Double- and Triple- parton scattering in p-A collisions

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Istituto Nazionale di Fisica Nucleare

Outline

- Introduction to double parton scattering (DPS) and hadronic Physics
- Nuclear DPS (pA)
- Triple Parton Scattering (TPS)
- Nuclear TPS (pA)

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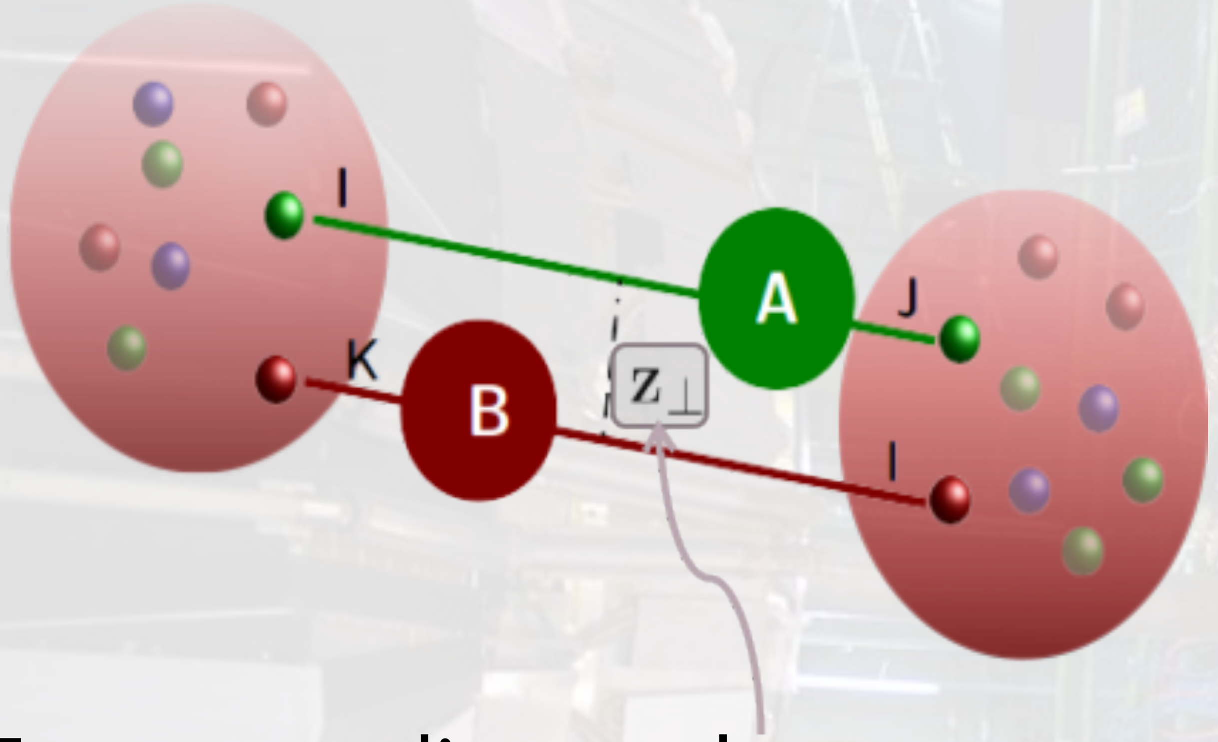
Double Parton Scattering

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



Transverse distance between two partons

$$d\sigma \propto \int d^2 z_\perp \underbrace{F_{ij}(x_1, x_2, z_\perp, \mu_A, \mu_B)}_{\text{Double Parton Distribution (DPD)}} F_{kl}(x_3, x_4, z_\perp, \mu_A, \mu_B)$$

N. Paver and D. Treleani, Nuovo Cimento 70A, 215 (1982)
Mekhfi, PRD 32 (1985) 2371
M. Diehl et al, JHEP 03 (2012) 089

$$F_{ij}^{\lambda_1,\lambda_2}(x_1, x_2, \vec{k}_\perp) = (-8\pi P^+)\frac{1}{2}\sum_\lambda \int d\vec{z}_\perp \, e^{i\vec{z}_\perp \cdot \vec{k}_\perp}$$
$$\times \int \left[\prod_l^3 \frac{dz_l^-}{4\pi}\right] e^{ix_1 P^+ z_1^-/2} e^{ix_2 P^+ z_2^-/2} e^{-ix_1 P^+ z_3^-/2}$$
$$\times \langle \lambda, \vec{P} = \vec{0} | \hat{\mathcal{O}}_i^1 \left(z_1^- \frac{\bar{n}}{2}, z_3^- \frac{\bar{n}}{2} + \vec{z}_\perp\right) \hat{\mathcal{O}}_j^2 \left(z_2^- \frac{\bar{n}}{2} + \vec{z}_\perp, 0\right) | \vec{P} = \vec{0}, \lambda \rangle$$

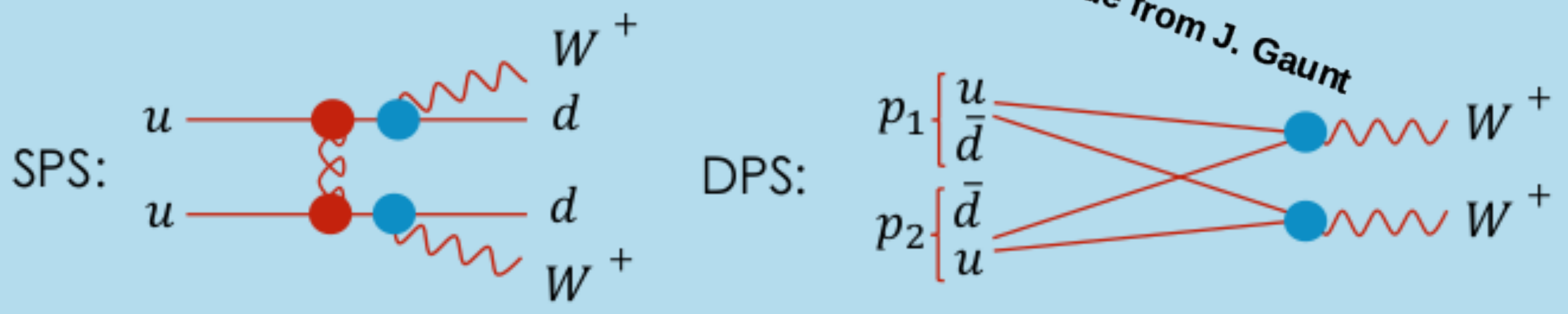
$$\hat{\mathcal{O}}_i^k(z, z') = \bar{q}_i(z)\hat{O}(\lambda_k) q_i(z')$$

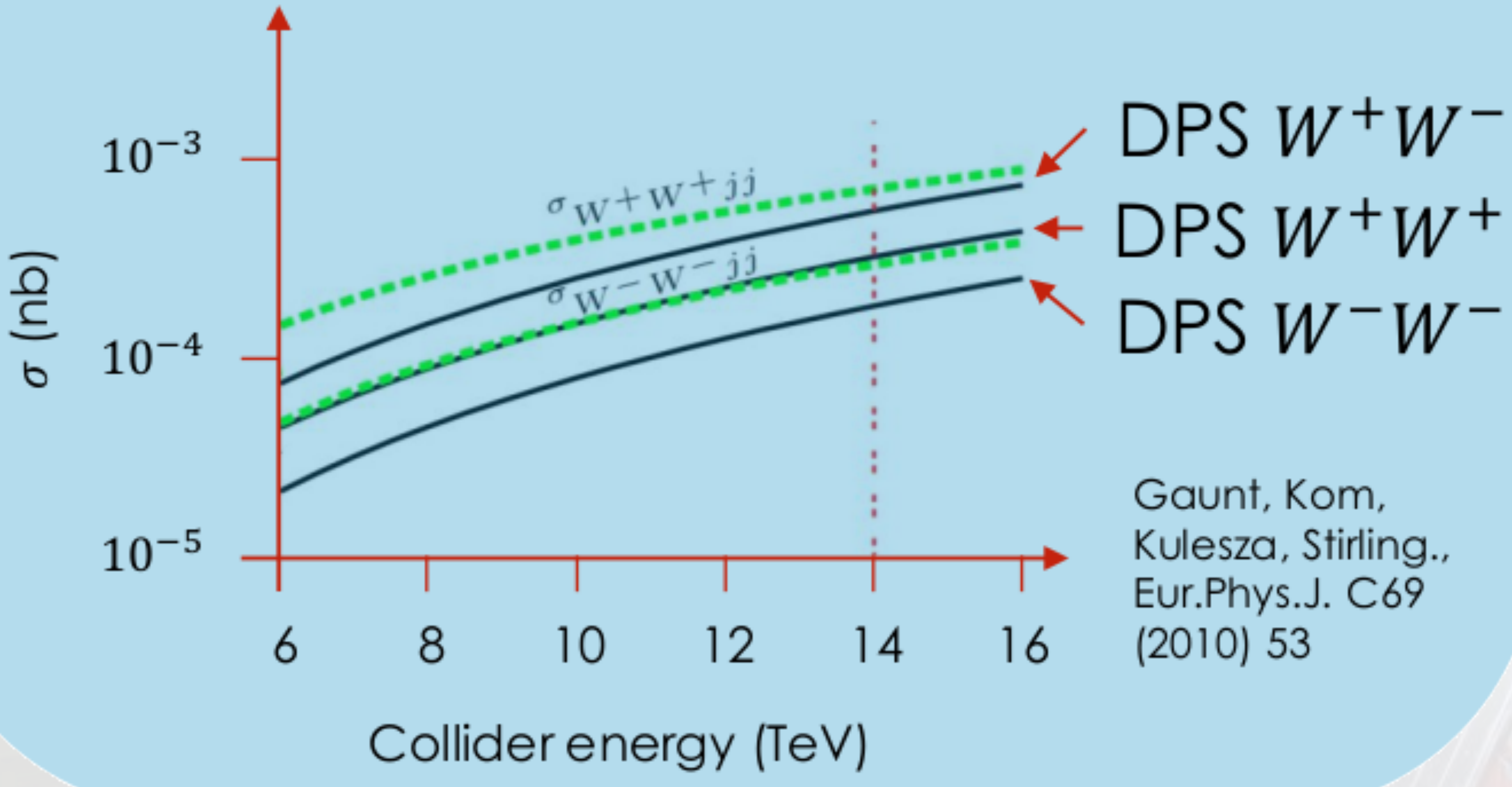
$$\hat{O}(\lambda_k) = \frac{\not{n}}{2}\frac{1 + \lambda_k \gamma_5}{2} \, .$$

Where and Why DPS?

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

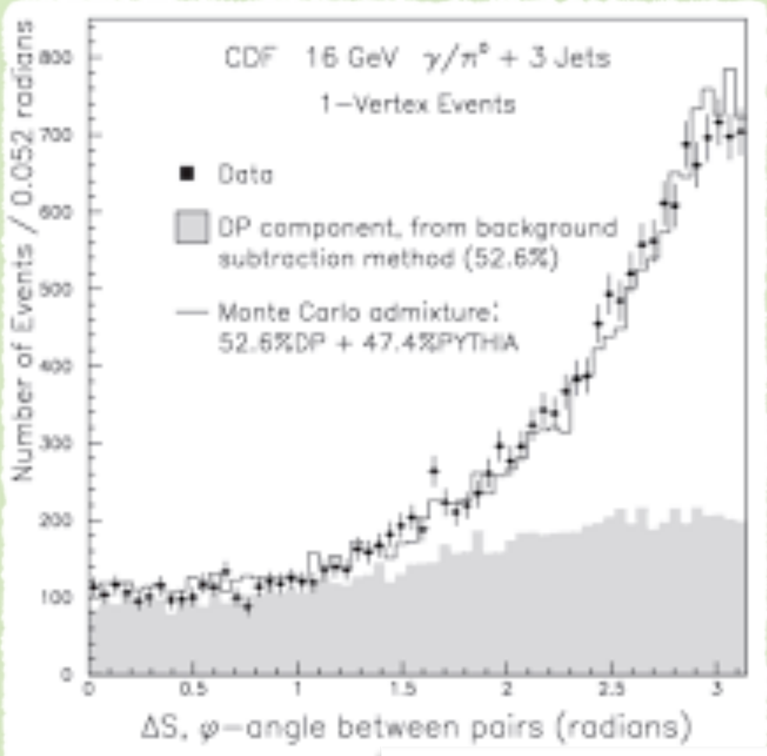
Slide from J. Gaunt





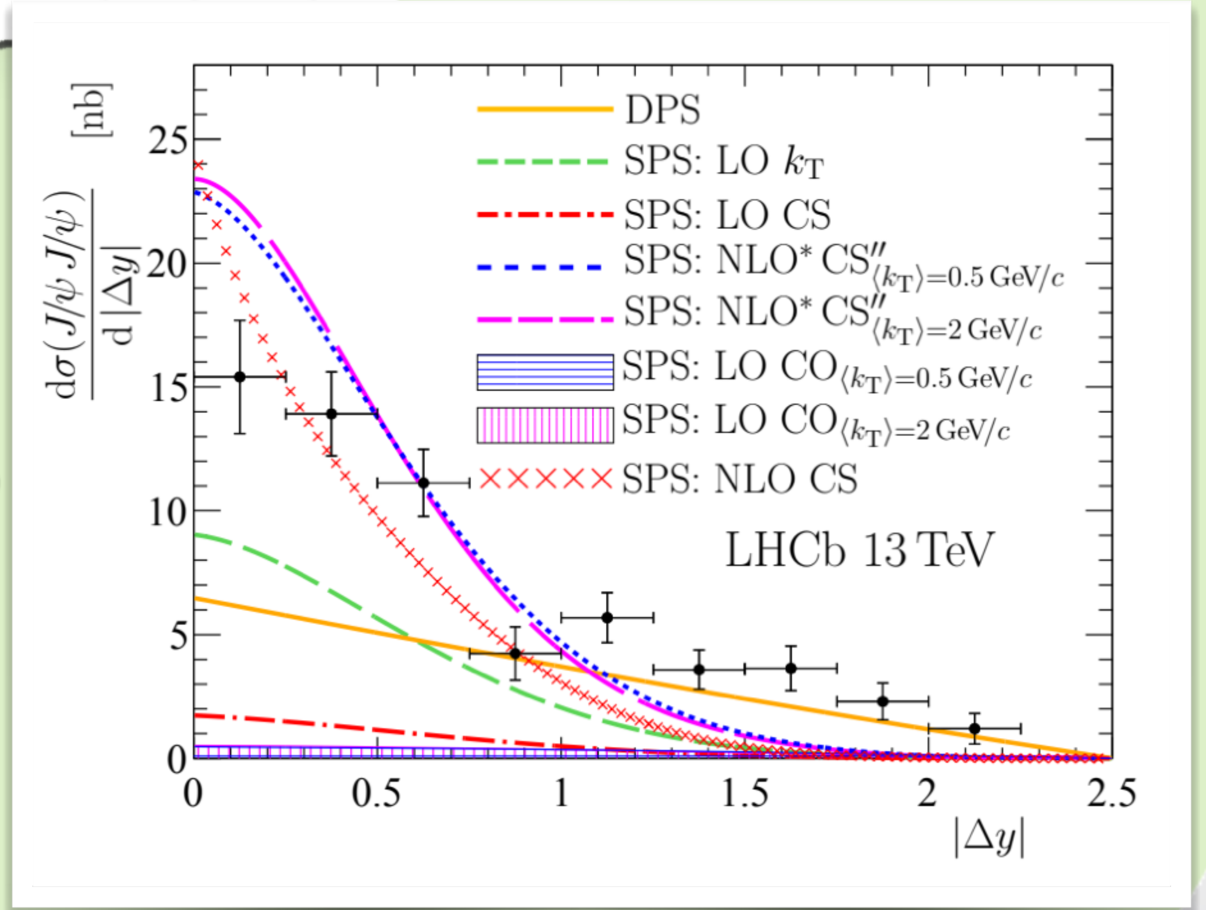
Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

...or in certain phase space regions

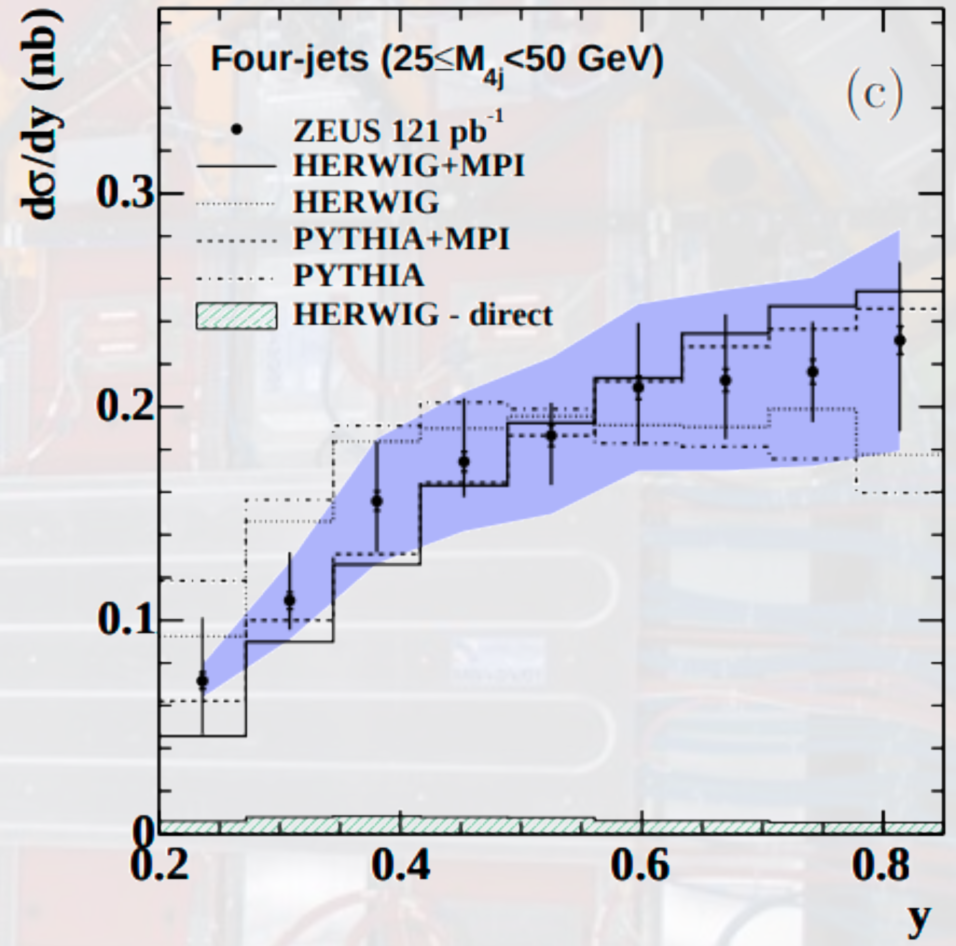


CDF, $\gamma + 3j$, Phys.Rev. D56 (1997) 3811-3832

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



in ep Colliders?

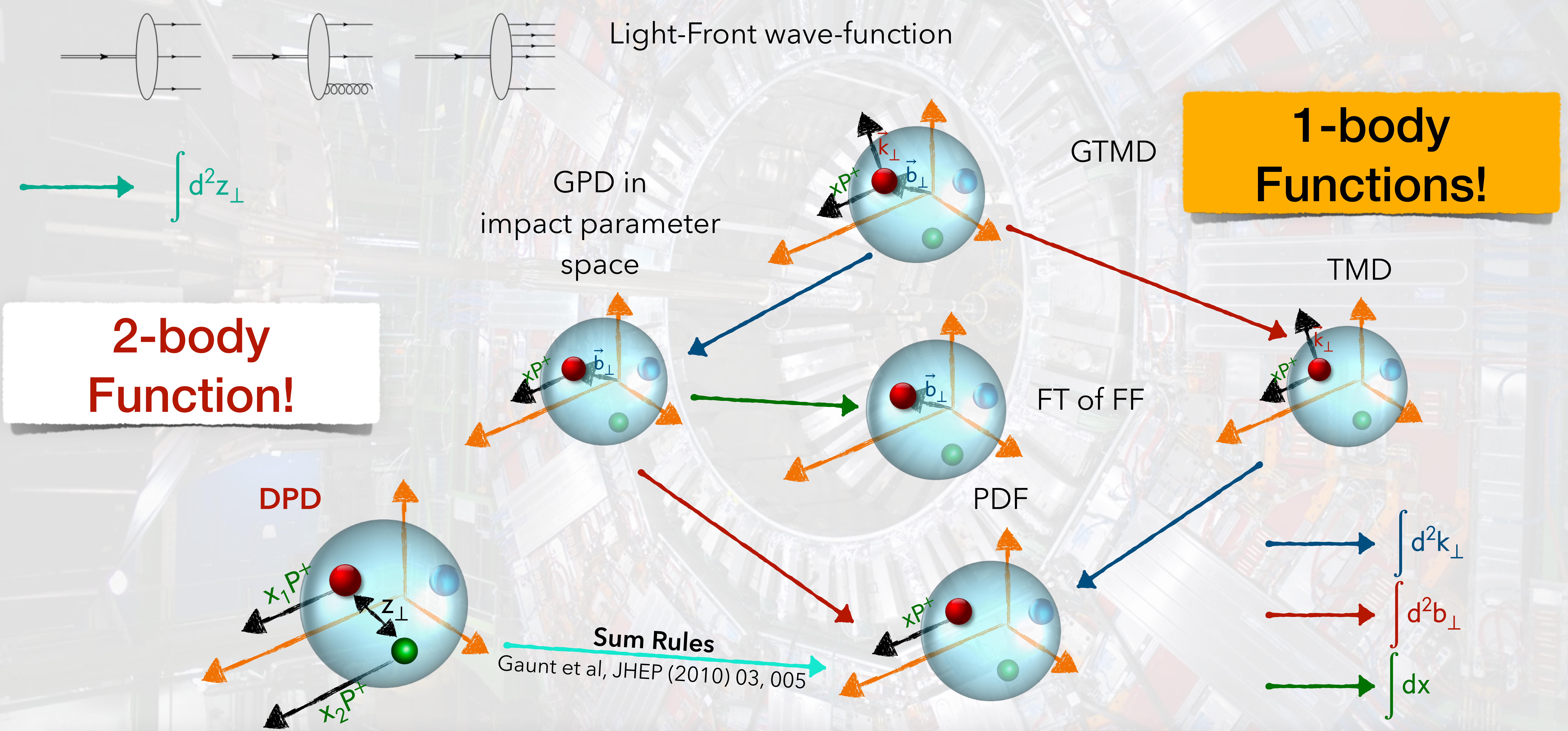


HERA data, ZEUS coll, Nucl. Phys. B 729, 1 (2008)

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

all **UNKNOWN**

Multidimensional picture of hadrons



How to build up a DPD

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

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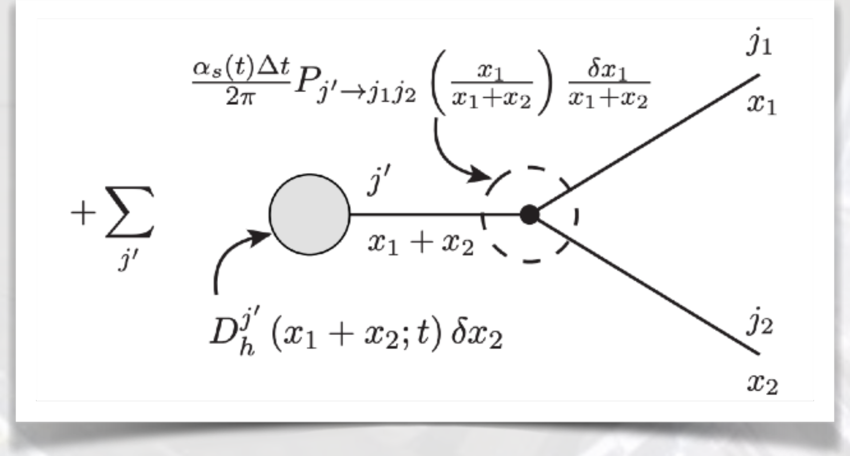
double PDF

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

Sum Rules

pQCD evolution



PDF(x_1)*PDF(x_2)
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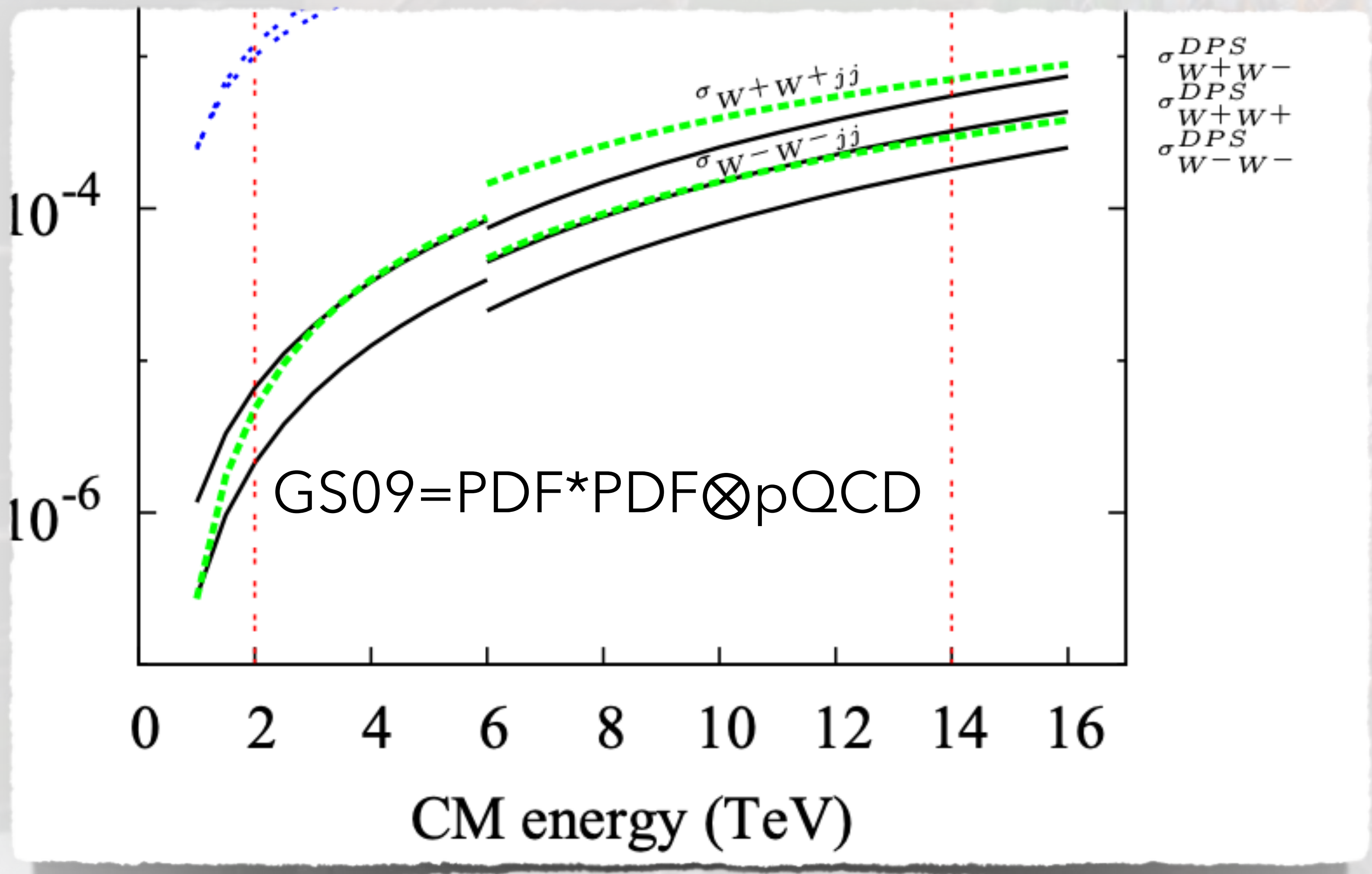
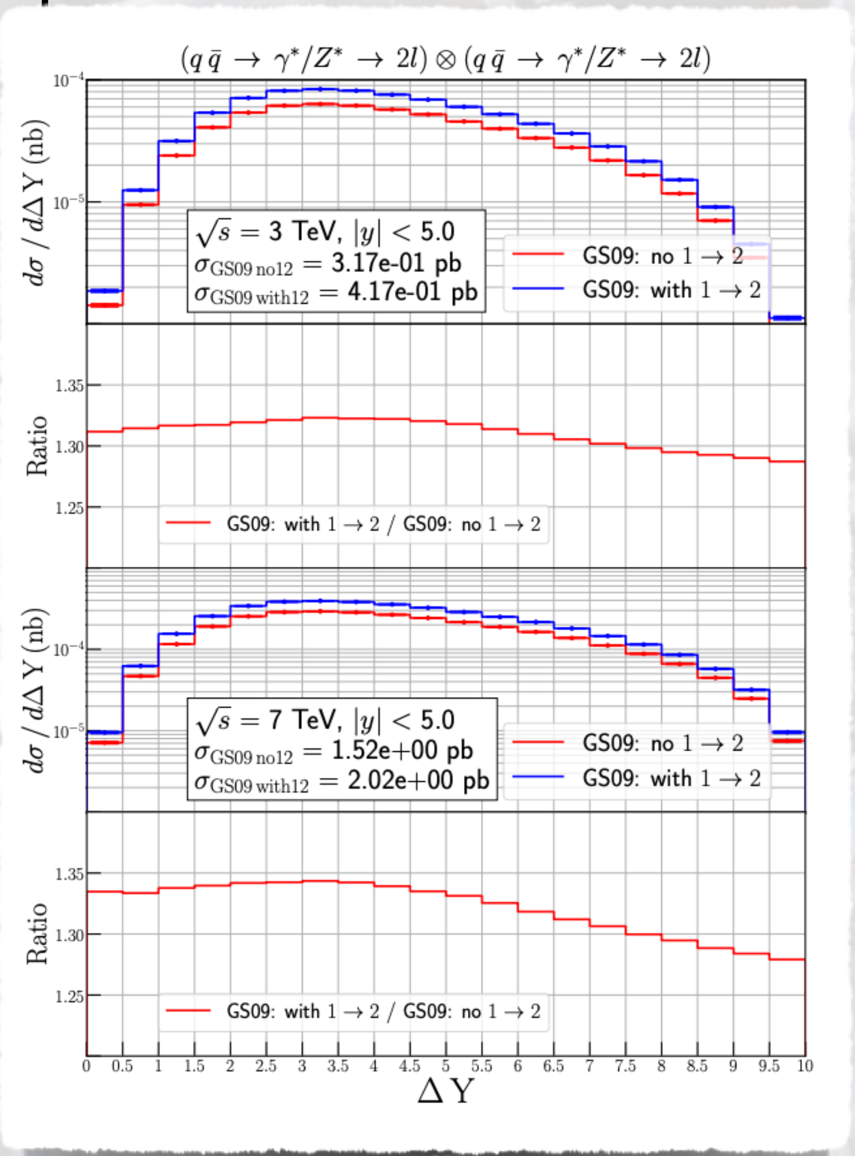
J. R. Gaunt et al, EPJC 69 (2010) 54-65





O. Fedkevych, J. R. Gaunt, JHEP 02 (2023) 090

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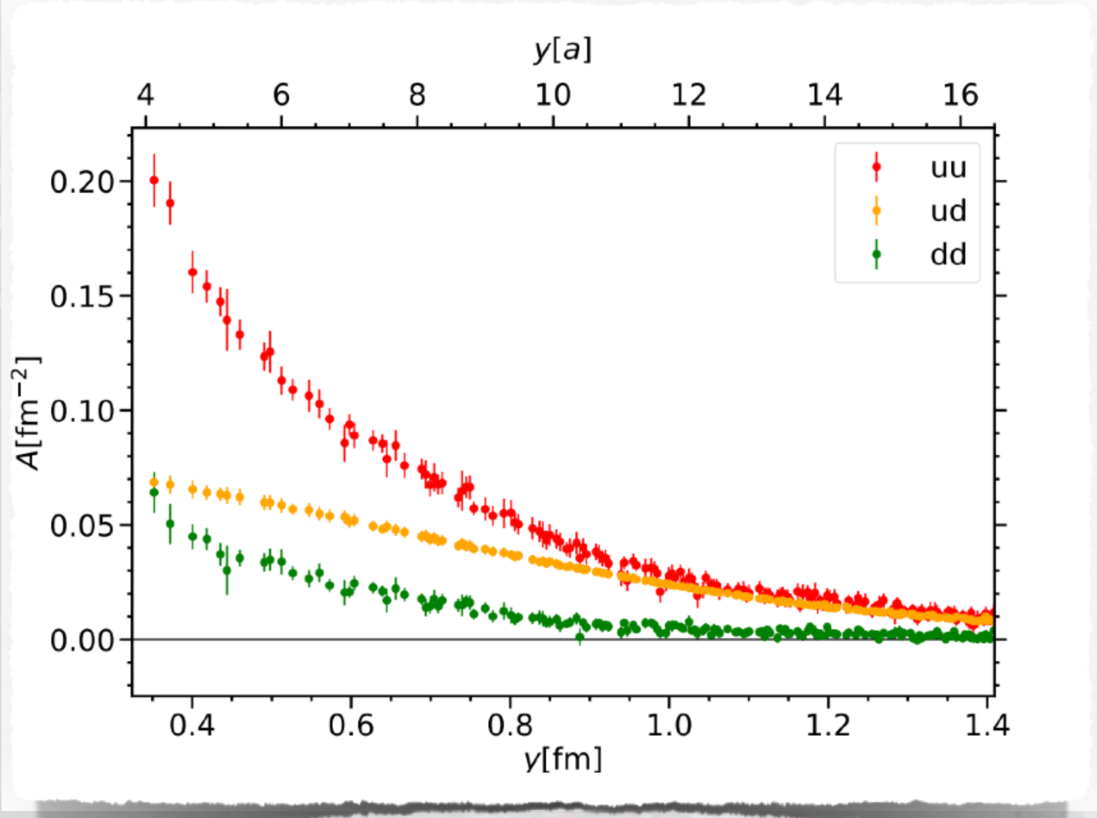
uncorrelated scenario: $$F_{ik}(x_1, x_2, \vec{z}_\perp) \sim \underbrace{\boxed{g(x_1, x_2)}}_{\text{double PDF}} \boxed{\tilde{T}(\vec{z}_\perp)}$$

Probability distribution of two partons at given distance

Unknown Non perturbative object

Some information from lattice
(no factorization in terms of form factors)

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



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Probability distribution of two partons at given distance

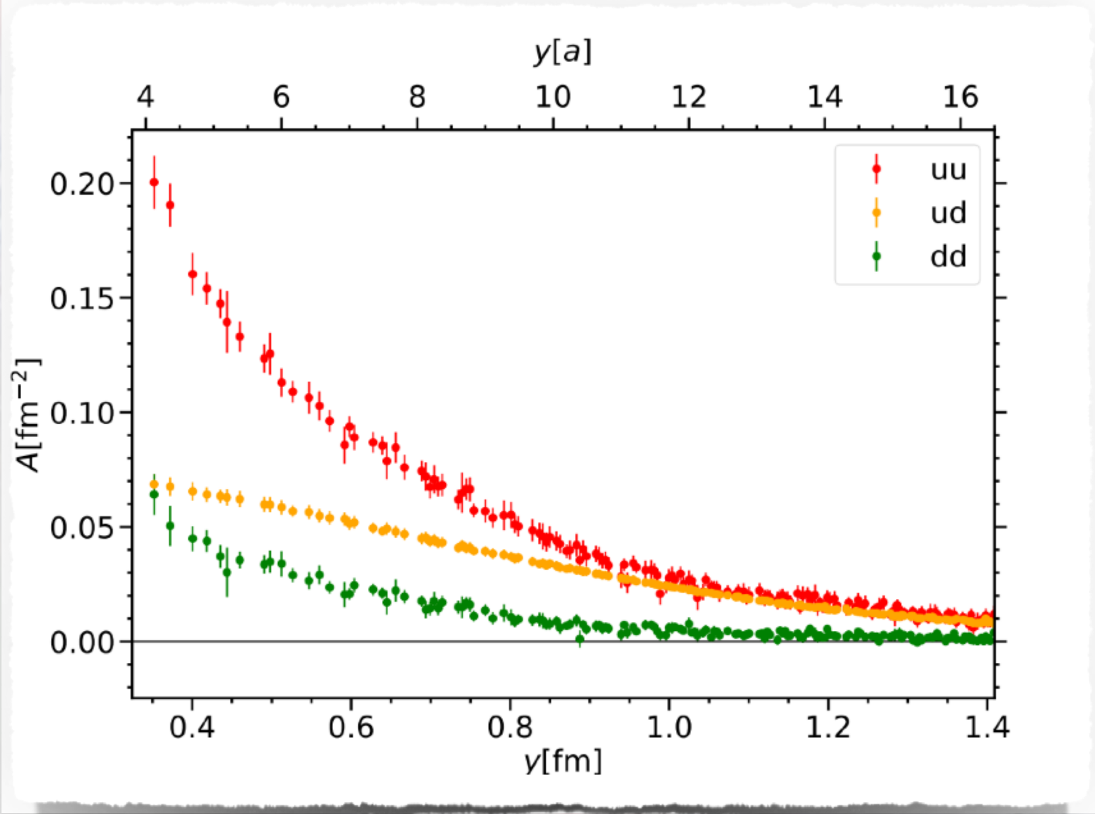
Unknown Non perturbative object

Some information from lattice (no factorization in terms of form factors)

Some constraints from data

Some Constraints from general properties

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



$$\sigma_{\text{eff}}^{-1} = \int d^2 z_\perp \, \tilde{T}(z_\perp)^2$$

Some Data and Effective Cross Section

$$\underbrace{\sigma_{\rm eff}^{\rm pp} = \frac{m}{2}\frac{\sigma_{\rm A}^{\rm pp}\boxed{\sigma_{\rm B}^{\rm pp}}}{\sigma_{\rm DPS}^{\rm pp}}}_{\text{POCKET FORMULA}}$$

Differential X-section single parton scattering for the process: $\mathrm{pp} \longrightarrow \mathrm{A(B)} + \mathrm{X}$

Differential X-section double parton scattering for the process: $\mathrm{pp} \longrightarrow \mathrm{A} + \mathrm{B} + \mathrm{X}$

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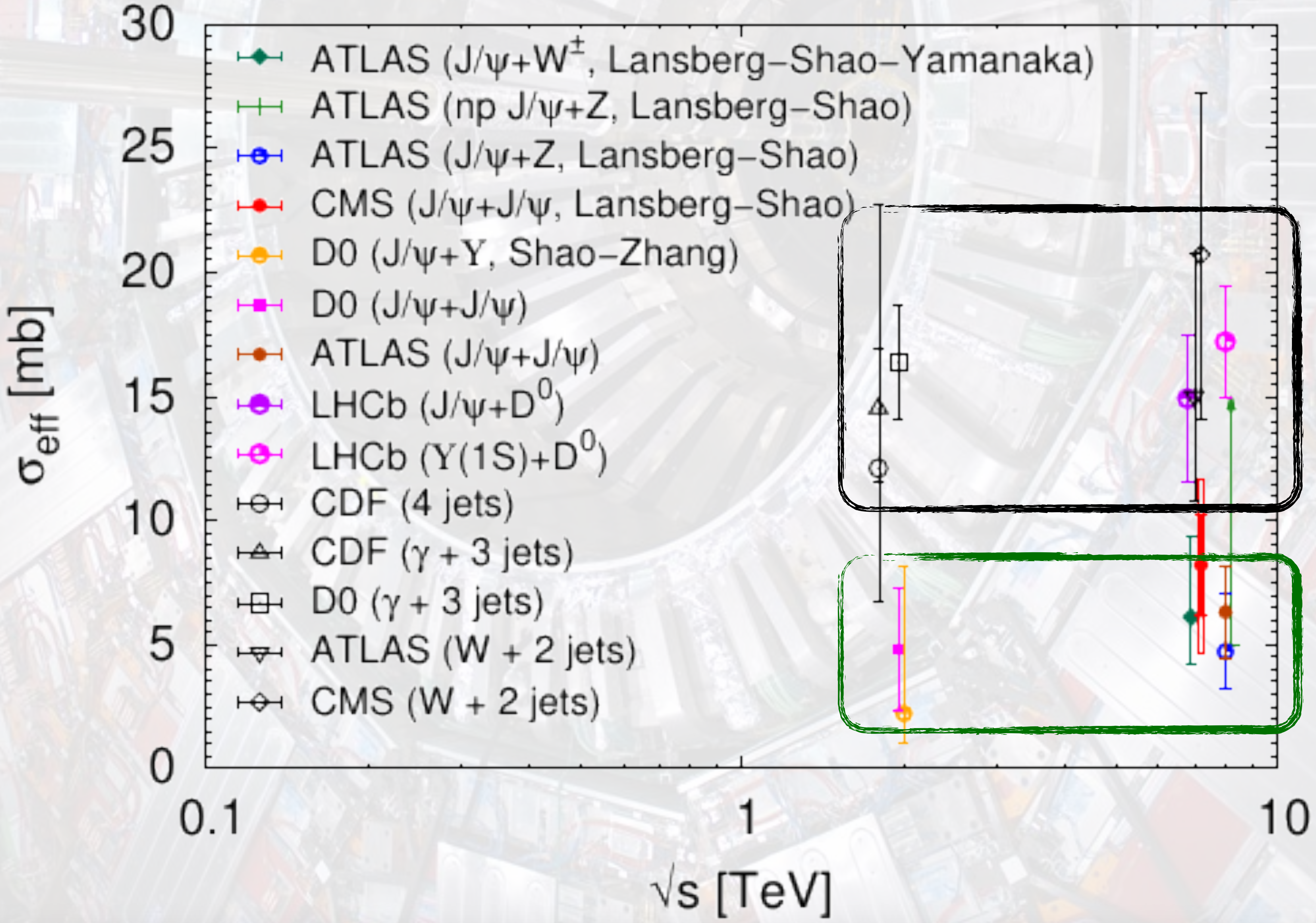
Differential X-section single parton scattering for the process: $pp \longrightarrow A(B) + X$

Differential X-section double parton scattering for the process: $pp \longrightarrow A + B + X$

Results for W, Jet productions…

Results for quarkonium productions



First observation of same sign WW via DPS:

$$\sigma_{\text{eff}} = 12.2^{+2.9}_{-2.2} \quad \text{mb}$$

[CMS coll.], PRL 131 (2023) 091803

$$\sigma^{DPS} \sim 6.28 \text{ fb}$$

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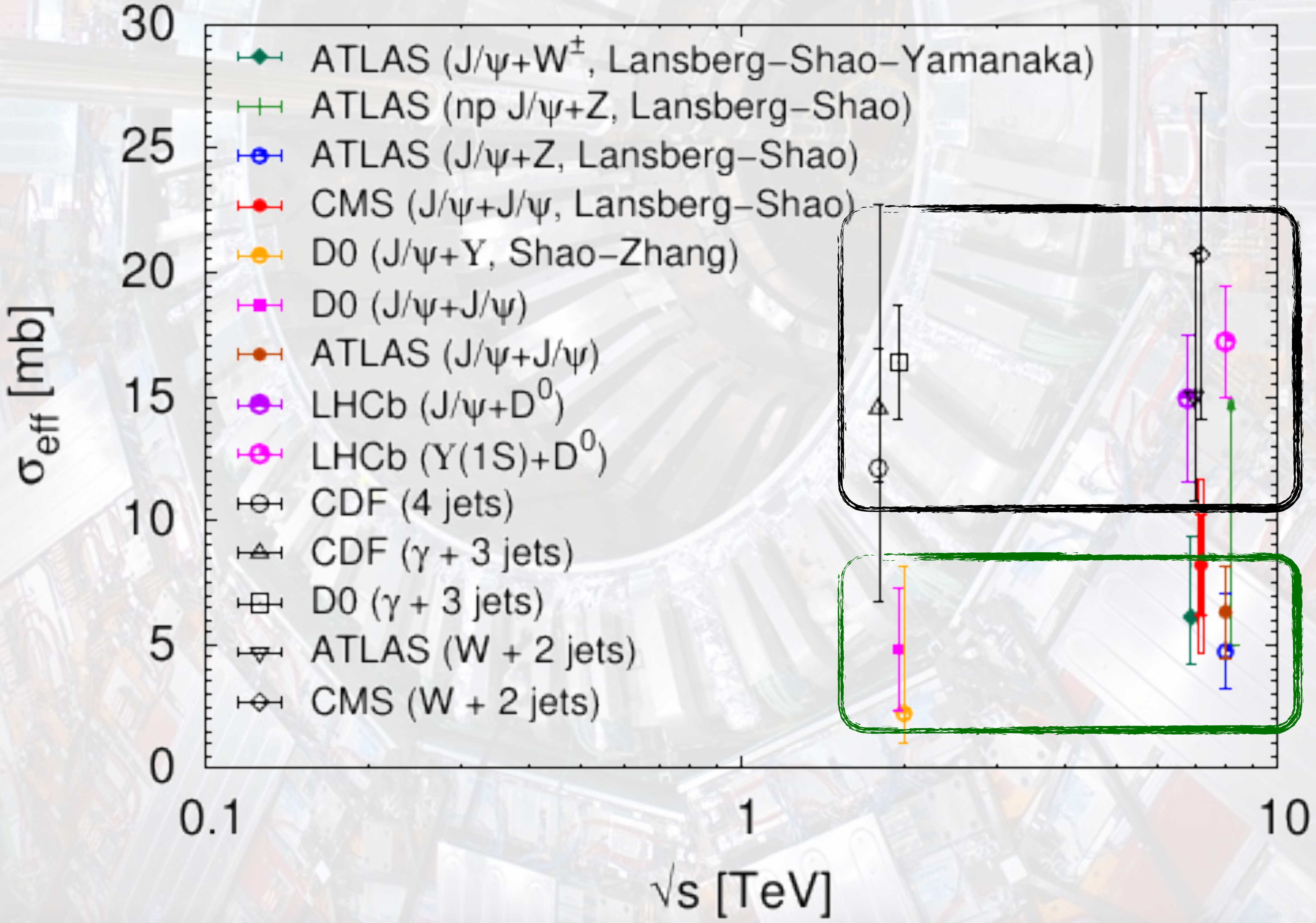
Differential X-section double parton scattering for the process: $pp \longrightarrow A + B + X$

1) Process dependent?
2) Sensitive to correlations
3) Sensitive to the inner structure?

predicted by all 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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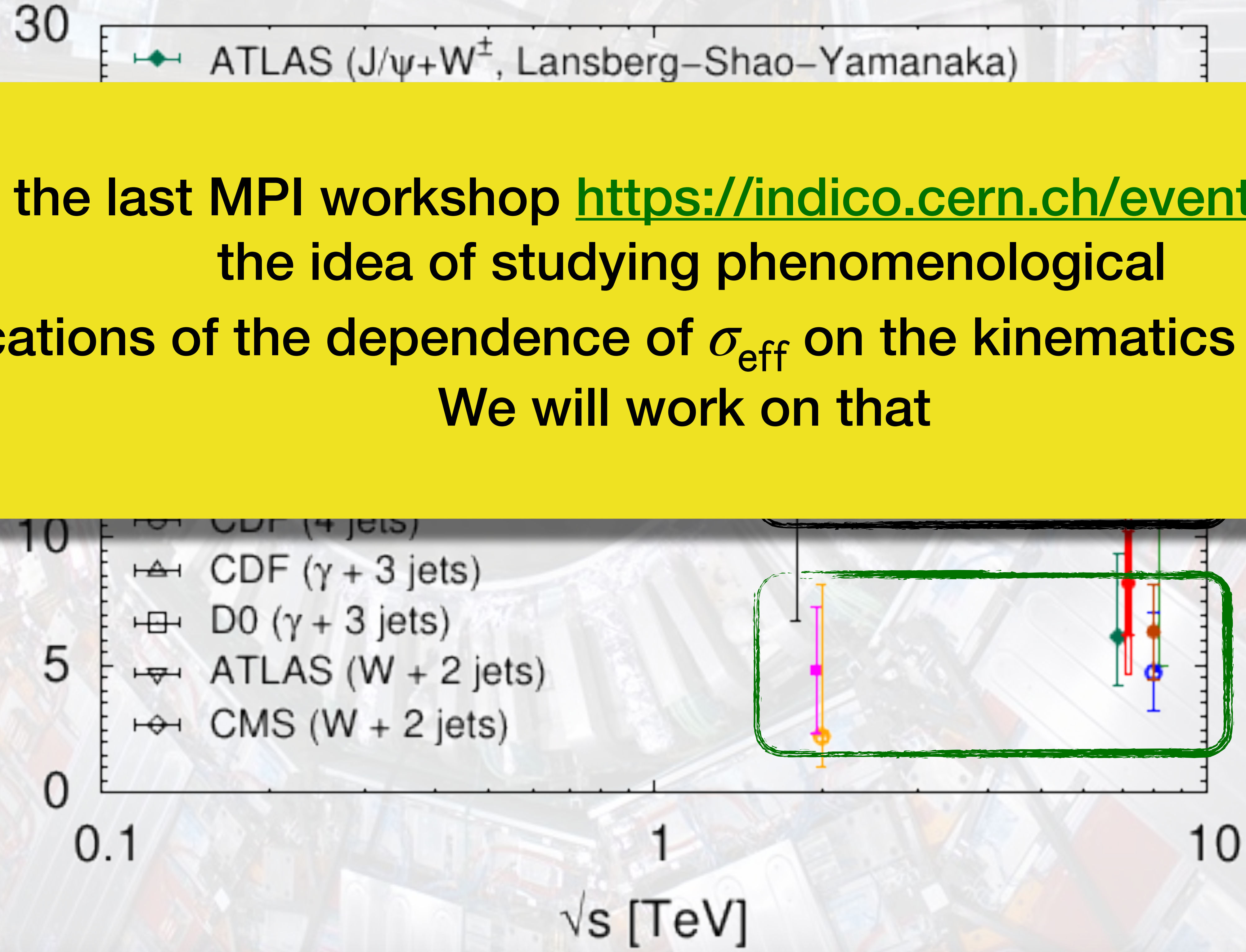


From the last MPI workshop https://indico.cern.ch/event/1281679/
the idea of studying phenomenological
implications of the dependence of σ_{eff} on the kinematics came out!!
We will work on that

First observation of
WW via DPS:

$.2.2^{+2.9}_{-2.2}$ mb

PRL 131 (2023) 091803

~ 6.28 fb

Effective Cross Section and proton structure

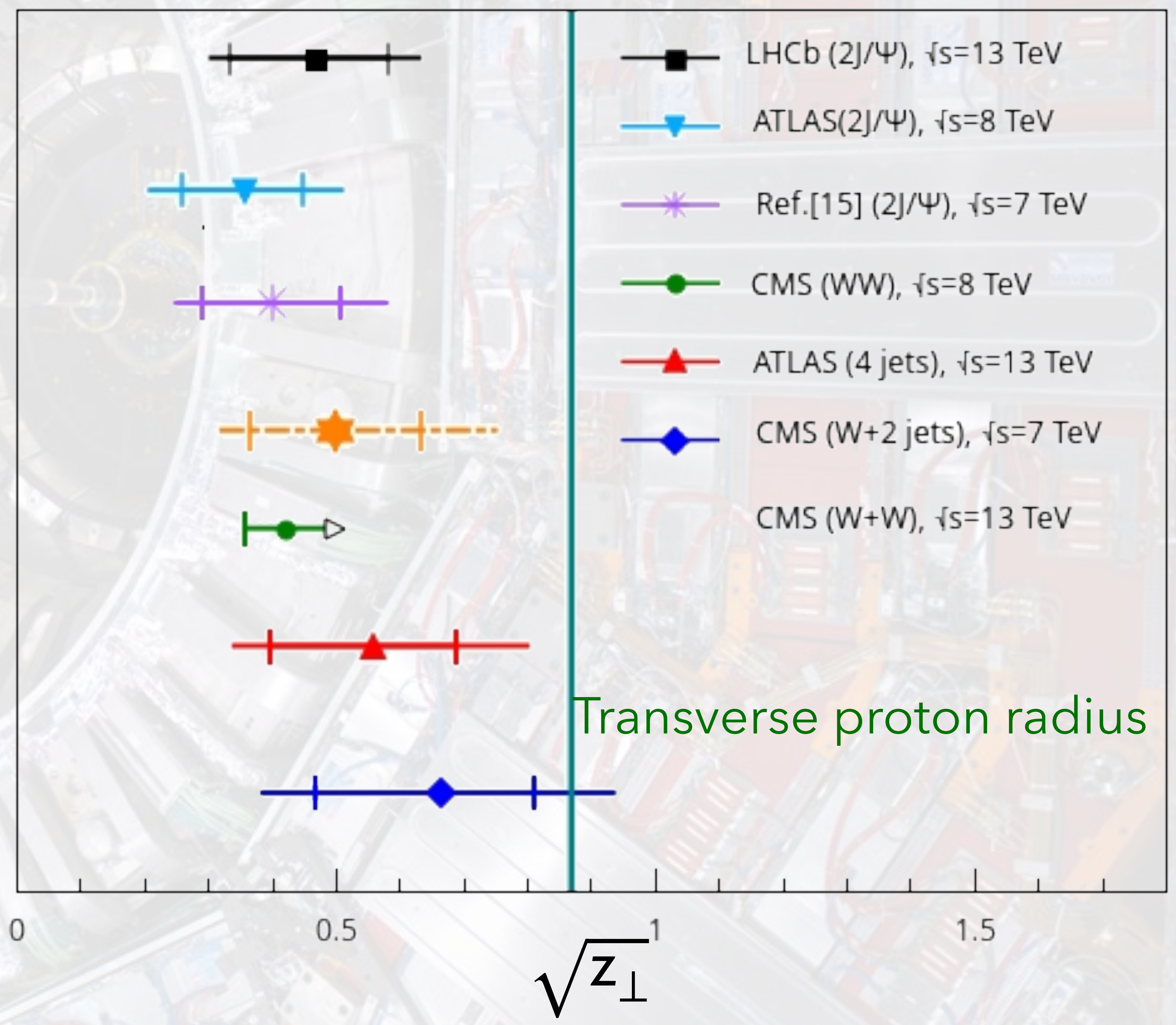
If DPDs factorize in terms of PDFs then $\sigma_{\text{eff}}^{-1} = \int d^2 z_\perp \; \tilde{T}(z_\perp)^2 = \int \frac{d^2 k_\perp}{(2\pi)^2} \boxed{T(k_\perp)^2}$

As for the standard FF:

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

From the asymptotic behavior we got the following relation:

$$\frac{\sigma_{\text{eff}}}{3\pi} \leq \langle z_\perp^2 \rangle \leq \frac{\sigma_{\text{eff}}}{\pi}$$



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

DPS in pA collisions - why?

1) Increase the DPS cross-section
2) easier to extract $\sigma_{eff,pp}$
3) in the future we can extract information on **NEUTRON** DPDs
4) Nuclear effects in DPDs!!
5) Are DPDs of free proton the same of those for bound protons?

DPS in pA collisions

1)Same-sign WW production in proton-nucleus collisions at the LHC as a signal for double parton scattering
D. d'E. & A. Snigirev, PLB 718 (2013) 1395-1400

2)Enhanced J/ΨJ/\PsiJ/Ψ-pair production from double parton scatterings in nucleus-nucleus collisions at the Large Hadron Collider
D. d'E. & A. Snigirev, PLB 727 (2013) 157-162

3)Pair production of quarkonia and electroweak bosons from double-parton scatterings in nuclear collisions at the LHC
D. d'E. & A. Snigirev, Nucl. Phys. A 931 (2014) 303-308

4) **B. Blok et al, EPJC (2013) 73:2433**

5) **B. Blok and F. A. Ceccopieri, PRD 101, 094029 (2020)**

6) **B. Blok and F. A. Ceccopieri, EPJC (2020) 80:278**

7) **D. Treleani and G. Calucci, PRD 86, 036003 (2012)**

8) **M. Strickman and D. Treleani, PRL 88, 031801 (2002)**

9) **E. Cattaruzza, A. del Fabbro and D. Treleani, PRD 70, 034022 (2004)**

DPS in pA collisions

$$\mathsf{F}_{\mathsf{a}_1\mathsf{a}_2}(\mathsf{x}_1, \mathsf{x}_2, \mathbf{y}_\perp) = 2p^+ \int \frac{dz_1^-}{2\pi} \frac{dz_2^-}{2\pi} dy^- e^{i(x_1 z_1^- + x_2 z_2^-)p^+}$$
$$\times \langle \mathsf{A} | \mathcal{O}_{\mathsf{a}_2}(0, \mathsf{z}_2) \mathcal{O}_{\mathsf{a}_1}(\mathsf{y}, \mathsf{z}_1) | \mathsf{A} \rangle$$

In this case we have two mechanisms that contribute:

DPS in pA collisions

$$F_{a_1a_2}(x_1,x_2,\mathbf{y}_\perp) = 2p^+ \int \frac{dz_1^-}{2\pi}\frac{dz_2^-}{2\pi}\, dy^-\, e^{i(x_1 z_1^- + x_2 z_2^-)p^+} \times \langle A|\mathcal{O}_{a_2}(0,z_2)\mathcal{O}_{a_1}(y,z_1)|A\rangle$$

In this case we have two mechanisms that contribute:

B. Blok et al, EPJC (2013) 73:2422

DPS 1: The two partons belong to the SAME nucleon in the nucleus!

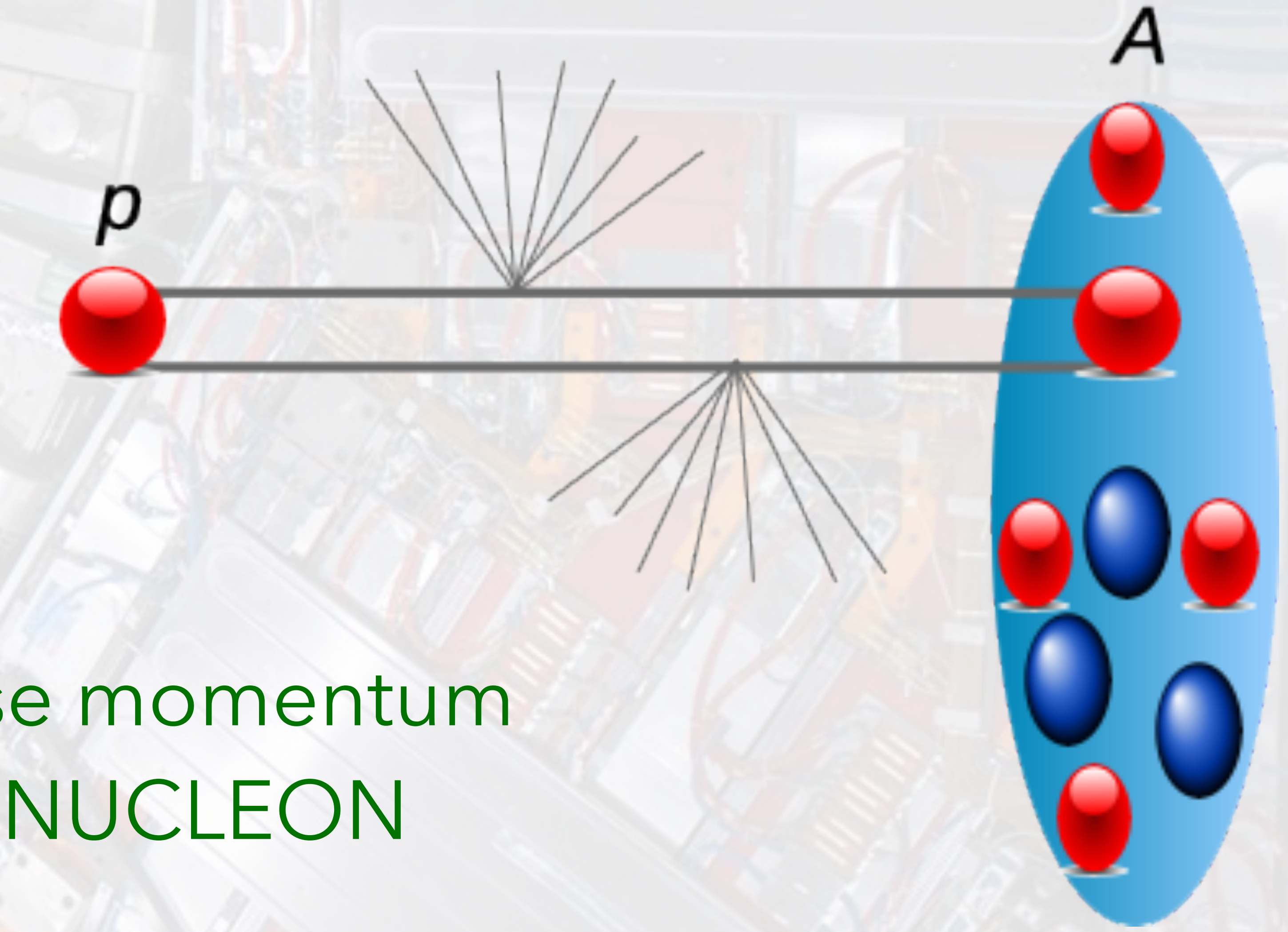
DPD of te nucleon inside the nucleus

$$\tilde{F}^1_{a_1a_2}(x_1,x_2,k_\perp) = \sum_{N=p,n}\int \frac{1}{\xi}\boxed{\tilde{F}^N_{a_1a_2}\left(\frac{x_1}{\xi},\frac{x_2}{\xi},k_\perp\right)}\boxed{\rho^N_A(\xi,p_{t,N})}\frac{d\xi}{\xi}\boxed{d^2p_{t,N}}$$

Momentum fraction carried by a NUCLEON

Light-Cone Momentum Distribution

Transverse momentum of the NUCLEON



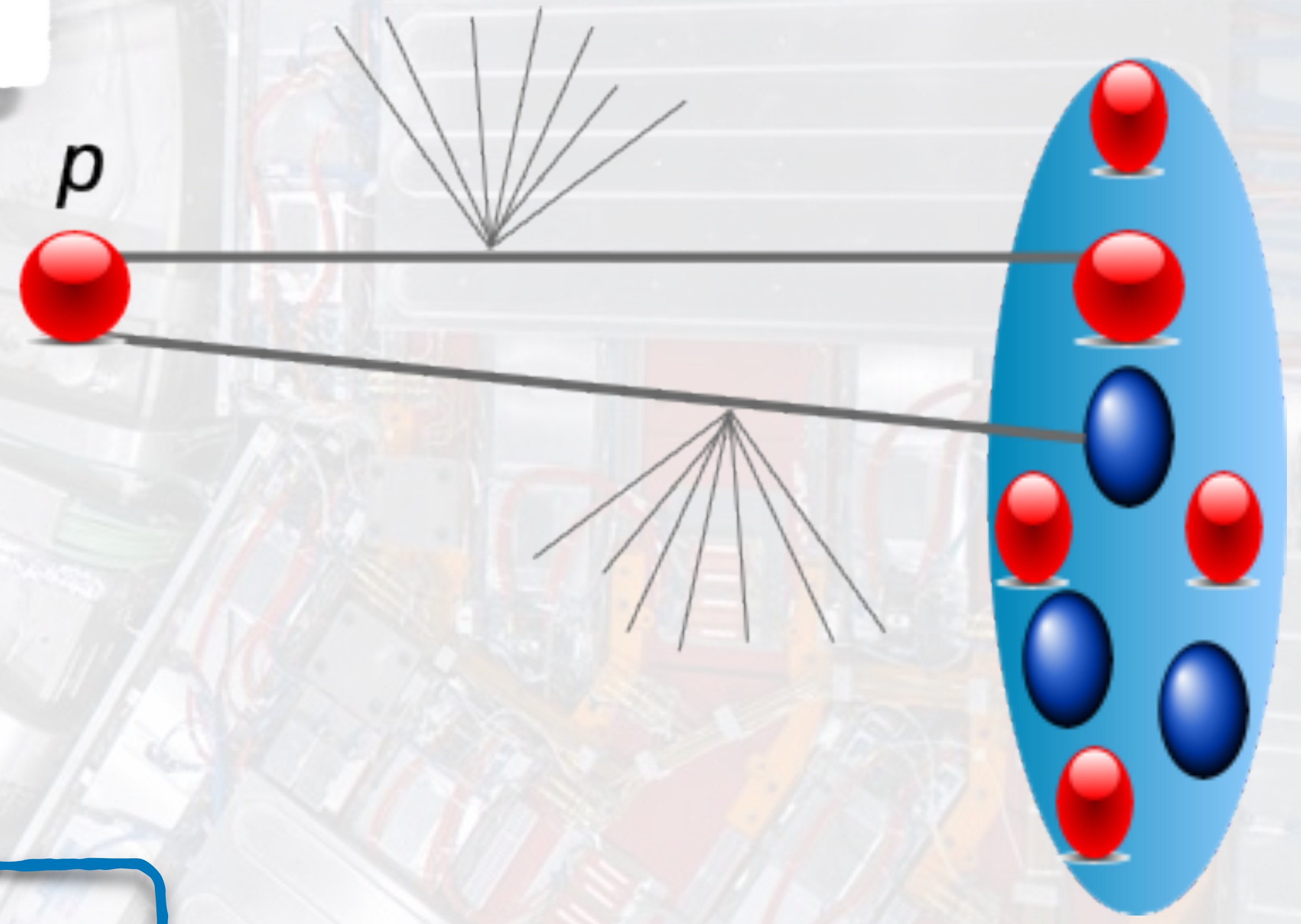
DPS in pA collisions

$$F_{a_1a_2}(x_1, x_2, \mathbf{y}_\perp) = 2p^+ \int \frac{dz_1^-}{2\pi}\frac{dz_2^-}{2\pi} dy^- e^{i(x_1 z_1^- + x_2 z_2^-)p^+} \times \langle A | \mathcal{O}_{a_2}(0, z_2)\mathcal{O}_{a_1}(y, z_1) | A \rangle$$

In this case we have two mechanisms that contribute:

B. Blok et al, EPJC (2013) 73:2422

DPS 2: The two partons belong to the DIFFERENT nucleons in the nucleus!



$$\tilde{F}^2_{a_1a_2}(x_1, x_2, \vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2 p_{ti}}{\xi_i} \delta\left(\sum_i \xi_i - A\right) \delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right) \boxed{\psi_A^*(\xi_1, \xi_2, p_{t1}, p_{t2}, \dots)}$$

$$\times \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp, \dots\right) G_{a_1}^{N_1}\left(x_1/\xi_1, |\vec{k}_\perp|\right) \boxed{G_{a_2}^{N_2}\left(x_2/\xi_2, |\vec{k}_\perp|\right)}$$

Nucleus wf

Nucleon GPD

DPS in pA collisions

D. d' Enterria and A. Snigirev, PLB 718 (2013)

One can generalize the "Pocket formula":

$$\sigma_{\mathrm{pA}}^{\mathrm{DPS}} = \sigma_{\mathrm{pA}}^{\mathrm{DPS,1}} + \sigma_{\mathrm{pA}}^{\mathrm{DPS,2}}$$

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$$\sigma_{pA}^{DPS,1} \longrightarrow A\sigma_{pp}^{DPS}$$

$$\sigma_{pA}^{DPS,2} \longrightarrow \sigma_{pp}^{DPS} \cdot \sigma_{eff,pp} \cdot \boxed{F_{pA}}$$

$\boxed{F_{pA}}$ Related to the transverse nuclear distribution. Can be evaluated with some models for heavy ions and realistically for light-nuclei

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$$\boxed{\sigma_{eff,pA} = \frac{\sigma_{eff,pp}}{A + \sigma_{eff,pp} F_{pA}}}$$

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$$\sigma_{pA}^{DPS,2} \longrightarrow \sigma_{pp}^{DPS} \cdot \sigma_{\mathrm{eff,pp}} \cdot \boxed{F_{pA}}$$

$$\boxed{\sigma_{\mathrm{eff,pA}} = \frac{\sigma_{\mathrm{eff,pp}}}{A + \sigma_{\mathrm{eff,pp}} F_{pA}}}$$

For pPb: $\begin{cases} \text{Wood-Saxon density} \\ \sigma_{\mathrm{eff,pp}} \sim 13\ mb \end{cases}$

$$\sigma_{\mathrm{eff,pPb}} \sim 22\ \mu\mathrm{b}$$

DPS in pA collisions

D. d' Enterria and A. Snigirev, PLB 718 (2013)

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$$\sigma_{pA}^{DPS,2} \longrightarrow \sigma_{pp}^{DPS} \cdot \sigma_{eff,pp} \cdot \boxed{F_{pA}}$$

$$\boxed{\sigma_{eff,pA} = \frac{\sigma_{eff,pp}}{A + \sigma_{eff,pp} F_{pA}}}$$

If $\sigma_{eff,pA}$ is experimentally obtained then we can extract $\sigma_{eff,pp}$

DPS in pA collisions

Some examples of prediction:

W+di-jets

B. Blok and F. A. Ceccopieri EPJC (2020) 80, 278

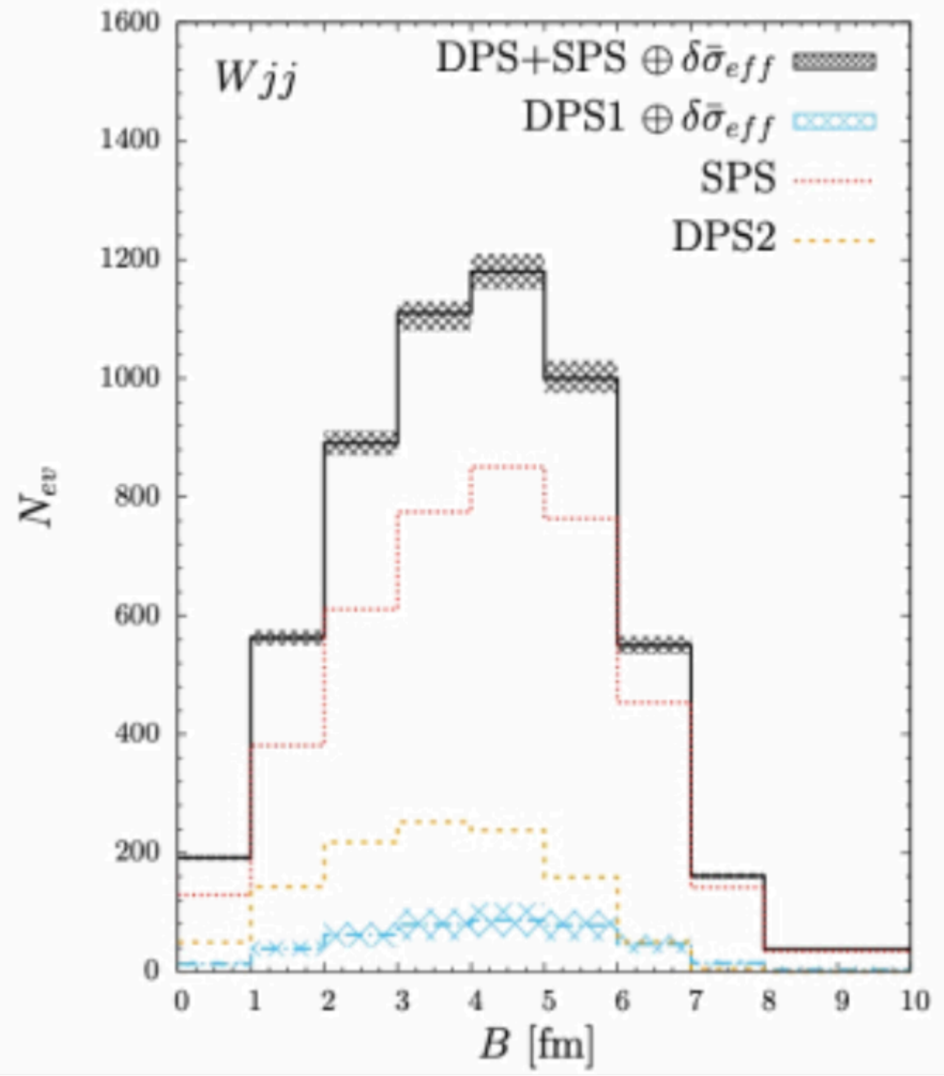
DPS in pA collisions

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

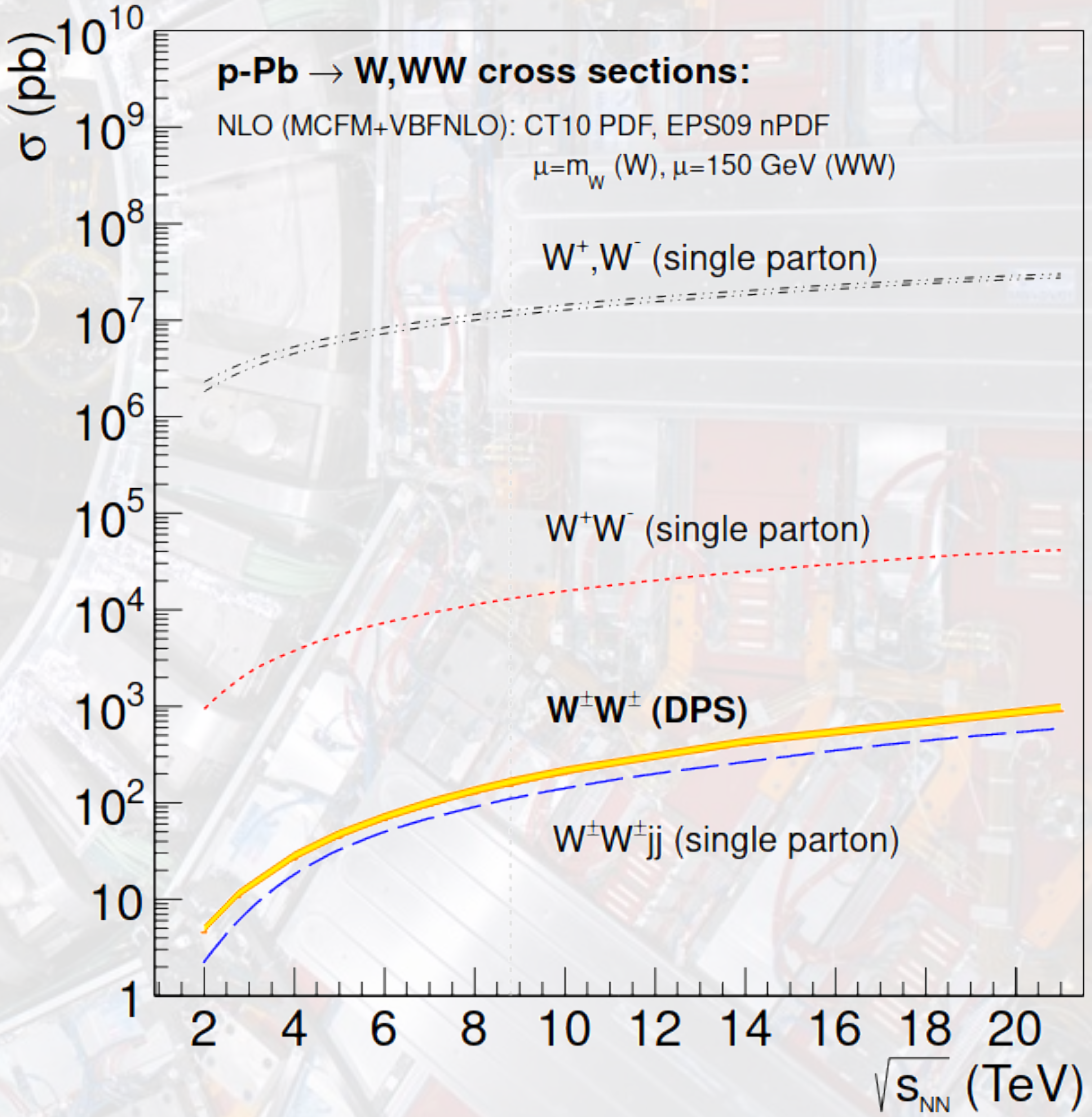
- SPS dominant
- DPS2 bigger then DPS1 has expected

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



Same sign WW

D. D'Enterria and Snigirev, PLB 718 (2013) 1395-1400



DPS in pA collisions - predictions

[DdE, Snigirev, NPA 931 (2014) 303]

- Cross sections & rates for DPS processes with J/ψ,ϒ & W, Z bosons
  [Also V. Goncalves (2018): double-J/ψ; Paukunen (2019): double-D,...]

pPb (8.8 TeV)	$J/\psi + J/\psi$	$J/\psi + \Upsilon$	J/ψ+W	J/ψ+Z
$\sigma^{\rm SPS}_{{\rm pN}\to a}, \sigma^{\rm SPS}_{{\rm pN}\to b}$	45 μb ($\times$2)	45 μb, 2.6 μb	45 μb, 60 nb	45 μb, 35 nb
$\sigma^{\rm DPS}_{\rm pPb}$	45 μb	5.2 μb	120 nb	70 nb
$N^{\rm DPS}_{\rm pPb}$ (1 pb^{-1})	~65	~60	~15	~3
	$\Upsilon + \Upsilon$	Υ+W	Υ+Z	ss WW
$\sigma^{\rm SPS}_{{\rm pN}\to a}, \sigma^{\rm SPS}_{{\rm pN}\to b}$	2.6 μb ($\times$2)	2.6 μb, 60 nb	2.6 μb, 35 nb	60 nb ($\times$2)
$\sigma^{\rm DPS}_{\rm pPb}$	150 nb	7 nb	4 nb	150 pb
$N^{\rm DPS}_{\rm pPb}$ (1 pb^{-1})	~15	~8	~1.5	~4

Leptonic final states: BR(J/ψ,ϒ,W,Z) = 6%, 2.5%, 11%, 3.4%
Accept.*Effic.= 1% (J/ψ, |y|=0,2), 20% (ϒ, |y|<2.5), 50% (W,Z |y|<2.4)

- Many double hard scatterings processes with visible p-Pb x-sections at the LHC. (Note: J/ψ values are per unit-|y|).
- Useful independent extraction of $\sigma_{\rm eff,pp}$!

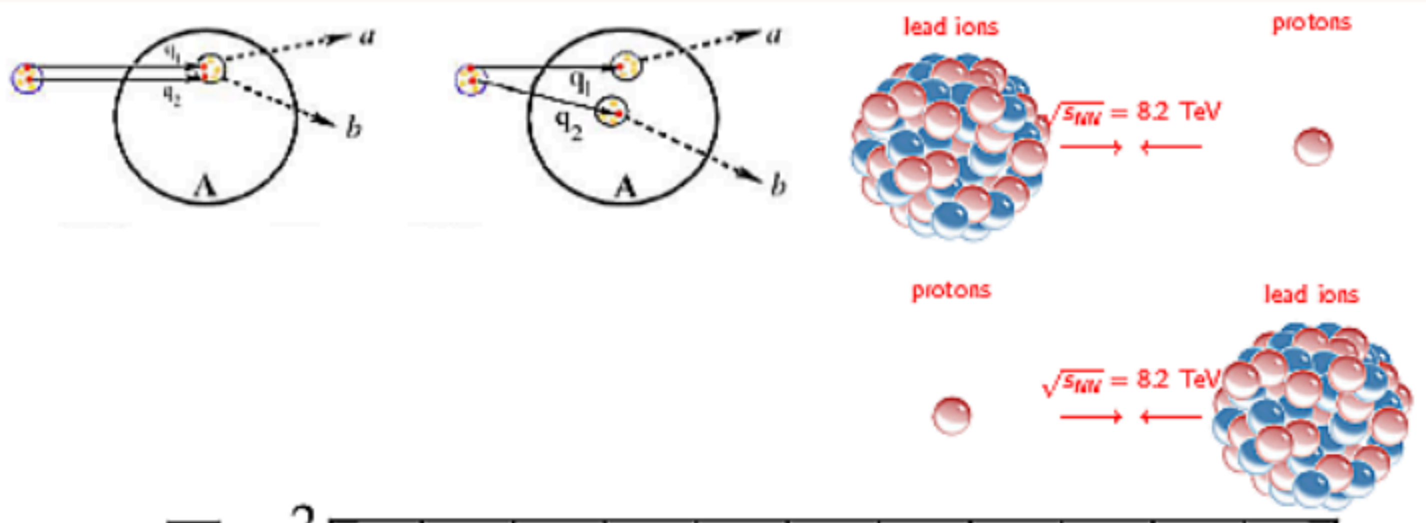
D. d'Enterria's slide

DPS in pA collisions

[LHCb, PRL 125 (2020) 212001]

Double-charm production in p-Pb collisions:

- select pairs of D^0, $\bar{D}^0$, D^+, D^-, D_s^+, D_s^- and J/ψ
- sort them into pair production and "DPS" categories $\sigma_{C_1,C_2} = \alpha \frac{\sigma_{C_1}\sigma_{C_2}}{\sigma_{\text{eff}}}$



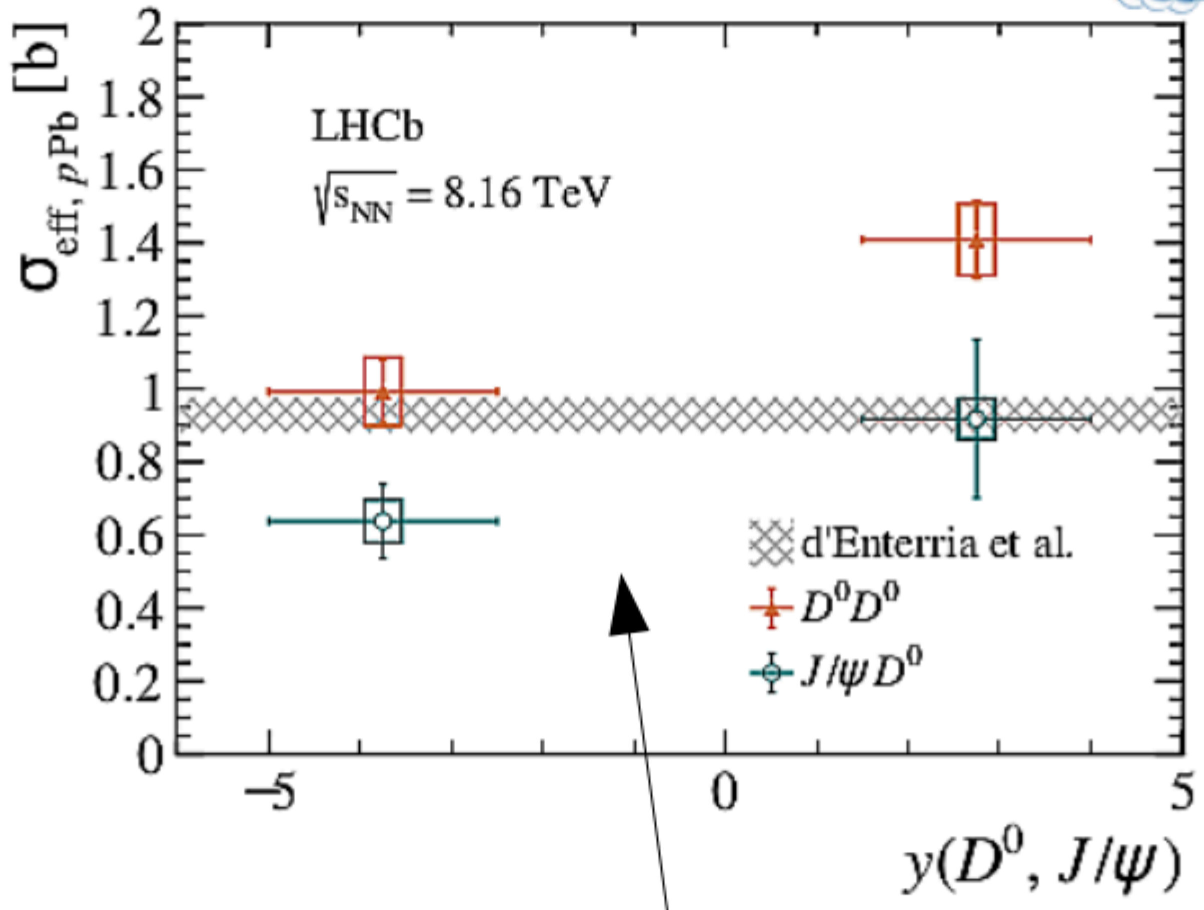
$$R^{D_1D_2}_{forward} = \frac{\sigma_{D_1D_2}}{\sigma_{D_1\bar{D}_2}} = 0.308 \pm 0.015 \pm 0.010$$

$$R^{D_1D_2}_{backward} = 0.391 \pm 0.019 \pm 0.025$$

$$R^{D^0D^0}_{pp} = 0.109 \pm 0.008$$

Like sign charm fraction tripled!

$\sqrt{s_{NN}} = 8.2$ TeV *Phys. Rev. Lett. 125 (2020) 212001*



Albert Bursche | charming DPS | 10^{th} October 2021 | 15 / 17

- Useful independent extraction of $\sigma_{\text{eff,pp}}$: $\sigma_{\text{eff,pA}} = \frac{\sigma_{\text{eff,pp}}}{A + \sigma_{\text{eff,pp}} F_{\text{pA}}}$

$\sigma_{\text{eff,pp}}(D^0D^0)$ = 7–16 mb
$\sigma_{\text{eff,pp}}(J/\psi D^0)$ = 13–40 mb

nPDF effects visible in -y/+y results.

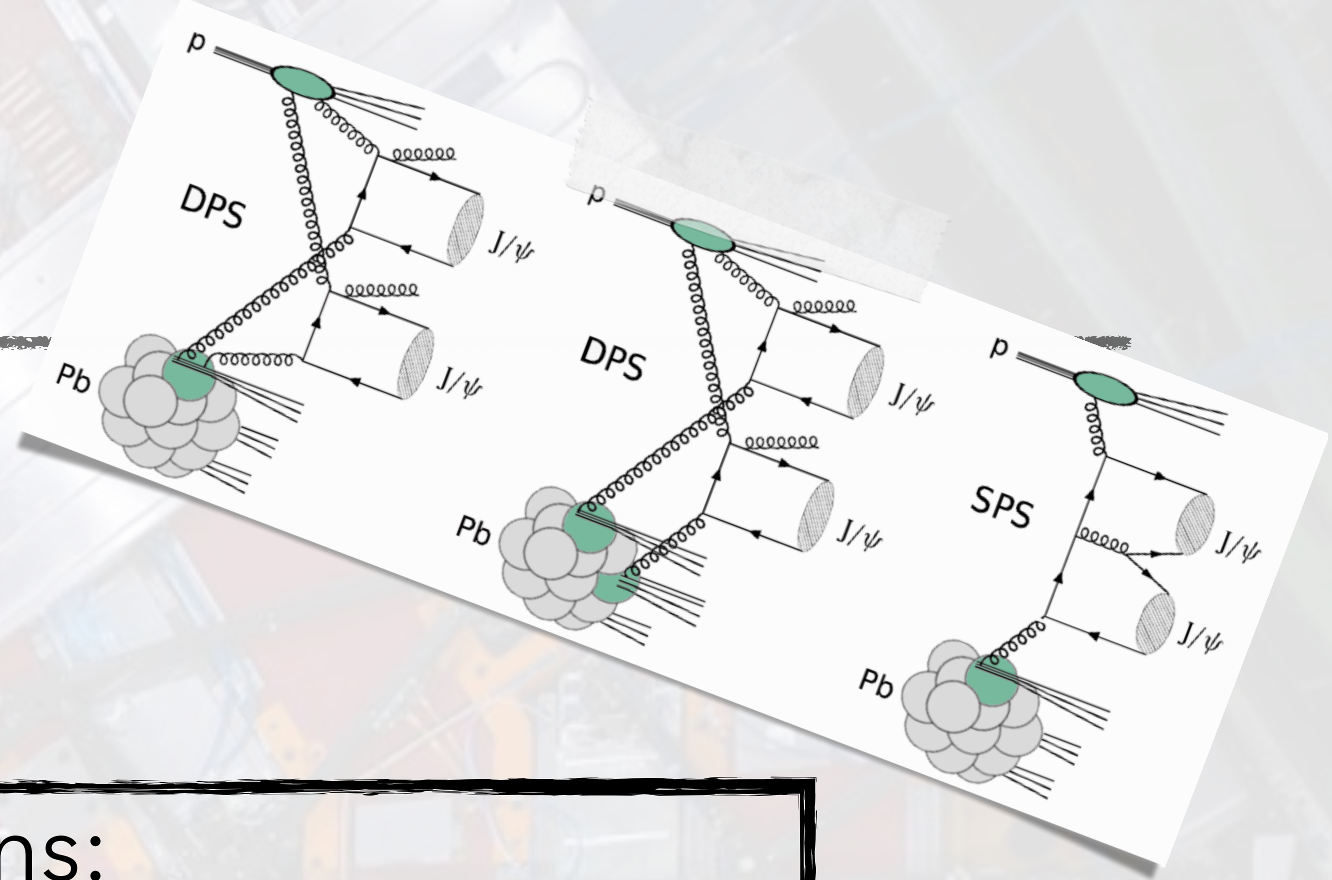
(LHCb should quote the equivalent $\sigma_{\text{eff,pp}}$ values...)

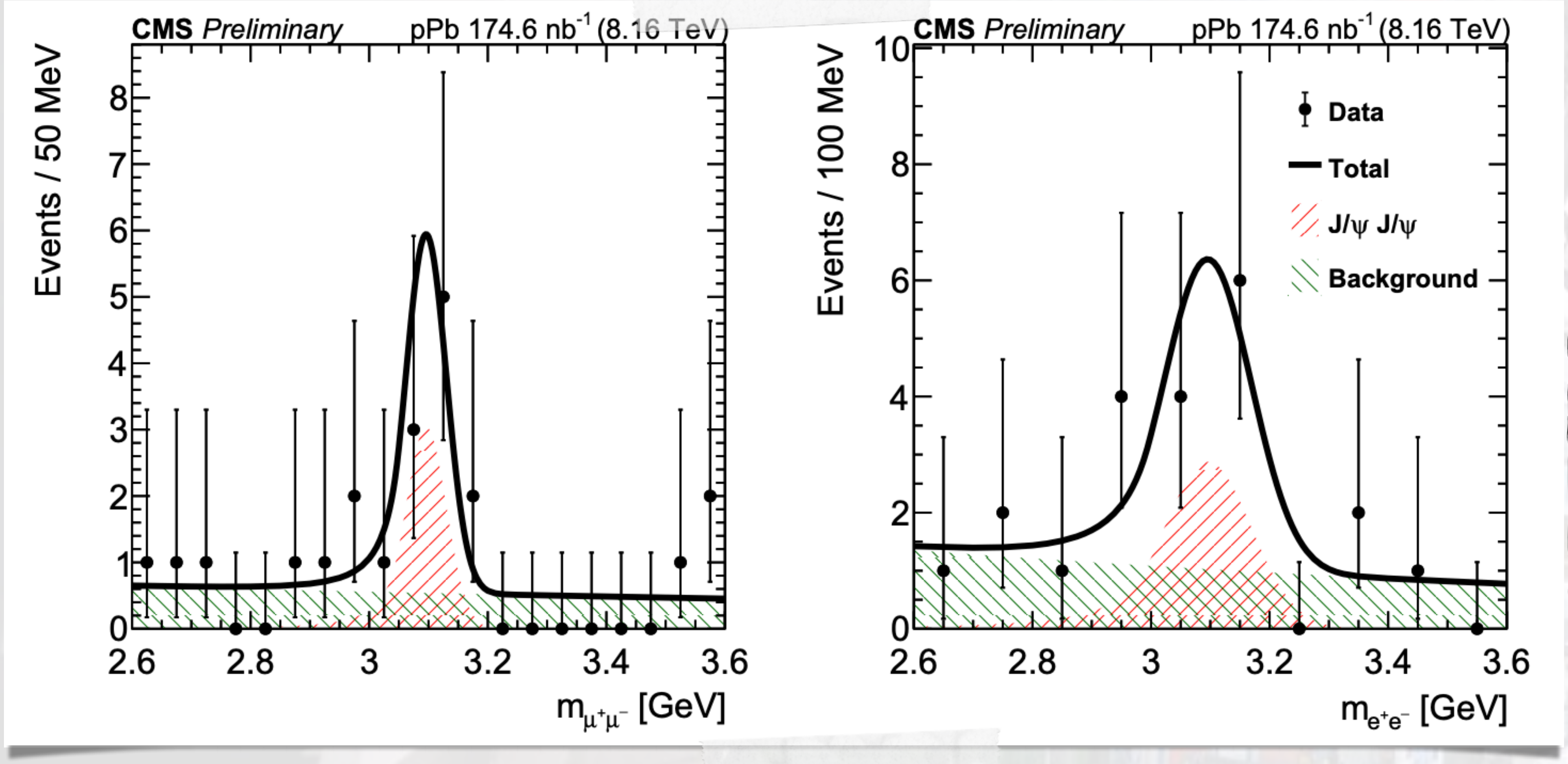
QaT2024, Aussois, Jan'24 — 11/26 — David d'Enterria (CERN)

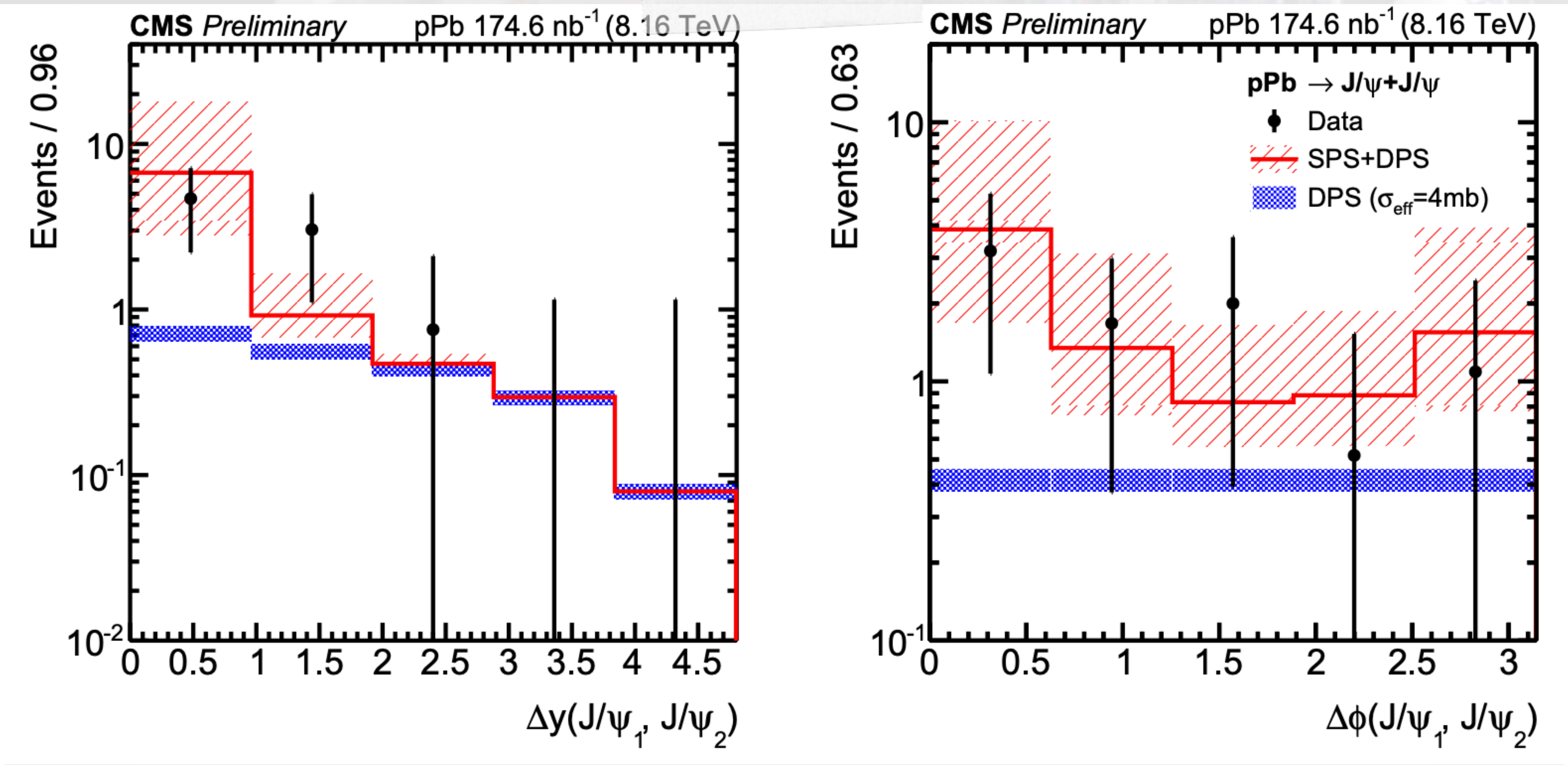
D. d'Enterria's slide

DPS in pA collisions

double-J/ψ meson production in pPb collisions at 8.16 TeV







The relative cross-section contributions:

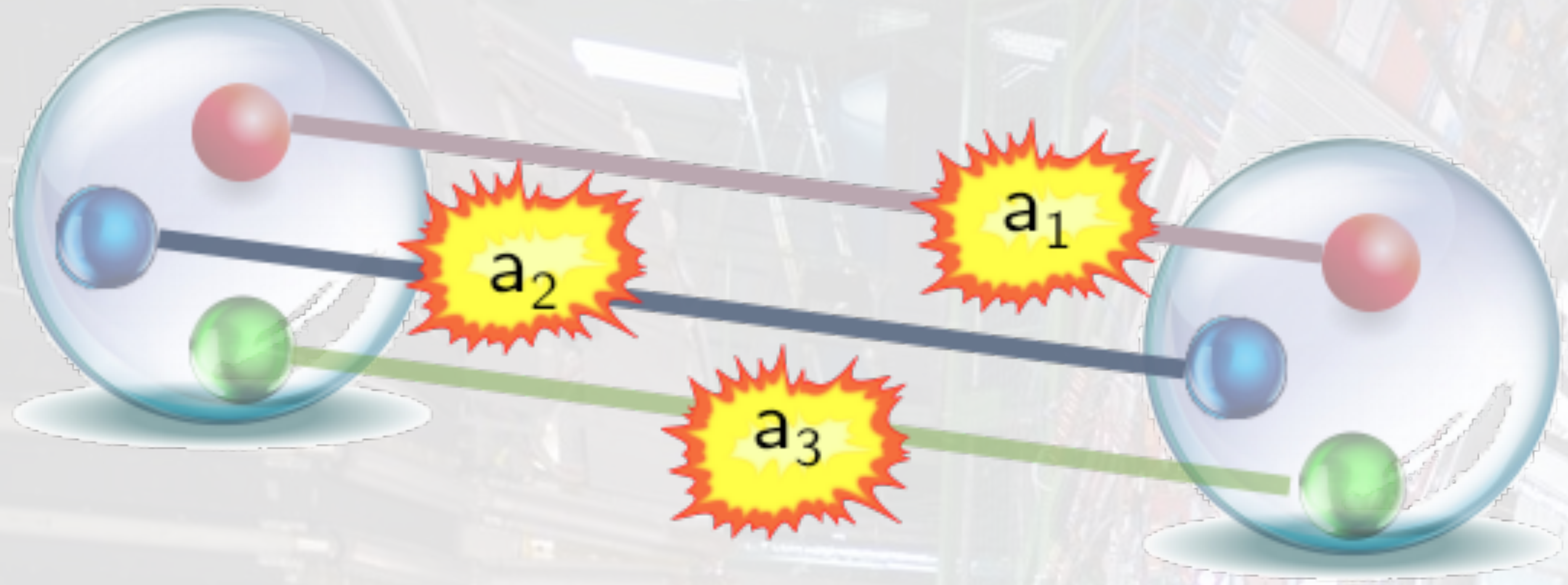
$$\sigma_{\mathrm{SPS}}^{\mathrm{PPb}\to \mathrm{J}/\psi \mathrm{J}/\psi+\mathrm{X}} = 16.5 \pm 10.8\ (\mathrm{stat})\ \pm 0.1\ (\mathrm{syst})\ \mathrm{nb}$$

$$\sigma_{\mathrm{DPS}}^{\mathrm{pPb}\to \mathrm{J}/\psi \mathrm{J}/\psi+\mathrm{X}} = 5.4 \pm 6.2\ (\mathrm{stat})\ \pm 0.4\ (\mathrm{syst})\ \mathrm{nb}$$

The extracted pp effective X-section:

$$\sigma_{\mathrm{eff,pp}} = 4.0^{+\infty}_{-1.5}\ \mathrm{mb}$$

Triple Parton Scattering



A pocket formula for Triple parton Scattering (TPS)

$$\sigma_{\text{TPS}} \propto \frac{\sigma_{a_1}^{\text{SPS}} \sigma_{a_2}^{\text{SPS}} \sigma_{a_3}^{\text{SPS}}}{\sigma_{\text{eff,TPS}}^2}$$

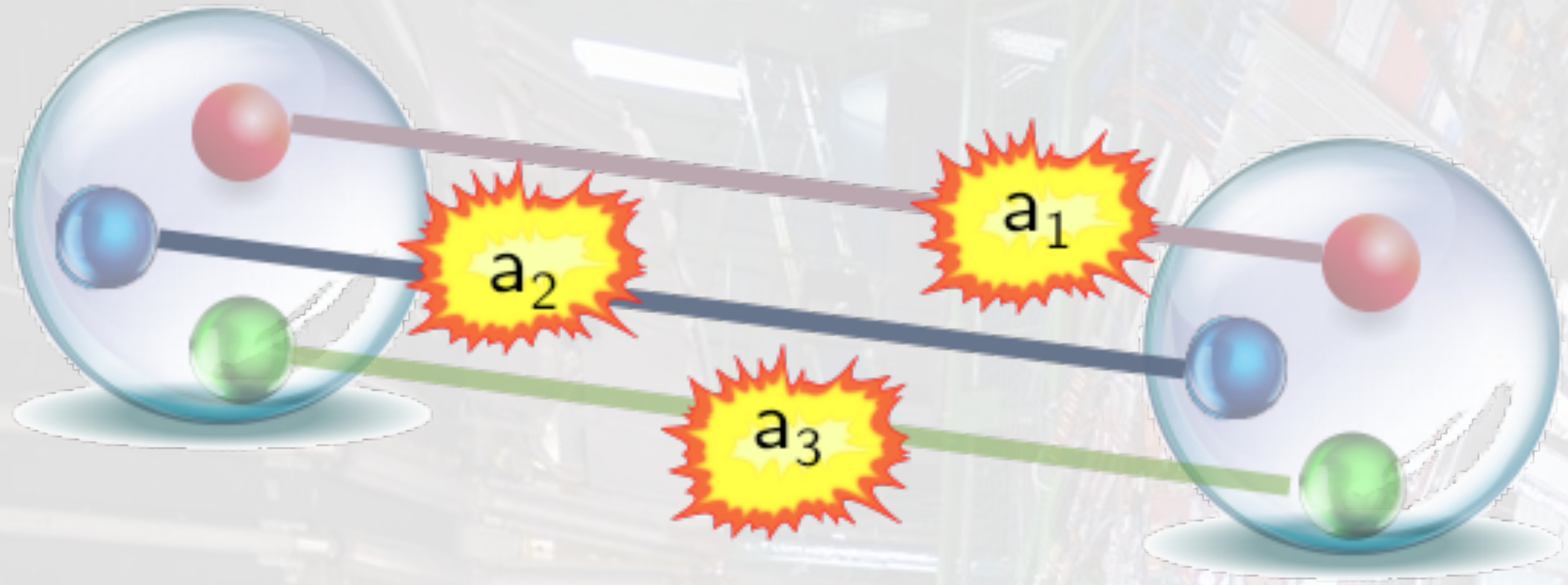
D. d' E. et al PRL 118 (2017) 122001

TPS is a new window to access new information on the hadron structure:

$$\sigma_{\text{eff,TPS}}^2 = \left[\int d^2 b T^3(\mathbf{b}) \right]^{-1} \xrightarrow{\text{Model calculations}} \boxed{\sigma_{\text{eff,TPS}} = k \times \sigma_{\text{eff,DPS}}, \;\; \text{with} \;\; k = 0.82 \pm 0.11}$$

1) $\sigma_{\text{eff,TPS}}$ encodes new details on the geometrical structure
2) Triple Parton Distributions (tPDFs) could depend from unknown triple parton correlations!

Triple Parton Scattering



A pocket formula for Triple parton Scattering (TPS)

$$\sigma_{\mathrm{TPS}} \propto \frac{\sigma^{\mathrm{SPS}}_{a_1}\sigma^{\mathrm{SPS}}_{a_2}\sigma^{\mathrm{SPS}}_{a_3}}{\sigma^2_{\mathrm{eff,TPS}}}$$

D. d' E. et al PRL 118 (2017) 122001

SUM rules can be used to build phenomenological distributions: **O. Fedkevych and J. R. Gaunt, JHEP 02, 090 (2023)**

$$\sum_{j_3}\int_0^{1-x_1-x_2} dx_3 x_3 T^B_{j_1j_2j_3}(x_1,x_2,x_3) = (1-x_1-x_2)D^B_{j_1j_2}(x_1,x_2)$$

Momentum Sum Rule

$$\int_0^{1-x_1-x_2} dx_3 \underbrace{\boxed{T^B_{j_1j_2j_{3v}}(x_1,x_2,x_3)}}_{\text{tPDF}} = \left(N_{j_{3v}} - \delta_{j_3j_1} - \delta_{j_3j_2} + \delta_{\bar{j}_3j_1} + \delta_{\bar{j}_3j_2}\right)\underbrace{\boxed{D^B_{j_1j_2}(x_1,x_2)}}_{\text{dPDF}}$$

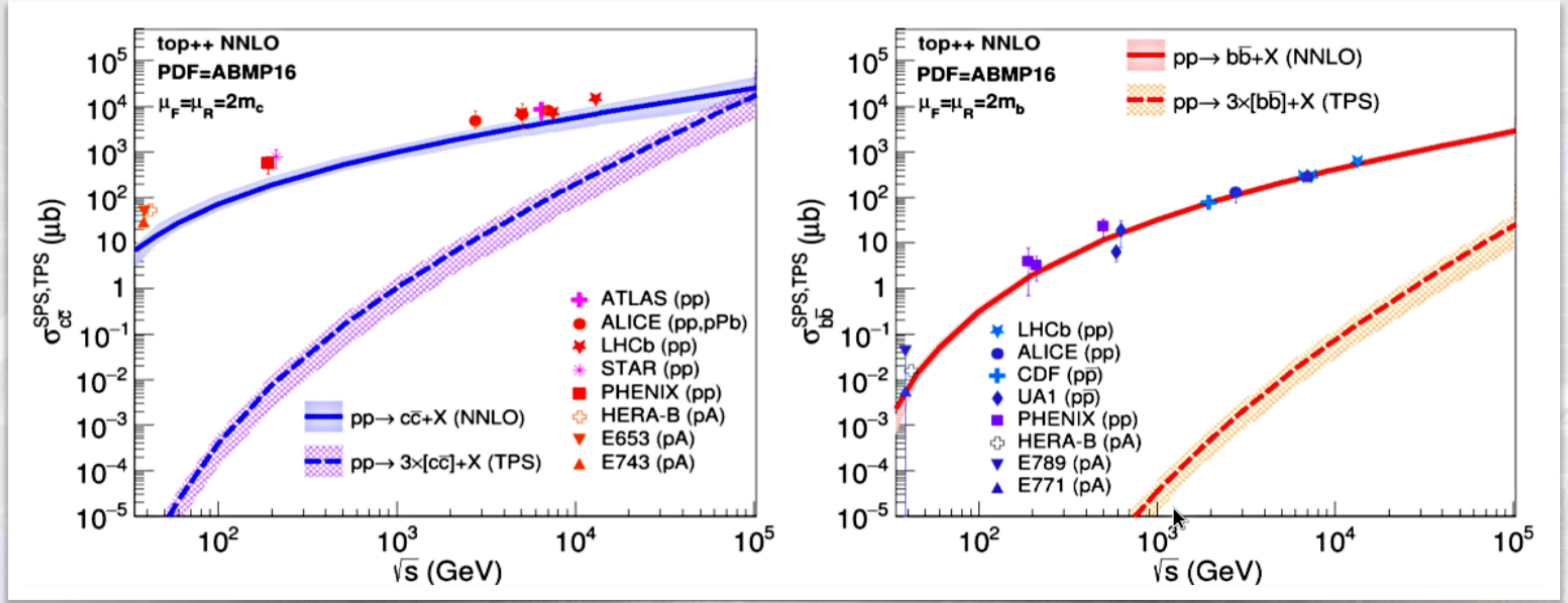
Number Sum Rule

Distribution integrated on transverse dependence

Triple Parton Scattering - where?

Triple Charm and Beauty production

D. d'Enterria and A. M. Snigirev, Phys. Rev. Lett. 118, no.12, 122001 (2017)

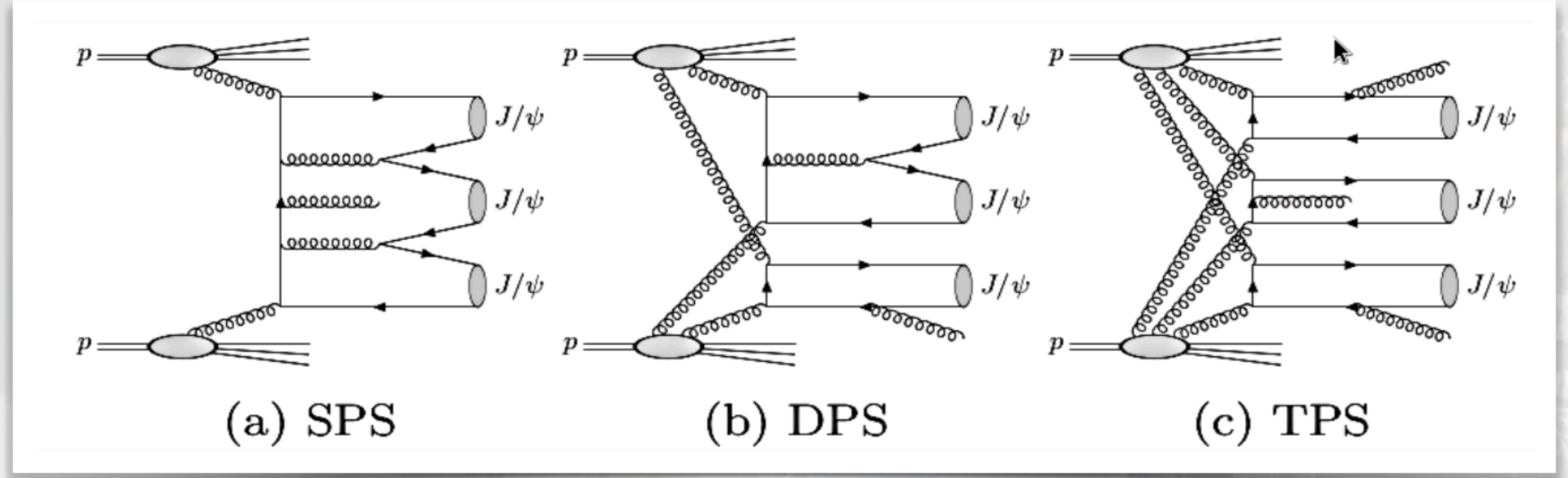


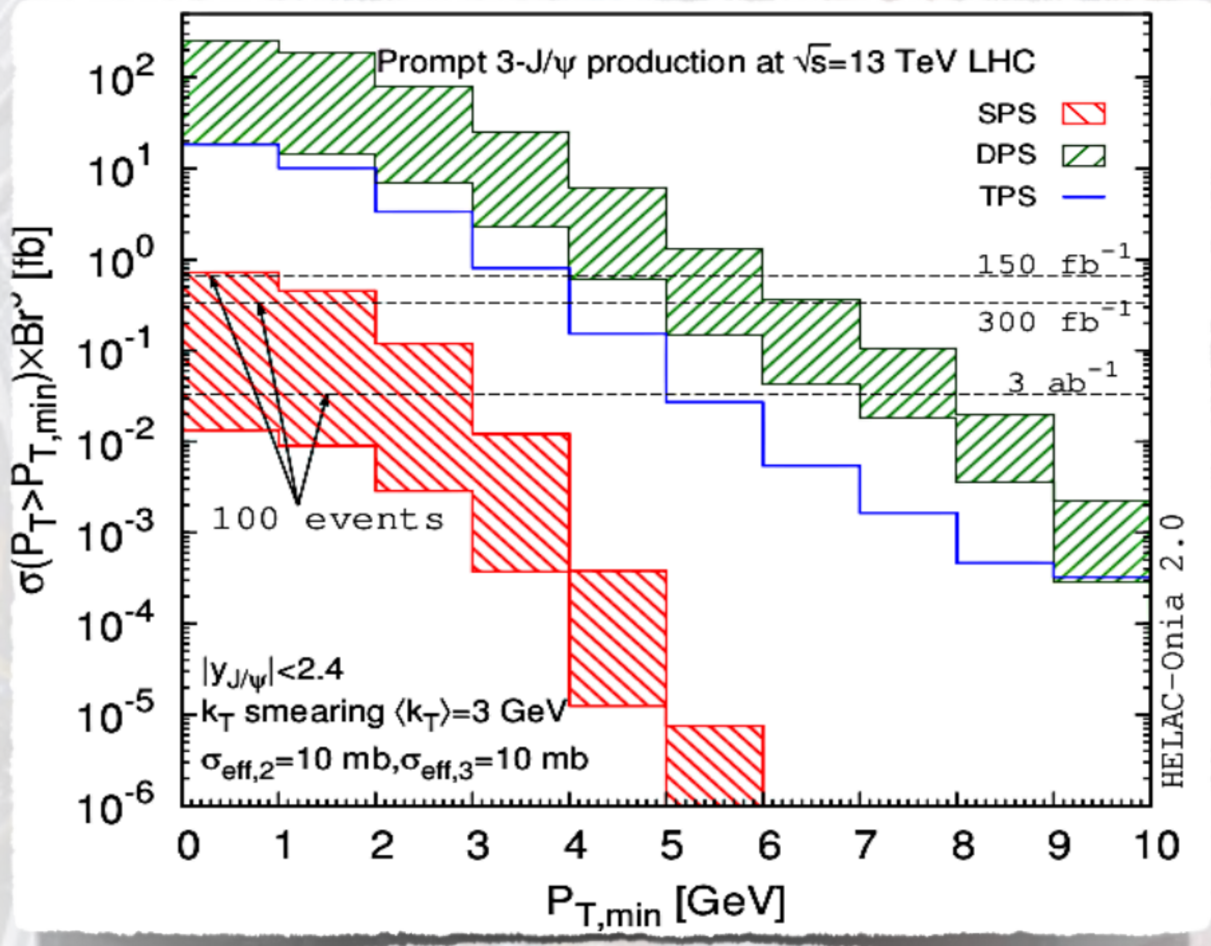
- small x-section, but it increases fast with the c.m. energy
- Since triple charm is > 15% of the inclusive charm production

→ Important channel to extract the DPS and TPS contributions

Triple Parton Scattering - where?

Triple J/Ψ production! **H. S. Shao and Y. J. Zhang, Phys. Rev. Lett. 122, no.19, 192002 (2019)**





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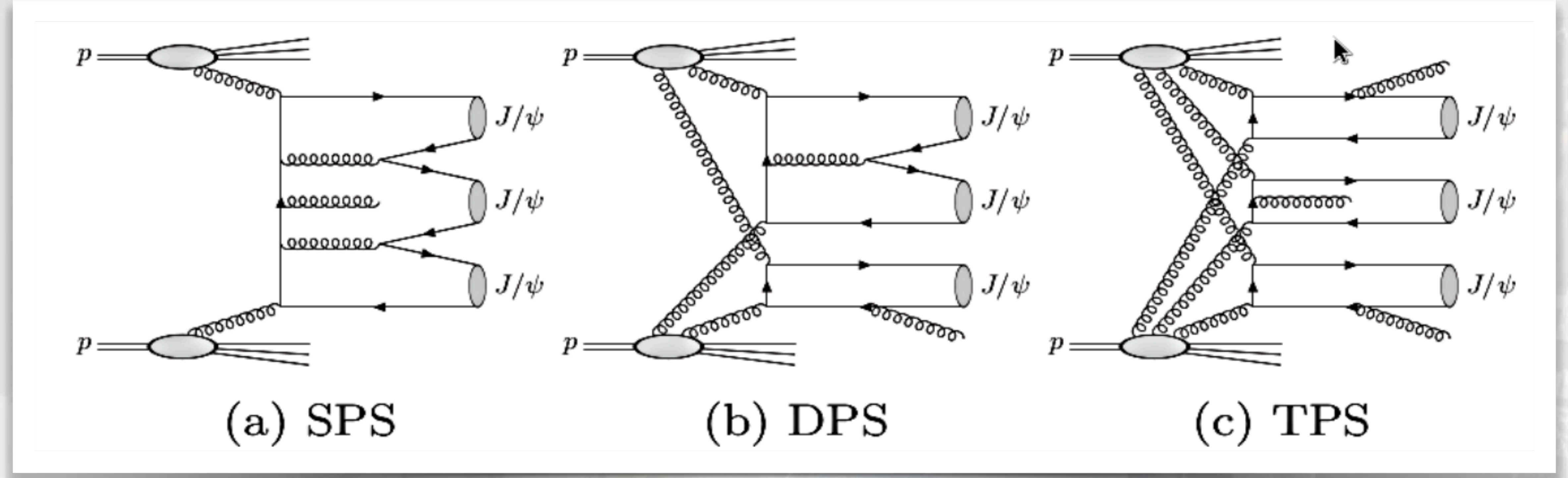

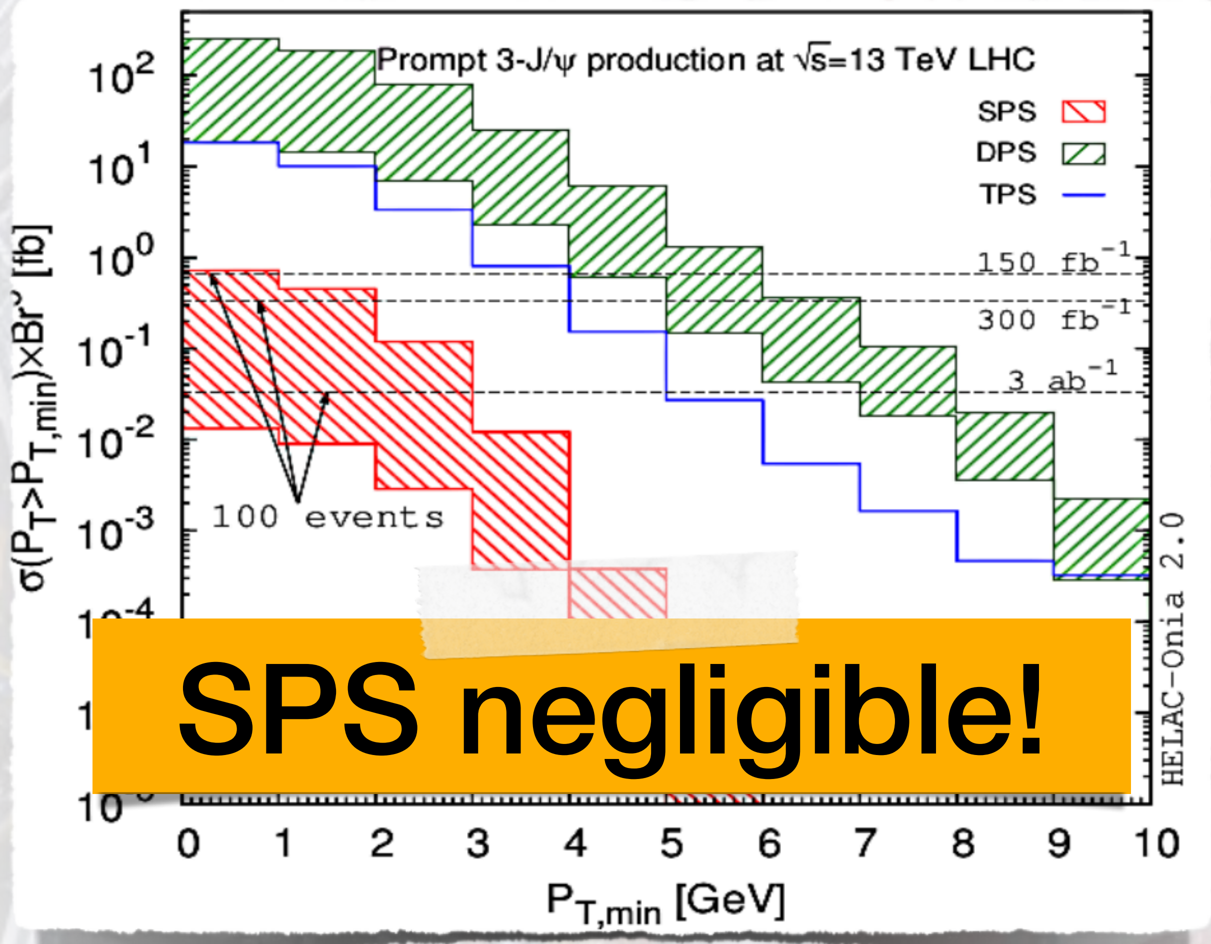

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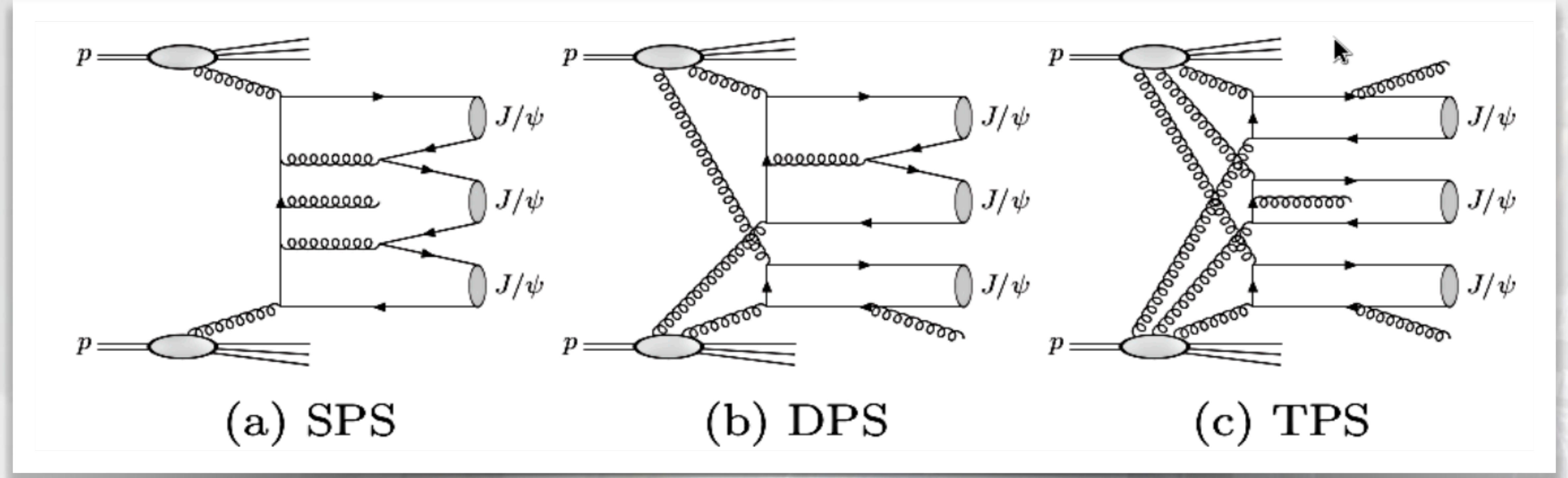

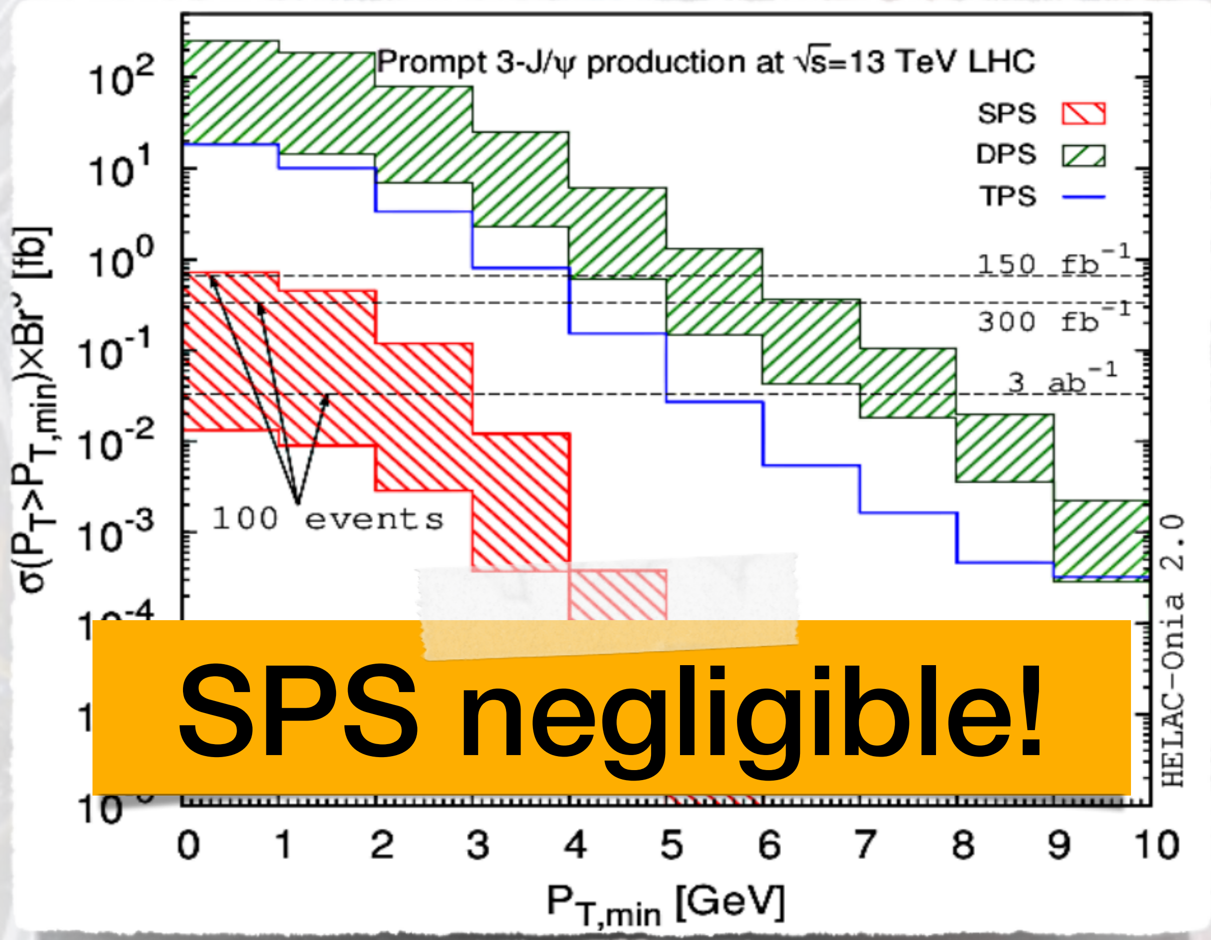

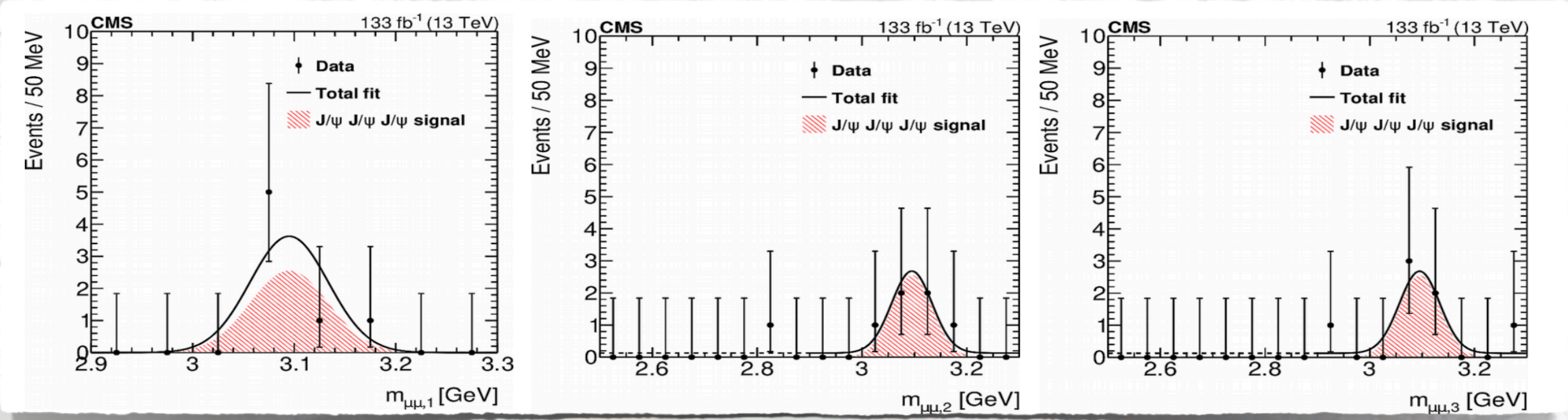

- $\sigma = 272^{+141}_{104}$ (stat) $\pm$ 17 (syst) fb

A. Tumasyan et al [CMS], Nature Phys. 19, no.3, 338-350 (2023)

Triple Parton Scattering - where?

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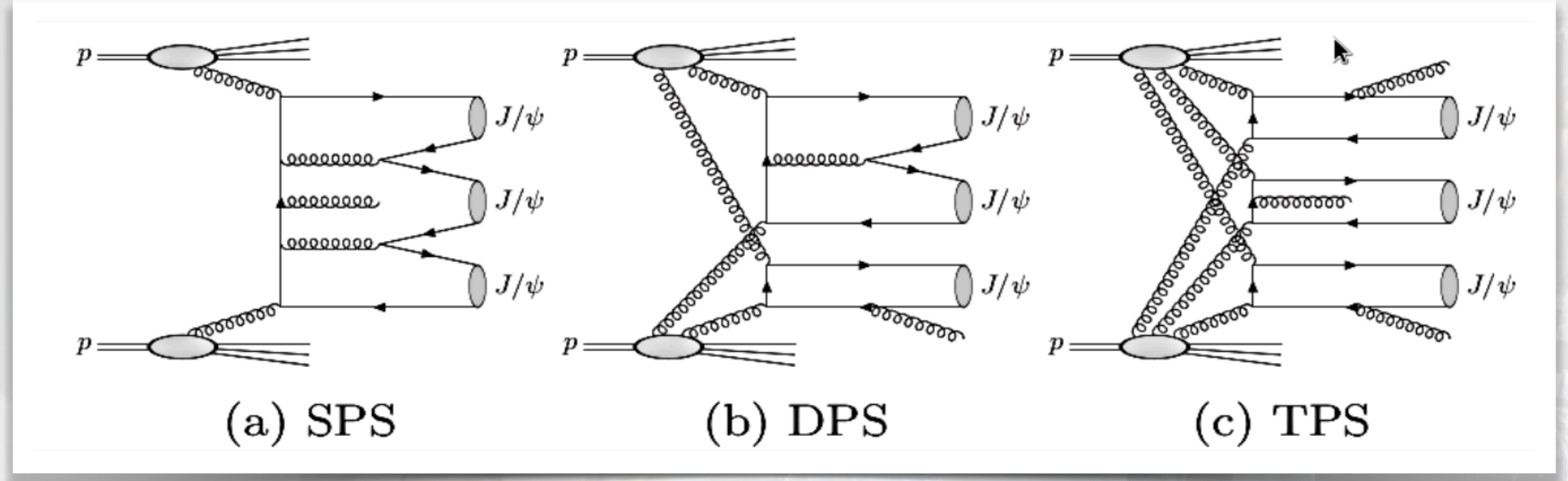

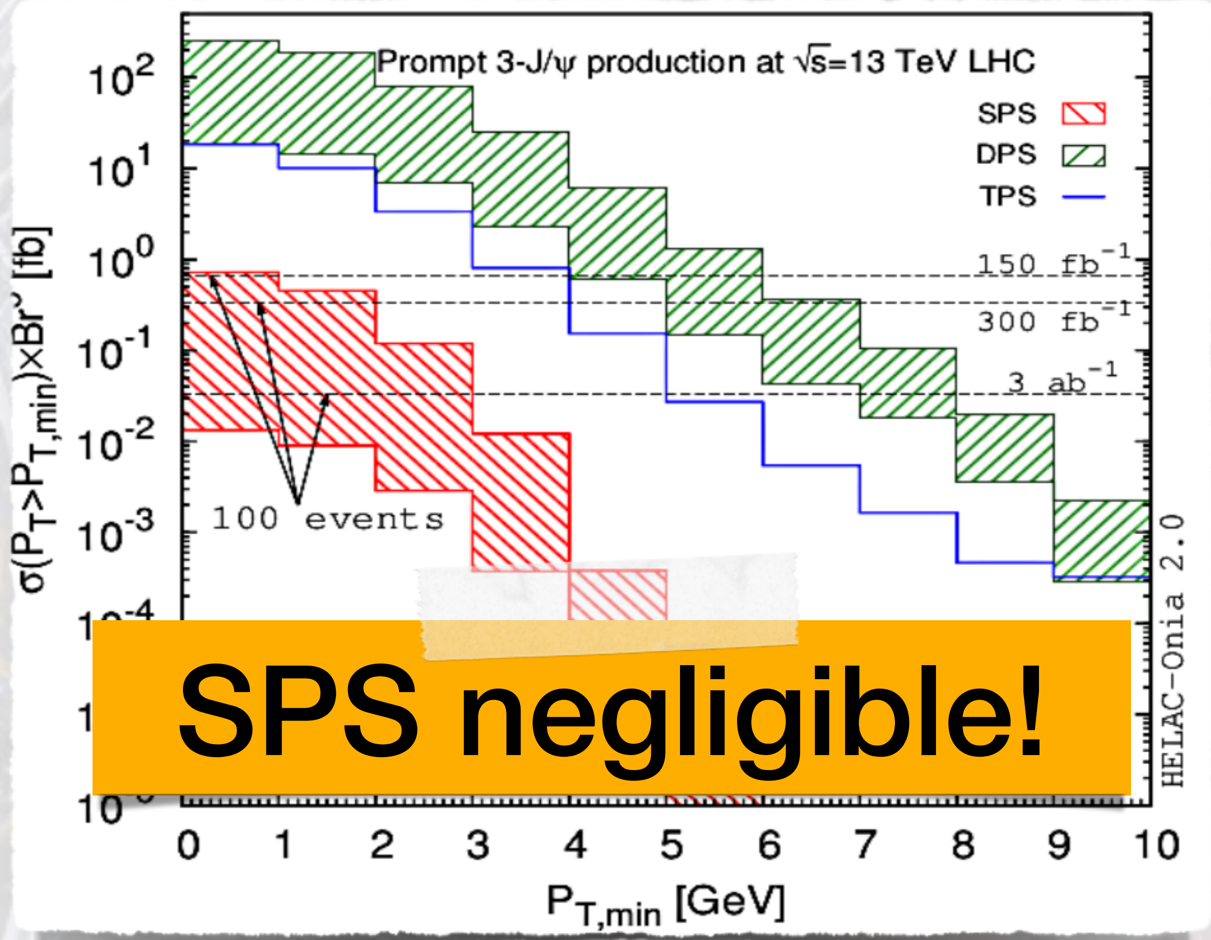

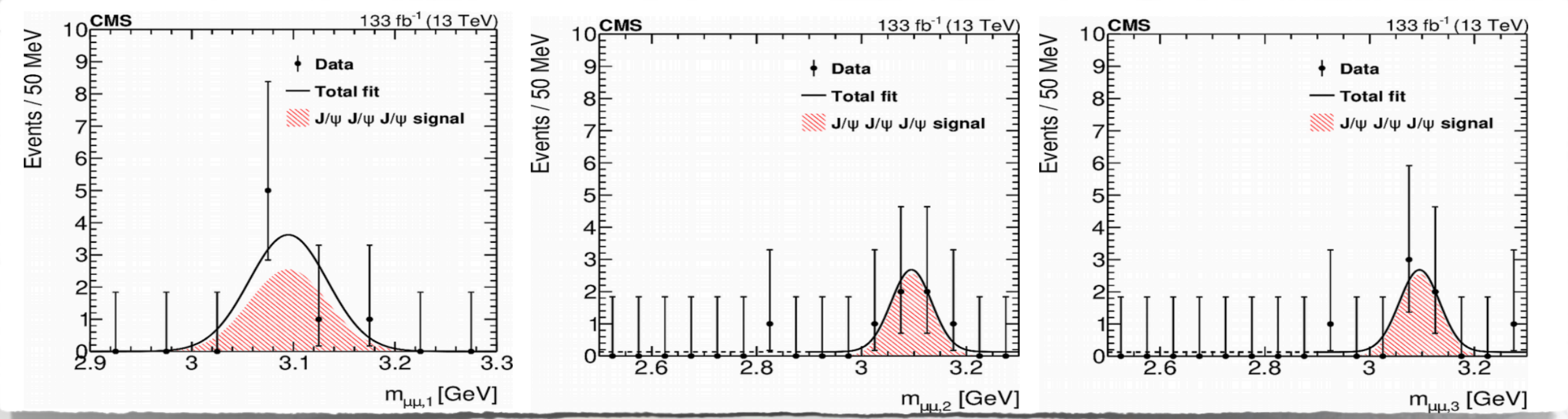

- $\sigma = 272^{+141}_{104}$ (stat) $\pm$ 17 (syst) fb

SPS -> 6%
DPS -> 74%
TPS ->20%

A. Tumasyan et al [CMS], Nature Phys. 19, no.3, 338-350 (2023)

Triple Parton Scattering - where?

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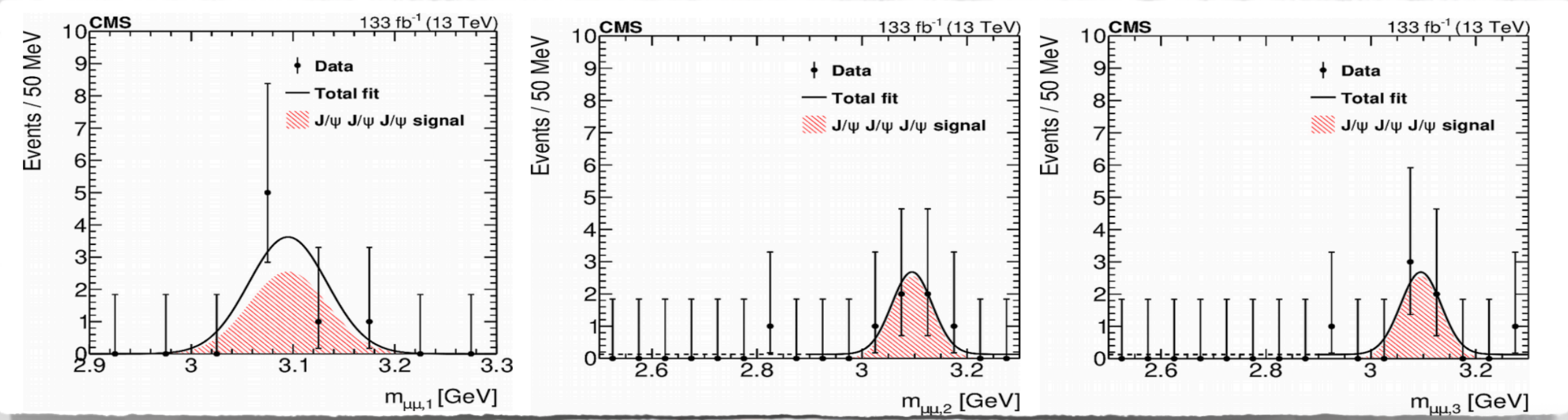
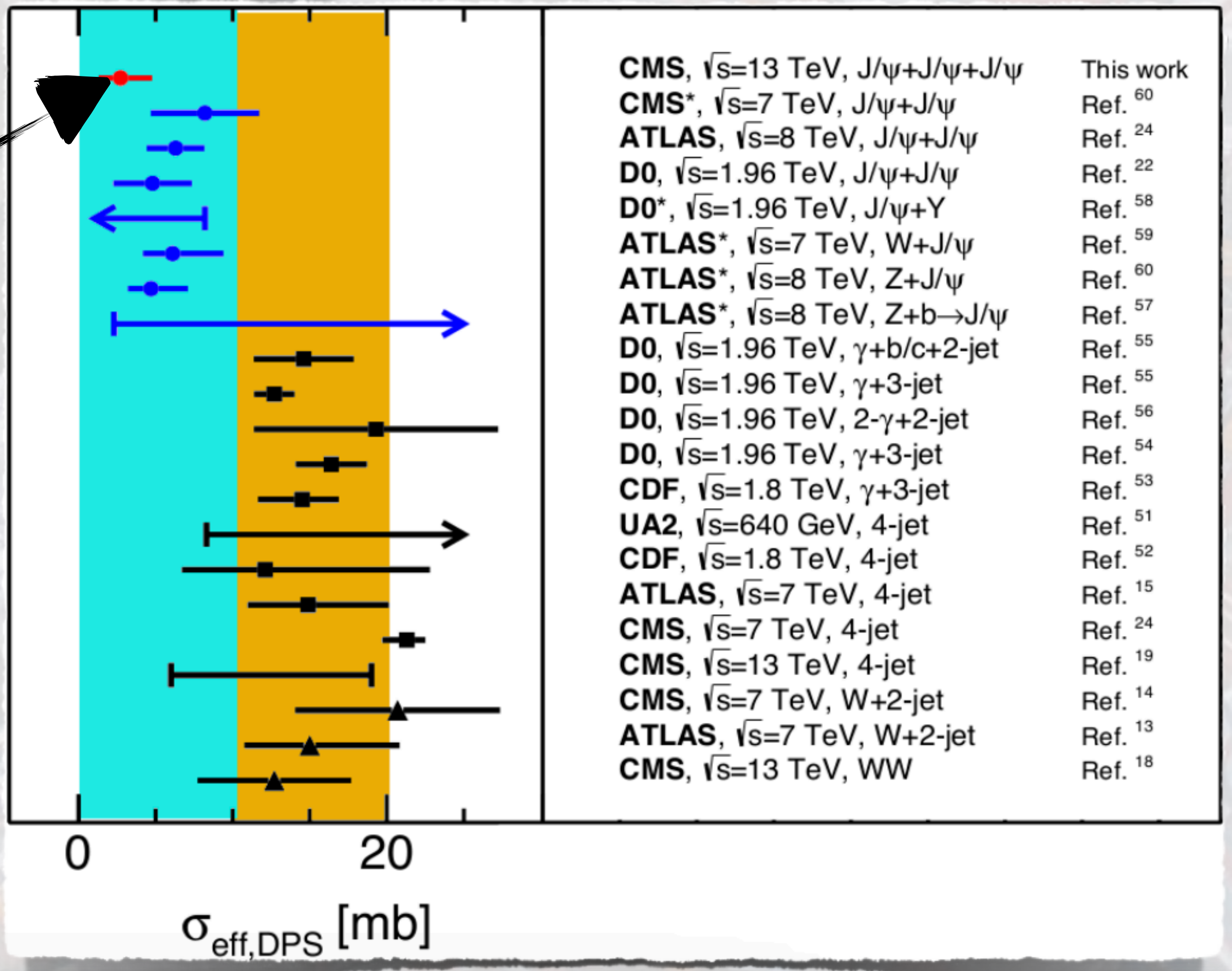


- $\sigma = 272^{+141}_{104}$ (stat) $\pm$ 17 (syst) fb

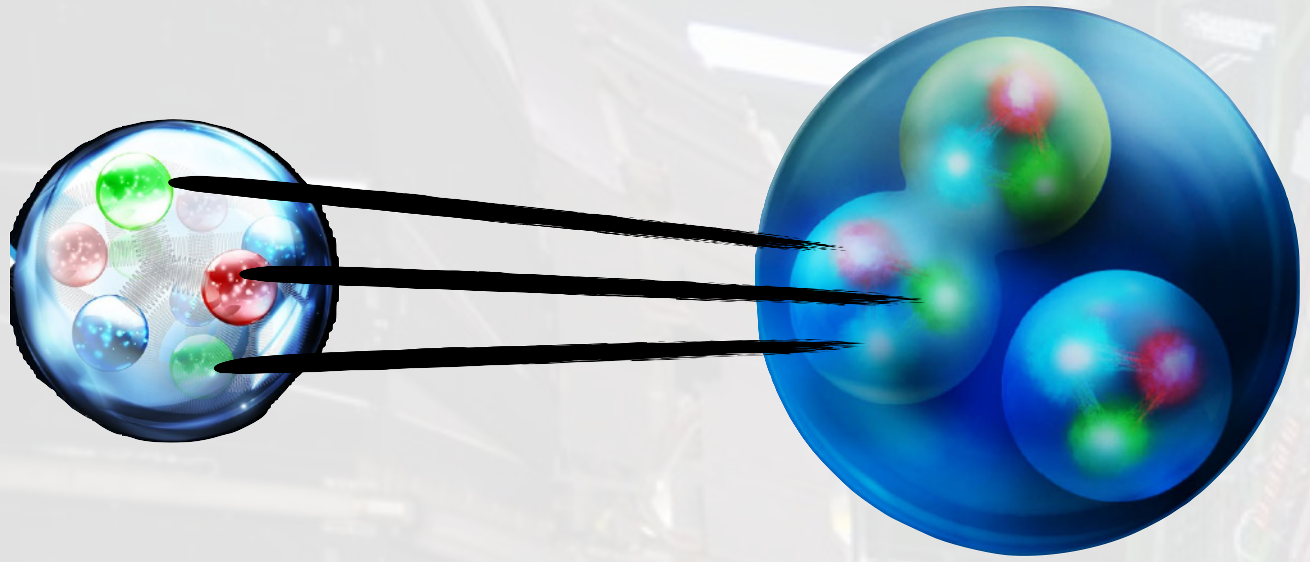
SPS -> 6%
DPS -> 74%
TPS ->20%

Novel way to extract the DPS effective cross-section:

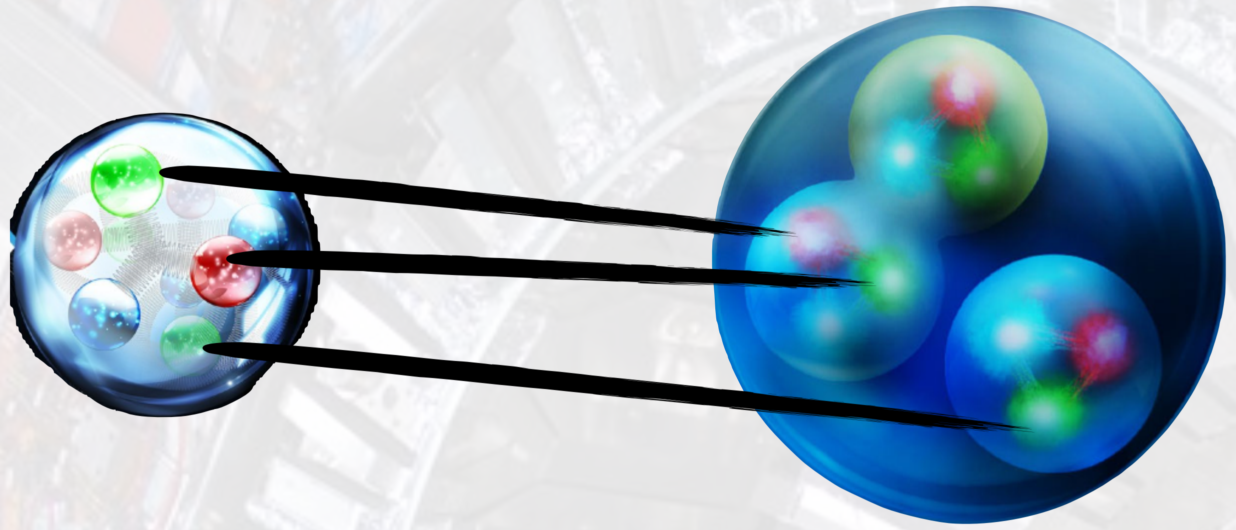
$$\sigma_{\text{eff,DPS}} = 2.7^{\ 1.4}_{-1.0}\ (\text{exp})^{+1.5}_{-1.0}\ (\text{theo})\ \text{mb}$$



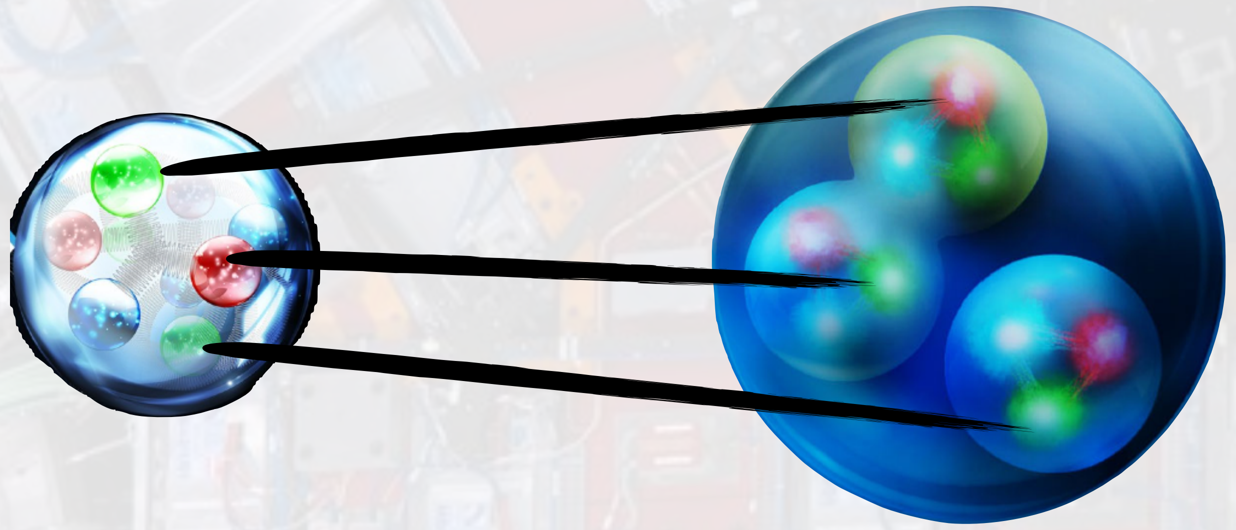
Triple Parton Scattering - pA



TPS1 =TPS



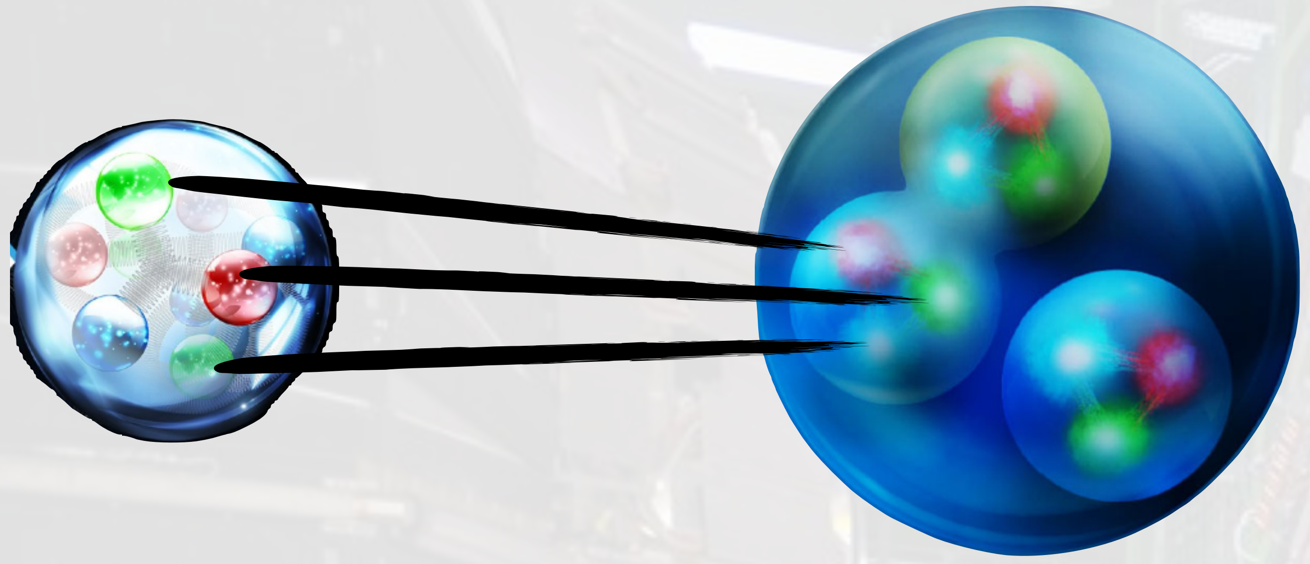
TPS2=DPS ⊗ SPS



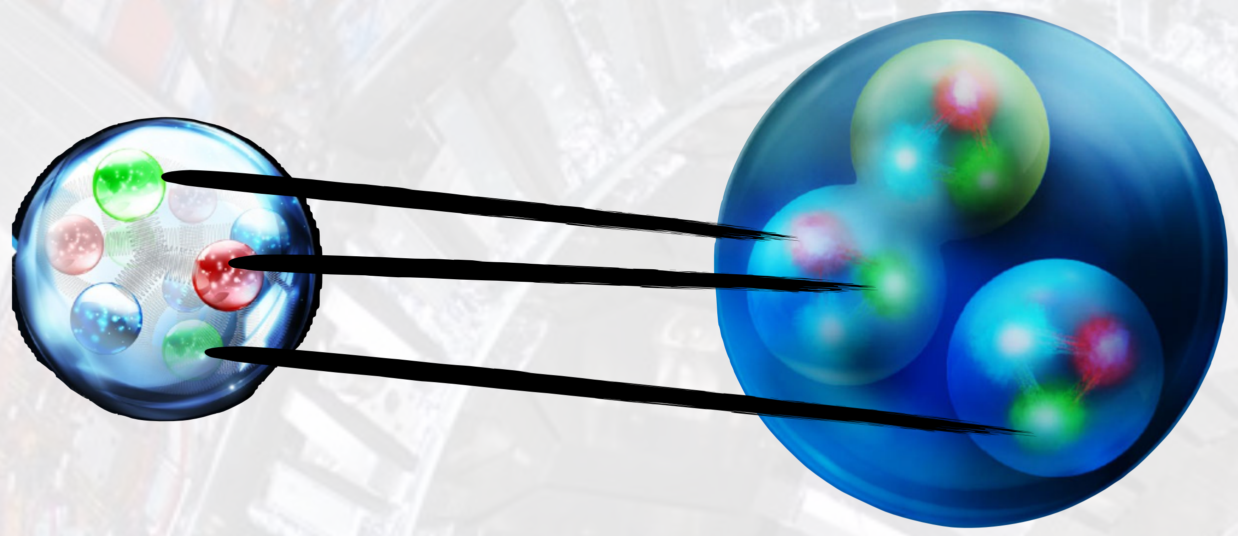
TPS3=SPS ⊗ SPS⊗ SPS

Relative size: **1:4.54:3.56** **D. d'Enterria et al, EPJC 78 (2018) 359**

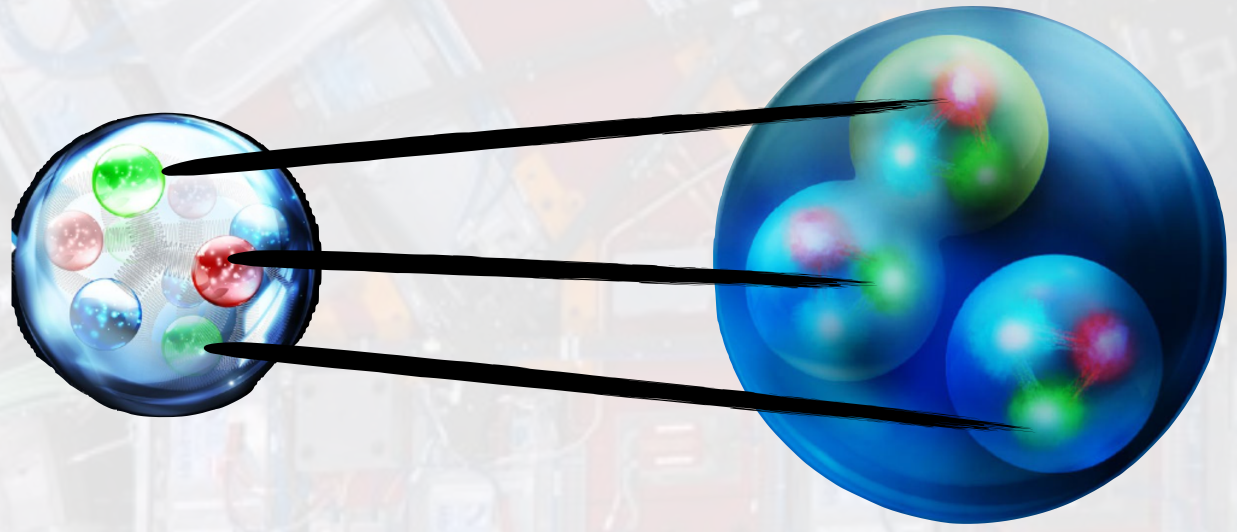
Triple Parton Scattering - pA



TPS1 =TPS



TPS2=DPS ⊗ SPS



TPS3=SPS ⊗ SPS⊗ SPS

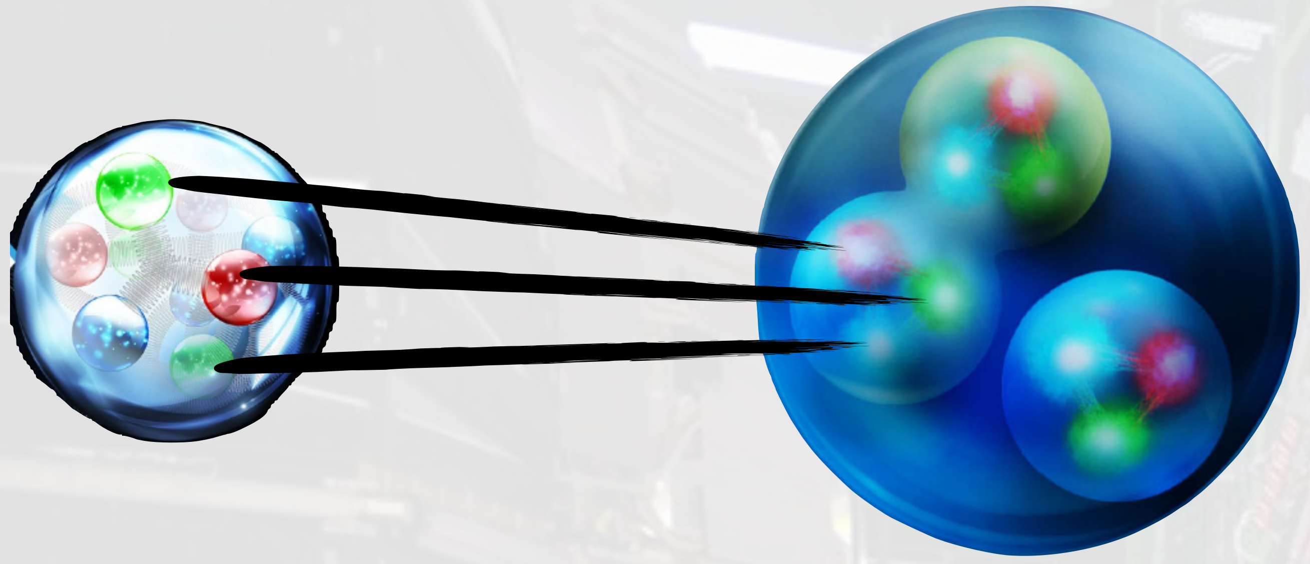
Relative size: **1:4.54:3.56** **D. d'Enterria et al, EPJC 78 (2018) 359**

Pocket Formula:

$$\sigma^{\mathrm{TPS}}_{\mathrm{pA}\to \mathsf{abc}} = \left(\frac{\mathsf{m}}{6}\right) \frac{\sigma^{\mathrm{SPS}}_{\mathrm{pN}\to \mathsf{a}} \cdot \sigma^{\mathrm{SPS}}_{\mathrm{pN}\to \mathsf{b}} \cdot \sigma^{\mathrm{SPS}}_{\mathrm{pN}\to \mathsf{c}}}{\sigma^2_{\mathrm{eff,TPS,pA}}}$$

$$\sigma_{\mathrm{eff,TPS,pA}} = \left[\frac{\mathsf{A}}{\sigma^2_{\mathrm{eff,TPS}}} + \frac{3\mathsf{F}_{\mathrm{pA}}\left[\mathrm{mb}^{-1}\right]}{\sigma_{\mathrm{eff,DPs}}} + \mathsf{C}_{\mathrm{pA}}\left[\mathrm{mb}^{-2}\right]\right]^{-1/2}$$

Triple Parton Scattering - pA



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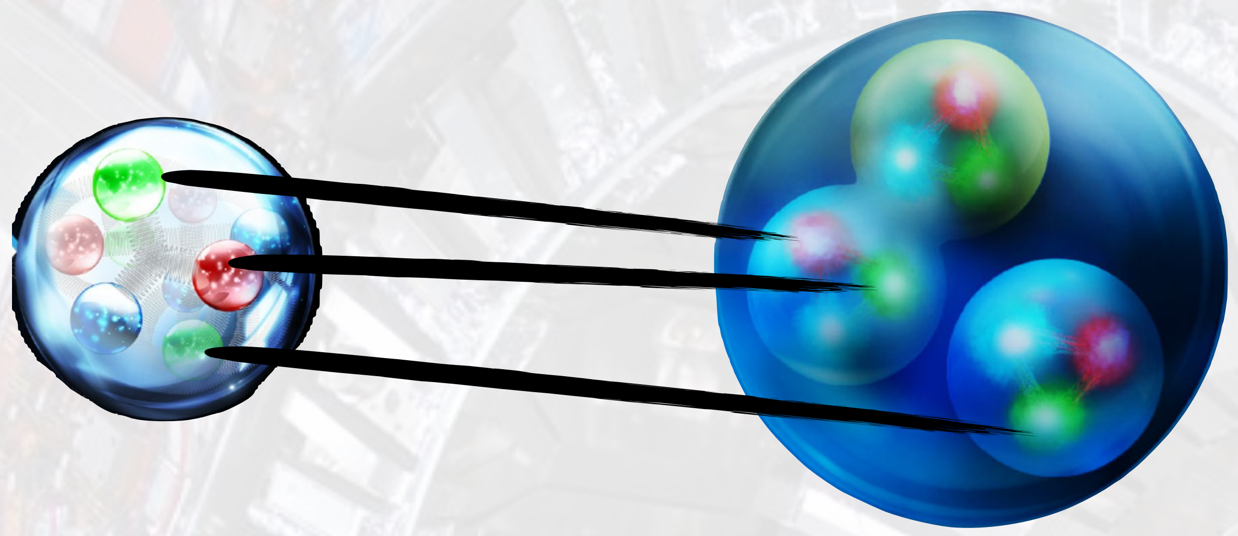
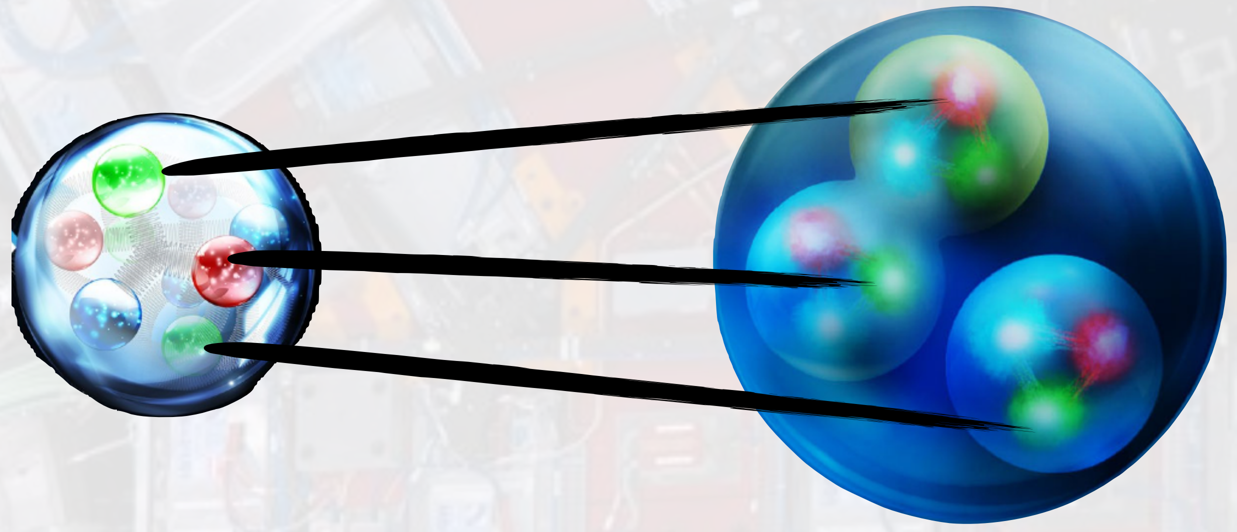


TPS2=DPS $\otimes$ SPS



TPS3=SPS $\otimes$ SPS$\otimes$ SPS

Relative size: **1:4.54:3.56** **D. d'Enterria et al, EPJC 78 (2018) 359**

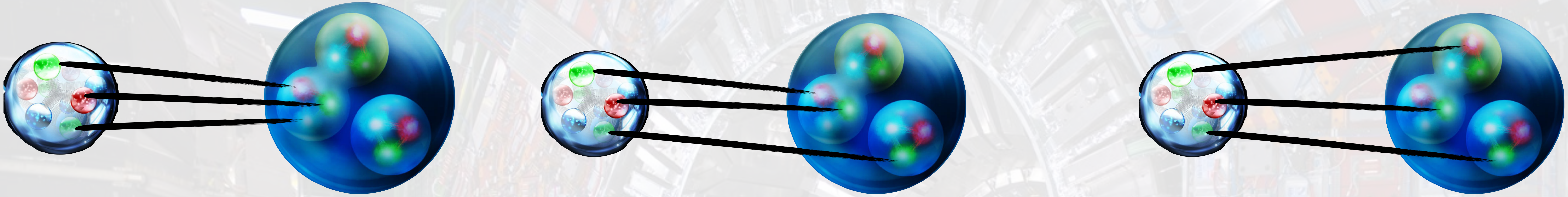
Pocket Formula:

$$\sigma^{\mathrm{TPS}}_{\mathrm{pA}\to\mathsf{abc}} = \left(\frac{\mathsf{m}}{6}\right)\frac{\sigma^{\mathrm{SPS}}_{\mathrm{pN}\to\mathsf{a}}\cdot\sigma^{\mathrm{SPS}}_{\mathrm{pN}\to\mathsf{b}}\cdot\sigma^{\mathrm{SPS}}_{\mathrm{pN}\to\mathsf{c}}}{\sigma^2_{\mathrm{eff,TPS,pA}}}$$

$$\sigma_{\mathrm{eff,TPS,pA}} = \left[\frac{\mathsf{A}}{\sigma^2_{\mathrm{eff,TPS}}} + \frac{3\boxed{\mathsf{F}_{\mathrm{pA}}\left[\mathrm{mb}^{-1}\right]}}{\sigma_{\mathrm{eff,DPs}}} + \boxed{\mathsf{C}_{\mathrm{pA}}\left[\mathrm{mb}^{-2}\right]}\right]^{-1/2}$$

$\left.\begin{array}{l} \mathsf{F}_{\mathrm{pA}} \\ \\ \mathsf{C}_{\mathrm{pA}} \end{array}\right\}$ Coefficients that should be calculated within a model of the nuclear structure

Triple Parton Scattering - pA



TPS1 =TPS

TPS2=DPS $\otimes$ SPS

TPS3=SPS $\otimes$ SPS$\otimes$ SPS

Relative size: **1:4.54:3.56**

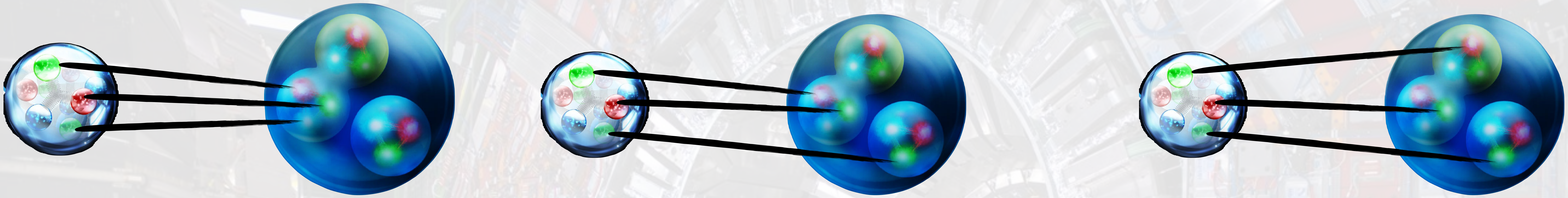
D. d'Enterria et al, EPJC 78 (2018) 359

$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\sigma^2_{\rm eff,TPS}} + \frac{3F_{\rm pA}\left[\rm mb^{-1}\right]}{\sigma_{\rm eff,DPs}} + C_{\rm pA}\left[\rm mb^{-2}\right] \right]^{-1/2}$$

$$\sigma_{\rm eff,TPS} = 12.5\ \text{mb} \xrightarrow[\text{45 times}]{} \sigma_{\rm eff,TPS,pPb}\ 0.29\ \text{mb}$$

$$\sigma_{\rm TPS,pPb} \sim 45\sigma_{\rm TPS,pp}$$

Triple Parton Scattering - pA



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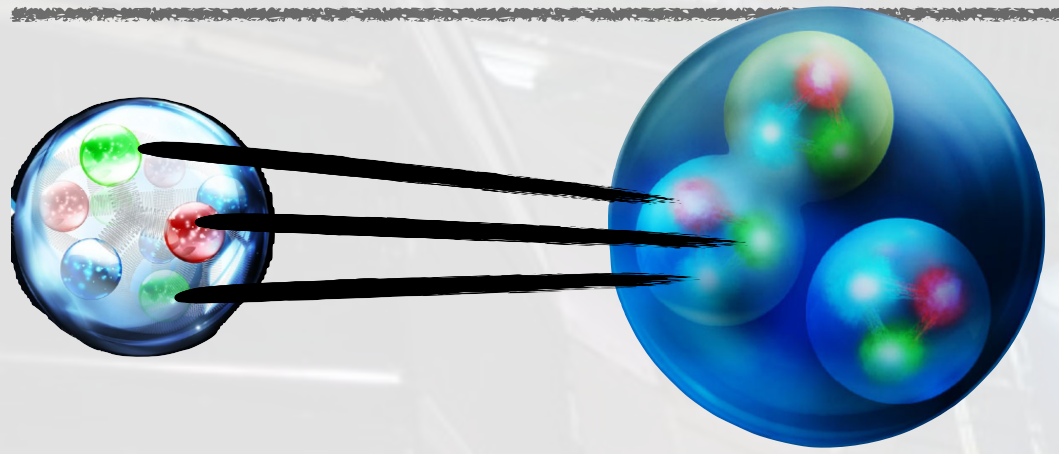
$$\sigma_{\rm eff,TPS,pA} = \left[\frac{A}{\boxed{\sigma^2_{\rm eff,TPS}}} + \frac{3F_{\rm pA}\left[\rm mb^{-1}\right]}{\boxed{\sigma_{\rm eff,DPs}}} + C_{\rm pA}\left[\rm mb^{-2}\right] \right]^{-1/2}$$

Novel way to extract them!!

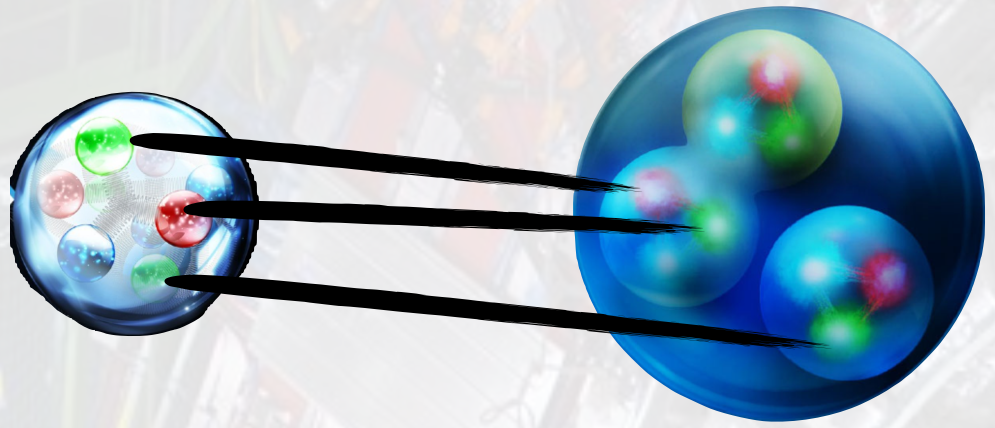
$$\sigma_{\rm eff,TPS} = 12.5 \text{ mb} \xrightarrow[\text{45 times}]{} \sigma_{\rm eff,TPS,pPb}\ 0.29 \text{ mb}$$

$$\sigma_{\rm TPS,pPb} \sim 45\sigma_{\rm TPS,pp}$$

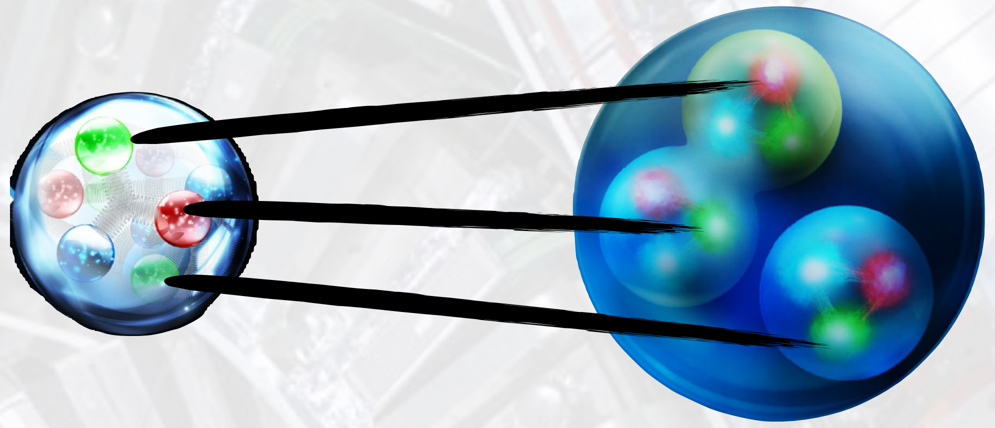
Triple Parton Scattering - pA



TPS1 =TPS



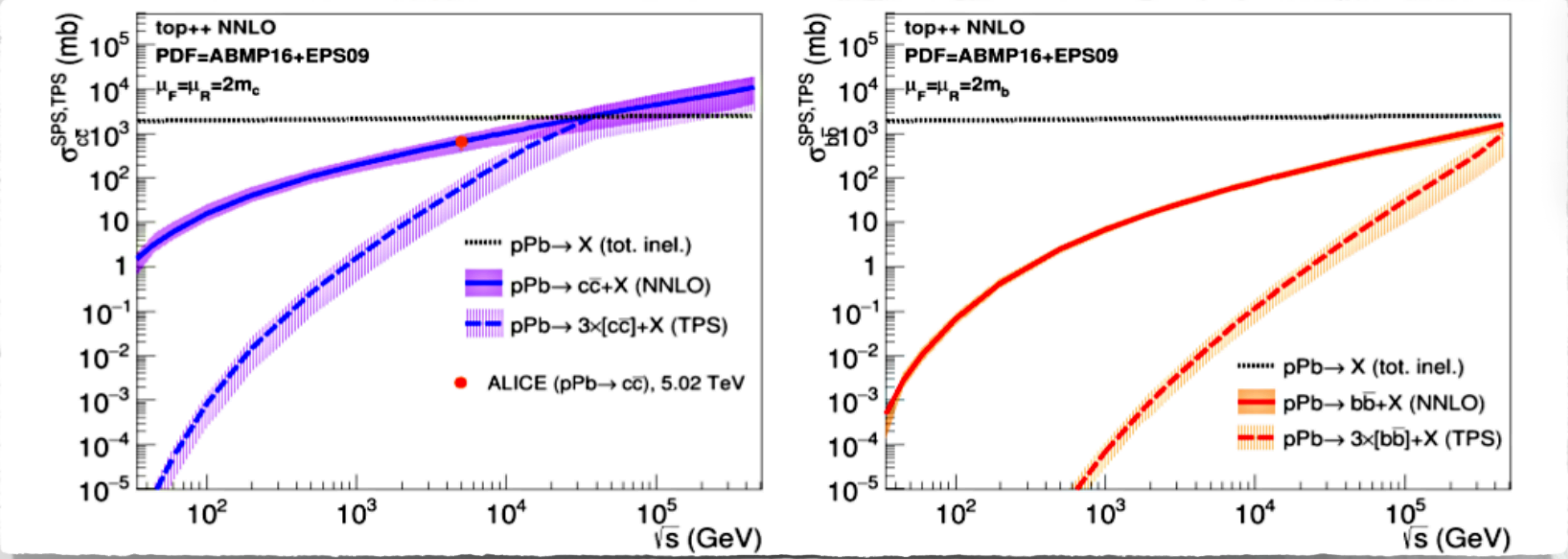
TPS2=DPS ⊗ SPS



TPS3=SPS ⊗ SPS⊗ SPS

Triple charm & beauty production:

D. d'Enterria and A. M. Snigirev, Eur. Phys. J. C 78 , no.5, 359 (2018)



Process	pPb(8.8 TeV)	pPb(63 TeV)	p-Air(430 TeV)
σ_{pA}^{inel}	2.2 ± 0.4 b	2.4 ± 0.4 mb	0.61 ± 0.10 b
$\sigma_{c\bar{c}+X}^{SPS}$	$0.96 \pm 0.45_{sc} \pm 0.10_{PDF}$ b	$3.4 \pm 1.9_{sc} \pm 0.4_{PDF}$ b	$0.75 \pm 0.5_{sc} \pm 0.1_{PDF}$ b
$\sigma_{c\bar{c}\,c\bar{c}\,c\bar{c}+X}^{TPS}$	$200 \pm 140_{tot}$ mb	$8.7^* \pm 6.2_{tot}$ b	$5.0^* \pm 3.6_{tot}$ b
$\sigma_{b\bar{b}+X}^{SPS}$	$72 \pm 12_{sc} \pm 5_{PDF}$ mb	$370 \pm 75_{sc} \pm 30_{PDF}$ mb	$110 \pm 25_{sc} \pm 5_{PDF}$ mb
$\sigma_{b\bar{b}\,b\bar{b}\,b\bar{b}+X}^{TPS}$	$0.084 \pm 0.045_{tot}$ μb	$11 \pm 7_{tot}$ μb	$17 \pm 11_{tot}$ μb

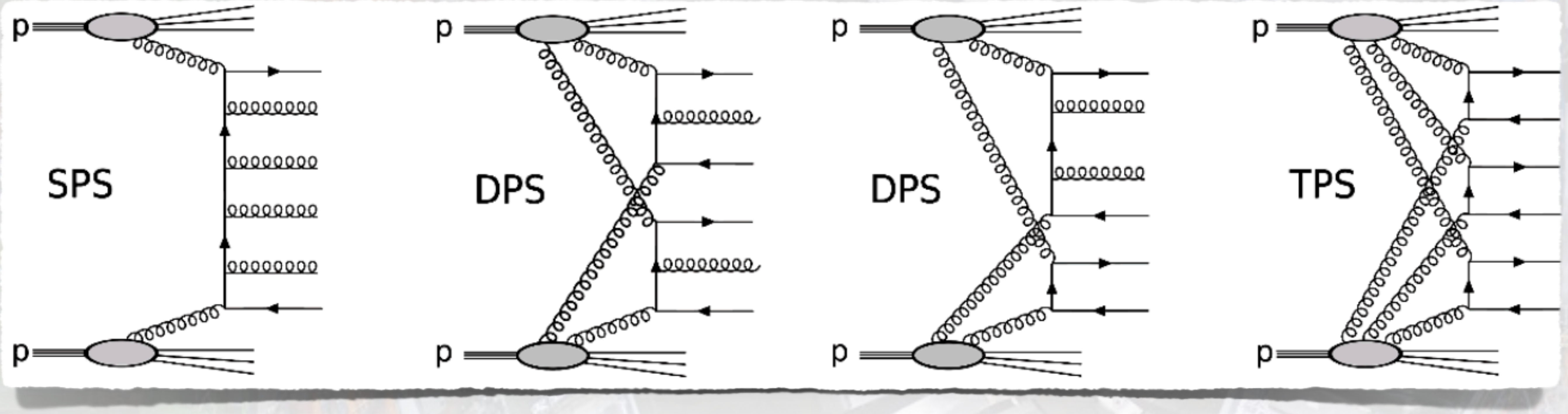
- Triple charm amounts to ~20% (~100%!) of inclusive charm x-sections at LHC (FCC).
- Large triple J/Ψproduction at FCC:
- Triple beauty amounts to ~3% of inclusive beauty x-sections at FCC.

MT thanks D. d'enterria for slides

Triple Parton Scattering - pA

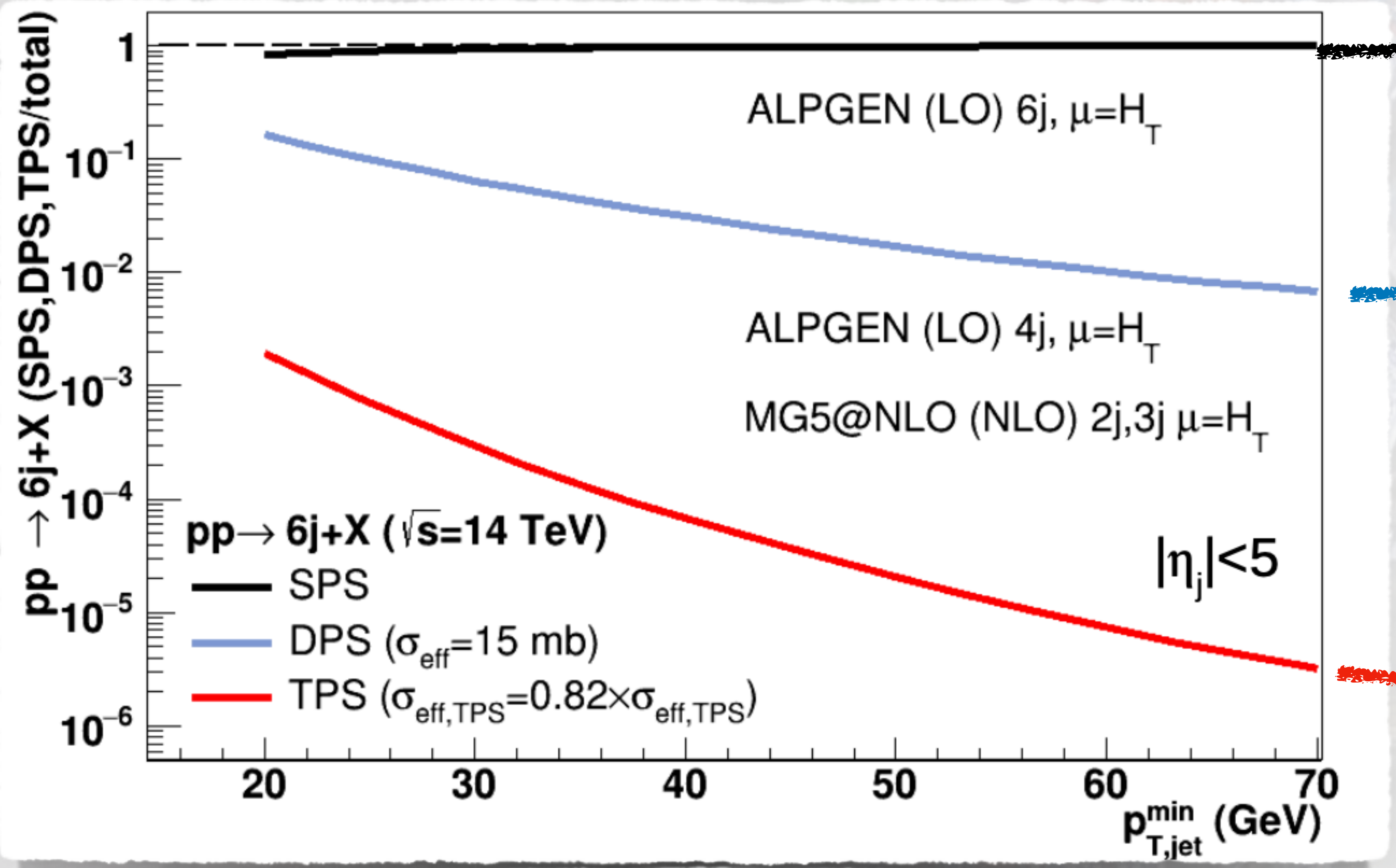
6-jet production in pp (14 TeV) and pPb (8.8 TeV)

M. Maneyro & D. d'Enterria



Triple Parton Scattering - pA

pp



$\sigma_{\rm SPS}(6j) \approx 30$ nb $(pT > 35{\rm GeV}, |\eta| < 5)$

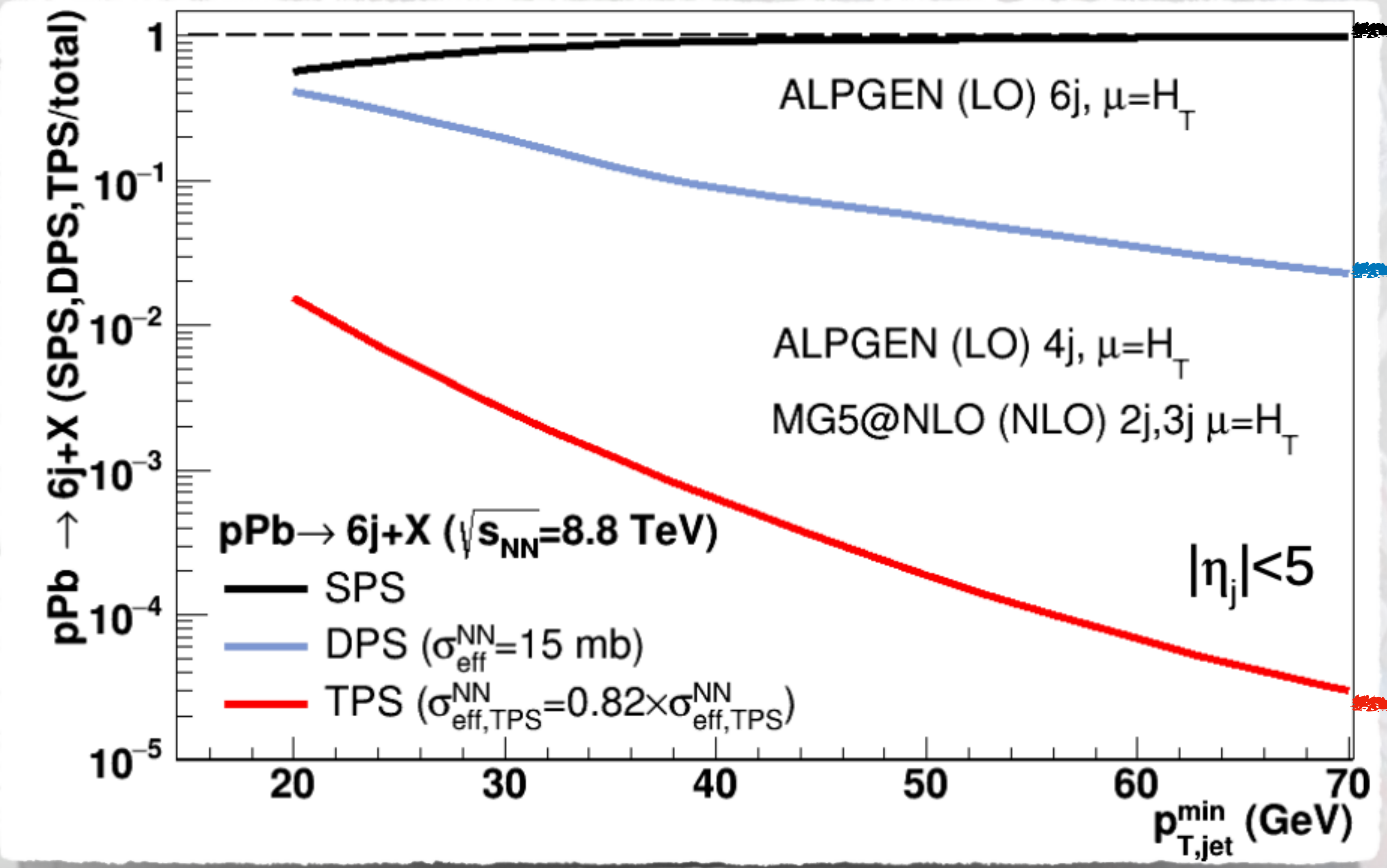
$\sigma_{\rm DPS}(6j) \approx 4$ nb $(pT > 35{\rm GeV}, |\eta| < 5)$

DPS $\rightarrow$ 20% – 2 %

$\sigma_{\rm TPS}(6j) \approx 3$ pb $(pT > 35{\rm GeV}, |\eta| < 5)$

TPS $\leq 10^{-3}$ %

pPb



$\sigma_{\rm SPS}(6j) \approx 1.2\ \mu$b $(pT > 35{\rm GeV}, |\eta| < 5)$

$\sigma_{\rm DPS}(6j) \approx 800$ nb $(pT > 35{\rm GeV}, |\eta| < 5)$

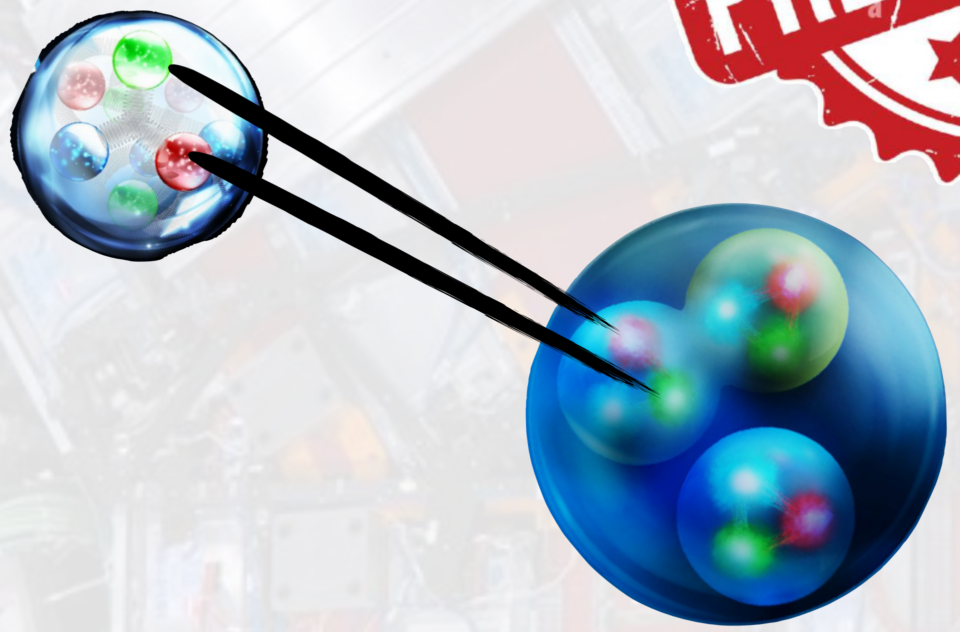
DPS $\rightarrow$ 40% – 6 %

$\sigma_{\rm TPS}(6j) \approx 1.2$ nb $(pT > 35{\rm GeV}, |\eta| < 5)$

TPS $\leq$ 2 %

Nulcear DPS and double EMC effect

Nuclear DPD (in momentum space) corresponding to the DPS1 mechanism:



$$\tilde{F}^{1}_{a_1 a_2}(x_1, x_2, k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^{N}_{a_1 a_2}\left(\frac{x_1}{\xi}, \frac{x_2}{\xi}, k_\perp\right) \boxed{\rho^{N}_{A}(\xi, p_{t,N})} \frac{d\xi}{\xi} d^2 p_{t,N}$$

The nuclear light-cone distribution can be evaluated with realistic wave-function (from Av18 +UIV potential) for light nuclei and modeled for heavy ions.

We can define the double structure functions (dSF): $F^{2,A}(x_1, x_2) \equiv \sum_{ij} e_i^2 e_j^2 x_1 x_2 \tilde{F}^{1}_{ij}(x_1, x_2, 0)$

Nulcear DPS and double EMC effect

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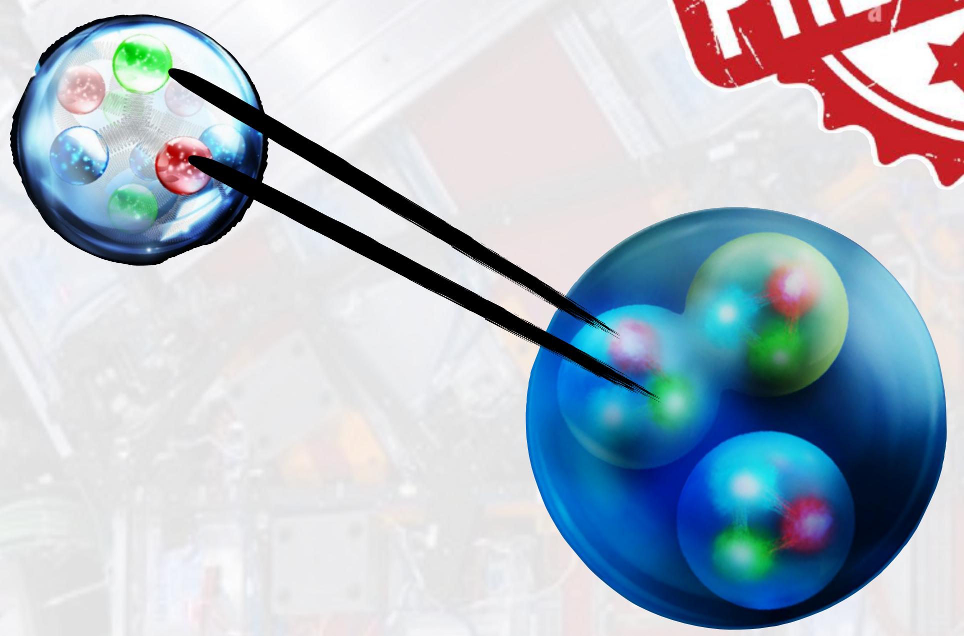

$$\tilde{F}^{1}_{a_1 a_2}(x_1, x_2, k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^{N}_{a_1 a_2}\left(\frac{x_1}{\xi}, \frac{x_2}{\xi}, k_\perp\right) \boxed{\rho^N_A(\xi, p_{t,N})} \frac{d\xi}{\xi} d^2 p_{t,N}$$

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We can generalize the EMC ratio: $R^A_{EMC}(x) = \frac{F_2^A(x)}{A} \frac{2}{\boxed{F_2^2(x)}}$ $\longrightarrow$ $R^A_{2EMC}(x_1, x_2) = \frac{F^{2,A}(x_1, x_2)}{A} \frac{2}{\boxed{F^{2,2}(x_1, x_2)}}$

^2H $\qquad$ ^2H

Nulcear DPS and double EMC effect

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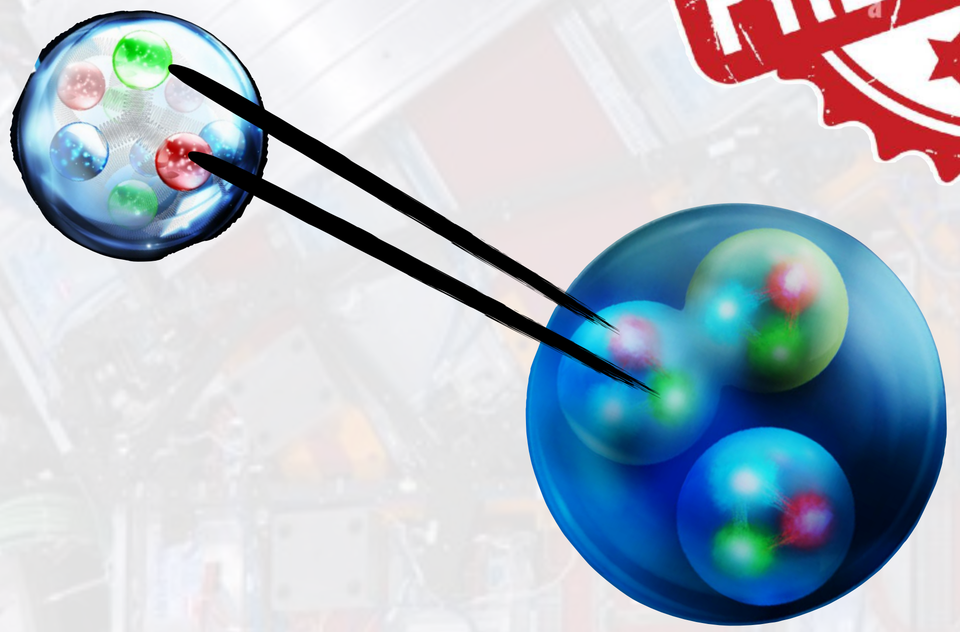

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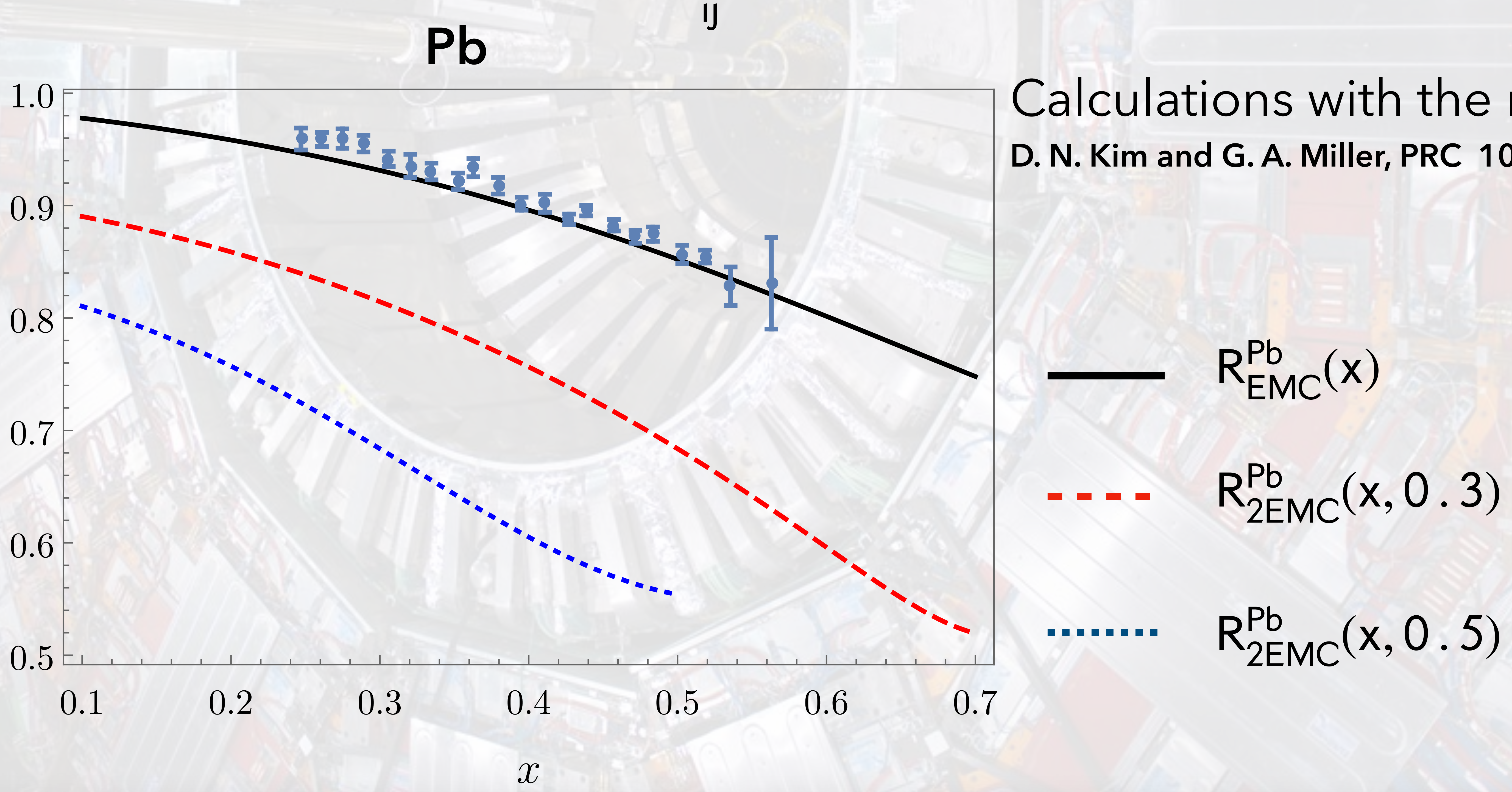

Calculations with the model of:

D. N. Kim and G. A. Miller, PRC 106, no.5, 055202 (2022)

Nulcear DPS and double EMC effect

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$$\tilde{F}^{1}_{a_1 a_2}(x_1, x_2, k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^{N}_{a_1 a_2} \left(\frac{x_1}{\xi} \right. \quad \ldots \, d\xi$$

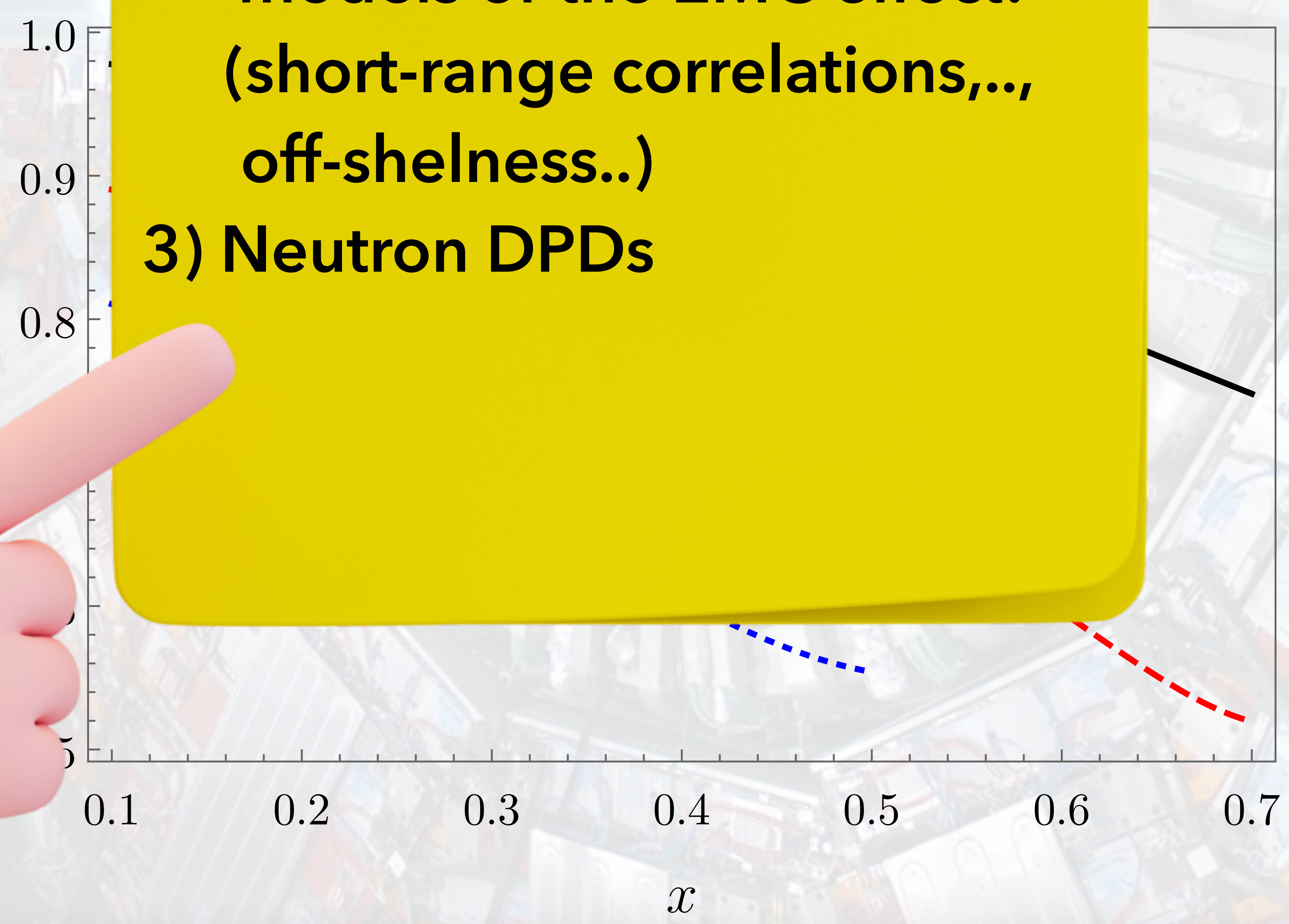
We can define the double structure functi... $x_2 \tilde{F}^1_{ij}(x_1, x_2, 0)$

We can generalize the EMC ratio:

$$R^A_{EMC}(x) = \frac{F^A_2(x)}{A} \frac{2}{F^2_2(x)}$$

$$R^A_{2EMC}(x_1, x_2) = \frac{F^{2,A}(x_1, x_2)}{\ldots}$$

1) EMC like effect more deep!
2) A novel way to test our models of the EMC effect! (short-range correlations,.., off-shelness..)
3) Neutron DPDs



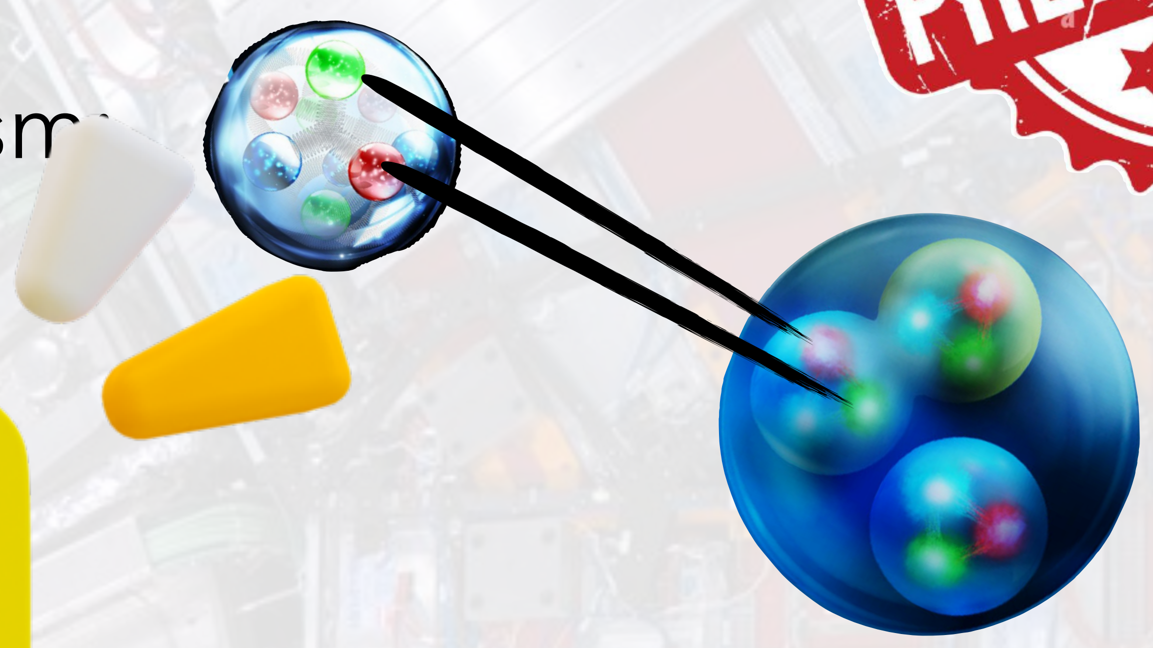
$R^{Pb}_{EMC}(x)$

$R^{Pb}_{2EMC}(x, 0.3)$

$R^{Pb}_{2EMC}(x, 0.5)$

Calculations with the model of:

D. N. Kim and G. A. Miller, PRC 106, no.5, 055202 (2022)



PRELIMINARY

CONCLUSIONS (a world beyond SPS)

1) DPS represents a new and unique window towards the inner structure of hadrons

2) DPS in pA will be essential to increase the signal and to access the DPS effective cross-section:

a) $J/\Psi + J/\Psi$, $J/\Psi + \Upsilon$, $J/\Psi + W$, $J/\Psi + Z$, $\Upsilon + \Upsilon$, $\Upsilon + W$, and $\Upsilon + Z$

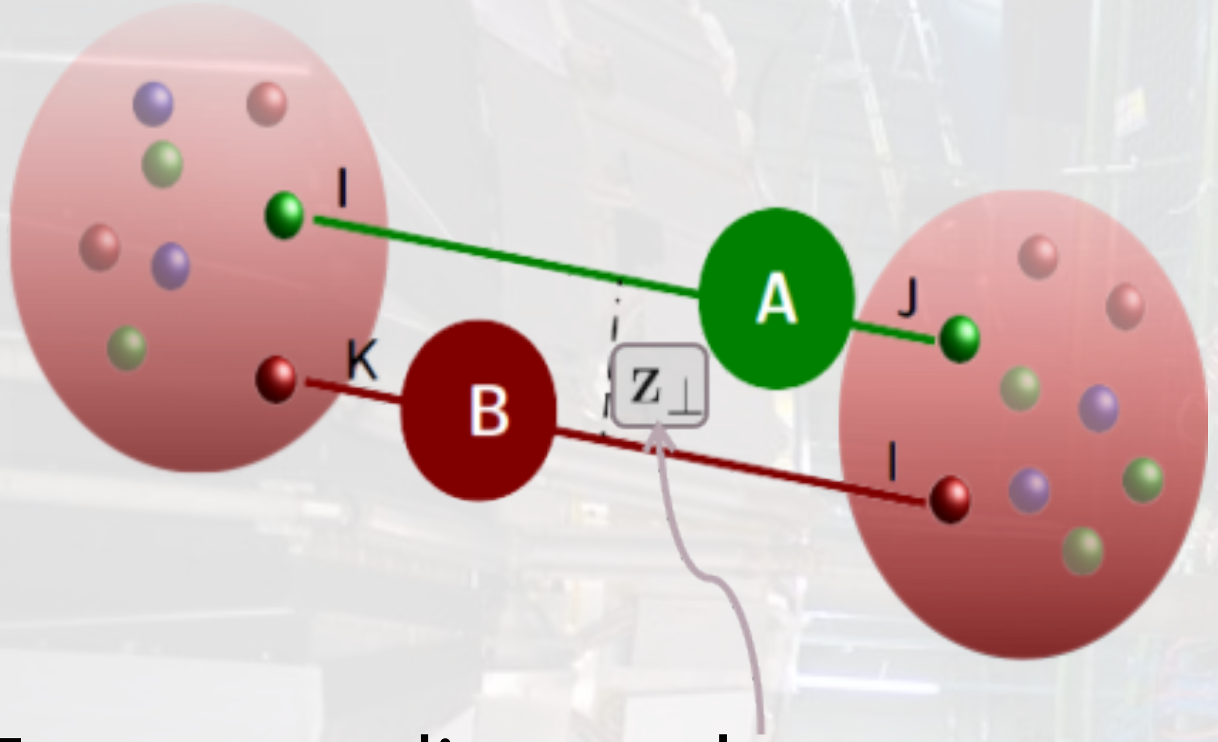
b) W+di jets, same sign WW, 4-jet, 2jet+2b

3) TPS and TPS in pA can be very important for the study of new exciting channels (like tirple J/Ψ production) offering unique opportunities:

a) Access information beyond 1- and 2- body distributions
b) Access Triple Parton Correlations
c) properly estimate the background for rare processes
d) Help in accessing information related to DPS

Double Parton Scattering

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



Transverse distance between two partons

$$d\sigma \propto \int d^2z_\perp \underbrace{F_{ij}(x_1, x_2, z_\perp, \mu_A, \mu_B)F_{kl}}_{\text{Double Parton Distribution (DPD)}}(x_3, x_4, z_\perp, \mu_A, \mu_B)$$

N. Paver and D. Treleani, Nuovo Cimento 70A, 215 (1982)
Mekhfi, PRD 32 (1985) 2371
M. Diehl et al, JHEP 03 (2012) 089

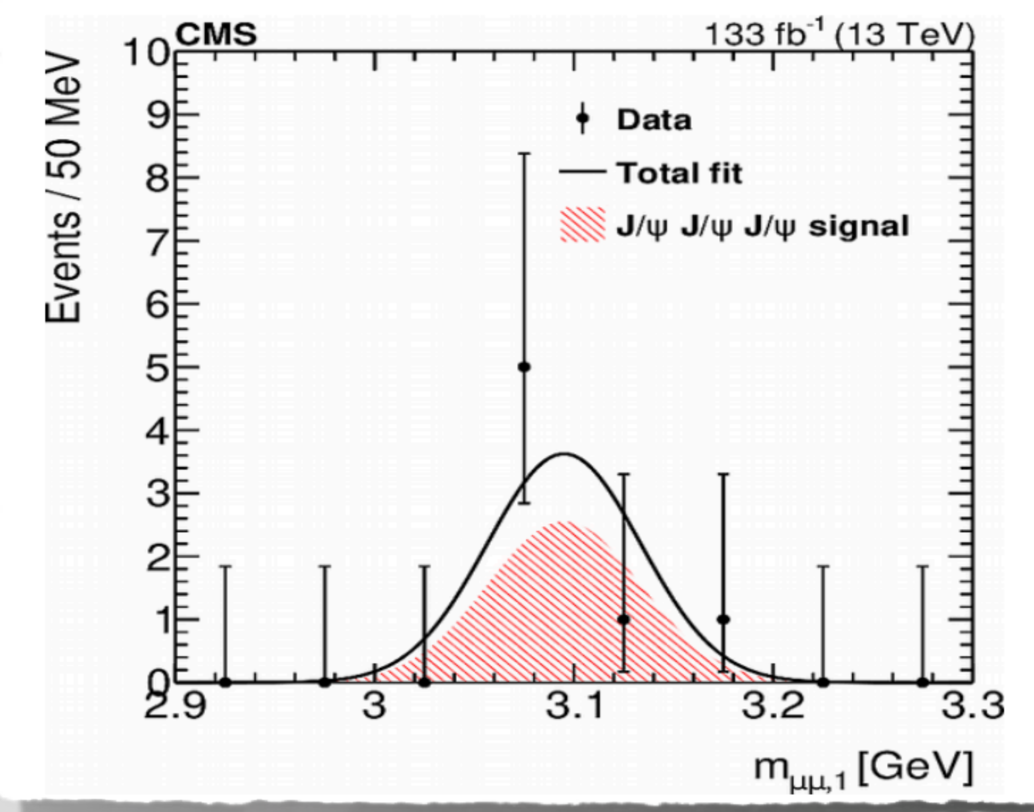
A **formal all-order proof** of the factorization formulae in perturbative QCD **has been achieved for DPS** in the case of a **colorless final state**, both for the TMD and the collinear case. Current status is at the **same level as for the SPS** counterpart.

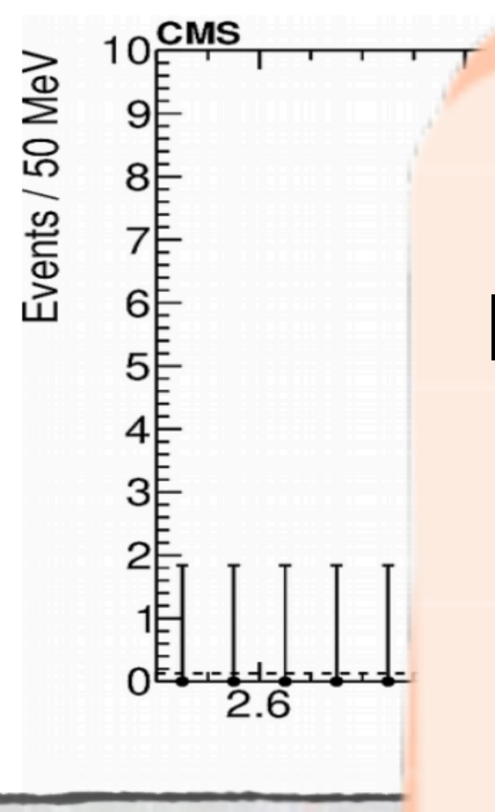
Diehl et al. JHEP 03 (2012) 089, JHEP 01 (2016) 076
Vladimirov JHEP 04 (2018) 045
Buffing et al. JHEP 01 (2018) 044
Diehl, RN JHEP 04 (2019) 124

R. Nagar's talk MPI 2021

Triple Parton Scattering - where?

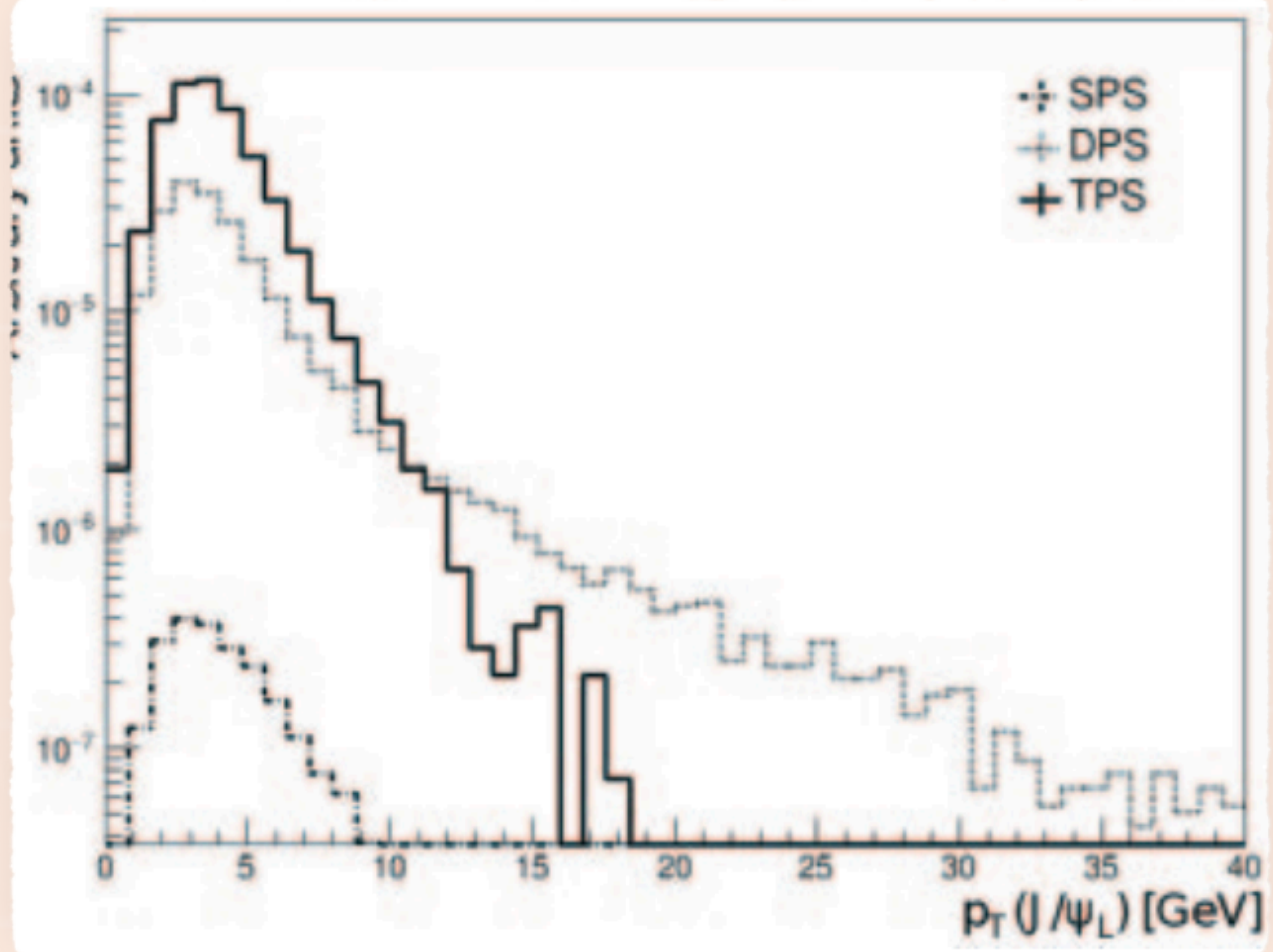
Triple J/Ψ production! **A. Tumasyan et al [CMS], Nature Phys. 19, no.3, 338-350 (2023)**





Promising also the study of TPS for the production of 2 J/Ψ and a D *

M. E. Ascioti [CMS], Nuovo Cimento 46 C (2023) 82



$\cdot\ \sigma = 272^{+141}_{104}$ (stat) ± 17 (syst) fb

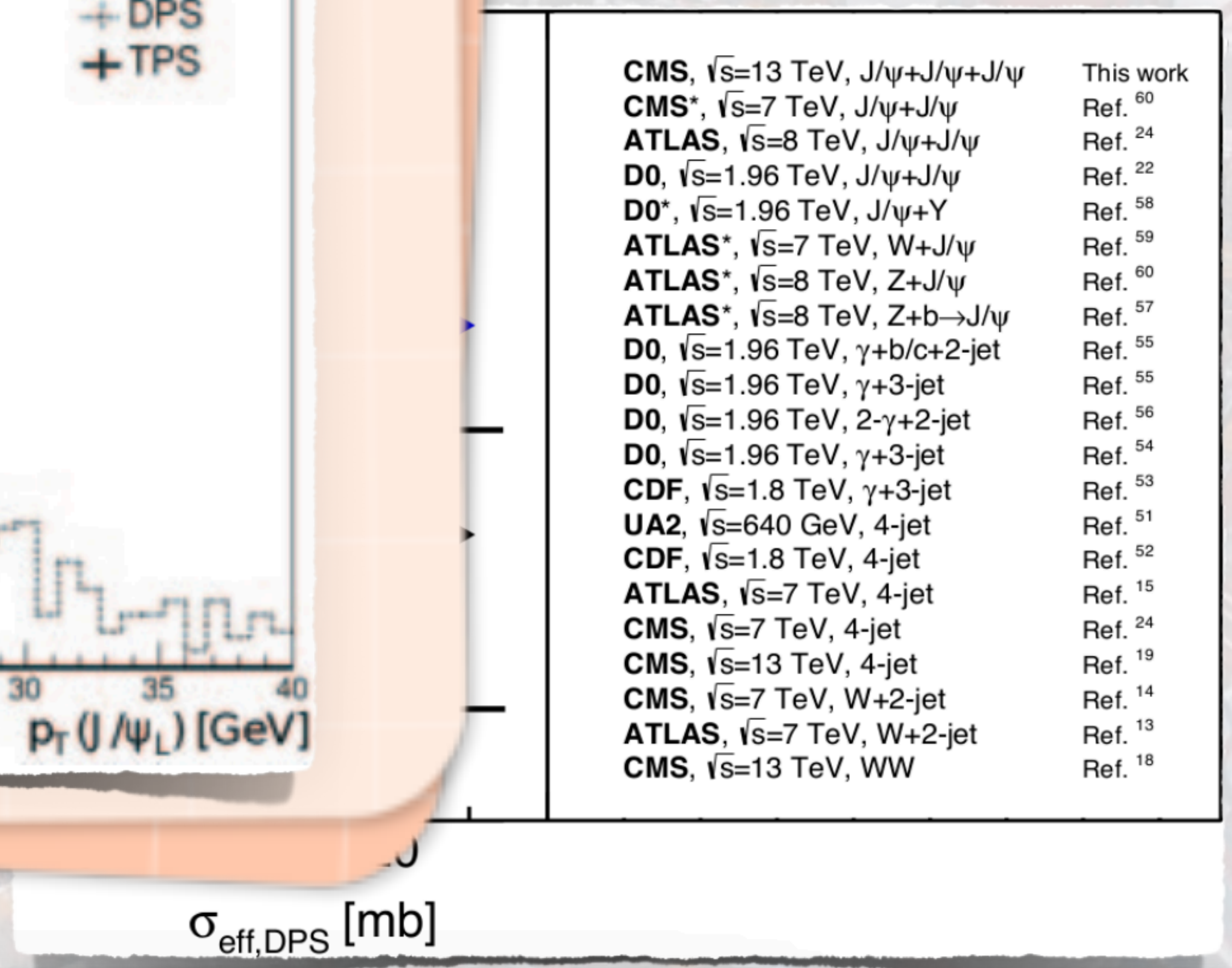
SPS -> 6%

DPS -> 74%

TPS ->20%

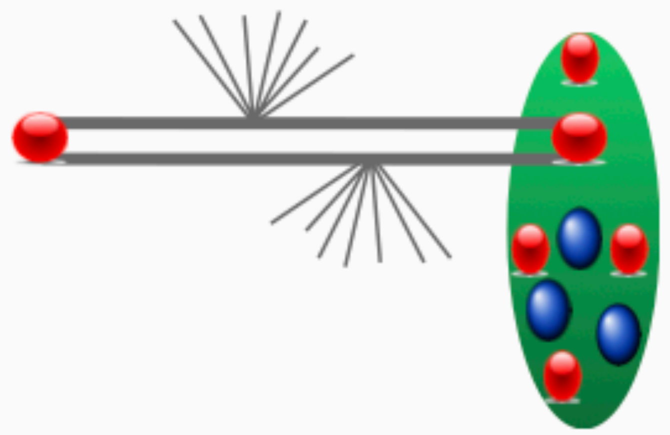
Novel way to extract the DPS effe

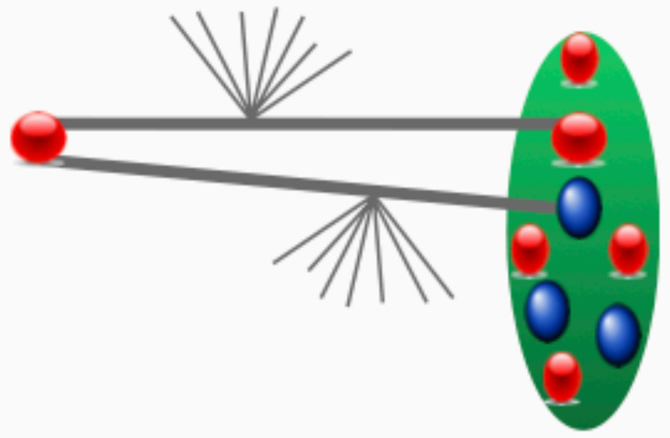
$\sigma_{\text{eff,DPS}} = 2.7^{1.4}_{-1.0}\ (\text{exp})^{+1.5}_{-1.0}$ (th



DPS in pA collisions - predictions

DPS in pA collisions

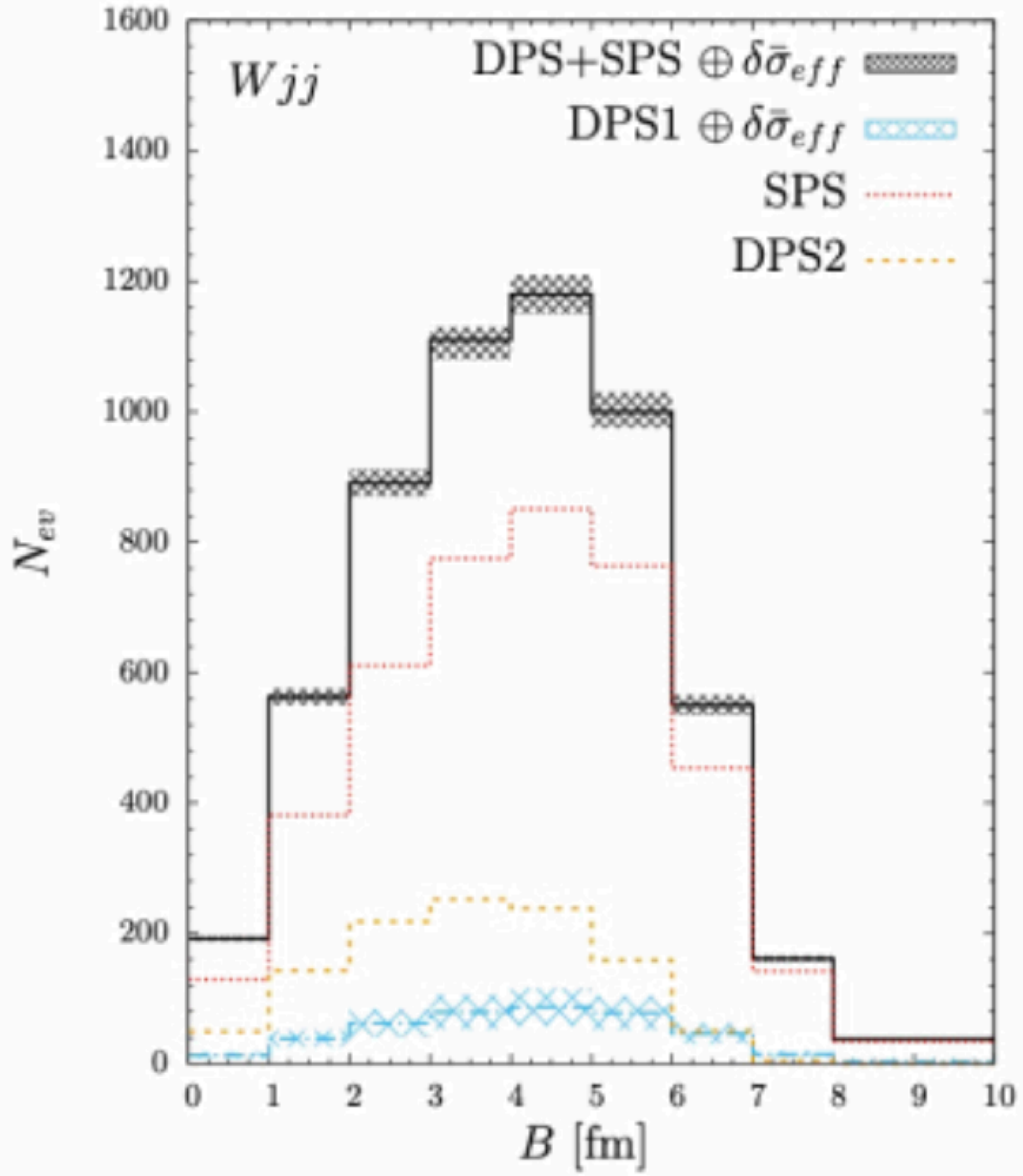




A lot of effort (slides from):
- Boris Blok
- Federico Alberto Ceccopi
- Mark Strikman
- Massimiliano Alvioli
- Daniele Treleani

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

Effective Cross Section and proton structure

If DPDs factorize in terms of PDFs then $\sigma_{\rm eff}^{-1} = \int d^2 z_\perp \, \tilde{T}(z_\perp)^2 = \int \frac{d^2 k_\perp}{(2\pi)^2} \boxed{T(k_\perp)^2}$

As for the standard FF:

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

DPD = GPD $\otimes$ GPD

From the asymptotic behavior we got the following relation:

$$\frac{\sigma_{\rm eff}}{3\pi} \leq \langle z_\perp^2 \rangle \leq \frac{\sigma_{\rm eff}}{\pi}$$

Verified in all model calculations:

Constituent quark models for:

proton

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

Pion

M.R. EPJC 80 (2020) 7, 678

W. Broniovski and E. R. Arriola PRD 101 (2020), 1, 014019

ρ

M.R. EPJC 80 (2020) 7, 678

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

DPS in γA collisions with light nuclei?

M.R. in progress

In p-Pb collisions there are some difficulties (personal view):

1) both cross-sections (DPS1 and DPS2) depends on proton DPD (still almost unknown) therefore both mechanisms are very important → could be difficult to extract some information on the proton DPD

2) for heavy nuclei is difficult to perform calculation with wave-function obtained from realistic potentials

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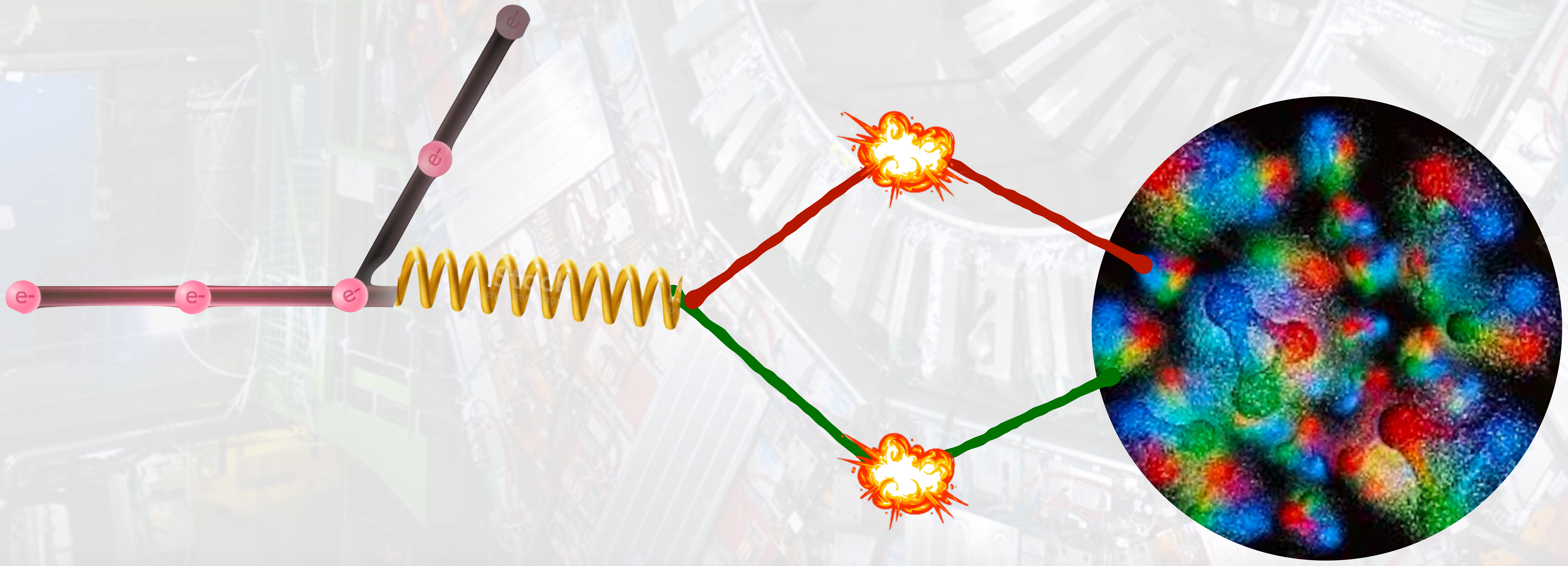
POSSIBLE SOLUTION?



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POSSIBLE SOLUTION?

1) In γA the DPS2 will not contain any DPD of the proton $\Rightarrow$ this mechanism can now be viewed as a background that can be evaluated if we properly treat the photon (as previously discussed) and the Nuclear geometry

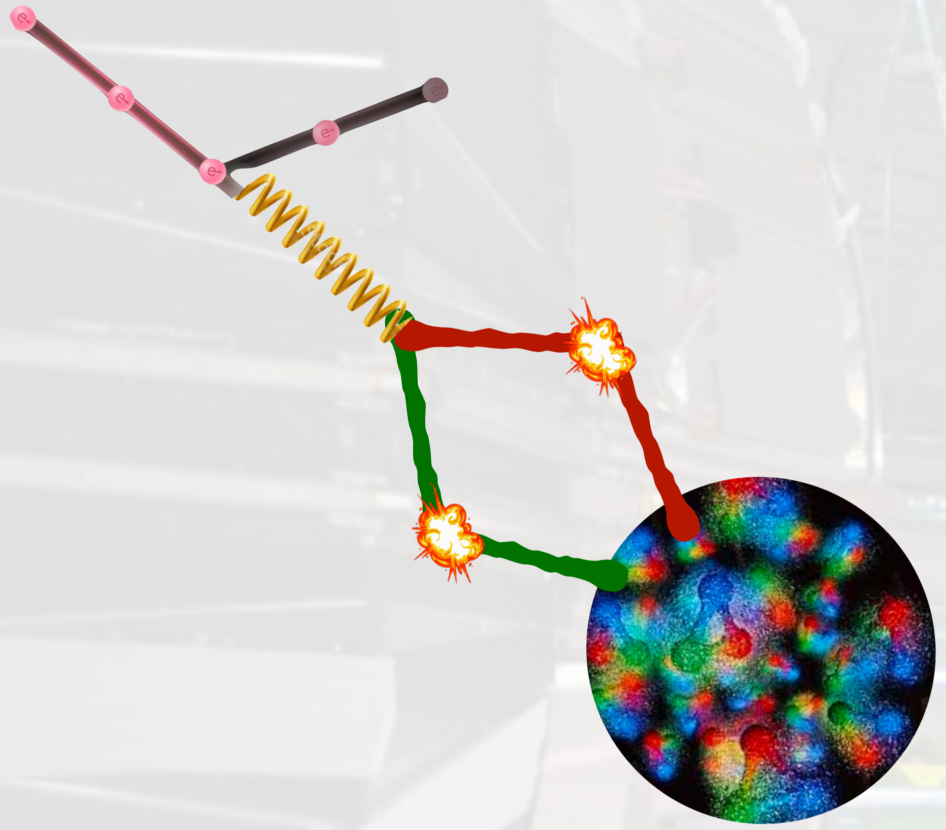
2) For light nuclei these calculations can be done starting from realistic wave-function (Av18 or chiral potential)!

Could we access the DPD of bound nucleons? Double EMC effect?

DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS1:



$$\tilde{F}^{1}_{a_1a_2}(x_1,x_2,k_\perp) = \sum_{N=p,n}\int \frac{1}{\xi}\tilde{F}^{N}_{a_1a_2}\left(\frac{x_1}{\xi},\frac{x_2}{\xi},k_\perp\right)\boxed{\rho^N_A(\xi,p_{t,N})}\frac{d\xi}{\xi}d^2p_{t,N}$$

The nuclear light-cone distribution can be evaluated with realistic wave-function (from Av18 +UIV potential) in a fully relativistic and Poincaré covariant approach for:

1) H^2 in **E. Pace and G. Salmé, TNPI2000 (2001), arXiv:nucl-th/0106004**

2) He^3 in e.g. **A. Del Dotto et al, PRC 95, 014001 (2017), M.R. et al, PLB 839 (2023), 137810**

3) He4 from **F. Fornetti, E. Pace, M. R., G. Salmé, S. Scopetta and M. Viviani, PLB submitted**

DPS in γA collisions with light nuclei?

M.R. in progress

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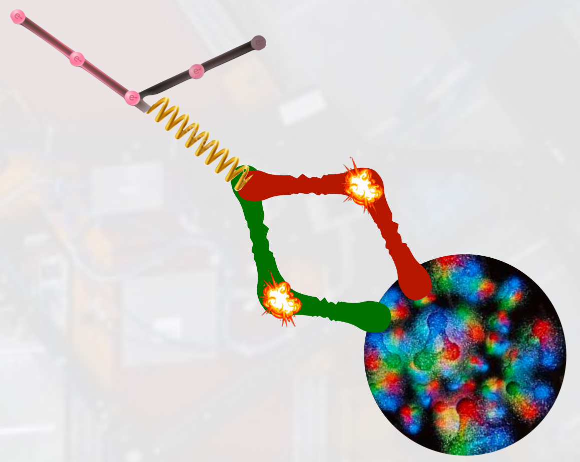

Let us check sum rules:

$$\int_0^1 dx_1 \int_0^{1-x_1} dx_2 F_{i_1 i_2}(x_1, x_2, k_\perp = 0) = \begin{cases} N_{i_1} N_{i_2} & \text{for } i_1 \neq i_2 \\ \left(N_{i_1} - 1\right) N_{i_2} & \text{for } i_1 = i_2 \end{cases}$$

Gaunt's sum rules

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

DPS in γA collisions with light nuclei?

M.R. in progress

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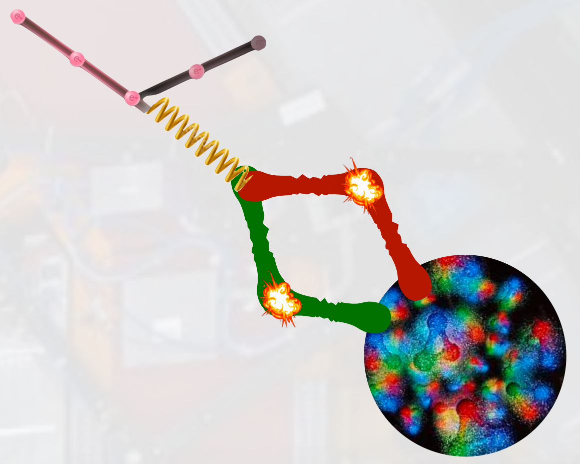

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Gaunt's sum rules

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

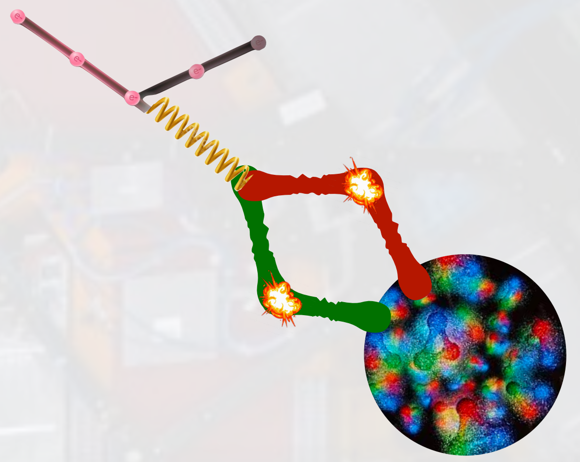
However for the nuclear case one needs also the DPS2

Thus we can introduce approximated partial sum rules (APSR)

DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS1: $\tilde{F}^{1}_{a_1 a_2}(x_1, x_2, k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^{N}_{a_1 a_2}\left(\frac{x_1}{\xi}, \frac{x_2}{\xi}, k_\perp\right) \boxed{\rho^N_A(\xi, p_{t,N})} \frac{d\xi}{\xi} d^2 p_{t,N}$



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Gaunt's sum rules

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

APSR: Since $f^A_n(\xi) = \int d^2 p_{t,N}\, \rho^N_A(\xi, p_{t,N})$ is peaked around 1/A

$$\int_0^A dx_1 \int_0^{A-x_1} dx_2 \tilde{F}^{A,1}_{i_1 i_2}(x_1, x_2, 0) \sim \sum_{n=N,P} \boxed{\int d\xi f^A_n(\xi)} \boxed{\begin{cases} \left(N^n_{i_1} - 1\right) N^n_{i_2} & i_1 = i_2 \\ N^n_{i_1} N^n_{i_2} & i_1 \neq i_2 \end{cases}}$$

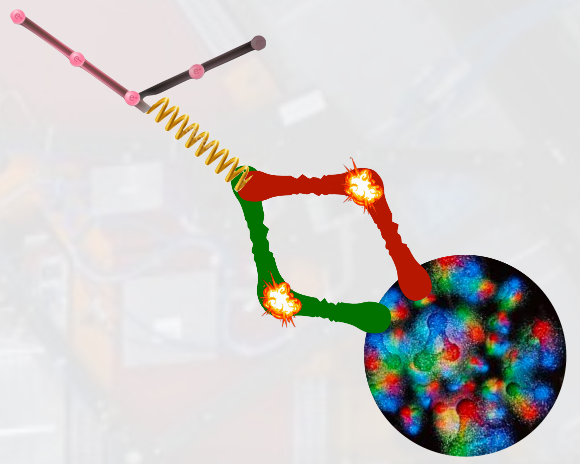
Gaunt's sum rules for the nucleon DPD: numbers of quarks with given flavor i in the nucleon n

Normalized to 1

DPS in γA collisions with light nuclei?

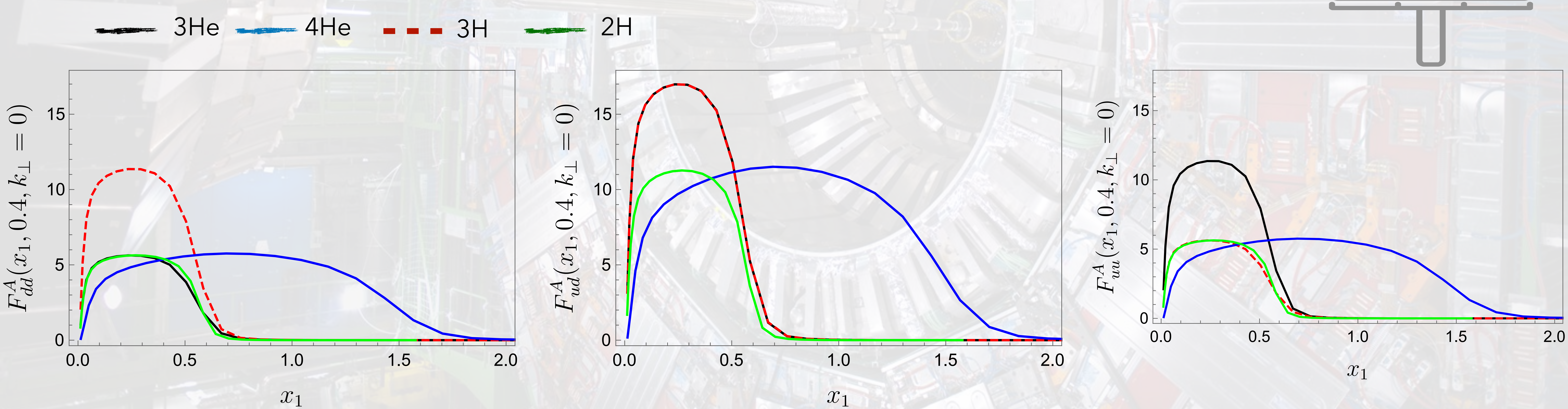
M.R. in progress

For example in DPS1: $$\tilde{F}^{1}_{a_1 a_2}(x_1, x_2, k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^{N}_{a_1 a_2}\left(\frac{x_1}{\xi}, \frac{x_2}{\xi}, k_\perp\right) \boxed{\rho^N_A(\xi, p_{t,N})} \frac{d\xi}{\xi} d^2 p_{t,N}$$



- Only for valence quarks. We used a relativistic constituent quark model for the nucleon DPD
- verified approximated partial sum rules (numerically)

$0 < x_i < A$



DPS in γA collisions with light nuclei?

M.R. in progress

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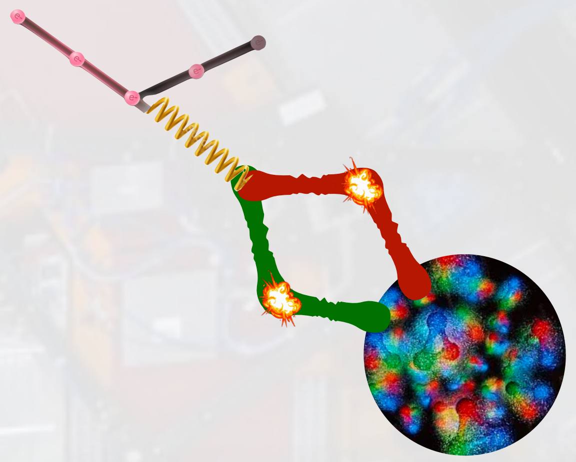

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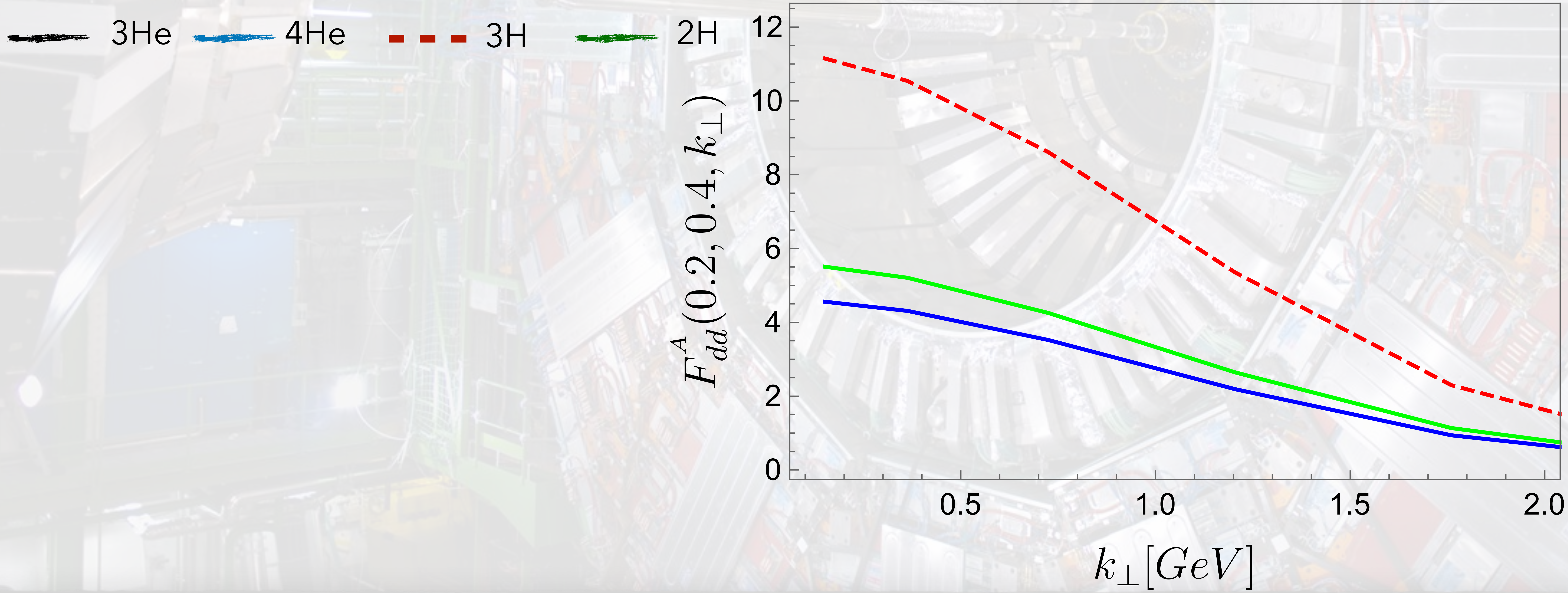

DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS2:

$$\tilde{F}^2_{a_1a_2}(x_1, x_2, \vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2p_{ti}}{\xi_i} \delta\left(\sum_i \xi_i - A\right) \delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right) \psi^*_A(\xi_1, \xi_2, p_{t1}, p_{t2}) \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\right)$$
$$\times\, G^{N_1}_{a_1}\left(\frac{x_1}{\xi_1}, |\vec{k}_\perp|\right) G^{N_2}_{a_2}\left(\frac{x_2}{\xi_2}, |\vec{k}_\perp|\right);$$
$$\underset{\xi_i \sim 1}{\sim} G^{N_1}_{a_1}\left(x_1, |\vec{k}_\perp|\right) G^{N_2}_{a_2}\left(x_2, |\vec{k}_\perp|\right)$$
$$\times \boxed{\left[\int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2p_{ti}}{\xi_i} \delta\left(\sum_i \xi_i - A\right) \delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right) \psi^*_A(\xi_1, \xi_2, p_{t1}, p_{t2}) \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\right)\right]}$$

Nuclear 2-body form factor $\quad F_2(\vec{k}_\perp, -\vec{k}_\perp)$

DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS2:

$$\tilde{F}^2_{a_1a_2}(x_1, x_2, \vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2 p_{ti}}{\xi_i} \delta\left(\sum_i \xi_i - A\right) \delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right) \psi_A^*(\xi_1, \xi_2, p_{t1}, p_{t2}) \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\right)$$

$$\times G_{a_1}^{N_1}\left(\frac{x_1}{\xi_1}, |\vec{k}_\perp|\right) G_{a_2}^{N_2}\left(\frac{x_2}{\xi_2}, |\vec{k}_\perp|\right);$$

$$\underset{\xi_i \sim 1}{\sim} G_{a_1}^{N_1}\left(x_1, |\vec{k}_\perp|\right) G_{a_2}^{N_2}\left(x_2, |\vec{k}_\perp|\right)$$

$$\times \boxed{\left[\int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2 p_{ti}}{\xi_i} \delta\left(\sum_i \xi_i - A\right) \delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right) \psi_A^*(\xi_1, \xi_2, p_{t1}, p_{t2}) \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\right)\right]}$$

Nuclear 2-body form factor $F_2(\vec{k}_\perp, -\vec{k}_\perp)$

Calculated $F_2(\vec{k}_2, \vec{k}_1)$ for ^{3}He and ^{4}He in:

V. Guzey, M.R., S. Scopetta, M. Strikman and M. Viviani et al, "*Coherent J/Ψ electroproduction on He4 and He3 at the EIC: probing Nuclear shadowing one nucleon at a time*", PRL 129 (2022) 24, 242503

DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS2:

$$\tilde{F}^2_{a_1a_2}(x_1, x_2, \vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2}\prod_{i=1}^{i=A}\frac{d\xi_i d^2p_{ti}}{\xi_i}\delta\left(\sum_i \xi_i - A\right)\delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right)\psi_A^*(\xi_1, \xi_2, p_{t1}, p_{t2})\psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\right)$$

$$\times G^{N_1}_{a_1}\left(\frac{x_1}{\xi_1}, |\vec{k}_\perp|\right) G^{N_2}_{a_2}\left(\frac{x_2}{\xi_2}, \right. \ldots$$

$$\underset{\xi_i \sim 1}{\sim} G^{N_1}_{a_1}\left(x_1, |\vec{k}_\perp|\right) G^{N_2}_{a_2}\left(x_2, |\vec{k} \right. \ldots$$

$$\boxed{\times \left[\int \frac{1}{\xi_1\xi_2}\prod_{i=1}^{i=A}\frac{d\xi_i d^2p_{ti}}{\xi_i}\delta\left(\sum \ldots \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\right)\right]}$$

WE HAVE A LINK BETWEEN 2 DIFFERENT PROCESSES!

Nuclear 2 ... $_\perp, -\vec{k}_\perp)$

Calculated $F_2(\vec{k}_2, \vec{k}_1)$ for ³He and ⁴...

V. Guzey, M.R., S. Scopetta, M. Strikman and ... *electroproduction on He4 and He3 at the EIC: probing Nuclear shadowin*... RL 129 (2022) 24, 242503

DPS in γA collisions with light nuclei?

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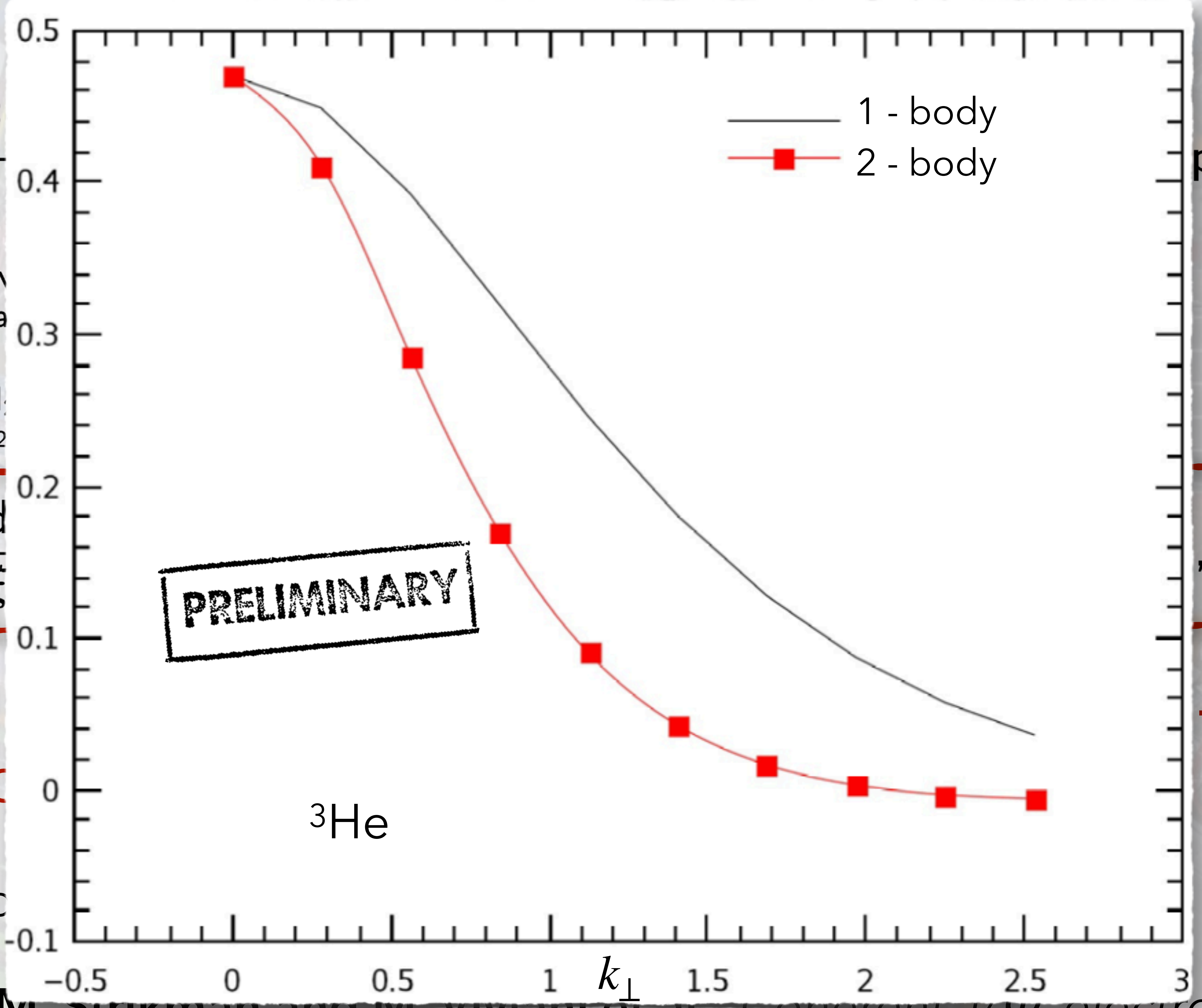
$$\tilde{F}^2_{a_1a_2}(x_1,x_2,\vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2}\prod_{i=1}^{i=A}\frac{d\xi_i d^2}{\xi_i} \ldots p_{t1}+\vec{k}_\perp, p_{t2}-\vec{k}_\perp\Big)$$

$$\times\, G^{N_1}_{a_1}\left(\frac{x_1}{\xi_1},|\vec{k}_\perp|\right)G^{N}_{a} \ldots$$

$$\underset{\xi_i\sim 1}{\sim}\, G^{N_1}_{a_1}\left(x_1,|\vec{k}_\perp|\right)G^{N}_{a_2} \ldots$$

$$\times\left[\int \frac{1}{\xi_1\xi_2}\prod_{i=1}^{i=A}\frac{d\xi_i d}{\xi} \ldots, p_{t1}+\vec{k}_\perp, p_{t2}-\vec{k}_\perp\Big)\right]$$



Nuc … $\vec{k}_\perp)$

Calculated $F_2(\vec{k}_2,\vec{k}_1)$ fo…

V. Guzey, M.R., S. Scopetta, M. Strikman and M. Viviani et al, "*Coherent J/Ψ electroproduction on He4 and He3 at the EIC: probing Nuclear shadowing one nucleon at a time*", PRL 129 (2022) 24, 242503

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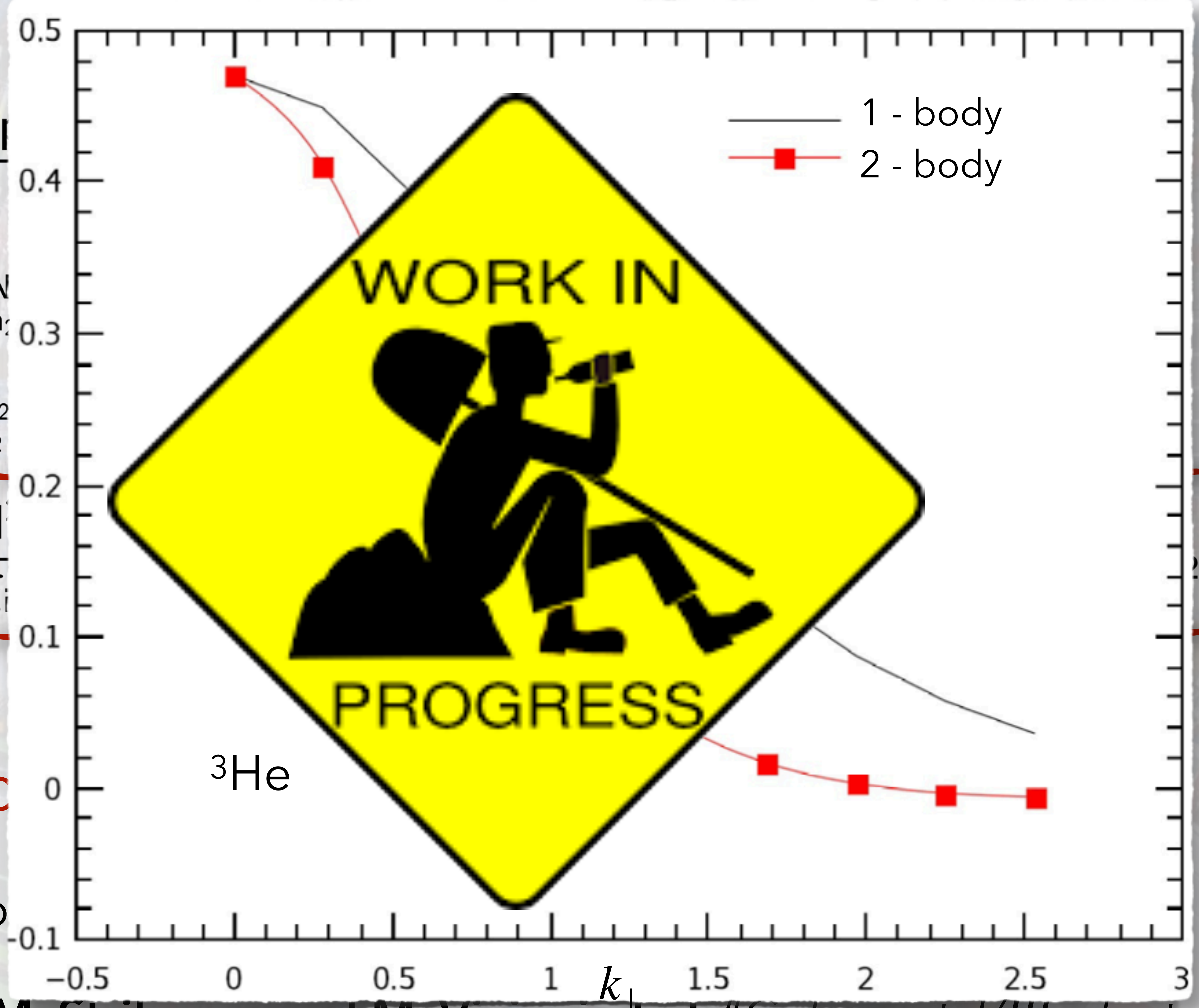
$\times\, G^{N_1}_{a_1}\left(\frac{x_1}{\xi_1}, |\vec{k}_\perp|\right) G^{N}_{a_2}$ …

$\underset{\xi_i \sim 1}{\sim}\, G^{N_1}_{a_1}\left(x_1, |\vec{k}_\perp|\right) G^{N_2}_{a_2}$ …

$\times \Big[\int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d}{\xi_i}$ … $, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp\Big)\Big]$

Nuc … $\vec{k}_\perp)$

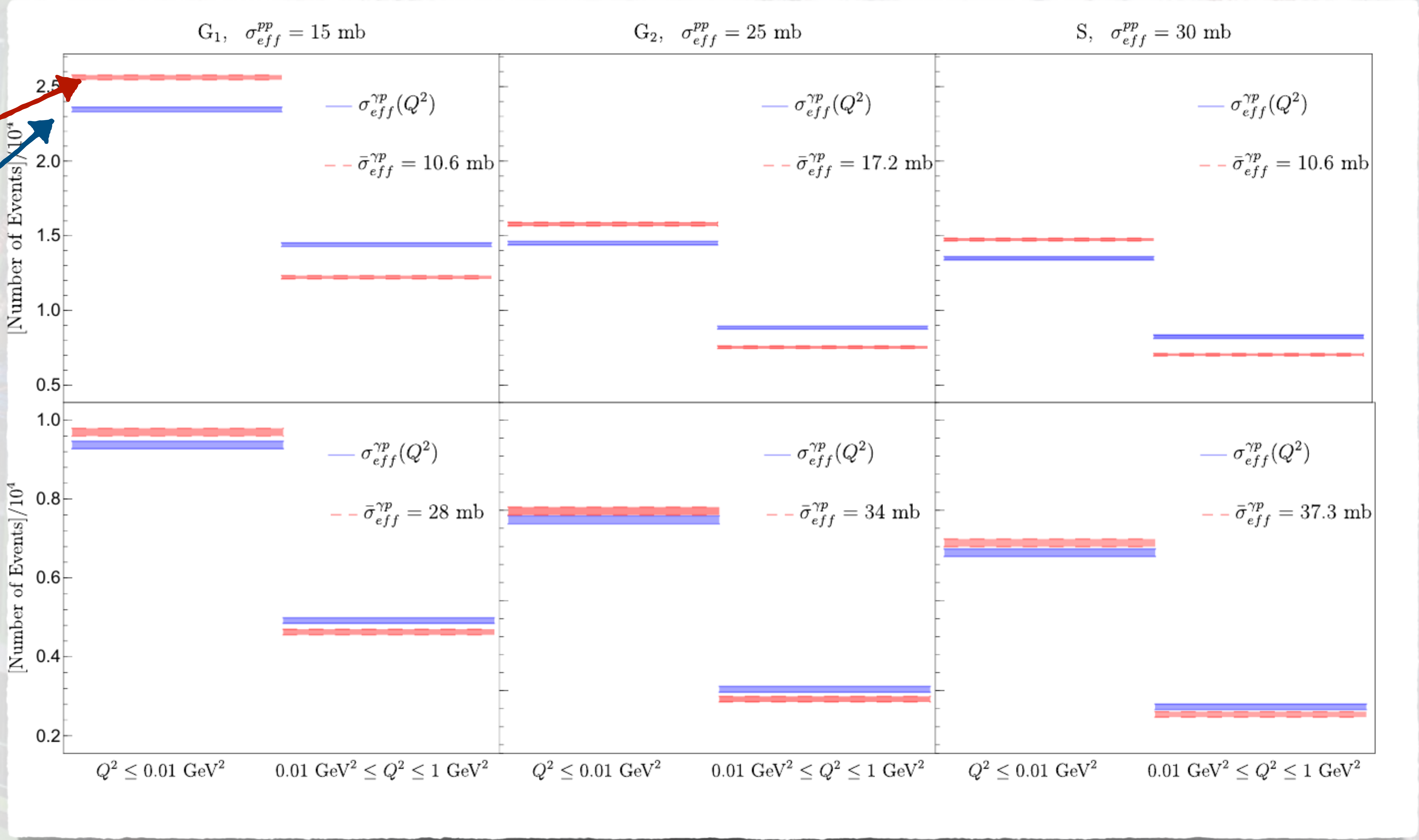


Calculated $F_2(\vec{k}_2, \vec{k}_1)$ fo

V. Guzey, M.R., S. Scopetta, M. Strikman and M. Viviani et al, *"Coherent J/Ψ electroproduction on He4 and He3 at the EIC: probing Nuclear shadowing one nucleon at a time"*, PRL 129 (2022) 24, 242503

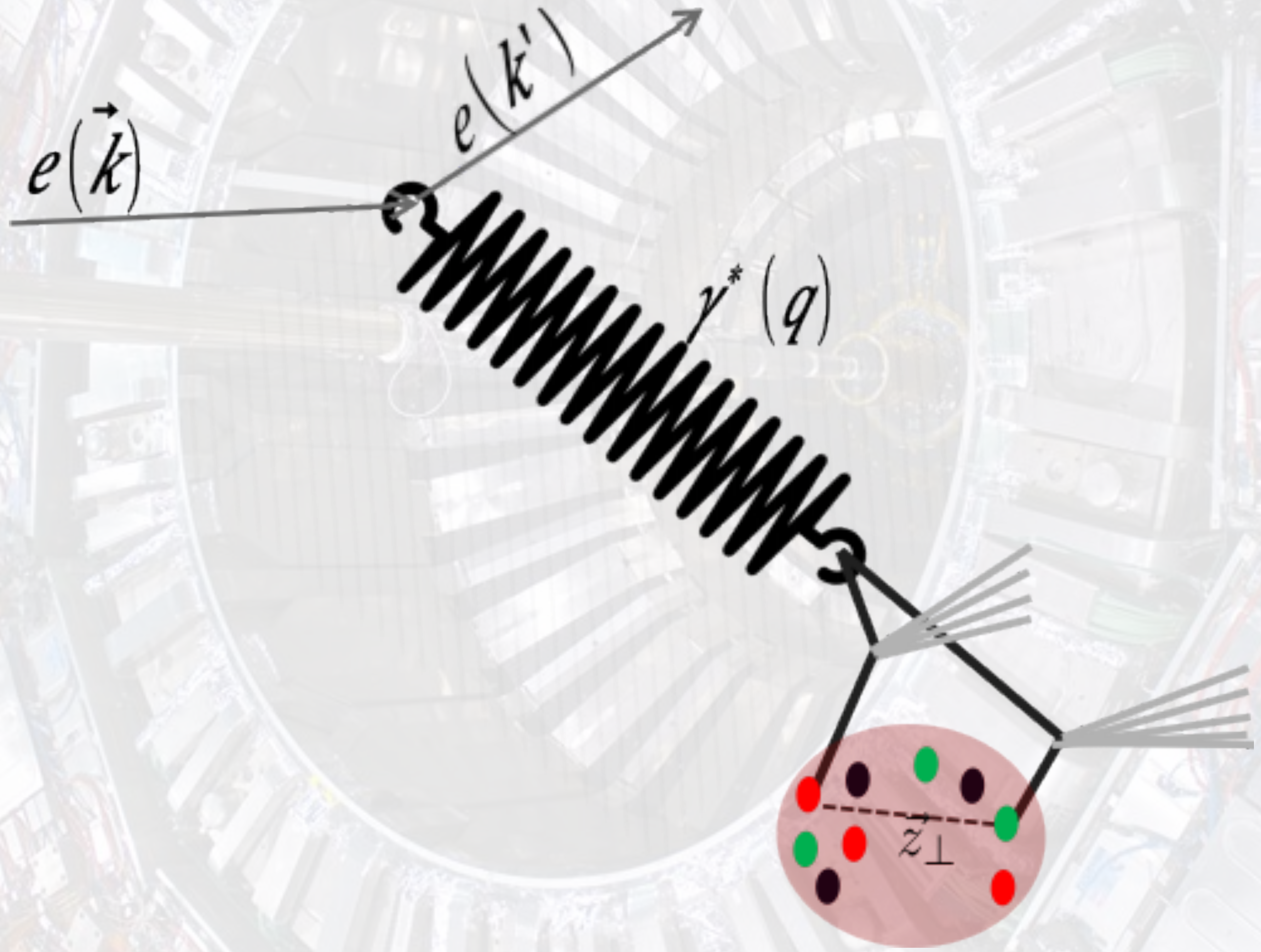
Backup - Luminosity II

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



DPS in $\gamma - p$ interactions

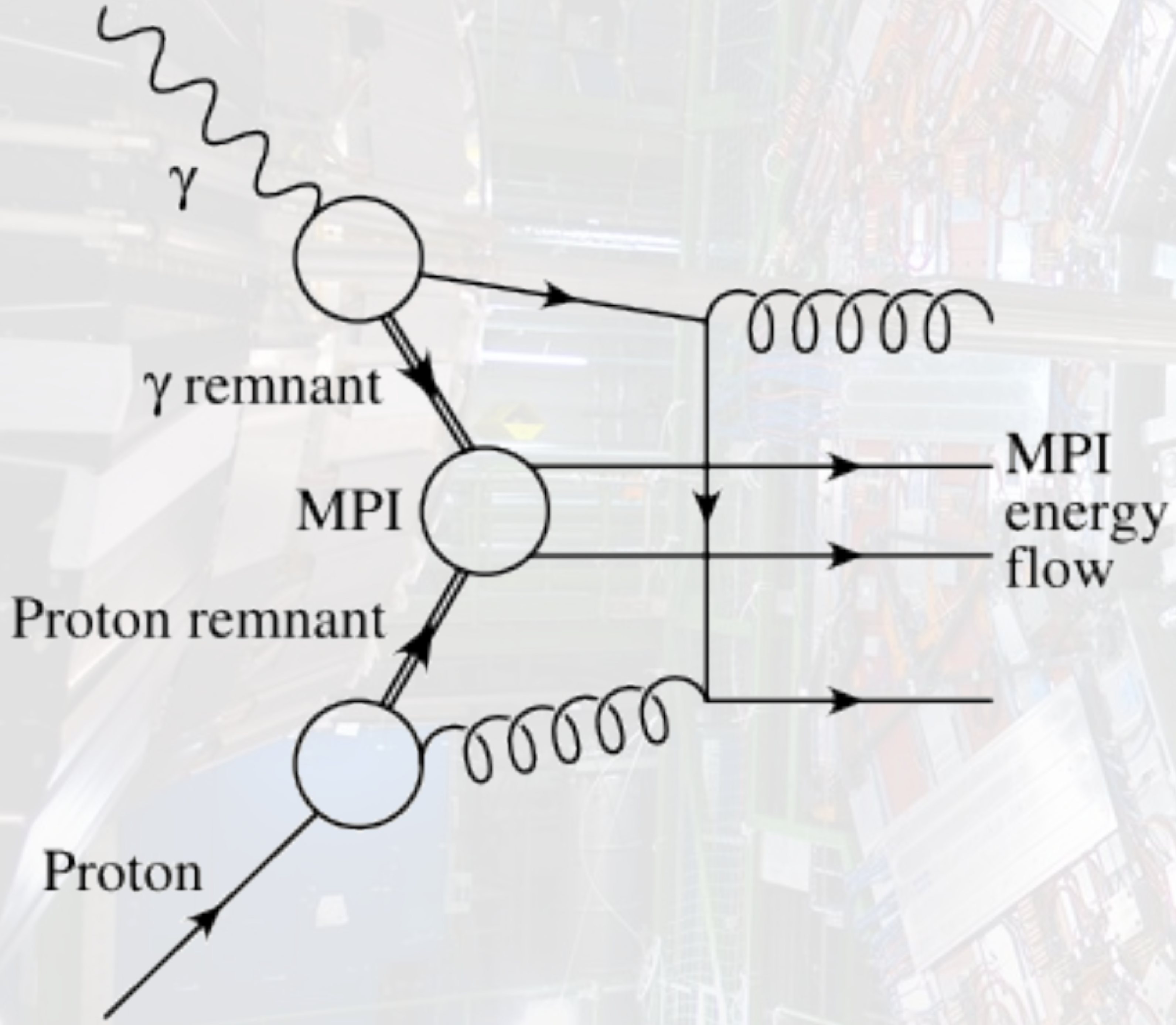
We consider the possibility offered by a DPS process involving a photon FLACTUATING in a quark-antiquark pair interacting with a proton:

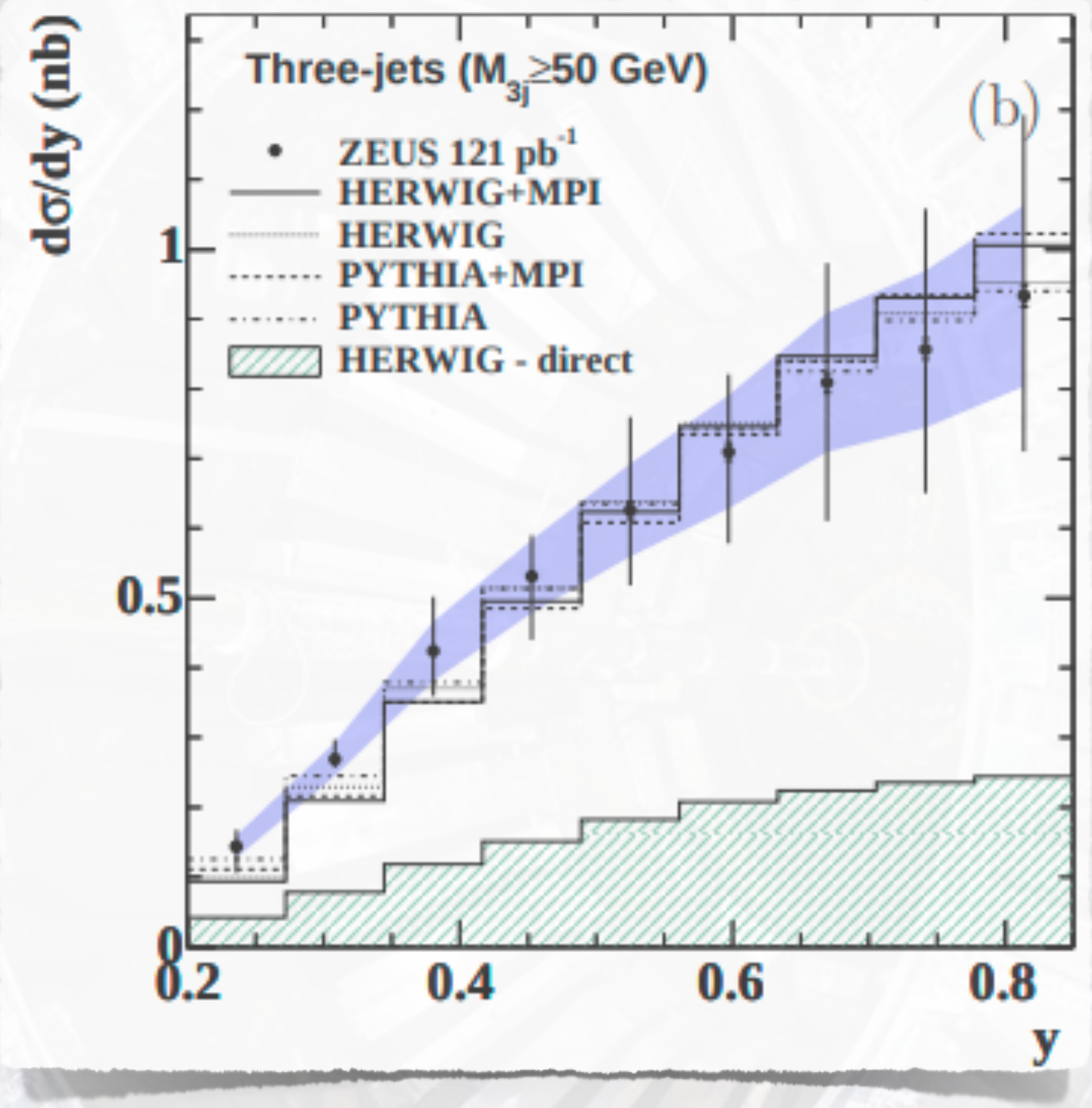


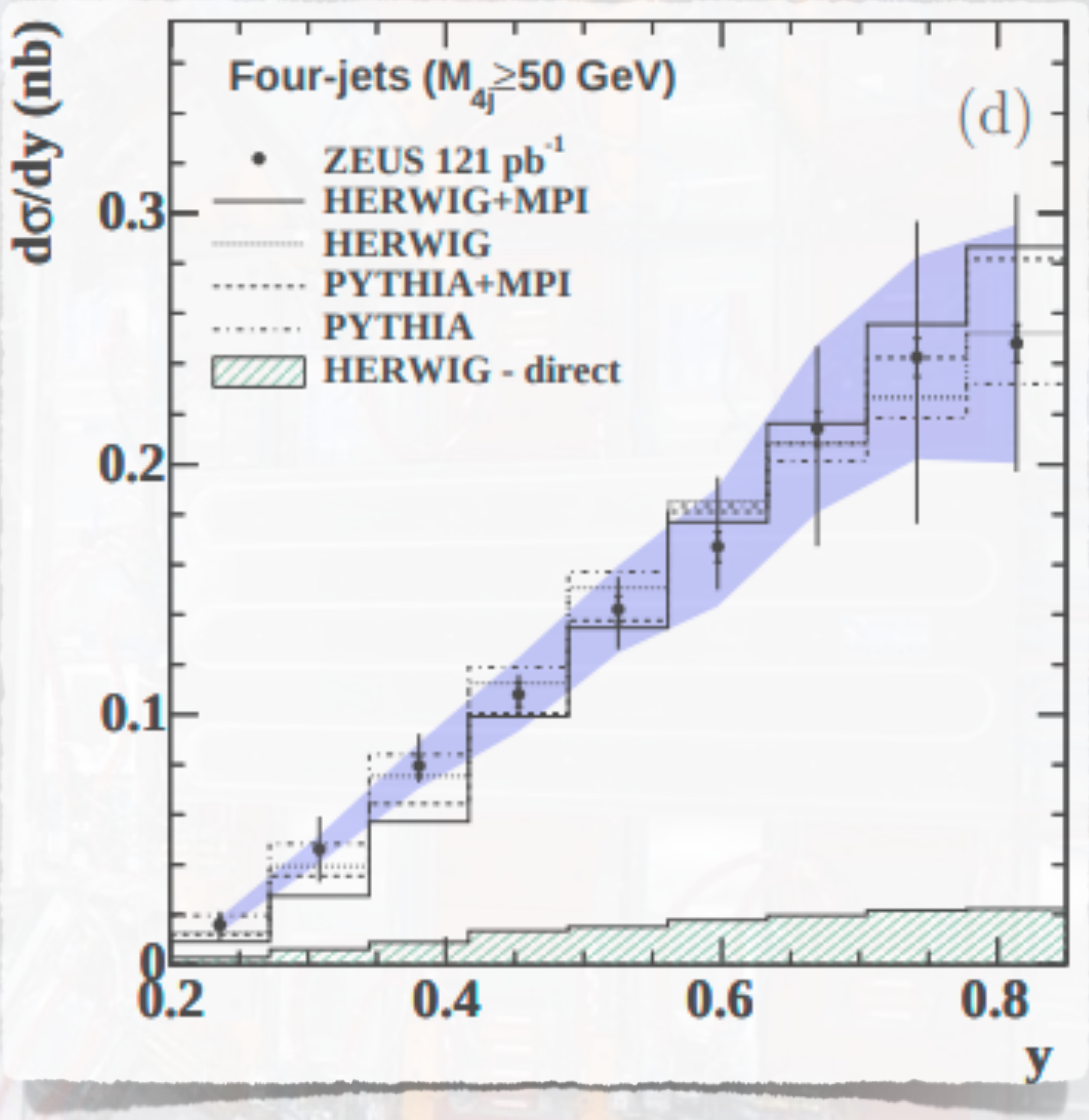
M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

DPS in $\gamma - p$ interactions

Already at HERA the importance of MPI for the **3,4 jets photo-production** has been addressed:





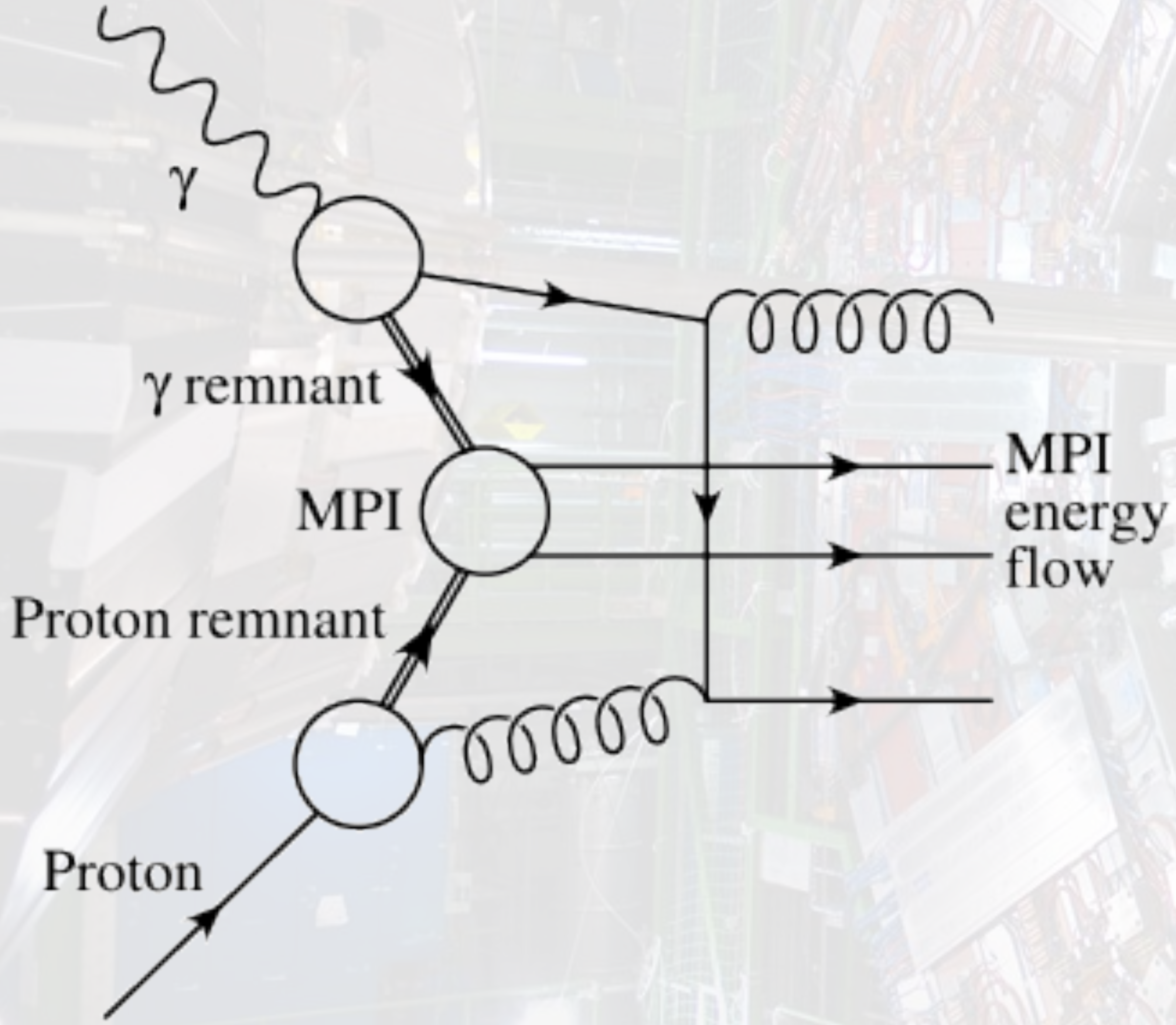


J. R. Forshaw et al, Z phys. C 72, 637

S. Chekanov et al [ZEUS coll.], Nucl. Phys B 792,1 (2008)

DPS in $\gamma - p$ interactions

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:

Flux Factor
P. Nason et al,PLB319

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

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

Proton PDF
(J. Pumplin et al. JHEP 07, 012 (2002)

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

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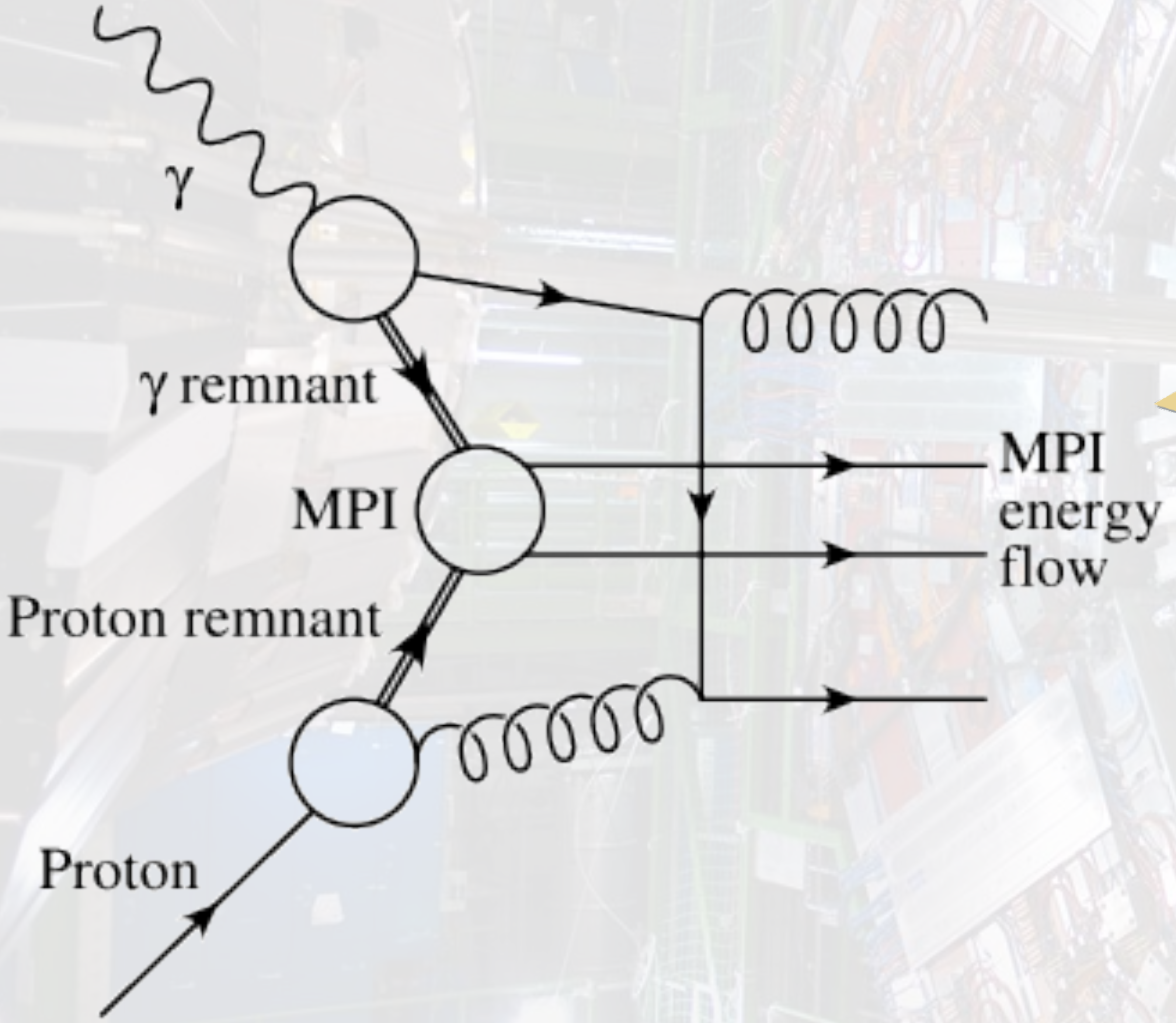

For this first investigation, we make use of the
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Flux Factor
P. Nason et al,PLB319

$$\boxed{f_{\gamma/e}(y, Q^2)} \times \frac{}{\sigma_{\rm eff}^{\gamma p}(Q^2)}$$

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

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

SPS
*
SPS

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

(J. Pumplin et al.

The main quantity we have to evaluate is:

$$\sigma_{\rm eff}^{\gamma p}(Q^2)$$

The $\gamma - p$ effective cross-section

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

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

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

Photon EFF

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

The $\gamma - p$ effective cross-section

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

The main ingredients of the calculations:

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

$\boxed{T_p(k_\perp) \quad \text{proton EFF}}$

2

3 ψ^γ Photon WF

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

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

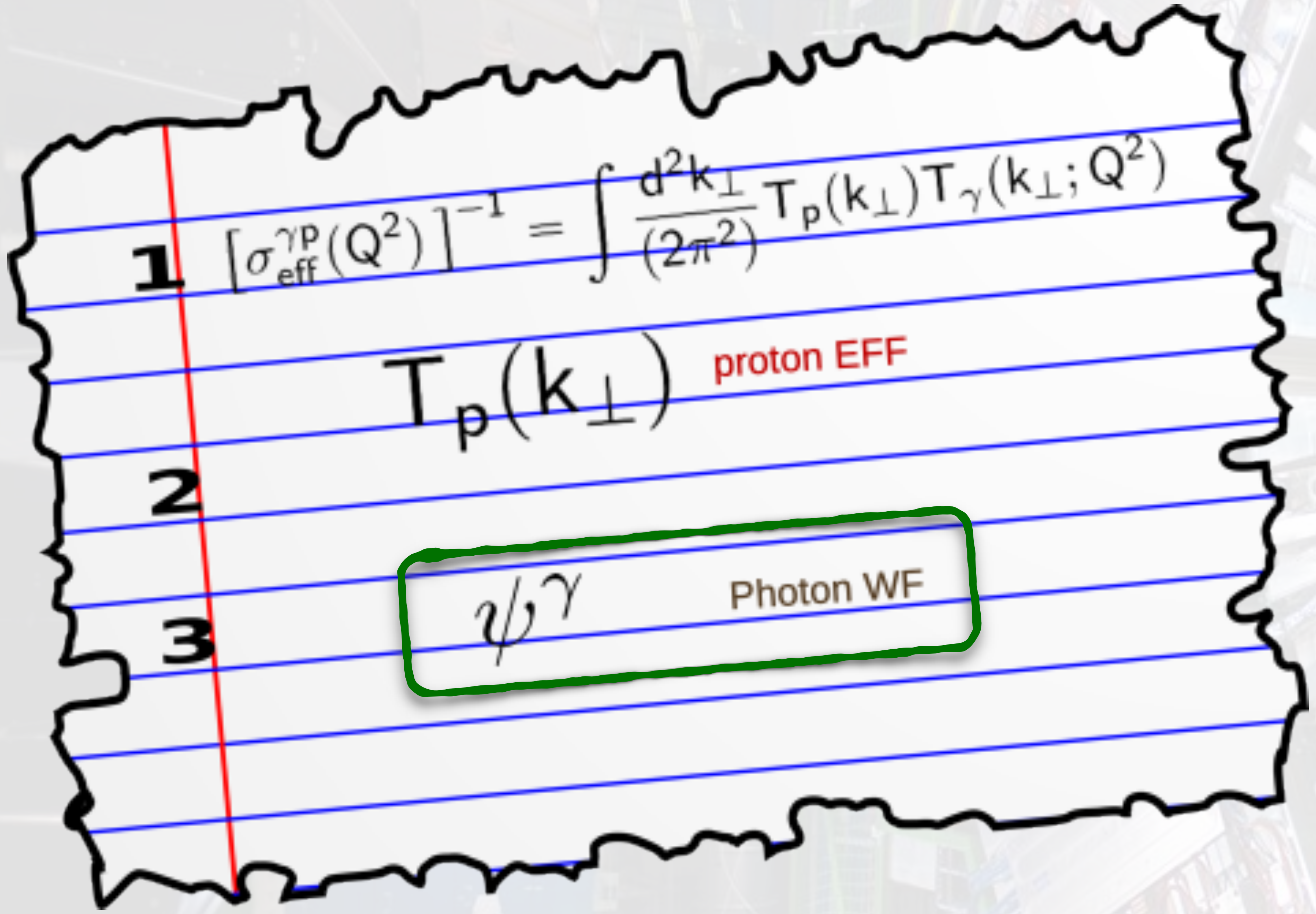
2) G2 $\quad \boxed{e^{-\alpha_2 k_\perp^2}}, \quad \alpha_2 = 2.56 \text{ GeV}^{-2} \Longrightarrow \sigma_{eff}^{pp} = 25 \text{ mb}$

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

The $\gamma - p$ effective cross-section

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

The main ingredients of the calculations:



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))**:

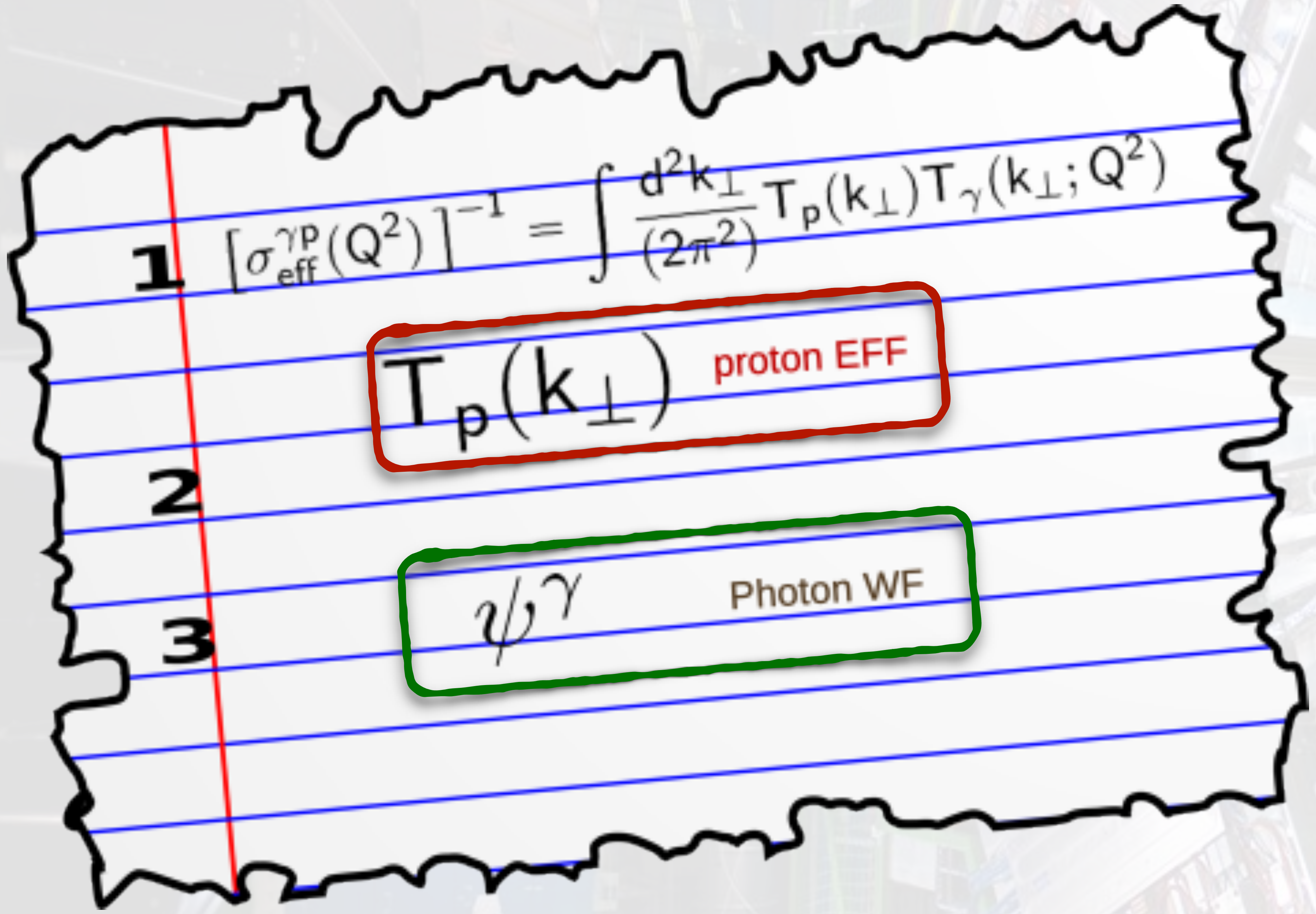
$$\psi_{q,\bar{q}}^{\lambda=\pm}(x, k_{1\perp}; Q^2) = -e_f \frac{\bar{u}_q(k)\ \gamma \cdot \varepsilon^\lambda\ v_{\bar{q}}(q-k)}{\sqrt{x(1-x)}\left[Q^2 + \frac{k_{1\perp}^2 + m^2}{x(1-x)}\right]}$$

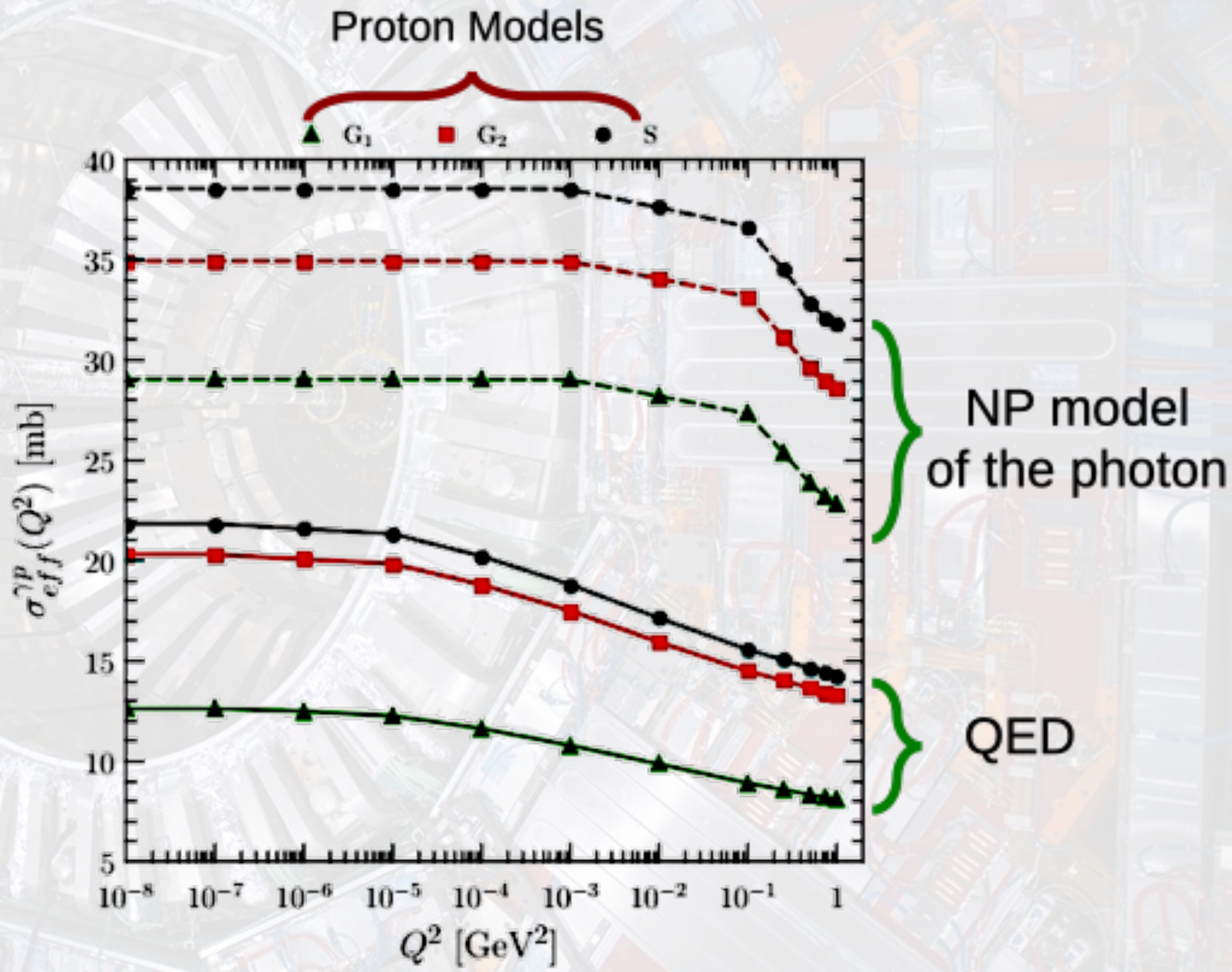
2) Non-Pertubative (NP) effects **(E.R.Arriola et al, PRD74,054023 (2006))**

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

The $\gamma - p$ effective cross-section

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





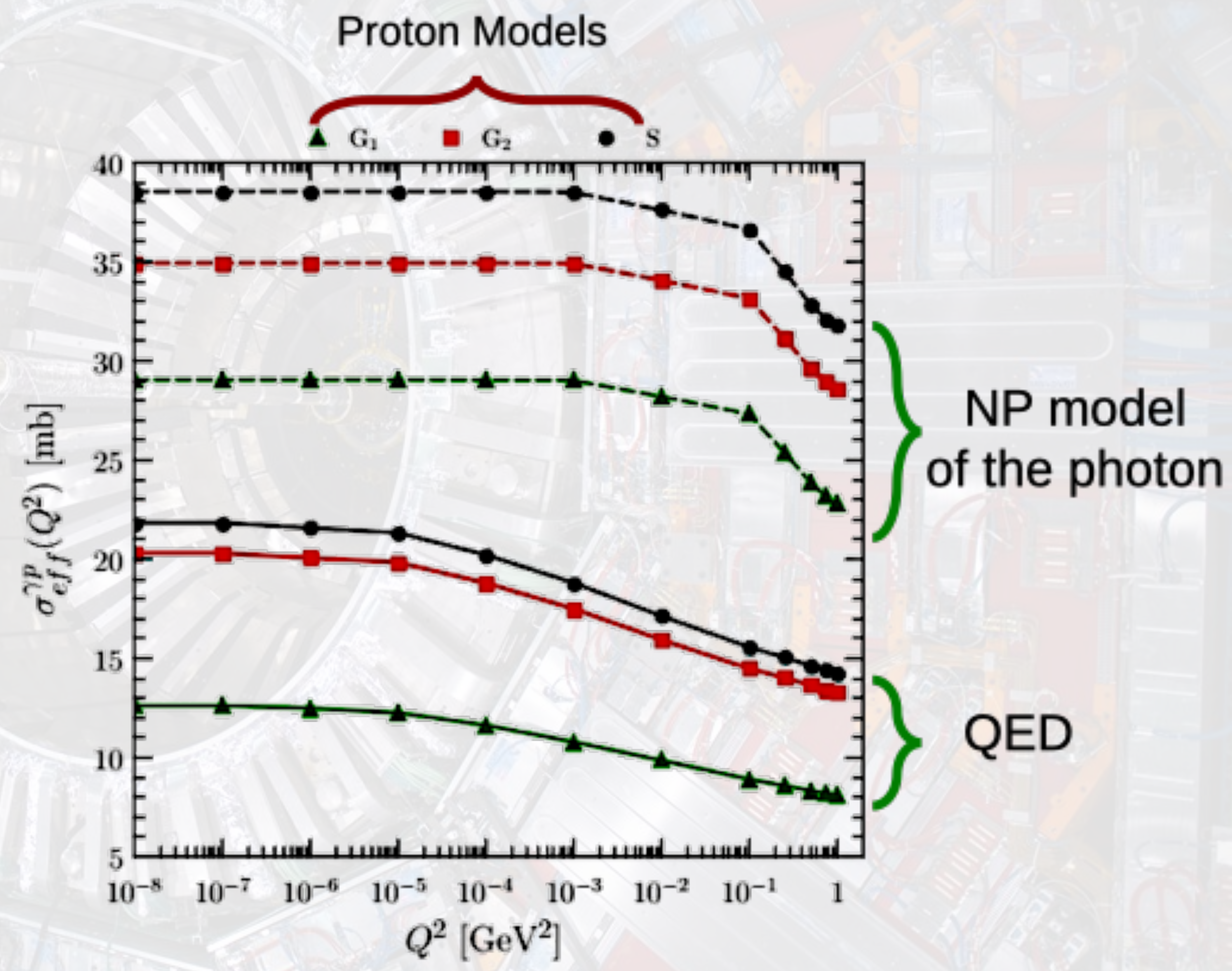
The $\gamma - p$ effective cross-section

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

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

2 $\boxed{T_p(k_\perp) \quad \text{proton EFF}}$

3 $\boxed{\psi^\gamma \quad \text{Photon WF}}$

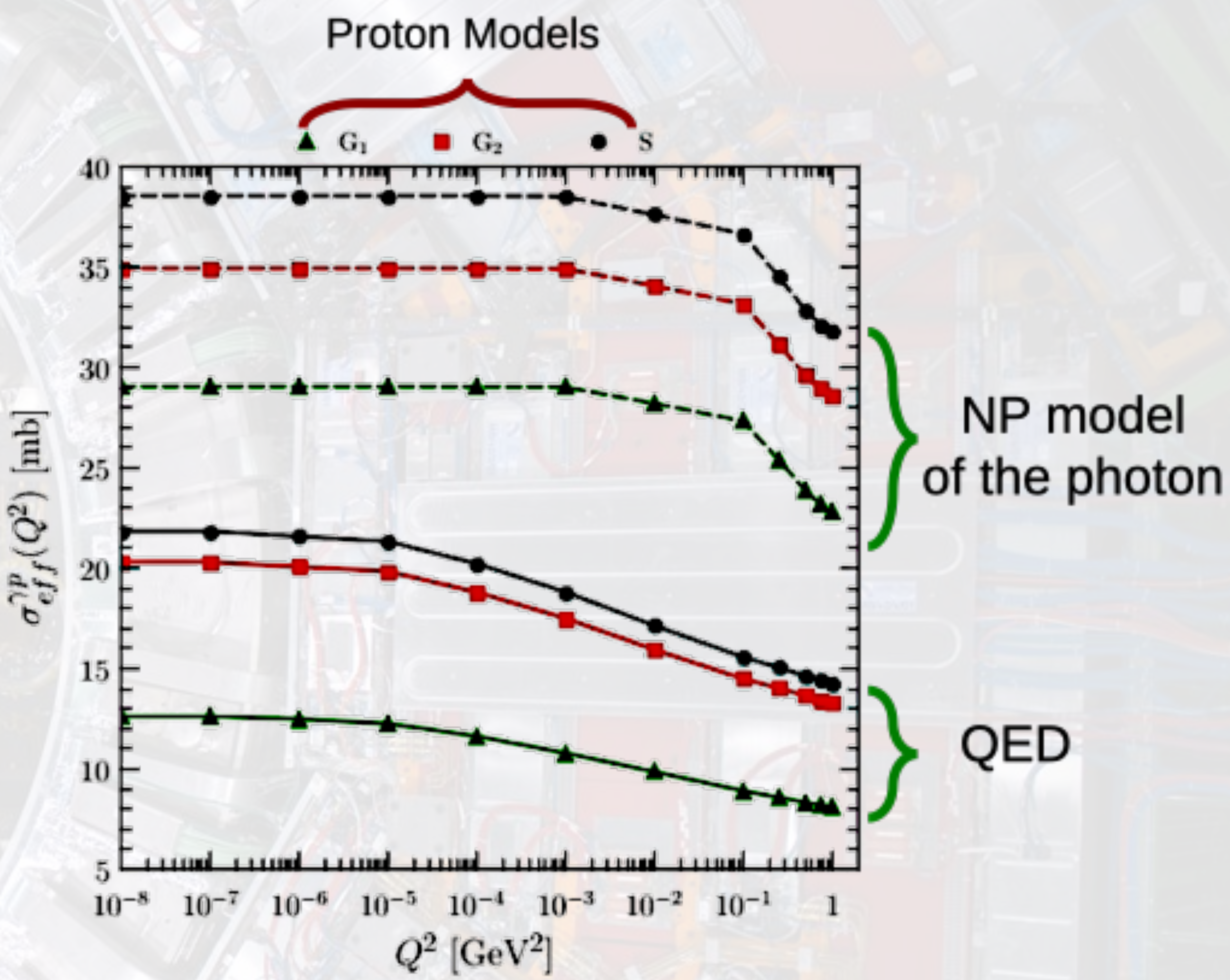


The effective cross-section depends on the photon virtuality! (NEW)

The 4-jets DPS cross-section

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

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



KINEMATICS:

$E_T^{jet} > 6$ GeV

$|\eta_{jet}| < 2.4$

$Q^2 < 1$ GeV^2

$0.2 \leqslant y \leqslant 0.85$

The ZEUS collaboration quoted an integrated total 4-jet cross section of 136 pb
S. Checkanov et al. (ZEUS), Nucl. Phys B792, 1 (2008)

The 4-jets DPS cross-section

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

$$d\sigma^{4j}_{DPS} = \frac{1}{2}\sum_{ab,cd}\int \ldots$$

$$\times \int dx_{p_a} dx_{\gamma_b} f_{a/p}(\ldots$$

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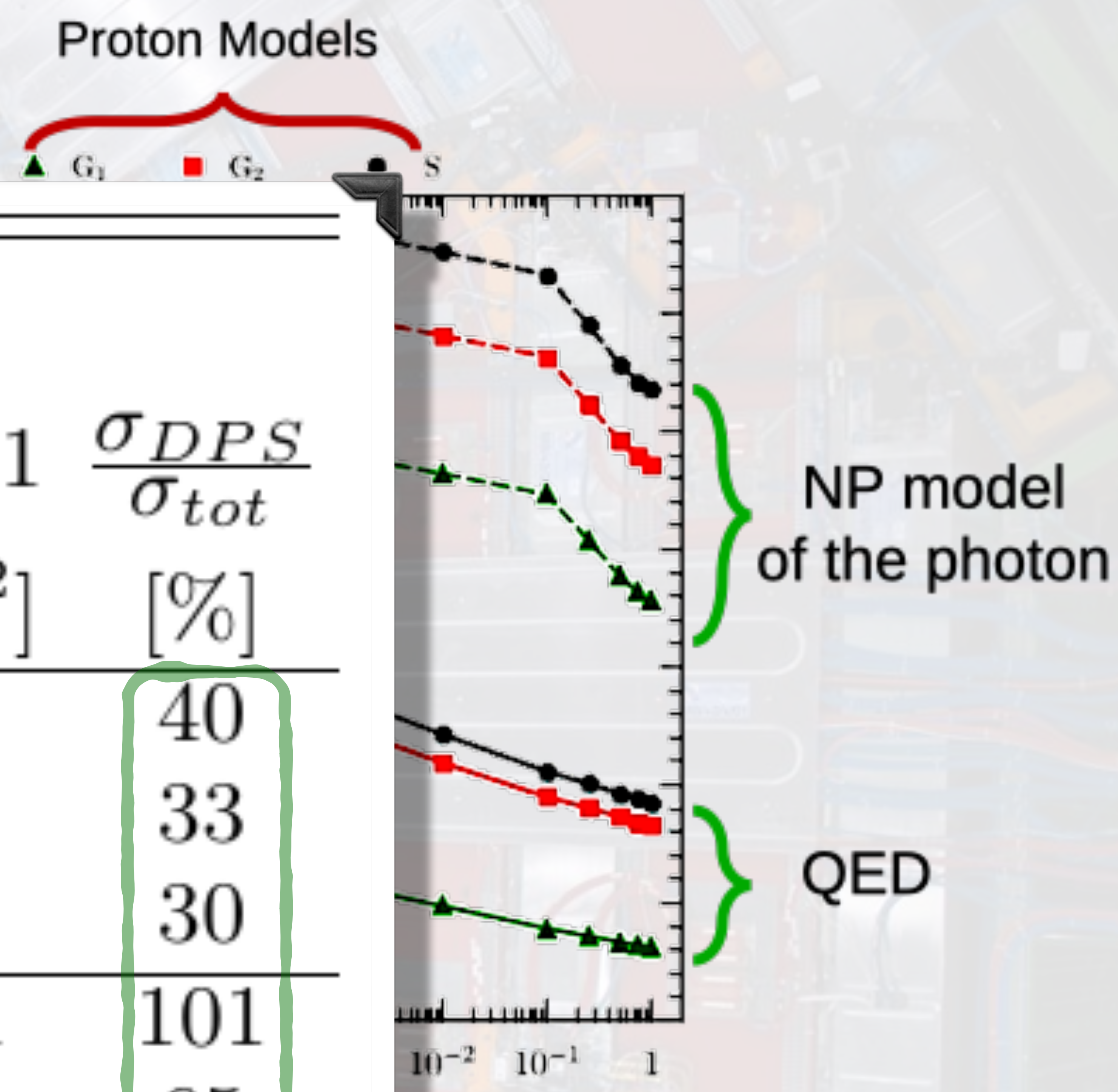
Photon	Proton	σ_{DPS} [pb] $Q^2 \le 10^{-2}$ [GeV^2]	$10^{-2} \le Q^2 \le 1$ [GeV^2]	$Q^2 \le 1$ [GeV^2]	$\frac{\sigma_{DPS}}{\sigma_{tot}}$ [%]
NP Model	G_1	35.1	18.6	53.7	40
	G_2	29.1	15.2	44.3	33
	S	26.4	13.7	40.1	30
QED	G_1	87.8	54.3	142.1	101
	G_2	54.3	33.4	87.7	65
	S	50.5	31.1	81.6	60



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The 4-jets DPS cross-section

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

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$$\times \int dx_{p_a} dx_{\gamma_b} f_{a/p}($$

$$\times \int dx_{p_c} dx_{\gamma_d} f_{c/p}($$

KINEMATICS:

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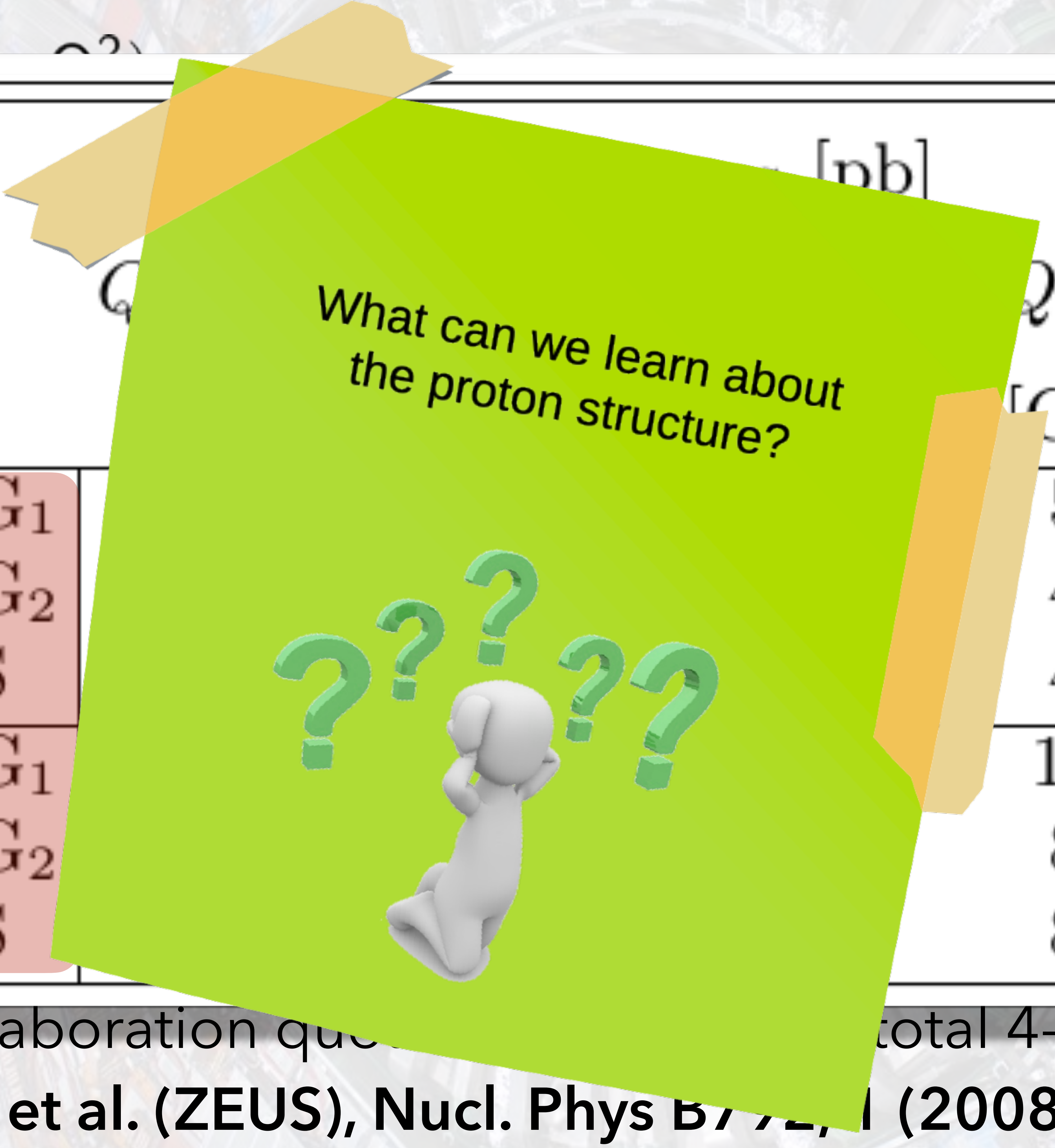
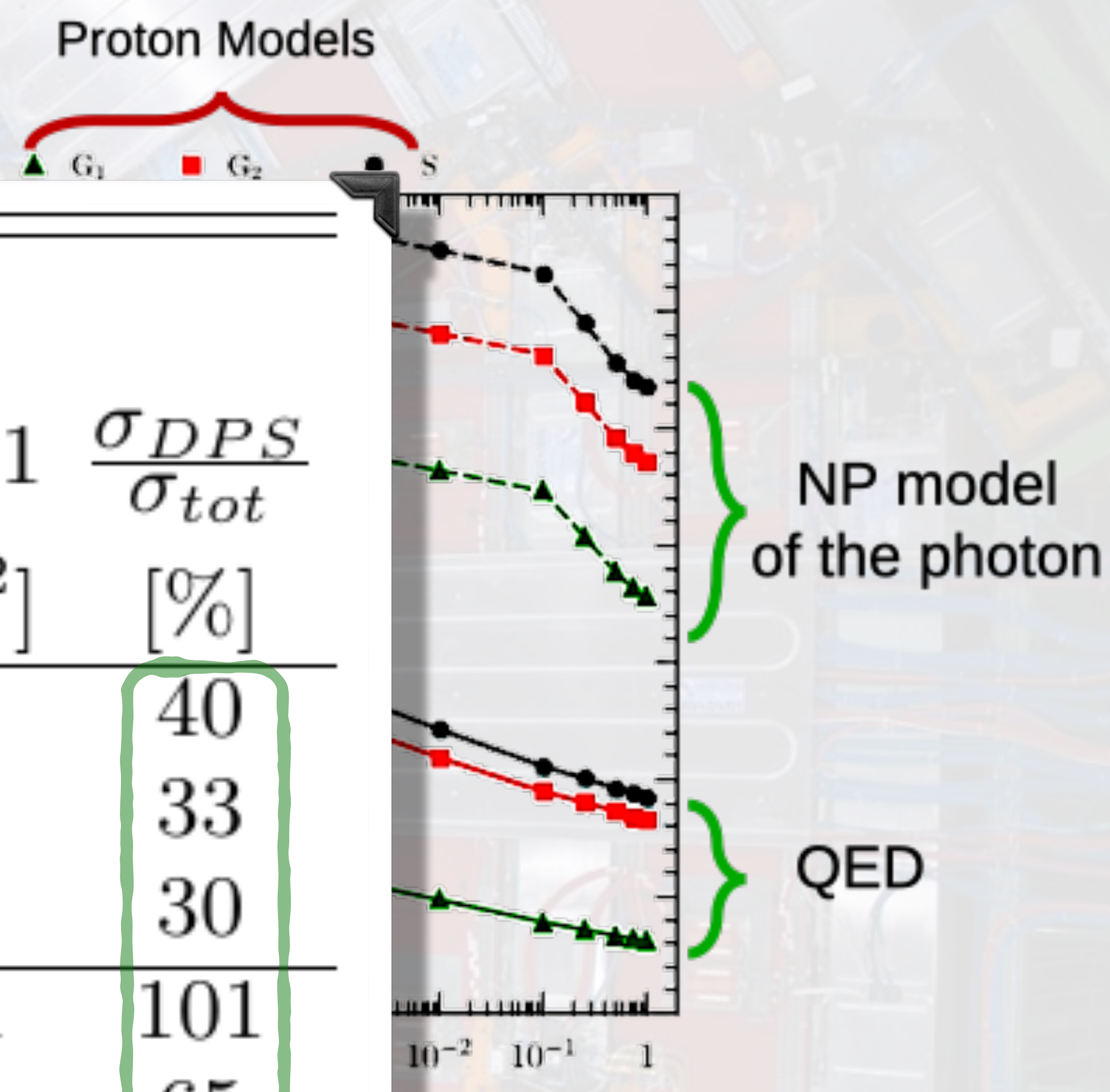
Photon	Proton		$Q^2 \leq 1$ [GeV^2]	$\frac{\sigma_{DPS}}{\sigma_{tot}}$ [%]
NP Model	G_1		53.7	40
	G_2		44.3	33
	S		40.1	30
QED	G_1		142.1	101
	G_2		87.7	65
	S		81.6	60



The ZEUS collaboration qu... total 4-jet cross section of 136 pb

S. Checkanov et al. (ZEUS), Nucl. Phys B7... (2008)



A key to the proton structure

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

The effective cross section can be also written in terms of probability distribution:

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

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We can expand the distribution related to the photon:

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

Coefficients determined in a given approach describing the photon structure

A key to the proton structure

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$$\left[\sigma_{\text{eff}}^{\gamma p}(Q^2)\right]^{-1} = \sum_n C_n(Q^2) \boxed{\langle z_\perp^n \rangle_p}$$

Mean value of the transverse distance between two partons in the PROTON

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

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Mean value of the transverse distance between two partons in the PROTON

If we could measure $\sigma_{eff}^{\gamma p}(Q^2)$ we could access NEW INFORMATION ON THE PROTON STRUCTURE

A key to the proton structure

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

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We can exp... photon:

$\tilde{F}_2^\gamma(z_\perp ...$

Coefficients determined in a given approach describing the photon structure

$\left[\sigma_{\rm eff}^{\gamma p}(Q ... z_\perp^n\rangle_p$

Mean value of the transverse distance between two partons in the PROTON

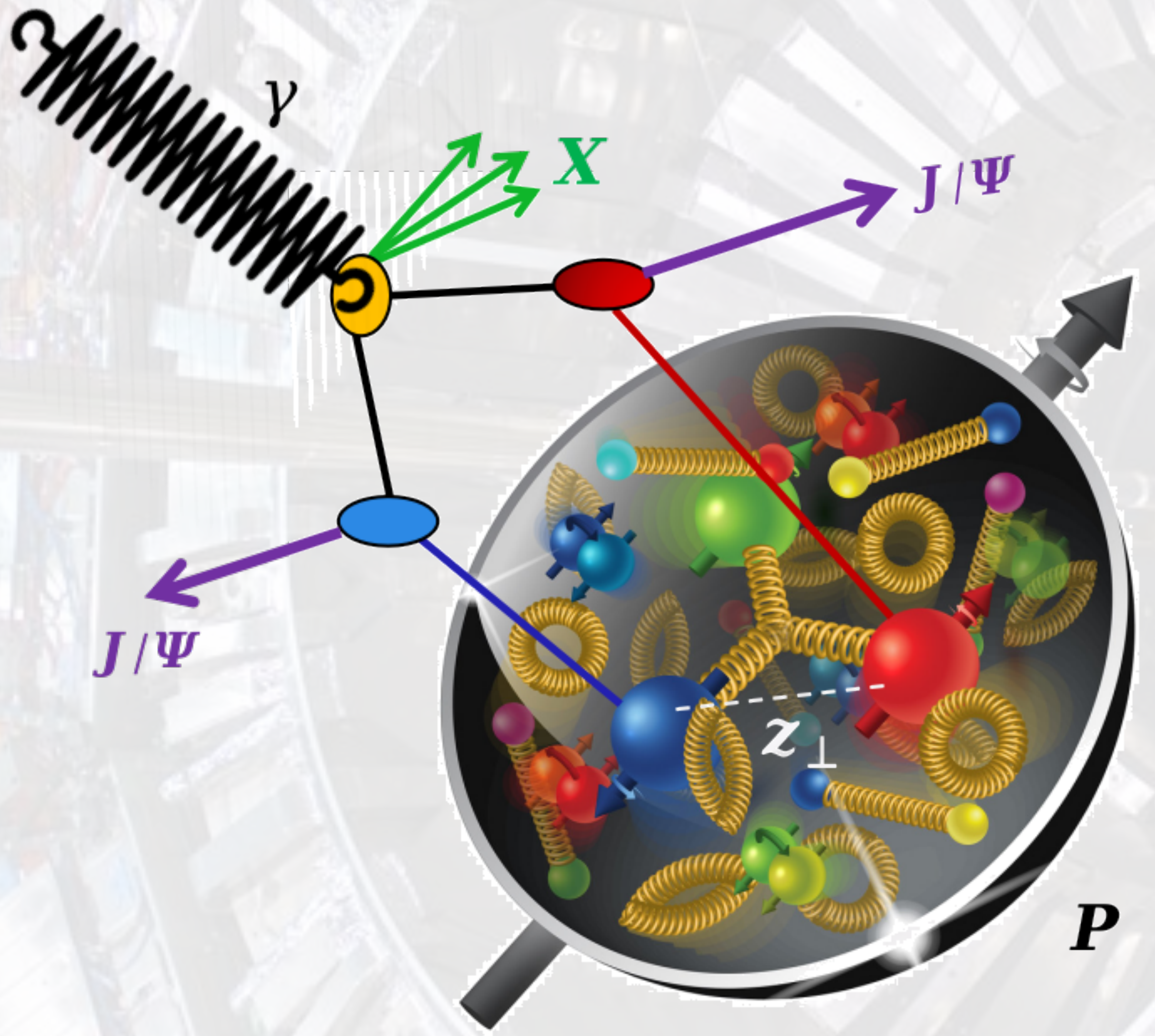
We estimated that with an integrated luminosity of 200 pb^{-1} Q^2 effects can be observed

If we could measure $\sigma_{\rm eff}^{\gamma p}(Q^2)$ we could access NEW INFORMATION ON THE PROTON STRUCTURE

Di J/ψ photo-production@EIC

F. A. Ceccopieri, H. S. Shao, J. P. Lansberg, M. R. and R. Sangem in prep.

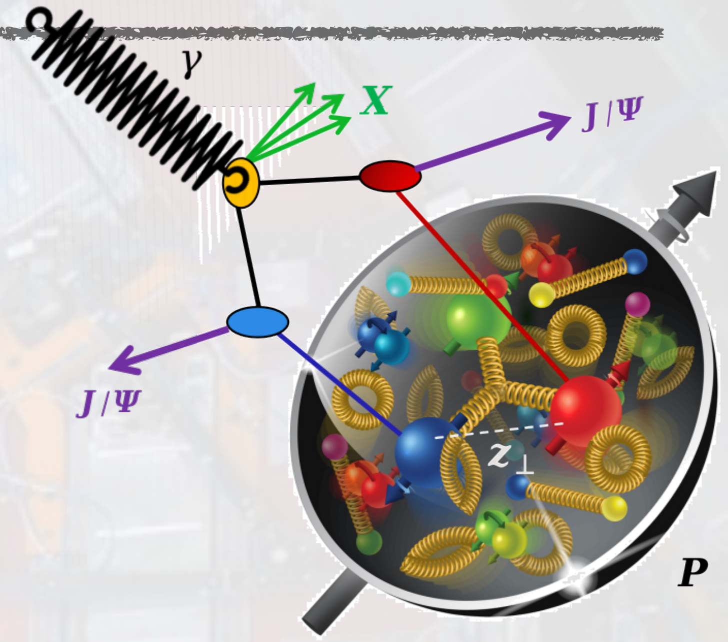
Illustration of DPS for $\gamma + p \to J/\psi + J/\psi + X$



We consider the possibility of **resolved** photon to estimate the DPS cross section in quarkonium-pair photoproduction at the EIC

Di J/ψ photo-production@EIC

F. A. Ceccopieri, H. S. Shao, J. P. Lansberg, M. R. and R. Sangem in prep.



*Slide from R. Sangem

$$\sigma_{SPS}^{(J/\psi,J/\psi)} \propto \sum_{a=g,q} \int dx_{p_a}\, f_{a/p}(x_{p_a},\mu)\, d\hat{\sigma}^{\gamma a\to J/\psi+J/\psi+a}$$

unresolved/direct

$$\sigma_{SPS}^{(J/\psi,J/\psi)} \propto \sum_{a,b=g,q} \int dx_{\gamma_a}\, dx_{p_b}\, f_{a/\gamma}(x_{\gamma_a},\mu)\, f_{b/p}(x_{p_b},\mu)\, d\hat{\sigma}^{ab\to J/\psi+J/\psi}$$

resolved

$$\sigma_{DPS}^{(J/\psi,J/\psi)} \propto \frac{1}{2}\frac{1}{\sigma_{eff}^{\gamma p}} \sum_{a,b,c,d} \int dx_{\gamma_a}\, dx_{p_b}\, f_{a/\gamma}(x_{\gamma_a},\mu)\, f_{b/p}(x_{p_b},\mu)\, d\hat{\sigma}_{SPS}^{ab\to J/\psi}(x_{\gamma_a},x_{p_b})$$
$$\times\, dx_{\gamma_c}\, dx_{p_d}\, f_{c/\gamma}(x_{\gamma_c},\mu)\, f_{d/p}(x_{p_d},\mu)\, d\hat{\sigma}_{SPS}^{cd\to J/\psi}(x_{\gamma_c},x_{p_d})$$

Proton PDF

Photon PDF

Partonic x-sections

Single SPS resolved (namely same partonic cross section as hadroproduction)

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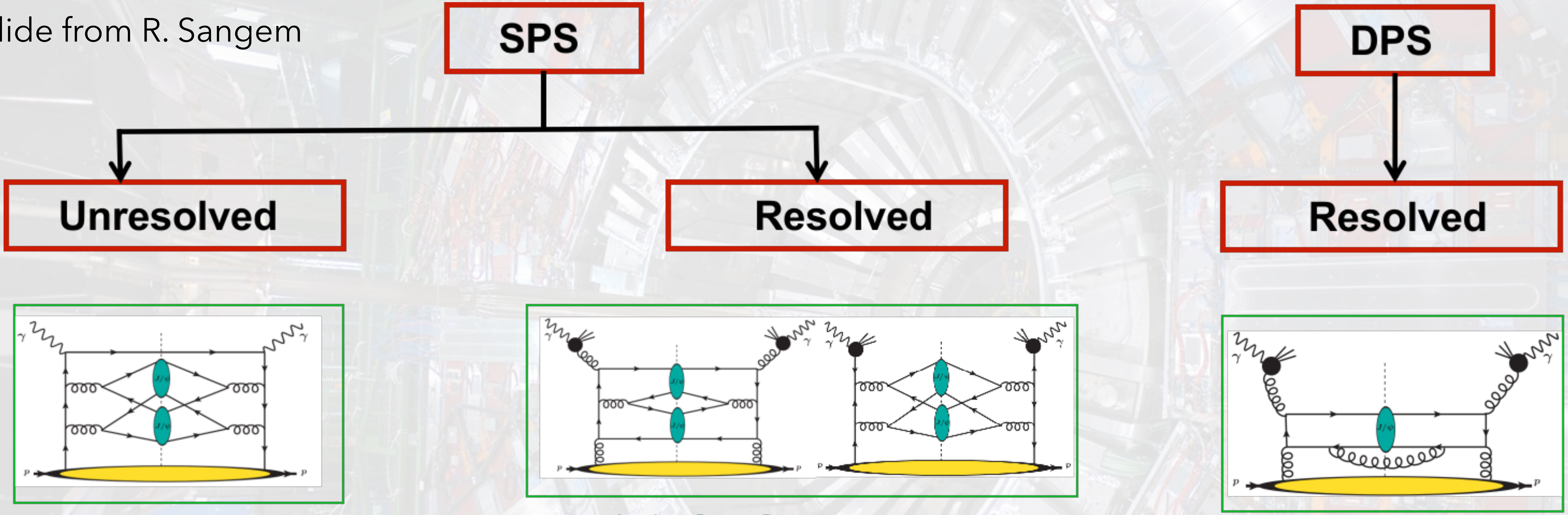

$\gamma + q \rightarrow J/\psi + J/\psi + q$

$i + j \rightarrow J/\psi + J/\psi$ $\quad i, j = g, q$

$|g + g \rightarrow J/\psi + g|^2$

- GRV photon PDF is used PRD 46, 1973 (1992) , while CT18NLO PDF for proton T.J. Hou et al., PRD 103, 014013 (2021)
- HELAC-Onia latest version is used for generating matrix elements HS Shao, CPC 184, 2562 (2013), 198, 238 (2016)
- CO LDMEs are taken from M. Butenschoen and B. A. Kniehl, PRD 84, 051501 (2011)
- We expect at least 600 four-muon events with 100 fb^{-1} luminosity

Numerical Results

PRELIMINARY

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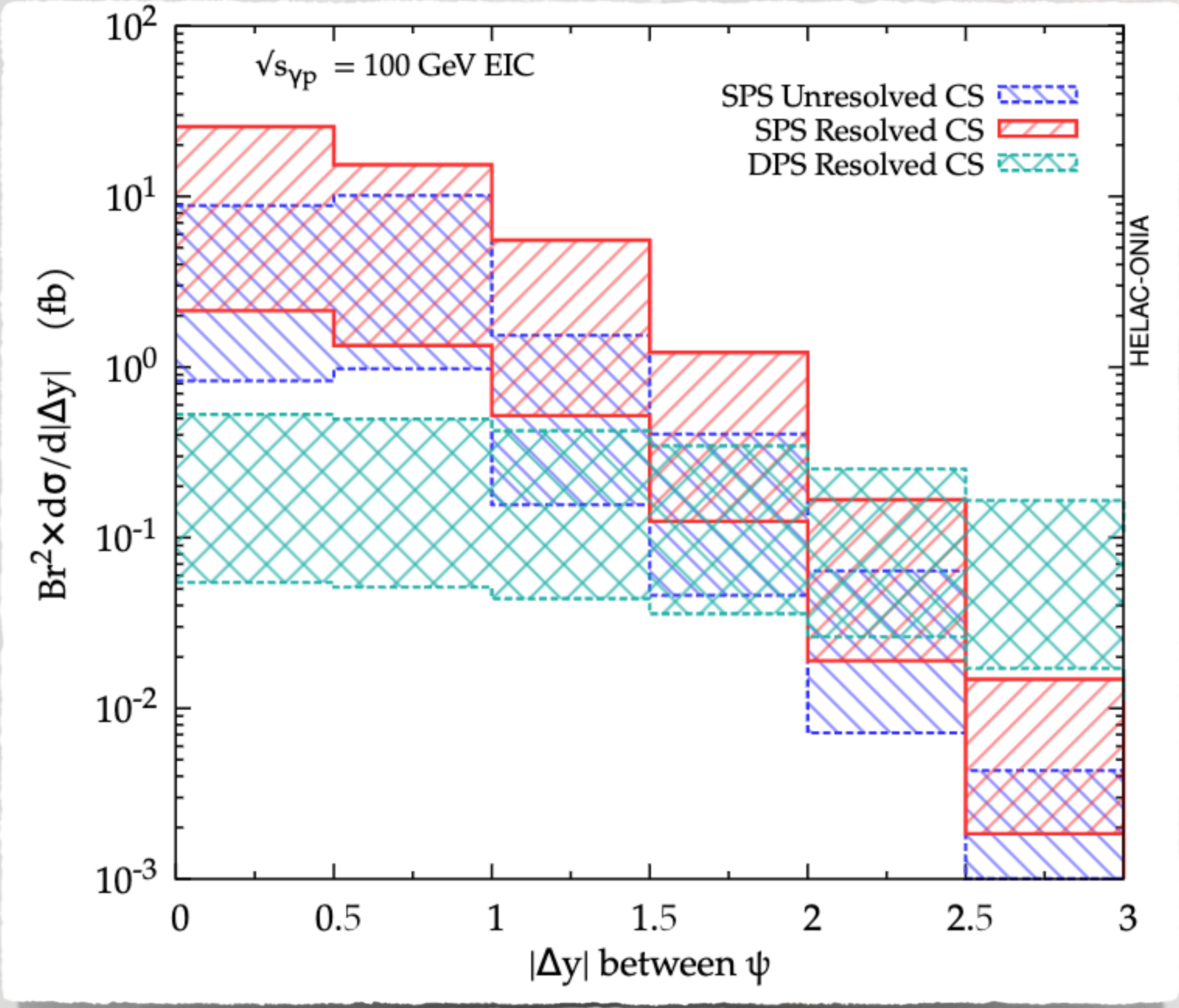
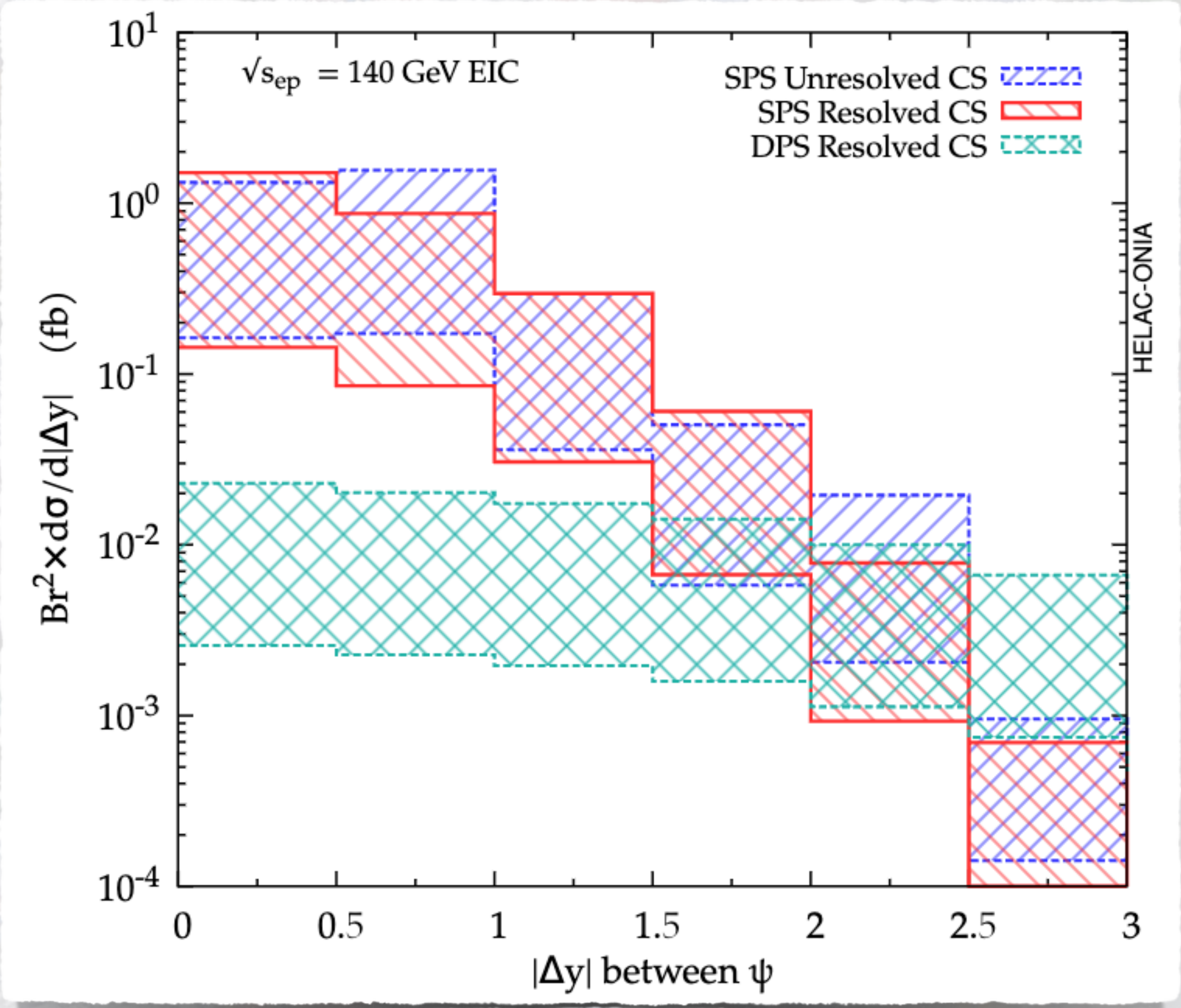
Absolute rapidity difference between the two J/ψ

$\sqrt{s_{\gamma p}} = 100$ GeV



- DPS dominates at high $|\Delta y|$
- DPS is suppressed at low $|\Delta y|$

$\sqrt{s_{\gamma p}} = 140$ GeV



Numerical Results

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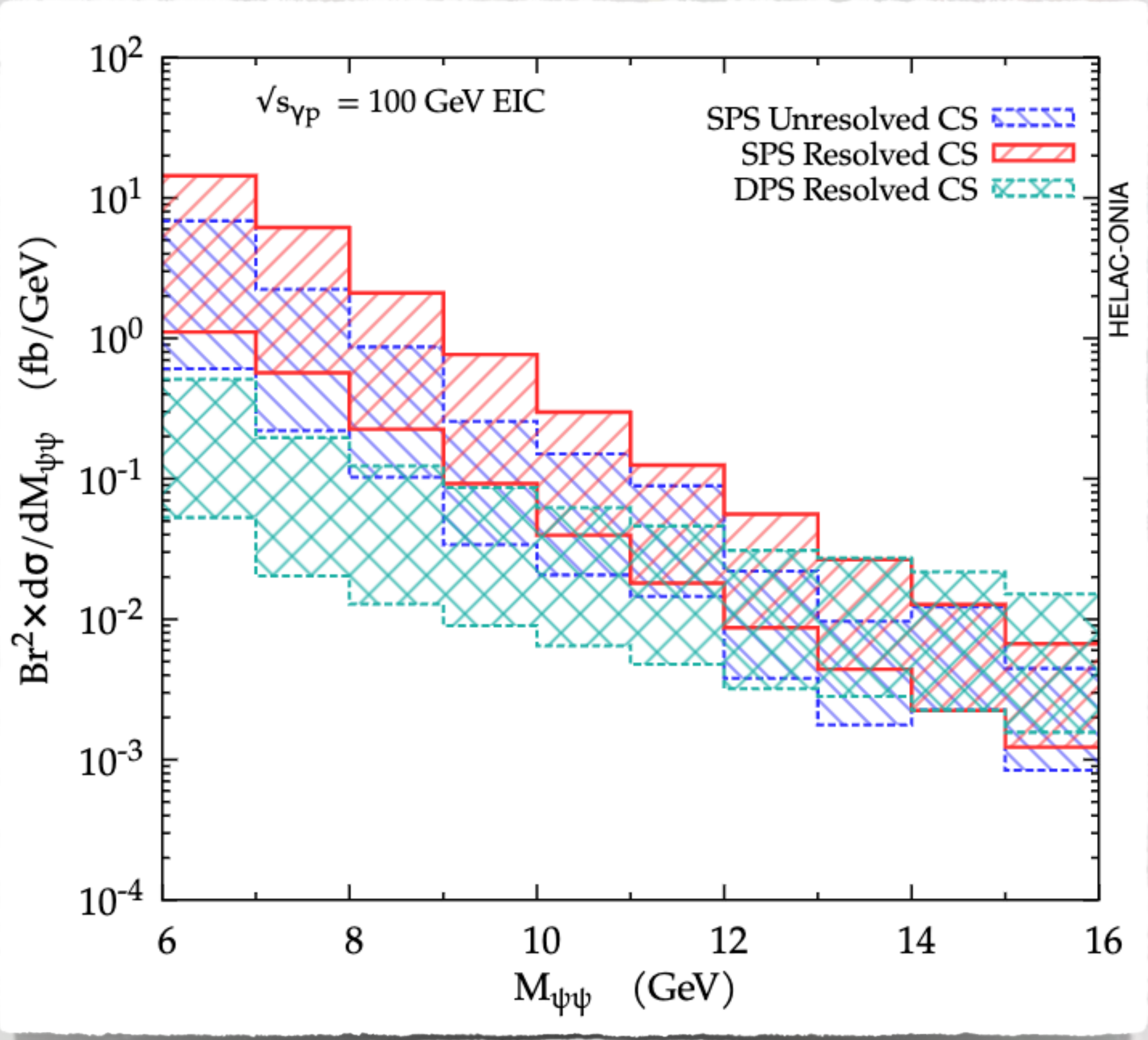
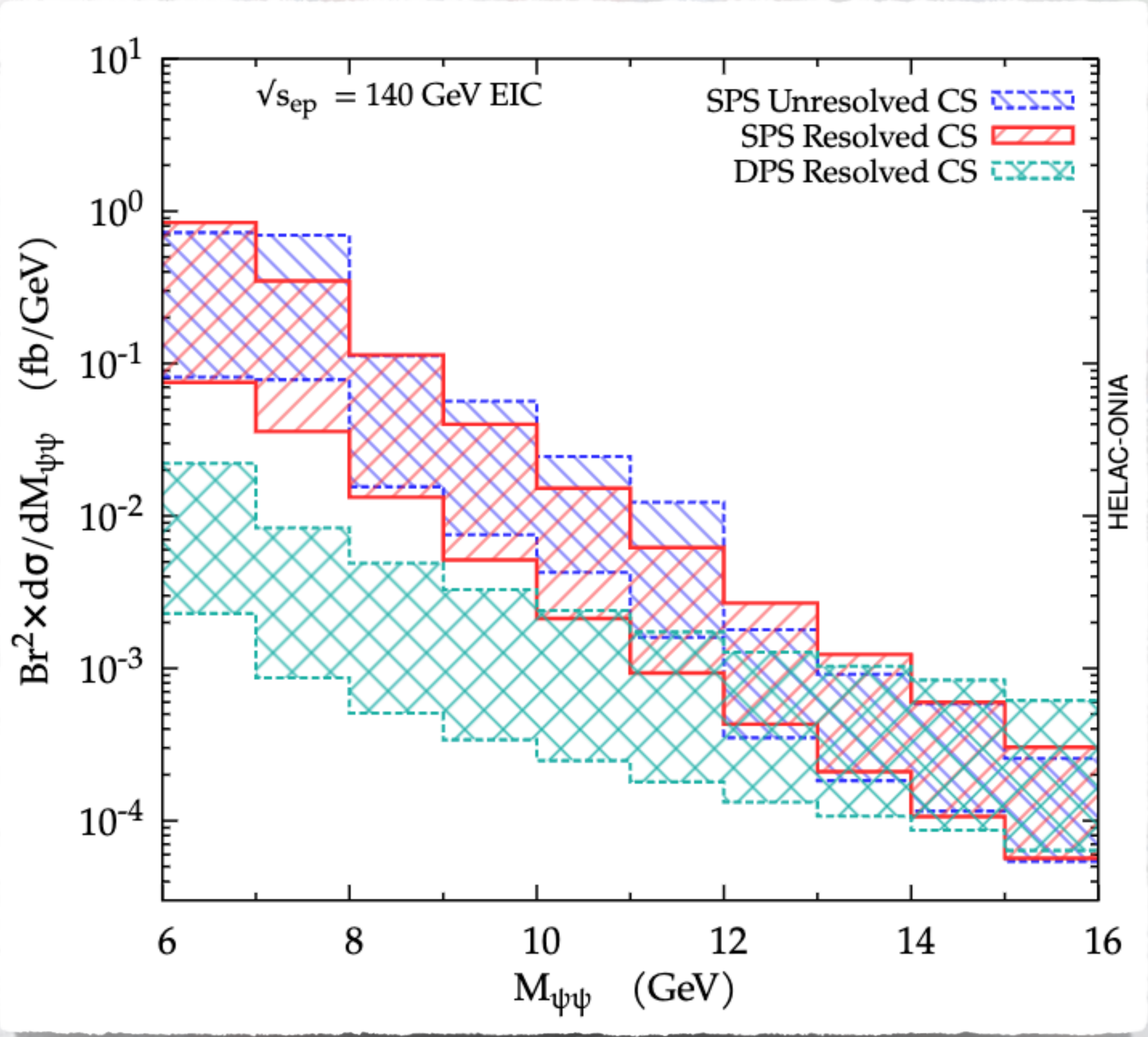
Invariant mass of the J/ψ pair

$\sqrt{s_{\gamma p}} = 100$ GeV



$\sqrt{s_{\gamma p}} = 140$ GeV



Numerical Results

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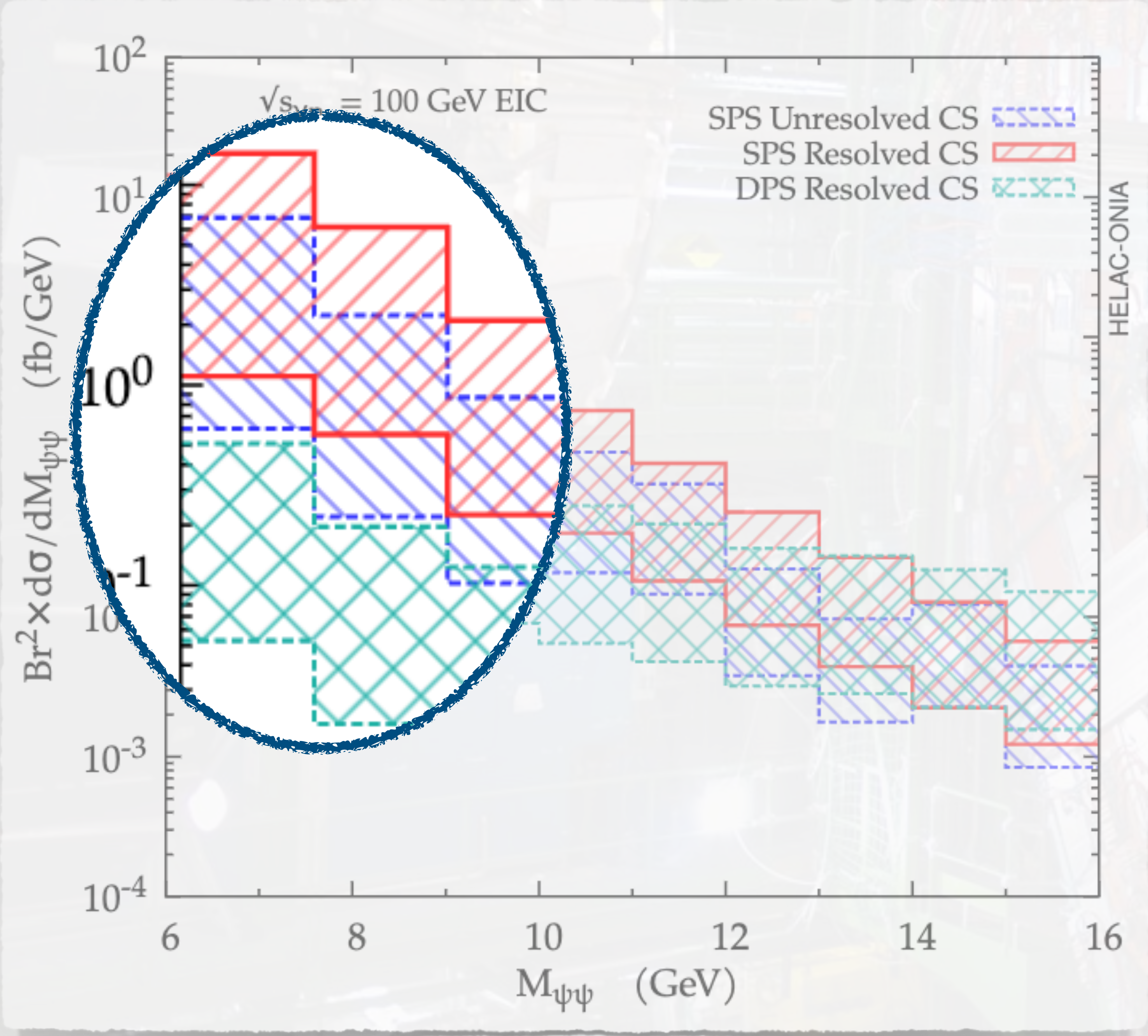
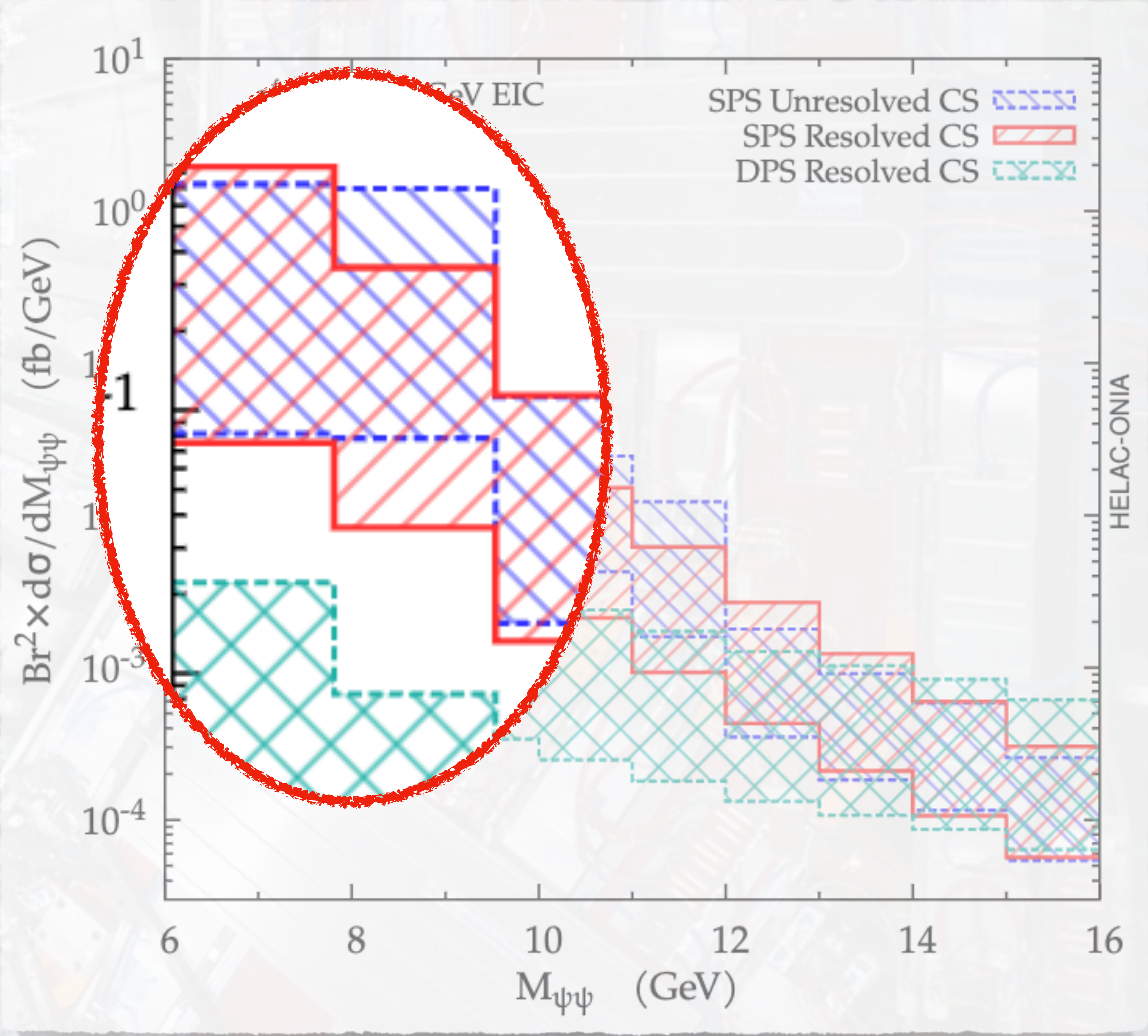


a) at low invariant mass:

- DPS smaller then SPS, but not negligible
- DPS negligible

$\sqrt{s_{\gamma p}} = 140$ GeV



Numerical Results

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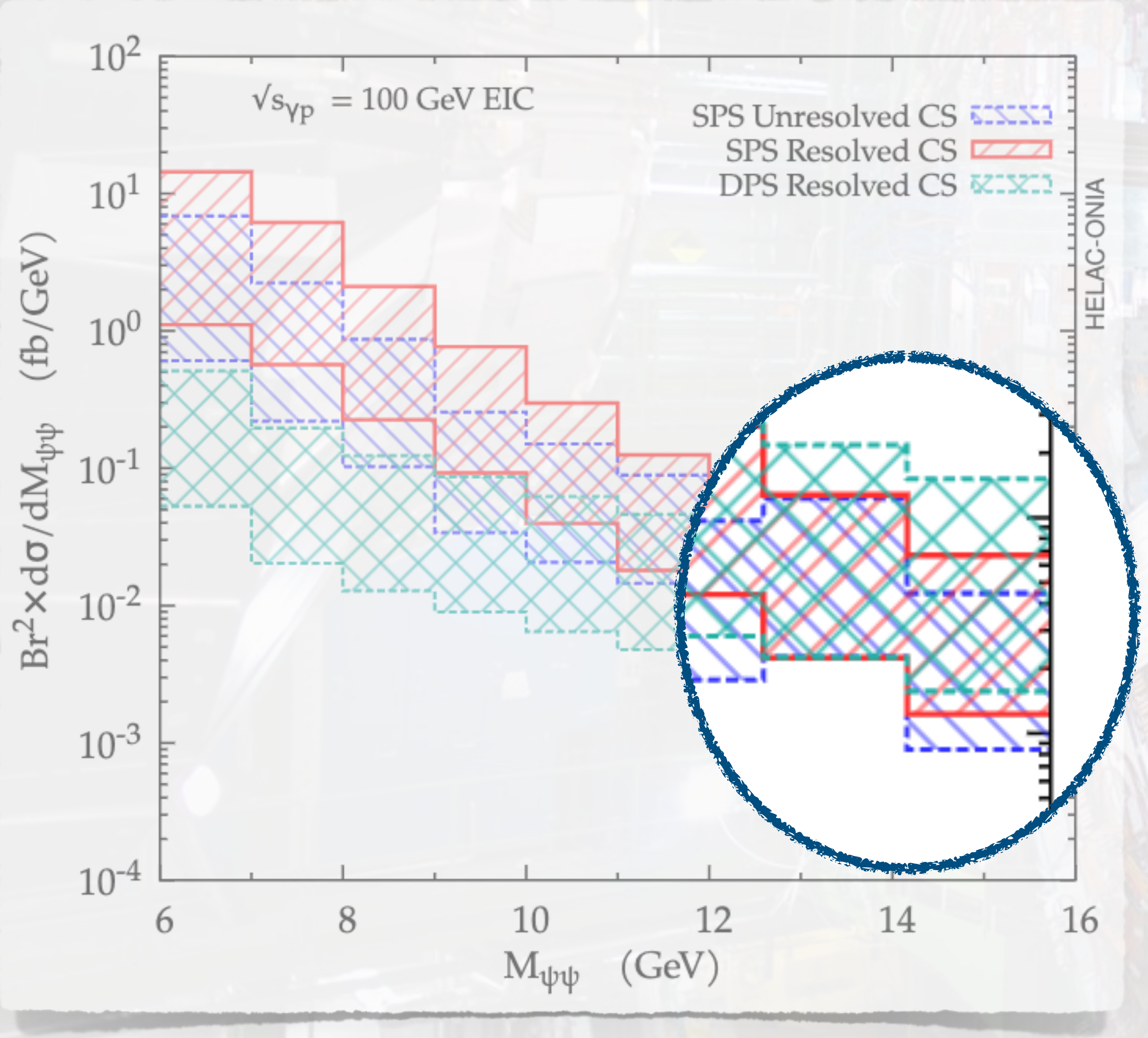
Invariant mass of the J/ψ pair

$\sqrt{s_{\gamma p}} = 100$ GeV



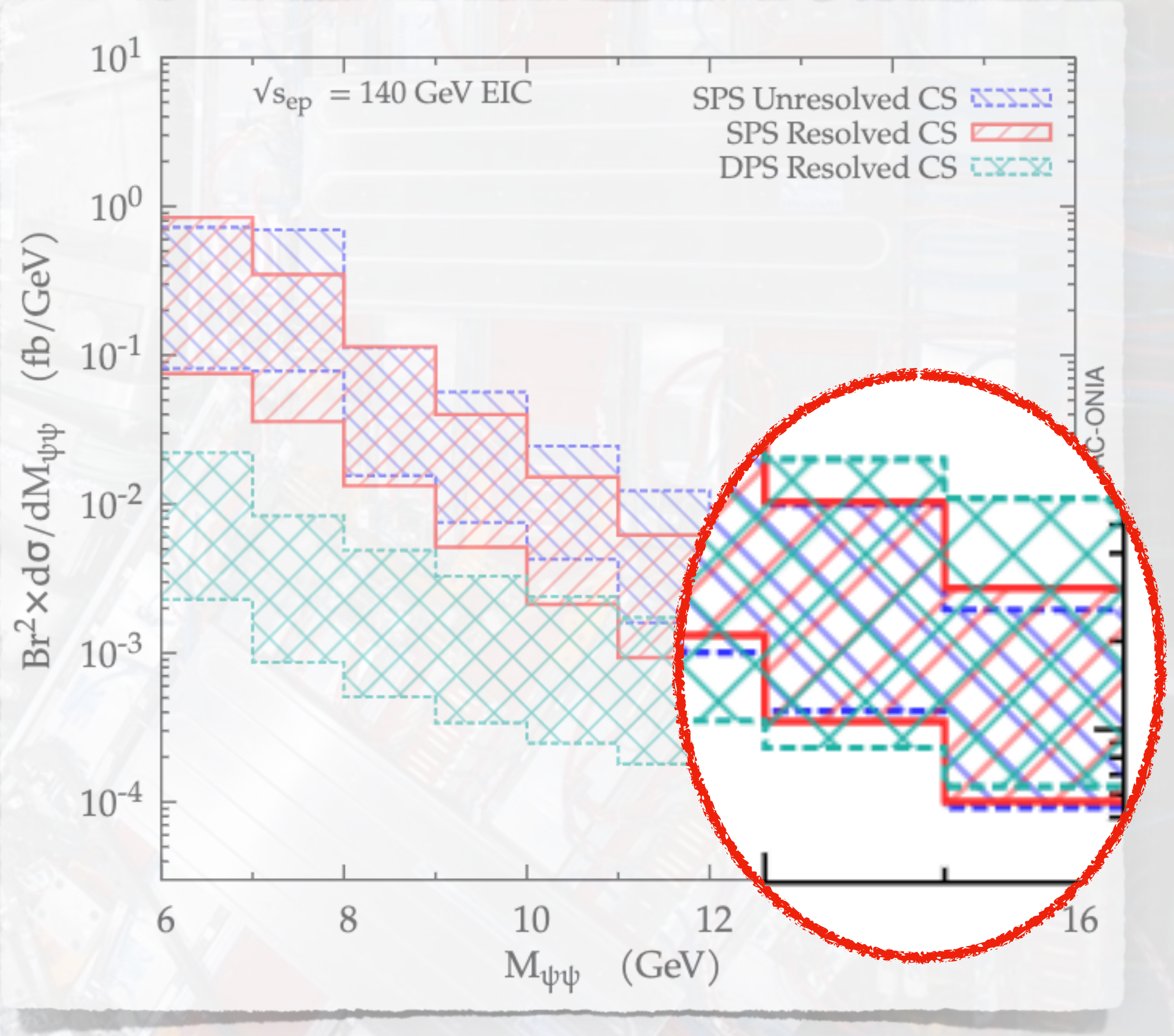
a) at low invariant mass:

- DPS smaller then SPS, but not negligible
- DPS negligible

b) at low invariant mass:

- DPS bigger then SPS
- DPS similar to SPS

$\sqrt{s_{\gamma p}} = 140$ GeV



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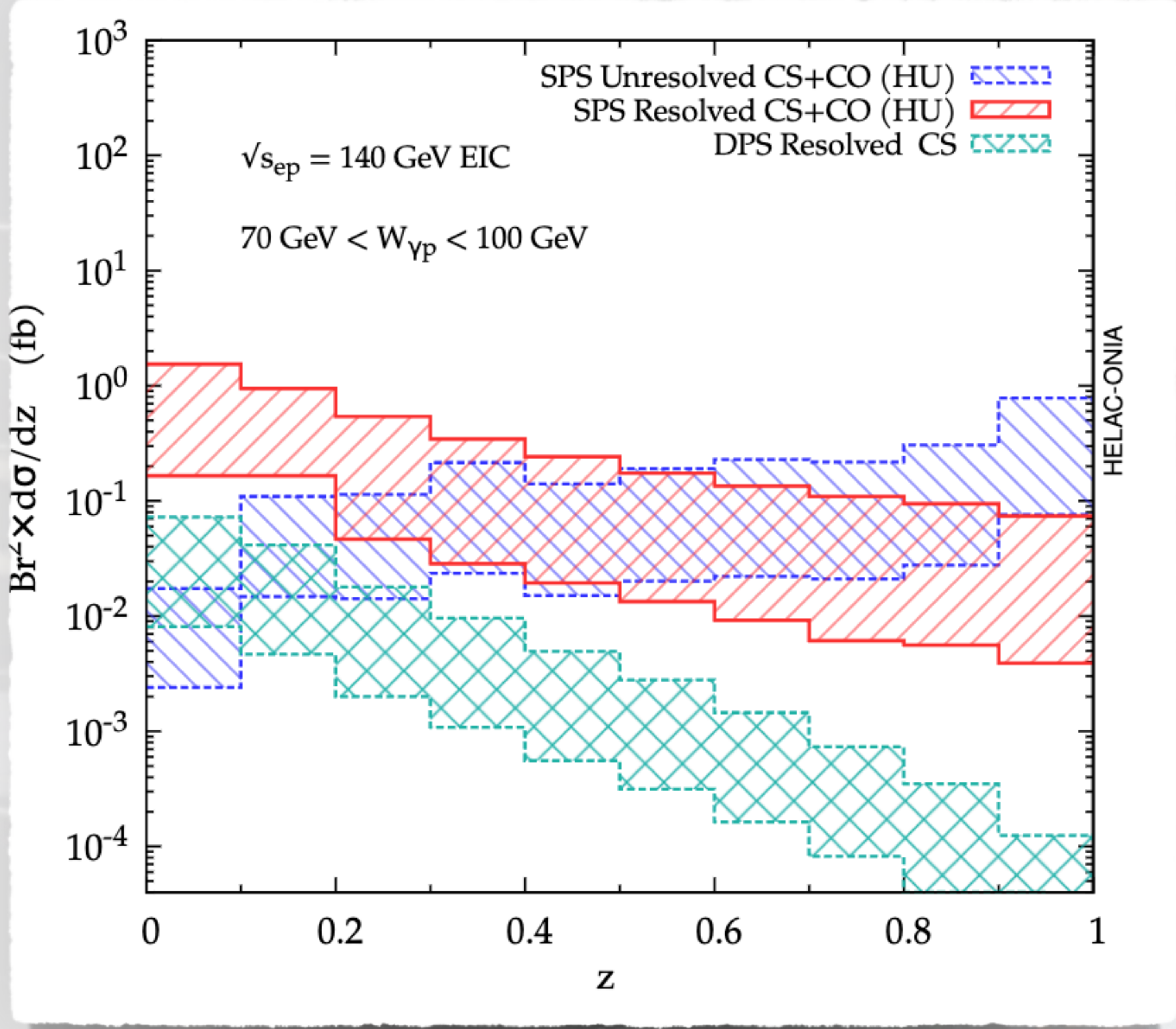

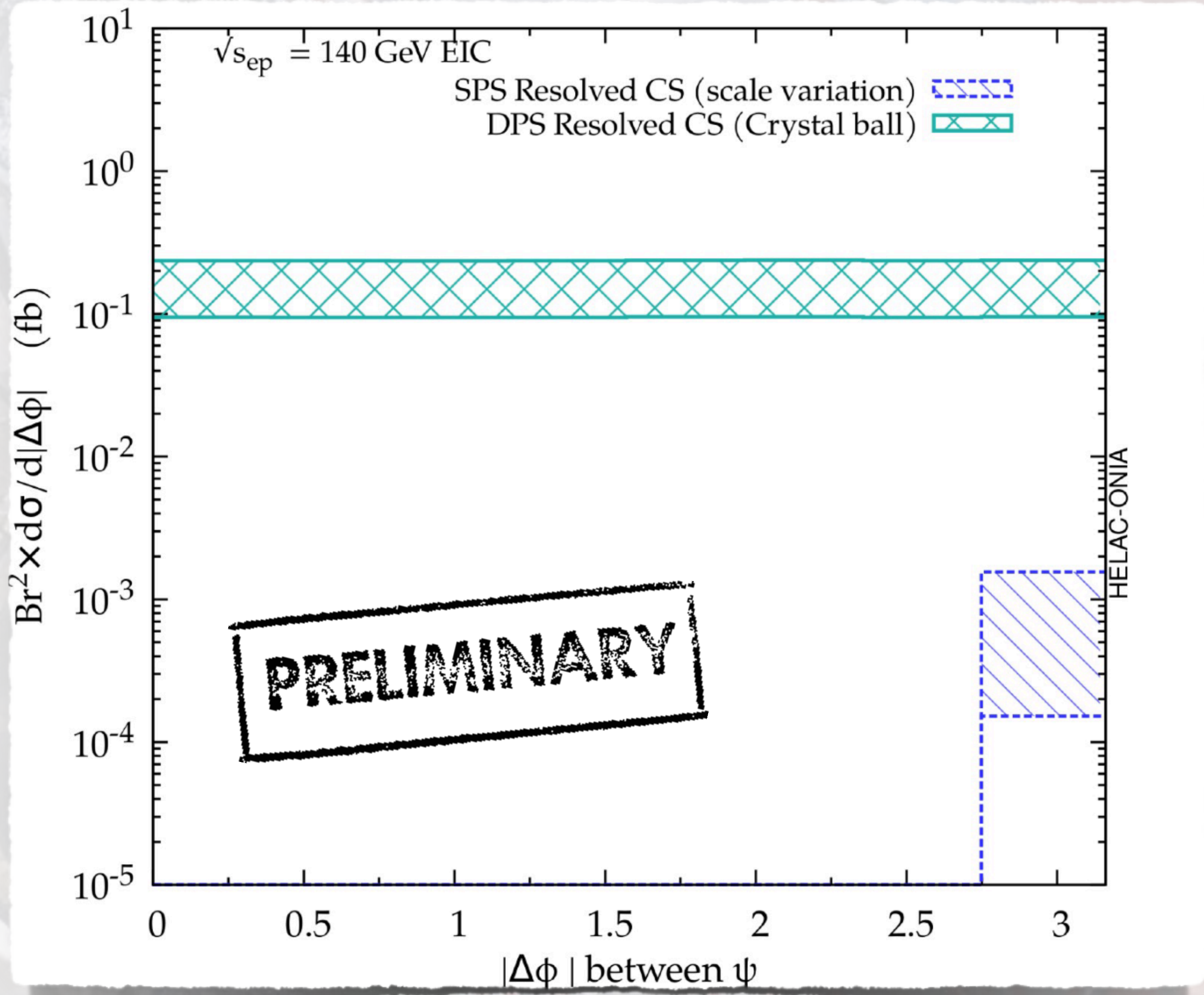

- for $z<0.1$, SPS resolved dominates ⟶ unique opportunity to investigate the PHOTON structure

Numerical Results

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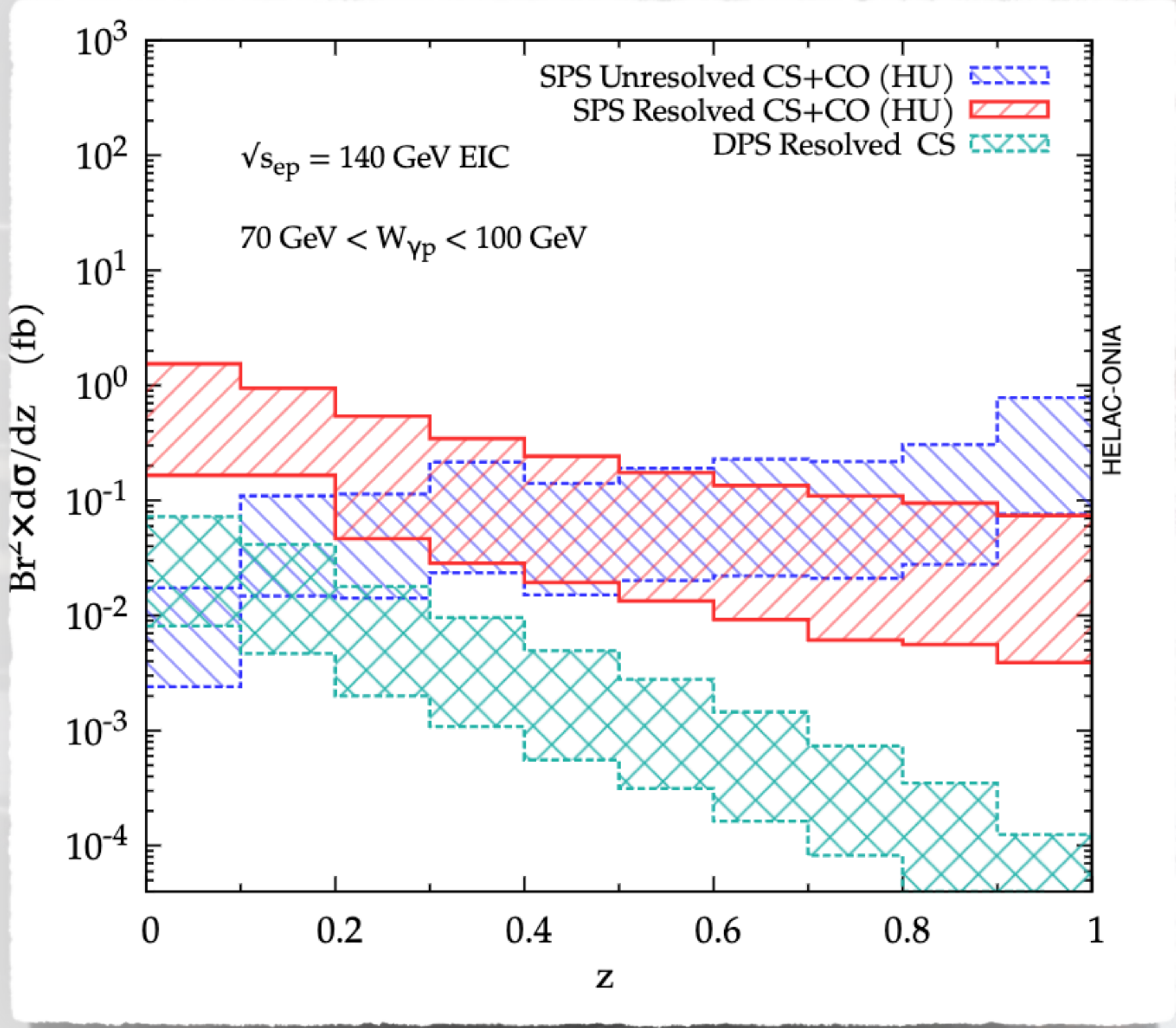

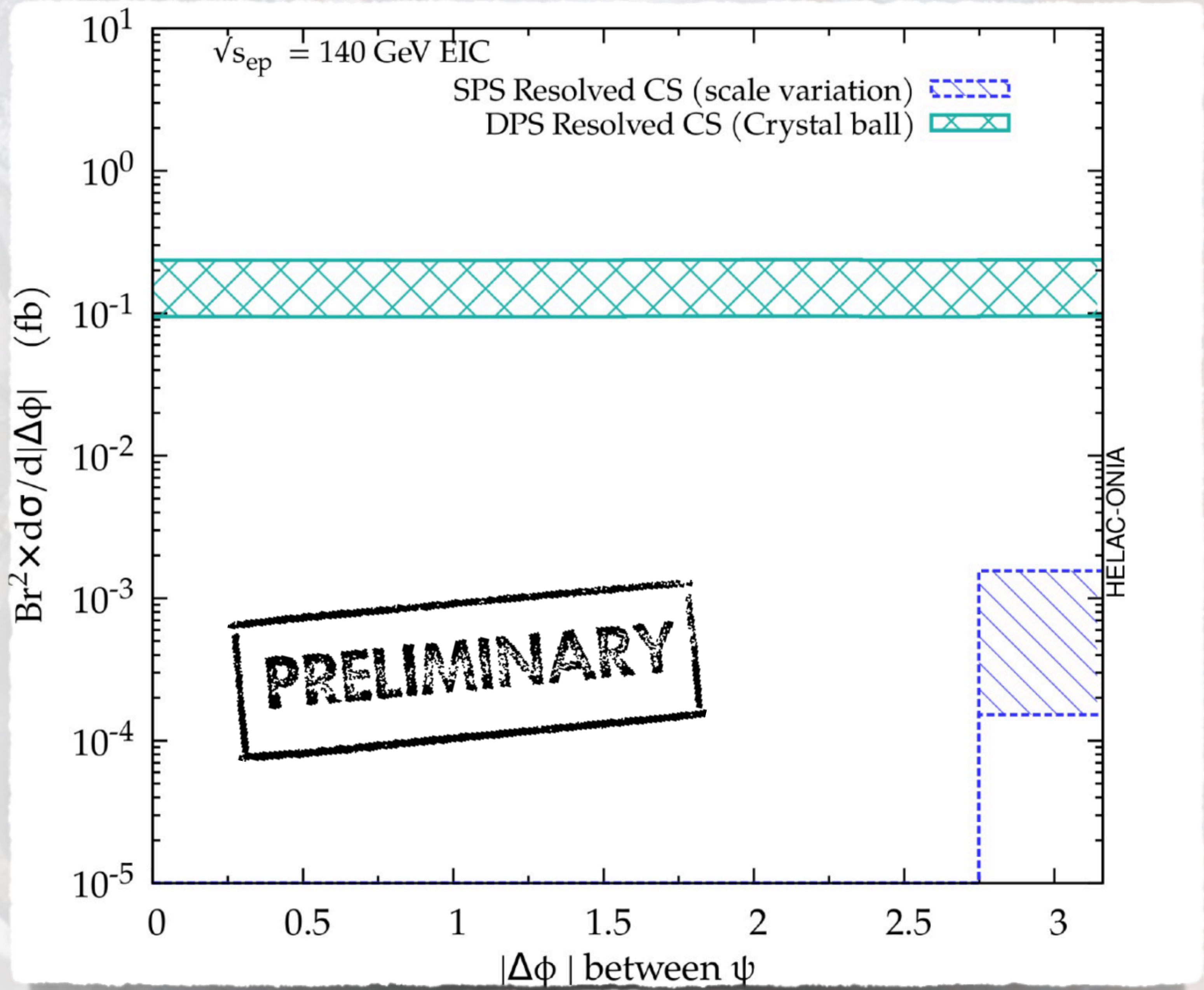

- for z<0.1, SPS resolved dominates ⟶ unique opportunity to investigate the PHOTON structure
- for high z, the direct SPS contribution dominates ⟶ we test the quarkonia production via direct photoproduction

Numerical Results

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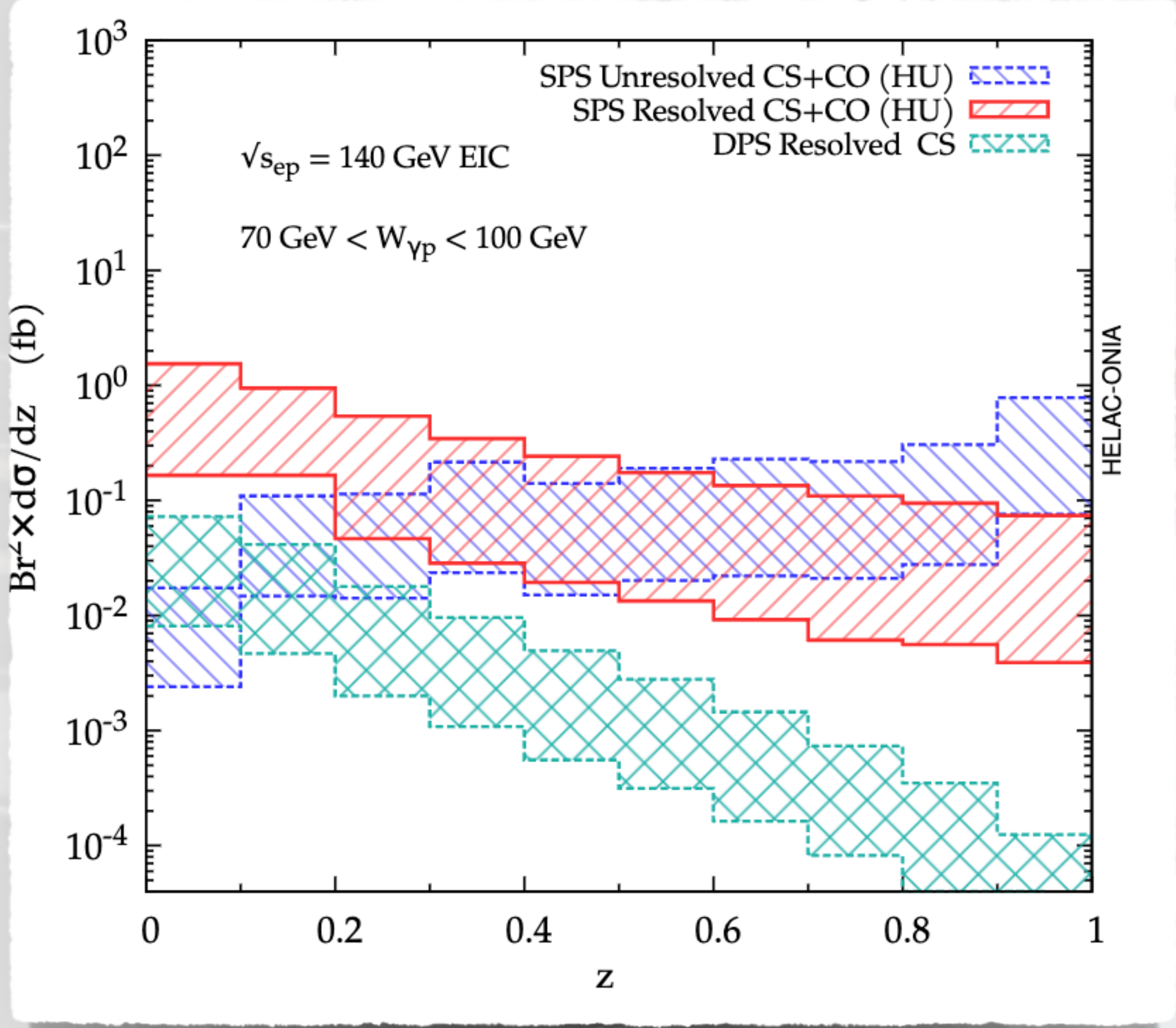

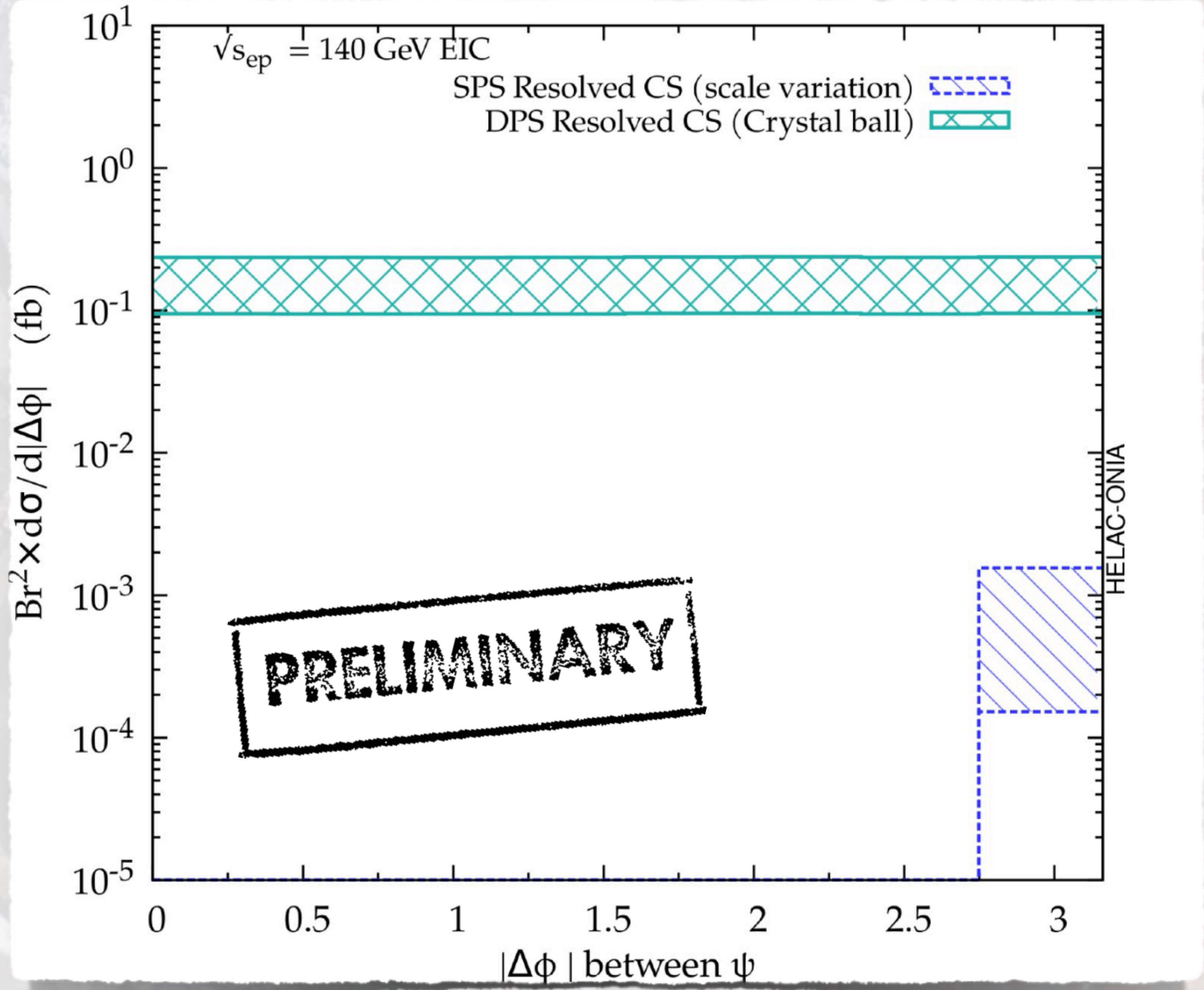

- for $z<0.1$, SPS resolved dominates → unique opportunity to investigate the PHOTON structure
- for high z, the direct SPS contribution dominates → we test the quarkonia production via direct photoproduction
- as for DPS studies @LHC, the cross-section dependence on the relative azimuthal angle is relevant to access the DPS contribution!

Numerical Results

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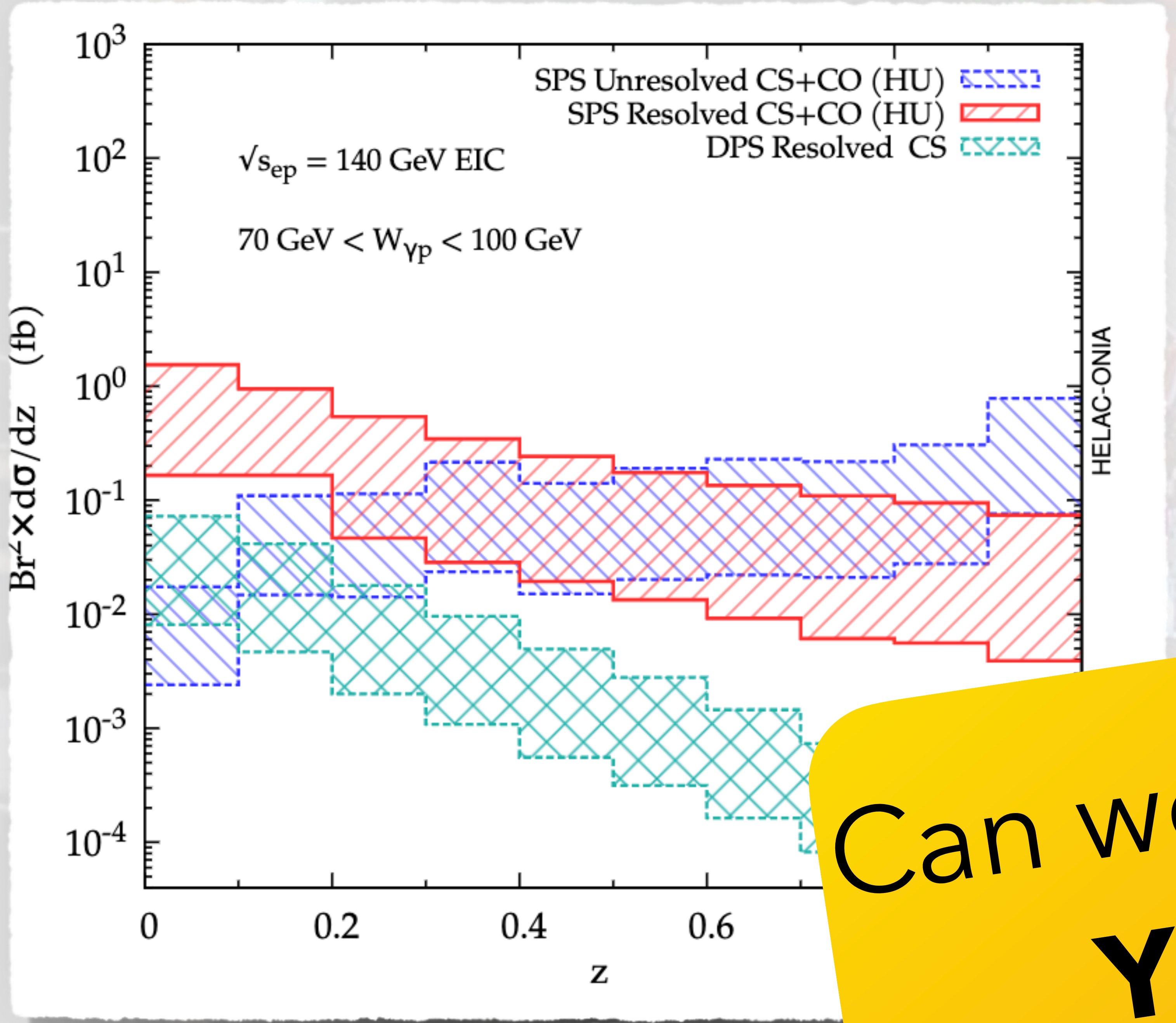
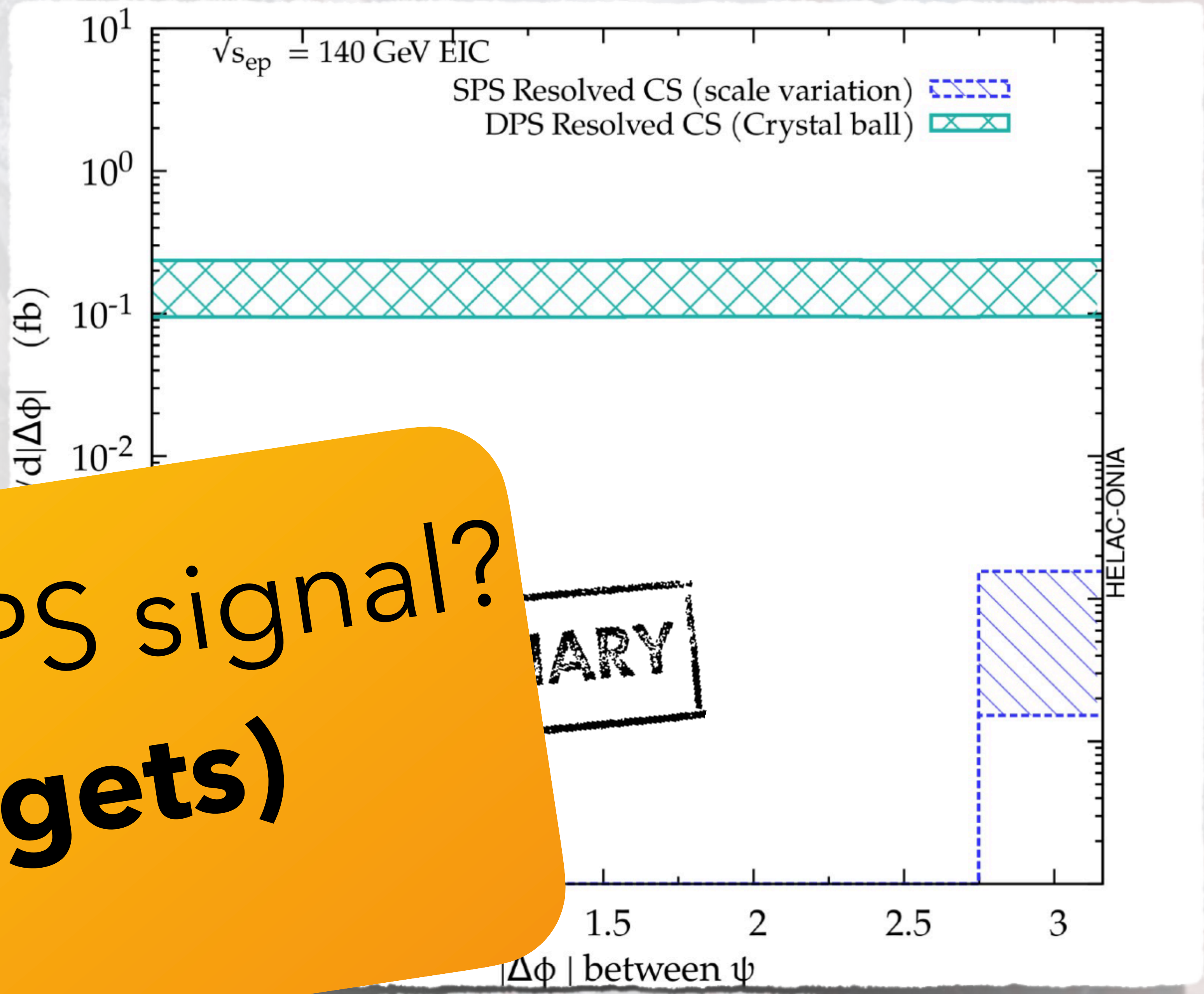
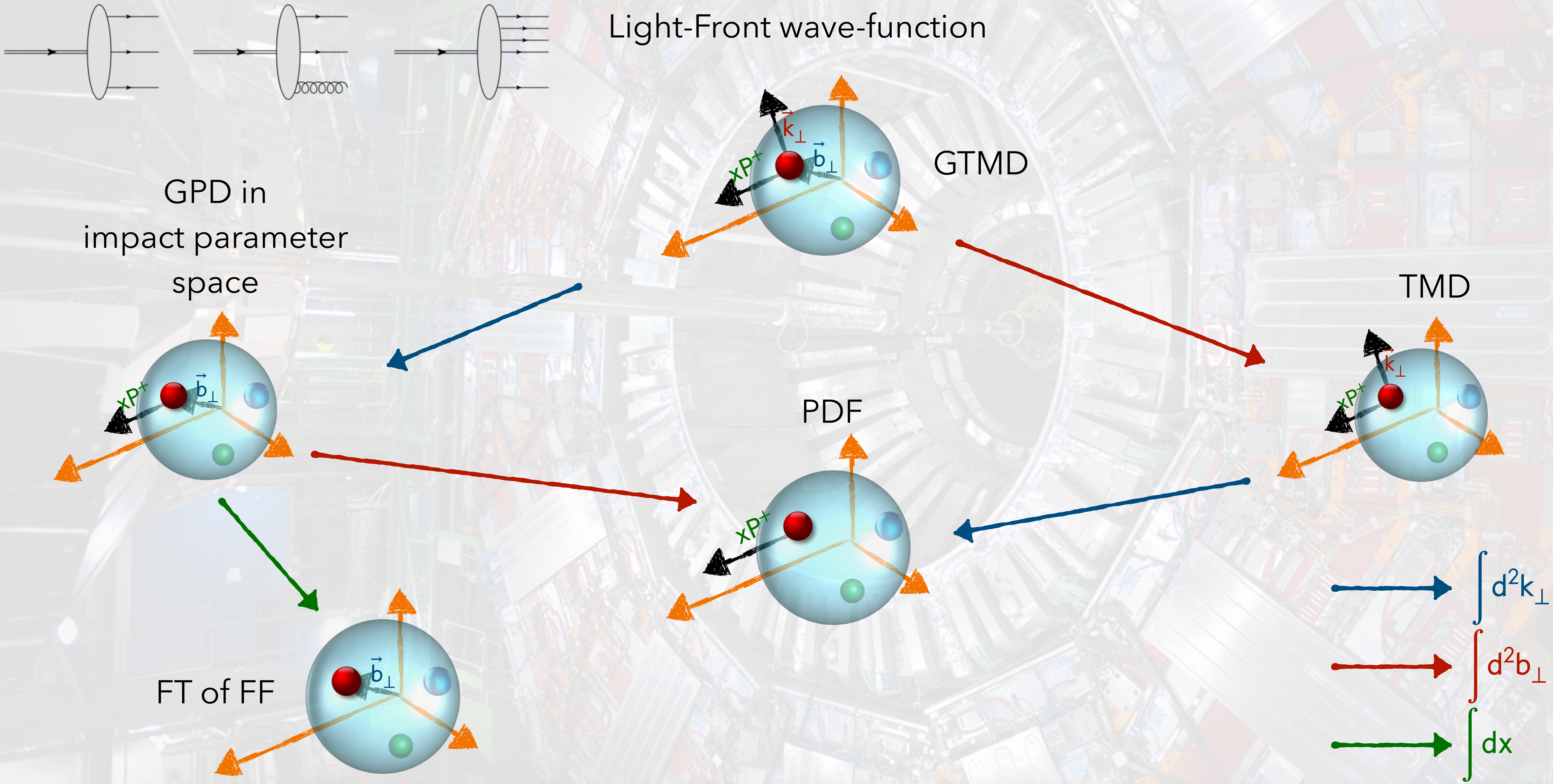




Can we increase the DPS signal?
YES! (Nuclear targets)

- for z<0.1, SPS resolved domi… → unique opportunity to investigate the PHOTON structure
- for high z, the direct SPS contribution dominates → we test the quarkonia production via direct photoproduction
- as for DPS studies @LHC, the cross-section dependence on the relative azimuthal angle is relevant to access the DPS contribution!

Multidimensional picture of hadrons



Multidimensional picture of hadrons