Double parton scattering
What is that? Why bother? What do we know?

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Hadron-hadron collisions

- standard description based on factorization formulae

\[
\text{cross sect} = \text{parton distributions} \times \text{parton-level cross sect}
\]

example: \(Z\) production

\[
pp \rightarrow Z + X \rightarrow \ell^+ \ell^- + X
\]

- most common: integrate over net transv. momentum \(q_T\) of particles produced in parton-level scattering (vector boson for Drell-Yan)

\(\leadsto k_T\) integrated (collinear) parton distributions

- for selected proc’s (Drell-Yan, Higgs prod’n) also have theory description with measured \(q_T\)

\(\leadsto k_T\) dependent (unintegrated) parton distributions (TMDs)
Hadron-hadron collisions

- standard description based on factorization formulae

\[ \text{cross sect} = \text{parton distributions} \times \text{parton-level cross sect} \]

example: \( Z \) production

\[ pp \rightarrow Z + X \rightarrow \ell^+\ell^- + X \]

- factorization formulae are for inclusive cross sections \( pp \rightarrow Y + X \)
  where \( Y = \) produced in parton-level scattering, specified in detail
  \( X = \) summed over, no details
Hadron-hadron collisions

- standard description based on factorization formulae

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\text{cross sect} = \text{parton distributions} \times \text{parton-level cross sect}
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example: \( Z \) production

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pp \rightarrow Z + X \rightarrow \ell^+ \ell^- + X
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- factorization formulae are for inclusive cross sections \( pp \rightarrow Y + X \)

where \( Y \) = produced in parton-level scattering, specified in detail

\( X \) = summed over, no details

- also have interactions between “spectator” partons

their effects cancel in inclusive cross sections \text{thanks to unitarity} but they affect the final state \text{(namely} \( X \))
Multiparton interactions (MPI)

- secondary (and tertiary etc.) interactions generically take place in hadron-hadron collisions
- predominantly low-$p_T$ scattering
  - $\rightsquigarrow$ underlying event (UE)
- at high collision energy (esp. at LHC) can be hard
  - $\rightsquigarrow$ multiple hard scattering
- many studies:
  - theory: phenomenology, theoretical foundations (1980s, recent activity)
  - experiment: ISR, SPS, HERA (photoproduction), Tevatron, LHC
  - Monte Carlo generators: Pythia, Herwig++, Sherpa, ...
- and ongoing activity: see e.g. the MPI@LHC workshop series
  - [http://indico.cern.ch/event/305160](http://indico.cern.ch/event/305160)
Relevance for LHC

example: \( pp \rightarrow H + Z \rightarrow b\bar{b} + Z \)

- multiple interactions contribute to signal and background

same for \( pp \rightarrow H + W \rightarrow b\bar{b} + W \)

study for Tevatron: Bandurin et al, 2010
Multiparton interactions

- phenomenology based on simple, physically intuitive formula

\[
\text{cross sect} = \text{multiparton distributions} \times \text{parton-level cross sect's}
\]

and ansatz

\[
\text{multiparton distribution} = \text{factor} \times \prod \text{single-parton distributions}
\]

Paver, Treleani 1982, 1984; Mekhfi 1985, ...

also underlies implementation in many event generators

- questions:
  - to which extent can these formulae be derived in QCD?
  - where and how do they need to be modified?
  - can factorization theorems for multiparton interactions be formulated and proven?

- no definitive answers to all points, but some results and identified problems

- ultimate goal: improved theory as a guide for phenomenology
Space-time structure

- Large (plus or minus) momenta of partons $x_i p$, $\bar{x}_i \bar{p}$ fixed by final state exactly as for single hard scattering
- Transverse parton momenta not the same in amplitude $A$ and in $A^*$
  cross section $\propto \int d^2 r \, F(x_i, k_i, r) F(\bar{x}_i, \bar{k}_i, -r)$
- Fourier trf. to impact parameter: $F(x_i, k_i, r) \to F(x_i, k_i, y)$
  cross section $\propto \int d^2 y \, F(x_i, k_i, y) F(\bar{x}_i, \bar{k}_i, y)$
- Interpretation: $y = \text{transv. dist. between two scattering partons}$
  $\quad = \text{equal in both colliding protons}$
Cross section formula

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

- \( C \) = combinatorial factor
- \( \hat{\sigma}_i \) = parton-level cross sections
- \( F(x_1, x_2, y) \) = double parton distribution (DPD)
- \( y \) = transv. distance between partons

- follows from Feynman graphs and hard-scattering approximation
  no semi-classical approximation required
- can make \( \hat{\sigma}_i \) differential in further variables (e.g. for jet pairs)
- can extend \( \hat{\sigma}_i \) to higher orders in \( \alpha_s \)
  get usual convolution integrals over \( x_i \) in \( \hat{\sigma}_i \) and \( F \)

Paver, Treleani 1982, 1984; Mekhfi 1985, . . ., MD, Ostermeier, Schäfer 2012
Cross section formula

- for measured transv. momenta

\[
\frac{d\sigma_{\text{double}}}{dx_1 \, d\bar{x}_1 \, d^2 q_1 \, dx_2 \, d\bar{x}_2 \, d^2 q_2} = \frac{1}{C} \hat{\sigma}_1 \hat{\sigma}_2 \\
\times \left[ \prod_{i=1}^{2} \int d^2 k_i \, d^2 \bar{k}_i \, \delta(q_i - k_i - \bar{k}_i) \right] \int d^2 y \, F(x_i, k_i, y) \, F(\bar{x}_i, \bar{k}_i, y)
\]

- \( F(x_i, k_i, y) = k_T \) dependent two-parton distribution

- has structure of a Wigner function:
  - \( k_1, k_2 = \) transv. parton momenta averaged over \( A \) and \( A^* \)
  - \( y = \) transv. distance between partons averaged over \( A \) and \( A^* \)
Cross section formula

- for measured transv. momenta

\[
\frac{d\sigma_{\text{double}}}{dx_1 d\bar{x}_1 d^2q_1 dx_2 d\bar{x}_2 d^2q_2} = \frac{1}{C} \hat{\sigma}_1 \hat{\sigma}_2 \\
\times \left[ \prod_{i=1}^{2} \int d^2k_i d^2\bar{k}_i \delta(q_i - k_i - \bar{k}_i) \right] \int d^2y F(x_i, k_i, y) F(\bar{x}_i, \bar{k}_i, y)
\]

- \(F(x_i, k_i, y) = k_T\) dependent two-parton distribution

- operator definition as for TMDs

schematically:

\[
F(x_i, k_i, y) = \mathcal{FT}_{z_i \rightarrow (x_i, k_i)} \langle p| \bar{q} \left( -\frac{1}{2}z_2 \right) \Gamma_2 q \left( \frac{1}{2}z_2 \right) \bar{q} \left( y - \frac{1}{2}z_1 \right) \Gamma_1 q \left( y + \frac{1}{2}z_1 \right) |p\rangle
\]

- essential for studying factorization, scale dependence, etc.

- similar def for collinear distributions \(F(x_i, y)\)

renormalized bilinear op’s \(\bar{q} \Gamma_i q\) at different transv. positions

⇒ not a twist-four operator but product of two twist-two operators
Power behavior: single versus double hard scattering

- from scattering formulae readily find

\[ s \frac{d\sigma}{dx_1 \, d\bar{x}_1 \, d^2q_1 \, dx_2 \, d\bar{x}_2 \, d^2q_2} \sim \frac{1}{Q^2 \Lambda^2} \]

\[ Q^2 \sim q_i^2, \, \Lambda^2 \sim \text{GeV} \]

for both

\[ \Rightarrow \text{double scattering not power suppressed} \]
Power behavior: single versus double hard scattering

- from scattering formulae readily find

\[
    s \frac{d\sigma}{dx_1 d\bar{x}_1 d^2 q_1 dx_2 d\bar{x}_2 d^2 q_2} \sim \frac{1}{Q^2 \Lambda^2}
\]

\(Q^2 \sim q_i^2, \Lambda^2 \sim \text{GeV}\)

- double scattering not power suppressed

- but if integrate over \(q_1\) and \(q_2\) then

  single: \(s \frac{d\sigma}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} \sim 1\) since \(\int d^2(q_1 + q_2) \sim \Lambda^2\)

  and \(\int d^2(q_1 - q_2) \sim Q^2\)

  double: \(s \frac{d\sigma}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2} \sim \frac{\Lambda^2}{Q^2}\) since \(\int d^2q_1 \int d^2q_2 \sim \Lambda^4\)

  i.e. single hard scattering has larger phase space for transv. momenta
Power behavior: single versus double hard scattering

- from scattering formulae readily find

\[
s \frac{d\sigma}{dx_1 d\bar{x}_1 d^2q_1 dx_2 d\bar{x}_2 d^2q_2} \sim \frac{1}{Q^2 \Lambda^2}
\]

\[Q^2 \sim q_i^2, \, \Lambda^2 \sim \text{GeV}\]

for both

\[s d\sigma \]  \[dx_1 d\bar{x}_1 dx_2 d\bar{x}_2 d^2q_1 \]

and

\[d\sigma \]  \[dx_1 d\bar{x}_1 d^2q_1 \]

⇒ double scattering not power suppressed

- if integrate only over \(q_1 + q_2\) then no power suppression yet

\[
s \frac{d\sigma}{dx_1 d\bar{x}_1 dx_2 d\bar{x}_2 d^2(q_1 - q_2)} \sim \frac{1}{Q^2}
\]
Energy dependence

\[
\frac{sd\sigma}{\prod_{i=1}^{2} dx_i d\bar{x}_i d^2q_i} \quad \frac{sd\sigma}{\prod_{i=1}^{2} dx_i d\bar{x}_i}
\]

- interference between single and double scattering:
  - leading power when differential in \( q_i \)
  - power suppressed when \( \int d^2q_i \), twist-three parton distributions

- at small \( x_1 \sim x_2 \sim x \) expect
  - single scattering \( \propto x^{-4-2\lambda} \) with \( xf(x) \sim x^{-\lambda} \)
  - double scattering \( \propto x^{-4-4\lambda} \)
  - interference? how do three-particle correlators behave for small \( x \)?
Pocket formula

- if two-parton density factorizes as
  \[ F(x_1, x_2, y) = f(x_1) f(x_2) G(y) \]
  where \( f(x_i) \) = usual PDF

- if assume same \( G(y) \) for all parton types
  then cross sect. formula turns into
  \[
  \frac{d\sigma_{\text{double}}}{dx_1 \, d\bar{x}_1 \, dx_2 \, d\bar{x}_2} = \frac{1}{C} \frac{d\sigma_1}{dx_1 \, d\bar{x}_1} \frac{d\sigma_2}{x_2 \, \bar{x}_2} \frac{1}{\sigma_{\text{eff}}}
  \]
  with \( 1/\sigma_{\text{eff}} = \int d^2 y \, G(y)^2 \)
  \( \sim \) scatters are completely independent

- underlies bulk of phenomenological estimates

- pocket formula fails if any of the above assumptions is invalid
  and if further terms must be added to original expression of cross sect.
Experimental investigations  (only a sketch)

- further studies:
  - double charm production ($c\bar{c}c\bar{c}$)
    - $J/\Psi + J/\Psi$, $J/\Psi + C$, $C + C$ with $C = D^0, D^+, D_s^+, \Lambda_c^+$  
      - LHCb 2011, 2012; CMS 2014
  - $W + J/\Psi$
    - ATLAS 2014
Parton correlations

- if neglect correlations between two partons

\[ F(x_1, x_2, y) = \int d^2b \ f(x_2, b) \ f(x_1, b + y) \]

where \( f(x_i, y) \) = impact parameter dependent single-parton density

and if neglect correlations between \( x \) and \( y \) of single parton

\[ f(x_i, y) = f(x_i)F(y) \]

with same \( F(y) \) for all partons

then \( G(y) = \int d^2b \ F(b) \ F(b + y) \)
Parton correlations

- if neglect correlations between two partons

\[ F(x_1, x_2, y) = \int d^2 b \ f(x_2, b) f(x_1, b + y) \]

where \( f(x_i, y) = \) impact parameter dependent single-parton density

and if neglect correlations between \( x \) and \( y \) of single parton

\[ f(x_i, y) = f(x_i) F(y) \]

with same \( F(y) \) for all partons

then \[ G(y) = \int d^2 b \ F(b) F(b + y) \]

- for Gaussian \( F(y) \) with average \( \langle y^2 \rangle \)

\[ \sigma_{\text{eff}} = 4\pi\langle y^2 \rangle = 41 \text{ mb} \times \langle y^2 \rangle / (0.57 \text{ fm})^2 \]

determinations of \( \langle y^2 \rangle \) from GPDs and form factors: \( (0.57 \text{ fm} - 0.67 \text{ fm})^2 \)
is \( \gg \sigma_{\text{eff}} \sim 5 \) to 20 mb from experimental extractions

if \( F(y) \) is Fourier trf. of dipole then 41 mb \( \rightarrow 36 \) mb

- complete independence between two partons is disfavored

or pocket formula misses important contributions to cross section

cf. Calucci, Treleani 1999; Frankfurt, Strikman, Weiss 2003-04; Blok et al 2013
Correlations involving $x$

- $F(x_1, x_2, y) = f(x_1) f(x_2) G(y)$ cannot hold for all $x_1, x_2$
- most obvious: energy conservation $\Rightarrow x_1 + x_2 \leq 1$
  - often used to suppress region of large $x_1 + x_2$:
    $$F(x_1, x_2, y) = (1 - x_1 - x_2)^n f(x_1) f(x_2) G(y)$$
- significant $x_1 - x_2$ correlations found in constituent quark model
  - Rinaldi, Scopetta, Vento: arXiv:1302.6462

![Plot showing the function $F_{uu}(x_1, x_2, y)/f_u(x_2)$ for different values of $x_2$.](image)

- plot shows $\int d^2y \frac{F_{uu}(x_1, x_2, y)}{f_u(x_2)}$ is $x_2$ independent if factorization holds
- unknown: size of correlations when one or both of $x_1, x_2$ small
Correlations involving $x$ and $y$

- $f(x, y)$ related to generalized parton distribution (GPD) by Fourier transform of $\text{GPD} \sim \langle p'|\bar{q}\Gamma q|p\rangle$ w.r.t. $p' - p$

- HERA results on $\gamma p \rightarrow J/\Psi p$ give

$$\langle b^2 \rangle \propto \text{const} + 4\alpha' \log(1/x)$$

with $\alpha' \approx 0.15 \text{GeV}^{-2} = (0.08 \text{fm})^2$ for gluons at $x \sim 10^{-3}$

$\rightarrow$ weak but nonzero correlation between $x$ and $b$
Correlations involving $x$ and $y$

- $f(x, y)$ related to generalized parton distribution (GPD)
  - by Fourier transform of $\text{GPD} \sim \langle p' | \bar{q} \Gamma q | p \rangle$ w.r.t. $p' - p$
  - lattice simulations $\rightarrow$ strong decrease of $\langle b^2 \rangle$ with $x$ above $\sim 0.1$
  - seen by comparing moments $A_{n0}(t) = \int dx x^{n-1} H(x, t)$

$$t = -(p' - p)^2$$

\[ m_s = 498\text{MeV}, 20^3, u+d \]

LHCP Collaboration, in Ph. Hägler, arXiv:0912.4583
Correlations involving $x$ and $y$

- $f(x, y)$ related to generalized parton distribution (GPD) by Fourier transform of $\text{GPD} \sim \langle p' | \bar{q} \Gamma q | p \rangle$ w.r.t. $p' - p$

- indirect determination:
  
  MD, Th Feldmann, R Jakob, P Kroll 2004
  MD, P Kroll 2013

fit ansatz $H^{q-\bar{q}}(x, t) = q_{\text{val}}(x) \exp[tf_q(x)]$

to e.m. form factors of proton and neutron

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{correlations}
\end{figure}

\begin{itemize}
  \item u-ubar
  \item d-dbar
\end{itemize}
Correlations involving $x$ and $y$

- $f(x, y)$ related to generalized parton distribution (GPD) by Fourier transform of $\text{GPD} \sim \langle p'|\bar{q}\Gamma q|p\rangle$ w.r.t. $p' - p$

- Expect similar correlations between $x_i$ and $b$ in two-parton dist’s even if $F(x_1, x_2, y) \approx \int d^2b f(x_2, b) f(x_1, b + y)$ does not hold

- If interaction 2 produces high-mass system
  $\rightarrow$ have large $x_2, \bar{x}_2$
  $\rightarrow$ smaller $y$ $\rightarrow$ more central collision
  $\rightarrow$ secondary interactions enhanced

Frankfurt, Strikman, Weiss 2003
study in Pythia 8: Corke, Sjöstrand 2011
Spin correlations

\[ F(x_i, k_i, y) = \mathcal{F} \mathcal{T} \langle p| \bar{q}\left(-\frac{1}{2}z_2\right) \Gamma_2 q\left(\frac{1}{2}z_2\right) \bar{q}(y - \frac{1}{2}z_1) \Gamma_1 q(y + \frac{1}{2}z_1)|p\rangle \]

- polarizations of two partons can be correlated even in unpolarized target already pointed out by Mekhfi (1985)
  - quarks: longitudinal and transverse pol., e.g.
    \[ F_{\Delta q\Delta q} : \Gamma_1 = \Gamma_2 = \frac{1}{2} \gamma^+ \gamma_5 \quad \Leftrightarrow \quad q_1^\uparrow q_2^\uparrow + q_1^\downarrow q_2^\downarrow - q_1^\uparrow q_2^\downarrow - q_1^\downarrow q_2^\uparrow \]
  - gluons: longitudinal and linear pol.
- can be included in factorization formula
  - e.g. \[ F_{\bar{q}g} F_{qg} \sigma(q\bar{q} \rightarrow Z) \sigma(gg \rightarrow 2\,\text{jets}) + F_{\Delta q\Delta g} F_{\Delta q\Delta g} \Delta \sigma(q\bar{q} \rightarrow Z) \Delta \sigma(gg \rightarrow 2\,\text{jets}) \]

- if spin correlations are large \( \rightarrow \) large effects for rate and final state distributions of double hard scattering

T. Kasemets, MD 2012; A. Manohar, W. Waalewijn 2011
How large are spin correlations in the proton?

- polarized DPDs fulfil positivity constraints analogous to Soffer bound for usual PDFs, e.g.

\[
F_{qq} - F_{\Delta q\Delta q} \geq 2|F_{\delta q\delta q}|
\]

\(q = \text{unpol.}, \Delta q = \text{long.}, \delta q = \text{transv.};\) schematic notation

- large effects expected in valence quark region

  toy model: \(SU(6)\) symmetric proton wave function

  spin-flavor part: \(\frac{1}{\sqrt{6}} \left( |u^+u^-d^+\rangle + |u^-u^+d^-\rangle - 2|u^+u^+d^-\rangle \right)\)

gives

\[
\Delta u/u = 2/3 \quad \Delta d/d = -1/3
\]

\[
F_{\Delta u\Delta u}/F_{uu} = 1/3 \quad F_{\Delta u\Delta d}/F_{ud} = -2/3
\]

- large correlations found in bag model study

  Chang, Manohar, Waalewijn 2012

- unknown: size of correlations when one or both of \(x_1, x_2\) small
Color structure

- quark lines in amplitude and its conjugate can couple to color singlet or octet:

\[ 1^F \rightarrow (\bar{q}_2 \mathbb{1} q_2) \ (\bar{q}_1 \mathbb{1} q_1) \]
\[ 8^F \rightarrow (\bar{q}_2 t^a q_2) \ (\bar{q}_1 t^a q_1) \]

- \(8^F\) describes color correlation between quarks 1 and 2 is essentially unknown (no probability interpretation as a guide)

- for two-gluon dist's more color structures: 1, 8\(_S\), 8\(_A\), 10, 10\(_\bar{1}\), 27

- for \(k_T\) integrated distributions: color correlations suppressed by Sudakov logarithms

\[ \ldots \text{but not necessarily negligible for moderately hard scales} \]

Manohar, Waalewijn arXiv:1202:3794 used SCET methods

\[ U = \text{Sudakov factor, } Q = \text{hard scale} \]
Behavior at small interparton distance

- for \( y \ll 1/\Lambda \) in perturbative region \( F(x_1, x_2, y) \) dominated by graphs with splitting of single parton

- find strong correlations in \( x_1, x_2 \), spin and color between two partons e.g. 100% correlation for longitudinal pol. of \( q \) and \( \bar{q} \)

- can compute short-distance behavior:

\[
F(x_1, x_2, y) \sim \frac{1}{y^2} \text{ splitting fct } \otimes \text{ usual PDF}
\]
Scale evolution for collinear distributions without color correlation

- if define two-parton distributions as operator matrix elements in analogy with usual PDFs

\[ F(x_1, x_2, y; \mu) \sim \langle p | O_1(0; \mu) O_2(y; \mu) | p \rangle \quad f(x; \mu) \sim \langle p | O(0; \mu) | p \rangle \]

where \( O(y; \mu) = \) twist-two operator renormalized at scale \( \mu \)

- \( F(x_i, y) \) for \( y \neq 0 \):
  
  separate DGLAP evolution for partons 1 and 2

\[ \frac{d}{d \log \mu} F(x_i, y) = P \otimes x_1 F + P \otimes x_2 F \]

  two independent parton cascades

- \( \int d^2 y F(x_i, y) \):
  
  extra term from \( 2 \to 4 \) parton transition
  
  since \( F(x_i, y) \sim 1/y^2 \)

Kirschner 1979; Shelest, Snigirev, Zinovev 1982

Gaunt, Stirling 2009; Ceccopieri 2011

- which evolution eq. is relevant for double hard scattering?
Deeper problems with the splitting graphs

- contribution from splitting graphs in cross section gives divergent integrals
  \[ \int d^2 y \ F(x_1, x_2, y) F(\bar{x}_1, \bar{x}_2, y) \sim \int dy^2 / y^4 \]

- double counting problem between double scattering with splitting and single scattering at loop level

  MD, Ostermeier, Schäfer 2011; Gaunt, Stirling 2011; Gaunt 2012
  Blok, Dokshitzer, Frankfurt, Strikman 2011; Ryskin, Snigirev 2011, 2012
  same problem for jets: Cacciari, Salam, Sapeta 2009

- possible solution:
  subtract splitting contribution from two-parton dist’s when \( y \) is small
  will also modify their scale evolution; remains to be worked out
Deeper problems with the splitting graphs

- contribution from splitting graphs in cross section gives divergent integrals $\int d^2y \; F(x_1, x_2, y) F(\bar{x}_1, \bar{x}_2, y) \sim \int dy^2 / y^4$
- also have graphs with single PDF for one and double PDF for other proton

What is double parton scattering?

Blok et al, 2011-13; Gaunt 2012
**Sudakov factors**

- for $k_T$ dependent distributions, i.e. measured $q_i$:
  - Sudakov logarithms for all color channels
  - close relation with physics of parton showers

- for double Drell-Yan process
  - can adapt Collins-Soper-Sterman formalism for single Drell-Yan
  - include and resum Sudakov logs in $k_T$ dependent parton dist’s
    - MD, D Ostermeier, A Schäfer 2011

  for jet production inherit problems of usual TMD factorization

- at leading double log accuracy: singlet and octet dist’s $^1F$ and $^8F$
  - have same Sudakov factor as in single scattering

- beyond double log: Sudakov factors mix singlet and octet dist’s
Factorization?

- open problem (for TMD and collinear formulations): exchange of gluons in Glauber region

Not discussed in this talk:

- multiparton interactions in $pA$ collisions
- small-$x$ approach connection with diffraction, AGK rules ridge effect in $pp$ and $pA$  
  
Bartels, Salvadore, Vacca 2008  
Dumitru et al 2011; ...
Conclusions

▶ multiple hard scattering is not generically suppressed in sufficiently differential cross sections
▶ current phenomenology relies on strong simplifications
▶ have several elements for a formulation of factorization but important open questions still unsolved
  ● crosstalk with single hard scattering at small distances closely related with evolution equations (1 $\rightarrow$ 2 parton splitting)
  ● Glauber gluon exchange
▶ double hard scattering depends on detailed hadron structure including correlation and interference effects
  ● corresponding nucleon matrix elements largely unknown theoretical activity only started
  ● transverse distance between partons essential
▶ subject remains of high interest for
  ● understanding high-multiplicity final states at LHC
  ● study of hadron structure in its own right