Polarization in Double Parton Scattering

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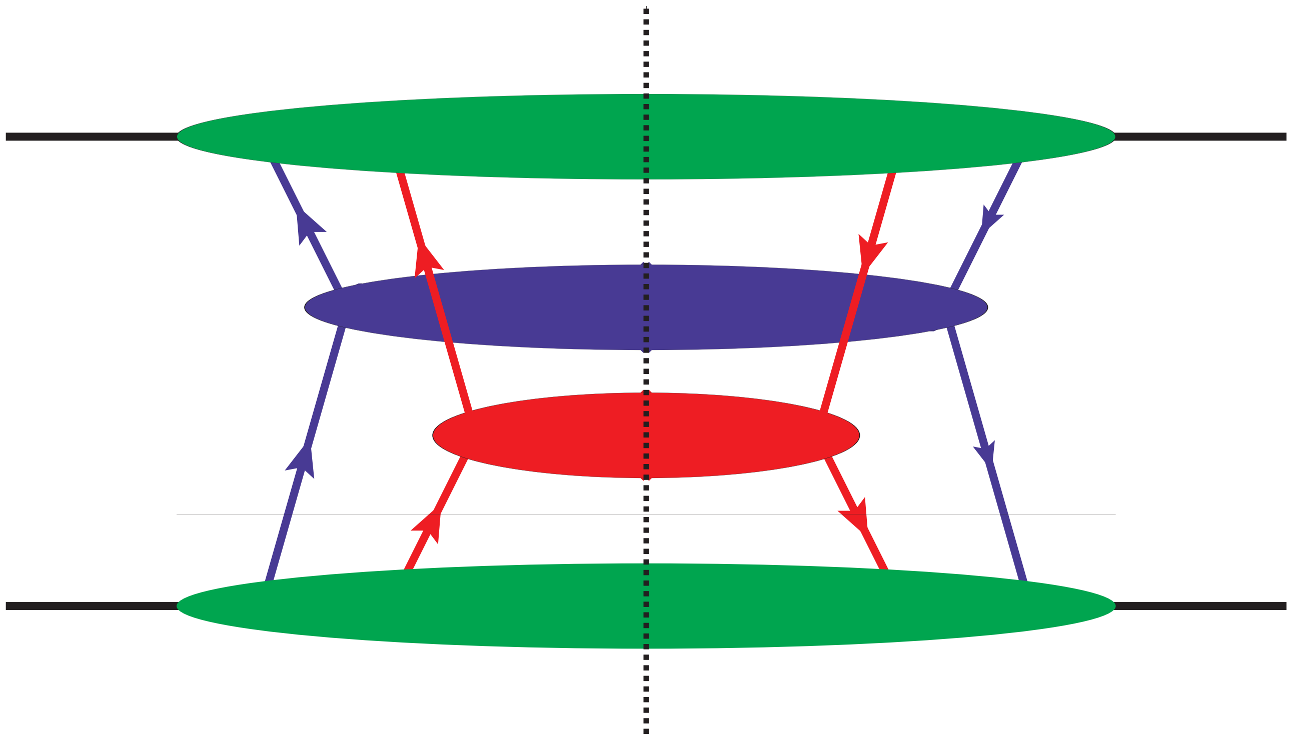
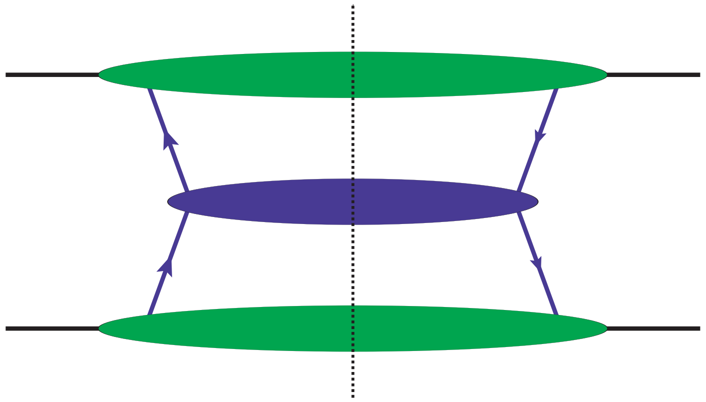
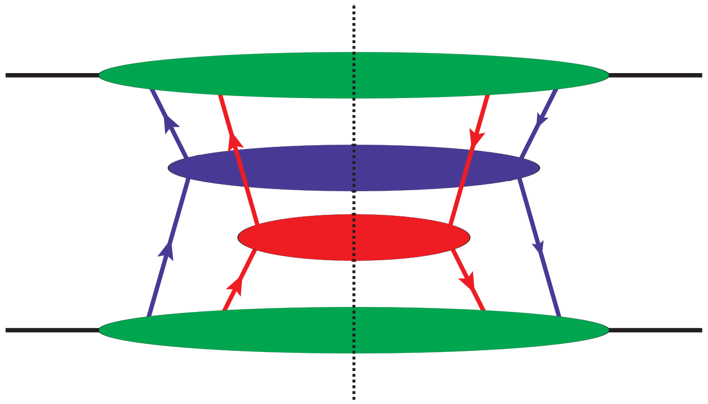


DIS2015 - Dallas, April 29, 2015

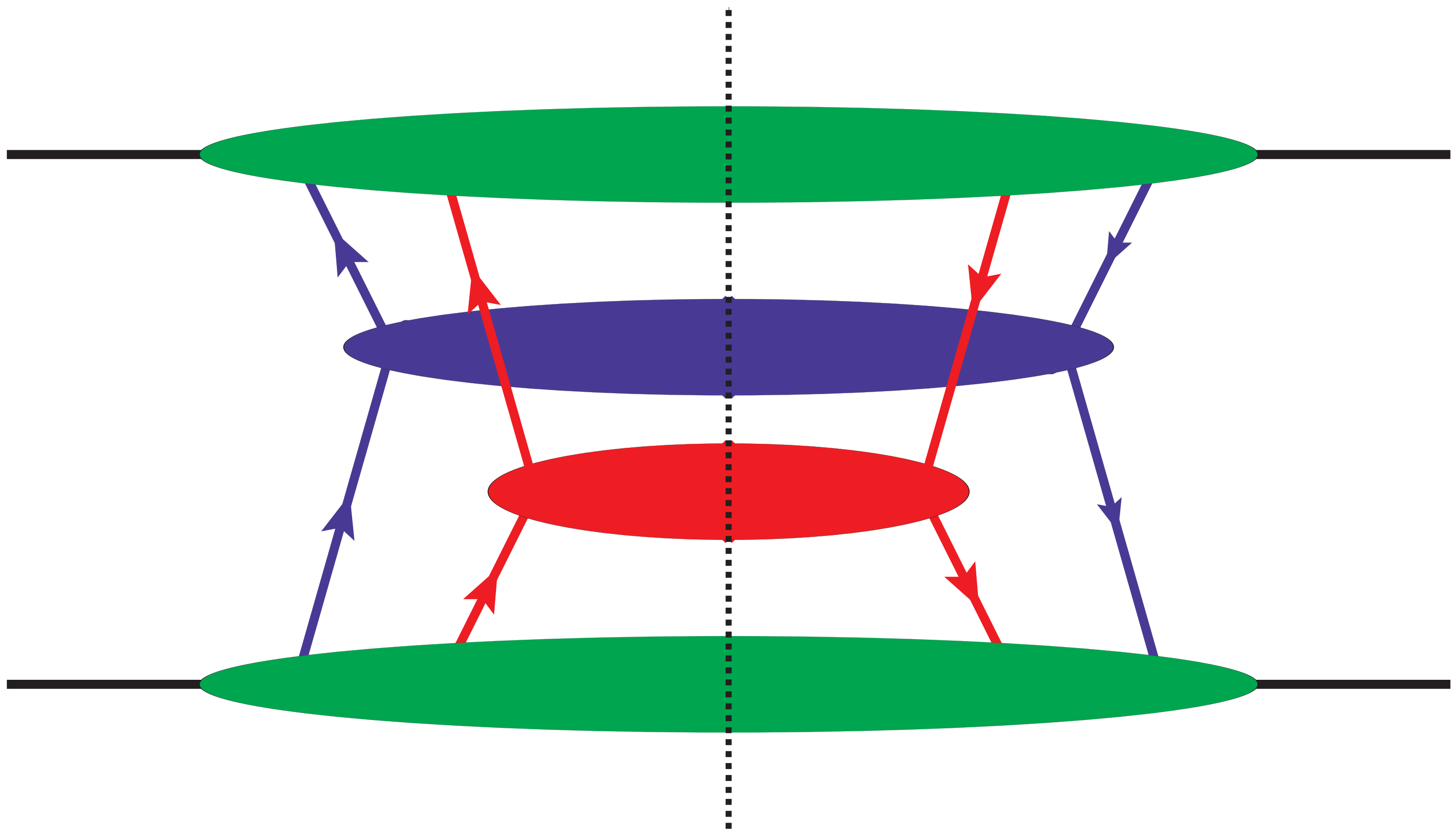
What is Double Parton Scattering..


What is Double Parton Scattering..



What is Double Parton Scattering..



What is Double Parton Scattering..

What is Double Parton Scattering..

DPS in hadron-hadron collisions

- Cross section calculations based on factorization

  cross section = parton distribution × partonic cross section

  - single parton example: $pp \to Z + X \to l^+ l^- + X$

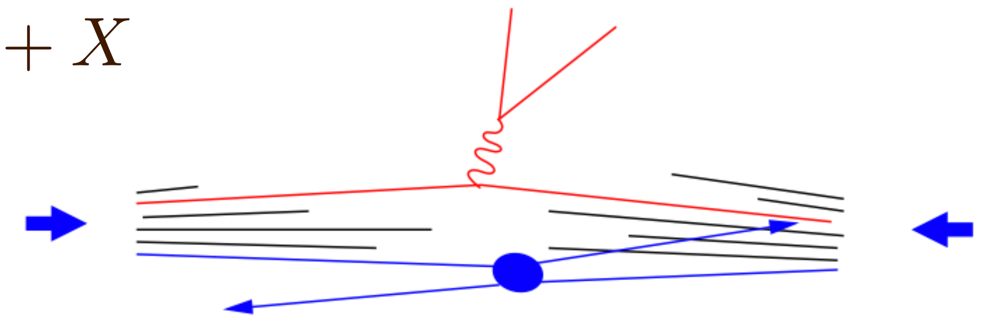


figure from M. Diehl, QCD Evolution 2014

- 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: $pp \to Z + H + X \to l\bar{l} + b\bar{b} + X$

Proton collisions at LHC

- Double parton scattering contribute both to signal and background
  - $pp \to H + Z + X \to b\bar{b} + \mu^+\mu^- + X$ Del Fabbro, Treleani, 1999

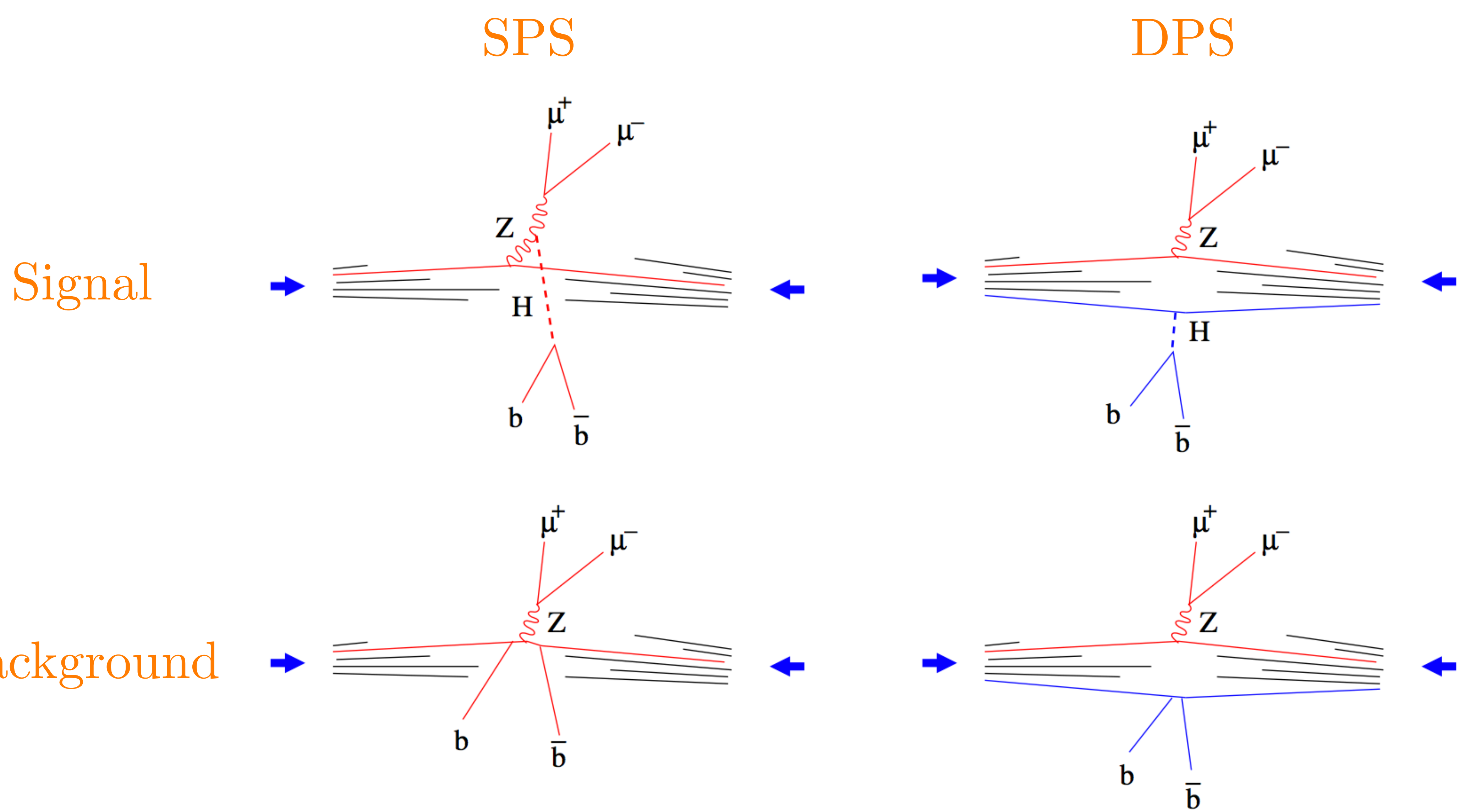


figure from Diehl, QCD Evolution 2014

When should one care about DPS?

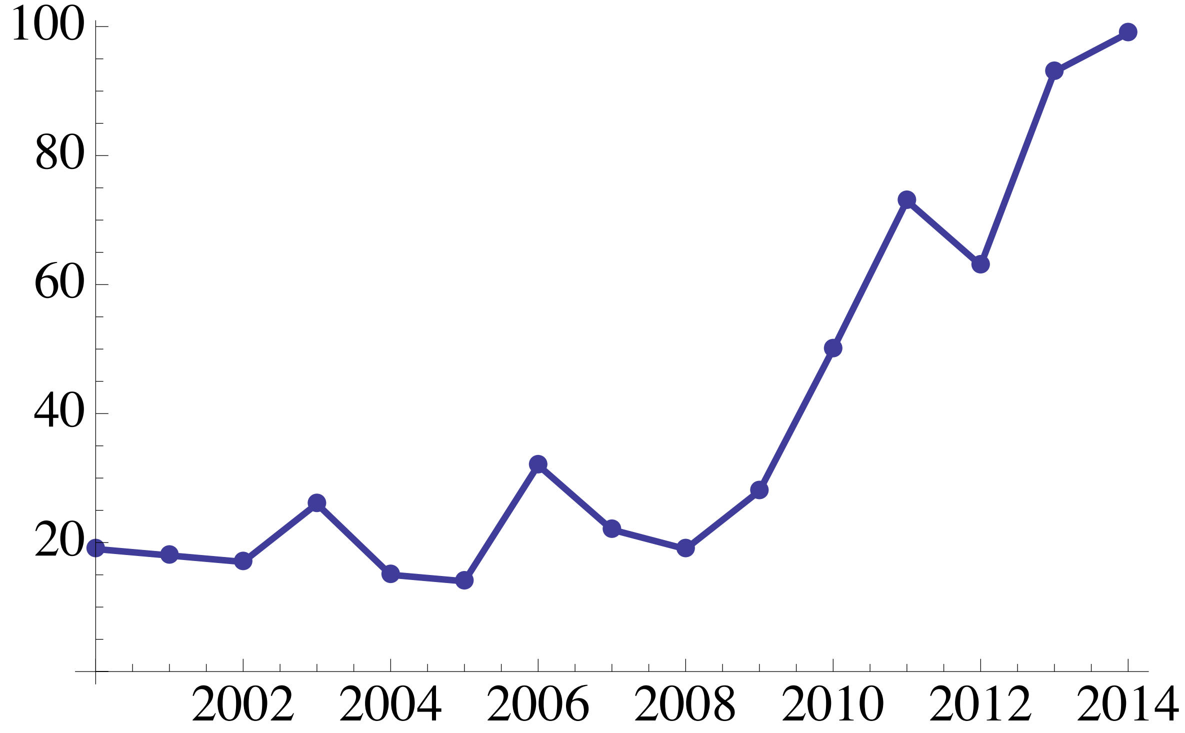
- Rule of thumb:
  - Several particles in the final state (typically 4 or more)
  - High energy hadron collisions
    — where low momentum fractions are probed (low x)
  - And/or SPS is suppressed — two single production cross sections are large compared to their “combination”
- These conditions are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

    Hameren, Maciula, and Szczurek, 2014
  - Double J/Psi production,
  - W+b (rough estimates about 20% DPS)

    ATLAS Collaboration, 2013
  - 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

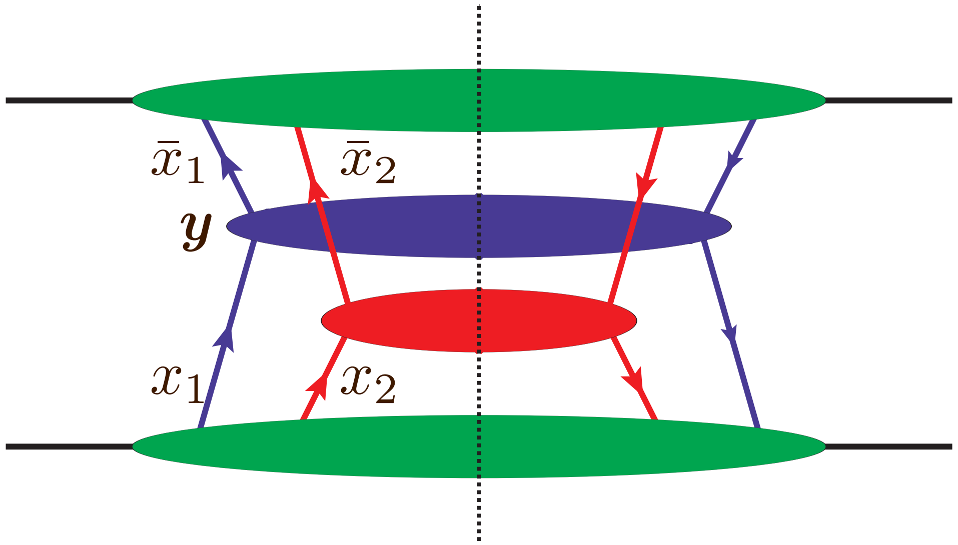
How does one do DPS phenomenology

- Write down the cross section in a factorized form

  cross section = parton distributions × 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 x1 and x2



- Schematically (leading order)

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

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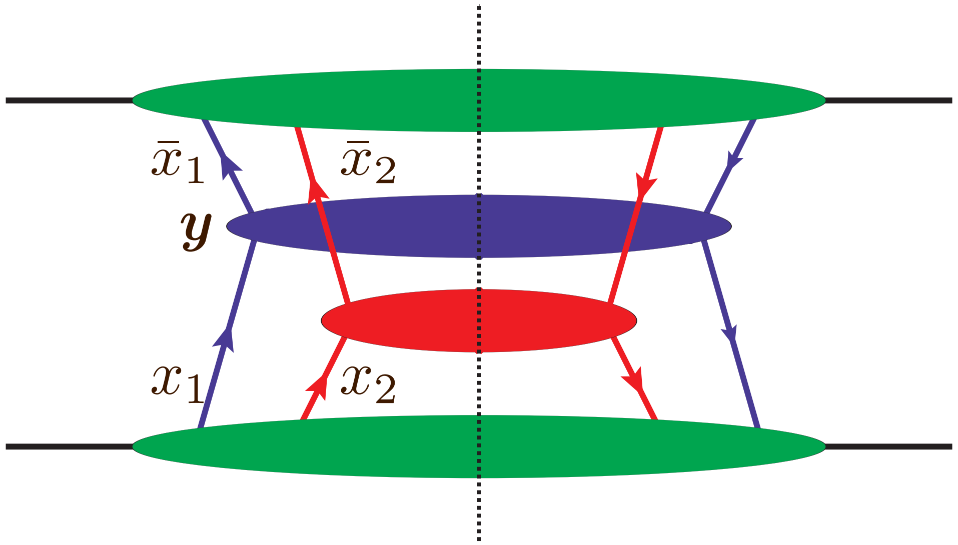

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transverse distance

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

$$F_{ij}(x_1, x_2, \boldsymbol{y}) = f_i(x_1) f_j(x_2) G(\boldsymbol{y}) \qquad 1/\sigma_{\text{eff}} = \int d^2\boldsymbol{y} G(\boldsymbol{y})^2$$

  - Assume complete universality of $G(\boldsymbol{y})$
- Then the cross section become extremely simple:

$$\sigma_{DPS} \sim \frac{\sigma_1 \sigma_2}{\sigma_{\text{eff}}}$$

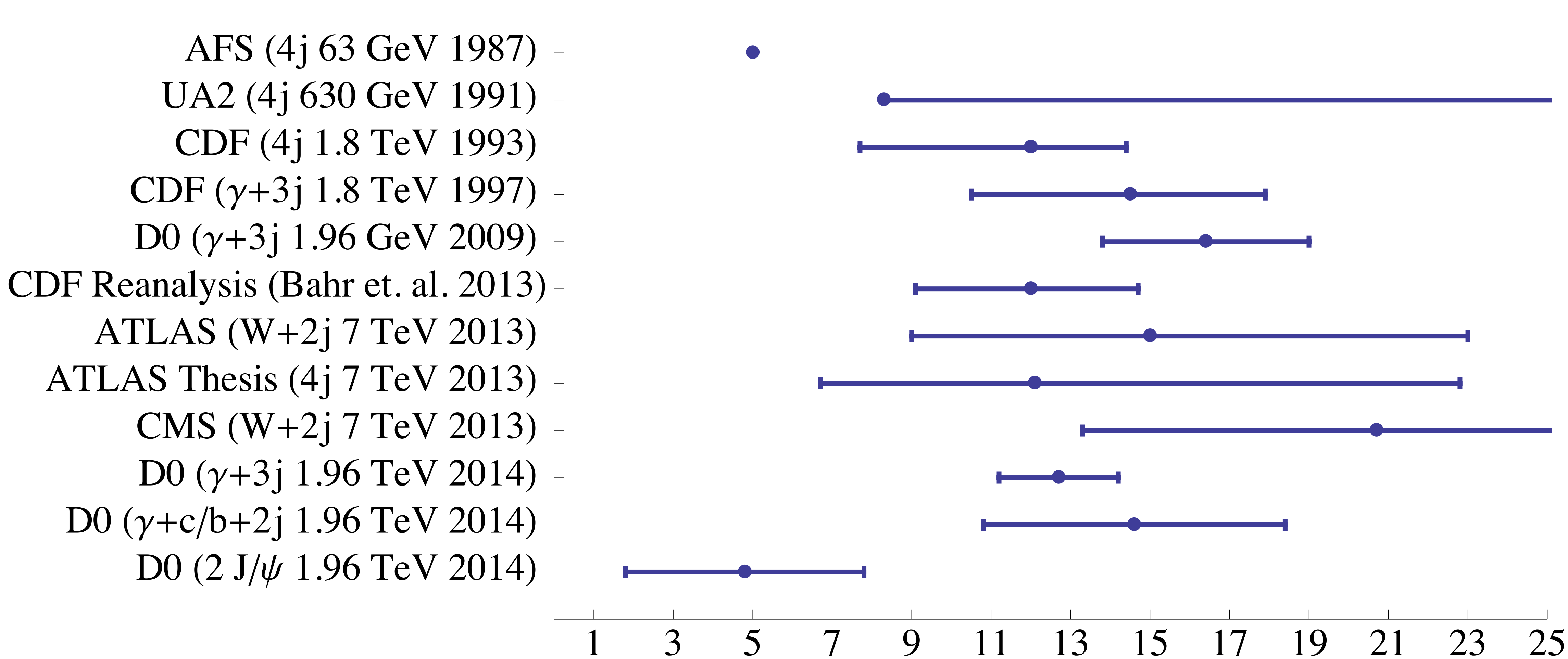
- Extract σ_{eff} from measurements (typically set to 15 mb)
- In this approximation, the DPS cross section is known as soon as we know the single parton cross sections
- Study rates, distributions, variables for DPS extraction etc.

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;
  - Heavy quarks, E.R. Cazaroto, V.P. Goncalves and F.S. Navarra1. 2013;
  - W+2-jets G. Calucci, S. Salvini and D. Treleani, 2013;
  - etc...

Experimental measurements

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



- Neglecting parton correlations, gives $\sigma_{\text{eff}} \sim 40$ 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

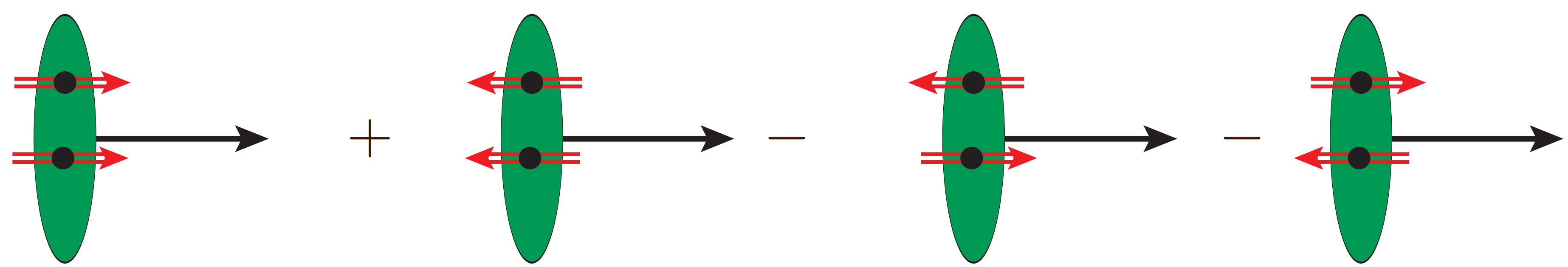
Polarized DPDs

- Spin of the two partons can be correlated $\longrightarrow$ 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 Δq and transversely polarized δq
- Gluons: unpolarized g, longitudinally polarized Δg and linearly polarized δg
- Linear/transverse polarization from helicity interference

Similar description, different physics than TMDs!

Polarized quark DPDs

- The different polarized quark DPDs:

Diehl, Schäfer, Ostermeier, 2011

$$
\begin{aligned}
F_{qq}(x_1,x_2,\boldsymbol{y}) &= f_{qq}(x_1,x_2,\boldsymbol{y})\,, \\
F_{\Delta q\Delta q}(x_1,x_2,\boldsymbol{y}) &= f_{\Delta q\Delta q}(x_1,x_2,\boldsymbol{y})\,, \\
F^{j}_{q\,\delta q}(x_1,x_2,\boldsymbol{y}) &= \epsilon^{jj'}\boldsymbol{y}^{j'} M f_{q\,\delta q}(x_1,x_2,\boldsymbol{y})\,, \\
F^{j}_{\delta q\,q}(x_1,x_2,\boldsymbol{y}) &= \epsilon^{jj'}\boldsymbol{y}^{j'} M f_{\delta q\,q}(x_1,x_2,\boldsymbol{y})\,, \\
F^{jj'}_{\delta q\delta q}(x_1,x_2,\boldsymbol{y}) &= \delta^{jj'} f_{\delta q\delta q}(x_1,x_2,\boldsymbol{y}) \\
&\quad + (2\boldsymbol{y}^{j}\boldsymbol{y}^{j'} - \boldsymbol{y}^2\delta^{jj'})M^2 f^{t}_{\delta q\delta q}(x_1,x_2,\boldsymbol{y})
\end{aligned}
$$

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

Polarized quark DPDs

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unpolarized

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longitudinally polarized

mixed unpolarized/ transversely polarized

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\end{aligned}
$$

unpolarized (f_{qq})

longitudinally polarized ($f_{\Delta q\Delta q}$)

mixed unpolarized/ transversely polarized ($f_{q\,\delta q}$, $f_{\delta q\,q}$)

transversely polarized ($f_{\delta q\delta q}$, $f^{t}_{\delta q\delta q}$)

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

What has been done for polarized DPS?

Polarization in DPS

- Setting up the framework for polarized DPS

  Mekhfi, 1985; Diehl, Schäfer, 2011;
  Diehl, Schäfer, Ostermeier, 2011; Manohar, Waalewijn, 2012;

- Polarization limited by positivity bounds combined with scale evolution

  Diehl, TK, 2013; Diehl, TK, Keane 2014

- DPDs studied in a number of different quark models
  - Correlations typically found to be sizable

  Chang, Manohar, Waalewijn, 2012;
  Rinaldi, Scopetta, Traini, Vento, 2014

- Have been included in cross section calculations of double vector boson production (γ, Z, W) and double $c\bar{c}$

  Manohar, Waalewijn, 2012; Diehl, TK, 2012;
  Echevarria, TK, Mulders, Pisano, 2015

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

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

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

TK, M. Diehl, 2012

for transversely polarize quarks

- Double $q\bar{q}$ production

$$d\sigma_{DPS}(pp \to c_1 \bar{c}_1 c_2 \bar{c}_2) \subset B \cos(2\Delta\phi) f_{\delta g g} f_{g \delta g} + C \cos(4\Delta\phi) f_{\delta g \delta g} f_{\delta g \delta g}$$

for linearly polarized gluons

Echevarria, TK, Mulders, Pisano, 2015

- Linearly polarized gluons also affect the overall rate

Getting quantitative..

- Standard approach

$$F_{ij}(x_1, x_2, \boldsymbol{y}) = f_i(x_1) f_j(x_2) G(\boldsymbol{y})$$

- Build on this, but lets 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

$$f_{ab} + h_{\delta a \delta b} - h^t_{\delta a \delta b} \pm \sqrt{(h_{\delta a b} + h_{a \delta b})^2 + (f_{\Delta a \Delta b} - h_{\delta a \delta b} - h^t_{\delta a \delta b})^2} \geq 0$$

$$f_{ab} - h_{\delta a \delta b} + h^t_{\delta a \delta b} \pm \sqrt{(h_{\delta a b} - h_{a \delta b})^2 + (f_{\Delta a \Delta b} + h_{\delta a \delta b} + h^t_{\delta a \delta b})^2} \geq 0$$

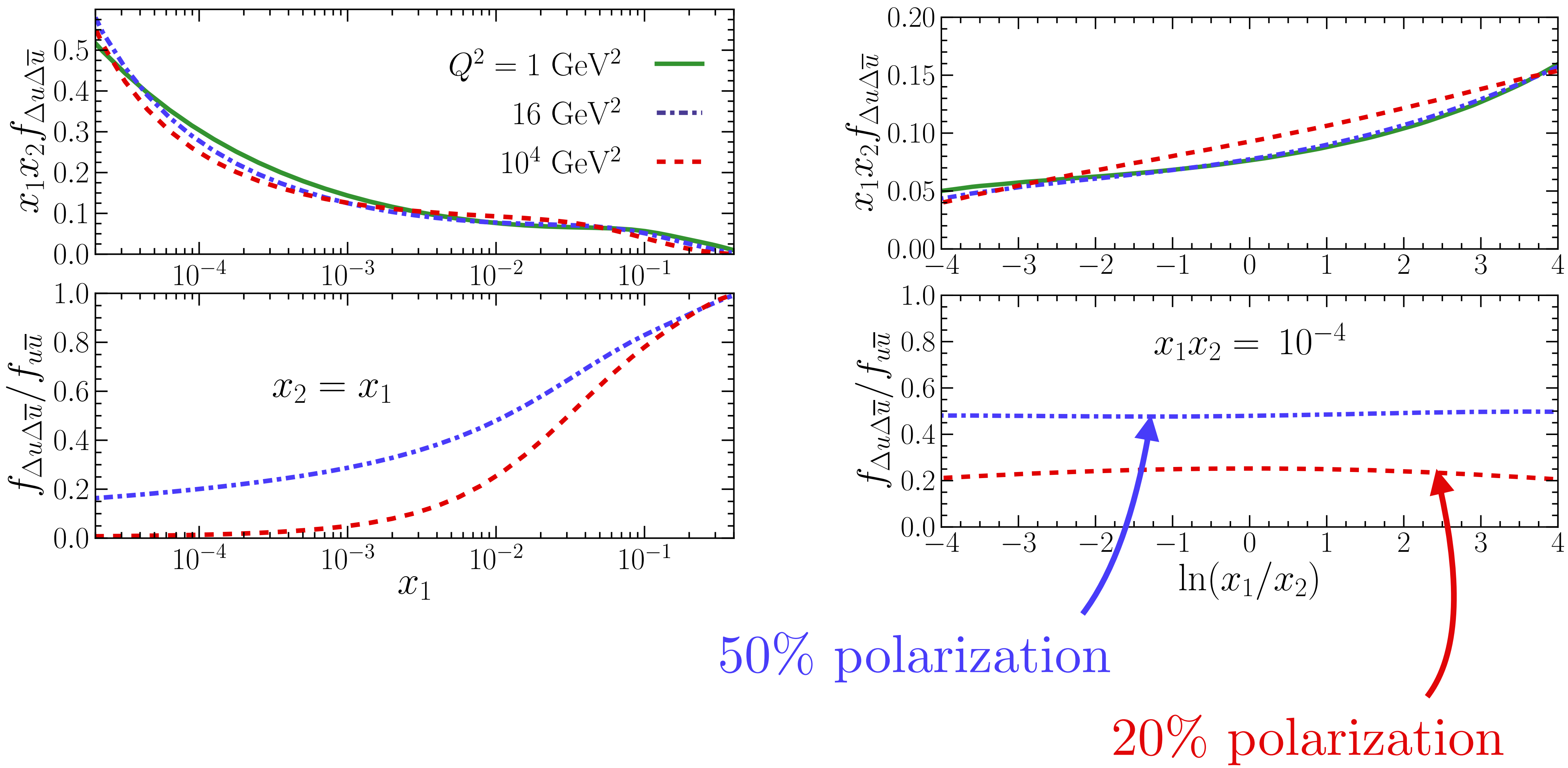
M. Diehl, TK, 2012

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

$\Rightarrow$ Polarized DPDs equal to unpolarized at starting scale

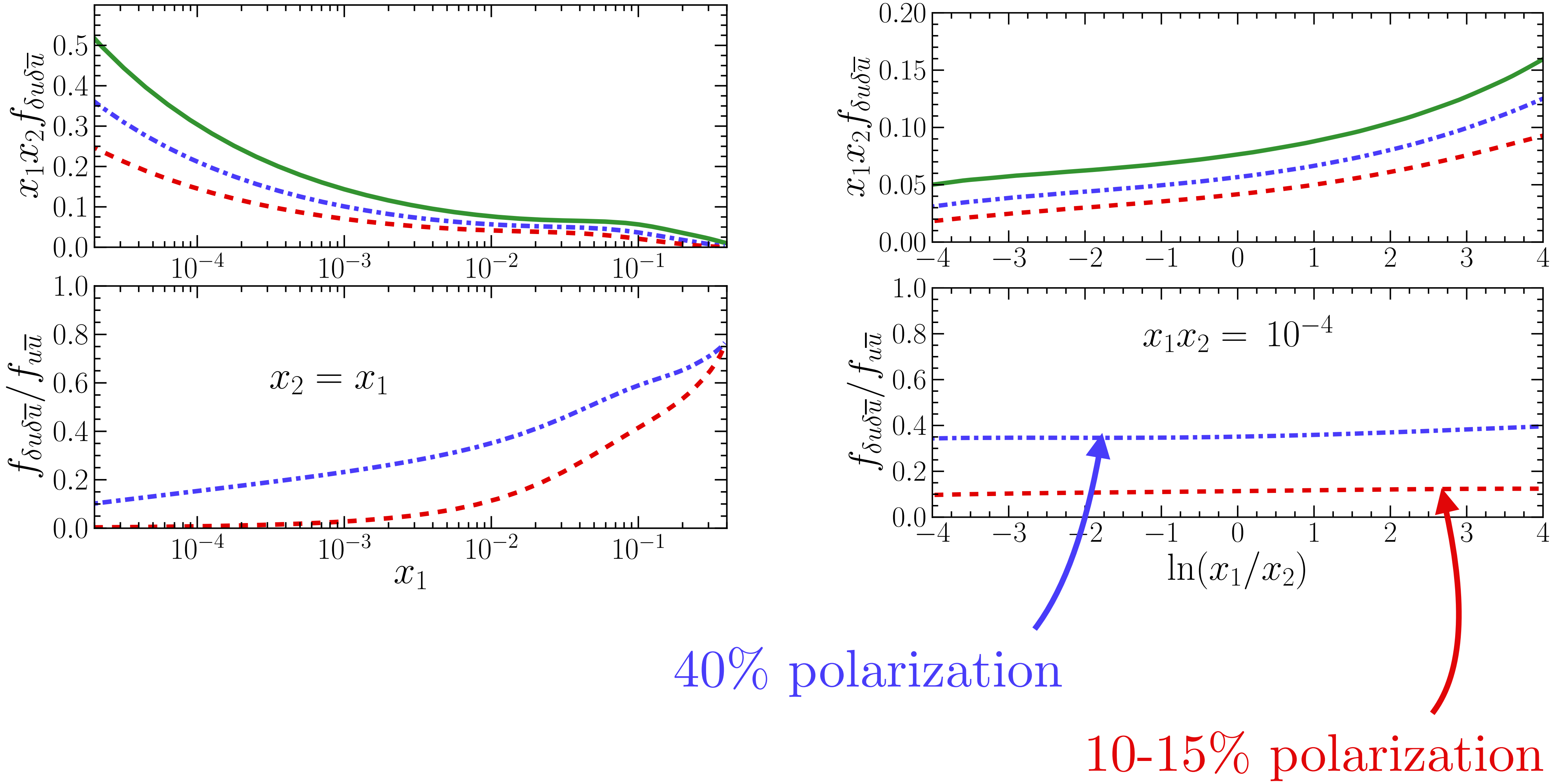
- Evolve with double DGLAP evolution to higher scales

Longitudinal quark polarization



- *Max scenario*: Diehl, TK, Keane 2014
  - 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



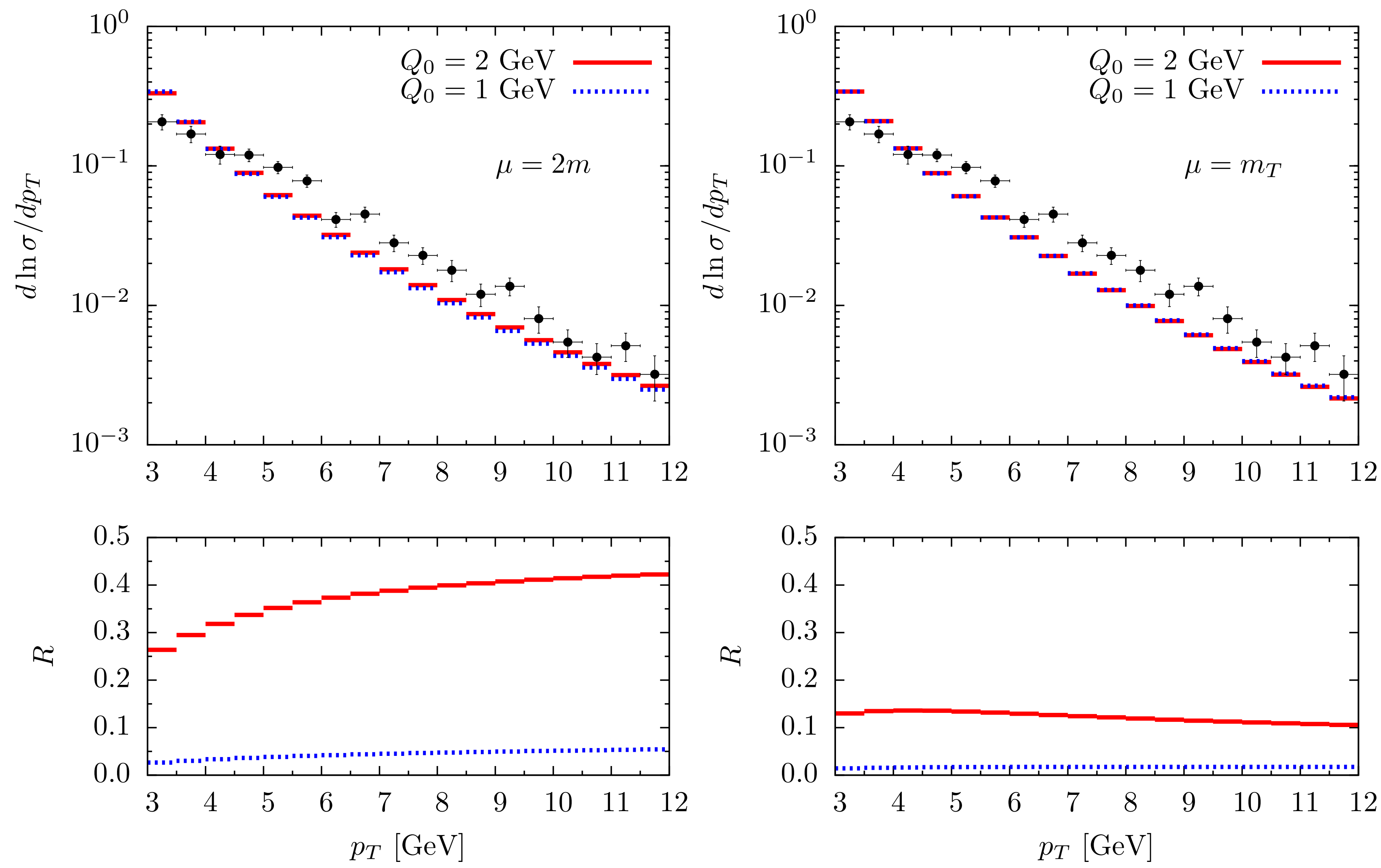
- *Max scenario*:

Diehl, TK, Keane 2014

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

Double open charm at LHCb

- $D^0 D^0$ 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



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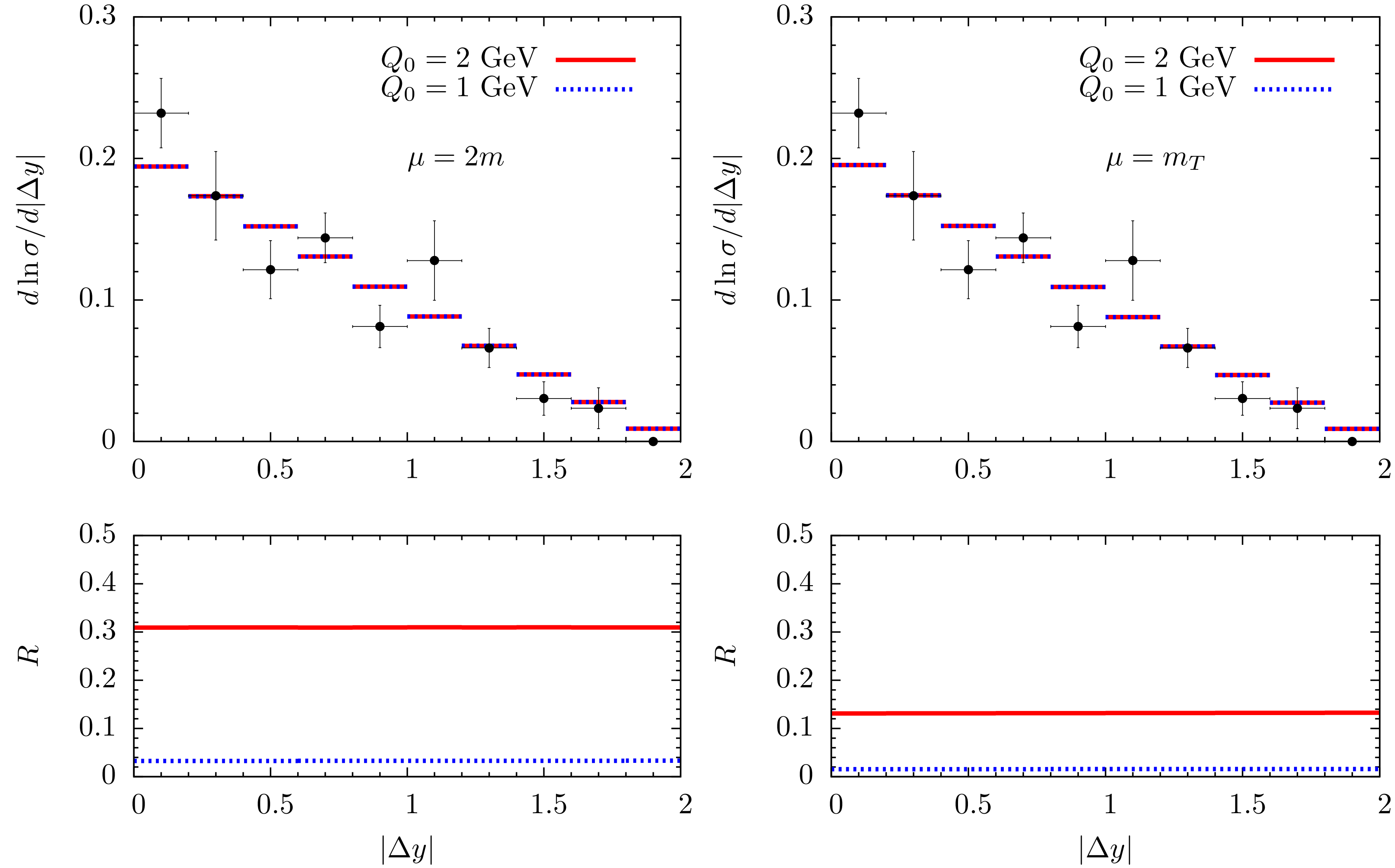
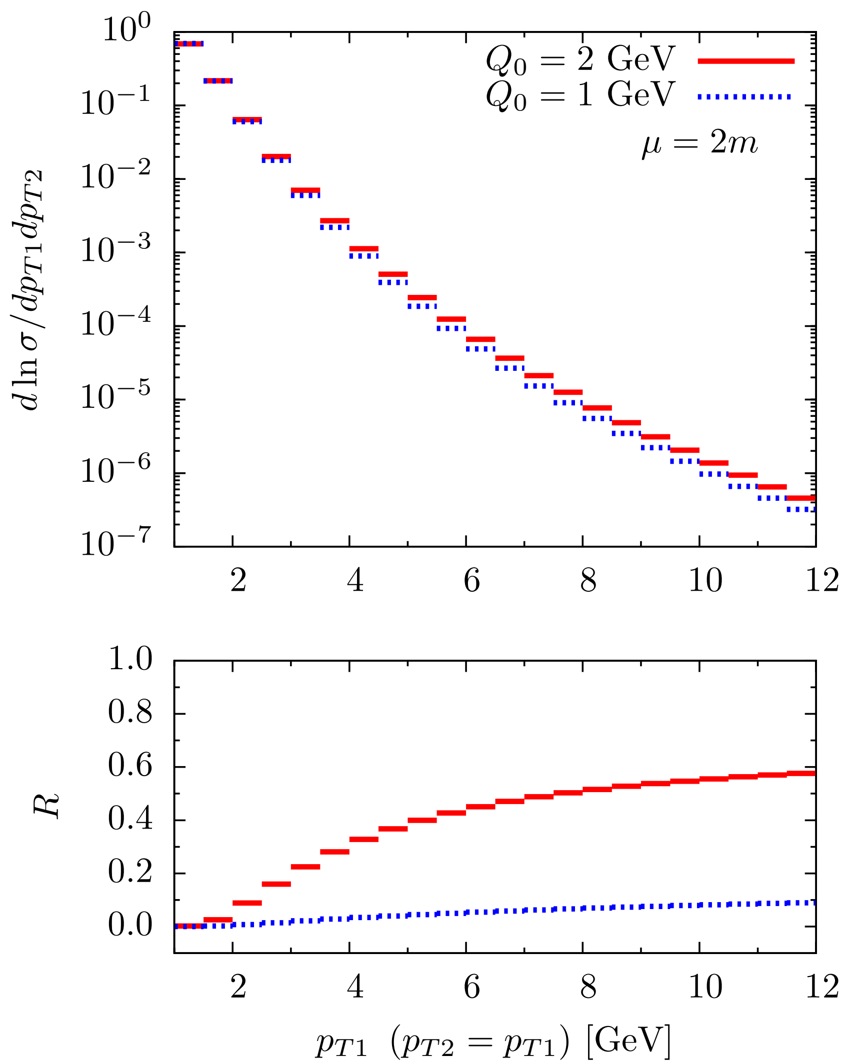


Echevarria, TK, Mulders, Pisano, 2015

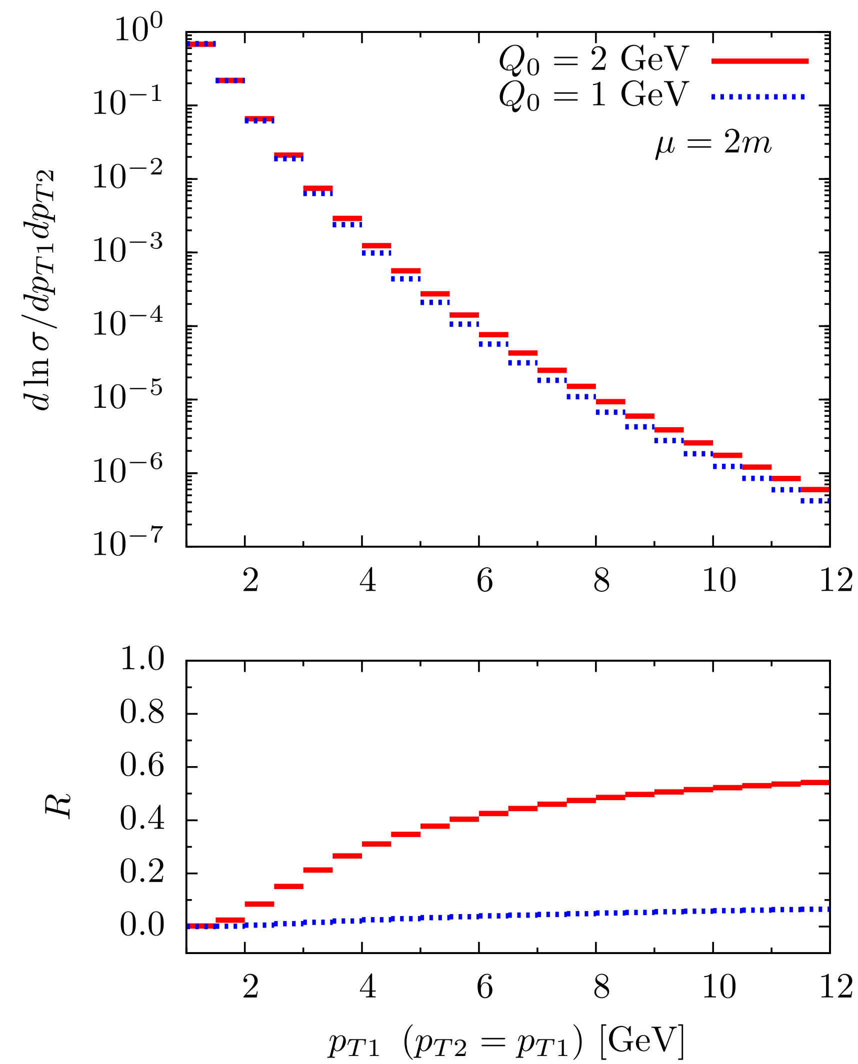
Double open charm at LHCb

- 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

  $\Rightarrow$ 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