F Hautmann

TMDs from low to high energies and the parton branching method

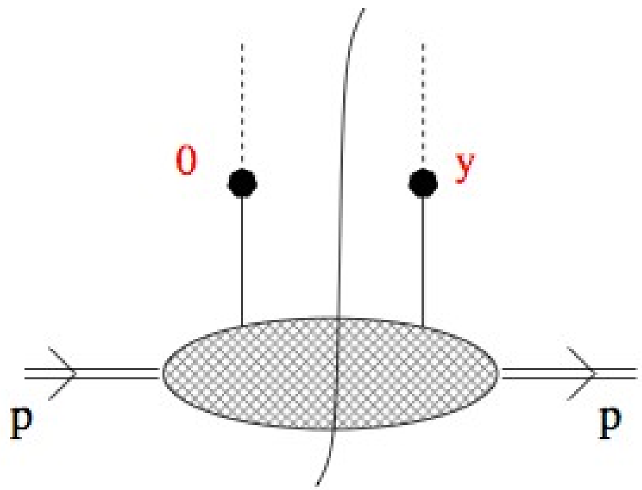
INT Program 18-3 “Probing Nucleons and Nuclei in High Energy Collisions” - EIC Symposium

Institute for Nuclear Theory, Seattle, October 2018

Overview

TRANSVERSE MOMENTUM DEPENDENT (TMD)
PARTON DISTRIBUTION FUNCTIONS

- Parton correlation functions at non-lightlike distances:



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

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

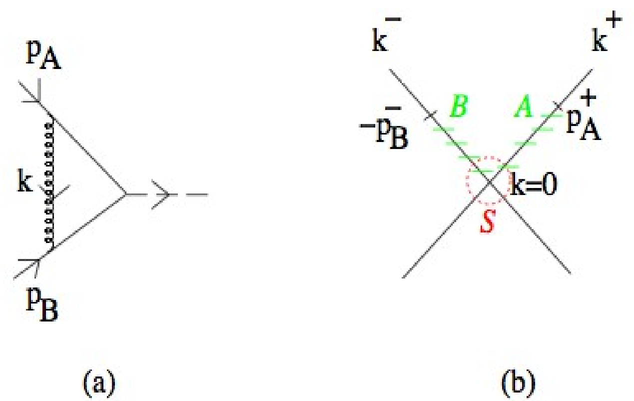
$$V_y(n) = \mathcal{P} \exp \left(i g_s \int_0^\infty d\tau \; n \cdot A(y + \tau\, n) \right)$$

- TMD pdfs:

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

Evolution equations for TMD parton distribution functions

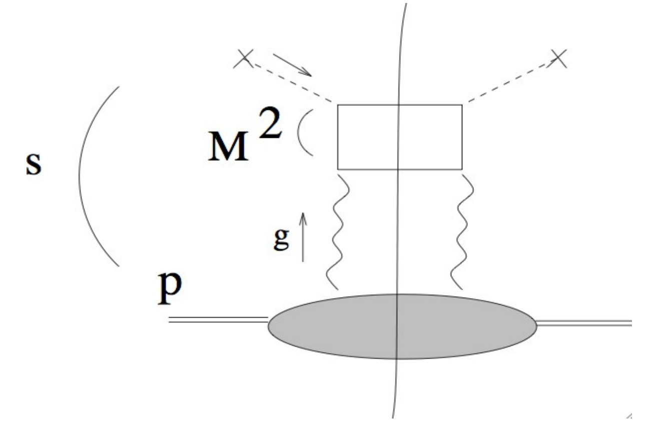
low q_T : $q_T \ll Q$



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

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

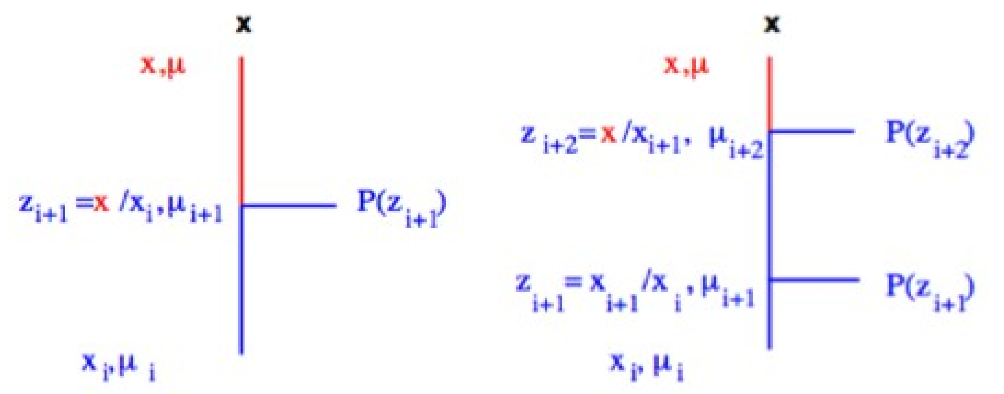
(Colour on-line) Gluon TMD pdfs: columns represent gluon polarization, rows represent hadron polarization. Distributions encircled by a dashed line are the ones which survive integration over transverse momentum. The shades of the boxes (light gray (blue) *versus* medium gray (pink)) indicate structures 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

Parton Branching (PB) approach

Jung, Lelek, Radescu, Zlebcik & H, "Collinear and TMD quark and gluon densities from parton branching", JHEP 1801 (2018) 070



PB evolution equation motivated by

– applicability over large kinematic range from low to high transverse momenta

– applicability to exclusive final states and Monte Carlo event generators

Outline of this talk

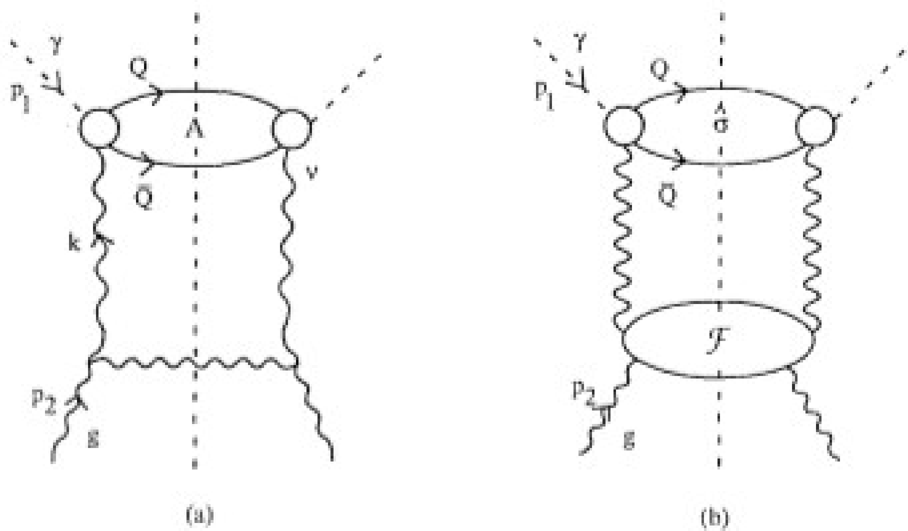
- TMDs at high $\sqrt{s}$ and at low qT

- The parton branching (PB) method

- New results and applications

I. INTRODUCTION
TMDs at high energies

Ex.: heavy flavor electroproduction for $s \gg M^2 \gg \Lambda^2_{\rm QCD}$



$$\gamma + h \to Q + \bar{Q} + X$$

$$4M^2\, \sigma(x, M^2) = \int d^2\mathbf{k}_\perp \int_x^1 \frac{dz}{z}\, \hat{\sigma}_{\gamma g}(x/z, \mathbf{k}_\perp^2/M^2, \alpha_{\rm S}(M^2))\, \mathcal{A}_{g/h}(z, \mathbf{k}_\perp)$$

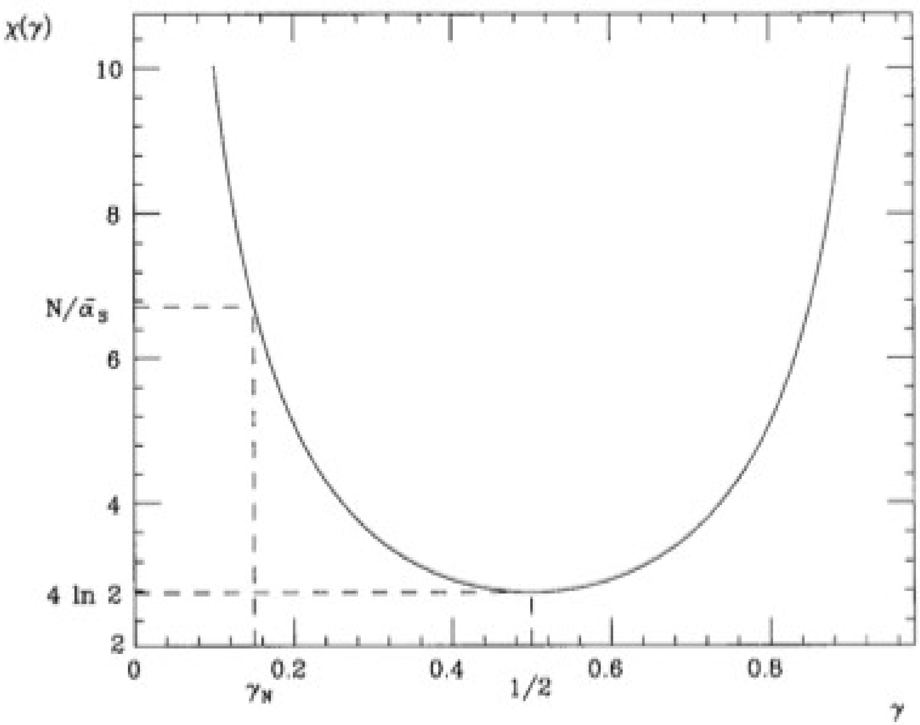
where TMD gluon distribution is given by
Balitsky-Fadin-Kuraev-Lipatov (BFKL) evolution:

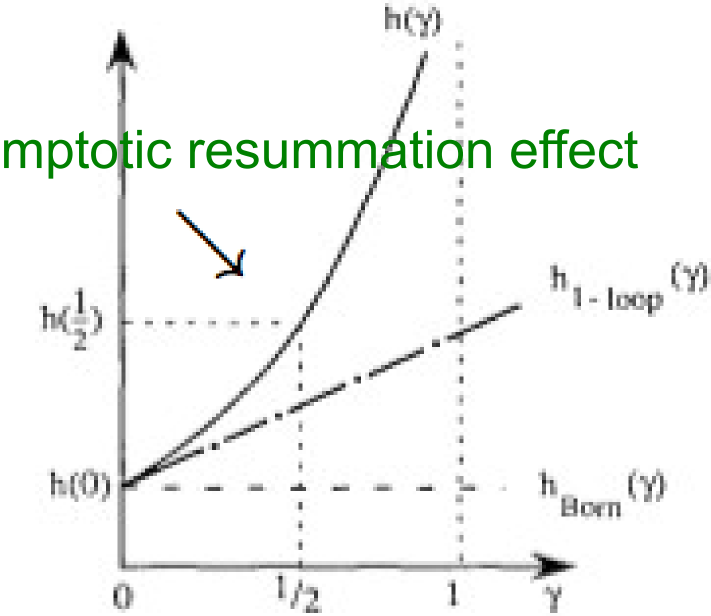
$$\mathcal{A}_{g/h}(x, \mathbf{k}_\perp) \sim \frac{1}{2\pi}\, e^{-\lambda\, \ln x}\, (\mathbf{k}_\perp^2)^{-\frac{1}{2}} \quad , \quad \lambda = 4\, C_A\, \frac{\alpha_{\rm S}}{\pi}\, \ln 2$$

TMDs at high energies

$$\Rightarrow 4M^2\sigma(x,M^2) \sim x^{-\lambda}\,(M^2)^{\frac{1}{2}}\;h(1/2)\;,$$

$$\text{where}\;\; h(1/2) = \frac{1}{2}\int_0^\infty \frac{d\mathbf{k}_\perp^2}{\mathbf{k}_\perp^2}\left(\frac{\mathbf{k}_\perp^2}{M^2}\right)^{\frac{1}{2}}\int_0^1 \frac{dx}{x}\;\hat{\sigma}_{\gamma g}(x,\mathbf{k}_\perp^2/M^2,\alpha_S)$$





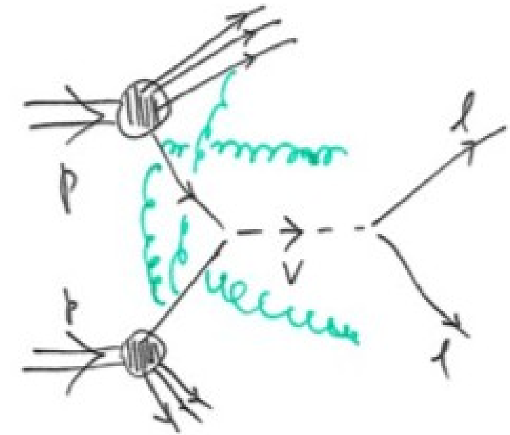
asymptotic resummation effect

realistic effects at EIC, LHeC, VHEeP?

NB: - incorporate sub-asymptotic, finite-x terms → CCFM evolution
- dense-medium modifications in nucleons and nuclei → nonlinear evolution

TMDs for low qT

Ex.: Drell-Yan production qT spectra for Q >> qT



$$\frac{d\sigma}{d^2\mathbf{q}_T dQ^2 dy} = \sum_{i,j} \frac{\sigma^{(0)}}{s} H(\alpha_S) \int \frac{d^2\mathbf{b}}{(2\pi)^2} e^{i\mathbf{q}_T\cdot\mathbf{b}} \mathcal{A}_i(x_1, \mathbf{b}, \mu, \zeta) \mathcal{A}_j(x_2, \mathbf{b}, \mu, \zeta) + \{\mathbf{q}_T\text{–finite}\} + \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{Q^2}\right)$$

where $$\frac{\partial \ln \mathcal{A}}{\partial \ln \sqrt{\zeta}} = K(\mathbf{b}, \mu)$$ Collins-Soper-Sterman (CSS) evolution

and $$\frac{d \ln \mathcal{A}}{d \ln \mu} = \gamma_f(\alpha_s(\mu), \zeta/\mu^2) \ , \quad \frac{dK}{d\ln\mu} = -\gamma_K(\alpha_s(\mu))$$ RG evolution

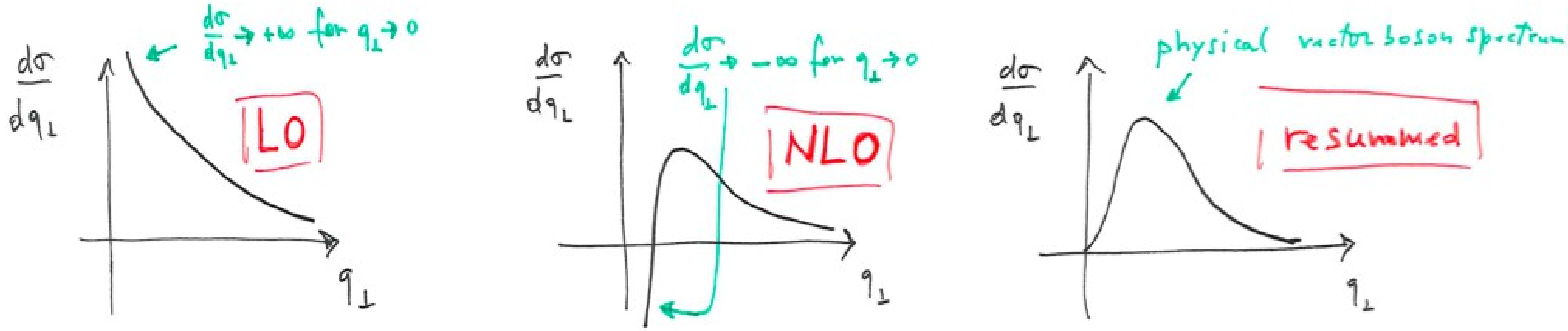
↖ cusp anomalous dimension

$$\Rightarrow \quad -\gamma_K = \frac{\partial}{\partial \ln\sqrt{\zeta}} \gamma_f \qquad \text{i.e.} \quad \gamma_f(\alpha_s(\mu), \zeta/\mu^2) = \gamma_f(\alpha_s(\mu), 1) - \frac{1}{2}\gamma_K \ln\zeta$$

- Soft Collinear Effective Theory (SCET) provides alternative approach leading to same results

TMDs for low qT

• OUTCOME: SUM $\alpha_s^m \ln^k Q^2/q_\perp^2$ TO ALL ORDERS IN α_s



NOTE: SHOWER MONTE CARLO GENERATORS DO THIS "EFFECTIVELY"

(0)

• A MORE "PARTON-LIKE" FORMULATION IS ACHIEVED BY DECOMPOSING THE TMD PDF IN TERMS OF ORDINARY PDF's ("OPE")

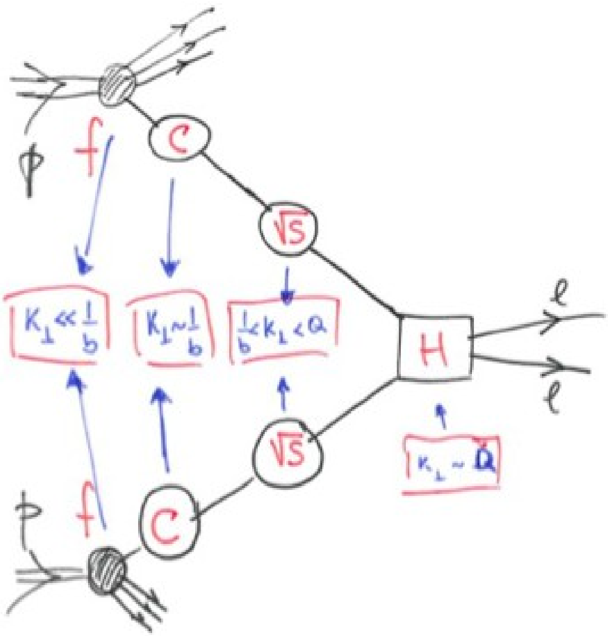
$$\zeta = \mu \sim Q \sim b^{-1}$$

$$f_j(b, \mu) = S^{(j)}(Q, b) \quad C_{ja}(b \; \mu) \otimes f_a(\mu)$$

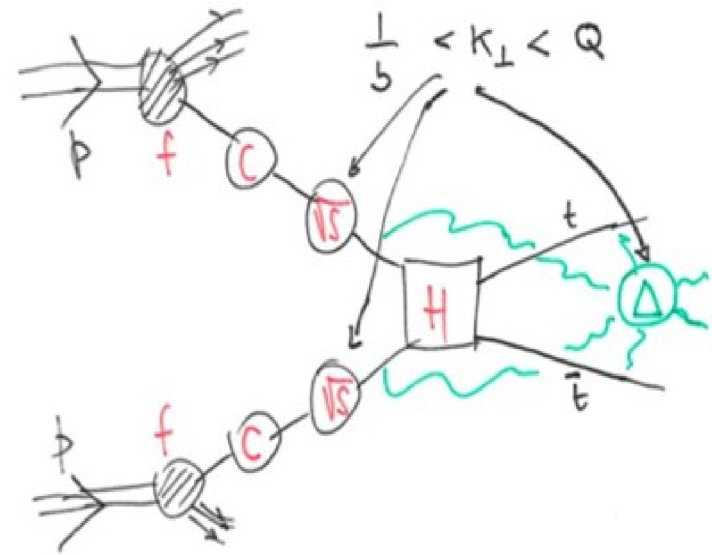
SUDAKOV FORM FACTOR (soft radiation) — EVOLUTION KERNELS (collinear radiation) — INCLUSIVE PDF

From color-neutral to color-charged final states

Color neutral:



Color charged:



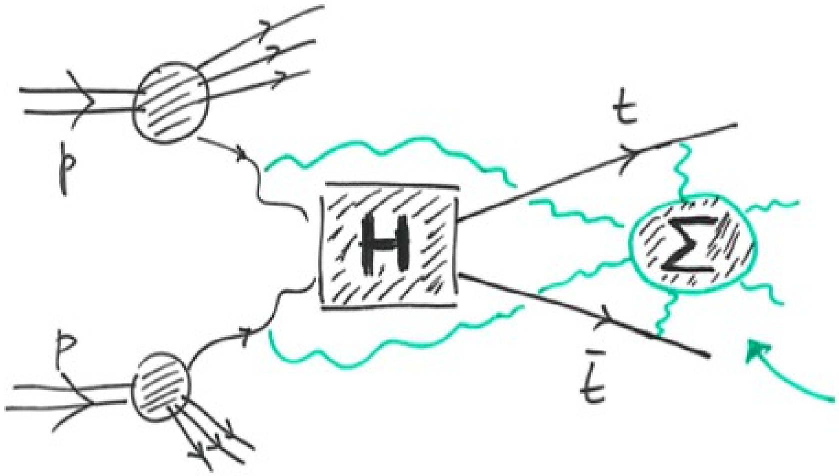
- New long-time correlations in color-charged case:

$$\left(\frac{d\sigma}{d^4q}\right)_{t\bar{t}} = \sum_{ija_1a_2} \int d^2\mathbf{b}\; e^{i\mathbf{q}_T\cdot\mathbf{b}} \int dz_1 \int dz_2\; S(Q,\mathbf{b})\; f_{a_1} \otimes [\mathrm{Tr}(H\Delta)C_1C_2]_{ija_1a_2} \otimes f_{a_2}$$

- Generate azimuthal asymmetries
- Observable for $\Delta p_\perp$ high compared to $\Lambda_{\rm QCD}$?

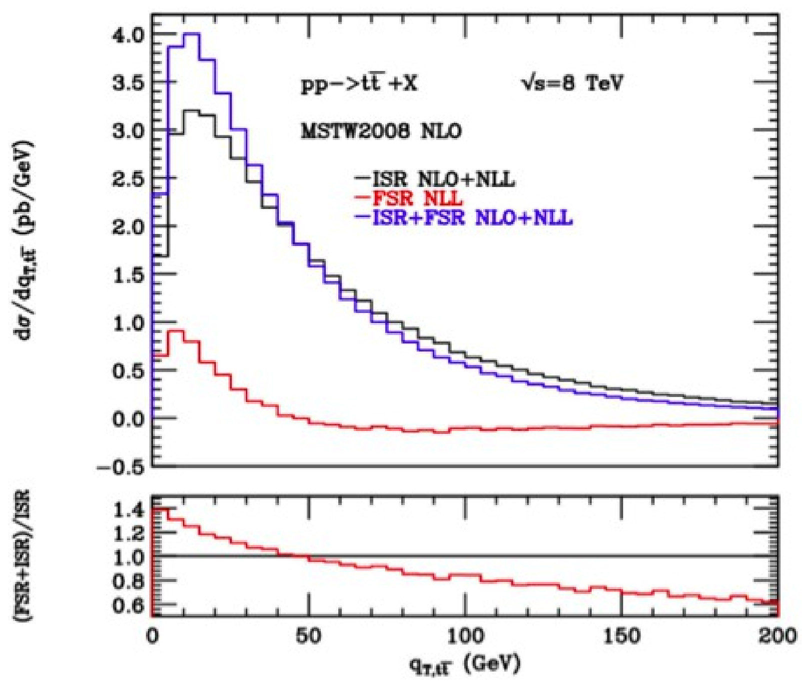
↖ soft gluons coupling initial and final states

Color correlations in jet and heavy-flavor production



- Initial state / final state soft-gluon correlations → new “color entanglement” effects?

- A recent quantitative estimate of the size of color correlations for the top quark pair spectrum at the LHC:



Catani, Grazzini,Sargsyan
JHEP 1706 (2017) 017

II. The Parton Branching (PB) method

MOTIVATION

- Provide 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

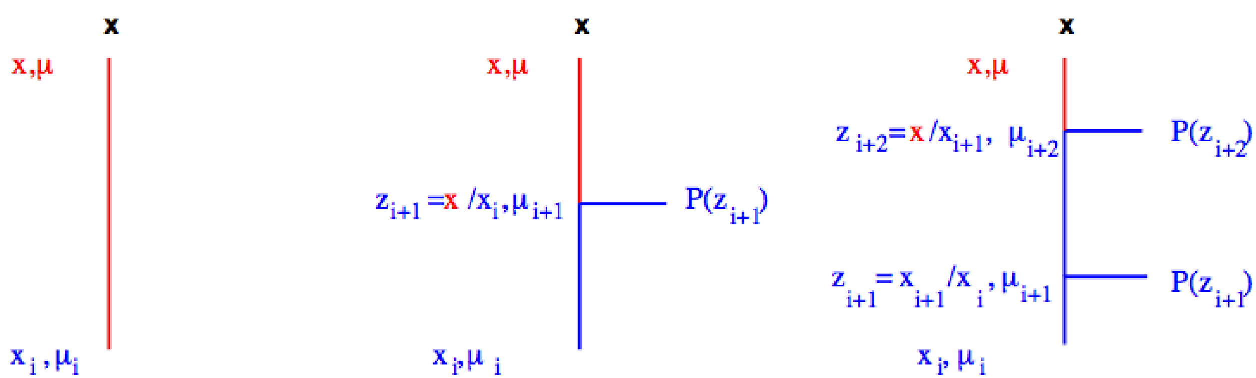
Parton Branching (PB) method: collinear PDFs

QCD evolution and soft-gluon resolution scale

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

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

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



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

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

- Equivalent to DGLAP evolution equation for zM → 1

Parton Branching (PB) method: TMD PDFs

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

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

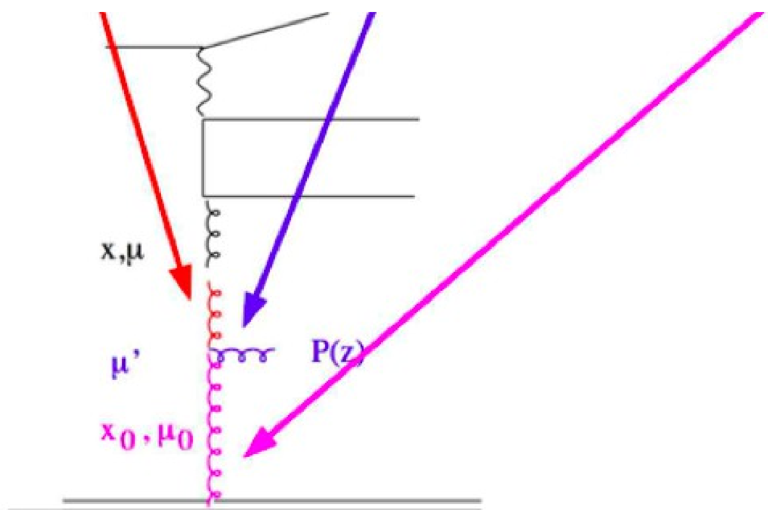
$$\text{Solve iteratively}: \quad \widetilde{\mathcal{A}}_a^{(0)}(x,\mathbf{k},\mu^2) = \Delta_a(\mu^2)\,\widetilde{\mathcal{A}}_a(x,\mathbf{k},\mu_0^2)\,,$$

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

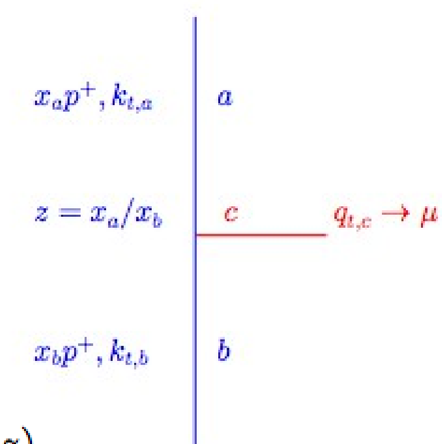
$$\times \frac{\Delta_a(\mu^2)}{\Delta_a(\mathbf{q}'^2)} \int_x^{z_M} dz\, P_{ab}^{(R)}(\alpha_s(\mathbf{q}'^2),z)\,\widetilde{\mathcal{A}}_b(x/z,\mathbf{k}+(1-z)\mathbf{q}',\mu_0^2)\,\Delta_b(\mathbf{q}'^2)$$

↖ NB: angular ordering

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

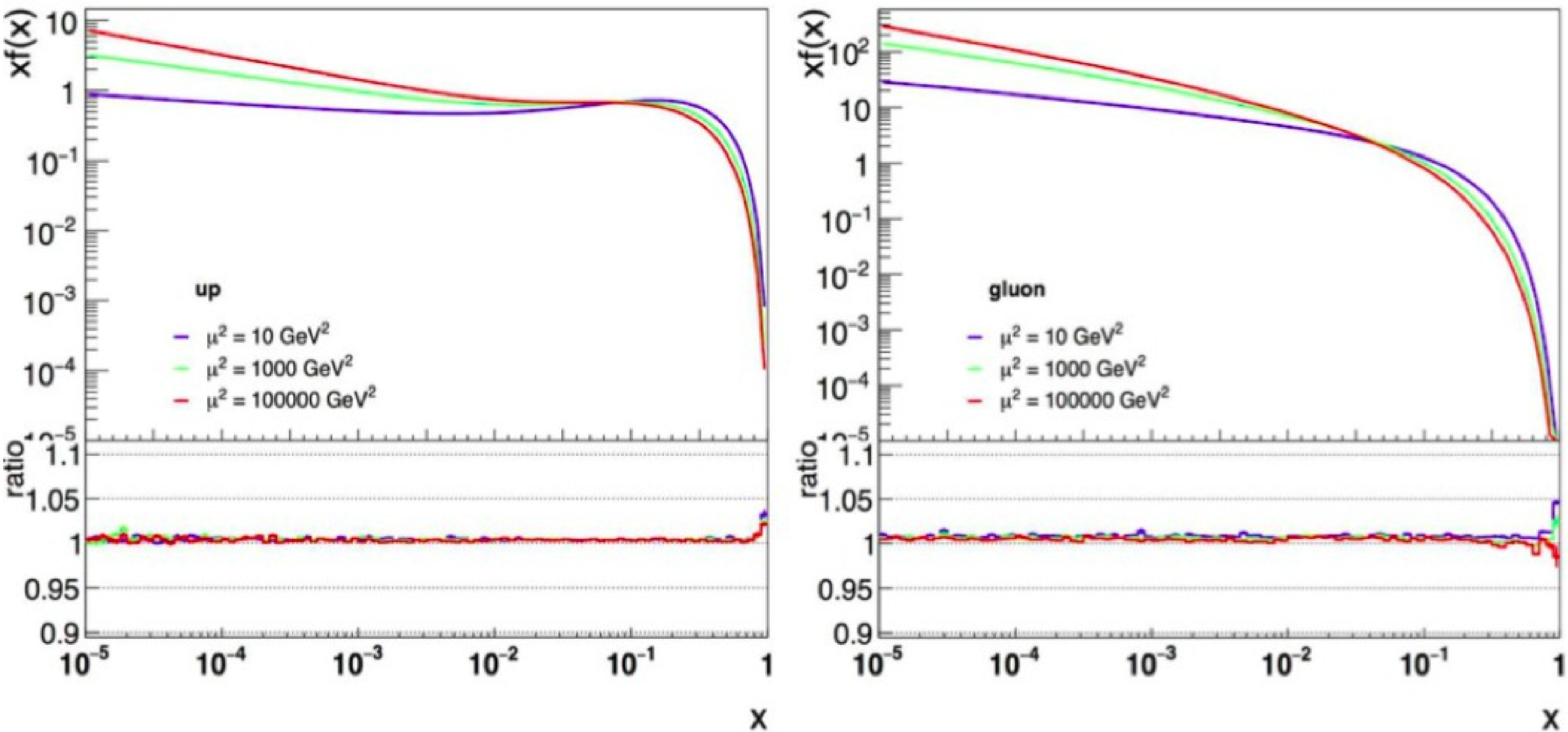


- A new evolution equation!



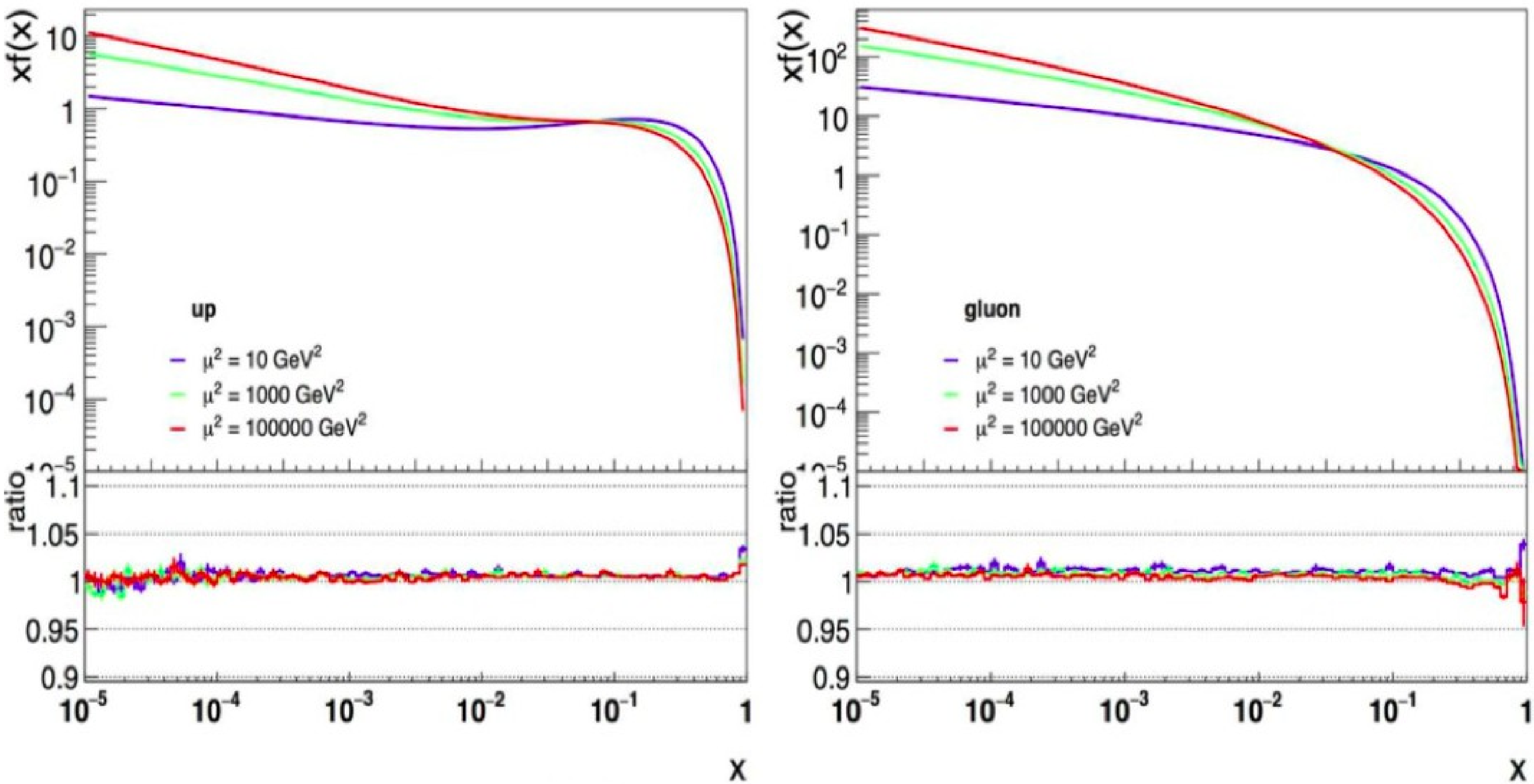
$$\mu = |\mathbf{q}_c|/(1-z)$$

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



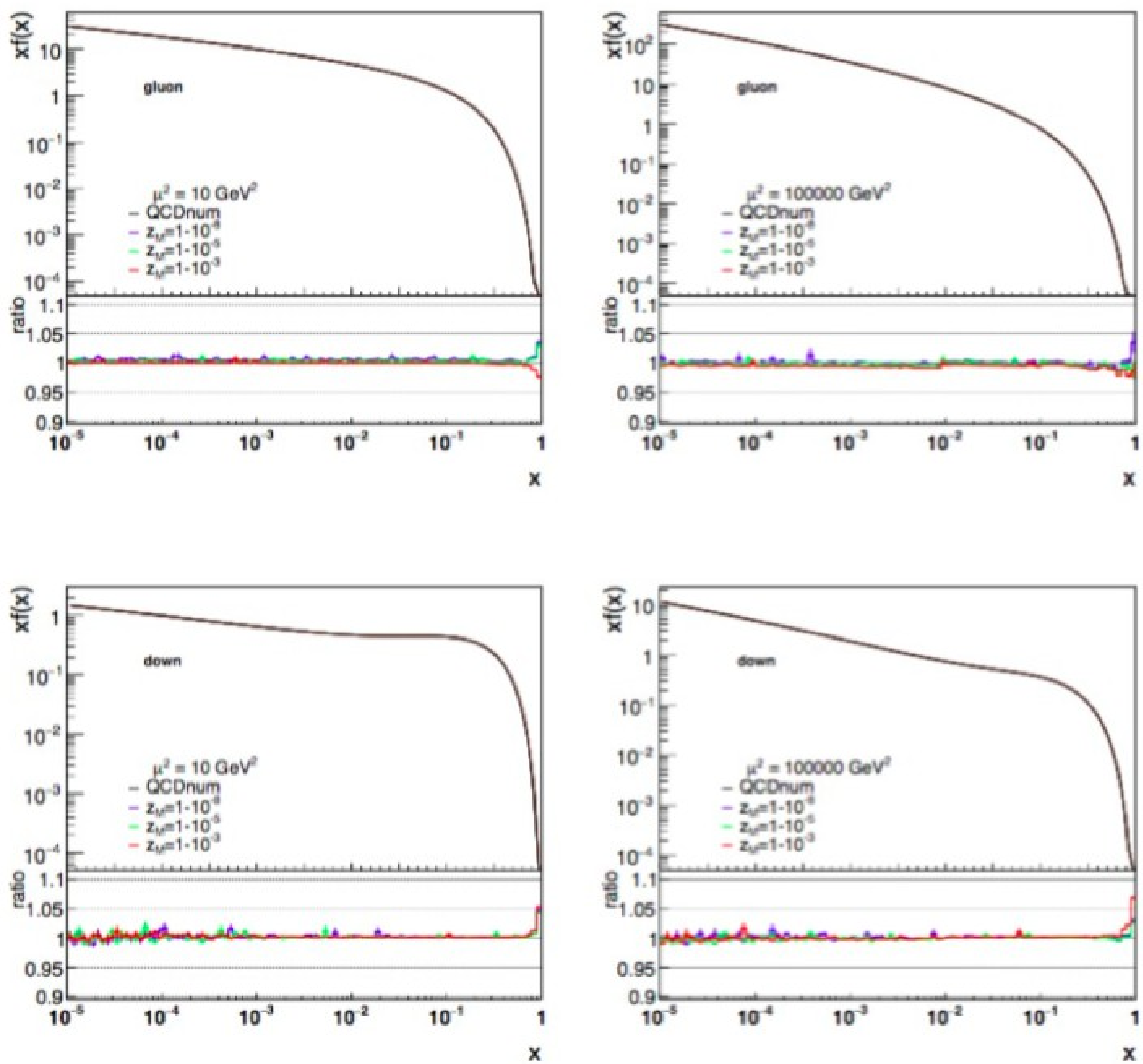
Agreement to better than 1 % over several orders of magnitude in x and mu

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

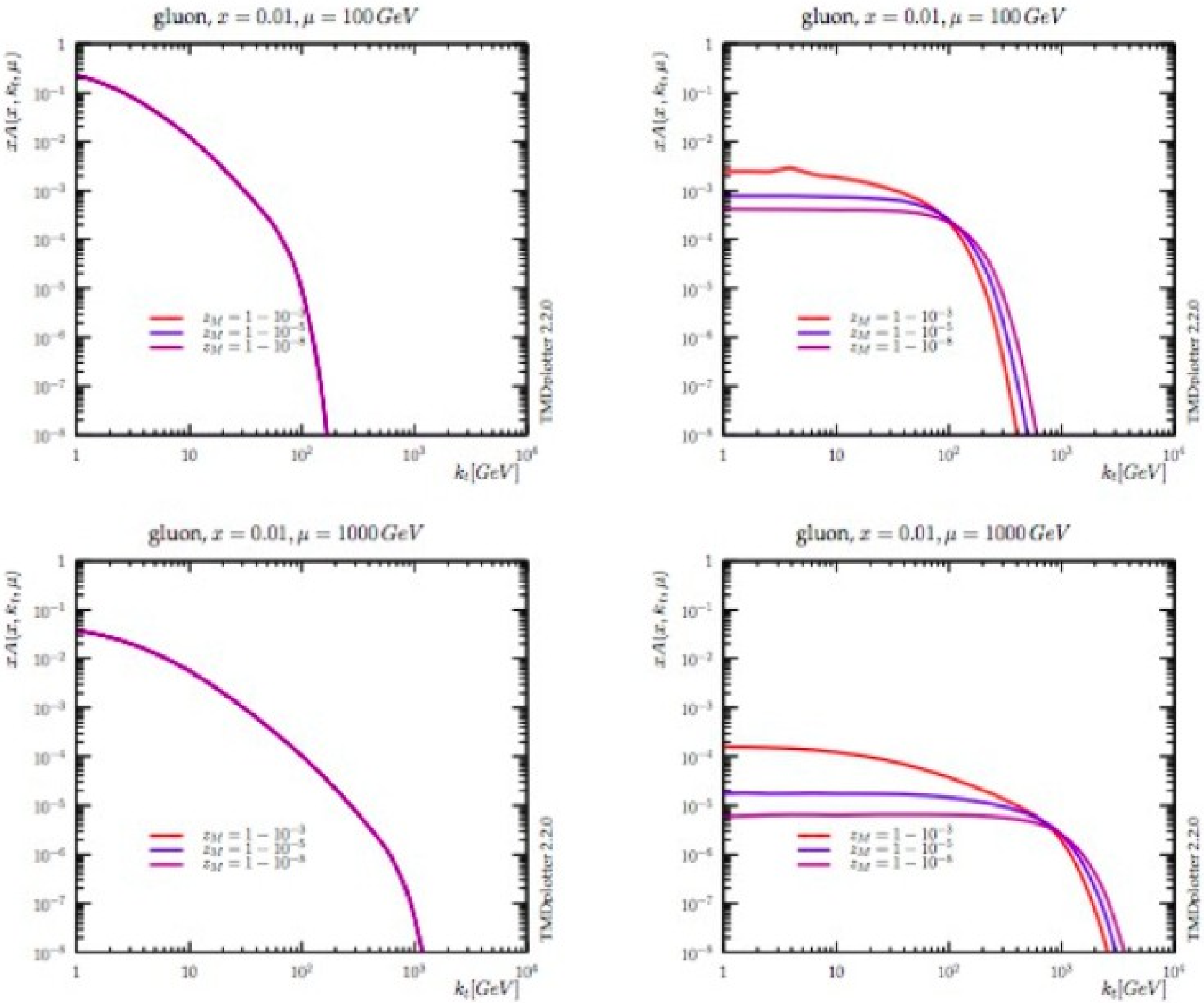


Very good agreement at NLO over all x and mu.
NB: the same approach is designed to work at NNLO.

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

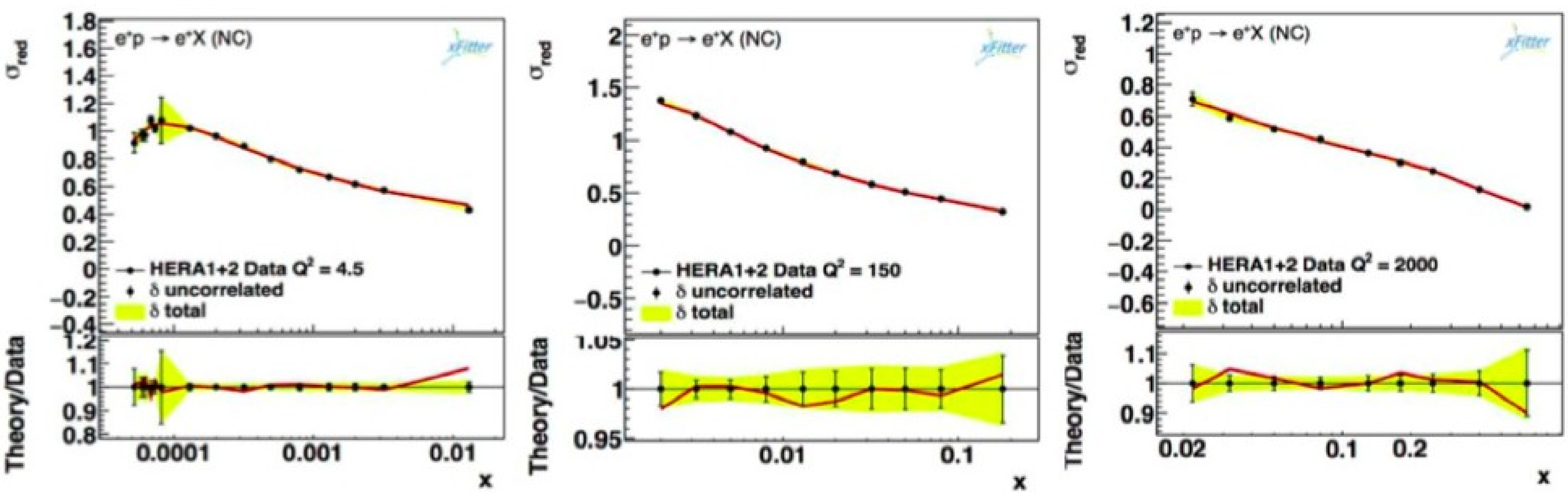
- Determine starting distribution

A Bermudez et al, arXiv:1804.11152

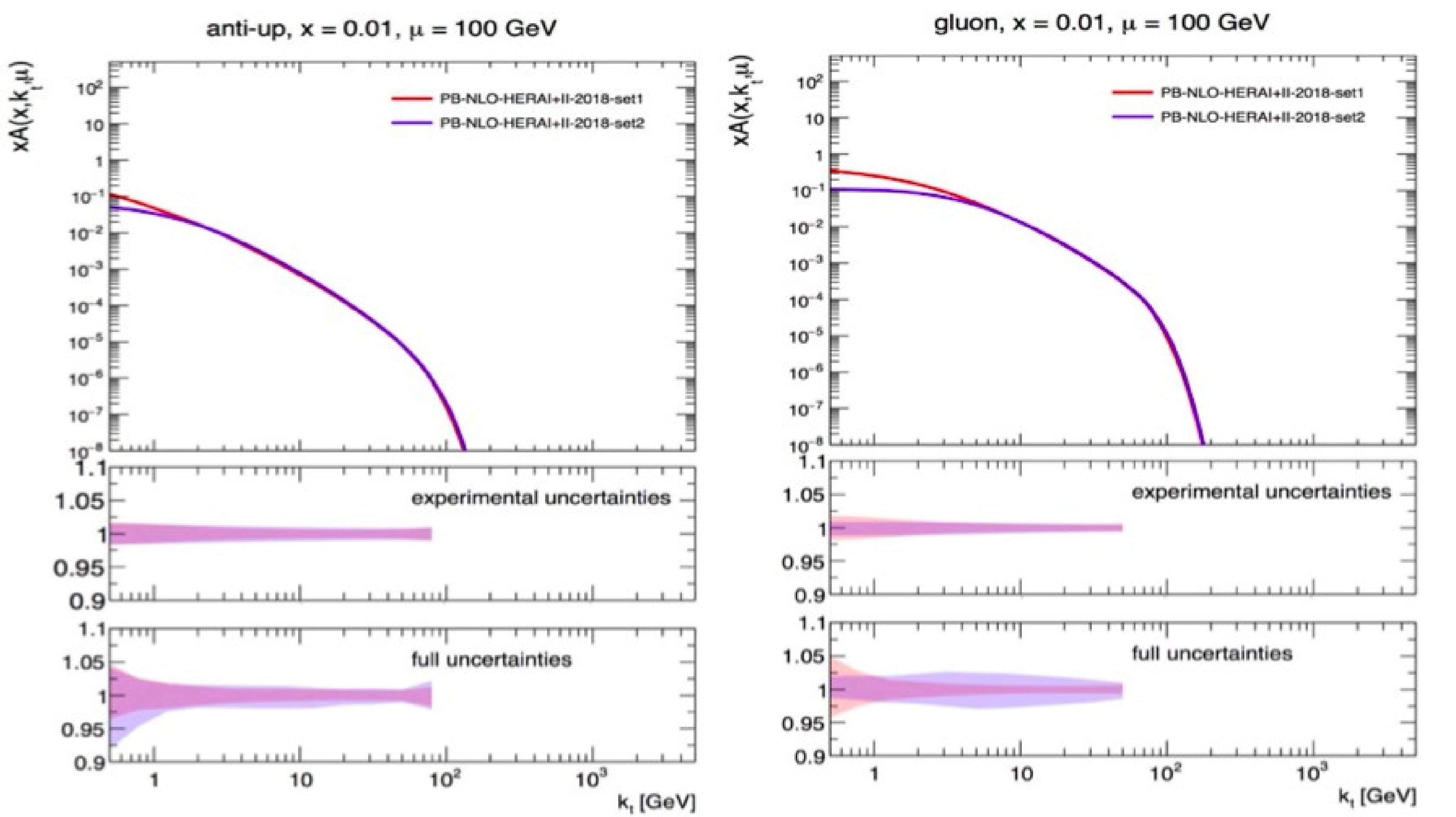
A. Lelek et al REF 2016

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

- 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

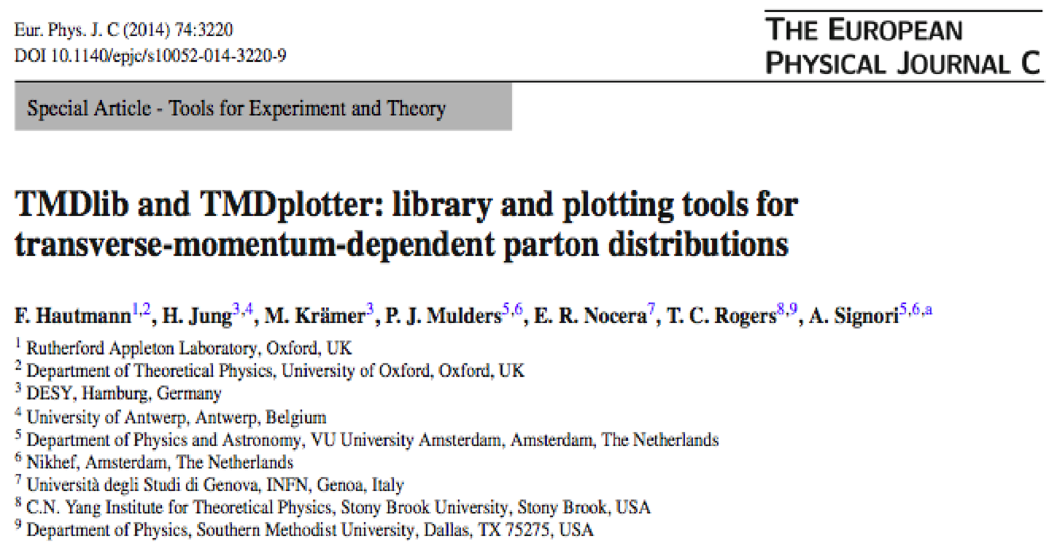
Where to find TMDs? TMDlib and TMDplotter

- 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

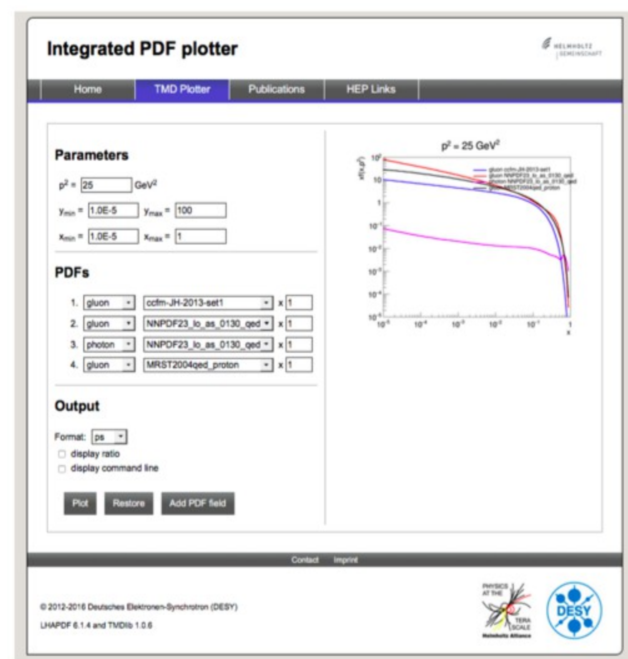
THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

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

F. Hautmann[1,2], H. Jung[3,4], M. Krämer[3], P. J. Mulders[5,6], E. R. Nocera[7], T. C. Rogers[8,9], A. Signori[5,6,a]

[1] Rutherford Appleton Laboratory, Oxford, UK
[2] Department of Theoretical Physics, University of Oxford, Oxford, UK
[3] DESY, Hamburg, Germany
[4] University of Antwerp, Antwerp, Belgium
[5] Department of Physics and Astronomy, VU University Amsterdam, Amsterdam, The Netherlands
[6] Nikhef, Amsterdam, The Netherlands
[7] Università degli Studi di Genova, INFN, Genoa, Italy
[8] C.N. Yang Institute for Theoretical Physics, Stony Brook University, Stony Brook, USA
[9] Department of Physics, Southern Methodist University, Dallas, TX 75275, USA



Next 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

Search...

- Overview
- Timetable
- Participant List
- Venue
- Travel

Contact

krzysztof.kutak@ifj.edu.pl
jolanta.mosurek@ifj.edu.pl

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)

Scientific committee:

Elke Aschenauer Daniel Boer
Igor Cherednikov Markus Diehl
Didar Dobur David Dudal
Miguel García Echevarría
Laurent Favart Francesco Hautmann
Hannes Jung Fabio Maltoni
Piet Mulders Gunar Schnell
Andrea Signori Pierre Van Mechelen

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)

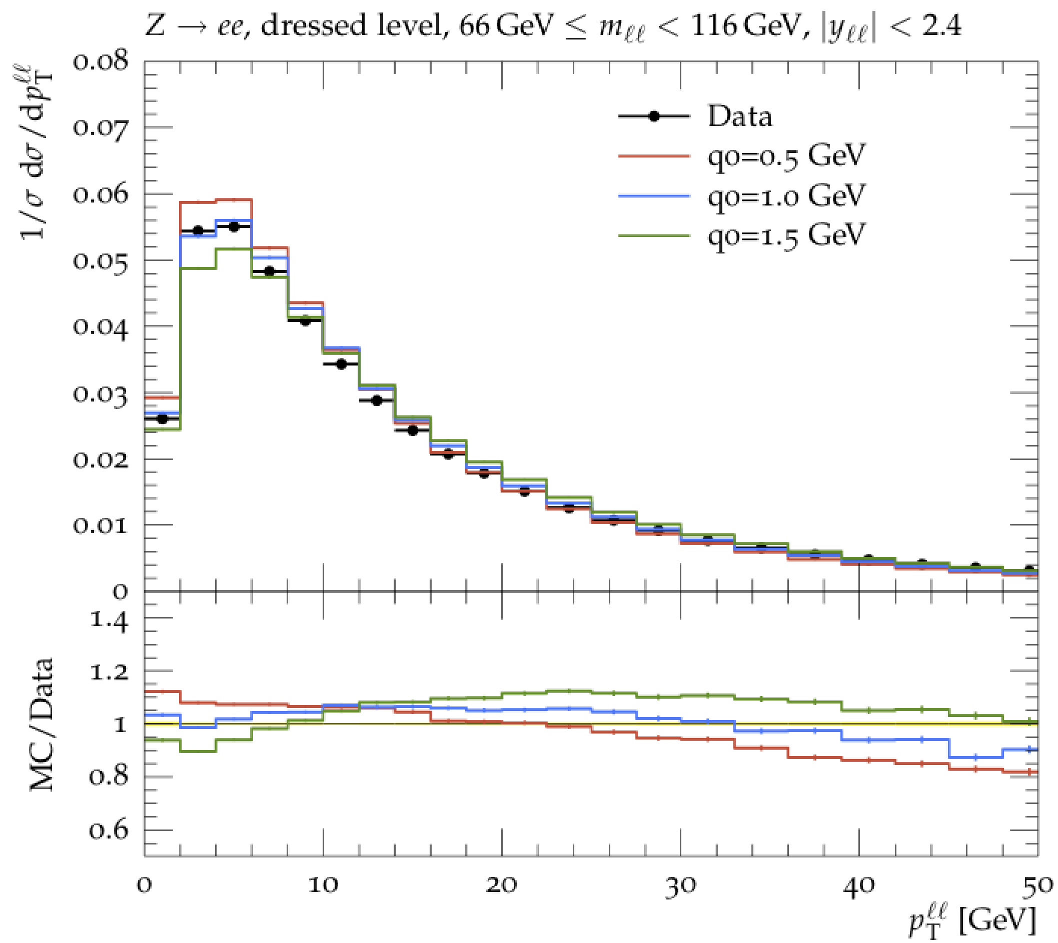
Application of PB method to Z-boson transverse momentum spectrum in Drell-Yan production

- 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

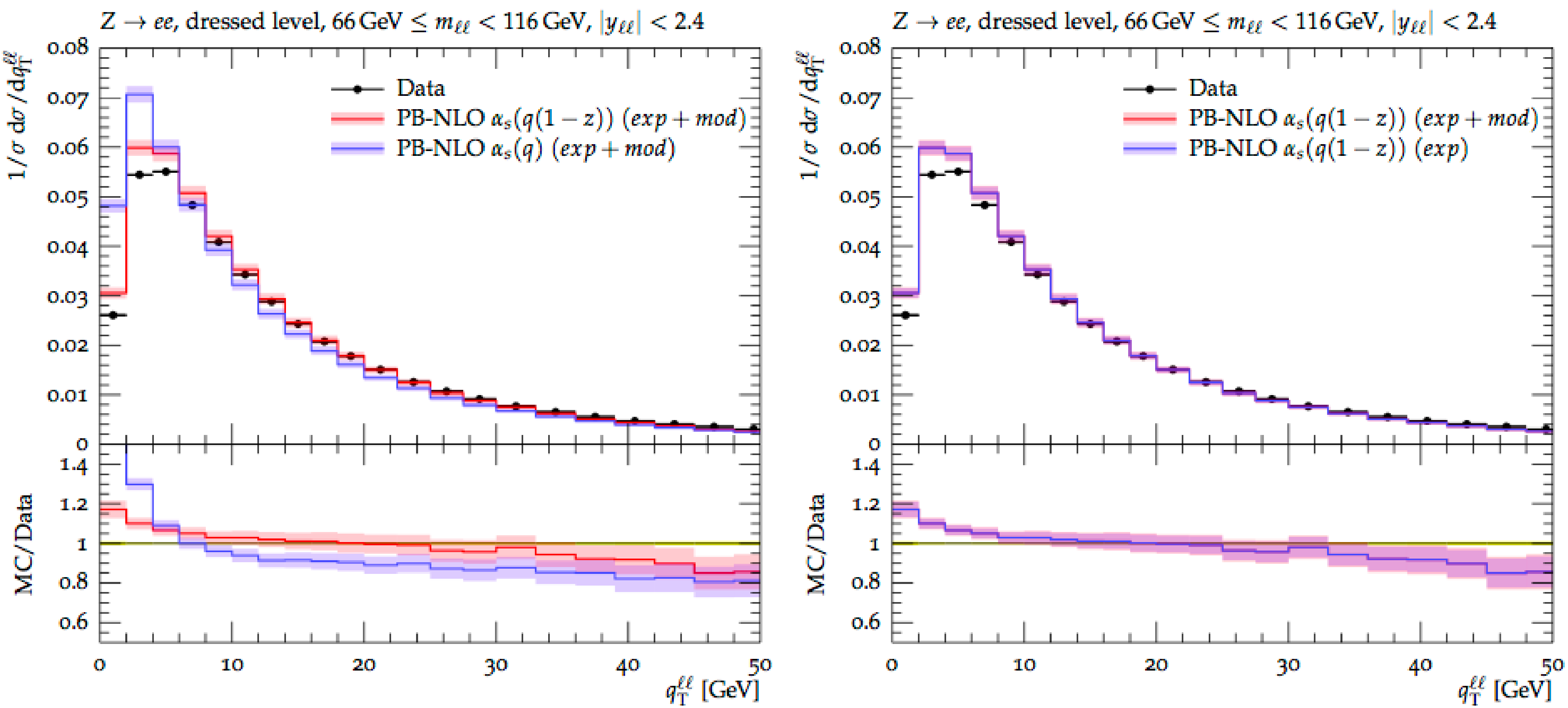
$$z_M(\mu) = 1 - q_0/\mu$$



LHC Electroweak WG Meeting, CERN, June 2018

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

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

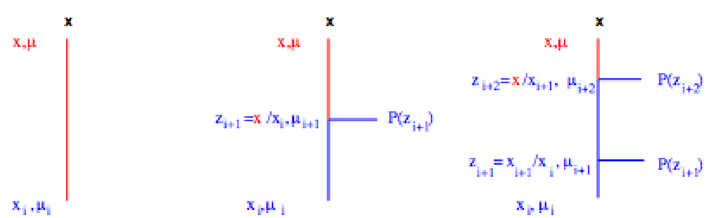
◇ The resummed DY differential cross section is given by

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

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

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

$$\text{one}-\text{loop}\ :$$

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

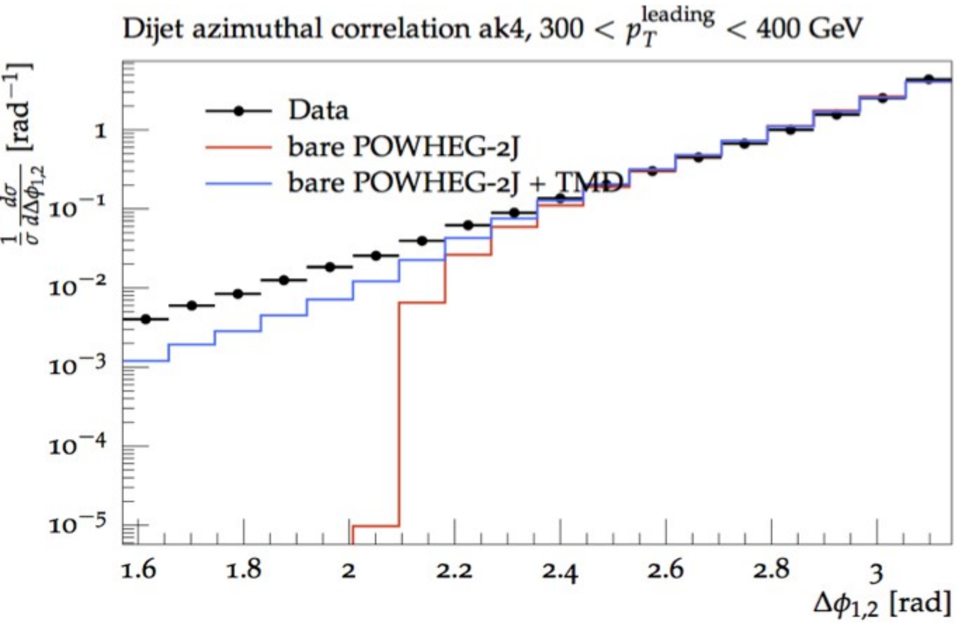
$$\text{two}-\text{loop}\ :$$

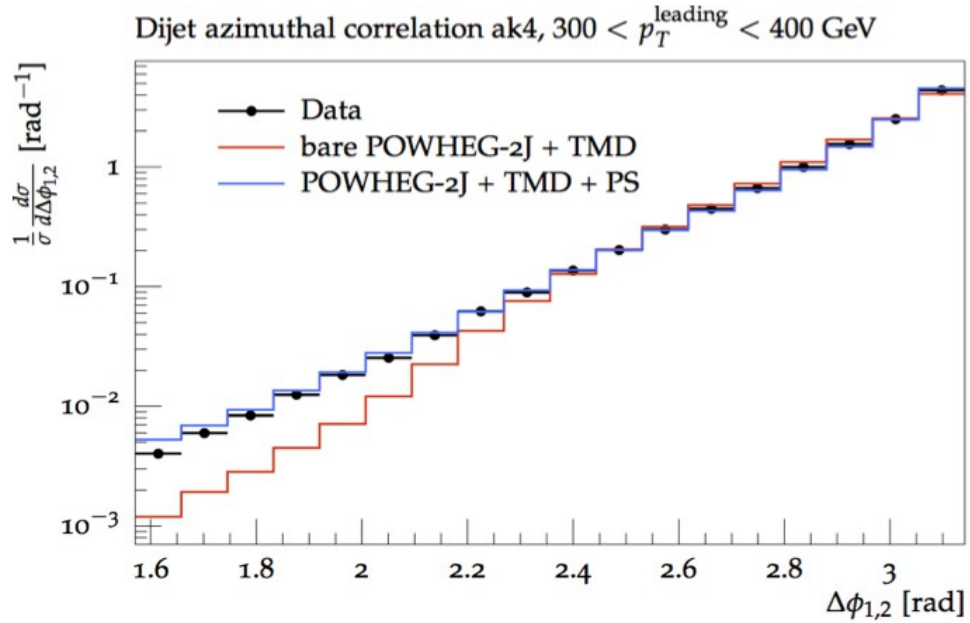
$$d_q^{(1)} = C_F^2 \left(\frac{3}{8} - \frac{\pi^2}{2} + 6\ \zeta(3) \right) + C_F C_A \left(\frac{17}{24} + \frac{11\pi^2}{18} - 3\ \zeta(3) \right) - C_F T_R N_f \left(\frac{1}{6} + \frac{2\pi^2}{9} \right) ,$$

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

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

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

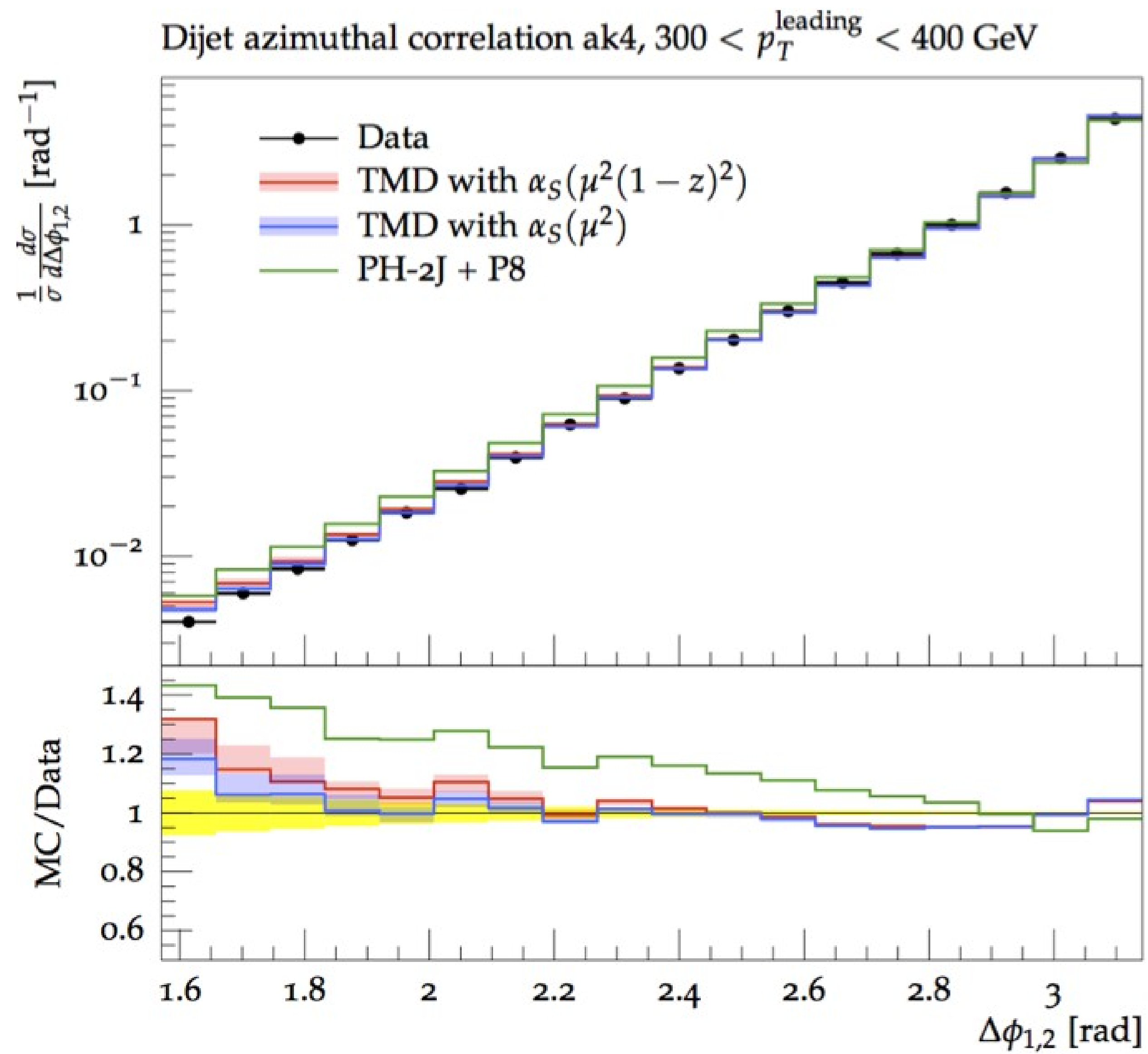




- Events by NLO POWHEG 2 jets
- Parton branching TMD (with angular ordering)
- TMD parton shower

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)
- TMD parton shower

Conclusions

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

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

  $\longrightarrow$ cf. parton shower calculations and analytic resummation

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

- systematic studies of ordering effects and color coherence

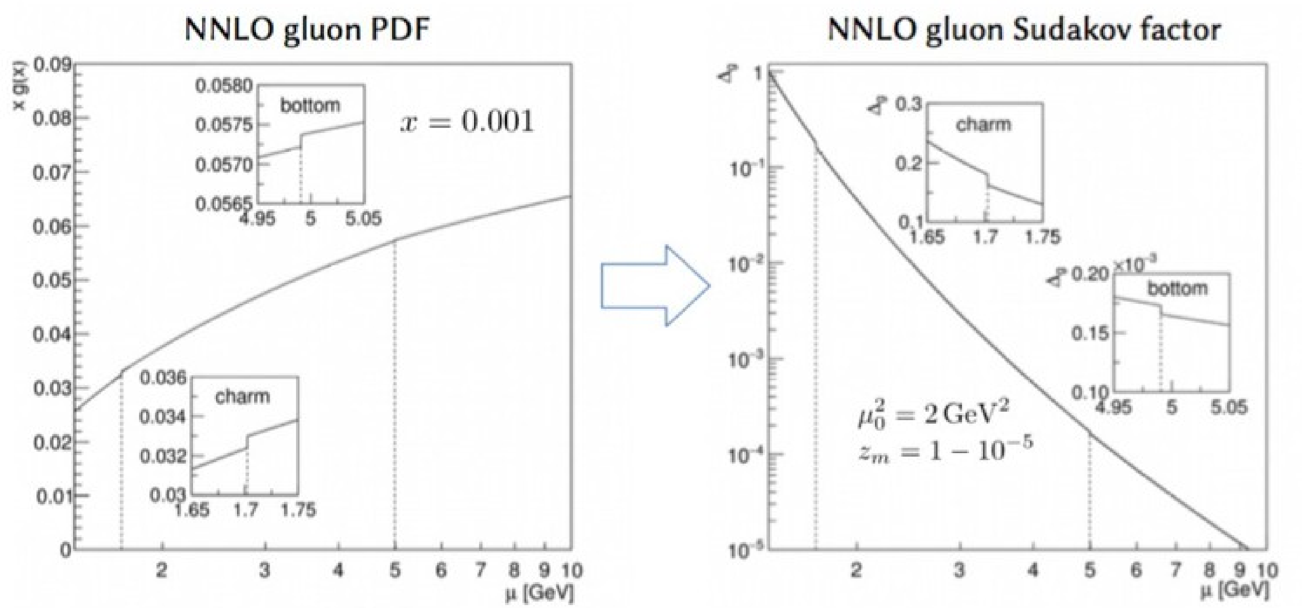
  $\to$ helpful to analyze long-time color correlations?

EXTRA SLIDES

PB 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

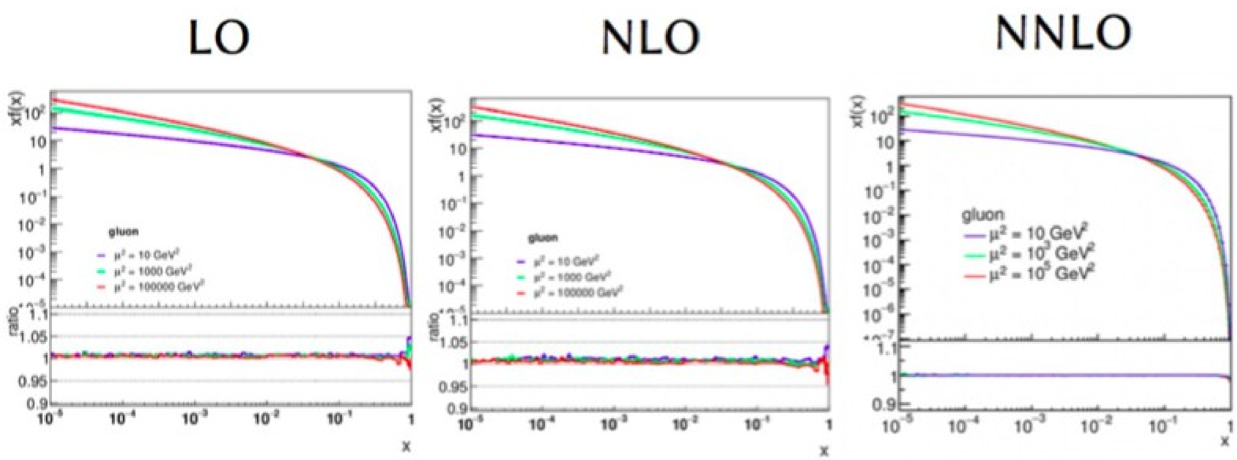


R. Zlebcik, talk at REF 2017, November 2017

Workshop REF2017, Universidad Complutense Madrid, 13-16 November 2017

PB method at NNLO

The Monte Carlo solution vs QCDNUM



The Monte Carlo evolution implemented up to NNLO and cross-checked against the semi-analytical solution of DGLAP

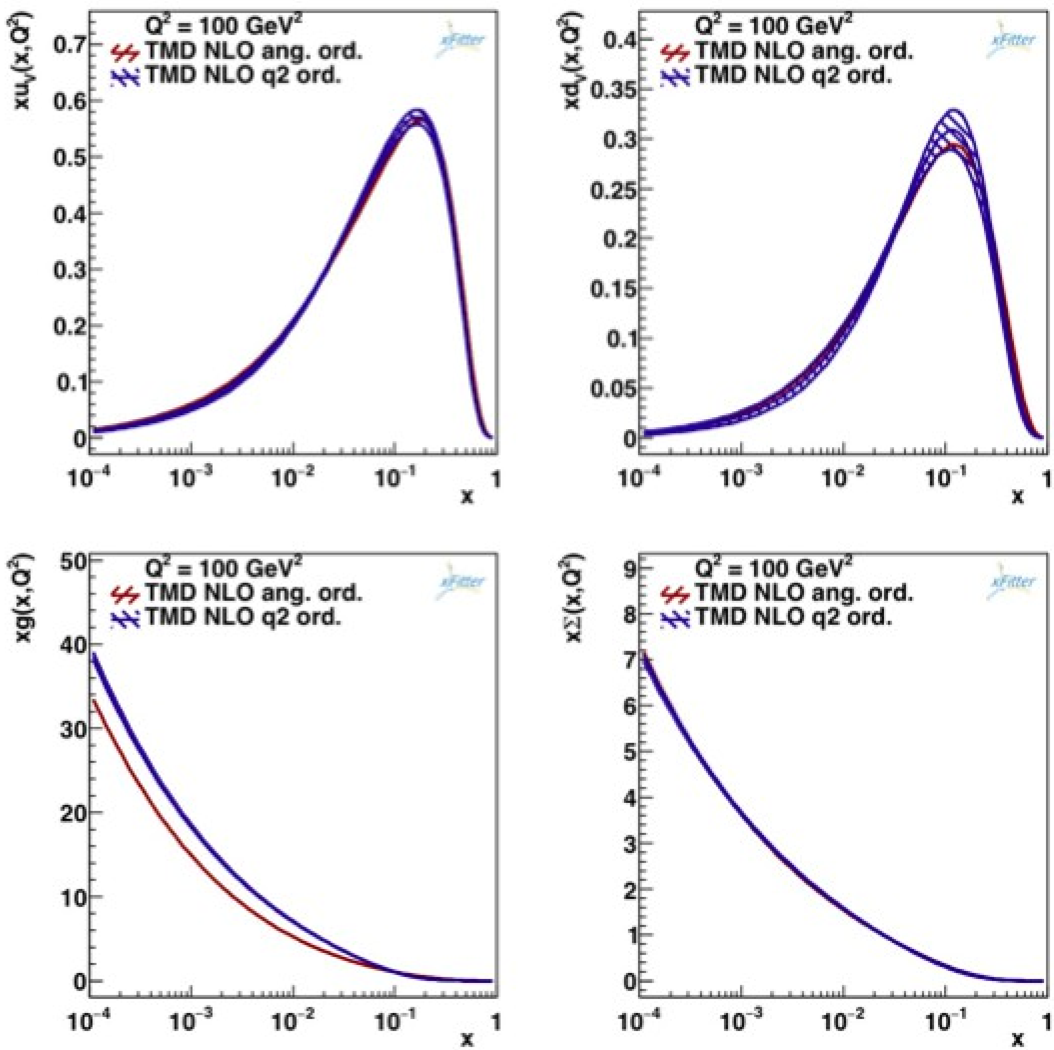
The solution's uncertainties are mainly statistical
(~ number of generated MC evolutions)

8

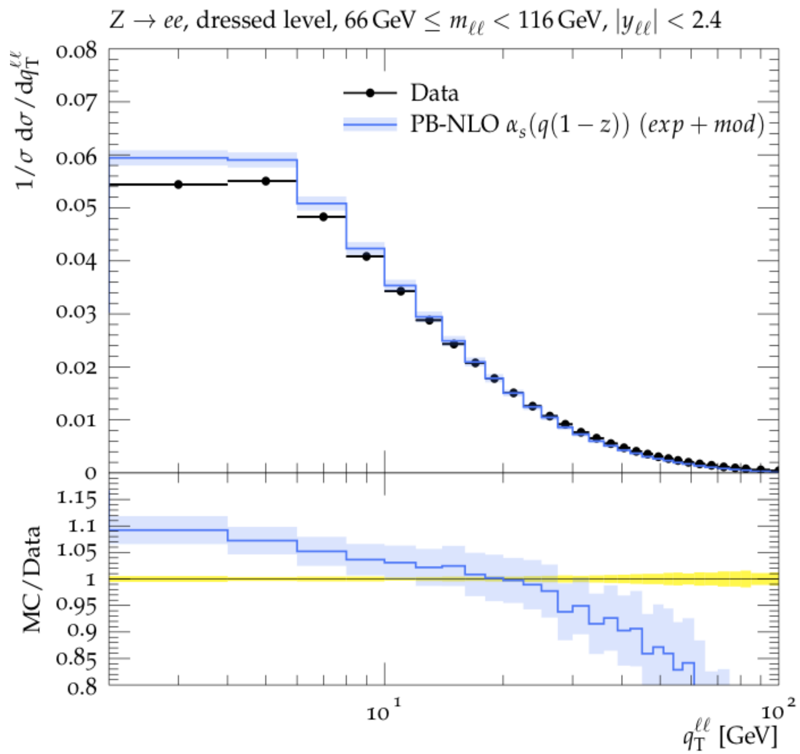
R. Zlebcik, talk at REF 2017, November 2017

Workshop REF2017, Universidad Complutense Madrid, 13-16 November 2017

Effects of coupling's scale and angular ordering in integrated parton distributions



Z-boson pT spectrum including TMD uncertainties



- Cf. predictions from fixed-order + resummed calculations Bizon et al., arXiv:1805.05916