TMDs from parton branching method at LO and NLO and first applications

Hannes Jung (DESY)

- Why TMDs are needed
  - TMDs for hadron-hadron collisions
- New developments (together with F. Hautmann, A. Lelek, V. Radescu, R. Zlebcik)
  - parton branching algorithm to solve evolution equations
    - benchmark tests
    - advantages for integrated PDFs
  - determination of TMD densities at LO and NLO with xFitter
- Applications: DY production using TMDs

TMDs – what is it ?

- TMDs (Transverse Momentum Dependent parton distribution)
  - at very small transverse momenta
    - typically for very 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)
  - for an overview of different approaches and state-of-the-art discussion see

    R. Angeles-Martinez et al
    Transverse momentum dependent (TMD) parton distribution functions: status and prospects. Acta Phys. Polon., B46(12):2501–2534, 07 2015, arXiv 1507.05267

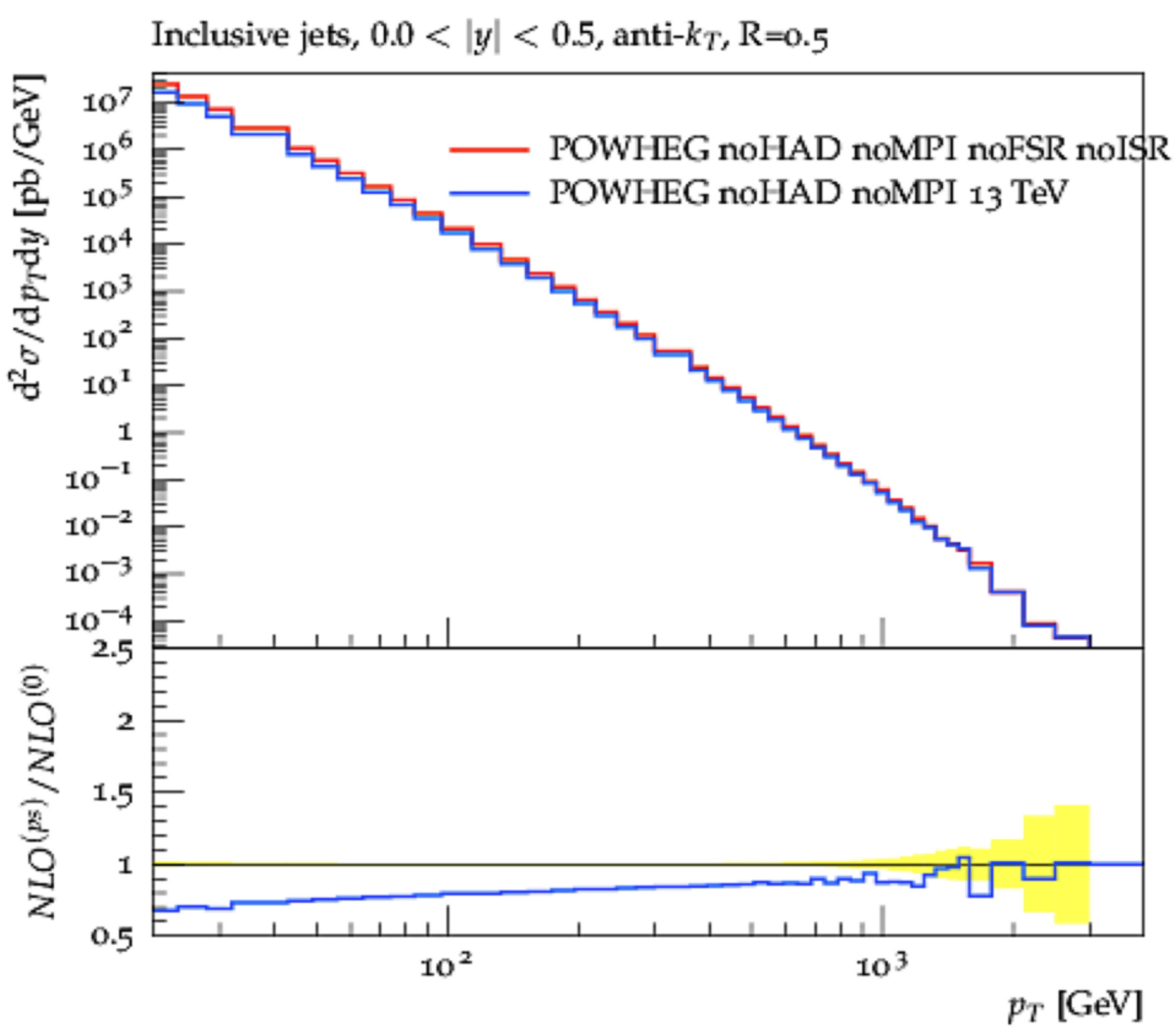
Why TMDs are needed even at large scales ?

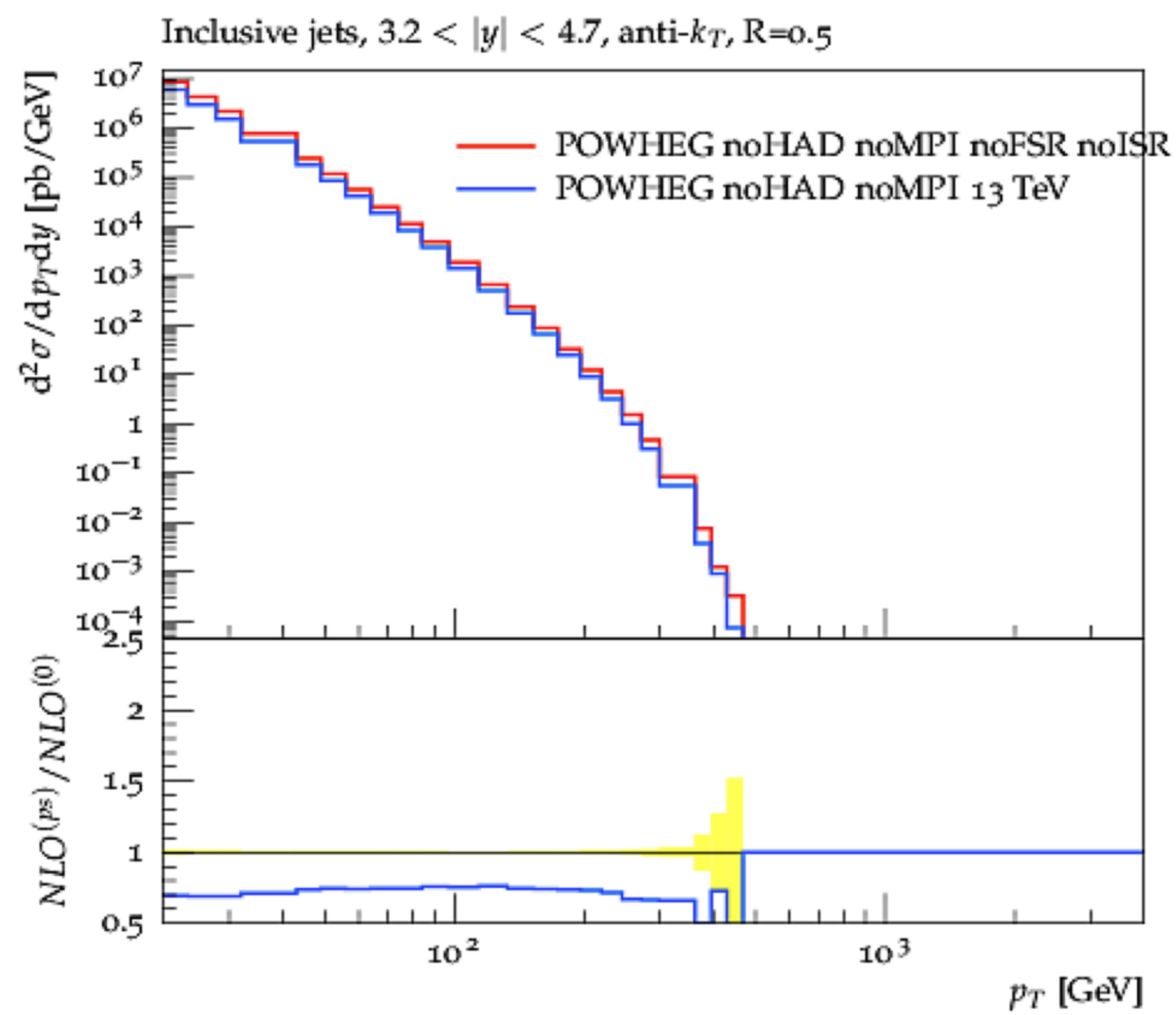
Approach described in: S. Dooling et al Phys.Rev., D87:094009, 2013.

- use NLO+PS to calculate:

$$K^{PS} = \frac{N^{(ps)}_{NLO-MC}}{N^{(0)}_{NLO-MC}}$$

- Corrections to be applied to fixed order NLO calculations:
  - kinematic effects: TMDs !
  - radiation outside of jet-cone





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 p_t

- New: parton branching method
  - perform evolution using a parton branching method
  - determine integrated PDF from parton branching solution of evolution equation
    - 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

for similar approaches see also:
W. Placzek, K. J. Golec-Biernat, S. Jadach, M. Skrzypek. Acta Phys. Polon., B38:2357–2368, 2007.
H. Tanaka. Prog. Theor. Phys., 110:963–973, 2003.

How to obtain TMDs – the parton branching method

- F. Hautmann, H. Jung, A. Lelek, V. Radescu, R. Zlebcik.
  Soft-gluon resolution scale in QCD evolution equations.
  arXiv 1704.01757, DESY 16-174.

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 evolution – 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:

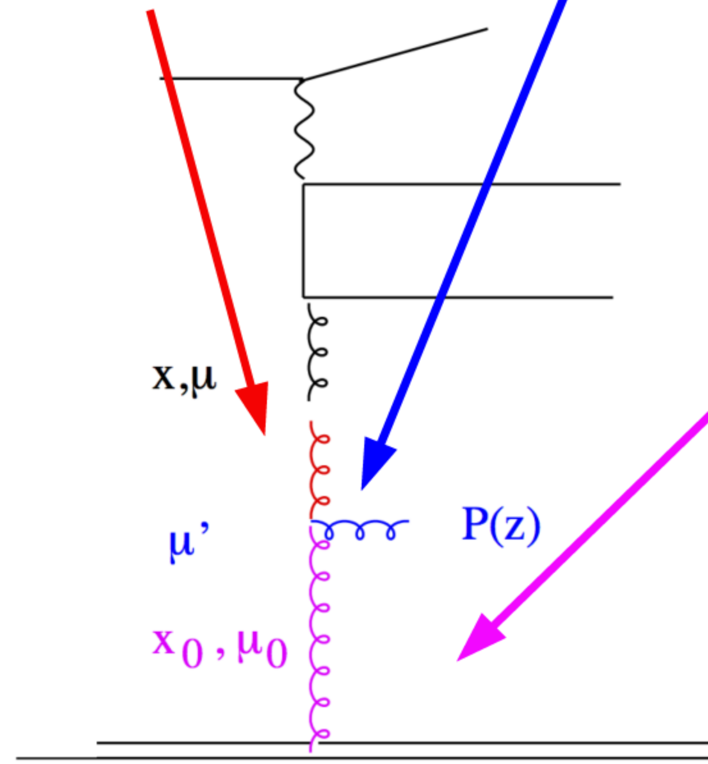
$$f_0(x,\mu^2) = f(x,\mu_0^2)\Delta(\mu^2)$$

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

from *t'* to *t*
w/o branching

branching at *t'*

from t_0 to *t'*
w/o branching



Evolution equation and parton branching method

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

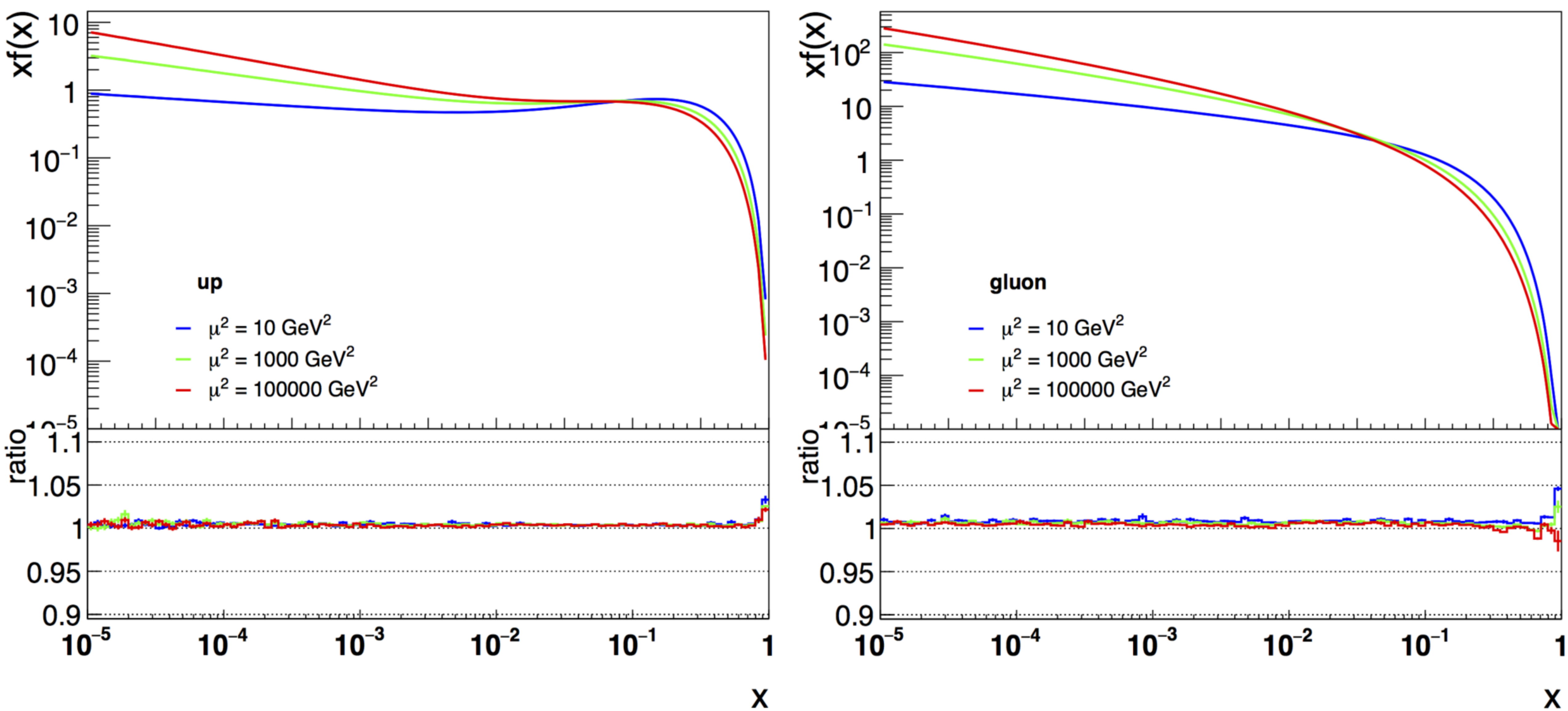
$$
\begin{aligned}
x f_a(x, \mu^2) &= \Delta_a(\mu^2)\; x f_a(x, \mu_0^2) \\
&+ \sum_b \int_{\mu_0}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s, z)\; \frac{x}{z} f_b\left(\frac{x}{z}, \mu'^2\right)
\end{aligned}
$$

  - 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

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

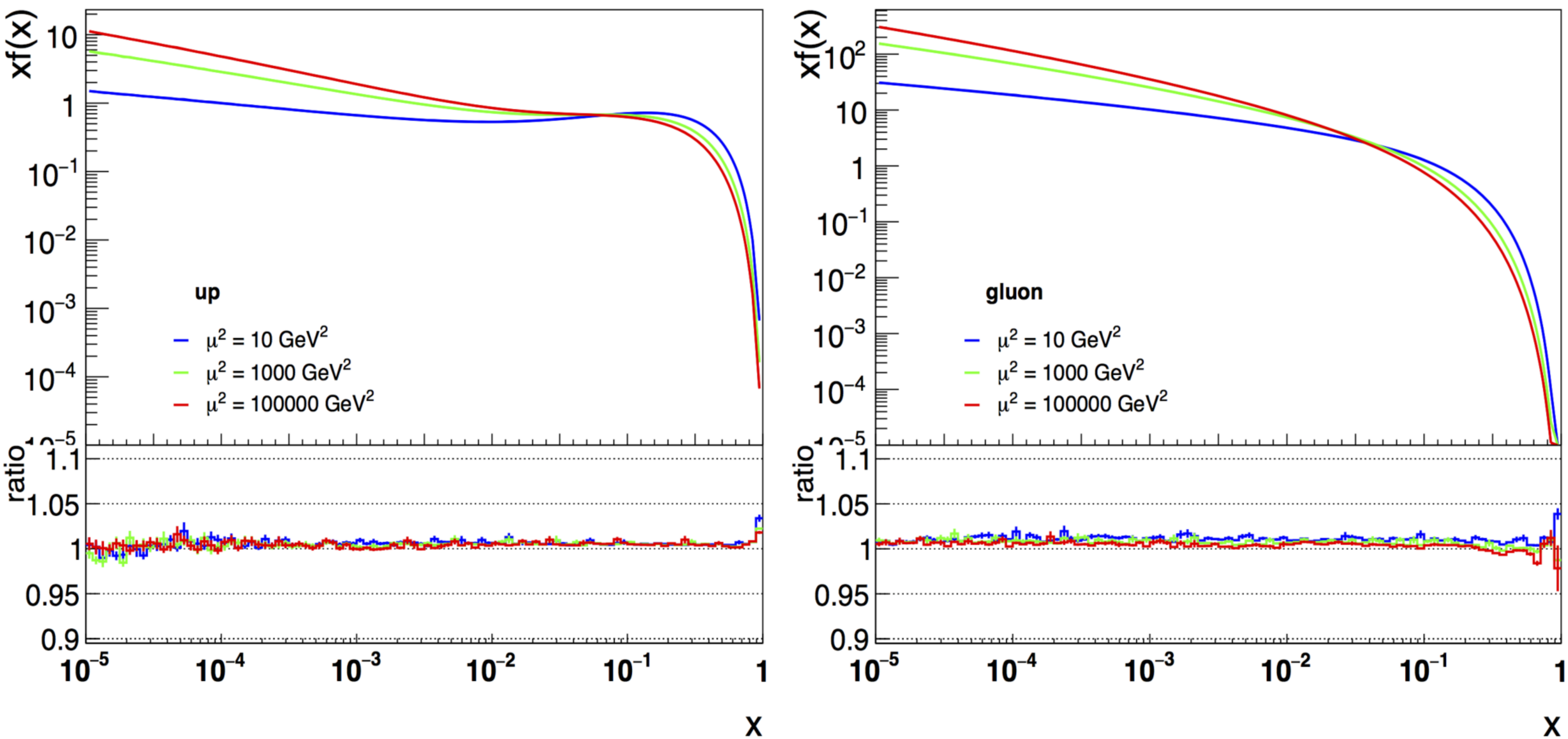
$$
\Delta_a(z_M, \mu^2, \mu_0^2) = \exp\left(- \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_0^{z_M} dz\; z\; P_{ba}^{(R)}(\alpha_s), z) \right)
$$

Validation of method with semi-analytic result at LO



- Very good agreement with LO – semi-analytic method (QCDnum) over all x and μ^2

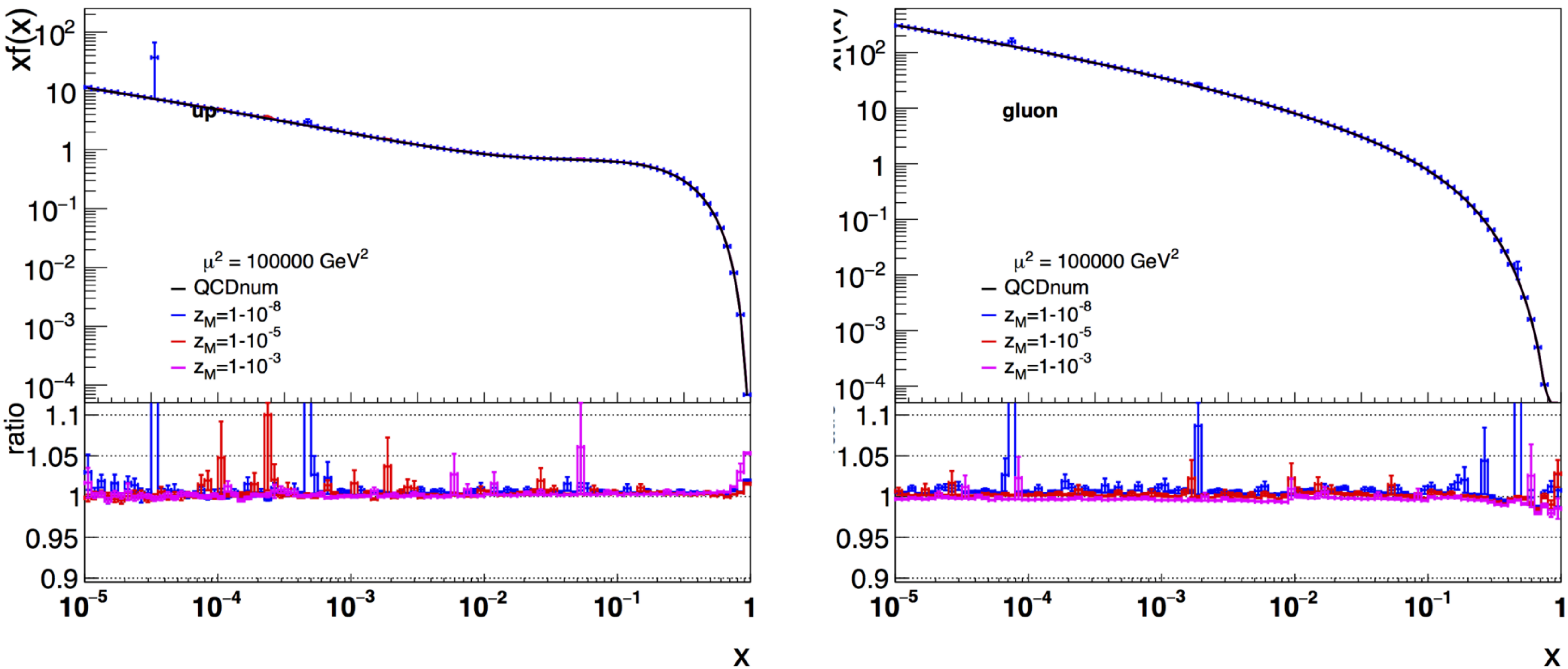
Validation of method with semi-analytic result at NLO



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

Resolvable branching – at LO and NLO

- Investigate dependence on z_M : separate resolvable from virtual and non-resolvable branchings



- for large enough z_M : results are stable, both at LO and NLO (shown)
  - Sudakov treats non-resolvable and virtual branchings to all orders !

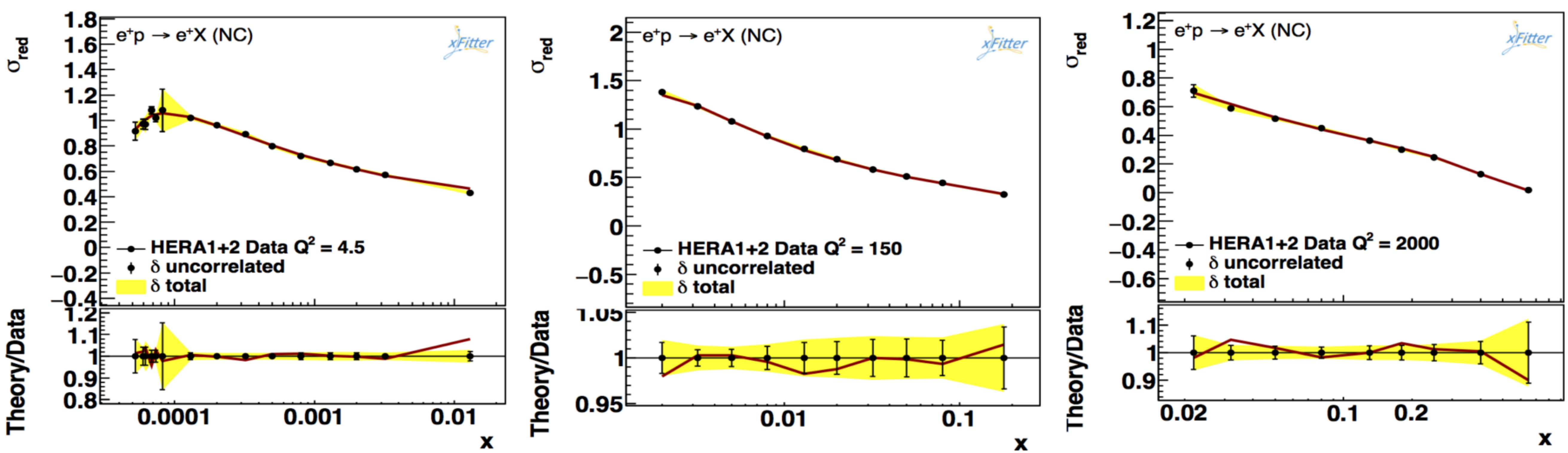
Parton branching method in xFitter

- Determine starting distribution

A. Lelek et al REF 2016

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

- fit to HERA data (using xFitter) with $Q^2 \geq 3.5$ GeV^2 gives $\chi^2/ndf \sim 1.2$

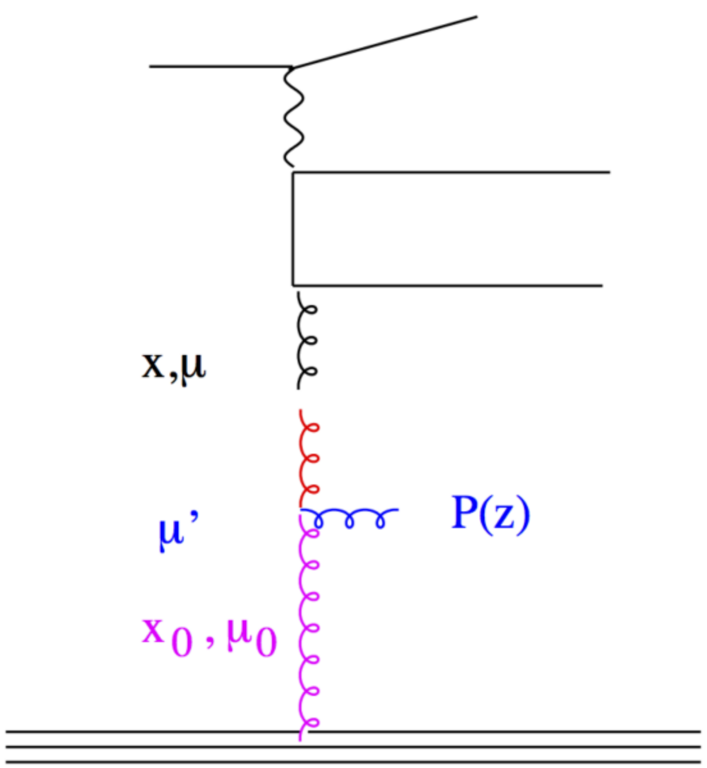


- procedure to fit initial distribution is working and producing results as expected

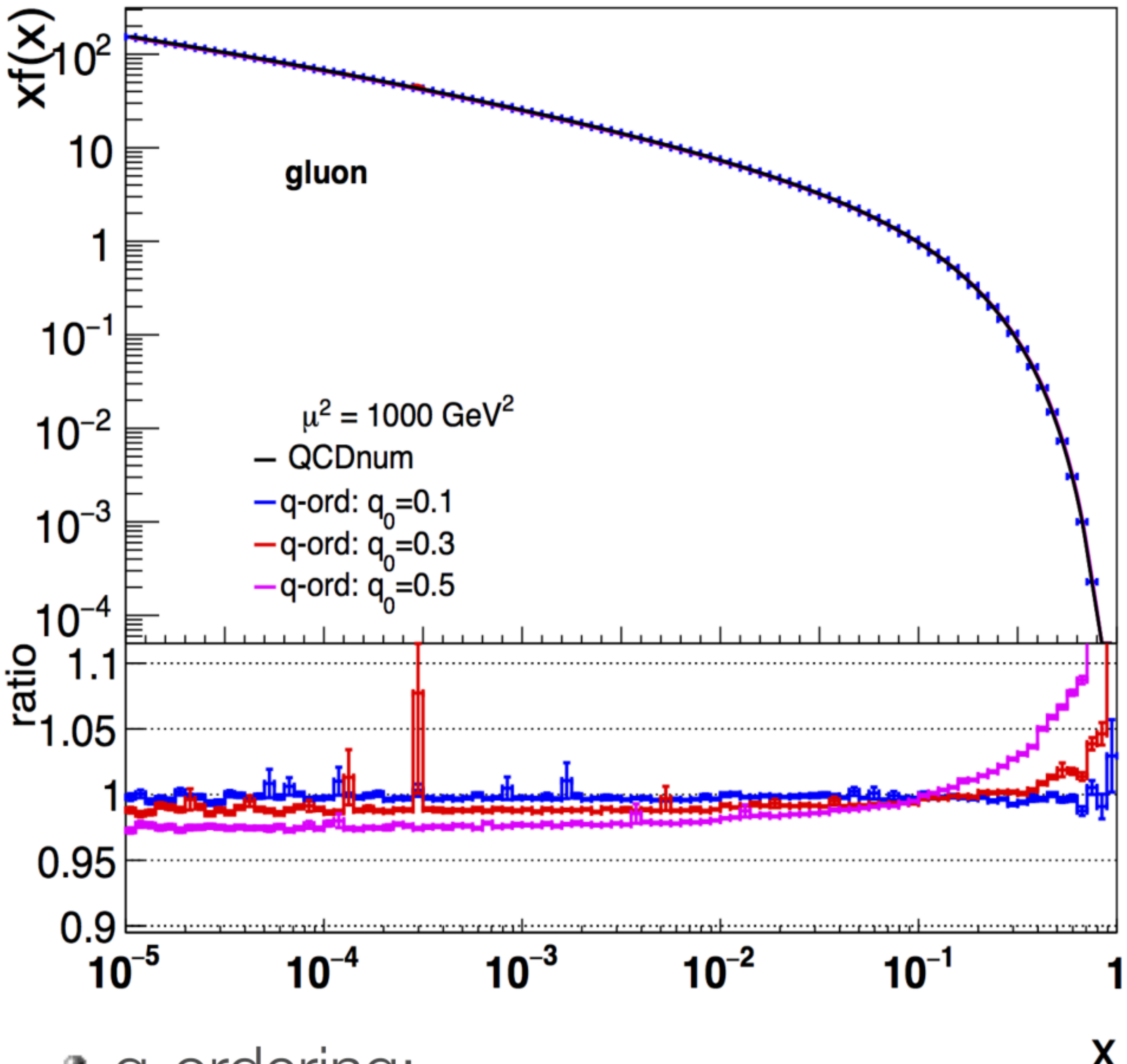
Advantages of parton branching method

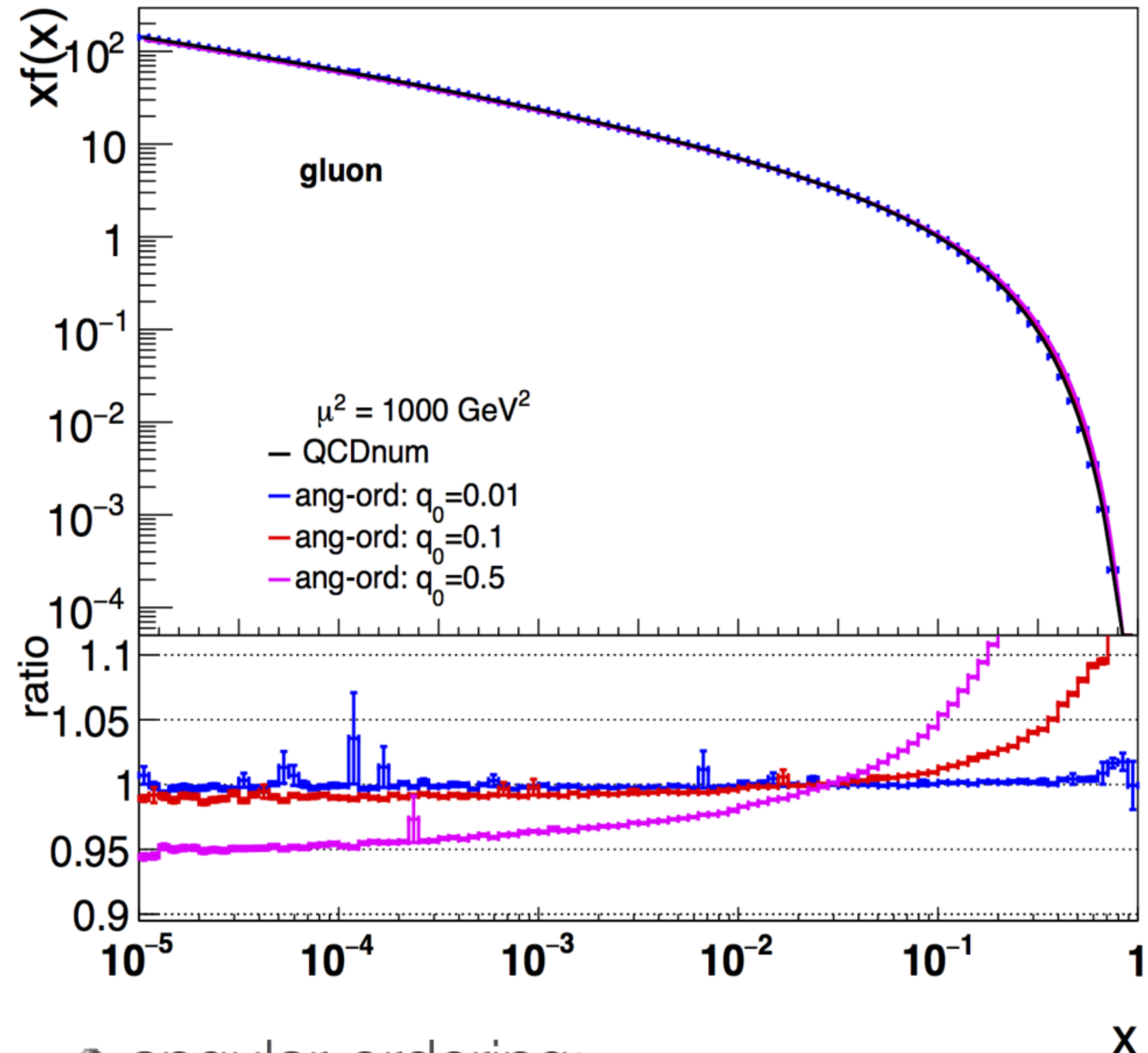
- Consistency checks with QCDnum show agreement for inclusive distributions at the 0.1% level

- Advantages of parton branching method for collinear PDFs:
  - studies of different ordering conditions possible for the first time
    - resolvable branchings as defined by (q is evolution variable):
      - angular-ordering with varying $z_M = 1 - q_0/\mu'$
      - q^2 - ordering with varying $z_M = 1 - q_0^2/\mu'^2$



parton branching: different ordering conditions





- q-ordering:
  - dependence on parameter for resolvable branching $z_M = 1 - q_0^2/\mu'^2$
- angular-ordering:
  - strong dependence on parameter for resolvable branching $z_M = 1 - q_0/\mu'$

- large x resummation effects in parton densities: resolvable branchings !

Advantages of parton branching method

- Consistency checks with QCDnum show agreement for inclusive distributions at the 0.1% level

- Advantages of parton branching method for collinear PDFs:
  - studies of different ordering conditions possible for the first time
    - resolvable branchings as defined by:
      - angular ordering with varying $z_M = 1 - q_0/\mu'$
      - Q^2 ordering with varying $z_M = 1 - q_0^2/\mu'^2$
  - different choices of scales in $\alpha_s(\mu)$ possible
  - any investigation which involves details of parton branching kinematics

- further advantages – determination of TMD parton densities
  - since parton branching kinematics are known, transverse momenta of propagating partons can be calculated – determine TMD

Determination of TMD distribution

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

- solve integral equation via iteration:

from t' to t w/o branching

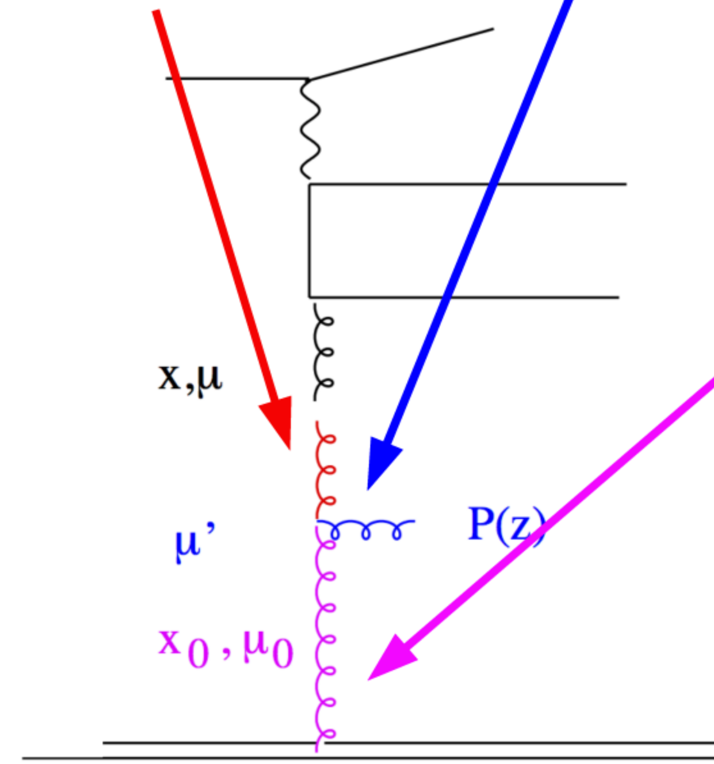
branching at t'

from t_0 to t' w/o branching

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

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

- in every step, kinematics are known:
  - calculate k_t of propagator



Determination of TMD distribution

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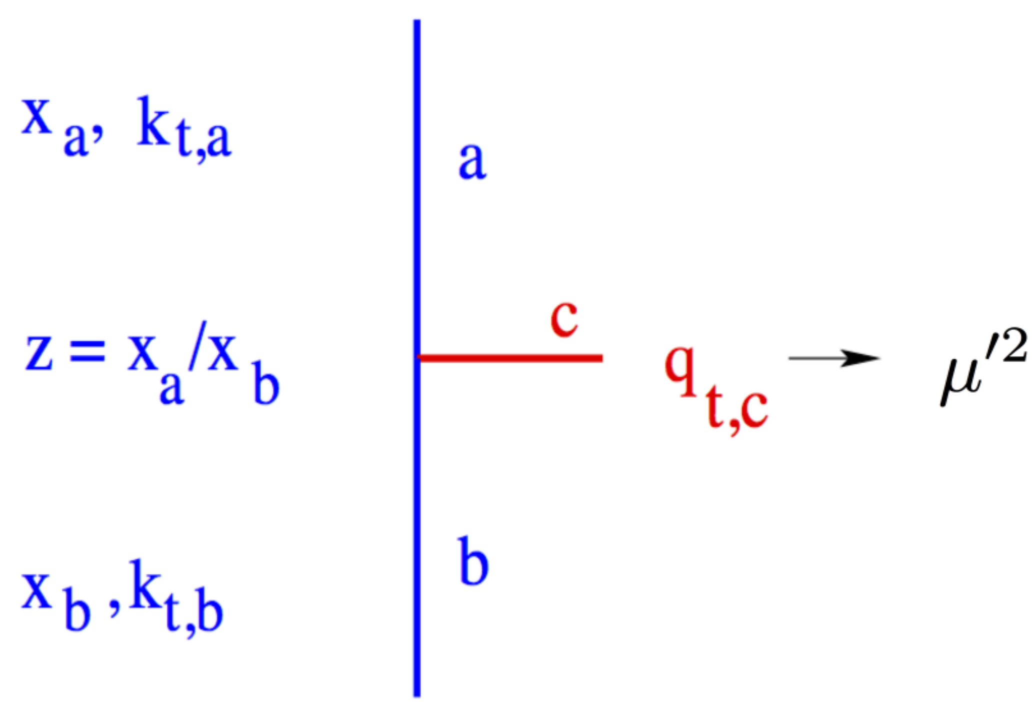
- in every step, kinematics are known:
  - calculate k_t of propagator
  - need correspondence:
    - $q_t{}^2 = \mu'^2$ with q_t emitted parton

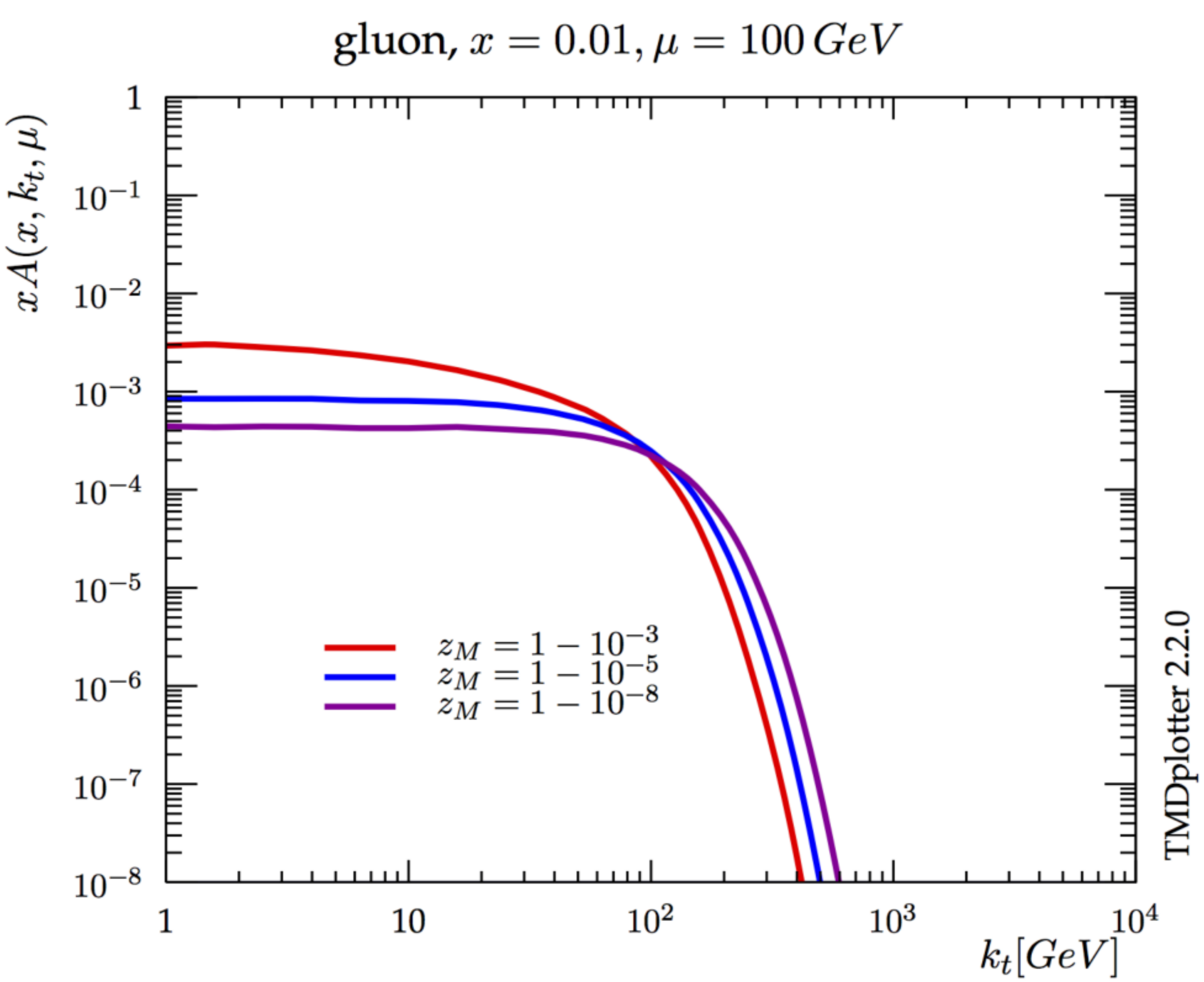
      OR
    - $q_t{}^2 = (1-z)\,\mu'^2$, q^2 - ordering

      OR
    - $q_t{}^2 = (1-z)\,\mu'$ angular - ordering



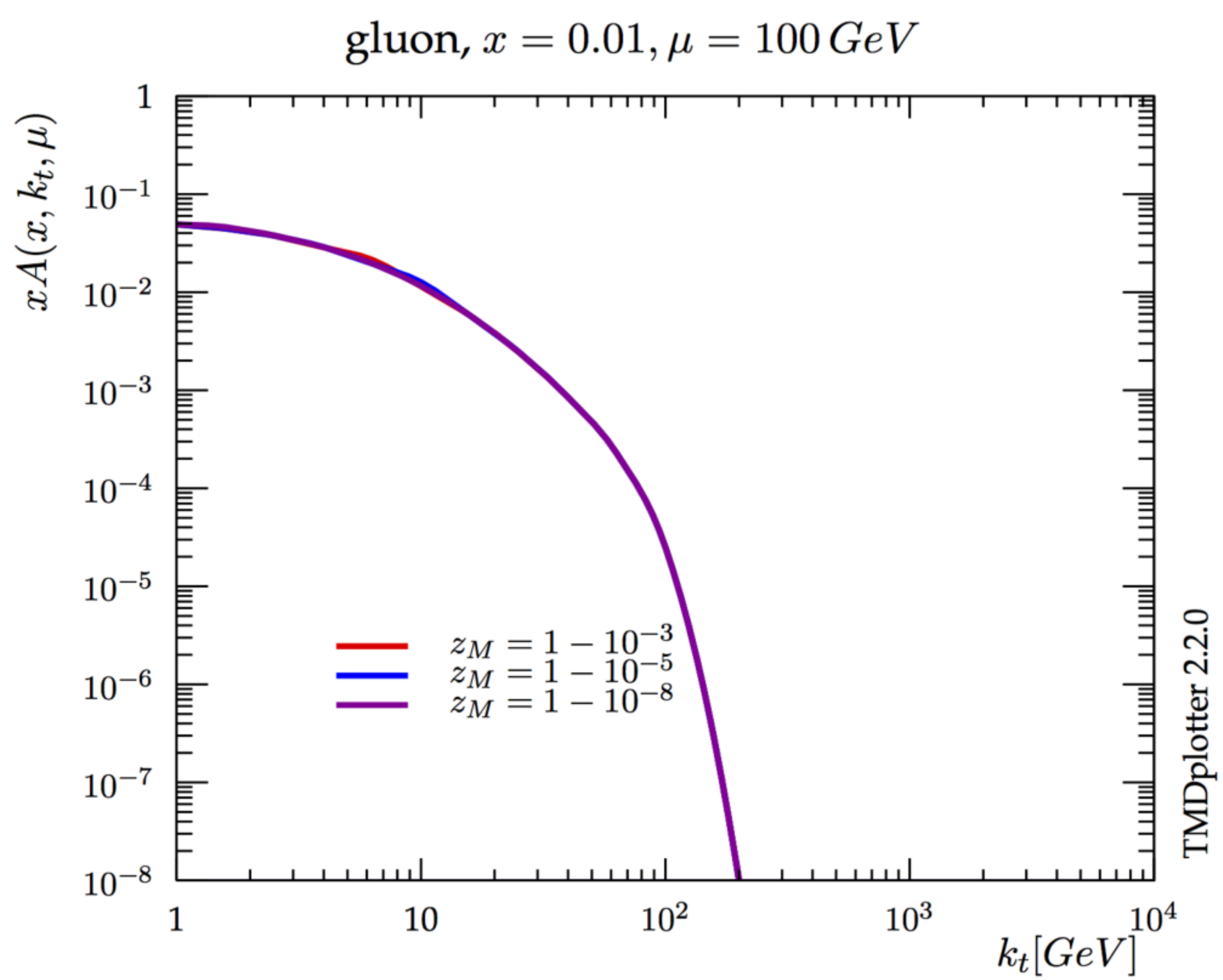
Determination of TMD distribution

- naïve q_t - ordering
  - $q_t^2 = \mu^2$ with q_t emitted parton
    - $k_t = k'_t + q_t$



- Huge z_{max} dependence due to many soft gluons ($z_{max} \to 1$)

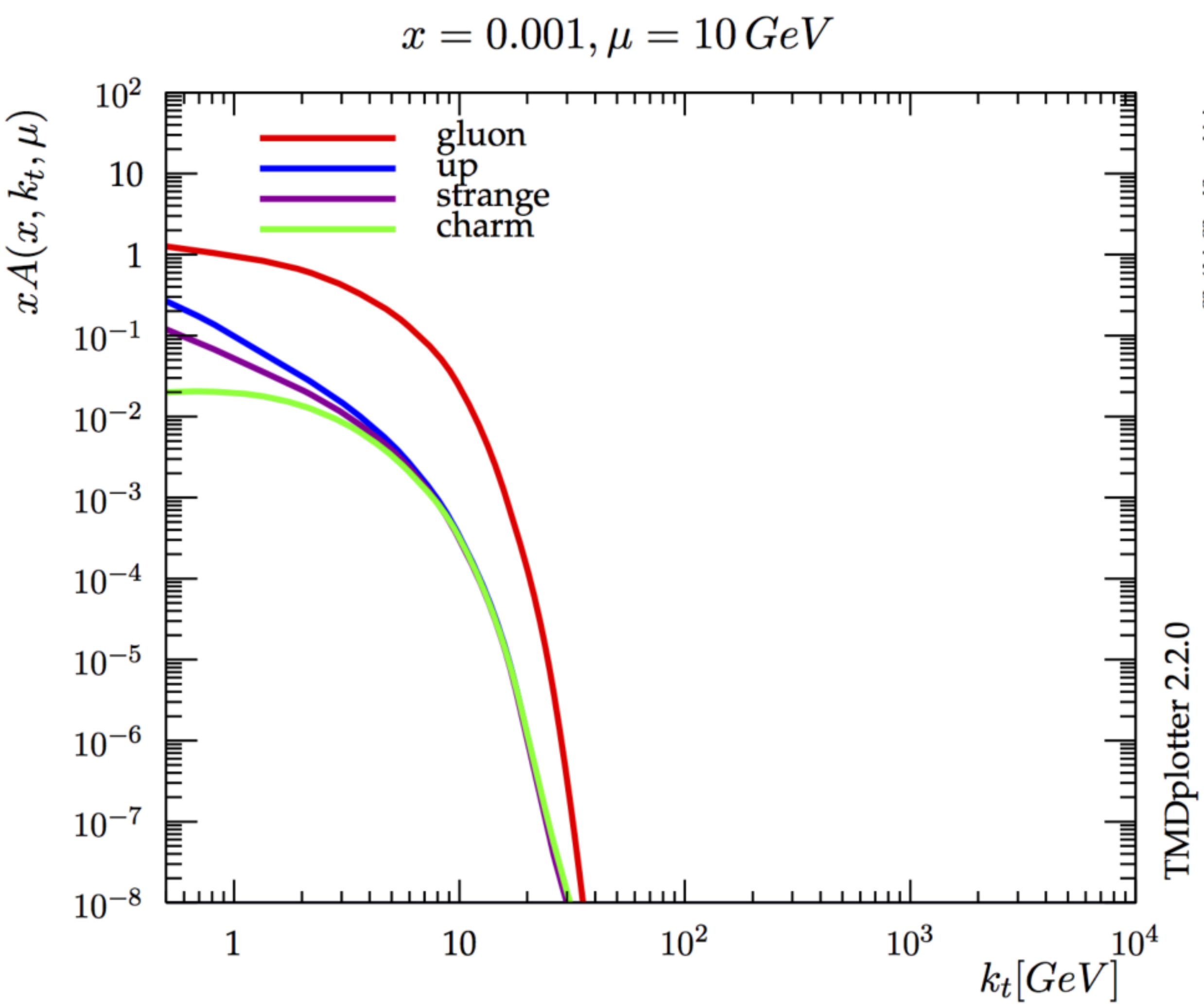
- q^2 - ordering
  - $q_t^2 = (1 - z)\, \mu'^2$
    - $k_t = k'_t + q_t \sqrt{(1-z)}$

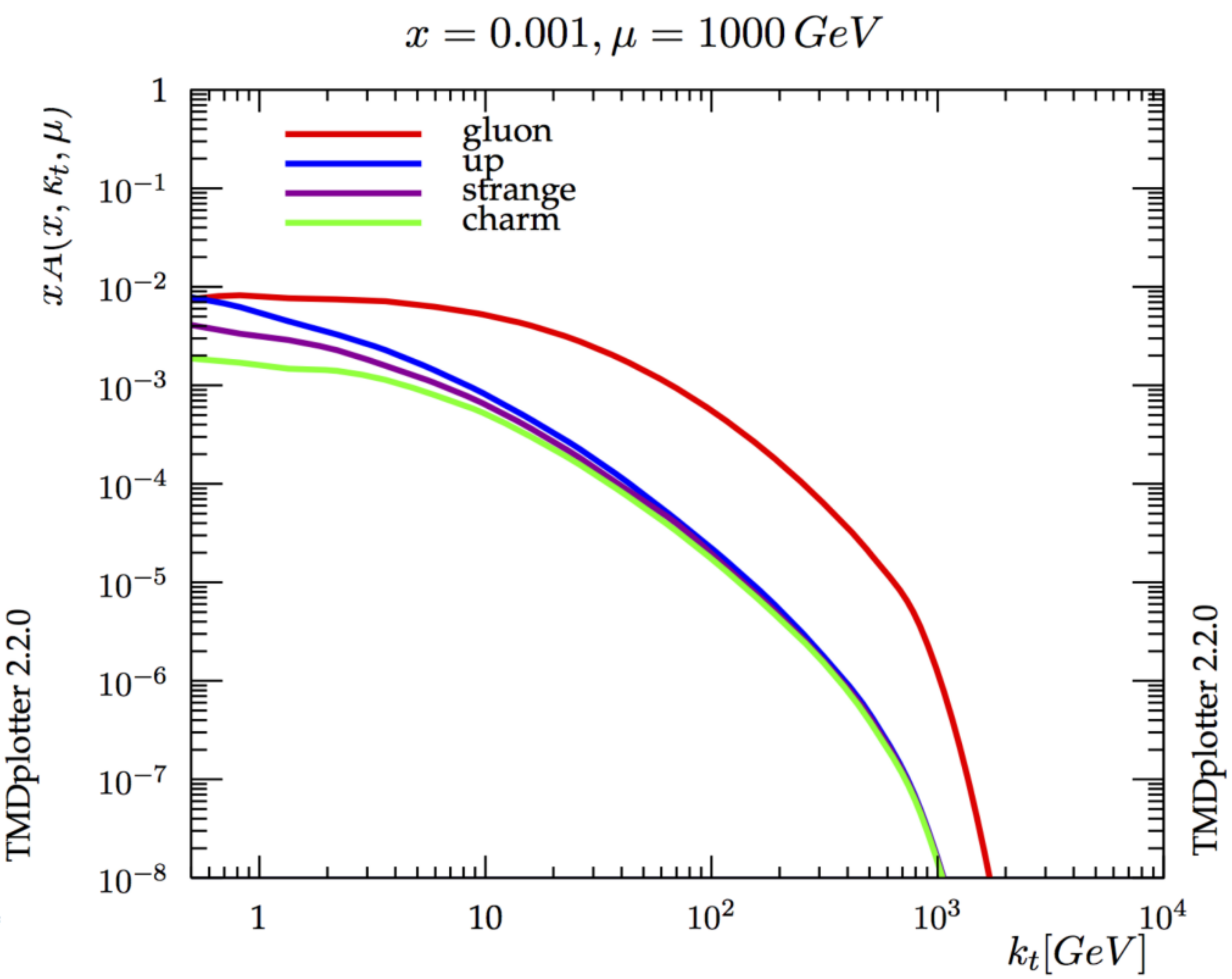


- Due to q^2 -ordering, soft gluons are suppressed → stable results

TMD distributions for different flavors

- with parton-branching method, TMD distribution for all flavors can be determined.





- at small k_t intrinsic (gauss) distribution is used $\rightarrow$ subject to fit at small k_t
- at $k_t \geq Q_0$, k_t – distribution comes entirely from evolution,
  - no free parameters, except association of evolution scale with q_t

TMD distributions for different flavors

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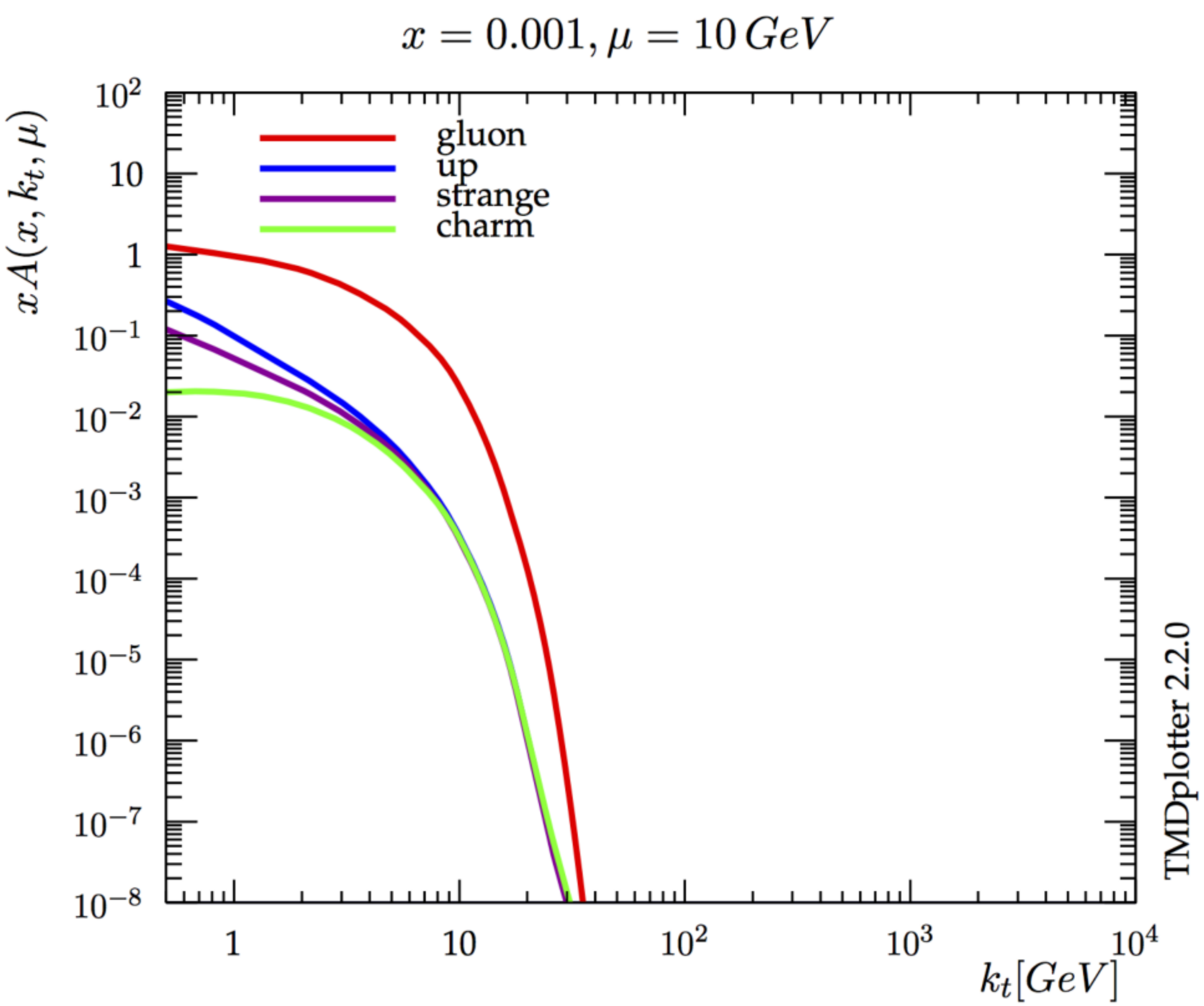
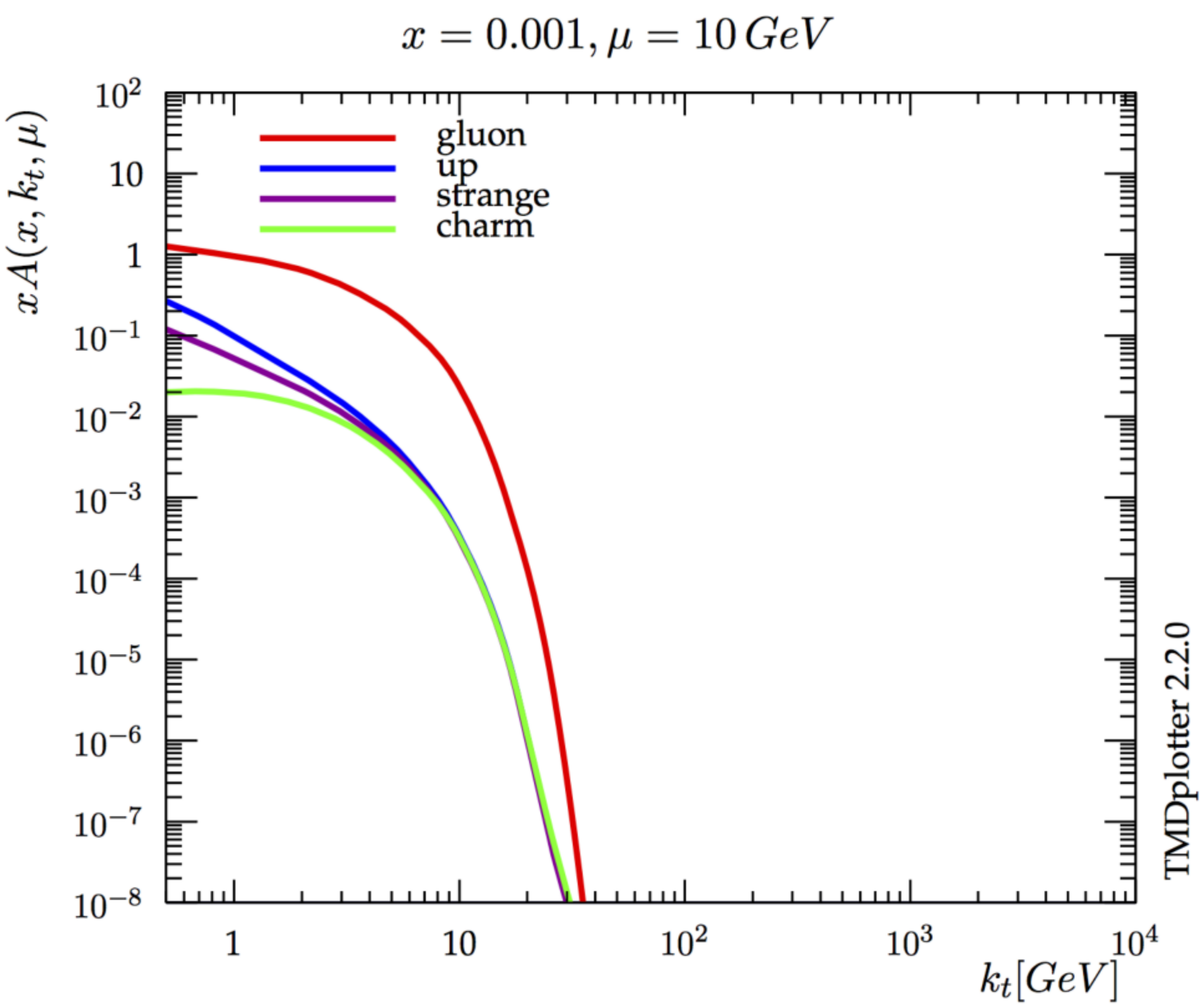


- small k_t: distributions are different

TMD distributions for different flavors

- with parton-branching method, TMD distribution for all flavors can be determined.



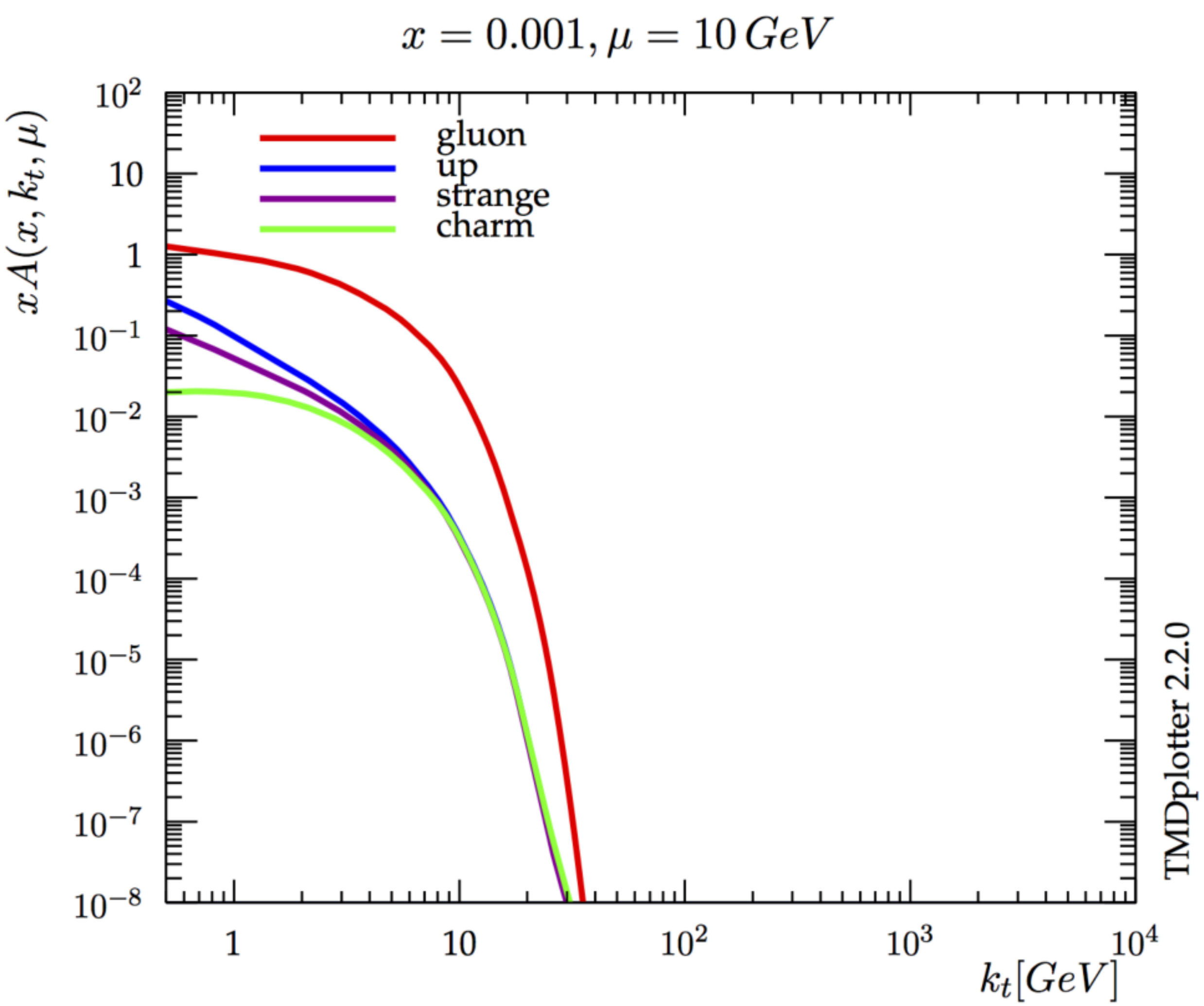
- small k_t: distributions are different

$$x f_a(x,\mu^2) \quad = \quad \Delta_a(\mu^2)\; x f_a(x,\mu_0^2) + \cdots$$

➔ depends on distribution at starting scale

TMD distributions for different flavors

- with parton-branching method, TMD distribution for all flavors can be determined.



- small k_t: distributions are different

$$xA(x, k_\perp^2, \mu^2) = \Delta_a(\mu^2)\; xA(x, k_\perp^2, \mu_0^2) + \cdots$$

➔ depends on distribution at starting scale

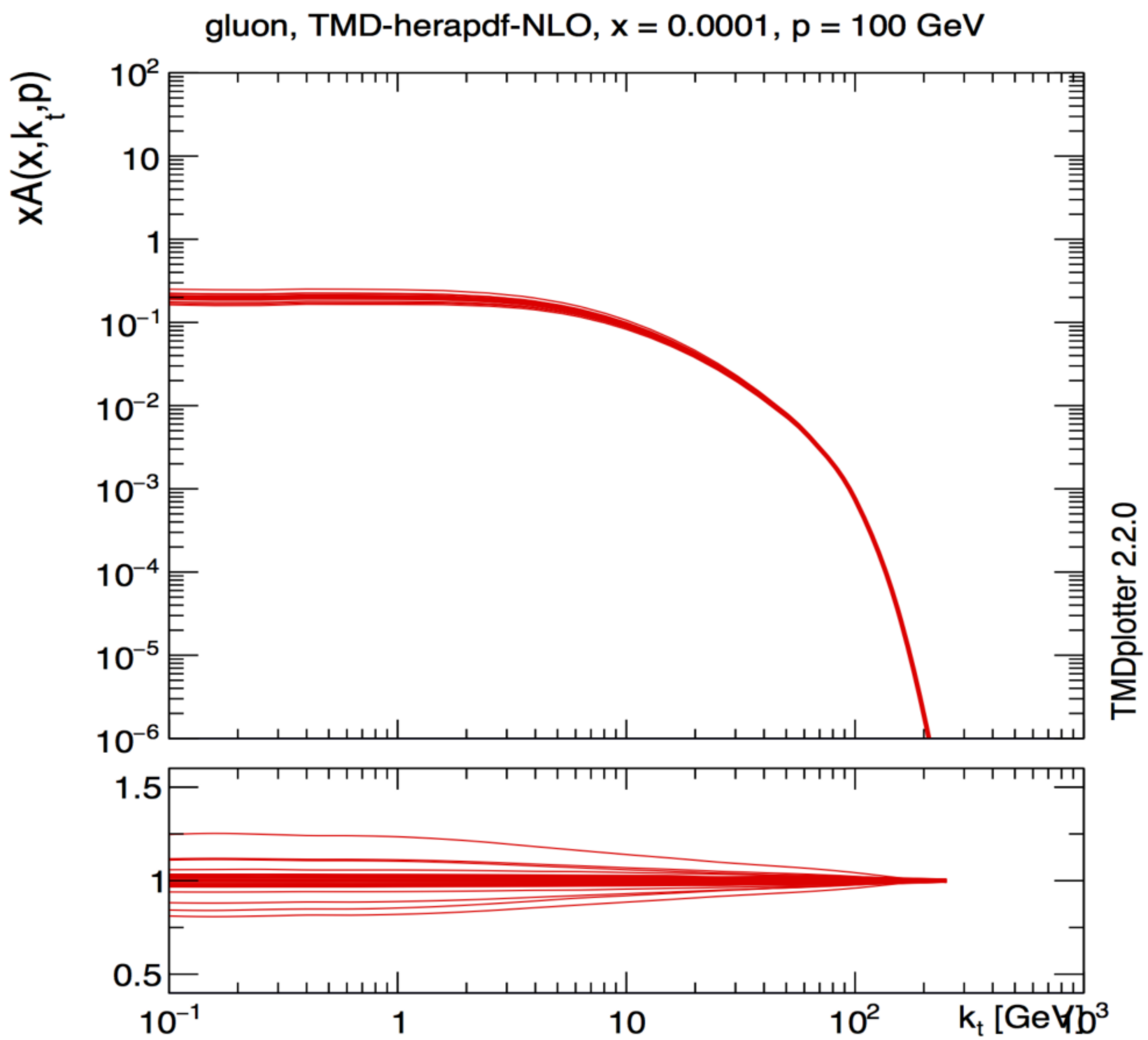
- large k_t : quarks have similar shape

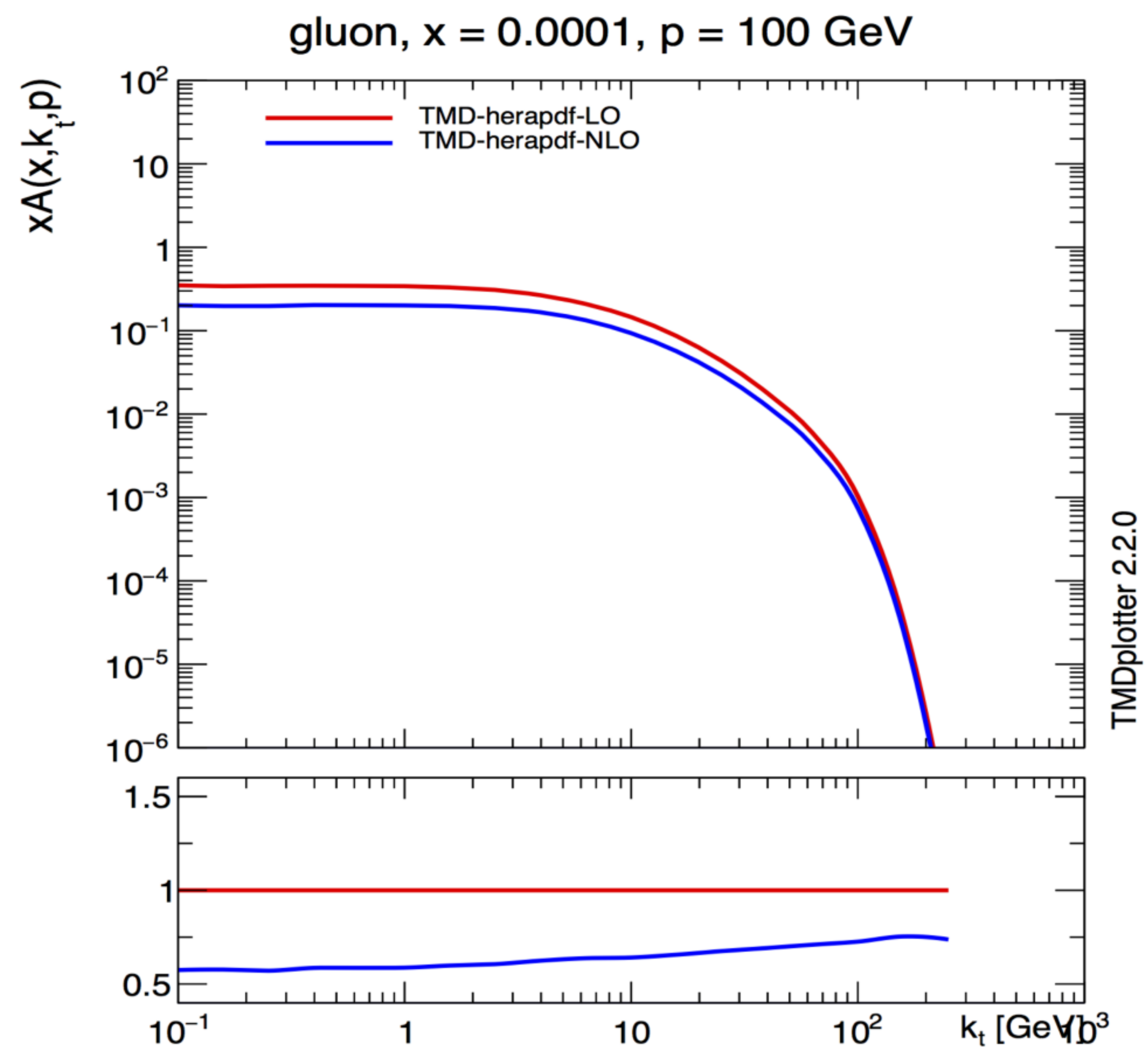
$$xA(x, k_\perp^2, \mu^2) = \cdots + \sum_b \int_{\mu_0}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \int_x^{z_M} dz P_{ab}^{(R)} \frac{x}{z} \mathcal{A}\left(\frac{x}{z}, k_\perp'^2, \mu'^2\right)$$

➔ distributions similar due to parton evolution

- k_t -distributions at large scales depend on initial and evolved distributions

TMD distributions from xFitter: herapdf-type



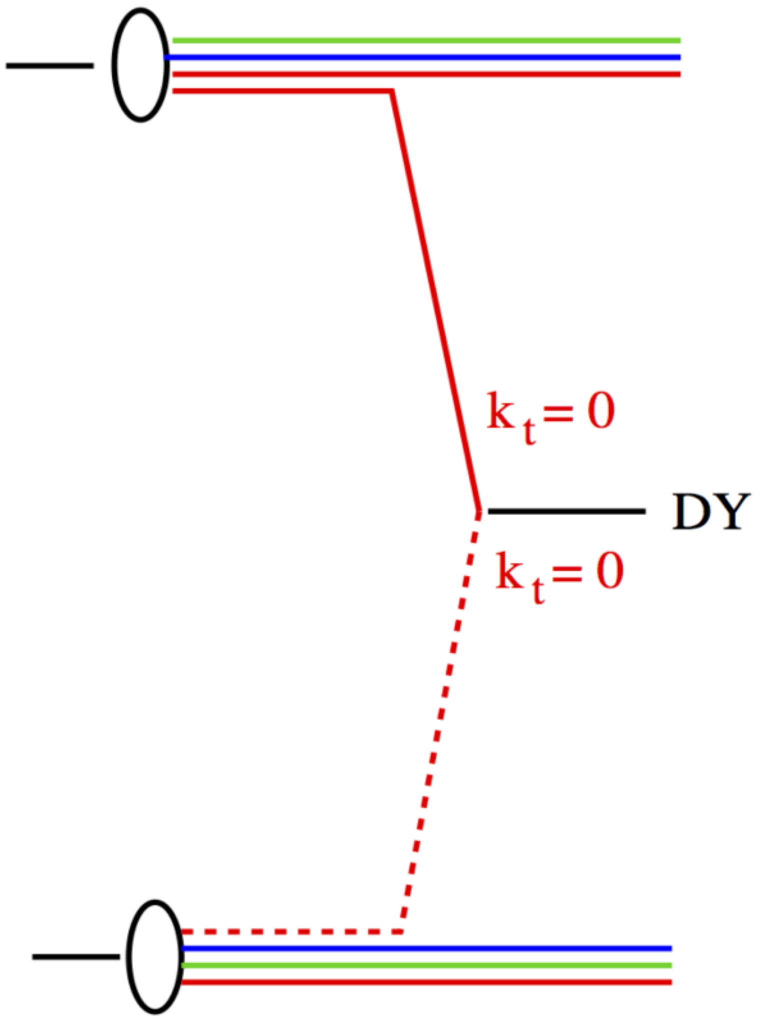


- Transverse momentum distributions including uncertainties from herapdf fit
    - only experimental uncertainties
- TMD distribution is different for NLO and LO
    - LO and NLO have different number of branchings !

Application: DY production using TMDs

together with: A. Lelek, R. Zlebcik

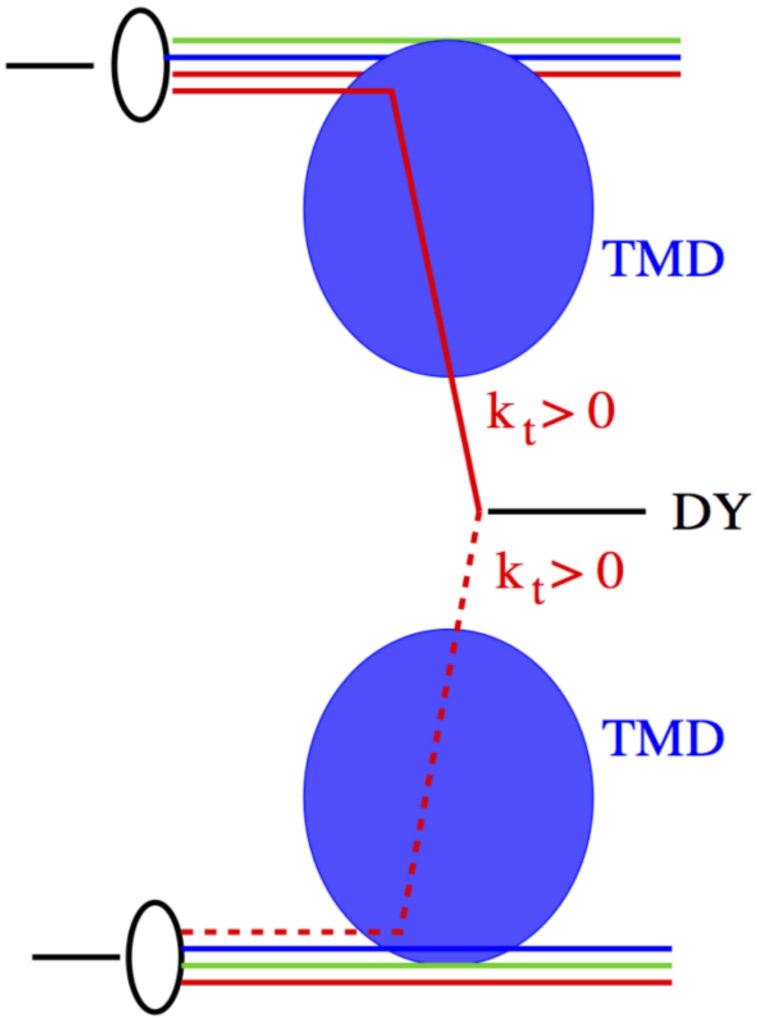
- Use LO DY production
  - $q\bar{q} \to Z_0$



Application: DY production using TMDs

together with: A. Lelek, R. Zlebcik

- Use LO DY production
  - $q\bar{q} \rightarrow Z_0$
  - 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: DY production using TMDs

- Use LO DY production
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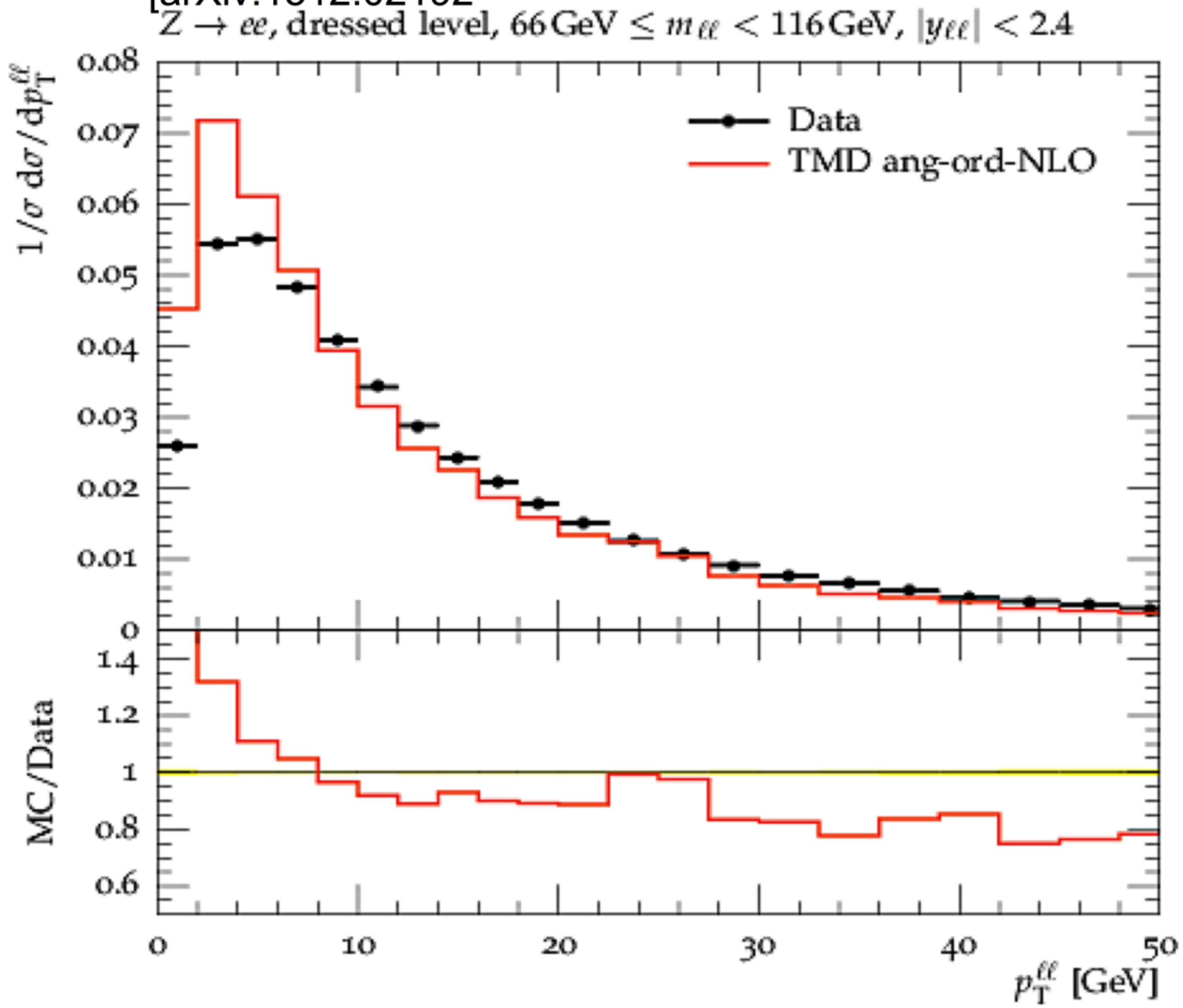
  - keep final state mass fixed:
    - x_1 and x_2 (light-cone fraction) are different after adding k_t
- Use TMD with angular ordering

together with: A. Lelek, R. Zlebcik

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



Application: DY production using TMDs

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  - keep final state mass fixed:
    - x_1 and x_2 (light-cone fraction) are different after adding k_t
- Use TMD with angular ordering
- TMD with q^2 -ordering gives different distribution (including experimental uncertainties from herapdf fit)

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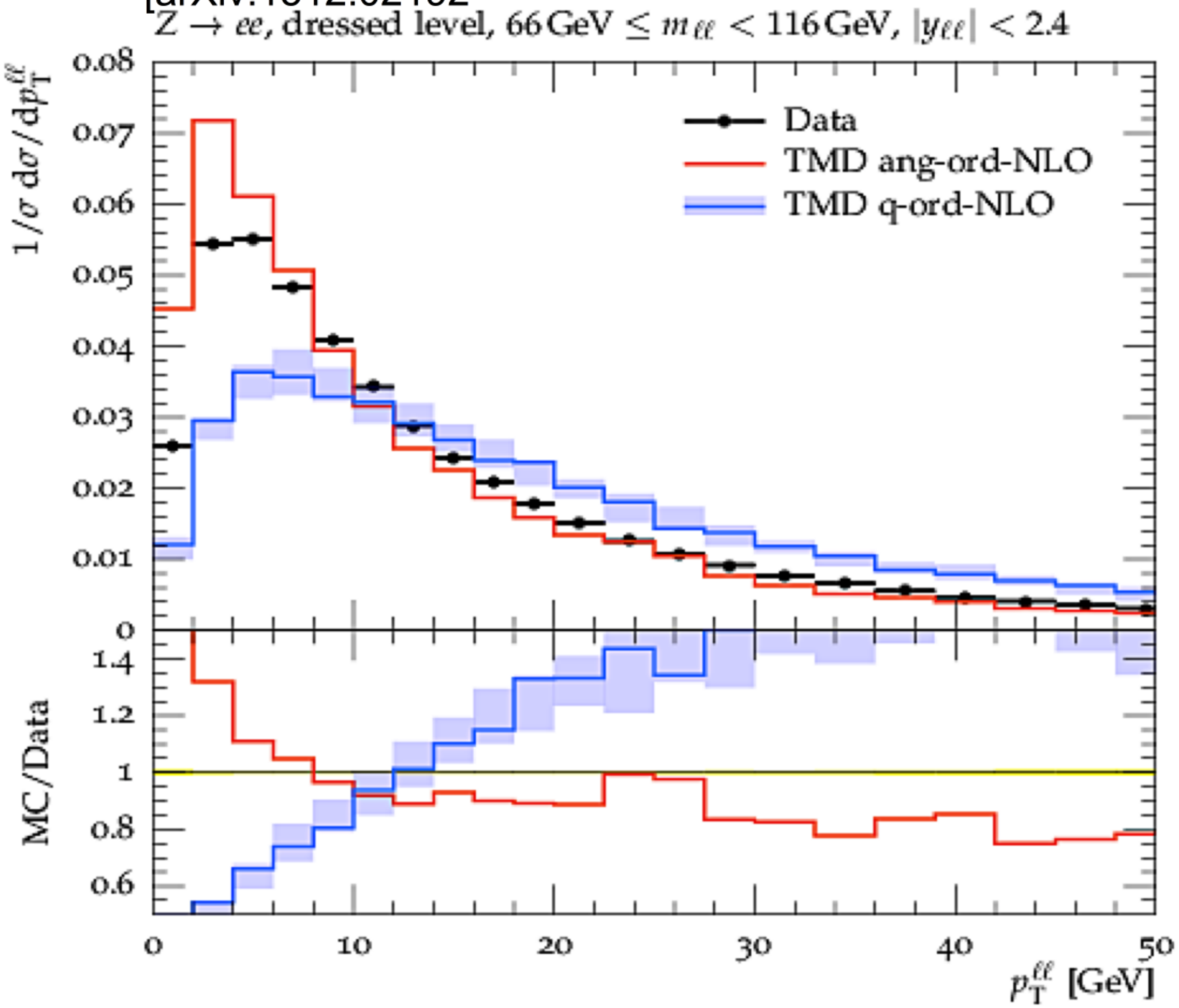

Application: DY production using TMDs

- Use LO DY production
  - $q\bar{q} \to Z_0$
  - add k_t for each parton as fct 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
  - no free parameters, once TMD is determined
    - depends on intrinsic k_t as used in parton evolution (here gauss with mean=0)
    - can be determined in fit!

together with: A. Lelek, R. Zlebcik

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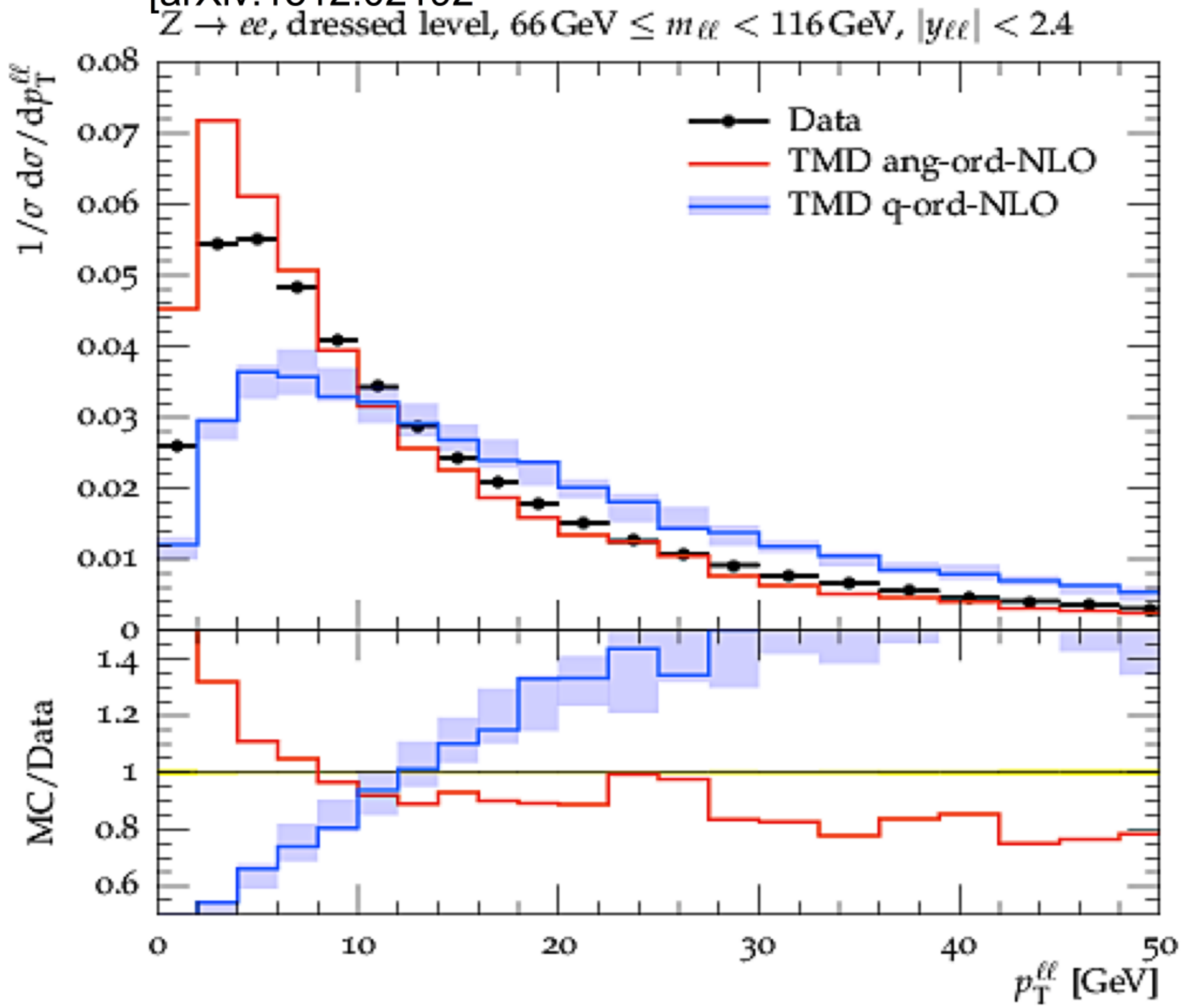


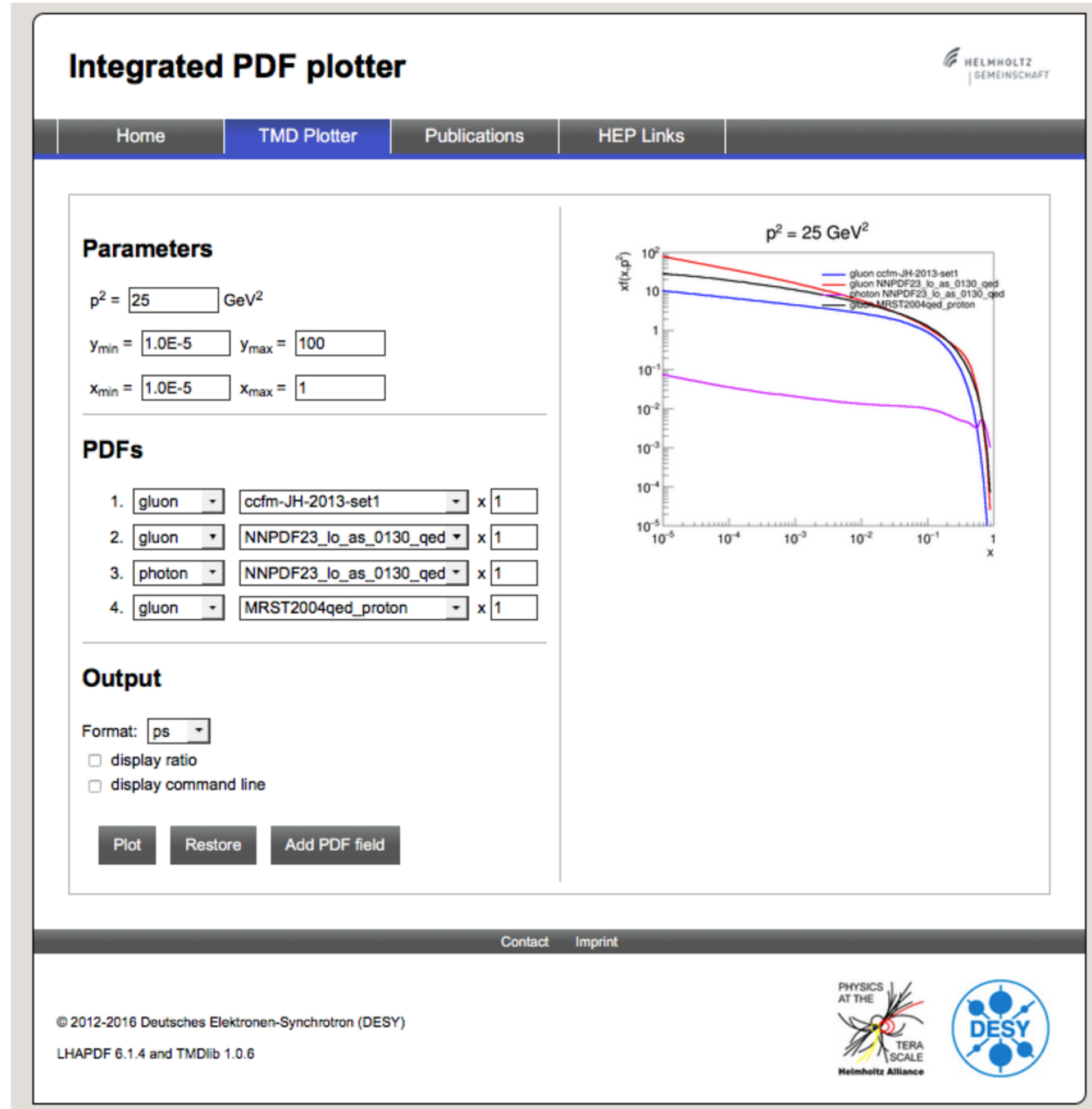
Where to find TMDs ? TMDlib and TMDplotter

- 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 !

Resummation, Evolution, Factorization 2017

http://jacobi.fis.ucm.es/REF2017/index.html

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Presentation

Dates: 13/11/2017 (AFTERNOON)-16/11/2017

REF 2017 is the 6th workshop in the series of workshops on **Resummation, Evolution, Factorization**. Previous discussion meetings and workshops were

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2-5 November 2015 DESY Hamburg (Germany)
1-3 June 2015 Amsterdam (The Netherlands)
8-11 December 2014 Antwerp (Belgium)
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Resummation, Evolution, Factorization 2017

You are very welcome to join !

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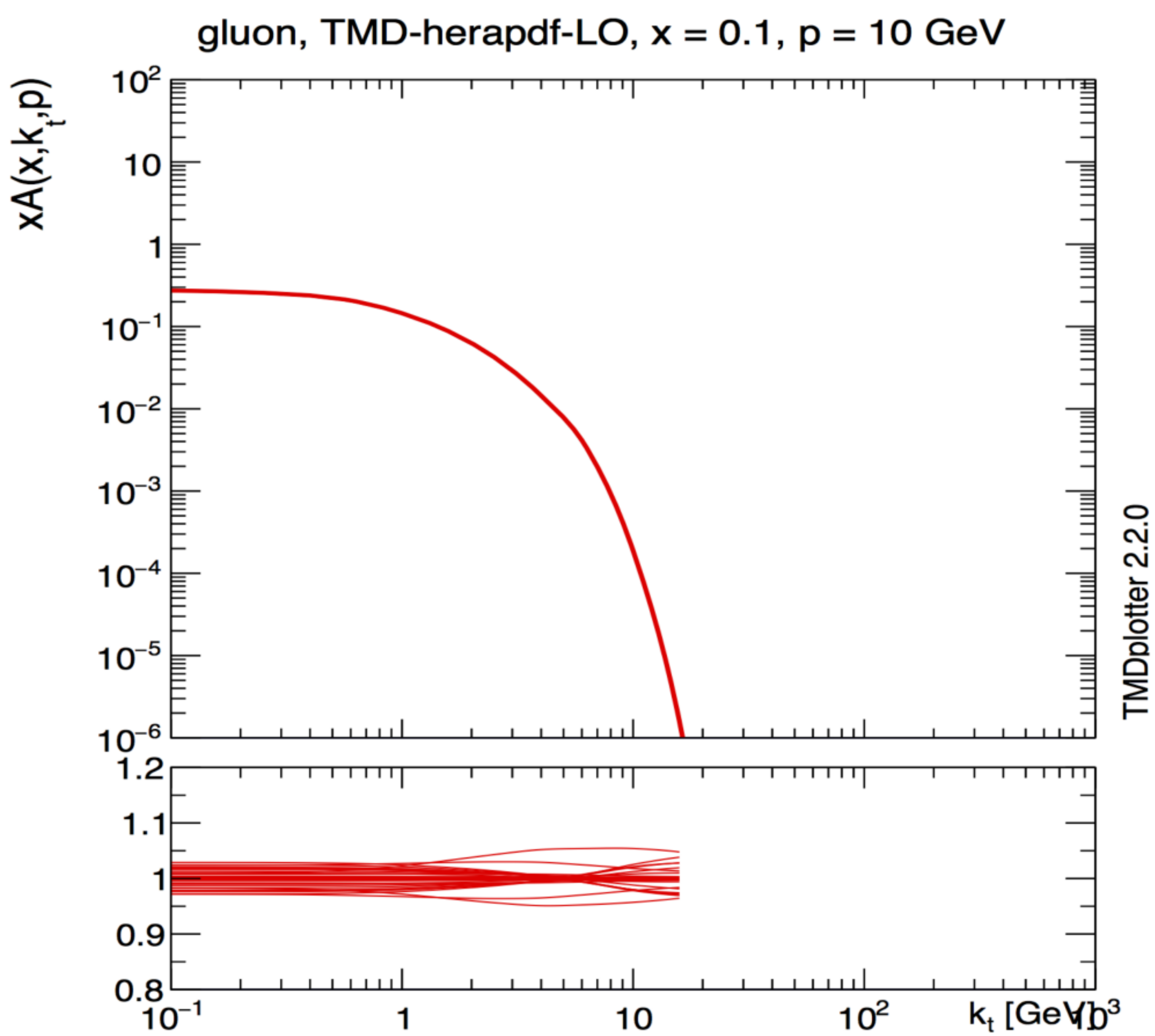
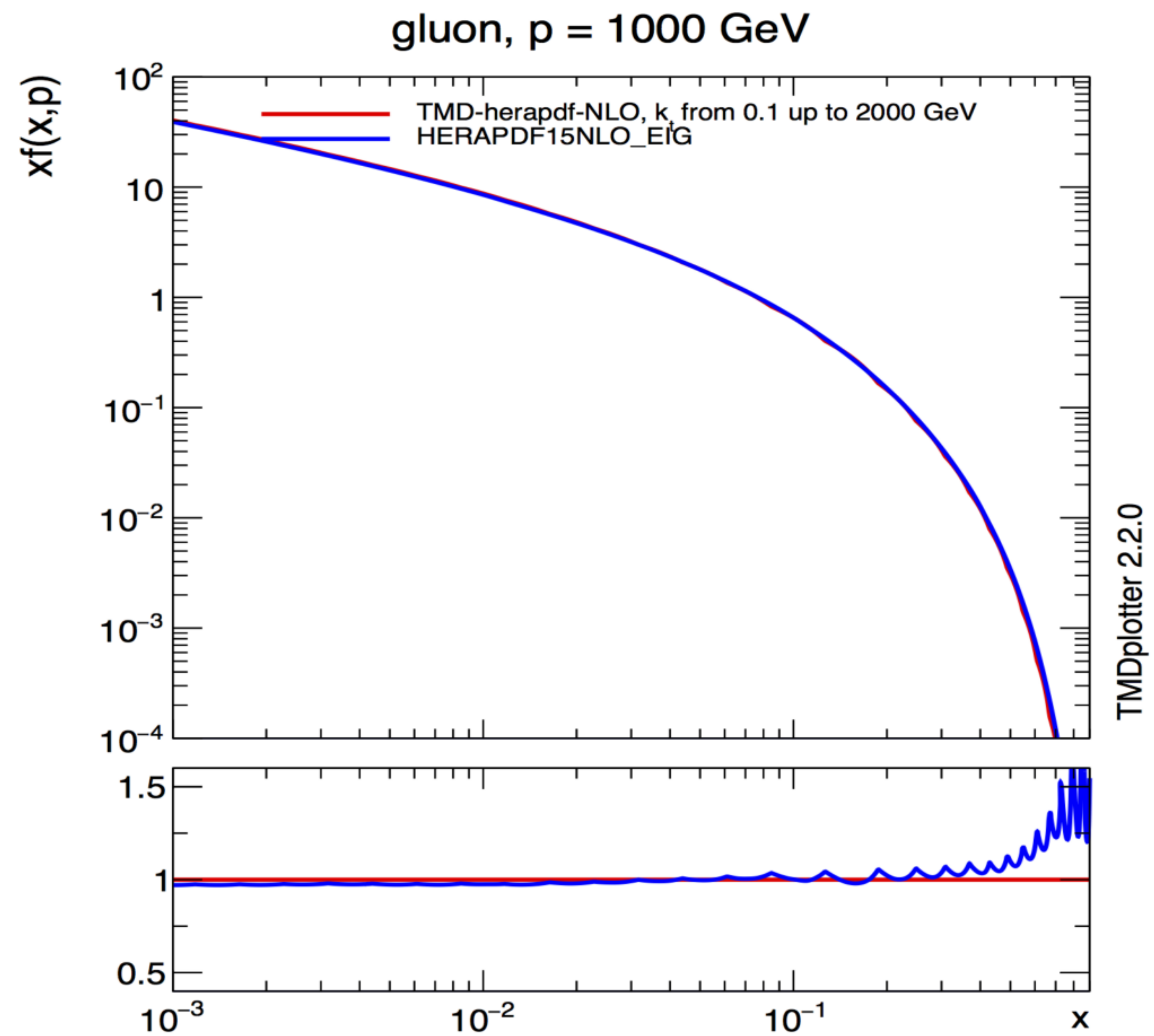
Conclusion

- transverse momenta of interaction partons can be important for precision physics
  - ➔ need for TMDs
- Parton Branching method developed for solving DGLAP equation at LO, NLO and NNLO
  - ➔ consistence for collinear (integrated) PDFs shown
- 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 – applicable for DIS processes
- First application to DY production
  - ➔ using TMD distributions gives reasonable q_t spectrum of DY
  - ➔ no free parameters
- Parton branching method for PDFs and TMD successful !

Appendix

TMD distributions from xFitter: herapdf-type





- Transverse momentum distributions including uncertainties from herapdf fit
  - essentially constant at fixed x and μ^2

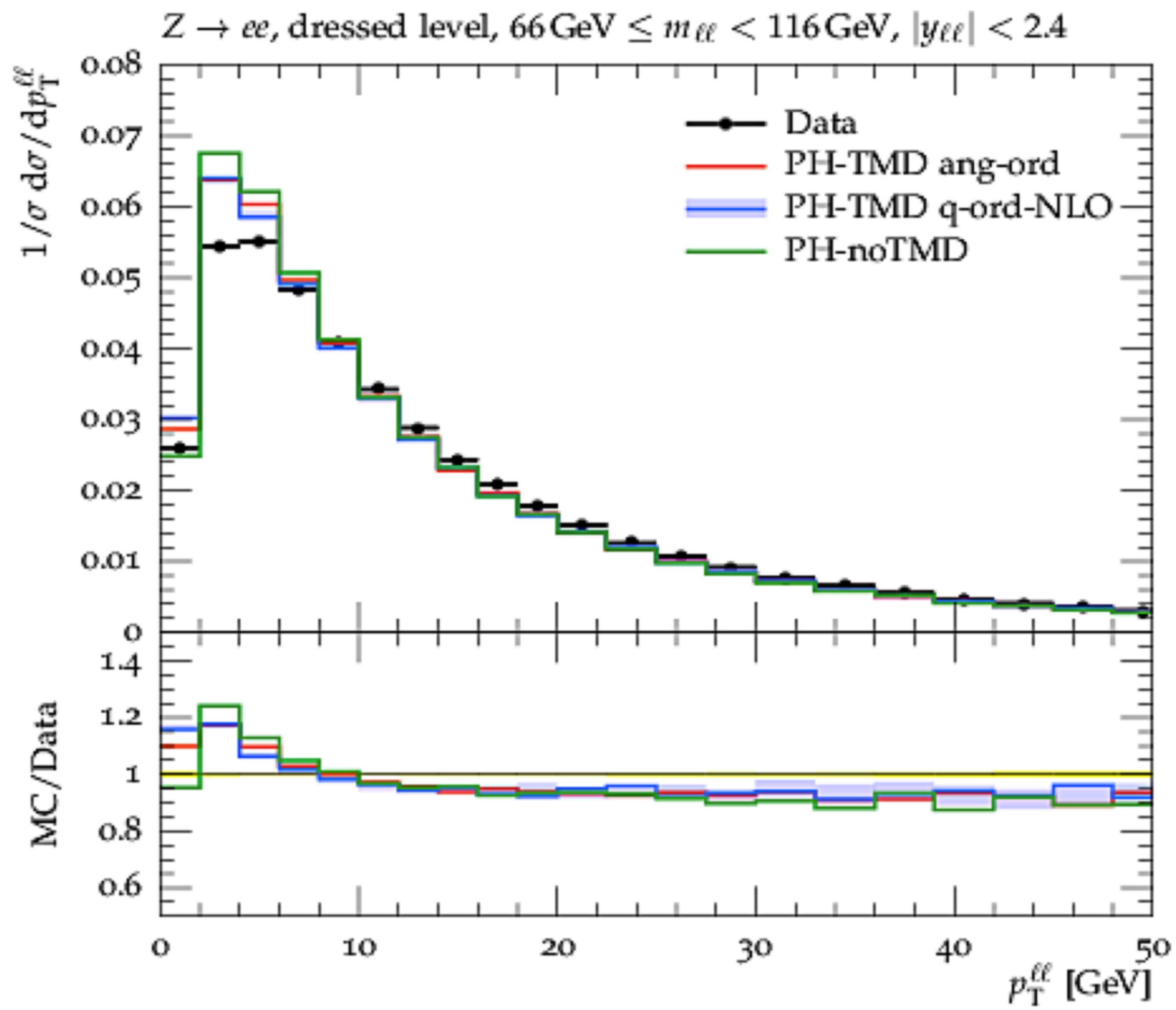
- iTMD distribution: (integrated TMD) compared to herapdf

Application: DY production using TMDs

- Use LO DY production
  - $q\bar{q} \to Z_0$
  - add k_t for each parton as fct 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 TMD with angular ordering
- TMD with q^2 -ordering gives different distribution (including experimental uncertainties from herapdf fit)
- Using POWHEG, leaves very little room for TMD contribution:
  - Sudakov term is already included in POWHEG.

together with: A. Lelek, R. Zlebcik

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



Application: DY production using TMDs

together with: A. Lelek, R. Zlebcik

- Use LO DY production
  - $q\bar{q} \to Z_0$
  - comparison to NLO calculations