MCEG Workshop
DESY, February 2019

F Hautmann

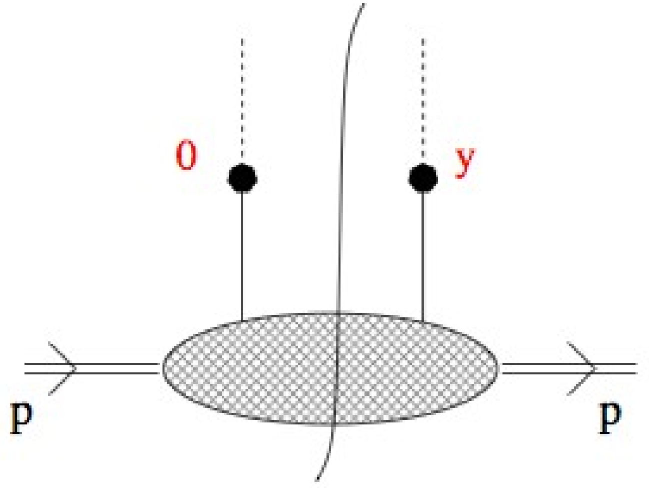
TMDs from Parton Branching

- Introduction
- The Parton Branching (PB) method
- New results and applications

I. Introduction

TRANSVERSE MOMENTUM DEPENDENT (TMD)
PARTON DISTRIBUTION FUNCTIONS

- Parton correlation functions at non-lightlike distances:



$$p = (p^+ , m^2/2p^+ , 0_\perp)$$

$$\widetilde{f}(y) = \langle\, P \mid \overline{\psi}(y)\; V_y^\dagger(n)\; \gamma^+\; V_0(n)\; \psi(0) \mid P \,\rangle \quad , \qquad y = (0, y^-, y_\perp)$$

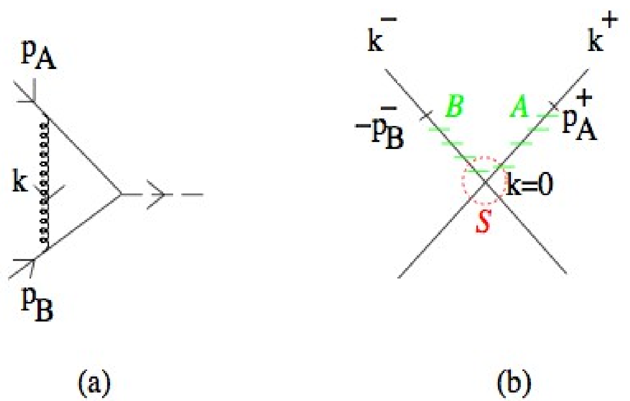
$$V_y(n) = \mathcal{P} \exp\left(i g_s \int_0^\infty d\tau\; n \cdot A(y + \tau\, n)\right)$$

- TMD pdfs:

$$f(x, k_\perp) = \int \frac{dy^-}{2\pi} \frac{d^{d-2} y_\perp}{(2\pi)^{d-2}} e^{-ixp^+ y^- + i k_\perp \cdot y_\perp} \tilde{f}(y)$$

Evolution equations for TMD parton distribution functions

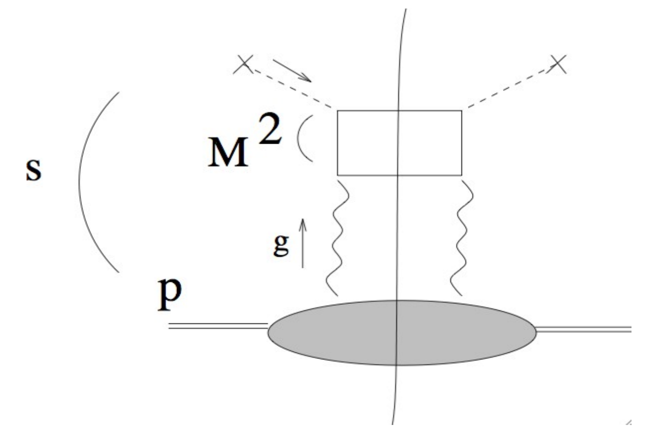
low q_T : $q_T \ll Q$



$\alpha_s^n \ln^m Q/q_T$

CSS evolution equation

high $\sqrt{s}$: $\sqrt{s} \gg M$



$(\alpha_s \ln \sqrt{s}/M)^n$

CCFM evolution equation

R. Angeles-Martinez et al., "Transverse momentum dependent (TMD) parton distribution functions: status and prospects", Acta Phys. Polon. B46 (2015) 2501

TMD distributions (unpolarized and polarized)

TABLE I

(Colour on-line) Quark TMD pdfs: columns represent quark polarization, rows represent hadron polarization. Distributions encircled by a dashed line are the ones which survive integration over transverse momentum. The shades of the boxes (light gray (blue) *versus* medium gray (pink)) indicate structures that are T-even or T-odd, respectively. T-even and T-odd structures involve, respectively, an even or odd number of spin-flips.

QUARKS	*unpolarized*	*chiral*	*transverse*
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

TABLE II

(Colour on-line) Gluon TMD pdfs: columns represent gluon polarization, rows represent hadron polarization. Distributions encircled by a dashed line are the ones which survive integration over transverse momentum. The shades of the boxes (light gray (blue) *versus* medium gray (pink)) indicate structures that are T-even or T-odd, respectively. T-even and T-odd structures involve, respectively, an even or odd number of spin-flips. Linearly polarized gluons represent a double spin-flip structure.

GLUONS	*unpolarized*	*circular*	*linear*
U	f_1^g		$h_1^{\perp g}$
L		g_{1L}^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_{1T}^g, $h_{1T}^{\perp g}$

R. Angeles-Martinez et al., “Transverse momentum dependent (TMD) parton distribution functions: status and prospects”, Acta Phys. Polon. B46 (2015) 2501

II. The Parton Branching (PB) approach:

MOTIVATION

- Evolution equation connected in a controllable way with DGLAP evolution of collinear parton distributions
- Applicable over broad kinematic range from low to high transverse momenta, for inclusive as well as non-inclusive observables
- Implementable in Monte Carlo event generators

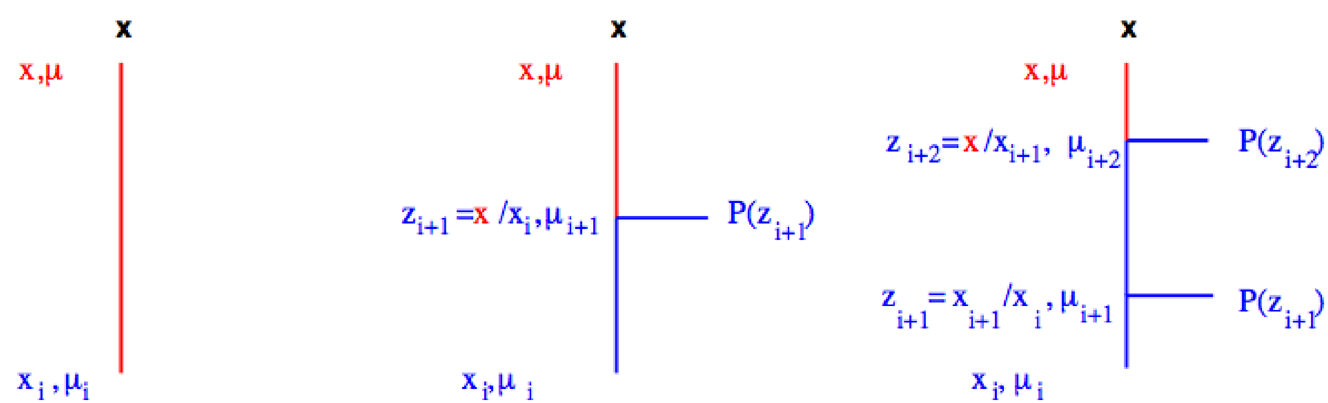
Parton Branching (PB) method: collinear PDFs

QCD evolution and soft-gluon resolution scale

[Jung, Lelek, Radescu, Zlebcik & H, PLB772 (2017) 446 + in progress]

$$\widetilde{f}_a(x,\mu^2) = S_a(\mu^2)\,\widetilde{f}_a(x,\mu_0^2) + \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2}\frac{S_a(\mu^2)}{S_a(\mu'^2)} \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mu'^2),z)\,\widetilde{f}_b(x/z,\mu'^2)$$

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



▷ soft-gluon resolution parameter z_M separates resolvable and nonresolvable branchings

▷ no-branching probability S; real-emission probability $P^{(R)}$

- Equivalent to DGLAP evolution equation for zM → 1

Non-resolvable emissions and unitarity method

- Introduce resolution scale z_M, where $1 - z_M \sim \mathcal{O}(\Lambda_{\rm QCD}/\mu)$.

- Classify singular behavior of splitting kernels $P_{ab}(z, \alpha_s)$ in non-resolvable region $1 > z > z_M$:

$$P_{ab}(\alpha_{\rm S}, z) = D_{ab}(\alpha_{\rm S})\delta(1-z) + K_{ab}(\alpha_{\rm S}) \ \frac{1}{(1-z)_+} + R_{ab}(\alpha_{\rm S}, z)$$

$$\text{where} \quad \int_0^1 \frac{1}{(1-z)_+} \, \varphi(z) \, dz = \int_0^1 \frac{1}{1-z} \, [\varphi(z) - \varphi(1)] \, dz$$

and $R_{ab}(\alpha_{\rm S}, z)$ contains logarithmic and analytic contributions for $z \to 1$

- Expand plus-distributions in non-resolvable region and use sum rule $\sum_c \int_0^1 z \, P_{ca}(\alpha_{\rm S}, z) \, dz = 0 \ \ (\text{for any } a)$ to eliminate D-terms in favor of K- and R-terms

$\Rightarrow$ real-emission probabilities exponentiate into Sudakov form factors

Parton Branching (PB) method: TMD PDFs

$$\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu^2) \;=\; S_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2) + \sum_b \int \frac{d^2\mathbf{q}'}{\pi \mathbf{q}'^2}\,\frac{S_a(\mu^2)}{S_a(\mathbf{q}'^2)}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$

$$\times \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mathbf{q}'^2)$$

$$\text{Solve iteratively}:\quad \widetilde{\mathcal{A}}_a^{(0)}(x,\mathbf{k},\mu^2) = S_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2)\;,$$

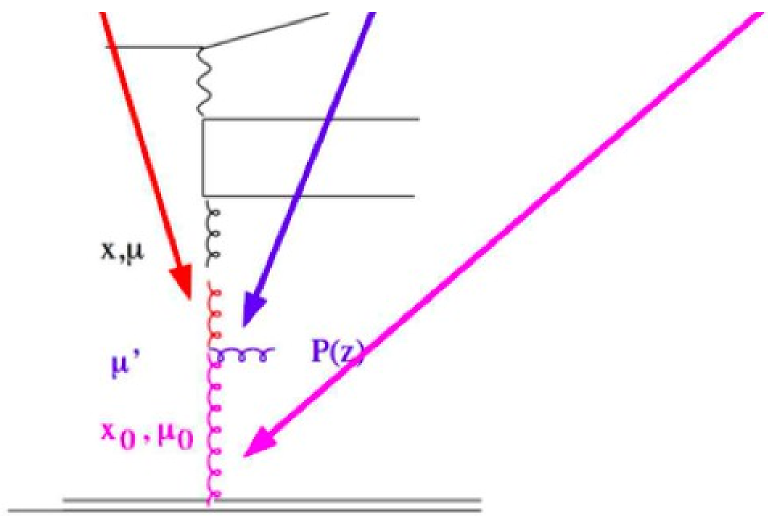
$$\widetilde{\mathcal{A}}_a^{(1)}(x,\mathbf{k},\mu^2) = \sum_b \int \frac{d^2\mathbf{q}'}{\pi \mathbf{q}'^2}\,\Theta(\mu^2-\mathbf{q}'^2)\,\Theta(\mathbf{q}'^2-\mu_0^2)$$

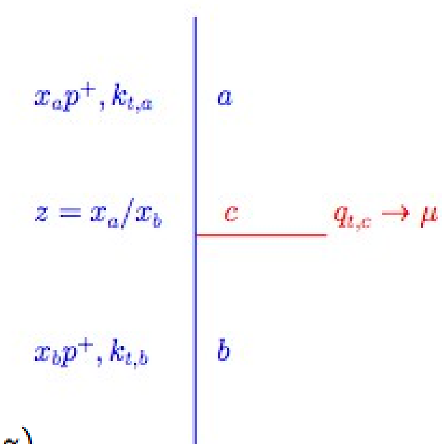
$$\times \frac{S_a(\mu^2)}{S_a(\mathbf{q}'^2)} \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mu_0^2)\, S_b(\mathbf{q}'^2)$$

↖ NB: angular ordering

Jung, Lelek, Radescu, Zlebcik & H, JHEP 01 (2018) 070

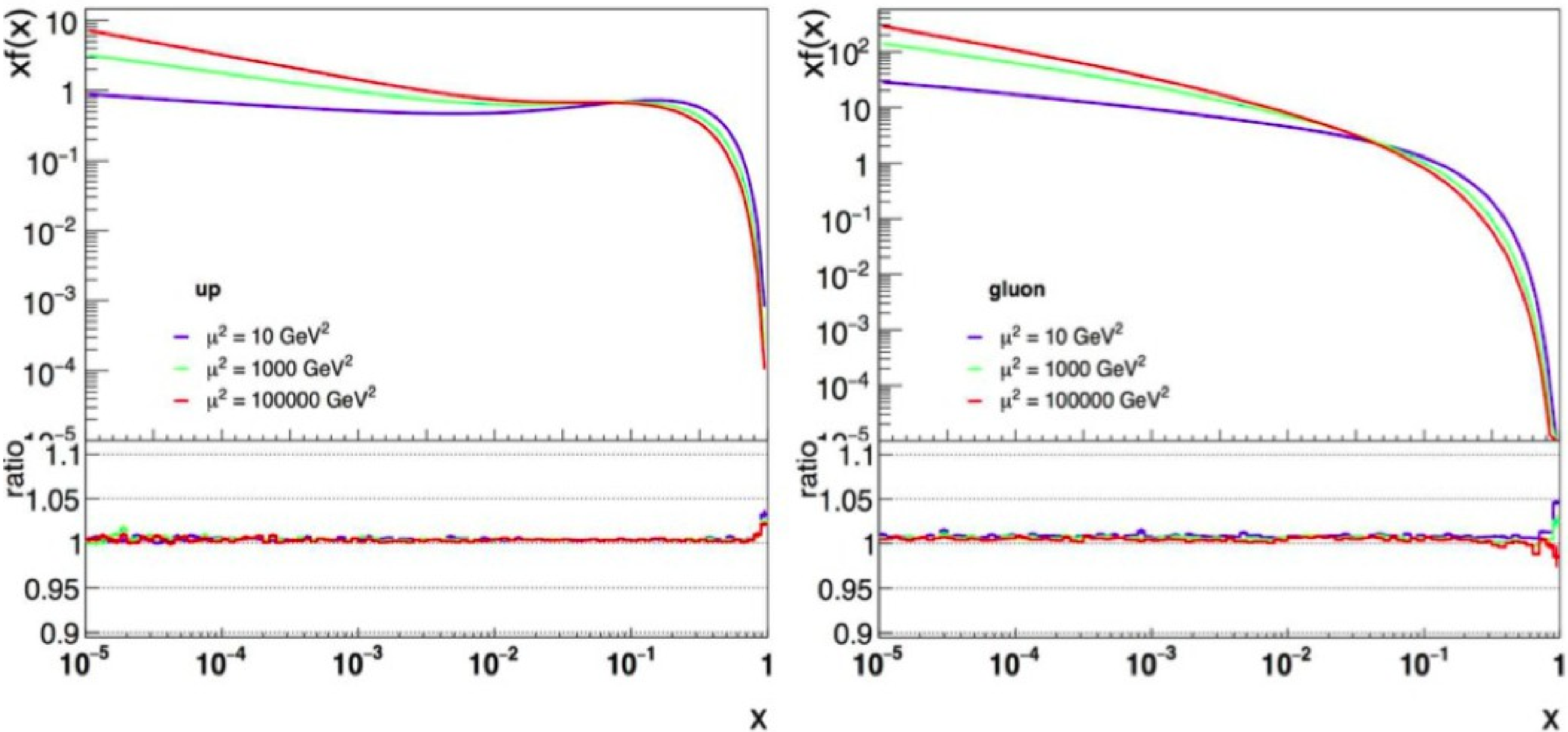
- A new evolution equation!





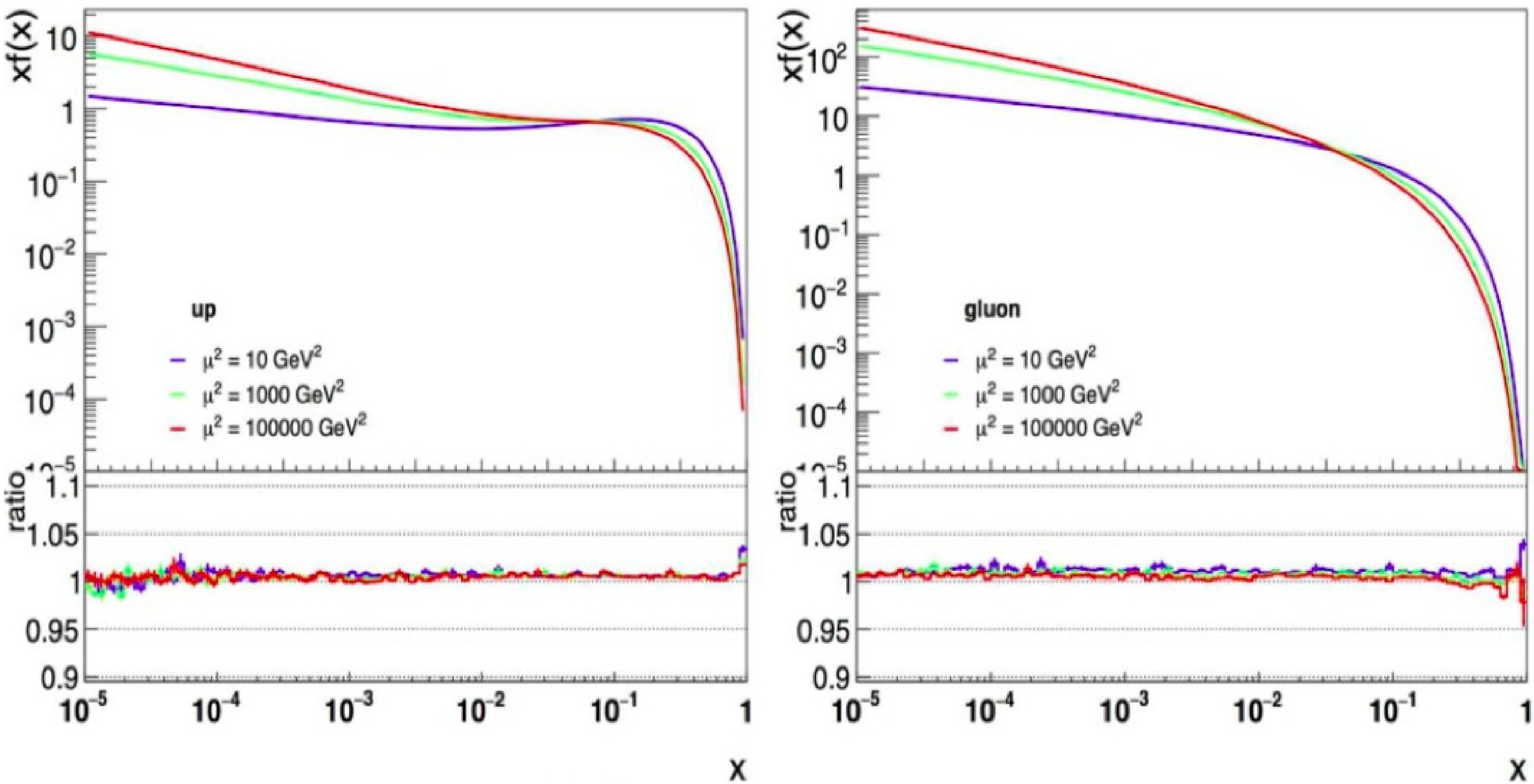
$$\mu = |\mathbf{q}_c|/(1-z)$$

Validation of the method with semi-analytic result from QCDNUM at LO



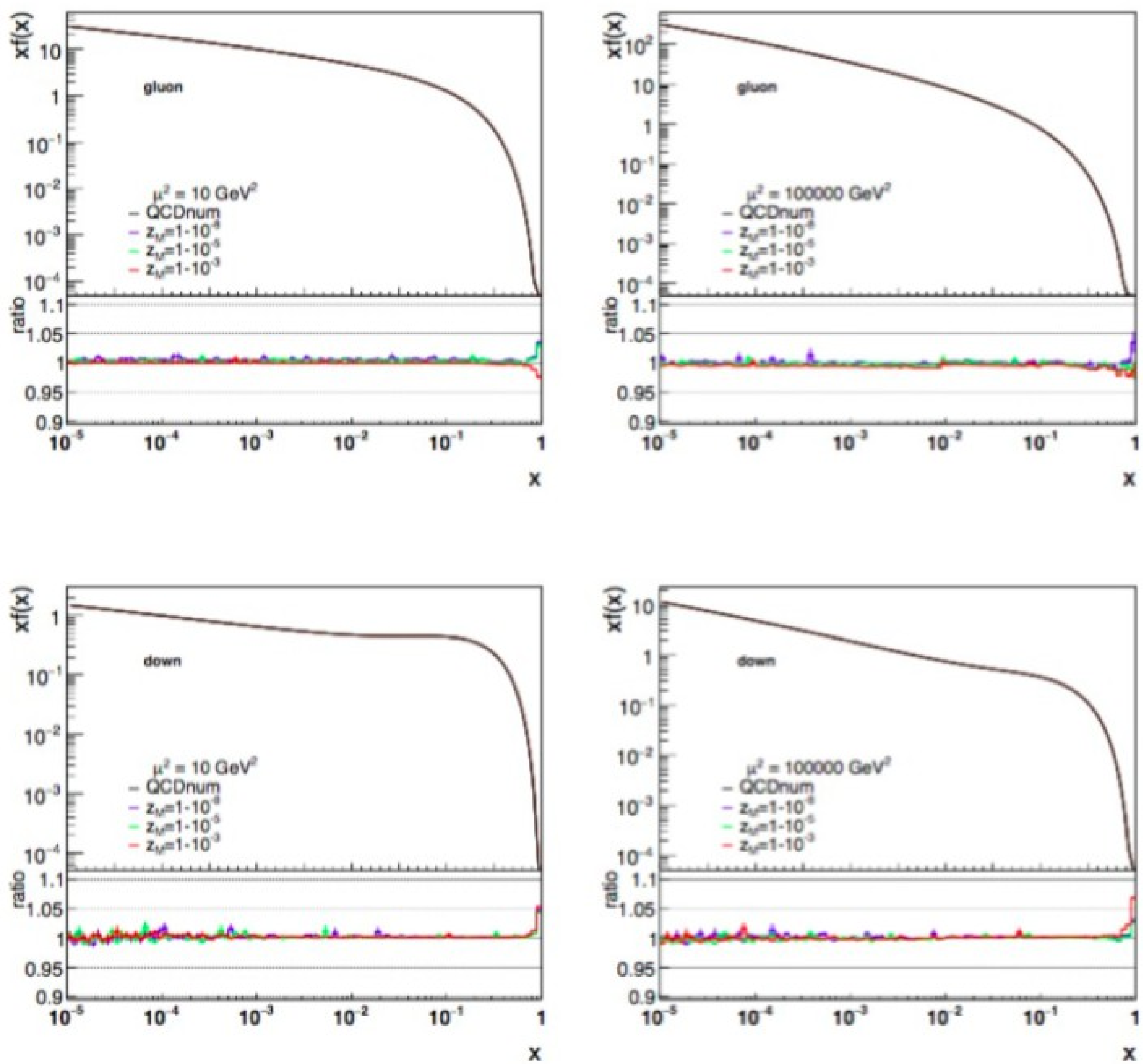
Agreement to better than 1 % over several orders of magnitude in x and mu

Validation of the method with semi-analytic result from QCDNUM at NLO

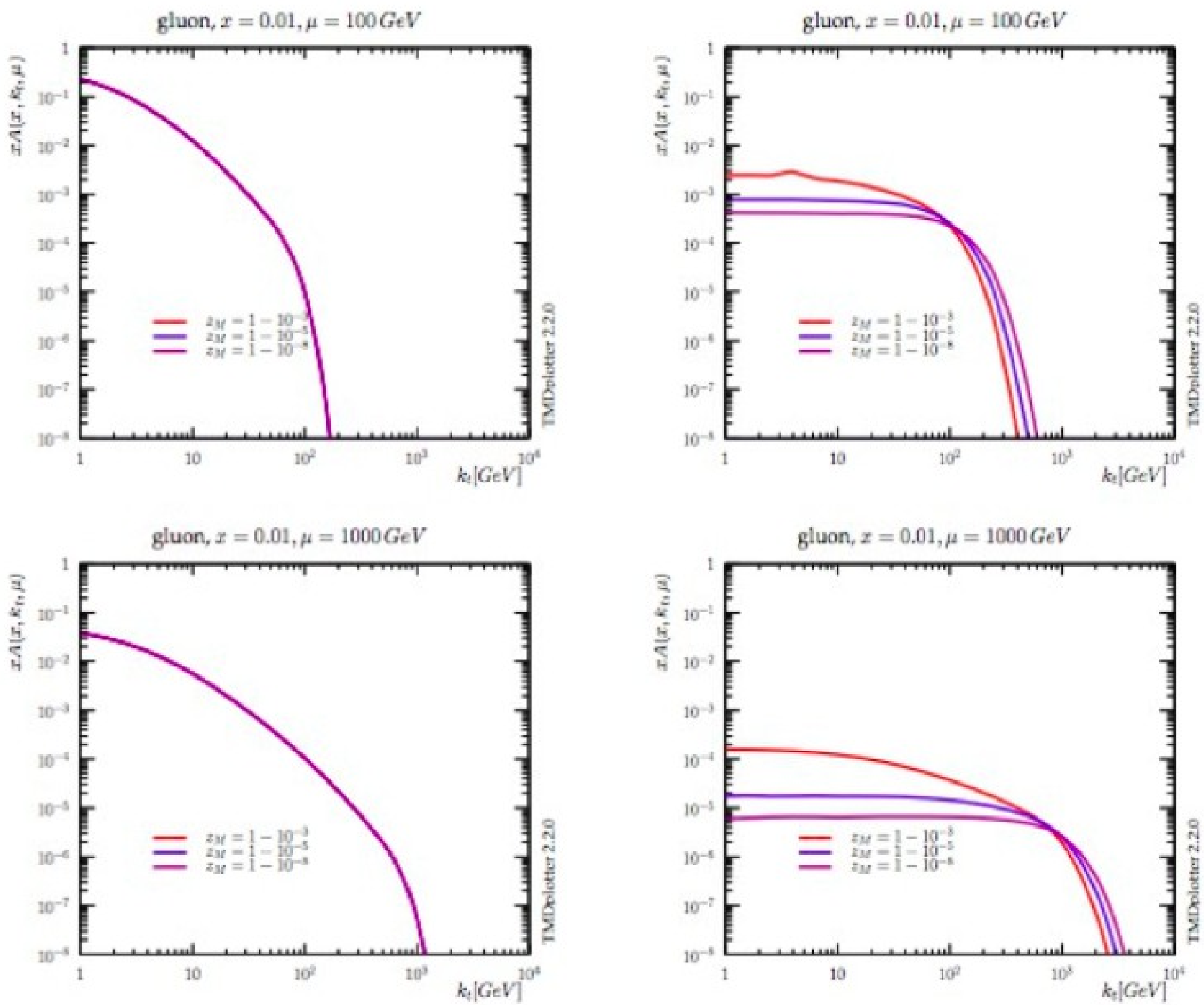


Very good agreement at NLO over all x and mu.
NB: the same approach is designed to work at NNLO.

Stability with respect to resolution scale z_M



TMDs and soft gluon resolution effects



angular ordering

transverse momentum ordering

Well-defined TMDs require appropriate ordering condition

PB method in xFitter

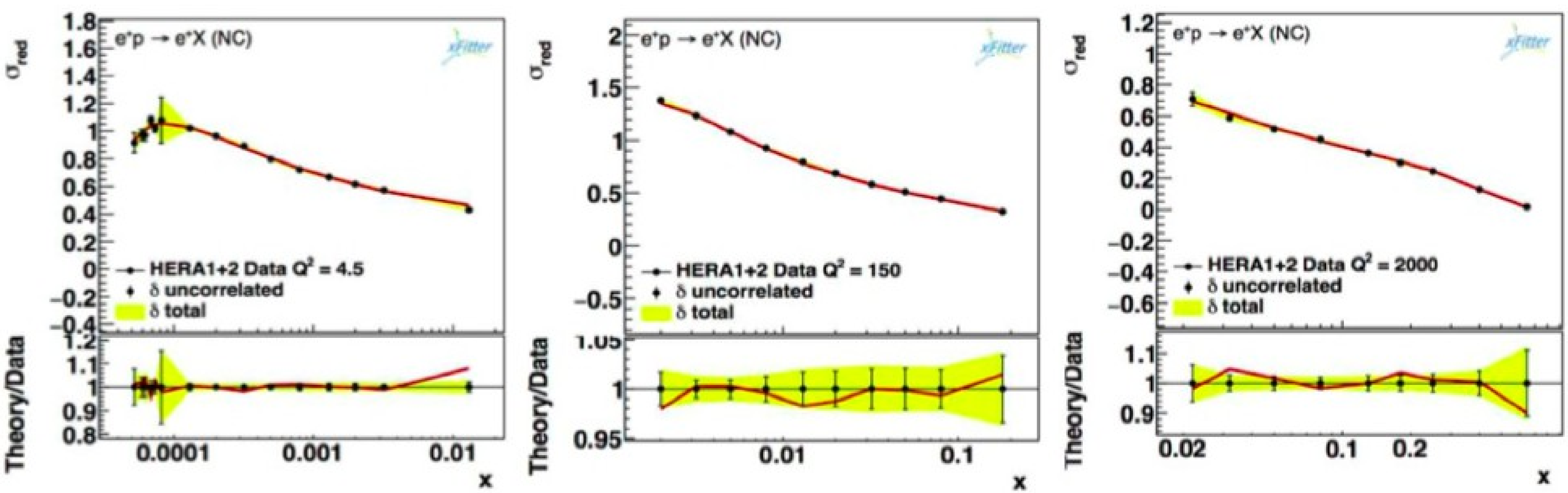
- Determine starting distribution

A Bermudez et al, arXiv:1804.11152

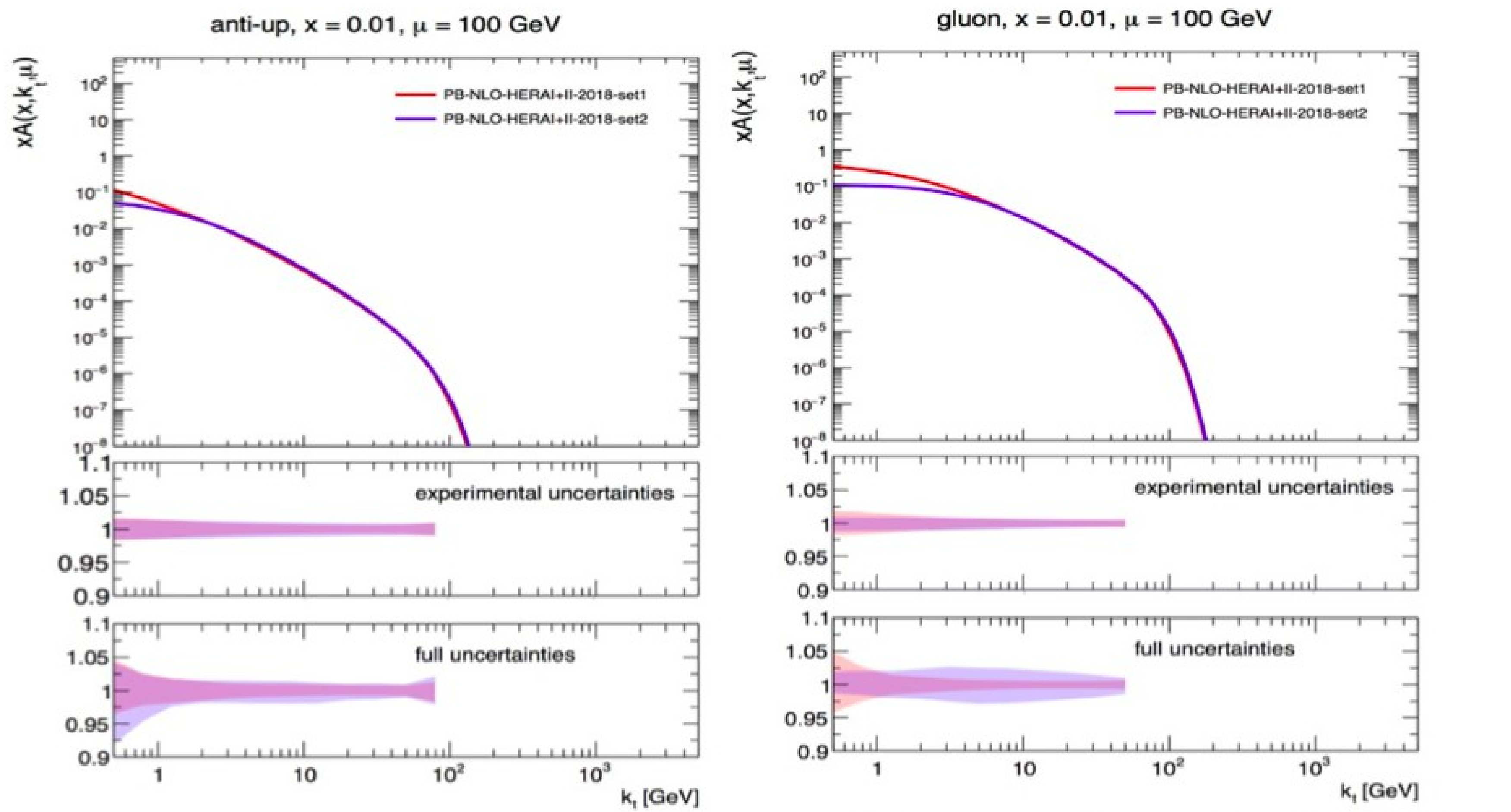
A. Lelek et al REF 2016

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

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



TMD distributions from fits to precision HERA data



A Bermudez et al, arXiv:1804.11152

- NLO determination of TMDs with uncertainties

Where to find TMDs? TMDlib and TMDplotter

- TMDlib proposed in 2014 as part of the REF Workshop and developed since

- A library of parameterizations and fits of TMDs (LHAPDF-style)

  http://tmdlib.hepforge.org
  http://tmdplotter.desy.de

- Also contains collinear (integrated) pdfs

Eur. Phys. J. C (2014) 74:3220
DOI 10.1140/epjc/s10052-014-3220-9

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions

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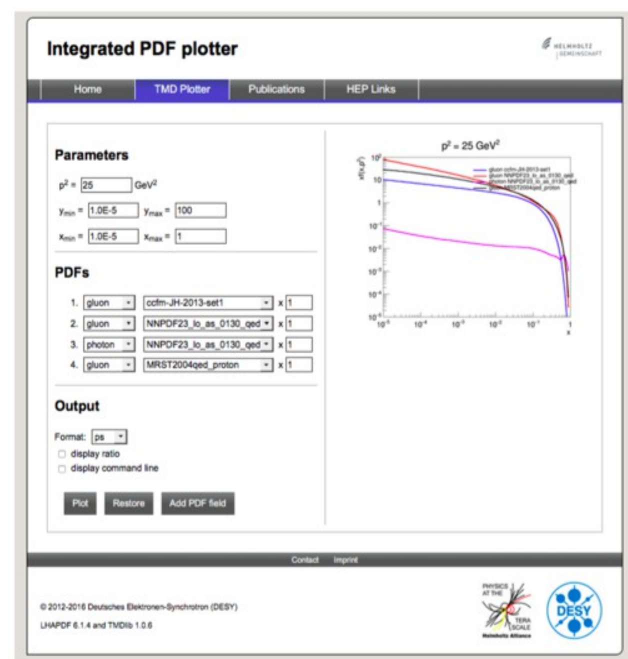

Last REF Workshop: Cracow, 19-22 November 2018

https://indico.cern.ch/event/696311

Workshop on Resummation, Evolution, Factorization 2018

19-22 November 2018
Other Institutes
Europe/Warsaw timezone

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- Overview
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REF 2018 is the 5th workshop in the series of workshops on Resummation, Evolution, Factorization. The workshop wishes to bring together experts of different communities specialized in: nuclear structure; transverse momentum dependend distributions; small-x physics; effective field theories.

Previous meetings

- 13-16 November 2017 Madrid (Spain)
- 7-10 November 2016 Antwerp (Belgium)
- 2-5 November 2015 DESY Hamburg (Germany)
- 8-11 December 2014 Antwerp (Belgium)

Scientiffic committee:

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Piet Mulders Gunar Schnell
Andrea Signori Pierre Van Mechelen

Next workshop in Pavia – November 2019

III. New results and applications

ONGOING WORK:

- Drell-Yan pT spectrum from convolution of two transverse momentum dependent distributions

- Comparison of parton branching results with analytic TMD resummation (Collins-Soper-Sterman method)

- First implementation for jets (using NLO matrix elements for color-charged final states)

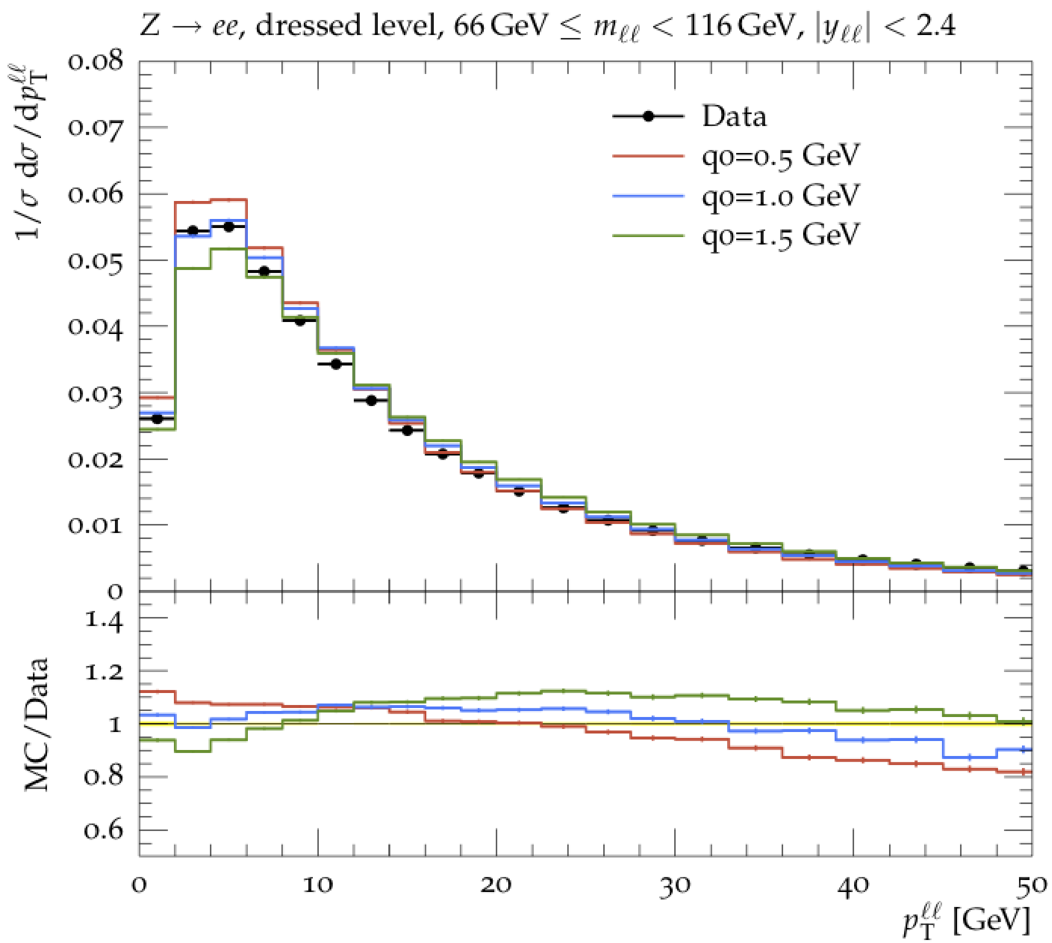
Application of PB method to Z-boson transverse momentum spectrum in Drell-Yan production

- Parton branching TMD defined by using angular ordering
  - Scale in running coupling also by angular ordering

$$\alpha_s(\mu^2(1-z)^2)$$

- mu-dependent soft-gluon resolution scale parameter zM

$$z_M(\mu) = 1 - q_0/\mu$$

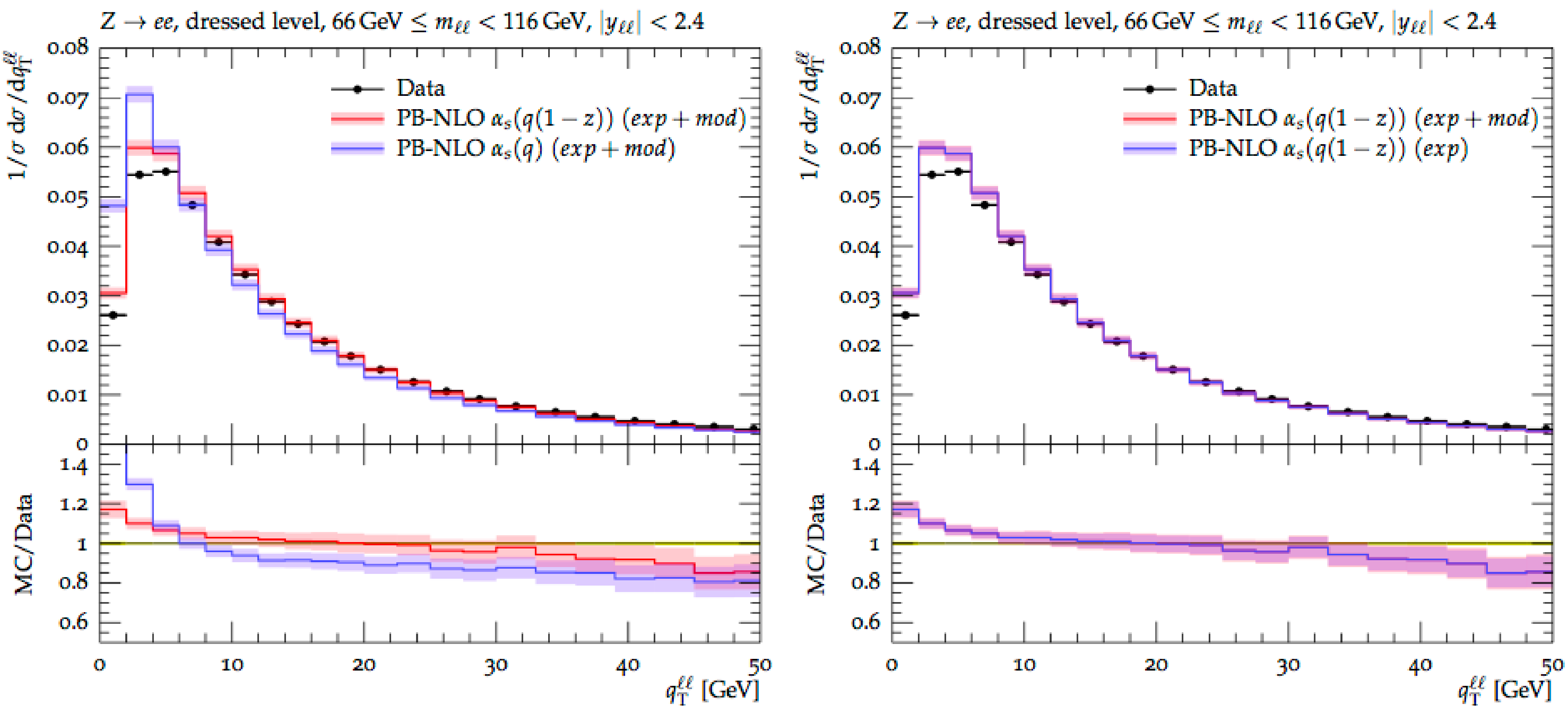


LHC Electroweak WG Meeting, CERN, June 2018

Z-boson transverse momentum spectrum: soft-gluon angular ordering effects

can be extended to Drell-Yan on nuclei – see talk by K Kutak

Zlebcik, Radescu, Lelek, Jung & H, JHEP 1801 (2018) 070;
A Bermudez Martinez et al., arXiv:1804.11152 [hep-ph]



ATLAS data, EPJC 76 (2016) 291

Comparison with CSS (Collins-Soper-Sterman) resummation

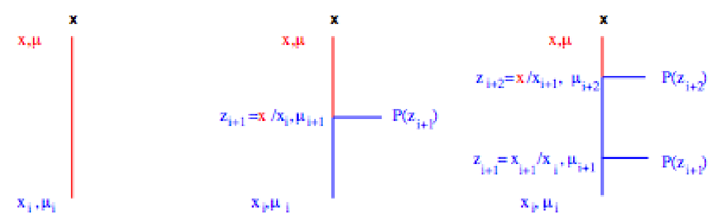
◇ The resummed DY differential cross section is given by

$$\frac{d\sigma}{d^2\mathbf{q}dQ^2dy} = \sum_{q,\bar{q}} \frac{\sigma^{(0)}}{s} H(\alpha_S) \int \frac{d^2\mathbf{b}}{(2\pi)^2}\, e^{i\mathbf{q}\cdot\mathbf{b}} \mathcal{A}_q(x_1,\mathbf{b},Q)\mathcal{A}_{\bar{q}}(x_2,\mathbf{b},Q) + \mathcal{O}\left(\frac{|\mathbf{q}|}{Q}\right) \quad \text{where}$$

$$\begin{aligned}\mathcal{A}_i(x,\mathbf{b},Q) \quad &= \quad \exp\left\{\frac{1}{2}\int_{c_0/b^2}^{Q^2} \frac{d\mu'^2}{\mu'^2}\left[A_i(\alpha_S(\mu'^2))\ln\left(\frac{Q^2}{\mu'^2}\right) + B_i(\alpha_S(\mu'^2))\right]\right\} G_i^{(\mathrm{NP})}(x,\mathbf{b}) \\ &\times \quad \sum_j \int_x^1 \frac{dz}{z} C_{ij}\left(z,\alpha_S\left(\frac{c_0}{\mathbf{b}^2}\right)\right) f_j\left(\frac{x}{z},\frac{c_0}{\mathbf{b}^2}\right)\end{aligned}$$

and the coefficients H, A, B, C have power series expansions in α_S.

◇ The parton branching TMD is expressed in terms of real-emission $P^{(R)}$:



▷ via momentum sum rules, use unitarity to relate $P^{(R)}$ to virtual emission

▷ identify the coefficients in the two formulations, order by order in α_S, at LL, NLL, . . .

Comparison with CSS (Collins-Soper-Sterman) resummation

More precisely:

▷ The parton branching TMD contains Sudakov form factor in terms of

$$P_{ab}^{(R)}(\alpha_S, z) = K_{ab}(\alpha_S)\,\frac{1}{1-z} + R_{ab}(\alpha_S, z) \quad \text{where}$$

$$K_{ab}(\alpha_S) = \delta_{ab} k_a(\alpha_S)\,, \quad k_a(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^n k_a^{(n-1)}\,, \quad R_{ab}(\alpha_S, z) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^n R_{ab}^{(n-1)}(z)$$

▷ Via momentum sum rules, use unitarity to re-express this in terms of

$$P^{(V)} = P - P^{(R)}\,, \quad \text{where}$$

$$P_{ab}(\alpha_S, z) = D_{ab}(\alpha_S)\delta(1-z) + K_{ab}(\alpha_S)\,\frac{1}{(1-z)_+} + R_{ab}(\alpha_S, z)$$

is full splitting function (at LO, NLO, etc.)

$$\text{with} \quad D_{ab}(\alpha_S) = \delta_{ab} d_a(\alpha_S)\,, \quad d_a(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{2\pi}\right)^n d_a^{(n-1)}$$

▷ Identify $d_a(\alpha_S)$ and $k_a(\alpha_S)$ with resummation formula coefficients (LL, NLL, . .)

Comparison with CSS (Collins-Soper-Sterman) resummation

- $d_a(\alpha_S)$ and $k_a(\alpha_S)$ perturbative coefficients

$$\mathrm{one-loop} \; :$$

$$d_q^{(0)} = \frac{3}{2} C_F \quad , \quad k_q^{(0)} = 2 \, C_F$$

$$\mathrm{two-loop} \; :$$

$$d_q^{(1)} = C_F^2 \left(\frac{3}{8} - \frac{\pi^2}{2} + 6 \, \zeta(3) \right) + C_F C_A \left(\frac{17}{24} + \frac{11\pi^2}{18} - 3 \, \zeta(3) \right) - C_F T_R N_f \left(\frac{1}{6} + \frac{2\pi^2}{9} \right) ,$$

$$k_q^{(1)} = 2 \, C_F \, \Gamma \, , \quad \mathrm{where} \;\; \Gamma = C_A \left(\frac{67}{18} - \frac{\pi^2}{6} \right) - T_R N_f \frac{10}{9}$$

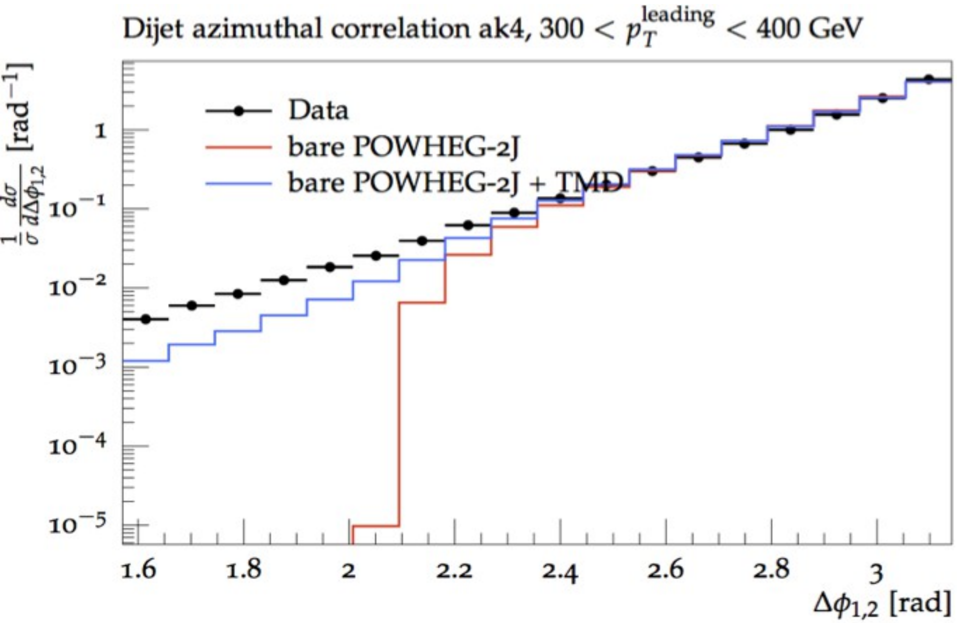
- The k and d coefficients of the PB formalism match, order by order, the A and B coefficients of the CSS formalism:

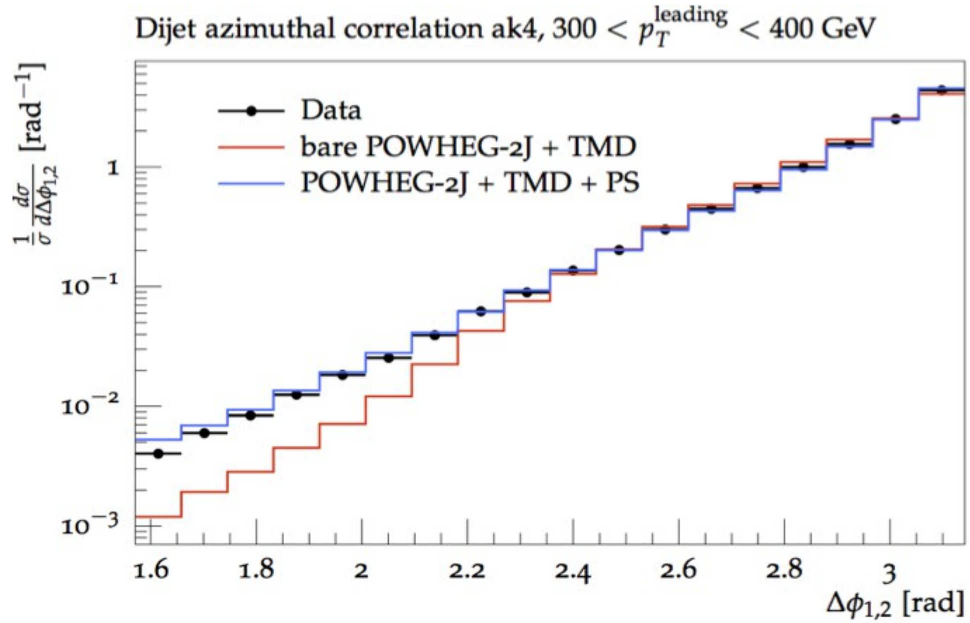
$$\mathrm{LL} \; : \quad k_q^{(0)} = 2 \, C_F = 2 \, A_q^{(1)}$$

$$\mathrm{NLL} \; : \quad k_q^{(1)} = 2 \, C_F \, \Gamma = 4 \, A_q^{(2)} \; ; \;\; d_q^{(0)} = \frac{3}{2} C_F = - B_q^{(1)}$$

$$\mathrm{NNLL} \; : \quad \text{analysis in progress}$$

Di-jets from PB method:
towards NLO-matched parton-shower Monte Carlo generators with TMDs





- Events by NLO POWHEG 2 jets
- Parton branching TMD (with angular ordering)
- TMD parton shower

Di-jets from PB method:
towards NLO-matched parton-shower Monte Carlo generators with TMDs

- Events by NLO POWHEG 2 jets
- Parton branching TMD (with angular ordering)
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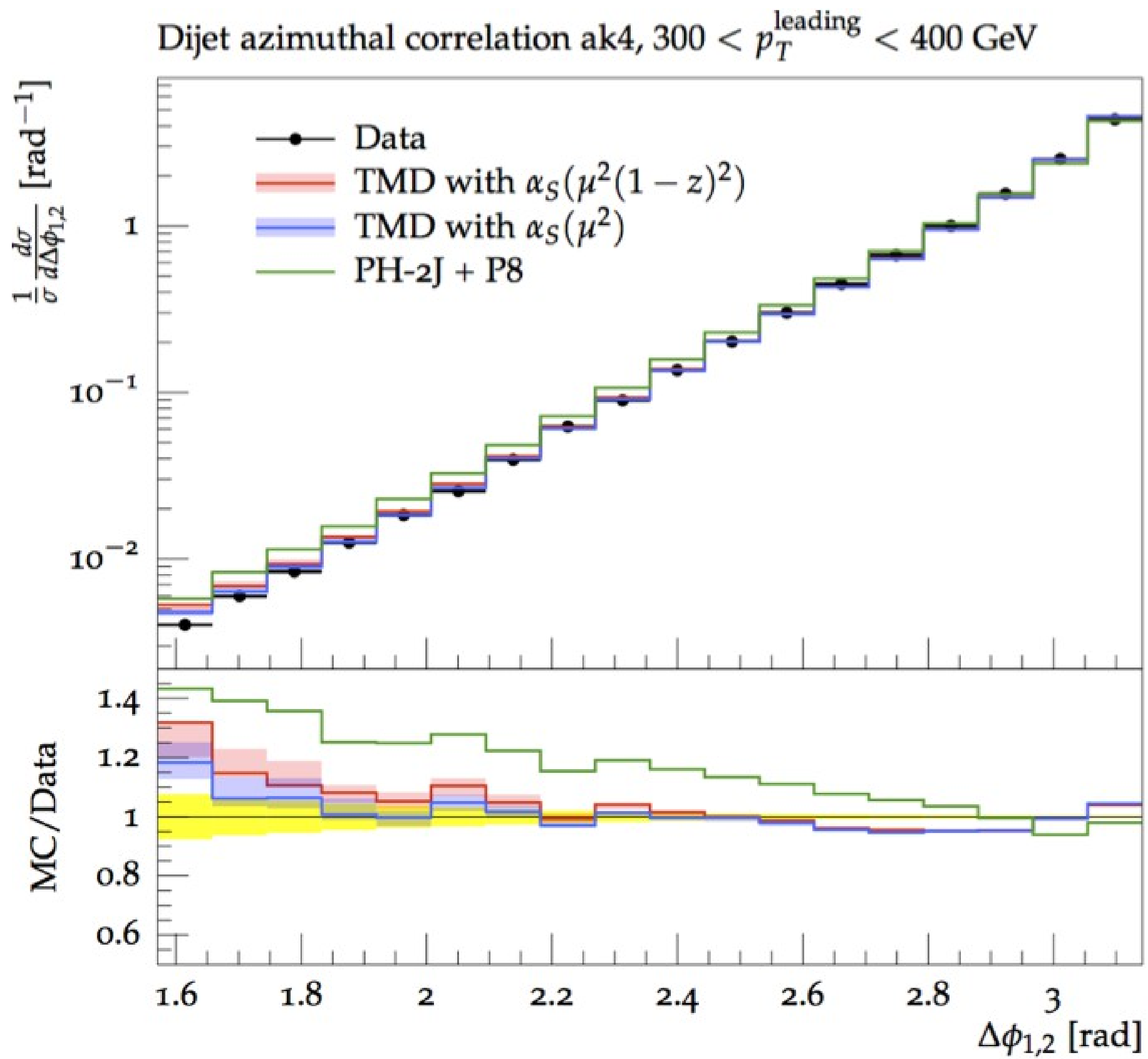
see talk by H Jung on TMD showers



Conclusions

- PB method to take into account simultaneously soft-gluon emission at $z \to 1$ and transverse momentum q_T recoils in the parton branchings along the QCD cascade

- potentially relevant for calculations both in collinear factorization and in TMD factorization

  → cf. parton shower calculations and analytic resummation

- terms in powers of ln (1 – zM) can be related to large-x resummation? → relevant to near-threshold, rare processes to be investigated at high luminosity

- systematic studies of ordering effects and color coherence

  → helpful to analyze long-time color correlations?