DPS: polarization, azimuthal dependence and proton size effects

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Diehl, TK, Keane, arXiv:1401.1233

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DPS cross section

- Example: DPS cross-section

\[
d\sigma_{DPS} \sim d\sigma_1 d\sigma_2 \int d^2y \left[ f_{qq}(x_1, x_2, y) f_{q\bar{q}}(\bar{x}_1, \bar{x}_2, y) + \ldots \right]
\]

- QCD requires inclusion of the transverse separation between hard scatterings

Paver, Treleani, 1982; Mekhfi, 1985; Diehl, Ostermeier, Schäfer, 2011

+ New phenomena!?!
Double parton distributions

\[ f_{ab}(x_1, x_2, y) \]

New way to access information on the non-perturbative structure of the proton!

from Matteo Rinaldi, MPI@LHC 2015
Correlations in DPS

- Color
- Fermion number interference
- Spin (polarization)
  - longitudinal
  - transverse/linear
- Flavor interference
- Between $y$ and $x$’s
- Parton type and $y$
- Between $x$’s

$$(a + b) = (a' + b') \iff \begin{cases} a = a' \\ b = b' \end{cases}$$
Road to the pocket formula

- What approximations goes into $\sigma_{eff}$

- Approximations step 1: Separation of transverse dependence
  
  \[ F_{ab}(x_1, x_2; y; \mu) = f_{ab}(x_1, x_2; \mu)G(y) \]

- Approximations step 2: Separation of longitudinal dependence
  
  \[ f_{ab}(x_1, x_2) = f_a(x_1)f_b(x_2) \]

- Results in the (infamous) pocket formula
  
  \[ \sigma_{DPS} \sim \frac{\sigma_1\sigma_2}{\sigma_{eff}} \]

- Both steps problematic and difficult to control or systematize

- What can we do beyond $\sigma_{eff}$?
Towards a DPS license
Towards a DPS license
Towards a DPS license
Evolution of DPDs

\[
\frac{df_{qq}(x_1, x_2, y; Q)}{d \ln Q^2} = \frac{\alpha_s(Q)}{2\pi} \left[ P_{qq} \otimes_1 f_{qq} + P_{qg} \otimes_1 f_{qg} + P_{qq} \otimes_2 f_{qq} + P_{qg} \otimes_2 f_{qg} \right],
\]

\[
\frac{d}{d \ln Q^2} \begin{array}{c}
\xrightarrow{\text{x}_1} \\
\xrightarrow{\text{x}_2}
\end{array} = \begin{array}{c}
\xrightarrow{\text{x}_1} \\
\xrightarrow{\text{x}_2}
\end{array} + \begin{array}{c}
\xrightarrow{\text{x}_1} \\
\xrightarrow{\text{x}_2}
\end{array} + \text{second parton}
\]

- Convolution with Altarelli-Parisi splitting kernels

\[
P_{ab}(.) \otimes_1 f_{bc}(., x_2, y; Q) = \int_{x_1}^{1-x_2} \frac{dz}{z} P_{ab} \left( \frac{x_1}{z} \right) f_{bc}(z, x_2, y; Q),
\]

- Analogously for polarized partons

- Separate branchings - expect evolution to wash out correlations
Transverse dependence of DPDs

- Evolution of $y$ dependence
  - Unpolarized DPDs
  - Need initial condition (DPDs at initial scale)
- Gaussian ansatz, longitudinal — transverse interplay
- Ansatz: DPDs in terms of GPDs

$$F_{ab}(x_1, x_2, y) = \int d^2bf_a(x_1, b)f_b(x_2, b + y)$$

$$f_a(x, b) = f_a(x) \frac{1}{4\pi h_a(x)} \exp \left[ - \frac{b^2}{4h_a(x)} \right] \quad h_a(x) = \alpha'_a \ln \frac{1}{x} + B_a$$

- $h_a(x)$ connected to measurements of exclusive $t$ slopes

$$f_a(x, r) = f_a(x) \exp \left[ -h_a(x)r^2 \right] \quad r^2 = -t$$
Transverse dependence of DPDs

- Gives ansatz for transverse dependence of the DPDs at initial scale:

\[
F_{ab}(x_1, x_2, y) = f_a(x_1) f_b(x_2) \\
\times \frac{1}{4\pi h_{ab}(x_1, x_2)} \exp \left[-\frac{y^2}{4h_{ab}(x_1, x_2)}\right]
\]

\[
h_{ab}(x_1, x_2) = \alpha'_a \ln \frac{1}{x_1} + \alpha'_b \ln \frac{1}{x_2} + B_a + B_b
\]

- Parameters from GPD fits (\(q^\pm = q \pm \bar{q}\))

\[
\begin{align*}
\alpha'_{q^-} &= 0.9 \text{ GeV}^{-2} , \\
\alpha'_{q^+} &= 0.164 \text{ GeV}^{-2} , \\
\alpha'_g &= 0.164 \text{ GeV}^{-2} ,
\end{align*}
\]

\[
\begin{align*}
B_{q^-} &= 0.59 \text{ GeV}^{-2} , \\
B_{q^+} &= 2.4 \text{ GeV}^{-2} , \\
B_g &= 1.2 \text{ GeV}^{-2}
\end{align*}
\]

- MSTW2008lo for single PDFs

Diehl, Kugler, 2008

Diehl, Feldmann, Jakob, Kroll, 2005

Martin, Stirling, Thorne, Watt, 2009
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\]

strength of correlation

\[
h_{ab}(x_1, x_2) = \alpha'_a \ln \frac{1}{x_1} + \alpha'_b \ln \frac{1}{x_2} + B_a + B_b
\]

- Parameters from GPD fits (\(q^{\pm} = q \pm \bar{q}\))

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- MSTW2008lo for single PDFs
• Evolution of $u^+ u^+$ distribution

![Graph showing evolution of $u^+ u^+$ distribution](image)

*Pushed up by gluon distribution*

- Distributions stays approximately Gaussian up to high scale
  - ⇒ Allows us to examine the evolution of the exponent $h$
Taking the log of the distributions gives us access to the exponential

\[
\ln F_{aa}(x, x, y) - \ln F_{aa}(x, x, 0) \bigg|_{y=0.4 \, \text{fm}} = -\frac{1}{4h_{aa}^{\text{eff}}(x, x)}
\]

- Gluon width evolve slowly
- \(u^-\) and \(u^+\) decrease
- Differences in transverse dependence up to large scale - even between \(u^+\) and gluon

- Differences at the initial scale to a large extent remain after evolution up to larger scales
• \( x \) dependence of \( h \)

• \( u^- \) and \( g \) approx. linear in \( \ln x \) (away from the large \( x \) region)

• Fit \( \alpha'_a \) describing correlation between \( x_1, x_2 \) and \( y \)

• Slow decrease in correlations

• \( u^+ \) slope highly dependent on \( x \) region

• Correlations remain up to large scales - transverse profile changes
Color correlations:

- Color singlet and octet distributions

\[ F_{q_1, q_2} \rightarrow (\bar{q}_21q_2)(\bar{q}_11q_1) \]

\[ F_{q_1, q_2} \rightarrow (\bar{q}_2 t^a q_2)(\bar{q}_1 t^a q_1) \]

- Color correlations enter cross section weighted by a Sudakov factor

\[ \Rightarrow \text{Suppressed at large } Q \]

\[ \tilde{U}_\mu(\Lambda, Q) = \exp \left[ -\frac{\alpha_s C_A}{2\pi} \ln^2 \frac{Q^2}{\Lambda^2} \right] \]

- Color correlations should not be relevant at large scales.

- Interpretation:
  Transportation of color over hadronic distance

Manohar, Waalewijn, 2012; Mekhfi, Artru, 1985
Polarization

Two partons in an unpolarized proton can each be unpolarized, longitudinally polarized and linearly/transversely polarized,

- Correlations between spin, transverse momenta and separation of the two partons

- Several polarized DPDs which contribute to DPS cross sections

- Large in model calculations

\[ f_{qq} \sim + + \]
\[ f_{\Delta q \Delta q} \sim + - \]

Changes total cross sections, distributions of final state particles and cause azimuthal asymmetries/spin asymmetries


- Manohar, Scopetta, Traini, Vento, 2014; Chang, Manohar, Waalewijn, 2011

Polarized DPDs - direct effect on final state

- Longitudinal polarization:
  - Changes rate as well as rapidity and $|p_T|$ distributions
- Transverse quark/linear gluon polarization
  - Leads to azimuthal asymmetries
- Double Drell-Yan
  \[ d\sigma_{DPS}(pp \rightarrow ZZ \rightarrow l_1\bar{l}_1l_2\bar{l}_2) \subset A\cos 2(\phi_1 - \phi_2)f_{\delta q\delta q}f_{\delta \bar{q}\delta \bar{q}} \]
  for transversely polarized quarks
- Double $q\bar{q}$ production
  \[ d\sigma_{DPS}(pp \rightarrow c_1\bar{c}_1c_2\bar{c}_2) \subset B\cos 2(\phi_1 - \phi_2)f_{\delta g\delta g}f_{g\delta g} + C\cos 4(\phi_1 - \phi_2)f_{\delta g\delta g}f_{\delta g\delta g} \]
  for linearly polarized gluons
  - Linearly polarized gluons also affect the overall rate

TK, M. Diehl, 2012

Echevarria, TK, Mulders, Pisano, 2015
• Need an ansatz for the initial DPDs in order to study the effect of evolution on the polarization

\[ f_{p_1p_2}(x_1, x_2, y; Q) = \tilde{f}_{p_1p_2}(x_1, x_2; Q) G(y), \]

Not interested in normalization and set \( G(y) = 1 \)

• For unpolarized DPDs \( \tilde{f}_{ab}(x_1, x_2; Q_0) = f_a(x_1; Q_0) f_b(x_2; Q_0), \)

**Graphs**

- MSTW2008lo

  Martin, Stirling, Thorne, Watt, 2009; Glück, Jimenez-Delgado, Reya, 2007
• Need an ansatz for the initial DPDs in order to study the effect of evolution on the polarization

\[ f_{p_1p_2}(x_1, x_2, y; Q) = \tilde{f}_{p_1p_2}(x_1, x_2; Q) G(y), \]

Not interested in normalization and set \( G(y) = 1 \)

• For unpolarized DPDs \( \tilde{f}_{ab}(x_1, x_2; Q_0) = f_a(x_1; Q_0) f_b(x_2; Q_0) \),

\[ \text{Large difference for gluon} \]

MSTW2008lo  
GJR08lo

Martin, Stirling, Thorne, Watt, 2009; Glück, Jimenez-Delgado, Reya, 2007
**Max scenario**

- Polarized DPDs more complicated
  - No single parton equivalence (parton-parton vs parton-proton)
- Upper bounds on polarized distributions from probability interpretation - stable under leading-order double DGLAP evolution
  - Analogue to Soffer bounds for polarized single PDFs

\[
\begin{align*}
  f_{ab} + h_{\delta a\delta b} - h_{\delta a\delta b}^t & \pm \sqrt{(h_{\delta a\delta b} + h_{a\delta b})^2 + (f_{\Delta a\Delta b} - h_{\delta a\delta b} - h_{\delta a\delta b}^t)^2} \geq 0 \\
  f_{ab} - h_{\delta a\delta b} + h_{\delta a\delta b}^t & \pm \sqrt{(h_{\delta a\delta b} - h_{a\delta b})^2 + (f_{\Delta a\Delta b} + h_{\delta a\delta b} + h_{\delta a\delta b}^t)^2} \geq 0
\end{align*}
\]

**Max scenario** - each polarized DPD as large as possibly allowed

- Polarized DPDs equal to unpolarized at starting scale

Diehl, TK, 2012
Longitudinal quark polarization

- **Max scenario:**
  - Large longitudinal polarization up to high scales in wide range of $x_i$
  - Degree of polarization flat in rapidity - generic feature in max scenario

50% polarization

20% polarization
Longitudinal quark polarization

- **Max scenario:**
  - Large longitudinal polarization up to high scales in wide range of $x_i$
  - Degree of polarization flat in rapidity - generic feature in *max scenario*
Transverse quark polarization

- **Max scenario:**
  - Sizable transverse polarization up to high scales in wide range of $x_i$
  - Degree of polarization flat in rapidity - generic feature in *max scenario*

40% polarization

10-15% polarization
Max scenario:

- Sizable transverse polarization up to high scales in wide range of $x_i$
- Degree of polarization flat in rapidity - generic feature in max scenario
Longitudinal gluon polarization

- **Max scenario** starting from GJR distributions
  - Much larger degree of polarization than with MSTW;
    - by factor 2-3 at larger scales
  - Difference mainly due to the unpolarized gluon PDF at low scales
  - Smaller degree of polarization than for quarks and antiquarks

30% polarization

20% polarization
Longitudinal gluon polarization

- **Max scenario** starting from GJR distributions
  - Much larger degree of polarization than with MSTW;
    - by factor 2-3 at larger scales
  - Difference mainly due to the unpolarized gluon PDF at low scales
  - Smaller degree of polarization than for quarks and antiquarks

\[
\begin{align*}
\text{30\% polarization} & \quad \text{some polarization remains} \\
\text{20\% polarization} & \quad x_1 x_2 = 10^{-4}
\end{align*}
\]
Linear gluon polarization

- Max scenario starting from GJR distributions
- Double linear gluon polarization rapidly suppressed by evolution - even in most positive scenario
Linear gluon polarization

- **Max scenario** starting from GJR distributions
- Double linear gluon polarization **rapidly suppressed by evolution** - even in most positive scenario
Double ccbar production

- Promising for separation of DPS from SPS
  - Dominated by DPS
  - Studied in a series of papers
- Measured by LHCb (D0D0)
- Polarization (or any other quantum number interferences) has not been taken into account
- Focus on polarization
- Pure gluon channel dominates
- Gluon polarization suppressed by evolution
  - low scale $\Rightarrow$ little room for evolution

Hameren, Maciula, Szczurek, 2014
Gaunt, Hameren, Luszczak, Maciula, Szczurek
Double ccbar production

- Unpolarized

\[ d\sigma_{(gg)(gg)} \sim \frac{(1 - z_1)^2 + z_1^2 - 1/N_c^2}{(1 - z_1)z_1} \left[ (1 - z_1^2)^2 + z_1^2 + 4z_1(1 - z_1) + \mathcal{O}(\frac{m^2}{m_{T1}^2}) \right] \]

\[ \times \{1 \leftrightarrow 2\} \int d^2y \tilde{f}_{gg}(x_1, x_2, y) f_{gg}(\bar{x}_1, \bar{x}_2, y) \]

\[ m_{T_i}^2 = m^2 + p_{T_i}^2 \quad m_{T_i}^2 = m^2 + p_{T_i}^2 < < m^2 \quad z_i = \frac{m^2 - \hat{t}_i}{\hat{s}_i} \]

- Longitudinally polarized contribution

\[ d\sigma_{(\Delta g\Delta g)(\Delta g\Delta g)} \sim \frac{(1 - z_1)^2 + z_1^2 - 1/N_c^2}{(1 - z_1)z_1} \left[ (1 - z_1^2)^2 + z_1^2 + 4z_1(1 - z_1) \right] \]

\[ \times \left( 1 - 2 \frac{m^2}{m_{T1}^2} \right) \{1 \leftrightarrow 2\} \int d^2y \tilde{f}_{\Delta g\Delta g}(x_1, x_2, y) f_{\Delta g\Delta g}(\bar{x}_1, \bar{x}_2, y) \]

- Differences in hard scattering suppressed by \( m^2/m_{T_i}^2 \)
Double ccbar production

- Mixed linear-unpolarized contribution

\[
d\sigma_{(\delta gg)(g\delta g)} \sim ((1 - z_1)^2 + z_1^2 - 1/N_c^2) \frac{m^2}{m_{T1}^2} \left(1 - \frac{m^2}{m_{T1}^2}\right)
\times \{1 \leftrightarrow 2\} \cos 2(\phi_1 - \phi_2) \int d^2y \ y^4 M^4 f_{\delta gg}(x_1, x_2, y) \bar{f}_{g\delta g}(\bar{x}_1, \bar{x}_2, y)
\]

- Suppressed by \(m^2/m_{T_i}^2\) in each hard part (due to helicity flip)

- Doubly linearly polarized contribution

\[
d\sigma_{(\delta g\delta g)(\delta g\delta g)} \sim ((1 - z_1)^2 + z_1^2 - 1/N_c^2) \frac{(m^2 - m_{T1}^2)^2}{m_{T1}^4}
\times \{1 \leftrightarrow 2\} \left(\cos 4(\phi_1 - \phi_2) + \mathcal{O}\left(\frac{m^8}{p_{T1}^4 p_{T2}^4}\right)\right)
\times \int d^2y f_{\delta g\delta g}(x_1, x_2, y) \bar{f}_{\delta g\delta g}(\bar{x}_1, \bar{x}_2, y)
\]

- Less suppression in hard, but more from evolution of distributions
Double ccbar production

- In order to do numerics we need input for the DPDs
- For unpolarized we take
  \[ f_{gg}(x_1, x_2, y; Q_0) = f_g(x_1, Q_0) f_g(x_2; Q_0) G(y). \]
  - GJR2008lo for PDFs
  \[ f_{gg}(x_1, x_2, y; Q_0) = f_{gg}(x_1, x_2, y; Q_0) \]
  - For polarized we saturate the positivity bounds on polarized distributions, for example
    \[ f_{\Delta g \Delta g}(x_1, x_2, y; Q_0) = f_{gg}(x_1, x_2, y; Q_0) \]
    - M. Diehl, TK, 2013
- Cuts:
  \[ 3 \text{ GeV} \leq |p_{Ti}| \leq 12 \text{ GeV} \quad 2 \text{ GeV} \leq |y_i| \leq 4 \]
- Evolve DPDs with double DGLAP evolution
  - Polarized splitting kernels for polarized distributions
- Results for two choices of initial scales
  (and two choices for the hard scale in the DPDs)

Glück, Jimenez-Delgado, Reya, 2007
M. Diehl, TK, 2013
**Cross section vs rapidity difference**

- $D^0 D^0$ data from LHCb
- Polarization does not affect shape of distribution
- With $Q_0 = 1$ GeV small contribution of polarized gluons
- With $Q_0 = 2$ GeV large contribution of polarized gluons
- Strong dependence on scale choice
Cross section vs transverse momentum

- $D^0 D^0$ data from LHCb
- Polarization does not affect shape of distribution
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- With $Q_0 = 2$ GeV, large contribution of polarized gluons
- Strong dependence on scale choice
Polarization in double ccbar summary

- Size of polarization has strong dependence on input scale
  - With $Q_0 = 1 \text{ GeV}$, get polarization effects of a few percent
  - With $Q_0 = 2 \text{ GeV}$, get polarization effects of up to 50%
- Significant longitudinal polarization can be there in the data,
  - Difficult to disentangle
  - Other variables, more differential?
- Linearly polarized gluons gives dependence on azimuthal angles
  - The effect of linearly polarized gluons is small

![Graph](image-url)
Summary

• We can do more than $\sigma_{eff}$
• DPS theory advances towards a full treatment in QCD
• Learning piece by piece - moving towards a DPS license

• Future (utopia or realistic scenario?) with DPDs and correlations measured from data

• Thoughts from experimentalists, how can theory help you go further?
• Thoughts from pA and AA, can DPS teach you anything or vice versa?
• Thoughts from quarkonia perspective, benefits from DPS - quarkonia interactions?