New parton densities with Parton Branching method

A. Bermudez Martinez (DESY)
in collaboration with
P. Connor, F. Hautmann, H. Jung, A. Lelek, V. Radescu, R. Zlebcik

- Why TMDs are needed
  - TMDs for hadron-hadron collisions

- New developments
  - parton branching algorithm to solve evolution equations
    - benchmark tests
    - advantages for integrated PDFs
  - determination of TMD densities at NLO with xFitter

- Application to DY production and high $p_T$ dijets
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 $\mu^2$
    - parton branching method (described here)
Why TMDs?

- Measurements with $p_T > 200$ GeV
  - at least 2 jets

- NLO-dijet (Powheg) w/o PS cannot describe small $\Delta \phi$
- NLO-dijet (Powheg) with TMDs describes spectrum at small and large $\Delta \phi$
- Region of higher order emissions described by TMDs
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 pt

**New: parton branching method**

- 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 is fulfilled and transverse momentum distributions can be obtained
How to obtain TMDs – the evolution equation


DGLAP evolution – solution with parton branching method

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

  \[ \Delta_s(\mu^2) = \exp\left( - \int_{\mu_0^2}^{\mu^2} d\mu'^2 \int \frac{\alpha_s}{2\pi} \frac{d\mu'^2}{\mu'^2} P^{(R)}(z) \right) \]

- differential form using \( f/\Delta_s \) 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 \( \mu_0^2 \) to \( \mu^2 \)**

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DGLAP – 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:

\[ f_0(x, \mu^2) = f(x, \mu_0^2) \Delta(\mu^2) \]
\[ f_1(x, \mu^2) = f(x, \mu_0^2) \Delta(\mu^2) + \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta(\mu^2)}{\Delta(\mu'^2)} \int \frac{dz}{z} P^{(R)}(z) f(x/z, \mu_0^2) \Delta(\mu'^2) \]

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Evolution equation and parton branching method

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

\[
x f_a(x, \mu^2) = \Delta_a(\mu^2) \, x f_a(x, \mu_0^2) \\
+ \sum_b \int_{\mu_0^2}^{\mu^2} \frac{d\mu'^2}{\mu'^2} \frac{\Delta_a(\mu^2)}{\Delta_a(\mu'^2)} \int_x^{z_M} dz P_{ab}^{(R)}(\alpha_s, z) \frac{x}{z} f_b \left( \frac{x}{z}, \mu'^2 \right)
\]

- 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
- reproduces DGLAP up to \( O(1 - z_M) \)

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

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

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Validation of method with QCDnum at NLO

- Very good agreement with NLO - QCDnum if $z_M$ is large enough:
  - approximation is of $O(1 - z_M)$
Transverse Momentum Dependence

- Parton Branching evolution generates every single branching:
  - kinematics can be calculated at every step

- Give physics interpretation of evolution scale:
  - in high energy limit: $p_T$-ordering:
    \[ \mu = q_T \]
  - angular ordering:
    \[ \mu = q_T/(1-z) \]
Transverse Momentum: dependence on $z_M$

- $p_T$ ordering ($\mu = q_T$) shows significant dependence on $z_M$: unstable result because of soft gluon contribution
- angular ordering ($\mu = q_T/(1-z)$) is independent of $z_M$: stable results since soft gluons are suppressed (angular ordering)
Parton branching method in xFitter

- Convolution of kernel with starting distribution

\[
x f_a(x, \mu^2) = x \int dx' \int dx'' A_{0,b}(x') \tilde{A}^b_a(x'', \mu^2) \delta(x' x'' - x)
\]

\[
= \int dx' A_{0,b}(x') \cdot \frac{x}{x'} \tilde{A}^b_a \left( \frac{x}{x'}, \mu^2 \right)
\]

- Kernel defined on grid (for integrated and TMD distribution)
- Validation of method:

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Advantages of parton branching method

- **DGLAP equation:**

\[
\mu^2 \frac{\partial}{\partial \mu^2} f(x, \mu^2) = \int \frac{dz}{z} \frac{\alpha_s(\mu_r)}{2\pi} P_+(z) f\left(\frac{x}{z}, \mu^2\right)
\]

- **Advantages of parton branching method for collinear PDFs:**
  - access to all kinematic variables and combinations between them
    - full freedom of choosing:
      - renormalisation scale: \(\alpha_s(\mu_r)\)
      - evolution scale: \(\mu_f\)
  - studies of different ordering conditions possible for the first time
    - angular ordering with \(\alpha_s(q)\)
    - but angular ordering suggests that renormalization scale is \(p_T\) and not angle
      - angular ordering with \(\alpha_s(p_T) \rightarrow \alpha_s(q(1-z))\)
    - repeat fits with changed renormalisation scale in pdf (but not yet in coefficient fct)
Fit with changed $\alpha_s(p_T)$: at small $Q^2$

- fit 1 with $\alpha_s(q)$
  - as good as HERAPDF2.0
  - $\chi^2/ndf = 1.2$

- fit 2 with $\alpha_s(q(1-z))$
  - $\chi^2/ndf = 1.21$

- very different gluon distribution obtained at small $Q^2$
TMD distributions

anti-up, $x = 0.01, \mu = 100$ GeV

- PB-NLO-HERAI+II-2018-set1
- PB-NLO-HERAI+II-2018-set2

experimental uncertainties

full uncertainties

$yA(x, k_t, \mu)$

$10^0$ $10^{-1}$ $10^{-2}$ $10^{-3}$ $10^{-4}$ $10^{-5}$ $10^{-6}$ $10^{-7}$ $10^{-8}$

$1.1$ $1.05$ $1$ $0.95$ $0.9$ $0.85$ $0.8$ $0.75$

$k_t [\text{GeV}]$

$10^0$ $10^1$ $10^2$ $10^3$

model dependence larger than experimental uncertainties

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Application to DY $q_T$ - spectrum

- Use LO DY production
  - $q\bar{q} \rightarrow Z_0$
- add $k_t$ for each parton as function of $x$ and $\mu$ according to TMD
- keep final state mass fixed:
  - $x_1$ and $x_2$ (light-cone fraction) are different after adding $k_t$
Application to DY $q_T$ - spectrum

- Use LO DY production
  $$q \bar{q} \rightarrow Z_0$$
- TMD with angular ordering including $\alpha_s(q)$
Application to DY $q_T$ - spectrum

- Use LO DY production
  
  $q\bar{q} \rightarrow Z_0$
  
- TMD with angular ordering including $\alpha_s(q)$
- TMD with angular ordering including $\alpha_s(p_T)$
  - in low $p_T$ much better!

- Additional issues:
  - resolvable branching
  - freeze $\alpha_s$
  - intrinsic $k_T$

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[arXiv:1512.02192]

$Z \rightarrow ee$, dressed level, $66\text{ GeV} \leq m_{\ell\ell} < 116\text{ GeV}, |y_{\ell\ell}| < 2.4$

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Application to high $p_T$ dijets in pp

- Dijet production at in pp, a test for TMDs and PS:

- TMDs with NLO dijets get closer to data!
Application to high $p_T$ dijets in pp

- Dijet production at in pp, a test for TMDs and PS:

- TMDs with NLO dijets + parton shower (following TMD) describes data!
Application to high $p_T$ dijets in pp

- Dijet production at in pp, a test for TMDs and PS:

- TMDs with NLO dijets + parton shower (following TMD) describes data!
  - different TMD sets are very similar
  - TMD + NLO dijets + PS $\rightarrow$ better than conventional treatment!

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Conclusion

- Parton Branching method to solve DGLAP equation at LO, NLO and NNLO
  - consistence for collinear (integrated) PDFs shown
  - advantages of Parton Branching method!

- 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 – fits to DIS processes at the moment

- Application for pp, ep processes, like DY, jets:
  - DY $q_T$ - spectrum without new parameters
  - TMD initial parton shower:
    - backward evolution following exactly the TMD density
    - dijet $\Delta \phi$ very well described with NLO dijets + TMD + TMD shower
Appendix
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://tdm.hepforge.org/
  - http://tmdplotter.desy.de

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


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

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

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Validation of method with QCDnum at NLO

- Very good agreement with NLO - QCDnum over all $x$ and $\mu^2$
- 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