Double parton scattering: what (not) to expect

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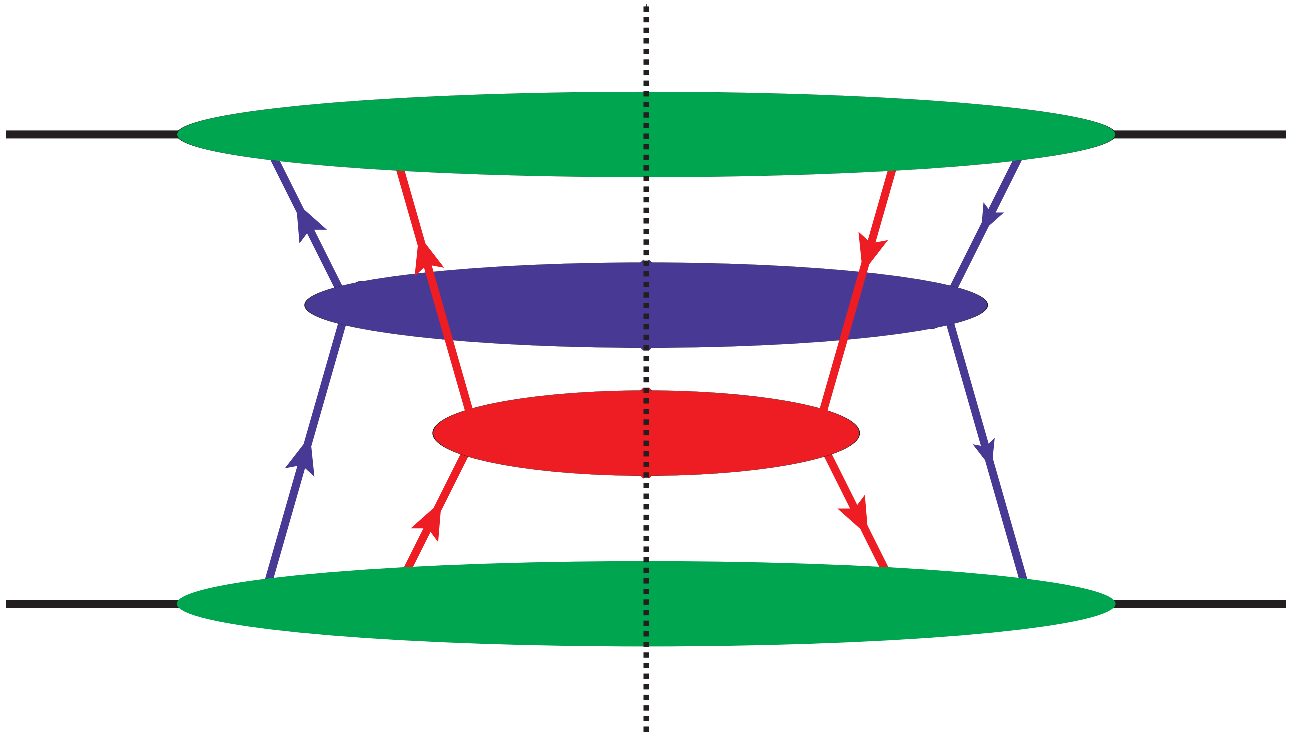
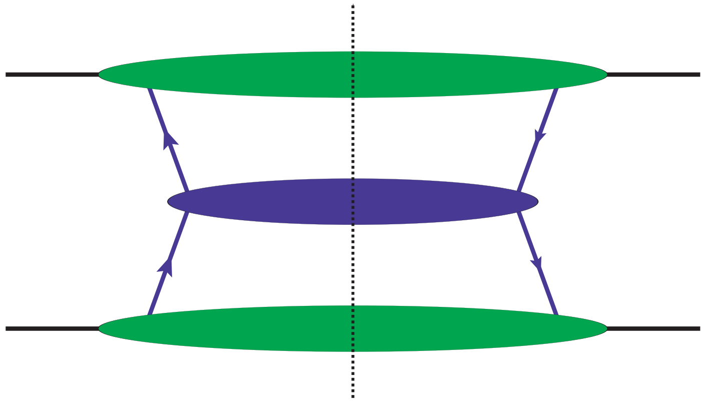
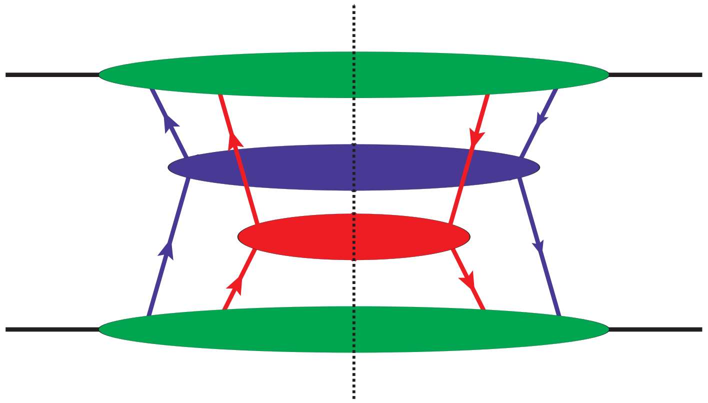


Quarkonia 2016 - Trento, March 1, 2016

What is Double Parton Scattering..



What is Double Parton Scattering..



DPS in hadron-hadron collisions

- Cross section from factorization

  cross section = parton distribution × partonic cross section

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

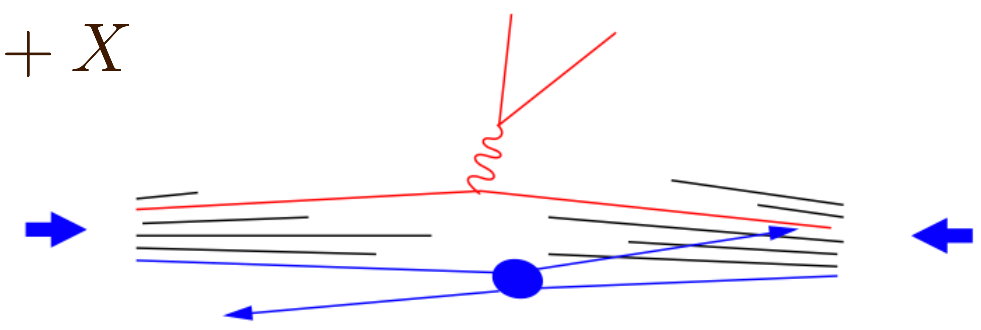


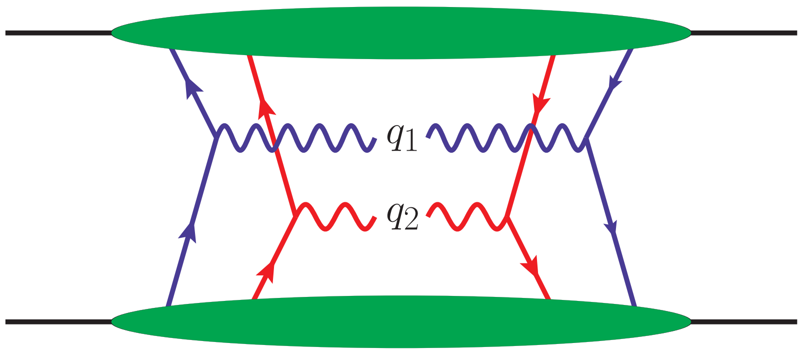
figure from M. Diehl, QCD Evolution 2014

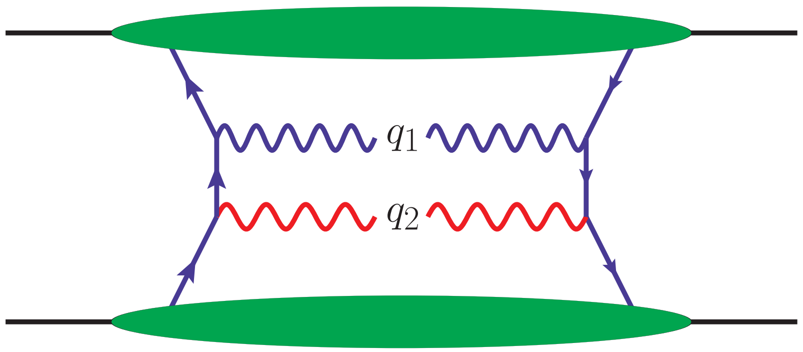
- Spectator-spectator interactions
  - cancel in inclusive cross sections (unitarity)
  - affects final state X
- Ask questions about X ⇨ sensitivity to additional interaction
- Second interaction hard — Double Parton Scattering (DPS)

  example: $pp \to Z + H + X \to l\bar{l} + b\bar{b} + X$
- DPS contributes to signals and to backgrounds in many analyses at the LHC

for DPS in pA and AA collisions, see talk by David d'Enterria

Double vs single hard scattering





- Differential cross section

$$|q_{T1}|,\ |q_{T2}| \sim \Lambda << Q : \qquad \frac{d\sigma_{SPS}}{d^2q_1 d^2q_2} \sim \frac{d\sigma_{DPS}}{d^2q_1 d^2q_2} \sim \frac{1}{Q^4\Lambda^2}$$

- Inclusive cross section

$$\sigma_{DPS} \sim \frac{\Lambda^2}{Q^4} \qquad \sigma_{SPS} \sim \frac{1}{Q^2}$$

- Large parton density ⇨ enhanced DPS

$$\sigma_{DPS} \sim (\text{parton density})^4$$

- DPS cross section from region of small(ish) momentum fractions

Double vs single hard scattering

- Size of DPS cross sections?
  - IF!? no partonic correlations, all partons have the same transverse profile etc. etc.

    $\Rightarrow$ DPS cross section:

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

$$\sigma_{\text{eff}} \sim 15\text{mb}$$

Pocket formula gives order of magnitude estimates of DPS cross section

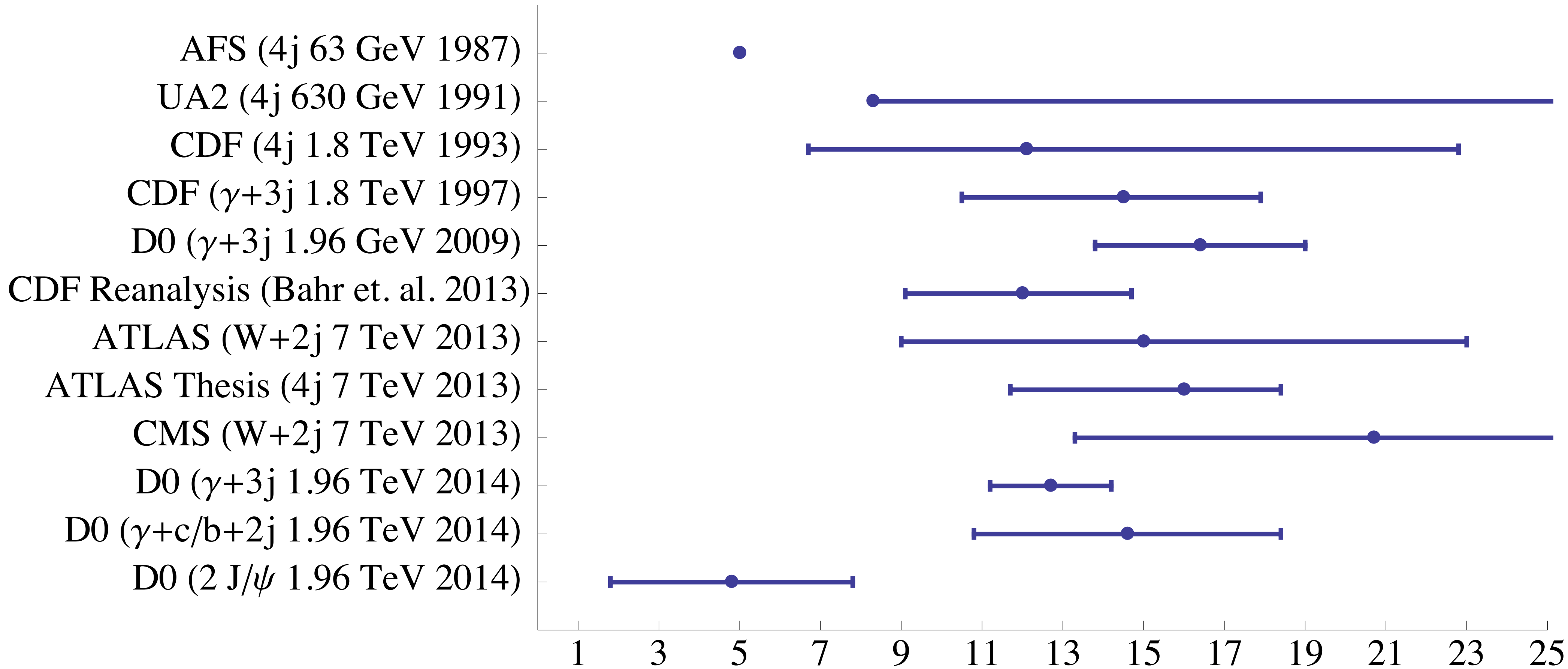
- Where is DPS important?
- What is the uncertainty of this approach? 10%? 100%? 1000%? ...
- Where does it break down?

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
- A few examples:
  - 2x same sign W's (small cross section but very clean) Gaunt, Kom, Kulesza, Stirling, 2010
  - Double open charm production (D0D0) - Double dominates single parton scattering Hameren, Maciula, and Szczurek, 2014
  - Double J/Psi production, Lansberg, Shao, 2015; Kom, Kulesza, Stirling, 2011
  - W+b (rough estimates about 20% DPS) ATLAS Collaboration, 2013
  - double meson productions, W+bbar, 4 jets, photon + 3 jets, etc. etc.

Experimental status

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



- Additional measurements in hadronic final states by LHCb in similar range
- Neglecting parton correlations, gives $\sigma_{\text{eff}} \sim 40$ mb
  - Much larger than experimental measurements of 5-20 mb

    $\Rightarrow$ complete independence between partons disfavored

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

Doubling...

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Doubling...

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Doubling...

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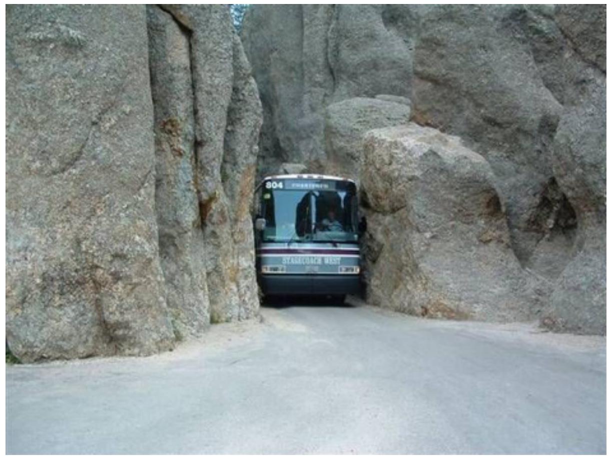

Doubling...

$\neq$

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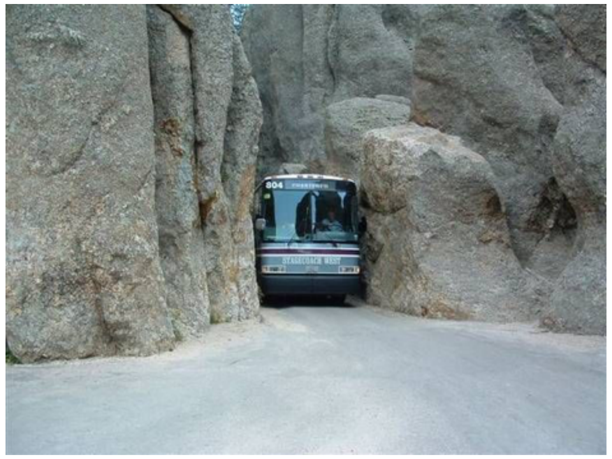
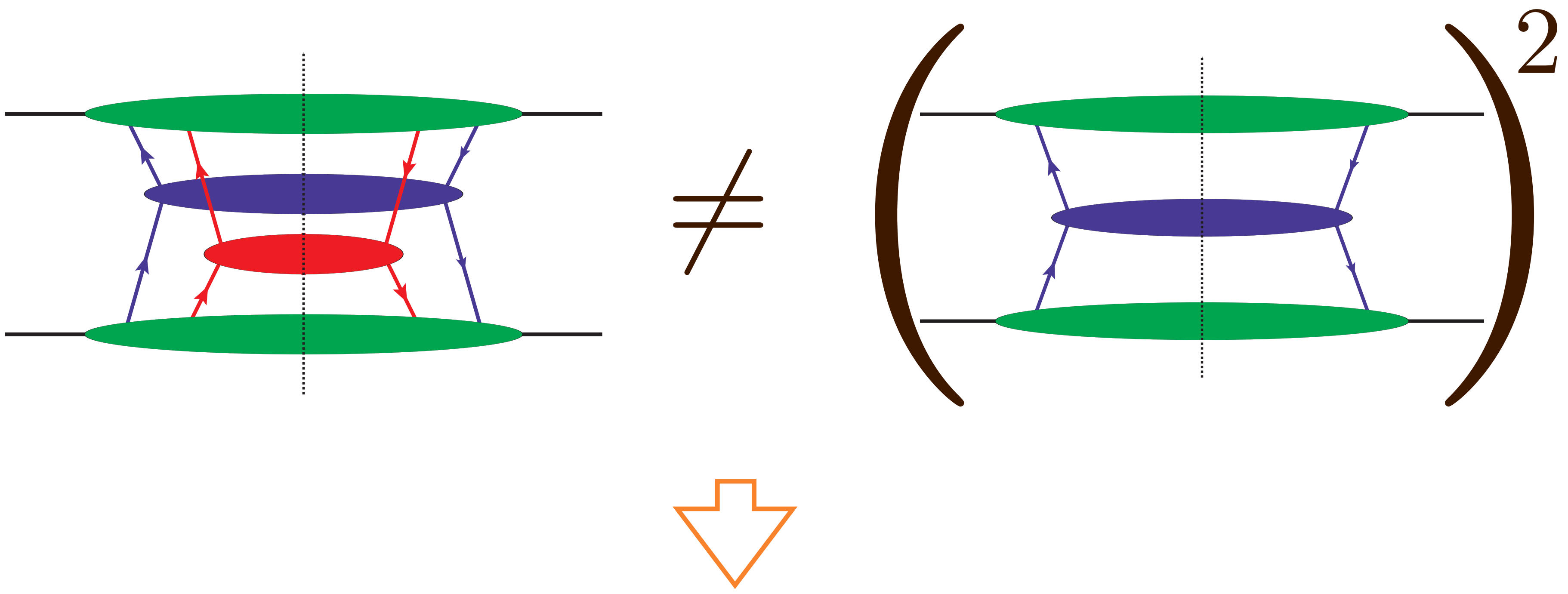


... leads to new (unexpected) challenges

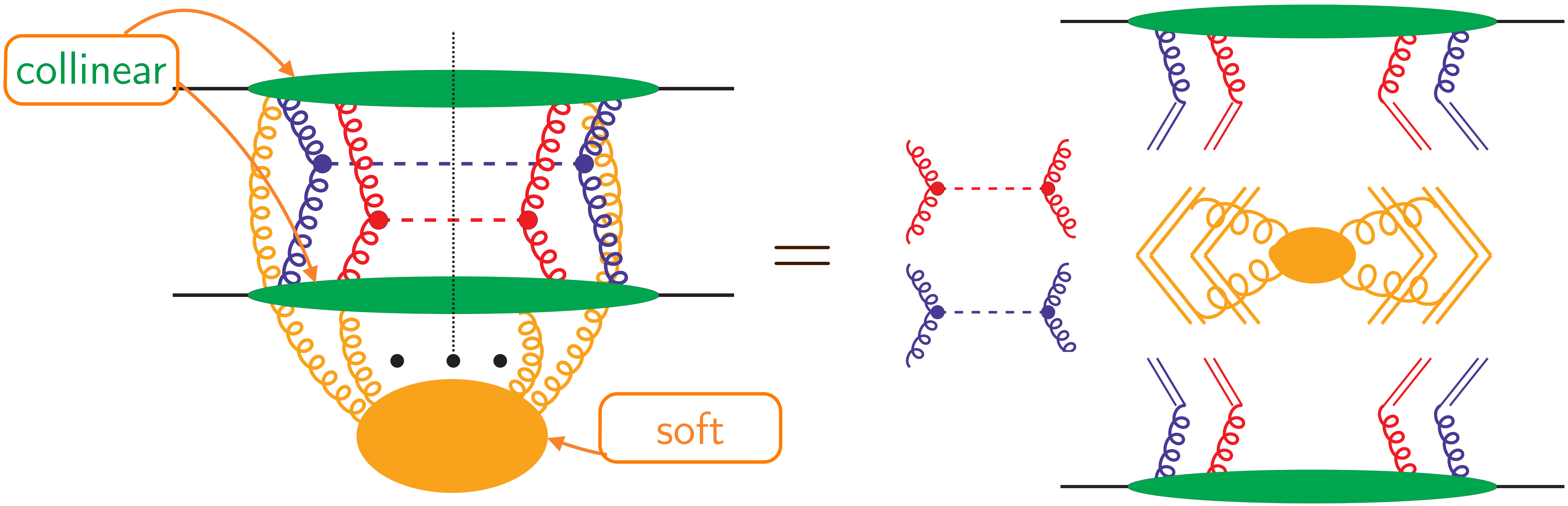


but what is important?

theory + experiment

Double parton scattering - factorization

- Factorization theorem (largely) proven for color singlet final states

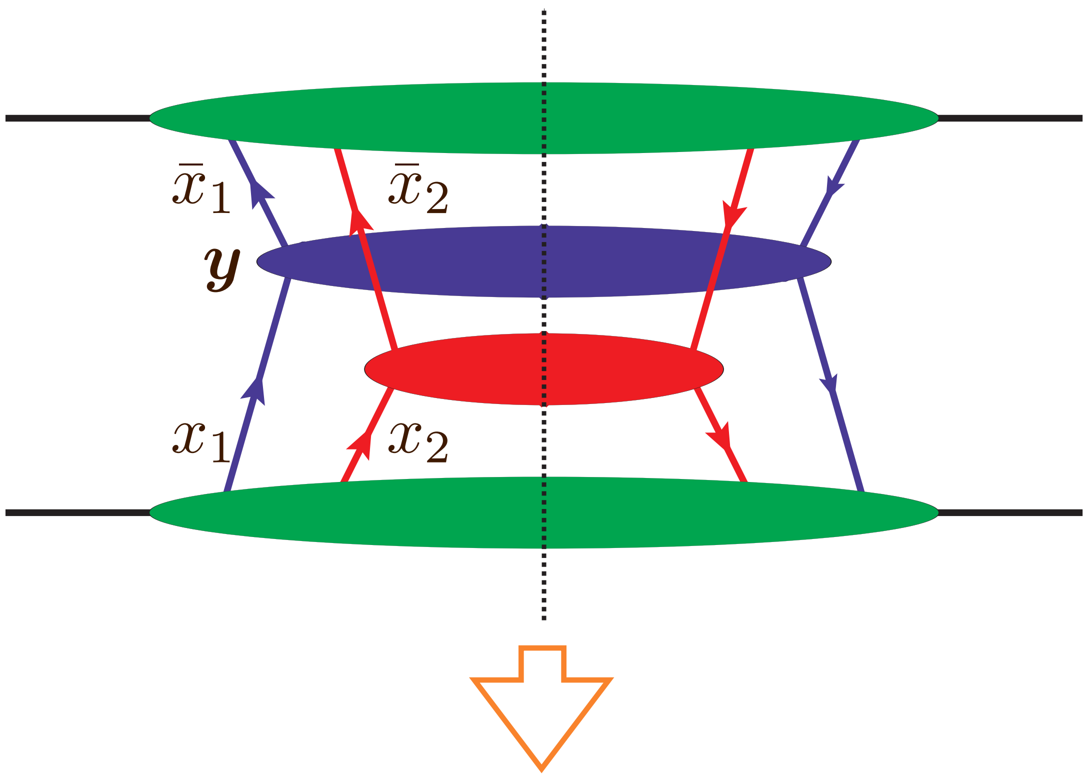


- Glauber gluons cancel in color singlet final state
- Leading regions:
  - Hard, $n-$collinear, $\bar{n}-$collinear and soft regions
- Factorize into Hard part, Soft and Collinear matrix elements

Diehl, Gaunt, Ostermeier, Plößl, Schäfer, 2015;
Manohar and Waalewijn, 2012;
Diehl, Ostermeier, Schäfer, 2011

DPS cross section

- Example: DPS cross-section



- QCD requires inclusion of the transverse separation between hard scatterings

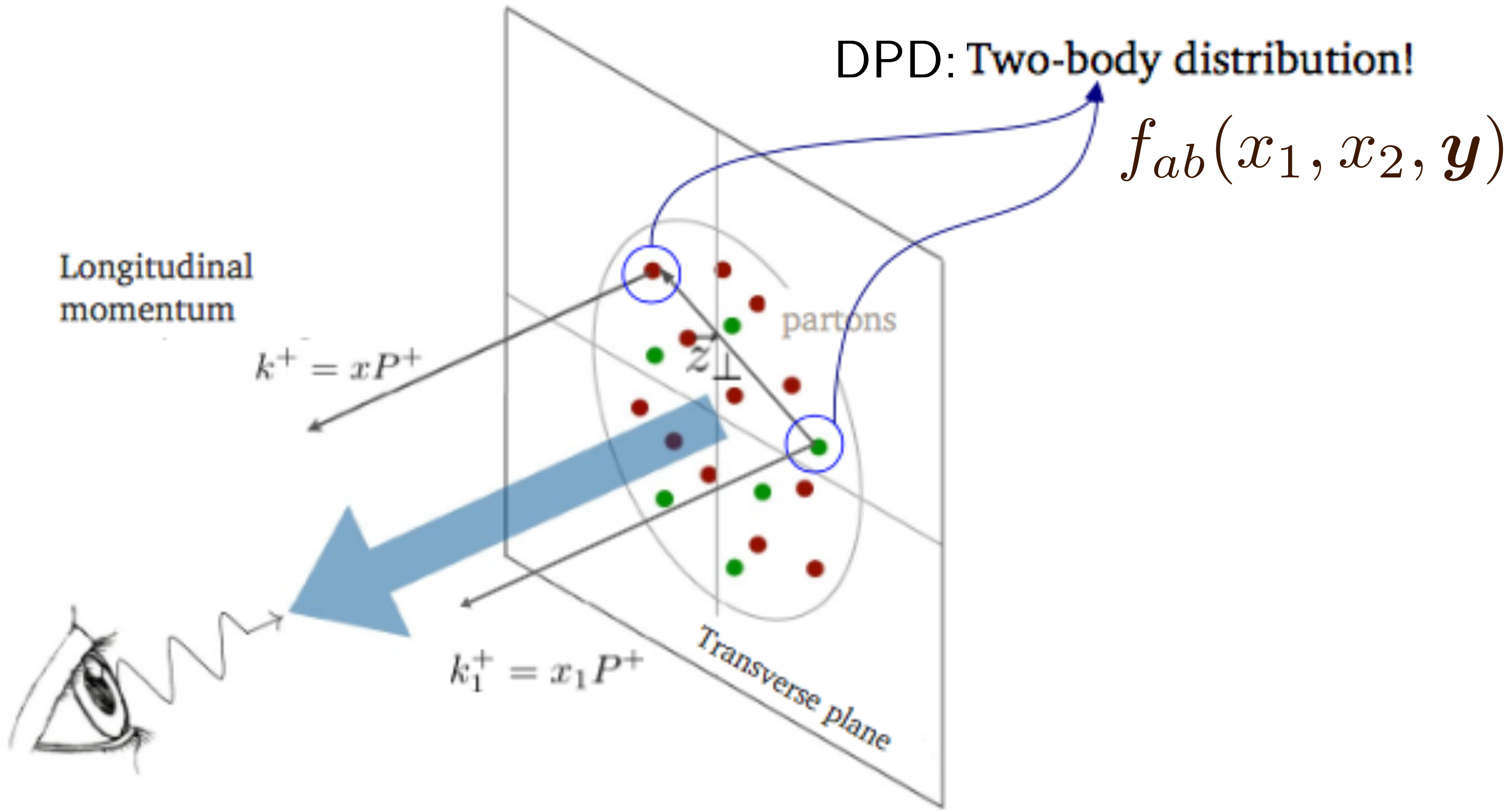
Paver, Treleani, 1982; Mekhfi, 1985;
Diehl, Ostermeier, Schäfer, 2011

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

- + New phenomena!?!

Double Parton Distributions (DPDs)

Double parton distributions

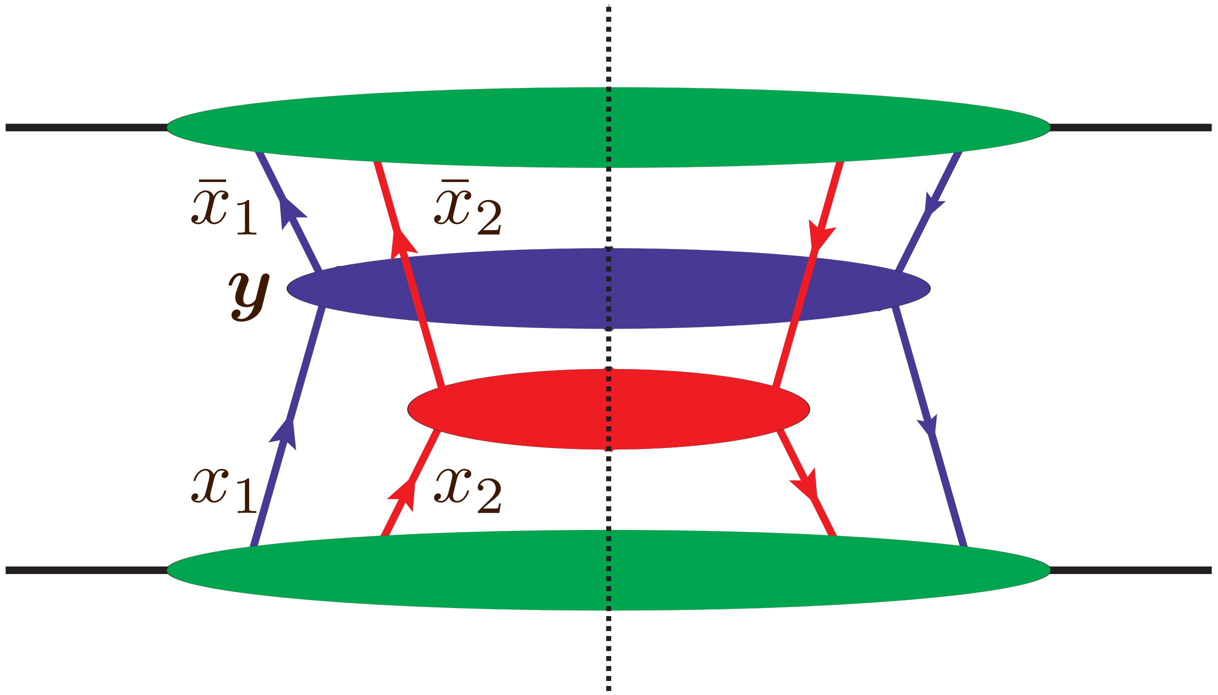


New way to access information on the non-perturbative structure of the PROTON!

from Matteo Rinaldi, MPI@LHC 2015

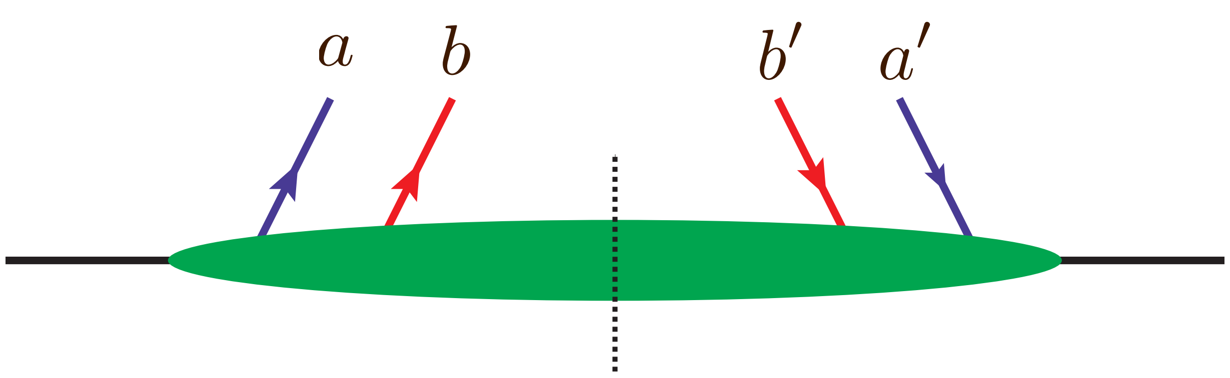
Double parton scattering

- DPS cross section:



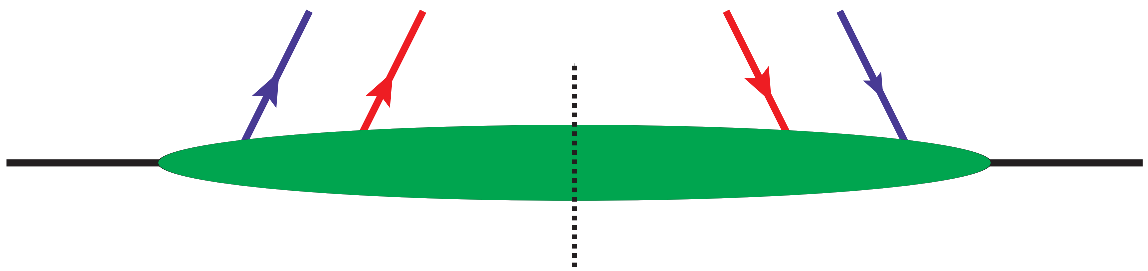
$$\frac{d\sigma_{DPS}}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} = \frac{1}{C}\hat{\sigma}_1\hat{\sigma}_2 \int d^2\boldsymbol{y} F(x_1, x_2, \boldsymbol{y}) F(\bar{x}_1, \bar{x}_2, \boldsymbol{y})$$

- Correlations encoded in the double parton correlator



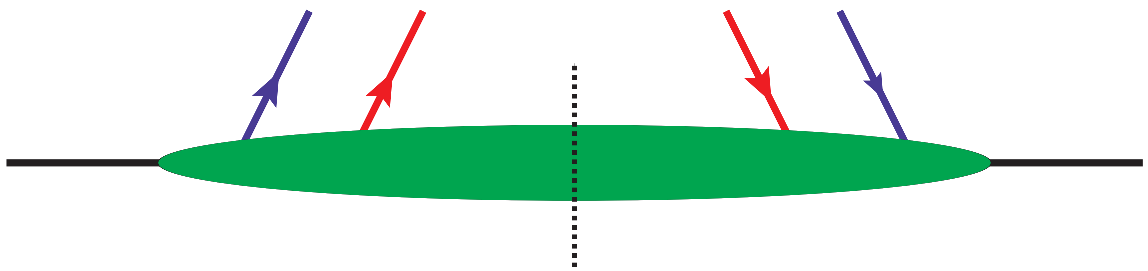
$$(a+b) = (a'+b') \not\Leftrightarrow \begin{cases} a = a' \\ b = b' \end{cases}$$

Correlations in DPS



- Color
- Fermion number interference
- Spin (polarization)
  - longitudinal
  - transverse/linear
- Flavor interference
- Between $\boldsymbol{y}$ and x's
- Parton type and $\boldsymbol{y}$
- Between x's

Correlations in DPS



- Color
- Fermion number interference
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  - longitudinal
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- Between $\boldsymbol{y}$ and x's
- Parton type and $\boldsymbol{y}$
- Between x's

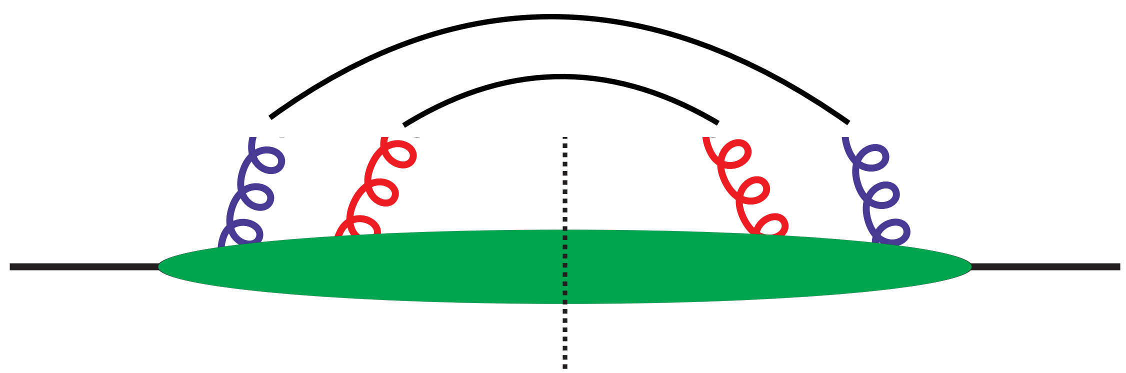
- DPS cross section:

Depend on x_1, x_2, $\boldsymbol{y}$, spin, flavor, color and scale

$$\frac{d\sigma}{dx_1\, dx_2\, dx_3\, dx_4} = \frac{1}{C} \sum_{p_1,p_2,p_3,p_4} \hat{\sigma}_{p_1 p_3}(x_1, x_3)\, \hat{\sigma}_{p_2 p_4}(x_2, x_4)$$
$$\times \int d^2\boldsymbol{y}\, F_{p_1 p_2}(x_1, x_2, \boldsymbol{y})\, F_{p_3 p_4}(x_3, x_4, \boldsymbol{y})$$
$$+ \ \{\text{color, flavour and fermion number interference terms}\}$$

Color structure

- Color structure for double gluon distribution:



- Coupling the gluons with their partners in the conjugate amplitude into:

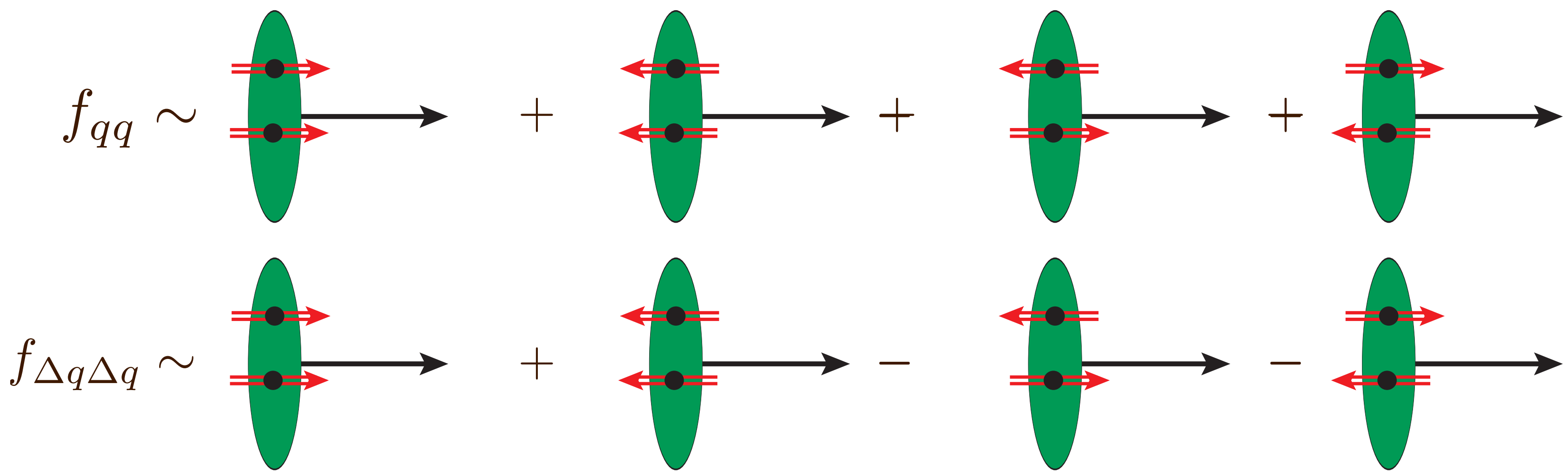
$$8 \otimes 8 = 1 \oplus 8^A \oplus 8^S \oplus 10 \oplus \bar{10} \oplus 27$$

- Results in 5 independent double gluon distributions with different color structures - which all do contribute to the cross sections

$${}^{1}F_{gg},\ {}^{8^S}F_{gg},\ {}^{8^A}F_{gg},\ {}^{10+\bar{10}}F_{gg},\ {}^{27}F_{gg}$$

Diehl, Schäfer, Ostermeier, 2011;
TK, Mulders, 2014;

Polarization



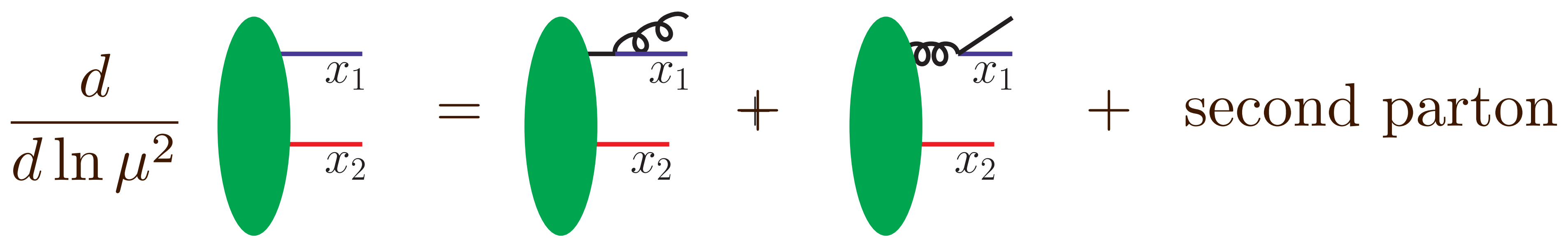
- Two partons in an unpolarized proton can each be unpolarized, longitudinally polarized and linearly/transversely polarized,
  - Correlations between spin, transverse momenta and separation of the two partons

    Mekhfi, 1985; Diehl, Schäfer, 2011; Diehl, Ostermeier, Schäfer, 2011
  - Several polarized DPDs which contribute to DPS cross sections
  - Large in model calculations

    Rinaldi, Scopetta, Traini, Vento, 2014; Chang, Manohar, Waalewijn, 2011
- Changes total cross sections, distributions of final state particles and cause azimuthal asymmetries/spin asymmetries

Manohar, Waalewijn, 2011; Diehl, TK, 2012; Echevarria, TK, Mulders, Pisano 2015

Evolution of DPDs



- DGLAP splitting kernels (for color singlet unpolarized DPDs)
- Separate branchings - expect evolution to wash out correlations
- Evolution + positivity bounds -upper limits on correlations

Diehl, TK, 2013; TK, Mulders, 2014

- At larger scales color correlations suppressed

Manohar, Waalewijn, 2011

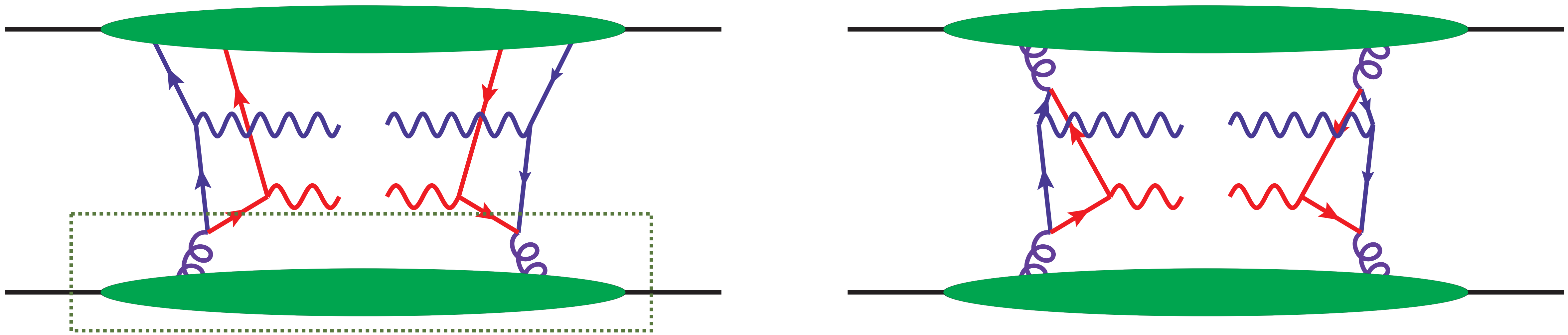
- At medium to large scales and small momentum fractions - gluon polarization suppressed

  Diehl, TK, 2014

  - Because of rapid increase of unpolarized distribution

Double or single?

- Double or single — and solving the problem with integration



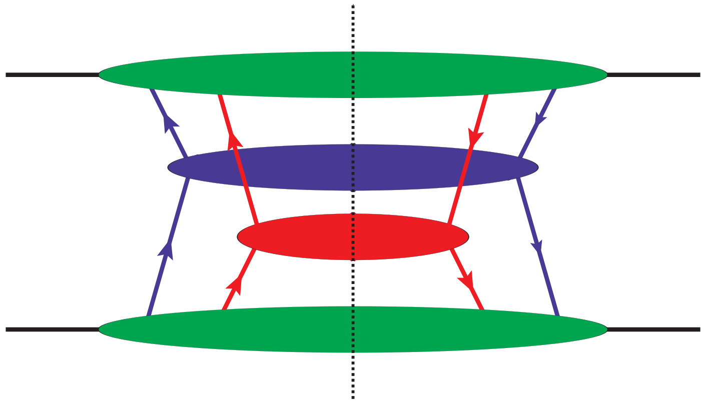
- Small y — perturbative scale $\quad f_{ab}(x_1, x_2, \boldsymbol{y}) \sim \frac{1}{\boldsymbol{y}^2} [T_{c \to ab} \otimes f_c(x_1 + x_2)]$
- Naive 1v1 cross section:

$$\Longrightarrow \sigma \propto \int d^2\boldsymbol{y} \left(\frac{1}{\boldsymbol{y}^2}\right)^2 \to \text{UV divergent!}$$

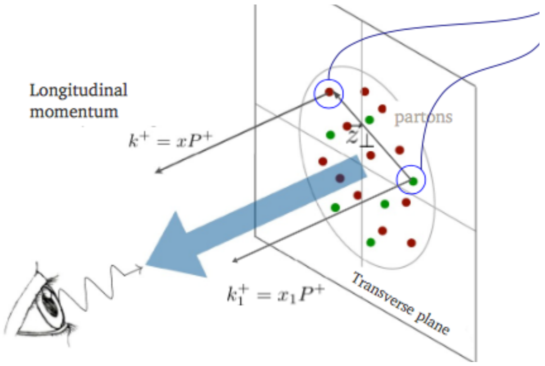
- Solution: DPD includes splitting, regulate small y limit of cross section and subtract to avoid double counting $\qquad$ Diehl, Gaunt, MPI@LHC 2015

$$\sigma = \sigma_{DPS} - \sigma_{sub} + \sigma_{SPS}$$

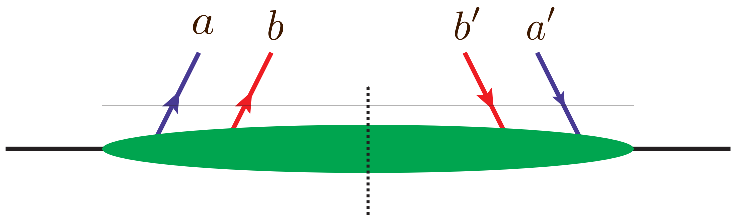
DPS Summary



- Increasingly relevant;
  - high energy of the LHC
  - large luminosity/search for rare events.



- Large contribution to many analyses at LHC
- Factorization (largely) established
- New way to look inside the proton!
- New phenomena:
  - color connections: can be large in small/medium scale processes
  - spin correlations: can be large for quark induced processes or for gluons at small/medium scales
  - kinematic correlations: can be large but might be small at small momentum fractions



- Many questions to be answered;
  LHC is moving into range of measuring more than the effective cross section
- What to expect? Expect news and expect some surprises