3D structure of the proton from double parton distribution functions

Matteo Rinaldi

In collaboration with:

Federico Alberto Ceccopieri, Sergio Scopetta, Marco Traini, Vicente Vento

1Dep. of Theor. Physics, Valencia University, IFIC and CSIC, Valencia, Spain

2IFPA, Université de Liège, B4000, Liège, Belgium

3Dep. of Physics and Geology, Perugia University and INFN, Perugia, Italy

4Dep. of Physics Trento University and INFN-TIFPA, Italy
Outlook

- **Introduction:**
  - Double parton scatterings (DPS) & **double parton distribution functions** (dPDFs)
  - Double parton distribution functions & 3D structure of the proton
  - Double parton correlations (DPCs) in double parton distribution functions

- **dPDFs in constituent quark models, a proton “imaging” via DPS?**

- **Analysis of correlations in dPDFs**

- **Calculation and analyses of experimental observables: effects of correlations**

- **Conclusions**
DPS and dPDFs from multiparton interactions

Multiparton interaction (MPI) can contribute to the, $pp$ and $pA$, cross section @ the LHC:

The cross section for a DPS event can be written in the following way:

$$d\sigma = \frac{1}{S} \sum_{i,j,k,l} \hat{\sigma}_{ij}(x_1, x_3, \mu_A) \hat{\sigma}_{kl}(x_2, x_4, \mu_B) \int d\tilde{z} \left[ F_{ik}(x_1, x_2, z, \mu_A, \mu_B) F_{jl}(x_3, x_4, z, \mu_A, \mu_B) \right]$$

DPS processes are important for fundamental studies, e.g. the background for the research of new physics and to grasp information on the 3D PARTONIC STRUCTURE OF THE PROTON.
How 3-Dimensional structure of a hadron can be investigated?

The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SiDIS, DVCS, double parton scattering ...), measuring different kind of parton distributions, providing different kind of information:

**DVCS**  
Generalized Parton Distributions in impact parameter space  
\[ \mathcal{H}(x_1, b_\perp) \quad \mathcal{E}(x_1, b_\perp) \ldots \]

- longitudinal momentum fraction carried by the parton
- transverse distance between the parton and center of proton

**SIDIS**  
Transverse Momentum Dependent parton distribution functions  
\[ f_1(x_1, k_\perp) \quad g_{1L}(x_1, k_\perp) \quad h_1(x_1, k_\perp) \quad f_{1T}(x_1, k_\perp) \ldots \]

- transverse component of the parton momentum

**DPS**  
Double Parton Distribution Functions  
\[ F_{UU}(x_1, x_2, z_\perp) \quad F_{LL}(x_1, x_2, z_\perp) \ldots \]

dPDFs are in principle sensitive to DPCs
How 3-Dimensional structure of a hadron can be investigated?

The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SIDIS, DVCS, double parton scattering …), measuring different kind of parton distributions, providing different kind of information. The parton distribution puzzle is:

- **PDFs**: \( f \) \( dx \)
- **TMDs**: \( f \) \( d^2k_\perp \)
- **GTMDs**: \( \Delta = 0 \)
- **Phase-space (Wigner) distribution**: \( \xi = 0 \)
- **Charges**
How 3-Dimensional structure of a hadron can be investigated?

The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SIDIS, DVCS, double parton scattering ...), measuring different kind of parton distributions, providing different kind of information. The parton distribution puzzle is:

- 2+1D
- 2+0D
- 2+3D

**LFWFs**

**Phase-space (Wigner) distribution**

**GTMDs**

**TMDs**

**FFs**

**GPDs**

**PDFs**

**dPDFs**

**Charges**

**dx**

**d^2z_1**

**dx_2**

**\Delta = 0**

**f dx**

**f d^2k_\perp**
Parton correlations and dPDFs

At LHC kinematics it is often used a factorized form of the dPDFs: \( (x_1, x_2) \rightarrow z_\perp \) factorization:

\[
F_{ij}(x_1, x_2, z_\perp, \mu) = F_{ij}(x_1, x_2, \mu) T(z_\perp, \mu)
\]

and \( x_1, x_2 \) factorization:

\[
\text{dPDF (2-Body)} \quad \text{PDF (1-Body)}
\]

\[
F_{ij}(x_1, x_2, \mu) = q_i(x_1, \mu) q_j(x_2, \mu) \theta(1 - x_1 - x_2)(1 - x_1 - x_2)^n
\]

* Here and in the following: \( \mu = \mu_A = \mu_B \)

In this scenario, parton correlations inside the proton are neglected. NO CORRELATION ANSATZ

In principle, correlations are present! NO NEW INFORMATION!

In principle, correlations are present!

dPDFs are non-perturbative quantities

DPCs not calculated directly from QCD

HOW CAN WE BE SURE OF THE ACCURACY OF SUCH APPROXIMATION?

WHAT CAN WE LEARN ABOUT dPDFs AND THE PROTON STRUCTURE?
DPCs in constituent quark models (CQM)

- Main features:
  - potential model
  - effective particles
  - particles are strongly bound and correlated

- CQM are a proper framework to describe DPCs, but their predictions are reliable ONLY in the valence quark region at low energy scale, while LHC data are available at small $x$.

- At very low $x$, due to the large population of partons, the role of correlations may be less relevant. BUT theoretical microscopic estimates are necessary.

**pQCD evolution of the calculated dPDFs is necessary to move towards the experimental kinematics:**

1) dPDF evaluated at the initial scale of the model

2) dPDF evaluated at high generic scale

CQM calculations are able to reproduce the gross-feature of experimental PDFs in the valence region. CQM calculations are useful tools for the interpretation of data and for the planning of measurements of unknown quantities (e.g., TMDs in SiDIS, GPDs in DVCS...)

Similar expectations motivate the present investigation of dPDFs.
The Light-Front approach

Relativity can be implemented, for a CQM, by using a Light-Front (LF) approach yielding, among other good features, the correct support. In the Relativistic Hamiltonian Dynamics (RHD) of an interacting system, introduced by Dirac (1949), one has:

\[ a^\pm = a_0 \pm a_3 \]

- Full Poincaré covariance
- fixed number of on-mass-shell particles

Among the 3 possibles forms of RHD we have chosen the LF one since there are several advantages. The most relevant are the following:

- 7 Kinematical generators (maximum number): i) three LF boosts (at variance with the dynamical nature of the Instant-form boosts), ii) \( P^+ \), \( P^- \), iii) Rotation around z.

- The LF boosts have a subgroup structure, then one gets a trivial separation of the intrinsic motion from the global one (as in the non relativistic (NR) case).

- By using the Bakamjian-Thomas construction of the Poincaré generators, it is possible to obtain a Mass equation, Schrödinger-like. A clear connection to the NR limit.

- The IMF (Infinite Momentum Frame) description of DIS is easily included.

The LF approach is extensively used for hadronic studies (e.m. form factors, PDFs, GPDs, TMDs...).
Extending the procedure developed in S. Boffi, B. Pasquini and M. Traini, Nucl. Phys. B 649, 243 (2003) for GPDs, we obtained the following expression of the dPDF in momentum space, often called \(_2\)GPDs from the Light-Front description of quantum states in the intrinsic system:

\[
F_{ij}(x_1, x_2, k_\perp) = 3(\sqrt{3})^3 \int \prod_{i=1}^{3} d\vec{k}_i \delta \left( \sum_{i=1}^{3} \vec{k}_i \right) \Phi^*(\{\vec{k}_i\}, k_\perp) \Phi(\{\vec{k}_i\}, -k_\perp)
\]

Conjugate to \(\bar{z}_\perp\) \(\times \delta \left( x_1 - \frac{k_1^+}{M_0} \right) \delta \left( x_2 - \frac{k_2^+}{M_0} \right)\)

\[
\Phi(\{\vec{k}_i\}, \pm k_\perp) = \Phi \left( \vec{k}_1 \pm \frac{\vec{k}_\perp}{2}, \vec{k}_2 \pm \frac{\vec{k}_\perp}{2}, \vec{k}_3 \right)
\]

\[
\Phi(\vec{k}_1, \vec{k}_2, \vec{k}_3) = D^{1/2}(R_{ii}(\vec{k}_1)) D^{1/2}(R_{ii}(\vec{k}_2)) D^{1/2}(R_{ii}(\vec{k}_3)) \psi[i](\vec{k}_1, \vec{k}_2, \vec{k}_3)
\]

\(M_0 = \sum_i \sqrt{k_i^2 + m^2}\)

Now we need a model to properly describe the hadron wave function in order to estimate the LF \(_2\)GPDs.

\[x_1 + x_2 > 1 \Rightarrow F_{ij}(x_1, x_2, k_\perp) = 0\]

GOOD SUPPORT

Transversity2017
Matteo Rinaldi
What we would like to learn: partonic mean distance

Since, in coordinates space, dPDFs get a number density interpretation, in principle one can calculated the mean distance between partons!

For example, for 2 gluons perturbatively generated:

1) HP model

2) HO model

\[ x_1 = 10^{-4} \text{ and } x_2 = 10^{-2} \]

\[ \vec{b}_\perp = \vec{z}_\perp \]

One can also define, the mean distance \((x_1 - x_2)\) distribution as follows:

\[
\langle d^2 \rangle^{ij}_{x_1, x_2} = \frac{\int d^2b_\perp b_\perp^2 F_{ij}(x_1, x_2, b_\perp)}{\int d^2b_\perp F_{ij}(x_1, x_2, b_\perp)}
\]

For example, for 2 gluons and two different models, one gets:

\[ \sqrt{\langle d^2 \rangle^{10^{-2}, 10^{-2}}_{10^{-4}, 10^{-4}}} = \begin{cases} 0.365 \text{ fm} \quad \text{HP} \\ 0.310 \text{ fm} \end{cases} \]

\[ \sqrt{\langle d^2 \rangle^{10^{-4}, 10^{-4}}_{10^{-4}, 10^{-4}}} = \begin{cases} 0.391 \text{ fm} \quad \text{HP} \\ 0.393 \text{ fm} \quad \text{HO} \end{cases} \]
What we would like to learn: partonic mean distance

Since, in coordinates space, dPDFs get a number density interpretation, in principle one can calculated the mean distance between partons!

For example, for 2 gluons perturbatively generated:

\[ \langle d^2 \rangle_{x_1, x_2} = \int d^2 b_\perp b^2_{\perp} F_{ij}(x_1, x_2, b_\perp) / \int d^2 b_\perp F_{ij}(x_1, x_2, b_\perp) \]

One can also define, the mean distance \( (x_1 - x_2) \) distribution as follows:

For example, for 2 gluons and two different models, one gets:

1) HP model

2) HO model

\[ x_1 = 10^4 \text{ and } x_2 = 10^2 \]

\[ \vec{b}_\perp = \vec{z}_\perp \]

\[ \sqrt{\langle d^2 \rangle_{10^{-2}}} \]

Are two slow partons closer then two slow partons?

\[ 0.365 \text{ fm} \]

\[ 0.310 \text{ fm} \]

\[ 0.391 \text{ fm} \]

\[ 0.393 \text{ fm} \]


The harmonic oscillator (HO)
What we learned:


Here, ratios, sensitive to correlations, are shown in order to test the factorization ansatz!
Use has been made of relativistic Hyper-Central CQM.

The $(x_1, x_2) - k_\perp$ and $x_1 - x_2$ factorizations are violated! Also for longitudinally polarized quarks.

The factorization ansatz is basically violated in all quark model analyses!
M.R., S. Scopetta and V. Vento, PRD 87, 114021 (2013)
The expressions of dPDF in the canonical (e.g. NR limit) and LF forms are quite similar for small values of $x$:

\[
F_{[NR]}(x_1, x_2, k_\perp) = \int d\vec{k}_1 d\vec{k}_2 f(\vec{k}_1, \vec{k}_2, k_\perp) \delta \left( x_1 - \frac{k_1^+}{M_P} \right) \delta \left( x_2 - \frac{k_2^+}{M_P} \right)
\]

\[
F_{[LF]}(x_1, x_2, k_\perp) = \int d\vec{k}_1 d\vec{k}_2 f(\vec{k}_1, \vec{k}_2, k_\perp) \left\langle SPIN \right| O_1(\vec{k}_1, \vec{k}_2, k_\perp) O_2(\vec{k}_1, \vec{k}_2, k_\perp) \left| SPIN \right\rangle \\
\times \delta \left( x_1 - \frac{k_1^+}{M_0} \right) \delta \left( x_2 - \frac{k_2^+}{M_0} \right)
\]

\[
f(\vec{k}_1, \vec{k}_2, k_\perp) = \text{product of the canonical proton wave-functions}
\]

For very small values of $x_1$ and $x_2$, the main difference in the two approaches, in the calculation of dPDF, is due to Melosh operators!

\[
DD^\dagger = \left\langle SU(6) \right| O_1(\vec{k}_1, \vec{k}_2, k_\perp) O_2(\vec{k}_1, \vec{k}_2, k_\perp) \left| SU(6) \right\rangle
\]

Correlations between $x_i$ and $k_\perp$
Melosh effects are studied in a quantity which simulates a ratio of DPS cross-sections:

\[ R_\sigma(x_1, x_2) = \frac{\int dB_{\perp} F_{[LF]}(x_1, x_2, b_{\perp})^2}{\int dB_{\perp} F_{[NR]}(x_1, x_2, b_{\perp})^2} \]

Full calculation of dPDFs within the LF approach

Calculation of dPDFs neglecting Melosh rotation

Notice: \( R_\sigma \sim 1 \) no correlation effects!

Similar results found at high energy scale for GLUONS!

Melosh effects are great at both low and high energies scales for different kind of partons!
Correlations at high energy scales: the $k_\perp = 0$ case


Usual in experimental analyses it is assumed that for gluons:

$$\text{ratio}_{gg} = \frac{F_{gg}(x_1, x_2, k_\perp = 0; Q^2)}{g(x_1; Q^2)g(x_2; Q^2)} \sim 1$$

Factorization ansatz

However, $\text{ratio}_{gg}$ can be sensitive to:

- **Perturbative correlations**
- **Non-perturbative correlations**

due to the different pQCD evolution scheme of PDFs and dPDFs

due to the difference of dPDFs and the product of PDFs at the hadronic scale

Only sea quarks and gluons perturbatively generated

Sea quarks and gluons perturbatively and non perturbatively generated (*details on backup slides)

$$\text{ratio}_{gg} \neq 1$$

CORRELATIONS
A fundamental tool for the comprehension of the role of DPS in hadron-hadron collisions is the so called “effective X-section”\(\sigma_{\text{eff}}\).

This object can be defined through a “pocket formula”:

\[
\sigma_{\text{eff}} = \frac{m}{2} \frac{\sigma_{pp}^{pp} \sigma_{pp}^{pp}}{\sigma_{\text{double}}^{pp}}
\]

### Sensitive to correlations?

Combinatorial factor

### Differential cross section for the process:

\[pp' \rightarrow A(B) + X\]

Differential cross section for a DPS event:

\[pp' \rightarrow A + B + X\]

#### EXPERIMENTAL STATUS:
- Difficult extraction, approved analysis for the same sign \(W\)’s production @LHC (RUN 2)
- the model dependent extraction of \(\sigma_{\text{eff}}\) from data is consistent with a “constant”, nevertheless there are large errorbars (uncorrelated ansatz assumed!)
- different ranges in \(X_i\) accessed in different experiments.

Within our CQM framework, we can calculate \(\sigma_{\text{eff}}\) without any approximations, studying the effect of correlations directly on \(\sigma_{\text{eff}}\).
The Effective X-section calculation


\[ \sigma_{\text{eff}} = \frac{m}{2} \frac{\sigma_A^{pp'}}{\sigma_B^{pp'}} \]

This quantity can be written in terms of PDFs and dPDFs (GPDs)

If factorization between dPDF and PDFs held:

\[ \sigma_{\text{eff}}(x_1, x'_1, x_2, x'_2) = \frac{\sum_{i,k,j,l} F_i(x_1) F_k(x'_1) F_j(x_2) F_1(x'_2) C_{ik} C_{jl}}{\sum_{i,j,k,l} C_{ik} C_{jl} \int F_{ij}(x_1, x_2; k_\perp) F_{kl}(x'_1, x'_2; -k_\perp) \frac{dk_\perp}{(2\pi)^2}} \]

Here the scale is omitted

\[ \sum_{i,k,j,l} \frac{\sigma_{\text{double}}^{pp'}}{C_{ik} C_{jl}} \int F_{ij}(x_1, x_2; k_\perp) F_{kl}(x'_1, x'_2; -k_\perp) \frac{dk_\perp}{(2\pi)^2} \]

Non trivial \( x \)-dependence

\[ \text{Constant value w.r.t. } x_i \]

\[ \text{NO CORRELATIONS!} \]

\[ \text{"EFFECTIVE FORM FACTOR"} \]
Our predictions of $\sigma_{eff}$, without any approximation, in the valence region at different energy scales:

$$\sigma_{eff}(x_1, x_2, \mu_0^2) \xrightarrow{\text{pQCD evolution of PDFs}} \sigma_{eff}(x_1, x_2, Q^2 = 250 \text{ GeV}^2)$$

Similar results obtained with dPDFs calculated within AdS/QCD soft-wall model

- $x_i$ dependence of $\sigma_{eff}$ may be model independent feature
- Absolute value of $\sigma_{eff}$ is a model dependent result
The Effective $\sigma$-section calculation


\[ \sigma_{\text{eff}} = \frac{m}{2} \frac{\sigma_{AP}^{pp'} \sigma_{BP}^{pp'}}{\sigma_{\text{double}}} \]

This quantity can be written in terms of PDFs and dPDFs ($G$PDs)

If factorization between dPDF and PDFs held:

Here the scale is omitted

\[ \sigma_{\text{eff}}(x_1, x'_1, x_2, x'_2) \rightarrow \sigma_{\text{eff}} = \left[ \int \frac{d\vec{k}_\perp}{(2\pi)^2} \bar{T}(\vec{k}_\perp) T(-\vec{k}_\perp) \right]^{-1} = \left[ \int d\vec{b}_\perp (T(\vec{b}_\perp))^2 \right]^{-1} \]

Constant value w.r.t. $x_i$

NO CORRELATIONS!
In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

"Same-sign $W$ boson pairs production is a promising channel to look for signature of double Parton interactions at the LHC."
In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

Can double parton correlations be observed for the first time in the next LHC run?
In order to estimate the role of double parton correlations we have used as input of dPDFs:

**Relativistic model:** QM  M. R., S. Scopetta, M. Traini and V. Vento, JHEP 12, 028 (2014)

Longitudinal and transverse correlations arise from the relativistic CQM model describing three valence quarks

These correlations propagate to sea quarks and gluons through pQCD evolution
Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC


**DPS cross section:**

$$\frac{d^4\sigma_{pp \rightarrow \mu^+\mu^-X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,l} \frac{1}{2} \int d^2\vec{b}_1 F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W)$$

**Kinematical cuts**

- $pp, \sqrt{s} = 13$ TeV
- $p_{T,\mu}^{\text{leading}} > 20$ GeV, $p_{T,\mu}^{\text{subleading}} > 10$ GeV
- $|p_{T,\mu}^{\text{leading}}| + |p_{T,\mu}^{\text{subleading}}| > 45$ GeV
- $|\eta_\mu| < 2.4$
- $20$ GeV $< M_{inv} < 75$ GeV or $M_{inv} > 105$ GeV

In order to estimate the role of double parton correlations, we have used as input of dPDFs:

Relativistic model: QM


$$\sigma^{++} + \sigma^{--} [\text{fb}] \sim 0.69 \pm 0.18 (\delta \mu_F) + 0.12 (\delta Q_0)$$

*details on the error in backup slides*
In order to understand whether correlations can be accessed in experimental observations, using dPDF evaluated within the QM model, the effective cross section has been calculated for this process and compared with its mean value:

\[
\langle \sigma_{\text{eff}} \rangle = 21.04^{+0.07}_{-0.07} (\delta Q_0)^{+0.06}_{-0.07}(\delta \mu_F) \text{ mb}.
\]

```
\tilde{\sigma}_{\text{eff}} = \frac{m \sigma_{pp}^A \sigma_{pp}^B}{2 \sigma_{\text{double}}}
```

*details in backup slides

```
\eta_1 \cdot \eta_2 \simeq \frac{1}{4} \ln \frac{x_1}{x_3} \ln \frac{x_2}{x_4}
```

“Assuming that the results of the first and the last bins can be distinguished if they differ by 1 sigma, we estimated that

\[
\mathcal{L} = 1000 \text{ fb}^{-1}
\]

is necessary to observe correlations”
In order to understand whether correlations can be accessed in experimental observations, using dPDF evaluated within the QM model, the effective cross section has been calculated for this process and compared with its mean value:

\[ \langle \sigma_{\text{eff}} \rangle = 21.04^{+0.07}_{-0.07} \langle \delta Q_0 \rangle^{+0.06}_{-0.07} \langle \delta \mu_F \rangle \text{ mb}. \]

| \text{\eta_1 \cdot \eta_2} | \begin{array}{c} \text{\tilde{\sigma}}_{\text{eff}} \\
\end{array} |
|-----------------|----------------|
| \begin{array}{c} 19 \\
20 \\
21 \\
22 \\
23 \\
24 \\
\end{array} | \begin{array}{c} 19 \\
20 \\
21 \\
22 \\
23 \\
24 \\
\end{array} |

\[ \begin{array}{c} \text{\tilde{\sigma}}_{\text{eff}} \\
\end{array} \]

Difference between green and red line is due to correlations effects

To observe correlations, \( \mathcal{L} = 1000 \text{ fb}^{-1} \) is needed!

REACHABLE IN THE PLANNED LHC RUN
In order to understand whether correlations can be accessed in experimental observations, using dPDF evaluated within the QM model, the effective cross section has been calculated for this process and compared with its mean value:

$$\langle \sigma_{\text{eff}} \rangle = 21.04 \pm 0.07 (\delta Q_0) \pm 0.06 (\delta \mu_F) \text{ mb}.$$
A clue from data?


Considering the factorization ansatz, for which some estimates of $\sigma_{\text{eff}}$ are available, then one has:

$$\sigma_{\text{eff}} = \left[ \int \frac{d\vec{k}_\perp}{(2\pi)^2} \tilde{T}(\vec{k}_\perp) T(-\vec{k}_\perp) \right]^{-1}$$

**Effective form factor (Eff)**

Eff can be formally defined as **FIRST MOMENT** of dPDF (like for GPDs) through the proton wave function:

$$\tilde{T}(k_\perp) = \int d\vec{k}_1 d\vec{k}_2 \Psi(\vec{k}_1 + \vec{k}_2, \vec{k}_\perp) \Psi^\dagger(\vec{k}_1, \vec{k}_2 + \vec{k}_\perp)$$

From the above quantity the mean distance in the transverse plane between two partons can be defined:

$$\langle b_\perp^2 \rangle \sim \left. -2 \frac{d}{k_\perp dk_\perp} \tilde{T}(k_\perp) \right|_{k_\perp=0}$$

Eff is completely unknown but using general model independent properties we analytically found that:

$$\langle b_\perp^2 \rangle > \frac{\sigma_{\text{eff}}}{3\pi}$$

For gluon-gluon DPS processes:

$$0.3 < \sqrt{\langle b_\perp^2 \rangle_{\text{min}}} < 0.4 \text{ fm}$$

We are working on:
- Getting an upper limit (possible thanks to comparisons with standard ffns)
- Extending the approach to the most general unfactorized case
Conclusions

- A CQM calculation of the dPDFs with a fully covariant approach
  - Longitudinal and transverse correlations are found;
  - Deep study on relativistic effects: transverse and longitudinal model-independent correlations have been found;
  - pQCD evolution of dPDFs, including non-perturbative degrees of freedom into the scheme: correlations are present at high energy scales and in the low $x$ region;
  - Calculation of the effective X-section within different models in the valence region: $x$-dependent quantity obtained!

- Study of DPS in same sign WW production at the LHC
  - Calculations of the DPS cross section of same sign WW production
  - Dynamical correlations are found to be measurable in the next run at the LHC

- A proton imagining (complementary to the one investigated by means of electromagnetic probes) can/will be obtained in the next LHC runs!

- DPS at the next EIC facility?
What next: Meson double PDF

The dPDF expression, at the hadronic scale, evaluated in the intrinsic frame, in term of meson wave function:

\[ f_2(x, k_{\perp}) = \sum_{h,h'} \int \frac{d^2k_{1\perp}}{2(2\pi)^3} \psi_{h,h'}(x, \vec{k}_{1\perp}) \psi_{h^*,h'}^*(x, \vec{k}_{1\perp} + \vec{k}_{\perp}) \]

Parton helicities Intrinsic parton momentum

Meson wave function

Pion: w.f. calculated within the AdS/QCD soft-wall model
S. J. Brodsky et al, PRD 77, 056007 (2008)

Hadronic component of the virtual Photon:
w.f. calculated within the spectator model
A. E. Dorokhov et al, PRD 74, 054023 (2014)

\[ f_2^{\pi}(x, Q^2) \]

\[ f_2^{\gamma}(x, Q^2) \]

\[ f_2^\rho(x, Q^2) \]

ρ: w.f. calculated within the AdS/QCD soft-wall model
J. R. Forshaw et al, PRL 109,081601 (2012)
A Light-Front wave function representation

The proton wave function can be represented in the following way:

\[ |p, P^+, \vec{P}_\perp\rangle = \psi_{qqq} |qqq\rangle + \psi_{qqg} |qqq \ g\rangle + \psi_{qqgq} |qqq \ qq\rangle \]

\[ P^+ x_i, \vec{P}_\perp x_i + \vec{k}_\perp \]

\[ \psi_n^{[l]} (x_i, \vec{k}_\perp i, \lambda_i) \]

Invariant under LF boosts!
Here we have calculated:  \( \Delta u \Delta u(x_1, x_2, k_\perp) = \sum_{i=\uparrow, \downarrow} u_i u_i - \sum_{i \neq j=\uparrow, \downarrow} u_i u_j; \)

\[ |\Delta u \Delta u| \leq uu \]

(defined in M. Diehl et al, JHEP 03, 089 (2012), M. Diehl and T. Kasemets, JHEP 05, 150 (2013))

This particular distribution, different from zero also in an unpolarized proton, contains more information on spin correlations, which could be important at small \( x \) and large \( t \) (LHC)!

Also in this case, both factorizations, \( x_1 - x_2 \) and \( (x_1, x_2) - k_\perp \) are strongly violated!
A pQCD evolution results: the non-singlet sector


*Here $g_{2}GPDs$ at $k_{\perp} = 0$

\[ r_{u}(x_{1}, x_{2}; Q^{2}) = C_{u} \frac{u u(x_{1}, x_{2}; Q^{2})}{u(x_{1}; Q^{2})u(x_{2}; Q^{2})} \]

\[ r_{\Delta u}(x_{1}, x_{2}; Q^{2}) = C_{\Delta u} \frac{\Delta u \Delta u(x_{1}, x_{2}; Q^{2})}{\Delta u(x_{1}; Q^{2})\Delta u(x_{2}; Q^{2})} \]

\[ C_{i} = \frac{[\int dx F_{i}]^{2}}{\int dx_{1}dx_{2}F_{ii}(x_{1}, x_{2}, k_{\perp} = 0)} \]

\[ Q^{2} = \mu_{0}^{2} \simeq 0.1 \text{ GeV}^{2} \]

\[ Q^{2} = 10 \text{ GeV}^{2} \]

All these ratios would be 1 if there were no correlations!
The evolution equations for the dPDFs are based on a generalization of the DGLAP equations used, e.g., for the single PDFs (Kirschner 1979, Shelest, Snigirev, Zinovev 1982).

Introducing the Mellin moments:

\[
\langle x_1 x_2 F_{q_1,q_2}(Q^2) \rangle_{n_1,n_2} = \int_0^1 dx_1 \int_0^{1-x_1} dx_2 \; x_1^{n_1-2} x_2^{n_2-2} x_1 x_2 F_{q_1,q_2}(x_1, x_2, Q^2) ,
\]

defining the moments of the quark-quark NS splitting functions at LO as follows:

\[
P_{NS}^{(0)}(n_1) = \int dx \; x^{n_1} P_{NS}^{(0)}(x) ,
\]

using the modified DGLAP evolution equations, without the inhomogeneous term, since we are evaluating the valence dPDFs, one gets

\[
\langle x_1 x_2 F_{q_1,q_2}(Q^2) \rangle_{n_1,n_2} = \left( \frac{\alpha(Q^2)}{\alpha(\mu_0^2)} \right) \frac{-P_{NS}^{(0)}(n_1) - P_{NS}^{(0)}(n_2)}{\beta_0} \langle x_1 x_2 F_{q_1,q_2}(\mu_0^2) \rangle_{n_1,n_2}
\]

The dPDF at any high energy scale is obtained by inverting the Mellin transformation:

\[
x_1 x_2 F_{q_1,q_2}(x_1, x_2, Q^2) = \frac{1}{2\pi i} \oint_C dn_1 \frac{1}{2\pi i} \oint_C dn_2 \\
x_1^{(1-n_1)} x_2^{(1-n_2)} \langle x_1 x_2 F_{q_1,q_2}(Q^2) \rangle_{n_1,n_2}
\]
In the analysis of $\sigma_{\text{eff}}$, the factorized ansatz for dPDF in terms of PDFs, is commonly used. This is consistent with

$$F_{ab}(x_1, x_2, k_\perp = 0; Q^2) \over a(x_1; Q^2)b(x_2; Q^2) \sim 1$$

**It is worth to notice that dPDFs and PDFs obey to different pQCD evolution scheme:**

In order to distinguish effects of dynamical correlations, from those arising from the pQCD evolution, we have studied different ratios:

**Full Correlations**

$$T_{ab}^{[1]} = \frac{F_{ab}(x_1, x_2, k_\perp = 0; Q^2)}{a(x_1; Q^2)b(x_2; Q^2)}$$

The numerator, being a dPDF, evolves with the usual pQCD evolution of dPDFs

The denominator evolves as the product of evolved single PDFs

**Perturbative Correlations**

$$T_{ab}^{[2]} = \frac{[a(x_1; Q^2)b(x_2; Q^2)]^{dPDF}}{a(x_1; Q^2)b(x_2; Q^2)}$$

The numerator, product of PDFs, evolves with the pQCD evolution equations of dPDFs (PDF x PDF = dPDF !)

The denominator evolves as the product of evolved single PDFs

**Non-Perturbative Correlations**

$$T_{ab}^{[3]} = \frac{F_{ab}(x_1, x_2, k_\perp = 0, Q^2)}{[a(x_1; Q^2)b(x_2; Q^2)]^{dPDF}}$$

The numerator, being a dPDF, evolves with the usual pQCD evolution of dPDFs

The numerator, product of PDFs, evolves with the pQCD evolution equation of dPDFs (PDF x PDF = dPDF !)
Ratios previously shown are calculated for the following partonic spaces:

\[ a = u_v, \quad b = u_v \quad \text{and} \quad a = b = g \]

\[ r_{ab}^{[1]} = \frac{F_{ab}(x_1, x_2, k_{\perp} = 0; Q^2)}{a(x_1; Q^2)b(x_2; Q^2)} \]

\[ r_{ab}^{[2]} = \frac{\int_{PDF} [a(x_1; Q^2)b(x_2; Q^2)] dPDF}{a(x_1; Q^2)b(x_2; Q^2)} \]

\[ r_{ab}^{[3]} = \frac{F_{ab}(x_1, x_2, k_{\perp} = 0, Q^2)}{a(x_1; Q^2)b(x_2; Q^2)} \]

Let us remark that usually in MC analyses, the effective X-section is estimated consistently with:

\[ r_{ab}^{[1]} = r_{ab}^{[2]} r_{ab}^{[3]} \approx 1 \]

For \( a = u_v, b = u_v \), perturbative correlations compensate the non-perturbative ones!

For \( a = b = g \), perturbative and non-perturbative correlations coherently interfere.
From PDF analyses it is clear the necessity of including non-perturbative sea quarks and gluons at the initial scale of the model. In order to face this problem, a simplified approach has been used:

\[ F_{uu}(x_1, x_2, k_\perp = 0; Q_0^2) \sim F_{u\bar{u}}(x_1, x_2, k_\perp = 0; Q_0^2) + (1 - x_1 - x_2)^n \theta(1 - x_1 - x_2) \]

\[ + u_v(x_1; Q_0^2) \bar{u}(x_2; Q_0^2) + \bar{u}(x; Q_0^2) u_v(x; Q_0^2) \]

- Pure valence contribution obtained evolving in pQCD the model calculation of dPDF from the initial scale \( \mu_0^2 \) to the scale \( Q_0^2 \)

- Non-perturbative sea quark contributions (effective high Fock states)

\[ n=0.2 \]

![PDF LO MSTW2008](image)

\[ \bar{u}(x; Q_0^2) \quad u_v(x; Q_0^2) \quad Q_0^2 = 1 \text{ GeV}^2 \]

\[ x_2 = 0.8; \quad x_2 = 0.6; \quad x_2 = 0.4; \quad x_2 = 0.2; \]
We can estimate Melosh effects in dPDF studying this ratio:

\[ R(x_1, x_2, b_{\perp}) = \frac{F_{[L]}(x_1, x_2, b_{\perp})}{F_{[NR]}(x_1, x_2, b_{\perp})} \]

In these plots we can still appreciate correlations between \( x \) and \( b_{\perp} \). Moreover, the calculation has been performed using different quark models in order to show model independent effects!

- Relativistic Hyper central Model
- NR Hyper central Model
- Relativistic Harmonic Oscillator (HO) model \( \alpha_{rel}^2 = 25 \text{ fm}^{-2} \)
- NR Harmonic Oscillator model \( \alpha_{nrel}^2 = 6 \text{ fm}^{-2} \)
Our predictions of $\sigma_{eff}$ in the valence region at different energy scales:

$$\sigma_{eff}(x_1, x_2, \mu_B^2) / \sigma_{eff}(x_1 = 10^{-3}, x_2, \mu_B^2)$$

- (1) $x_2 = 10^{-3}$
- (2) $x_2 = 10^{-2}$
- (3) $x_2 = 10^{-1}$
- (4) $x_2 = 0.2$
- (5) $x_2 = 0.2$

**Ratio of $\sigma_{eff}$ calculated by using:**

$$F_{12}(x_1, x_2, \bar{z}_\perp) \sim \int d\bar{b} f(x_1, 0, \bar{b} + \bar{z}_\perp) f(x_2, 0, \bar{b})$$

GPDs calculated within ADS/QCD soft wall model

Valence quark $\otimes$ Gluon

Also in this case, a strong $x$ dependence is found!

Valence quark $\otimes$ Sea quark

Partons involved in, e.g., same sign WW production.

The old data lie in the obtained range of $\sigma_{eff}$
We have used as input 3 models of dPDFs:

1) Model: PDFs of the parametrization:

2) Model: MSTW

\[ F_{ab}(x_1, x_2, \vec{b}_\perp, M_W) = \left[ a(x_1, M_W) b(x_2, M_W) \right] T(\vec{b}_\perp) \]

3) Model: Fixed by:
\[ \bar{\sigma}_{eff} = \frac{1}{\int d\vec{b}_\perp |T(\vec{b}_\perp)|^2} \]

\[ \bar{\sigma}_{eff} = 17.8 \pm 4.2 \text{ mb} \]

Kinematical cuts

- pp, \( \sqrt{s} = 13 \) TeV
- \( p_{T,\mu}^{leading} > 20 \) GeV, \( p_{T,\mu}^{subleading} > 10 \) GeV
- \( |p_{T,\mu}^{leading}| + |p_{T,\mu}^{subleading}| > 45 \) GeV
- \( |\eta_\mu| < 2.4 \)
- \( 20 \text{ GeV} < M_{inv} < 75 \text{ GeV} \) or \( M_{inv} > 105 \text{ GeV} \)

DPS cross section:

\[ \frac{d^4 \sigma_{pp \rightarrow \mu^+ \mu^- X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2 \vec{b}_1 F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W) \frac{d^2 \sigma_{ik}^{pp \rightarrow \mu^+ X}}{d\eta_1 dp_{T,1}} \frac{d^2 \sigma_{jl}^{pp \rightarrow \mu^- X}}{d\eta_2 dp_{T,2}} I(\eta_i, p_{T,i}) \]

MW → Momentum scale

Average of CMS and ATLAS extractions from the analysis of W+dijet.
New results on same sign W's
We have used as input 3 models of dPDFs:

**3) Model: GS09**


\[ \sigma_{pp \rightarrow \mu^+ \mu^-} = \sum_{i,k,l} \frac{1}{2} \int d^2 \vec{b}_\perp \, F_{ij}(x_1, x_2, b_{\perp}, M_W) F_{kl}(x_3, x_4, b_{\perp}, M_W) \frac{d^2 \sigma_{pp \rightarrow \mu^+ \mu^-}}{d\eta_1 dp_{T,1}} \frac{d^2 \sigma_{pp \rightarrow \mu^+ \mu^-}}{d\eta_2 dp_{T,2}} I(\eta_i, p_{T,i}) \]

**DPS cross section:**

\[ \frac{d^4 \sigma_{pp \rightarrow \mu^+ \mu^- X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sigma_{pp \rightarrow \mu^+ \mu^-} \]

\[ M_W \rightarrow \text{Momentum scale} \]

\[ F_{ab}(x_1, x_2, b_{\perp}, Q_0) = a(x_1, Q_0) b(x_2, Q_0) T(\vec{b}) \rho_{ab}(x_1, x_2) \]

\[ Q_0 = \text{Initial scale} \]

**PDFs of the parametrization:**


Kinematical cuts

- \( pp, \sqrt{s} = 13 \text{ TeV} \)
- \( p_{T,\mu}^{leading} > 20 \text{ GeV}, \quad p_{T,\mu}^{subleading} > 10 \text{ GeV} \)
- \( |p_{T,\mu}^{leading}| + |p_{T,\mu}^{subleading}| > 45 \text{ GeV} \)
- \( |\eta_\mu| < 2.4 \)
- \( 20 \text{ GeV} < M_{inv} < 75 \text{ GeV} \) or \( M_{inv} > 105 \text{ GeV} \)

Fixed by:

\[ \bar{\sigma}_{eff} = \frac{1}{\int d\vec{b}_\perp [T(\vec{b}_\perp)]^2} \]

\[ \bar{\sigma}_{eff} = 17.8 \pm 4.2 \text{ mb} \]
Fixing the initial scale $Q_0^2$ of dPDFs evaluated within the QM model:

➔ Since in this model the initial scale is originally located in the infrared regime, pQCD evolution and related observables, calculated by means of this model, are very sensitive to value of the initial scale $Q_0$.

➔ In order to fix $Q_0$ in this analysis use has been made of results on single parton scattering for $pp \rightarrow W^+ \rightarrow (\mu^+ \bar{\nu}_\mu) \ X$; $pp \rightarrow W^- \rightarrow (\mu^- \nu_\mu) \ X$

THE STRATEGY:

✓ $\sigma^+$, $\sigma^-$ have been evaluated through DYNNLO [1] code by using PDFs of MSTW08 parametrization [2] (straight lines)


✓ $\sigma^+$, $\sigma^-$ have been evaluated through the PDFs calculated by means of the QM model starting from different values of $Q_0$

RESULT:

We found a range of values of $Q_0$ where the calculations within the LF approach get close to DYNNLO results

We associate a theoretical error to $Q_0$:

$$\delta Q_0^2 \rightarrow 0.24 < Q_0^2 < 0.28 \text{ GeV}^2$$
The uncertainty due to neglected higher order perturbative corrections has been simulated by varying the final momentum scale:

\[ \delta \mu_F \rightarrow 0.5 M_W < \mu_F < 2.0 M_W \]

The total cross section has been evaluated within the three models.

The differential cross section, converted in numbers of events, has been calculated w.r.t.:

\[ \eta_1 \cdot \eta_2 \simeq \frac{1}{4} \ln \frac{x_1}{x_3} \ln \frac{x_2}{x_4} \]

<table>
<thead>
<tr>
<th>dPDFs</th>
<th>( \sigma^{++} + \sigma^{-} ) [fb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTW</td>
<td>( 0.77^{+0.23}<em>{-0.21} \ (\delta \mu_F) +^{0.18}</em>{-0.18} \ (\delta \sigma_{\text{eff}}) )</td>
</tr>
<tr>
<td>GS09</td>
<td>( 0.82^{+0.24}<em>{-0.26} \ (\delta \mu_F) +^{0.19}</em>{-0.19} \ (\delta \sigma_{\text{eff}}) )</td>
</tr>
<tr>
<td>QM</td>
<td>( 0.69^{+0.18}<em>{-0.18} \ (\delta \mu_F) +^{0.12}</em>{-0.16} \ (\delta Q_0) )</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>dPDFs</th>
<th>( \sigma^{++} ) [fb]</th>
<th>( \sigma^{-} ) [fb]</th>
<th>( \sigma^{++}/\sigma^{-} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS09</td>
<td>0.54</td>
<td>0.28</td>
<td>1.9</td>
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<tr>
<td>QM</td>
<td>0.53</td>
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<td>3.4</td>
</tr>
<tr>
<td>GS09/QM</td>
<td>1.01</td>
<td>1.78</td>
<td>-</td>
</tr>
</tbody>
</table>

**RESULTS:**

- results of the three models are comparable within the errors;
- with \( L = 300 \, \text{fb}^{-1} \) the central value of the predictions of the three models can experimentally discriminated;
- for the expected number of events:

- The maximum is found for \( \eta_1 \cdot \eta_2 \sim 0 \) where interacting partons share same momentum;
- For large \( \eta_1 \cdot \eta_2 \) the decreasing of the cross section is related to the decreasing behaviour of the dPDFs in the high \( x_i \) region.
What we would like to learn:
A link between dPDFs and GPDs?

The dPDF is formally defined through the Light-cone correlator:

$$ F_{12}(x_1, x_2, \vec{z}_\perp) \propto \sum_X \int d\vec{z}^- \left[ \prod_{i=1}^{2} dl_i^- e^{ix_i l_i^- p^+} \right] \langle p | O(z, l_1) | X \rangle \langle X | O(0, l_2) | p \rangle | l_1^- = l_2^- = 0 \rangle | l_1^+ = l_2^+ = z^+ = 0 \rangle $$

M. Diehl, D. Ostermeier, A. Schafer, JHEP 03 (2012) 089

Approximated by the proton state!

$$ \int \frac{dp'^+ dp'^{\perp}}{p'^+} | p' \rangle \langle p' | $$

In GPDs, the variables $\vec{b}$ and $x$ are correlated!

Correlations between $\vec{z}_\perp$ and $x_1, x_2$ could be present in dPDFs!