Effects of parton shower dynamics on PDF evolution

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Parton Branching method

1) Introduction to the Parton Branching solution of DGLAP

2) Comparing of the collinear part with QCDnum

3) Parton showers with virtuality or angle as an ordering variable, resolvable branching

4) Extracting of TMDs from HERA DIS data

5) Prediction of $p_T(Z)$ in DY process

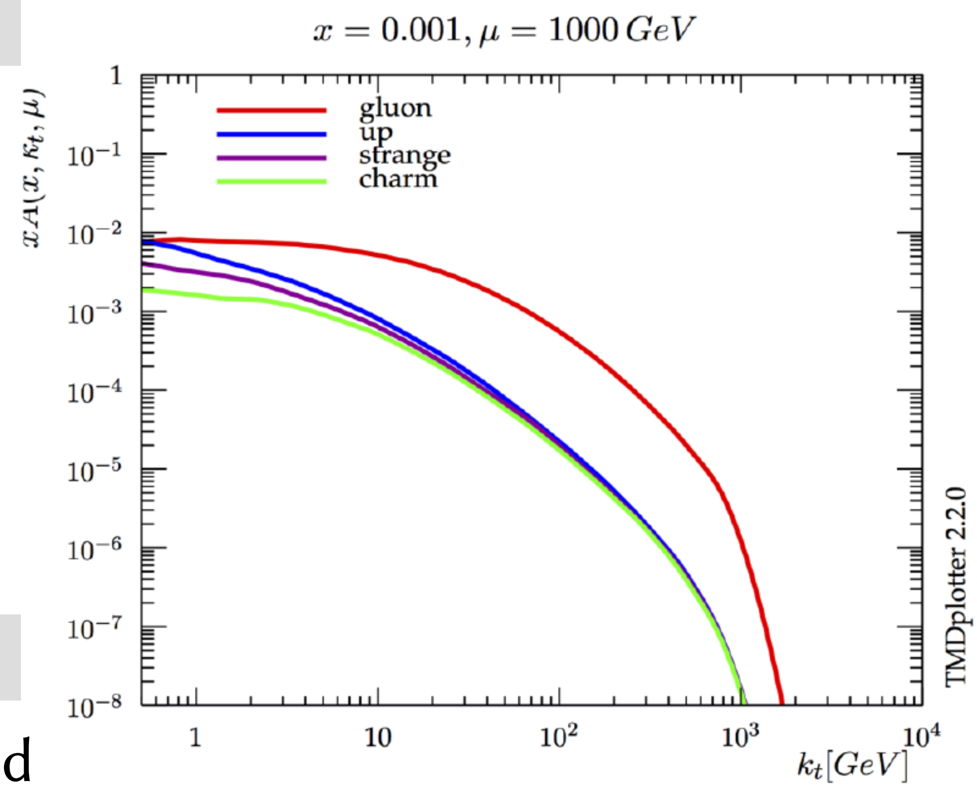
Motivation

Parton branching method is:

- An analogy to the MC parton showers but is used to solve evolution equation
- In case of DGLAP equation the collinear part exactly reproduce semi-analytical solution

And allows:

- Trace the k_T of each emissions and determine the k_T part of PDFs
- Study different kinds of branching branching dynamics (ordering conditions, resolution condition) and determine their effect on PDFs



Different flavors have different shapes of kT distribution.

F. Hautmann, H. Jung, A. Lelek, V. Radescu, R. Zlebcik: Soft-gluon resolution scale in QCD evolution equations [arXiv:1704.01757].

DGLAP splittings decomposition

- The evolution employs momentum weighted densities

$$f_a(x,\mu^2) \to \tilde{f}_a(x,\mu^2) = x f_a(x,\mu^2)$$

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}\tilde{f}_a(x,\mu^2) = \sum_b \int_x^1 \frac{\mathrm{d}z}{z} z P_{ab}\left(\alpha_s(\mu^2), z\right) \tilde{f}_b(x/z,\mu^2)$$

Parton Branching solution relays on:

1) Decomposition of the splitting kernels
(valid at least to NNLO)

$$zP_{ab}\left(\alpha_s, z\right) = D_{ab}(\alpha_s)\delta(1-z) + K_{ab}(\alpha_s, z)\frac{1}{(1-z)_+} + R_{ab}(\alpha_s, z)$$

Where K and R do not contain any power-like singularities like $1/z$ or $1/(1-z)$

2) Sum rules $\sum_b \int_0^1 \mathrm{d}z\, zP_{ba}\left(\alpha_s(\mu^2), z\right) = 0, \quad \text{for every flavor } a$

Sudakov Formalism

- With momentum sum rules and Sudakov, the evolution can be written as:

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}\frac{\tilde{f}_a(x,\mu^2)}{\Delta_a(\mu^2)} = \sum_b \int_x^{z_m} \frac{\mathrm{d}z}{z} z P_{ab}\left(\alpha_s(\mu^2), z\right) \frac{\tilde{f}_b(x/z,\mu^2)}{\Delta_a(\mu^2)}$$

- Where the Sudakov is:

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

- The cut-off $z_m < 1$ determine what is still resolvable branching
- The delta part and +prescription of splittings is outside of the integration range (soft emissions resumed by Sudakov)
- This solution is identical to DGLAP as soon as z_m is large enough

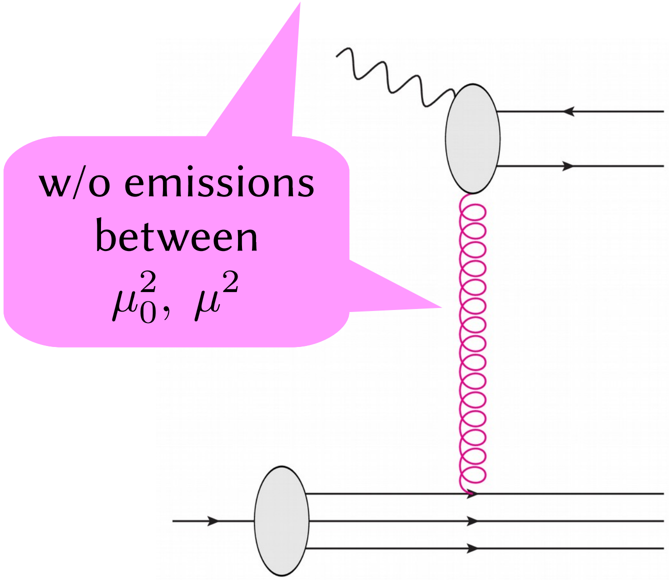
Iterative solution

- Integral form of the evolution equation:

$$\tilde{f}_a(x,\mu^2) = \Delta_a(\mu^2)\tilde{f}_a(x,\mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2}\frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_m} \frac{\mathrm{d}z}{z} z P_{ab}\left(\alpha_s(\mu'^2), z\right) \tilde{f}_b(x/z,\mu'^2)$$

- Iterative solution:

$$\tilde{f}_a^{(1)}(x,\mu^2) = \Delta_a(\mu^2)\tilde{f}_a^{(0)}(x,\mu_0^2)$$



Iterative solution

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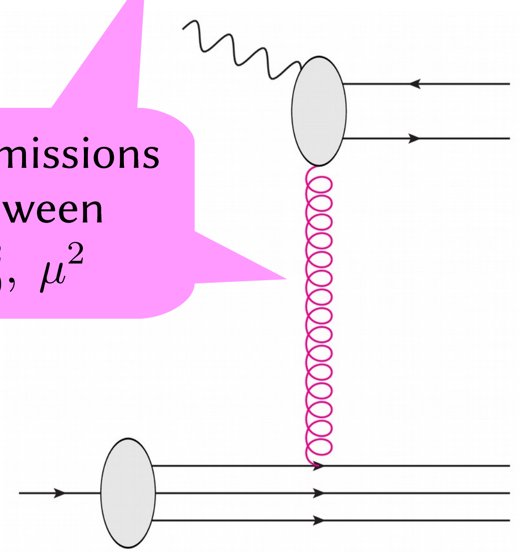
- Iterative solution:

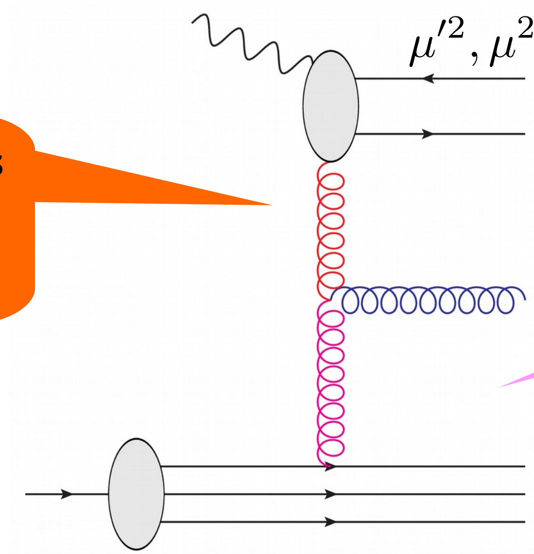
Splitting probability

$$\tilde{f}_a^{(2)}(x,\mu^2) = \Delta_a(\mu^2)\tilde{f}_a^{(0)}(x,\mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_m} \frac{\mathrm{d}z}{z} z P_{ab}\left(\alpha_s(\mu'^2), z\right) \Delta_b(\mu'^2) \tilde{f}_b^{(0)}(x/z,\mu_0^2)$$

w/o emissions between $\mu_0^2,\ \mu^2$



w/o emissions between $\mu'^2,\ \mu^2$

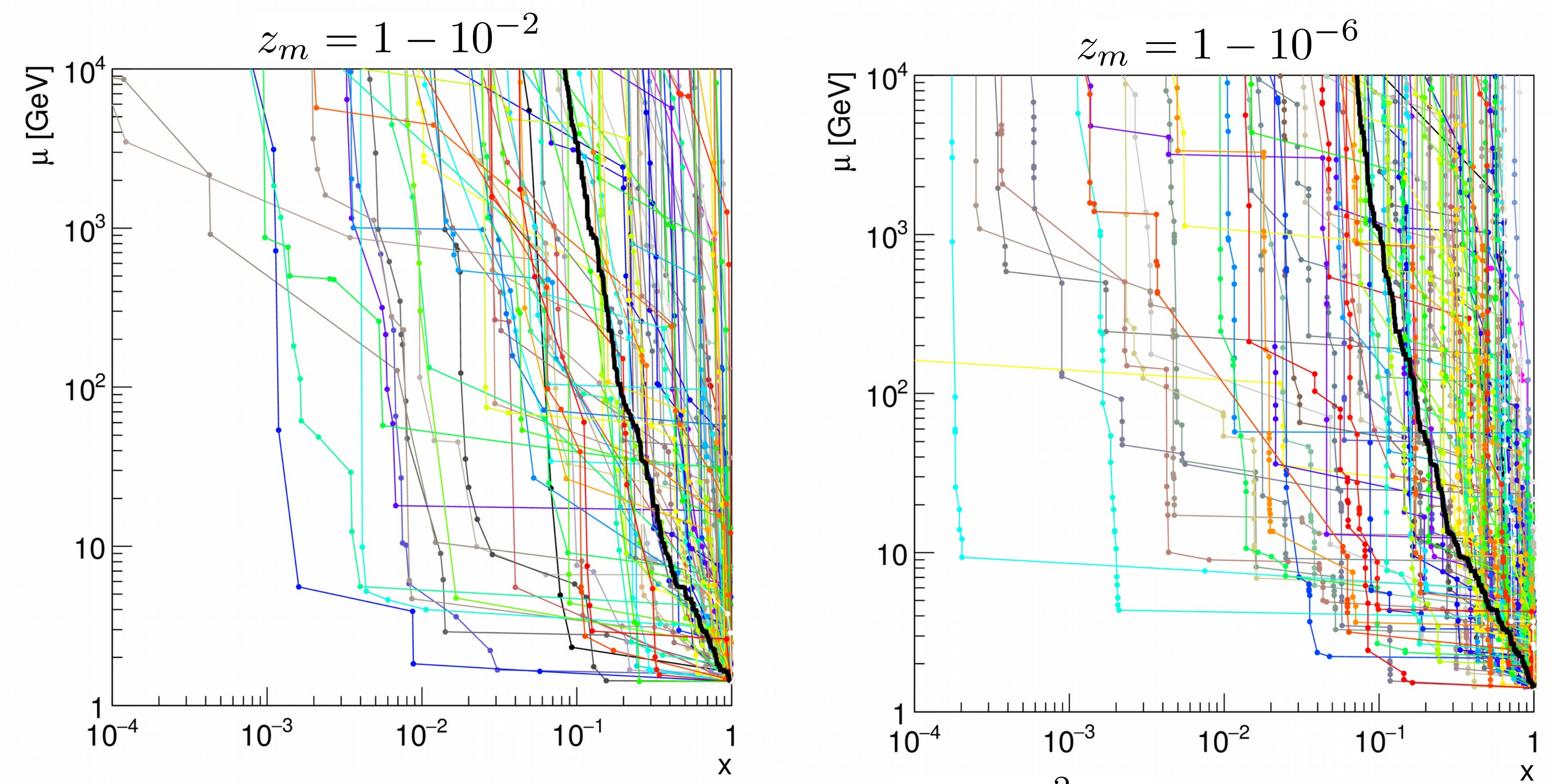


w/o emissions between $\mu_0^2,\ \mu'^2$

Monte Carlo solution

1) Starting with $\tilde{g}(x, \mu_0^2) = \tilde{g}(x, 2) = \delta(1 - x)$ (for these plots)
2) The position of every next branching (dot) depends only on the previous one and is randomly generated using Sudakov and splitting kernels

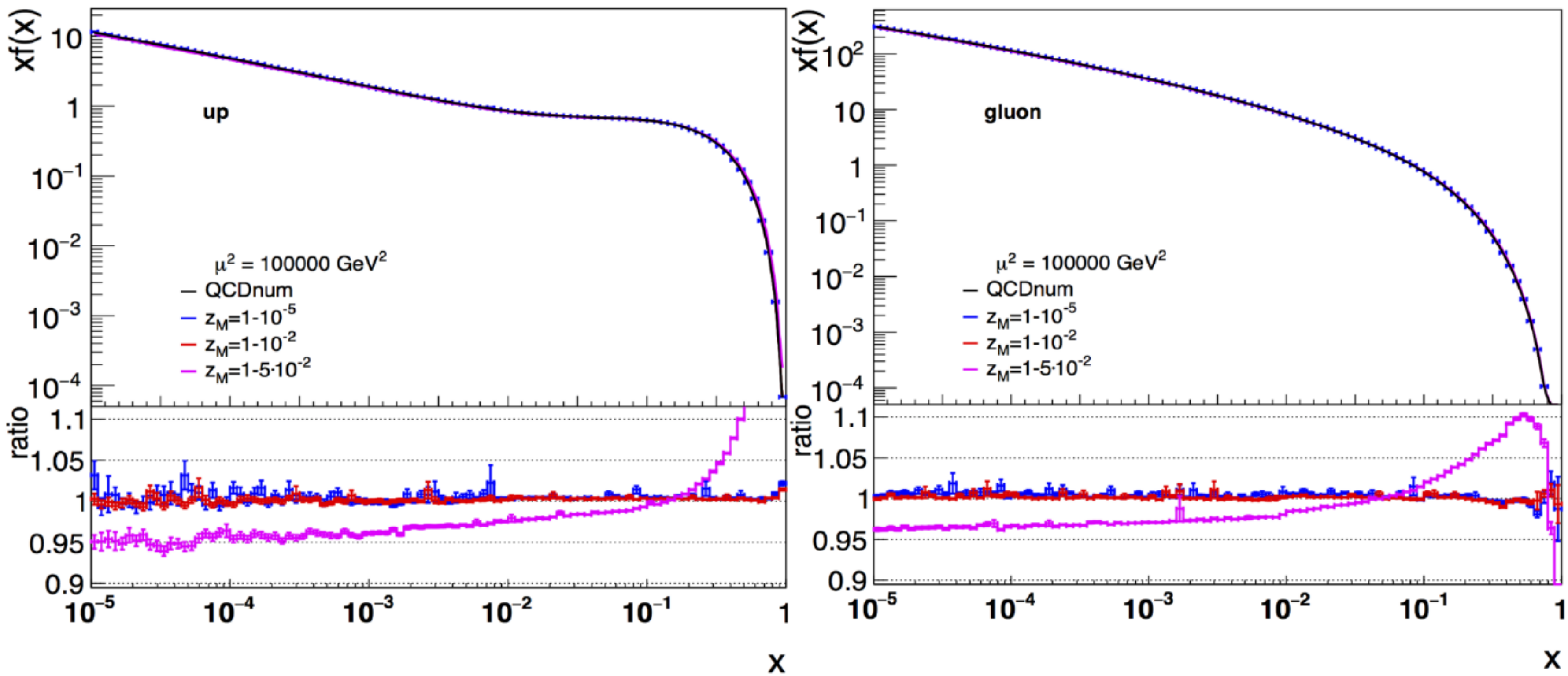
Higher z_m cut-off causes more soft emissions (dots with similar x)



100 LO MC evolution paths from the point $x = 1, \mu^2 = 2$ plotted

Resolvable branching dependence

- The parameter z_m separate resolvable branchings from non-resolvable and virtual one

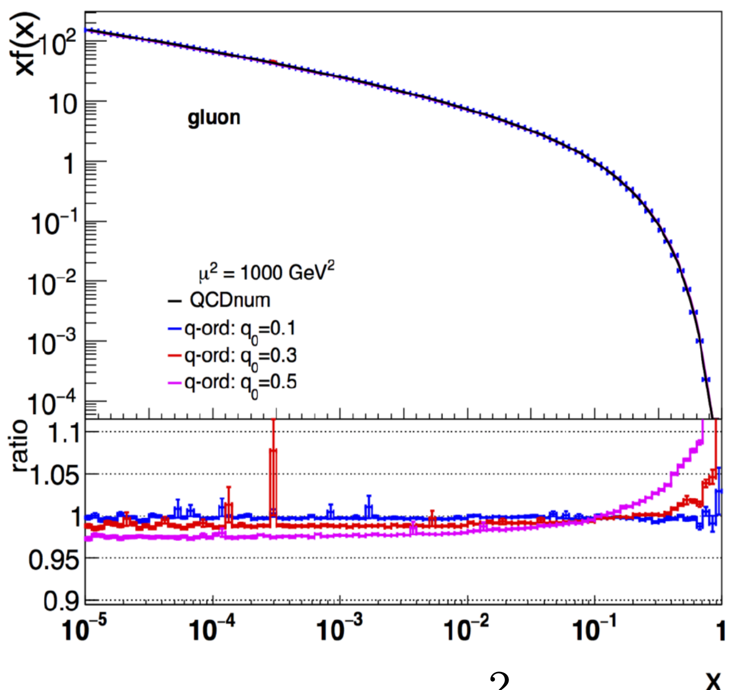


- The z_m affects high-x region, no difference if $z_m > 0.99$
- Momentum sum rules still holds irrespectively on z_m
- Possibility to use $z_m(\mu'^2)$ like in showers of MC generators.

Extension of the method by scale-dependent resolution parameter

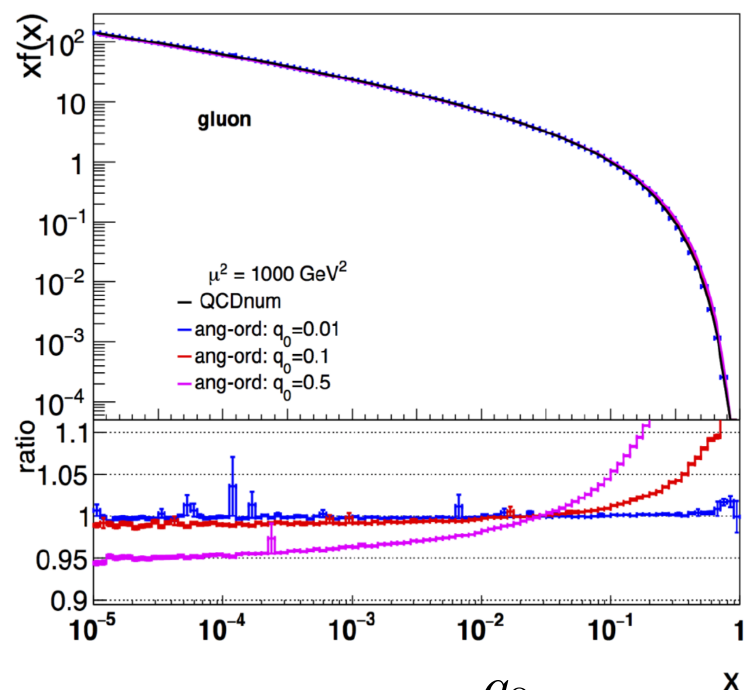
- Automatic sum rules conservation allows to study various definition of the resolvable branching $z_m(\mu'^2)$
- In case of $z_m(\mu'^2) \not\to 1$ the evolution in general differs from DGLAP

q-ordering condition



$$z_m = 1 - \frac{q_0^2}{\mu'^2}$$

Angular ordering condition

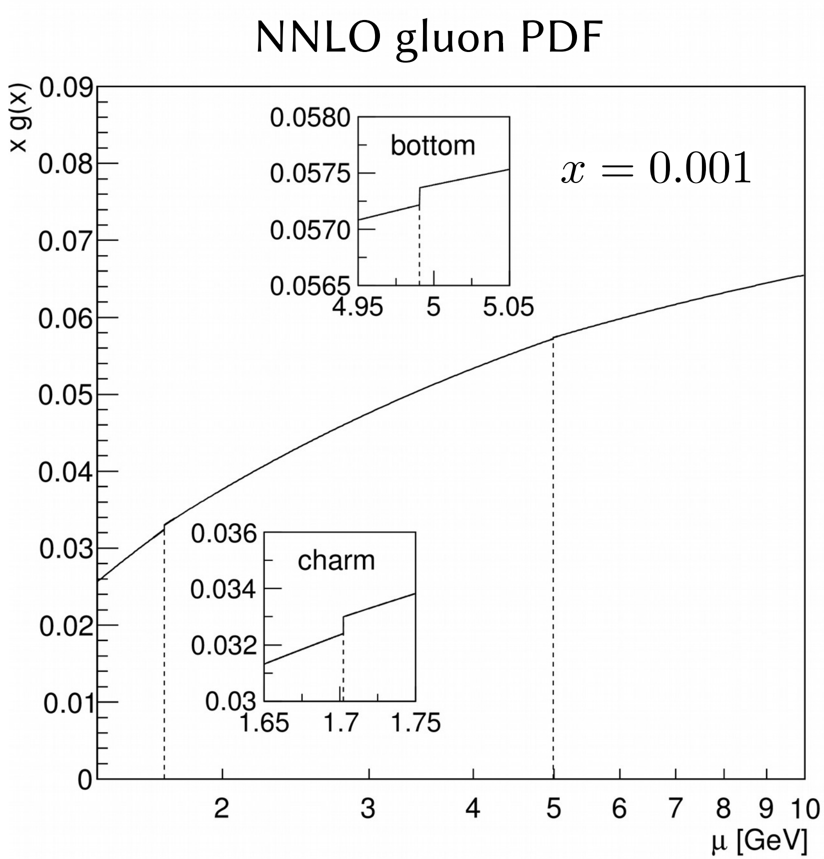


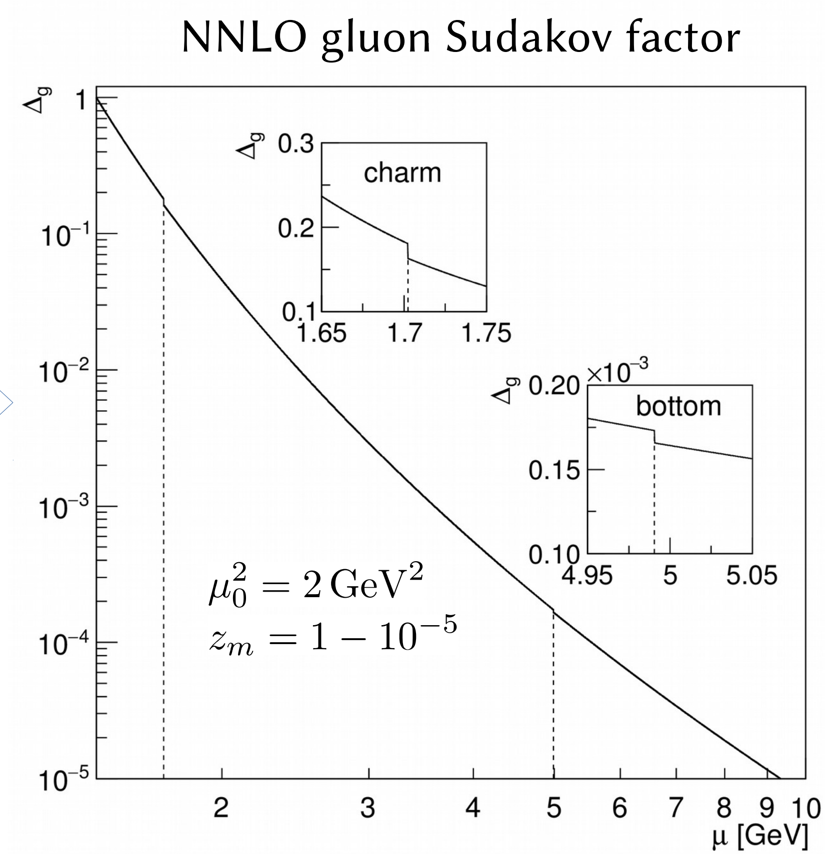
$$z_m = 1 - \frac{q_0}{\mu'}$$

Parton branching method at NNLO

- In NNLO VFNS discontinuities both in α_S and PDFs
- These discontinuities ensure continuity of observables, e.g. F_2

Discontinuities in the quark and gluon Sudakov factors

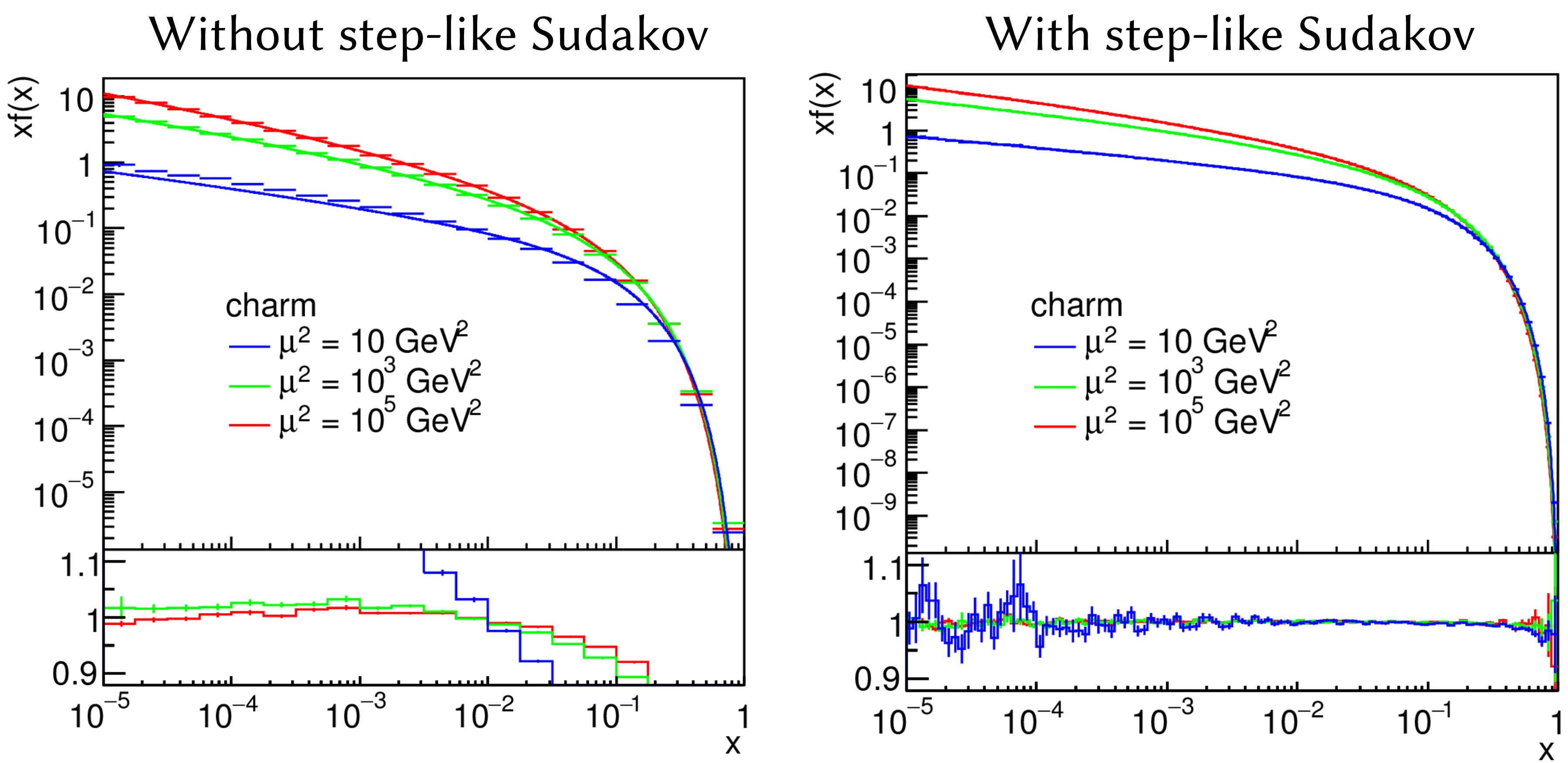




M. Buza et al., Eur. Phys. J. C1, 301 (1998), hep-ph/9612398

Parton branching method at NNLO

- The parton branching method with discontinuous Sudakov correctly describes all discontinuities emerging with NNLO



- Effect of discontinuities most prominent for charm distribution at lower scales ⟶ discontinuities matter

Virtuality and angular ordering

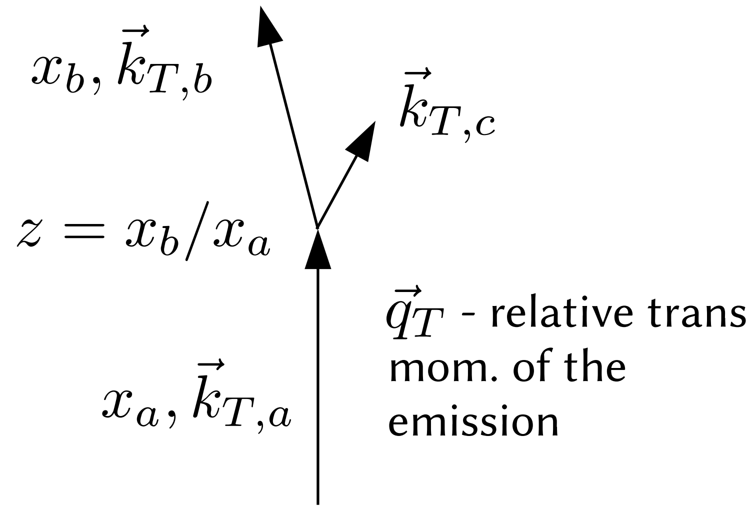
- The Parton Branching method allows to study different parton shower ordering conditions
  $\longrightarrow$ the bridge between MC parton showers and PDF fits from analytic DGLAP solution

- **Virtuality ordering** ($\mu^2 \stackrel{\text{def}}{=\!=} Q^2$)

  $$q_T^2 = (1-z)\, Q^2 \stackrel{\text{def}}{=\!=} (1-z)\ \mu^2$$

- **Angular ordering** ($\mu^2 \stackrel{\text{def}}{=\!=} \theta^2$)

  $$q_T^2 = (1-z)^2\theta^2 \stackrel{\text{def}}{=\!=} (1-z)^2\mu^2$$



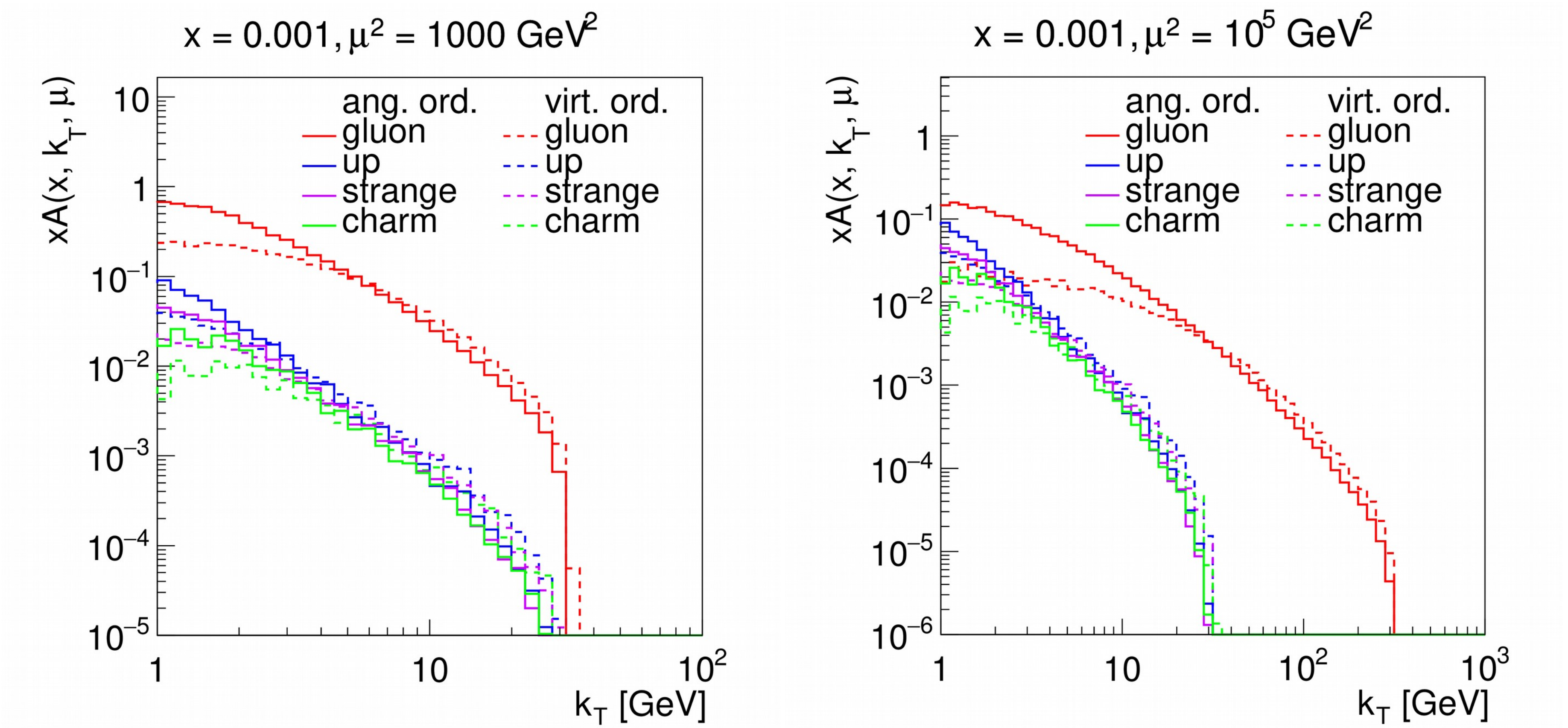
- k_T distribution as a probe of the parton shower coherence effects presented in case of angular ordered shower (e.g. in Drell-Yan process)

$$\vec{k}_{T,b} = z\vec{k}_{T,a} + \vec{q}_T$$

$$\vec{k}_{T,c} = (1-z)\vec{k}_{T,a} - \vec{q}_T$$

TMD distributions for various flavors

- At higher scales the quark k_T significantly smaller than the gluon one (quarks radiate less)
- Angular ordering leads to smaller k_T virtuality ordering



At the starting scale $\mu^2 = 2$ all flavors has the same Gaussian distribution of k_T with variance 1 GeV^2, correct assumption?

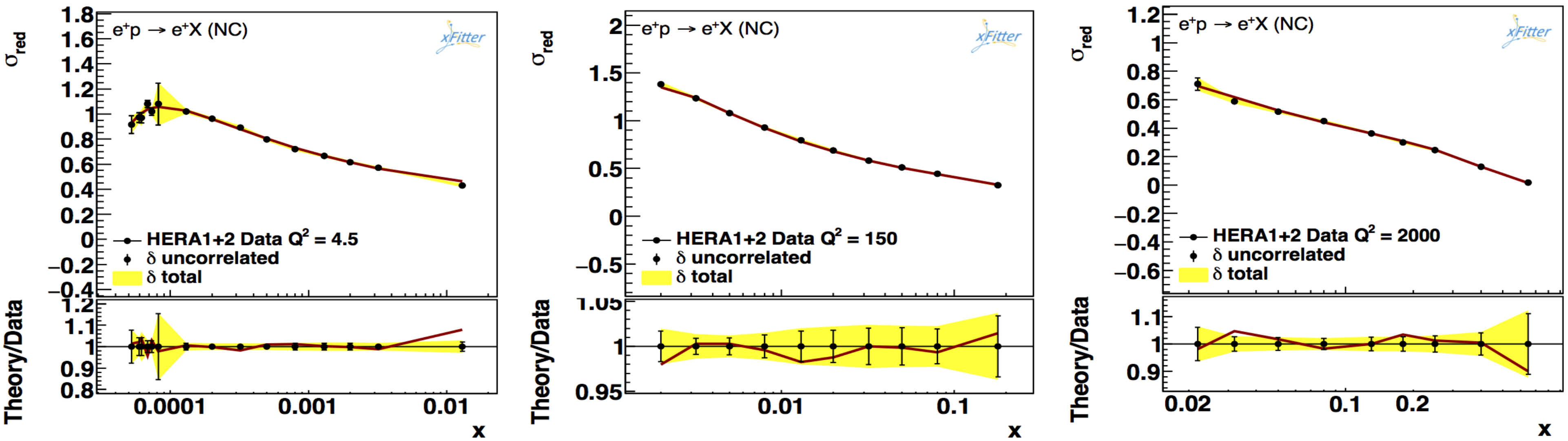
TMD fits using xFitter

- The evolution kernels extracted using parton branching method

$$A_a(x, k_T, \mu^2) = \int dx' A_{0,b}(x') \frac{x}{x'} A_a^b(\frac{x}{x'}, k_T, \mu^2)$$

- Fit of HERA DIS data ($Q^2 > 3.5\,\mathrm{GeV}^2$) gives $\chi^2/ndf \sim 1.2$ data set similar as in HERAPDF

- For now, the k_T distribution at starting scale kept fixed

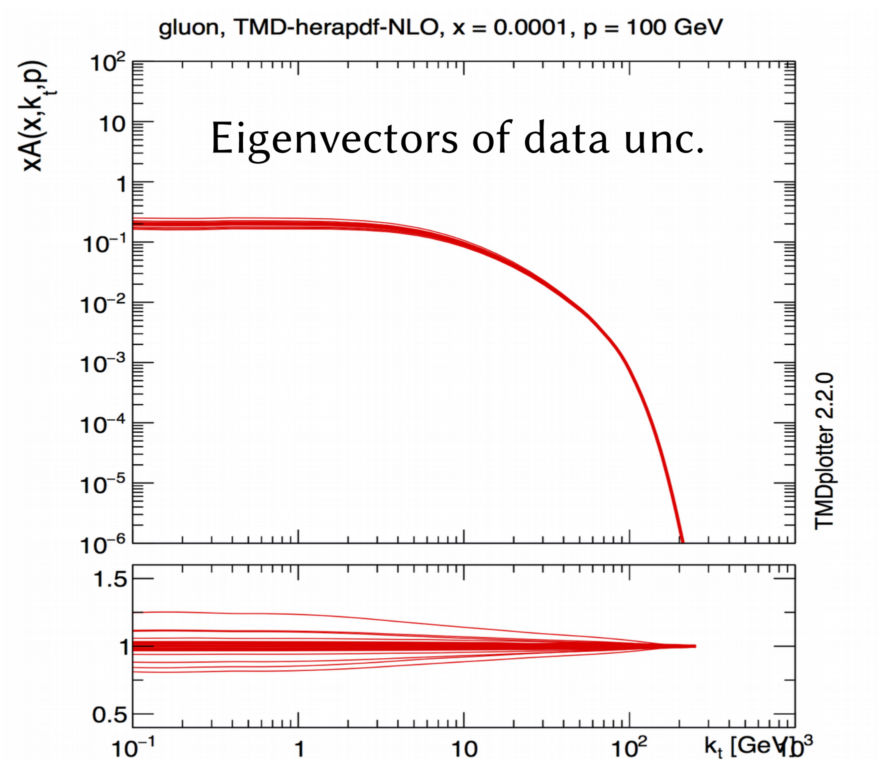


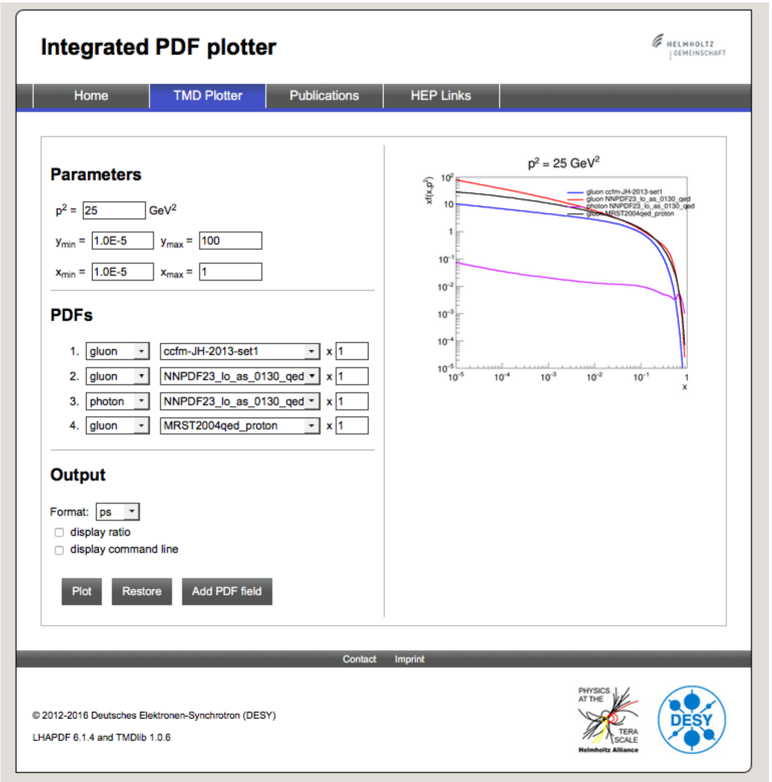
TMD densities

- Experimental uncertainties of the fitted data propagates into k_T spectrum of PDF
- The k_T spectra for LO and NLO evolution in general different

- For more information see the TMD library and TMD plotter
  http://tmd.hepforge.org
  http://tmdplotter.desy.de

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.



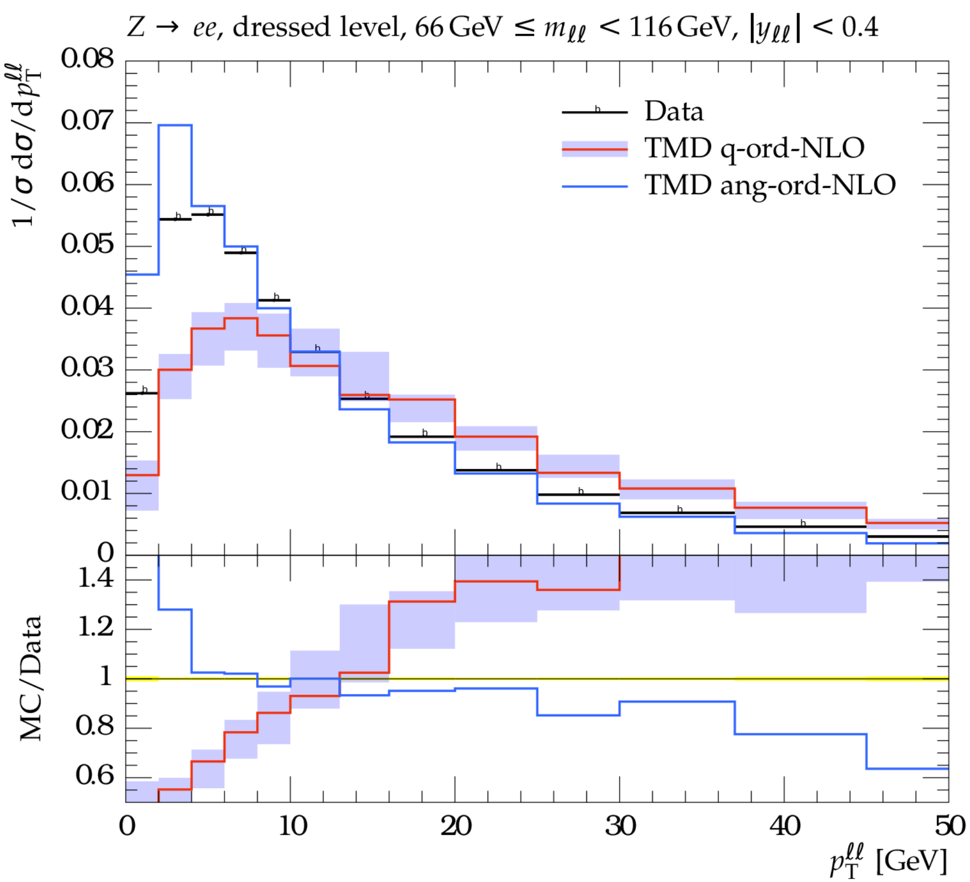


Application: DY production (LO)

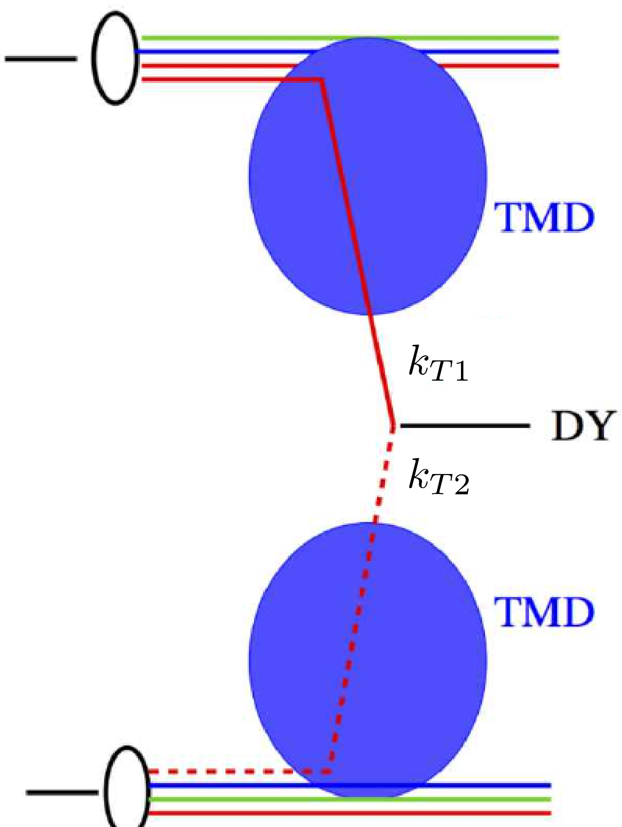
- Cross section as a convolution of TMDs and LO ME $q\bar{q} \rightarrow Z^0$

$$\sigma = A(x_1, k_{T1}, \mu^2) \otimes \hat{\sigma} \otimes A(x_2, k_{T2}, \mu^2)$$

- At LO the $p_T(Z)$ is somewhere between q-ordered and angular ordered solution



Measurement of the transverse momentum and ϕ^*_η distributions of Drell–Yan lepton pairs in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector [arXiv:1512.02192]



Application: DY production (NLO)

- We used POWHEG to generate events of Z production at NLO accuracy
- The POWHEG "events" are convoluted (matched) with our TMDs
- There are two sources affecting resulting $p_T(Z)$:
  1) The emission of the hardest jet (from ME of POWHEG)
  2) TMDs
- Possibility to generate whole hadronic system using TMD based parton shower (CASCADE)

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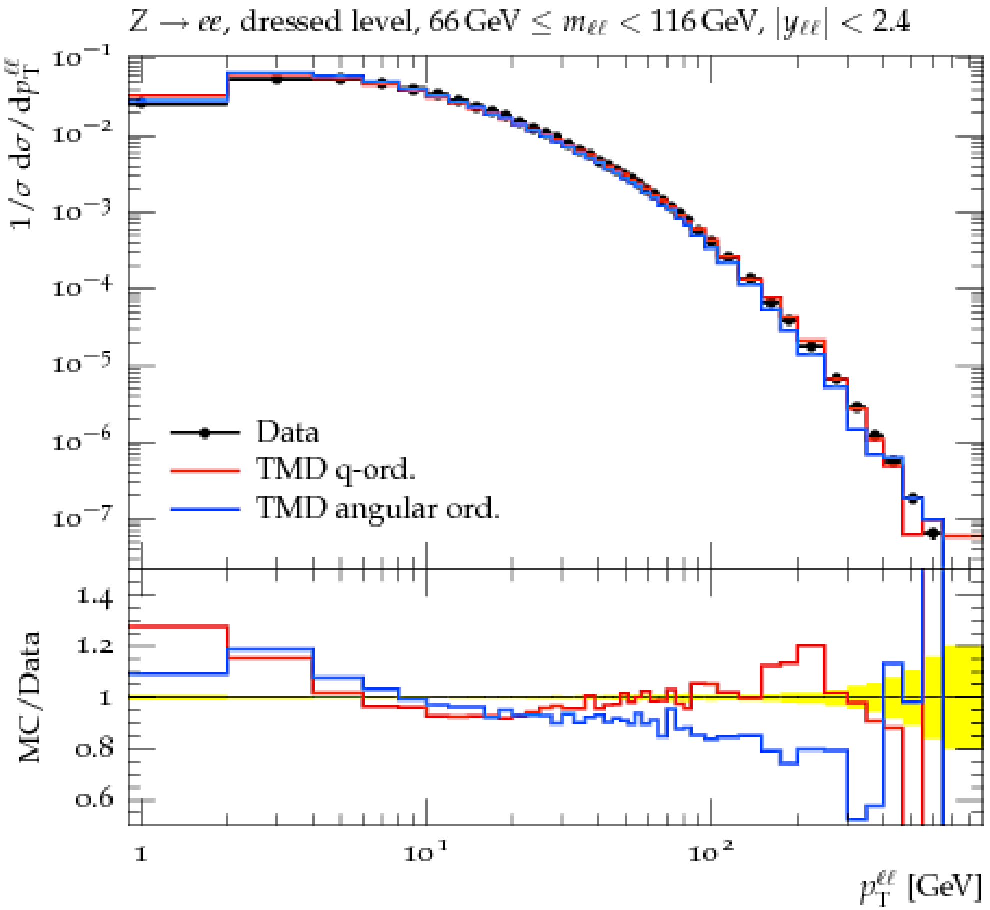

Conclusions

- The developed Parton Branching method solves DGLAP equation at LO, NLO and NNLO “collinear” accuracy
- Possibility to study effects of different ordering conditions and resolution criteria in the shower
- The Parton Branching evolution implemented within **xFitter**, $\longrightarrow$ first TMDs at LO and NLO obtained from HERA inclusive DIS data $\longrightarrow$ comparison of the p_T(Z)

Plans for the future:

- Predictions with off-shell matrix elements
- Better constrain the TMD evolution using p_T(Z) spectrum
- More NLO predictions