Towards mini-global parton-branching TMD fits

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Motivation

- PB TMDs together with PB TMD parton shower allow very good description of measurements over wide kinematic range
  → excellent description of the DY spectrum in a wide range of $p_T$
  → also for jet multiplicity even much beyond reach of corresponding fixed-order calculation

  **Is there still any room for improvement? YES!**

- PB-TMD NLO fits use HERA DIS data
  → can be improved by including different data sets in fits

- NuSea data studied in arXiv:2001.06488
  → generally well described by PB-TMD + NLO
  → this deteriorates for region of highest masses
    • large-$x$ region - parton densities used in calculation poorly constrained
    • NNPDF3.0 set fits better - more data used
  → can be improved in global fits
  → jet data constrain gluon at high $x$
What data can help constraining quarks and gluons?

• Looking at various global fits lots of data can be added
• We start small

  → adding slowly additional data sets from HERA and CMS

  → for data sets and bins to use we take recommendation from NNPDF3

  → Aiming for mini-global parton-branchingTMD fits
Jets @ HERA

At HERA direct information on gluon distribution and $\alpha_s$ comes from jet production

→ Possible simultaneous determination of parton densities and $\alpha_s$

Jets at HERA

\( \text{elweak coupling} \propto \alpha_s \)

\( \propto \alpha_s \)

\( \propto \alpha_s^2 \)
CMS W/Z production

W asymmetry

Drell-Yan Z production

CMS, L = 18.8 fb⁻¹ at \( |\not{p}_T| = 8 \) TeV

CMS NNLO

HERAPDF method

\( Q^2 = m_W^2 \)

HERA I+II DIS

HERA I+II DIS + CMS W 8 TeV

Fract. uncert.

\( x \cdot u_v (x, Q^2) \)

\( x \cdot d_v (x, Q^2) \)

HERA+CMS / HERA

\( p_T^W > 25 \) GeV

Data

CMS, \( \int \frac{dL}{dt} = 4.5 \) fb⁻¹ at \( \sqrt{s} = 7 \) TeV, \( 60 < m < 120 \) GeV

Data

\( \frac{1}{\sigma} \frac{d\sigma}{dy_\mu\mu} \)

Absolute dimuon rapidity, \( y_\mu\mu \)
## Data samples used in mini-global fit

| HERA1+2 CCep  |  |  |
| HERA1+2 CCem  |  |  |
| HERA1+2 NCem  |  |  |
| HERA1+2 NCep 820 |  |  |
| HERA1+2 NCep 920 |  |  |
| HERA1+2 NCep 460 |  |  |
| HERA1+2 NCep 575 |  |  |
| ZEUS inclusive dijet 98-00/04-07 data |  |  |
| H1 low Q2 inclusive jet 99-00 data |  |  |
| ZEUS inclusive jet 96-97 data |  |  |
| H1 normalised inclusive jets with unfolding |  |  |
| H1 normalised dijets with unfolding |  |  |
| H1 normalised trijets with unfolding |  |  |
| CMS W muon asymmetry |  |  |
| CMS W muon asymmetry 8 TeV |  |  |
| CMS 7 TeV Z Boson rapidity 2 |  |  |
| CMS 7 TeV Z Boson rapidity 3 |  |  |
| CMS 7 TeV Z Boson rapidity 4 |  |  |
| CMS 7 TeV Z Boson rapidity 5 |  |  |
We use HERAPDF2 approach for QCD fits (also model parameter values) + xFitter

xFitter
PDF Fitting package
**HERAPDF2.0-like parameterisation**

\[ xf(x) = Ax^B (1 - x)^C (1 + Dx + Ex^2) \]

- **Parameters obtained by parameterisation scan**

- **additional parameters**

\[
\begin{align*}
    xg(x) &= A_g x^{B_g} (1 - x)^{C_g} - A'_g x^{B'_g} (1 - x)^{C'_g}, \\
    xu_v(x) &= A_{u_v} x^{B_{u_v}} (1 - x)^{C_{u_v}} \left(1 + E_{u_v} x^2\right), + D_{uv} x \\
    xd_v(x) &= A_{d_v} x^{B_{d_v}} (1 - x)^{C_{d_v}} (1 + D_{d_v} x) \\
    x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}} (1 - x)^{C_{\bar{U}}} (1 + D_{\bar{U}} x), \\
    x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}} (1 - x)^{C_{\bar{D}}} (1 + D_{\bar{D}} x)
\end{align*}
\]
Comparison to HERAPDF2 NLO
Can we get PB PDFs & TMDs with new data?

→ start with few discussed new data sets

- TMDs: Transverse Momentum Dependent parton distributions
- extended collinear PDFs: transverse momentum effects from intrinsic $k_t$ + evolution

Why TMD?

- fixed order calculations are limited in application
- small transverse momentum & small-$x$ phenomena need TMDs

New approach: Parton Branching (PB) method

- evolution of TMDs and collinear PDFs at LO, NLO & NNLO
- automatically contain soft gluon resummation (at NLL identical to CSS approach)
- unique feature: backward evolution fully determines the TMD shower
- very successful for description of inclusive processes


Two angular ordered sets with different choice of scale in $\alpha_s$:

- set1: $\alpha_s$ (evolution scale)
- set2: $\alpha_s$ (transverse momentum): similar quality as the NLO + NNLL prediction in $p_t(z)$ description
Fitting procedure in a nutshell:

- parameterize collinear PDF at \( \mu_0^2 \)
- produce PB kernels for collinear & TMD distributions to evolve them to \( \mu^2 > \mu_0^2 \) 
- perform fits to measurements using xFitter frame to extract the initial parametrization 
  (with collinear coefficient functions at NLO)
- plot collinear and TMD pdfs within TMDplotter \[\text{[arXiv:2103.09741]}\]

**5 FLNS:**

- full coupled evolution with all flavors & \( \alpha_s(M_Z^{n_f=5}) = 0.118 \)
- HERAPDF parametrization form
- using full HERAL+II inclusive DIS data 
  \(3.5 < Q^2 < 50000 \text{ GeV}^2 \& 4.10^{-5} < x < 0.65\)
- \( \chi^2 / \text{dof} = 1.21 \)

**4 FLNS:**

- the same functional form & data as 5FL - parameters are re-fitted
- \( m_b \rightarrow \infty \& \alpha_s(M_Z^{n_f=4}) = 0.1128 \)
- \( \chi^2 / \text{dof} = 1.25 \)
  \[\text{[arXiv:2106.09791]}\]
TMDs with jets

now we do PB QCD analysis with new data sets:

→ PB method implemented in xFitter:

→ kernels for PB fit with HERA DIS:
Comparison of collinear and PB PDFs

- Collinear and PB set1 very similar → fixed $\alpha_s$
- $\chi^2$ also good for jet data after the fit
- At large scale set1 gets similar to set2
Comparison of PB mini-global and HERA-only

- Difference between PB mini-global and HERA-only larger for set2
  → especially for gluon
Comparison to data (examples)

<table>
<thead>
<tr>
<th>Dataset</th>
<th>DGLAP</th>
<th>set1</th>
<th>set2</th>
</tr>
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<tbody>
<tr>
<td>HERA1+2 CCep</td>
<td>40 / 39</td>
<td>41 / 39</td>
<td>42 / 39</td>
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</table>

H1 high-\(Q^2\) dijets

CMS DY Z mass peak

CMS W asymmetry 8 TeV
For jet data we need to “choose” scale for PDF fits

→ set2 sensitive to chosen factorisation scale
→ it needs to be sufficiently large

We chose \( \mu_r = \mu_f = \frac{Q^2 + p_T^2}{2} \)

Works well for all included HERA jet data sets except for H1 HERAI low \( Q^2 \) jets

We observe huge partial \( \chi^2 \) for H1 HERAI low \( Q^2 \) jets

→ situation dramatically improves when we use \( \mu_f = (Q^2 + p_T^2) \)

→ maybe \( \mu_f = \frac{(Q^2 + p_T^2)}{2} \) not large enough for low \( Q^2 \) jets? 

→ for presented here fit we use this scale only for this data

However does it actually make sense?? → we need to understand that!
Summary & outlook

- PB fits so far include only HERA inclusive data
  - Studies of other processes at HERA and LHC gives more information on TMD PDFs and better uncertainty constraints
  - Ultimate goal: global PB TMDs - why not start small, with mini-global?
    → HERA jets
    → CMS DY data + W asymmetries
- PB method implemented in xFitter → so far fits with HERA DIS
  - Preliminary results with HERA jets and CMS data added → good agreement with collinear PDFs
  - New precise PB-sets from mini-global fit will be used to repeat our previous studies on the inclusive jet, Z+b, ... where our predictions were in general 10-20% below measurements
- Work ongoing to add more LHC and fixed target data
Additional slides
HERA combined DIS data are core of every modern PDF extraction

- 2927 data points combined to 1307
- impressive precision

HERAPDF approach uses ONLY HERA data in global QCD fit

\[ \sigma_{\text{NC}} x^2 \]

\[ Q^2/\text{GeV}^2 \]

Recap of Parton Branching method (I)

- PB evolution equation for collinear and TMD PDFs:

\[ f_a(x, \mu^2) = f_a(x, \mu_0^2) \Delta_s(\mu^2, \mu_0^2) + \sum_b \int_x^{Z_M} \frac{dz}{z} \int_{\mu_0}^{\mu} \frac{d\mu'}{\mu'} \cdot \frac{\Delta_s(\mu^2, \mu_0^2)}{\Delta_s(\mu'^2, \mu_0^2)} P^{(R)}(z) f_b\left(\frac{x}{z}, \mu'^2\right) \]

\[ \tilde{A}_a(x, k, \mu^2) = \Delta_a(\mu^2, \mu_0^2) \tilde{A}_a(x, k, \mu_0^2) + \sum_b \int \frac{d^2\mu'}{\pi \mu'^2} \frac{\Delta_a(\mu^2, \mu_0^2)}{\Delta_a(\mu'^2, \mu_0^2)} \Theta(\mu^2 - \mu'^2) \Theta(\mu'^2 - \mu_0^2) \]

\[ \times \int_x^{Z_M} dz \, p_{ab}^{(R)}(as(\mu'^2), z) \tilde{A}_b(x/z, k + (1 - z)\mu', \mu'^2) \]

- Iterative solution:

\[ f_0(x, \mu^2) = f(x, \mu_0^2) \Delta_s(\mu^2, \mu_0^2) \]

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

Recap of Parton Branching method (II)

- kinematics governed by momentum conservation \( (k_{t,b} = k_{t,a} + q_{t,c}) \) [JHEP 01 (2018), 070]

- gives physics interpretation of evolution scale:
  - \( p_t \)-ordering: \( \mu^2 = q^2_t \)
  - angular ordering: \( \mu^2 = q^2_t / (1 - z)^2 \)

- Two angular ordered sets with different choice of scale in \( \alpha_s \):
  - set1: \( \alpha_s \) (evolution scale)
  - set2: \( \alpha_s \) (transverse momentum): similar quality as the NLO + NNLL prediction in \( p_t(z) \) description

- TMD parametrization:

\[
f_{0,b}(x, k_{t,0}^2, \mu_0^2) = f_{0,b}(x, \mu_0^2) \cdot \exp\left(-\frac{|k_{T,0}^2|}{2\sigma^2}\right) \quad \sigma^2 = q_s^2 / 2 \quad \text{&} \quad q_s = 0.5 \text{ GeV}
\]