A Light-Front analysis of Nucleon 3D structure from double parton scattering

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In collaboration with :

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Outlook

- Double parton scattering (DPS) and
  double parton distribution functions (dPDFs)
- The 3D proton structure in single & double parton scatterings
- Double parton correlations (DPCs) in double parton distribution functions
- dPDFs in constituent quark models and first proton "imaging" from 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., F. A. Ceccopieri, arXiv: submit/1723392
- Calculation of the "effective X-section"

  M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2016)
  M. Traini, S. Scopetta, M. R. , arXiv:1609.07242 [hep-ph], submitted.
- Analyses of perturbative e non perturbative correlations

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

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

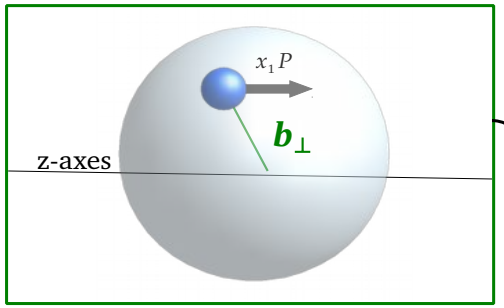
The 3D structure of a strongly interacting system (e.g. nucleon, nucleus..) could be accessed through different processes (e.g. SIDIS, DVCS, double parton sattering …), measuring different kind of Parton Distributions, providing different kind of information:

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

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

longitudinal momentum fraction carried by the parton

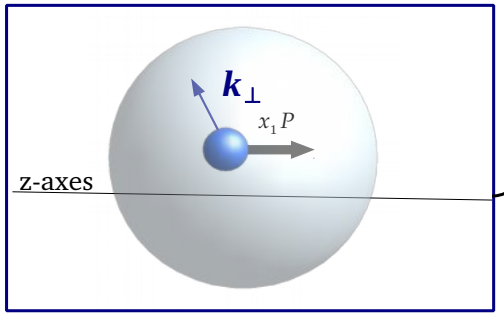
transverse distance between the parton and center of proton



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

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

transverse component of the parton momentum



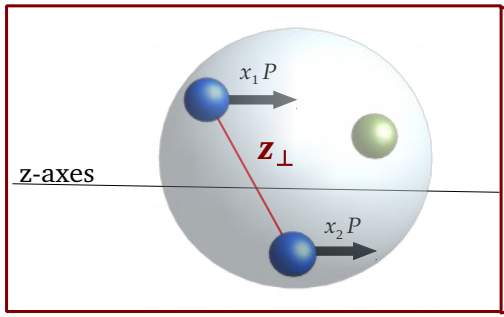
1 BODY

NEW POSSIBILITY

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

$$F_{ij}(x_1, x_2, \boldsymbol{z}_\perp)$$

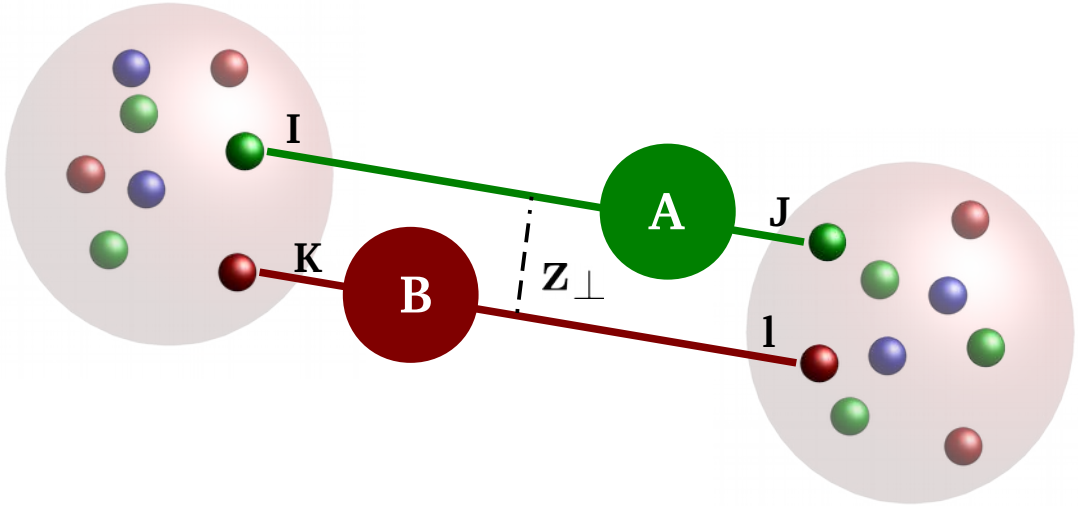
*ij = different spin polarizations



2 BODY

DPS and dPDFs from multi parton interactions

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

dPDF

Momentum scale

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

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

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: $\mu = \mu_A = \mu_B$

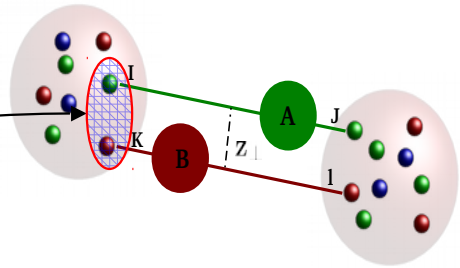
and $\mathbf{x_1}, \mathbf{x_2}$ factorization:

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

Unknown

Data available

NO CORRELATION ANSATZ

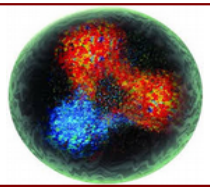


In this scenario, parton correlations inside the proton are neglected.

NO NEW INFORMATION

- In principle, they are present!
- dPDFs are non-perturbative quantities ⟺ DPCs not calculated directly from QCD

Constituent Quark Models (CQM)



Particles are strongly bound and correlated

Data, taken at the LHC, are related to very high energies and the very small *x*-region is investigated

→ **pQCD evolution of the calculated dPDFs is necessary to reach the experimental kinematic conditions**

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 $(x_1 + x_2 < 1)$. 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

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

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).
- In a peculiar construction of the Poincaré generators (Bakamjian-Thomas) it is possible to obtain a Mass equation, Schrödinger-like. A clear connection to NR.
- The IMF (Infinite Momentum Frame) description of DIS is easily included.

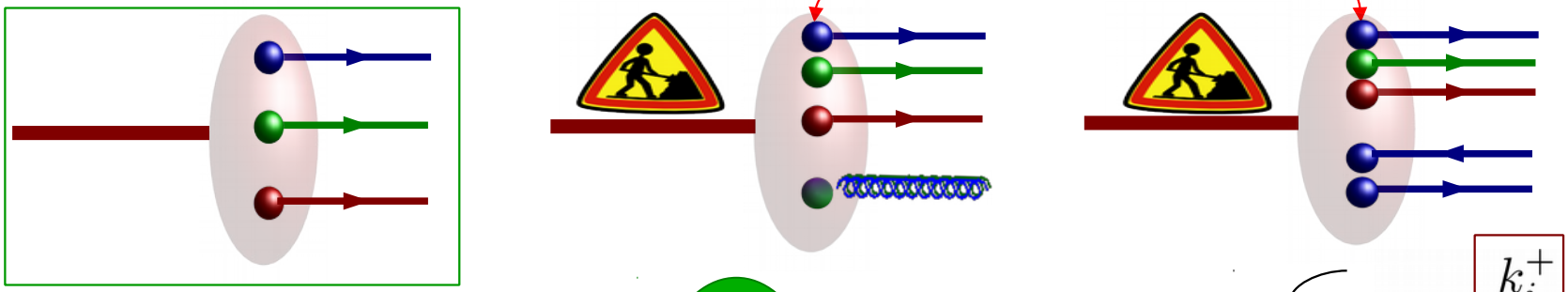
The **LF** approach is extensively used for hadronic studies (e.m. form factors, PDFs, GPDs, TMDs.....)

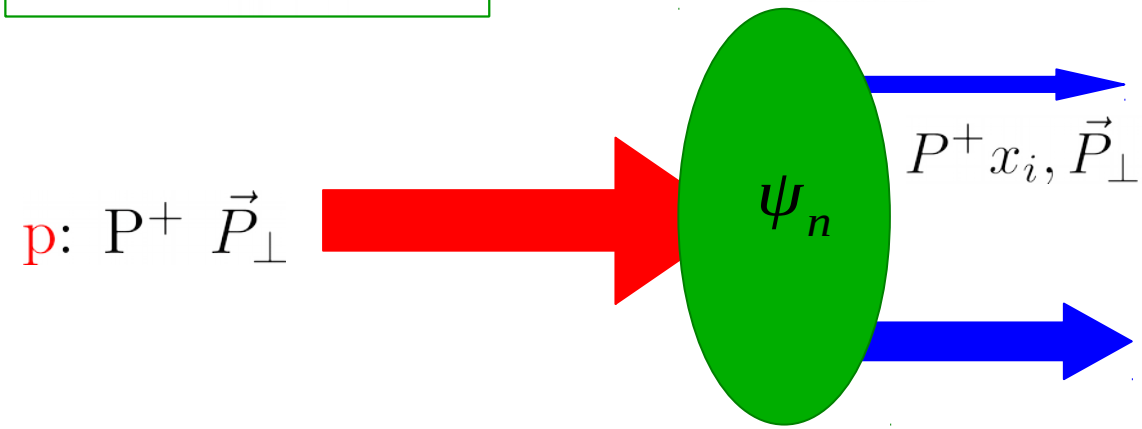
A Light-Front wave function representation

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)**

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





$$x_i = \frac{k_i^+}{P^+}$$ Quark Momentum / Proton Momentum

$$\sum_i^n x_i = 1 \qquad \sum_i^n \vec{k}_{\perp i} = 0$$ Momentum conservation

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

First look at two partons inside the proton

M.R., F. A. Ceccopieri, arXiv: submit/1723392

$$F_{u_v d_v}(x_1, x_2, \vec{b}_\perp, \mu_0^2) = \int d\vec{k}_\perp e^{i\vec{k}_\perp \cdot \vec{b}_\perp} \; u_v d_v(x_1, x_2, \vec{k}_\perp, \mu_0^2)$$

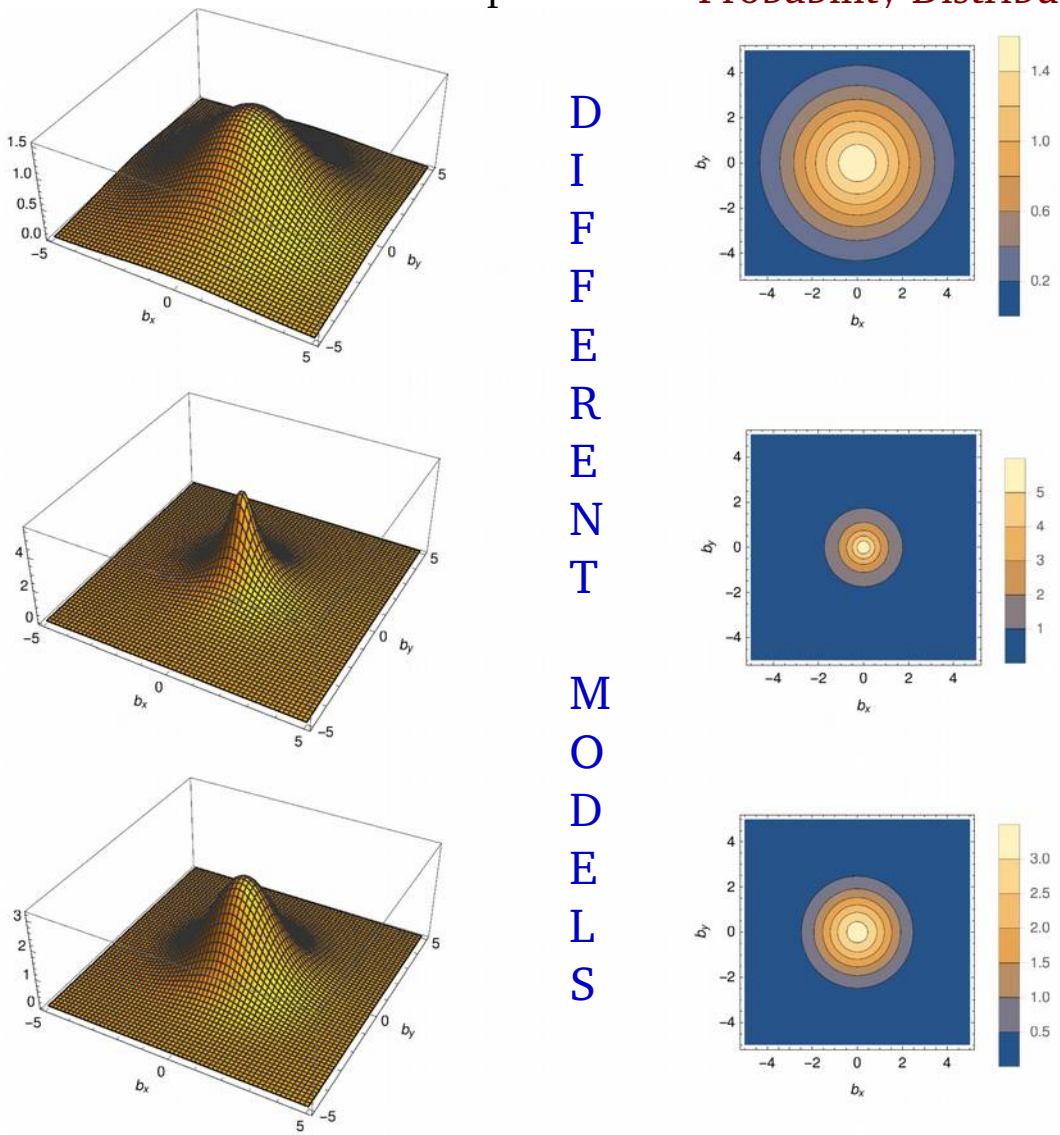
Transverse distance between partons

Probability Distribution

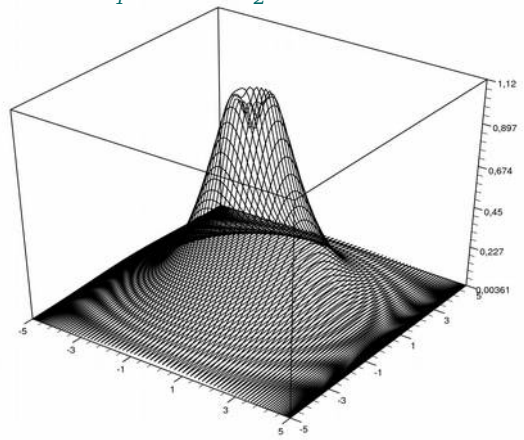
The distribution has been calculated within different CQM models.
The harmonic oscillator and the ones of Refs.:

P. Faccioli *et al*, Nucl. Phys. A 656, 400-420 (1999)

E. Santopinto *et al*, PLB 364 (1995)



$x_1 = 0.3 \quad x_2 = 0.04$



E.g., in our model, quarks with similar longitudinal momentum fraction "prefer" to be close to each other!

Results on distributions with longitudinally and transversely polarized quarks are coming!

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

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

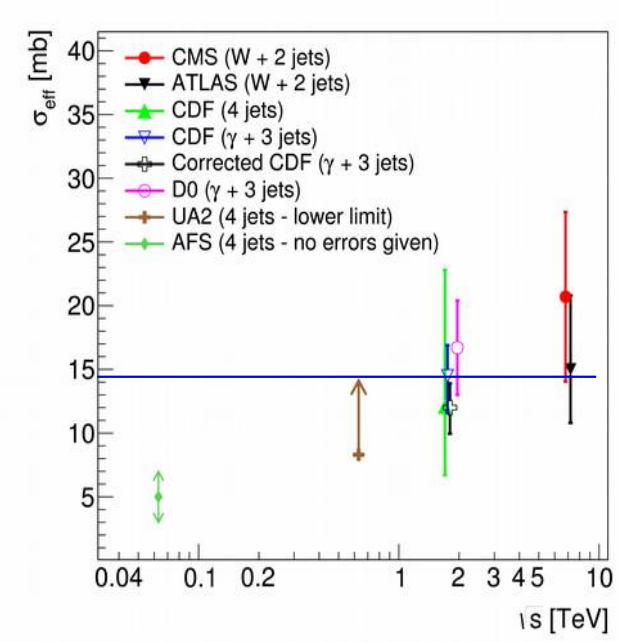
Combinatorial factor

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

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

....EXPERIMENTAL STATUS:

- Difficult extraction, approved analysis for the production of same sign *WW* @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!



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

AFS ⟶ $y \sim 0;\ x_1 \sim x_2;\ 0.2 < x_{1,2} < 0.4$

CDF ⟶ $0.02 < x_{1,2,3,4} < 0.4$

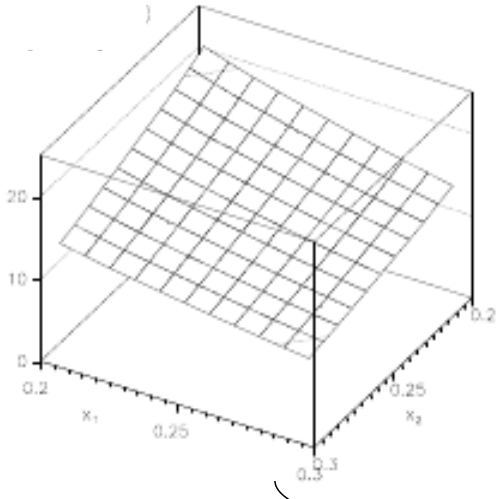
valence region included!

Numerical results

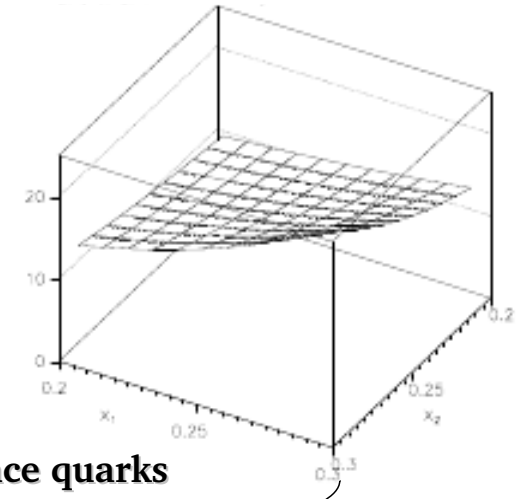
M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2016)

Our predictions of σ_{eff} in the valence region at different energy scales:

$\sigma_{eff}(x_1, x_2, \mu_0^2)$

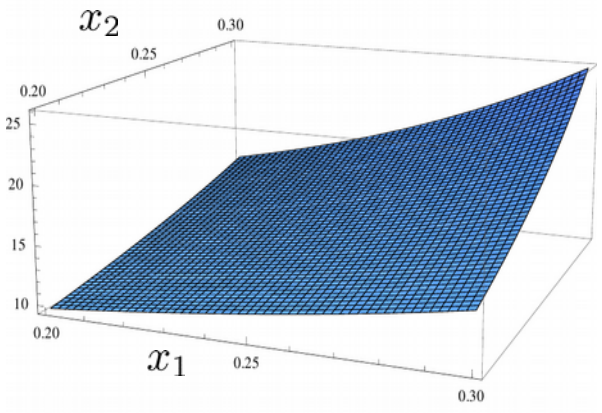


$\sigma_{eff}(x_1, x_2, Q^2 = 250\ \mathrm{GeV}^2)$



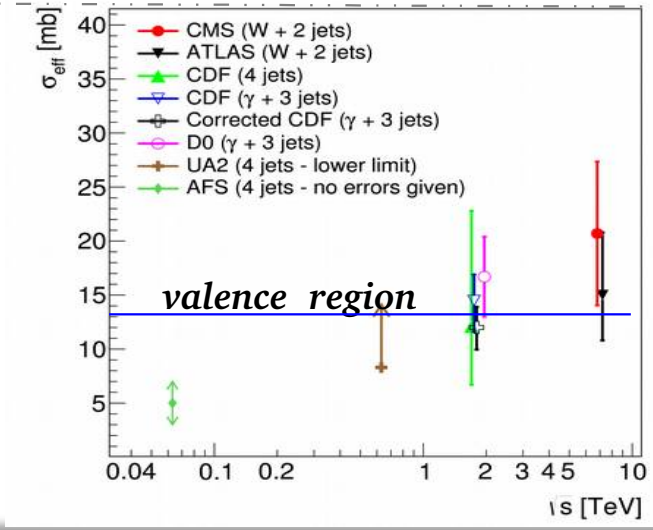
Valence quarks

$\sigma_{eff}(x_1, x_2, Q^2 = 250\ \mathrm{GeV}^2)$



Valence quark ⊗ Gluon

$$\overline{\sigma_{eff}} \sim 11\ \mathrm{mb}$$



***X* DEPENDENCE**

ACCESS THE DOUBLE PARTON CORRELATIONS

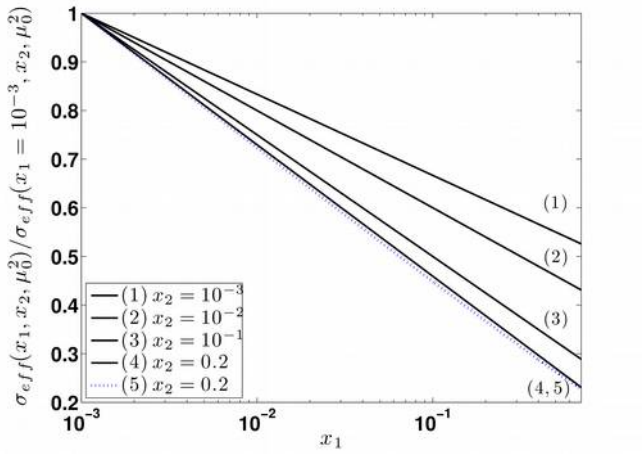
ACCESS THE PARTONIC STRUCTURE OF THE PROTON

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

Effects of evolution and correlations

M. R., S. Scopetta, M. Traini and V.Vento, JHEP 10, 063 (2016)
M. R., S. Scopetta, M. Traini and V.Vento, arXiv:1609.07242 [hep-ph], submitted.

In the analysis of σ_{eff}, the factorized ansatz for dPDF in terms of PDF, at the scale of the experiment is commonly used. In this scenario all possible correlations are neglected. How ever our model calculations of such quantities shows that correlations can be important also at high energies scales. Due to this results, a deep studies in order to identify which kind of correlations are present in the calculation is worth.



Ratio of effective cross sections calculated within the ADS/QCD approach. Strong x dependence found at low energy scale.

After evolution in pQCD the x dependence is still found!

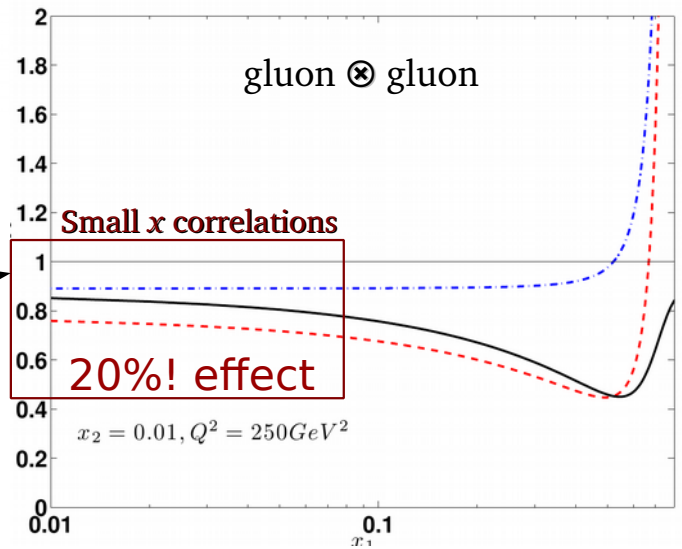
DUE TO

Perturbative Correlations
Due to evolution equation

DUE TO

Non-Perturbative Correlations
Due to proton structure assumed for the calculation

Full Correlations



This quantity should be equal to 1 if there were not correlations!

In this example perturbative and non perturbative correlations coherently interfere

Conclusions

A CQM calculation of the dPDFs with a fully covariant approach

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

- symmetry in the exchange of two partons in the dPDFs correctly restored
- violations of both the $(x_1, x_2) - k_\perp$ and x_1, x_2 factorizations for the polarized and unpolarized $_2$GPDs
- Analysis of effects of perturbative and non perturbative correlations: for some partonic species, sizable correlations are found also at small x

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

Calculation of the effective X-section

M. R., S. Scopetta, M. Traini and V.Vento, PLB 752, 40 (2015)
M. R., S. Scopetta, M. Traini and V.Vento, submitted

- Calculation of the effective X-section at the hadronic and at high energy scales within different models
- **x-dependent quantity obtained!** Qualitatively in agreement with data
- The x-dependence of the "effective X-section" could give information on the

3d structure of the proton!

What are we working on

M. R., F. A. Ceccopieri, arXiv: submit/1723392

- First model analysis of the 3D structure of the proton through dPDF and study of relativistic effects
- analysis of the inhomogeneous contribution in the pQCD evolution

Direct link to LHC Physics