Proton structure via double parton scattering

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In collaboration with :

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Outlook

- **Introduction**:
  - 3D structure of the proton
  - Double parton distribution functions
  - Double parton correlations (DPCs) in double parton distribution functions
- **dPDFs in constituent quark models, a proton "imaging" via DPS?**

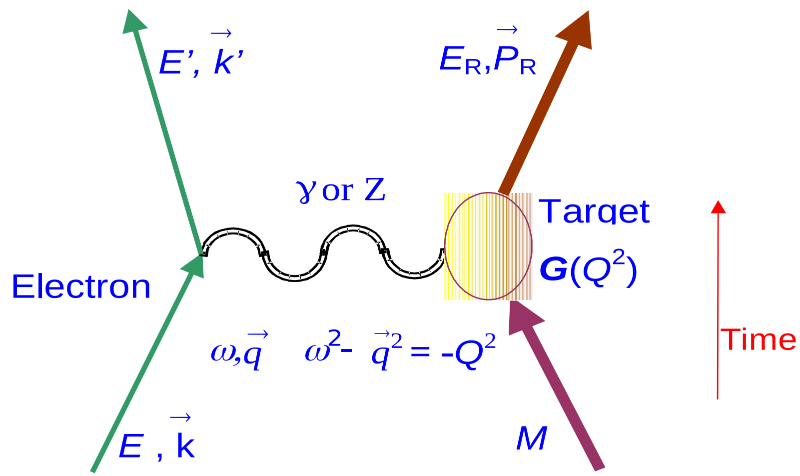
  M.R., S. Scopetta and V. Vento, PRD 87, 114021 (2013)
  M.R., S. Scopetta, M. Traini and V.Vento, JHEP 12, 028 (2014)
  M.R., S. Scopetta, M. Traini and V.Vento, arXiv: 1806.10112
- **Analysis of correlations in dPDFs**

  M. R., S. Scopetta, M. Traini and V.Vento, JHEP 10, 063 (2016)
  M. R., F. A. Ceccopieri, PRD 95, no. 3, 034040 (2017)
- **Calculation and analyses of experimental observables: effects of correlations**

  M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2016)
  M. Traini, S. Scopetta, M. R. and V. Vento, PLB 768, 270 (2017)
  F. A. Ceccopieri, M. R., S. Scopetta, PRD 95, no. 11, 114030 (2017)
  M. R. and F. A. Ceccopieri, PRD 97, no. 7, 071501 (2018) rapid communication
  M. R. and F. A. Ceccopieri, in preparation
- **Conclusions**

Fundamental information on the internal structure of the nucleon can be obtained by studying:

ELASTIC processes



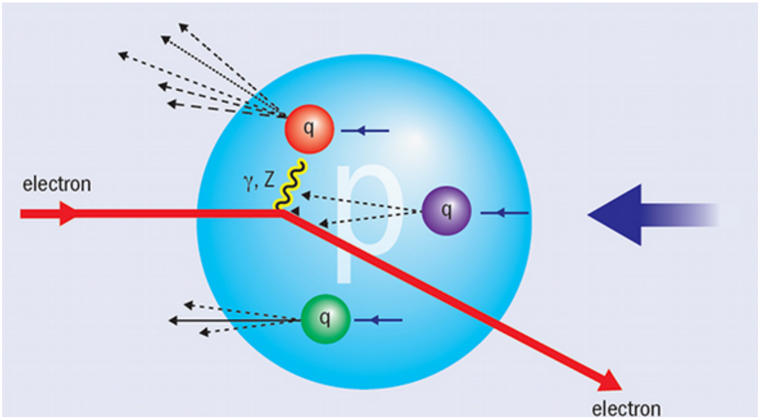
$$\langle N(P')|J^{\mu}_{EM}(0)|N(P)\rangle =$$

$$\bar{u}(P')\left[\gamma^{\mu}F_1(Q^2)+i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2(Q^2)\right]u(P)$$

DIRAC
Form Factor

PAULI
Form Factor

DEEP INELASTIC processes



$$f(x) =$$

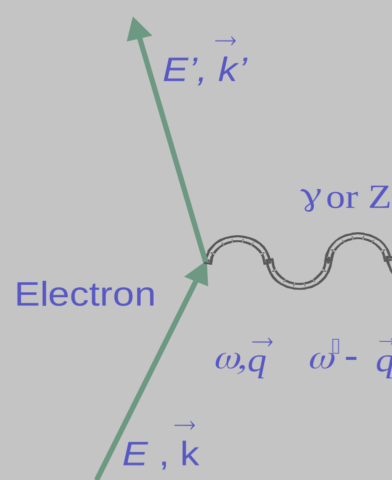
$$\underbrace{\int dz^- e^{ixP^+z^-}\langle N(P)|\bar{q}\left(\frac{-z^-}{2}\right)\gamma^+ q\left(\frac{z^-}{2}\right)|N(P)\rangle}$$

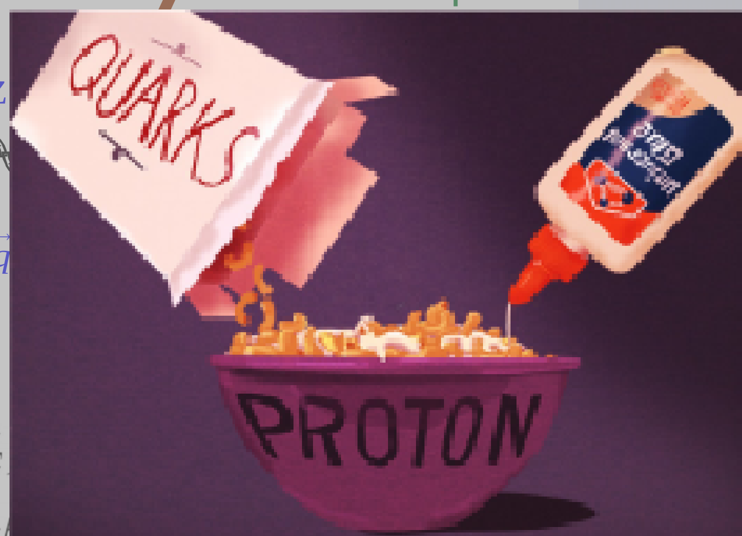
Parton Distribution Function (PDF)

$x =$ *Longitudinal momentum fraction carried by the parton*

Fundamental information on the internal structure of the nucleon can be obtained by studying:

ELASTIC processes





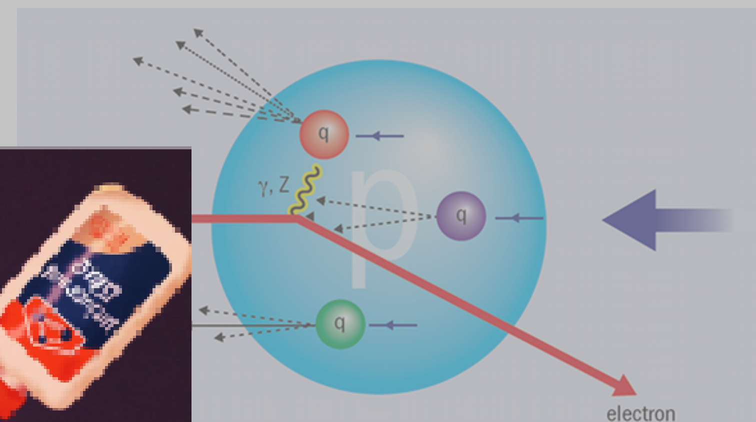
$$\langle N(P')|J_E^{\mu} \ldots$$

$$\bar{u}(P') \left[\gamma^\mu F_1(Q^2) + i\sigma \ldots \frac{\ldots}{2M} \ldots F_2(Q^2)\right] u(P)$$

DIRAC Form Factor

PAULI Form Factor

DEEP INELASTIC processes



$$f(x) = \underbrace{\langle N(P)|\bar{q}\left(\frac{-z^-}{2}\right)\gamma^+ q\left(\frac{z^-}{2}\right)|N(P)\rangle}_{}$$

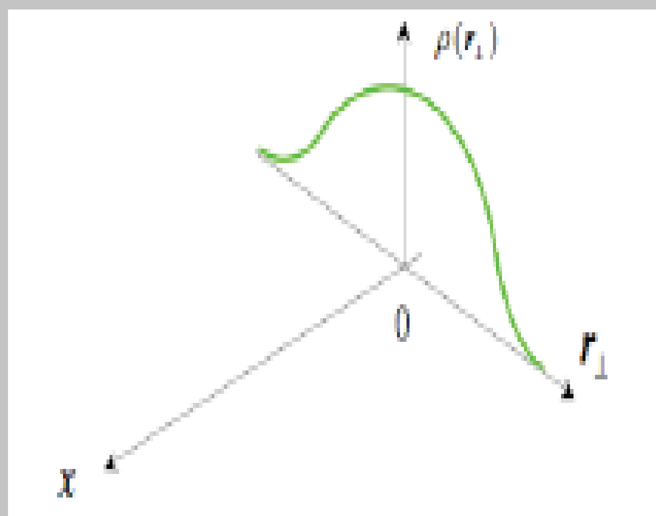
Parton Distribution Function (PDF)

x = Longitudinal momentum fraction carried by the parton

The 3D structure of the proton III

Fundamental information on the internal structure of the nucleon can be obtained by studying:

ELASTIC processes



Time

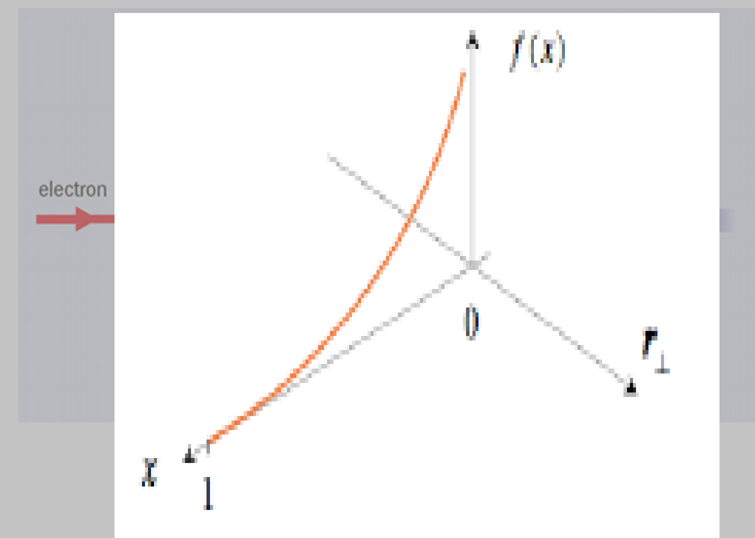
$$\langle N(P')|J^\mu_{EM}(0)|N(P)\rangle =$$

$$\bar{u}(P') \left[\gamma^\mu F_1(Q^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M}F_2(Q^2)\right] u(P)$$

DIRAC
Form Factor

PAULI
Form Factor

DEEP INELASTIC processes



$$\int dz^- e^{ixP^+z^-} \langle N(P)|\bar{q}\left(\frac{-z^-}{2}\right)\gamma^+ q\left(\frac{z^-}{2}\right)|N(P)\rangle$$

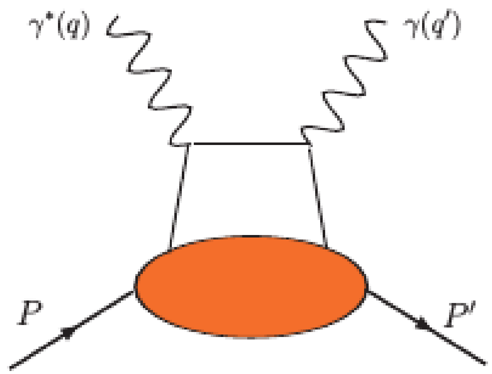
PDF)

x = Longitudinal momentum fraction carried by the parton

1-DIMENSIONAL INFORMATION!

In order to get new information, we need to study new process:

DEEPLY VIRTUAL COMPTON SCATTERING

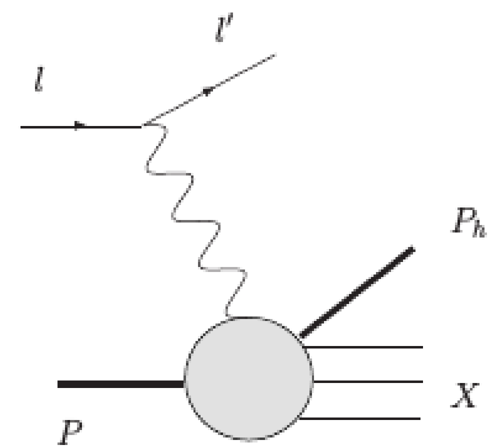


$$\int dz^- e^{ixP^+z^-} \langle N(P')|\bar{q}\left(\frac{-z}{2}\right)\gamma^+ q\left(\frac{z}{2}\right)|N(P)\rangle =$$

$$\bar{u}(P')\left[\gamma^+ H(x,\xi,\Delta^2) + i\sigma^{\mu\nu}\frac{q_\nu}{2M} E(x,\xi,\Delta^2)\right] u(P)$$

GENERALIZED PARTON DISTRIBUTION FUNCTIONS (GPDs)

SEMI INCLUSICE DEEP INELASTIC SCATTERING



$$\int dz^- d^2 z_\perp e^{ik\cdot z}\langle N(P')|\bar{q}\left(\frac{-z}{2}\right)\Gamma W\ q\left(\frac{z}{2}\right)|N(P)\rangle|_{z^+=0}$$

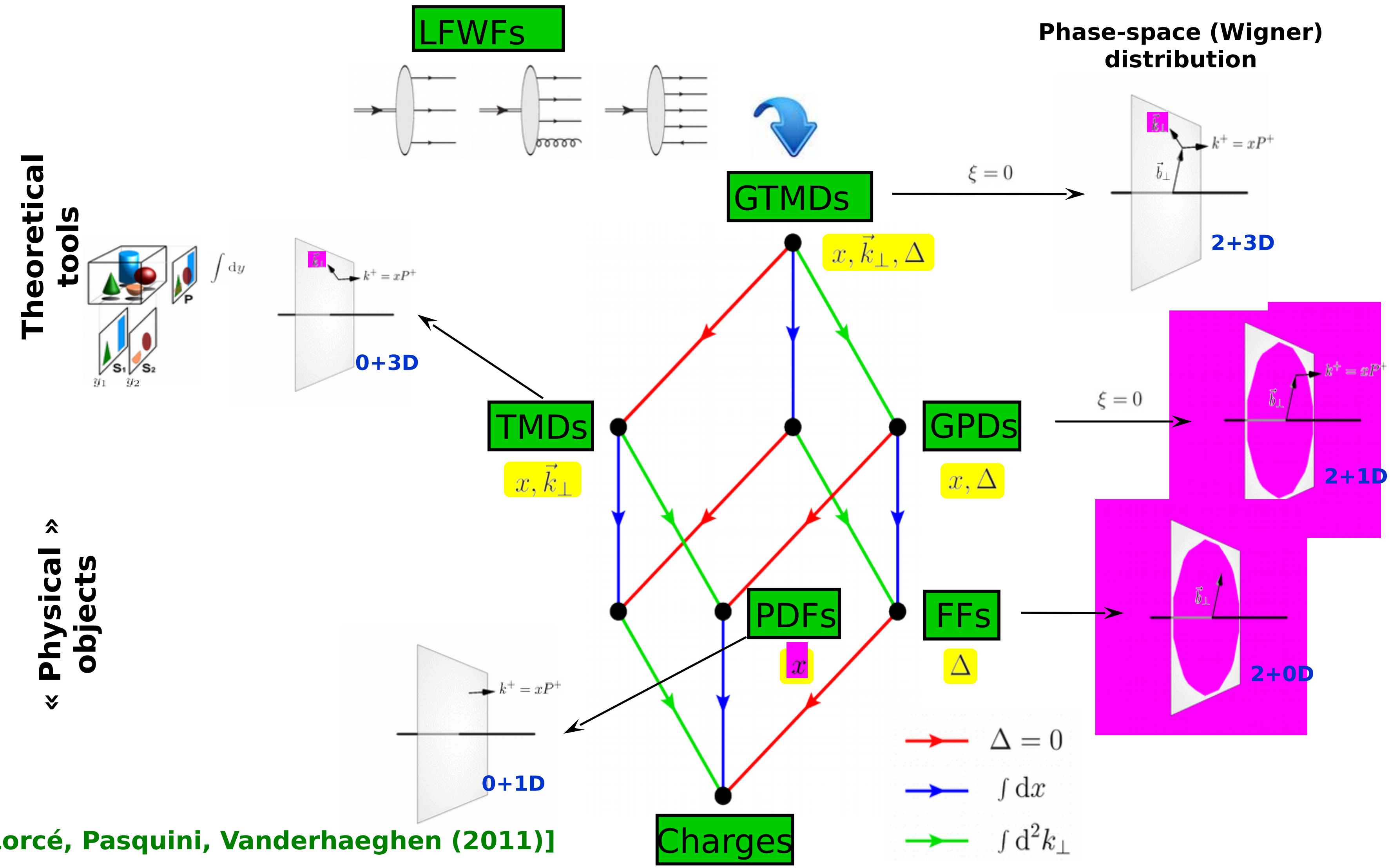
Quark polarization / **Nucleon polarization**

	U	T_x	T_y	L
U	f_1	$\frac{k_y}{M} h_1^\perp$	$-\frac{k_x}{M} h_1^\perp$	
T_x	$\frac{k_y}{M} f_{1T}^\perp$	$h_1 + \frac{k_x^2-k_y^2}{2M^2} h_{1T}^\perp$	$\frac{k_x k_y}{M^2} h_{1T}^\perp$	$\frac{k_x}{M} g_{1T}$
T_y	$-\frac{k_x}{M} f_{1T}^\perp$	$\frac{k_x k_y}{M^2} h_{1T}^\perp$	$h_1 - \frac{k_x^2-k_y^2}{2M^2} h_{1T}^\perp$	$\frac{k_y}{M} g_{1T}$
L		$\frac{k_x}{M} h_{1L}^\perp$	$\frac{k_y}{M} h_{1L}^\perp$	g_{1L}

Transverse Momentum Dependent PDF (TMD)

The 3D structure of the proton V

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

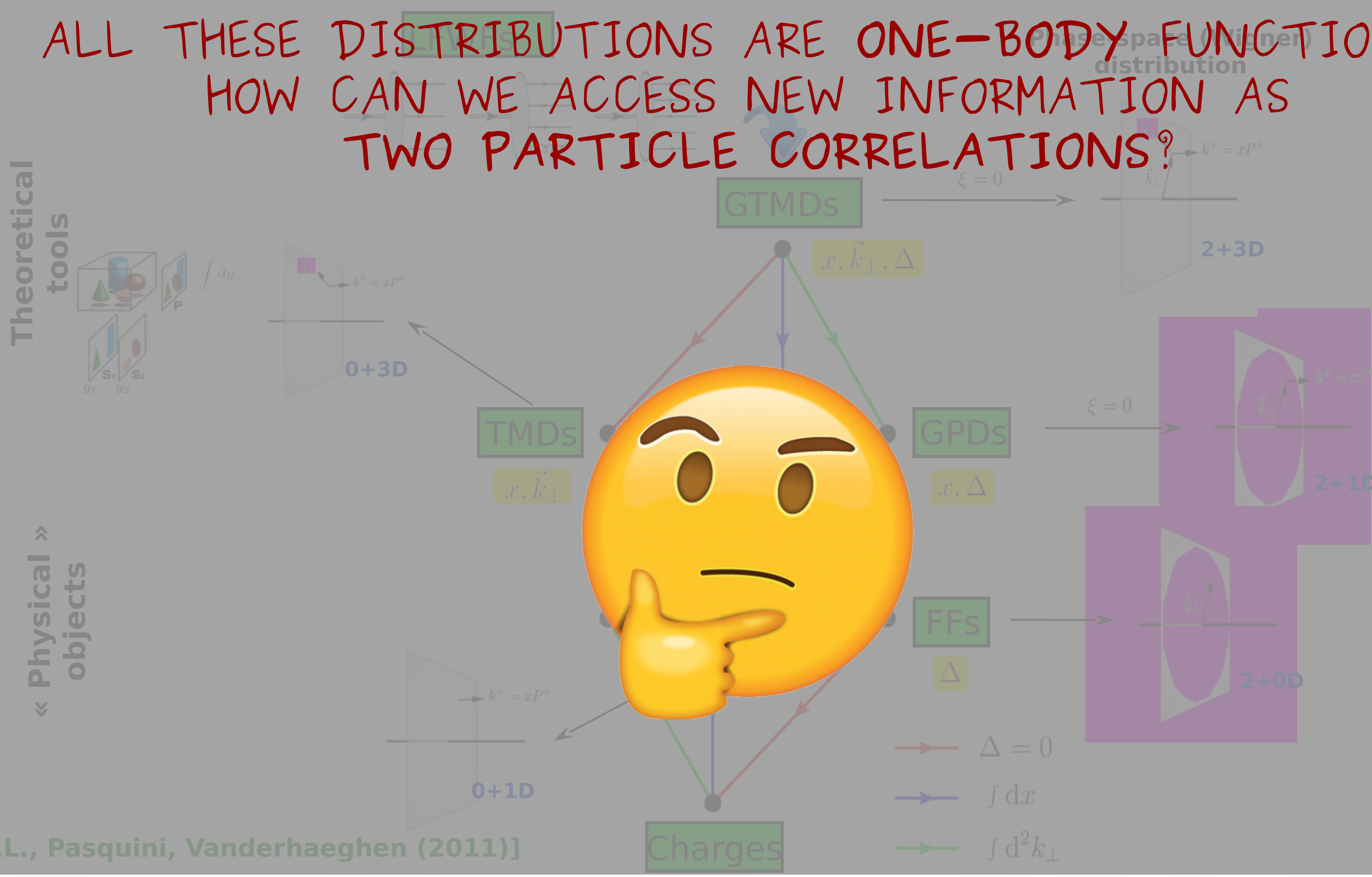


[Lorcé, Pasquini, Vanderhaeghen (2011)]

The 3D structure of the proton VI

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

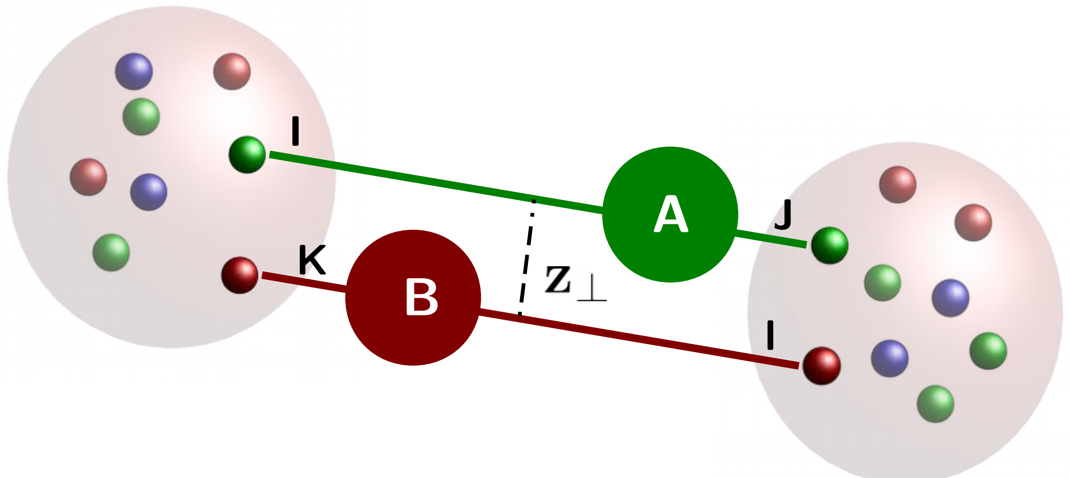
ALL THESE DISTRIBUTIONS ARE **ONE-BODY FUNCTIONS!**
HOW CAN WE ACCESS NEW INFORMATION AS
TWO PARTICLE CORRELATIONS?



[C.L., Pasquini, Vanderhaeghen (2011)]

Answer: MULTIPARTON interactions

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



The cross section for a double parton scattering (DPS) event can be written in the following way:

(N. Paver, D. Treleani, Nuovo Cimento 70A, 215 (1982))

dPDF

Momentum scale

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

Momentum fraction carried by the parton inside the hadron

Transverse distance between the two partons

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?

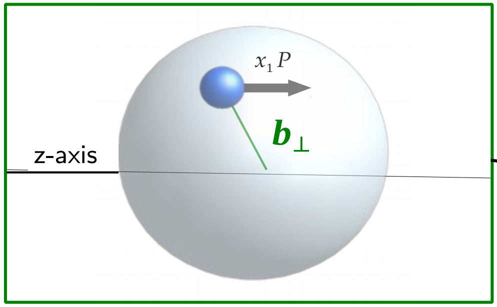
The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SiDIS, DVCS, double parton scattering ...), measuring different kind of parton distributions, providing different kind of information:

DVCS — ***Generalized Parton Distributions in impact parameter space*** →

$$\mathcal{H}(x_1, \boldsymbol{b}_\perp) \quad \mathcal{E}(x_1, \boldsymbol{b}_\perp)\ldots$$

longitudinal momentum fraction carried by the parton

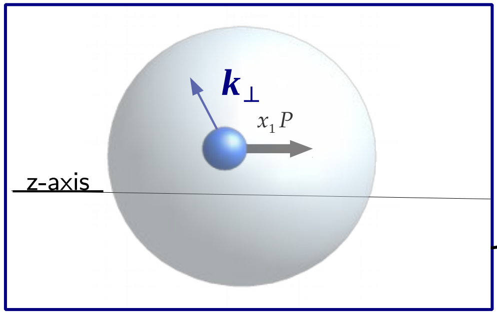
transverse distance between the parton and center of proton



SIDIS.. — ***Transverse Momentum Dependent parton distribution functions*** →

$$f_1(x_1, \boldsymbol{k}_\perp) \; g_{1L}(x_1, \boldsymbol{k}_\perp) \, h_1(x_1, \boldsymbol{k}_\perp) \; f_{1T}^{\perp}(x_1, \boldsymbol{k}_\perp)\ldots$$

transverse component of the parton momentum

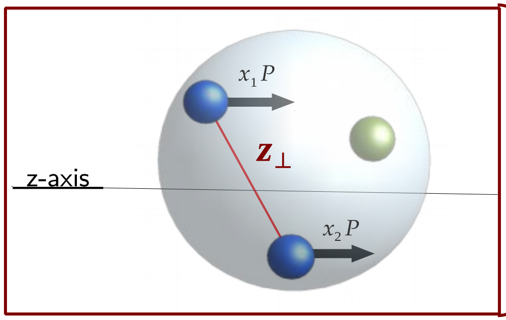


1 BODY

DPS — ***Double Parton Distribution Functions*** →

$$F_{UU}(x_1, x_2, \mathbf{z}_\perp) \quad F_{LL}(x_1, x_2, \mathbf{z}_\perp)\ldots$$

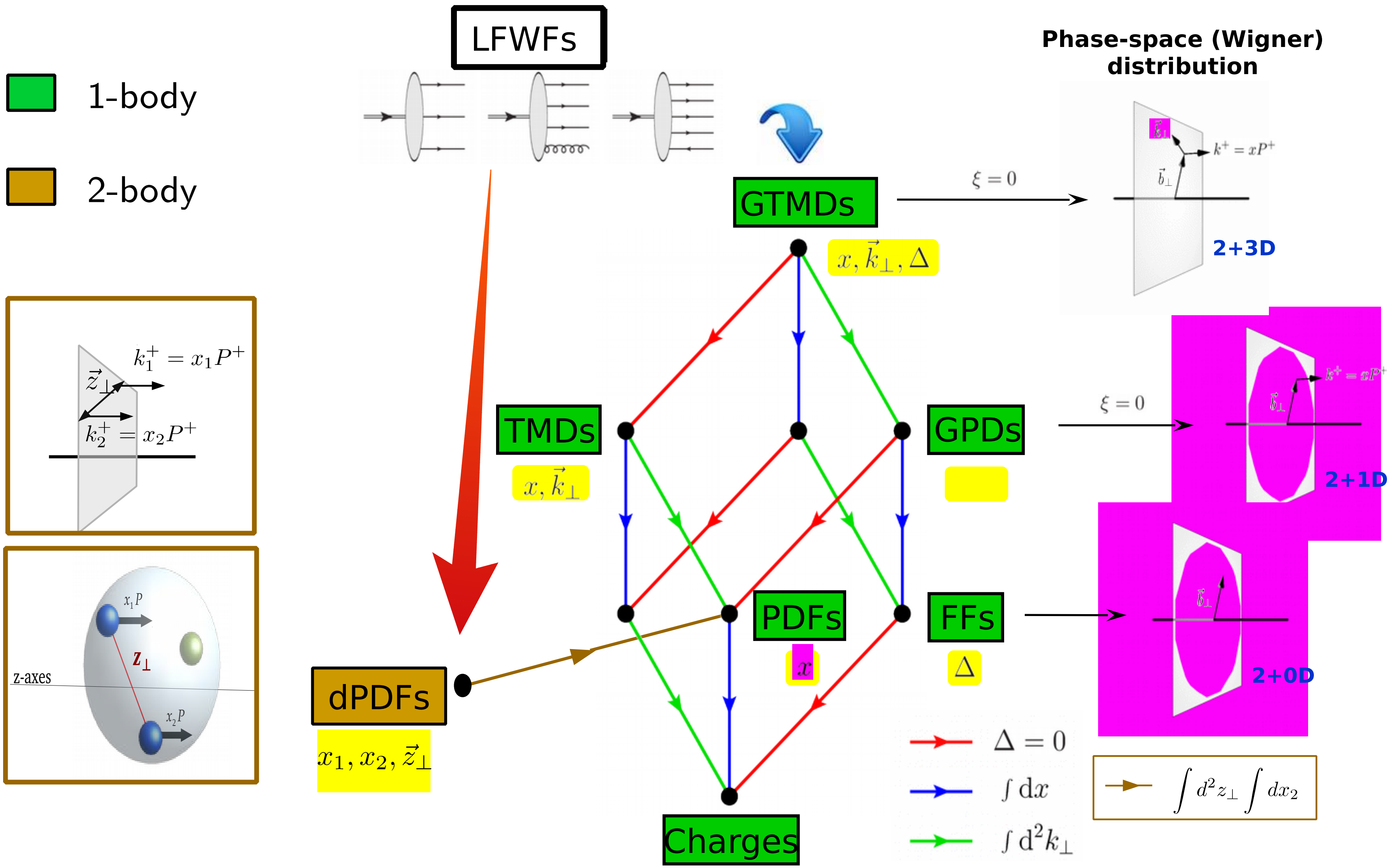
dPDFs are in principle sensitive to DPCs



2 BODY

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:



How 3-Dimensional structure of a hadron can be investigated?

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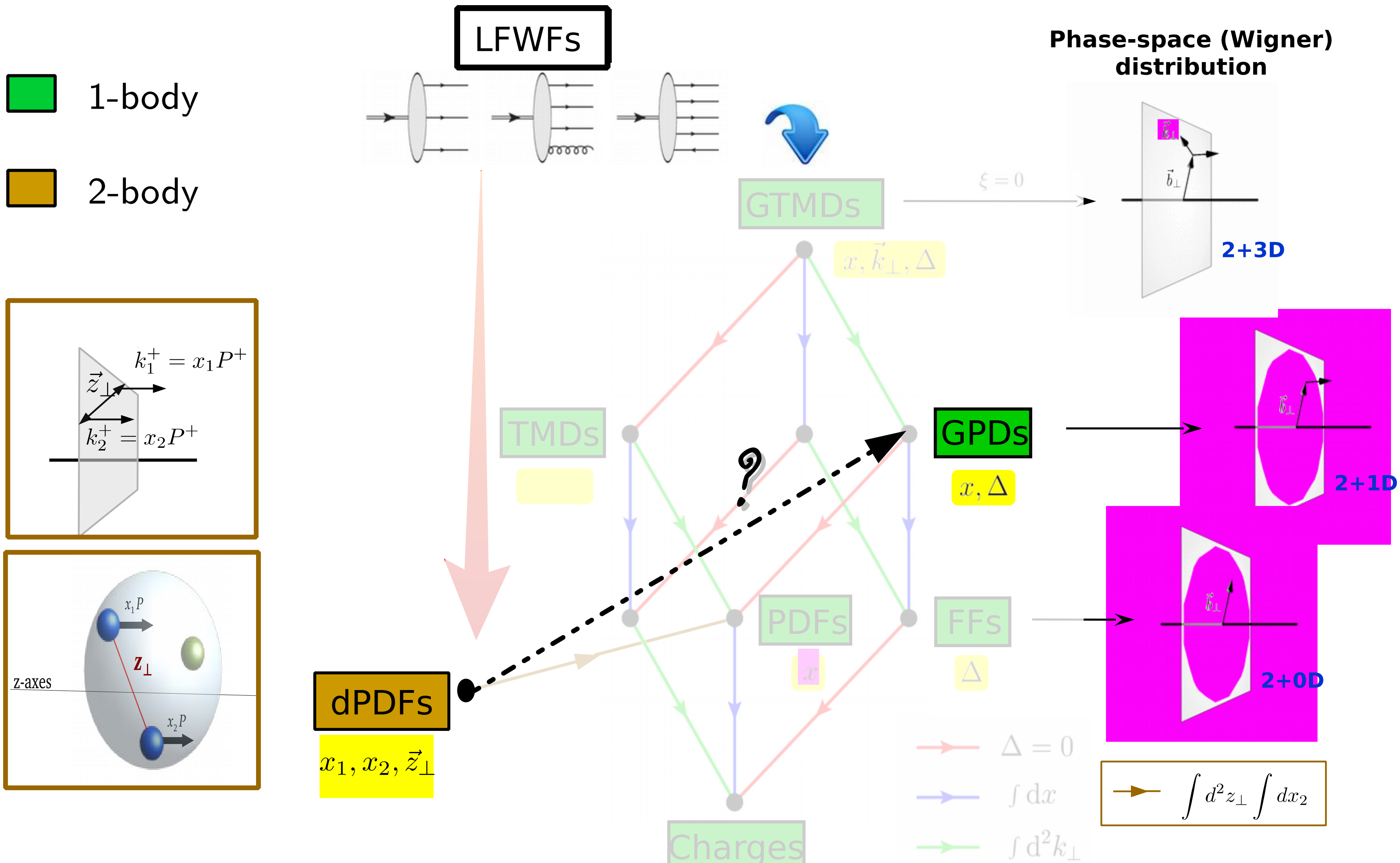


Parton correlations and dPDFs

@ LHC kinematics it is often used a factorized form of the dPDFs: $(\mathbf{x_1}, \mathbf{x_2}) - \mathbf{z}_\perp$ factorization:

$$F_{ij}(x_1, x_2, \vec{z}_\perp, \mu) = F_{ij}(x_1, x_2, \mu) T(\vec{z}_\perp, \mu)$$

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

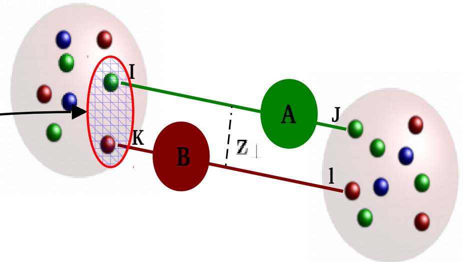
and $\mathbf{x_1}, \mathbf{x_2}$ factorization:

$$\overbrace{F_{ij}(x_1, x_2, \mu)}^{\text{dPDF (2-Body)}} = \underbrace{\overbrace{q_i(x_1, \mu)}^{\text{PDF (1-Body)}} \boxed{q_j(x_2, \mu)}}\theta(1 - x_1 - x_2)(1 - x_1 - x_2)^n$$

Unknown

Data available

NO CORRELATION ANSATZ



In this scenario, parton correlations inside the proton are neglected ⟹ NO NEW INFORMATION!

BUT:

- 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 could be less relevant BUT theoretical microscopic estimates are necessary

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

i) dPDF evaluated at the initial scale of the model $\xrightarrow{\text{pQCD}}$ *ii)* 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 I

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: $\boxed{a^{\pm} = a_0 \pm a_3}$

RHD
- Instant Form: $t_0=0$
- Evolution Operator: $P^0 = E$
- Front Form (LF): $x^+ = t_0 + z = 0$
- Evolution Operator: P^-

- 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) $\mathbf{P}^+$, $\mathbf{P}_\perp$, 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.

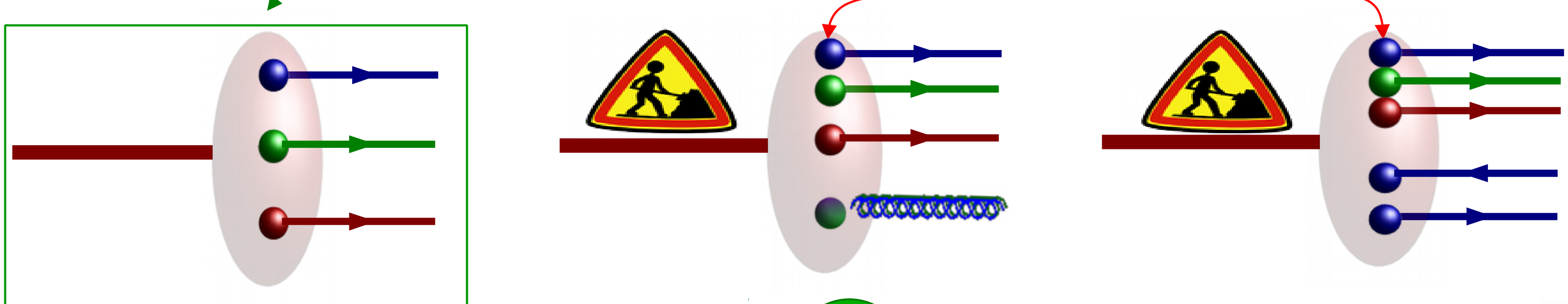
The LF approach is extensively used for hadronic studies (e.m. form factors, PDFs, GPDs, TMDs........)

The Light-Front approach II

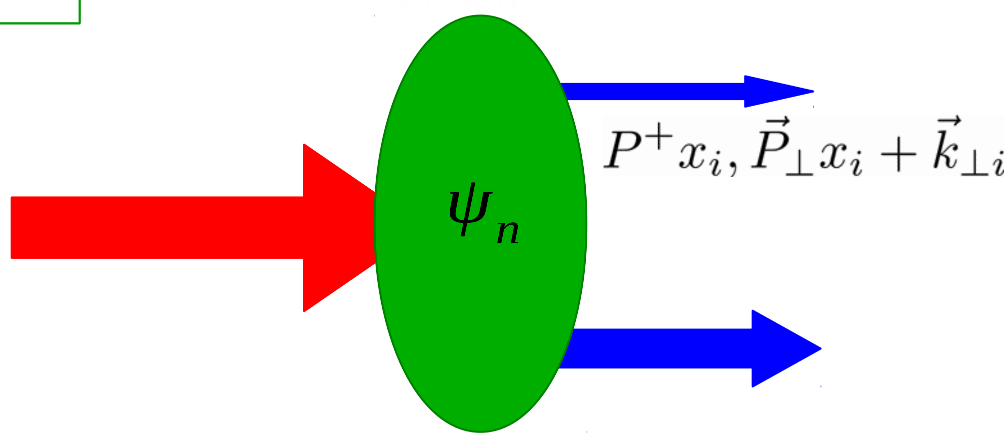
The proton wave function can be represented in the following way:

see *e.g.*: **S. J. Brodsky, H. -C. Pauli, S. S. Pinsky, Phys.Rept. 301, 299 (1998)**

$$|p, P^+\ \vec{P}_\perp\rangle = \psi_{qqq}|qqq\rangle + \psi_{qqq\ g}|qqq\ g\rangle + \psi_{qqq\ q\bar{q}}|qqq\ q\bar{q}\rangle$$



p: $\mathrm{P}^+\ \vec{P}_\perp$



$$\left\{ \begin{array}{l} x_i = \dfrac{k_i^+}{P^+} \\ \sum_i^n x_i = 1 \\ \sum_i^n \vec{k}_{\perp i} = 0 \end{array} \right.$$

LF wave function

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

Invariant under LF boosts!

dPDFs in a Light-Front approach

M. R., S. Scopetta, M. Traini and V.Vento, JHEP 12, 028 (2014)

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 $z_\perp$

$$\times \quad \delta\left(x_1 - \frac{k_1^+}{M_0}\right)\delta\left(x_2 - \frac{k_2^+}{M_0}\right)$$

$$\boxed{M_0 = \sum_i \sqrt{\vec{k}_i^2 + m^2}}$$

GOOD SUPPORT

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

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

Now we need a model to properly describe the hadron wave function in order to estimate the LF $_2$GPDs

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

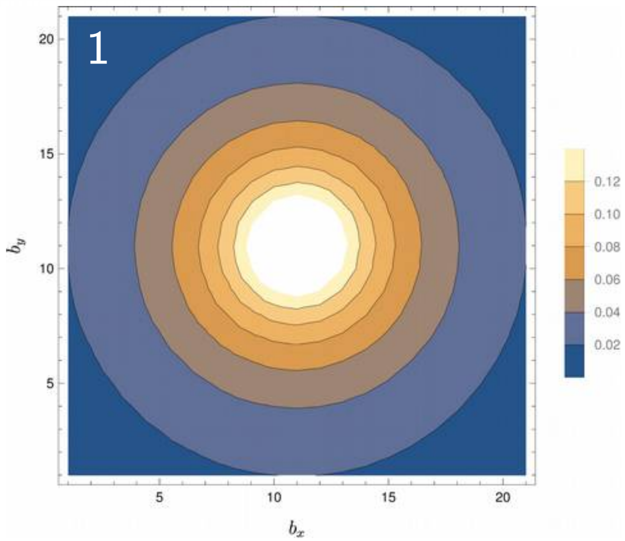
Melosh operator rotates canonical spin in LF one

Instant form proton w.f.
We need a CQM!

What we would like to learn: partonic mean distance

M. R. and F. A. Ceccopieri, in preparation

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:

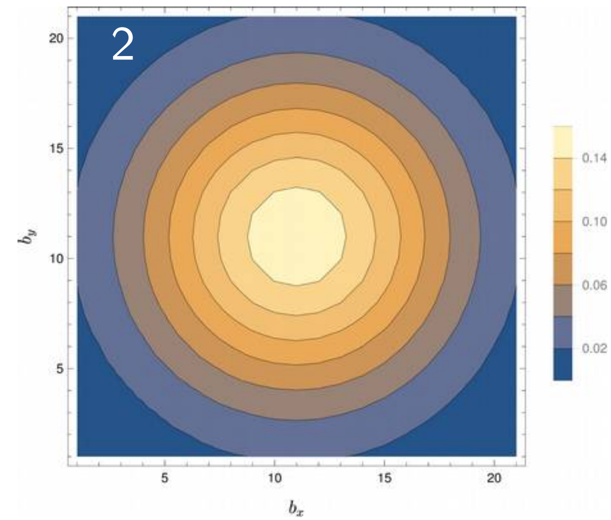


1) HP model

2) HO model

$x_1 = 10^{-4}$ and $x_2 = 10^{-2}$

$$\vec{d}_\perp = \vec{b}_\perp = \vec{z}_\perp$$



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

$$\boxed{\langle d_\perp^2 \rangle_{x_1,x_2}^{ij} = \frac{\int d^2b_\perp \; b_\perp^2 F_{ij}(x_1,x_2,b_\perp,Q^2=M_W^2)}{\int d^2b_\perp \; F_{ij}(x_1,x_2,b_\perp,Q^2=M_W^2)}}$$

M. Traini *et al*, Nucl. Phys. A 656, 400-420 (1999), non relativistic Hyper-Central CQM (potential by M. Ferraris *et al*, PLB 364 (1995)) (HP)

The harmonic oscillator (HO)

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

$$\sqrt{\langle d_\perp^2 \rangle_{10^{-2},10^{-2}}} = \begin{cases} 0.404 \text{ fm} \\ 0.365 \text{ fm} \end{cases}$$

$$\sqrt{\langle d_\perp^2 \rangle_{10^{-4},10^{-4}}} = \begin{cases} 0.391 \text{ fm} & \text{HP} \\ 0.393 \text{ fm} & \text{HO} \end{cases}$$

What we would like to learn: partonic mean distance

M. R. and F. A. Ceccopieri, in preparation

COMING SOON!

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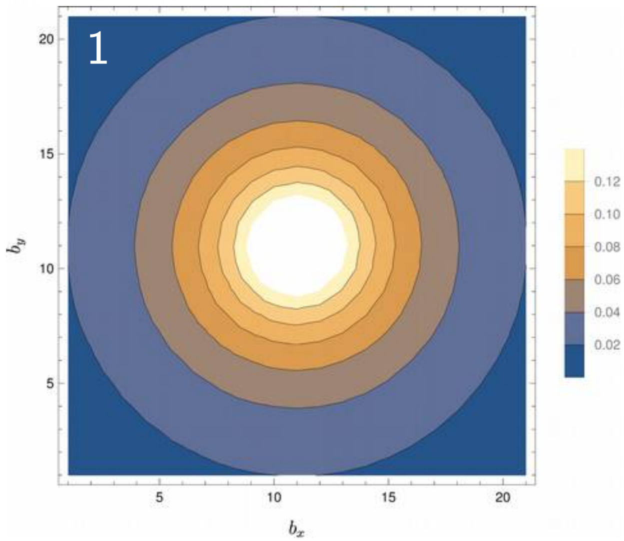

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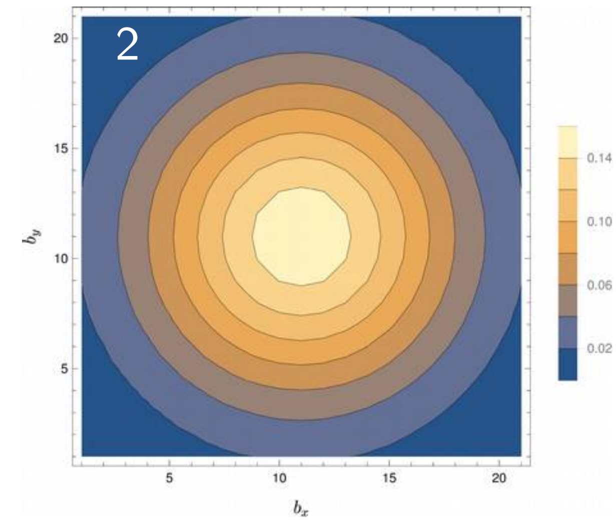
$\vec{d}_\perp = \vec{b}_\perp = \vec{z}_\perp$



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The harmonic oscillator (HO)

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

0.404 fm

0.365 fm

0.391 fm HP

0.393 fm HO

Are two slow partons closer (in $\perp$ plane) then two slow partons?

What we learned:

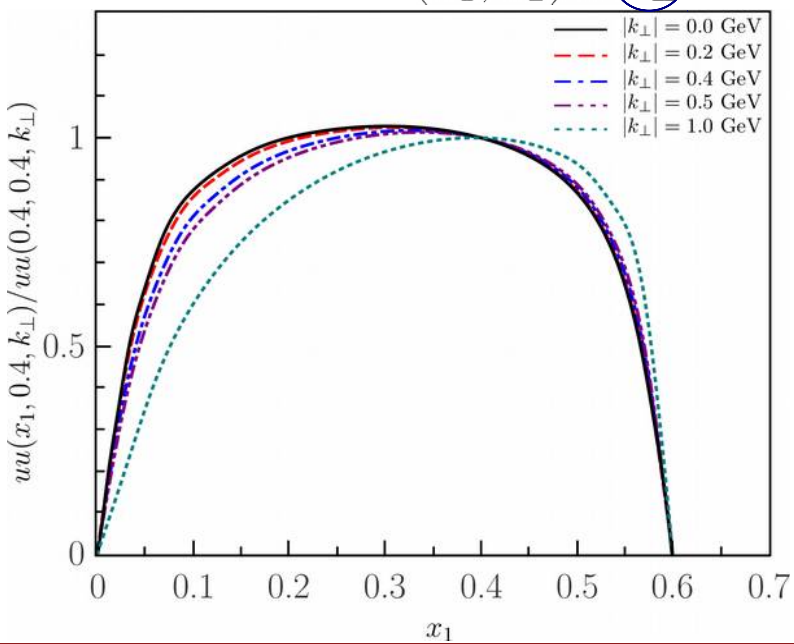
M. R., S. Scopetta, M. Traini and V. Vento, JHEP 12, 028 (2014)

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

$$\frac{F_{uu}(x_1, 0.4, k_\perp)}{F_{uu}(0.4, 0.4, k_\perp)}$$

Conjugate to $z_\perp$

Factorization: $(x_1, x_2) - k_\perp$

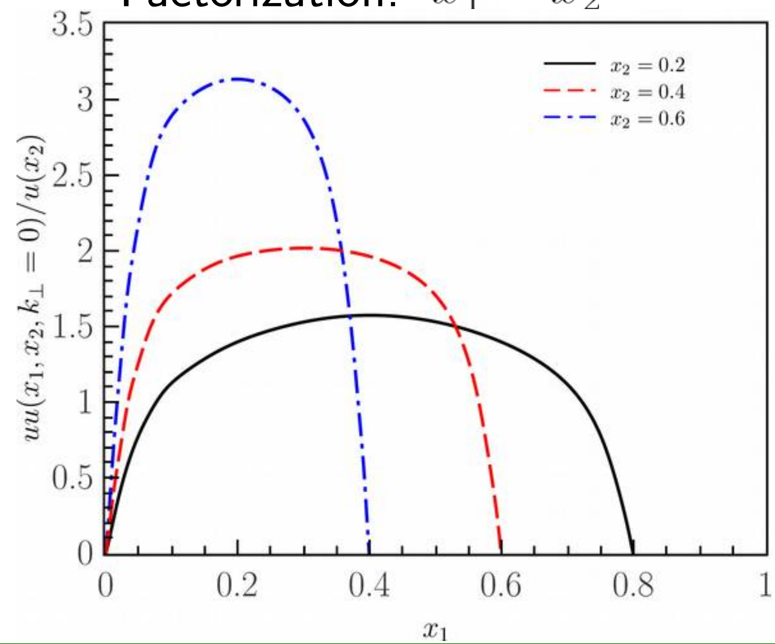


${}_2$GPD

$$\frac{F_{uu}(x_1, x_2, k_\perp = 0)}{F_u(x_2)}$$

PDF

Factorization: $x_1 - x_2$

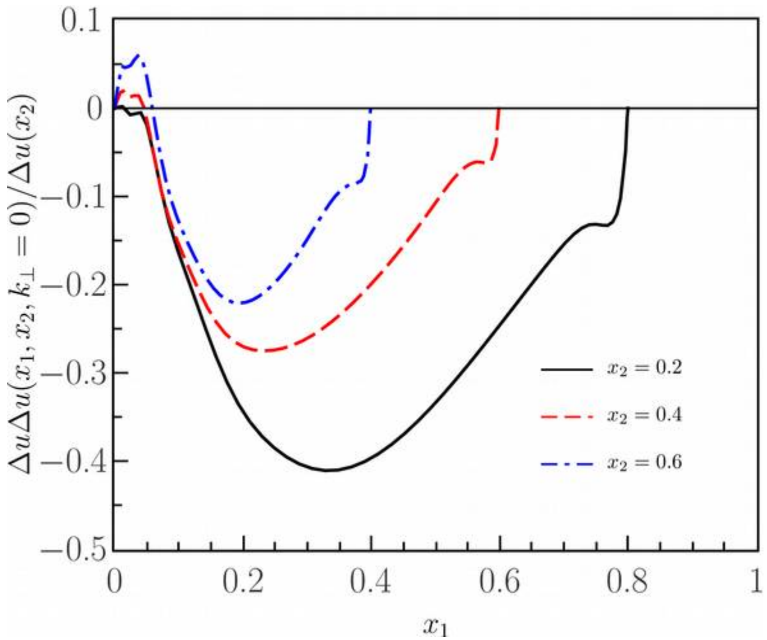


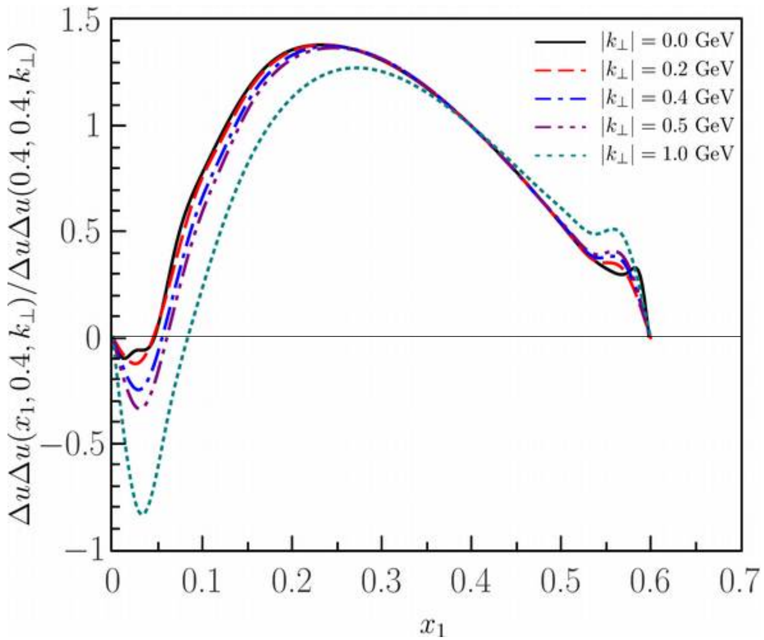
- The $(x_1, x_2) - k_\perp$ and $x_1 - x_2$ factorizations are violated!

The factorization ansatz is basically violated in **all quark model analyses**!
M.R., S. Scopetta and V. Vento, PRD 87, 114021 (2013)
H.-M. Chang, A.V. Manohar, and W.J. Waalewijn, PRD 87, 034009 (2013)

What we learned:

M. R., S. Scopetta, M. Traini and V.Vento, JHEP 12, 028 (2014)





$$u_{\uparrow(\downarrow)}u_{\uparrow(\downarrow)}(x_1,x_2,k_\perp)3(\sqrt{3})^3 \int \prod_{i=1}^{3} d\vec{k}_i \delta\left(\sum_{i=1}^{3}\vec{k}_i\right)\delta\left(x_1 - \frac{k_1^+}{M_0}\right)\delta\left(x_2 - \frac{k_2^+}{M_0}\right)\Phi^*(\{\vec{k}_i\},k_\perp)\frac{1\pm\sigma_3(1)}{2}\frac{1\pm\sigma_3(2)}{2}\Phi(\{\vec{k}_i\},-k_\perp)$$

Here we have calculated: $\Delta u \Delta u(x_1, x_2, k_\perp) = \sum_{i=\uparrow,\downarrow} u_i u_i - \sum_{i\neq j=\uparrow,\downarrow} u_i u_j;$ $\boxed{|\Delta u \Delta u| \leq uu}$

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

Positivity bound

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!

M.R., F. A. Ceccopieri, PRD 95, no. 3, 034040 (2017)

The expressions of dPDF in the canonical (e.g. NR limit) and LF forms are quite similar for small values of x_i:

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

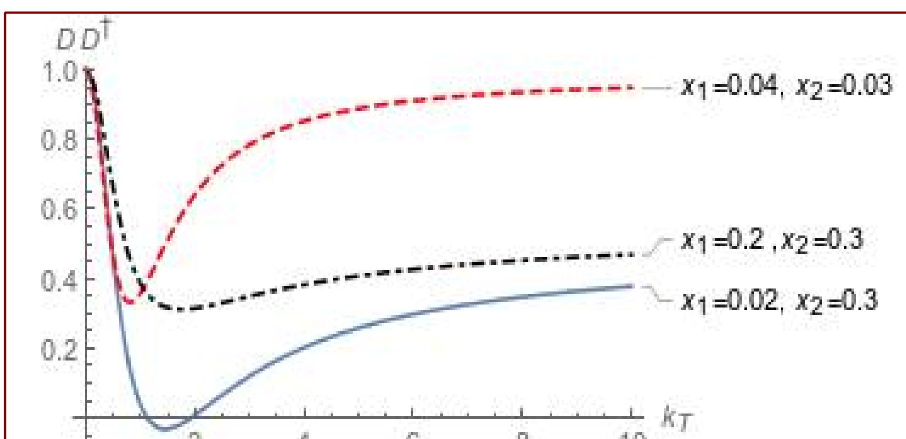
$$F_{[LF]}(x_1, x_2, k_\perp) = \int d\vec{k}_1 d\vec{k}_2 f(\vec{k}_1, \vec{k}_2, k_\perp) \langle SPIN | \boxed{O_1(\vec{k}_1, \vec{k}_2, k_\perp) O_2(\vec{k}_1, \vec{k}_2, k_\perp)} | SPIN \rangle \times \delta\left(x_1 - \frac{k_1^+}{M_0}\right) \delta\left(x_2 - \frac{k_2^+}{M_0}\right)$$

Melosh Operators!

No constant quantities. They depend on momentum of partons!

$f(\vec{k}_1, \vec{k}_2, k_\perp)$ = 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!



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

Correlations between x_i and $k_\perp$

KINEMATICAL CORRELATIONS: the $\mathbf{k}_\perp \neq \mathbf{0}$ case I

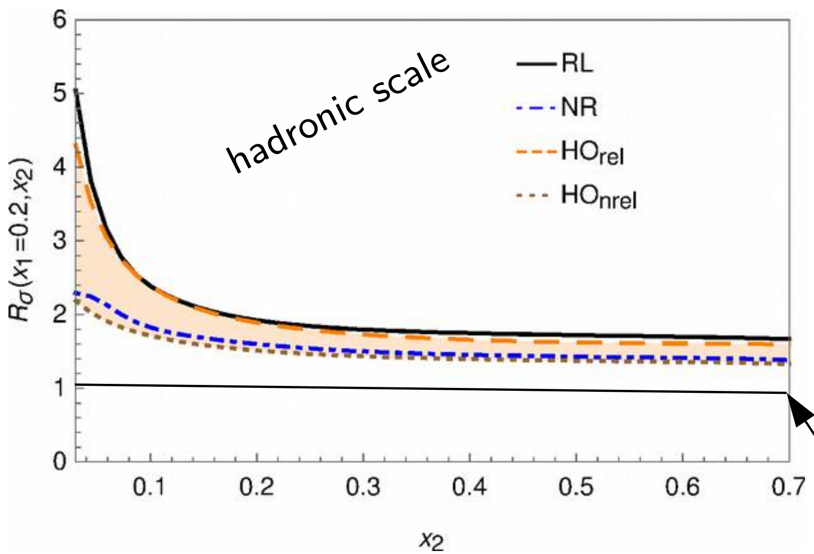
M.R., F. A. Ceccopieri, PRD 95, no. 3, 034040 (2017)
M.R., F. A. Ceccopieri, in preparation

Melosh effects are studied in a quantity which **simulates a ratio of DPS cross-sections**:

$$R_\sigma(x_1,x_2) = \frac{\int d\vec{b}_\perp F_{[LF]}(x_1,x_2,b_\perp,Q^2)^2}{\int d\vec{b}_\perp F_{[NR]}(x_1,x_2,b_\perp,Q^2)^2}$$

Full calculation of dPDFs within the LF approach

Calculation of dPDFs neglecting Melosh rotation



Relativistic Hyper central Model (HP and RL in legends)

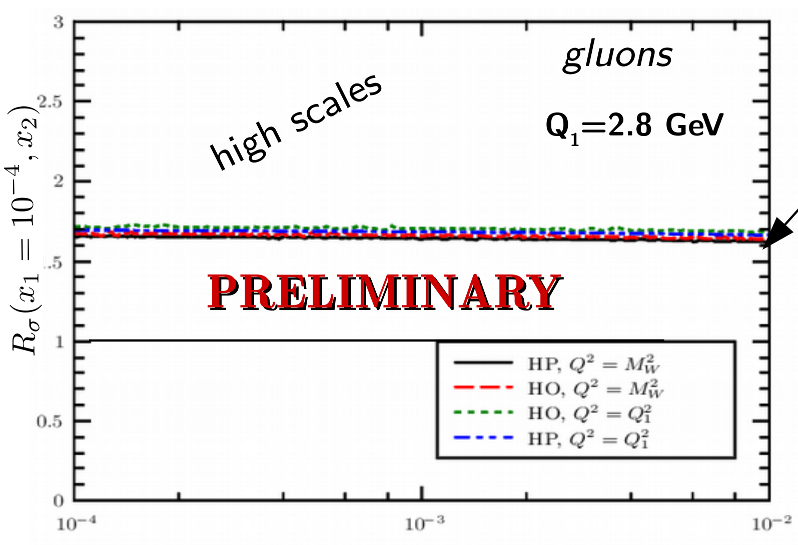
NR Hyper central Model

$\alpha^2_{nrel} < \alpha^2 < \alpha^2_{rel}$

Relativistic Harmonic Oscillator (HO) model $\alpha^2_{rel} = 25 \text{ fm}^{-2}$

NR Harmonic Oscillator model $\alpha^2_{nrel} = 6 \text{ fm}^{-2}$

Notice: $\mathbf{R}_\sigma \sim \mathbf{1}$ **no correlation effects!**



Similar results found at high energy scales for GLUONS!

Melosh effects are great at both low and high energy scales for different kind of partons!

Correlations at high energy scales: the $\mathbf{k}_\perp = \mathbf{0}$ case

M. R., S. Scopetta, M. Traini and V.Vento, JHEP 10, 063 (2016)

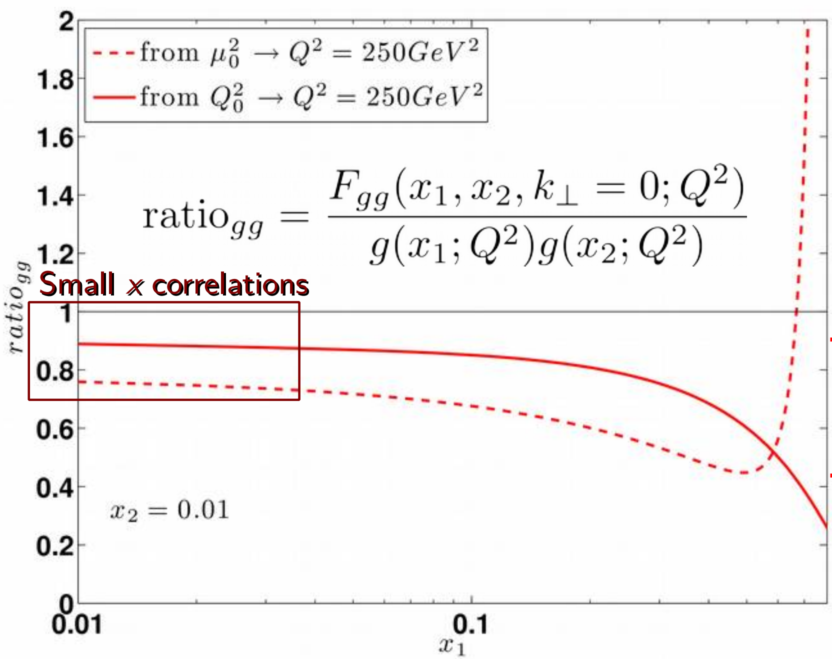
Usual in experimental analyses it is assumed that for gluons:

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

However, ratio_{gg} can be sensitive to:

Perturbative correlations → due to the different pQCD evolution scheme of PDFs and dPDFs

Non perturbative correlations → 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)

$ratio_{gg} \neq 1$
and x dependent
CORRELATIONS

What we would like to learn: A link between dPDFs and GPDs?

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

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

What we would like to learn: A link between dPDFs and GPDs?

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

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

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

Approximated by the proton state!

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

GPDs depending on the impact parameter

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

What we would like to learn: A link between dPDFs and GPDs?

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

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

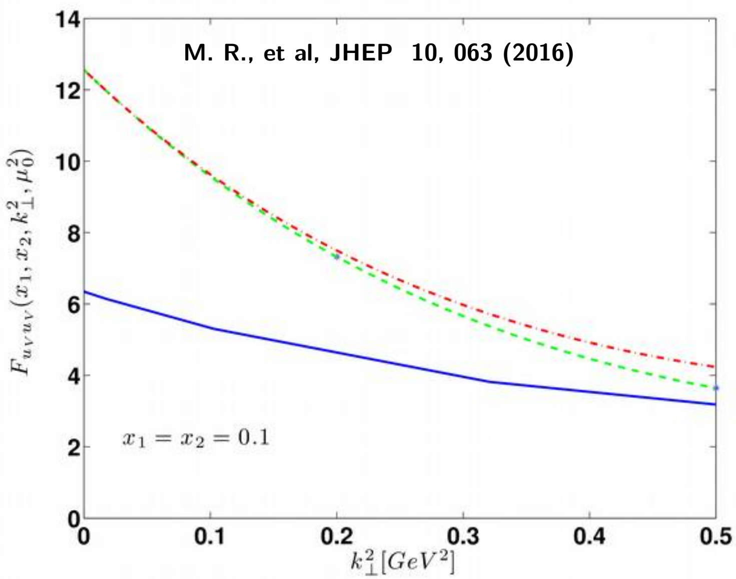
M. Diehl, D. Ostermeier, A. Schafer, JHEP 03 (2012) 089

Approximated by the proton state!

$$\boxed{\int \frac{dp'^+ d\vec{p}'_\perp}{p'^+} |p'\rangle\langle p'|}$$

$$F_{12}(x_1, x_2, \vec{k}_\perp) \sim f(x_1, 0, \vec{k}_\perp)\boxed{f(x_2, 0, \vec{k}_\perp)}$$

GPDs



dPDF app

dPDF

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 !

The Effective X-section

A fundamental tool for the comprehension of the role of DPS in hadron-hadron collisions is the so called "effective X-section": σ_{eff}

This object can be defined through a "pocket formula":

Sensitive to correlations

$$\sigma_{eff} = \boxed{\frac{m}{2}} \frac{\sigma_A^{pp'} \boxed{\sigma_B^{pp'}}}{\sigma_{double}^{pp}}$$

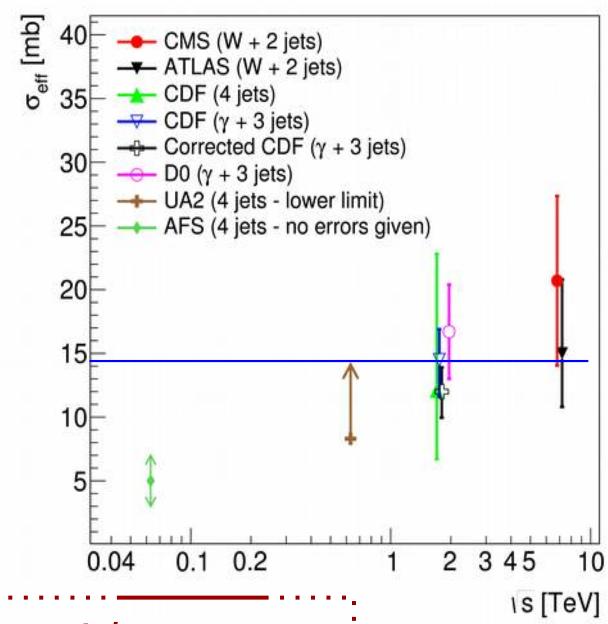
Differential cross section for the process: $\mathrm{pp'} \to A(B) + X$

Combinatorial factor

Differential cross section for a DPS event: $\mathrm{pp'} \to A + B + X$

....EXPERIMENTAL STATUS:

- Difficult extraction, approved analysis for the same sign *W's* production @LHC (RUN 2)
- the model dependent extraction of σ_{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 σ_{eff} without any approximations, studying the effect of correlations directly on σ_{eff}

The Effective X-section calculation

M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2016)

$$\sigma_{eff} = \frac{m}{2}\frac{\sigma_A^{pp'}\ \sigma_B^{pp'}}{\sigma_{double}^{pp}}$$

This quantity can be written in terms of PDFs and dPDFs ($_2$GPDs)

Here the scale is omitted

Colour coefficient

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

Non trivial
x-dependence

If factorization between dPDF and PDFs held:

$$F_{ab}(x_1,x_2,\vec{k}_\perp) = F_a(x_1)F_b(x_2)\tilde{T}(\vec{k}_\perp)$$

"EFFECTIVE FORM FACTOR"

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

Constant value w.r.t. x_i

Conjugated variable to $\vec{k}_\perp$

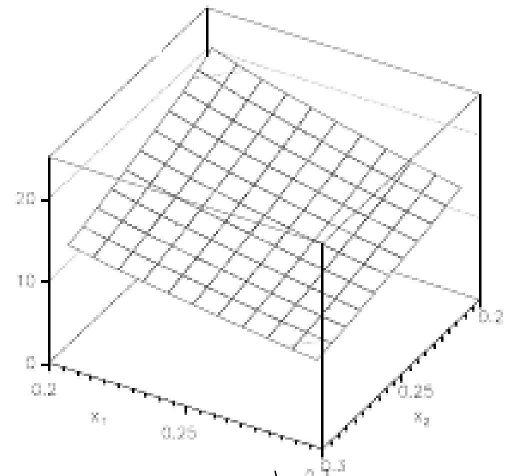
NO CORRELATIONS!

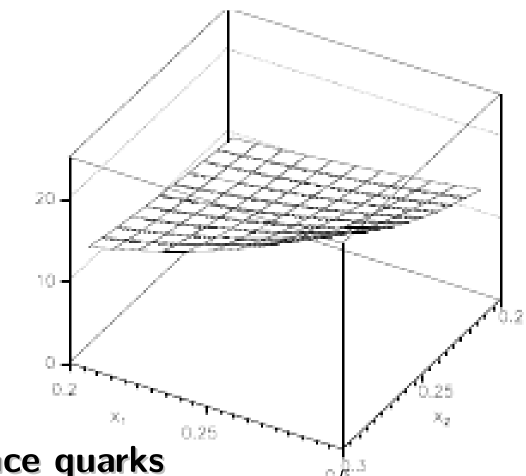
The Effective X-section calculation

M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2016)

Our predictions of σ_{eff} , **without any approximation**, in the valence region at different energy scales:

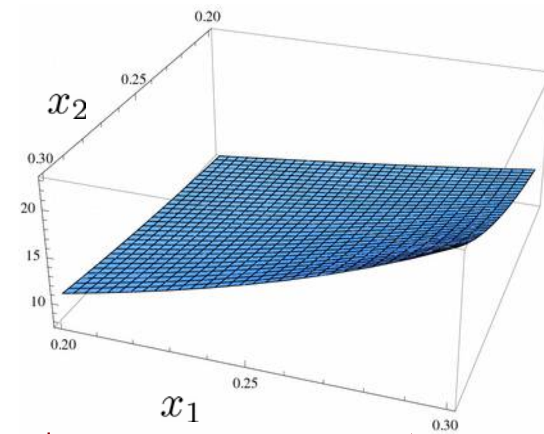
$$\sigma_{eff}(x_1, x_2, \mu_0^2) \xrightarrow[\text{pQCD evolution of dPDFs}]{\text{pQCD evolution of PDFs}} \sigma_{eff}(x_1, x_2, Q^2 = 250\ \text{GeV}^2)$$





Valence quarks

$$\boxed{\overline{\sigma_{eff}} \sim 11 \text{ mb}}$$



Valence quark ⊗ Sea quark
Partons involved in, e.g., same sign WW production.

Similar results obtained with dPDFs calculated within AdS/QCD soft-wall model
M. Traini, M. R., S. Scopetta and V.Vento, PLB 768, 270 (2017)

- **x_i dependence of σ_{eff} may be model independent feature**
- **Absolute value of σ_{eff} is a model dependent result**

The old data lie in the obtained range of σ_{eff}

The Effective X-section calculation

M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2016)

$$\boxed{\sigma_{eff} = \frac{m}{2}\frac{\sigma_A^{pp'}\,\sigma_B^{pp'}}{\sigma_{double}^{pp}}}$$

This quantity can be written in terms of PDFs and dPDFs ($_2$GPDs)

Here the scale is omitted

Colour coefficient

$$\sigma_{\rm eff}(x_1,x_1',x_2,x_2') = \frac{\sum_{i,k,j,l} F_i(x_1)F_k(x_1')F_j(x_2)F_l(x_2')C_{ik}\boxed{C_{jl}}}{\sum_{i,j,k,l} C_{ik}C_{jl}\int F_{ij}(x_1,x_2;k_\perp)F_{kl}(x_1',x_2';-k_\perp)\frac{dk_\perp}{(2\pi)^2}}$$

Non trivial x-dependence

If factorization between dPDF and PDFs held:

$$F_{ab}(x_1,x_2,\vec{k}_\perp) = F_a(x_1)F_b(x_2)\tilde{T}(\vec{k}_\perp)$$

"EFFECTIVE FORM FACTOR"

$$\sigma_{eff}(x_1,x_1',x_2,x_2') \to \sigma_{eff} = \left[\int \frac{d\vec{k}_\perp}{(2\pi)^2}\tilde{T}(\vec{k}_\perp)T(-\vec{k}_\perp)\right]^{-1} = \left[\int d\vec{b}_\perp (T(\vec{b}_\perp))^2\right]^{-1}$$

Constant value w.r.t. x_i

Conjugated variable to $\vec{k}_\perp$

NO CORRELATIONS!

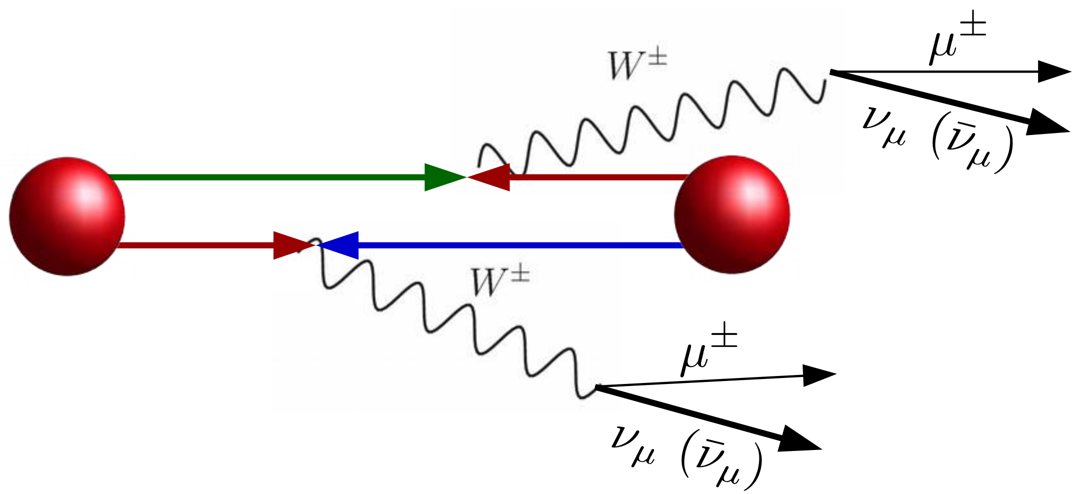
x DEPENDENCE on σ_{eff}

ACCESS THE DOUBLE PARTON CORRELATIONS

ACCESS THE PARTONIC STRUCTURE OF THE PROTON

Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030



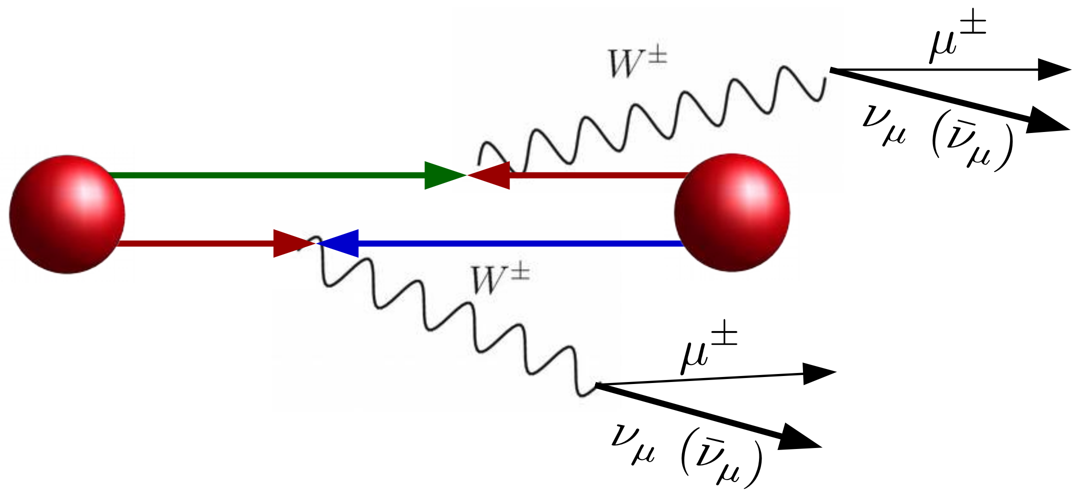
In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

⬇

"Same-sign W boson pairs production is a promising channel to look for signature of double Parton interactions at the LHC."

Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030

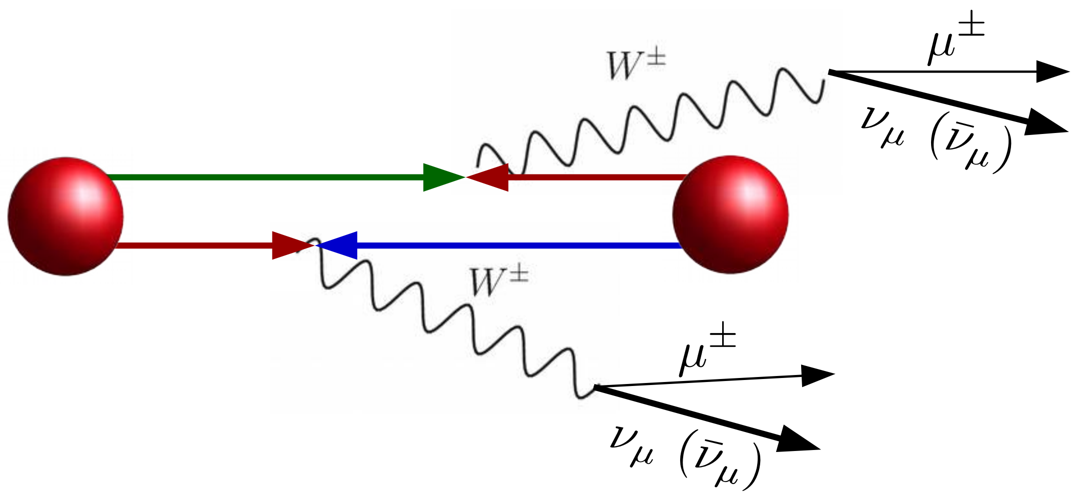


In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

Can double parton correlations be observed for the first time in the next LHC run ?

Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030



Kinematical cuts

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

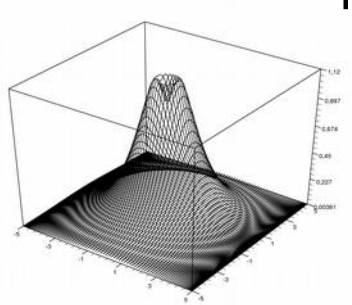
DPS cross section:

$$\frac{d^4\sigma^{pp\to\mu^\pm\mu^\pm X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2\vec{b}_\perp \boxed{F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W)} \frac{d^2\sigma_{ik}^{pp\to\mu^\pm X}}{d\eta_1 dp_{T,1}} \frac{d^2\sigma_{jl}^{pp\to\mu^\pm X}}{d\eta_2 dp_{T,2}} \boxed{\mathcal{I}(\eta_i, p_{T,i})}$$

$M_W \longrightarrow$ Momentum scale

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)

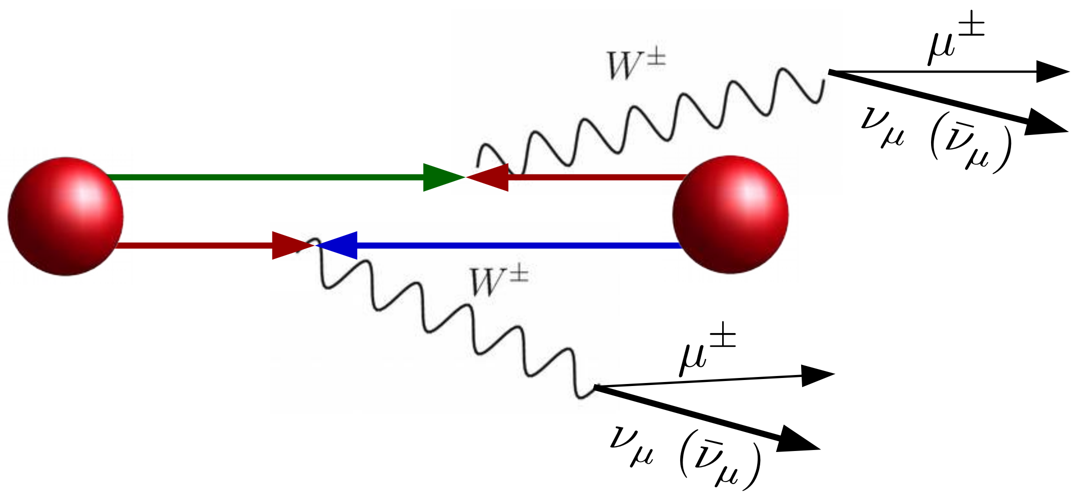


Longitudinal and transverse correlations arise from the relativistic CQM model describing three valence quarks

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

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030



Kinematical cuts

pp, $\sqrt{s} = 13$ TeV

$p_{T,\mu}^{leading} > 20$ GeV, $\quad p_{T,\mu}^{subleading} > 10$ GeV

$|p_{T,\mu}^{leading}| + |p_{T,\mu}^{subleading}| > 45$ GeV

$|\eta_\mu| < 2.4$

20 GeV $< M_{inv} <$ 75 GeV or $M_{inv} >$ 105 GeV

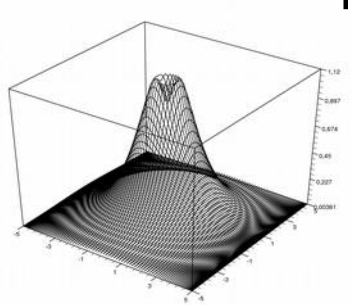
DPS cross section:

$$\frac{d^4\sigma^{pp\to\mu^\pm\mu^\pm X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2\vec{b}_\perp \boxed{F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W)} \frac{d^2\sigma_{ik}^{pp\to\mu^\pm X}}{d\eta_1 dp_{T,1}} \frac{d^2\sigma_{jl}^{pp\to\mu^\pm X}}{d\eta_2 dp_{T,2}} \boxed{\mathcal{I}(\eta_i, p_{T,i})}$$

$M_W \longrightarrow$ Momentum scale

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)



$$\sigma^{++} + \sigma^{--}[\text{fb}] \sim 0.69 \pm 0.18(\delta\mu_F)^{+0.12}_{-0.16}(\delta Q_0)^*$$

*details on the error in backup slides

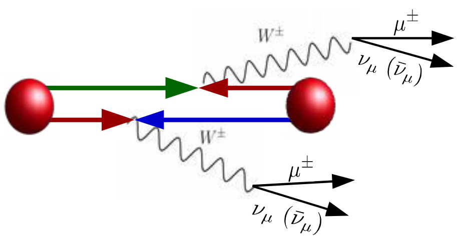
Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030

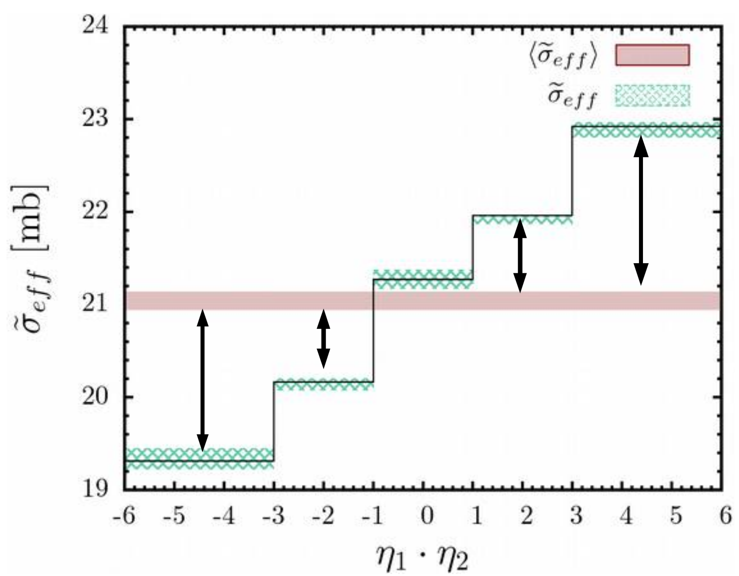
In order to understand whether correlations can be accessed in experimental observations, using dPDF evaluated within the QM model, the effective cross section has been calculated for this process and compared with its mean value:

$$\langle \tilde{\sigma}_{eff} \rangle = 21.04\,^{+0.07}_{-0.07}\,(\delta Q_0)\,^{+0.06}_{-0.07}(\delta \mu_F)\ \text{mb}\ .$$

*details in backup slides



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



$$\tilde{\sigma}_{eff} = \frac{m}{2} \frac{\sigma_A^{pp'}\ \sigma_B^{pp'}}{\sigma_{double}^{pp}}$$

Difference between green and red line is due to correlations effects

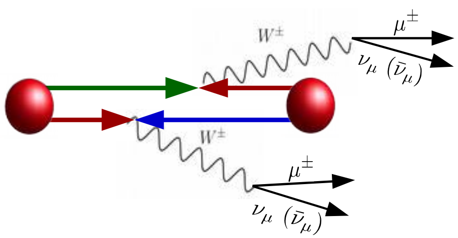
"Assuming that the results of the first and the last bins can be distinguished if they differ by 1 sigma, we estimated that

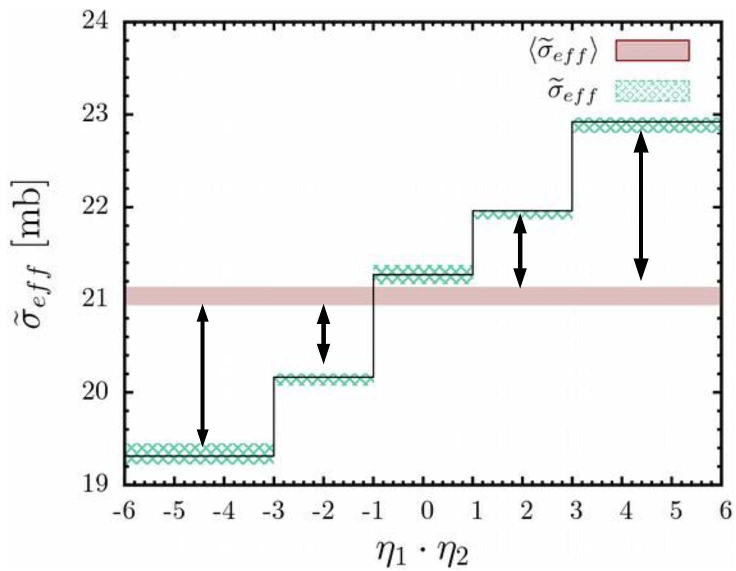
$$\boxed{\mathcal{L} = 1000\ \text{fb}^{-1}}$$

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:

$$\langle \tilde{\sigma}_{eff} \rangle = 21.04\,^{+0.07}_{-0.07}\,(\delta Q_0)\,^{+0.06}_{-0.07}(\delta \mu_F)\ \text{mb}\ .$$





Difference between green and red line is due to correlations effects

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

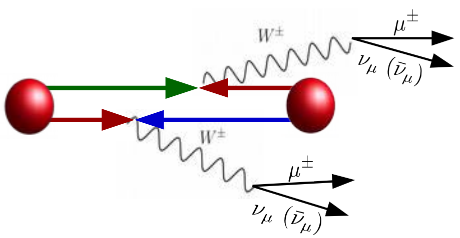
REACHABLE IN THE PLANNED LHC RUN

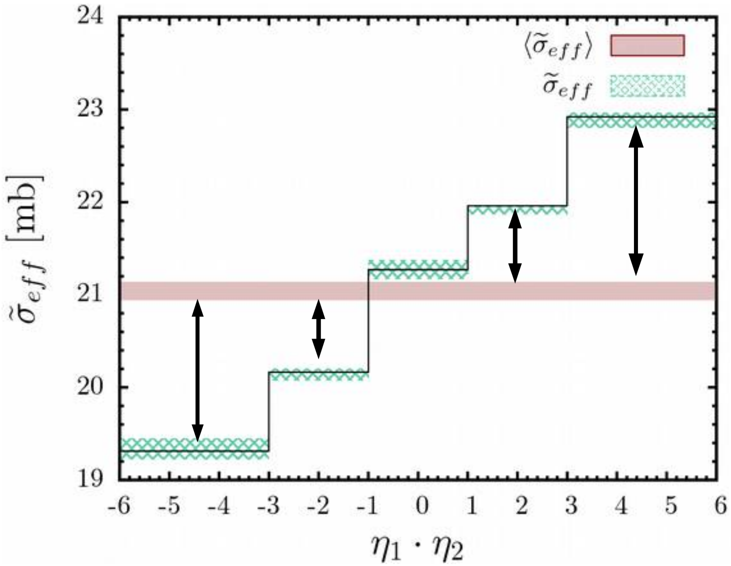
Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030

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:

$$\langle \tilde{\sigma}_{eff} \rangle = 21.04 \,^{+0.07}_{-0.07} \, (\delta Q_0) \,^{+0.06}_{-0.07} (\delta \mu_F) \text{ mb} \; .$$





Difference [↕] between green and red line is due to correlations effects

IN THIS CHANNEL, THANKS TO THIS ANALYSIS, THE POSSIBILITY TO OBSERVE FOR THE FIRST TIME TWO-PARTON CORRELATIONS, IN THE NEXT LHC RUN, HAS BEEN ESTABLISHED

A clue from data?

M. R. and F. A. Ceccopieri, PRD 97, no. 7, 071501 (2018) rapid communication

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

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

Effective form factor (Eff)

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

$$\tilde{T}(k_\perp) = \frac{1}{2} \int dx_1 dx_2 F(x_1, x_2, k_\perp) = \int d\vec{k}_1 d\vec{k}_2 \Psi(\vec{k}_1 + \vec{k}_\perp, \vec{k}_2) \Psi^\dagger(\vec{k}_1, \vec{k}_2 + \vec{k}_\perp)$$

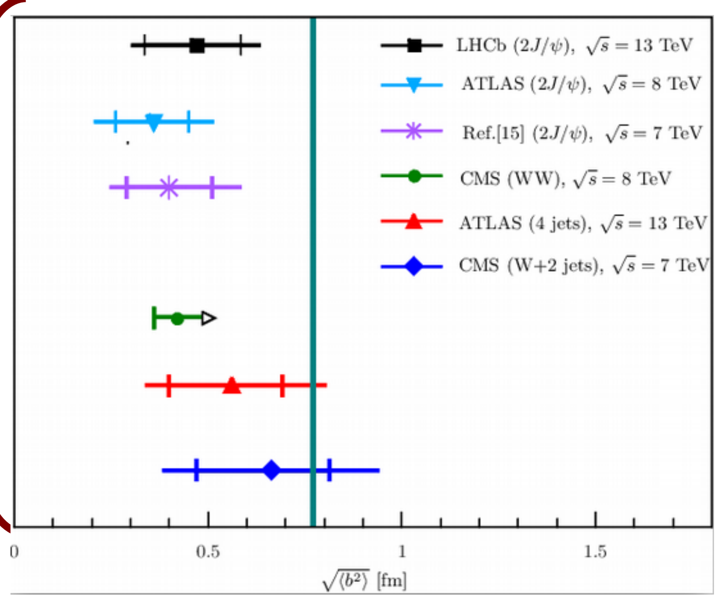
From the above quantity the mean distance in the transverse plane between two partons can be defined:

$$\langle b^2 \rangle \sim -2 \frac{d}{k_\perp dk_\perp} \tilde{T}(k_\perp) \Big|_{k_\perp = 0}$$

Eff is completely unknown but using general model independent properties, obtained by comparing Eff with standard proton ff, we analytically found that:

$$\frac{\sigma_{eff}}{3\pi} \leq \langle b^2 \rangle \leq \frac{\sigma_{eff}}{\pi}$$

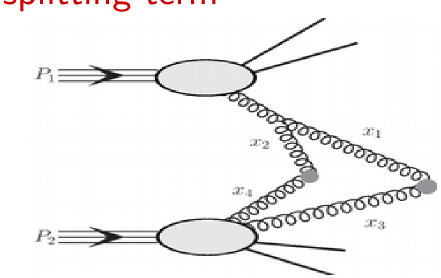
For gluon-gluon DPS processes:



The vertical line stands for the two dimensional proton radius

We are working on:

- Extending the approach including splitting term



- Extending the approach to the most general unfactorized case

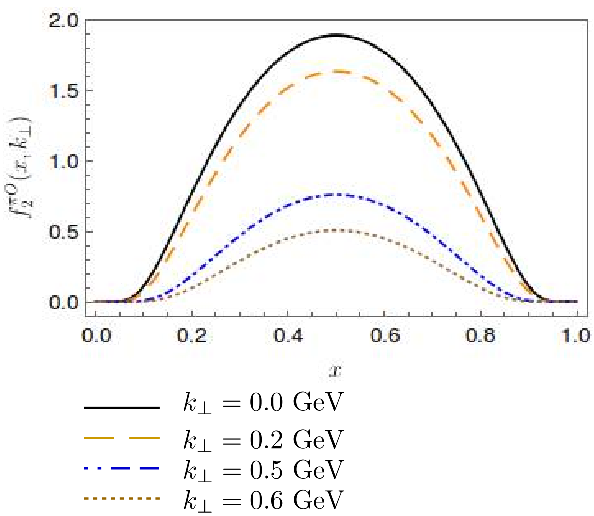
M. R., S. Scopetta, M. Traini and V.Vento, arXiv: 1806.10112

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

$$f_2(x,k_\perp) = \frac{1}{2}\sum_{h,h'}\int \frac{d^2k_{1\perp}}{2(2\pi)^3}\psi_{h,h'}(x,\vec{k}_{1\perp})\underbrace{\psi^*_{h,h'}(x,\vec{k}_{1\perp}+\vec{k}_\perp)}_{\text{Meson wave function}}$$

Parton helicities

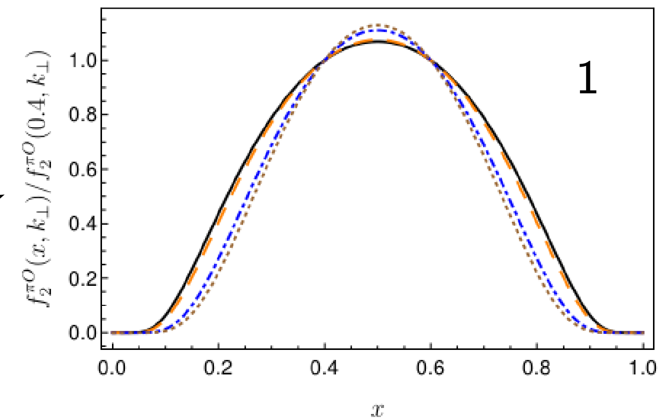
Intrinsic parton momentum



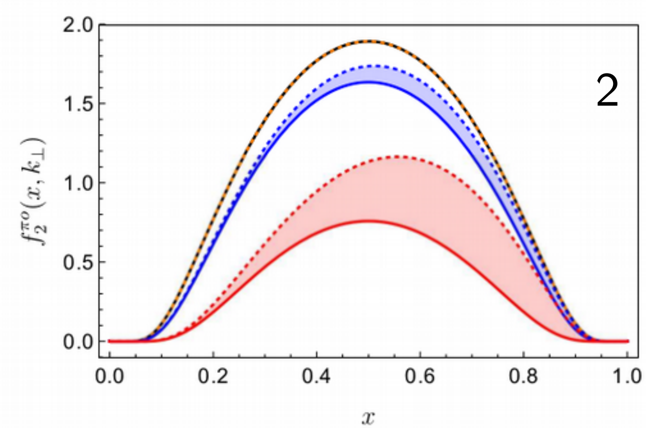
Pion: w.f. calculated within the AdS/QCD soft-wall model

S. J. Brodsky et al, PRD 77, 056007 (2008)

1) Also for pion, model calculations indicate that the $x - k_\perp$ factorization does not work!



2) Also for pion, model calculations indicate that dPDF can not be described in terms of GPDs (Dotted line=dPDF approximated).



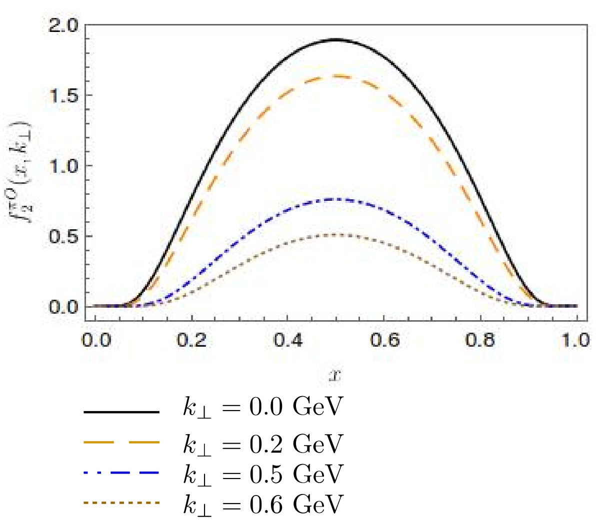
What next: pion double PDF

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

$$f_2(x, k_\perp) = \frac{1}{2} \sum_{h,h'} \int \frac{d^2 k_{1\perp}}{2(2\pi)^3} \underbrace{\psi_{h,h'}(x, \vec{k}_{1\perp}) \psi^*_{h,h'}(x, \vec{k}_{1\perp} + \vec{k}_\perp)}_{\text{Meson wave function}}$$

Parton helicities

Intrinsic parton momentum

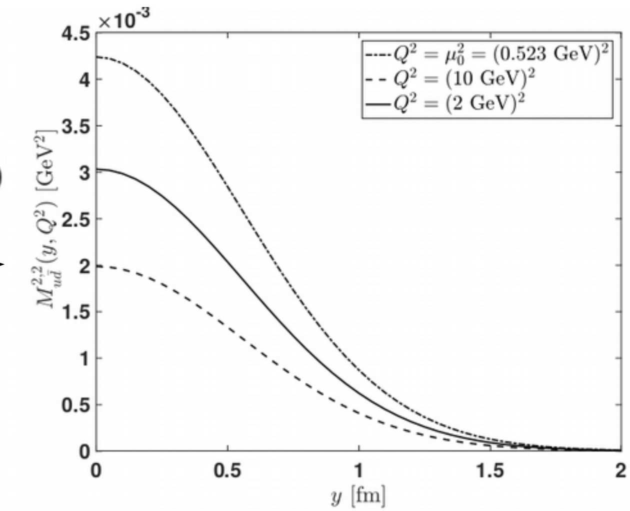


Pion: w.f. calculated within the AdS/QCD soft-wall model

S. J. Brodsky et al, PRD 77, 056007 (2008)

$$M^{22}_{u\bar{d}}(y, Q^2) = \int_0^1 dx_1 \int_0^{1-x_1} dx_2\, x_1 x_2 \bar{F}_{u\bar{d}}(x_1, x_2, y, Q^2)$$

2[nd] moment of dPDF evaluated at different final scales by means of pQCD evoultion of dPDFs.



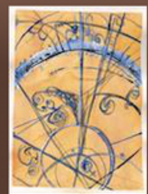
The latter is a quantity close to those evaluated in "new" lattice studies of DPS. Future comparison are in principle possible to obtain new information on dPDF from lattice QCD.

Conclusions

- **A CQM calculation of the dPDFs with a Poincare' invariant 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!**
  - calculation of mean partonic distance from present experimental amalyses
  - calculation of pion dPDF
- **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!**

MPI at work

Next MPI workshop in Perugia:



10th International Workshop on Multiple Partonic Interactions at the LHC

10-14 diciembre 2018
Auditorium Santa Cecilia , Perugia, Italy
Europe/Zurich timezone

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- Lista de participantes

Workshop Secretariat

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MPI@LHC 2018 is the 10th-anniversary edition of the International Workshop on Multiple Partonic Interactions at the LHC (MPI@LHC). The first event of this series of successful meetings took place in Perugia, the MPI community decided to complete a first 10-years cycle precisely in the same place, Perugia, Italy, in December 10-14, 2018 where the scientific adventure started.

From the start of the operations at the Large Hadron Collider, Multiple Partonic Interactions (MPIs) are experiencing a growing attention and are widely invoked to account for observations that cannot be explained otherwise. Examples are the associated hadron production (Underlying Event) in high-energy hadronic collisions, the rates for multiple heavy flavor production, the survival probability of large rapidity gaps in hard diffraction.

In particular, Double Parton Interactions were observed directly and studied by several FNAL and LHC experiments in different reaction channels. Our present understanding and the available experimental data are now opening the possibility to perform an unprecedented investigation of the proton structure.

More recently, a novel issue is the study of high multiplicity final states in pp and pA interactions, where correlations in soft MPI may give rise to flow-like effect. At the LHC a new QCD regime can be reached, where MPIs occur with high rates, due to unprecedented high parton densities.

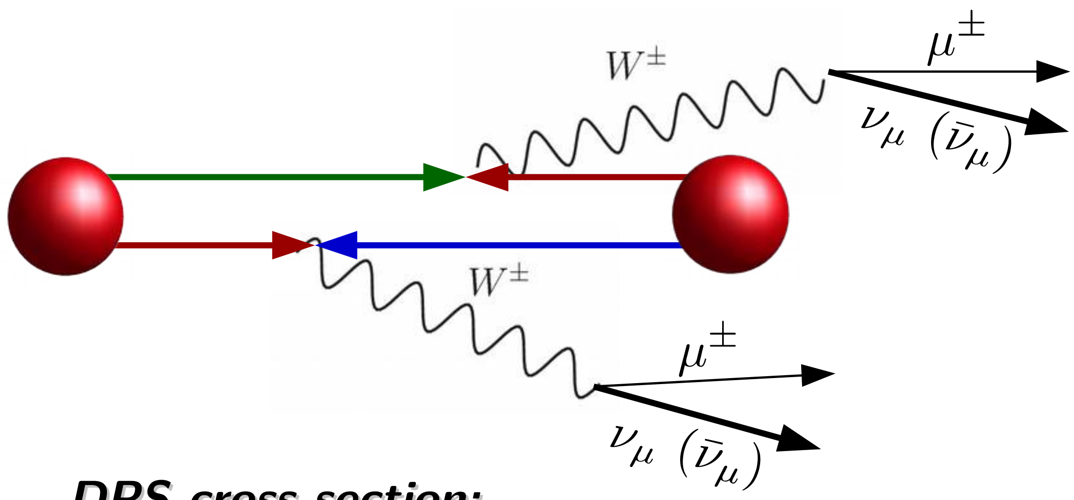
Understanding of MPIs is therefore crucial, both for their significant contribution to the background of various processes of interest for the search of new physics and because MPIs allow to probe high energy - high density QCD dynamics and, as a consequence of the geometrical characteristics of the interaction, to obtain unprecedented information on the correlated structure of QCD bound states.

The aim of this workshop is to provide, after 10 years, a more complete and updated view of MPI studies, and to strengthen contacts between the theoretical and experimental communities.

We really look forward to meeting with all the interested scientists and everyone who contributed to MPI studies in Perugia.

Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030



Kinematical cuts

$pp,\ \sqrt{s} = 13$ TeV

$p_{T,\mu}^{leading} > 20$ GeV, $\quad p_{T,\mu}^{subleading} > 10$ GeV

$|p_{T,\mu}^{leading}| + |p_{T,\mu}^{subleading}| > 45$ GeV

$|\eta_\mu| < 2.4$

20 GeV $< M_{inv} < 75$ GeV or $M_{inv} > 105$ GeV

DPS cross section:

$$\frac{d^4\sigma^{pp\to\mu^\pm\mu^\pm X}}{d\eta_1 dp_{T,1} d\eta_2 dp_{T,2}} = \sum_{i,k,j,l} \frac{1}{2} \int d^2\vec{b}_\perp \boxed{F_{ij}(x_1, x_2, \vec{b}_\perp, M_W) F_{kl}(x_3, x_4, \vec{b}_\perp, M_W)} \frac{d^2\sigma_{ik}^{pp\to\mu^\pm X}}{d\eta_1 dp_{T,1}} \frac{d^2\sigma_{jl}^{pp\to\mu^\pm X}}{d\eta_2 dp_{T,2}} \boxed{\mathcal{I}(\eta_i, p_{T,i})}$$

$M_W \longrightarrow$ Momentum scale

We have used as input 3 models of dPDFs:

2)Model: **MSTW**

$$F_{ab}(x_1, x_2, \vec{b}_\perp, M_W) = \boxed{a(x_1, M_W)}\, b(x_2, M_W) \boxed{T(\vec{b}_\perp)}$$

PDFs of the parametrization:
A.D. Martin *et al*. Eur. Phys. J. **C63,** 189 (2009)

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

$$\bar{\sigma}_{\mathbf{eff}} = \mathbf{17.8 \pm 4.2}\ \mathrm{mb}$$

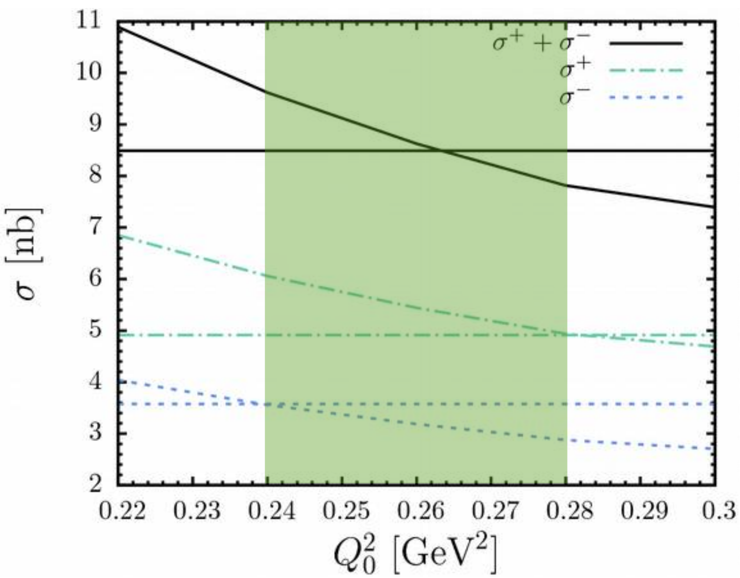
Average of CMS and ATLAS extractions from the analysis of W+dijet.
New results on same sign W's

Same sign W's in pp collisions at $\sqrt{s} = 13$ TeV at the LHC

F. A. Ceccopieri, M. R., S. Scopetta, Phys.Rev. D95 (2017) no.11, 114030

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 $pp \to W^+ \to (\mu^+ \bar{\nu}_\mu)\ X;\ pp \to W^- \to (\mu^- \nu_\mu)\ X$



THE STRATEGY:

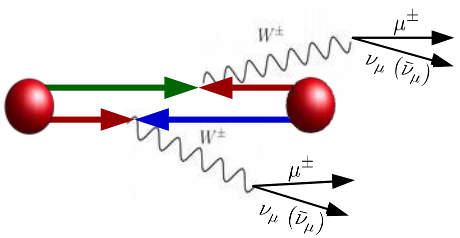
✔ σ^+, σ^- have been evaluated through DYNNLO [1] code by using PDFs of MSTW08 parametrization [2] (straight lines)

[1] S. Catani et. al., PRL 103, 082001 (2009); S. Catani et al., PRL 98, 222002 (2007)
[2] A.D. Martin *et al*. Eur. Phys. J. C63, 189 (2009)

✔ σ^+, σ^- 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:

$$\boxed{\delta Q_0^2 \Longrightarrow 0.24 < Q_0^2 < 0.28\ \mathrm{GeV}^2}$$

✔ The uncertainty due to neglected higher order perturbative corrections has been simulated by varying the final momentum scale:

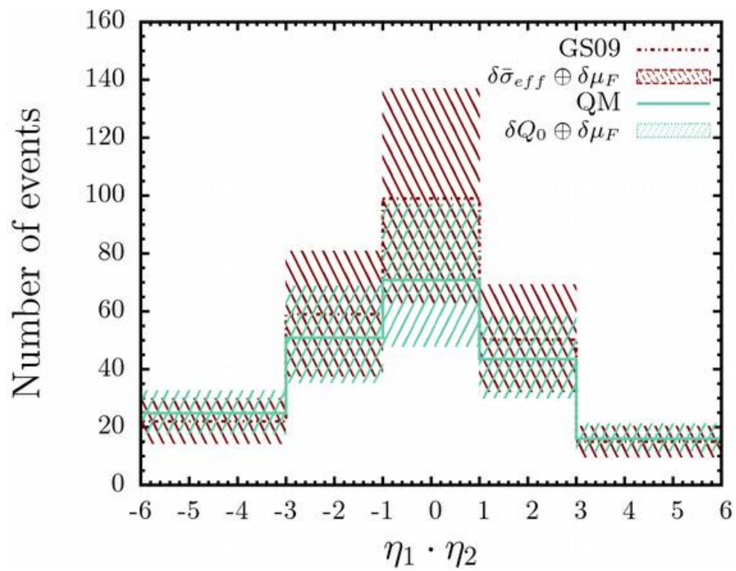
$$\delta\mu_F \Longrightarrow 0.5 M_W < \mu_F < 2.0 M_W$$

✔ 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.: $\eta_1 \cdot \eta_2 \simeq \frac{1}{4} ln\frac{x_1}{x_3} ln\frac{x_2}{x_4}$

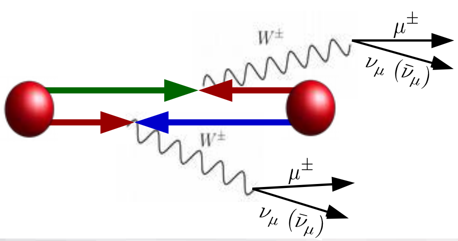
dPDFs	$\sigma^{++} + \sigma^{--}$ [fb]
MSTW	$0.77\ ^{+0.23}_{-0.21}\ (\delta\mu_F)\ ^{+0.18}_{-0.18}\ (\delta\bar{\sigma}_{eff})$
GS09	$0.82\ ^{+0.24}_{-0.26}\ (\delta\mu_F)\ ^{+0.19}_{-0.19}\ (\delta\bar{\sigma}_{eff})$
QM	$0.69\ ^{+0.18}_{-0.18}\ (\delta\mu_F)\ ^{+0.12}_{-0.16}\ (\delta Q_0)$

dPDFs	σ^{++} [fb]	σ^{--} [fb]	σ^{++}/σ^{--}
GS09	0.54	0.28	1.9
QM	0.53	0.16	3.4
GS09/QM	1.01	1.78	-



RESULTS:

- results of the three models are comparable within the errors;
- with $\mathcal{L} = 300\ \text{fb}^{-1}$ 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