Determination and application of TMDs obtained by the Parton Branching method

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in collaboration with
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Outline

- Parton Branching (PB) method
- TMD determination and validation
- TMD fit to data
- Application to LHC processes
- Summary and conclusions

TMDs

- small momentum transfer
- small-x
- high energy limit

Parton Branching method

- Novel method to solve the TMD evolution equation
- fully exclusive solution
- valid at LO, NLO and NNLO

Parton Branching method and TMDs

Parton Branching method

- PB evolution equation:

$$Q^2 \frac{\partial \hat{f}_a(x, Q^2)}{\partial Q^2} = \sum_b \int_x^{z_{\max}} dz \; P^R_{ab}\left(z, \alpha_s(Q_r^2)\right) \hat{f}_b(\frac{x}{z}, Q^2)$$
$$- \hat{f}_a(x, Q^2) \sum_b \int_0^{z_{\max}} dz \; z P^R_{ba}\left(z, \alpha_s(Q_r^2)\right)$$

- $z_{\max}$ separates the resolvable and non-resolvable phase space regions
- non-resolvable solution $\Rightarrow$ Sudakov factor:

$$\Delta_a(Q^2, Q_0^2) \equiv \exp\left[- \sum_b \int_{Q_0^2}^{Q^2} \frac{dQ'^2}{Q'^2} \int_0^{z_{\max}} dz \; z P^R_{ba}\left(z, \alpha_s(Q_r'^2)\right) \right]$$

Parton Branching method

- evolution equation, integral form:

$$\hat{f}_a(x,Q^2) = \hat{f}_a(x,Q_0^2)\Delta_a(Q^2,Q_0^2) +$$

$$+\int_{Q_0^2}^{Q^2} \frac{dQ'^2}{Q'^2} \frac{\Delta_a(Q^2,Q_0^2)}{\Delta_a(Q'^2,Q_0^2)} \int_x^{z_{\max}} dz \sum_b P_{ba}^R\left(z, \alpha_s(Q_r'^2)\right) \hat{f}_b(\frac{x}{z}, Q'^2)$$

- iterative solution:

$$\hat{f}_a^{(0)}(x,Q^2) = \hat{f}_a(x,Q_0^2)\Delta_a(Q^2,Q_0^2)$$

$$\hat{f}_a^{(1)}(x,Q^2) = \hat{f}_a(x,Q_0^2)\Delta_a(Q^2,Q_0^2) +$$

$$\int_{Q_0^2}^{Q^2} \frac{dQ'^2}{Q'^2} \frac{\Delta_a(Q^2,Q_0^2)}{\Delta_a(Q'^2,Q_0^2)} \int_x^{z_{\max}} dz \sum_b P_{ba}^R(z,\alpha_s)\, \hat{f}_b(\frac{x}{z}, Q_0^2)\Delta_b(Q'^2,Q_0^2)$$

$$\hat{f}_a^{(2)}(x,Q^2) = \dots$$

$$\vdots$$

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◦ example: first iteration, $a, b = g$

$$\hat{f}_g^{(1)}(x, Q^2) = \hat{f}_g(x, Q_0^2)\Delta_g(Q^2, Q_0^2) +$$

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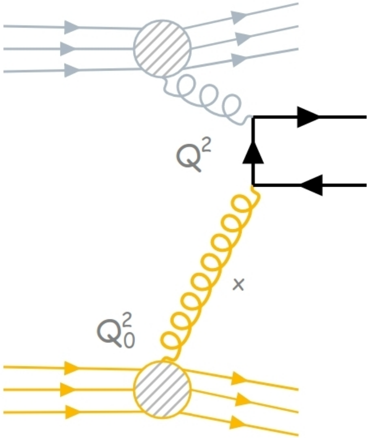

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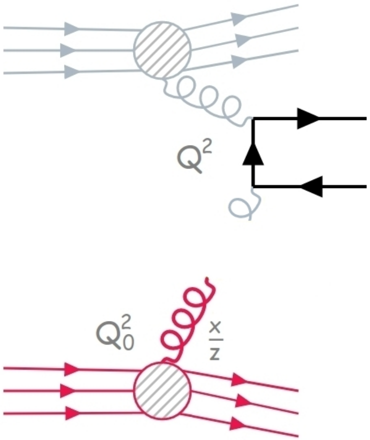

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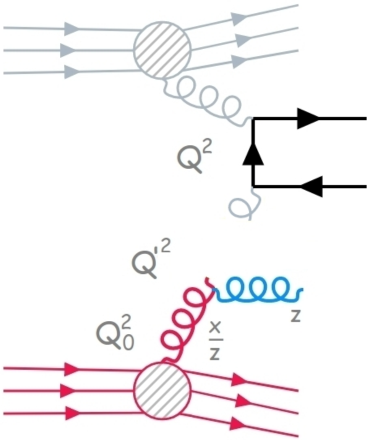

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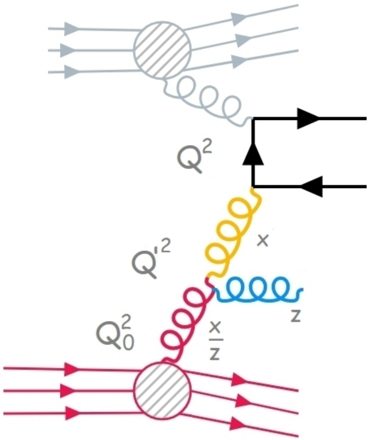
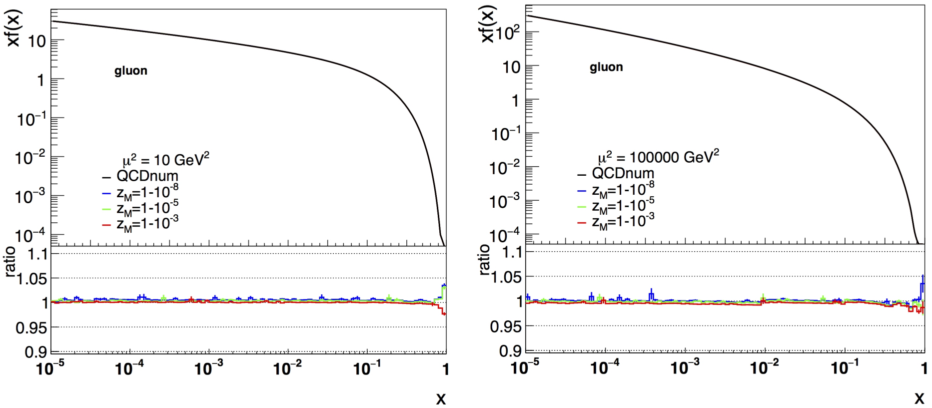


PB iterative solution:

- kinematics of the splittings is known
- cumulative k_T of the branchings $\Rightarrow$ TMD
- physics $\longrightarrow$ evolution variables to splitting kinematics mapping

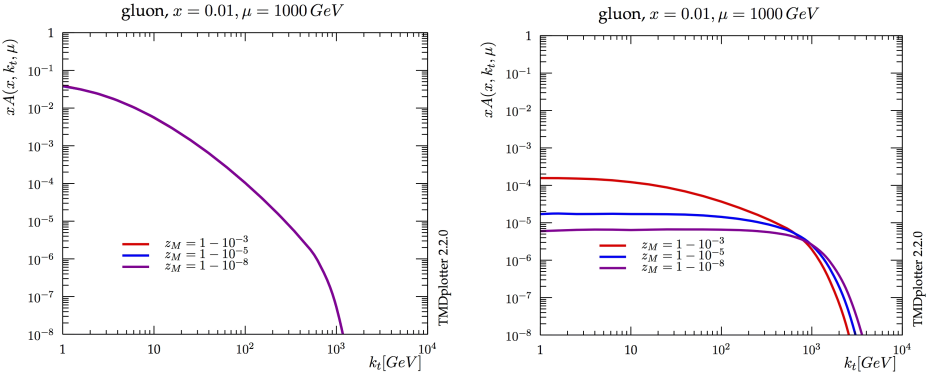
Validation with QCDnum at NLO



- correction $\mathcal{O}(1 - z_{\max})$
- $z_{\max}$ large $\Rightarrow$ good agreement!

Mapping $z, p_T \to Q, Q_r$

- evolution variable Q:
  - p_T ordered $Q = p_T$
  - angular ordered $Q = p_T/(1-z) \Rightarrow$ coherence

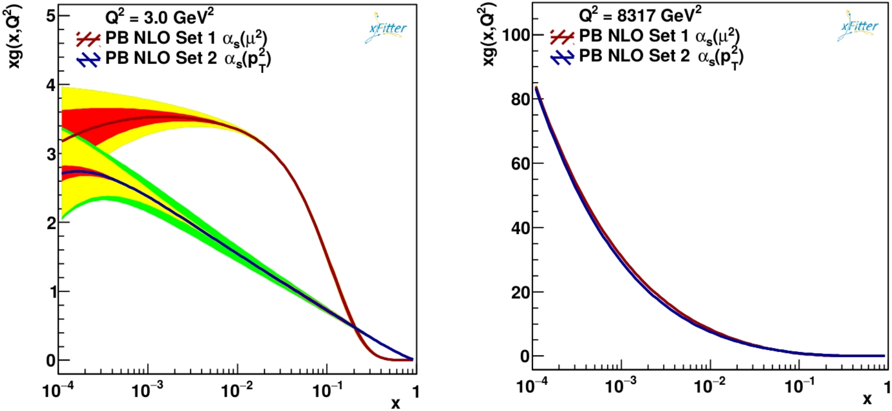


Mapping $z, p_T \to Q, Q_r$

○ renormalization scale at the splitting vertex Q_r:

$Q_r = Q$

$Q_r = p_T$ (under the aforementioned coherence assumption)



- partonic content differs at small scales
- uncertainty sources $\to$ next slides

Fit to data

Fit to data

- DIS measurements from HERA I+II
- kinematic range:
  $3.5 < Q^2 < 50000\text{GeV}^2$, $4 \cdot 10^5 < x < 0.65$
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  - store the **TMD** in a grid for later use

    (TMDlib, complementary slides)

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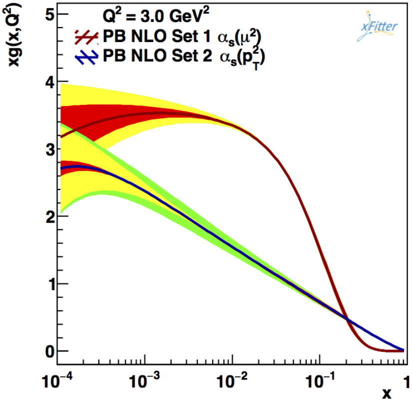
$\Rightarrow$ First TMD fit to precision data!

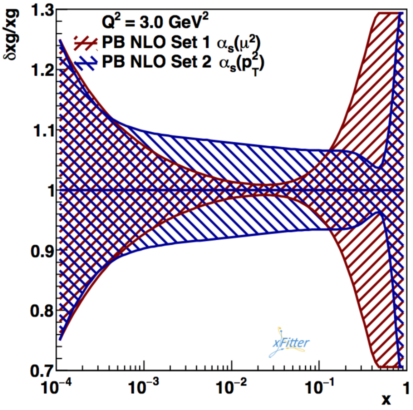
Parton density uncertainty sources

- experimental uncertainty → Hessian method $\Delta\chi^2 = 1$
- model dependence → b, c masses at Q_0

  $+$ Q_r threshold for set 2

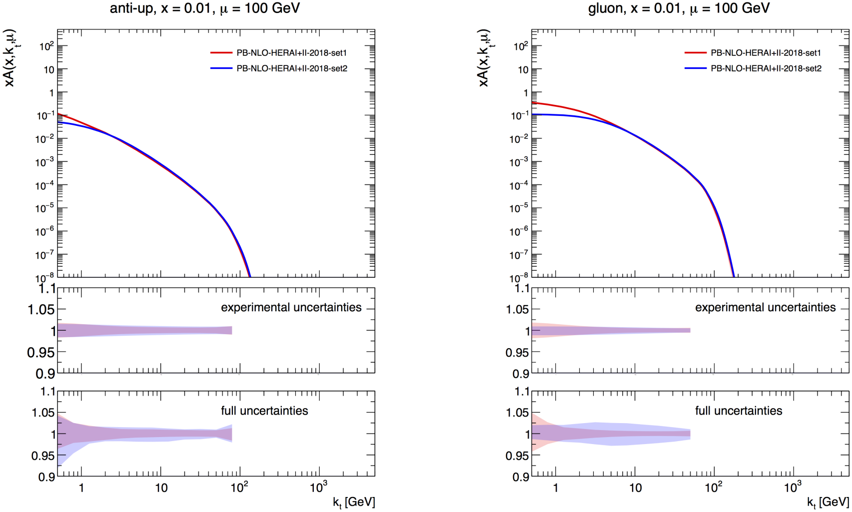


total uncertainty



TMD parton distributions

- set 1 $Q = p_T/(1-z)$, $Q_r = Q$ $(\chi^2/ndf = 1.2)$
- set 2 $Q = p_T/(1-z)$, $Q_r = p_T$ $(\chi^2/ndf = 1.21)$



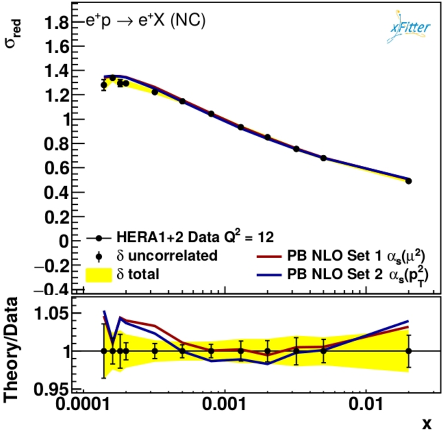
- model dependence dominant (set 2)

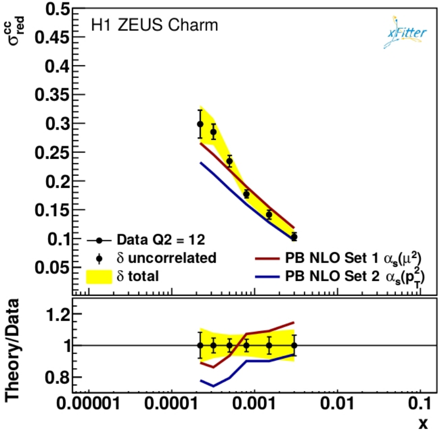
Comparison with HERA data

- set 1 $Q = p_T/(1-z)$, $Q_r = Q$ ($\chi^2/ndf = 1.2$)
- set 2 $Q = p_T/(1-z)$, $Q_r = p_T$ ($\chi^2/ndf = 1.21$)

inclusive DIS

inclusive charm





- inclusive DIS well described
- set 2 disagrees at small x for inclusive charm

Details

- F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Soft-gluon resolution scale in QCD evolution equations. Phys. Lett., B772:446451, 2017

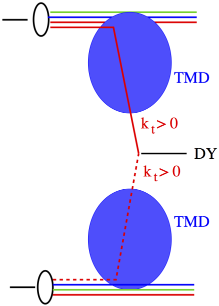
- F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD Quark and Gluon Densities from Parton Branching Solution of QCD Evolution Equations. JHEP, 01:070, 2018.

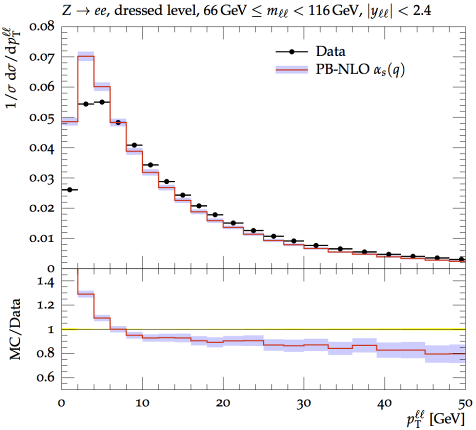
- A. Bermudez-Martinez, P. Connor, F. Hautmann, H. Jung, A. Lelek, V. Radescu, and R. Zlebcik. Collinear and TMD parton densities determined from fts to HERA DIS measurements, DESY-18-042

Application:
low momentum transfer

Drell-Yan p_T

- $Q = p_T/(1-z)$, $Q_r = Q$

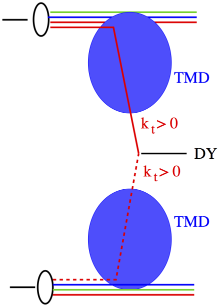


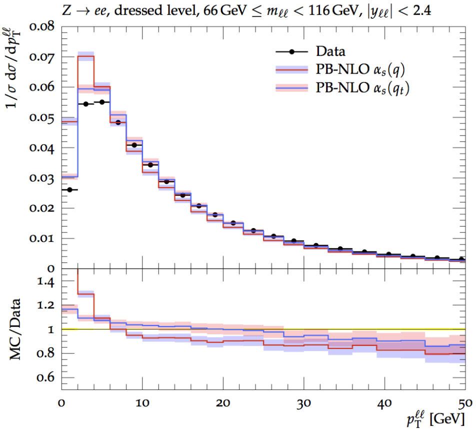


ATLAS Collaboration Eur. Phys. J. C76 (2016), 291, arXiv:1512.02192

Drell-Yan p_T

- $Q = p_T/(1-z)$, $Q_r = Q$
- $Q = p_T/(1-z)$, $Q_r = p_T$ (under angular ordering)





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- $Q = p_T/(1-z),\ Q_r = Q$
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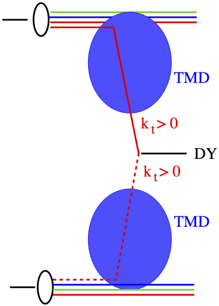
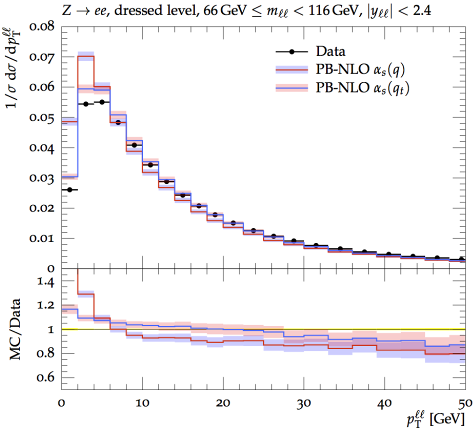
- shape described by both variants





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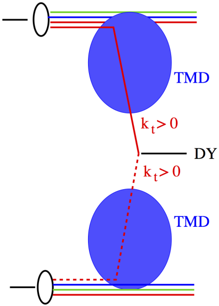
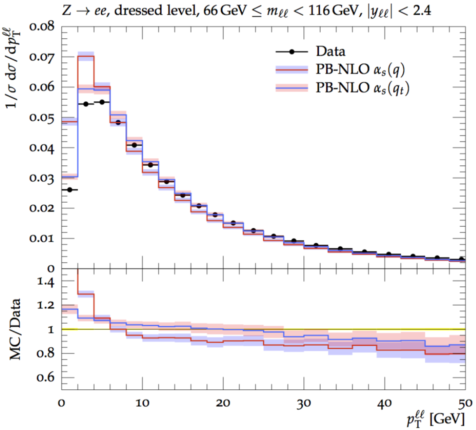
- $Q = p_T/(1-z)$, $Q_r = Q$
- $Q = p_T/(1-z)$, $Q_r = p_T$ (under angular ordering)
- shape described by both variants
- low $p_T^{\ell\ell}$ better described by $Q_r = p_T$





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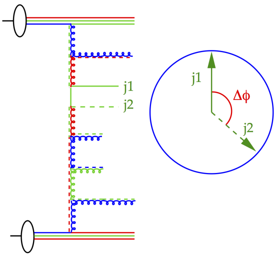
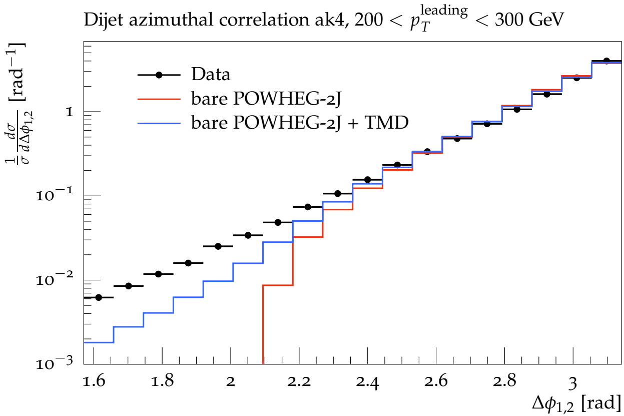
Application:
high momentum transfer

Dijets $\Delta\phi_{1,2}$

- opens up the ME phase space

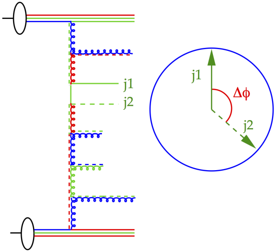


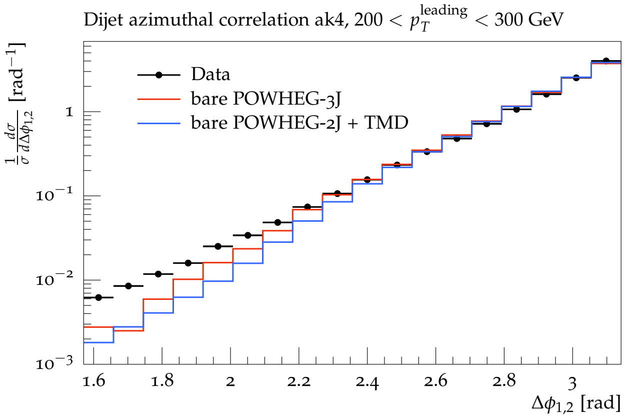


CMS Collaboration Eur. Phys. J. C78 (2018), 566, arXiv:1712.05471

Dijets $\Delta\phi_{1,2}$

- opens up the ME phase space
- catches higher-order contributions



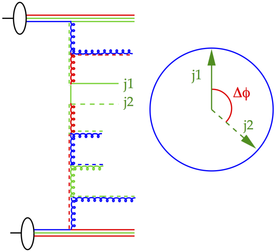


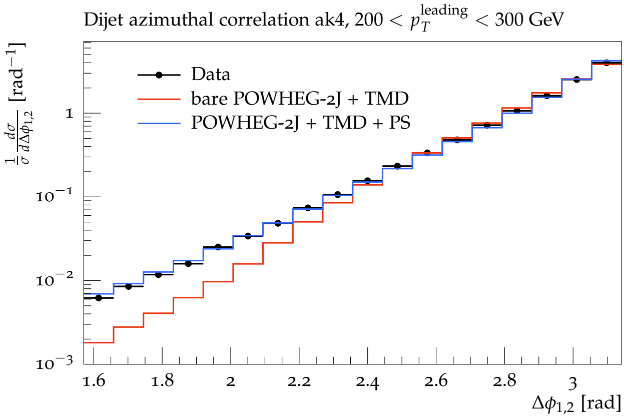
CMS Collaboration Eur. Phys. J. C78 (2018), 566, arXiv:1712.05471

Dijets $\Delta\phi_{1,2}$

- opens up the ME phase space
- catches higher-order contributions

$\Rightarrow$ smaller parton shower correction needed





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Summary and conclusions

◦ novel TMD evolution equation and new method (PB) to solve it
- PB method provides full access to splitting kinematics ⇒ k_T
- method consistency checked in integrated PDFs
- PB solution at LO, NLO, NNLO
- TMD determined, no extra parameters

◦ first TMD fit to data, including uncertainty band
- TMD evolution implemented in xFitter

◦ application to LHC processes:
- DY low p_T spectrum without extra parameters
- dijet $\Delta\phi_{1,2}$: TMD enhances ME phase space
- dijet $\Delta\phi_{1,2}$: PS correction drastically reduced ⇒ TMD catches higher order effects

Complementary slides

Where to find TMDs ? TMDlib and TMDplotter

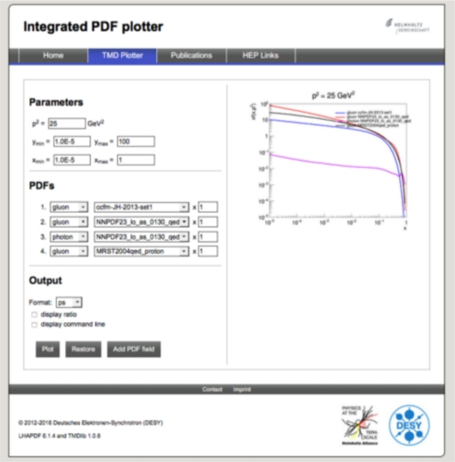
- TMDlib proposed in 2014 as part of REF workshop and developed since
- combine and collect different ansaetze and approaches:

  http://tmd.hepforge.org/ and
  http://tmdplotter.desy.de

→ TMDlib: a library of parametrization of different TMDs and uPDFs (similar to LHApdf)

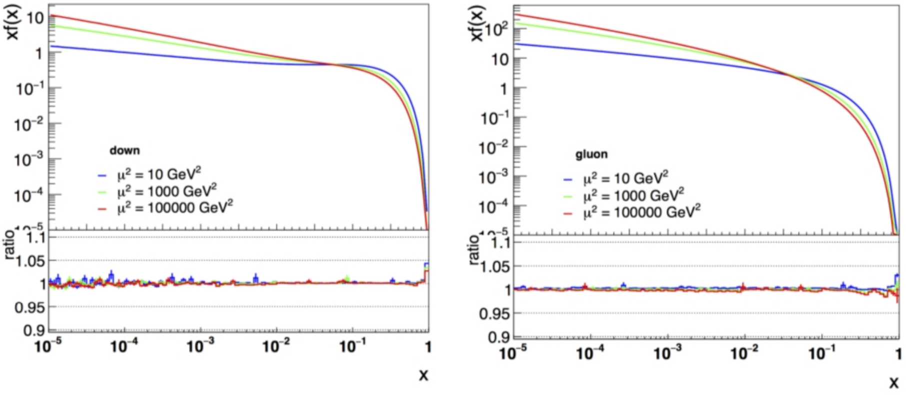
TMDlib and TMDplotter: library and plotting tools for transverse-momentum-dependent parton distributions, *F. Hautmann et al.* arXiv 1408.3015, Eur. Phys. J., C 74(12):3220, 2014.

→ Also integrated pdfs (including photon pdf are available via LHAPDF)



- Feedback and comments from community is needed – just use it !

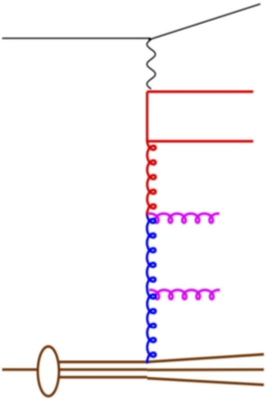
Validation of method with QCDnum at NLO



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

MCEG: TMDs, parton shower

- basic elements are:
  - Matrix Elements:
    - ➔ on shell/off shell
  - PDFs
    - ➔ TMDs
  - Parton Shower
    - ➔ following TMDs for initial state !
- Proton remnant and hadronization handled by standard hadronization program, e.g. PYTHIA



- Parton shower with TMDs follows exactly the evolution of the TMD
  - no (!) free parameter in shower
  - resolvable branchings and calculation of k_T defined in TMD
  - no adjustment of kinematics during/after shower