News on TMD parton distributions for LHC physics

Hannes Jung (DESY)

- Highlights from ResummationEvolutionFactorization 2016 workshop
  - Why TMDs are needed
  - TMDs for hadron-hadron collisions
- New developments (together with F. Hautmann, A. Lelek, R. Zlebcik)
  - parton branching algorithm to solve evolution equations
    - benchmark tests
    - advantages for integrated PDFs
  - determination of TMD densities at LO and NLO

REF 2016 workshop

Workshop on Resummation, Evolution, Factorization

7-10 November 2016
University of Antwerp
Europe/Zurich timezone

Search...

- Overview
- Scientific Program
- Timetable
- Call for Abstracts
- Book of Abstracts
- Registration
- Participant List
- Workshop venue
- Travel information

REF 2016

*Understanding high-energy hadronic processes within the **TMD** and **Small-X_B** frameworks: comparison and matching*

REF 2016 is the 3rd workshop in the series of workshops on `Resummation, Evolution, Factorization.

Previous discussion meetings and workshops were
2-5 November 2015 DESY Hamburg (Germany)
1-3 June 2015 Amsterdam (The Netherlands)
8-11 December 2014 in Antwerp (Belgium)
23-24 June 2014 Antwerp (Belgium)

- REF2016 link
- REF2017: Nov 13-17 Madrid

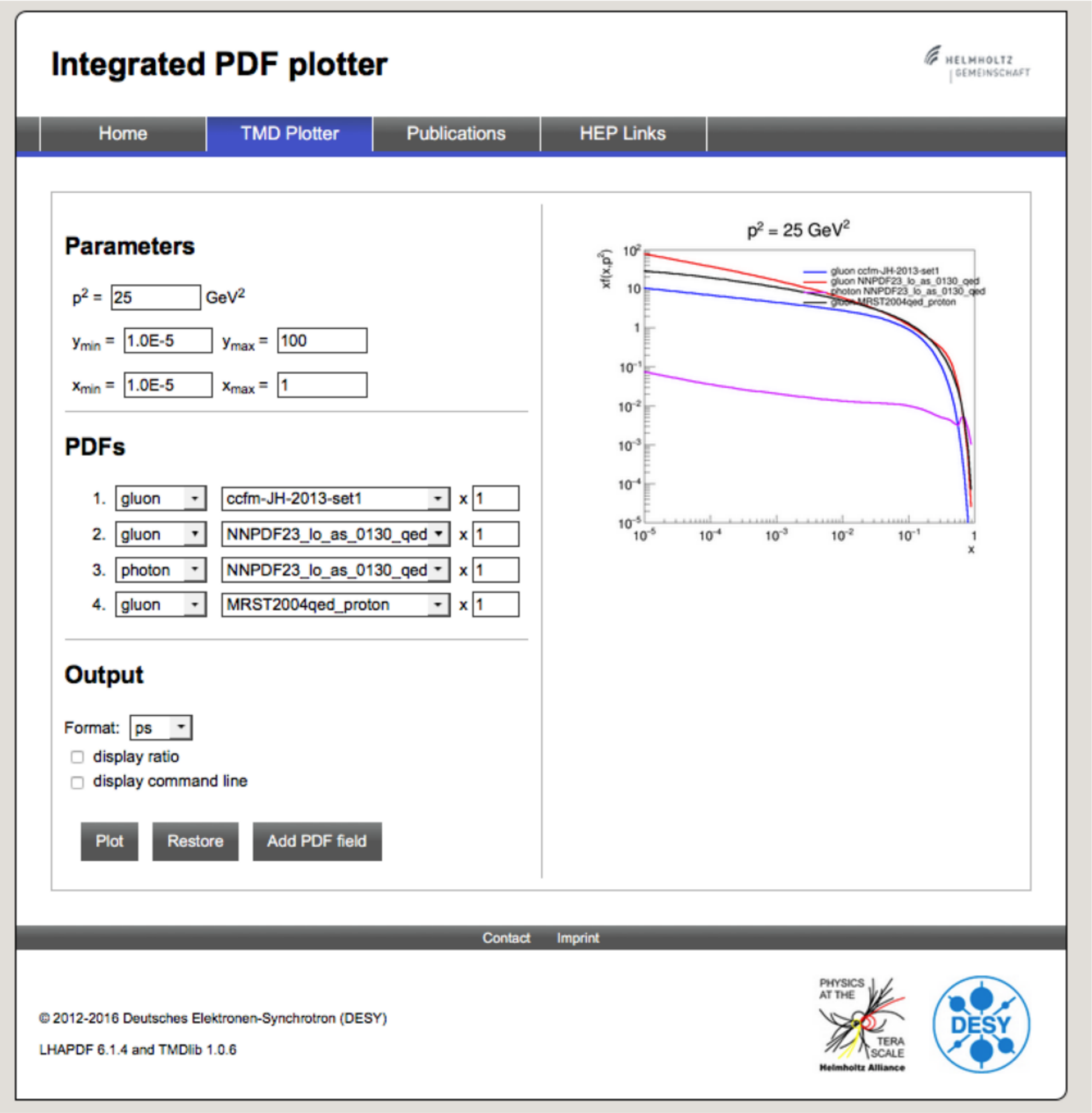
TMDlib and TMDplotter

- 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 !

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)
  - 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

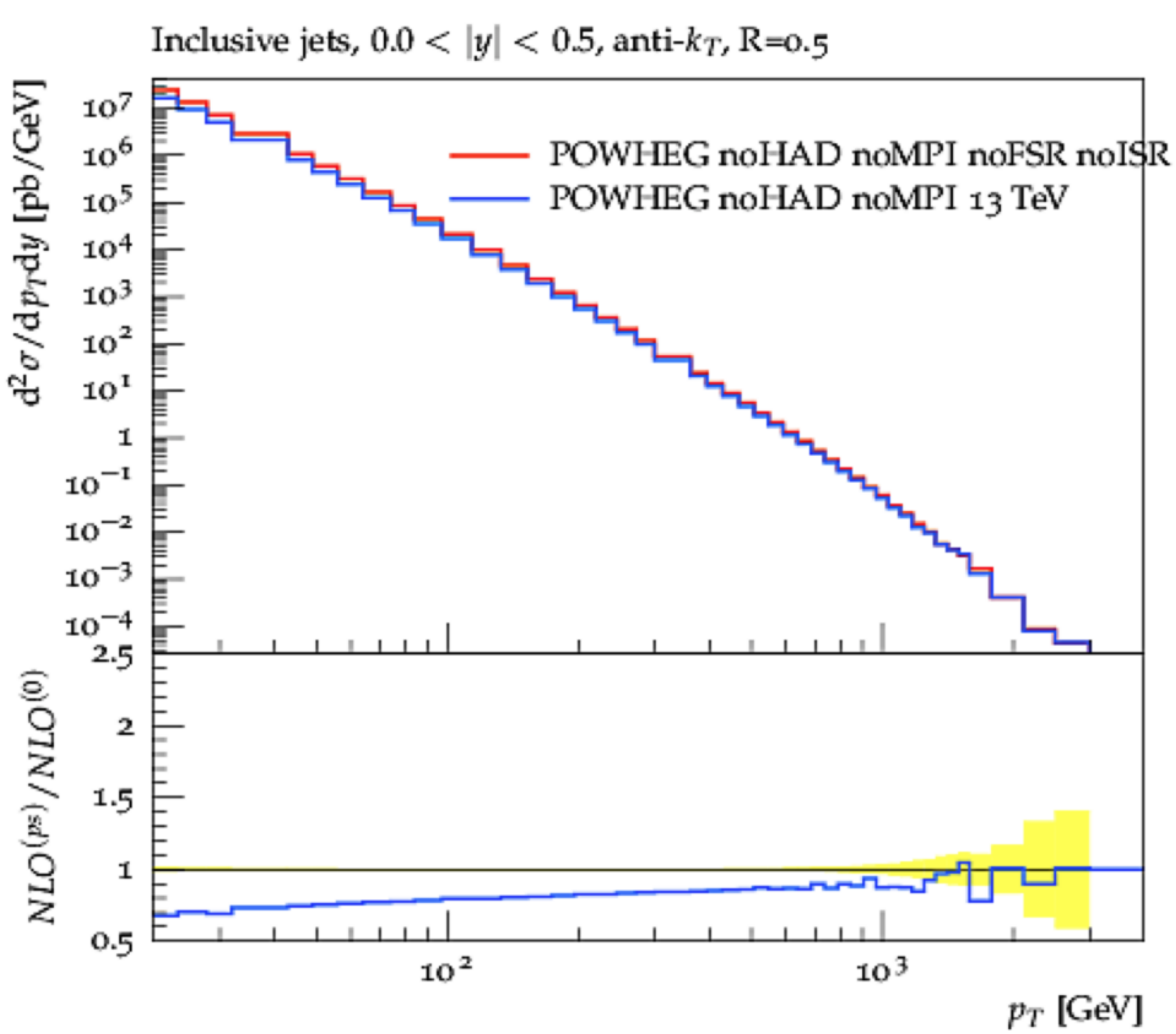
Why TMDs are needed ?

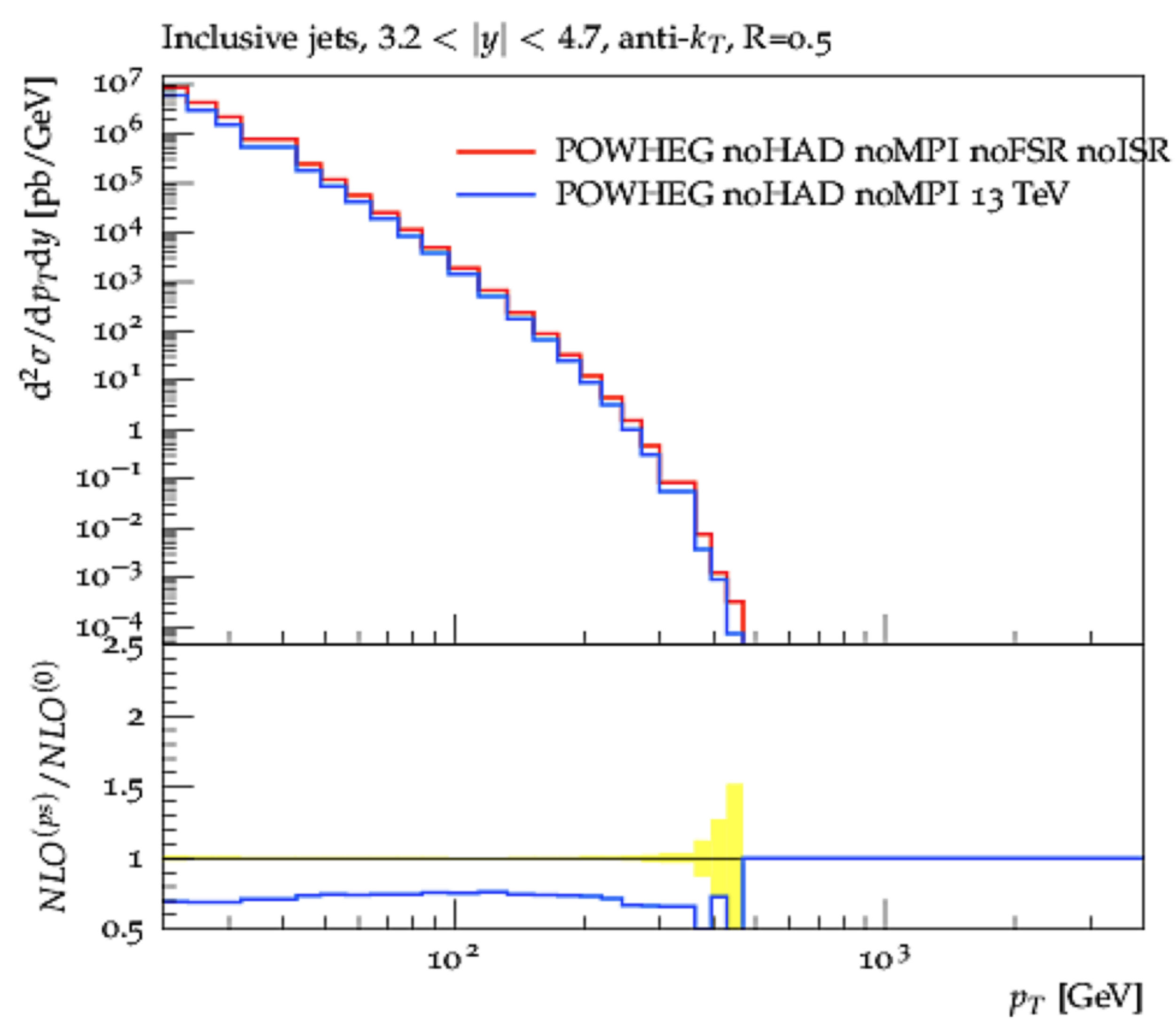
- use NLO+PS to calculate:

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

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

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





TMDs from Monte Carlo event generators

- Transverse momentum effects are naturally coming from intrinsic k_t and parton showers

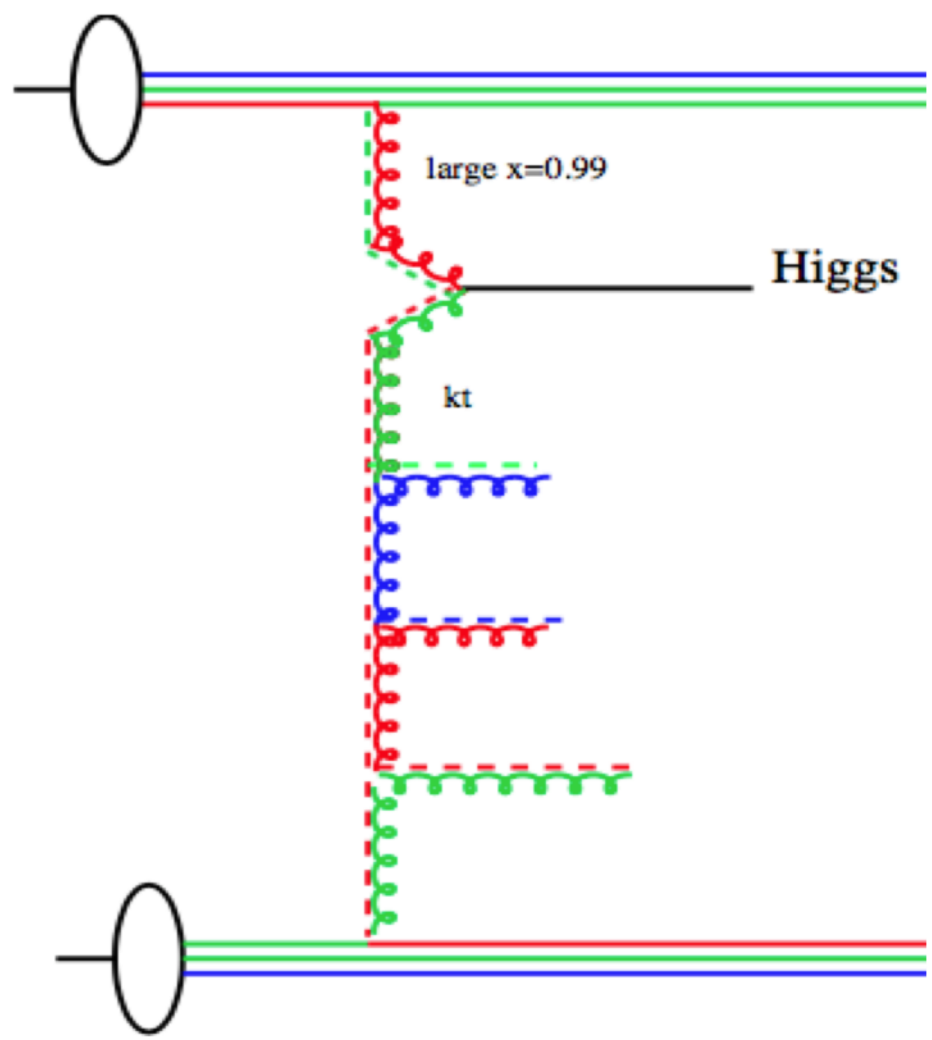
- TMD effects can be significant in all distributions, even for inclusive (or semi-inclusive) distributions at large pt

- **Can we extract an effective TMD from standard MC parton shower generators ?**

  - Project started with summer-students 2015/2016:
    - Pamela Ornelas Silva, Jose Fragoso Negrin, Tania Martinez Cortes, Aleksandra Lelek
    - with help from T. Sjostrand on PYTHIA

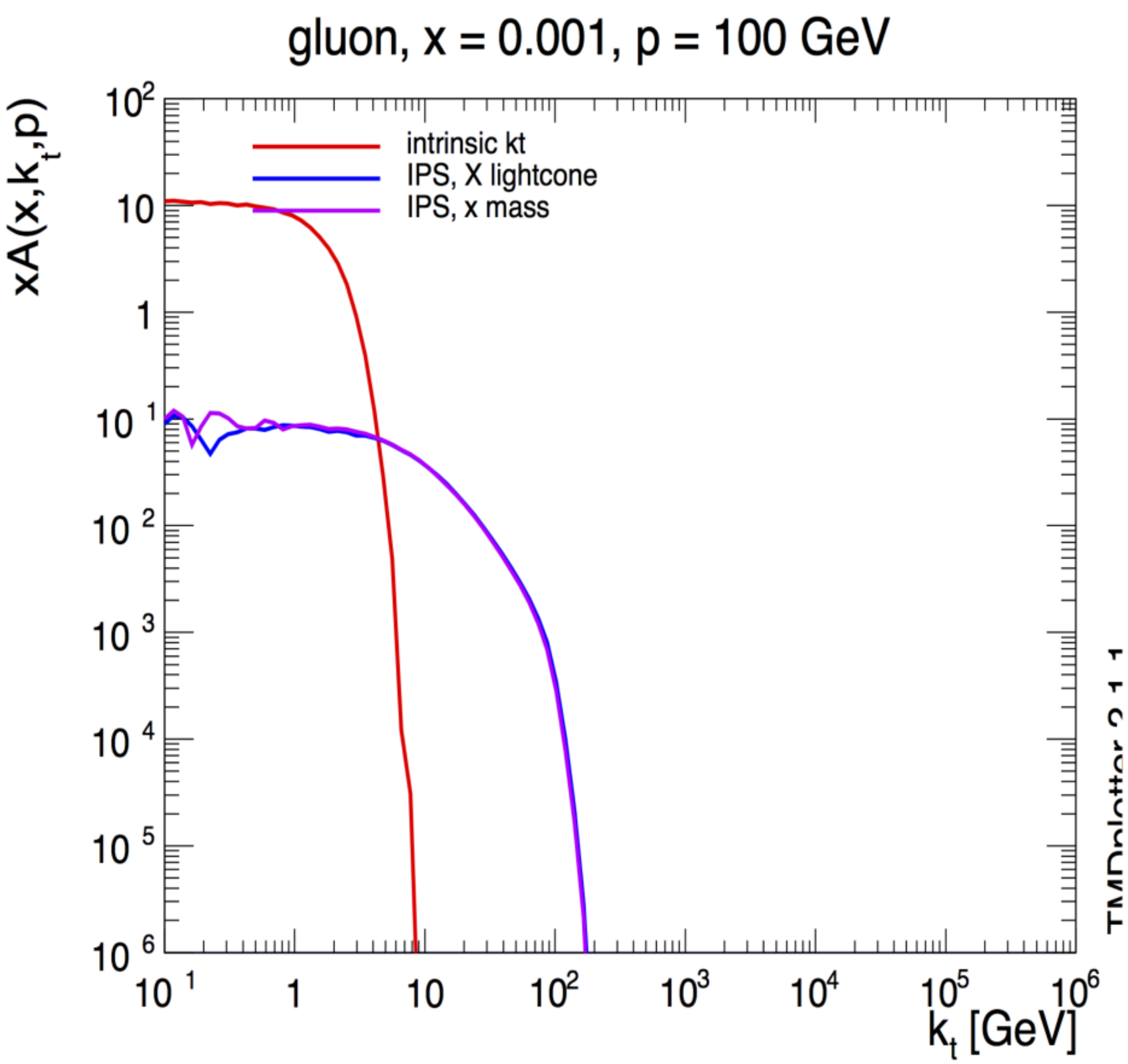
TMD effects from MC parton shower generators

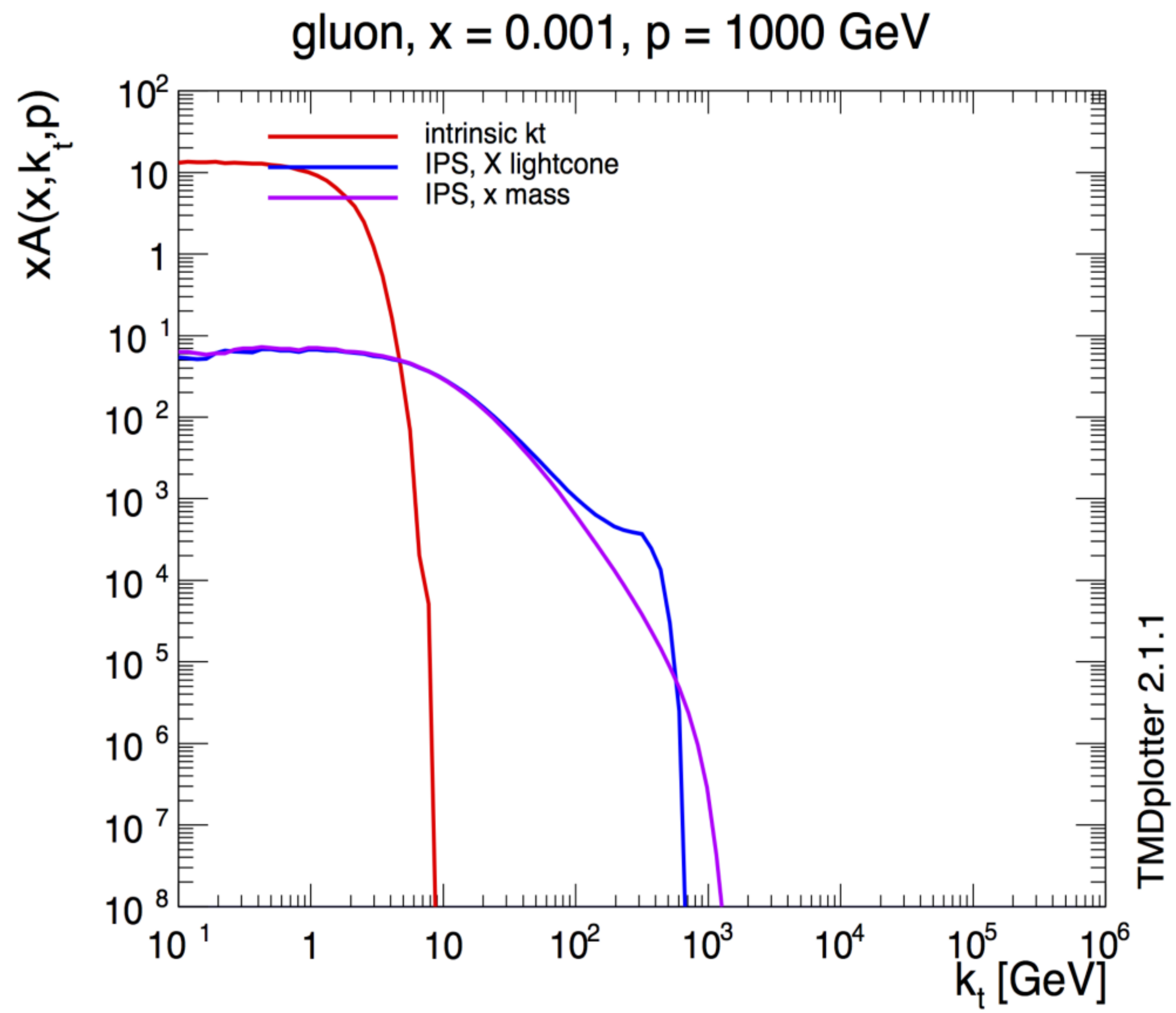
- Goal: define TMD from MC parton shower generator
  - Define a simple processes (for identifying hard probe after shower):
    - $gg \to H$ for a color singlet final state
  - do not rely on generator internal quantities, reconstruct k_t and x from 4-vector
  - fix $x_1 = 0.99$ (no intrinsic k_t, no PS from parton 1), mass 0.5< m <1000 GeV



TMDfromMC: initial parton shower TMD (PYTHIA8)

- determine quark and gluon TMDs (here only gluon is investigated)
  - watch out definition of x: $x = \frac{E+p_z}{(E+p_z)_{beam}}$ or $x = \frac{m}{\sqrt{s}} \exp(\pm y)$





- TMD from MC can be determined
  - allows easy comparison of parton shower effects

TMDs – can one do better and consistent ?

- TMD distributions from PS Monte Carlo generators do not change pdfs
  - but do affect the kinematics of the hard process !

- New approach:
  - 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 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 evolution equation

- work in progress, in collaboration with:
  - F. Hautmann (Oxford, Antwerp)
  - A. Lelek (DESY)
  - R. Zlebcik (DESY)

- preliminary results reported at REF2016 by
  - A. Lelek

- stay tuned for
  - QCD Moriond (A. Lelek)
  - DIS2017 (A. Lelek, R. Zlebcik)

DGLAP evolution – solution with parton branching method

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

$$\Delta_s(\mu^2) = \exp\left(- \int_0^{z_{max}} dz \int_{\mu_0^2}^{\mu^2} \frac{\alpha_s}{2\pi} \frac{d\mu'^2}{\mu'^2} P^{(R)}(z) \right)$$

- 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:

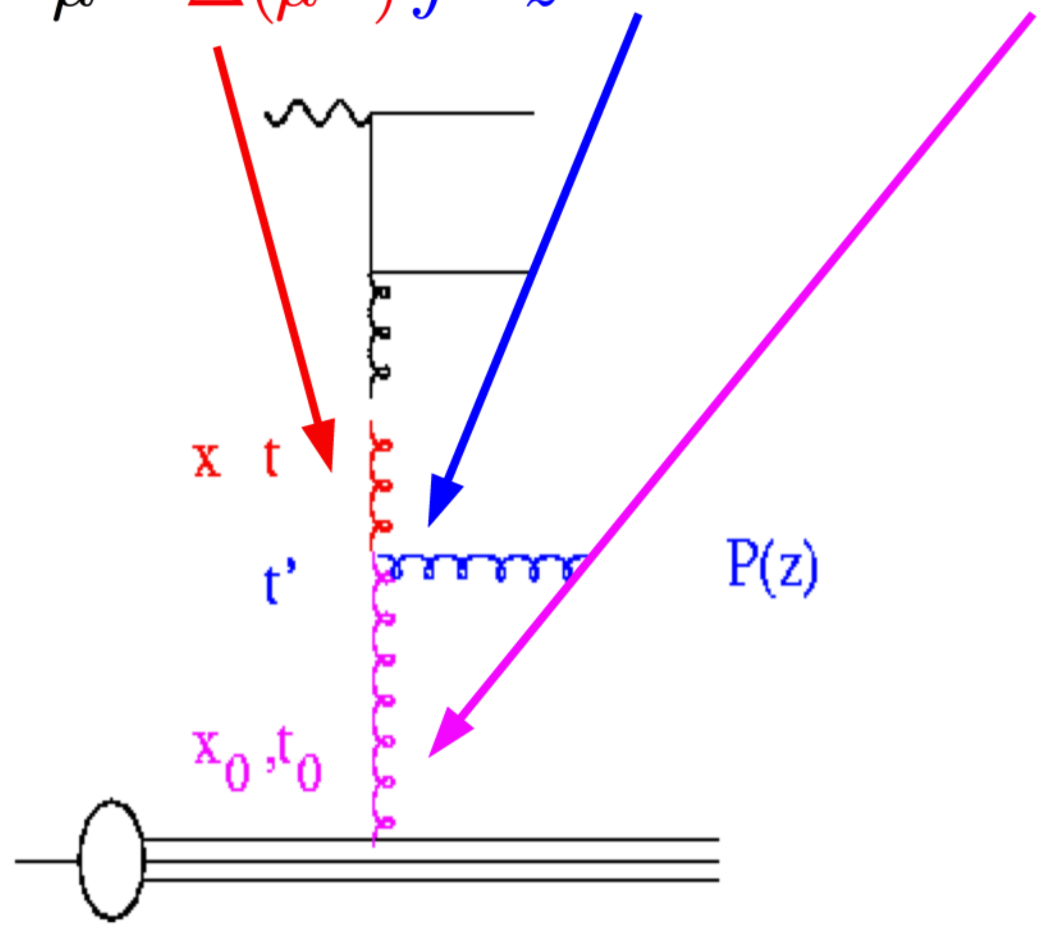
from *t'* to *t*
w/o branching

branching at *t'*

from t_0 to *t'*
w/o branching

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

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



Evolution equation and parton branching method

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

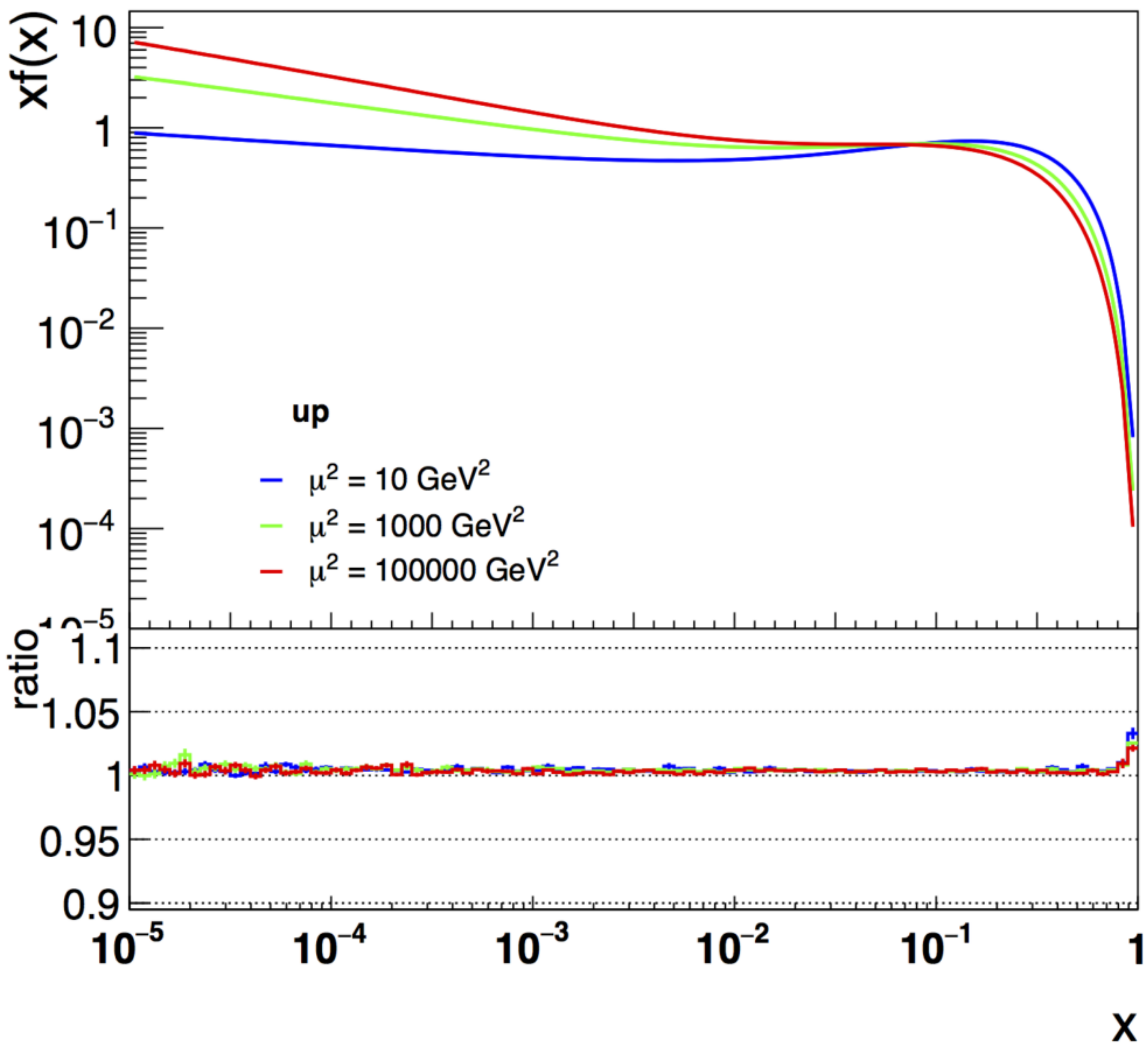
$$
\begin{aligned}
xf_a(x,\mu^2) \quad = \quad & \Delta_a(\mu^2)\; xf_a(x,\mu_0^2) \\
& + \sum_b \int_{\mu_0}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s, z)\, \frac{x}{z} f_b\left(\frac{x}{z}, \mu'^2\right)
\end{aligned}
$$

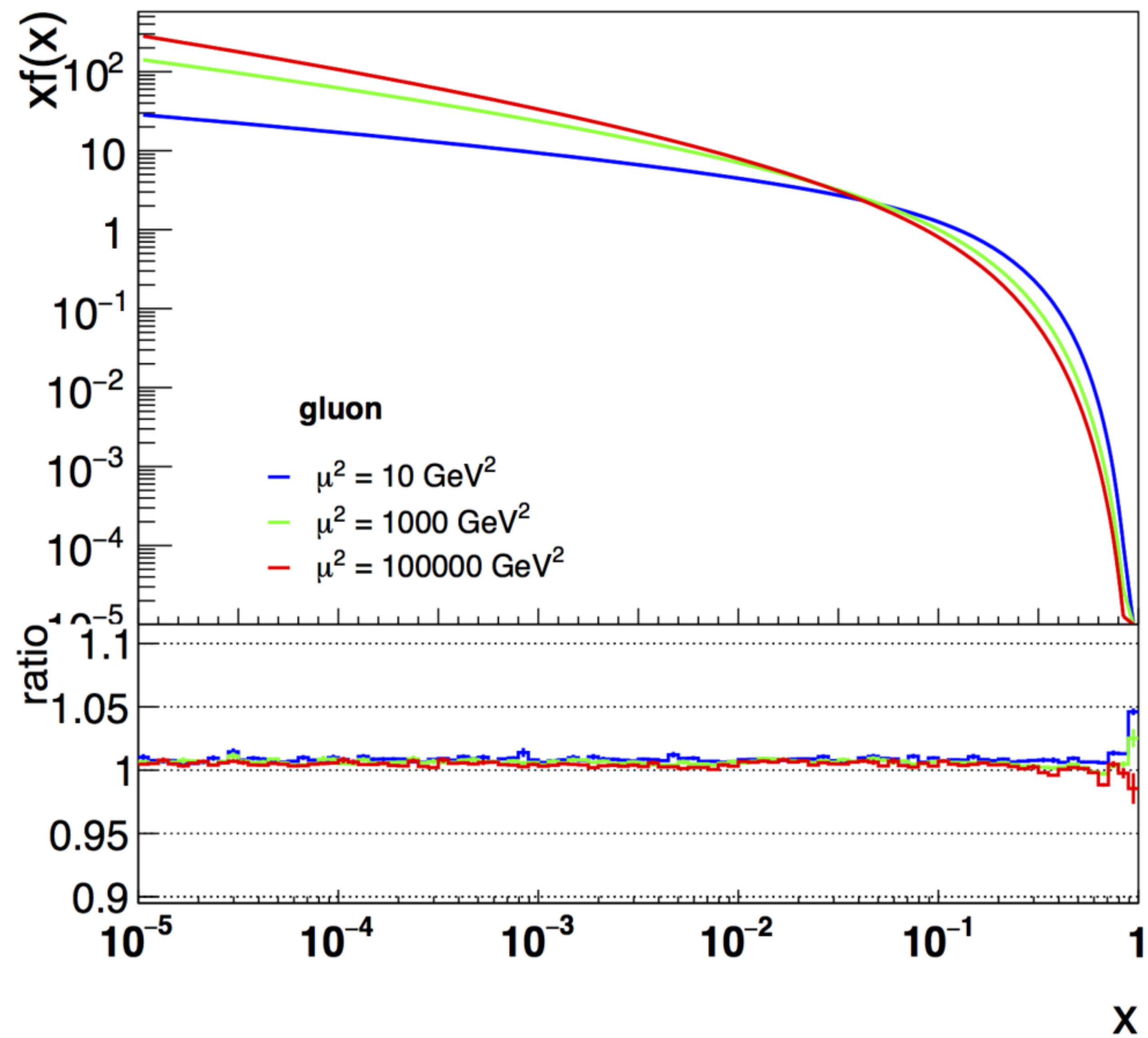
- with $P_{ab}{}^{(R)}\,(\alpha_s(t'),z)$ real emission probability (without virtual terms)
  - z_M introduced to separate real from virtual and non-emission probability

- make use of momentum sum rule to write Sudakov in closed form

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

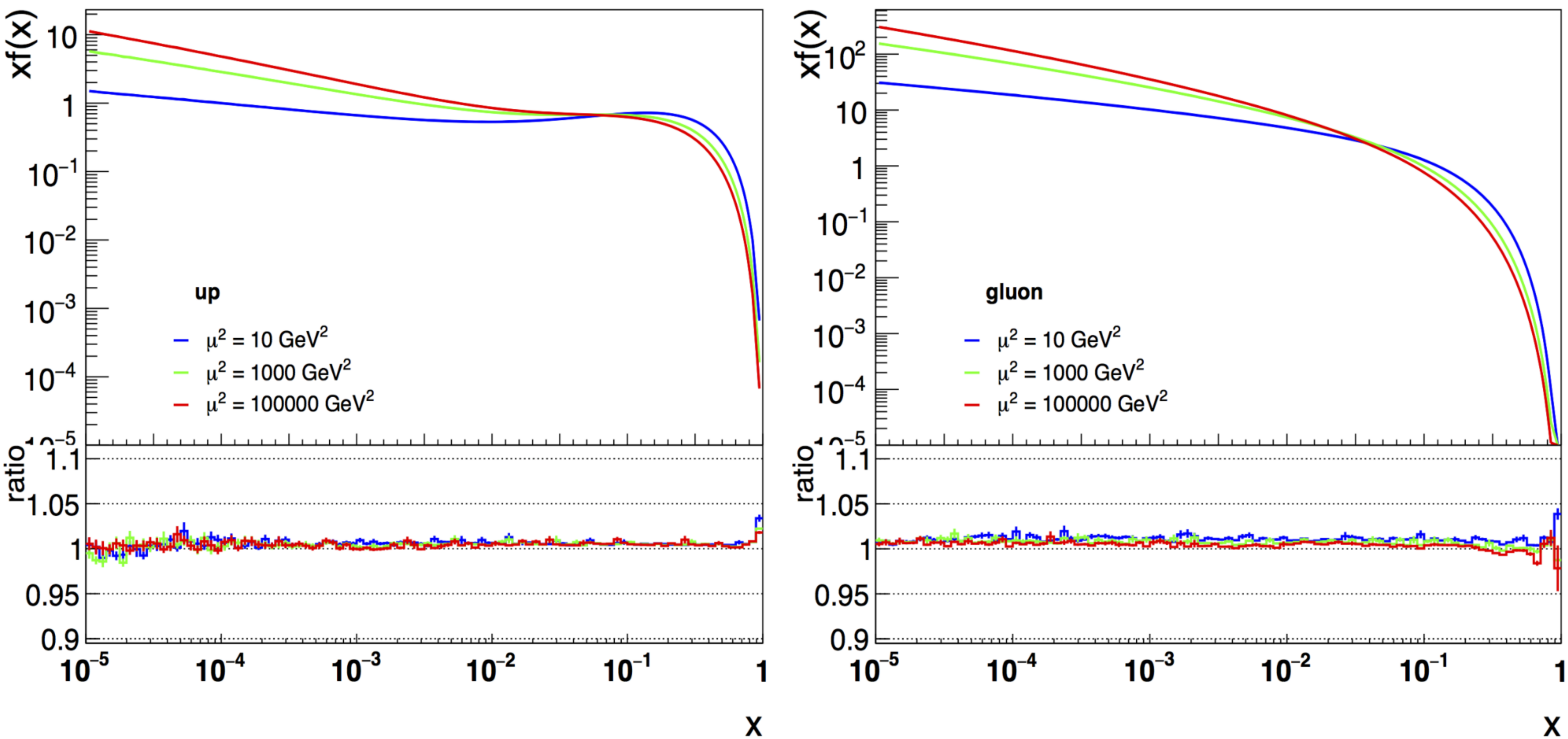
Validation of method with QCDnum at LO





- Very good agreement with LO - QCDnum over all x and μ^2

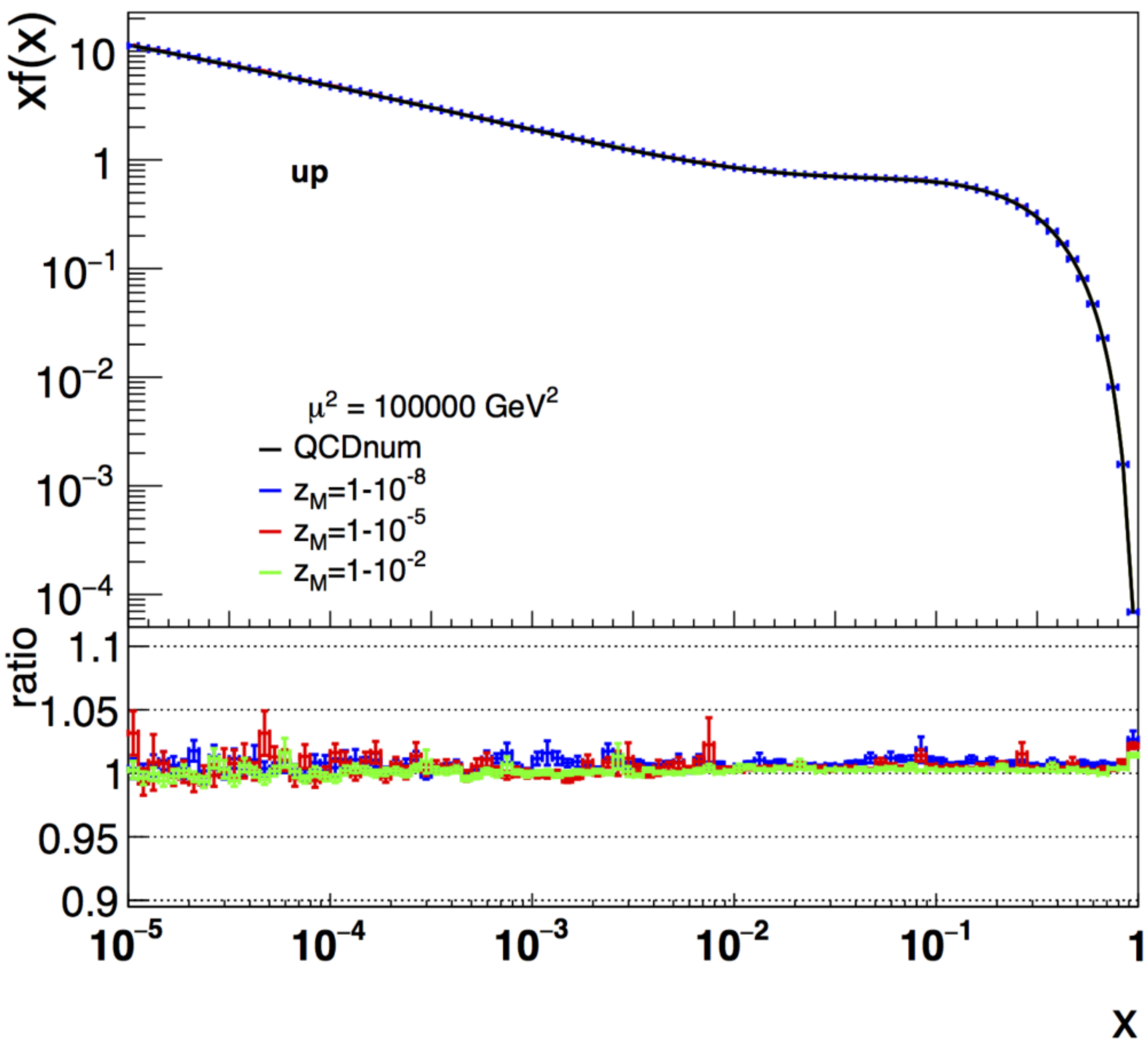
Validation of method with QCDnum at NLO

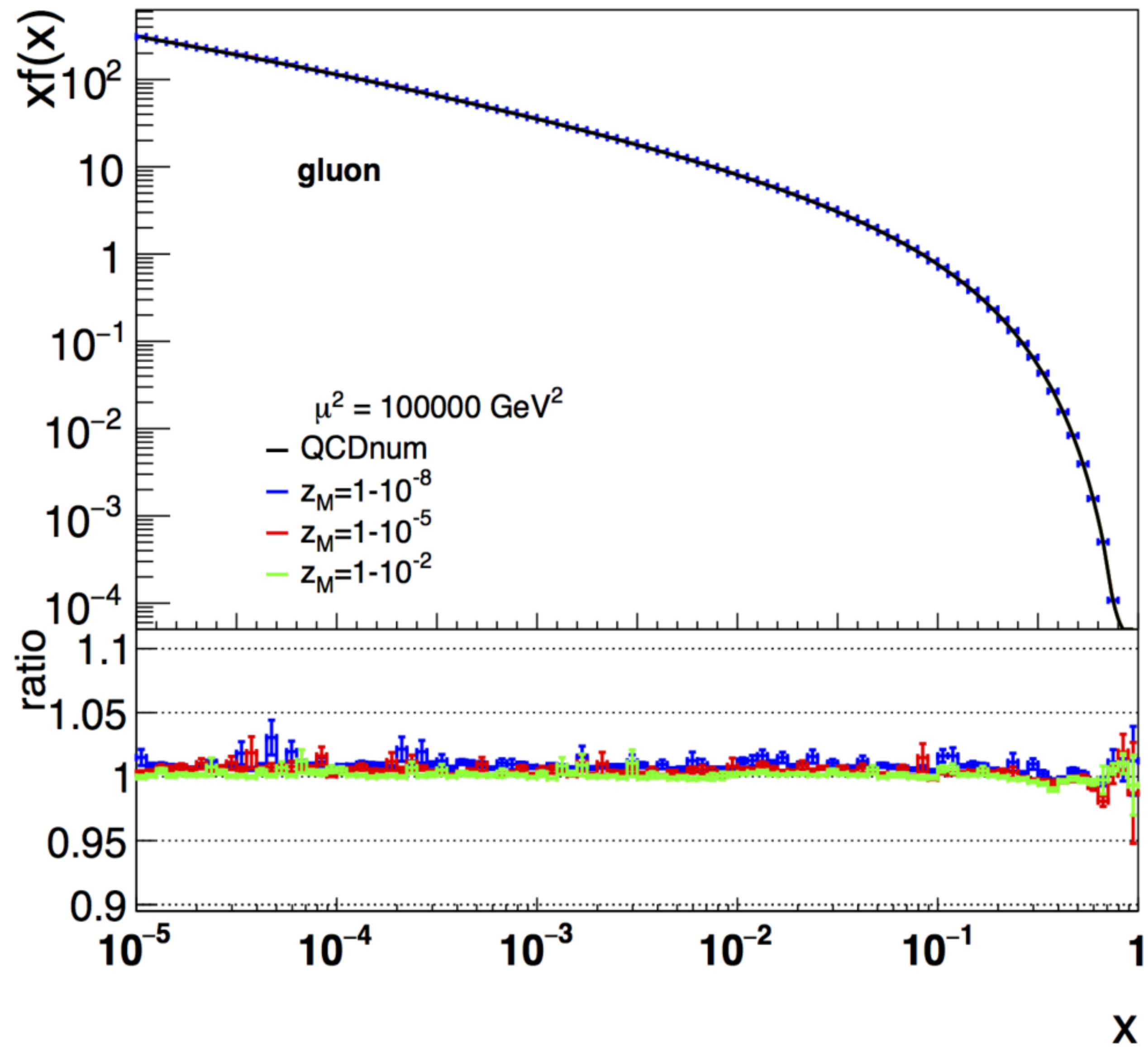


- Very good agreement with NLO - QCDnum over all x and μ^2
  - the same approach work also at NNLO !

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 !

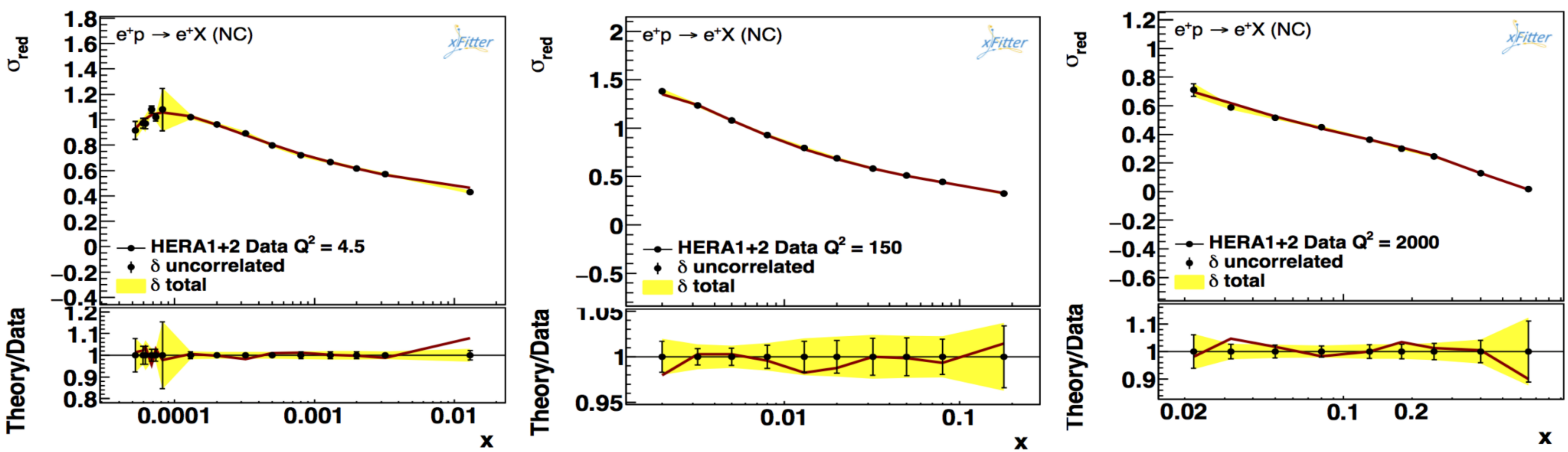
Determination of TMDs from fit to HERA precision data

- Determine starting distribution

A. Lelek et al REF 2016

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

- fit to HERA data (using xFitter) with $Q^2 \geq 3.5$ GeV 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:
      - angular ordering with varying $z_{max} = 1 - Q_0/Q$
        - large z resummation ?
      - Q^2 ordering with varying $z_{max} = 1 - Q_0{}^2/Q^2$
  - 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 know, 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

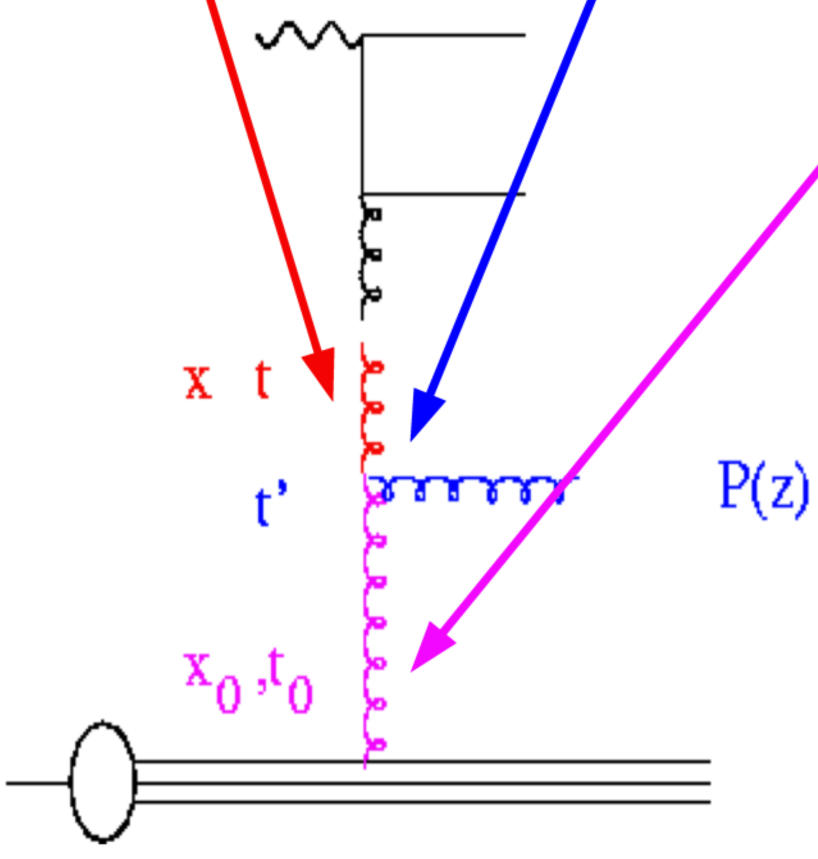
branching at t'

from t_0 to t' w/o branching

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

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

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



Determination of TMD distribution

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

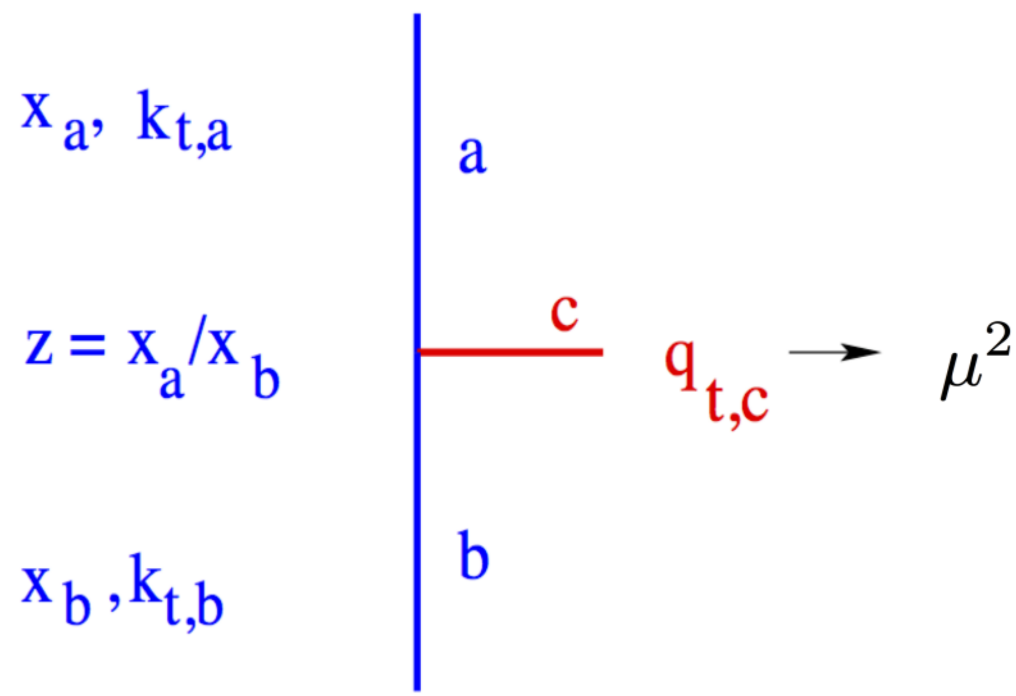
- solve integral equation via iteration:

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

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

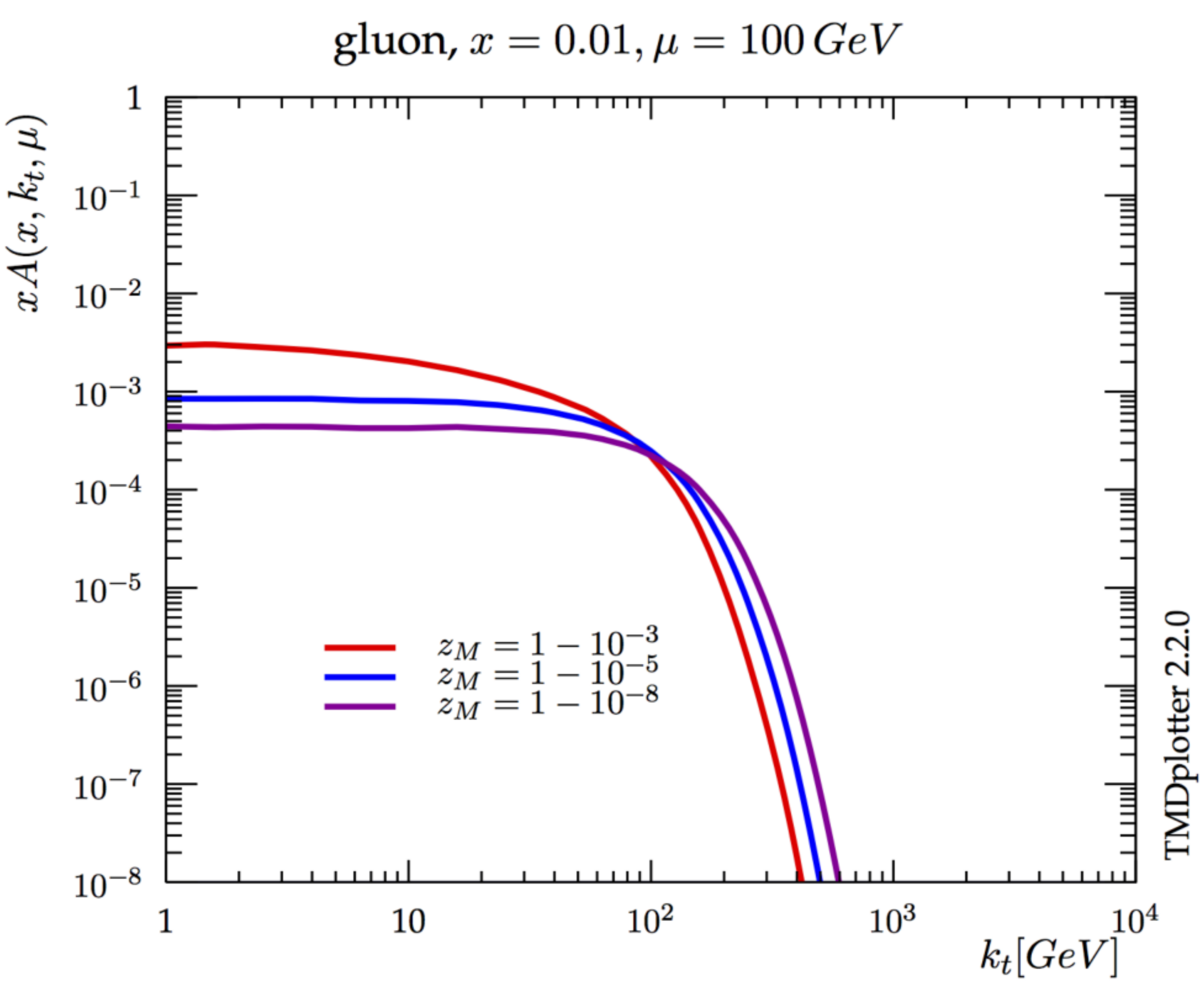
- in every step, kinematics are known:
  - calculate k_t of propagator
  - need correspondence:
    - $q_t{}^2 = \mu^2$ with q_t emitted parton

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



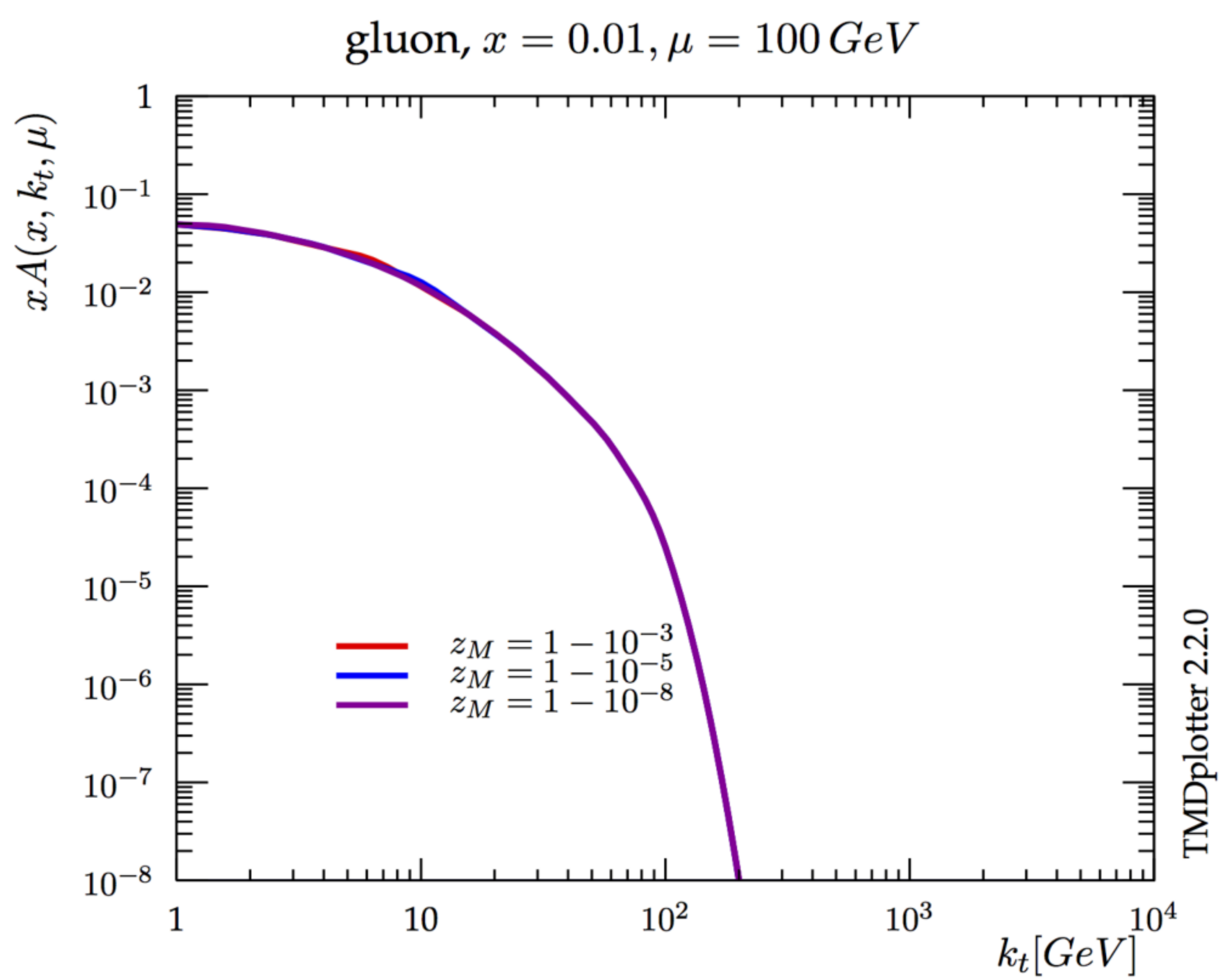
Determination of TMD distribution

- 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 ($z_{max} \to 1$)

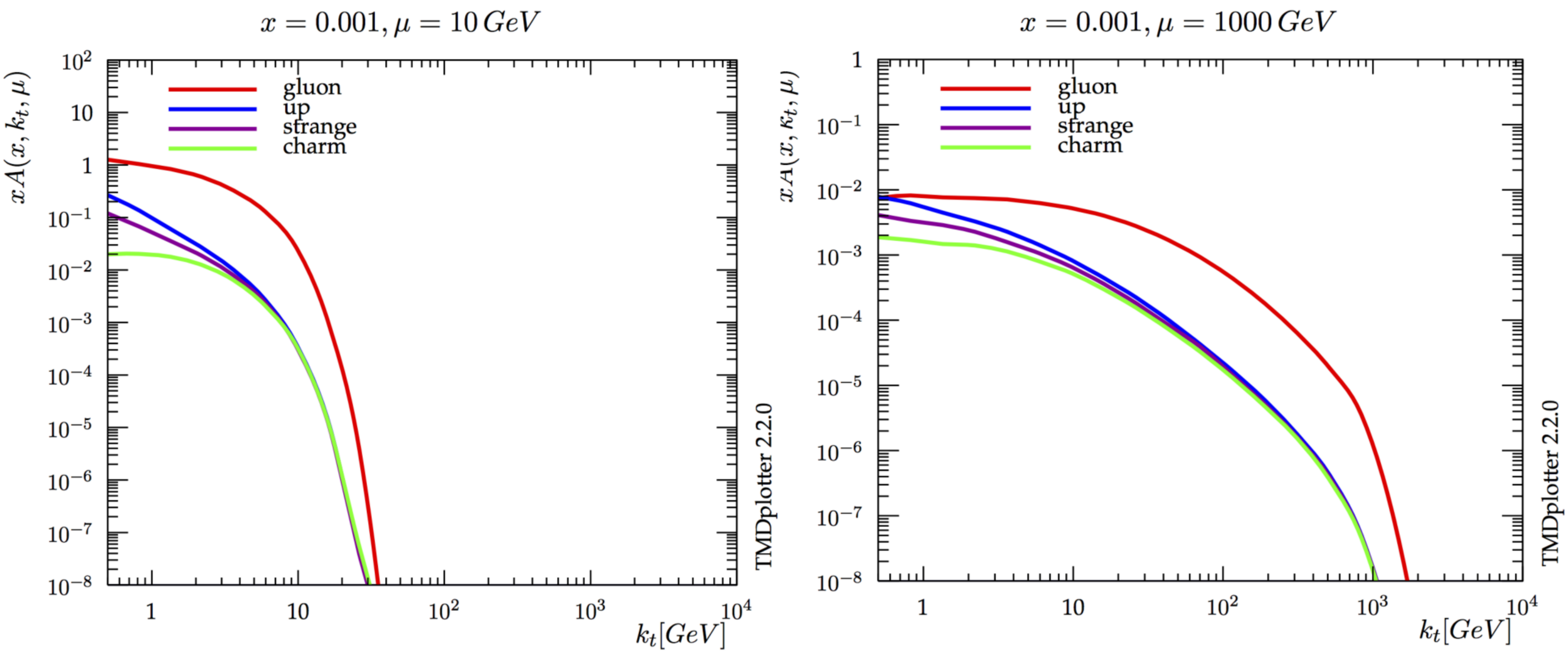
- q - ordering
  - $q_t^2 = (1-z)\,\mu^2$
    - $k_t = k'_t + q_t \sqrt{(1-z)}$



- Due to angular 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

Conclusion

- transverse momenta of interaction partons can be important for precision physics
  - ➔ need for TMDs

- TMD distributions naturally generated by PS Monte Carlo generator
  - but no direct connection of PS with parton densities (no k_t is used)

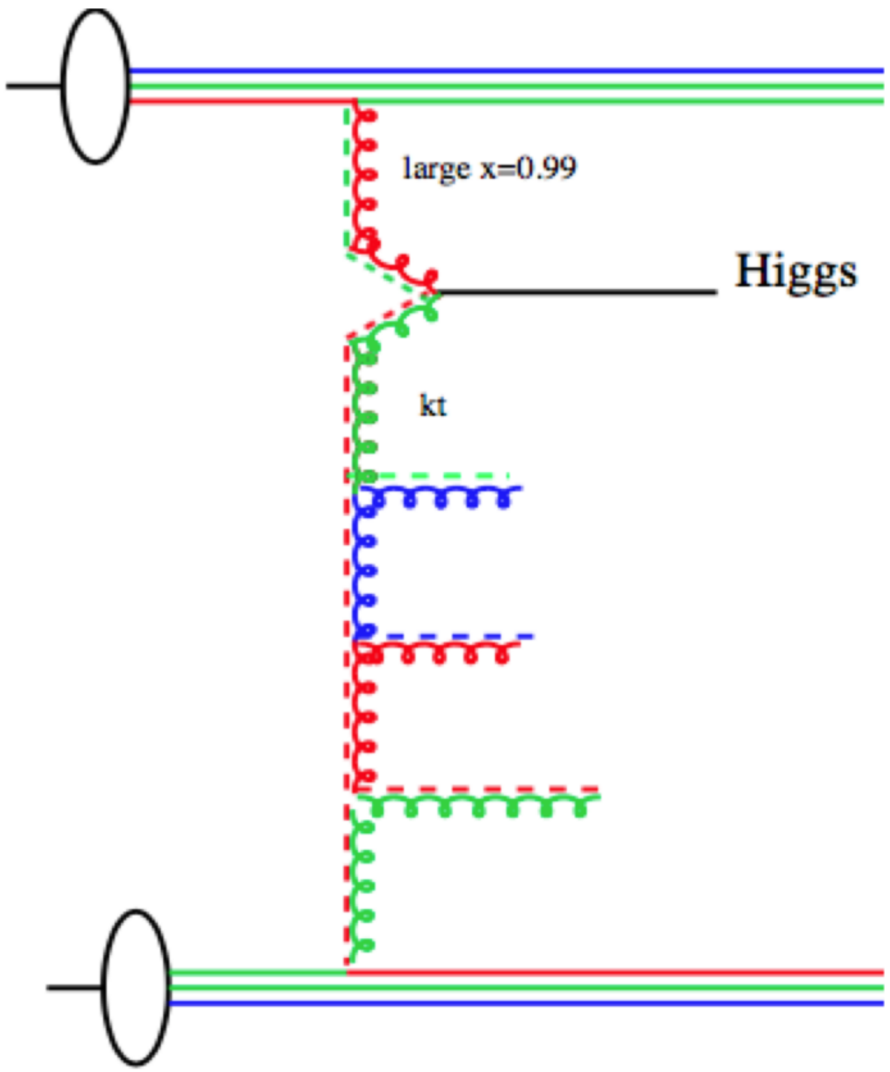
- Parton Branching method developed for solving DGLAP equation at LO, NLO and NNLO
  - ➔ consistence for collinear (integrated) PDFs shown

- method directly applicable to determine k_t distribution (as would be done in PS)
  - ➔ TMD distributions for all flavors determined, without free parameters

- Application in calculations for LHC processes, like DY, jets etc
  - ➔using TMD distributions which reproduce collinear PDFs at NLO and NNLO

Appendix

Calculation of x and k_t from MC events



- k_t is calculated from p_t of hard process
- longitudinal momentum fraction:
  - from mass of produced system:

$$x = \frac{m}{\sqrt{s}} \exp(\pm y)$$

    - will not change when PS is included
  - from light-cone momentum fraction:

$$x = \frac{E + p_z}{(E + p_z)_{beam}}$$

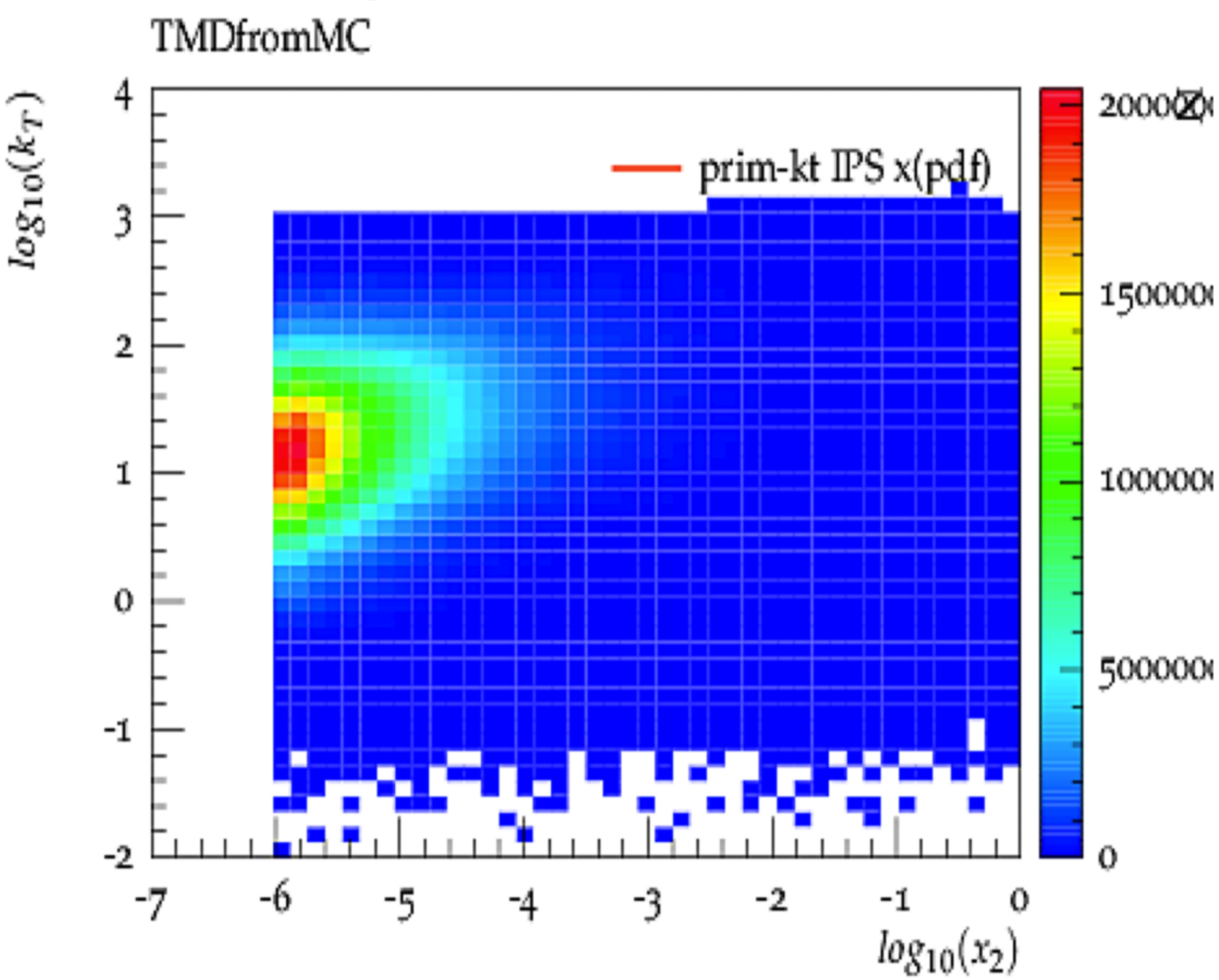
    - will change due to kinematics, if PS is included

The effect of initial state parton shower

fix $x_1 = 0.99$ (no intrinsic k_t, no PS from parton 1), mass 0.5< m <1000 GeV

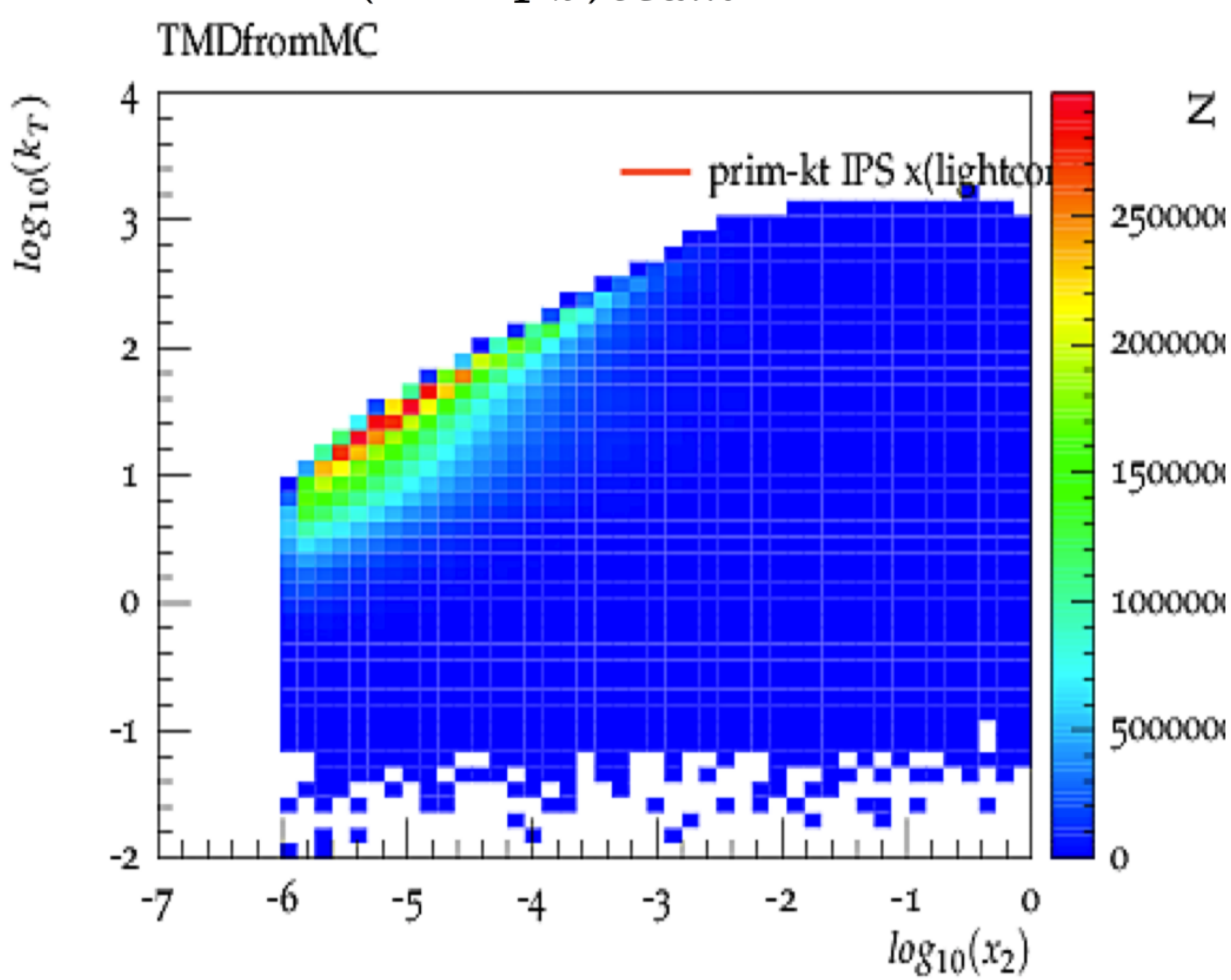
- momentum fraction definition:
  - from mass (or original pdf):

$$x = \frac{m}{\sqrt{s}} \exp(\pm y)$$



- from light-cone momentum fraction:

$$x = \frac{E + p_z}{(E + p_z)_{beam}}$$



- Significant differences from definition of momentum fraction after k_t