Double Parton Scattering

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Outline

- Qualitative picture of double parton scattering
- DPDFs
- Flavor, spin and color correlations
- Bag model estimates

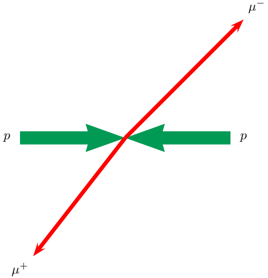
avoid technical details.

References

- AM and W. J. Waalewijn
  arXiv:1202.3794 [hep-ph]
  arXiv:1202.5034 [hep-ph]
- M. Diehl, D. Ostermeier, and A. Schäfer
  arXiv:1111.0910 [hep-ph]
- Previous Work
  - Politzer
  - Paver and Treleani
  - Mekhfi
  - Berger, Jackson, Quackenbush, Shaughnessy
  - Kirschner, Shelest, Snigirev, Zinovev
  - Gaunt and Stirling

Drell-Yan: Single Parton Scattering (SPS)

$$\text{Drell-Yan}: \quad p_1 p_2 \to \ell^+ \ell^-$$
$$W \text{ production}: \quad p_1 p_2 \to W \to \ell\nu$$

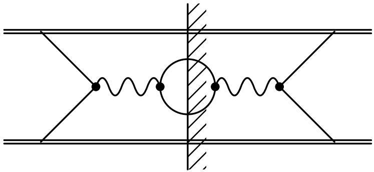


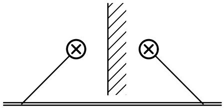
$$\mathbf{p}_\perp(\mu^+) \;=\; -\mathbf{p}_\perp(\mu^-)$$

There can be a longitudinal boost of the dilepton system

PDFs

$M^2 = s x_1 x_2$ and $e^{2Y} = x_1/x_2$ can measure x_1 and x_2





single PDF (sPDF) for each beam particle.

$$\frac{\mathrm{d}\sigma^{\mathrm{SPS}}}{\mathrm{d}x_1\mathrm{d}x_2} = \frac{\hat{\sigma}_0}{x_1\, x_2}\left[f_q(x_1)f_{\bar{q}}(x_2) + f_{\bar{q}}(x_1)f_q(x_2)\right]$$

$$\hat{\sigma}_0 = \frac{4\pi\alpha^2 Q_q^2}{3N_c Q^2}$$

Factorization of the cross section.

PDFs

PDFs are non-perturbative quantities.

Determine them from experiment — Since they are universal, they can be measured in DIS and used in Drell-Yan, W production, etc.

Various models (bag model, etc.) have been used to compute PDFs.

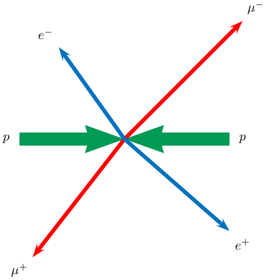
Difficult to compute on the lattice because they are light-cone correlation functions.

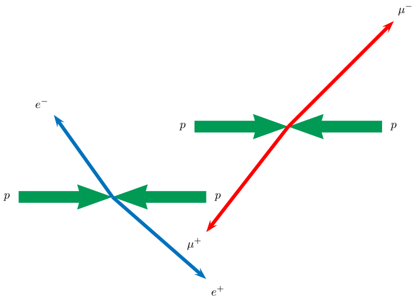
Double Parton Scattering (DPS)

1

Double Drell-Yan : $p_1 p_2 \to \ell^+ \ell^- \ell^+ \ell^-$

WW production : $p_1 p_2 \to W^+ W^+ \to \ell\nu\ell\nu$





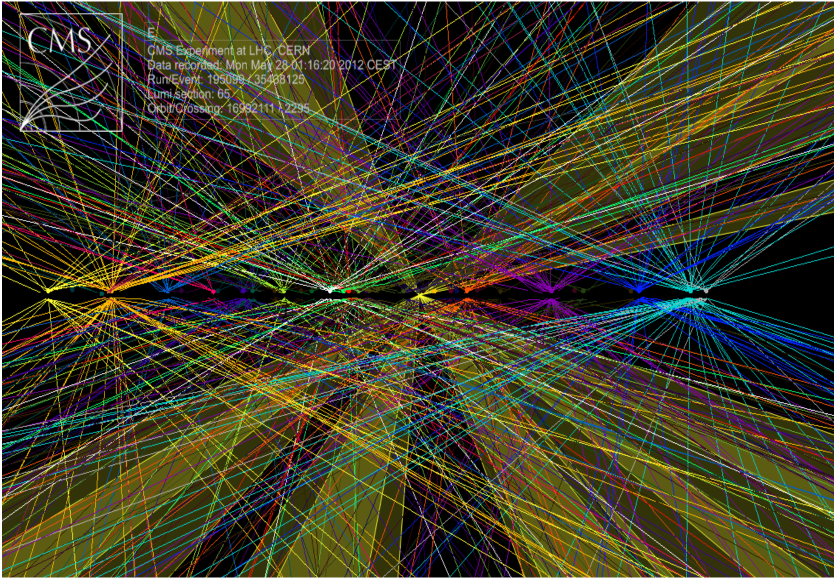
2 simultaneous hard interactions.

[Not pile-up: next page]

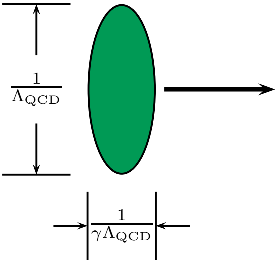
$$\begin{aligned} \mathbf{p}_\perp(\mu^+) &= -\mathbf{p}_\perp(\mu^-) \\ \mathbf{p}_\perp(e^+) &= -\mathbf{p}_\perp(e^-) \end{aligned}$$

4 lepton final state from single parton scattering only has total $p_\perp = 0$.

CMS event


CMS
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

Qualitative Picture



Hadrons longitudinally contracted by $\gamma \sim 4000$ at LHC

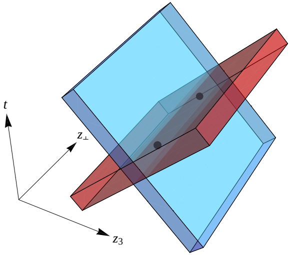
longitudinal size $1/(\gamma\Lambda_{\rm QCD}) \sim 1/Q$.

Transverse size $1/\Lambda_{\rm QCD}$.

Incoming parton flux $\propto \Lambda_{\rm QCD}^2$ (inversely proportional to transverse area)

Spacetime view of Scattering

Two hard interactions can be separated by $1/\Lambda_{\rm QCD}$ in $\mathbf{z}_\perp$



Two partons need to be within area $1/Q^2$ of each other to interact.

Probability to collide $\Lambda_{\rm QCD}^2/Q^2$

$$\text{single collision}: \frac{\Lambda_{\rm QCD}^2}{Q^2}\frac{1}{\Lambda_{\rm QCD}^2} \qquad \text{double collision}: \left(\frac{\Lambda_{\rm QCD}^2}{Q^2}\right)^2 \frac{1}{\Lambda_{\rm QCD}^2}$$

DPS is Higher Twist: $\Lambda_{\rm QCD}^2/Q^2$ suppressed (Politzer)

Rates

Rate is small

$$\frac{\sigma(pp \to WW : \text{DPS})}{\sigma(pp \to W)} \sim \frac{\Lambda_{\text{QCD}}^2}{M_W^2} \sim 10^{-6}$$

But we are comparing to big cross-sections at the LHC

DPS gives some interesting signatures

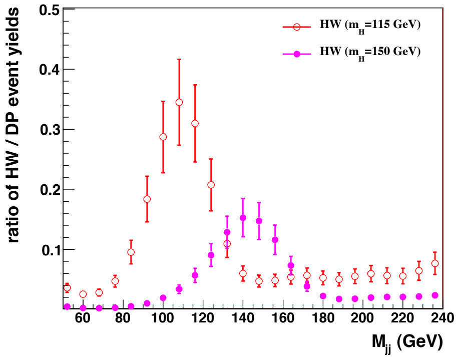
- $u\bar{d}u\bar{d} \to W^+W^+$ same sign diboson and dilepton production background to searches for new physics
- Already seen in same sign dilepton searches by CMS
- Also measured by ATLAS

Estimate of Rate

Del Fabbro, Treleani; Hussein; Berger, Jackson, Shaughnessy

Badurin, Golovanov, Skachkov [1011.2186]

light Higgs searches in $pp \to WH \to \ell\nu b\bar{b}$



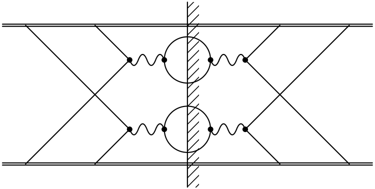
Ratio of *HW* rate to the DPS background in the $\ell\nu b\bar{b}$ channel.

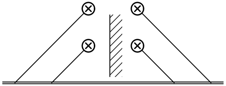
dPDFs

can measure 4 momentum fractions: x_1 collides with x_3 and x_2 with x_4

$$M_1^2 = s x_1 x_3, \qquad e^{2Y_1} = x_1/x_3, \qquad M_2^2 = s x_2 x_4, \qquad e^{2Y_2} = x_2/x_4$$

$$\frac{\mathrm{d}\sigma^{\mathrm{DPS}}}{\mathrm{d}x_1 \mathrm{d}x_2 \mathrm{d}x_3 \mathrm{d}x_4} \sim \hat{\sigma}_0^2 \int \mathrm{d}^2\mathbf{z}_\perp \, F(x_1, x_2, \mathbf{z}_\perp) F(x_3, x_4, \mathbf{z}_\perp) \,.$$

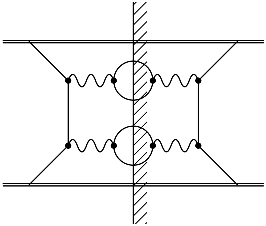




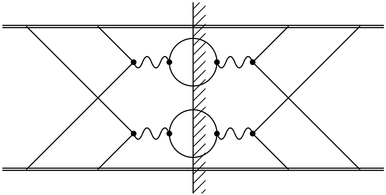
Described by double parton distribution functions (dPDFs)

Overlap with SPS

Double Drell-Yan or $W + 2$ jets

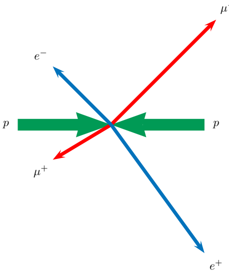


single parton scattering

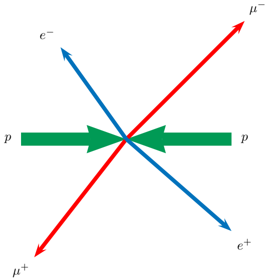


double parton scattering

- Drell-Yan rate: $\sigma_0 \sim \alpha^2/Q^2$
- SPS Double Drell-Yan rate: $[\alpha/(4\pi)]^2\ \sigma_0$
- DPS Double Drell-Yan rate: $\left(\sigma_0\, \Lambda^2_{\rm QCD}\right)\ \sigma_0$
- radiative corrections vs power corrections: $\alpha/(4\pi)$ vs $\Lambda^2_{\rm QCD}/Q^2$



SPS



DPS

- DPS: the lepton pairs have to have opposite $\mathbf{p}_\perp$
- SPS: can have acoplanar leptons of the same type

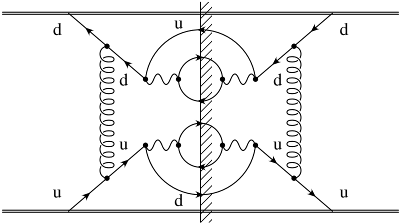
$$\Delta_{\rm jets} = \left|\vec{p}_{1,T} + \vec{p}_{2,T}\right| \qquad \Delta_{\rm jets}^{\rm normalized} = \frac{\left|\vec{p}_{1,T} + \vec{p}_{2,T}\right|}{\left|\vec{p}_{1,T}\right| + \left|\vec{p}_{2,T}\right|}$$

- DPS enchanced near $\Delta_{\rm jets} = 0$
- SPS in $\Delta_{\rm jets} \sim \Lambda_{\rm QCD}$ region $\Lambda_{\rm QCD}^2/Q^2$ suppressed by phase space cut. Same size as DPS.
- total rate = SPS + DPS cannot be separated

Interesting DPS process: Same sign W^+W^+

W^+W^+: charge 2 cannot be produced from $q\bar{q}$

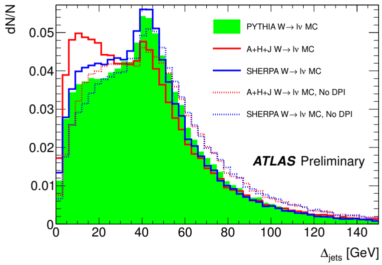
$u\overline{d} \to W^+W^+\overline{u}d$

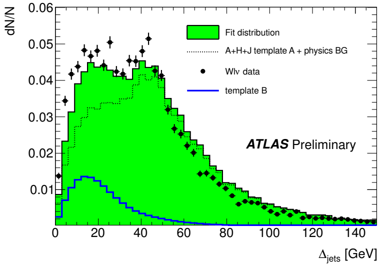


- SPS contribution, but with two extra jets in the final state.
- SPS has an extra $[\alpha_s/(4\pi)]^2$ suppression
- DPS dominates in $\Delta_{\rm jets} \sim \Lambda_{\rm QCD}$ region

DPS has been observed at the LHC

[ATLAS-CONF-2011-160]





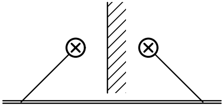
- $pp \to W + 2$ jets with $p_T^{\rm jet,lepton} > 20\,$GeV
- $\Delta_{\rm jets} = \left|\vec{p}_{1,T} + \vec{p}_{2,T}\right|$
- Fit to shape of SPS and DPS from Monte Carlo
- Find the fraction of DPS events is $f_{\rm DPS} = 16\%$
- DPS observed in 33 pb^{-1} of data

PDF definition

Parton distribution functions (PDF):

$$f(x) \;=\; \int \frac{\mathrm{d}z^+}{4\pi} e^{-ixp^- z^+/2} \, \langle p| \; \overline{\psi}(z^+) \frac{\bar{n}\!\!\!/}{2} \psi(0) \; |p\rangle$$

Light-cone fourier transform of two-point function.



dPDF definition

Given in terms of double parton distribution functions (dPDF)

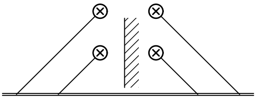
$$F(x_1, x_2, \mathbf{z}_\perp)$$

for example:

$$F^1_{qq}\left(x_1, x_2, \mathbf{z}_\perp\right) = -4\pi\, p^- \int \frac{\mathrm{d}z_1^+}{4\pi} \frac{\mathrm{d}z_2^+}{4\pi} \frac{\mathrm{d}z_3^+}{4\pi}\, e^{-ix_1 p^- z_1^+/2}\, e^{-ix_2 p^- z_2^+/2}\, e^{ix_1 p^- z_3^+/2}$$
$$\langle p| \left\{ \overline{\mathcal{T}} \left[\overline{\psi}(z_1^+, 0, \mathbf{z}_\perp) \Gamma_1 T_1 \right]_a \left[\overline{\psi}(z_2^+, 0, \mathbf{0}_\perp) \Gamma_2 T_2 \right]_b \right\} \mathcal{T} \left\{ \psi_a(z_3^+, 0, \mathbf{z}_\perp) \psi_b(0) \right\} |p\rangle$$

Like a PDF at $\mathbf{0}_\perp$ and one at $\mathbf{z}_\perp$.

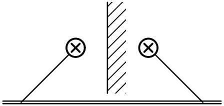
Annihilate quarks at 0 and $\mathbf{z}_\perp$ and put them back some distance along the light cone.



$$\frac{\mathrm{d}\sigma^{\mathsf{DPS}}}{\mathrm{d}x_1\mathrm{d}x_2\mathrm{d}x_3\mathrm{d}x_4} \sim \hat{\sigma}_0^2 \int \mathrm{d}^2\mathbf{z}_\perp\, F(x_1, x_2, \mathbf{z}_\perp) F(x_3, x_4, \mathbf{z}_\perp)$$

- dPDF is probability for simultaneously finding two partons
  - with momentum fractions x_1, x_2
  - transverse separation $\mathbf{z}_\perp$ (or momentum $\mathbf{k}_\perp$)
  - flavor, spin and color correlations to be discussed

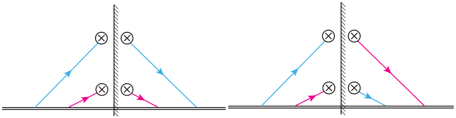
PDF



$$f(x) \quad \propto \quad \langle p| \; \overline{\psi}(z^+)\,\Gamma\; T\; \psi(0)\; |p\rangle$$

- $T = 1$ for color singlet
- $\Gamma = \bar{\not{n}}$: unpolarized distribution $q(x)$
- $\Gamma = \bar{\not{n}}\gamma_5$: polarized distribution $\Delta q(x)$
  needs a longitudinally polarized beam
- $\Gamma = i\sigma_\perp^{\bar{n}i}\gamma_5$: transversity distribution $h_1(x)$, $\delta q(x)$
  needs a transversely polarized beam

dPDF



$$\propto \overline{\psi}\, \Gamma_1\ T_1\ \psi\ \overline{\psi}\, \Gamma_2\ T_2\ \psi$$

- $1 \otimes 1$ and $T \otimes T$: color correlations
- $\Gamma \otimes \Gamma$: spin correlations even for unpolarized target
- qq, $\Delta q \Delta q$, $\delta q \delta q$

e.g. $ud(x_1, x_2, k_\perp)$, $\Delta u \Delta d(x_1, x_2, k_\perp)$, etc.

Flavor, Spin and Color Correlations

- uu vs ud vs dd measures flavor correlations
  e.g. $p = uud$, so dd should be suppressed relative to uu and ud
- $\Delta q \Delta q$ measures longitudinal spin correlations
  e.g. $u\uparrow$ with $u\uparrow$ vs $u\downarrow$
- $\delta q \delta q$ measures transverse spin correlations
- F^1 has $1 \otimes 1$ color structure, and F^8 has $T \otimes T$ color structure measure diparton color correlations

  Can measure if diquarks are in a color **6** or $\overline{\mathbf{3}}$

  Can measure if $q\overline{q}$ are in a color **1** or **8**

QCD Analysis

- Have a systematic QCD formulation
- Precise operator definition of dPDFs in QCD
- Flavor, Spin, Color and Interference effects
- Soft functions
- Can calculate evolution (analogous to Altarelli-Parisi)
- Can compute radiative corrections (loop corrections)

rapidity divergences need to be regulated for the $T \otimes T$ dPDFs which exchange color.

[Chiu, Jain, Neill, Rothstein, `1104.0881, 1202.0814`]

How do you measure them?

Short answer: the same way PDFs were measured

Much more difficult, since many more DPDFs, and the cross-section is smaller.

Can disentangle the pieces by looking at angular dependence.

Look at double Drell-Yan and compare γ^* vs Z^* vs W^*.

What has been done?

[Paver, Treleani]

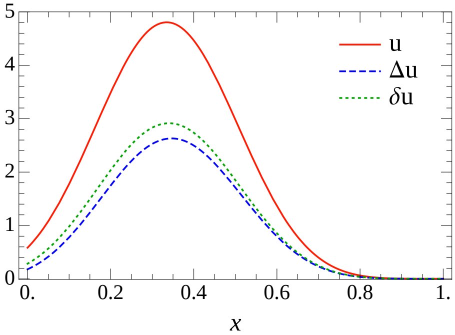
$$d\sigma = \int d^2\mathbf{z}_\perp \sum_{ijkl} F_{ij}(x_1, x_2, \mathbf{z}_\perp) F_{kl}(x_3, x_4, \mathbf{z}_\perp) \hat{\sigma}_{ik}(x_1 x_3 s) \hat{\sigma}_{jl}(x_2 x_4 s)$$

- Commonly used assumptions
  - x_i and $\mathbf{k}_\perp$ uncorrelated: $F(x_1, x_2, \mathbf{k}_\perp) = F(x_1, x_2)\widetilde{F}(\mathbf{k}_\perp)$
  - uncorrelated partons $F(x_1, x_2) = f(x_1) f(x_2)$
  - neglect color or spin correlations
  - $$\frac{d\sigma^{\text{DPS}}}{dx_1 dx_2 dx_3 dx_4} \sim \frac{1}{\sigma_{\text{eff}}} \frac{d\sigma^{\text{SPS}}}{dx_1 dx_3} \frac{d\sigma^{\text{SPS}}}{dx_2 x_4}$$ $$\frac{1}{\sigma_{\text{eff}}} = \int d^2\mathbf{k}_\perp \widetilde{F}(\mathbf{k}_\perp)^2 \sim \Lambda^2_{\text{QCD}}$$
  - experimentally $\sigma_{\text{eff}} \sim 1 - 15$ mb

Bag Model

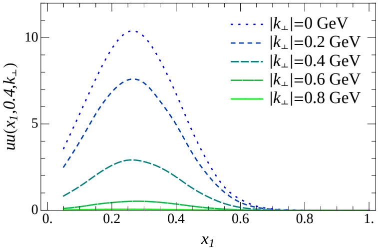
Gives a rough idea of DPDFs.

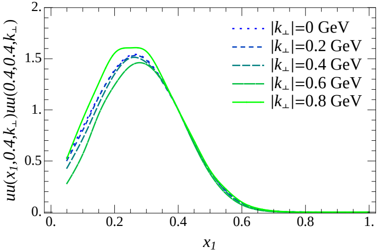
First look at regular sPDF:



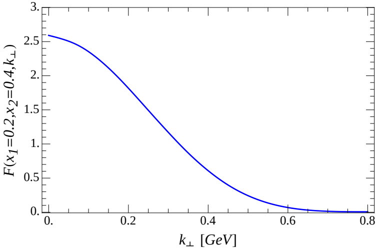
Often taken as input PDF at a low scale $\mu \sim 1 - 2\,\text{GeV}$, and then evolved using DGLAP.

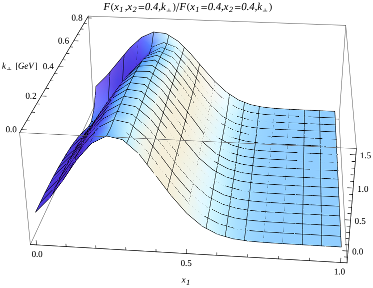
$k_\perp - x$ Correlation





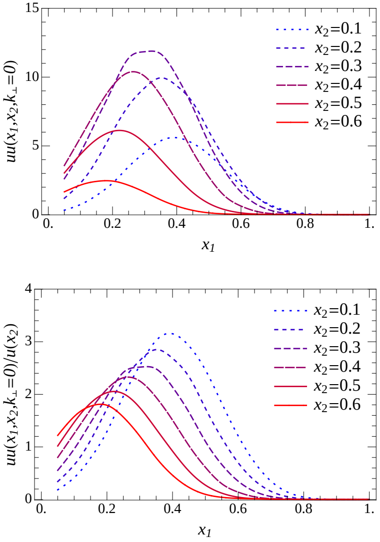
$k_\perp - x$ Correlation





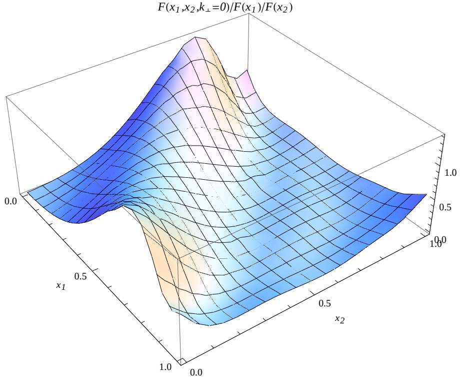
Weak $k_\perp$ correlation with x, $F(x_1, x_2, k_\perp) \approx F(x_1, x_2)\widetilde{F}(k_perp)$.

$x_1 - x_2$ Correlation



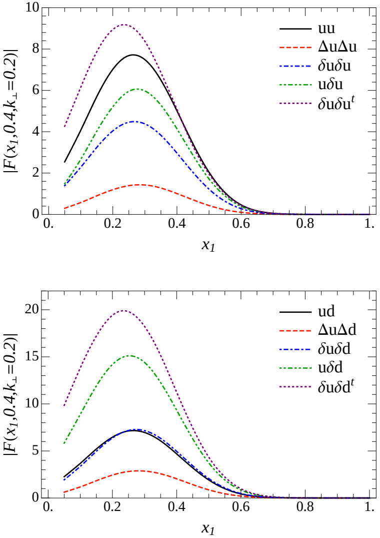
Strong correlation between x_1 and x_2. $F(x_1, x_2) \neq f(x_1)f(x_2)$.

$x_1 - x_2$ Correlation



If x_1 is big, x_2 is small, as one might expect.

Spin Correlations



The spin-correlations are not small.

Conclusions

- DPS already measured at the LHC
- Relevant for some important searches
- Consistent formalism including radiative corrections
- dPDFs have to eventually be extracted from data
  - similar to Drell-Yan or DIS
  - start with models
  - models for PDFs eventually replaced by those extracted from data
- Can be used to study quark flavor, spin and color correlations.