QCD and hadron structure

Lecture 5: Multiparton interactions

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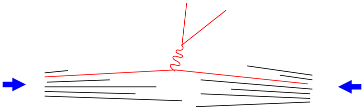
Hadron-hadron collisions

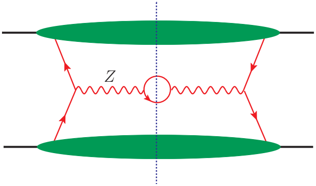
- standard description based on factorization formulae

  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

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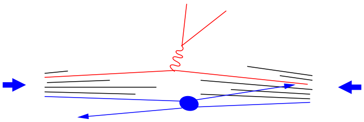
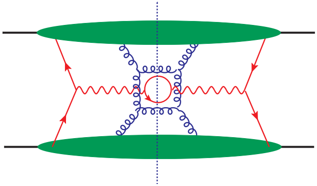
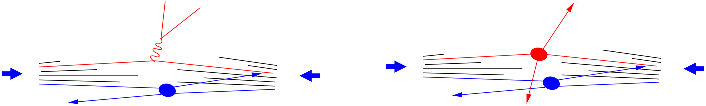




- factorization formulae are for inclusive cross sections $pp \to Y + X$
  where Y = produced in parton-level scattering, specified in detail
  X = summed over, no details
- also have interactions between "spectator" partons
  their effects cancel in inclusive cross sections thanks to unitarity
  but they affect the final state X

Multiparton interactions



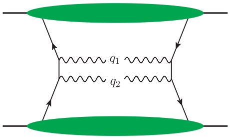
- secondary, tertiary etc. interactions generically take place in hadron-hadron collisions
- predominantly low-p_T scattering $\rightsquigarrow$ underlying event
- at high collision energy can be hard $\rightsquigarrow$ multiple hard scattering
- many studies

  theory: phenomenology, theory 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
- here: concentrate on double hard scattering (DPS)

Single vs. double hard scattering

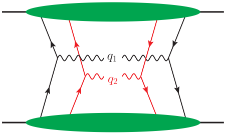
- example: prod'n of two gauge bosons, transverse momenta $\boldsymbol{q}_{T1}$ and $\boldsymbol{q}_{T2}$



single scattering:

$|\boldsymbol{q}_{T1}|$ and $|\boldsymbol{q}_{T1}| \sim$ hard scale Q^2

$|\boldsymbol{q}_{T1} + \boldsymbol{q}_{T2}| \ll Q^2$



double scattering:

both $|\boldsymbol{q}_{T1}|$ and $|\boldsymbol{q}_{T1}| \ll Q^2$

- for transv. mom. $\sim \Lambda \ll Q$:

$$\frac{d\sigma_{\text{single}}}{d^2\boldsymbol{q}_{T1}\, d^2\boldsymbol{q}_{T2}} \sim \frac{d\sigma_{\text{double}}}{d^2\boldsymbol{q}_{T1}\, d^2\boldsymbol{q}_{T2}} \sim \frac{1}{Q^4\,\Lambda^2}$$

but single scattering populates larger phase space :

$$\sigma_{\text{single}} \sim \frac{1}{Q^2} \gg \sigma_{\text{double}} \sim \frac{\Lambda^2}{Q^4}$$

Single vs. double hard scattering

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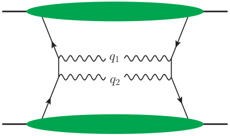

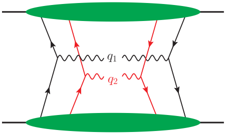

single scattering:

$|\boldsymbol{q}_{T1}|$ and $|\boldsymbol{q}_{T1}| \sim$ hard scale Q^2

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double scattering:

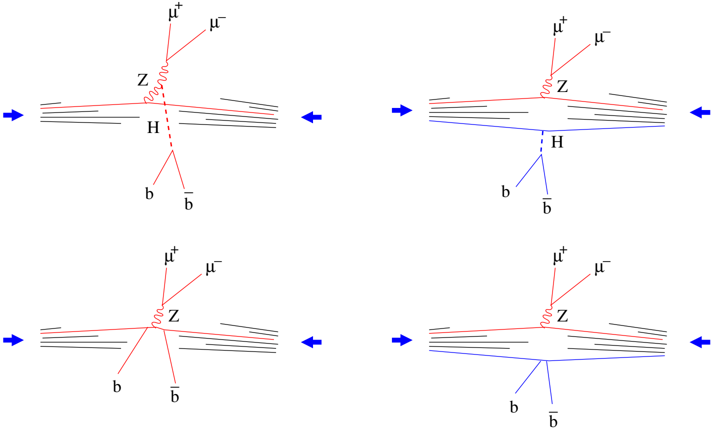
both $|\boldsymbol{q}_{T1}|$ and $|\boldsymbol{q}_{T1}| \ll Q^2$

- double scattering favored at small x (high energies): densities for two partons rise faster than for single parton

Relevance for LHC

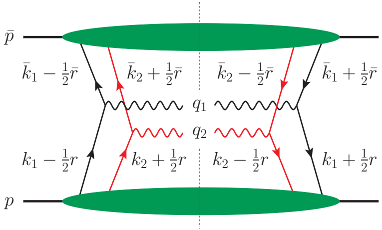
example: $pp \to H + Z \to b\bar{b} + Z$ Del Fabbro, Treleani 1999

- multiple interactions contribute to signal and background



same for $pp \to H + W \to b\bar{b} + W$ study for Tevatron: Bandurin et al, 2010

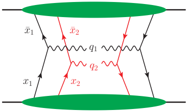
Feynman graphs: momentum vs. distance



momentum
conservation
$\Rightarrow r + \bar{r} = 0$

- 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 $\mathcal{A}$ and in $\mathcal{A}^*$
  cross section $\propto \int d^2\boldsymbol{r}\, F(x_i, \boldsymbol{k}_i, \boldsymbol{r}) F(\bar{x}_i, \bar{\boldsymbol{k}}_i, -\boldsymbol{r})$
- Fourier trf. to impact parameter: $F(x_i, \boldsymbol{k}_i, \boldsymbol{r}) \to F(x_i, \boldsymbol{k}_i, \boldsymbol{y})$
  cross section $\propto \int d^2\boldsymbol{y}\, F(x_i, \boldsymbol{k}_i, \boldsymbol{y}) F(\bar{x}_i, \bar{\boldsymbol{k}}_i, \boldsymbol{y})$
- interpretation: $\boldsymbol{y}$ = transv. dist. between two scattering partons
  = equal in both colliding protons

Cross section formula



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

$C =$ combinatorial factor

$\hat{\sigma}_i =$ parton-level cross sections

$F(x_1, x_2, \boldsymbol{y}) =$ double parton distribution (DPD)

$\boldsymbol{y} =$ 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 α_s get usual convolution integrals over x_i in $\hat{\sigma}_i$ and F

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

Parton correlations

- if neglect correlations between two partons

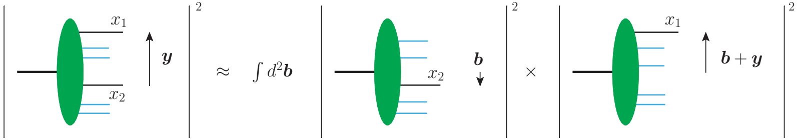
$$F(x_1, x_2, \boldsymbol{y}) = \int d^2\boldsymbol{b}\; f(x_2, \boldsymbol{b})\, f(x_1, \boldsymbol{b} + \boldsymbol{y})$$

where $f(x_i, \boldsymbol{b}) =$ impact parameter dependent single-parton density

and if neglect correlations between x and $\boldsymbol{y}$ of single parton

$$f(x_i, \boldsymbol{b}) = f(x_i)\, F(\boldsymbol{b})$$

then $F(x_1, x_2, \boldsymbol{y}) = f(x_1)\, f(x_2) \int d^2\boldsymbol{b}\; F(\boldsymbol{b})\, F(\boldsymbol{b} + \boldsymbol{y})$



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- information on $f(x, \boldsymbol{b})$ from study of GPDs and elastic form factors
  $\oplus$ measurements of double parton scattering
  $\rightarrow$ complete independence between two partons disfavored

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

Parton correlations

at certain level of accuracy expect correlations between

- x_1 and x_2 of partons
  - most obvious: energy conservation $\Rightarrow$ $x_1 + x_2 \leq 1$
  - significant x_1 – x_2 correlations found in constituent quark model

    Rinaldi, Scopetta, Vento 2013

- x_i and $\boldsymbol{y}$

  even for single partons see correlations between x and $\boldsymbol{b}$ distribution
  - HERA results on $\gamma p \to J/\Psi\, p$ give

    $\langle \boldsymbol{b}^2 \rangle \propto$ const $+ 4\alpha' \log(1/x)$ with $4\alpha' \approx (0.16\,\mathrm{fm})^2$

    for gluons with $x \sim 10^{-3}$
  - lattice calculations of x^0, x^1, x^2 moments

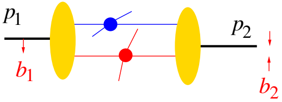
    $\rightarrow$ strong decrease of $\langle \boldsymbol{b}^2 \rangle$ with x above ~ 0.1

  plausible to expect similar correlations in double parton distributions

  even if two partons not uncorrelated

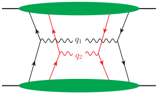
Consequence for multiple interactions

- indications for decrease of $\langle \boldsymbol{y}^2 \rangle$ with x
- if interaction 1 produces high-mass system
  $\rightarrow$ have large $x_1, \bar{x}_1$
  $\rightarrow$ smaller $\boldsymbol{y}$ $\rightarrow$ more central collision
  $\rightarrow$ secondary interactions enhanced



Frankfurt, Strikman, Weiss 2003
studies in Pythia: Corke, Sjöstrand 2011; Blok, Gunnellini 2015

Spin correlations



$$F(x_i, \boldsymbol{k}_i, \boldsymbol{y}) = \underset{z_i \to (x_i, \boldsymbol{k}_i)}{\mathcal{FT}} \langle p | \bar{q}\big(-\tfrac{1}{2}z_2\big) \Gamma_2\, q\big(\tfrac{1}{2}z_2\big)\; \bar{q}\big(y - \tfrac{1}{2}z_1\big) \Gamma_1\, q\big(y + \tfrac{1}{2}z_1\big) | p \rangle$$

- polarizations of two partons can be correlated even in unpolarized target
  - quarks: longitudinal and transverse pol., e.g.

$$F_{\Delta q \Delta q} : \Gamma_1 = \Gamma_2 = \tfrac{1}{2}\gamma^+ \gamma_5 \qquad \Leftrightarrow \quad q_1^{\uparrow} q_2^{\uparrow} + q_1^{\downarrow} q_2^{\downarrow} - q_1^{\uparrow} q_2^{\downarrow} - q_1^{\downarrow} q_2^{\uparrow}$$

  - gluons: longitudinal and linear pol.
- can be included in factorization formula
  $\rightsquigarrow$ extra terms with polarized DPDs and partonic cross sections
- if spin correlations are large $\to$ large effects for rate and final state distributions of double hard scattering

A. Manohar, W. Waalewijn 2011, T. Kasemets, MD 2012
M. Echevarria, T. Kasemets, P. Mulders, C. Pisano 2015

How large are spin correlations in the proton?

- large effects obtained in valence quark picture
  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

$$\Delta u/u = 2/3 \qquad \Delta d/d = -1/3$$

$$F_{\Delta u \Delta u}/F_{uu} = 1/3 \qquad F_{\Delta u \Delta d}/F_{ud} = -2/3$$

- large correlations found in bag model study
  Chang, Manohar, Waalewijn 2012

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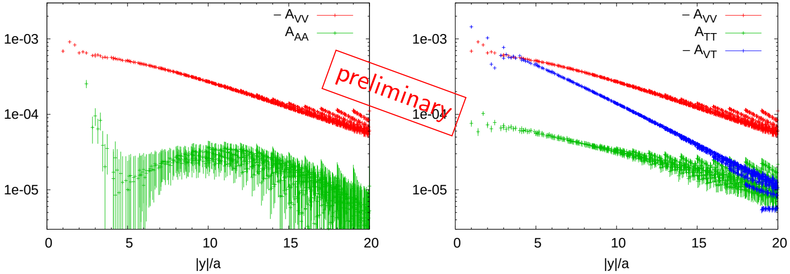
- lattice QCD?
  pilot study for the pion (easier to compute than nucleon)

  G. Bali, L. Castagnini, S. Collins, M.D., M. Engelhardt, J. Gaunt,
  B. Gläßle, A. Sternbeck, A. Schäfer, Ch. Zimmermann

  matrix elements of two currents with spacelike distance $y^2 < 0$

  - can take at equal time $y^0 = 0$
  - gives moments of DPDs in x_1, x_2 (almost)

A first lattice study for the pion: preliminary results



$40^3 \times 64$ lattice with spacing $a \approx 0.07$ fm

- AA: longitudinal spin correlation $u^{\uparrow}\bar{d}^{\uparrow} + u^{\downarrow}\bar{d}^{\downarrow} - u^{\uparrow}\bar{d}^{\downarrow} - u^{\downarrow}\bar{d}^{\uparrow}$
  moderate to small, unclear signal for small $|y|$
- TT: transverse spin correlation $\propto \boldsymbol{s}_u \cdot \boldsymbol{s}_{\bar{d}}$
  clear signal, $A_{TT} \sim -0.1 \times A_{VV}$
  very different from s-wave picture $|\pi^+\rangle \sim |u^{\uparrow}\bar{d}^{\downarrow}\rangle + |u^{\downarrow}\bar{d}^{\uparrow}\rangle$

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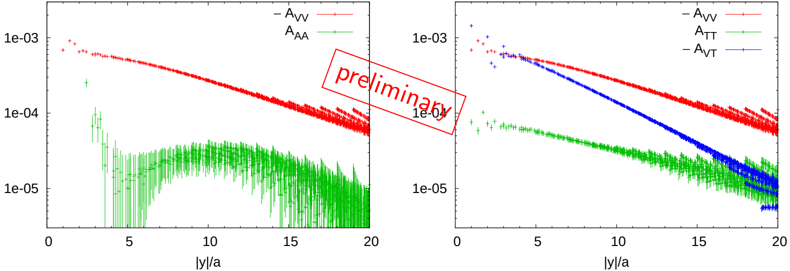

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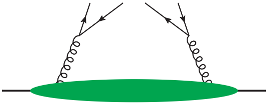
- VT: correlation $\propto\ \boldsymbol{y} \cdot \boldsymbol{s}_{\bar{d}}$
  maximal at small $|\boldsymbol{y}|$, then decreases

Behavior at small interparton distance

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



- can compute short-distance behavior:

$$F(x_1, x_2, \boldsymbol{y}) \sim \frac{1}{\boldsymbol{y}^2} \text{ splitting fct} \otimes \text{usual PDF}$$

- gives strong correlations in x_1, x_2, spin and color between two partons

  e.g. -100% correlation for longitudinal pol. of q and $\bar{q}$

- open question: how fast do correlations decrease with $\boldsymbol{y}$?

Summary

- multiparton interactions ubiquitous in hadron-hadron collisions
  multiple hard scattering often suppressed, but not necessarily
  - in specific kinematics
  - for multi-differential cross sections, high-multiplicity final states
- double hard scattering depends on detailed hadron structure
  - transverse spatial distribution
  - different correlation and interference effects
- subject remains of high interest for
  - control over final states at LHC
  - understanding QCD dynamics and hadron structure