Polarization in Double Parton Scattering

Tomas Kasemets
Nikhef / VU
What is Double Parton Scattering..
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DPS in hadron-hadron collisions

- Cross section calculations based on factorization
  \[
  \text{cross section} = \text{parton distribution} \times \text{partonic cross section}
  \]
  - single parton example: \( pp \rightarrow Z + X \rightarrow l^+ l^- + X \)
- Spectator-spectator interactions
  - cancel in inclusive cross sections (unitarity)
  - affects final state \( X \)
- Ask questions about \( X \), gives sensitivity to additional interaction
- Second interaction hard — Double Parton Scattering
  example: \( pp \rightarrow Z + H + X \rightarrow l \bar{l} + b \bar{b} + X \)

figure from M. Diehl, QCD Evolution 2014
Proton collisions at LHC

- Double parton scattering contribute both to signal and background
  
  \[ pp \rightarrow H + Z + X \rightarrow b\bar{b} + \mu^+\mu^- + X \]

Del Fabbro, Treleani, 1999

Figure from Diehl, QCD Evolution 2014
When should one care about DPS?

- Rule of thumb:
  - Several particles in the final state (typically 4 or more)
  - High energy hadron collisions — where low momentum fractions are probed (low x)
  - And/or SPS is suppressed — two single production cross sections are large compared to their “combination”

- These conditions are often fulfilled for processes studied at the LHC

- Some examples:
  - Two same sign W’s (small cross section but very clean)
  - Double open charm production (D0D0) - Double dominates single parton scattering
  - Double J/Psi production,
  - W+b (rough estimates about 20% DPS)
  - double meson productions, W+bbar, 4 jets, photon + 3 jets, etc. etc.
Increase in activity - still a lot to be done

- Inspire search for *double parton scattering* organized per year

- Spurred by the realization that it is an important background to several other processes of interest at the LHC and contains a rich and largely unexplored area of hadron collisions.

- Still much! to do regarding the spin structure (and other correlations) as the vast majority of studies neglects all polarizations.
How does one do DPS phenomenology

- Write down the cross section in a factorized form
  \[
  \text{cross section} = \text{parton distributions} \times \text{partonic cross section}
  \]

- The normal PDFs are replaced by Double Parton Distributions (DPDs)

- DPDs describe the probability to find two partons inside the proton, at a given transverse distance and with momentum fractions \( x_1 \) and \( x_2 \)

- Schematically (leading order)

\[
\frac{d\sigma_{DPS}}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} = \frac{1}{C \hat{\sigma}_1 \hat{\sigma}_2} \int d^2 y F(x_1, x_2, y) F(\bar{x}_1, \bar{x}_2, y)
\]
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\]

transverse distance

momentum fractions
and then..

- Double parton distributions unknown, so how to continue..
- Simplest possible approach to DPS
  - **Assume** the DPD factorize into normal PDFs and a transverse dependence
  
  \[ F_{ij}(x_1, x_2, y) = f_i(x_1)f_j(x_2)G(y) \]

  \[ 1/\sigma_{\text{eff}} = \int d^2y G(y)^2 \]

  - **Assume** complete universality of \( G(y) \)
  
  - Then the cross section become extremely simple:

  \[ \sigma_{DPS} \sim \frac{\sigma_1\sigma_2}{\sigma_{\text{eff}}} \]

  - Extract \( \sigma_{\text{eff}} \) from measurements (typically set to 15 mb)
  - In this approximation, the DPS cross section is known as soon as we know the single parton cross sections
  - Study rates, distributions, variables for DPS extraction etc.
Several such studies along these lines..

- A few recent ones are..
  - Double quarkonium, J.-P. Lansberg, H.-S. Shao, 2015;
  - $W + D^*$, S.P. Baranov et. al., 2015;
  - 2-gamma + 2-jets, J. Tao et. al. 2015;
  - Charm- + bottom-mesons, A.K. Likhoded et. al., 2015;
  - J/Psi pair production, J.-P. Lansberg, H.-S. Shao, 2015;
  - 4-jets, R. Maciuła, A. Szczurek, 2014;
  - Double c-cbar, A. Hameren, R. Maciula, A. Szczurek, 2014;
  - Quarkonia + vector bosons, D. d’Enterria, A. M. Snigirev, 2014;
  - $W+2$-jets G. Calucci, S. Salvini and D. Treleani, 2013;
  - etc...
Experimental measurements

- Extractions of $\sigma_{\text{eff}}$, $\sigma_{DPS} \sim \frac{\sigma_1\sigma_2}{\sigma_{\text{eff}}}$

- Neglecting parton correlations, gives $\sigma_{\text{eff}} \sim 40 \text{ mb}$
  - Much larger than experimental measurements of 5-20 mb
  - complete independence between partons disfavored

see Calucci, Treleani 1999; Frankfurt, Strikman, Weiss 2003; Blok et al 2013
Polarized DPDs

- Spin of the two partons can be correlated → polarized DPDs

Describe correlations between the spin of and distance between the two partons

- Example: DPD for two longitudinally polarized quarks

\[ f_{\Delta q \Delta q} \sim \]

- Quarks: unpolarized \( q \), longitudinally polarized \( \Delta q \) and transversely polarized \( \delta q \)

- Gluons: unpolarized \( g \), longitudinally polarized \( \Delta g \) and linearly polarized \( \delta g \)

- Linear/transverse polarization from helicity interference

Similar description, different physics than TMDs!
Polarized quark DPDs

- The different polarized quark DPDs:

\[ F_{qq}(x_1, x_2, y) = f_{qq}(x_1, x_2, y), \]
\[ F_{\Delta q\Delta q}(x_1, x_2, y) = f_{\Delta q\Delta q}(x_1, x_2, y), \]
\[ F_{q\delta q}^j(x_1, x_2, y) = \epsilon^{jj'} y^{j'} M f_{q\delta q}(x_1, x_2, y), \]
\[ F_{\delta q q}^j(x_1, x_2, y) = \epsilon^{jj'} y^{j'} M f_{\delta q q}(x_1, x_2, y), \]
\[ F_{\delta q\delta q}^{jj'}(x_1, x_2, y) = \delta^{jj'} f_{\delta q\delta q}(x_1, x_2, y) \]
\[ + (2y^j y^{j'} - y^2 \delta^{jj'}) M^2 f_{\delta q\delta q}^t(x_1, x_2, y) \]

- Appreciate the similarity to, for example, the decomposition of TMDs
- Note: All for distributions for an unpolarized proton

Diehl, Schäfer, Ostermeier, 2011
Polarized quark DPDs

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\[+ (2 y^{j} y^{j'} - y^2 \delta^{jj'}) M^2 f_{\delta q \delta q}^{t}(x_1, x_2, y)\]

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Diehl, Schäfer, Ostermeier, 2011
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- Appreciate the similarity to, for example, the decomposition of TMDs

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Diehl, Schäfer, Ostermeier, 2011
What has been done for polarized DPS?
Polarization in DPS

- Setting up the framework for polarized DPS
  
  - Polarization limited by positivity bounds combined with scale evolution
  
  - DPDs studied in a number of different quark models
    - Correlations typically found to be sizable
    - Have been included in cross section calculations of double vector boson production (\(\gamma, Z, W\)) and double \(c\bar{c}\)

- So far, limited literature on polarization effects in DPS — room for improvement

  Mekhfi, 1985; Diehl, Schäfer, 2011; Diehl, Schäfer, Ostermeier, 2011; Manohar, Waalewijn, 2012;
  
  Diehl, TK, 2013; Diehl, TK, Keane 2014
  
  Chang, Manohar, Waalewijn, 2012; Rinaldi, Scopetta, Traini, Vento, 2014
  
Polarization in DPS

- Longitudinal polarization:
  - Changes rate as well as rapidity
  - and $|p_T|$ distributions
- Transverse quark/linear gluon polarization
- Leads to azimuthal asymmetries
- Double Drell-Yan

$$d\sigma_{DPS}(pp \rightarrow ZZ \rightarrow l_1 \bar{l}_1 l_2 \bar{l}_2) \subset A \cos(2\Delta \phi) f_{\delta q\delta q} f_{\delta \bar{q}\delta \bar{q}}$$

for transversely polarize quarks

- Double $q\bar{q}$ production

$$d\sigma_{DPS}(pp \rightarrow c_1 \bar{c}_1 c_2 \bar{c}_2) \subset B \cos(2\Delta \phi) f_{\delta g\delta g} f_{g\delta g}$$

$$+ C \cos(4\Delta \phi) f_{\delta \bar{g}\delta \bar{g}} f_{\delta g\bar{g}g}$$

for linearly polarized gluons

Echevarria, TK, Mulders, Pisano, 2015

TK, M. Diehl, 2012

- Linearly polarized gluons also affect the overall rate
Getting quantitative..

- Standard approach
  \[ F_{ij}(x_1, x_2, y) = f_i(x_1)f_j(x_2)G(y) \]

- Build on this, but let's add polarization

- Simple model for upper estimates of polarization effects
  - Use the above formula for unpolarized partons
  - Saturate positivity bounds for polarized DPDs at a low initial scale
    \[
    f_{ab} + h_{\delta a \delta b} - h^t_{\delta a \delta b} \pm \sqrt{(h_{\delta a b} + h_{a \delta b})^2 + (f_{\Delta a \Delta b} - h_{\delta a \delta b} - h^t_{\delta a \delta b})^2} \geq 0
    \]
    \[
    f_{ab} - h_{\delta a \delta b} + h^t_{\delta a \delta b} \pm \sqrt{(h_{\delta a b} - h_{a \delta b})^2 + (f_{\Delta a \Delta b} + h_{\delta a \delta b} + h^t_{\delta a \delta b})^2} \geq 0
    \]

- Max scenario - each polarized DPD as large as possibly allowed
  \[ \Rightarrow \] Polarized DPDs equal to unpolarized at starting scale

- Evolve with double DGLAP evolution to higher scales

M. 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*

Diehl, TK, Keane 2014
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

$10\text{-}15\%$ polarization

Diehl, TK, Keane 2014
Double open charm at LHCb

- $D^0D^0$ 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

Echevarria, TK, Mulders, Pisano, 2015
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Echevarria, TK, Mulders, Pisano, 2015
Double open charm at LHCb

- Double differential cross section - shows strong shape dependence

7 TeV

14 TeV

Echevarria, TK, Mulders, Pisano, 2015
Summary

- Double parton scattering is an increasingly relevant topic, with the energy of the collider and the large luminosity/search for rare events.
- DPDs are interesting (non-pertubative) descriptions of the proton
- Ignoring correlations gives simple, order of magnitude, estimates for DPS cross sections
- Bulk of DPS phenomenology so far based on this simplified approach
- But, spins can be correlated
  \[ \Rightarrow \text{Gives polarized double parton distributions} \]
- A few studies has included polarization, but there is much work still to be done.
- Much of the knowledge, and even calculations, from TMD community can be directly used in calculations of spin asymmetries etc. in double parton scattering