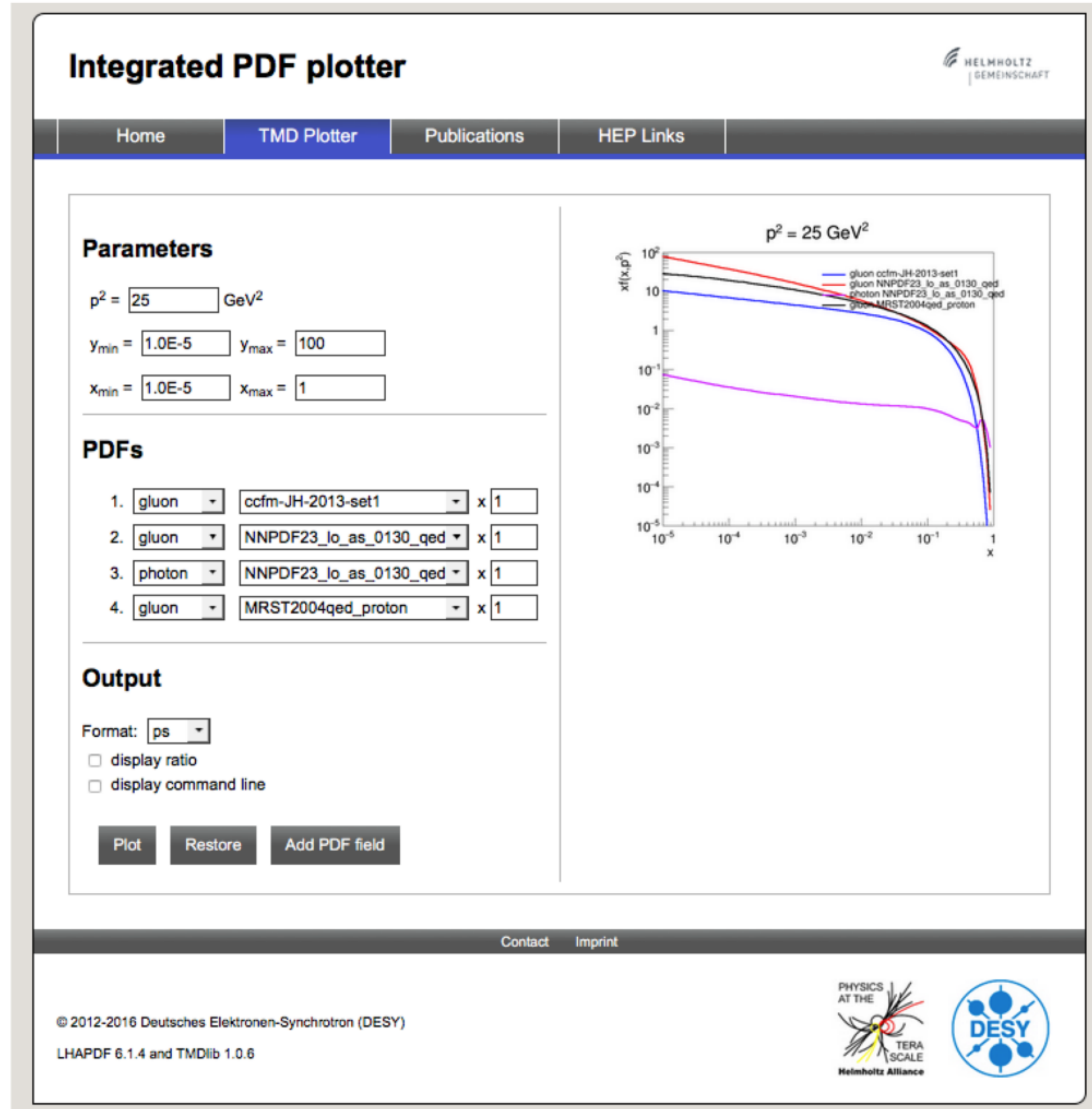
Where to find TMDs ? TMDlib and TMDplotter

- 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)

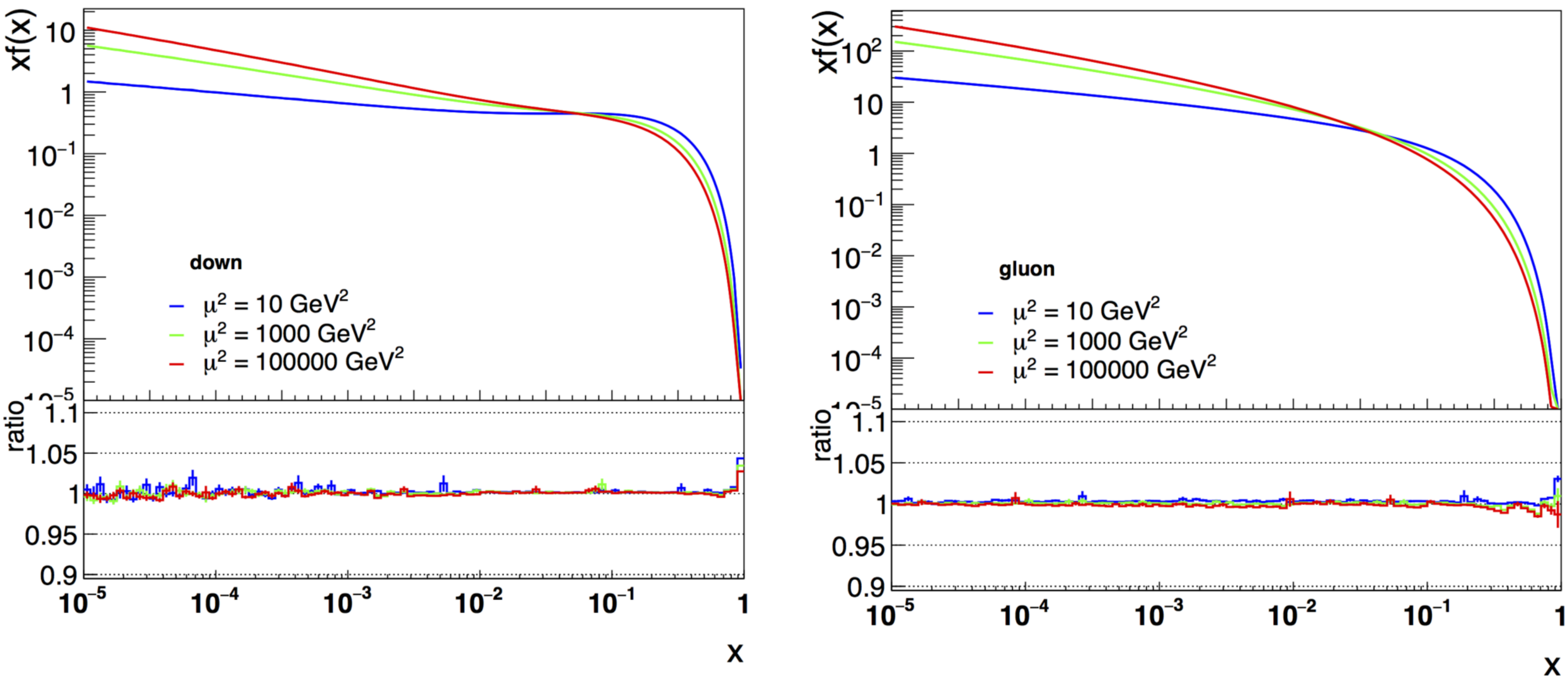
TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions, *F. Hautmann et al.* arXiv 1408.3015, **Eur. Phys. J., C 74(12):3220, 2014.**



→ 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



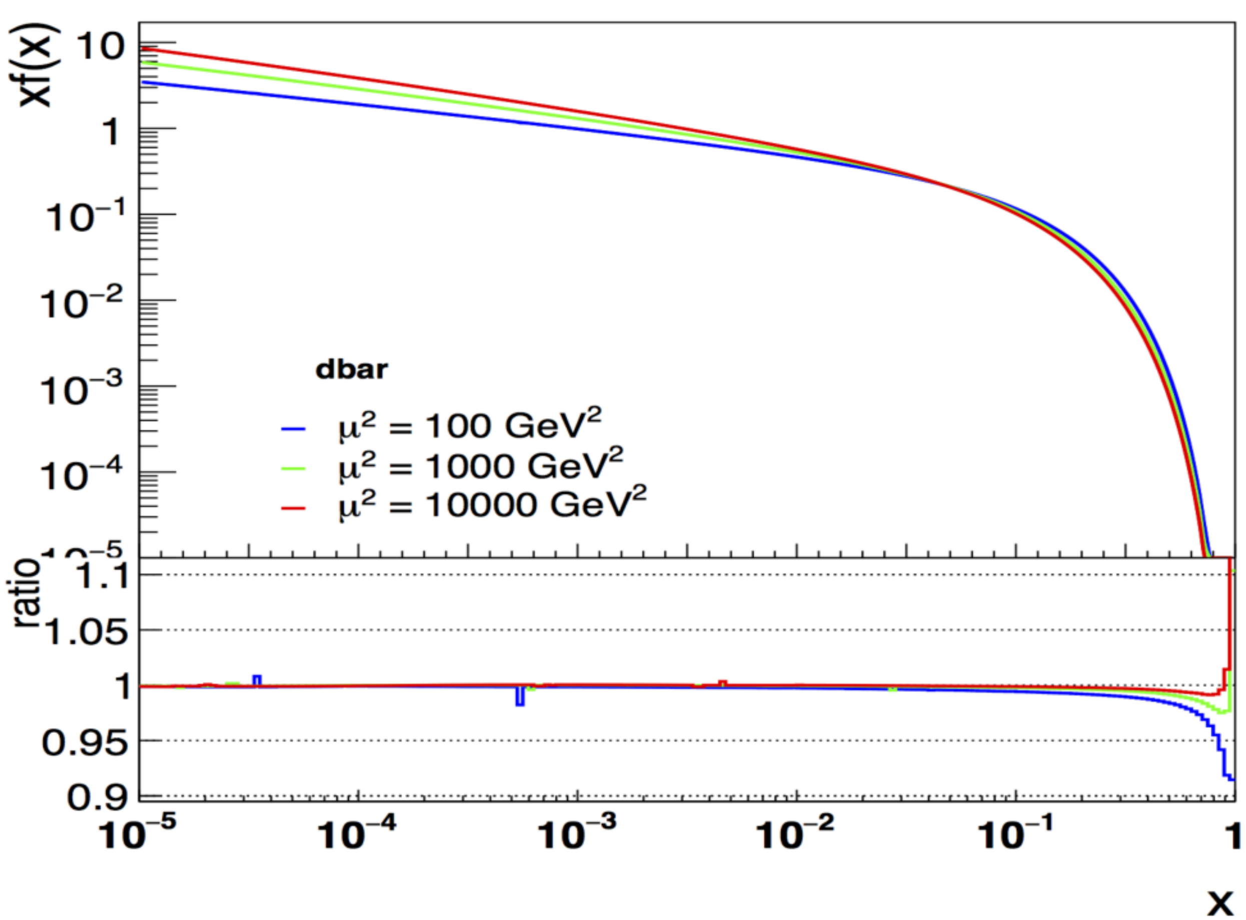
- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach works also at NNLO !

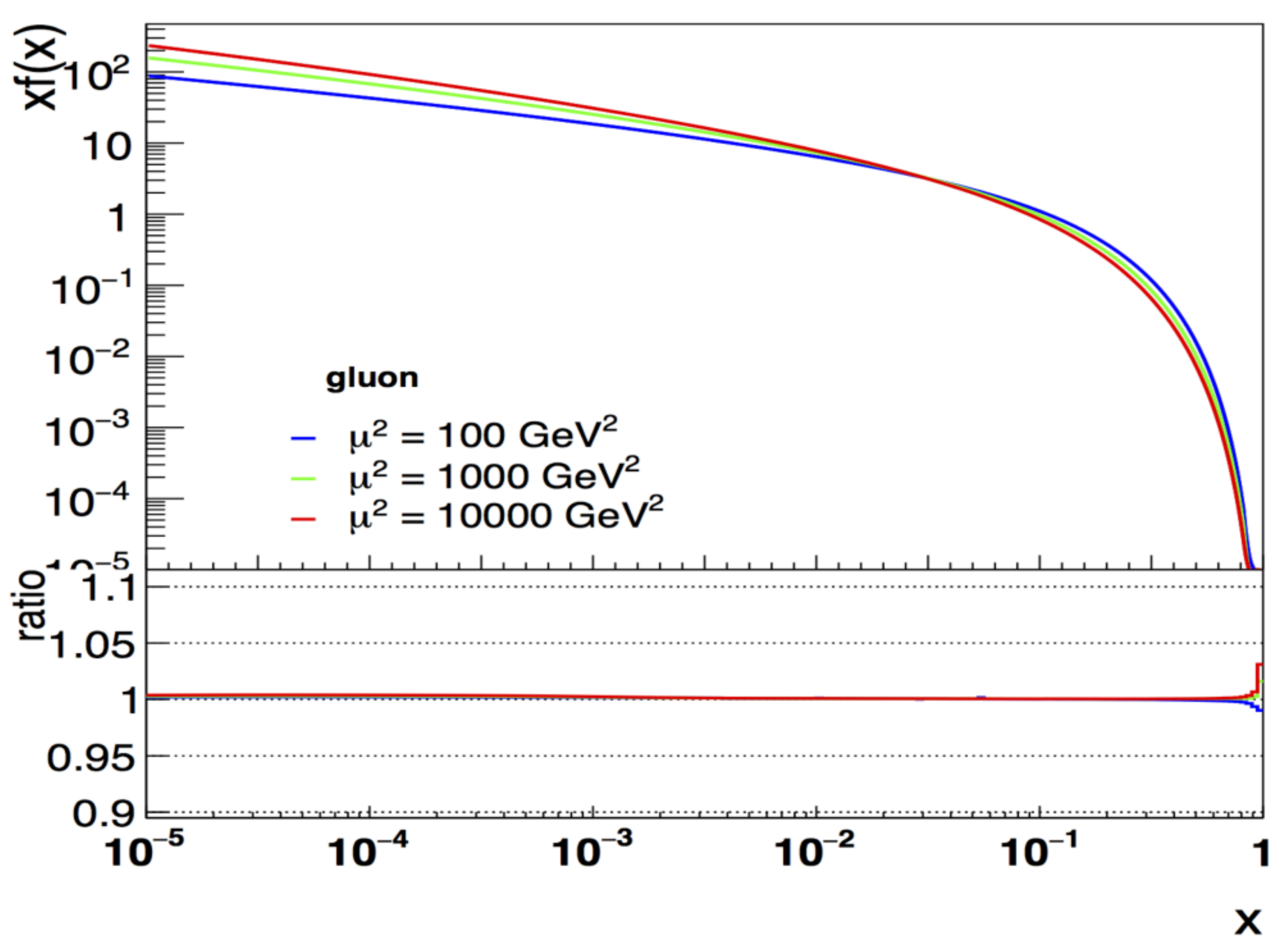
Parton branching method in xFitter

- Convolution of kernel with starting distribution

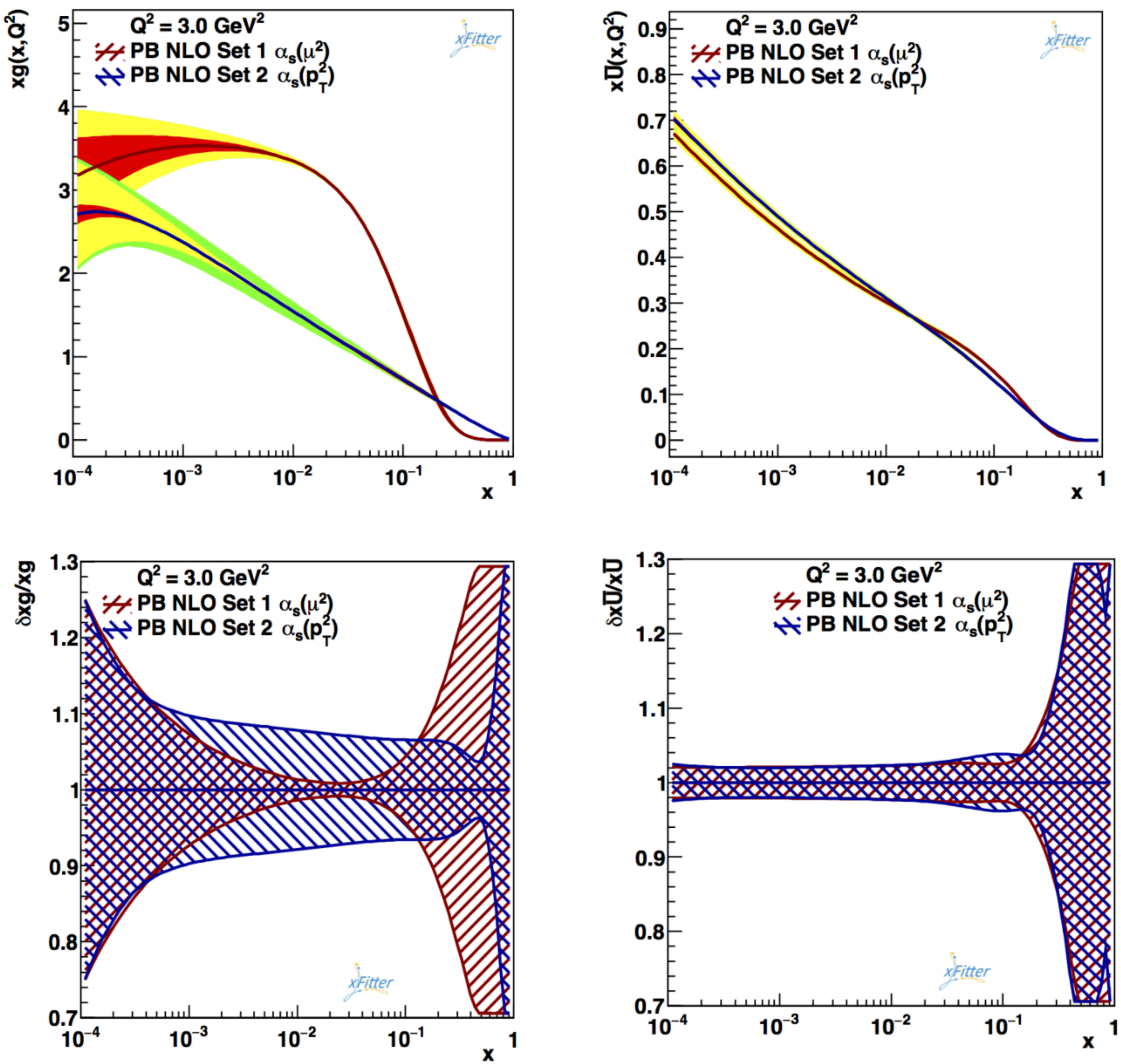
$$x f_a(x,\mu^2) \;=\; x \int dx' \int dx'' \mathcal{A}_{0,b}(x') \tilde{\mathcal{A}}_a^b\left(x'',\mu^2\right) \delta(x'x''-x)$$
$$\;=\; \int dx' \mathcal{A}_{0,b}(x') \cdot \frac{x}{x'} \; \tilde{\mathcal{A}}_a^b\left(\frac{x}{x'},\mu^2\right)$$

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



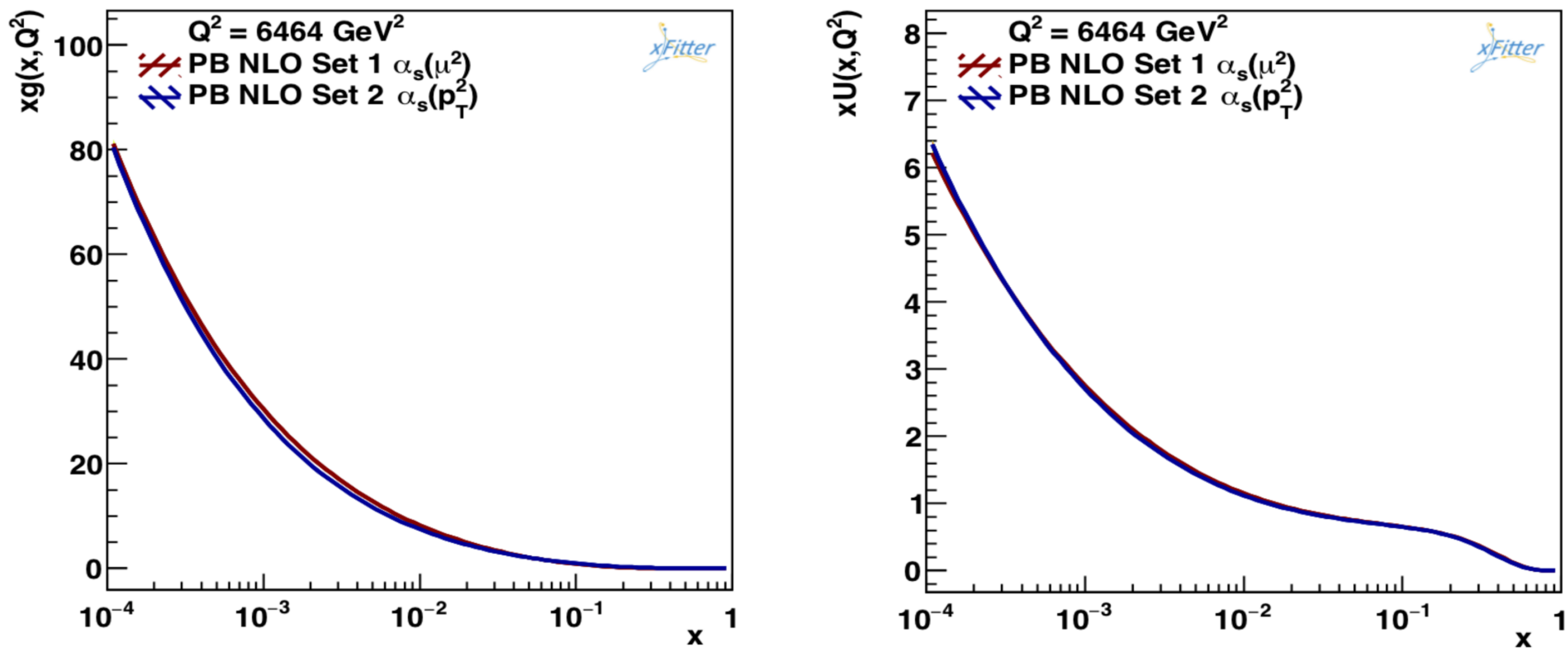


Fit with different scale in α_s: at small Q^2



- 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

Fit with different scale in α_s: at large Q^2



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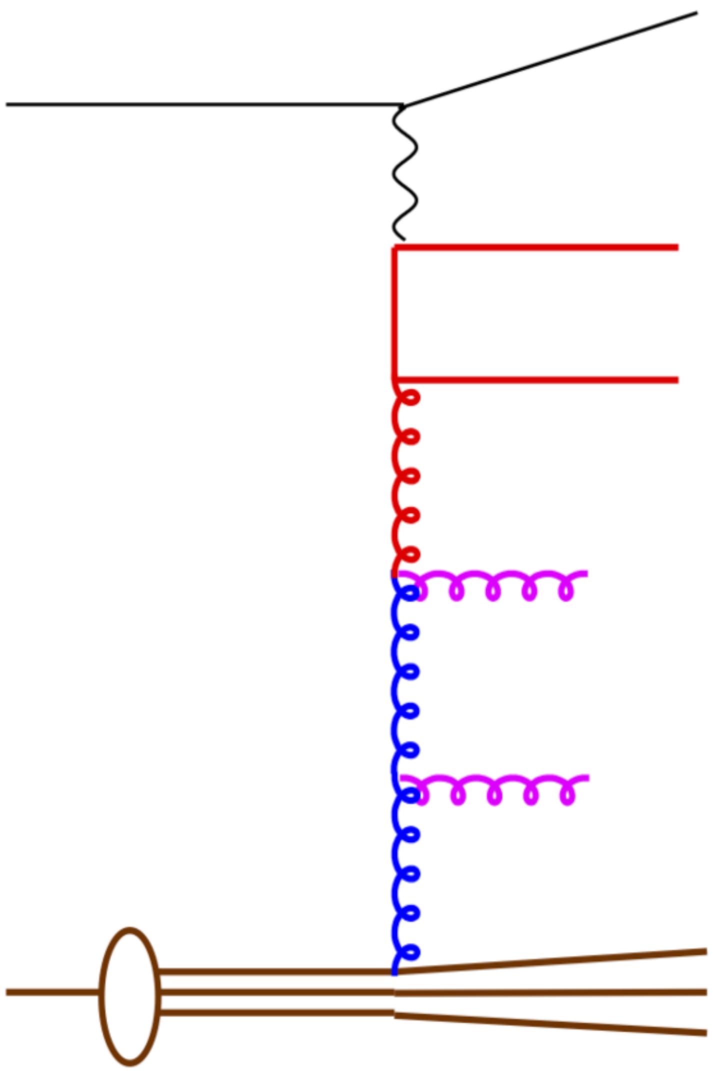
    - ➔ following TMDs for initial state !
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA



- 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