Correlation effects in multiple hard scattering

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HELMHOLTZ GEMEINSCHAFT

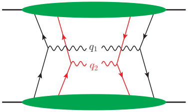
DESY

Introduction

- multiparton interactions are ubiquitous in hadron-hadron collisions
- populate characteristic part of phase space
  there they can be substantial part of rate
- important theory progress for hard double scattering
- but many open questions:
  - size of correlations between partons
  - parton splitting contributions evolution of DPDs
- promising experimental developments:
  - different processes
  - kinematic distributions
- use σ_{eff} as a handy tool, not as a precision instrument

summary of my talk yesterday

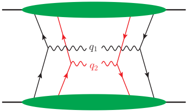
Double parton scattering: cross section formula



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

C = combinatorial factor
$\hat{\sigma}_i$ = parton-level cross section
$\boldsymbol{b}$ = transv. distance between partons
$F(x_i, \boldsymbol{b})$ = double parton distribution (DPD)

Double parton scattering: cross section formula



$$\frac{d\sigma_{\text{double}}}{dx_1\, d\bar{x}_1\, d^2\boldsymbol{q}_1\; dx_2\, d\bar{x}_2\, d^2\boldsymbol{q}_2} = \frac{1}{C}\,\hat{\sigma}_1\,\hat{\sigma}_2 \left[\prod_{i=1}^{2} \int d^2\boldsymbol{k}_i\, d^2\bar{\boldsymbol{k}}_i\, \delta(\boldsymbol{q}_i - \boldsymbol{k}_i - \bar{\boldsymbol{k}}_i)\right]$$

$$\times \int d^2\boldsymbol{b}\, F(x_i, \boldsymbol{k}_i, \boldsymbol{b})\, F(\bar{x}_i, \bar{\boldsymbol{k}}_i, \boldsymbol{b})$$

$F(x_i, \boldsymbol{k}_i, \boldsymbol{b}) =$ k_T dependent two-parton distribution

- $F(x_i, \boldsymbol{b}) = \int d^2\boldsymbol{k}_1 \int d^2\boldsymbol{k}_2\, F(x_i, \boldsymbol{k}_i, \boldsymbol{b})$ up to issues of regularization
- analogous to TMD formalism see talks in WG6, Wed from 11:20

Double parton scattering: pocket formula

- if two-parton density factorizes as

$$F(x_1, x_2, \boldsymbol{b}) = f(x_1)\, f(x_2)\, G(\boldsymbol{b})$$

  where $f(x_i) =$ usual PDF

- if assume same $G(\boldsymbol{b})$ 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 $1/\sigma_{\text{eff}} = \int d^2\boldsymbol{b}\; G(\boldsymbol{b})^2$

  $\rightsquigarrow$ scatters are completely independent

- analogous derivation for cross sect. dependent on $\boldsymbol{q}_i$
- pocket formula fails if any of the above assumptions is invalid
  and if further terms must be added to original expression of cross sect.

Parton correlations

- if neglect correlations between two partons

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

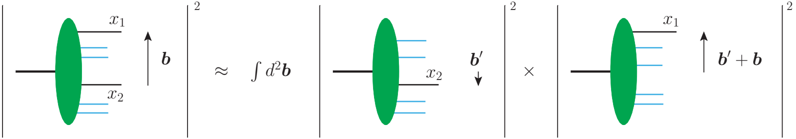
where $f(x_i, \boldsymbol{b})$ = impact parameter dependent single-parton density

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

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

with same $F(\boldsymbol{b})$ for all partons

then $G(\boldsymbol{b}) = \int d^2\boldsymbol{b}' \; F(\boldsymbol{b}' + \boldsymbol{b}) \, F(\boldsymbol{b}')$



Parton correlations

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- correlations in $\boldsymbol{b}$ space need not invalidate pocket formula
- for Gaussian $F(\boldsymbol{b})$ with average $\langle \boldsymbol{b}^2 \rangle$

$$\sigma_{\text{eff}} = 4\pi \langle \boldsymbol{b}^2 \rangle = 41\,\text{mb} \;\times \langle \boldsymbol{b}^2 \rangle / (0.57\,\text{fm})^2$$

determinations of $\langle \boldsymbol{b}^2 \rangle$ range from $\sim (0.57\,\text{fm} - 0.67\,\text{fm})^2$

is $\gg \sigma_{\text{eff}} \sim 10$ to $20\,\text{mb}$ from experimental extractions

if $F(\boldsymbol{b})$ is Fourier trf. of dipole then $41\,\text{mb} \to 36\,\text{mb}$

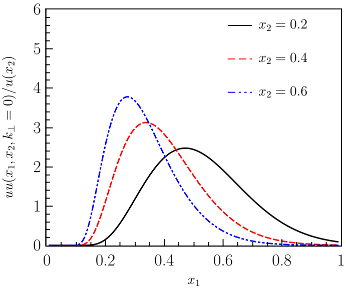
complete independence between two partons is disfavored
or somewthing is seriously wrong with σ_{eff}

cf. Calucci, Treleani 1999; Frankfurt, Strikman, Weiss 2003, 2004

Correlations involving x

- $F(x_1, x_2, \boldsymbol{b}) = f(x_1)\, f(x_2)\, G(\boldsymbol{b})$ cannot hold for all x_1, x_2
- most obvious: energy conservation $\Rightarrow\ x_1 + x_2 \leq 1$
  often used: $F(x_1, x_2, \boldsymbol{b}) = f(x_1)\, f(x_2)\, (1 - x_1 - x_2)^n\, G(\boldsymbol{b})$
  to suppress region of large $x_1 + x_2$
- significant x_1 – x_2 correlations found in constituent quark model

Rinaldi, Scopetta, Vento: arXiv:1302.6462



plot shows $\int d^2\boldsymbol{b}\; F_{uu}(x_1, x_2, \boldsymbol{b})/f_u(x_2)$
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 $\boldsymbol{b}$

- single-parton distribution $f(x, \boldsymbol{b})$ is Fourier trf. of generalized parton distributions at zero skewness
  - $\rightsquigarrow$ information from exclusive processes and theory
  - HERA results on $\gamma p \to J/\Psi\, p$ give

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

    with $\alpha' \approx 0.15\,\text{GeV}^{-2} = (0.08\,\text{fm})^2$ for gluons at $x \sim 10^{-3}$
  - lattice simulations $\to$ strong decrease of $\langle \boldsymbol{b}^2 \rangle$ with x above ~ 0.1 seen by comparing moments $\int dx\, x^{n-1} f(x, \boldsymbol{b})$ for $n = 0, 1, 2$
  - precise mapping of single-parton distributions $f(x, \boldsymbol{b})$ over wide x range in future lepton-proton experiments

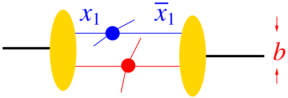
    JLab 12, COMPASS, EIC, LHeC

    $\to$ parallel talks in WG6 and WG7

- expect similar correlations between x_i and $\boldsymbol{b}$ in two-parton dist's even if factorization $F(x_1, x_2, \boldsymbol{b}) = f(x_1, \boldsymbol{b})\, f(x_2, \boldsymbol{b})$ does not hold

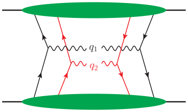
Consequence for multiple interactions

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



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

Spin correlations



- polarizations of two partons can be correlated even in unpolarized target — already pointed out by Mekhfi (1985)
  - quarks: longitudinal and transverse pol.
  - gluons: longitudinal and linear pol.

  have eight (k_T integrated leading-twist) distributions for each combination qq, qg, gg

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

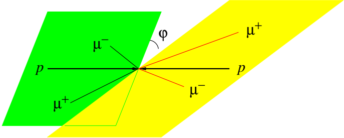
$$F_{qq} - F_{\Delta q \Delta q} \geq 2|F_{\delta q \delta q}|$$

$q =$ unpol., $\Delta q =$ long., $\delta q =$ transv.; schematic notation

MD, Kasemets 2013

- in general not suppressed in hard scattering
  consequences for rate and distributions

Spin and angular distributions



- detailed calc'n for gauge boson pair production followed by leptonic decay

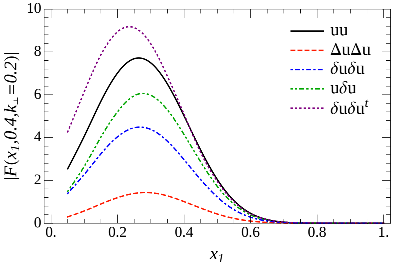
  T. Kasemets, MD 2012; see also A. Manohar, W. Waalewijn 2011

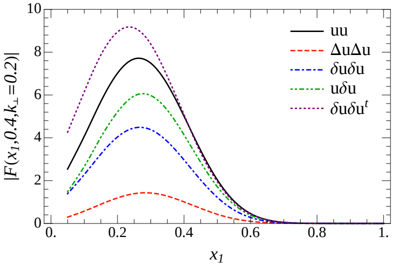
- longitudinal quark spin correlations
  - ⇝ overall rate and distribution in lepton rapidities
- transverse quark spin correlations
  - ⇝ azimuthal correlation between lepton planes
    - ⇝ two hard scatters are not independent
- expect similar effects for gluon initiated processes (esp. for jets) linear gluon pol. ⇝ azimuthal correlation between scattering planes
- note: independent scattering planes sometimes assumed as criterion to characterize double parton scattering

Spin correlations

- how important are spin correlations?
  large effects expected in valence quark region

  study in bag model: Chang, Manohar, Waalewijn: arXiv:1211:3132

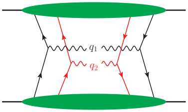




plots show $F(x_1, x_2 = 0.4, k_\perp)$ for different pol. combinations
$k_\perp$ = Fourier conjugate to $\boldsymbol{b}$

- unknown: size of correlations when one or both of x_1, x_2 small

Color structure



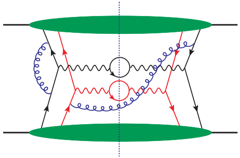
- quark lines in amplitude and its conjugate can couple to color singlet or octet:

$$^{1}F \to (\bar{q}_2 \mathbb{1} q_2)\,(\bar{q}_1 \mathbb{1} q_1) \qquad\qquad ^{8}F \to (\bar{q}_2\, t^a q_2)\,(\bar{q}_1\, t^a q_1)$$

- ^{8}F desribes 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, $\overline{10}$, 27
- for k_T integrated distributions: color correlations suppressed by Sudakov logarithms but not necessarily negligible for moderately hard scales

Mekhfi 1988; Manohar, Waalewijn 2011

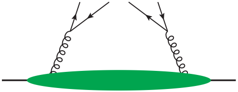
Sudakov factors



- for k_T dependent distributions, i.e. measured $\boldsymbol{q}_i$:
  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
  $\leadsto$ include and resum Sudakov logs in k_T dependent parton dist's
  MD, D Ostermeier, A Schäfer 2011
- at leading double log accuracy: singlet and octet dist's ${}^{1}F$ and ${}^{8}F$
  have same Sudakov factor as in single scattering
- for $q_T \sim \Lambda$
  - Sudakov factors mix singlet and octet dist's
    mixing only suppressed by $1/N_c$
  - generically Sudakov factors of same size for singlet and octet
- for $q_T \gg \Lambda$ and $|\boldsymbol{b}| \sim 1/\Lambda$
  - singlet ${}^{1}F$ decouples from octet ${}^{8}F$
  - octet contribution has extra suppression by fractional power of Λ/q_T

Conclusions

- various two-parton correlations can affect rate and kinematic distributions of double parton interactions
- correlations in $\boldsymbol{b}$ dependence, between x_1, x_2, and between x_1, x_2 and $\boldsymbol{b}$
- correlations in spin and color
  give rise to new double parton dist's
  not included in usual double scattering formula
- for x_i in valence region expect strong correlations between x_1, x_2, $\boldsymbol{b}$
  and strong spin correlations
  situation for small x_i not known
- note: at small $\boldsymbol{b}$ double parton distr's
  dominated by splitting graphs
  give strong correlations in x_1, x_2, spin and color



- physics of color correlations closely connected with Sudakov factors