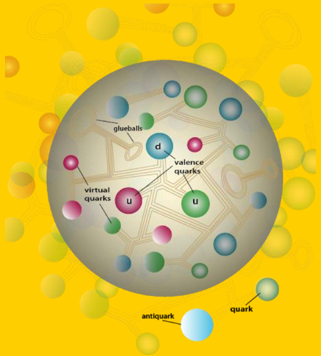
Photon initiated double parton scattering: a new light on the proton structure



Matteo Rinaldi

in collaboration with

Federico Alberto Ceccopieri
Marco Traini
Sergio Scopetta
Vicente Vento

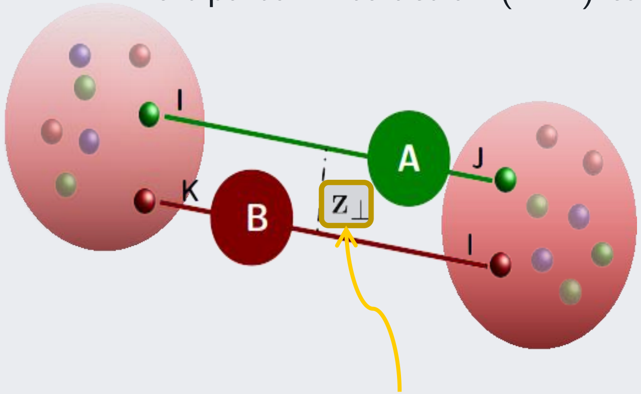
STRONG 2020
Istituto Nazionale di Fisica Nucleare

Roadmap

1. INTRODUCTION
2. 3D PROTON STRUCTURE VIA p-p DPS
3. INTERPRETATION OF LHC DATA
4. DPS VIA PHOTON-PROTON INTERACTIONS
5. PREDICTIONS AND OPPORTUNITIES
6. LATTICE DATA FOR THE PION AND MODEL COMPARISONS

1 Double Parton Scattering @LHC

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



Transverse distance between partons

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)
J.R. Gaunt et al, JHEP 07 (2014) 110, JHEP 01 (2016) 076

double PDF (dPDF)

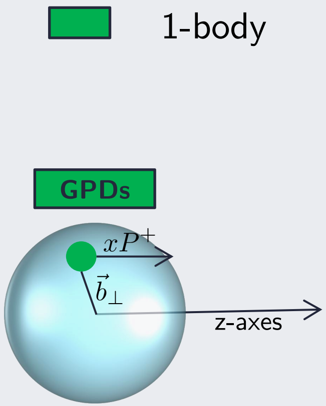
$$d\sigma \propto \int d^2 z_\perp \, F_{ik}(x_1, x_2, \vec{z}_\perp; \mu_A, \mu_B) \cdot F_{jl}(x_3, x_4, \vec{z}_\perp; \mu_A, \mu_B)$$

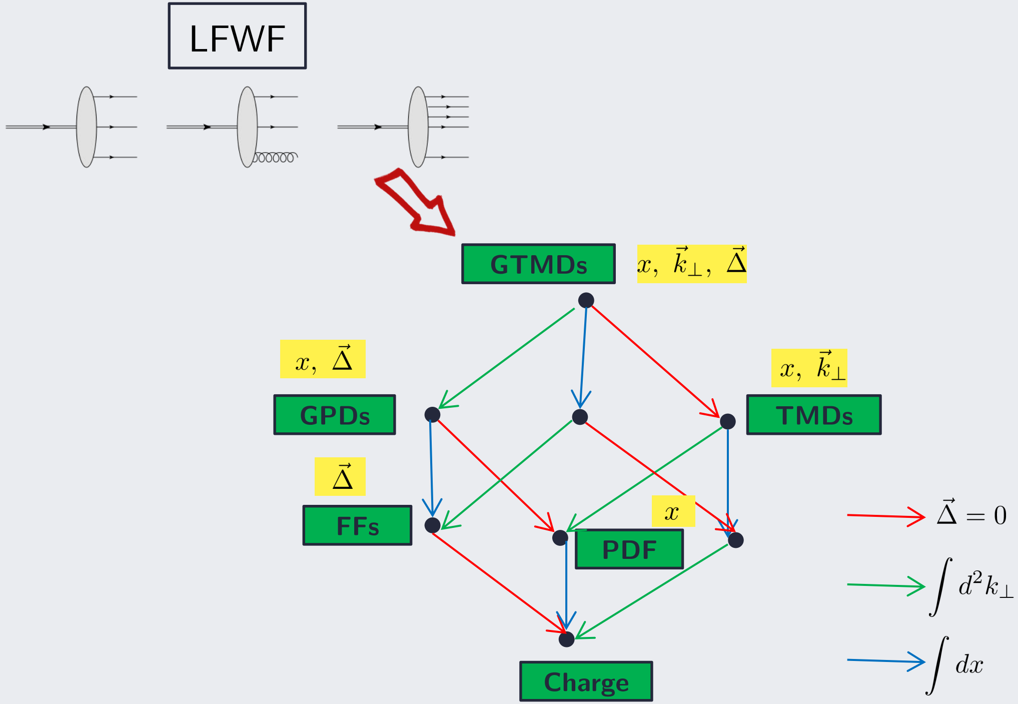
Momentum scales

Momentum fractions carried by the parton inside the proton

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**

1 Multidimensional Pictures of Hadron





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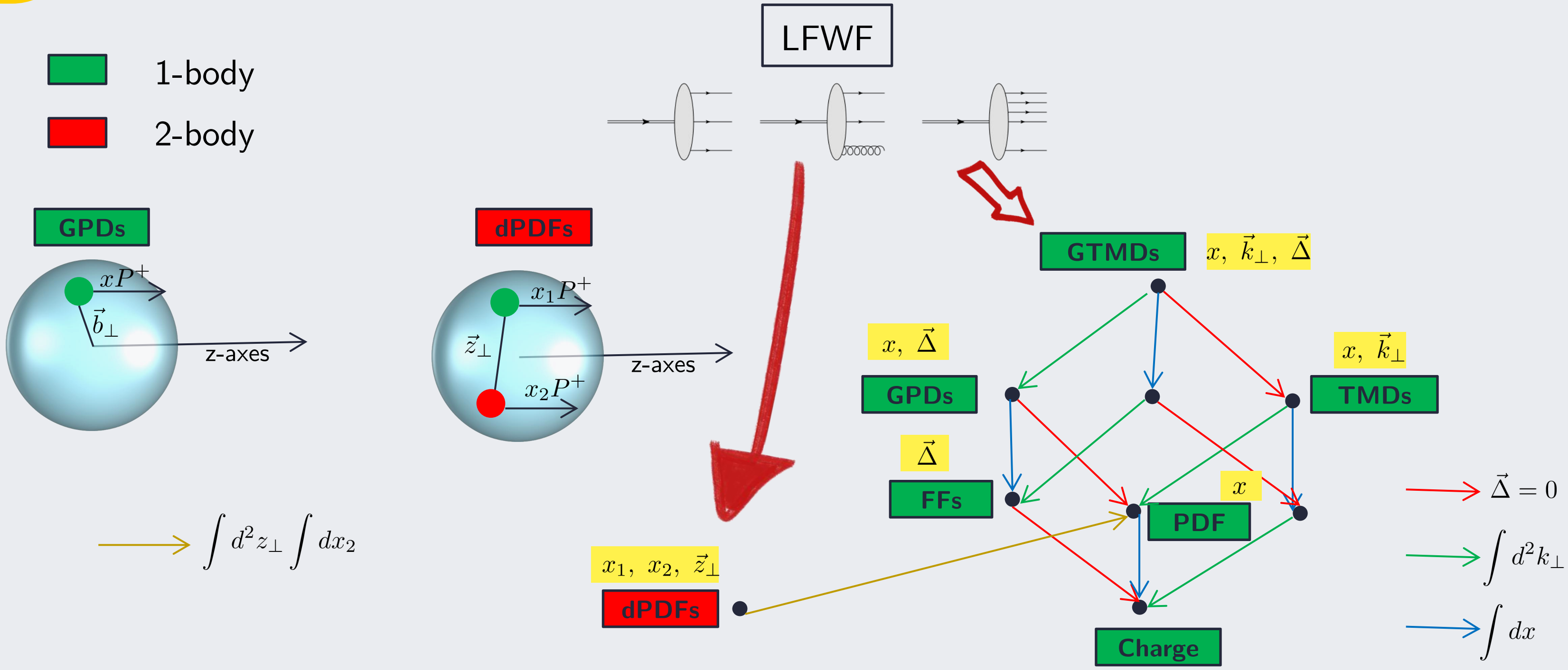

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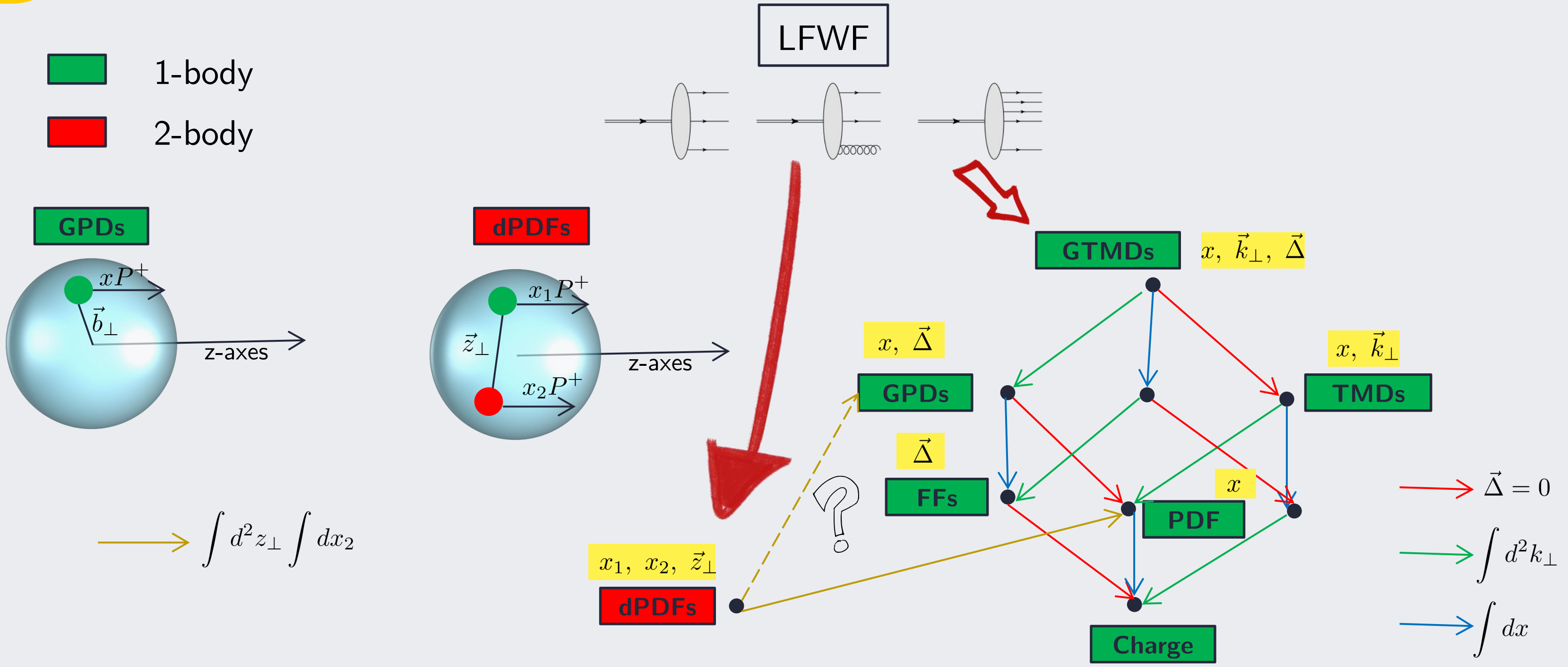

1 Double PDFs of the proton

$F_{ik}(x_1, x_2, \vec{z}_\perp)$ is unknown. However @LHC kinematics (small x and many partons produced)

$$F_{ik}(x_1, x_2, \vec{z}_\perp) \sim \overbrace{g(x_1, x_2)\tilde{T}(\vec{z}}^{\text{1st uncorrelated scenario}}{}_\perp)$$

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$g(x_1, x_2)$ → SUM RULES AVAILABLE J.R. Gaunt et al, JHEP 03 (2010) 005, EPJC 80 (2020) n°5, 468

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→ SUM RULES AVAILABLE

→ MODELS BASED ON SUM RULES

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1st uncorrelated scenario

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- SUM RULES AVAILABLE
- MODELS BASED ON SUM RULES
- PDF(x_1)*PDF(x_2)
- [PDF(x_1)*PDF(x_2)] ⊗ pQCD EVOLUTION

2nd uncorrelated scenario

J. R. Gaunt and W. J. Stirling, JHEP 03, 005 (2010)

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PERTURBATIVE CORRELATIONS

1 Double PDFs of the proton

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1st uncorrelated scenario

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Constituent quark models
used to grasp basic
NON PERTURBATIVE features

M.R., S. Scopetta et *al*, PRD 87 (2013) 114021
M.R., S, Scopetta et *al*, JHEP 12 (2014) 028

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$\tilde{T}(\vec{z}_\perp)$ → PROBABILITY DISTRIBUTION OF FINDING TWO PARTONS WITH GIVEN TRANSVERSE DISTANCE

F_{ik} → Constituent quark models used to grasp basic **NON PERTURBATIVE** features

M.R., S. Scopetta et *al*, PRD 87 (2013) 114021
M.R., S, Scopetta et *al*, JHEP 12 (2014) 028

$g(x_1, x_2)$ →

- SUM RULES AVAILABLE
- MODELS BASED ON SUM RULES
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(last two: **2nd uncorrelated scenario**)

PERTURBATIVE CORRELATIONS

1 Double PDFs of the proton

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Constituent quark models used to grasp basic non perturbative feature

M.R., S. Scopetta et *al*, PRD 87 (2013) 114021
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$\tilde{T}(\vec{z}_\perp)$:

- PROBABILITY DISTRIBUTION OF FINDING TWO PARTONS WITH GIVEN TRANSVERSE DISTANCE
- UNKNOWN: ONLY MODELS

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- SUM RULES AVAILABLE
- MODELS BASED ON SUM RULES
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- [PDF(x_1)*PDF(x_2)] $\otimes$ pQCD EVOLUTION

2nd uncorrelated scenario

PERTURBATIVE CORRELATIONS

1 Double PDFs of the proton

$F_{ik}(x_1, x_2, \vec{z}_\perp)$ is unknown. However @LHC kinematics (small x and many partons produced)

Some questions arose:

PROBABILITY DISTRIBUTION OF FINDING TWO PARTONS WITH GIVEN TRANSVERSE DISTANCE

1) HOW CAN WE BE SURE OF THE ACCURACY OF SUCH APPROXIMATION?
dPDFs are non perturbative in QCD ⟶ DPCs cannot be accessed from QCD

UNKNOWN: ONLY MODELS

Constituent quark models used to grasp basic non perturbative feature

SUM RULES AVAILABLE

2) WHICH INFORMATION ON THE PROTON STRUCTURE COULD BE ACCESSED FROM DPS?

MODELS BASED ON SUM RULES

M.R., S. Scopetta et *al*, PRD 87 (2013) 114021
M.R., S, Scopetta et *al*, JHEP 12 (2014) 028

PDF(x_1)*PDF(x_2)

[PDF(x_1)*PDF(x_2)] ⊗ pQCD EVOLUTION

2nd uncorrelated scenario

PERTURBATIVE CORRELATIONS

2 Double PDFs within the Light-Front

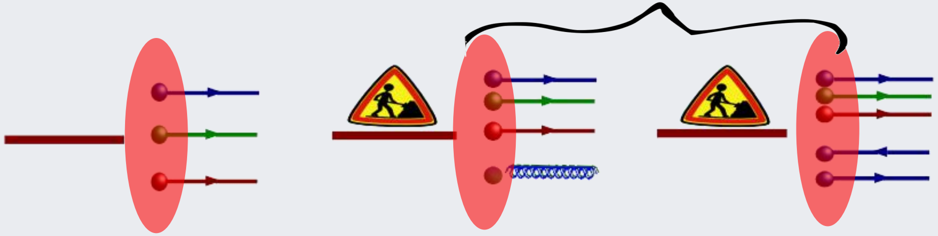
Extending the procedure developed in **S. Boffi, B. Pasquini and M. Traini, Nucl. Phys. B 649, 243 (2003)** for GPDs, we obtained the following expression of the dPDF in momentum space, often called $_2$GPDs:

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

Conjugate to $z_\perp$

LF wave-function

M.R., S. Scopetta et al, JHEP 10 (2016) 063



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

2 Double PDFs within the Light-Front: GPDxGPD?

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

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

Approximated by the proton state!

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

GPD

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

2 Double PDFs within the Light-Front: GPDxGPD?

The dPDF is formally defined through the Light-cone correlato[illegible]

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

Approximated by t[illegible]

$$\int \frac{dp'^+ d \ldots [illegible]}{\ldots}$$

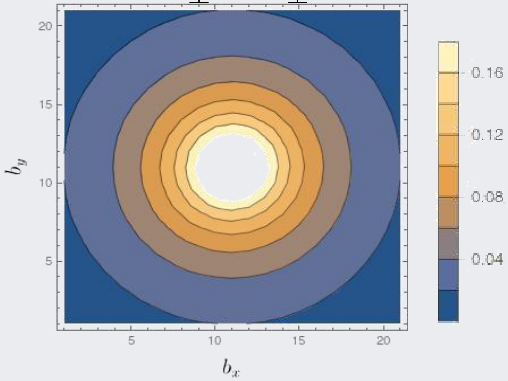
TO BE TESTED WITH MODELS

$$F_{12}(x_1, \ldots [illegible] \ldots) \sim f(x_1, 0, \vec{k}_\perp) f(x_2, 0, \vec{k}_\perp)$$

GPD

2 Information from Quark Models

$z_\perp = b_\perp$

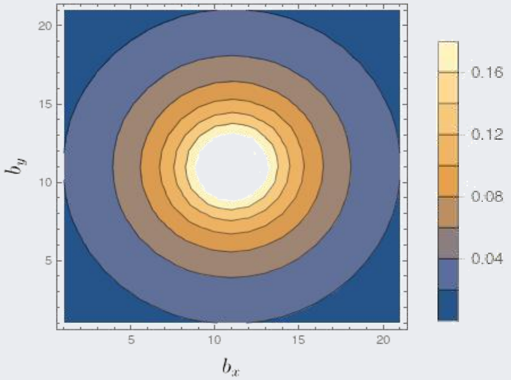


M.R. and F. A. Ceccopieri, JHEP 09 (2019) 097

1) e.g. the distance distribution of **two gluons** in the proton

$$\langle z_\perp^2 \rangle^{ij}_{x_1,x_2} = \frac{\int d^2 z_\perp \; z_\perp^2 F_{ij}(x_1, x_2, z_\perp)}{\int d^2 z_\perp \; F_{ij}(x_1, x_2, z_\perp)}$$

2 Information from Quark Models



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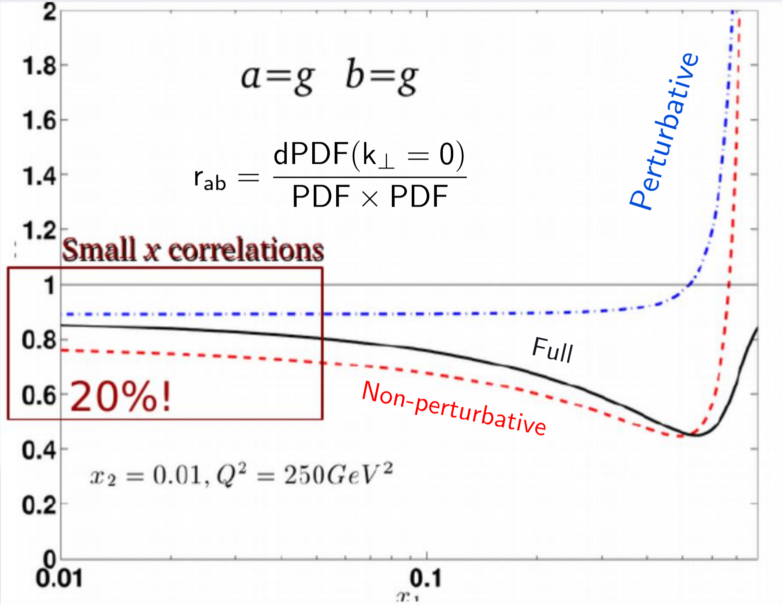

2) Correlations are important

M.R., S. Scopetta et al, JHEP 10 (2016) 063

M.R. and F. A. Ceccopieri PRD 95 (2017) 034040

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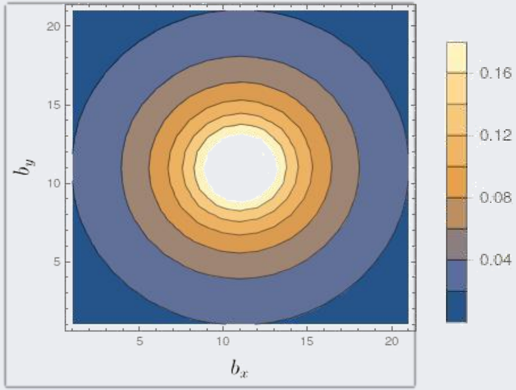

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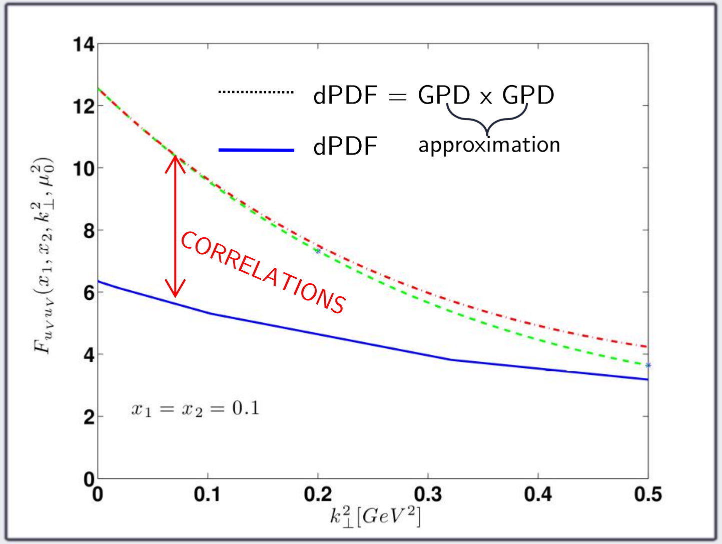

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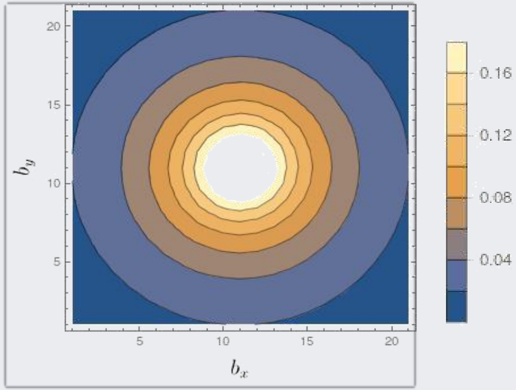

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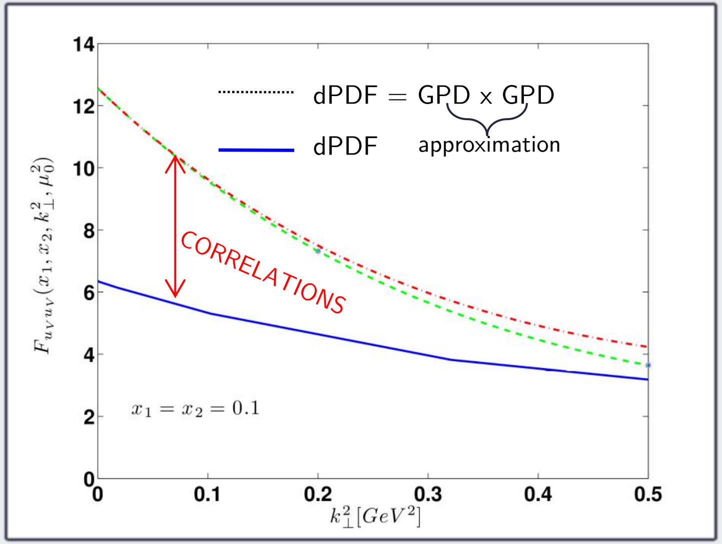

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IS IT POSSIBLE TO ACCESS DOUBLE PARTON CORRELATIONS?

3 Data and Effective Cross Section

A tool for the comprehension of the role of DPS in hadron-hadron collisions is the so called "effective X-section".

$$\sigma_{\text{eff}}^{\text{pp}} = \frac{m}{2} \frac{\sigma_A^{\text{pp}} \sigma_B^{\text{pp}}}{\sigma_{\text{DPS}}^{\text{pp}}}$$

POCKET FORMULA

Differential cross section for the process: $\text{pp} \longrightarrow \text{A(B)} + \text{X}$

Differential cross section for a DPS event: $\text{pp} \longrightarrow \text{A} + \text{B} + \text{X}$

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POCKET FORMULA

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

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

color factors — PDF

$$\sigma_{\text{eff}}(x_1, x_2, x_3, x_4) = \frac{\sum_{i,j,k,l} C_{ik} C_{jl} F_i(x_1) F_j(x_2) F_k(x_3) F_l(x_4)}{\sum_{i,j,k,l} C_{ik} C_{jl} \int d^2 z_\perp \; F_{ij}(x_1, x_3, z_\perp) F_{kl}(x_3, x_4, z_\perp)}$$

M.R., S. Scopetta et al, PLB 752

M. Traini, M.R., S. Scopetta and V. Vento, PLB 768 (2017)

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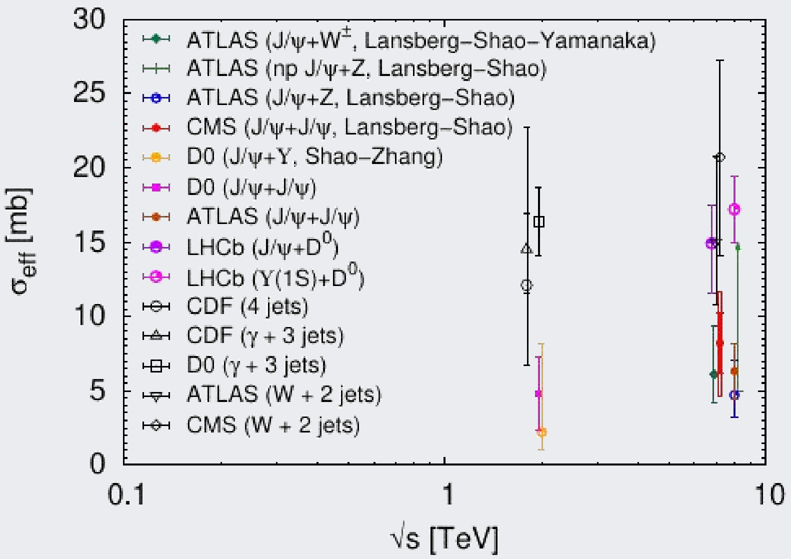

J.P. Lansberg's slide
MPI-2019 workshop

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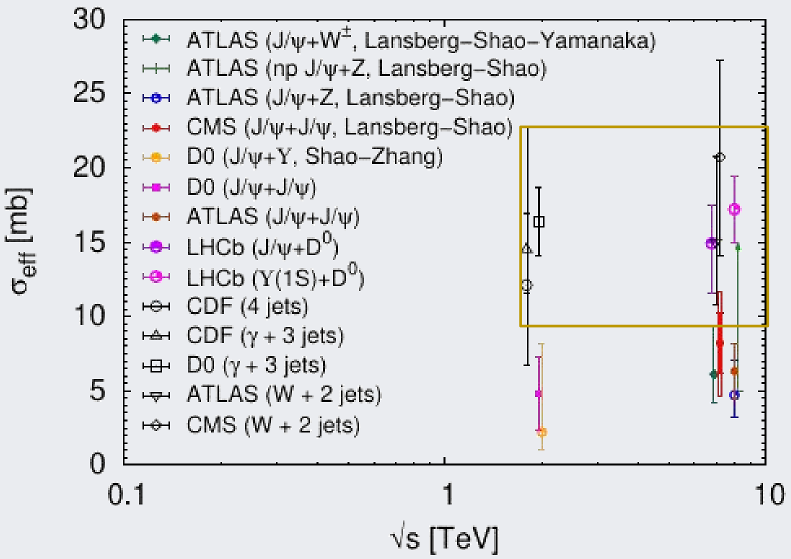

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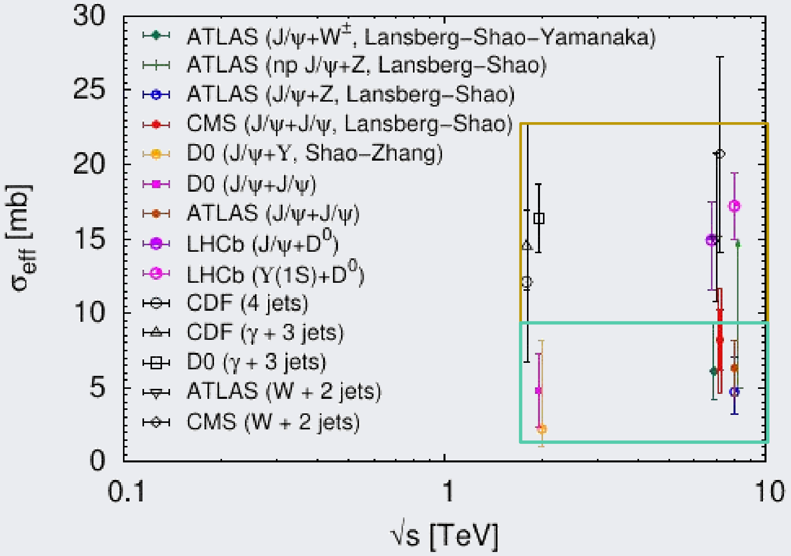
3 Data and Effective Cross Section

$$\sigma_{\text{eff}}^{\text{pp}} = \frac{m}{2} \frac{\sigma_A^{\text{pp}} \sigma_B^{\text{pp}}}{\sigma_{\text{DPS}}^{\text{pp}}}$$

- SENSITIVE TO CORRELATIONS
- PROCESS DEPENDENT?
- CAN WE DIRECTLY ACCESS THESE CORRELATIONS?



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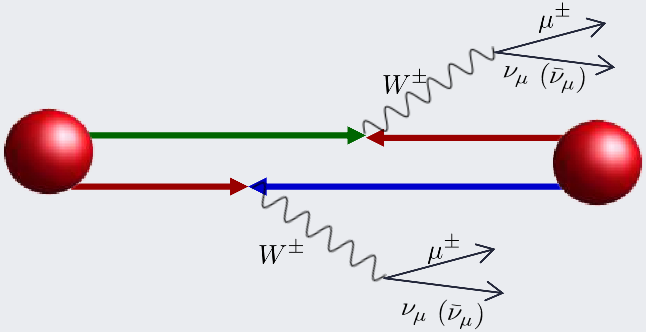
4 Same sign W's production at the LHC

M. R. et al, Phys.Rev. D95 (2017) no.11, 114030



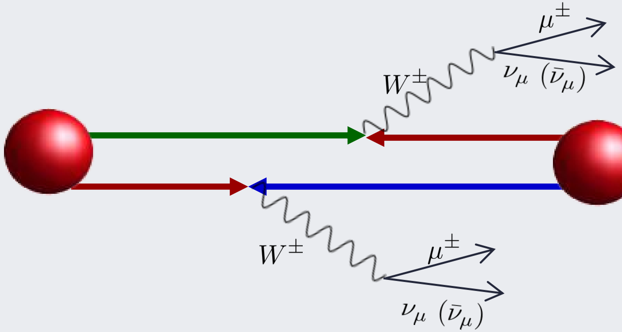
In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

⬇

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

4 Same sign W's production at the LHC

M. R. et al, Phys.Rev. D95 (2017) no.11, 114030



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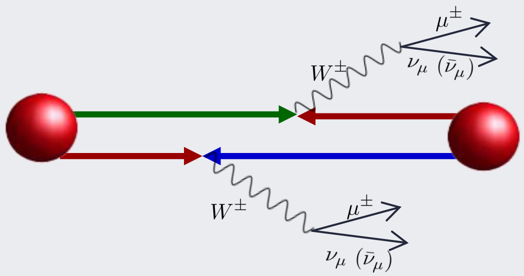
⬇

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

4 Same sign W's production at the LHC

M. R. et al, Phys.Rev. D95 (2017) no.11, 114030



Kinematical cuts

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

DPS cross section:

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

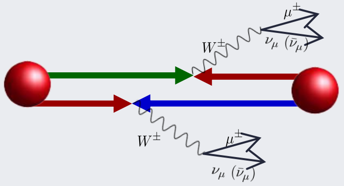
In order to estimate the role of double parton correlations we have used as input of dPDFs:

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

2) These correlations propagate to sea quarks and gluons through pQCD evolution

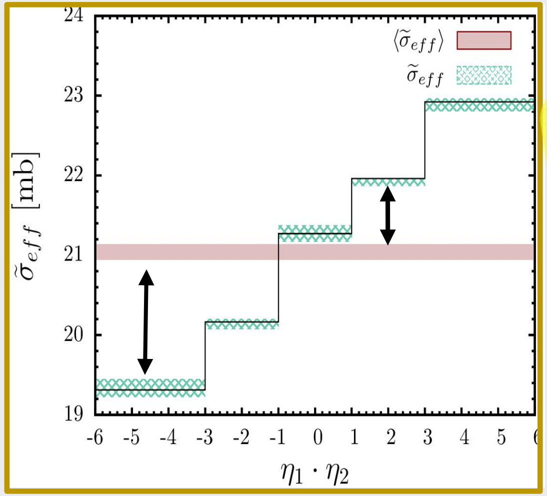
4 Same sign W's production at the LHC

M. R. et al, Phys.Rev. D95 (2017) no.11, 114030



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

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



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

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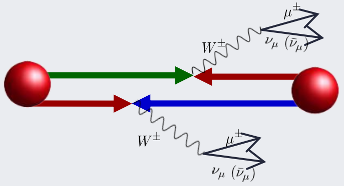
M. R. et al, Phys.Rev. D95 (2017) no.11, 114030



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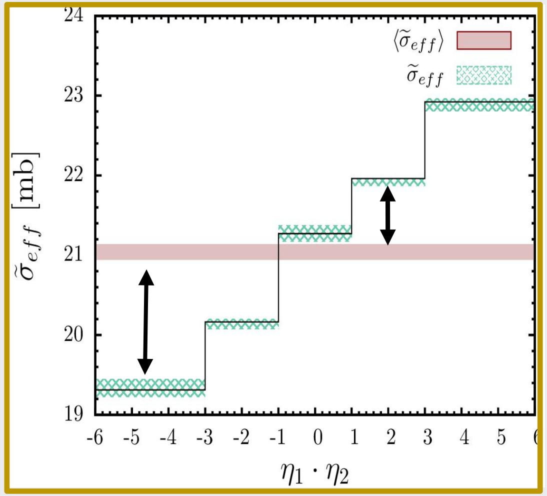


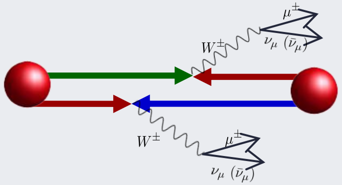
<u>x- dependence of effective x-section</u>
M.Rinaldi et al PLB 752,40 (2016)
M. Traini, M. R. et al, PLB 768, 270 (2017)

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

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

is necessary to observe correlations
* to be updated to new CMS cuts

4 Same sign W's production at the LHC



In Ref. **S. Cotogno et al, JHEP 10 (2020) 214**, it has been shon that several experimental observable are sensitive to **double spin correlations**.

The LHC has the potential to access these new information!

IN THIS CHANNEL, WE ESTABLISHED THE POSSIBILITY TO OBSERVE, FOR THE FIRST TIME, TWO-PARTON CORRELATIONS IN THE NEXT LHC RUN!

5 Clues from data?

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

If dPDFs factorize in terms of PDFs then

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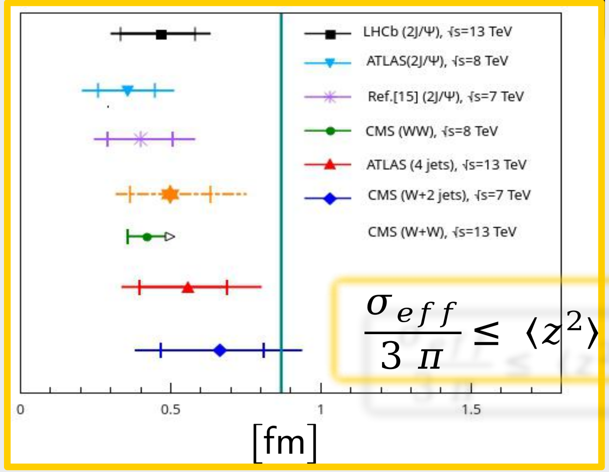
DPS processes:

The vertical line stands for the transverse proton radius



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

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

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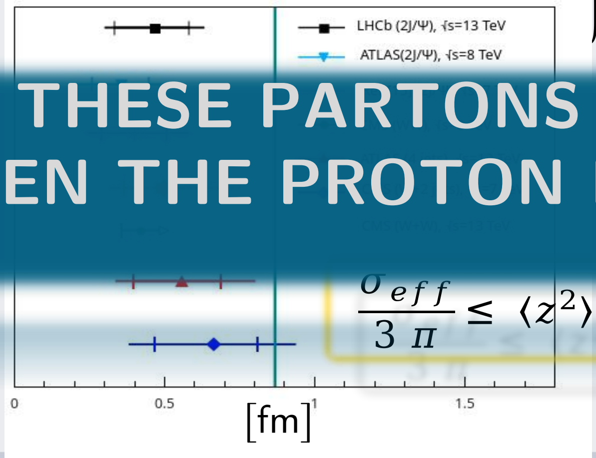
THE DISTANCE OF THESE PARTONS SEEMS TO BE SMALLER THEN THE PROTON RADIUS

the transverse proton radius



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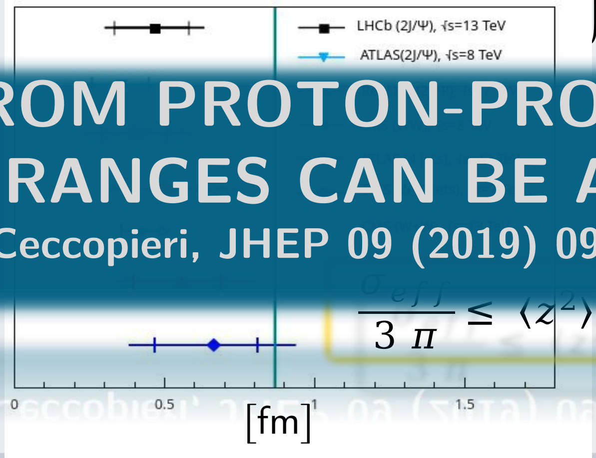

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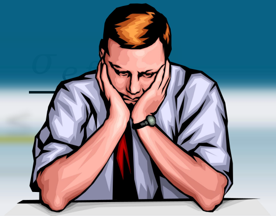
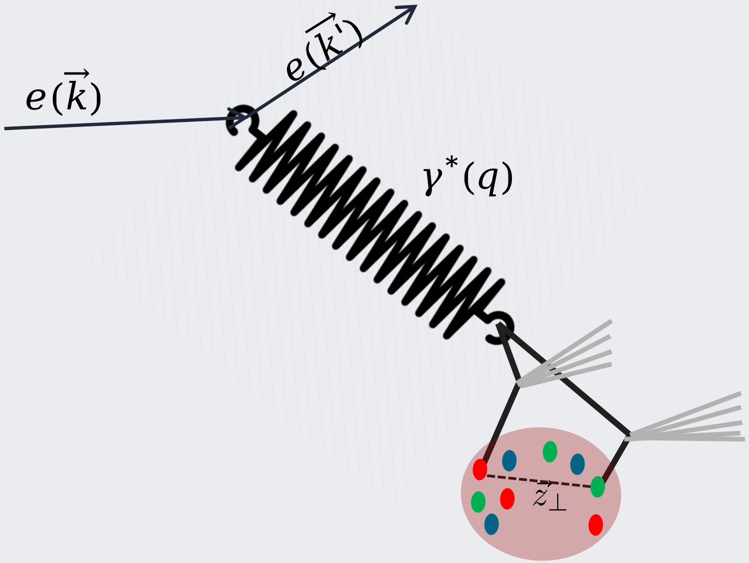
HOWEVER FROM PROTON-PROTON COLLISIONS ONLY RANGES CAN BE ACCESSED

M.R. and F. A. Ceccopieri, JHEP 09 (2019) 097



6 New Idea: DPS via γ-p interaction

We consider the possibility offered by a DPS process involving a photon FLACTUATING in a quark-antiquark pair interacting with a proton:



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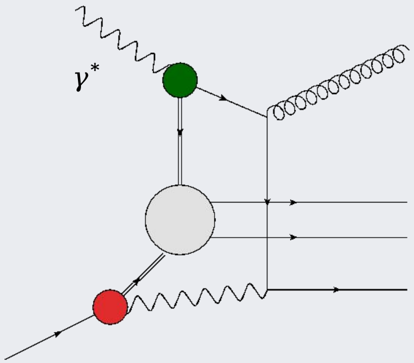
In order to study the impact of the DPS contribution to a process initiated via photon-proton interactions we evaluated the 4-JET photoproduction at HERA **(S. Checkanov et al. (ZEUS), Nucl. Phys B792, 1 (2008))**



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It has been shown that the agreement with data improves if MPI are included in the Monte Carlo

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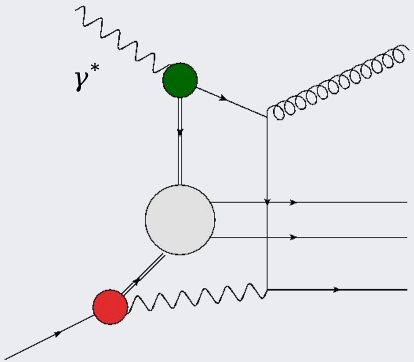

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⇓

WE EVALUATE THE DPS CONTRIBUTION TO THIS PROCESS

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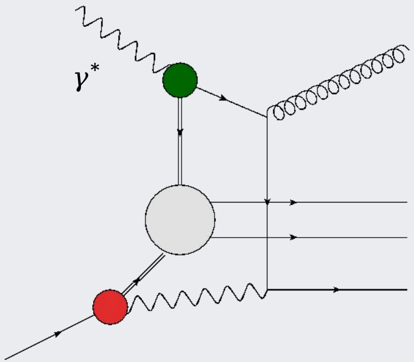

For this first investigation, we make use of the POCKET FORMULA:

$$d\sigma^{4j}_{DPS} = \frac{1}{2}\sum_{ab,cd}\int dy\, dQ^2 \frac{f_{\gamma/e}(y,Q^2)}{\sigma_{eff}^{\gamma p}(Q^2)} \times$$

$$\left.\begin{aligned} &\times \int dx_{p_a} dx_{\gamma_b} f_{a/p}(x_{p_a}) f_{b/\gamma}(x_{\gamma_b}) d\hat{\sigma}^{2j}_{ab}(x_{p_a}, x_{\gamma_b}) \\ &\times \int dx_{p_c} dx_{\gamma_d} \underbrace{f_{c/p}(x_{p_c})}_{\text{p-PDF}} \underbrace{f_{d/\gamma}(x_{\gamma_d})}_{\gamma\text{-PDF}} d\hat{\sigma}^{2j}_{cd}(x_{p_c}, x_{\gamma_d}) \end{aligned}\right\} \begin{matrix} \text{SPS*} \\ \times \\ \text{SPS} \end{matrix}$$

Flux Factor: P. Nason et al, PLB319 339 (1993)

p-PDF **(J. Pumplin et al. JHEP 07, 012 (2002))**

γ-PDF **(M. Gluck et al. PRD46, 1973 (1992))**

*Single Parton Scattering (SPS)

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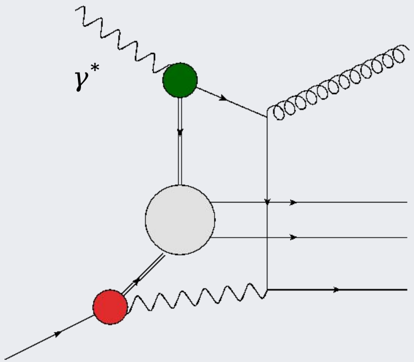

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$\times$ ... $) d\hat{\sigma}^{2j}_{ab}(x_{p_a}, x_{\gamma_b})$ SPS*

$\times$

$\times$ ... $) d\hat{\sigma}^{2j}_{cd}(x_{p_c}, x_{\gamma_d})$ SPS

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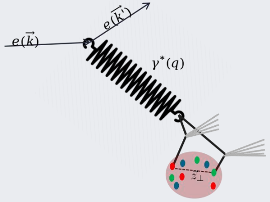
The main quantity we have to evaluate is:

$$\sigma^{\gamma p}_{eff}(Q^2)$$

*Single Parton Scattering (SPS)

6 The γ-p effective cross section



The expression of this quantity is very similar to the proton-proton collision case and can be formally derived by comparing the product of SPS cross sections and the DPS one obtained in **Gaunt, JHEP 01, 042 (2013)** and describing a DPS from a vector bosons splitting with given Q^2 virtuality

Proton EFF

$$\left[\sigma_{\text{eff}}^{\gamma p}(Q^2)\right]^{-1} = \int \frac{d^2 k_\perp}{(2\pi^2)} \boxed{T_p(k_\perp)} T_\gamma(k_\perp; Q^2)$$

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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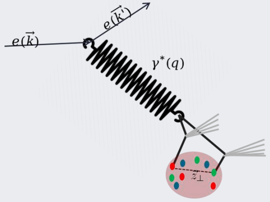

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M. R. and F. A. Ceccopieri, arXiv:2103.13480

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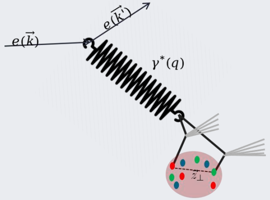

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Proton EFF

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The full DPS cross section depends on the amplitude of the splitting photon in a $q\,\bar{q}$ pair. The latter can be formally described within a Light-Front (LF) approach in terms of LF wave functions:

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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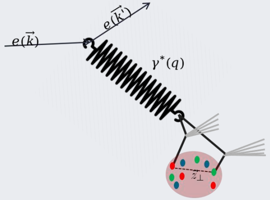

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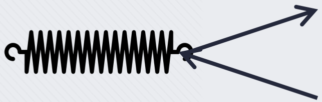

$q: (x, \vec{k}_{\perp,1})$

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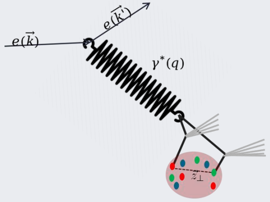

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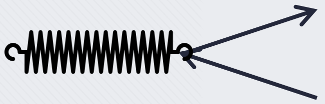

Similar definition of a meson dPDF

M. R. and F. A. Ceccopieri, arXiv:2103.13480

M. R. et al., EPJC78, 781 (2018)

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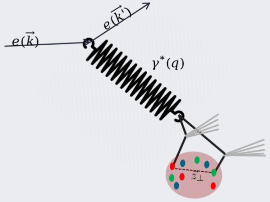

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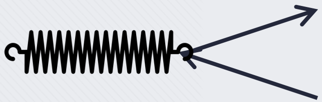

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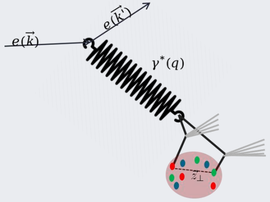

The expression of this quantity is very similar to ... collision case and can be formally deri... ss sections and the DPS on... DPS from a

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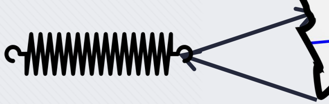
$$f_{q,\bar{q}}^{\gamma}(x, \tilde{k}_\perp; Q^2) = \int d^2 ...$$



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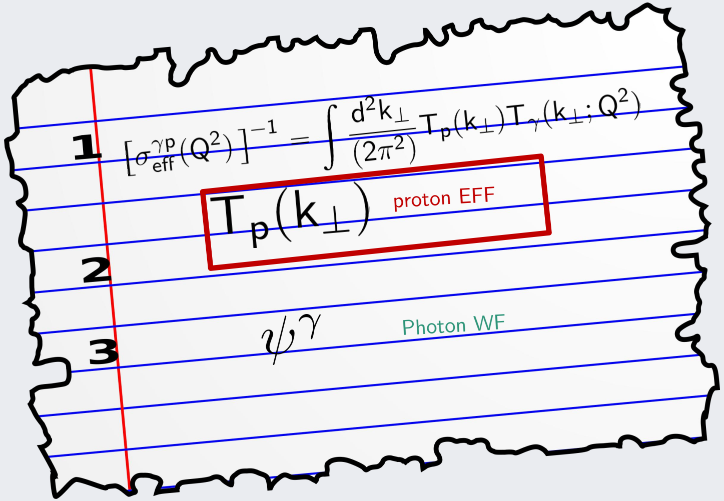
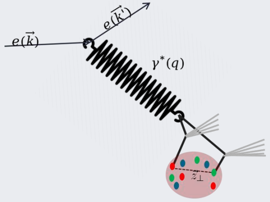
INGREDIENTS OF THE CALCULATION

1. $T_p(k_\perp)$ proton EFF
2. ψ^γ Photon WF
3.

M. R. and F. A. Ceccopieri, arXiv:2103.13480

6 The γ-p effective cross section





For the proton EFF use has been made of three choices:

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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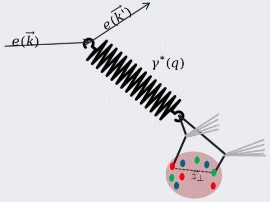

1 $\left[\sigma_{eff}^{\gamma p}(Q^2)\right]^{-1} = \int \frac{d^2 k_\perp}{(2\pi^2)} T_p(k_\perp) T_\gamma(k_\perp; Q^2)$

2 $T_p(k_\perp)$ proton EFF

3 ψ_γ Photon WF

For the proton EFF use has been made of three choices:

1) G1: $e^{-\alpha_1 k_\perp^2}$, $\alpha_1 = 1.53\ \text{GeV}^{-2} \implies \sigma_{eff}^{pp} = 15\ \text{mb}$

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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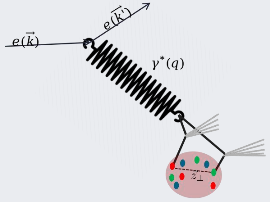

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M. R. and F. A. Ceccopieri, arXiv:2103.13480

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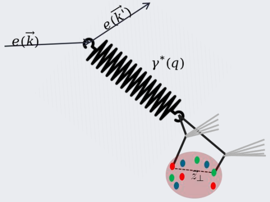

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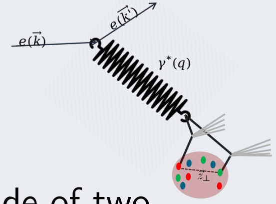
3) S: $\left(1 + \frac{k_\perp^2}{m_g^2}\right)^{-4}$, $m_g^2 = 1.1 \ \mathrm{GeV}^2 \Longrightarrow \sigma_{\rm eff}^{pp} = 30 \ \mathrm{mb}$

B. Blok et al, EPJC74, 2926 (2014)

M. R. and F. A. Ceccopieri, arXiv:2103.13480

6 The γ-p effective cross section



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3 ψ^γ Photon WF

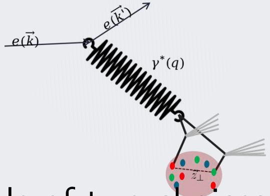
For the photon W.F. use has been made of two choices representing two extreme cases:

1) QED at LO (S.J. Brodsky et al. PRD50, 3134 (1994)):

$$\psi_{q,\bar{q}}^{\lambda=\pm}(x, k_{1\perp}; Q^2) = -e_f \frac{\bar{u}_q(k)\ \gamma \cdot \varepsilon^\lambda\ v_{\bar{q}}(q-k)}{\sqrt{x(1-x)}\left[Q^2 + \frac{k_{1\perp}^2 + m^2}{x(1-x)}\right]}$$

M. R. and F. A. Ceccopieri, arXiv:2103.13480

6 The γ-p effective cross section



1 $\left[\sigma_{eff}^{\gamma p}(Q^2)\right]^{-1} = \int \frac{d^2k_\perp}{(2\pi^2)} T_p(k_\perp) T_\gamma(k_\perp; Q^2)$

2 $T_p(k_\perp)$ proton EFF

3 ψ^γ Photon WF

For the photon W.F. use has been made of two choices representing two extreme cases:

1) QED at LO (S.J. Brodsky et al. PRD50, 3134 (1994)):

$$\psi_{q,\bar{q}}^{\lambda=\pm}(x, k_{1\perp}; Q^2) = -e_f \frac{\bar{u}_q(k)\ \gamma \cdot \varepsilon^\lambda\ v_{\bar{q}}(q-k)}{\sqrt{x(1-x)}\left[Q^2 + \frac{k_{1\perp}^2 + m^2}{x(1-x)}\right]}$$

2) Non-Pertubative (NP) effects (E.R.Arriola et al, PRD74,054023 (2006))

$$\psi_A^\gamma(x, k_{\perp 1}; Q^2) = \frac{6(1 + Q^2/m_\rho^2)}{m_\rho^2 \left(1 + 4\frac{k_{\perp 1}^2 + Q^2 x(1-x)}{m_\rho^2}\right)^{5/2}}$$

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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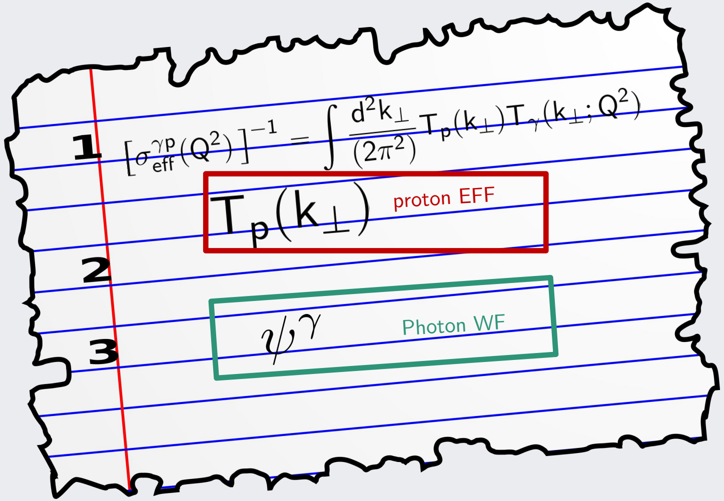

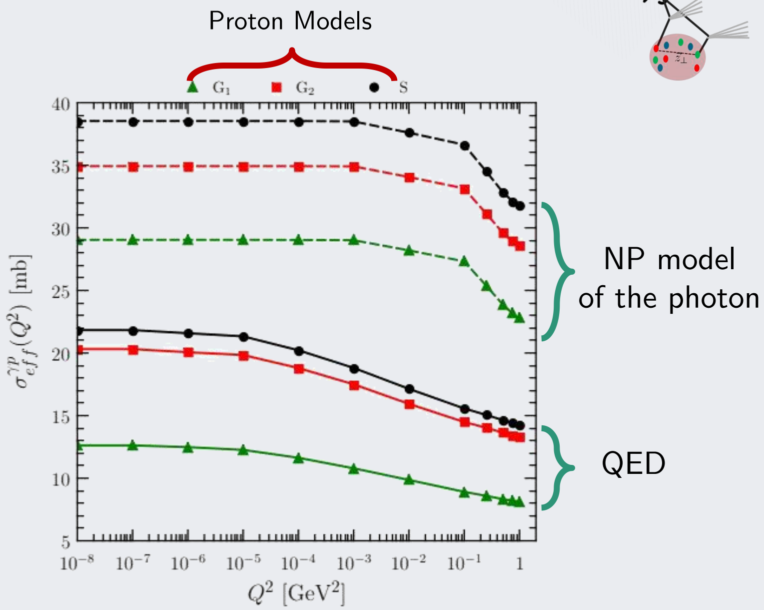

M. R. and F. A. Ceccopieri, arXiv:2103.13480

6 The 4 jet DPS cross section

The HERA KINEMATICS:
S. Checkanov et al. (ZEUS), Nucl. Phys B792, 1 (2008)

$E_T^{jet} > 6$ GeV	Transverse energy of the jets
$\lvert\eta_{jet}\rvert < 2.4$	Pseudorapidity
$Q^2 < 1$ GeV^2	Photon virtuality
$0.2 \leqslant y \leqslant 0.85$	Inelasticity

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The ZEUS collaboration quoted an integrated total 4-jet cross section of 200 pb
S. Checkanov et al. (ZEUS), Nucl. Phys B792, 1 (2008)

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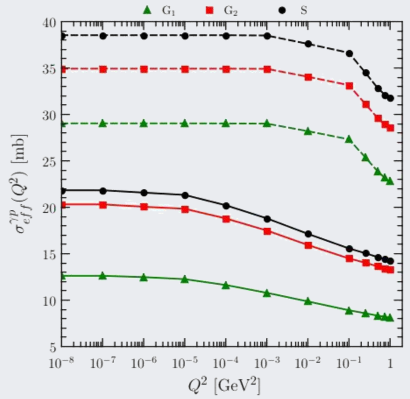
$0.2 \leqslant y \leqslant 0.85$

$$d\sigma_{DPS}^{4j} = \frac{1}{2}\sum_{ab,cd}\int dy\, dQ^2\, \frac{f_{\gamma/e}(y,Q^2)}{\sigma_{eff}^{\gamma p}(Q^2)} \times$$
$$\times \int dx_{p_a} dx_{\gamma_b} f_{a/p}(x_{p_a}) f_{b/\gamma}(x_{\gamma_b}) d\hat{\sigma}_{ab}^{2j}(x_{p_a}, x_{\gamma_b})$$
$$\times \int dx_{p_c} dx_{\gamma_d} f_{c/p}(x_{p_c}) f_{d/\gamma}(x_{\gamma_d}) d\hat{\sigma}_{cd}^{2j}(x_{p_c}, x_{\gamma_d})$$



M. R. and F. A. Ceccopieri, arXiv:2103.13480

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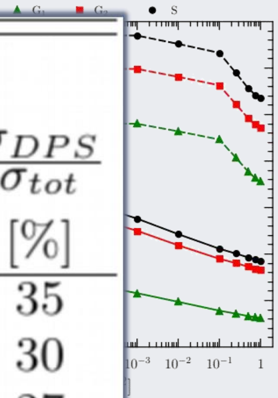
$0.2 \leqslant y \leqslant 0.$

photon		σ_{DPS} [pb] $Q^2 \leq 10^{-2}$ [GeV^2]	$10^{-2} \leq Q^2 \leq 1$ [GeV^2]	$Q^2 \leq 1$ [GeV^2]	$\frac{\sigma_{DPS}}{\sigma_{tot}}$ [%]
NP model	G_1	47	25	71	35
	G_2	39	20	59	30
	S	35	18	54	27
QED	G_1	117	72	189	95
	G_2	73	44	117	58
	S	64	41	109	54

proton



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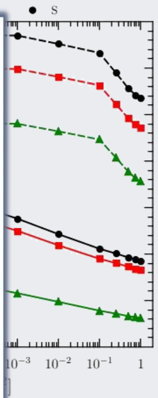

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photon			σ_{DPS} [pb] ≤ 1 $Q^2 \le 1$ [GeV^2]	$\frac{\sigma_{DPS}}{\sigma_{tot}}$ [%]
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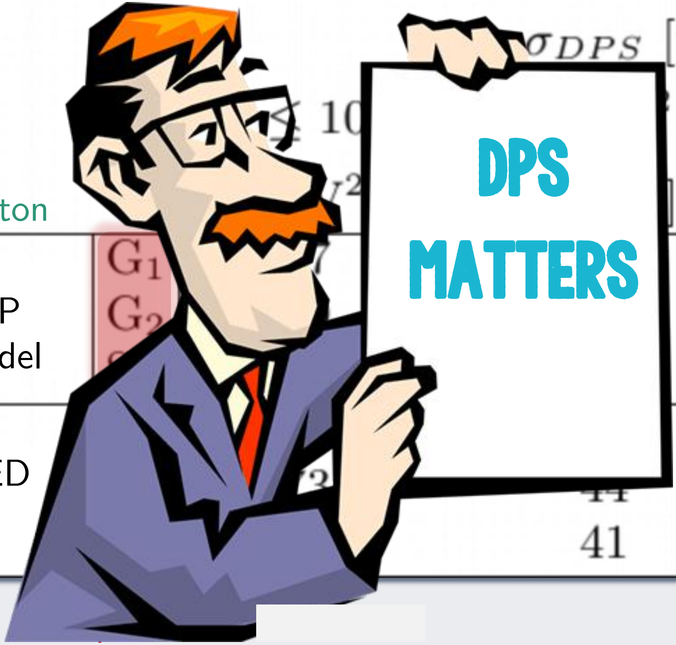

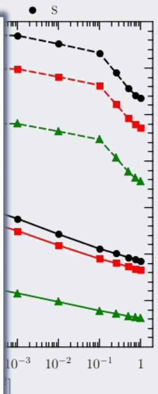

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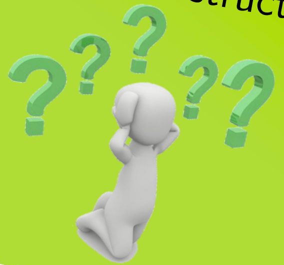
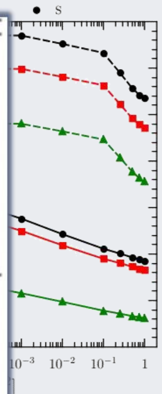
proton

What can we learn about the proton structure?





6 The effective cross section: a key for the proton structure

The effective cross section can be also written in terms of Fourier Transform of the EFF:

$$\tilde{F}(z_\perp)$$

The probability of finding a parton pair at distance

$$z_\perp$$

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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$$\tilde{F}_2^{\gamma}(z_\perp; Q^2) = \sum_n C_n(Q^2) z_\perp^n$$

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Mean value on proton states

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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If we can measure
the dependence of the
effective-cross section
on the photon
VIRTUALITY

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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This coefficient can be determined from the structure of the photon described in a given approach

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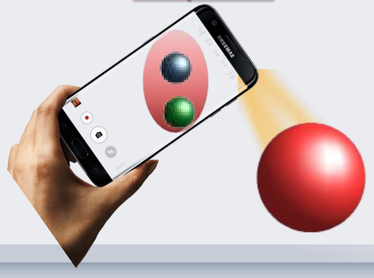
We could access for the first time the mean transverse distance between partons in the proton



M. R. and F. A. Ceccopieri, arXiv:2103.13480

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Is it possible to get this measure?

If we can measure the dependence of the effective-cross section on the photon VIRTUALITY

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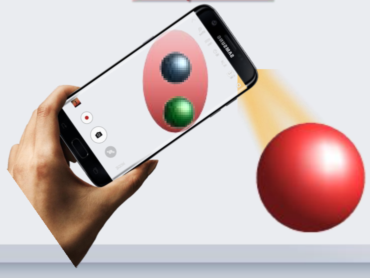

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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To test if in future a dependence of the effective cross section on the photon virtuality, we considered again the 4 JET photoproduction:

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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1) We divided the integral of the cross section on Q^2 in two intervals:

$$Q^2 \leqslant 10^{-2} \quad \text{and} \quad 10^{-2} \leqslant Q^2 \leqslant 1 \quad \text{GeV}^2$$

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2) We have estimated for each photon and proton models a constant effective cross section $\bar{\sigma}_{\text{eff}}^{\gamma p}$ (with respect to Q^2) such that the total integral of the cross section on Q^2 reproduce the full calculation obtained by means of $\sigma_{\text{eff}}^{\gamma p}(Q^2)$

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3) We estimate the minimum luminisity to distinguish the two cases

M. R. and F. A. Ceccopieri, arXiv:2103.13480

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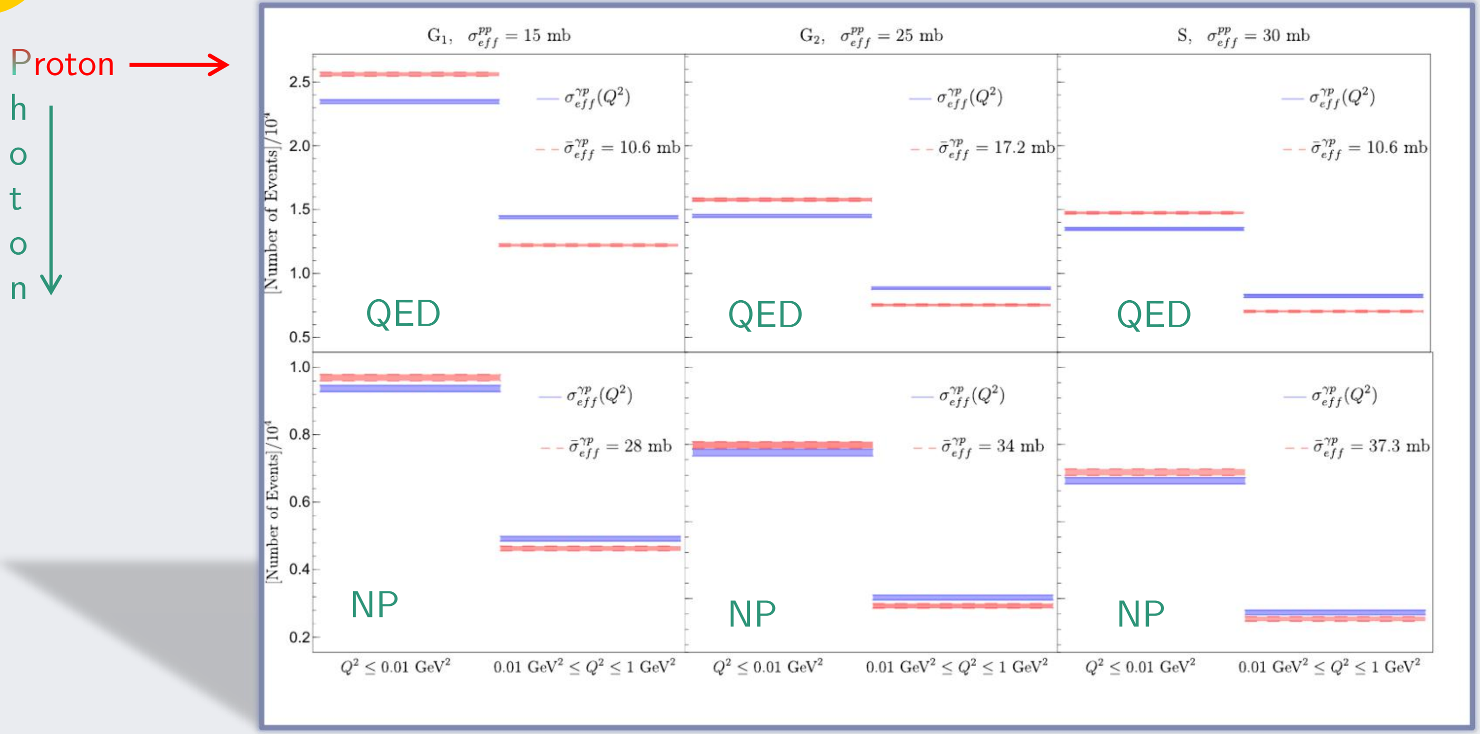
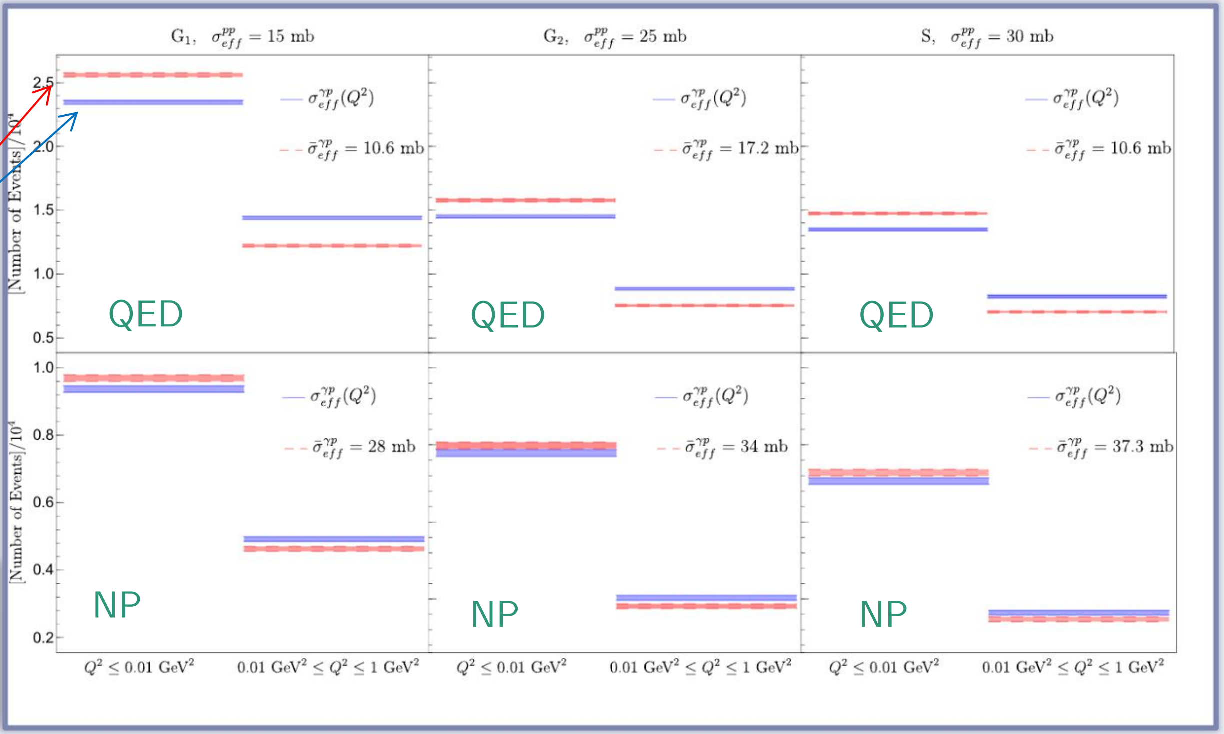


The effective cross section: a key for the proton structure

With an integrated luminosity of 200 pb^{-1} we can separate:



7 Double PDFs of pions and lattice data

The dPDF expression, at the hadronic scale, in term of the meson $q\bar{q}$ wave function:

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

Parton helicities — Intrinsic parton momentum — Meson-Wave function

M. R., S. Scopetta, M. Traini and V.Vento, EPJC 78, no. 9,782 (2018)

W. Broniovski et al, PRD 101 (2020) n°1. 014019
S. Scopetta et al, EPJC80 (2020) n°10, 909

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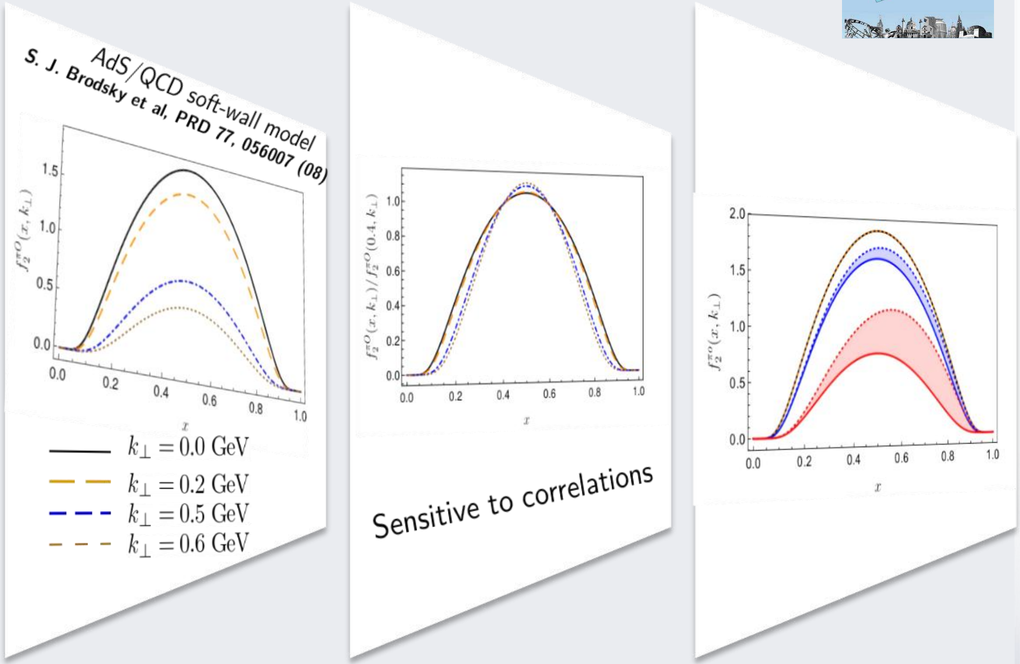
M. R., S. Scopetta, M. Traini and V.Vento, EPJC 78, no. 9,782 (2018)

1) Also for pion, model calculations indicate that factorization does not work!

2) The approximation:

$$f_2(x, \Delta_\perp) \sim H(x, 0, \Delta_\perp)F_\pi(\Delta_\perp^2)$$

does not work



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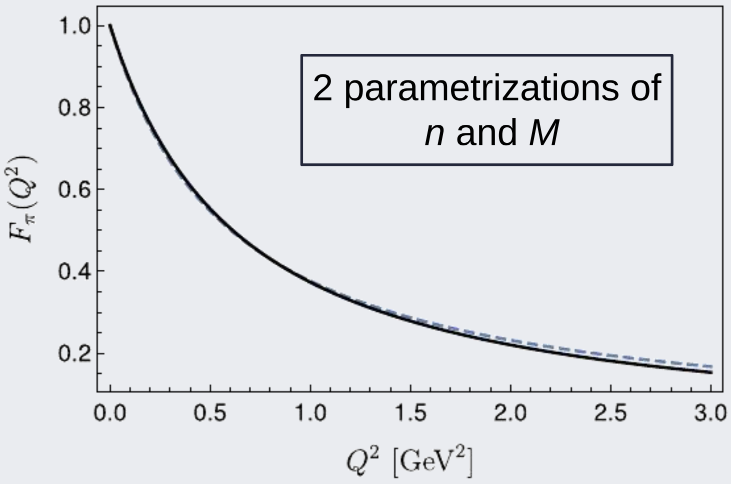
In **G.S. Bali et al, JHEP 12, 061 (2018)** a first analysis of the moments of dPDFs within the lattice QCD have been discussed. In **M.R., EPJC 80 (2020) n°7, 678** lattice data have been compared with pion quark models.

$$F_\pi(Q^2) \sim \left[1 + \frac{Q^2}{M^2}\right]^{-n}$$

FIT OF LATTICE DATA FOR THE FORM FACTOR



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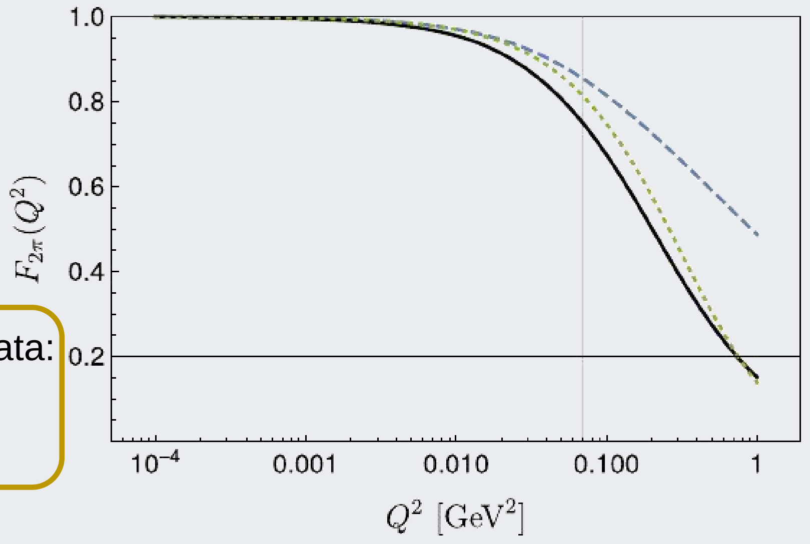
THE EFFECTIVE FORM FACTOR:

1) Full line: $F_{2\pi}(Q^2) \sim \left[1 + \langle d^2 \rangle \frac{Q^2}{6n}\right]^{-n}$

mean transverse distance fitted from lattice data:

$$\sqrt{\langle d^2 \rangle} \sim 1.046 \text{ fm}$$



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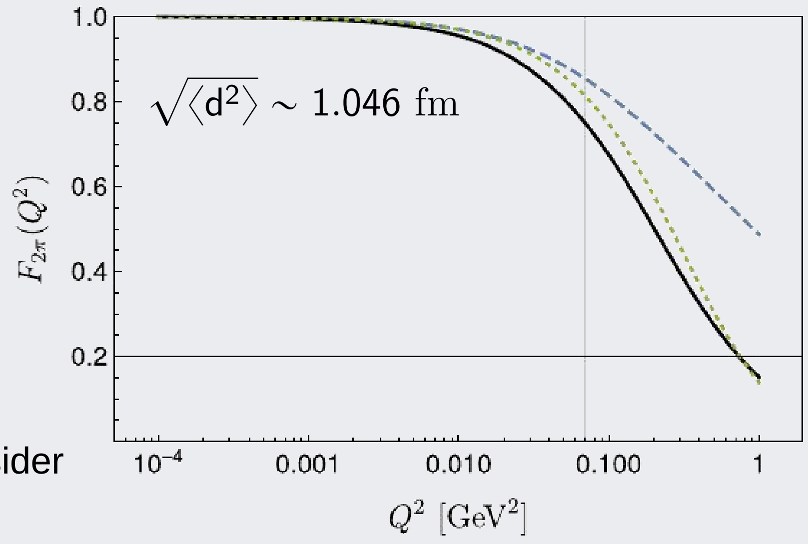

However, results have been obtained in the pion rest frame! $\vec{p} = 0$
Therefore in order to compare these results with LF models (IMF) calculations we consider

$$Q^2 << m_\pi^2, \qquad m_\pi \sim 0.3 \text{ GeV}$$

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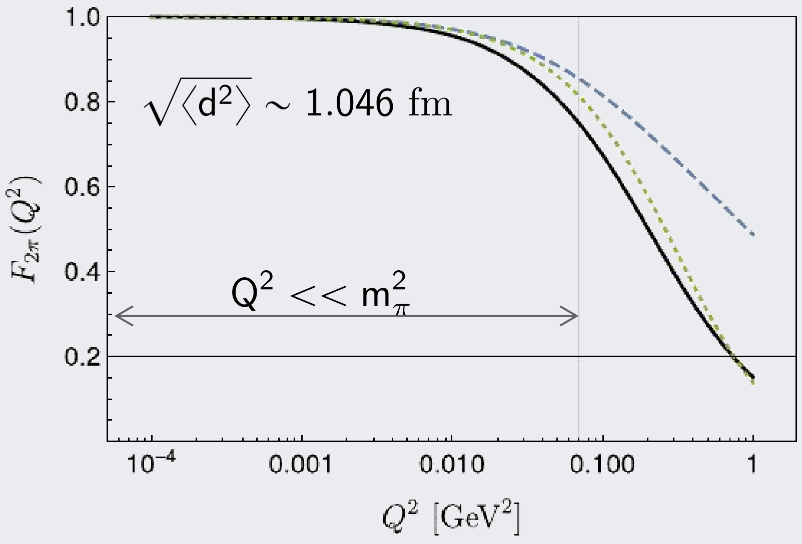
2) Dashed line:

$$F_{2\pi}(Q^2) \sim \frac{(m_\pi + E_q)^2}{4 m_\pi E_q} F_\pi(2 m_\pi E_q - 2 m_\pi^2)^2$$

1-body approximation in the pion rest frame and $E_q = \sqrt{m_\pi^2 + Q^2}$



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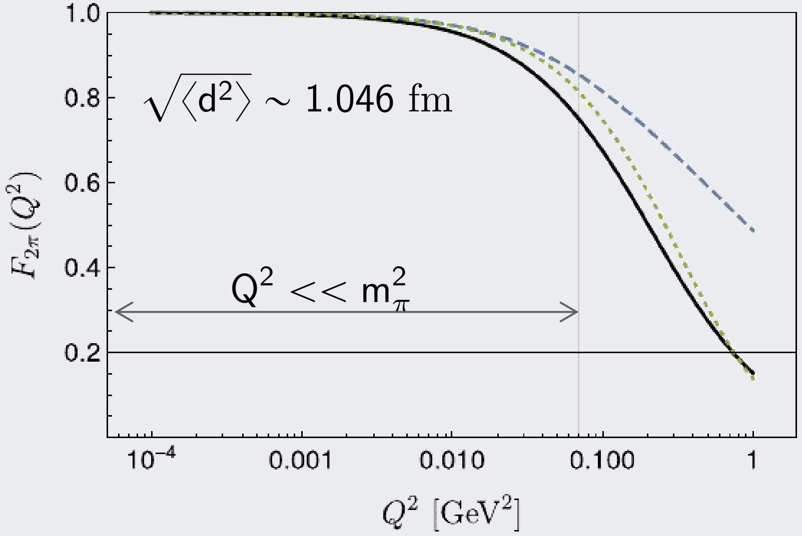
REST

3) Dotted line: $F_{2\pi}(Q^2) \sim F_\pi(Q^2)^2$

1-body approximation in the IMF



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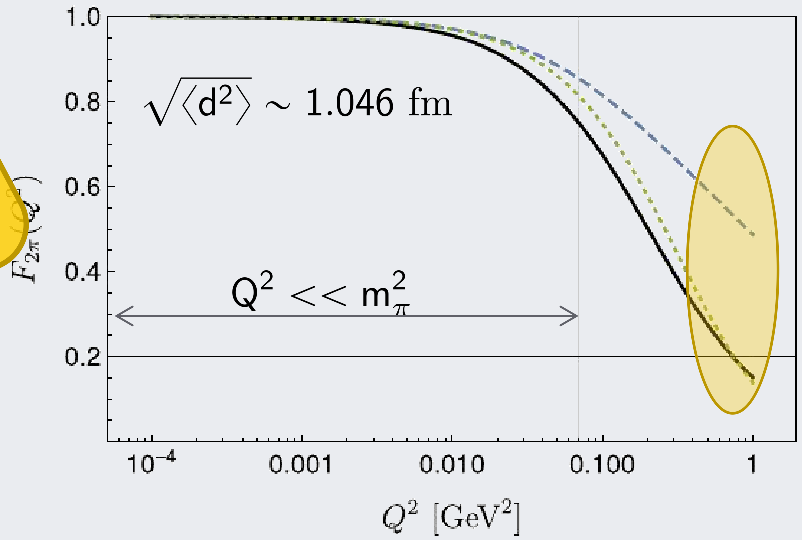
3) Dotted line: $F_{2\pi}(Q^2) \sim F_\pi(Q^2)^2$

CORRELATIONS ARE IMPORTANT



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I considered HOLOGRAPHIC models:

1) $\psi_0(x, \mathbf{k}_{\perp,1}) \propto \frac{4\pi}{\kappa_0\sqrt{x(1-x)}} e^{-\frac{m_0^2+\mathbf{k}_{\perp,1}^2}{x(1-x)2\kappa_0^2}}$

ORIGINAL MODEL

S.J. Brodsky, G.F. de Teramond, PRD 77, 056007 (2008)

$\kappa_0 = 0.548$ GeV; $m_0 = 0.33$ GeV

2) $\psi_s(x, \mathbf{k}_{\perp,1}) = S(x, \mathbf{k}_{\perp,1})\psi_0(x, \mathbf{k}_{\perp,1})$

DYNAMICAL SPIN MODEL

M. Ahmady, F. Chishtie, R. Sandapen, PRD 95(7), 074008 (2017)

3) $\psi_U^\tau(x, \mathbf{k}_{\perp,1}) = 8\pi \frac{\sqrt{q_\tau(x)f(x)}}{1-x} e^{\frac{2f(x)}{(1-x)^2}\mathbf{k}_{\perp,1}^2}$

UNIVERSAL MODEL

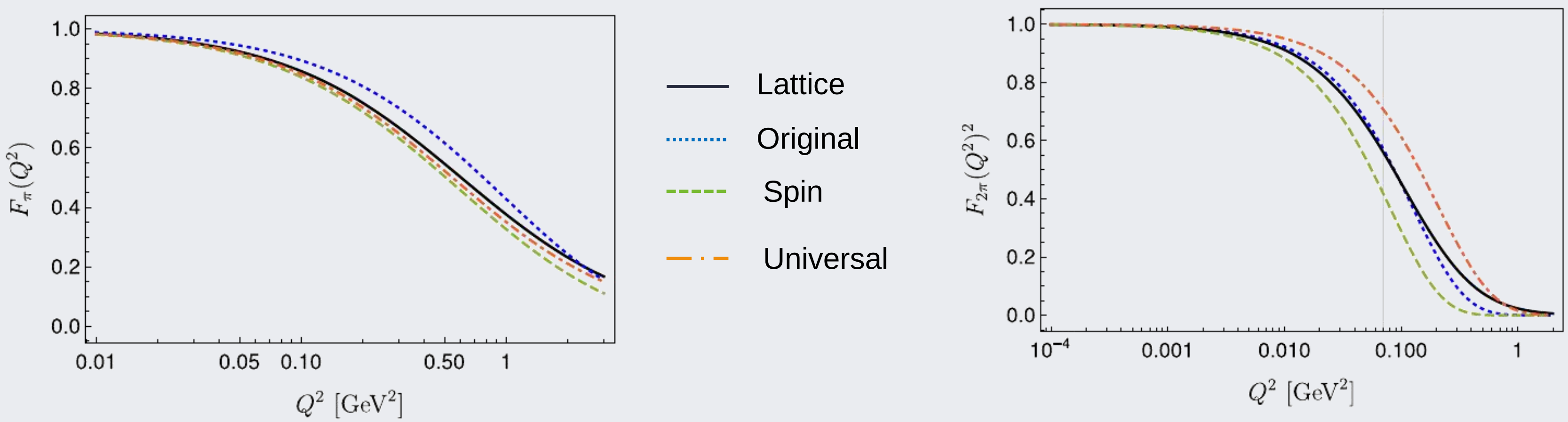
G.F. de Teramond et al., PRL. 120(18), 182001 (2018)

$\tau = 2 \rightarrow |q\bar{q}\rangle \quad \tau = 4 \rightarrow |q\bar{q}q\bar{q}\rangle$

7 Double PDFs of pions and lattice data

THE FORM FACTOR:

THE EFFECTIVE FORM FACTOR:



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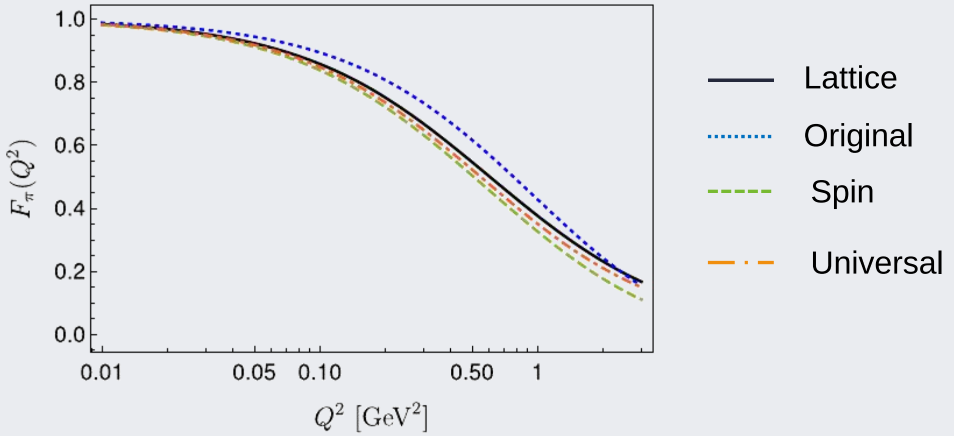
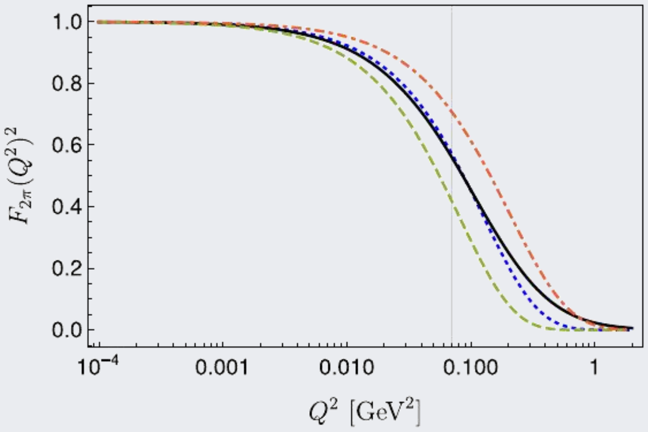


Improved models are close to data

THE EFFECTIVE FORM FACTOR:



Original model is the close to data!

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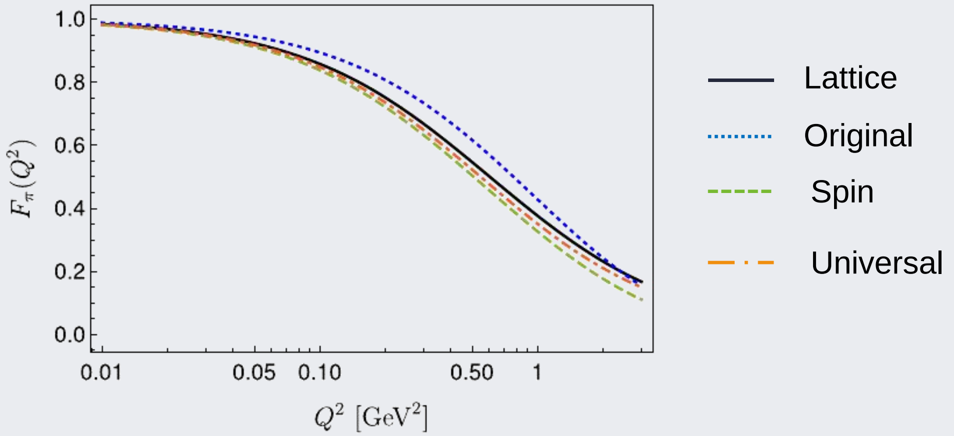

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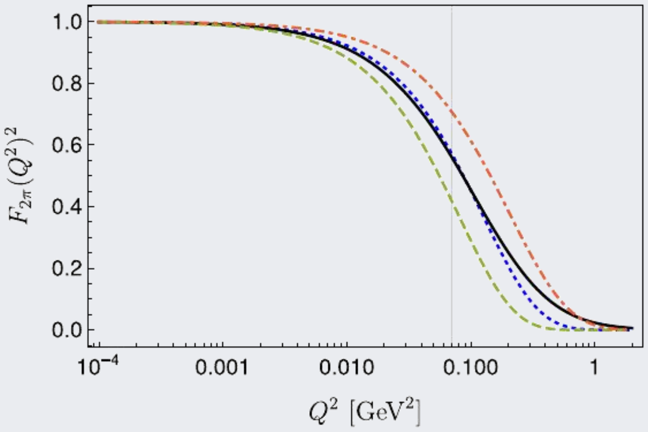

	Original model	Dynamical spin $A = B = 1$	Universal model	Lattice (A)
$\sqrt{\langle d^2 \rangle}$ [fm]	0.968	1.207	0.767	1.046 ± 0.049

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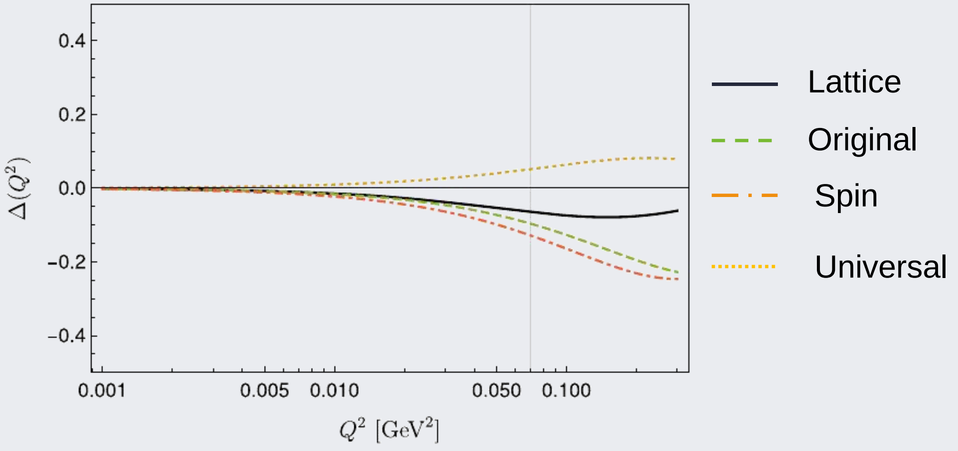
7 Double PDFs of pions and lattice data

CORRELATIONS? $\Delta(Q^2) = F_{2\pi}(Q^2) - F_\pi(Q^2)^2$



DOES THE DPS UNDERLYING PHYSICS REQUEST SOME IMPROVEMENTS?

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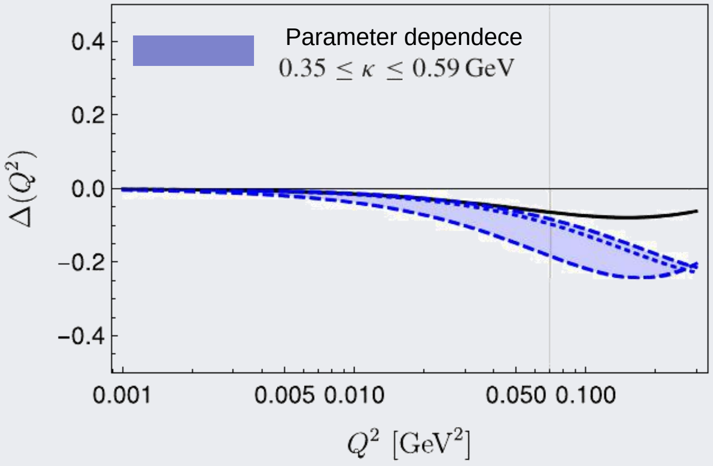

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YES!

If we change the parameter of the model we can get a better description of the FF but we lose the agreement with the EFF and viceversa. In fact the correlation distribution is not well reproduced.

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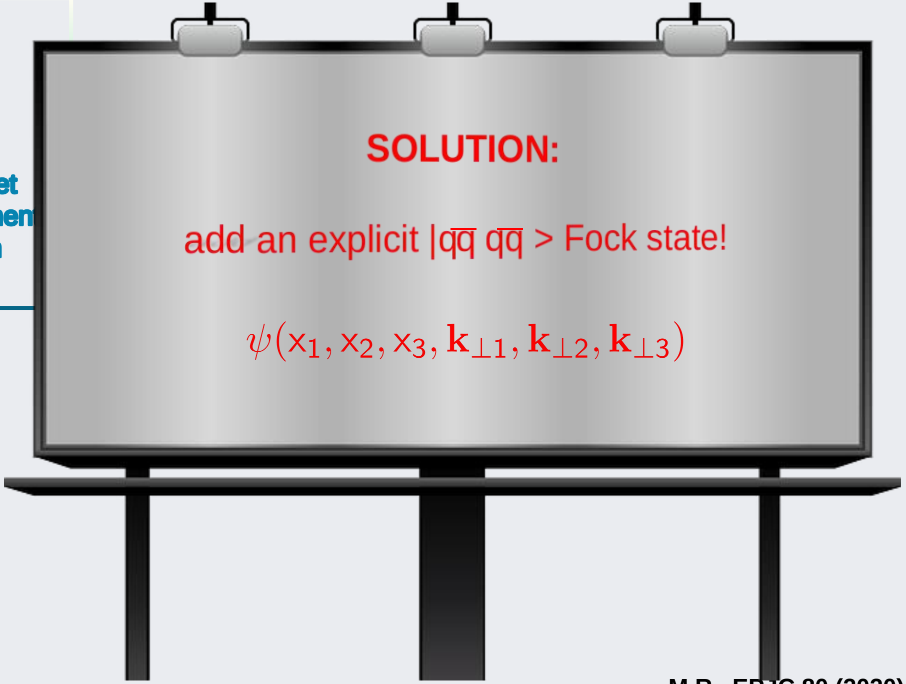

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New information from:

G.S. Bali et al, JHEP 02 (2021) 067 "Double parton distributions in the pion from lattice QCD"

C. Zimmermann, "Double parton distributions in the nucleon on the lattice QCD" arXiv: 2106.03451

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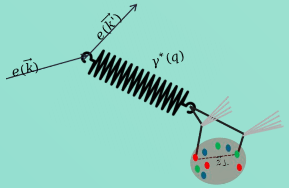
CONCLUSIONS



1) We investigated the impact of correlations in DPS proton-proton collisions to learn something new on the parton structure of the proton

2) We demonstrated that in p-p collisions only some limited information on the proton can be obtained

3) We proposed to consider DPS initiated via photon-proton interactions by showing that:

* DPS can contribute also in this case. Cross section of the 4 jet photo production strongly affected

* The dependence of $\sigma_{\text{eff}}^{\gamma p}(Q^2)$ on the Q^2 can unveil the mean distance of partons in the proton

* We show that by increasing the luminosity such a dependence can be exposed in future facilities such as the Electron Ion Collider

* In the future could be interesting to study other processes with different final states such as those associated to the QUARKONIUM PRODUCTION