Multiparton interactions
Part 3

M. Diehl

Deutsches Elektronen-Synchroton DESY

Correlations between Partons in Nucleons
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HELMHOLTZ
GEMEINSCHAFT

DESY

Approximating DPDs by single-parton distributions

- if neglect correlations between two partons

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

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

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

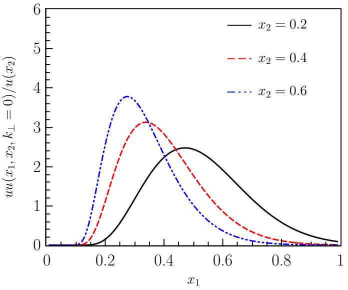
if $F(\boldsymbol{b})$ is Fourier trf. of dipole then $41\,\text{mb} \to 36\,\text{mb}$

complete independence between two partons is disfavored
or something is systematically wrong with σ_{eff} extractions

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 $\int d^2\boldsymbol{y}\; F_{uu}(x_1, x_2, \boldsymbol{y}) / f_u(x_2)$
is x_2 independent if factorization holds

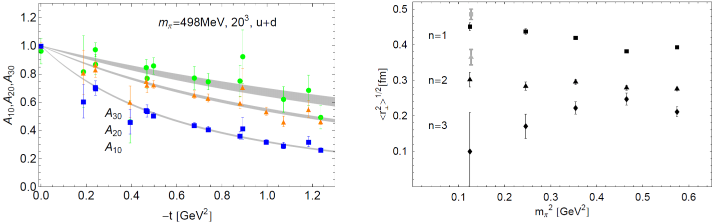
- unknown: size of correlations when one or both of x_1, x_2 small

Correlations involving x and $\boldsymbol{b}$

- have some knowledge of single-parton distribution $f(x, \boldsymbol{b})$ from studies of parton distributions (exclusive processes, lattice, 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 $x \sim 10^{-3}$
    $\to$ weak but nonzero correlation between x and $\boldsymbol{b}$
  - lattice simulations $\to$ strong decrease of $\langle \boldsymbol{b}^2 \rangle$ with x above ~ 0.1
    seen by comparing moments $A_{n0}(t) = \int dx\, x^{n-1} H(x, \xi, t)$



LHCP Collaboration, in Ph. Hägler, arXiv:0912.4583

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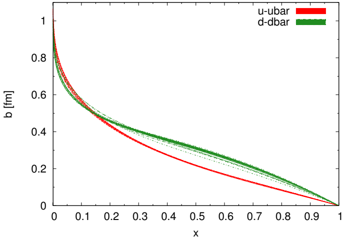
  - indirect determination M.D., P. Kroll 2013
    fit ansatz $H^{q-\bar{q}}(x, \xi = 0, t) = q_{\text{val}}(x) \exp\big[t f_q(x)\big]$
    to e.m. form factors of proton and neutron



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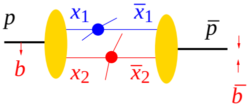
- expect similar correlations between x_i and $\boldsymbol{b}$ in two-parton dist's
  even if $F(x_1, x_2, \boldsymbol{y}) \approx \int d^2\boldsymbol{b}\, f(x_2, \boldsymbol{b})\, f(x_1, \boldsymbol{b} + \boldsymbol{y})$ does not hold

- if interaction 2 produces high-mass system
  $\to$ have large $x_2, \bar{x}_2$
  $\to$ smaller $\boldsymbol{b}$, $\bar{\boldsymbol{b}}$ $\to$ more central collision
  $\to$ secondary interactions enhanced



Frankfurt, Strikman, Weiss 2003
study in Pythia 8: Corke, Sjöstrand 2011 $\to$ tunes 4C, 4C*

Interlude: first look at scale evolution

for collinear distributions

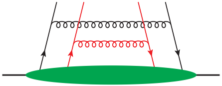
- if define DPD from renormalized twist-two operators $\mathcal{O}$ in analogy with usual PDFs

$$F(x_1, x_2, \boldsymbol{y}; \mu) \sim \langle p|\mathcal{O}_1(\mathbf{0}; \mu)\, \mathcal{O}_2(\boldsymbol{y}; \mu)|p\rangle \qquad f(x; \mu) \sim \langle p|\mathcal{O}(\mathbf{0}; \mu)|p\rangle$$

$\Rightarrow$ have

separate DGLAP evolution for partons 1 and 2

$$\frac{d}{d \log \mu} F(x_i, \boldsymbol{y}) = P \otimes_{x_1} F + P \otimes_{x_2} F$$

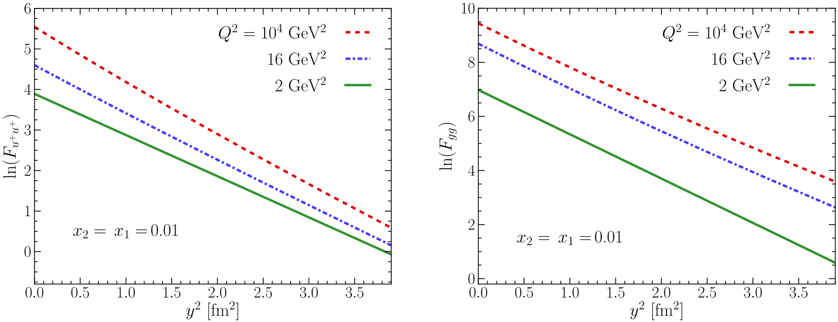


μ dep'ce of DPD $\leftrightarrow$ μ dep'ce of hard-scattering procs. at higher order

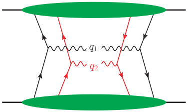
- if $\boldsymbol{y}$ dep'ce does not factorize
  $\rightarrow$ $F(x_i, \boldsymbol{y}; \mu)$ has different shape in x_1, x_2 for each $\boldsymbol{y}$
  $\rightarrow$ nontrivial behavior under evolution
- if DPDs for q and g have different $\boldsymbol{y}$ dependence
  $\rightarrow$ amount of quark-gluon mixing depends on $\boldsymbol{y}$
  $\rightarrow$ nontrivial behavior under evolution

Interlude: first look at scale evolution

- model study of evolution effects M.D., T. Kasemets, S. Keane 2014



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 — already pointed out by Mekhfi (1985)
  - quarks: longitudinal and transverse pol., e.g.

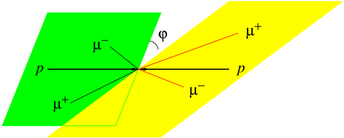
$$F_{\Delta q \Delta q} : \Gamma_1 = \Gamma_2 = \tfrac{1}{2}\gamma^+ \gamma_5 \qquad \Leftrightarrow \quad q_1^\uparrow q_2^\uparrow + q_1^\downarrow q_2^\downarrow - q_1^\uparrow q_2^\downarrow - q_1^\downarrow q_2^\uparrow$$

  - gluons: longitudinal and linear pol.
- can be included in factorization formula

$$\text{e.g.} \quad F_{\bar{q}g}\, F_{qg}\, \sigma(q\bar{q} \to Z)\, \sigma(gg \to 2 \text{ jets}) + F_{\Delta\bar{q}\Delta g}\, F_{\Delta q \Delta g}\, \Delta\sigma(q\bar{q} \to Z)\, \Delta\sigma(gg \to 2 \text{ jets})$$

- if spin correlations are large → large effects for rate and final state distributions of double hard scattering

Spin correlations



- 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 of lepton rapidities and p_T
- transverse quark spin correlations
  ⇝ azimuthal correlation between lepton planes
  ⇝ two hard scatters are not independent
- expect similar effects for other processes (esp. for jets)
- note: independent scattering planes sometimes assumed as criterion to characterize double parton scattering

How large are spin correlations in the proton?

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

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

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

- large effects expected in valence quark region
  toy model: $SU(6)$ symmetric proton wave function

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

gives

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

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

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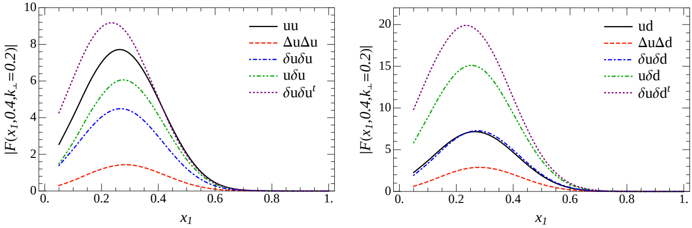
  toy model: study in bag model Chang, Manohar, Waalewijn: arXiv:1211:3132

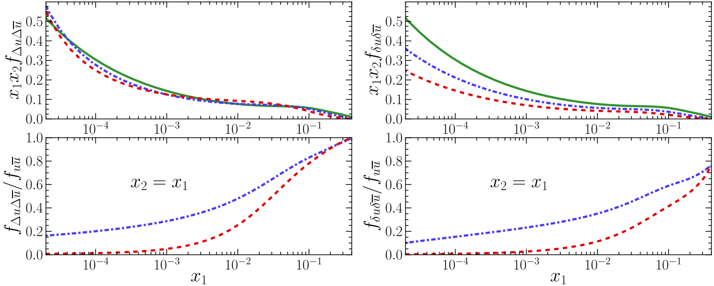


plots show $F(x_1, x_2 = 0.4, k_\perp)$ for different pol. combinations
$k_\perp = \boldsymbol{r} =$ Fourier conjugate to $\boldsymbol{y}$

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

How large are spin correlations in the proton?

- assume maximal polarization at starting scale, see how quickly evolution decreases spin correlations M.D., T. Kasemets, S. Keane 2014



$Q^2 = 1\,\mathrm{GeV}^2$, $16\,\mathrm{GeV}^2$, $10^4\,\mathrm{GeV}^2$

- at $Q^2 = 1$ take unpol. DPD as product of two PDFs

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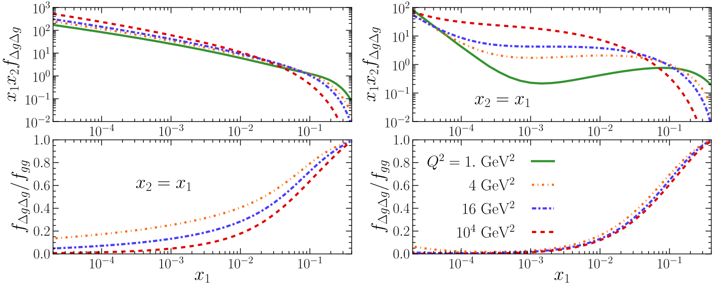

left: GJR 08 LO right: MSTW 08 LO

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- results for gluons strongly depend on chosen PDF

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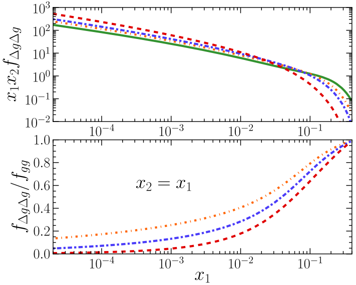

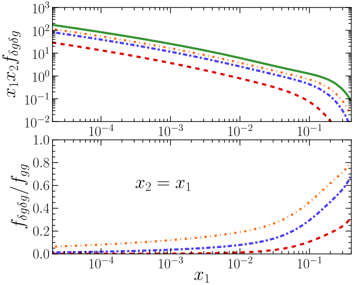

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