3D nucleon structure and Double Parton Scattering at the LHC

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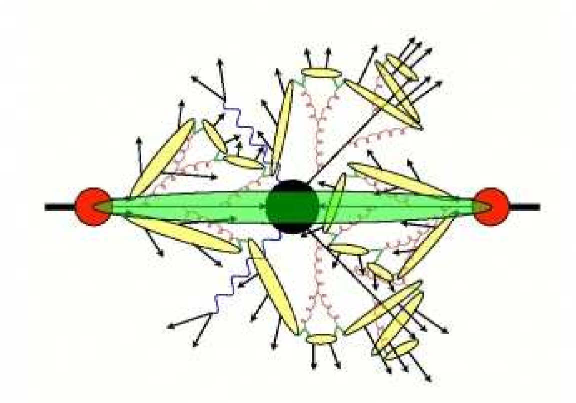
Outline

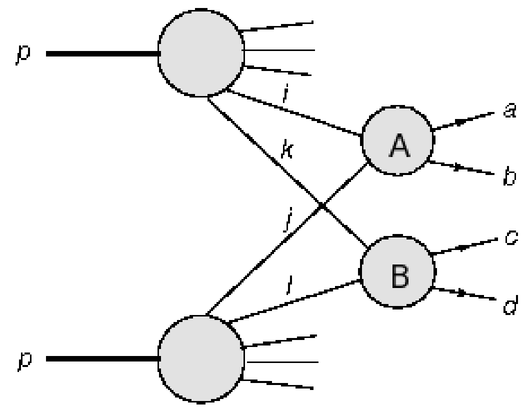
- *Hard* **multiple parton interactions (MPI) and double parton scattering (DPS) @LHC;**
  double Parton Distribution Functions (dPDFs) and 3D proton structure: 2-parton correlations
- **Our contribution: model calculation of dPDFs and DPS cross sections. Short summary of recent results:**

  M. Rinaldi, S.S. and V. Vento, PRD 87, 114021 (2013);
  M. Rinaldi, S.S., M. Traini and V. Vento, JHEP 12 (2014) 028;
  M. Rinaldi, S.S., M. Traini and V. Vento, PLB 752 (2016) 40;
  M. Rinaldi, S.S., M. Traini and V. Vento, JHEP 10 (2016) 063;
  M. Traini, M. Rinaldi, S.S. and V. Vento, arXiv:160907.242 [hep-ph]
- **Perspectives in $p-p$ and $p-A$ collisions**
- **Conclusions**

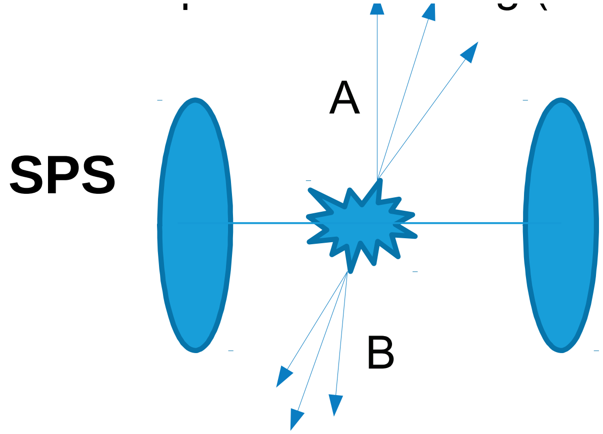
Hard MPI and Double Parton Scattering

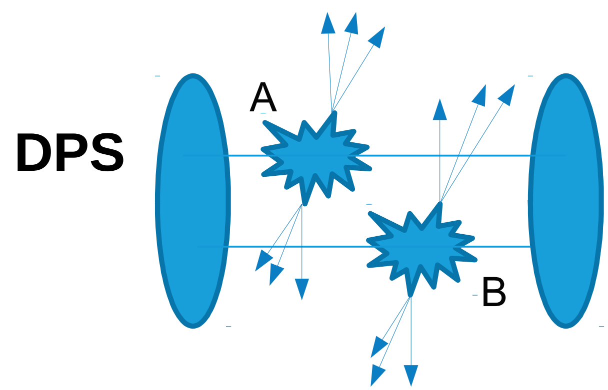
- In an LHC collision, MPI can occur:





- MPI are a wide subject; I will discuss *hard* double parton scattering (DPS). In the reaction $p + p \to A + B + X$, two (sets of) hard objects A and B, with associated scales Q_A and Q_B, can be produced through DPS, in addition to single parton scattering (SPS):





Hard MPI and Double Parton Scattering

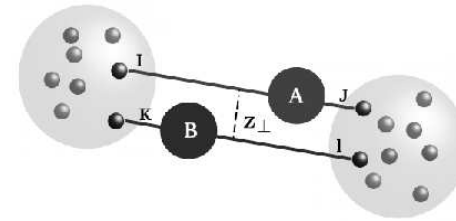
In terms of the total cross section, the DPS mechanism is power suppressed with respect to SPS (see, e.g., **M. Diehl, D. Ostermeier, A. Schäfer JHEP 03 (2012) 089**):

$$\sigma_{DPS}/\sigma_{SPS} = \Lambda^2/Q^2$$

However:

- DPS can compete with SPS if SPS process is suppressed by small or multiple coupling constants (e.g., same sign WW **J. Gaunt et al EPJC 69 (2010) 53**).
- DPS populates the final state phase space in a different way from SPS. In particular, it tends to populate the region of small $\mathbf{q_{A,T}}$, $\mathbf{q_{B,T}}$ and it is competitive with SPS in this region (used in experiments).
- DPS becomes more important relative to SPS as the collider energy grows. Smaller x values are probed where there is a larger density of partons (LHC!).
- DPS is important: a background for the search of new Physics
- DPS is mportant for us: it reveals new information about the structure of the nucleon. In particular, correlations between partons in the proton.

DPS and Double Parton Distributions (dPDFs)



- DPS cross section **(N. Paver, D. Treleani, Nuovo Cimento 70A, 215 (1982); M. Mekhfi PRD 32, 2371 (1985))** - proof of fact. still missing (**but see M. Diehl, J. Gaunt... JHEP 1 (2016) 76**)

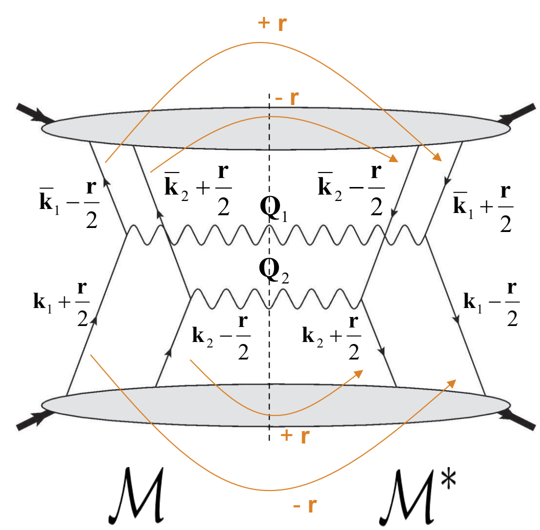
$$d\sigma = \frac{1}{S}\sum_{i,j,k,l} \hat{\sigma}_{ij}(x_1, x_3, \mu_A)\hat{\sigma}_{kl}(x_2, x_4, \mu_B)$$
$$\times \int d^2\vec{b}_\perp\, F_{ik}(x_1, x_2, \mathbf{b}_\perp, \mu_A, \mu_B) F_{jl}(x_3, x_4, \mathbf{b}_\perp, \mu_A, \mu_B)$$

x_i = momentum fraction carried by the parton inside the hadron;
$\mu_{A,B}$ = momentum scale; $\mathbf{b}_\perp$ = transverse distance between the two partons
the dPDF $F_{ik}(x_1, x_2, \mathbf{b}_\perp, \mu_A, \mu_B)$ in one of the protons is very interesting!

- In momentum space:

transverse momentum of partons, in general, is different in amplitude and conjugate

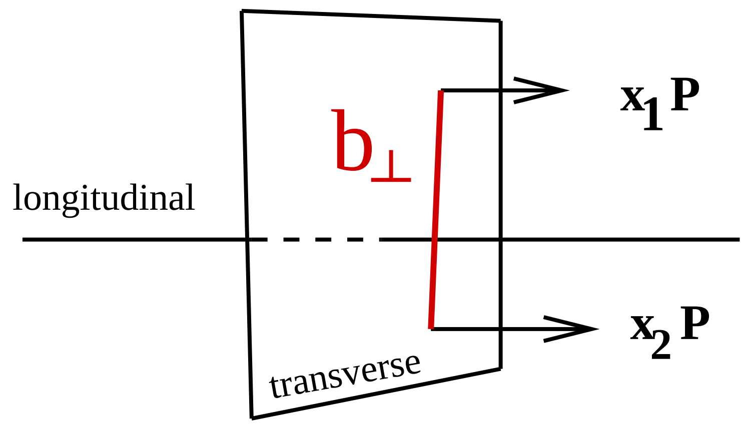
$\mathbf{k}_\perp$ = momentum imbalance of a parton line between amplitude and conjugate



Nucleon 3D structure from dPDFs?

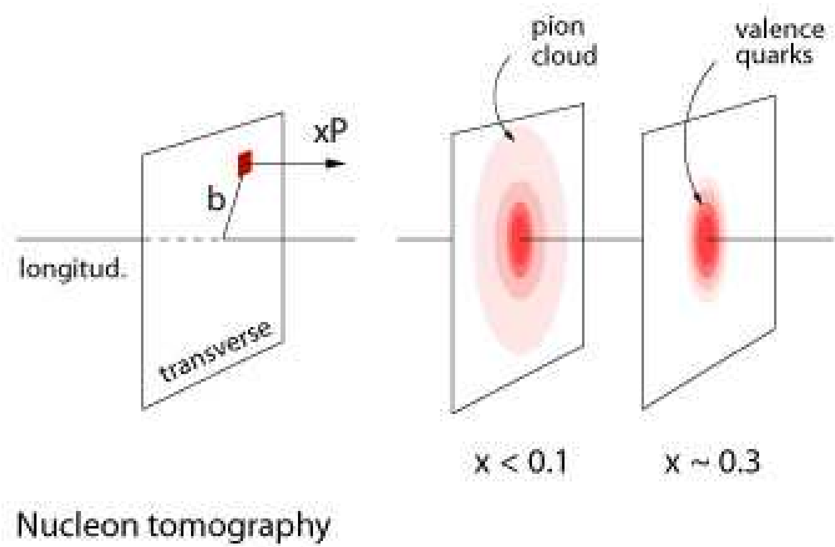
$F_{ij}(x_1, \mu_A, x_2, \mu_B, \mathbf{b}_\perp)$ is a 2-body density

- It is dimensioned;
- Its F.T. wrt $\mathbf{b}_\perp$, dimensionless, is NOT a density (sometimes it is called $_2GPD$)



"Nucleon tomography" is done through GPDs (in Impact parameter space)

- $H(x, \xi = 0, \mathbf{b}, \mu)$ is a 1-body density
- Its F.T. wrt $\mathbf{b}$, dimensionless, is NOT a density (standard GPD)



F_{ij} is very interesting: 2-body quantities are always theoretically intriguing (their measurement, challenging). The difference between a 2-body quantity and the product of two 1-body quantities is a measurement of CORRELATIONS

dPDFs and correlations

F_{ij} is usually factorized as follows ((x_1, x_2) $- k_\perp$ factorization):

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

AND (x_1, x_2 factorization):

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

NO CORRELATION ANSATZ

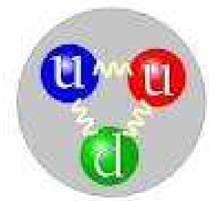
This means that correlations between the quarks in the proton are neglected.

- Is this a safe approximation? Important for LHC fundamental studies (actually it is broken even by QCD evolution)
- Taking into account correlations in the analysys, can one understand better the proton structure through MPI observation?

Double Parton Correlations (DPCs)

- In principle, correlations are there. At low x, due to the large population of partons, they may be less relevant **BUT** theoretical estimates are necessary.
  We are not alone in addressing this issue
  (**Calucci and Treleani (1999), Korotkikh et al. (2004), Gaunt and Stirling (2010), Diehl and Schäfer (2011), Snigirev (2011), Blok et al. (2012), Strikman et al. (2013)...**)

- Difficult to study DPCs, non perturbative quantities, from first principles



- Our contribution: a quark model analysis

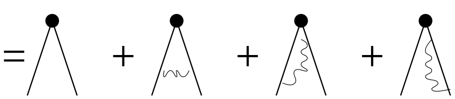
  Constituent Quark Models CQM provide a correlated framework.
  Widely used to guide measurements of NP quantities (e.g., TMDs, GPDs):
  they reproduce the gross features of experimental PDFs in the valence region...
  BUT present LHC date are at low x...

  One has to perform a perturbative QCD evolution to the experimental scale, Q^2 from a low momentum scale, μ_o^2

$$f(x,\mu_o^2) \xrightarrow{R.G.E.,\ p.\ QCD} f(x,Q^2),\ DIS$$

Twist-2

$L.O. =$



$+\ N.L.O.\ \ (2\ \text{loops})$

dPDFs in a Light-Front approach

M. Rinaldi, S.S., M. Traini and V.Vento, JHEP, 1412 (2014) 028

To improve the approach of our first calculation (**M. Rinaldi, S.S. and V.Vento, PRD 87, 114021 (2013)**), we implemented Relativity using a Light-Front (LF) approach. In the Relativistic Hamiltonian Dynamics (RHD) of an interacting system, (Dirac, 1949), one has:

- full Poincarè covariance
- fixed number of on-mass-shell constituents

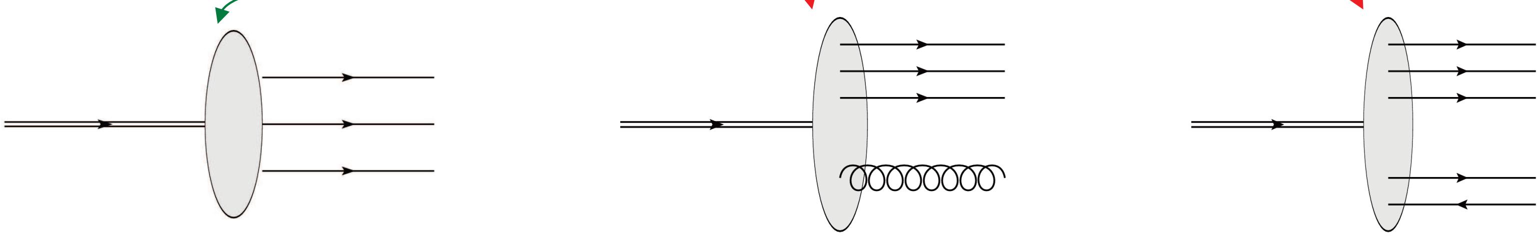
Among the 3 possible forms of RHD, the LF (initial hypersurface: $x^+ = x_0 + x_3 = 0$; in standard, "Instant Form" QM: $x_0 = 0$). has several advantages. The most relevant here:

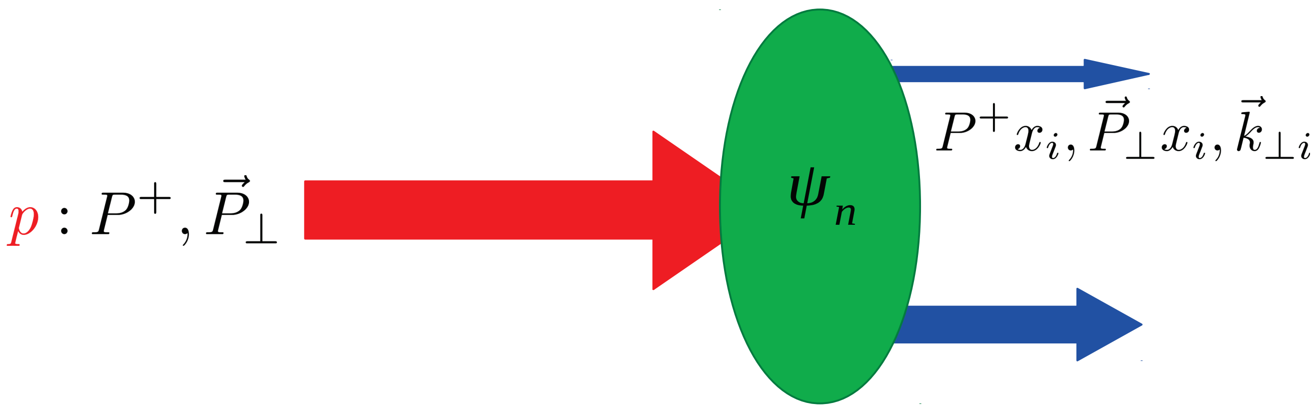
- 7 Kinematical generators (maximum number): i) three LF boosts (at variance with the dynamical nature of the Instant-form boosts), ii) $P^+, \mathbf{P}_\perp$, iii) Rotation around z.
- The LF boosts have a subgroup structure, then one gets a trivial separation of the intrinsic motion from the global one (as in the non relativistic (NR) case).
- in a specific construction of the Poincaré generators (Bakamjian-Thomas) it is possible to obtain a Mass equation, Schrödinger-like. A clear connection to NR.
- The IMF description of DIS is easily included. Systematically applied to calculate FFs, PDFs, GPDs, TMDs...

A Light-Front wave function representation

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)**

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





$$x_i = \frac{k_i^+}{P^+}$$

$$\sum_i^n x_i = 1$$

$$\sum_i^n \vec{k}_{\perp i} = 0$$

$\psi_n^{[l]}(x_i, \vec{k}_{\perp i}, \lambda_i) \longleftrightarrow$ Invariant under LF boosts!

A Light-Front wave function representation

In our approach, it is possible to connect LF states to IF ones, through the Melosh Rotations $D^{1/2}_{\lambda\lambda'}(R_{il}(\vec{k}))$

(see, e.g., B.D. Keister, W.N. Polyzou, Adv. Nucl. Phys. 20, 225 (1991))

$$|\vec{k}_\perp, \lambda, \tau\rangle_{[l]} \propto \sqrt{2k_0} \sum_{\lambda'} D^{1/2}_{\lambda\lambda'}(R_{il}(\vec{k}))|\vec{k}_\perp, \lambda', \tau\rangle_{[i]} \ ,$$

so that a relation between the LF $\psi^{[l]}_\lambda$ and the IF $\psi^{[i]}_\lambda$ is obtained

$$\psi^{[l]}_\lambda(\beta_1, \beta_2, \beta_3) \propto \left[\frac{\omega_1\omega_2\omega_3}{M_0 x_1 x_2 x_3}\right] \sum_{\mu_1\mu_2\mu_3} D^{1/2*}_{\mu_1\lambda_1}(R_{il}(\vec{k}_1)) D^{1/2*}_{\mu_2\lambda_2}(R_{il}(\vec{k}_2)) D^{1/2*}_{\mu_3\lambda_3}(R_{il}(\vec{k}_3))$$
$$\times \quad \psi^{[i]}_\lambda(\alpha_1, \alpha_2, \alpha_3)$$

with $\beta_i = \{x_i, \vec{k}_{i\perp}, \lambda_i, \tau_i\}, \ \alpha_i = \{\vec{k}_i, \mu_i, \tau_i\}, \ \omega_i = k_{i0}, \ M_0 = \sum_i \omega_i = \sum_i \sqrt{m^2 + \vec{k}_i^2}$

Now this formalism can be used in the definition of the dPDF...

dPDFs in the Light-Front approach

quark-quark dPDFs are defined through Light-Cone quantized states and fields (see, e.g., **M. Diehl, D. Ostermeier, A. Schäfer JHEP 03 (2012) 089**). From that, extending a procedure used, e.g., in **Pasquini, Boffi and Traini NPB 649 (2003) 243** for GPDs, the LF dPDF is obtained, **in mom. space**, in the intrinsic frame $\vec{k}_1 + \vec{k}_2 + \vec{k}_3 = 0$:

$$F_{12}(x_1, x_2, \vec{k}_\perp) = 3(\sqrt{3})^3 \int \prod_{i=1}^{3} d\vec{k}_i \, \delta\left(\sum_{i=1}^{3} \vec{k}_i\right) \Phi^*(\{\vec{k}_i\}, \vec{k}_\perp) \Phi(\{\vec{k}_i\}, -\vec{k}_\perp) \times \delta\left(x_1 - \frac{k_1^+}{M_0}\right) \delta\left(x_2 - \frac{k_2^+}{M_0}\right)$$

with

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

(**NB**: here $\vec{k}_\perp$ is the momentum conjugated to $\vec{b}_\perp$; it is a *relative* momentum, it is **NOT** the argument of TMDs. Sorry for a possibly confusing notation)

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

Now one always gets the correct support: $x_1 + x_2 > 1 \rightarrow F_{12}(x_1, x_2, k_\perp) = 0$

A model is needed for the usual IF wave function $\psi^{[i]}$

Example: dPDFs in a LF Hyper-central CQM

Hyper-central CQMs have a long tradition (see, i.e., **Giannini and Santopinto, arXiv:1501.03722**). We use here the relativistic version developed in **Faccioli, Traini, Vento NPA656,400 (1999)**. The proton w.f.

$$\psi^{[i]} = \frac{1}{\pi\sqrt{\pi}} \Psi(k_\xi) \times SU(6)_{spin-isospin}$$

is solution of the mass equation

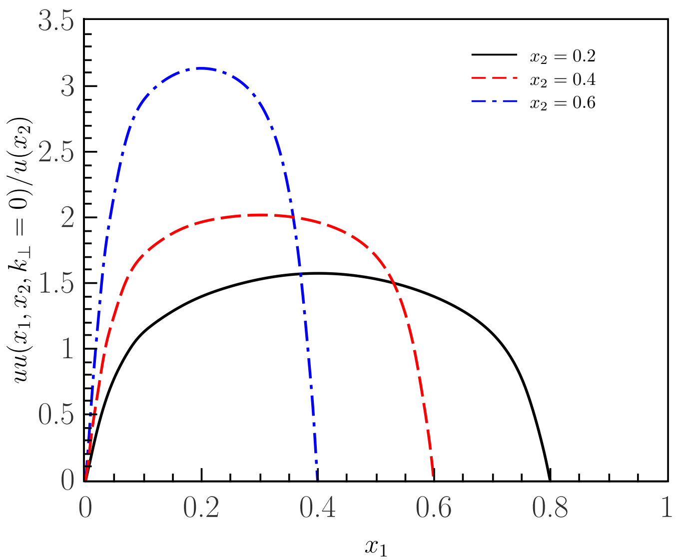
$$(M_0 + V)\Psi(k_\xi) \equiv \left(\sum_{i=1}^{3} \sqrt{m^2 + \vec{k}_i^2} - \frac{\tau}{\xi} + \kappa_l \xi \right) \Psi(k_\xi) = M\Psi(k_\xi)$$

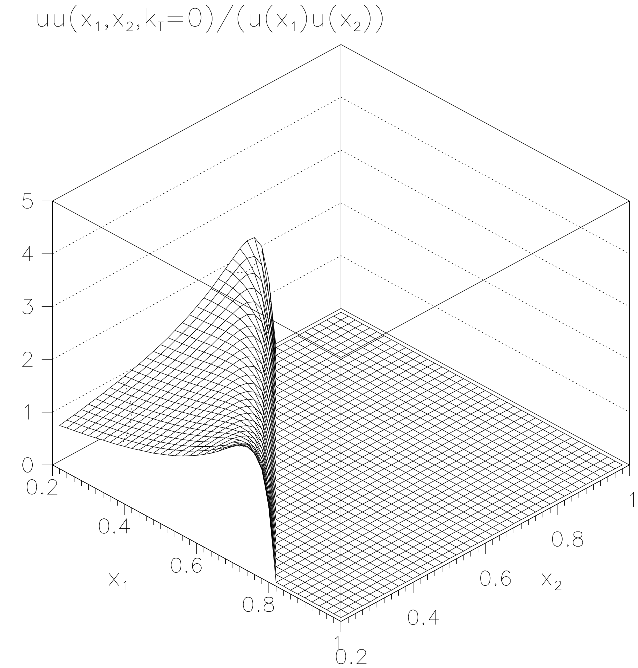
with $k_\xi = \sqrt{2(\vec{k}_1^2 + \vec{k}_2^2 + \vec{k}_1 \cdot \vec{k}_2)}$, $\tau = 3.30$ $\kappa_l = 1.80$ fm^{-2} and

$$\Psi(k_\xi) = \sum_{\nu=0}^{16} c_\nu \frac{(-1)^\nu}{\alpha^3} \left[\frac{2\nu!}{(\nu+2)!} \right]^{1/2} e^{-k_\xi^2/(2\alpha^2)} \sum_{m=0}^{\nu} \frac{(-1)^m}{m!} \frac{(\nu+2)}{(\nu-m)!(m+2)!} \left(\frac{k_\xi^2}{\alpha^2} \right)^m$$

The parameters have been chosen to reproduce the light baryon spectrum. Successful despite its simplicity. Used in several calculations of PDFs and GPDs (see **Pasquini, Boffi and Traini NPB 649 (2003) 243... Traini PRD (2014) 3 034021)**

Results: $x_1 - x_2$-factorization





LEFT: The ratio $uu(x_1, x_2, k_\perp = 0)/u(x_2)$, for three different values of x_2.

There should be no x_2 dependence in the ratio if the $x_1 - x_2$-factorization were realized;

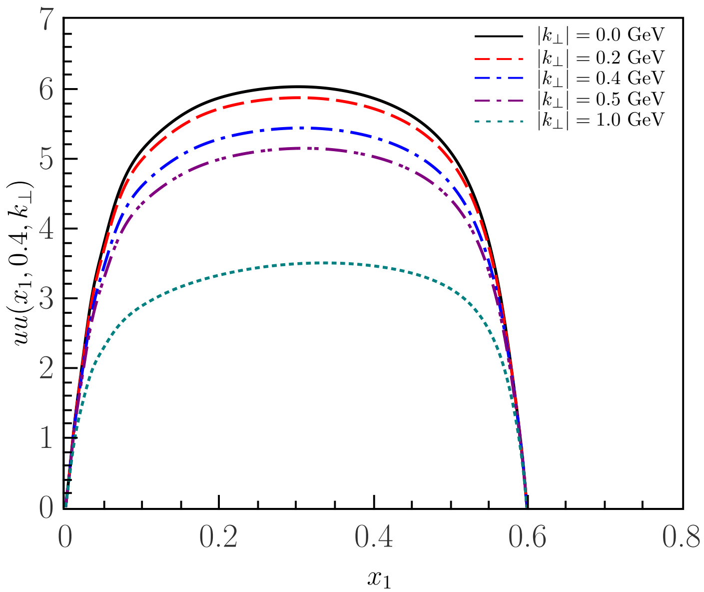
RIGHT: The ratio $uu(x_1, x_2, k_\perp = 0)/(u(x_2)u(x_1))$.

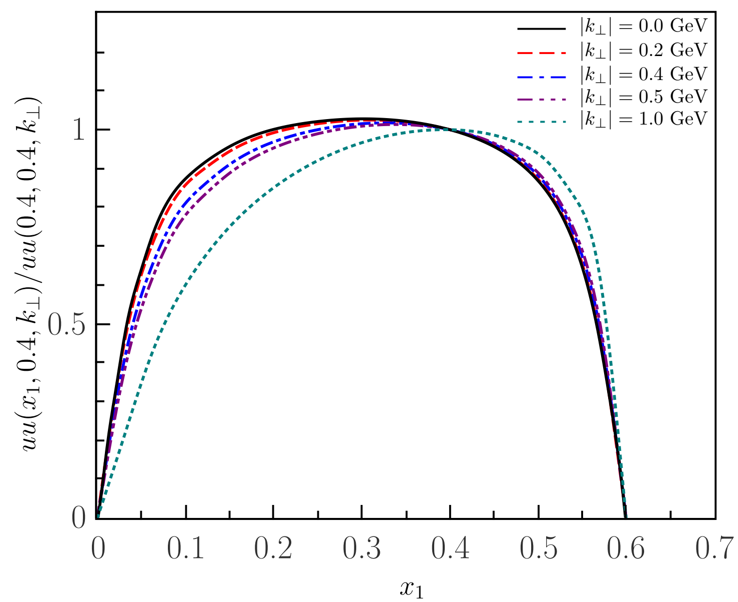
It should be 1 everywhere if the $x_1 - x_2$-factorization were realized;

- The $x_1 - x_2$-factorization is badly violated in the valence region
- Already found in bag model and NR calculations

Model independent feature

Results: $(x_1, x_2) - k_\perp$ factorization





LEFT: General trend increasing $k_\perp$

RIGHT: The ratio $uu(x_1, x_2 = 0.4, k_\perp)/uu(x_1 = 0.4, x_2 = 0.4, k_\perp)$,
for different $k_\perp$ values: there should be no $k_\perp$ dependence if factorization worked

- mildly violated as in the NR model (and in the Bag);

Model independent lesson

We have a fully correlated model with correct symmetries and dynamical (non-factorized) $k_\perp$ dependence. So far, at the model scale μ_0^2...

pQCD evolution of the LF dPDFs

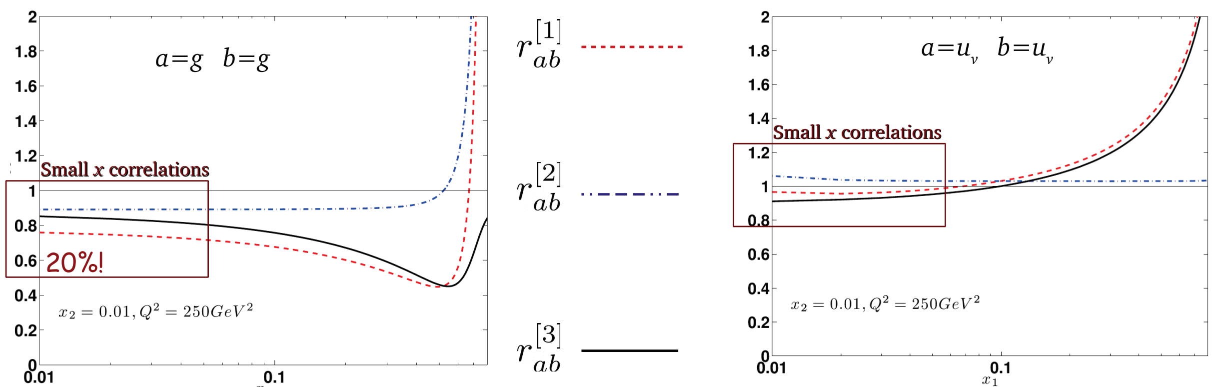
M. Rinaldi, S.S., M. Traini and V.Vento, JHEP 10 (2016) 063

dPDFs evolution known (**Kirshner et al., 1982...**).

We solved the LO evolution equations by inversion of double Mellin transforms.

Do correlations survive after evolution?

$$r^{[1]}_{ab} = \frac{F_{ab}(x_1, x_2, k_\perp = 0; Q^2)}{a(x_1; Q^2) b(x_2; Q^2)} \qquad r^{[2]}_{ab} = \frac{[a(x_1; Q^2) b(x_2; Q^2)]^{dPDF}}{a(x_1; Q^2) b(x_2; Q^2)} \qquad r^{[3]}_{ab} = \frac{F_{ab}(x_1, x_2, k_\perp = 0, Q^2)}{[a(x_1; Q^2) b(x_2; Q^2)]^{dPDF}}$$



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

$$r^{[1]}_{ab} = r^{[2]}_{ab}\, r^{[3]}_{ab}$$

$$r^{[1,2,3]}_{ab} \neq 1$$

CORRELATIONS

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.

Strong correlations in the valence region also at Q^2. Weaker, but sizeable, at low x.

Found also for polarized dPDFs (**e.g., M. Diehl, T. Kasemets and S. Keane, JHEP 05 (2014) 118**)

Comparison with existing data?

The effective Cross Section σ_{eff}

Defined through: $$\sigma^{pp}_{double} = \frac{m}{2}\frac{\sigma_A^{pp'}\sigma_B^{pp'}}{\sigma_{eff}}$$ σ_{eff} is the only measured quantity

$$\sigma_A^{pp'}(x_1,x_1') = single\, scattering = \sum_{i,k} q_i^p(x_1) q_k^{p'}(x_{1'})\hat{\sigma}_{ik}^A(x_1,x_1')\ ,$$

$$\sigma^{pp}_{double}(x_1,x_1',x_2,x_2') = \frac{m}{2}\sum_{i,j,k,l}\int D_{ij}(x_1,x_2;\mathbf{k}_\perp)\hat{\sigma}_{ik}^A(x_1,x_1')$$
$$\times\quad \hat{\sigma}_{jl}^B(x_2,x_2')D_{kl}(x_1',x_2';-\mathbf{k}_\perp)\frac{d\mathbf{k}_\perp}{(2\pi)^2}\ .$$

If (reasonable!): $\hat{\sigma}_{ij}(x,x') = C_{ij}\bar{\sigma}(x,x')$ with $C_{gg}:C_{qg}:C_{qq} = 1:(4/9):(4/9)^2$ then

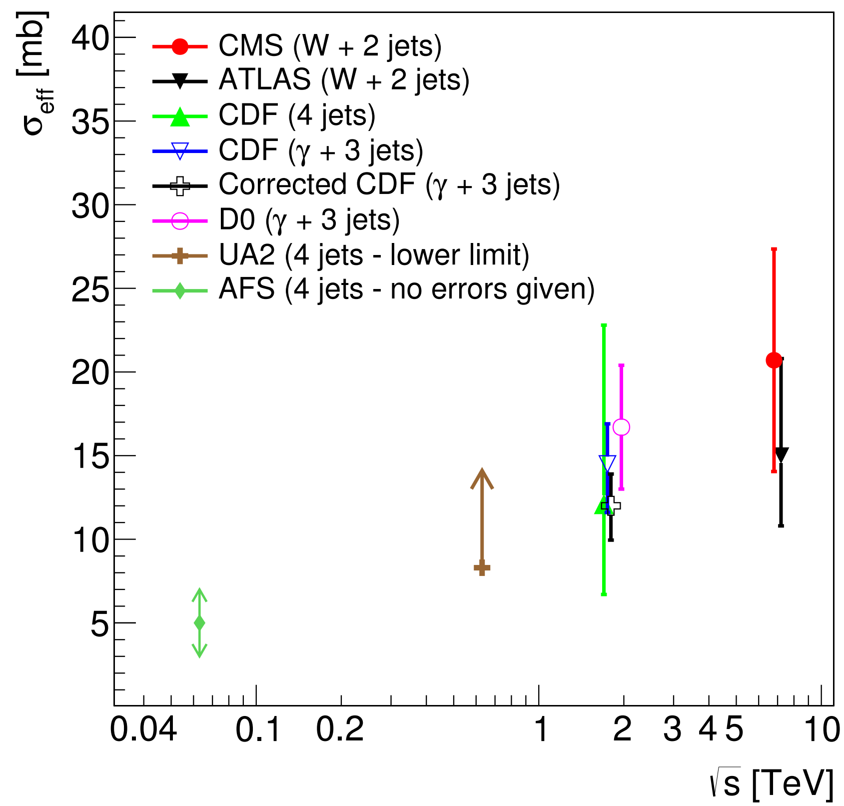
$$\sigma_{eff}(x_1,x_1',x_2,x_2') = \frac{\sum_{i,k,j,l} q_i(x_1)q_k(x_{1'})q_j(x_2)q_l(x_{2'})C_{ik}C_{jl}}{\sum_{i,j,k,l} C_{ik}C_{jl}\int D_{ij}(x_1,x_2;\mathbf{k}_\perp)D_{kl}(x_1',x_2';-\mathbf{k}_\perp)\frac{d\mathbf{k}_\perp}{(2\pi)^2}}$$

BUT $\longrightarrow if\ D_{ij} = q\, q\, f(\mathbf{k}_\perp) \longrightarrow \sigma_{eff} = \frac{1}{\int f^2(\mathbf{k}_\perp)\frac{d\mathbf{k}_\perp}{(2\pi)^2}} = \frac{1}{\int \tilde{f}^2(\mathbf{b}_\perp)d\mathbf{b}_\perp}$

No $x-$dependence, no scale dependence... No correlations

σ_{eff}: experimental situation

- model dependent extractions; σ_{pp}^{double} not measured...
- Older data at lower $\sqrt{S}$
- “constant” (large errorbars)
- Different ranges in x_i accessed in different experiments.



Kinematics:

$$x_{1,2} = \sqrt{\tau} e^{\pm y} \quad \tau = x_1 x_2 = \frac{s}{S} \quad y = \frac{1}{2} \ln \frac{x_1}{x_2} \simeq \eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

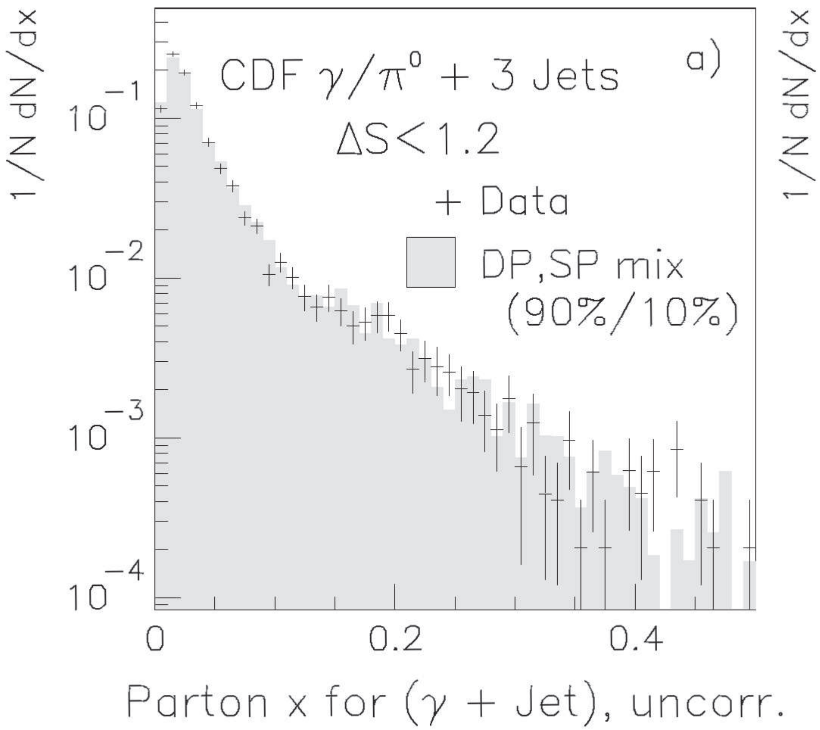
High x for hard jets (heavy particles detected, large partonic s

For example: AFS, $y \simeq 0$, $x_1 = x_2$ in $[0.2, 0.3]$

CDF: x_1, x_2, x_1', x_2' in $[0.02, 0.4]$

Valence region included...

σ_{eff}: x dependence (?)



CDF, F. Abe et al.

PRD 56, 3811 (1997)

Shaded area: Montecarlo $without$ correlations in x

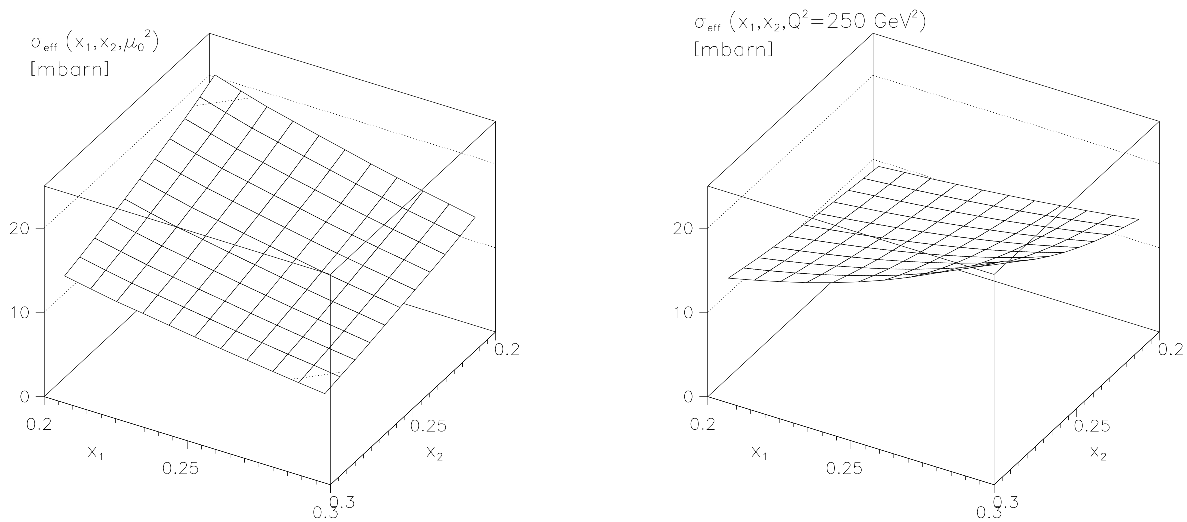
Data well described (?) for x_1, x_2, x_1', x_2' in $[0.02, 0.4]$ (also in the valence region...)

May be not enough accuracy for high x? No x dependence?

Actually, our understanding is that, in the valence region, x dependence has to be seen. Let the model guide us...

σ_{eff}: x dependence from the LF model

(M. Rinaldi, S.S., M. Traini, V. Vento PLB 752 (2016) 40)



- Shown at $y \simeq 0$, $x_i = x_i'$ in $[0.2, 0.3]$, at μ_0^2 (left) and at Q^2=250 GeV^2 (AFS kin.) Not constant at all. A factor of 2 easily found. **Expected!** Remember:

$$\sigma_{eff}(x_1,x_2) = \frac{\sum_{i,k,j,l} q_i(x_1)q_k(x_1)q_j(x_2)q_l(x_2)C_{ik}C_{jl}}{\sum_{i,j,k,l} C_{ik}C_{jl}\int D_{ij}(x_1,x_2;\mathbf{k}_\perp)D_{kl}(x_1,x_2;-\mathbf{k}_\perp)\frac{d\mathbf{k}_\perp}{(2\pi)^2}}$$

  Numerator and denominator decrease with x with different velocity (one must have $x_1 + x_2 > 1 \rightarrow D_{12}(x_1,x_2,k_\perp) = 0$). **Model independent result!**

- It ranges between 10 and 20 mbarn... But taking the global average in $x_{1,2}$, we get 10.9 mbarn... (Encouraging agreement! but this is a model dependent result...)

x dependence of σ_{eff} and 3D proton structure

- **The x dependence of σ_{eff}, recently found also in AdS/QCD (M. Traini et al. arXiv:160907.242 [hep-ph]), could give information on the 3D nucleon structure**

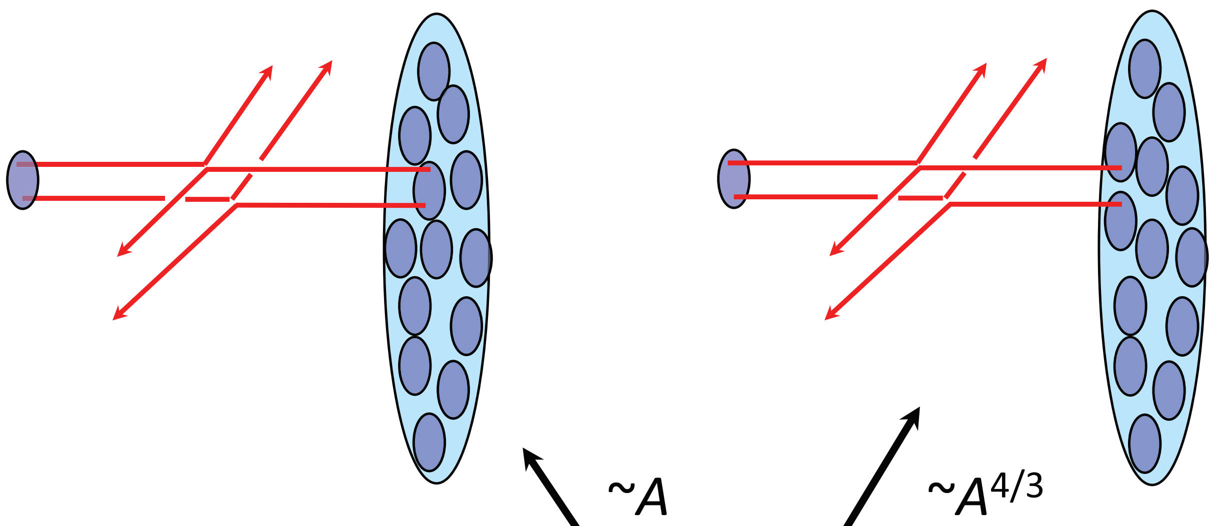
- **Our model calculation shows that either such a dependence is found or something is not well posed in the definition of σ_{eff}**

- **Other Authors, with different arguments, reach similar conclusions**
  (M. Diehl, talk at DIS 2013; Calucci Treleani 1999; Frankfurt, Strikman, Weiss 2003, 2004)

- **This information is a very interesting, DYNAMICAL, one: we could learn if fast (slow) partons like to stay close to (far from) each other (in transverse plane)**

DPS in $p - A$ Collisions

Significant enhancement of DPS in $p - A$ collisions, due to the fact that, in the nucleus, the two interacting partons can originate from two different nucleons:



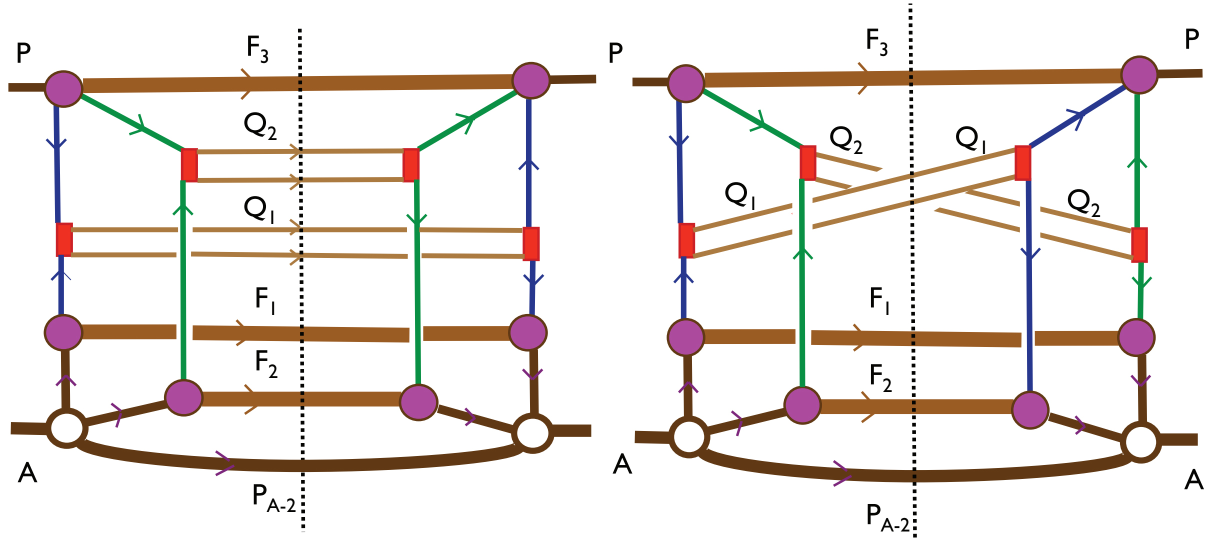
$$\sigma_D^A = \sigma_D^A\big|_1 + \sigma_D^A\big|_2$$

Easier access to DPS with respect to $p - p$

see **M. Strikman and D. Treleani, PRL 88 (2002) 031801**

GTMDs from DPS in $p - A$ Collisions (?)

Two terms in the forward scattering amplitude, in case of two active target nucleons



When the two target partons are identical, in addition to the ususally considered diagonal term one needs in fact also an interference term (**S. Salvini, D. Treleani et al. PRD 89 (2014) 016020**), which contains naturally the function

$$\hat{H}(x, \xi, \tilde{\mathbf{b}}, \Delta^2) = \int d\mathbf{k_T} e^{i\mathbf{k_T}\cdot\tilde{\mathbf{b}}} H(x, \xi, \mathbf{k_T}, \Delta^2) \ ,$$

i.e., it is sensitive to a (F.T.) GTMD (for $\mathbf{\Delta}_\perp = \mathbf{0}$), not easily accessed otherwise. Probably very dfficult to be extracted but the information is there...

...This is just an aspect of a wide subject

- MPI: a fast-moving field; annual conference:

- Crucial theoretical aspects still under debate:
  - * Proof of factorization (encouraging results by **M. Diehl at al. JHEP 1 2016 76**)
  - * Contribution of “inhomogeneus” evolution to DPS (**A. Snigirev, B. Blok, M. Strikman, M. Diehl, J. Gaunt...**)
  - * Polarization effects (e.g., **M. Echevarria et al. JHEP 4 (2015) 34**), color correlations (**X. Artru et al, PRD 37 (1988) 1628**)...
- A white paper to be published in 2017, edited by P. Bartalini and J. Gaunt (some 25 invited authors)

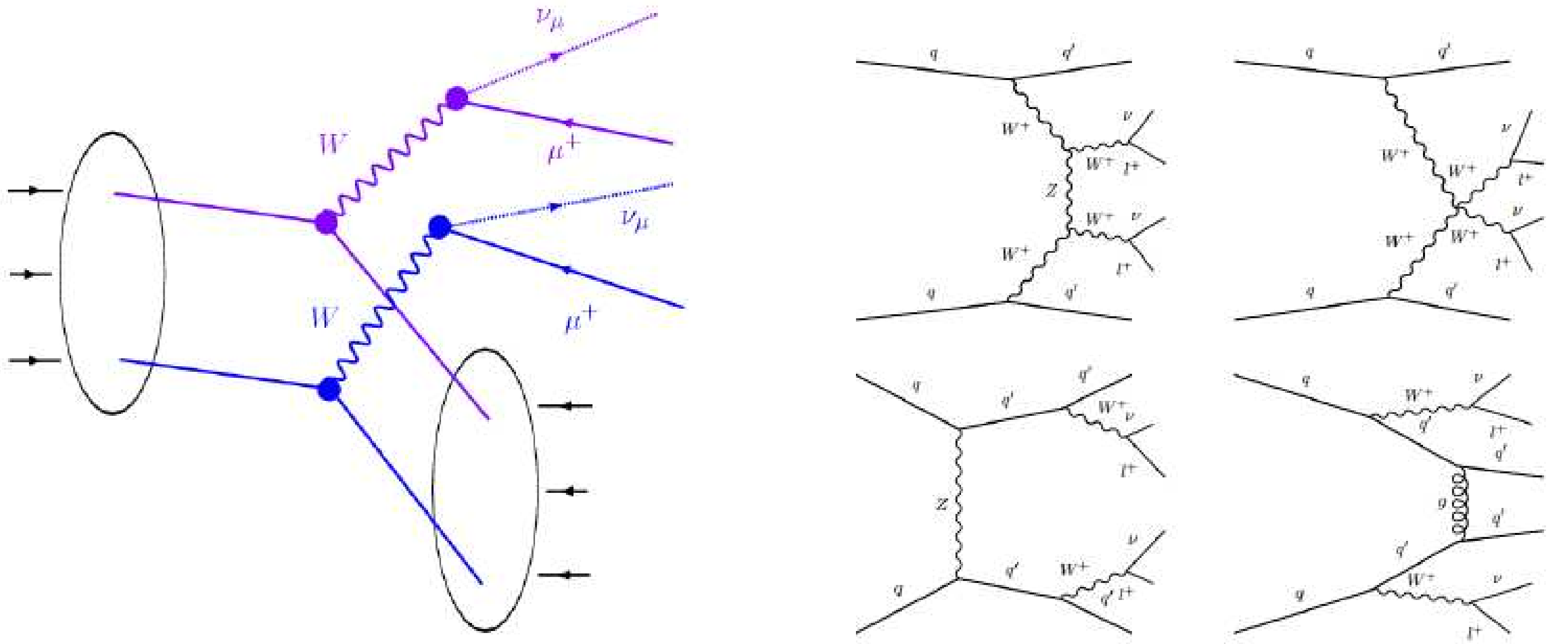
Conclusions

- **DPS: a fascinating subject rediscovered thanks to the LHC**
- **A LF-CQM calculation of DPCs has been presented:**
  - * relevant dynamical correlations in both longitudinal and transverse momentum are found, also after evolution;
  - * Analysis of σ_{eff}: non trivial $x-$dependence predicted
  - * Work in progress: model estimate of DPS cross sections in specific channels; 1) same sign WW production
- **Questions (and answers):**
  - * Are model calculations useful?
    Yes, they can guide the intuition, also in this framework
  - * Is the 3D nucleon structure accessible through MPI?
    May be. In this sense, σ_{eff} measurements in "narrow" x ($\longrightarrow$ rapidity) regions could be very useful.
    Are these measurements possible?
- **Interesting effects predicted in p-A scattering**

Backup: dPDF, formally

$$
\begin{aligned}
F_{q_1 q_2}(x_1, x_2, \mathbf{z}_\perp) &= -8\pi M^2 \int \frac{\mathrm{d}z_1^+}{4\pi}\frac{\mathrm{d}z_2^+}{4\pi}\frac{\mathrm{d}z_3^+}{4\pi} e^{-ix_1 M z_1^+/2}\, e^{-ix_2 M z_2^+/2}\, e^{ix_1 M z_3^+/2} \\
&\times \langle P, \mathbf{p}=\mathbf{0}| \left[\bar{q}_1\left(z_1^+ \frac{\bar{n}}{2} + z_\perp\right)\frac{\not{\bar{n}}}{2}\right]_c \\
&\times \left[\bar{q}_2\left(z_2^+ \frac{\bar{n}}{2}\right)\frac{\not{\bar{n}}}{2}\right]_d q_{1,c}\left(z_3^+ \frac{\bar{n}}{2} + z_\perp\right) q_{2,d}(0) |P, \mathbf{p}=\mathbf{0}\rangle\,. \qquad (1)
\end{aligned}
$$

Backup: $W^{\pm}W^{\pm}$ from DPS (a) and SPS (b)



(a) (b)

The preliminar cross section for charged inclusive same sign W boson production in pp collisions at 13 TeV, E_T^{μ}>25 GeV, $|\eta^{\mu}|$<2.4 is of the order of the femtobarn, calculated within the LF model of dPDFs and evolved according to homogeneous evolution equations at fixed b.

The effective cross sections calculated within this model is around 18 mb for this particular process in the given kinematics.