DPS as MPI in ep/pA collisions

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in collaboration with

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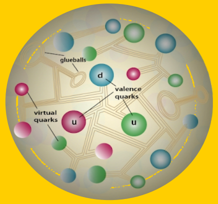
Vicente Vento
Rajesh Sangem



Istituto Nazionale di Fisica Nucleare

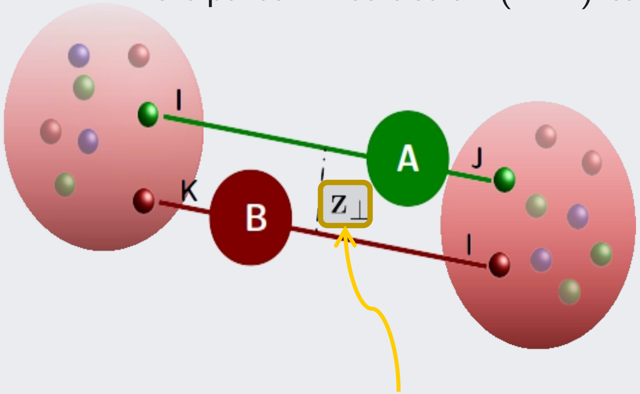
STRONG 2020

Outline

1. INTRODUCTION
2. DOUBLE PARTON DISTRIBUTION FUNCTION
3. DATA AND INTEPRETATION OF THE DATA
4. DPS VIA PHOTON-PROTON INTERACTIONS
5. DPS IN PROTON NUCLEUS INTERACTIONS
6. CONCLUSIONS

1 Double Parton Scattering

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)
Mekhfi, PRD 32 (1985) 2371
M. Diehl et all, JHEP 03 (2012) 089

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**

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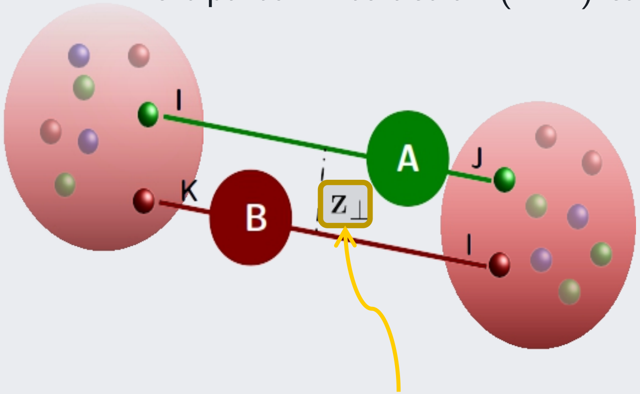

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A **formal all-order proof** of the factorization formulae in perturbative QCD **has been achieved for DPS** in the case of a **colorless final state**, both for the TMD and the collinear case. Current status is at the **same level as for the SPS** counterpart.

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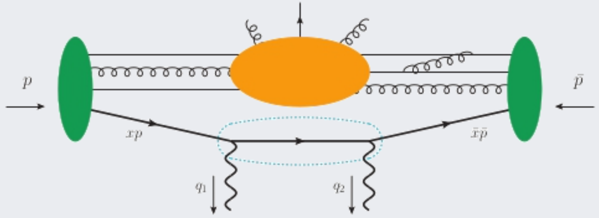
Diehl et al. JHEP 03 (2012) 089, JHEP 01 (2016) 076
Vladimirov JHEP 04 (2018) 045
Buffing et al. JHEP 01 (2018) 044
Diehl, RN JHEP 04 (2019) 124

1 Double Parton Scattering

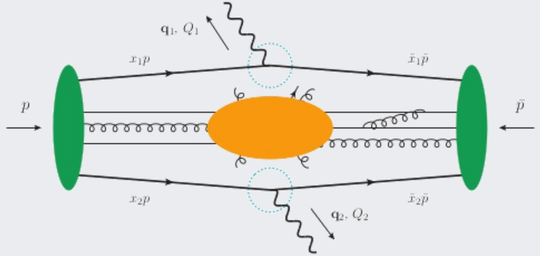
Scale analysis of SPS and DPS processes

SPS



$$|\mathbf{q}_1^\perp + \mathbf{q}_2^\perp| \sim \Lambda \ll Q$$

DPS



$$|\mathbf{q}_1^\perp| \sim \Lambda \ll Q$$
$$|\mathbf{q}_2^\perp| \sim \Lambda \ll Q$$

where:

- $Q = min(Q_1\,,\ Q_2)$
- Λ *transverse momentum scale*
- $\Lambda_{QCD} << \Lambda << Q$

Usually:

$$\frac{\sigma_{\mathrm{DPS}}}{\sigma_{\mathrm{SPS}}} \sim \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$

$$\frac{d^2\sigma_{\mathrm{SPS}}}{d^2q_1\ d^2q_2} \sim \frac{d^2\sigma_{\mathrm{DPS}}}{d^2q_1\ d^2q_2}$$

First appearance in theory studies:
Politzer Nucl. Phys. B172 (1980) 349
Paver, Treleani Nuovo Cim. A70 (1982) 215
Mekhfi Phys. Rev. D32 (1985) 2371

Other ground-setting works:
Gaunt, Stirling JHEP 03 (2010) 005
Blok et al. Eur. Phys. J. C72 (2012) 1963
Diehl et al. JHEP 03 (2012) 089
Manohar, Waalewijn Phys. Rev. D85 (2012) 114009
Ryskin, Snigierev Phys. Rev. D86 (2012) 014018
...

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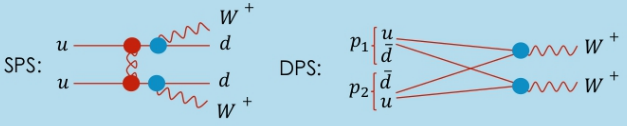
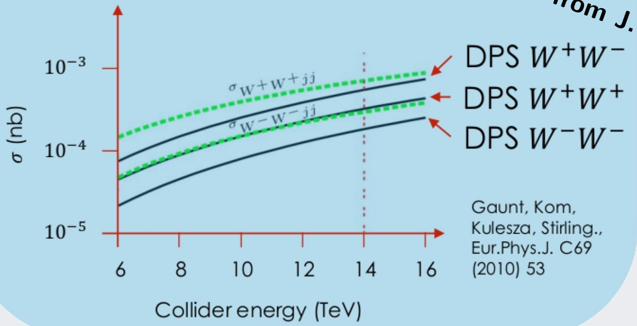
2 where and why DPS?

DPS can give a significant contribution to processes where SPS is suppressed by small/multiple coupling constants:

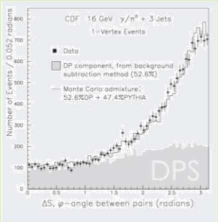




Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

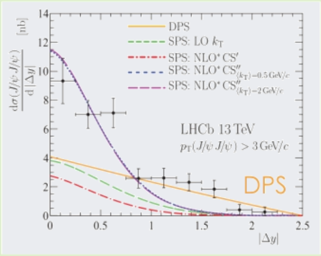
Slide from J. Gaunt

...or in certain phase space regions

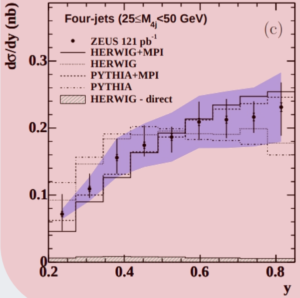


CDF, $\gamma + 3j$, Phys.Rev. D56 (1997) 3811-3832

LHCb, double J/ψ, JHEP 06, 047, (2017)



..or in ep colliders!



HERA data **ZEUS, nucl. phys. B 792,1 (2008)**

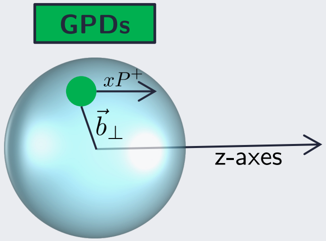
Access to:
- double parton correlations
- the transverse distance distribution of partons!!

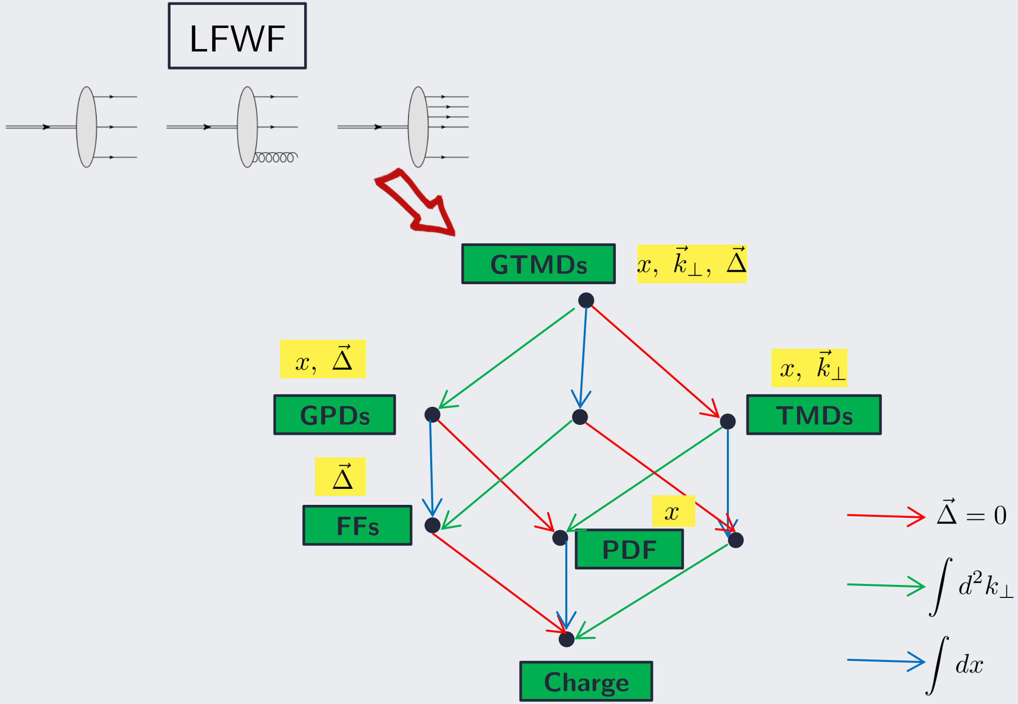
all **UNKNOWN**

Intrinsically interesting: tells us about **correlations** between partons!

3 Multidimensional Pictures of Hadron

1-body





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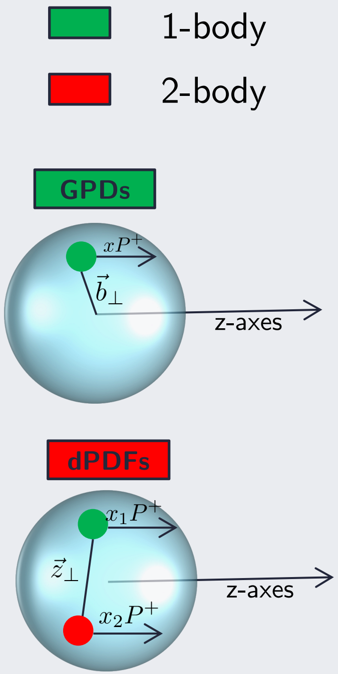

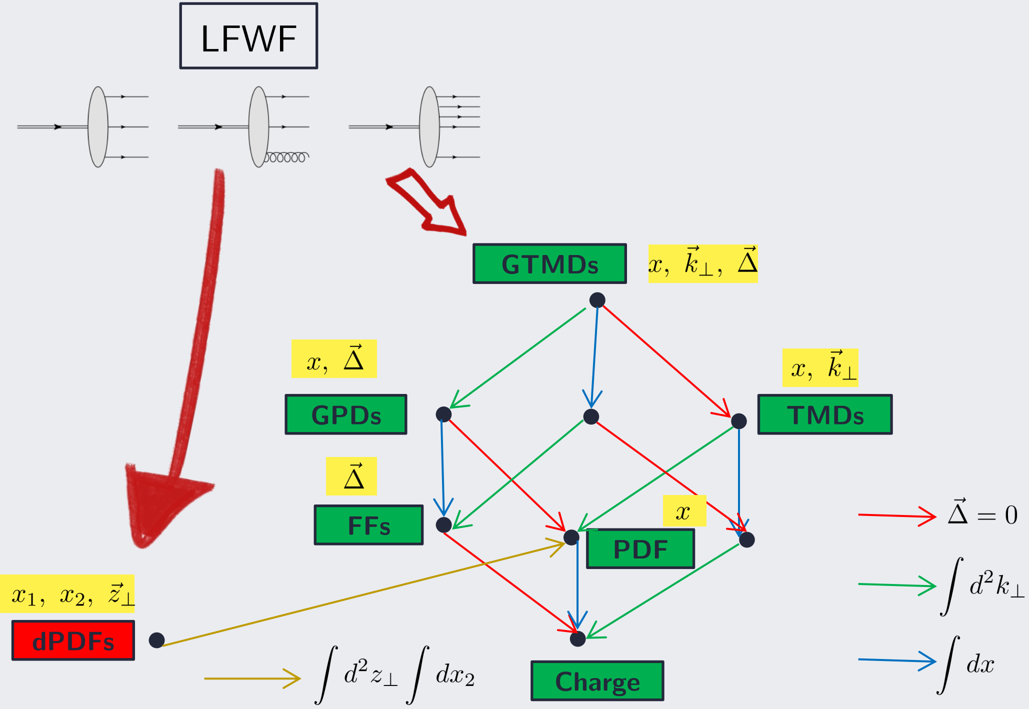

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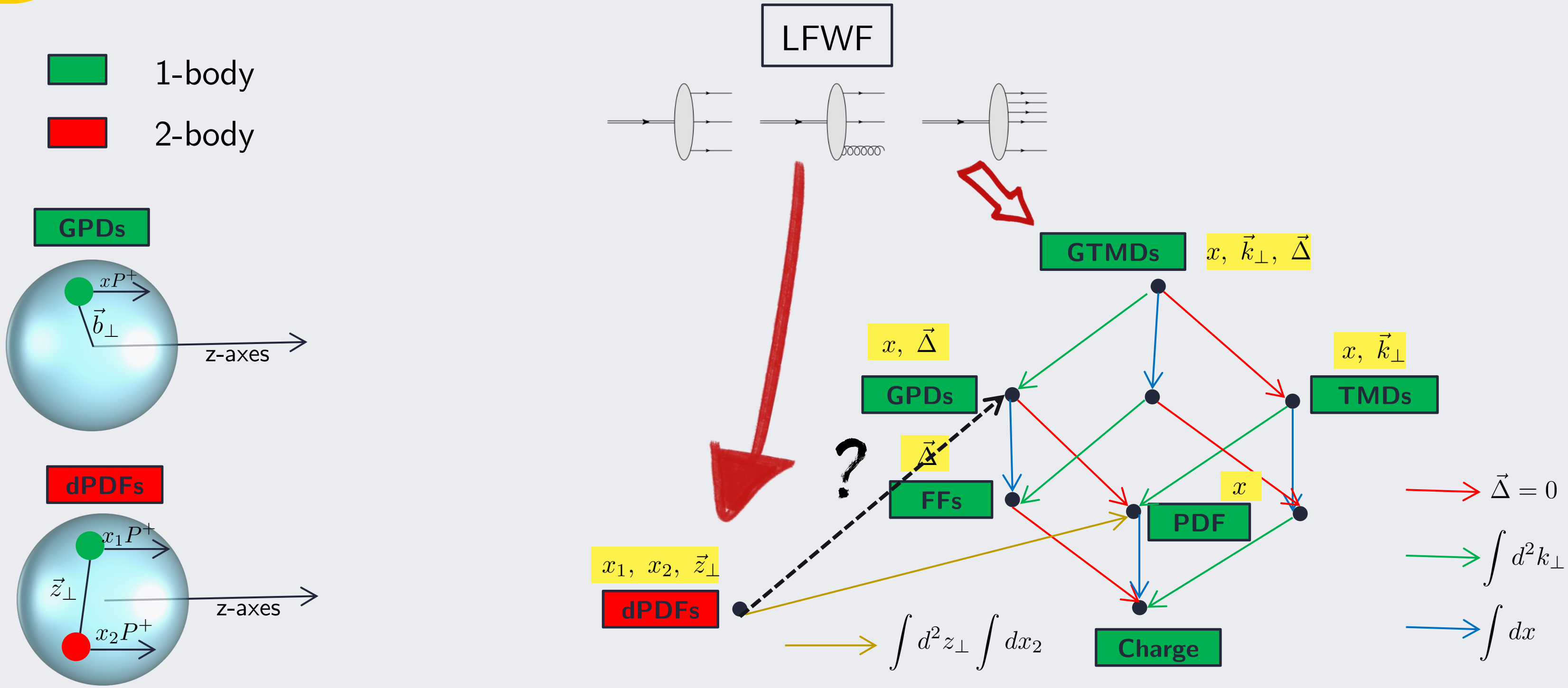

4 A link to GPDs?

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

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

Approximated by the proton state!

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

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

GPDs

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Approximated by the proton state!

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

$$F_{qq}(x_1, x_2, \vec{k}_\perp, Q^2) \approx H^q(x_1, \xi = 0, -k_\perp^2, Q^2) H^q(x_2, \xi = 0, -k_\perp^2, Q^2) + \frac{k_\perp^2}{4M_p^2} E^q(x_1, \xi = 0, -k_\perp^2, Q^2) E^q(x_2, \xi = 0, -k_\perp^2, Q^2)$$

M. R., et al, JHEP 10, 063 (2016)
M. Diehl et al, JHEP 03, 089 (2012)

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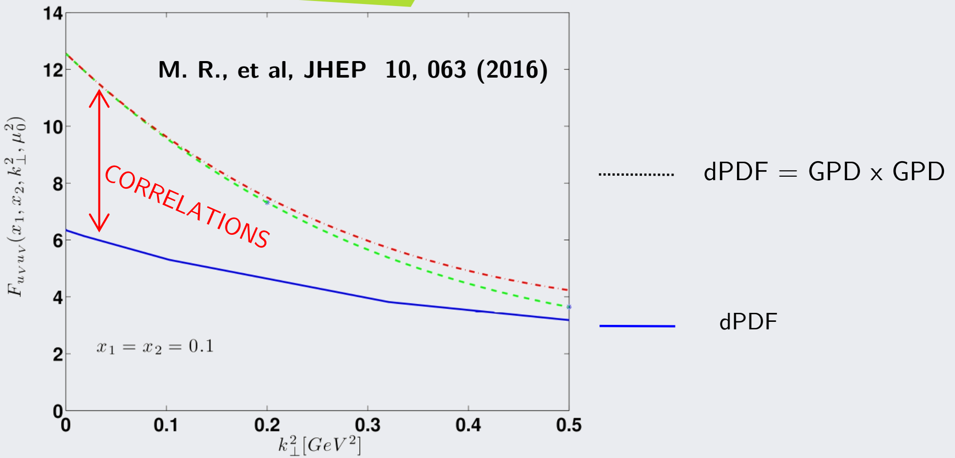

Violation due to:

- Correlations between (x_1, x_2)
  - M. R., et al, PRD 87, 114021 (2013)
  - M. R., et al, JHEP 12, 028 (2014)
  - M. R., et al, JHEP 10, 063 (2016)
- Correlations between $(x_1, x_2) - k_\perp$
  - M. R., et al, PRD 87, 114021 (2013)
  - M. R., et al, JHEP 12, 028 (2014)
  - M. R., and F.A. Ceccoperi, JHEP 09, 097 (2019)
  - M. R., and F.A. Ceccoperi, PRD 95, 034040 (2017)

4 A link to GPDs?

$$F_{qq}(x_1,x_2,\vec{k}_\perp,Q^2) \approx H^q(x_1,\xi=0,-k_\perp^2,Q^2)H^q(x_2,\xi=0,-k_\perp^2,Q^2) + \frac{k_\perp^2}{4M_n^2}E^q(x_1,\xi=0,-k_\perp^2,Q^2)E^q(x_2,\xi=0,-k_\perp^2,Q^2)$$

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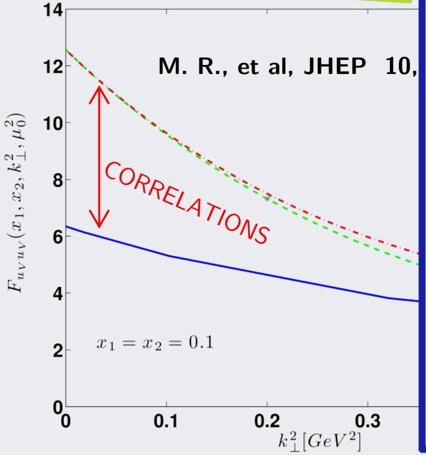
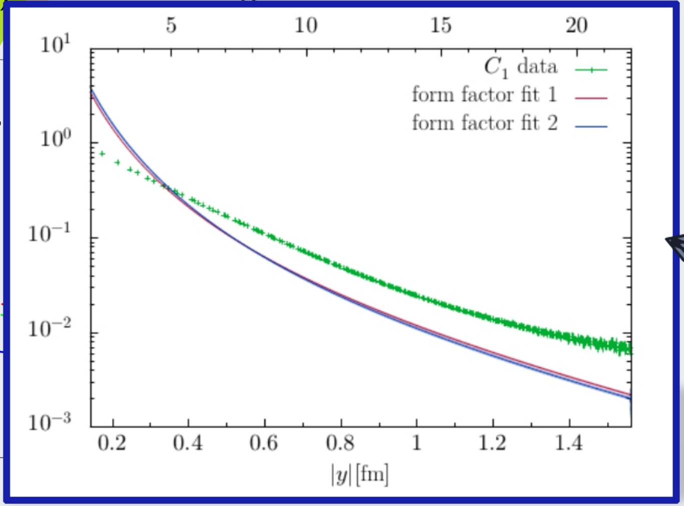




Similar violation observed in lattice analysis for the pion.

G. S. Bali et al, JHEP 12 (2018) 061

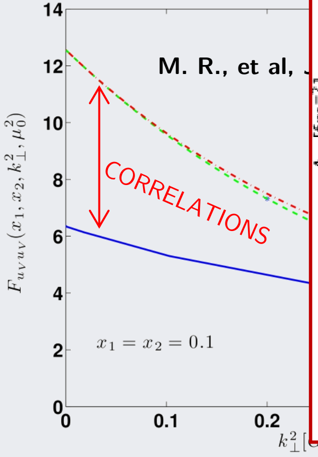
4 A link to GPDs?

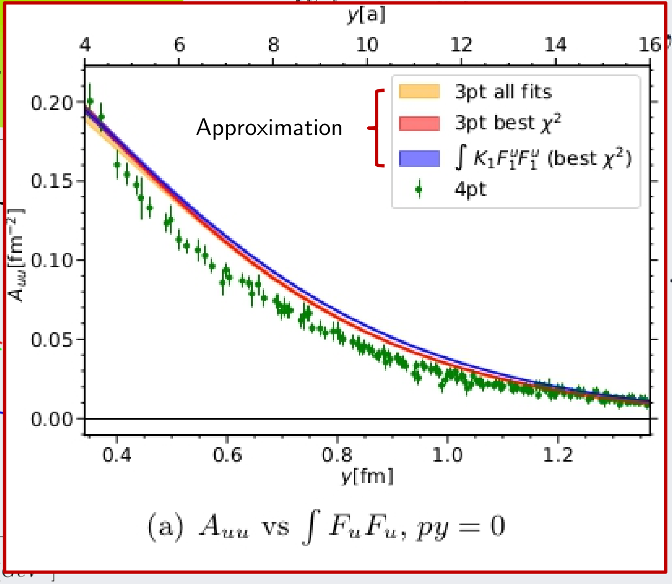
$$F_{qq}(x_1, x_2, \vec{k}_\perp, Q^2) \approx H^q(x_1, \xi = 0, -k_\perp^2, Q^2) H^q(x_2, \xi = 0, -k_\perp^2, Q^2) +$$

$$k^2 \; \ldots \; -k_\perp^2, Q^2) E^q(x_2, \xi = 0, -k_\perp^2, Q^2)$$

M. R., et al, JHEP 10,

M. Diehl et al, JHEP 03,





(a) A_{uu} vs $\int F_u F_u$, $py = 0$

Similar violation observed in lattice analysis

G. S. Bali et al, JHEP 09 (2021) 121

4 A link to GPDs? What can we learn?

$$F_{qq}(x_1, x_2, \vec{k}_\perp, Q^2) \approx H^q(x_1, \xi = 0, -k_\perp^2, Q^2) H^q(x_2, \xi = 0, -k_\perp^2, Q^2) +$$

$$+ \frac{k_\perp^2}{4M_p^2} E^q(x_1, \xi = 0, -k_\perp^2, Q^2) E^q(x_2, \xi = 0, -k_\perp^2, Q^2)$$

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

M. Diehl et al, JHEP 03, 089 (2012)

Since data on GPDs suggest that there is no factorization between (x_1, x_2) and $k_\perp$ we can think that also in dPDFs such an approximation does not hold.

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

We can build the proton eff, for example:

$$T(k_\perp) = (1 + k_\perp^2 / m_g^2)^{-4}$$

i.e., the square of the gluon form factor

B. Blok et al, EPJC 74, 2926 (2014)

5 Relativistic effects: the breaking of factorization

Usually the intrinsic dPDF, at a given scale, are phenomenological assumed to be:

$$\overbrace{F_{ij}(x_1, x_2, k_\perp; Q^2)}^{\text{pheno}} = \underbrace{q_i(x_1; Q^2) q_j(x_2; Q^2)}_{\text{phenomenology from PDFs}} \overbrace{\theta(1 - x_1 - x_2)}^{\text{good support}} \underbrace{f(x_1, x_2, Q^2)}_{\text{sum rules}} \left. F(k_\perp) \right\} \text{To be modeled: CQMs, GPDs...}$$

Then pQCD can also be applied!

5 Relativistic effects: the breaking of factorization

- Almost model independence
- Almost scale independence

SUGGEST: *parameterize the impact of Melosh effects in dPDFs to encode **some** general correlations between x_i and $k_\perp$*

$$\underbrace{F_{ij}(x_1,x_2,k_\perp;Q^2)}_{\text{pheno}} = \underbrace{q_i(x_1;Q^2)q_j(x_2;Q^2)}_{\text{phenomenology from PDFs}} \underbrace{\theta(1-x_1-x_2)}_{\text{good support}} \underbrace{f(x_1,x_2,Q^2)}_{\text{sum rules}} \underbrace{R(x_1,x_2,k_\perp)}_{\text{Melosh effects}} F(k_\perp) \Big\}$$

Melosh effects: correlations!

To be modeled: CQMs, GPDs...

$$R(x_1,x_2,k_\perp) \equiv \frac{F^{HO}_{[L]}(x_1,x_2,k_\perp;Q^2)}{F^{HO}_{[l]}(x_1,x_2,k_\perp;Q^2)} = w(k_\perp)\left[x_1x_2\right]^{t(k_\perp)}(1-x_2-x_2)^{|x_1-x_2|e(k_\perp)}e^{-(1-x_1-x_2)h(k_\perp)}$$

The parameters $w(k_\perp)$, $e(k_\perp)$, $t(k_\perp)$ and $h(k_\perp)$ are fixed to reproduce and READY TO BE USED!!!

M. R. and F. A. Ceccopieri, JHEP 1909 (2019) 097

6 Double PDFs contributions:

From pQCD (double DGLAP + inhomogeneus term) analyses we can build the following decomposition:

$$F(z_\perp) = F_{int}(z_\perp) + F_{sp}(z_\perp)$$

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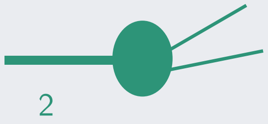
- it corresponds to:



- not divergent for $z_\perp \to 0$

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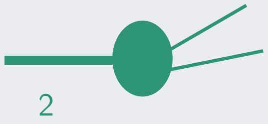

- not divergent for $z_\perp \rightarrow 0$

The **second** term:

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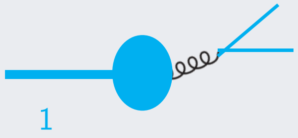

- divergent $1/z_\perp^2$

Diehl et al. JHEP 03 (2012) 089
Diehl et al. SciPost Phys. 7 (2019) 017
Diehl et al. JHEP 08 (2021) 040

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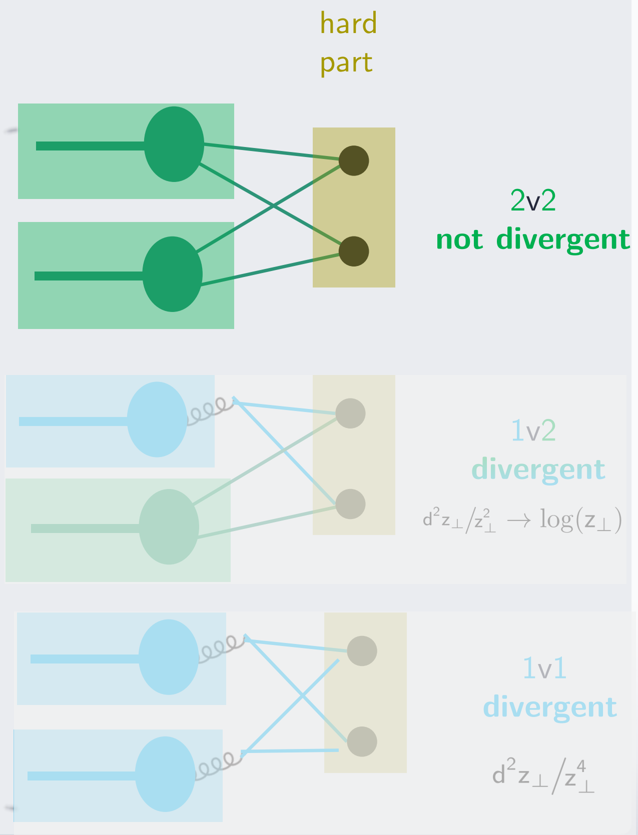
in principle we have the following terms:



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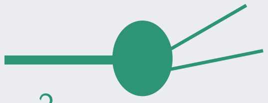

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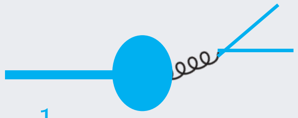

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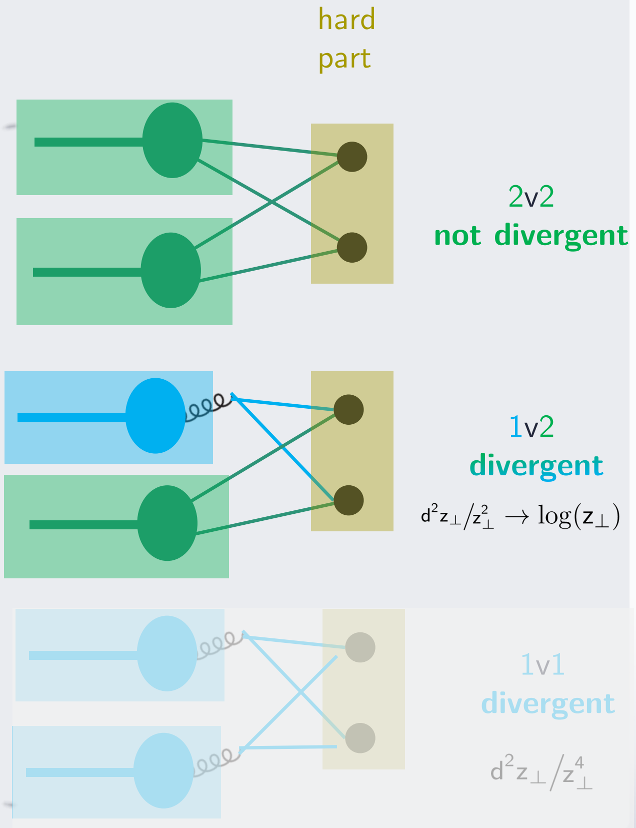

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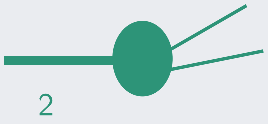

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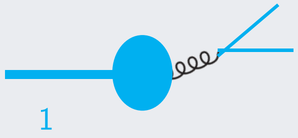

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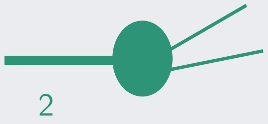

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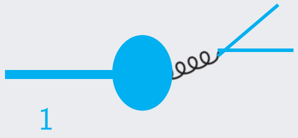

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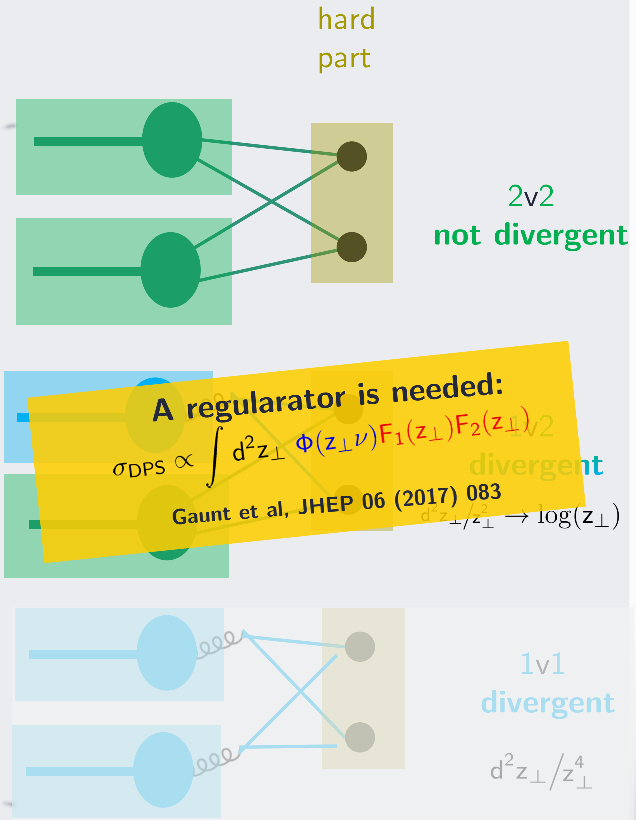

A regulator is needed:

$$\sigma_{DPS} \propto \int d^2z_\perp \, \Phi(z_\perp\nu) F_1(z_\perp) F_2(z_\perp)$$

Gaunt et al, JHEP 06 (2017) 083

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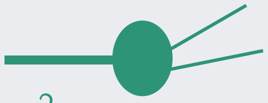
$$F(z_\perp) = F_{int}(z_\perp) + F_{sp}(z_\perp)$$ in principle we have the following terms:

The first term:

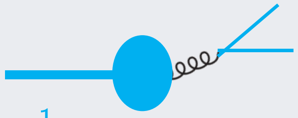
- it corresponds to:



- not divergent for $z_\perp \to 0$

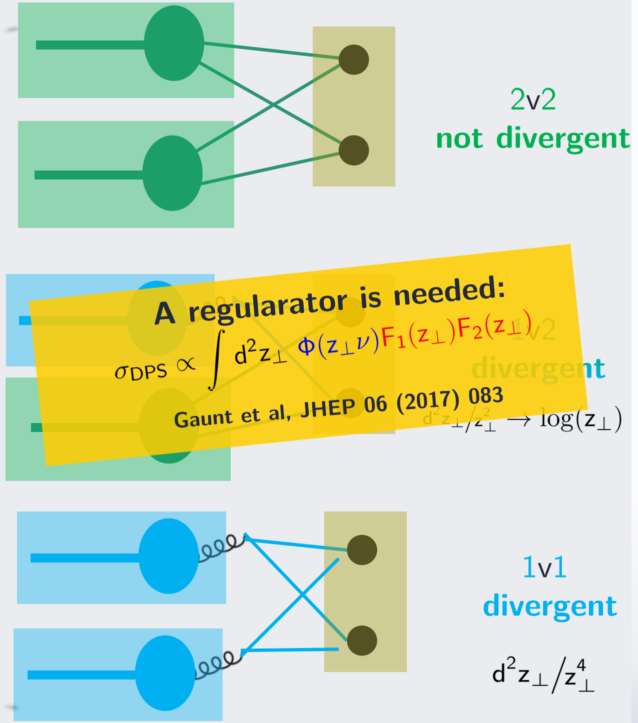
The second term:

- it corresponds to:



- divergent $1/z_\perp^2$

Diehl et al. JHEP 03 (2012) 089
Diehl et al. SciPost Phys. 7 (2019) 017
Diehl et al. JHEP 08 (2021) 040



A regulator is needed:

$$\sigma_{DPS} \propto \int d^2z_\perp \, \Phi(z_\perp\nu) F_1(z_\perp) F_2(z_\perp)$$

Gaunt et al, JHEP 06 (2017) 083

6 Double PDFs contributions:

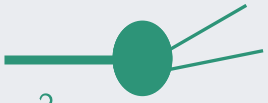
From pQCD analyses we can build the following decomposition:

$$F(z_\perp) = F_{int}(z_\perp) + F_{sp}(z_\perp)$$

in principle we have the following terms:

The **first** term:

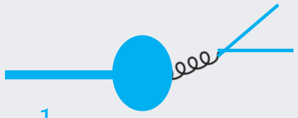
- it corresponds to:



- not divergent for $z_\perp \to 0$

The **second** term:

- it corresponds to:



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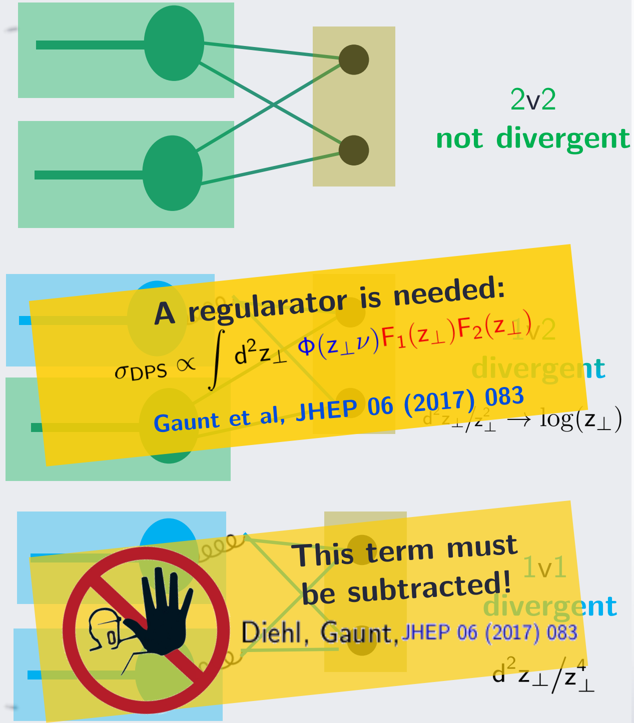
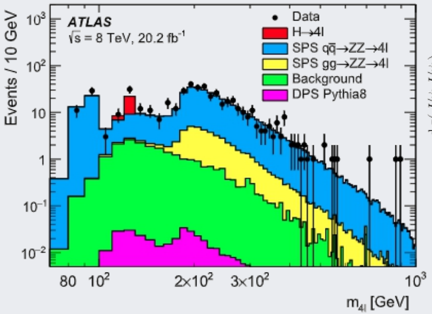


7 Some Data

Here some experimental and phenomenological analyses. Usually relevant final states are:

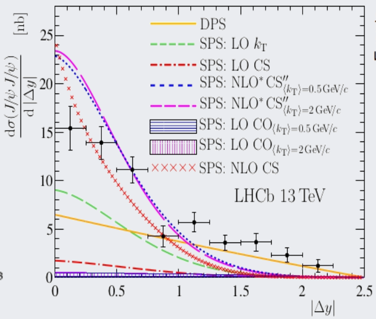
WW (same sign are very promising), W+J/Ψ ,J/Ψ+J/Ψ, W+jets, 4 jets, ϒ+3 jets, ZZ....

4l



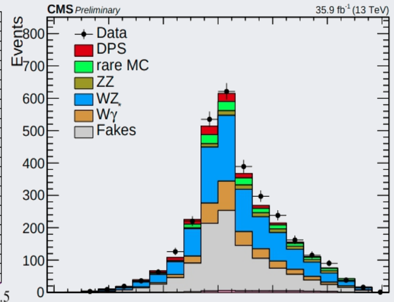
[ATLAS], PLB 790 (2019), 595-614

J/ Ψ pair

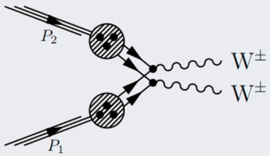


[LHCb] JHEP 06, 046 (2017)

Same sign WW



CMS PAS FSQ-16-009



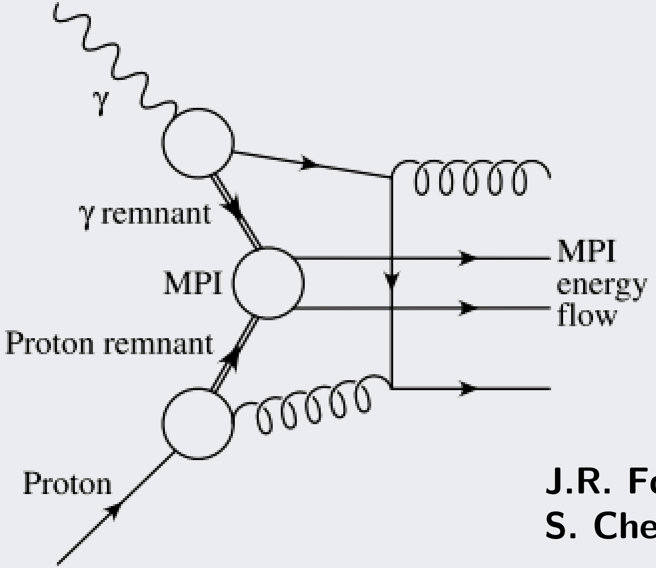
Gaunt et al, EPJC 69 (2010) 53
first pheno. predictions

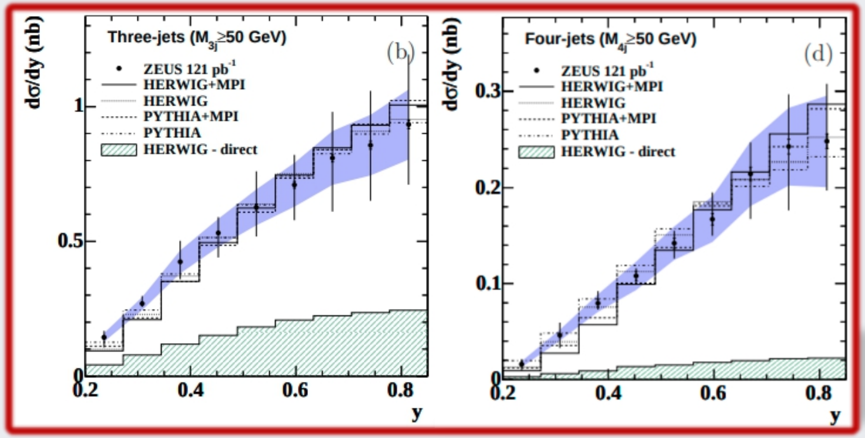
M.R. et al PRD 95 (2017) 3, 034040
Same sign WW= golden process to access double parton correlations!

T. Kasemets et al, JHEP 10 (2020) 214
Golden process to access spin correlations!

7 Some Data

We just mention here the importance of MPI for the **3,4 jets photo-production** at HERA:





J.R. Forshaw et al, Z phys. C 72, 637
S. Chekanov et al [ZEUS coll.], Nucl. Phys B 792,1 (2008)

8 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:
$pp \longrightarrow A(B) + X$

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

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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

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

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

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

8 Data and Effective Cross Section

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

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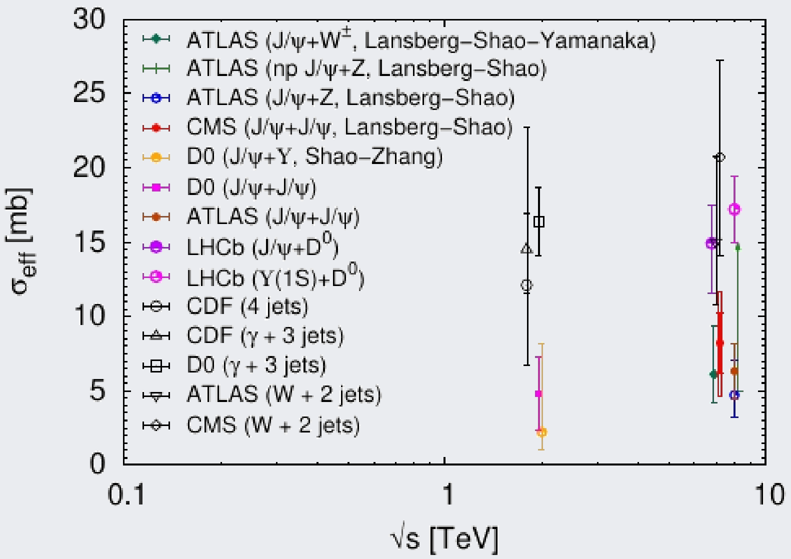

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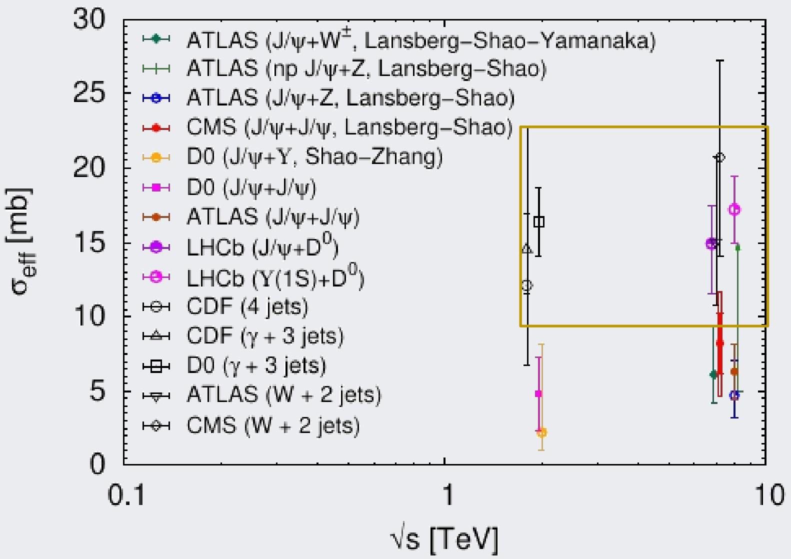

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MPI-2019 workshop

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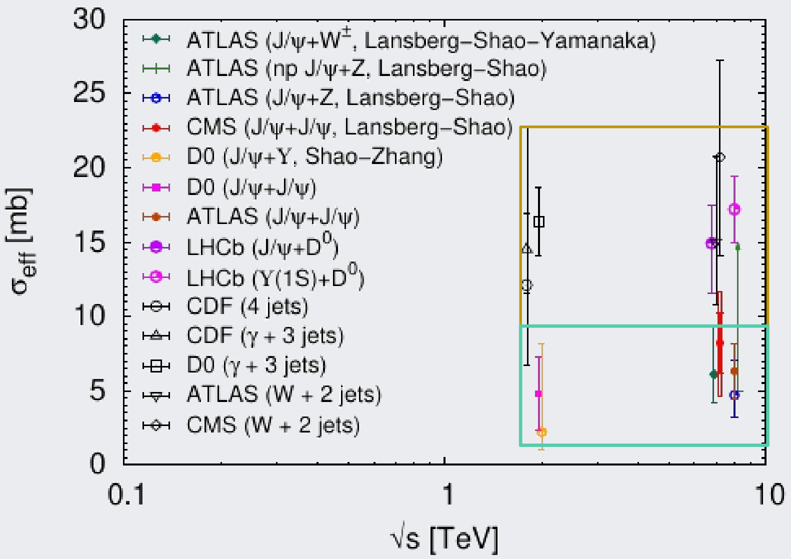
- SENSITIVE TO CORRELATIONS
- PROCESS DEPENDENT?
- SENSITIVE TO INFORMATION ON THE PROTON STRUCTURE?

As predicted by quark models

M.R. et al PLB 752,40 (2016)
M. Traini, M. R. et al, PLB 768, 270 (2017)
M. R. et al, Phys.Rev. D95 (2017) no.11, 114030



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

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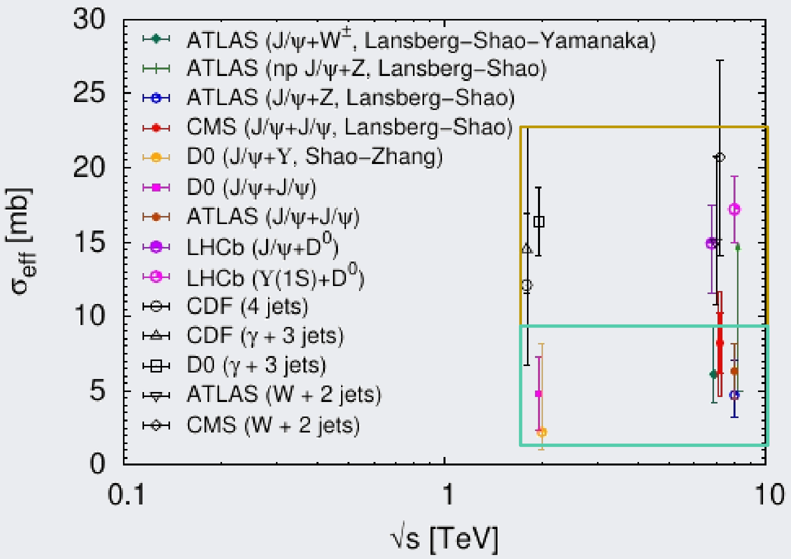
- SENSITIVE TO CORRELATIONS
- PROCESS DEPENDENT?
- SENSITIVE TO INFORMATION ON THE PROTON STRUCTURE? and phenomenological analyses

T. Kasemets et al, JHEP 10 (2020) 214
...



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

9 Clues from data?

If dPDFs factorize in terms of PDFs then

$$\sigma_{\text{eff}}^{-1} = \int \frac{d^2 k_\perp}{(2\pi)^2} \boxed{T(k_\perp)}^2$$

→ Effective form factor (EFF)

EFF can be formally defined as **FIRST MOMENT** of dPDF in momentum space

$$T(k_\perp) \propto \int dx_1 dx_2 \; \tilde{F}(x_1, x_2, k_\perp)$$

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$$\langle z_\perp^2 \rangle \propto \frac{d}{k_\perp dk_\perp} T(k_\perp) \Big|_{k_\perp = 0}$$

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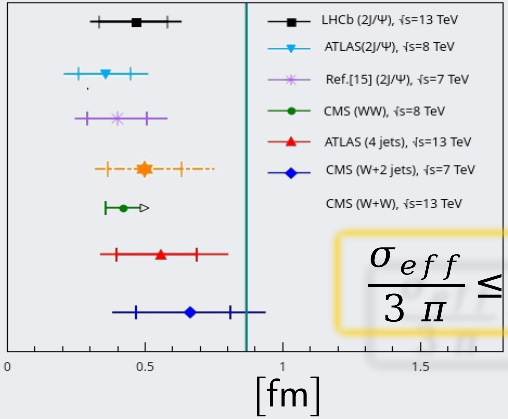
DPS processes:

The vertical line stands for the transverse proton radius



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

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

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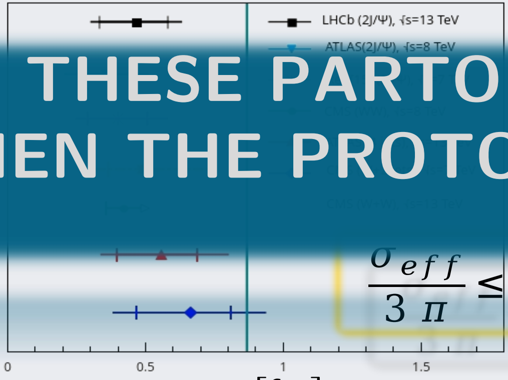

the transverse proton radius

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

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

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

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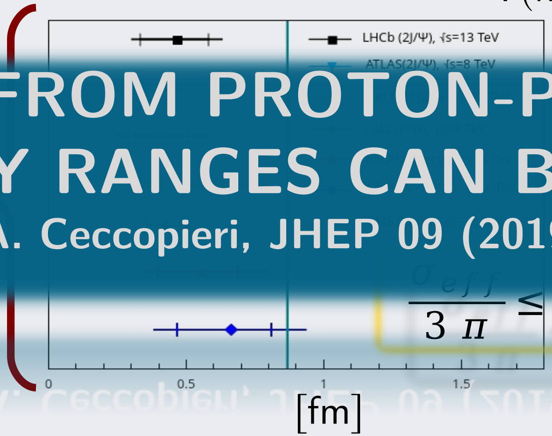


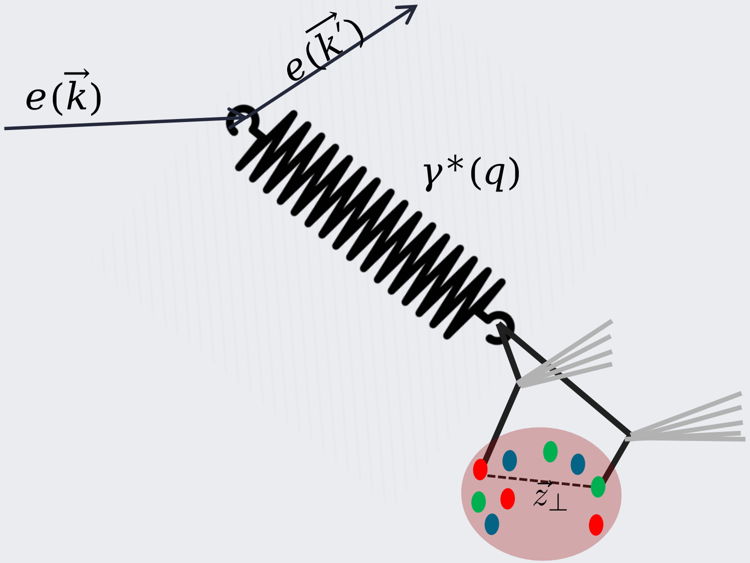
$$\frac{\sigma_{eff}}{3\pi} \le \langle z^2 \rangle \le \ldots$$

HOWEVER FROM PROTON-PROTON COLLISIONS ONLY RANGES CAN BE ACCESSED

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

10 New Idea: DPS via γ-p interaction

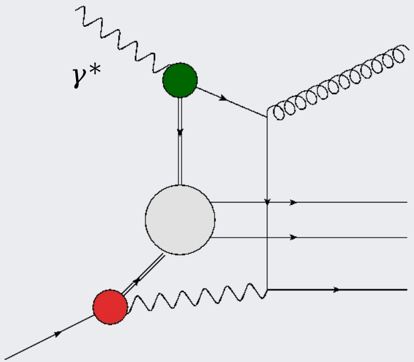
We consider the possibility offered by a DPS process involving a photon FLACTUATING in a quark-antiquark pair interacting with a proton:



M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

10 New Idea: DPS via γ-p interaction

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



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

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

$$\times \int dx_{p_a} dx_{\gamma_b} f_{a/p}(x_{p_a}) f_{b/\gamma}(x_{\gamma_b}) d\hat{\sigma}^{2j}_{ab}(x_{p_a}, x_{\gamma_b}) \quad \text{SPS*}$$

$$\times$$

$$\times \int dx_{p_c} dx_{\gamma_d} \underbrace{f_{c/p}(x_{p_c})}_{\text{p-PDF}} \underbrace{f_{d/\gamma}(x_{\gamma_d})}_{\gamma\text{-PDF}} d\hat{\sigma}^{2j}_{cd}(x_{p_c}, x_{\gamma_d}) \quad \text{SPS}$$

Flux Factor ($f_{\gamma/e}(y,Q^2)$): 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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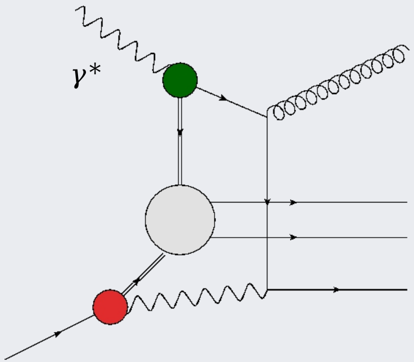

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$$\times \ldots) d\hat{\sigma}^{2j}_{ab}(x_{p_a}, x_{\gamma_b})$$ SPS*

×

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

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

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

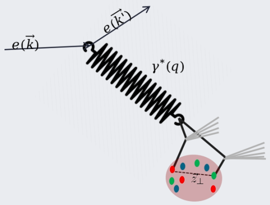
…2002))

The main quantity we have to evaluate is:

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

*Single Parton Scattering (SPS)

10 The γ-p effective cross section



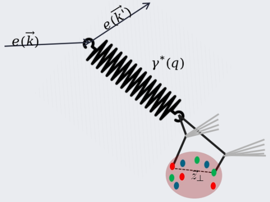
The expression of this quantity is very similar to the proton-proton collision case and can be formally derived by comparing the product of SPS cross sections and the DPS one obtained in **Gaunt, JHEP 01, 042 (2013)** and describing a DPS from a vector bosons splitting with given Q^2 virtuality

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, PRD 105 (2022) L011501

10 The γ-p effective cross section



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M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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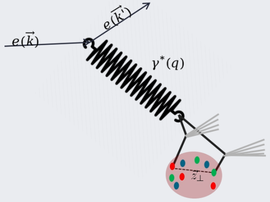

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This quantity is similar to an EFF

The full DPS cross section depends on the amplitude of the splitting photon in a $q\,\overline{q}$ 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, PRD 105 (2022) L011501

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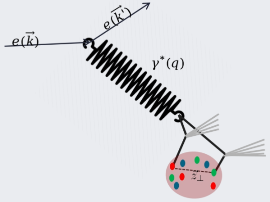

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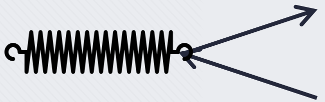
$$f^{\gamma}_{q,\bar{q}}(x, \tilde{k}_\perp; Q^2) = \int d^2k_{\perp,1}\, \psi^{\dagger\gamma}_{q\bar{q}}(x, \vec{k}_{\perp,1}; Q^2) \times \psi^{\gamma}_{q\bar{q}}(x, \vec{k}_{\perp,1} + \vec{k}_\perp; Q^2)$$



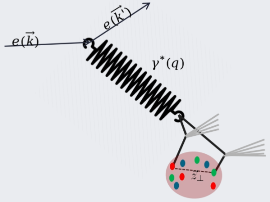
$q: (x, \vec{k}_{\perp,1})$

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

Similar definition of a meson dPDF

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

10 The γ-p effective cross section



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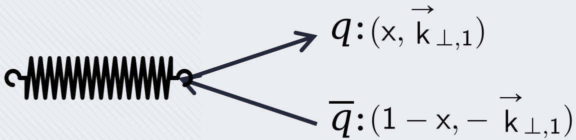
$$T_\gamma(k_\perp; Q^2) = \frac{\sum_q \int dx\, f^\gamma_{q,\bar{q}}(x, k_\perp; Q^2)}{\sum_q \int dx\, f^\gamma_{q,\bar{q}}(x, k_\perp = 0; Q^2)}$$



M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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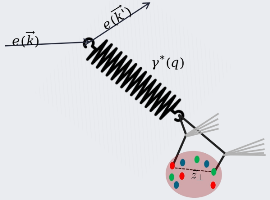


1 $$\left[\sigma_{\rm eff}^{\gamma p}(Q^2)\right]^{-1} = \int \frac{d^2k_\perp}{(2\pi^2)} T_p(k_\perp) T_\gamma(k_\perp; Q^2)$$

$T_p(k_\perp)$ proton EFF

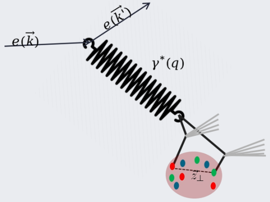
2

3 ψ_γ Photon WF

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

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

10 The γ-p effective cross section



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

2 $T_p(k_\perp)$ proton EFF

3 ψ^γ Photon WF

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

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

2) G2: $e^{-\alpha_2 k_\perp^2}$, $\alpha_2 = 2.56\ \text{GeV}^{-2} \Longrightarrow \sigma_{\text{eff}}^{pp} = 25\ \text{mb}$

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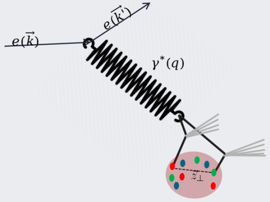

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3) S: $\left(1 + \frac{k_\perp^2}{m_g^2}\right)^{-4}$, $m_g^2 = 1.1\ \text{GeV}^2 \Longrightarrow \sigma_{\text{eff}}^{pp} = 30\ \text{mb}$

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

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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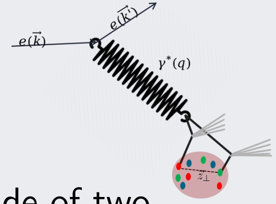

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For the photon W.F. use has been made of two choices representing two extreme cases:

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

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

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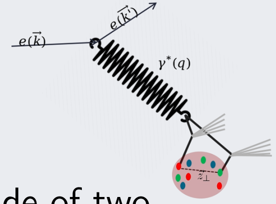

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2) Non-Pertubative (NP) effects (E.R.Arriola et al, PRD74,054023 (2006))

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

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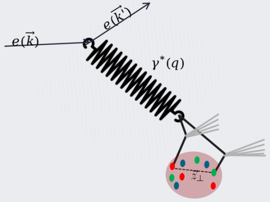

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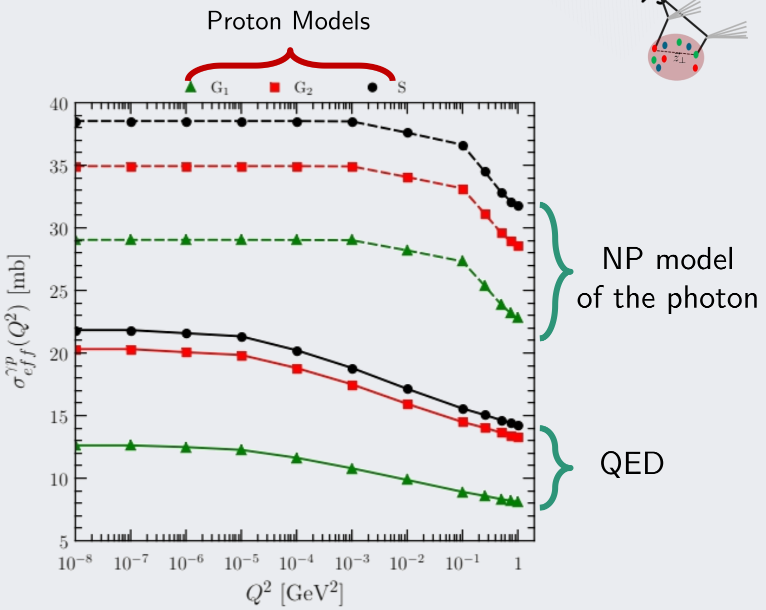

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

10 The 4 jet DPS cross section

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

$E_T^{jet} > 6\ \mathrm{GeV}$	Transverse energy of the jets
$\lvert\eta_{jet}\rvert < 2.4$	Pseudorapidity
$Q^2 < 1\ \mathrm{GeV}^2$	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 136 pb
S. Checkanov et al. (ZEUS), Nucl. Phys B792, 1 (2008)

10 The 4 jet DPS cross section

KINEMATICS:

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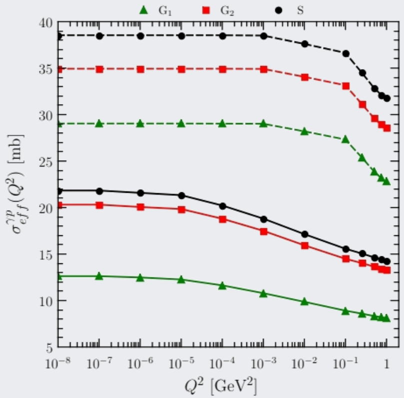
$|\eta_{jet}| < 2.4$

$Q^2 < 1\ \mathrm{GeV}^2$

$0.2 \leqslant y \leqslant 0.85$

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



M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

10 The 4 jet DPS cross section

KINEMATICS

$E_T^{jet} > 6$ Ge

$|\eta_{jet}| < 2.4$

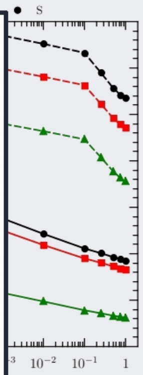
$Q^2 < 1$ GeV

$0.2 \leqslant y \leqslant 0$

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	35.1	18.6	53.7	40
	G_2	29.1	15.2	44.3	33
	S	26.4	13.7	40.1	30
QED	G_1	87.8	54.3	142.1	101
	G_2	54.3	33.4	87.7	65
	S	50.5	31.1	81.6	60

proton



10 The 4 jet DPS cross section

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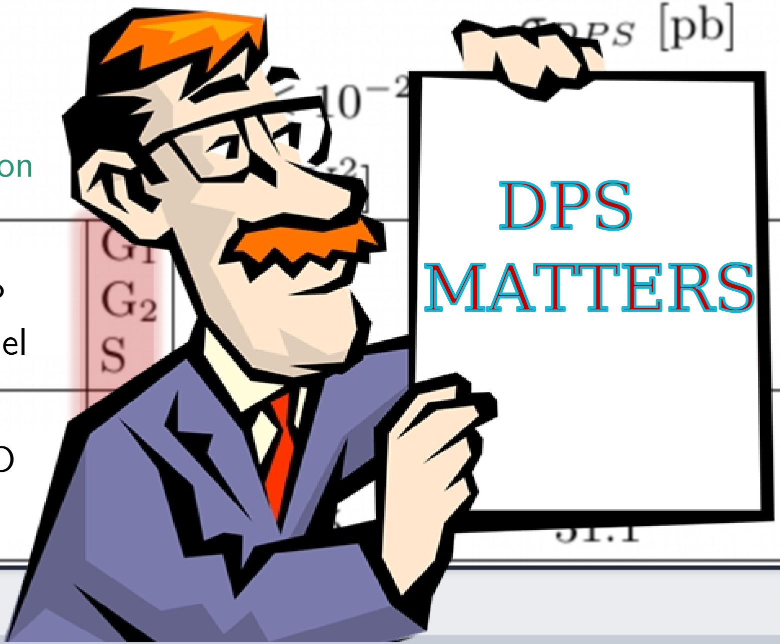
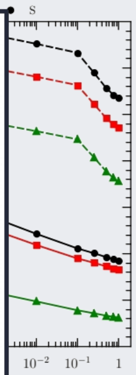
photon		σ_{DPS} [pb]	$Q^2 \leq 1$ [GeV^2]	$\frac{\sigma_{DPS}}{\sigma_{tot}}$ [%]
NP model	G_1		53.7	40
	G_2		44.3	33
	S		40.1	30
QED			142.1	101
			87.7	65
			81.6	60





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KINEMATICS

$E_T^{jet} > 6$ GeV

$|\eta_{jet}| < 2.4$

$Q^2 < 1$ GeV

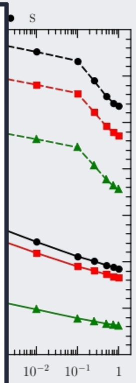
$0.2 \leqslant y \leqslant 0.$

photon

			σ_{DPS} [pb]		
			$Q^2 \leq 1$	$Q^2 \leq 1$ [GeV^2]	$\frac{\sigma_{DPS}}{\sigma_{tot}}$ [%]
NP model	G_1			3.7	40
	G_2			44.3	33
	S			40.1	30
QED	G_1			142.1	101
	G_2			87.7	65
	S	50.5		81.6	60

proton

What can we learn about the proton structure?



10 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:

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

$$\left[\sigma_{\text{eff}}^{\gamma p}(Q^2)\right]^{-1} = \int d^2 z_\perp \; \tilde{F}_2^p(z_\perp)\tilde{F}_2^{\gamma}(z_\perp; Q^2)$$

$$= \sum_n C_n(Q^2) \langle (z_\perp)^n \rangle_p$$

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

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

We could access for the first time the <u>mean transverse distance between partons in the proton</u>

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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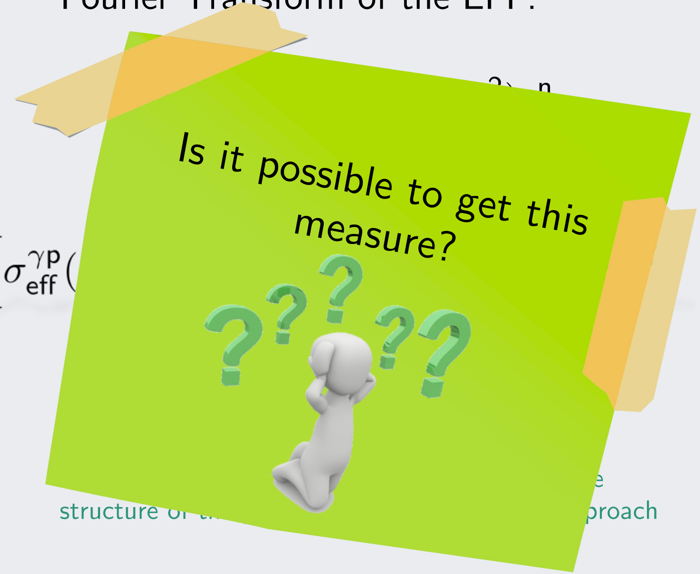

structure of th... ...proach

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

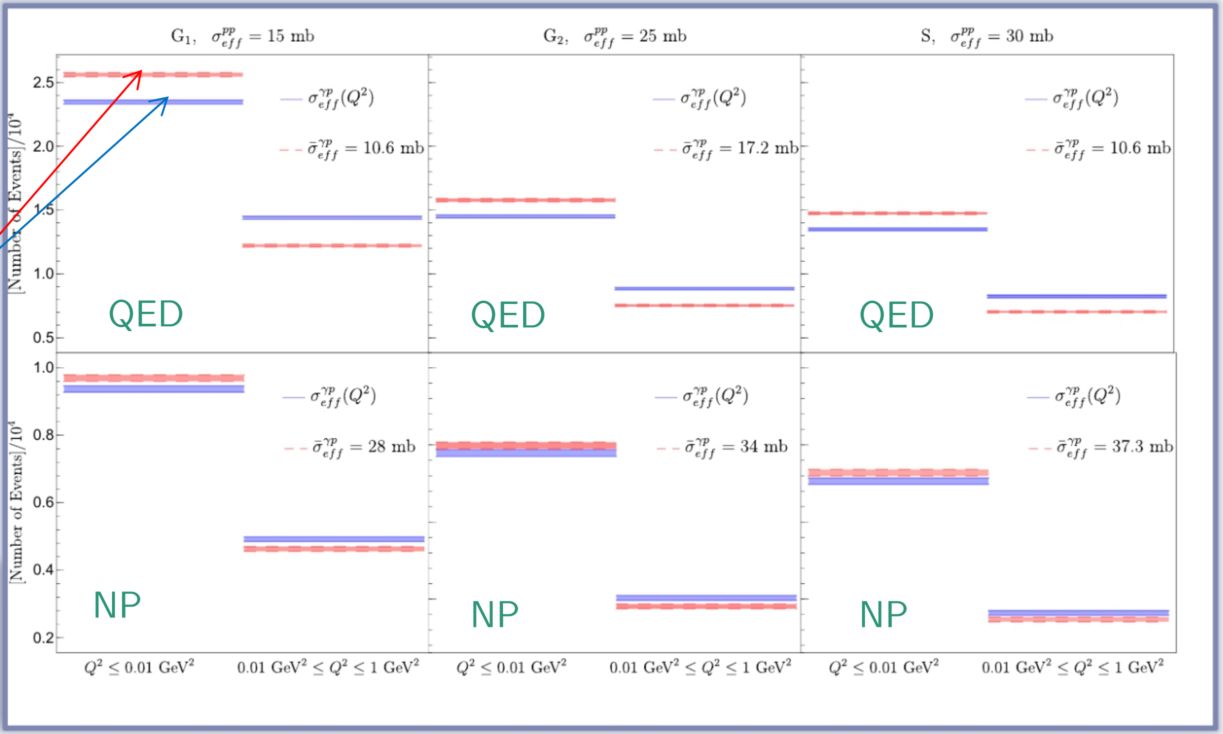
Proton →

photon ↓

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

effective X-section constant

Full effective X-section



11 DPS in pA collisions

A lot of effort (**slides from**):

- **Boris Blok**
- **Federico Alberto Ceccopieri**
- **Mark Strikman**
- **Massimiliano Alvioli**
- **Daniele Treleani**

References:

- **B. Blok and F. A. Ceccopieri, EPJC 80 (2020) 8, 762**
- **B. Blok and F. A. Ceccopieri, PRD 101 (2020) 9, 094029**
- **M. Alvioli and M. Strikman, PRC 100 (2019), no. 2, 024912**
- **M. Strikman and D. Treleani, PRL 88 (2002), 031801**
- **M. Alvioli, M. Azarkin, B. Blok and M . Strikman, EPJC 79 (2019), 482**

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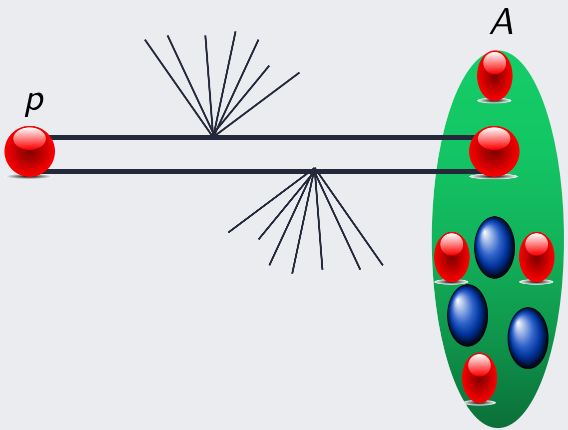
In this case we have two mechanisms that contribute:



DPS 1

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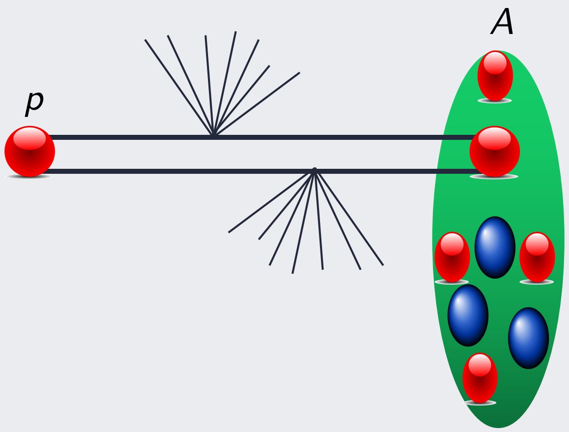
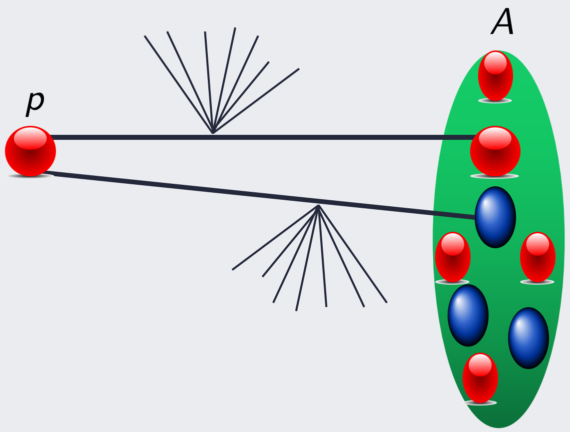


DPS 1



DPS 2

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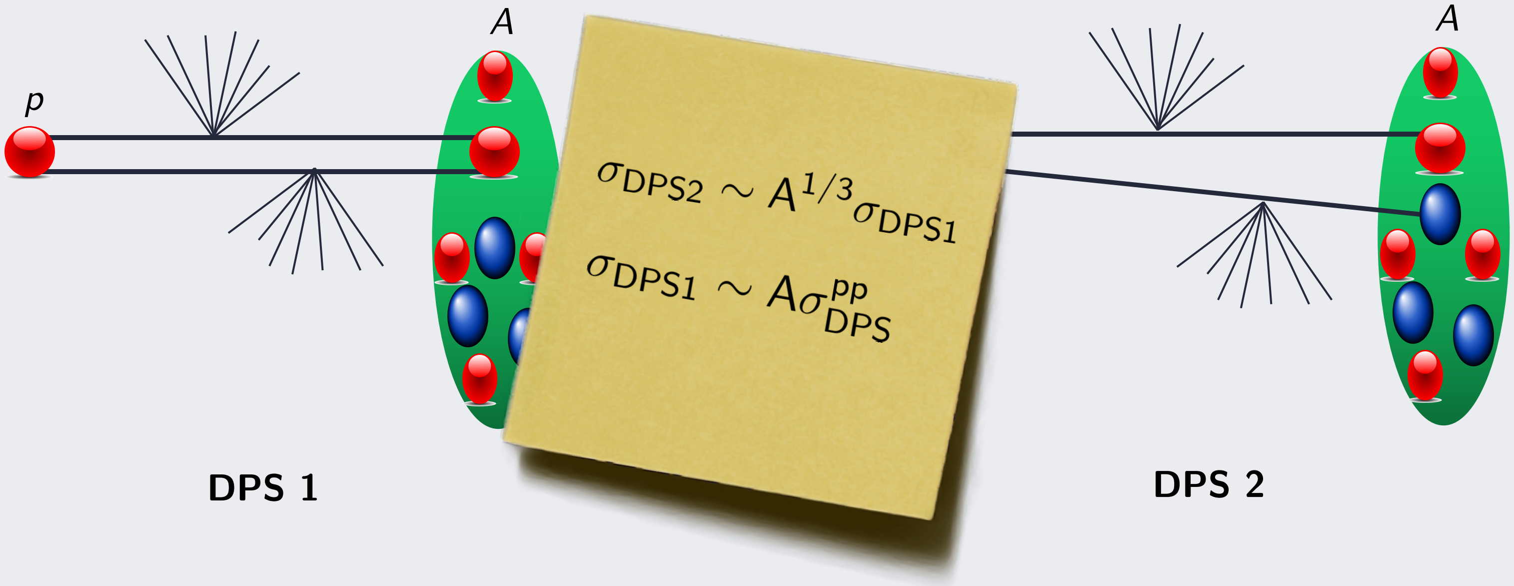

$$\sigma_{DPS2} \sim A^{1/3}\sigma_{DPS1}$$

$$\sigma_{DPS1} \sim A\sigma^{pp}_{DPS}$$

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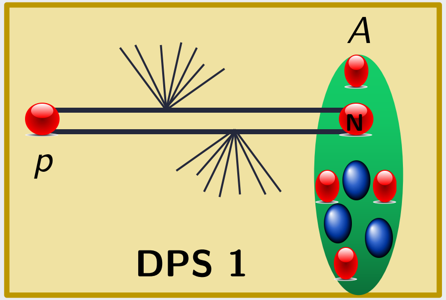
The DPS cross-section

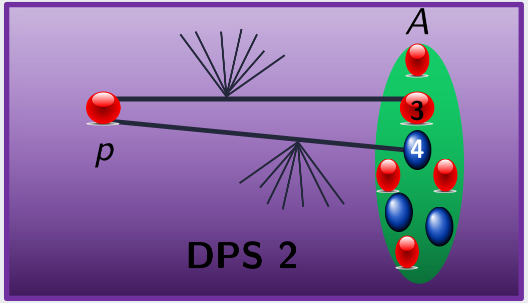
$$d\sigma^{ML}_{DPS} = \frac{m}{2}\sum_{i,j,k,l} d\hat{\sigma}^{M}_{ik} d\hat{\sigma}^{L}_{jl} \int d^2b_\perp\, F^{ij}_p(x_1, x_2, \vec{b}_\perp) \int d^2B \Bigg\{$$

$$\sum_{N=p,n} F^{kl}_N(x_3, x_4, \vec{b}_\perp)\bar{T}_N(B)$$



$$+$$

$$\sum_{N_3,N_4=p,n} f^k_{N_3/A}(x_3) f^l_{N_4/A}(x_4) \bar{T}_{N_3}(B)\bar{T}_{N_4}(B)$$



$$\Bigg\}$$

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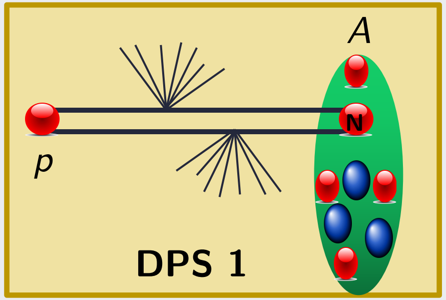
The ingredients:
- the nucleon dPDFs= PDF x PDF x $\tilde{T}(b_\perp)$

$$\int d^2 b_\perp \; \tilde{T}(b_\perp) = 1 \quad \int d^2 b_\perp \; \tilde{T}(b_\perp)^2 = 1/\sigma^{pp}_{eff}$$

$\sigma^{pp}_{eff} \sim 18 \pm 6$ mb (average ATLAS and CMS for W production)

$$\sum_{N=p,n} \boxed{F^{kl}_N(x_3, x_4, \vec{b}_\perp)} \bar{T}_N(B)$$



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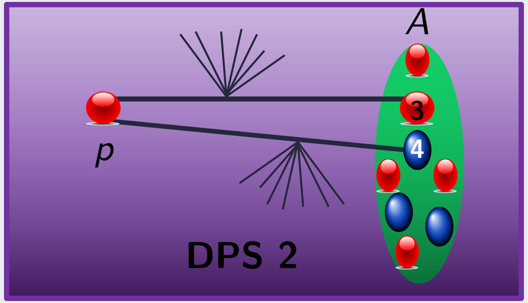

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- the contribution of nucleon to the nuclear PDF

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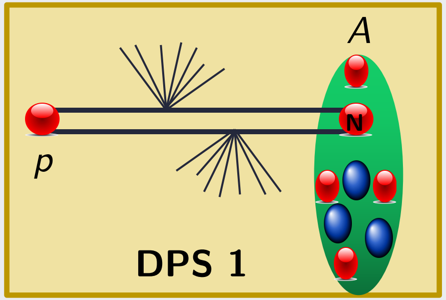

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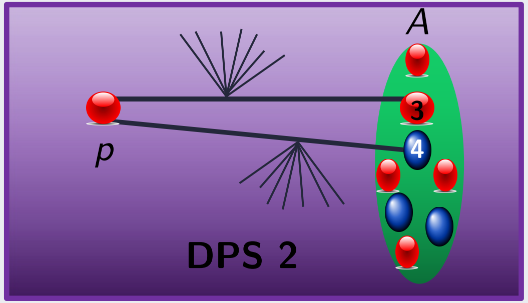

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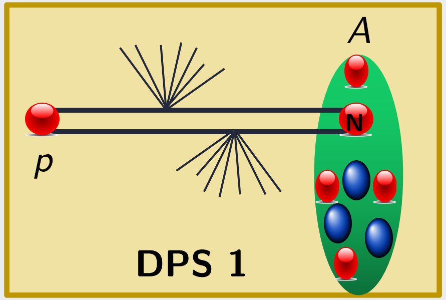

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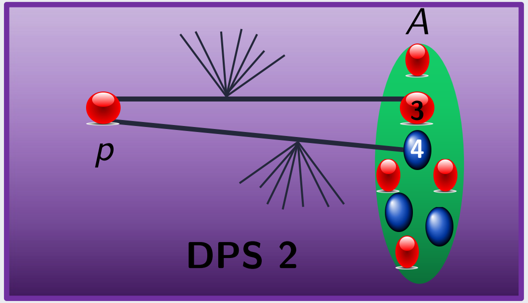

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$$\sigma^{pp}_{eff} \sim 18 \pm 6 \text{ mb}$$

- the contribution of nucleon to the nuclear PDF

- the thickness function as a function of the impact parameter *B*:

$$\bar{T}(\vec{b}_\perp + \vec{B}) \sim \bar{T}(\vec{B})$$

$$\bar{T}_N(B) = \int dz\, \underbrace{\rho_N}(\sqrt{B^2+z^2})$$

Wood-Saxon distribution for pb normalized to A

11 DPS in pA collisions

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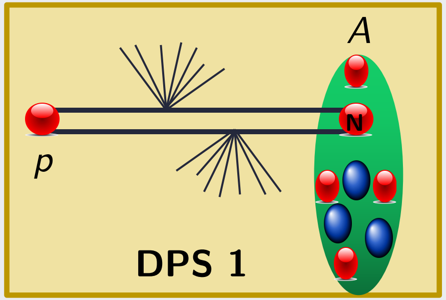
DPS1 LINEAR IN $\bar{T}(B)$

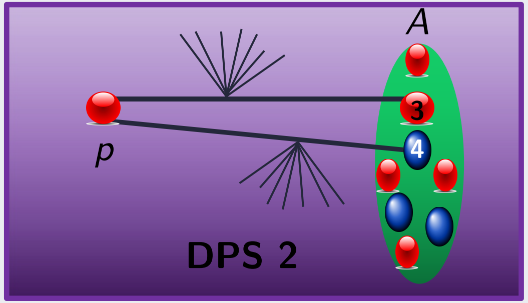
$$\sum_{N=p,n} F^{kl}_{N}(x_3, x_4, \vec{b}_\perp) \bar{T}_N(B)$$



$$+$$

$$\sum_{N_3,N_4=p,n} f^{k}_{N_3/A}(x_3) f^{l}_{N_4/A}(x_4) \bar{T}_{N_3}(B) \bar{T}_{N_4}(B)$$

$$\Bigg\}$$



DPS2 QUADRATIC IN $\bar{T}(B)$

11 DPS in pA collisions

A lot of effort (slides from):
- Boris Blok
- Federico Alberto Ceccopieri
- Mark Strikman
- Massimiliano Alvioli
- Daniele Treleani

The DPS cross-section

$$d\sigma^{ML}_{DPS} = \frac{m}{2}\sum_{i,j,k,l} d\hat{\sigma}^{M}_{ik} d\hat{\sigma}^{L}_{jl} \int d^2b_\perp \, F^{ij}_{p}(x_1, x_2, \vec{b}_\perp) \int d^2B \Big\{$$

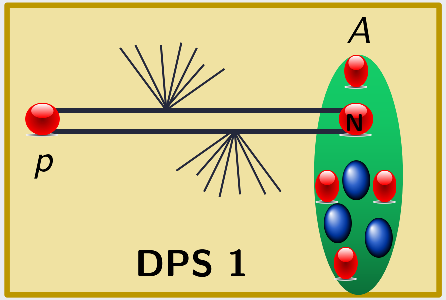
DPS1 LINEAR IN $\bar{T}(B)$

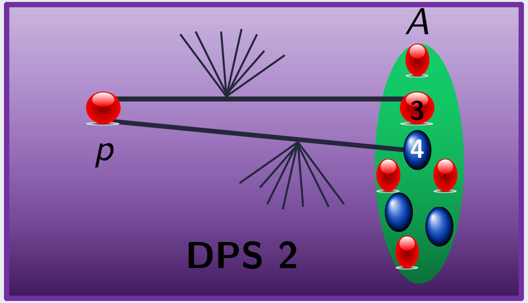
$$\sum_{N_3,N_4=p,n} f^{k}_{N_3}$$

DPS2 QUADRATIC IN $\bar{T}(B)$

Experimental techniques have been developed to estimate the **centrality (B) of the pA or AA** collisions.
In principle it is possible to separate these contributions!

LHCb, PRL 125 (2020),21, 212001





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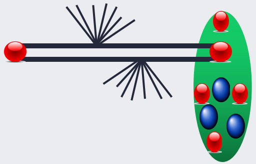

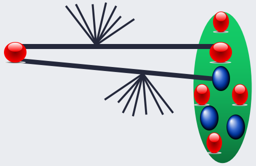

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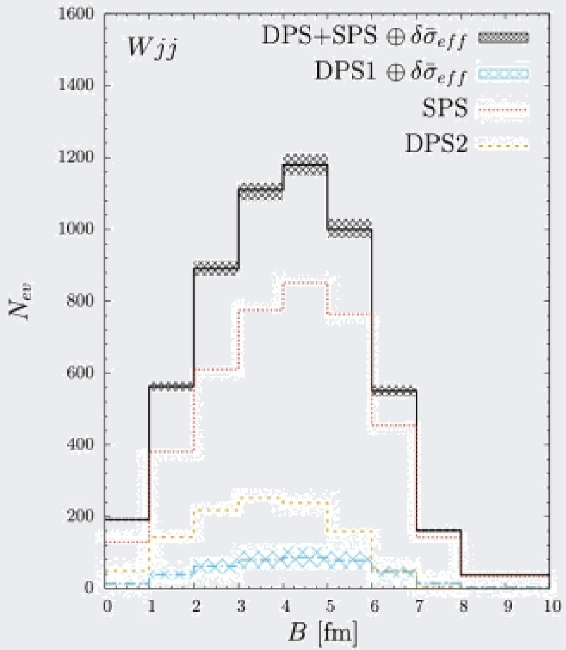
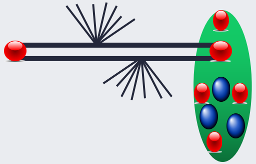
W+di-jets

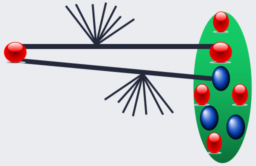
σ^{Wjj}	$p_T^j > 20$ GeV [nb]	$p_T^j > 25$ GeV [nb]	$p_T^j > 30$ GeV [nb]
DPS1	19 ± 6	8 ± 3	4 ± 2
DPS2	49	22	11
SPS	81	57	41
Tot	149 ± 6	87 ± 3	56 ± 2



- SPS dominant
- DPS2 bigger then DPS1 has expected

11 DPS in pA collisions





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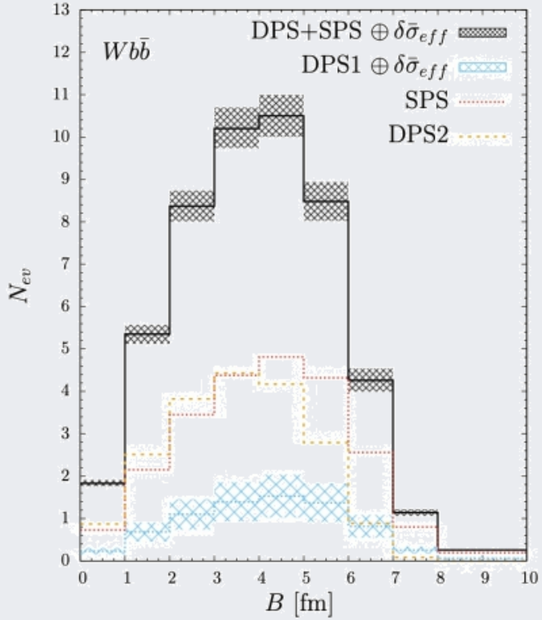
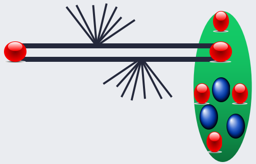
W+2 b-jets

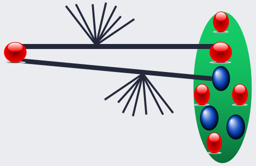
$\sigma^{Wb\bar{b}}$	$p_T^b > 20$ GeV [pb]	$p_T^b > 25$ GeV [pb]	$p_T^b > 30$ GeV [pb]
DPS1	74 ± 25	35 ± 12	18 ± 6
DPS2	196	92	48
SPS	234	158	114
Tot	504 ± 25	285 ± 12	180 ± 6



- for 20< p_T < 25 GeV the DPS is bigger then SPS
- also for B< 4 fm

11 DPS in pA collisions





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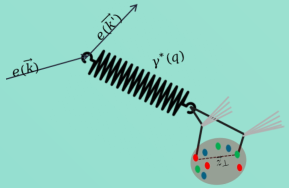
Zjj	DPS1 (pb)	DPS2 (pb)	SPS (pb)
$p_T^{j_1,j_2} > 20, 20$ GeV	2971	7814	15,940
$p_T^{j_1,j_2} > 25, 25$ GeV	1270	3341	11,024
$p_T^{j_1,j_2} > 30, 30$ GeV	621	1632	8030

$2b2j$	DPS1 (μb)	DPS2 (μb)	SPS (μb)	Sum (μb)
$p_T^{b,j} > 20$ GeV	2.2	6.2	13.0	21.4
$p_T^{b,j} > 25$ GeV	0.4	1.2	4.7	6.4
$p_T^{b,j} > 30$ GeV	0.1	0.3	1.9	2.3

$4j$	DPS1 (μb)	DPS2 (μb)	SPS (μb)	Sum (μb)
$p_T^{j_3,j_4} > 20$ GeV	26.0	72.2	170.9	269.2
$p_T^{j_3,j_4} > 25$ GeV	10.8	30.2	92.9	133.9
$p_T^{j_3,j_4} > 30$ GeV	5.1	14.3	51.4	70.9

CONCLUSIONS (?)



1) Properties of dPDF are better understood BUT could we go forward (relation to GPDs, TMDs or mechanical properties)?

2) Can we try to add non perturbative correlations in MC?

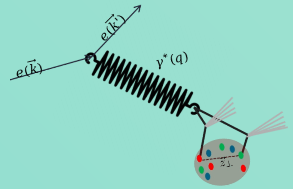
3) Can we observe DPS at EIC, also using quarkonium production?

4) Also DPS with nuclear targets at the EIC? We have the technology for light nuclei for which realistic calculations can be performed.

5) Moreover, DPS in ultra-peripheral AA collisions ?

6) many others......

CONCLUSIONS (?)

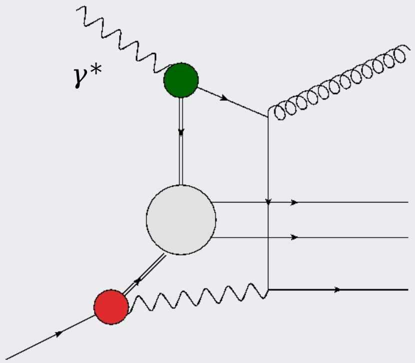


We are collecting ideas, feelings and impressions for a possible dedicated workshop on DPS where all these topics can be discussed merging these communities!

If you are interested any suggestion is welcome!

6 New Idea: DPS via γ-p interaction

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))**



In

1) **G. Abbiend et al, Phys. Commun 67, 465 (1992)**
2) **J.R. Forshaw et al, Z. Phys. C 72, 637 (1992)**

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

WE EVALUATE THE DPS CONTRIBUTION TO THIS PROCESS

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:

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

$$\left[\sigma_{eff}^{\gamma p}(Q^2)\right]^{-1} = \int d^2z_\perp \, \tilde{F}_2^{p}(z_\perp)\tilde{F}_2^{\gamma}(z_\perp; Q^2)$$

$$= \sum_n C_n(Q^2)\langle (z_\perp)^n \rangle_p$$

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

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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$$= \sum_n C_n(Q^2) \langle (z_\perp)^n \rangle_p$$

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

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

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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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, PRD 105 (2022) L011501

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$$= \sum_n C_n(Q^2) \langle z_\perp^n \rangle_p$$

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

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

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

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

M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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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 luminosity to distinguish the two cases

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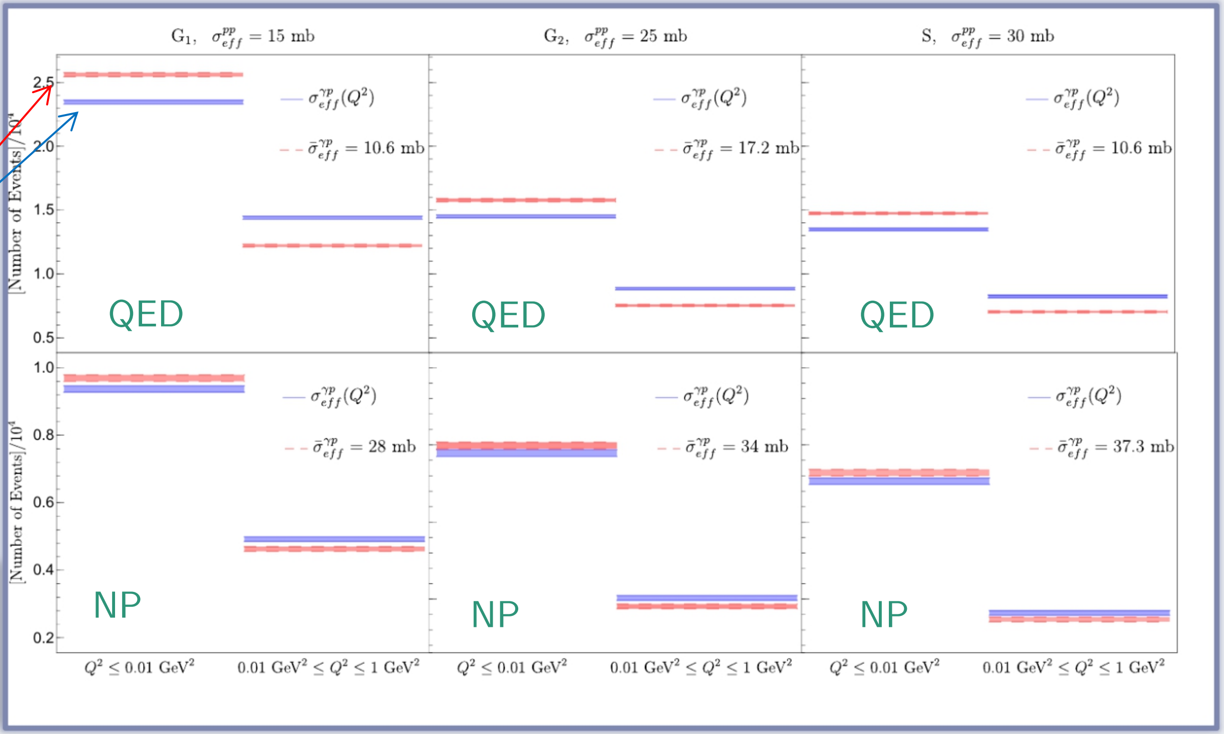
6 The effective cross section: a key for the proton structure

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



6 Relativistic effects

- Almost model independence
- Almost scale independence

SUGGEST: *parametrize the impact of Melosh effects in dPDFs to encode* ***some*** *general correlations between x_i and $k_\perp$*

$$\overbrace{F_{ij}(x_1, x_2, k_\perp; Q^2)}^{\text{pheno}} = \underbrace{q_i(x_1; Q^2) q_j(x_2; Q^2)}_{\text{phenomenology from PDFs}} \overbrace{\theta(1 - x_1 - x_2)}^{\text{good support}} \underbrace{f(x_1, x_2, Q^2)}_{\text{sum rules}} \overbrace{R(x_1, x_2, k_\perp)}^{\text{Melosh effects}} F(k_\perp) \}$$

correlations!

To be modeled: CQMs, GPDs...

$$R(x_1, x_2, k_\perp) \equiv \frac{F^{HO}_{[L]}(x_1, x_2, k_\perp; Q^2)}{F^{HO}_{[l]}(x_1, x_2, k_\perp; Q^2)} = w(k_\perp) \left[x_1 x_2\right]^{t(k_\perp)} (1 - x_2 - x_2)^{|x_1 - x_2| e(k_\perp)} e^{-(1 - x_1 - x_2) h(k_\perp)}$$

6 Relativistic effects

Let us consider the LF expression of the dPDF with its non relativistic (NR) limit:

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

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

$f(\vec{k}_1, \vec{k}_2, k_\perp)$ = product of canonical w.f. (momentum space)

Melosh Operators!

They rotate canonical spin into LF ones

In the small x region, the main difference between $F_{[I]}$ and $F_{[L]}$ is given by the Melosh operators.

More on the LO QED photon EFF and effective x-section

1) Since the photon starts to be a **small** system, the effective-form factor must be similar to a constant (to be properly related to the FT of the probability distribution)

2) as a conseguence, the effective cross section should be of the same order of that for pp collissions.

3) why this two effective x-section are similar if the system are different?

4) a possible explanation can be obtained by considering:

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

(proven for pp collisions)

Inverting this inequality one gets:

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

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$$\pi \langle b^2 \rangle \leq \sigma_{\rm eff}^{\rm pp} \leq 3\pi \langle b^2 \rangle \Longrightarrow$$

(proven for pp collisions)

therefore, similar effective x-sections can be related to different **distances,** i.e. **different gemetrical structures!**

(Proton) Model Independent conlcusions

1) in arXiv:2103.1340 we show that high virtual behavior of the effective cross sections correctly follows the result **in J.R. Gaunt JHEP 01, 042 (2013)**, i.e.:

$$\sigma_{eff}^{\gamma p}(Q^2 \to \infty) = \sigma_{1v2}^{pp} = \left[\int \frac{d^2 k_\perp}{(2\pi)^2} T_p(k_\perp) \right]^{-1}$$

2) In Ref. **M.Rinaldi and F.A: Ceccopieri JHEP 09, 097 (2019),** we prove, in a general framework:

$$\frac{\sigma_{\mathrm{eff,2v1}}}{2\pi} \leq \langle b^2 \rangle \leq \frac{2\ \sigma_{\mathrm{eff,2v1}}}{\pi}$$

therefore, by inverting this relation one gets:

$$\frac{\pi}{2}\langle b^2 \rangle \leq \sigma_{eff}^{\gamma p}(Q^2 \to \infty) \leq 2\pi \langle b^2 \rangle$$

(Proton) Model Independent conlcusions

$$\frac{\pi}{2}\langle b^2\rangle \leq \sigma_{eff}^{\gamma p}(Q^2 \to \infty) \leq 2\pi\langle b^2\rangle$$

3) in arXiv:2103.1340, for the moment being we considered proton model producing a (2v2) effective cross section of 15-30 mb (**in new analysis we can relax this condition**).
Now in **M. Rinaldi and F. A. Ceccopieri PRD 97 (2018) 7, 071501**, we prove:

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

combining everything:

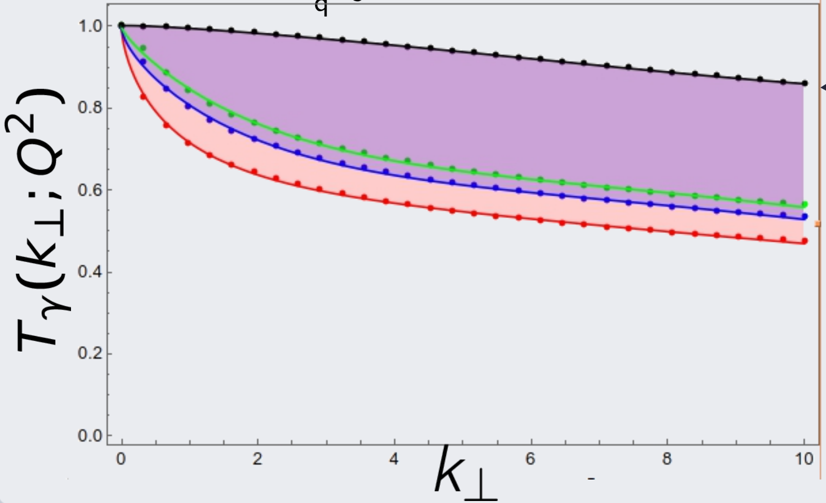
$$\frac{\sigma_{eff}^{pp}}{6} \leq \sigma_{eff}^{\gamma p}(Q^2 \to \infty) \leq 2\sigma_{eff}^{pp}$$

VERIFIED!!

More on the LO QED photon EFF and effective x-section

$$T_\gamma(k_\perp;Q^2) = \frac{\sum_q \int dx\, f^\gamma_{q,\bar q}(x,k_\perp;Q^2)}{\sum_q \int dx\, f^\gamma_{q,\bar q}(x,k_\perp=0;Q^2)}$$

$$f^\gamma_{q,\bar q}(x,\tilde k_\perp;Q^2) = \int d^2k_{\perp,1}\, \psi^{\dagger\gamma}_{q\bar q}(x,\vec k_{\perp,1};Q^2) \times \psi^\gamma_{q\bar q}(x,\vec k_{\perp,1}+\vec k_\perp;Q^2)$$



$Q^2 = 10\ \mathrm{GeV}^2$

$\langle z_\perp^2\rangle_\gamma \propto \frac{1}{Q^2}$

Small system ⇒ EFF **SLOWLY** decreasing:

$$T_\gamma(k_\perp;Q^2 >> 1\ \mathrm{GeV}^2) \sim 1$$

More on the LO QED photon EFF and effective x-section

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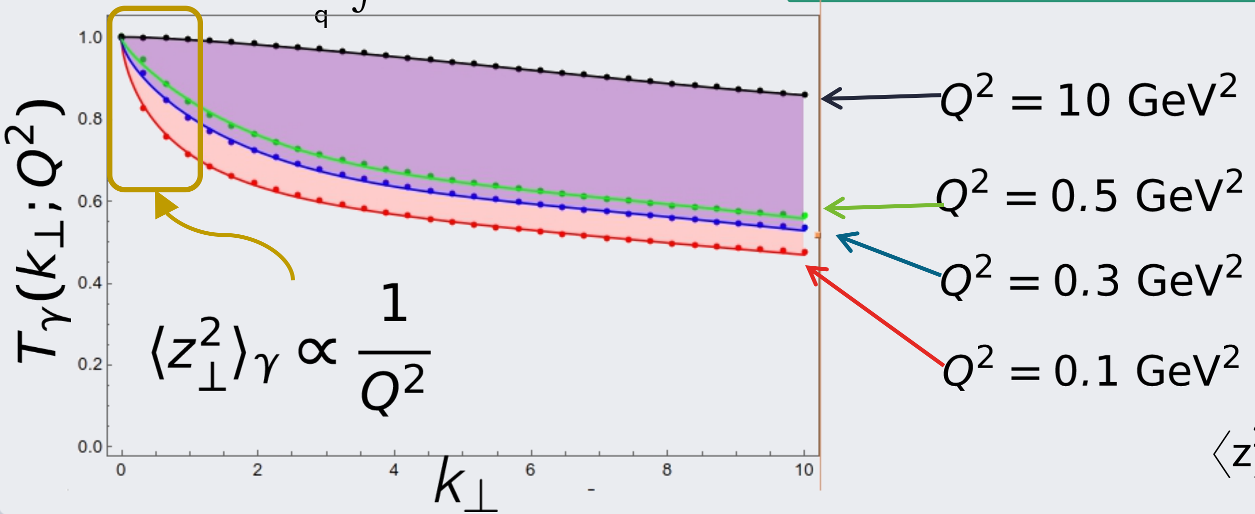
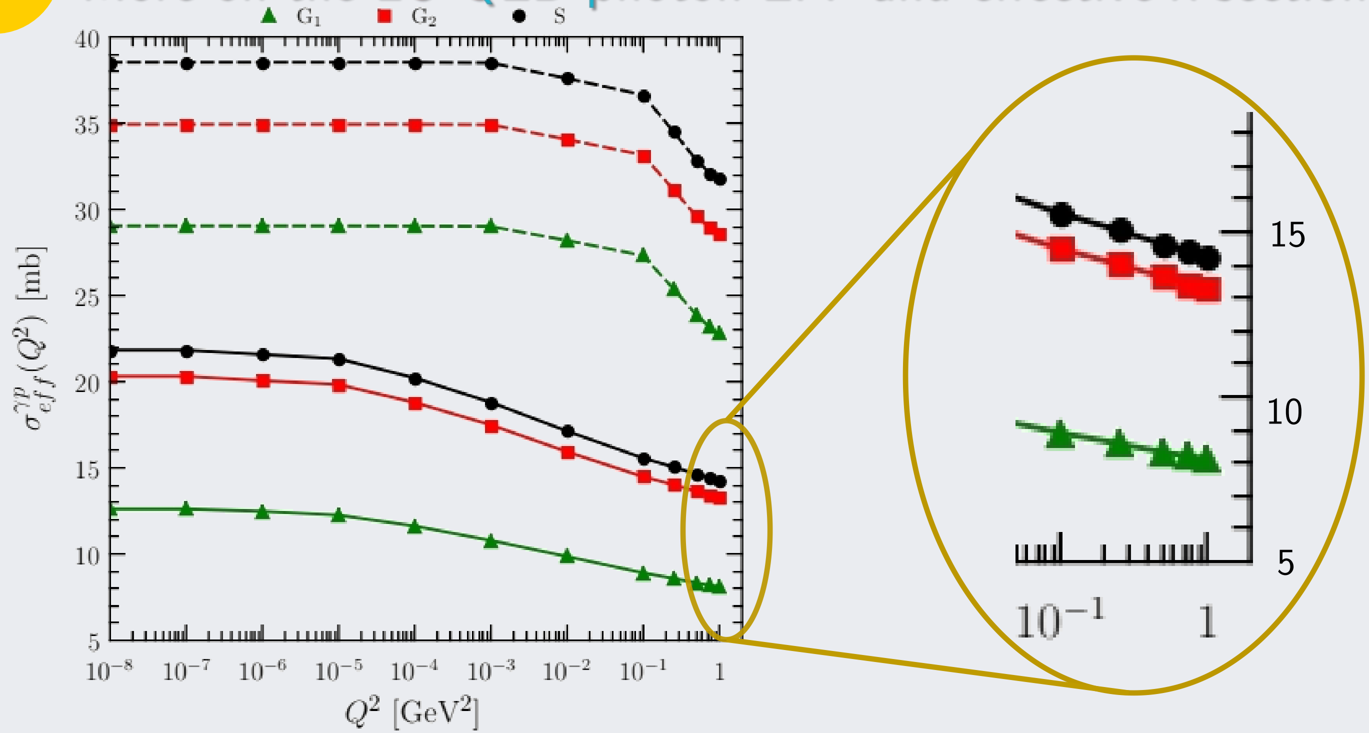


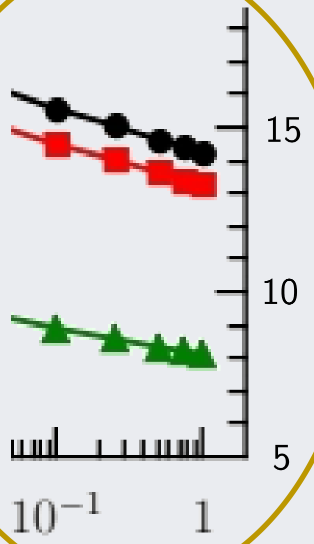
$$\langle z_\perp^2\rangle \propto \frac{d}{k_\perp dk_\perp} T(k_\perp)\Big|_{k_\perp=0}$$

More on the LO QED photon EFF and effective x-section



~ 30/2 mb
~ 25/2 mb
~ 15/2 mb

More on the LO QED photon EFF and effective x-section



$\sim 30/2$ mb
$\sim 25/2$ mb
$\sim 15/2$ mb

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

$$[\sigma_{eff}^{\gamma p}(Q^2)]^{-1} \underset{Q^2>>1}{\sim} \int \frac{d^2 k_\perp}{(2\pi)^2} T_p(k_\perp) \times 1$$

For the proton models we have used:

$$\int \frac{d^2 k_\perp}{(2\pi)^2} T_p(k_\perp) \sim 2 \int \frac{d^2 k_\perp}{(2\pi)^2} T_p(k_\perp)^2$$

$$\sigma_{eff}^{\gamma p}(Q^2 >> 1 \text{ GeV}^2) \sim \sigma_{eff}^{pp}/2$$

1 Double PDFs (intrinsic) of the proton

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

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

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DPD → SUM RULES AVAILABLE

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1st uncorrelated scenario

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DPD

→ SUM RULES AVAILABLE

→ MODELS BASED ON SUM RULES

1 Double PDFs (intrinsic) of the proton

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

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

DPD

- 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 (the last two)

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

1 Double PDFs (intrinsic) of the proton

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

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

DPD

- 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

PERTURBATIVE CORRELATIONS

1 Double PDFs (intrinsic) of the proton

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

1st uncorrelated scenario

$$F_{ik}(x_1, x_2, \vec{z}_\perp) \sim g(x_1, x_2)\tilde{T}(\vec{z}_\perp)$$

DPD

- 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

PERTURBATIVE CORRELATIONS

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

$$F_{ik}(x_1, x_2, \vec{z}_\perp) \sim g(x_1, x_2)\tilde{T}(\vec{z}_\perp)$$

$\tilde{T}(\vec{z}_\perp)$ → 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

$g(x_1, x_2)$ — DPD:

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

(last two: 2nd uncorrelated scenario)

PERTURBATIVE CORRELATIONS

1 Double PDFs (intrinsic) of the proton

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

$$F_{ik}(x_1, x_2, \vec{z}_\perp) \sim g(x_1, x_2)\tilde{T}(\vec{z}_\perp)$$

$\tilde{T}(\vec{z}_\perp)$:

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

$g(x_1, x_2)$ — DPD:

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

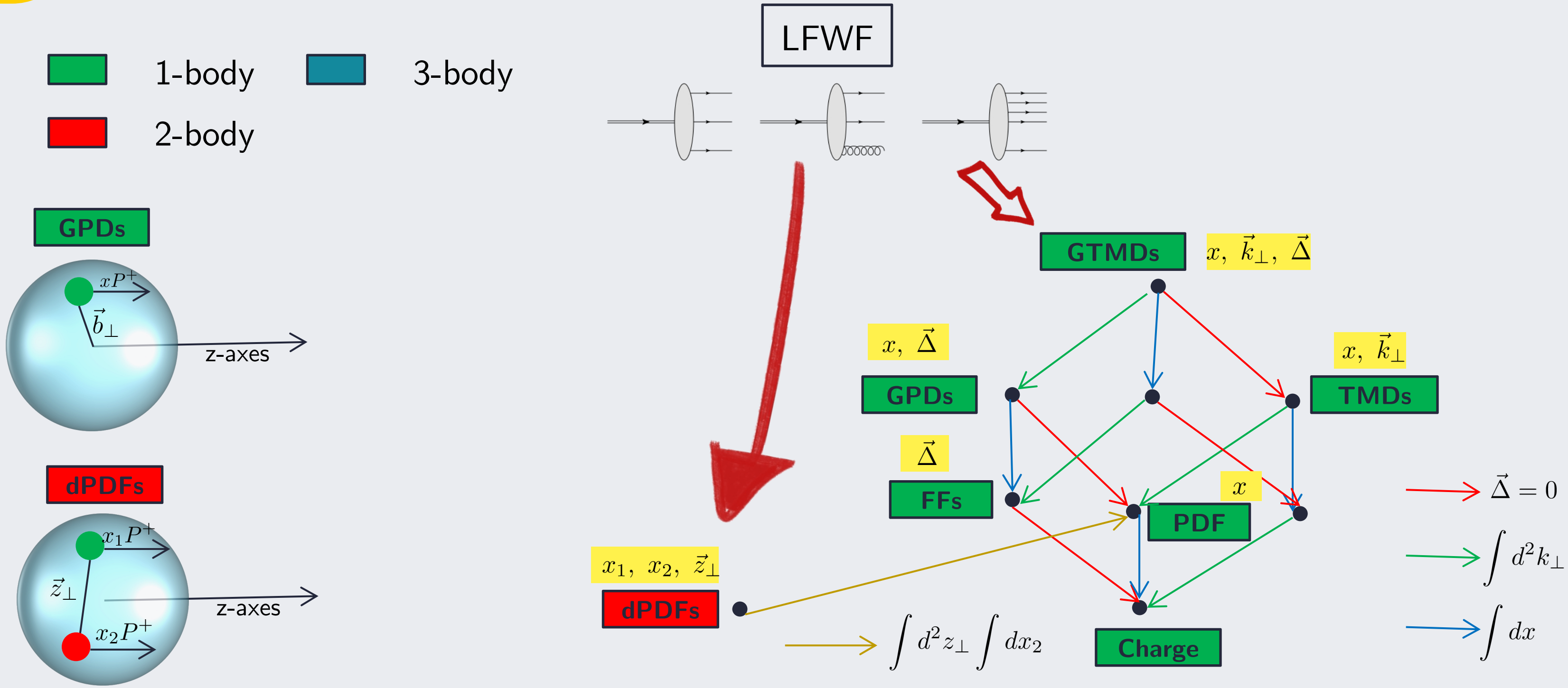
(last two: 2nd uncorrelated scenario)

PERTURBATIVE CORRELATIONS

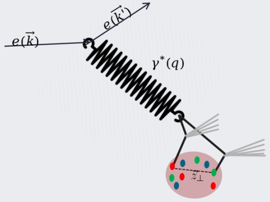
F_{ik}: Constituent quark models used to grasp basic non perturbative feature

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

1 Multidimensional Pictures of Hadron



6 The γ-p effective cross section



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

INGREDIENTS OF THE CALCULATIONS

1 $T_p(k_\perp)$ proton EFF

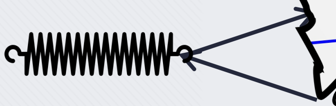
2 ψ^γ Photon WF

3

$$[\sigma_{\text{eff}}^{\gamma p}(Q^2)]^{-1} = \int \frac{d\ldots}{(2\ldots} \ldots \int dx\, f_{q,\bar{q}}^{\gamma}(x, k_\perp; Q^2)$$

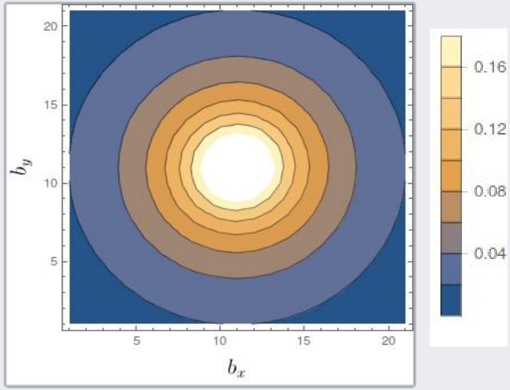
$$\ldots dx\, f_{q,\bar{q}}^{\gamma}(x, k_\perp = 0; Q^2)$$

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



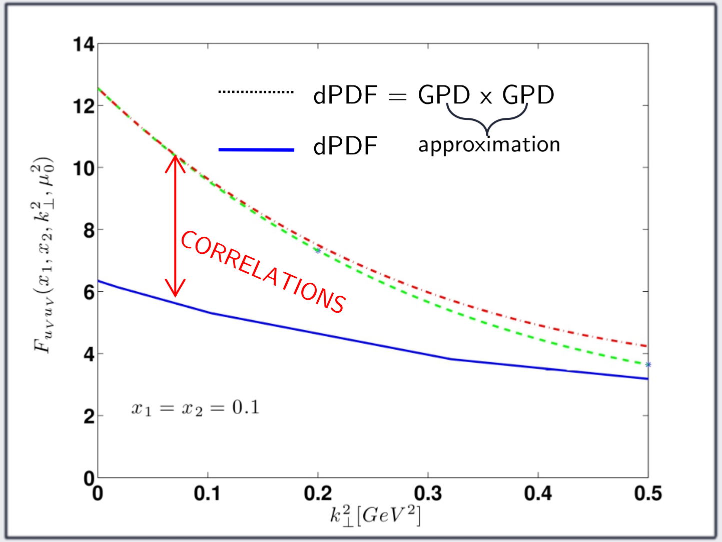
M. R. and F. A. Ceccopieri, arXiv:2103.13480

2 Information from Quark Models



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

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



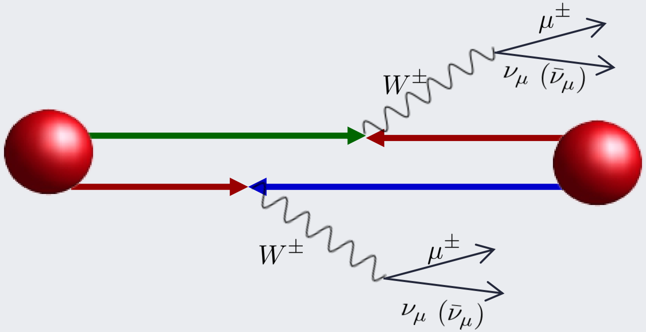
2) Correlations are important

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

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

4 Same sign W's production at the LHC

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

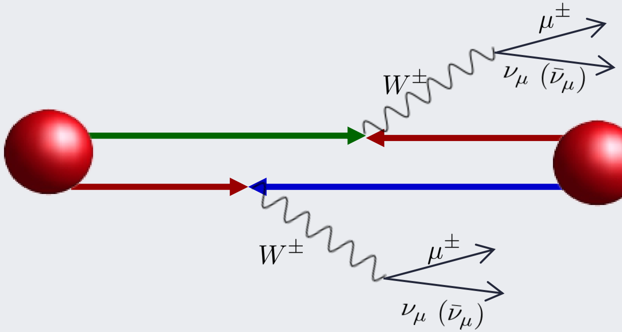


In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

"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

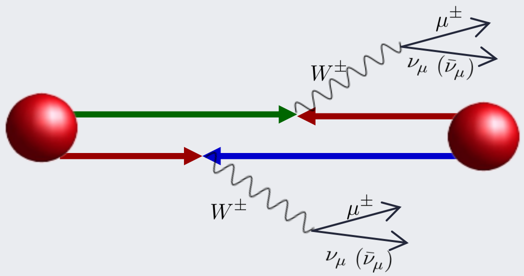


In this channel, the single parton scattering (usually dominant w.r.t to the double one) starts to contribute to higher order in strong coupling constant.

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

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, $\quad p_{T,\mu}^{subleading} > 10$ 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:

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

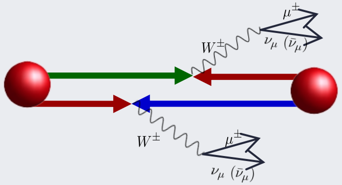
In order to estimate the role of double parton correlations we have used as input of dPDFs:

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

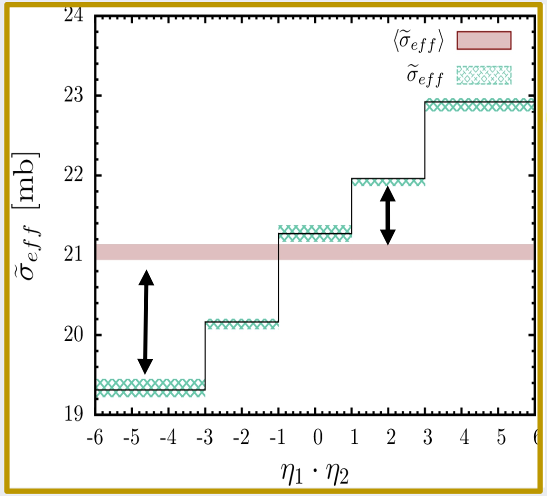
4 Same sign W's production at the LHC

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



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

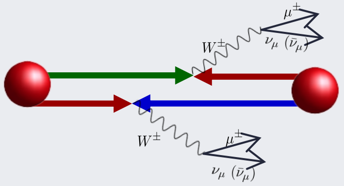
$$\langle\tilde{\sigma}_{eff}\rangle = 21.04\ ^{+0.07}_{-0.07}\,(\delta Q_0)\ ^{+0.06}_{-0.07}(\delta\mu_F)\ \text{mb}\ .$$



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

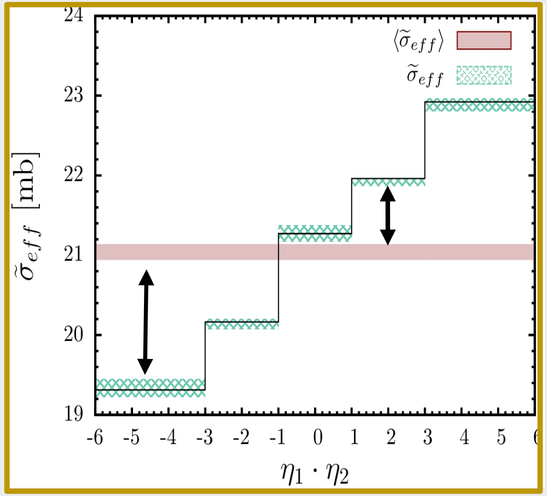
4 Same sign W's production at the LHC

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



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

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



<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)

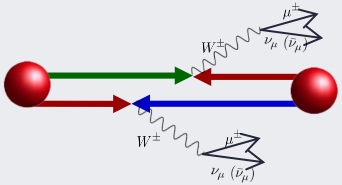
Assuming that the results of the first and the last bins can be distinguished if they differ by 1 sigma, we estimated that:

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

is necessary to observe correlations

* to be updated to new CMS cuts

4 Same sign W's production at the LHC

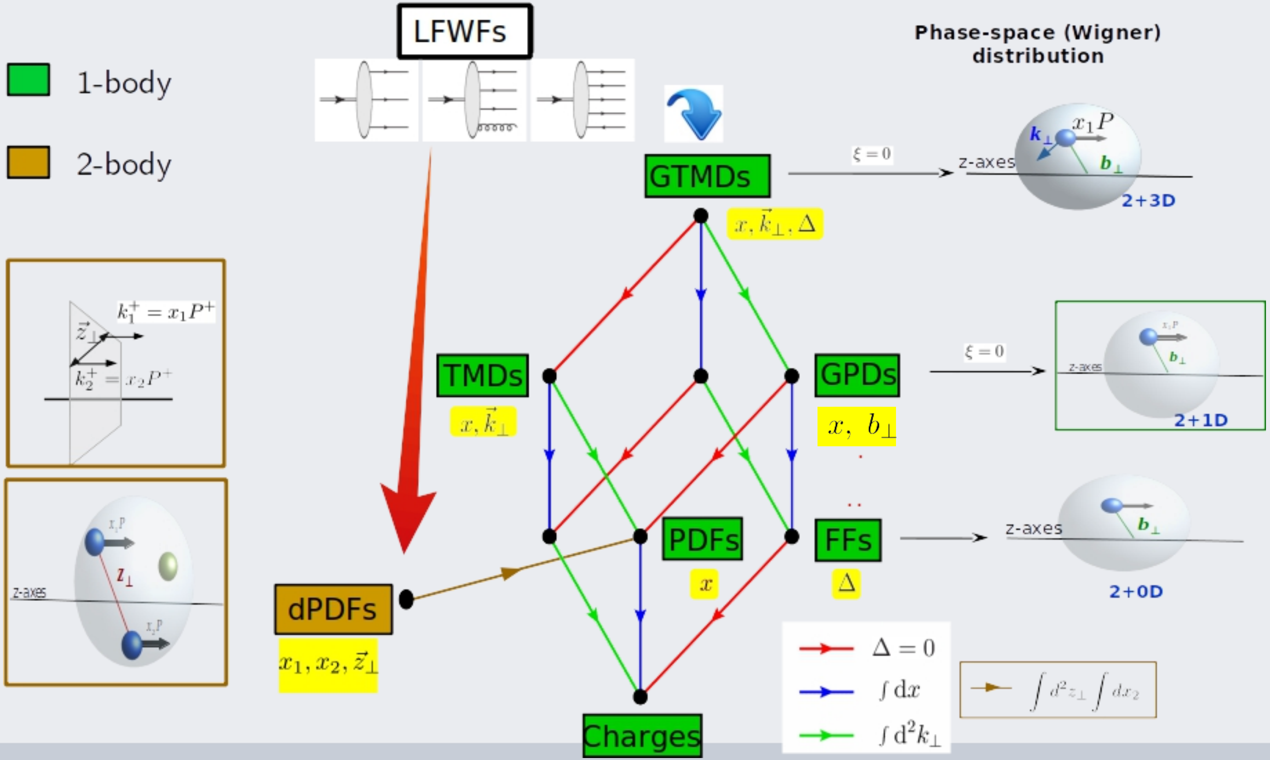


In Ref. **S. Cotogno et al, JHEP 10 (2020) 214**, it has been shown that several experimental observable are sensitive to **double spin correlations**.

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!

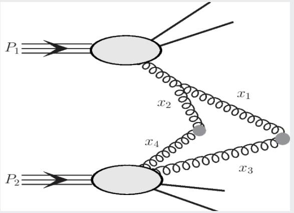
2 Multidimensional Pictures of Hadron



4 Further implementations

Relevant for processes involving heavy particles is the splitting term (1v2 mechanism) i.e.:

$^*D_{j_1,j_2}(x_1,x_2) = \int d^2 b_\perp \tilde{F}_{j_1,j_2}(x_1,x_2,b_\perp)$

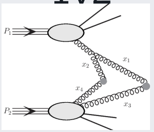


In pQCD evolution: $\frac{dD_{j_1 j_2}(x_1,x_2;t)}{dt} = \begin{cases} \text{Homogeneous term (double DGLAP)} \\ + \\ \sum_{j'} F_{j'}(x_1+x_2;t) \frac{1}{x_1+x_2} P_{j'\to j_1 j_2}\left(\frac{x_1}{x_1+x_2}\right) \end{cases}$

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

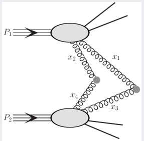
SPLITTING TERM

1v2



+

2v2



$$\frac{\sigma_{eff}}{3\pi}\left(1+\frac{3}{2}r_v\right) \leq \langle b^2 \rangle \leq \frac{\sigma_{eff}}{\pi}\left(1+2r_v\right)$$

$$r_v \sim \frac{F^{splitting}_{j_1 j_2}(x_1,x_2,k_\perp=0;t)}{F_{j_1 j_2}(x_1,x_2,k_\perp=0;t)}$$

with:
$0 \leq r_v \leq 1$

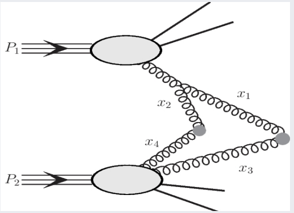
J.R. Gaunt, R. Maciula and A. Szczurek,
PRD 90 (2014) 054017

Due to the difficulty in the estimate of the 2 contributions:

Absolute minimum $r_v = 0$ $\quad \frac{\sigma_{eff}}{3\pi} \leq \langle b^2 \rangle \leq \frac{3\,\sigma_{eff}}{\pi}$ $\quad$ Absolute maximum $\mathbf{r_v = 1}$

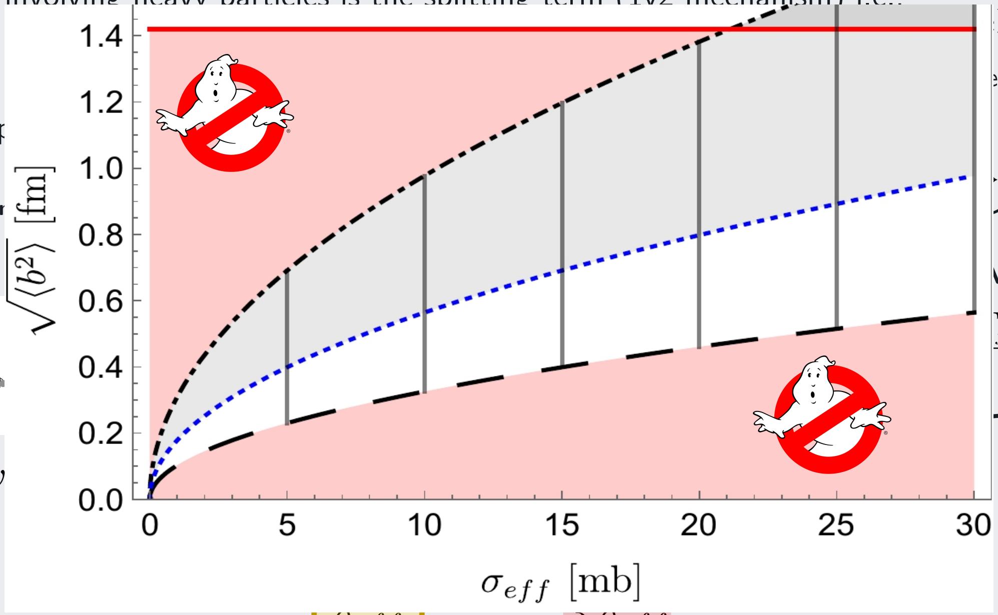
4 Further implementations

Relevant for processes involving heavy particles is the splitting term (1v2 mechanism) i.e.:



In p

Gaur



$) = \int d^2b_\perp \tilde{F}_{j_1,j_2}(x_1, x_2, b_\perp)$

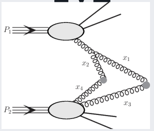
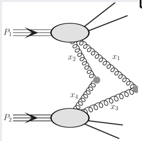
DGLAP)

$j_1 j_2 \left(\frac{x_1}{x_1 + x_2} \right)$

M

$\frac{{}^{splitting}_{j_1 j_2}(x_1, x_2, k_\perp = 0; t)}{F_{j_1 j_2}(x_1, x_2, k_\perp = 0; t)}$

1v2

 + 

with:

$0 \leq r_v \leq 1$

1) Minimum as function of r_v

$$m(r_v)$$

2) Maximum as function of r_v

$$M(r_v)$$

Absolute minimum $\frac{\sigma_{eff}}{3\pi} \leq \langle b^2 \rangle \leq \frac{3\,\sigma_{eff}}{\pi}$ Absolute maximum

$r_v = 0$ $\qquad$ $r_v = 1$

2 Double PDFs within the Light-Front

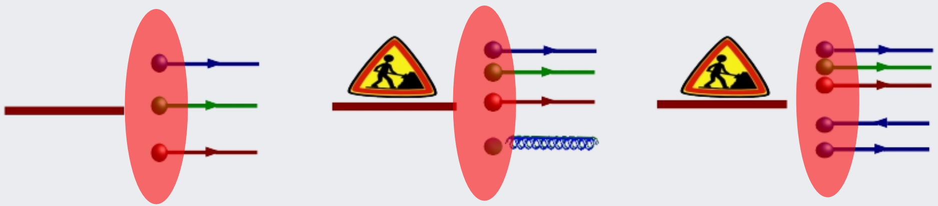
Extending the procedure developed in **S. Boffi, B. Pasquini and M. Traini, Nucl. Phys. B 649, 243 (2003)** for GPDs, we obtained the following expression of the dPDF in momentum space, often called $_2$GPDs:

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

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

Conjugate to $z_\perp$

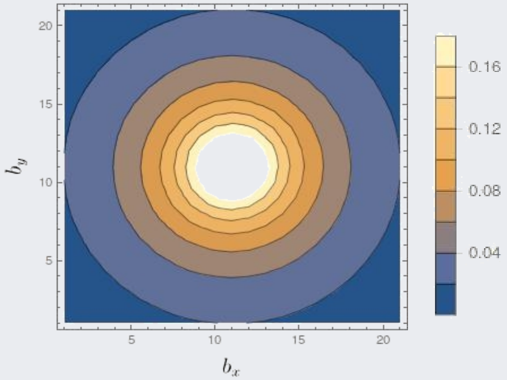
LF wave-function



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

2 Information from Quark Models

$z_\perp = b_\perp$



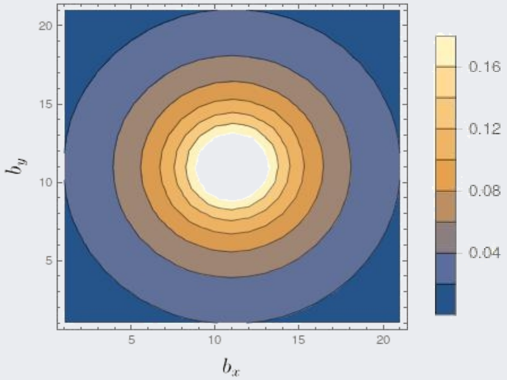
M.R. and F. A. Ceccopieri, JHEP 09 (2019) 097

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

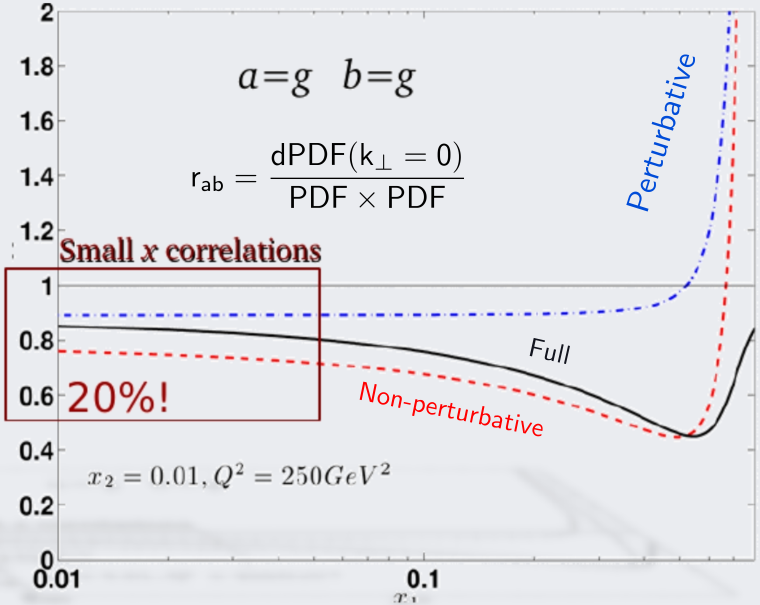
$$\langle z_\perp^2 \rangle^{ij}_{x_1,x_2} = \frac{\int d^2 z_\perp \; z_\perp^2 F_{ij}(x_1, x_2, z_\perp)}{\int d^2 z_\perp \; F_{ij}(x_1, x_2, z_\perp)}$$

2 Information from Quark Models

$z_\perp = b_\perp$



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



2) Correlations are important

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

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

4 Further implementations

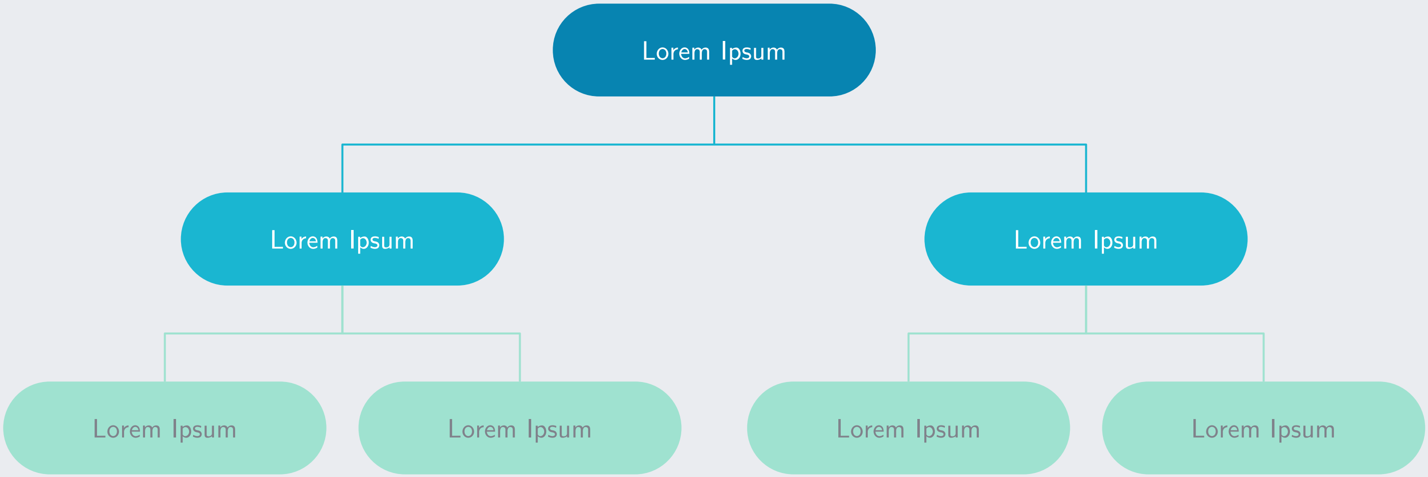
IF WE DO NOT CONSIDER ANY FACTORIZATION ANSATZ IN DOUBLE PDFs:

$$\frac{\sigma_{eff}(x_1,x_2)}{3\pi}\left[r^{2v2}(x_1,x_2)^2+\frac{3}{2}r^{2v1}(x_1,x_2)^2\ r_v\right]\leq\langle b^2\rangle_{x_1,x_2}\leq\frac{\sigma_{eff}(x_1,x_2)}{\pi}\left[r^{2v2}(x_1,x_2)^2+2r^{2v1}(x_1,x_2)^2\ r_v\right]$$

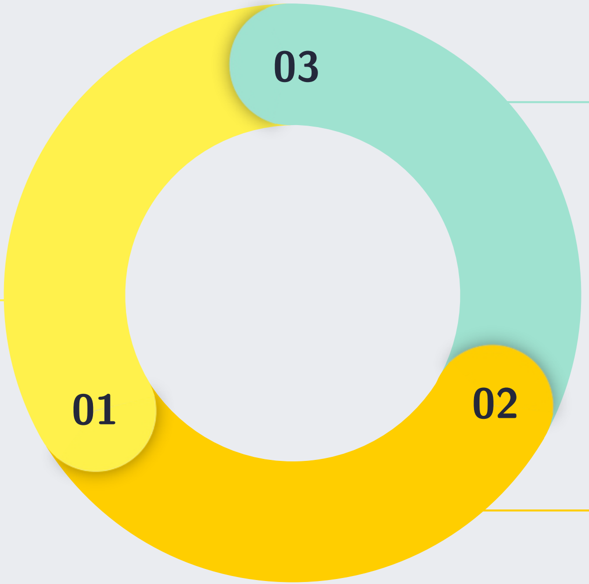
$$r^{2v2}(x_1,x_2)=\frac{F(x_1,x_2,k_\perp=0;t)}{F(x_1;t)F(x_2;t)}$$

$$r^{2v1}(x_1,x_2)=\frac{F^{splitting}(x_1,x_2,k_\perp=0;t)}{F(x_1;t)F(x_2;t)}$$

Use diagrams to explain your ideas



Our process is easy



Vestibulum congue tempus

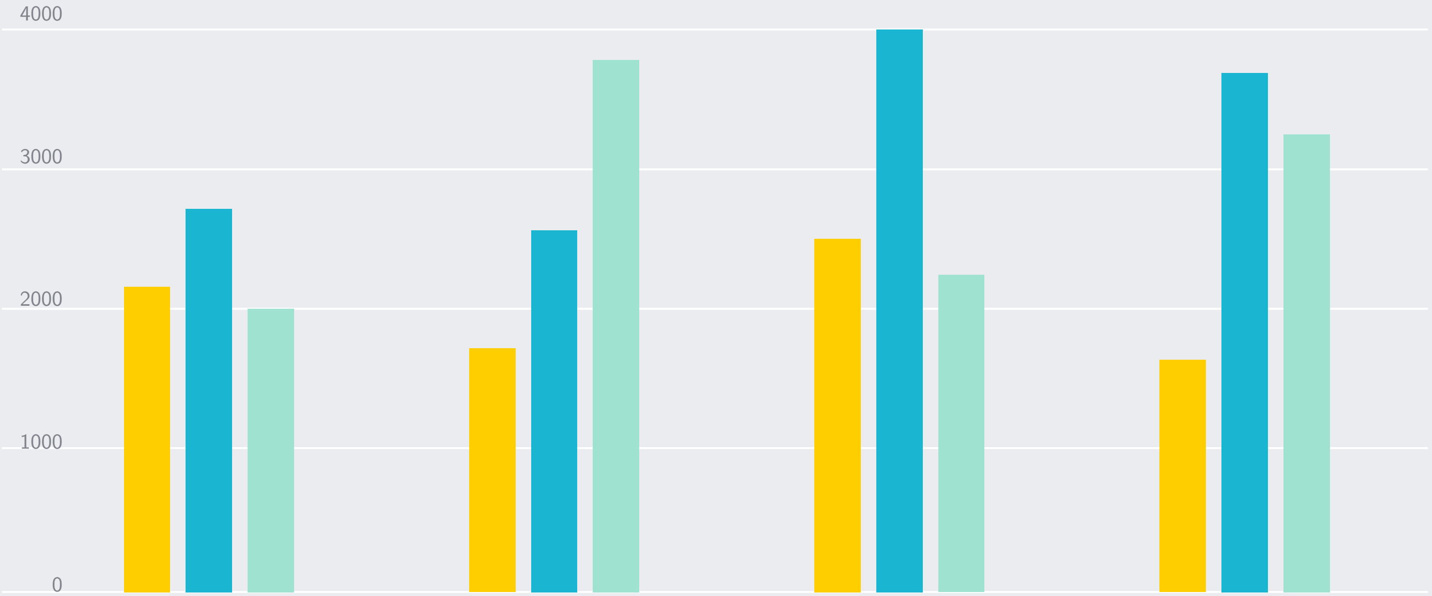
Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor. Donec facilisis lacus eget mauris.

Vestibulum congue tempus

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor. Donec facilisis lacus eget mauris.

Vestibulum congue tempus

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor. Donec facilisis lacus eget mauris.



You can insert graphs from Excel or Google Sheets

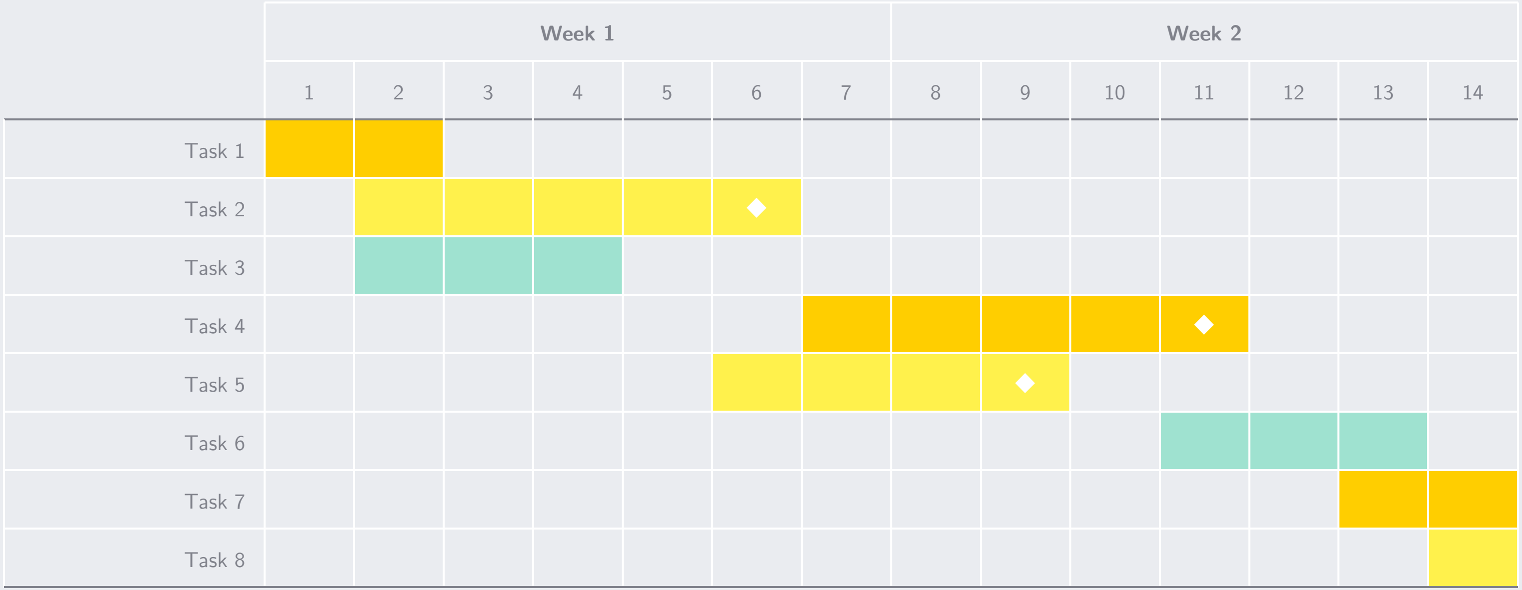
Desktop project

Show and explain your web, app or software projects using these gadget templates.

Timeline

- **JAN** — Blue is the colour of the clear sky and the deep sea
- **FEB** — Yellow is the color of gold, butter and ripe lemons
- **MAR** — Red is the colour of danger and courage
- **APR** — White is the color of milk and fresh snow
- **MAY** — Black is the color of ebony and of outer space
- **JUN** — Blue is the colour of the clear sky and the deep sea
- **JUL** — Yellow is the color of gold, butter and ripe lemons
- **AUG** — Red is the colour of danger and courage
- **SEP** — White is the color of milk and fresh snow
- **OCT** — Black is the color of ebony and of outer space
- **NOV** — Blue is the colour of the clear sky and the deep sea
- **DEC** — Yellow is the color of gold, butter and ripe lemons

Gantt chart


Week 1
Week 2
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Task 1
Task 2
Task 3
Task 4
Task 5
Task 6
Task 7
Task 8

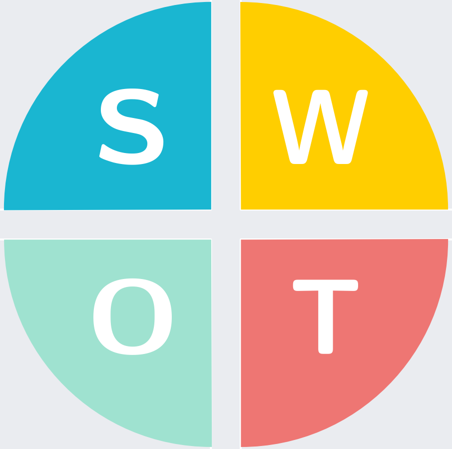
SWOT Analysis

STRENGTHS

Blue is the colour of the clear sky and the deep sea

WEAKNESSES

Yellow is the color of gold, butter and ripe lemons



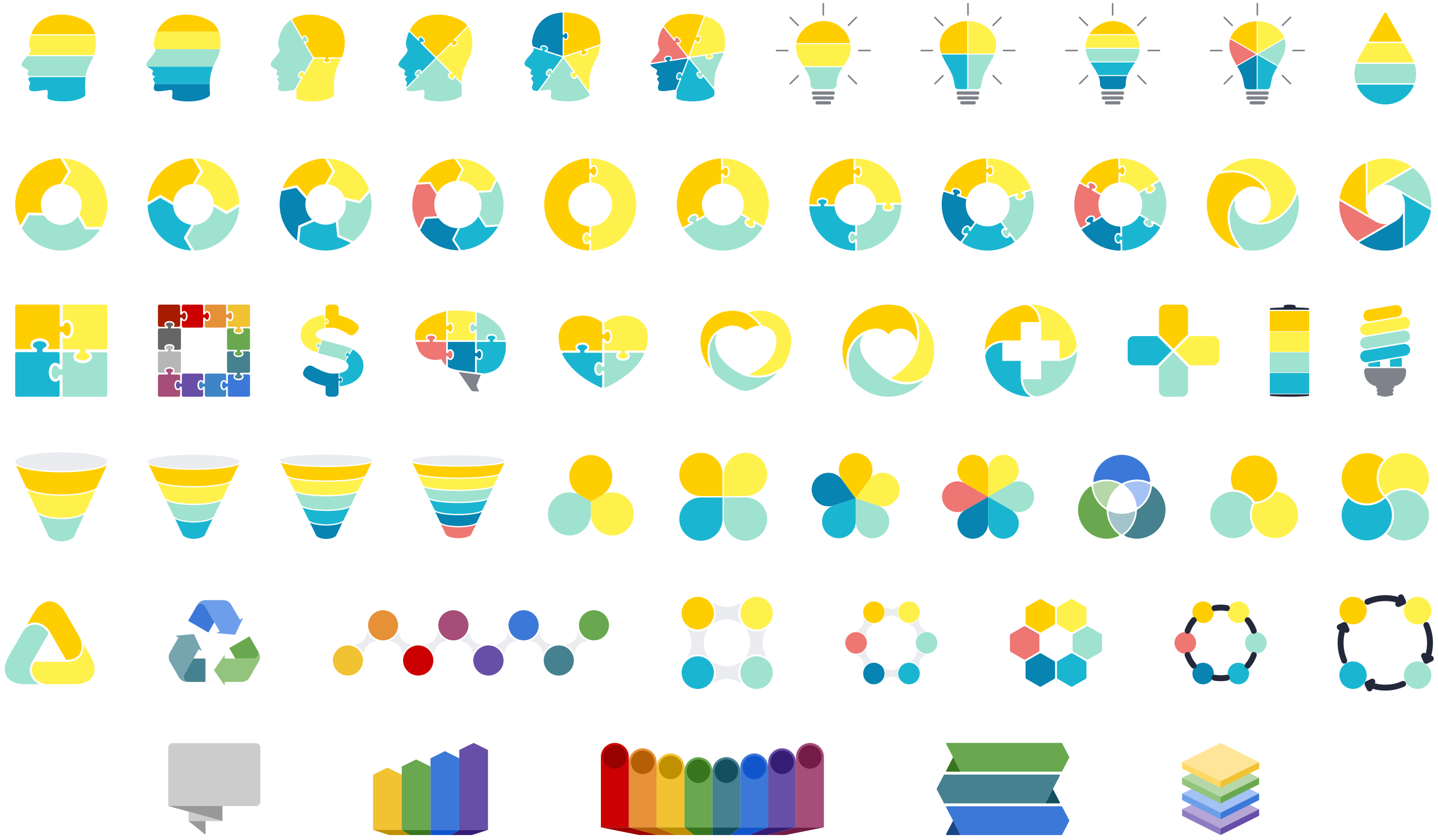
Black is the color of ebony and of outer space

OPPORTUNITIES

White is the color of milk and fresh snow

THREATS

Diagrams and infographics



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