Towards a theory for multiple hard scattering in QCD

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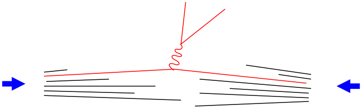
Hadron-hadron collisions

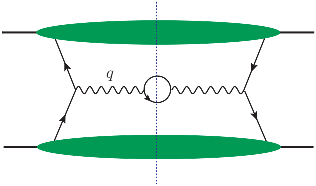
- standard description based on factorization formulae

  cross sect = parton distributions × parton-level cross sect

  example: Z production

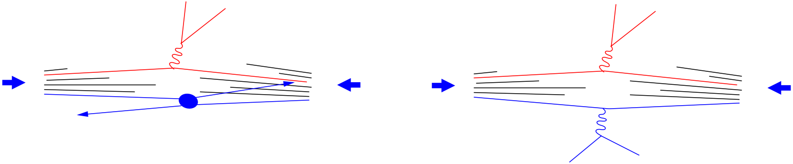
  $pp \to Z + X \to \ell^+\ell^- + X$





- factorization formulae are for inclusive cross sections $pp \to Y + X$
  where Y = produced in parton-level scattering, specified in detail
  X = summed over, no details
- have also interactions between "spectator" partons
  - typically affect unspecified system X $\rightsquigarrow$ underlying event
    these effects cancel in inclusive cross sections thanks to unitarity
  - but can also produce particles with large p_T or large mass
    $\rightsquigarrow$ multiparton interactions

Multiparton interactions (MPI)



- characteristic final-state signature:
  individual particles or groups of particles have

$$p_T \ll \text{large scale of process}$$

- can affect both signal and background processes
  e.g. $pp \to H + Z \to b\bar{b} + Z$ and $pp \to b\bar{b} + Z$ Del Fabbro, Treleani 1999
- expected to be important for many processes at LHC
  see e.g. Procs. of MPI 2011 (DESY-PROC-2012-03)
  significant effect found in $pp \to W + 2$ jets $+ X$, ATLAS-CONF-2011-160
- in the following restrict ourselves to double parton interactions

Double parton interactions (DPI)

- phenomenology based on simple, physically intuitive formula

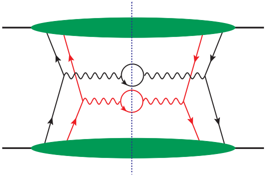
  cross sect = double parton distributions × parton-level cross sect's

  and simple ansatz for double parton distributions

- typically assume

  $$F_{ab}(x_1, x_2, \boldsymbol{y}) = f_a(x_1)\, f_b(x_2)\, F(\boldsymbol{y})$$

  where $\boldsymbol{y}$ = transverse distance between partons 1 and 2



- then get pocket formula $\sigma_{\text{double}} = \sigma_1\, \sigma_2 / \sigma_{\text{eff}}$
  with σ_{eff} depending on $F(\boldsymbol{y})$

  experimentally find: $\sigma_{\text{eff}} \sim 11 \ldots 15\, \text{mb}$ Tevatron, LHC

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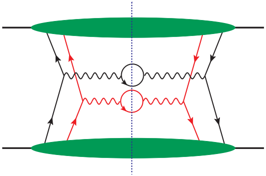

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- but independence of long. mom. and transv. positions is approximate
  for single partons have evidence for correlations from
  - diffractive vector meson production at HERA $(x \sim 10^{-3})$
  - lattice calculations (dominated by $x \sim 0.2 \ldots 0.4$)

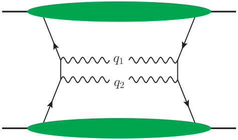
  correlations have observable effects in DPI Corke, Sjöstrand 2011

Single versus double hard scattering

- consider gauge boson pair prod'n (analogous results for other processes)

$$s \frac{d\sigma}{dx_1\, d\bar{x}_1\, d^2\boldsymbol{q}_1\;\, dx_2\, d\bar{x}_2\, d^2\boldsymbol{q}_2} \sim \frac{1}{Q^2\Lambda^2} \qquad Q^2 \sim q_i^2 \;\gg\; \Lambda^2 \sim \boldsymbol{q}_i^2$$

for both



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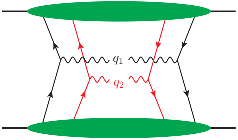

$\Rightarrow$ double scattering not power suppressed

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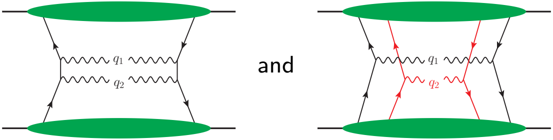

$\Rightarrow$ double scattering not power suppressed

- but if integrate over $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ then

single: $$s\,\frac{d\sigma}{dx_1\,d\bar{x}_1\;dx_2\,d\bar{x}_2} \sim 1$$ since $\int d^2(\boldsymbol{q}_1 + \boldsymbol{q}_2) \sim \Lambda^2$ and $\int d^2(\boldsymbol{q}_1 - \boldsymbol{q}_2) \sim Q^2$

double: $$s\,\frac{d\sigma}{dx_1\,d\bar{x}_1\;dx_2\,d\bar{x}_2} \sim \frac{\Lambda^2}{Q^2}$$ since $\int d^2\boldsymbol{q}_1 \int d^2\boldsymbol{q}_2 \sim \Lambda^4$

i.e. single hard scattering has larger phase space for transv. momenta

Single versus double hard scattering

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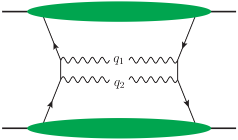
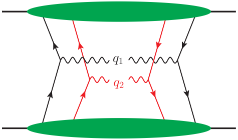
for both 

and 

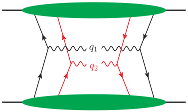
$\Rightarrow$ double scattering not power suppressed

- at small $x_1 \sim x_2 \sim x$ expect
  - single scattering $\propto x^{-\lambda}$
  - double scattering $\propto x^{-2\lambda}$

  with $xf(x) \sim x^{-\lambda}$

$\Rightarrow$ double scattering enhanced at small x

Toward a factorization formula



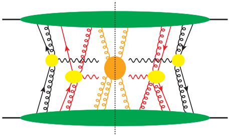
- master formula for measured transverse momenta

$$\frac{d\sigma}{dx_1\, d\bar{x}_1\, d^2\boldsymbol{q}_1\; dx_2\, d\bar{x}_2\, d^2\boldsymbol{q}_2} = \hat{\sigma}_{ac}(q_1^2)\, \hat{\sigma}_{bd}(q_2^2)$$
$$\times \left[\prod_{i=1,2} \int d^2\boldsymbol{k}_i\, d^2\bar{\boldsymbol{k}}_i\, \delta(\boldsymbol{q}_i - \boldsymbol{k}_i - \bar{\boldsymbol{k}}_i) \right] \int d^2\boldsymbol{y}\, F_{ab}(x_i, \boldsymbol{k}_i, \boldsymbol{y})\, F_{cd}(\bar{x}_i, \bar{\boldsymbol{k}}_i, \boldsymbol{y})$$

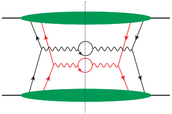
  can be derived at tree level from Feynman graphs and kinematic approx's
  no semi-classical arguments required — MD, Ostermeier, Schäfer 2011

- $F(x_i, \boldsymbol{k}_i, \boldsymbol{y}) = k_T$ dependent double parton distribution
  recover standard formalism by $\int$ over transv. momenta

- for factorization proof must show how to treat additional gluons
  - partly under theoretical control
    derivation of Sudakov factors from soft/collinear gluons
  - unsolved problem: gluons from Glauber region could spoil factorization



Spin structure



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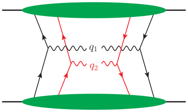
- even in unpolarized proton can have spin correlations between partons
  - unpolarized, longitudinal pol., transverse pol. quarks
  - unpol., longitudinal pol., linear pol. gluons
- in general not suppressed in hard scattering
  consequences for rate and distributions
- detailed calc'n for gauge boson pair production followed by leptonic decay
  Kasemets, MD 2012; see also Manohar, Waalewijn 2011
- transverse quark spin correlation
  $\rightsquigarrow$ $\cos 2\phi$ modulation between decay planes of the two bosons
  in general: correlated scattering planes
- how large are spin correlations?
  find large effects in constituent quark region
  MD, Ostermeier, Schäfer 2011; Chang, Manohar, Waalewijn 2012

Color structure

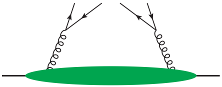


- quark lines with given x_i in amplitude and conjugate amp. can couple to color singlet or color octet
  for two-gluon dist's more color structures: $1,\ 8_S,\ 8_A,\ 10,\ \overline{10},\ 27$
  - color singlet distributions: analog to single-parton case
  - color octet distributions essentially unknown
    no probability interpretation as a guide
    not implemented in phenomenology
- for k_T integrated cross sections/distributions: color octet suppressed by Sudakov logarithms Mekhfi 1988; Manohar, Waalewijn 2011
  but not necessarily negligible for moderately hard scales
- in k_T unintegrated case:
  Sudakov factors for both color singlet and color octet
  slightly stronger suppression for octet MD, Ostermeier, Schäfer 2011

Problems at short distance

- for short interparton distance $\boldsymbol{y}$ can compute double parton distribution from splitting graphs

$$F(x_i, \boldsymbol{k}_i, \boldsymbol{y}) \sim \log \boldsymbol{y}^2$$
$$F(x_i, \boldsymbol{y}) \sim 1/\boldsymbol{y}^2$$



- changes scale evolution

Kirschner 1979; Shelest, Snigirev, Zinovev 1982, Gaunt, Stirling 2009

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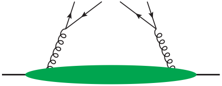
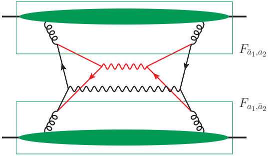
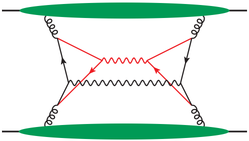


- contribution from splitting graphs in cross section gives divergent integrals $\int d^2\boldsymbol{y}\, F(x_i, \boldsymbol{k}_i, \boldsymbol{y})\, F(\bar{x}_i, \bar{\boldsymbol{k}}_i, \boldsymbol{y})$





- double counting problem between double scattering with splitting and single scattering at loop level Cacciari, Salam, Sapeta 2009

MD, Ostermeier, Schäfer 2011; Gaunt, Stirling 2011; Gaunt 2012
Blok, Dokshitzer, Frankfurt, Strikman 2011; Ryskin, Snigirev 2011, 2012

Summary

- multiple hard interactions are not suppressed
  in specific parts of phase space
- multi-parton dist's depend on transverse distance $\boldsymbol{y}$ between partons
  correlations with x have consequences for MPI
- nontrivial spin and color structure
  size of these effects presently unknown
  $\rightsquigarrow$ extra uncertainty in quantitative description
  in addition to uncertainty on "usual" multi-parton dist's
- should remove small $\boldsymbol{y}$ contribution in order to avoid divergences
  and double counting
- opportunity at LHC:
  investigate in detail final states susceptible to MPI
  $\rightsquigarrow$ help to sort out which effects are important and which are not