Di-J/ψ photoproduction at the EIC
(…and DPS off light-nuclei)

Matteo Rinaldi
INFN sezione di Perugia

STRONG 2020

INFN Istituto Nazionale di Fisica Nucleare

Outline

- Introduction to double parton scattering (DPS) and hadronic Physics
- Data and interpretation
- DPS at the EIC?
- Nuclear DPS at the EIC?

Outline

- Introduction to double parton scattering (DPS) and hadronic Physics
- Data and interpretation
- DPS at the EIC?
- Nuclear DPS at the EIC?

Outline

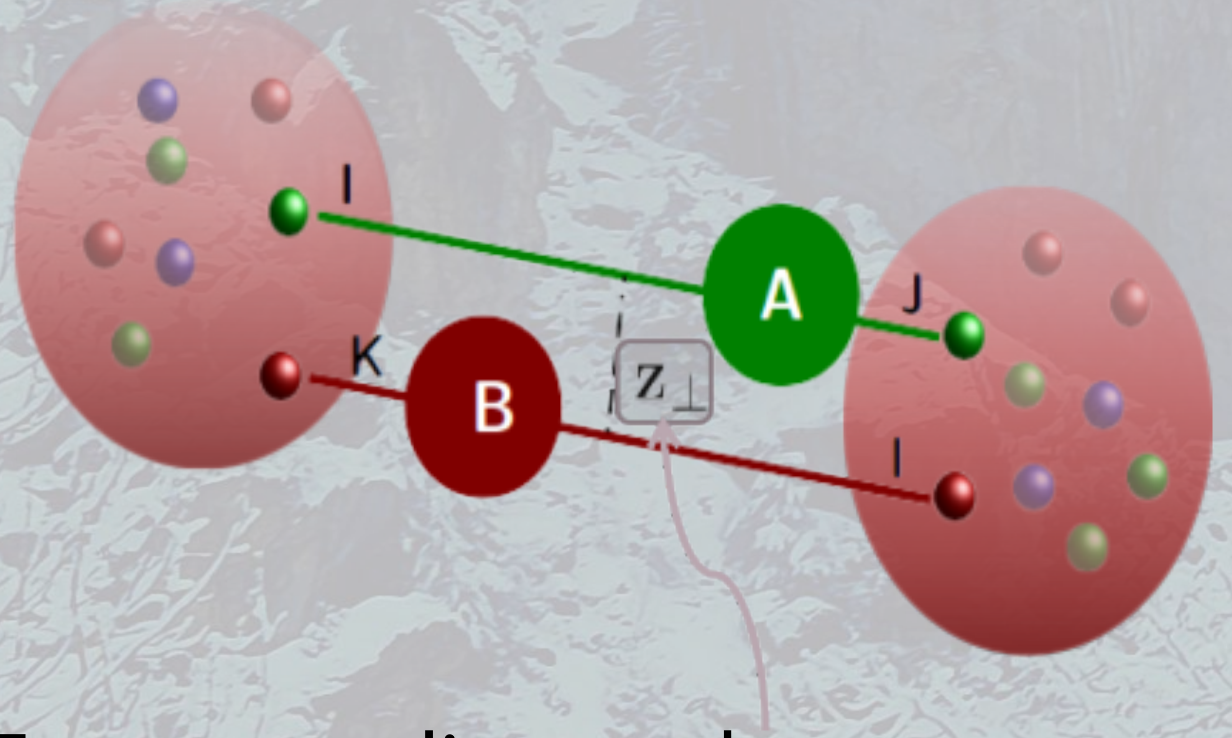
- Introduction to double parton scattering (DPS) and hadronic Physics
- Data and interpretation
- DPS at the EIC?
- Nuclear DPS at the EIC?

Outline

- Introduction to double parton scattering (DPS) and hadronic Physics
- Data and interpretation
- DPS at the EIC?
- Nuclear DPS at the EIC?

Double Parton Scattering

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



Transverse distance between two partons

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

Double Parton Distribution (DPD)

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

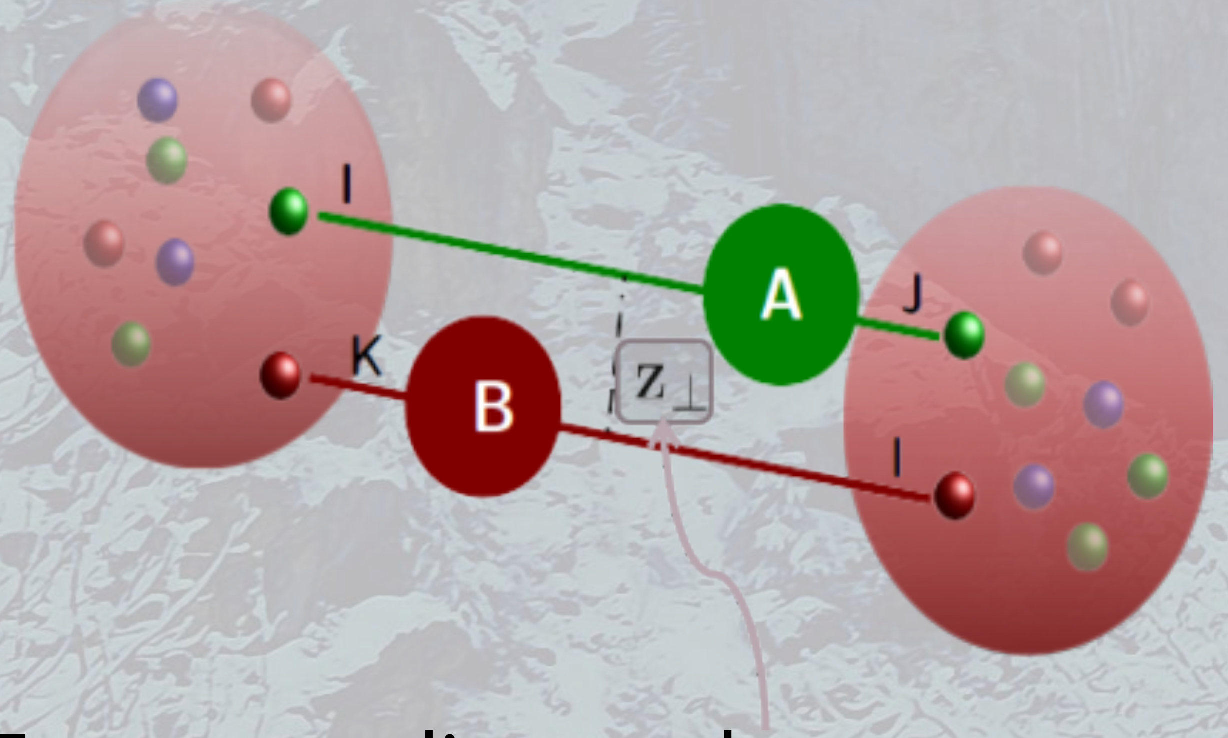
$$F_{ij}^{\lambda_1,\lambda_2}(x_1, x_2, \vec{k}_\perp) = (-8\pi P^+)\frac{1}{2}\sum_\lambda \int d\vec{z}_\perp\, e^{i\vec{z}_\perp\cdot\vec{k}_\perp}$$
$$\times \int \left[\prod_l^3 \frac{dz_l^-}{4\pi}\right] e^{ix_1P^+z_1^-/2} e^{ix_2P^+z_2^-/2} e^{-ix_1P^+z_3^-/2}$$
$$\times \langle \lambda, \vec{P} = \vec{0} | \hat{\mathcal{O}}_i^1 \left(z_1^- \frac{\bar{n}}{2}, z_3^- \frac{\bar{n}}{2} + \vec{z}_\perp\right) \hat{\mathcal{O}}_j^2 \left(z_2^- \frac{\bar{n}}{2} + \vec{z}_\perp, 0\right) | \vec{P} = \vec{0}, \lambda \rangle$$

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

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

Double Parton Scattering

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



Transverse distance between two partons

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

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

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.

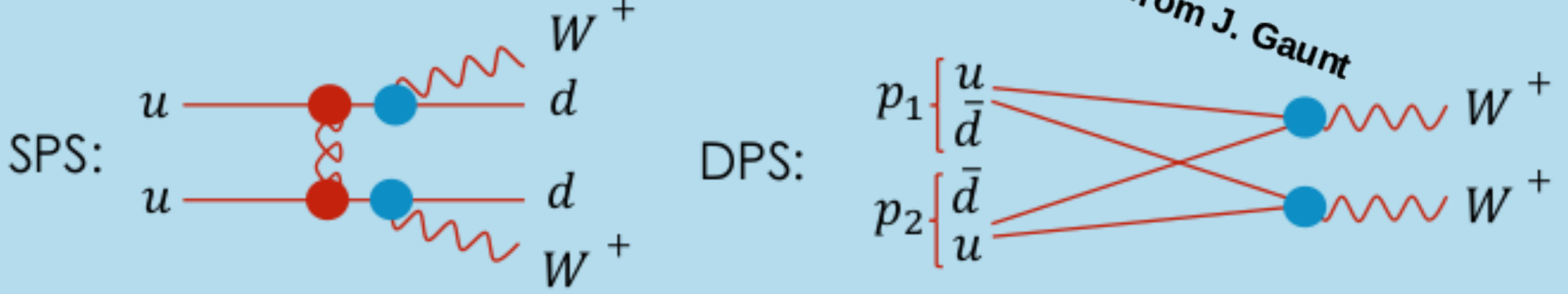
Diehl et al. JHEP 03 (2012) 089, JHEP 01 (2016) 076
Vladimirov JHEP 04 (2018) 045
Buffing et al. JHEP 01 (2018) 044
Diehl, RN JHEP 04 (2019) 124

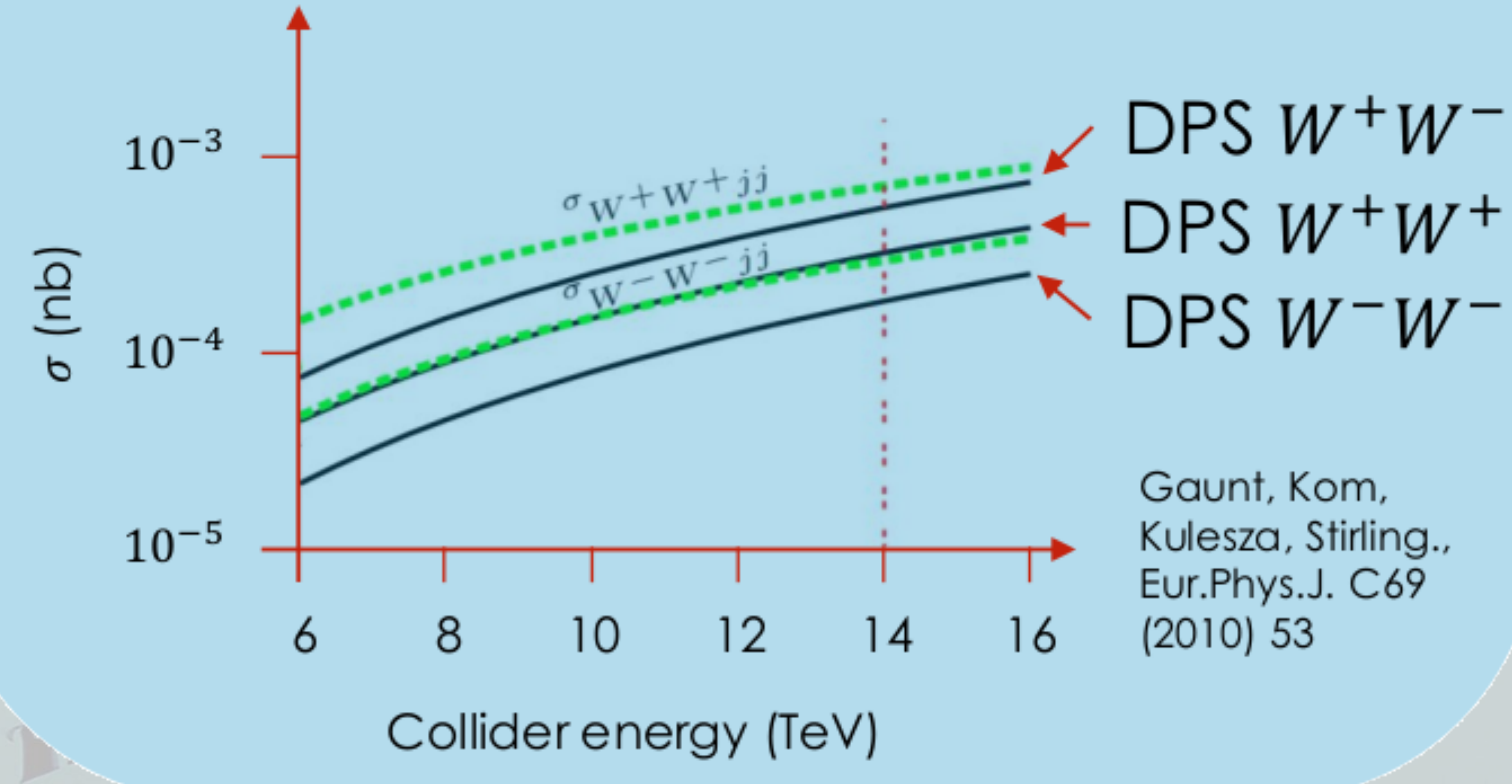
R. Nagar's talk MPI 2021

Where and Why DPS?

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

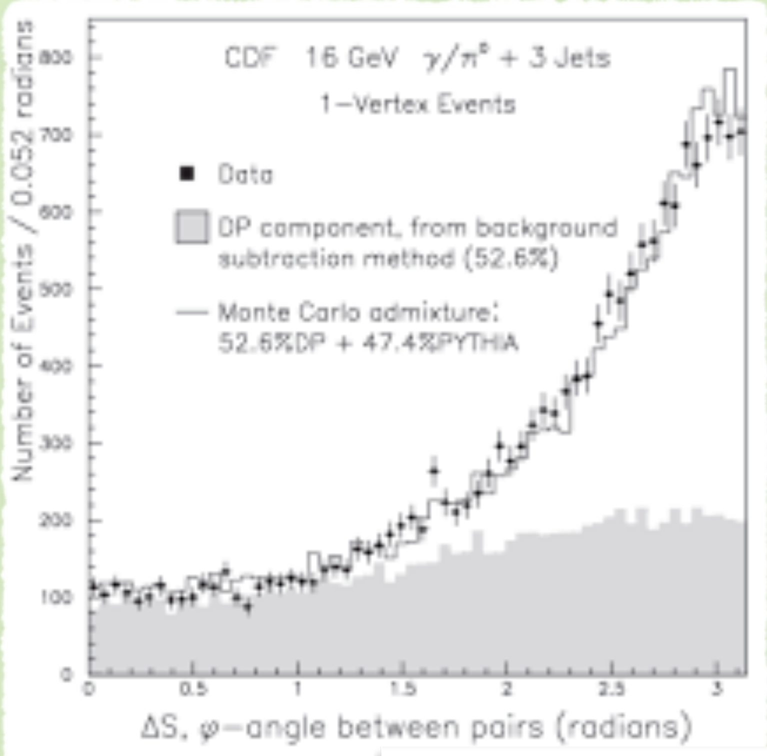
Slide from J. Gaunt





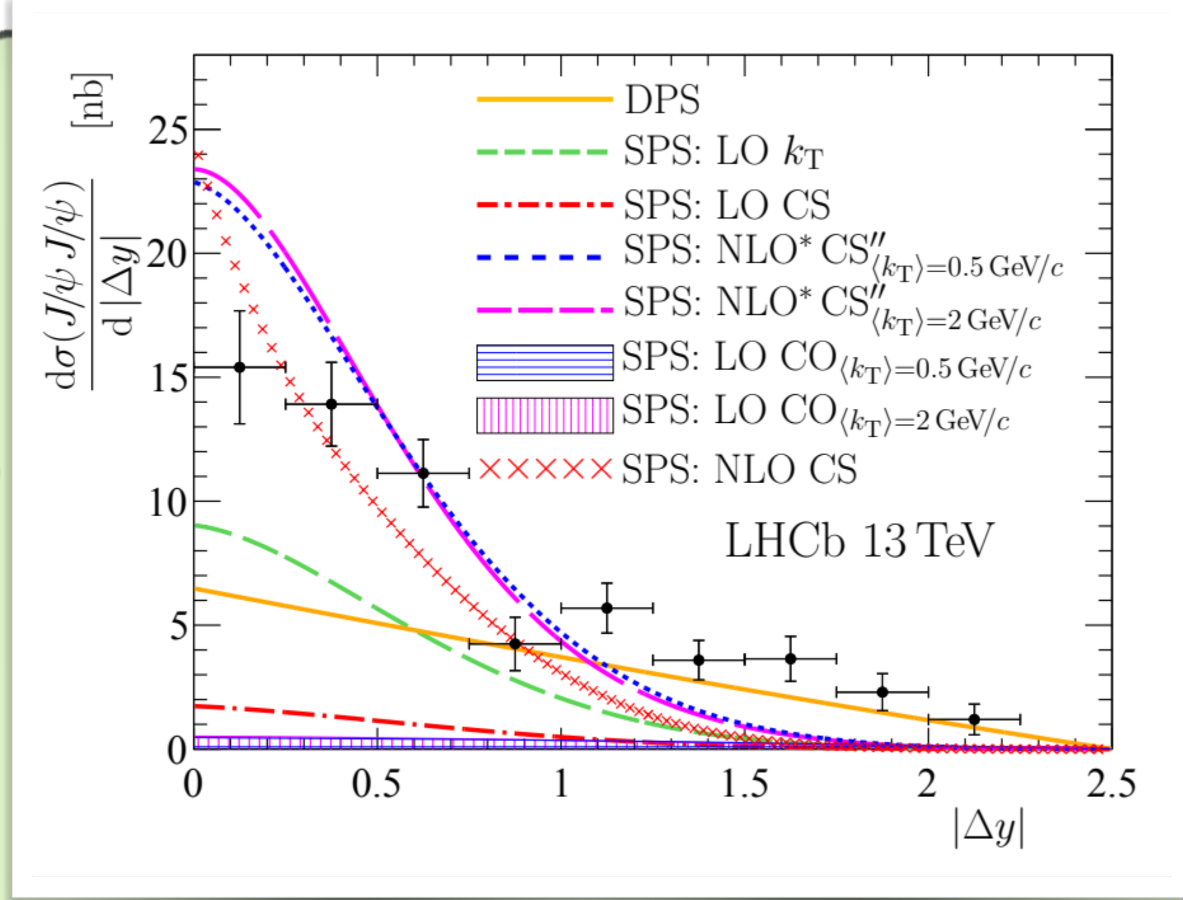
Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

...or in certain phase space regions

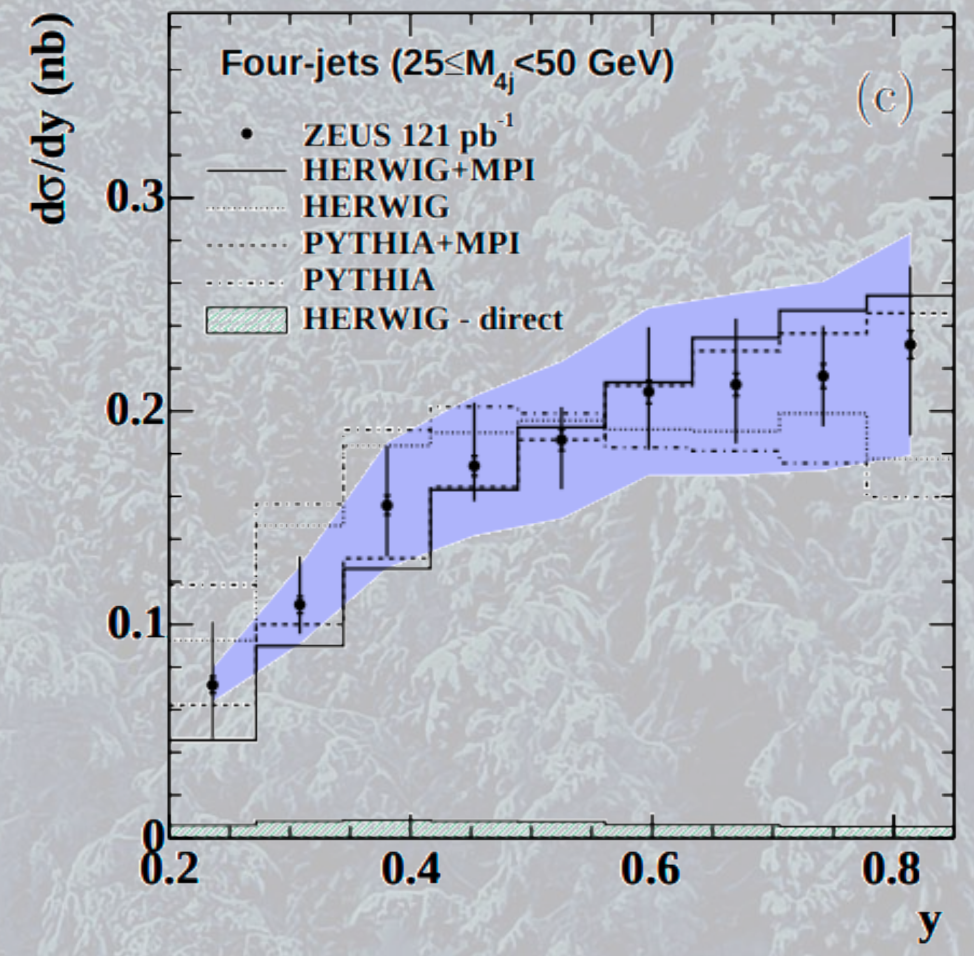


CDF, $\gamma + 3j$, Phys.Rev. D56 (1997) 3811-3832

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



in ep Colliders?

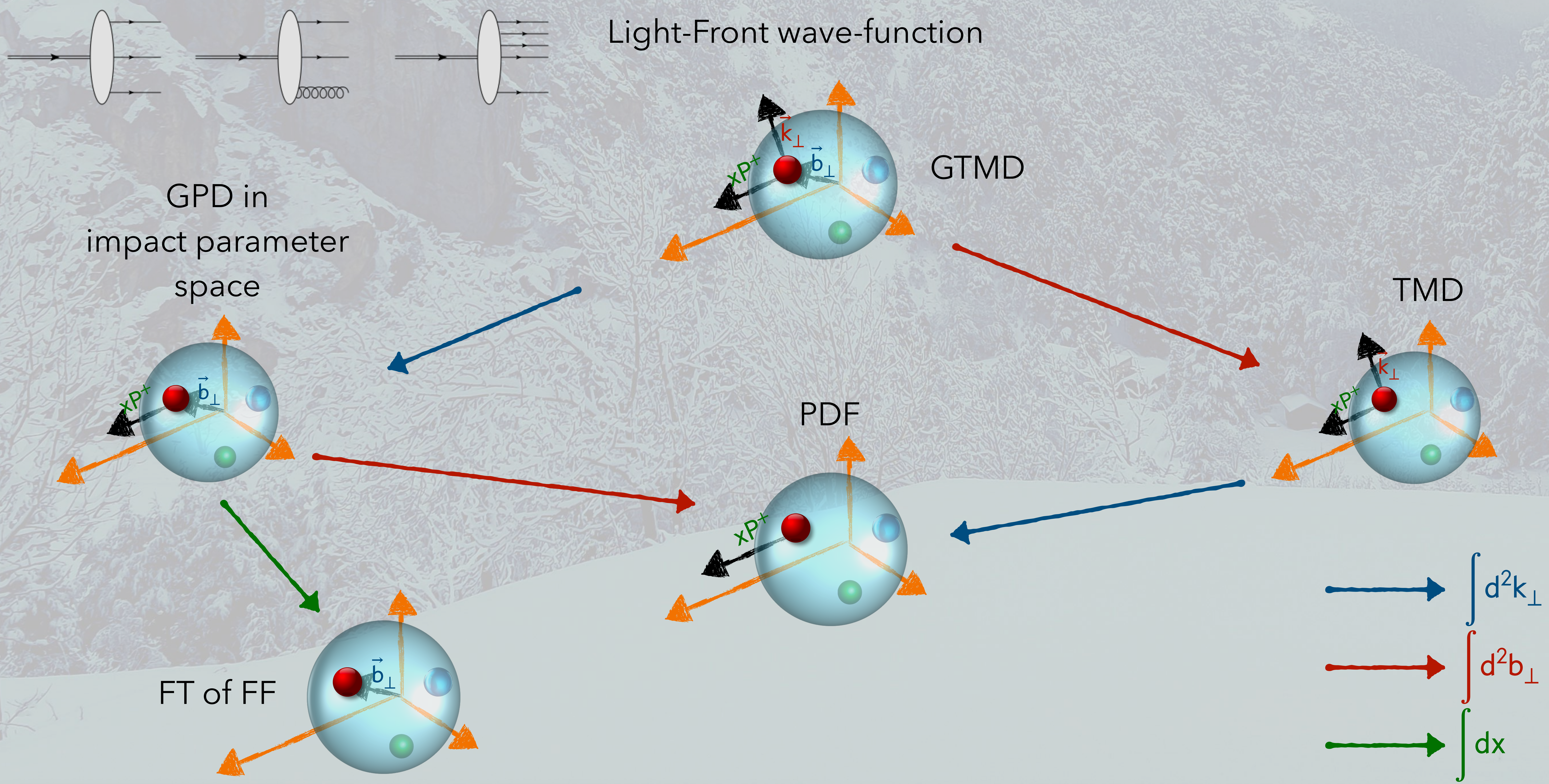


HERA data, ZEUS coll, Nucl. Phys. B 729, 1 (2008)

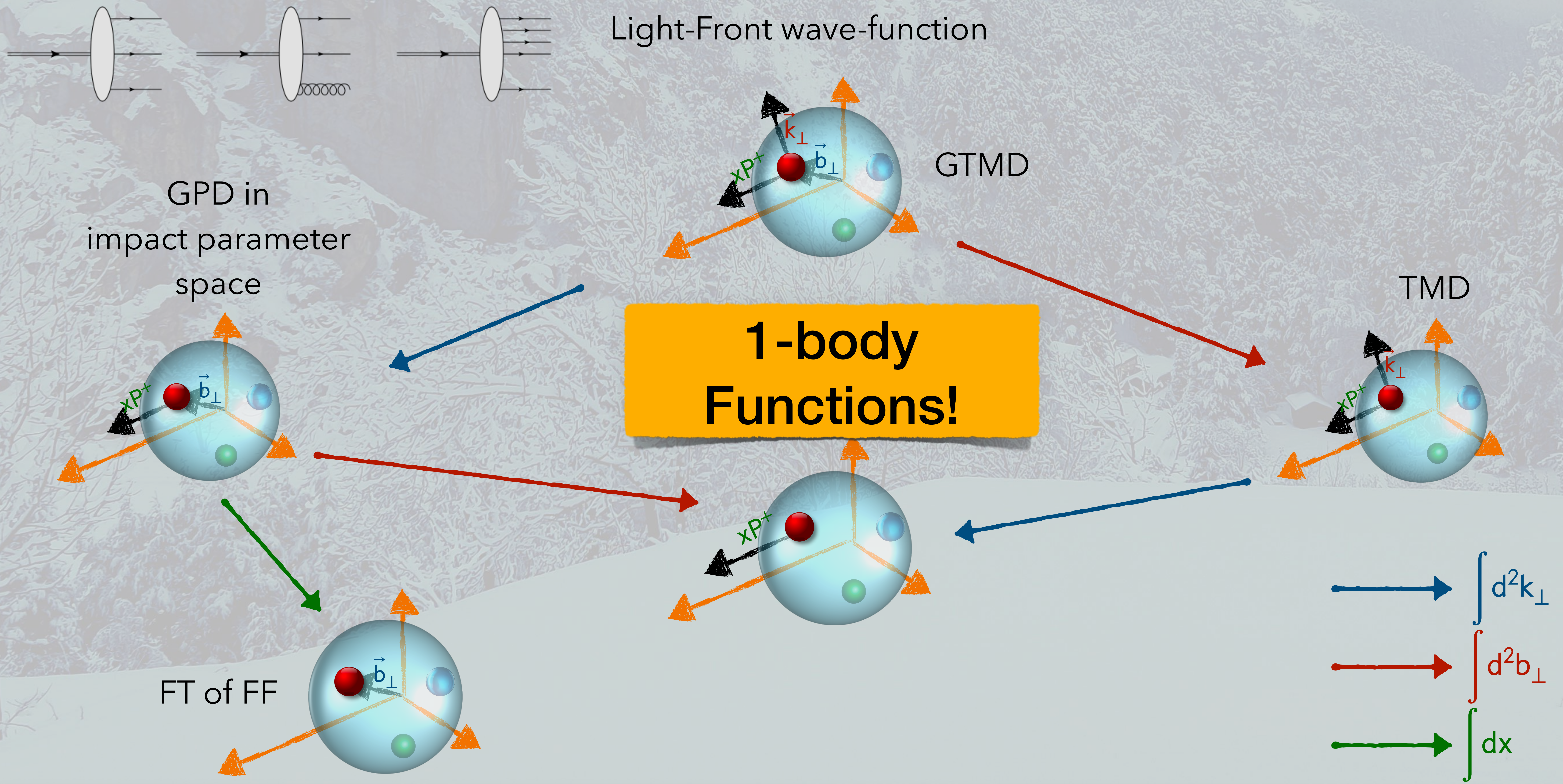
Access to:
- double parton correlations
- the transverse distance distribution of partons!!

all **UNKNOWN**

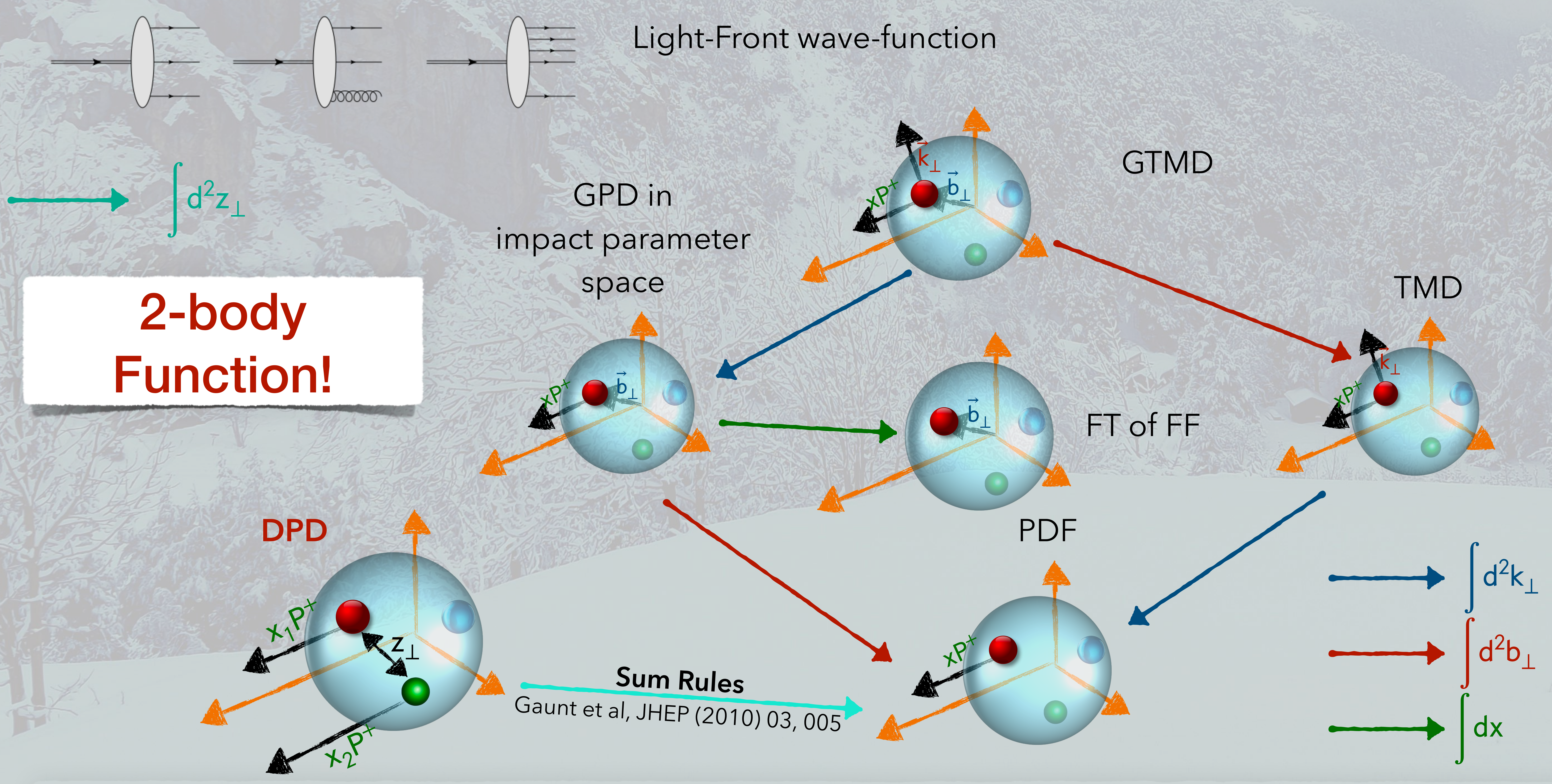
Multidimensional picture of hadrons



Multidimensional picture of hadrons



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)

How to build up a DPD

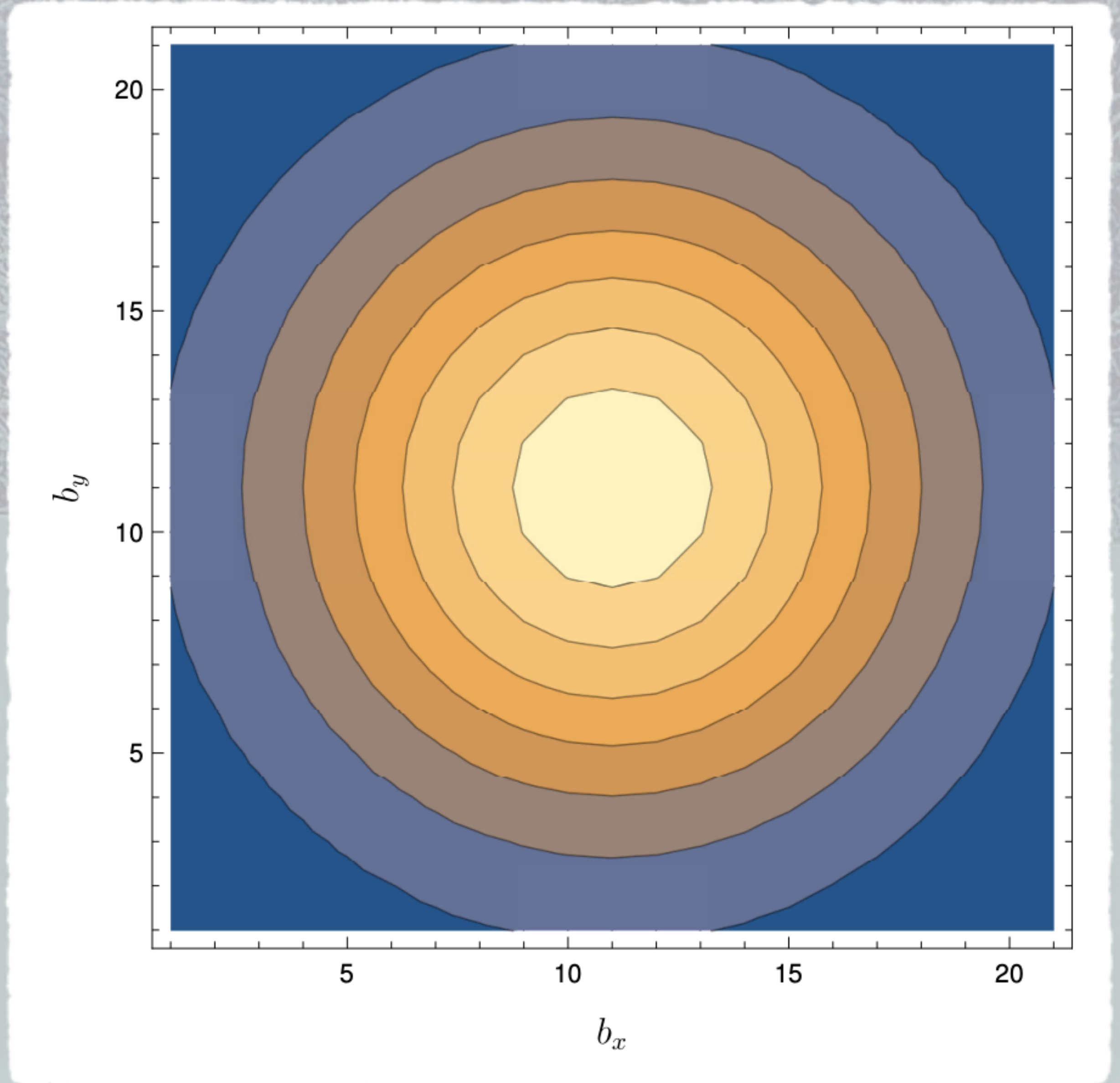
$F_{ik}(x_1, x_2, \vec{z}_\perp)$ is unknown. For phenomenology @LHC kinematics (small x and many partons produced)

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

Models can help to grasp general features

M.R., S. Scopetta et al, PRD 87 (2013) 114021
M.R., S, Scopetta et al, JHEP 12 (2014) 028
A. V. Manohar et al, PRD 87 (2013) 3, 034009

$$\langle b_\perp^2 \rangle^{ij}_{x_1,x_2} = \frac{\int d^2b_\perp b_\perp^2 \tilde{F}_{ij}(x_1, x_2, b_\perp, Q^2)}{\int d^2b_\perp \tilde{F}_{ij}(x_1, x_2, b_\perp, Q^2)}$$



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

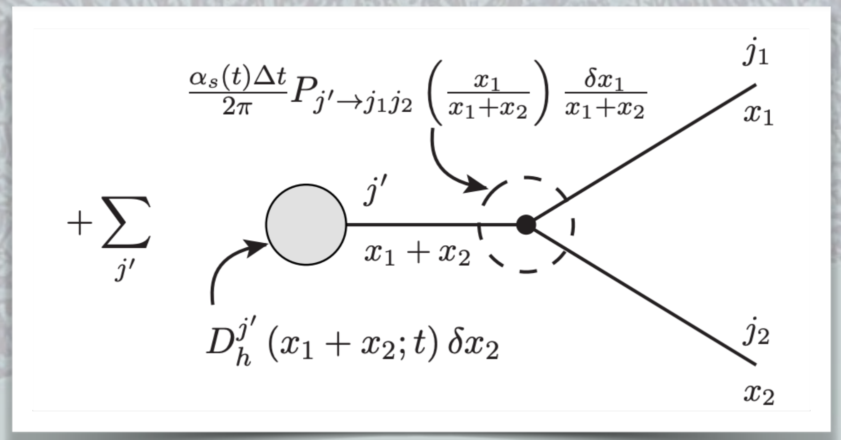
How to build up a DPD

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

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

double PDF

- Sum Rules
- pQCD evolution
- PDF(x_1)*PDF(x_2) uncorrelated scenario



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)

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

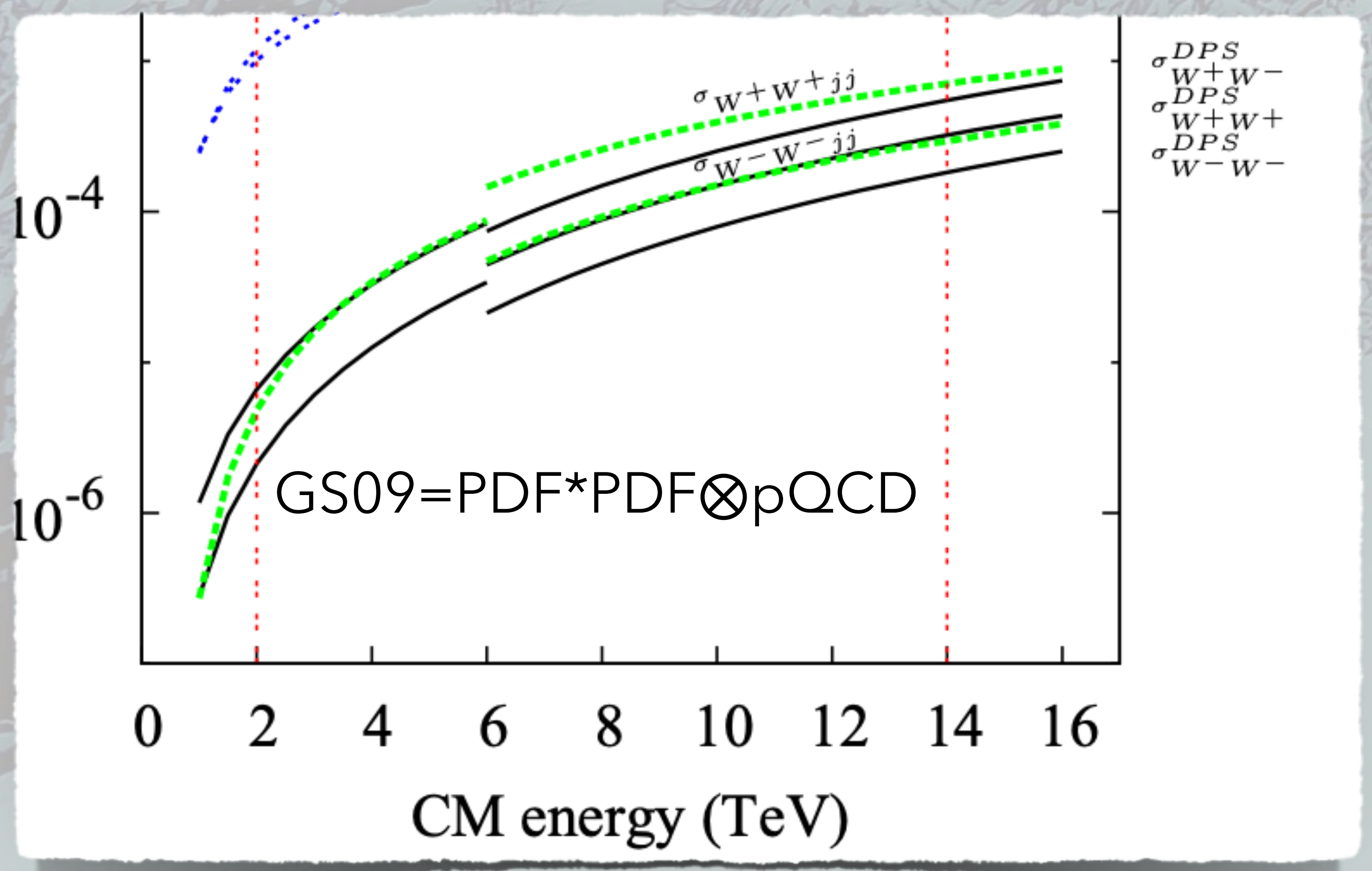
double PDF

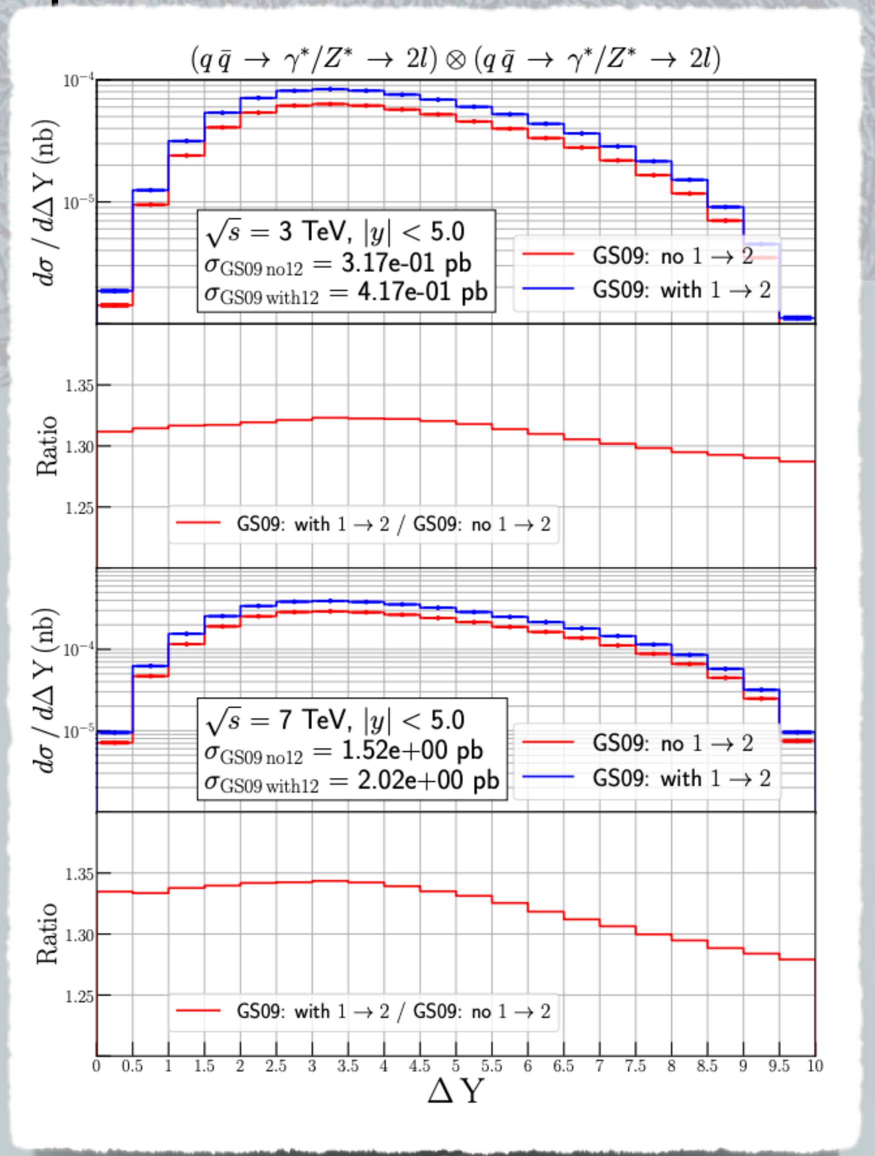
Sum Rules

pQCD evolution

PDF(x_1)*PDF(x_2) uncorrelated scenario

J. R. Gaunt et al, EPJC 69 (2010) 54-65





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

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)

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

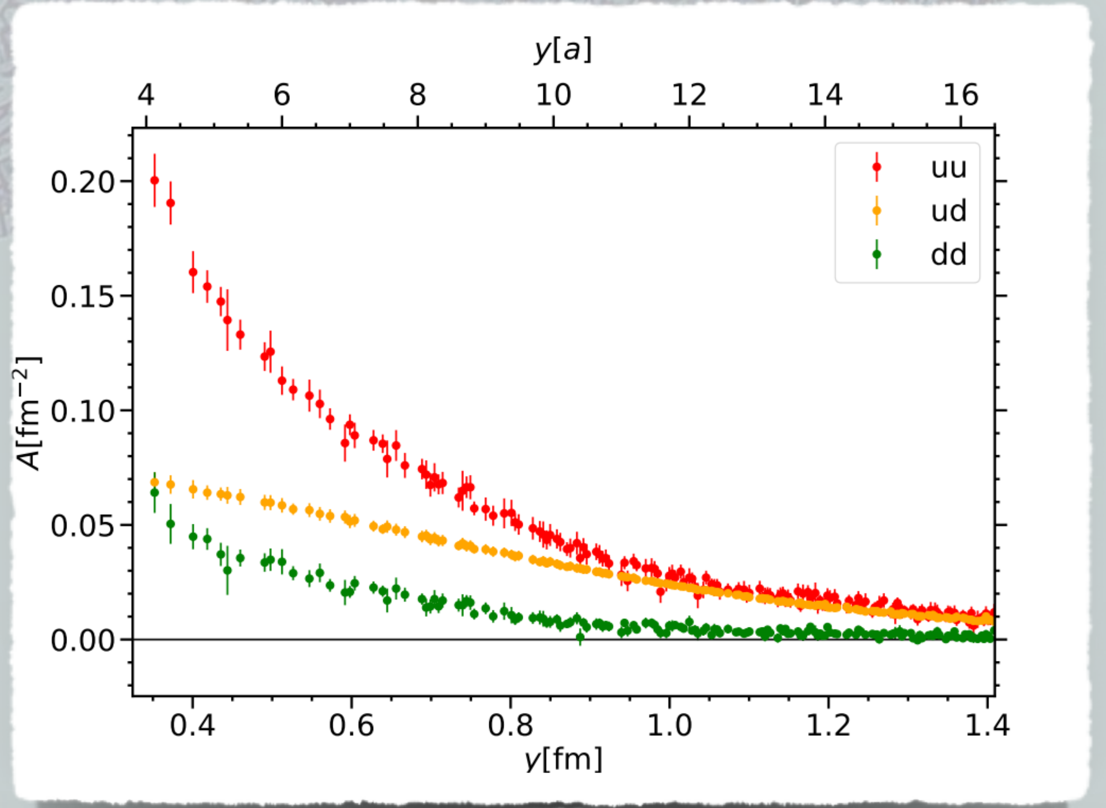
double PDF

Probability distribution of two partons at given distance

Unknown Non perturbative object

Some information from lattice

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



How to build up a DPD

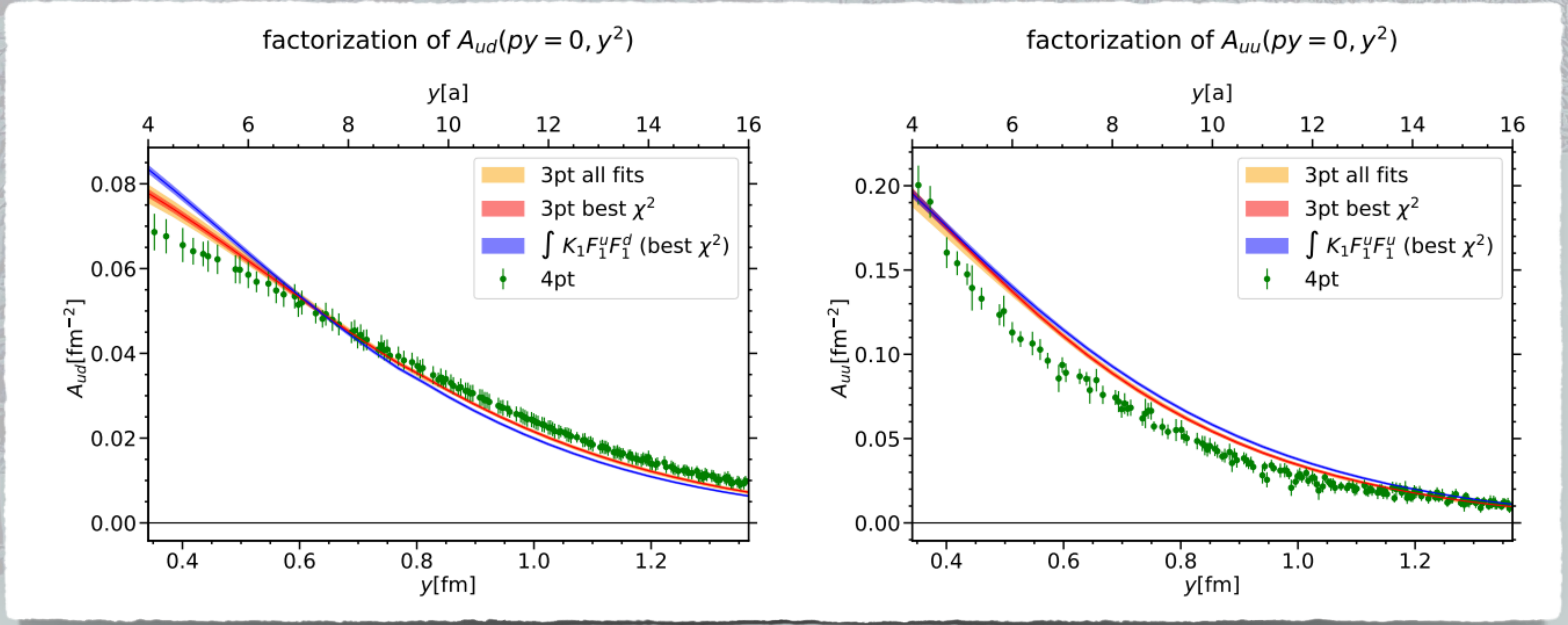
$F_{ik}(x_1, x_2, \vec{z}_\perp)$ is unknown. For phenomenology @LHC kinematics (small x and many partons produced)

double PDF

uncorrelated scenario: $F_{ik}(x_1, x_2, \vec{z}_\perp) \sim g(x_1, x_2)\tilde{T}(\vec{z}_\perp)$ → Probability distribution of two partons at given distance

↓ Unknown Non perturbative object

Some information from lattice



Comparison from $\tilde{T}(y)$ and the convolution of 2 form factors (FT)..this is a test for models in which the

DPD = GPD x GPD

NOT WELL REPRODUCED!

G. S. Bali et al, JHEP 09, 106 (2021)

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)

double PDF

uncorrelated scenario: $F_{ik}(x_1, x_2, \vec{z}_\perp) \sim g(x_1, x_2)\tilde{T}(\vec{z}_\perp)$ → Probability distribution of two partons at given distance

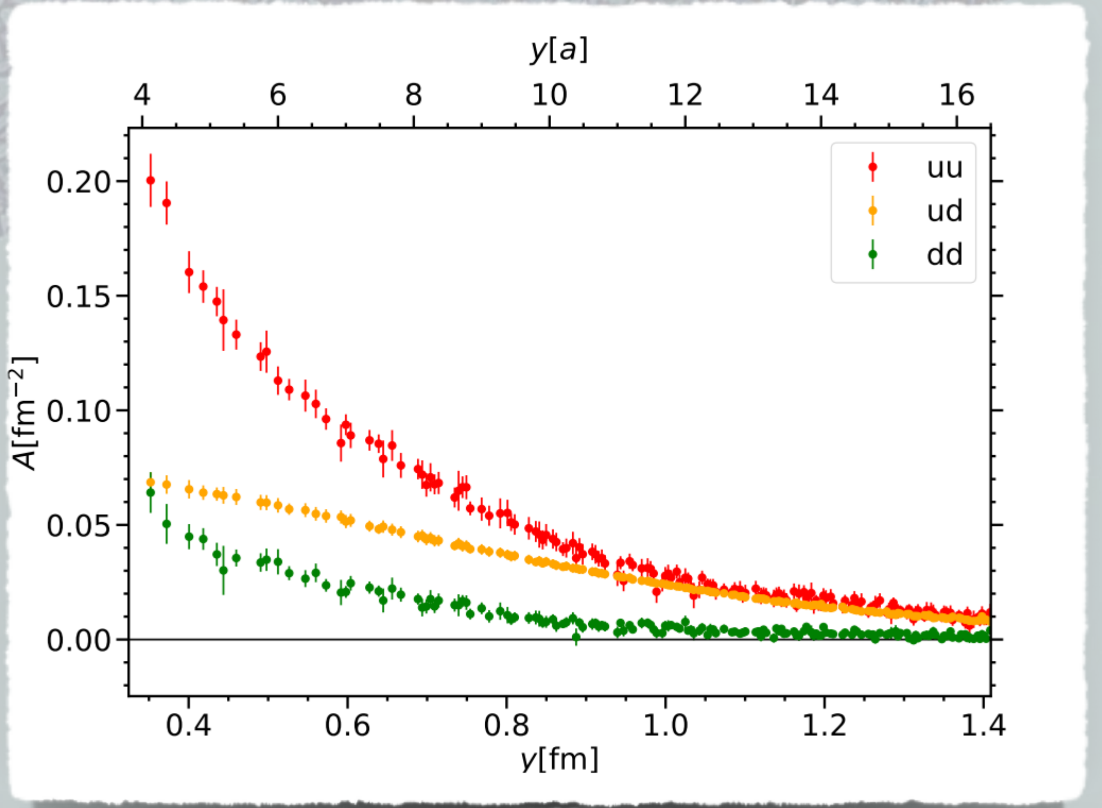
Unknown Non perturbative object

Some information from lattice

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

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

POCKET FORMULA

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

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

Some Data and Effective Cross Section

$$\sigma^{pp}_{eff} = \frac{m}{2}\frac{\sigma^{pp}_{A}\,\sigma^{pp}_{B}}{\sigma^{pp}_{DPS}}$$

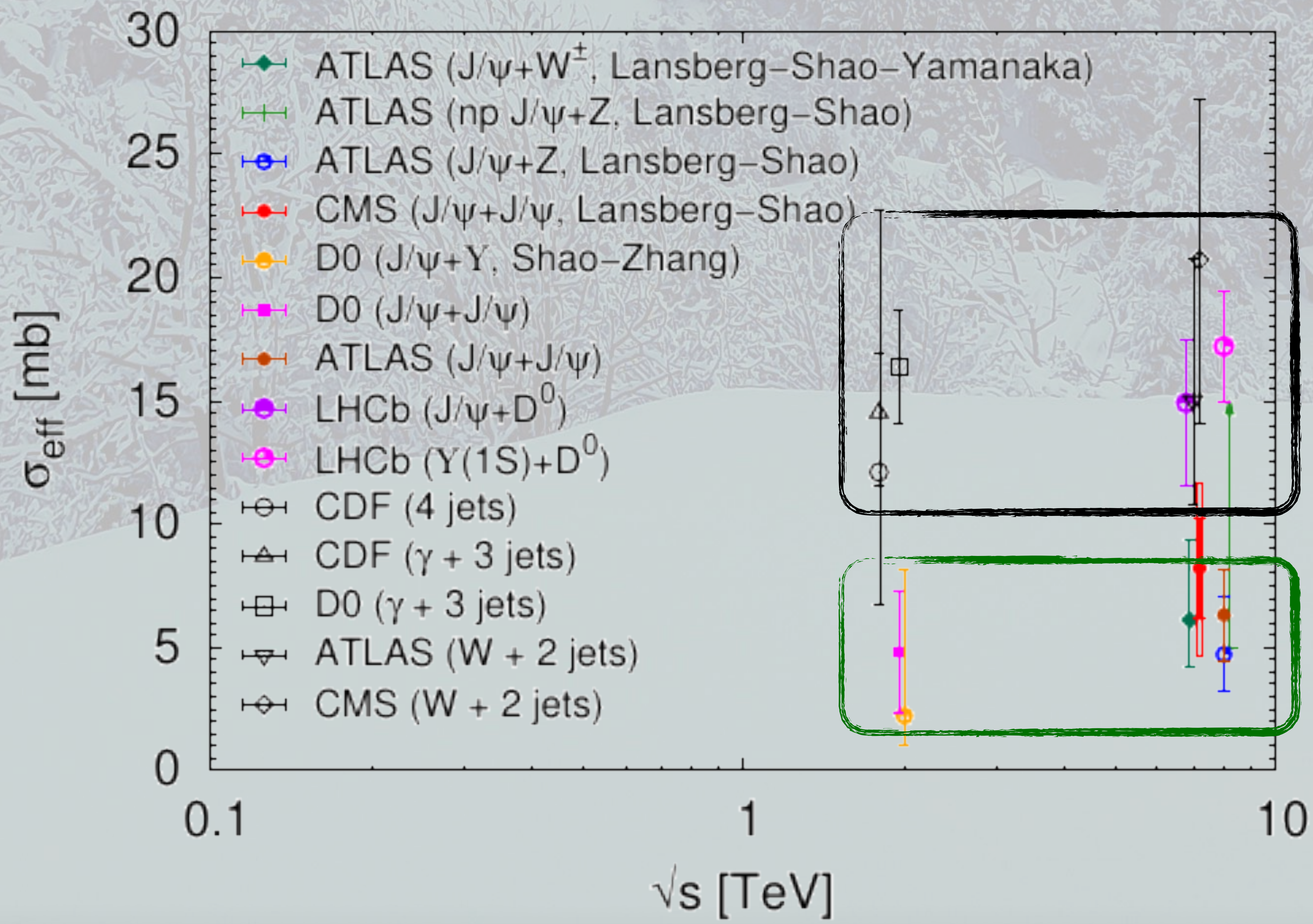
POCKET FORMULA

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:

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

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

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

Some Data and Effective Cross Section

$$\sigma^{pp}_{eff} = \frac{m}{2}\frac{\sigma^{pp}_A \sigma^{pp}_B}{\sigma^{pp}_{DPS}}$$

POCKET FORMULA

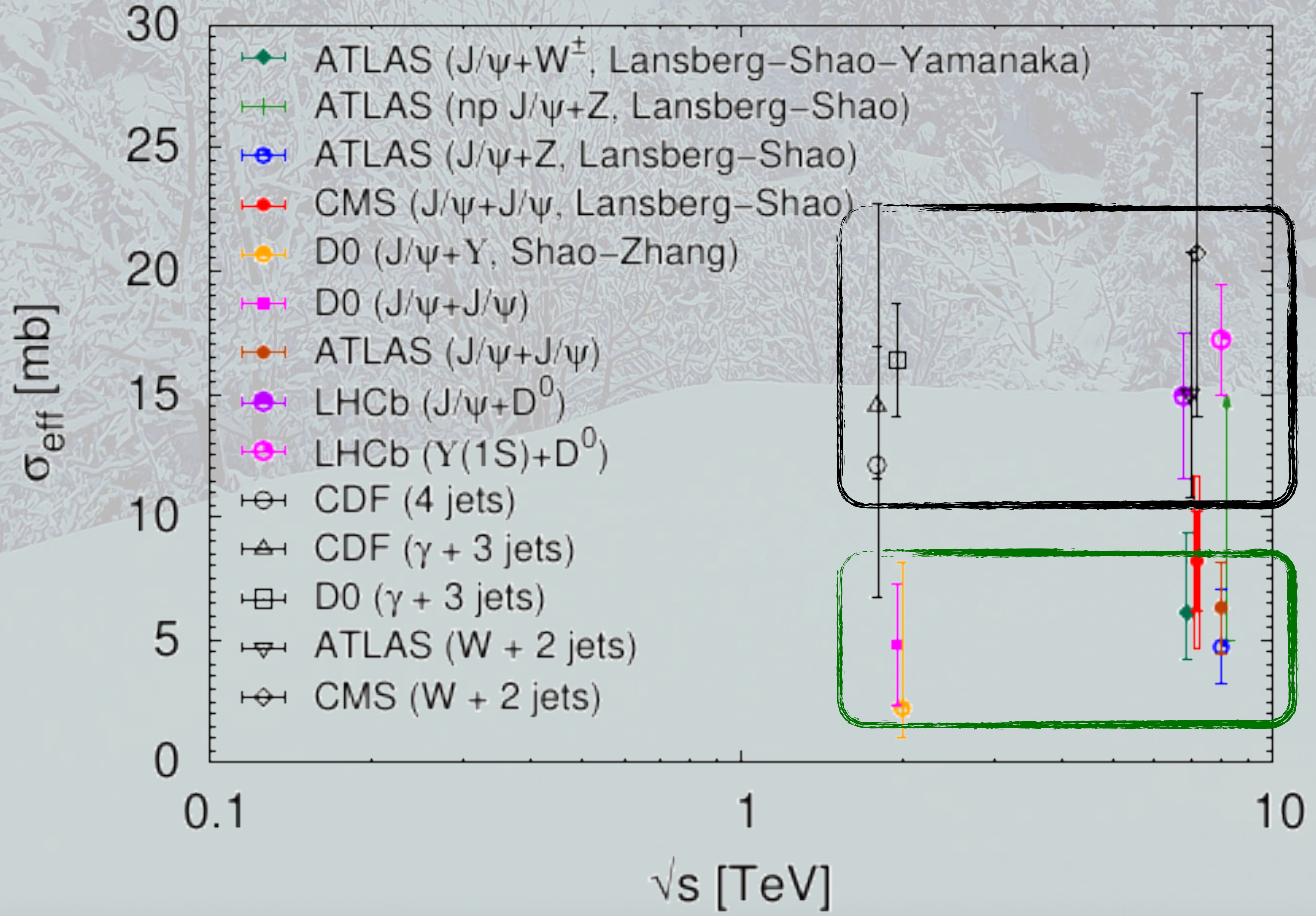
Differential X-section single parton scattering for the process: $pp \longrightarrow A(B) + X$

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

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



First observation of same sign WW via DPS:

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

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

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

Some Data and Effective Cross Section

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

POCKET FORMULA

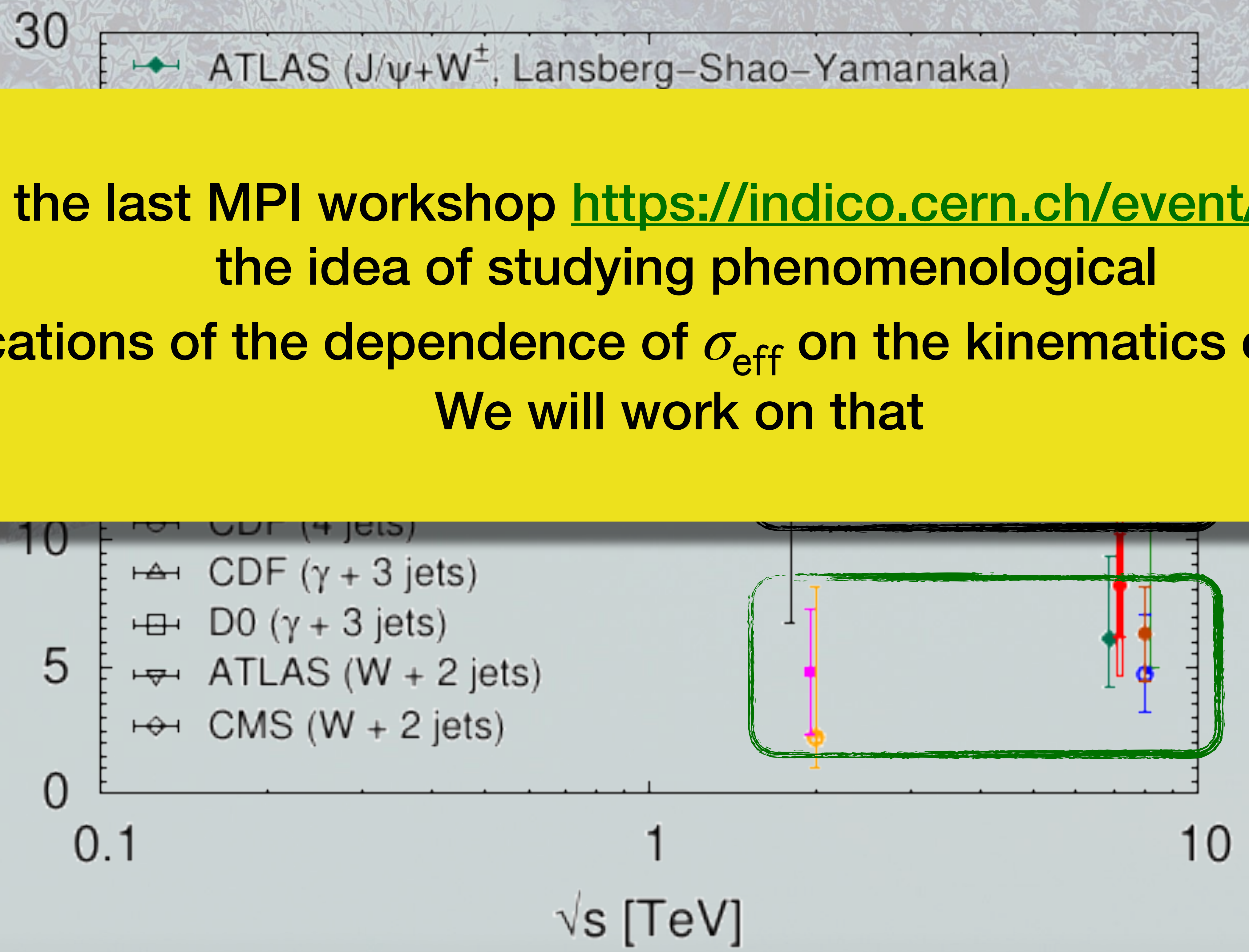
Differential X-section single parton scattering for the process: $pp \longrightarrow A(B) + X$

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

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



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

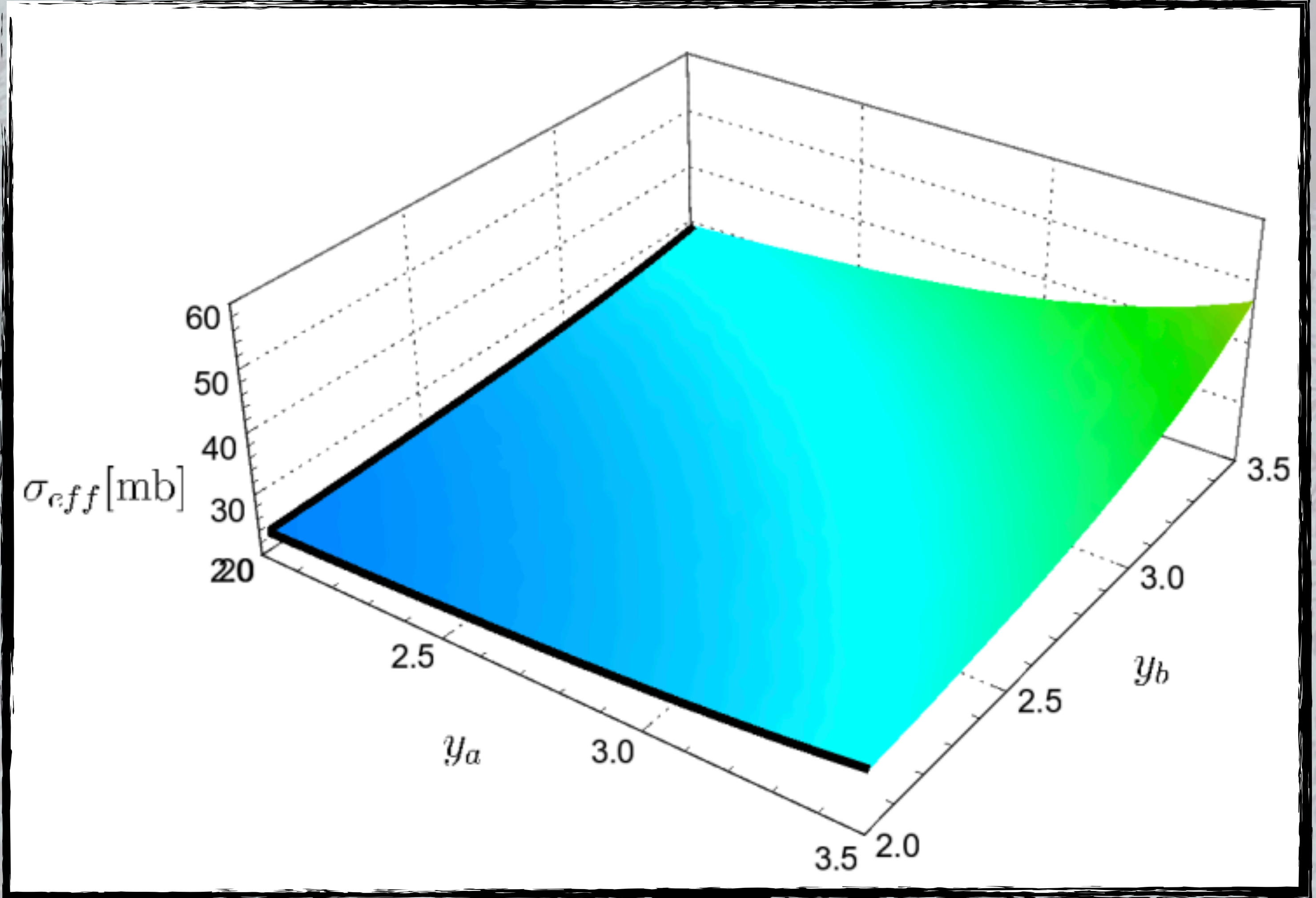
PRL 131 (2023) 091803

$\sigma \sim 6.28$ fb

Some Ideas on "*nonconstant*" $\sigma_{\rm eff}$

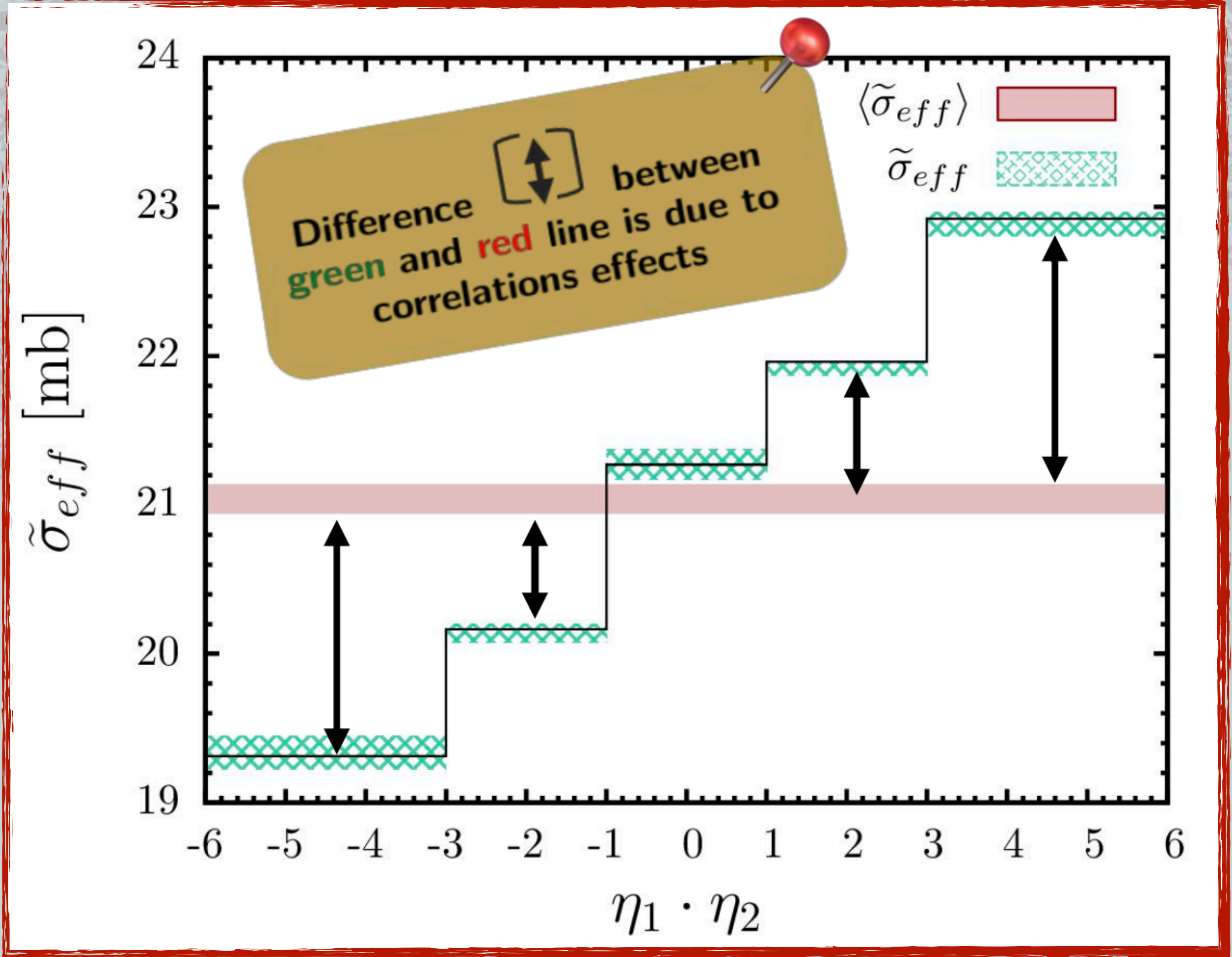
$$\sigma_{\rm eff} = \frac{m}{2}\frac{\sigma_A \sigma_B}{\sigma^{DPS}_{A+B}}$$

$$x_{1,3} = \frac{\sqrt{m_A^2 + k_{T,A}^2}}{\sqrt{s}} e^{\pm y_A}, \quad x_{2,4} = \frac{\sqrt{m_B^2 + k_{T,B}^2}}{\sqrt{s}} e^{\pm y_B}$$



An example for the calculation of $\sigma_{\rm eff}$ from gluon DPDs at high energy scales

M. R. and F. A. Ceccopieri, JHEP 09 (2019) 12, 125003



Predictions from the calculation of same sign W's production at the LHC

F. A. Ceccopieri, M. R. and S. Scopetta, PRD 95 (2017), no.11, 114030

Effective Cross Section and proton structure

If DPDs factorize in terms of PDFs then

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

Effective Form Factor (EFF) =
FT of the probability distribution T
i.e. the probability of finding two partons
at transverse distance $z_\perp$

Effective Cross Section and proton structure

If DPDs factorize in terms of PDFs then

$$\sigma_{\mathrm{eff}}^{-1} = \int d^2 z_\perp \; \tilde{T}(z_\perp)^2 = \int \frac{d^2 k_\perp}{(2\pi)^2} \, T(k_\perp)^2$$

Effective Form Factor (EFF) =
FT of the probability distribution T

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

First moment of DPD

Effective Cross Section and proton structure

If DPDs factorize in terms of PDFs then

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

Effective Form Factor (EFF) = FT of the probability distribution T

As for the standard FF:

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

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

First moment of DPD

Effective Cross Section and proton structure

If DPDs factorize in terms of PDFs then

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

Effective Form Factor (EFF) = FT of the probability distribution T

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

First moment of DPD

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)

Effective Cross Section and proton structure

If DPDs factorize in terms of PDFs then

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

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 ⊗ GPD

From the asymptotic behavior we got the following relation:

Constituent quark models for:

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

Verified in all model calculations:

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)

Effective Cross Section and proton structure

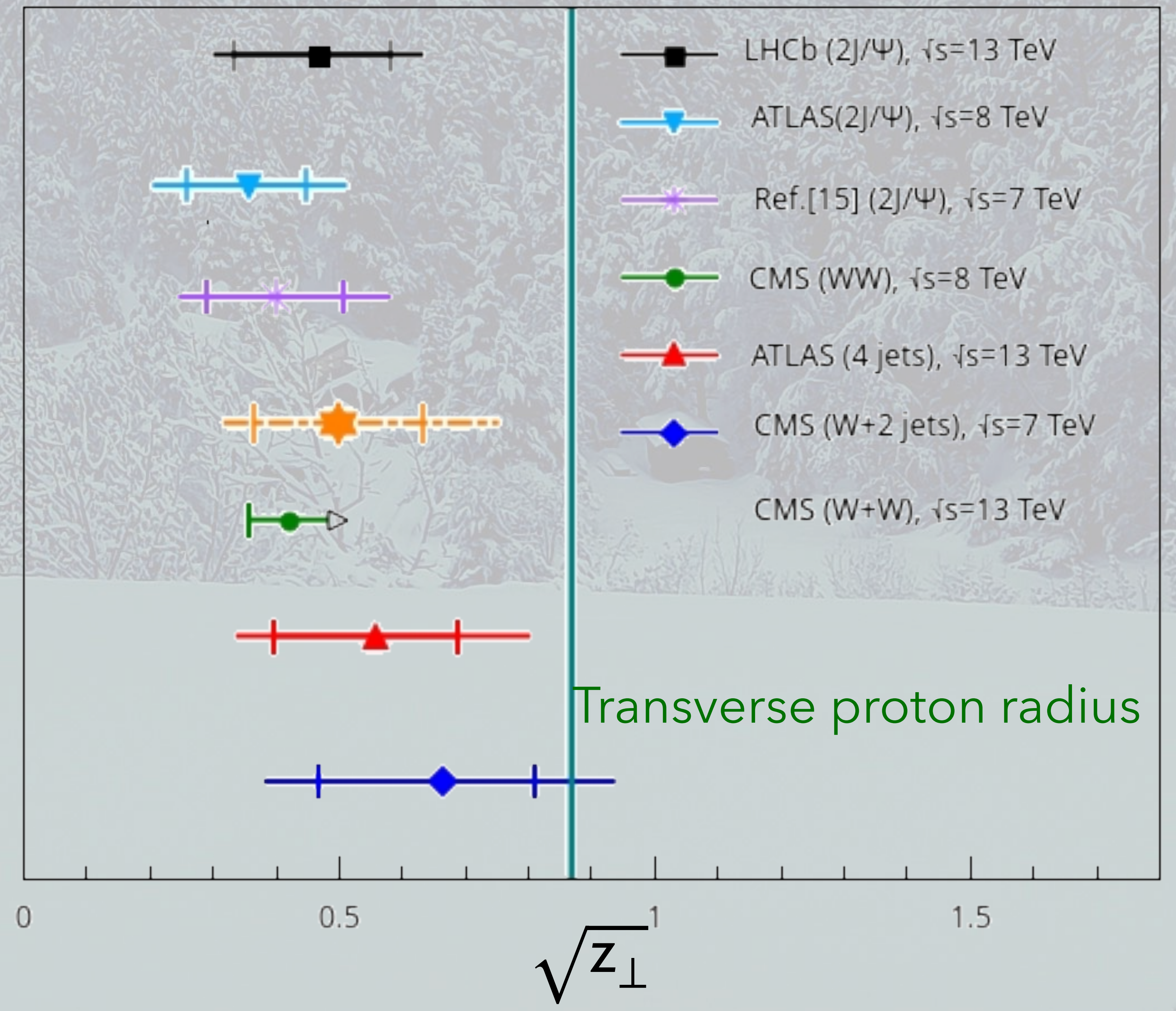
If DPDs factorize in terms of PDFs then $\sigma_{\text{eff}}^{-1} = \int d^2 z_\perp \, \tilde{T}(z_\perp)^2 = \int \frac{d^2 k_\perp}{(2\pi)^2} T(k_\perp)^2$

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)

Effective Cross Section and proton structure

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

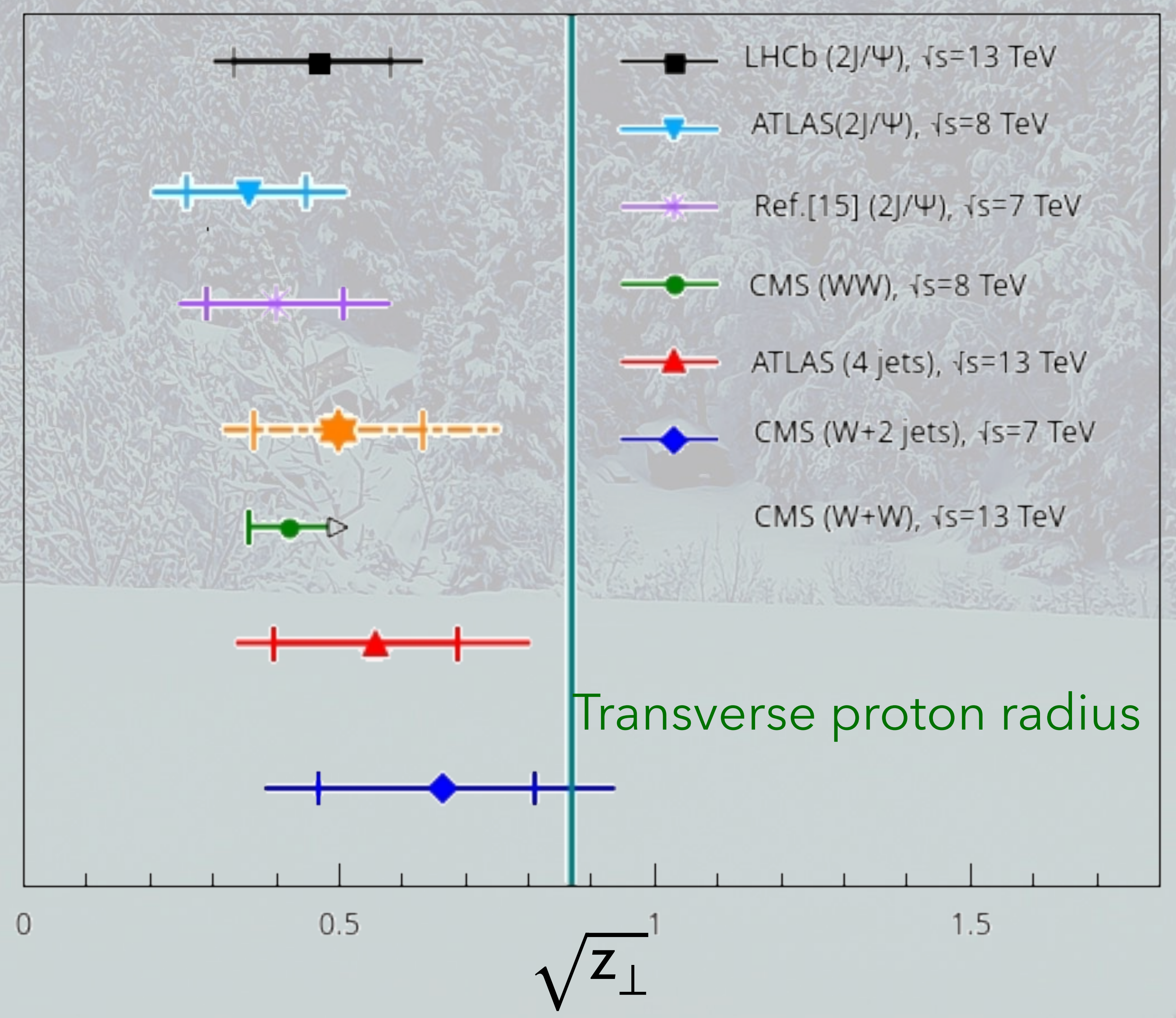
1) THE MEAN DISTANCE IS LOWER THEN THE PROTON RADIUS!

2) in hadron-hadron collisions we do not access directly the distance!

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

From the asymptotic behavior we got the following relation:

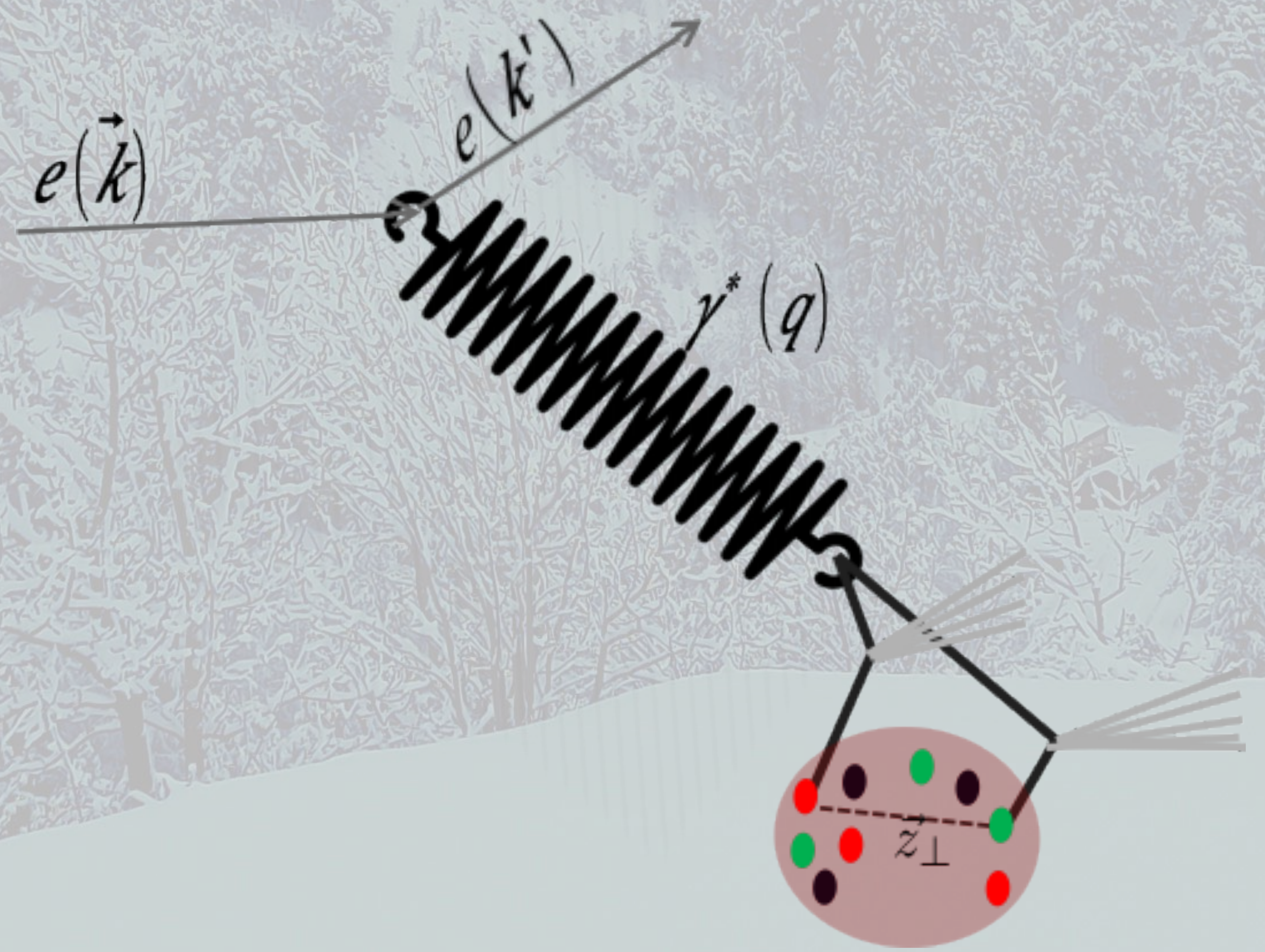
$$\frac{\sigma_{eff}}{3\pi} \leq \langle z_\perp^2 \rangle \leq \frac{\sigma_{eff}}{\pi}$$



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

DPS in $\gamma - p$ interactions

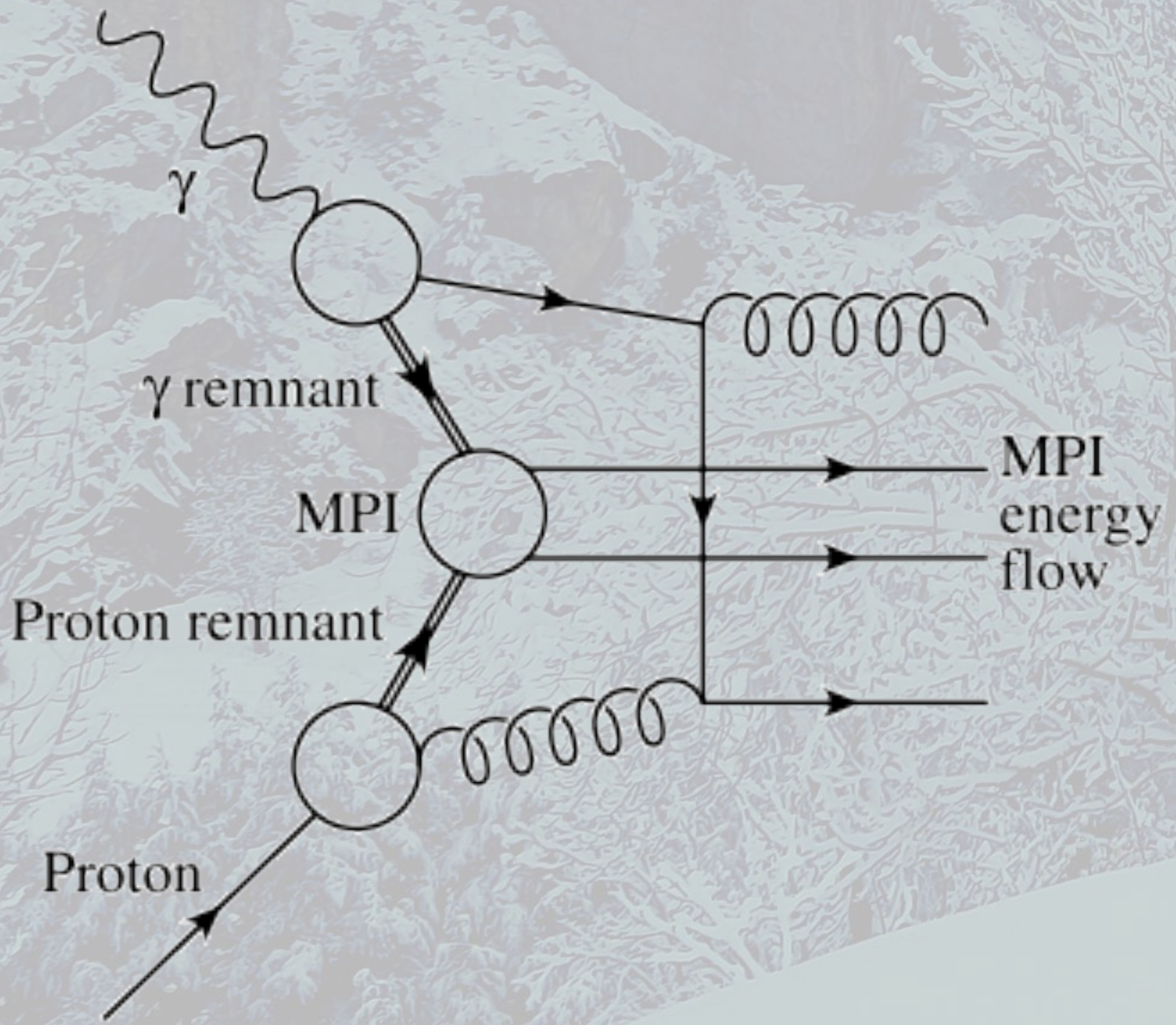
We consider the possibility offered by a DPS process involving a photon FLACTUATING in a quark-antiquark pair interacting with a proton:

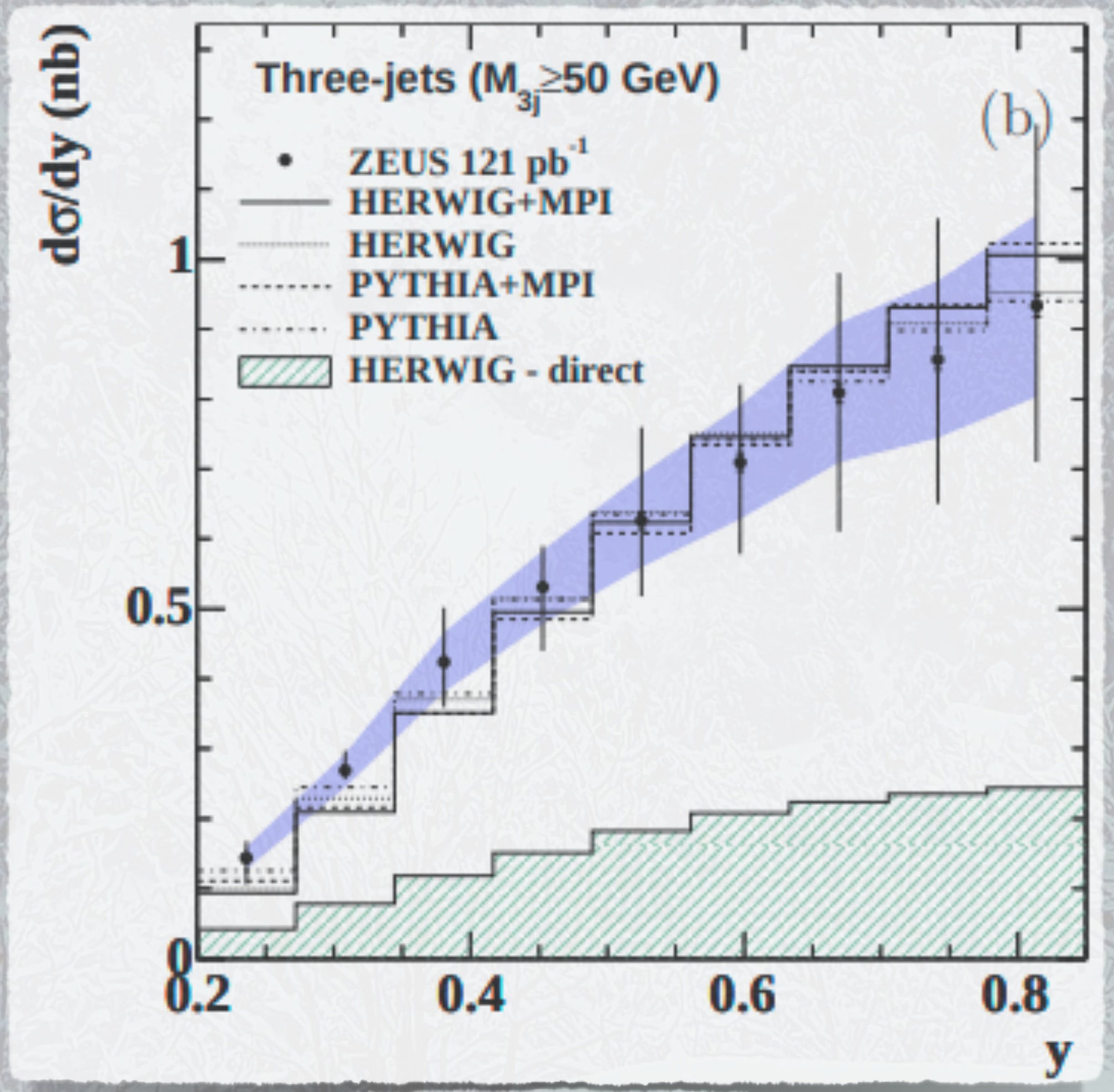


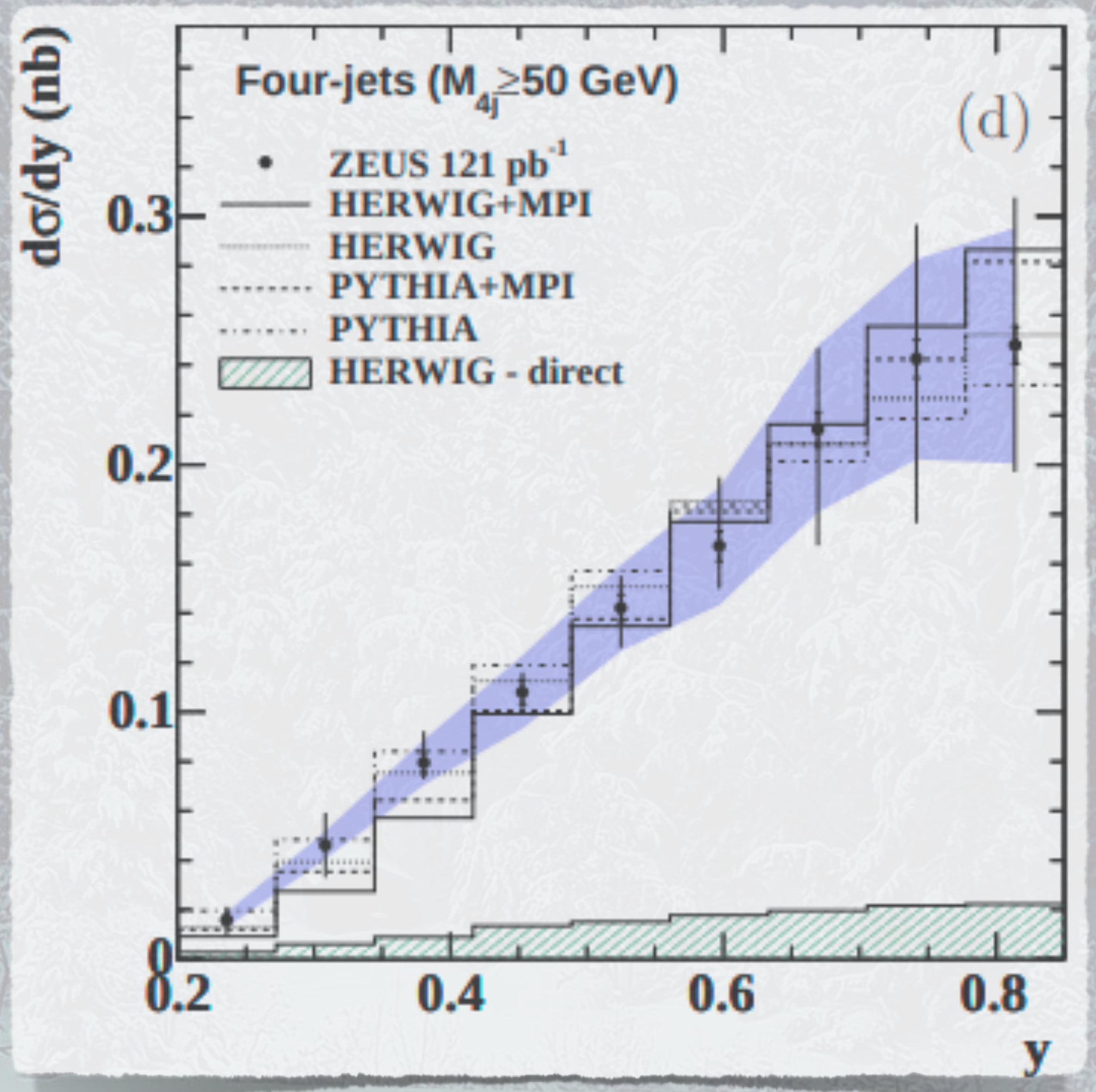
M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

DPS in $\gamma - p$ interactions

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





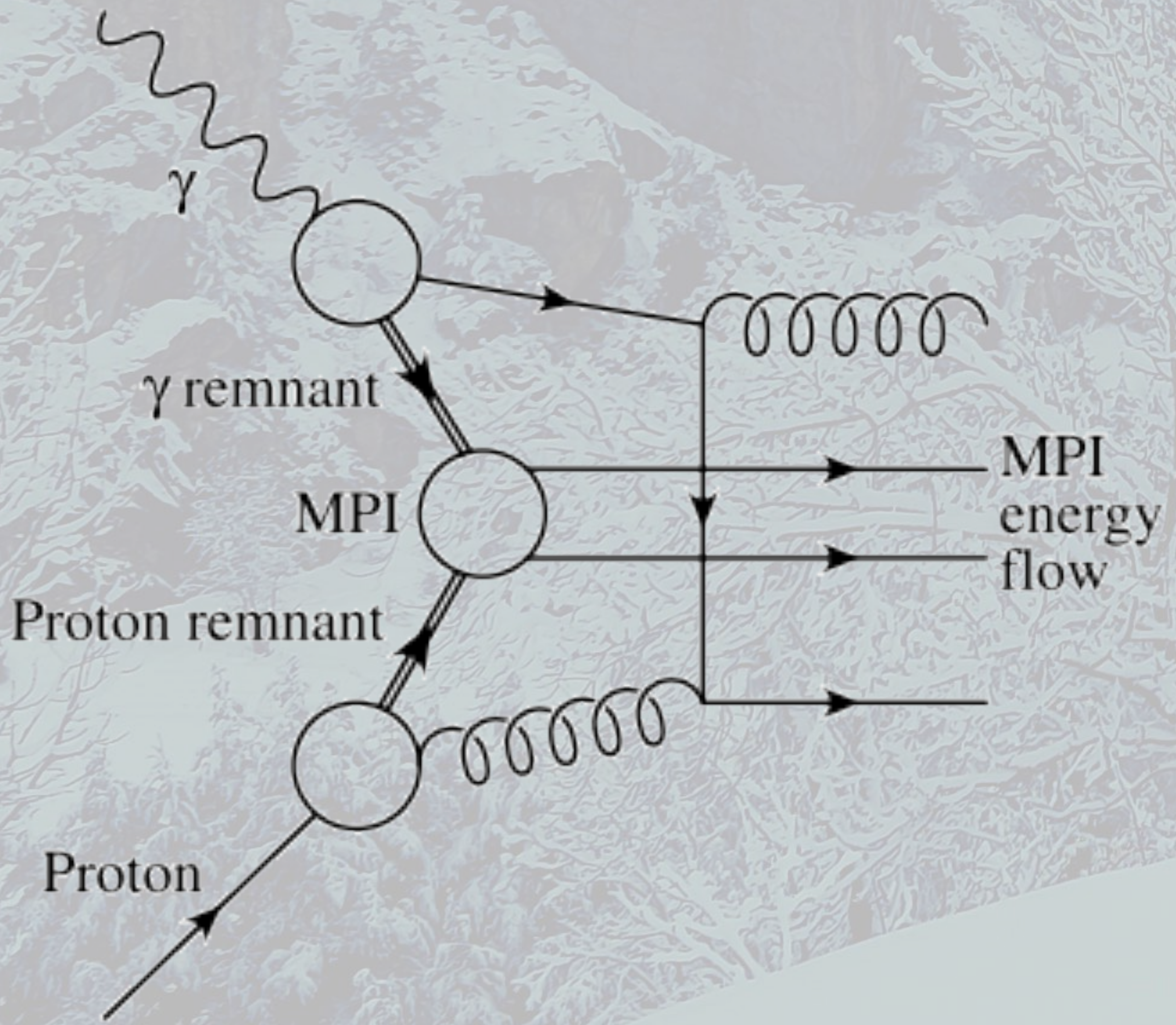


J. R. Forshaw et al, Z phys. C 72, 637

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

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

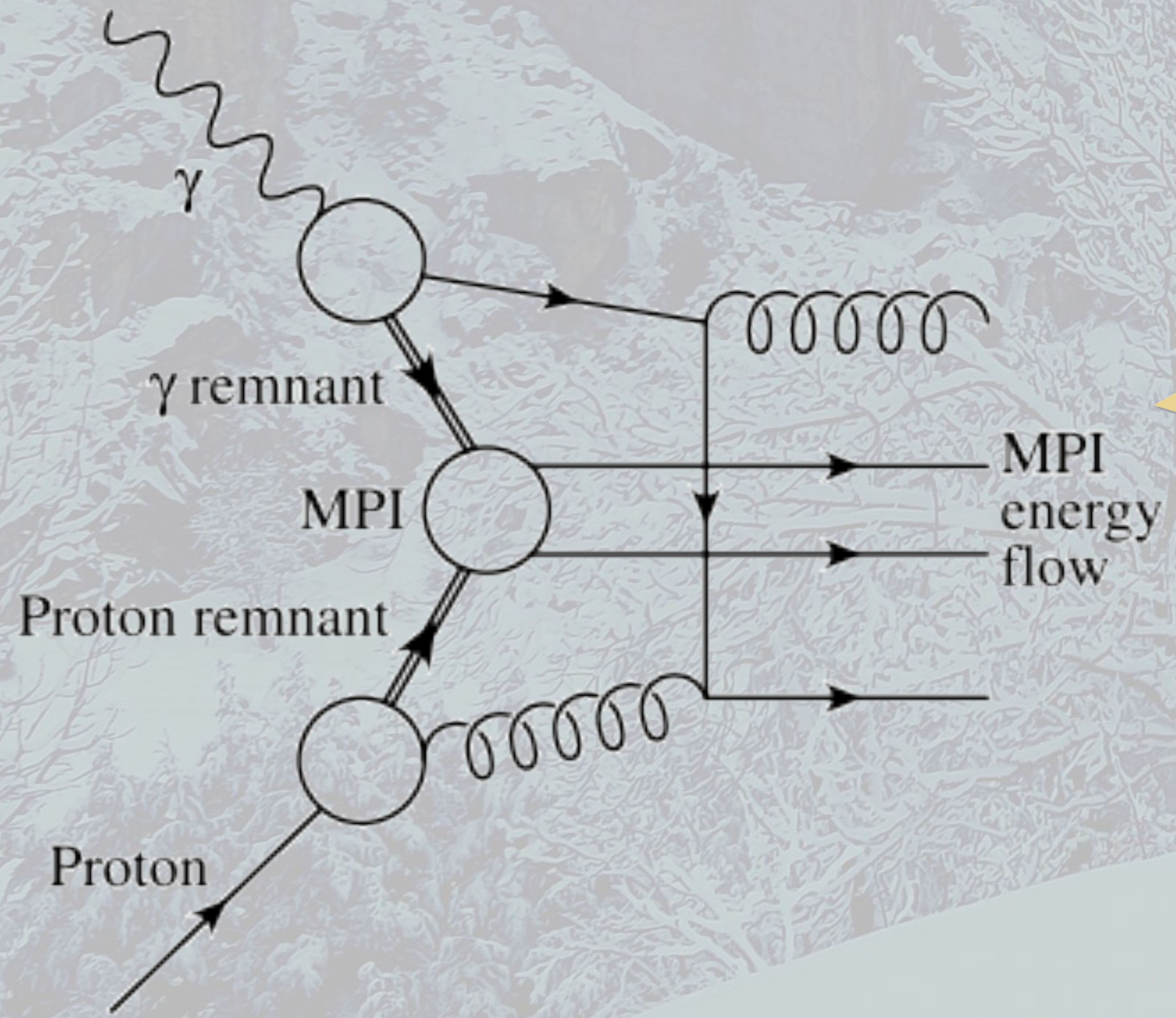
Proton PDF
(J. Pumplin et al. JHEP 07, 012 (2002)

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

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

$f_{\gamma/e}(y, Q^2)$ ×

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

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

*

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

The main quantity we have to evaluate is:

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

Photon PDF

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

(J. Pumplin et al.

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

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

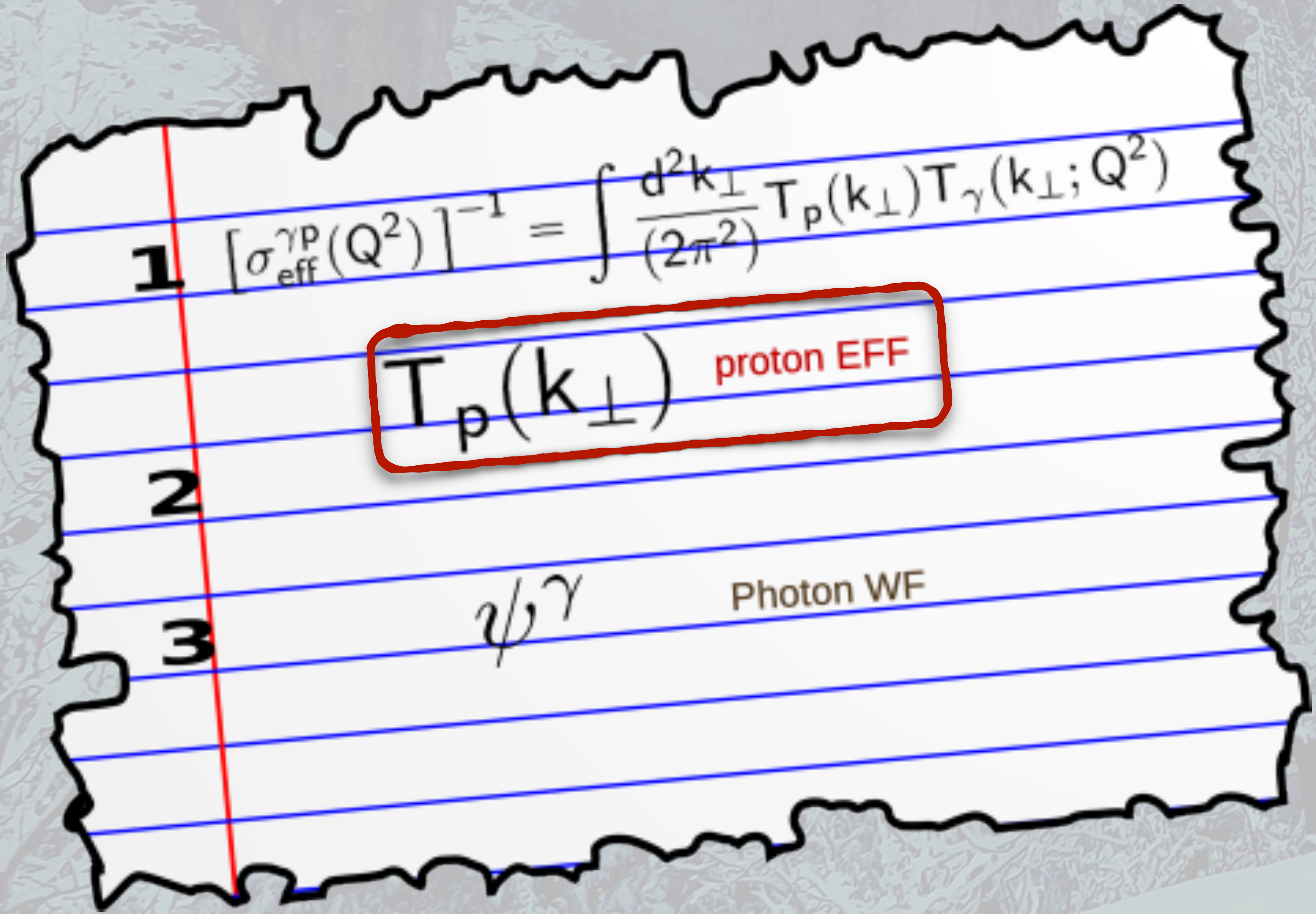
Photon EFF

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:



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

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

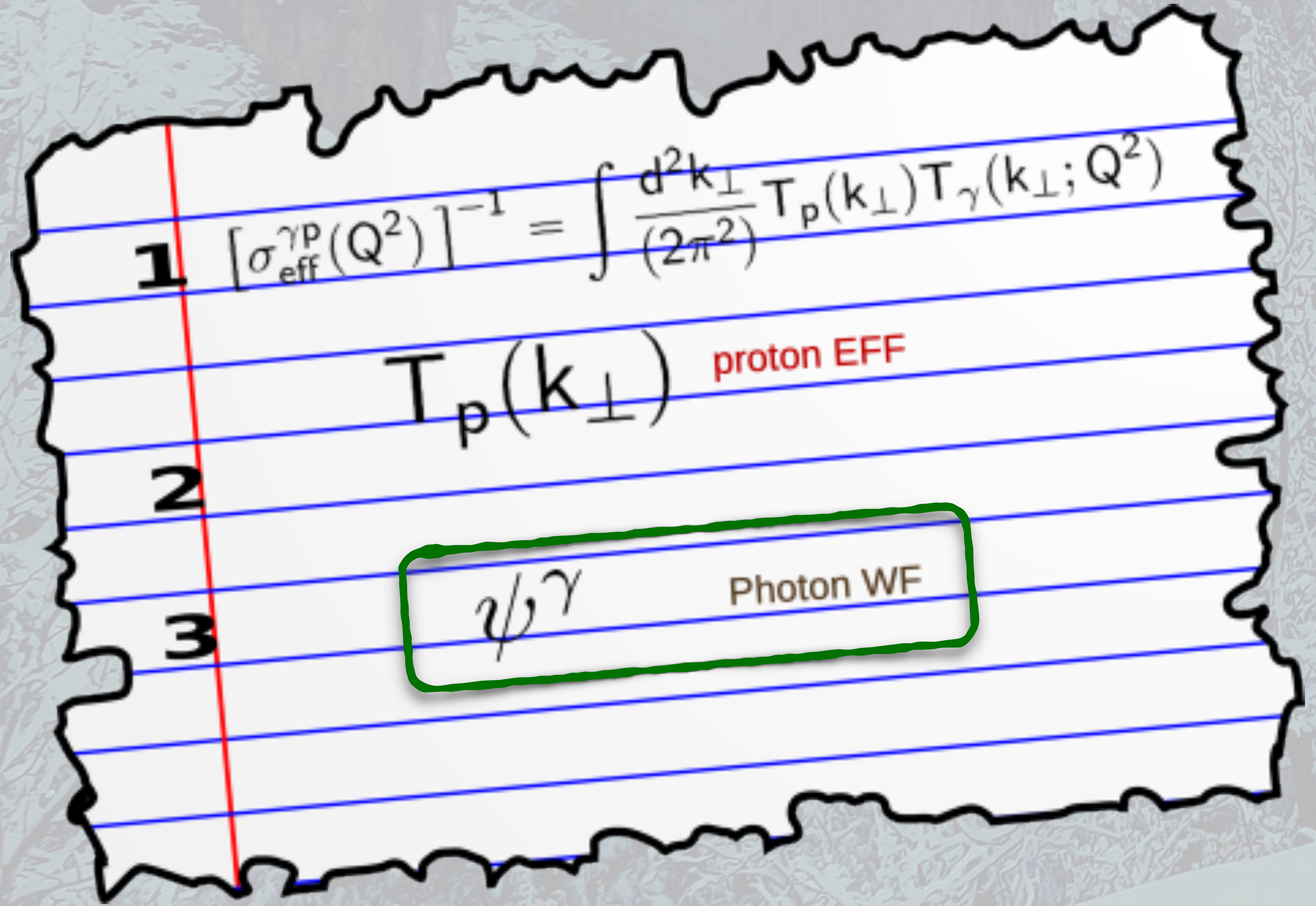
2) G2 $e^{-\alpha_2 k_\perp^2}$, $\alpha_2 = 2.56$ GeV^{-2} $\Longrightarrow \sigma_{eff}^{pp} = 25$ mb

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

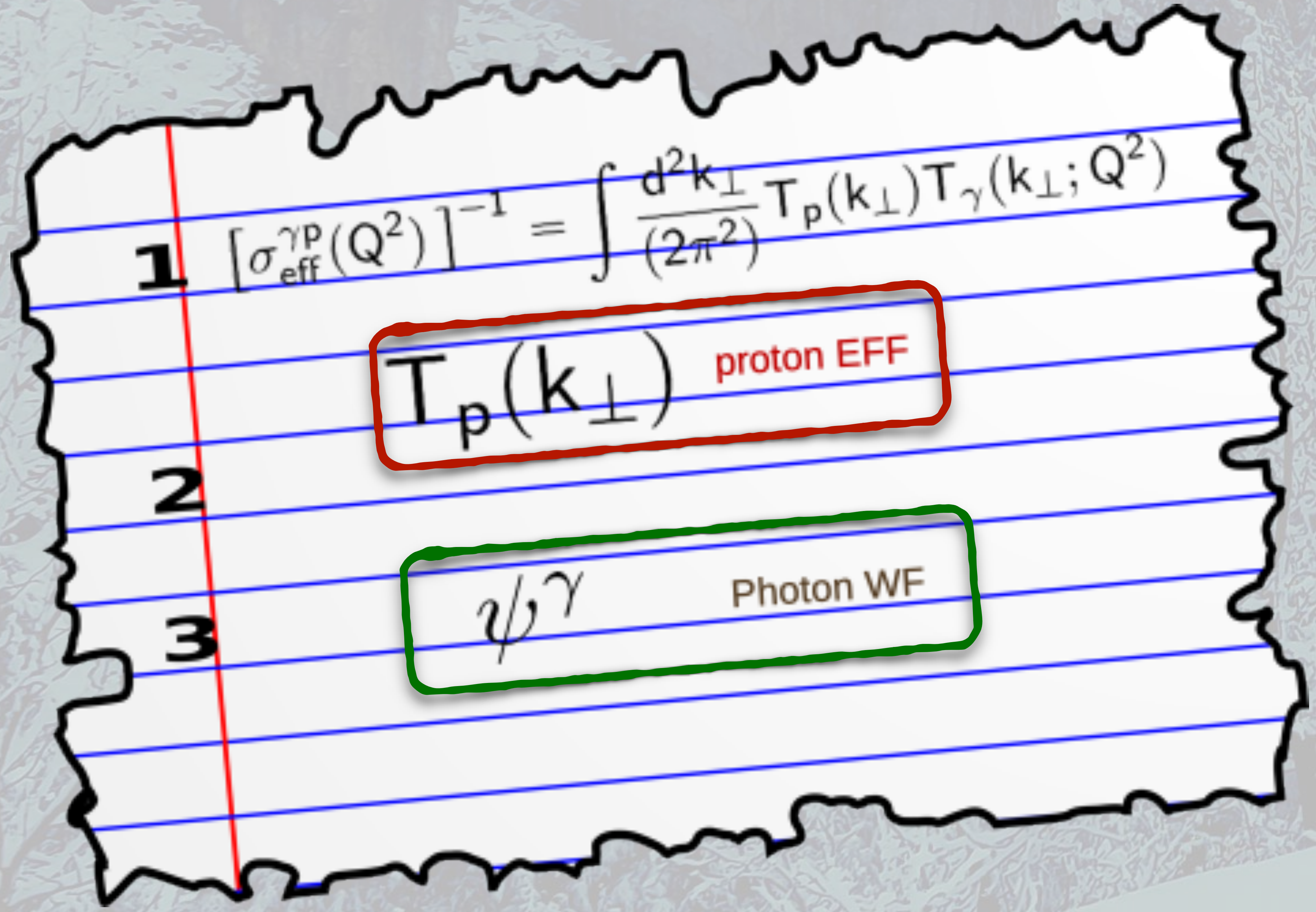
$$\psi_{q,\bar{q}}^{\lambda=\pm}(x, k_{1\perp}; Q^2) = -e_f \frac{\bar{u}_q(k)\ \gamma \cdot \varepsilon^\lambda\ v_{\bar{q}}(q-k)}{\sqrt{x(1-x)}\left[Q^2 + \frac{k_{1\perp}^2 + m^2}{x(1-x)}\right]}$$

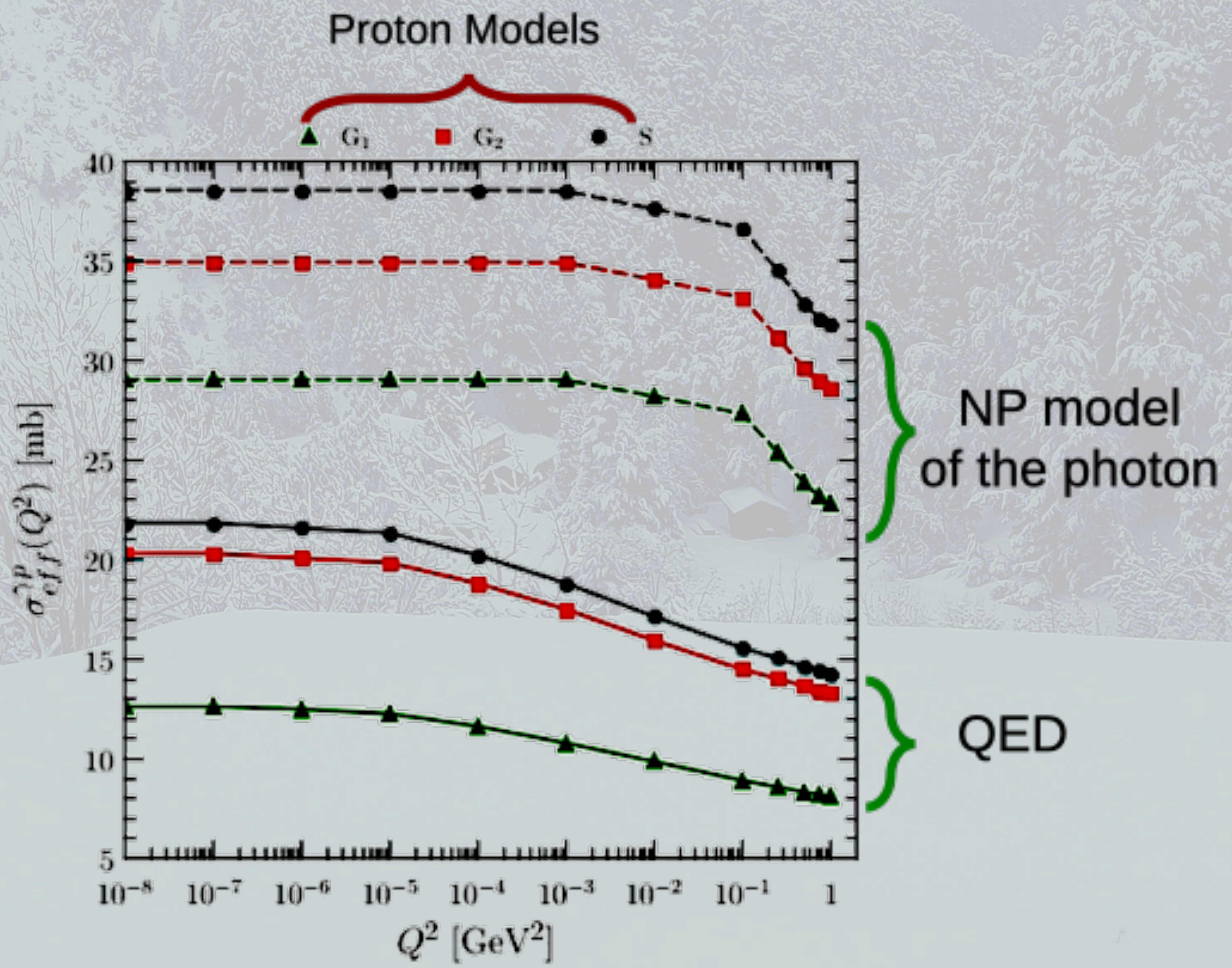
2) Non-Pertubative (NP) effects **(E.R.Arriola et al, PRD74,054023 (2006))**

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

The $\gamma - p$ effective cross-section

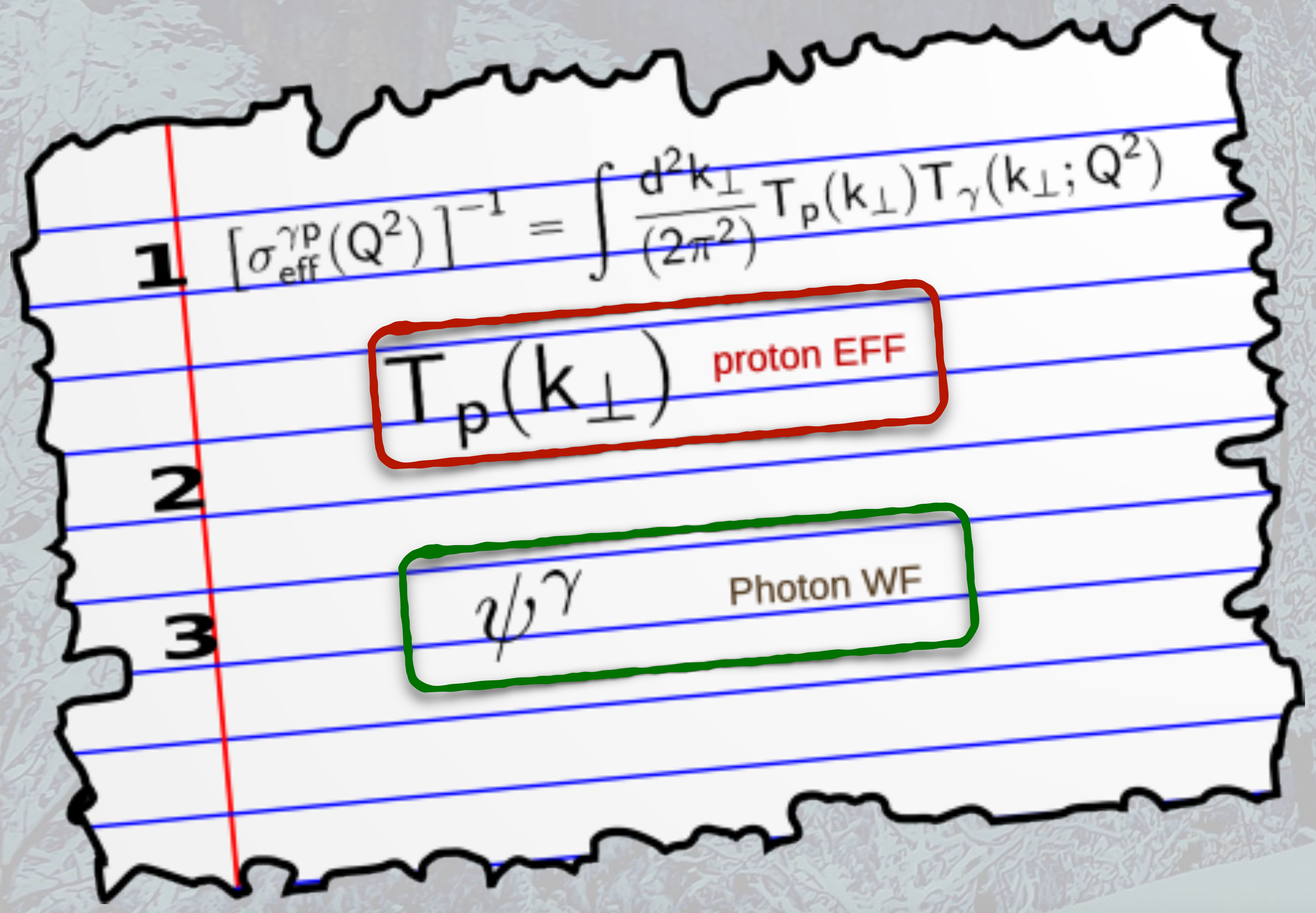
M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

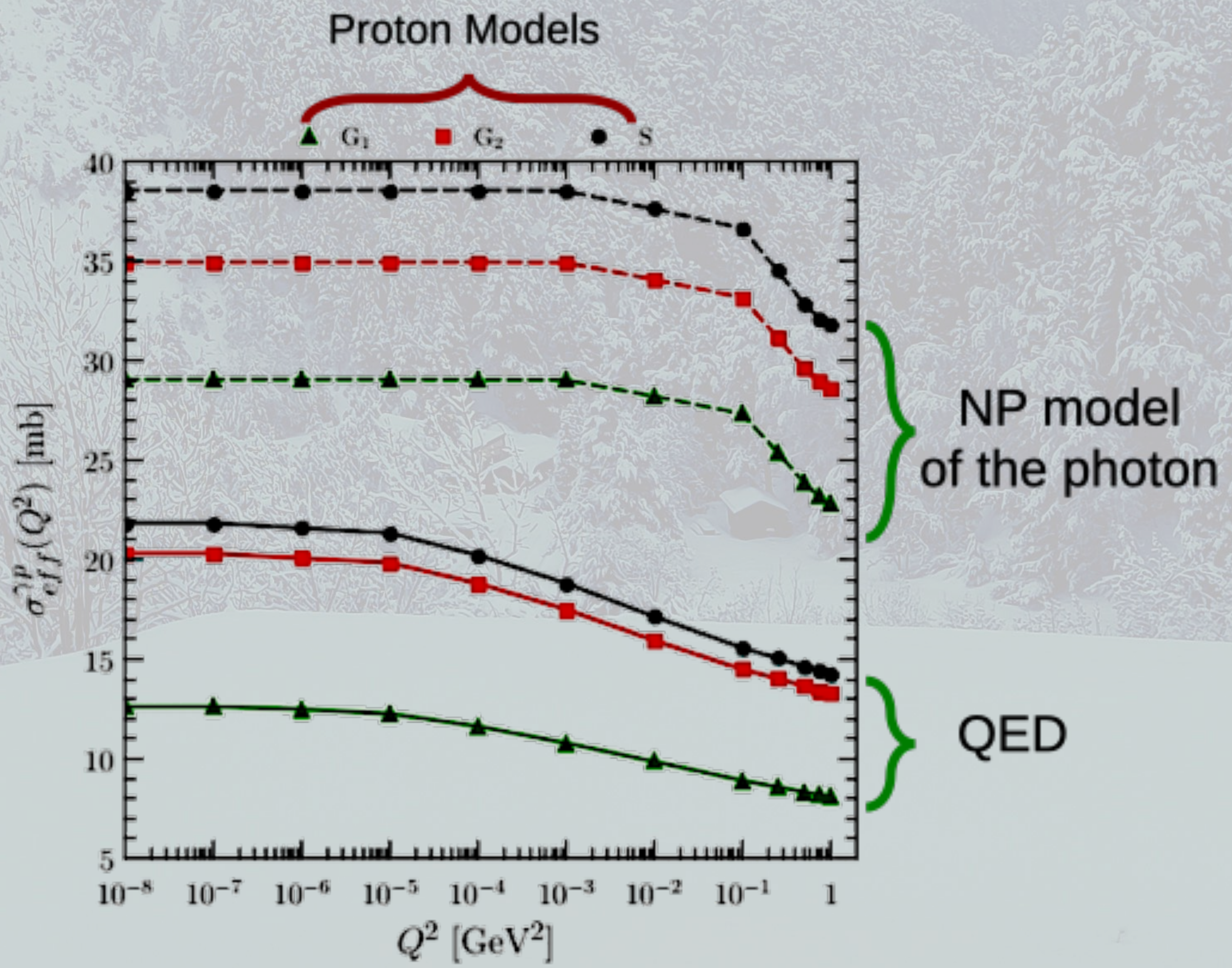




The $\gamma - p$ effective cross-section

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



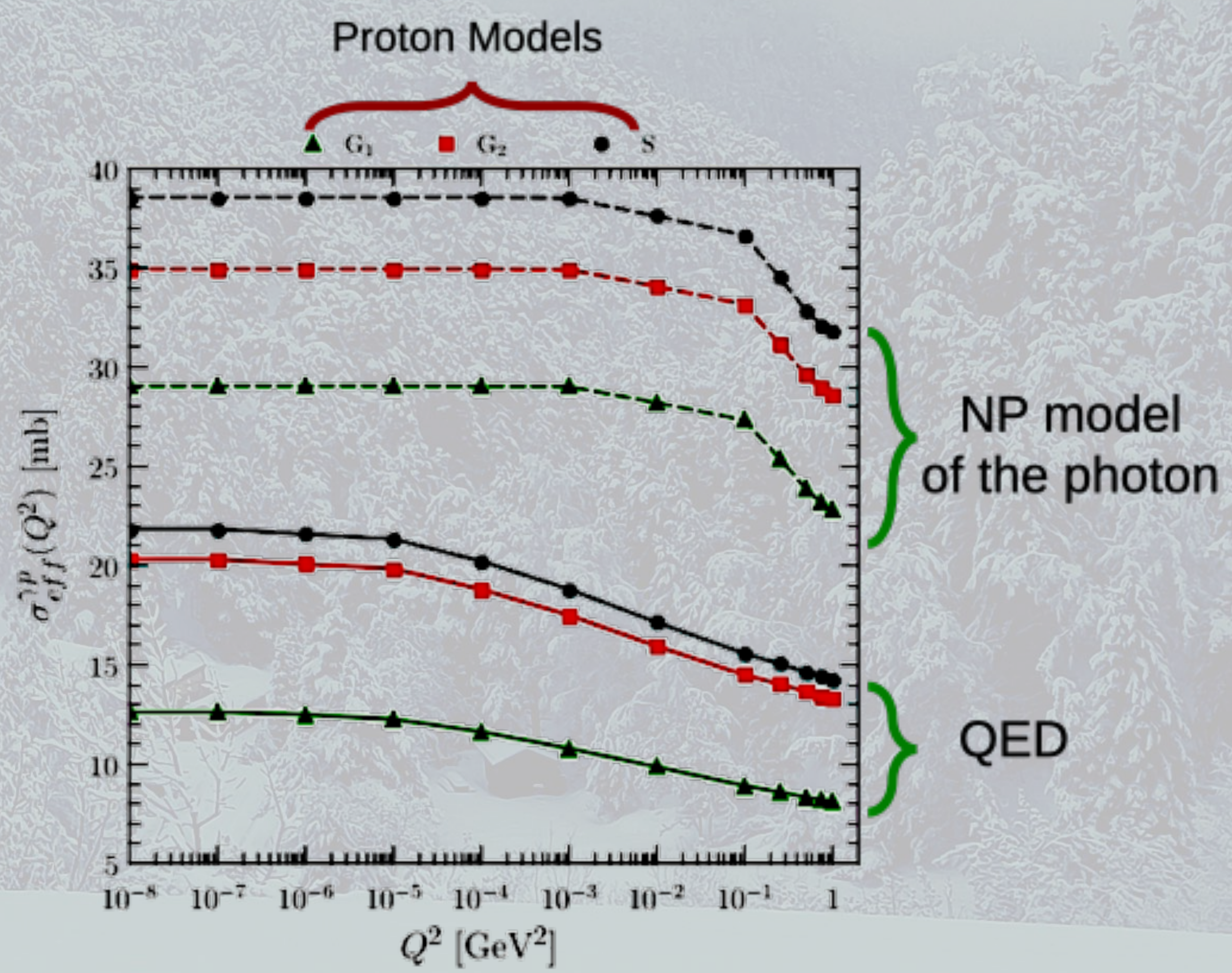


The effective cross-section depends on the photon virtuality! (NEW)

The 4-jets DPS cross-section

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

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



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

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

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

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

KINEMATICS:

$E_T^{jet} > 6$ GeV

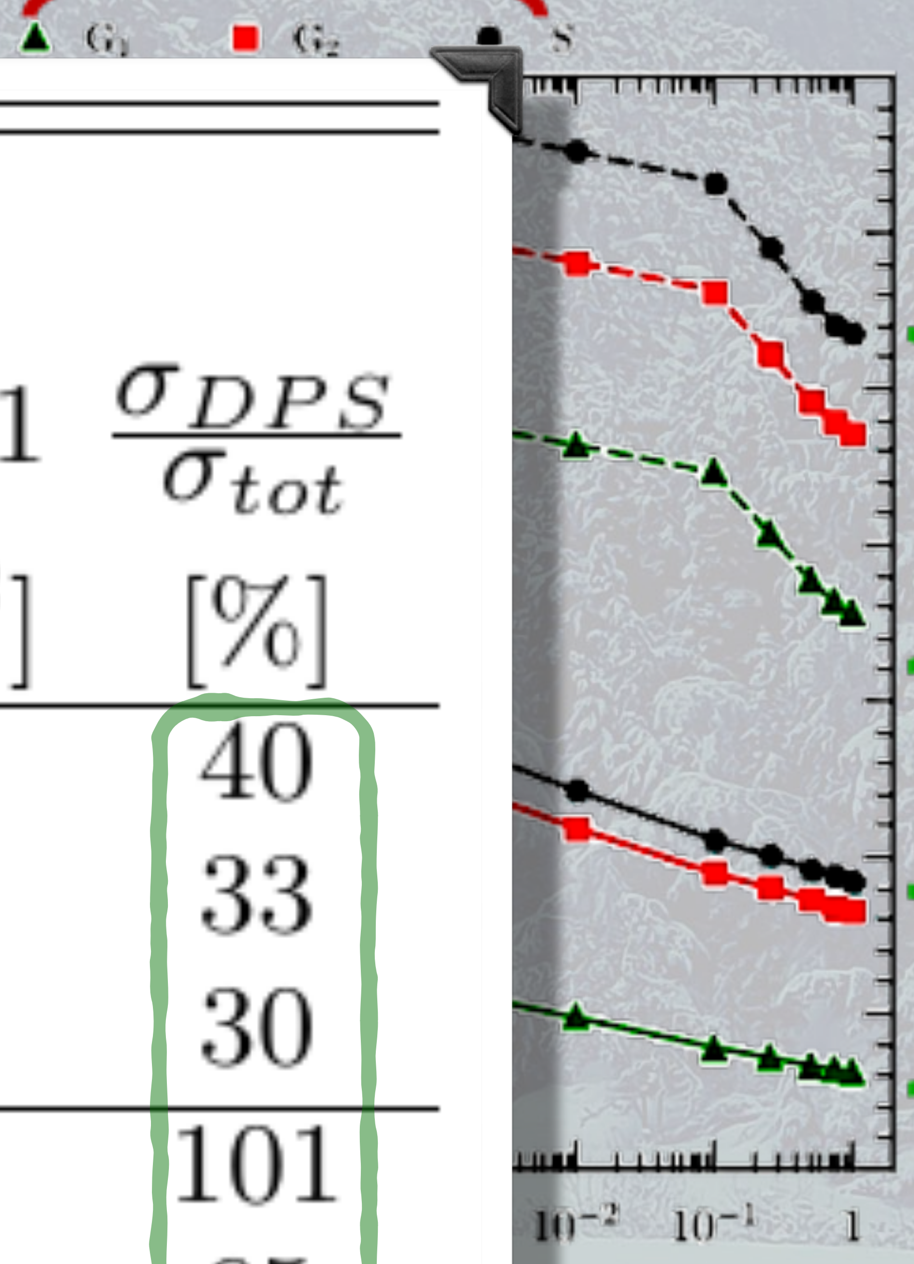
$|\eta_{jet}| < 2.4$

$Q^2 < 1$ GeV^2

$0.2 \leqslant y \leqslant 0.85$

Proton / Photon		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

Proton Models



NP model of the photon

QED

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

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

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

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

KINEMATICS:

$E_T^{jet} > 6$ GeV

$|\eta_{jet}| < 2.4$

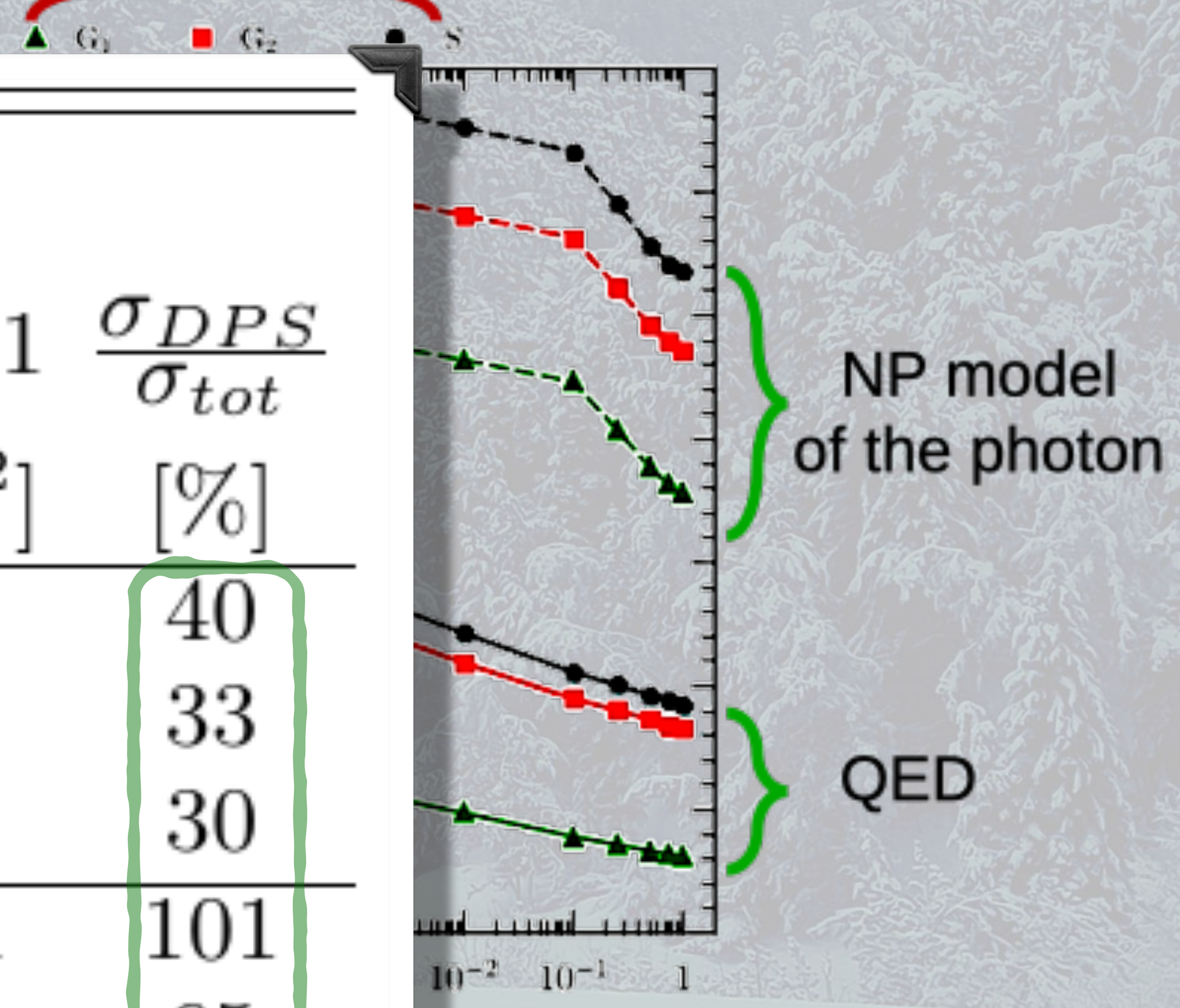
$Q^2 < 1$ GeV^2

$0.2 \leq y \leq 0.85$

Proton / Photon		$Q^2 \leq 1$ [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

What can we learn about the proton structure?

Proton Models



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

S. Checkanov et al. (ZEUS), Nucl. Phys B... (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:

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

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:

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

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

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

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

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

We can expand the distribution related to the photon:

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

Coefficients determined in a given approach describing the photon structure

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

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

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:

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

We can expand the distribution related to the photon:

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

Coefficients determined in a given approach describing the photon structure

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

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

If we could measure $\sigma_{\rm eff}^{\gamma p}(Q^2)$ 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

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

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

We can exp... photon:

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

Coefficients determined in a given approach describing the photon structure

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

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

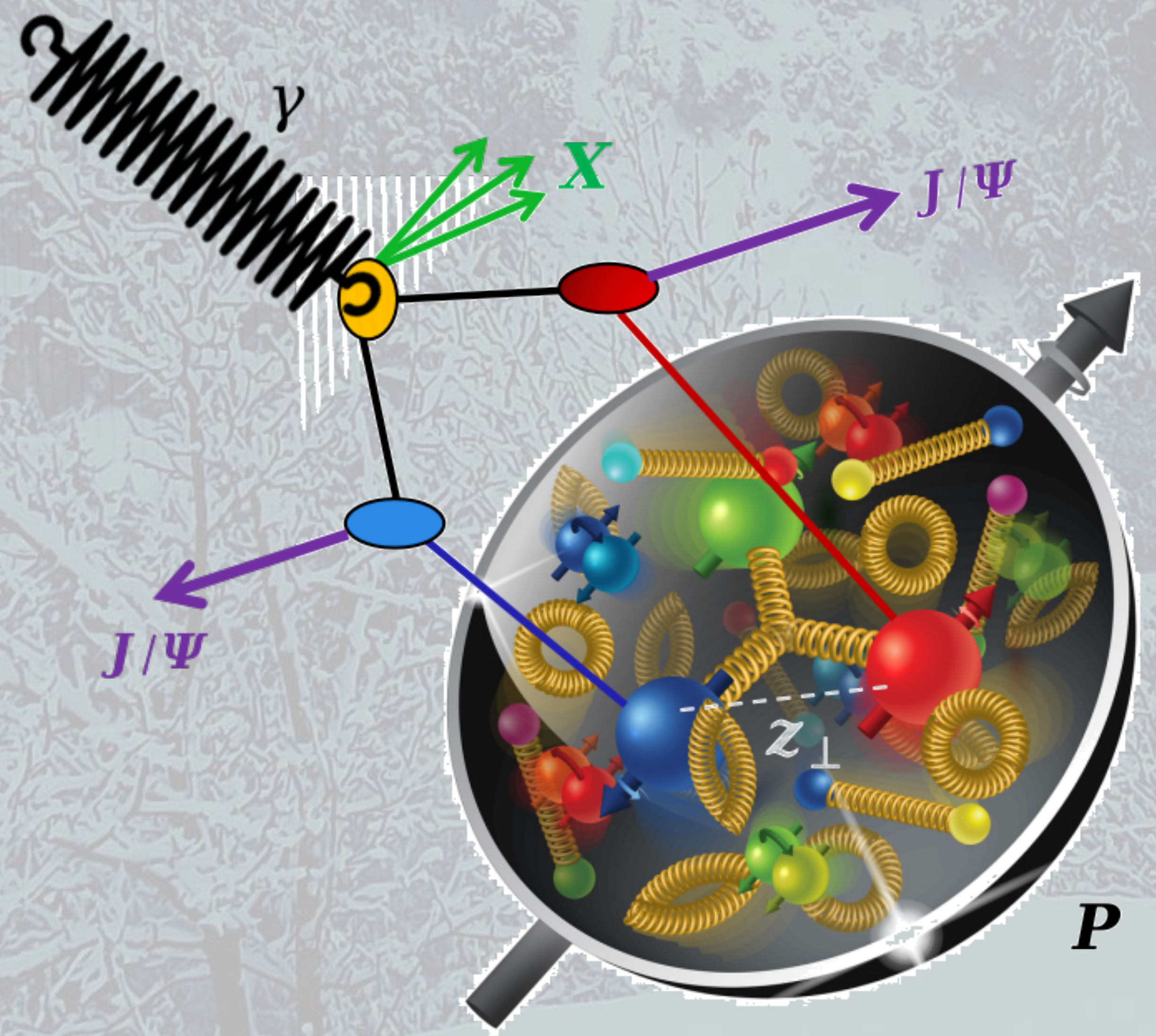
Mean value of the transverse distance between two partons in the PROTON

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

Di J/ψ photo-production@EIC

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

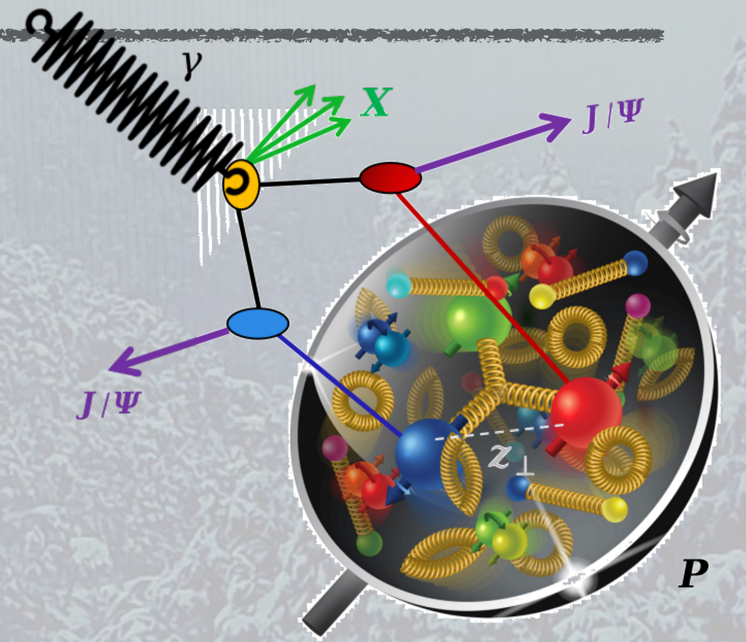
Illustration of DPS for $\gamma + p \to J/\psi + J/\psi + X$



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)

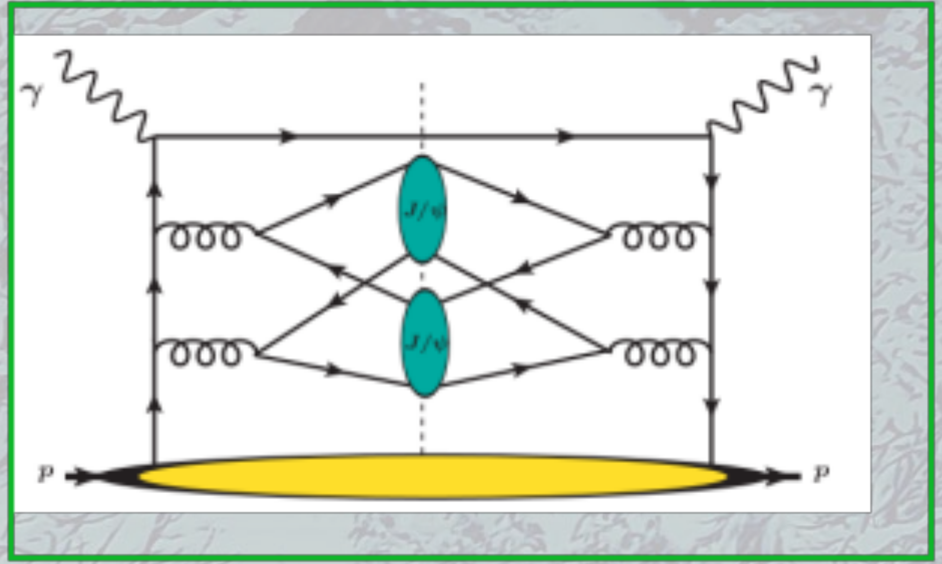
Di J/ψ photo-production@EIC

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

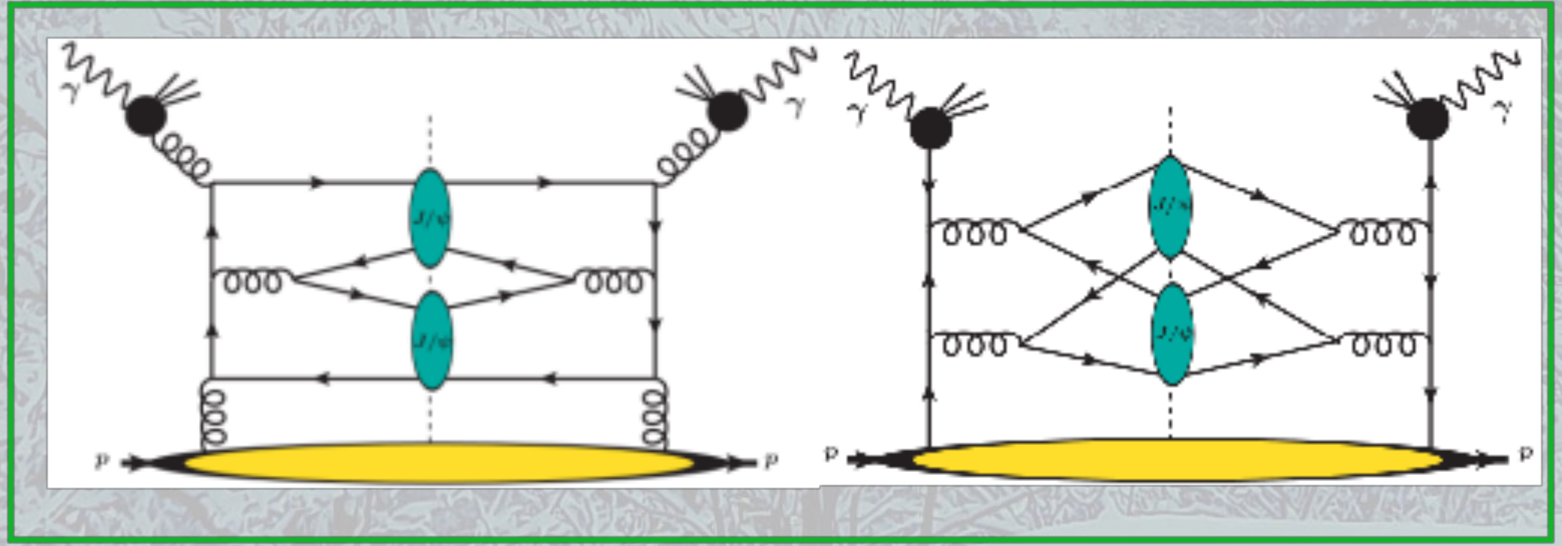
*Slide from R. Sangem

SPS → **Unresolved**, **Resolved**

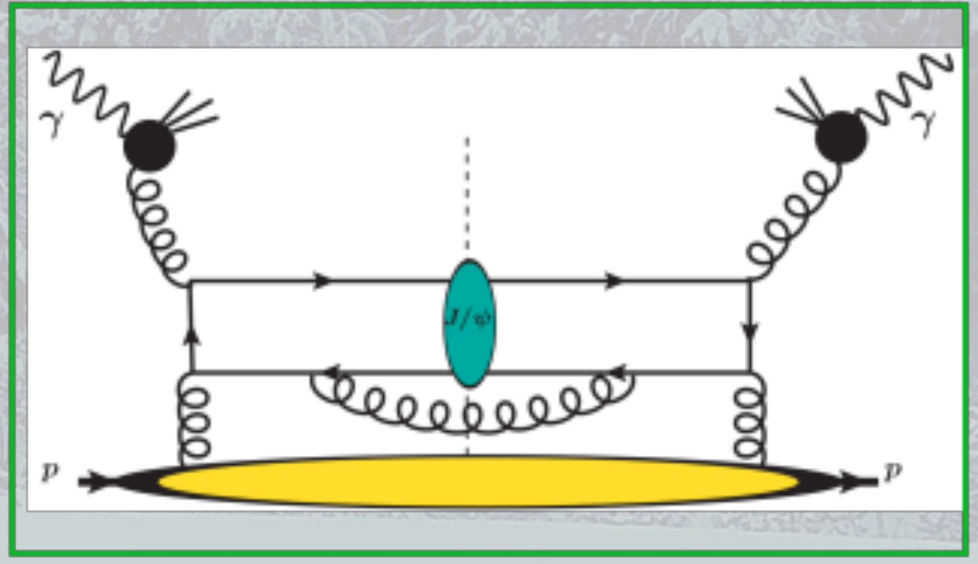
DPS → **Resolved**



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



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



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

- 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

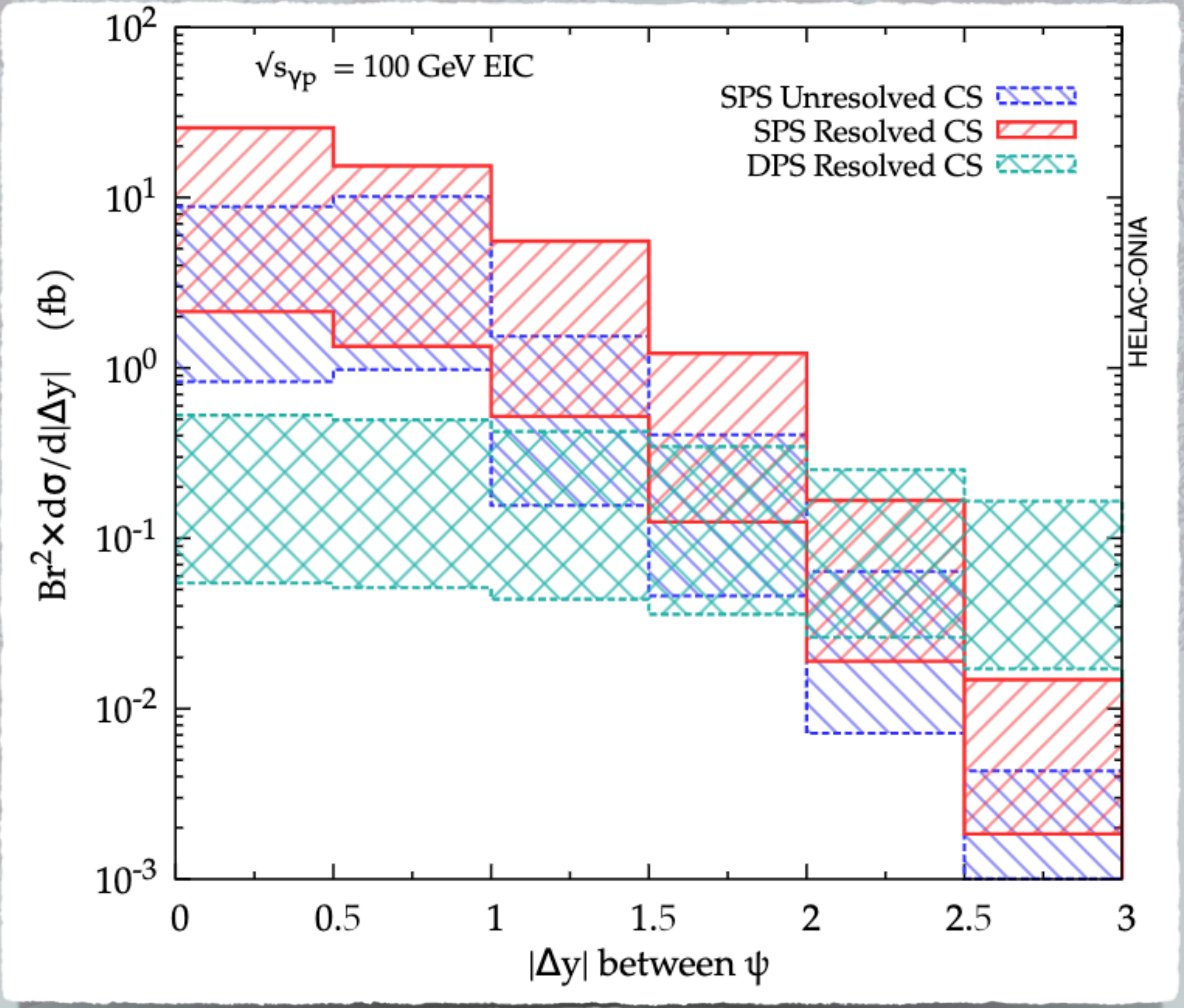
Numerical Results

PRELIMINARY

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

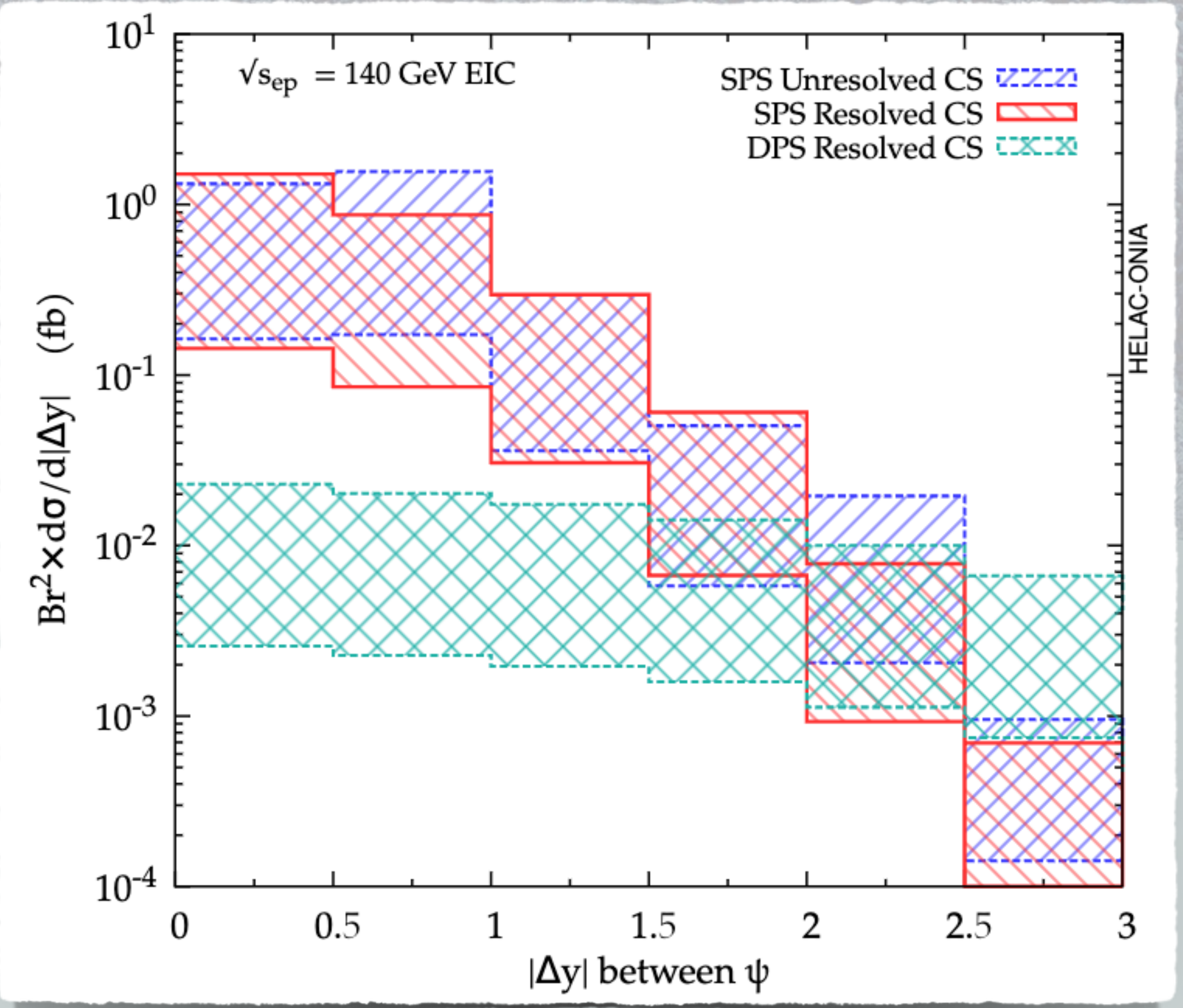
Absolute rapidity difference between the two J/ψ

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



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

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



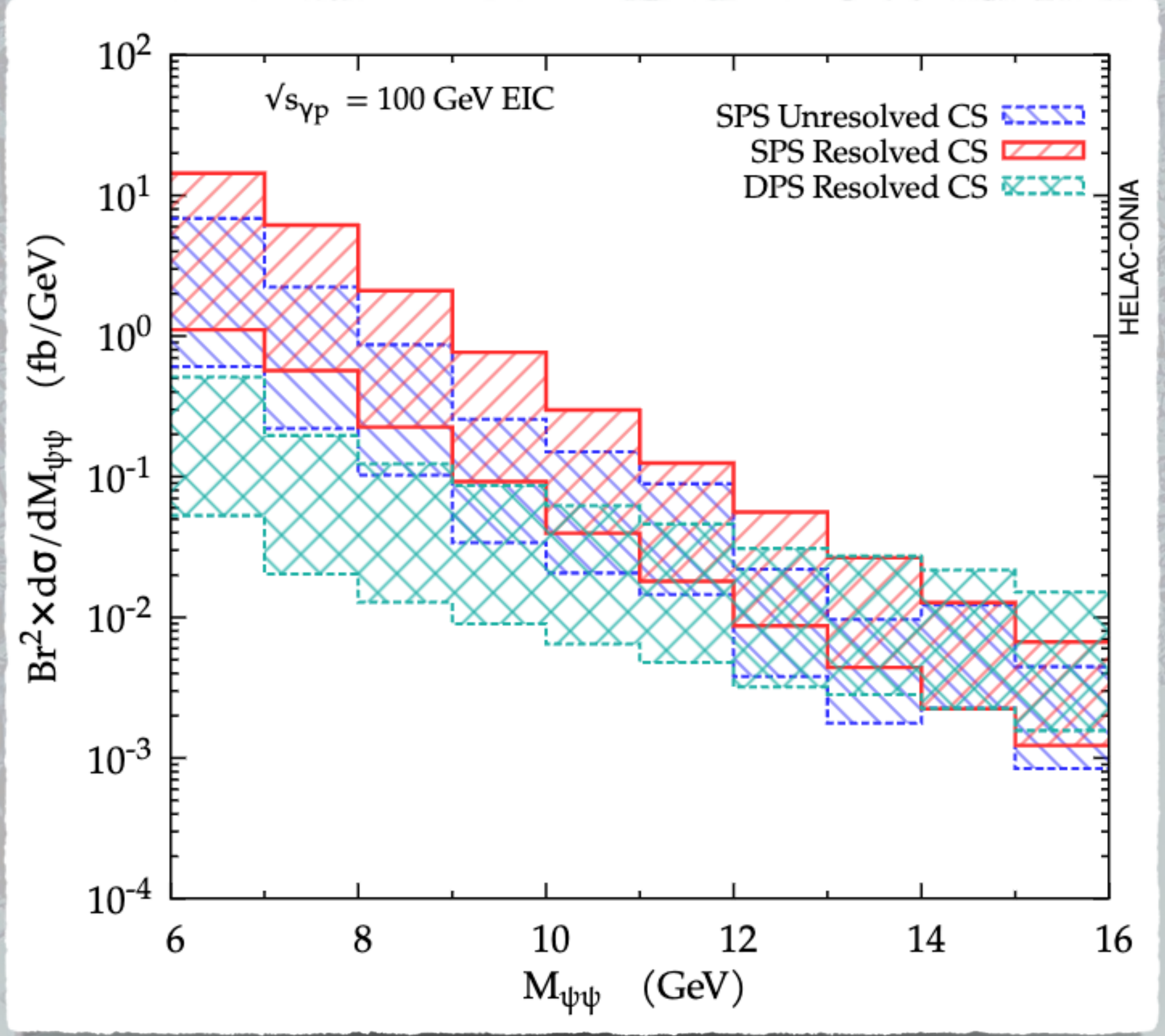
Numerical Results

PRELIMINARY

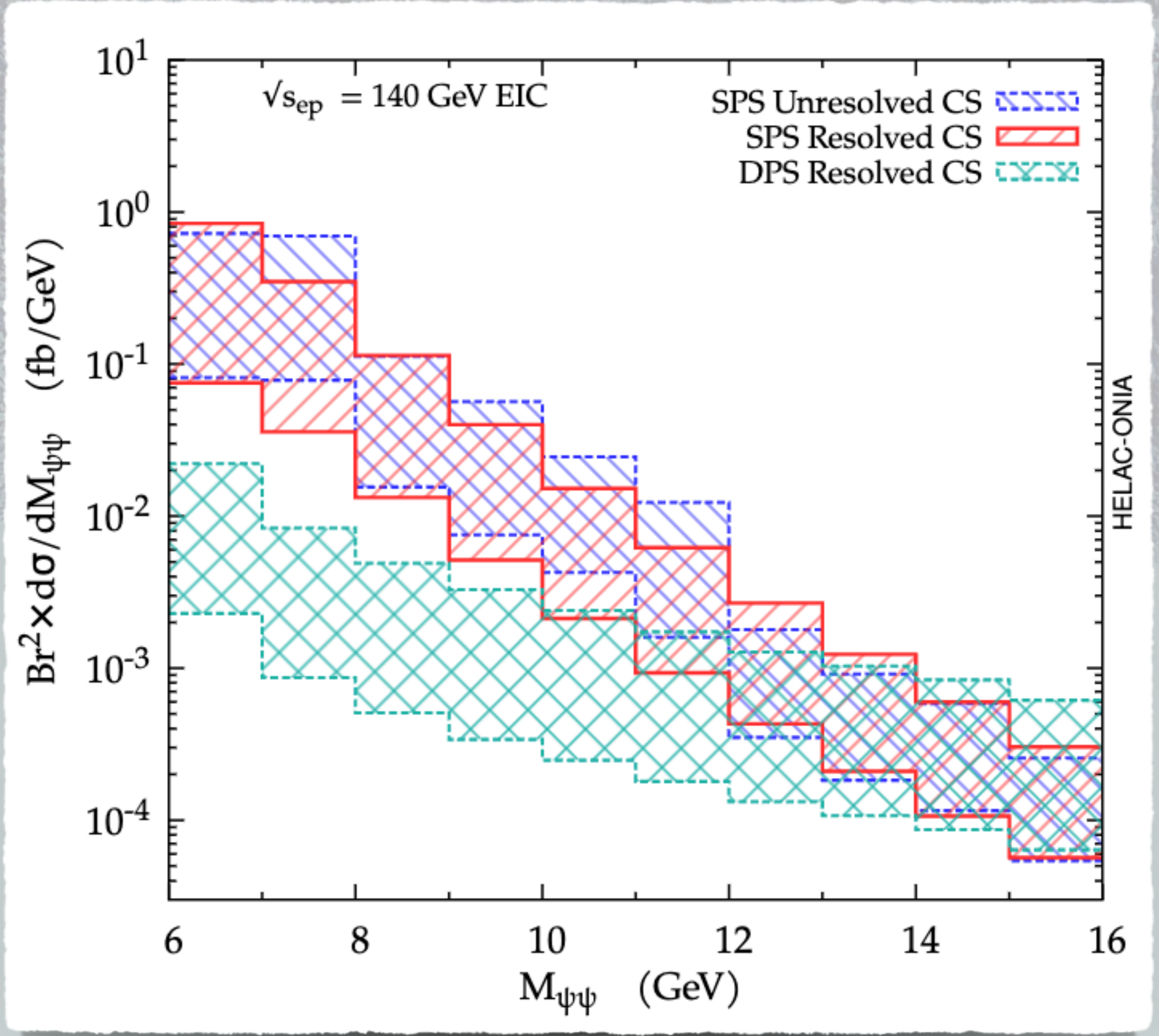
F. A. Ceccopieri, H. S. Shao, J. P. Lansberg, M. R. and R. Sangem in prep.

Invariant mass of the J/ψ pair

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



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



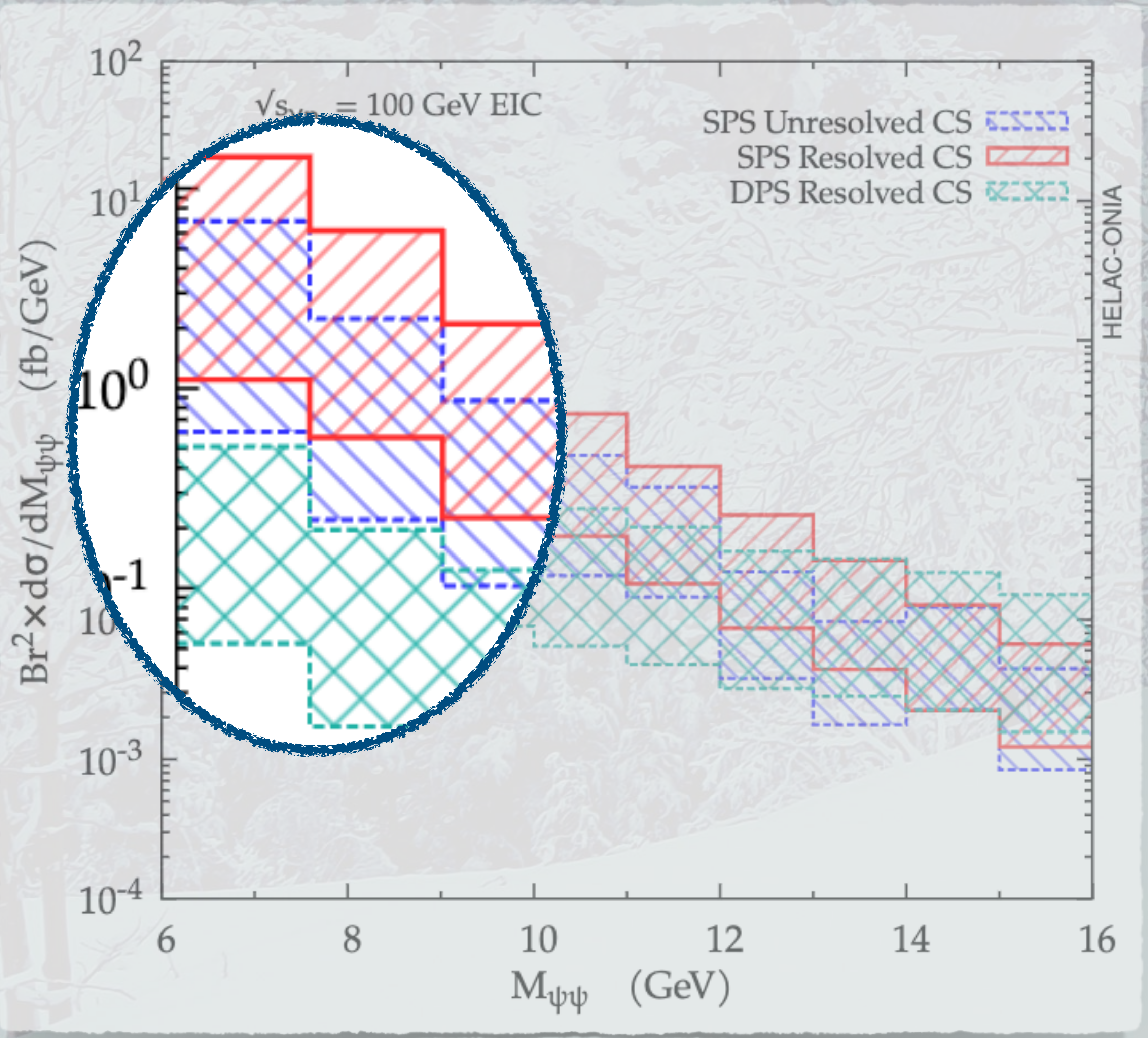
Numerical Results

PRELIMINARY

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

Invariant mass of the J/ψ pair

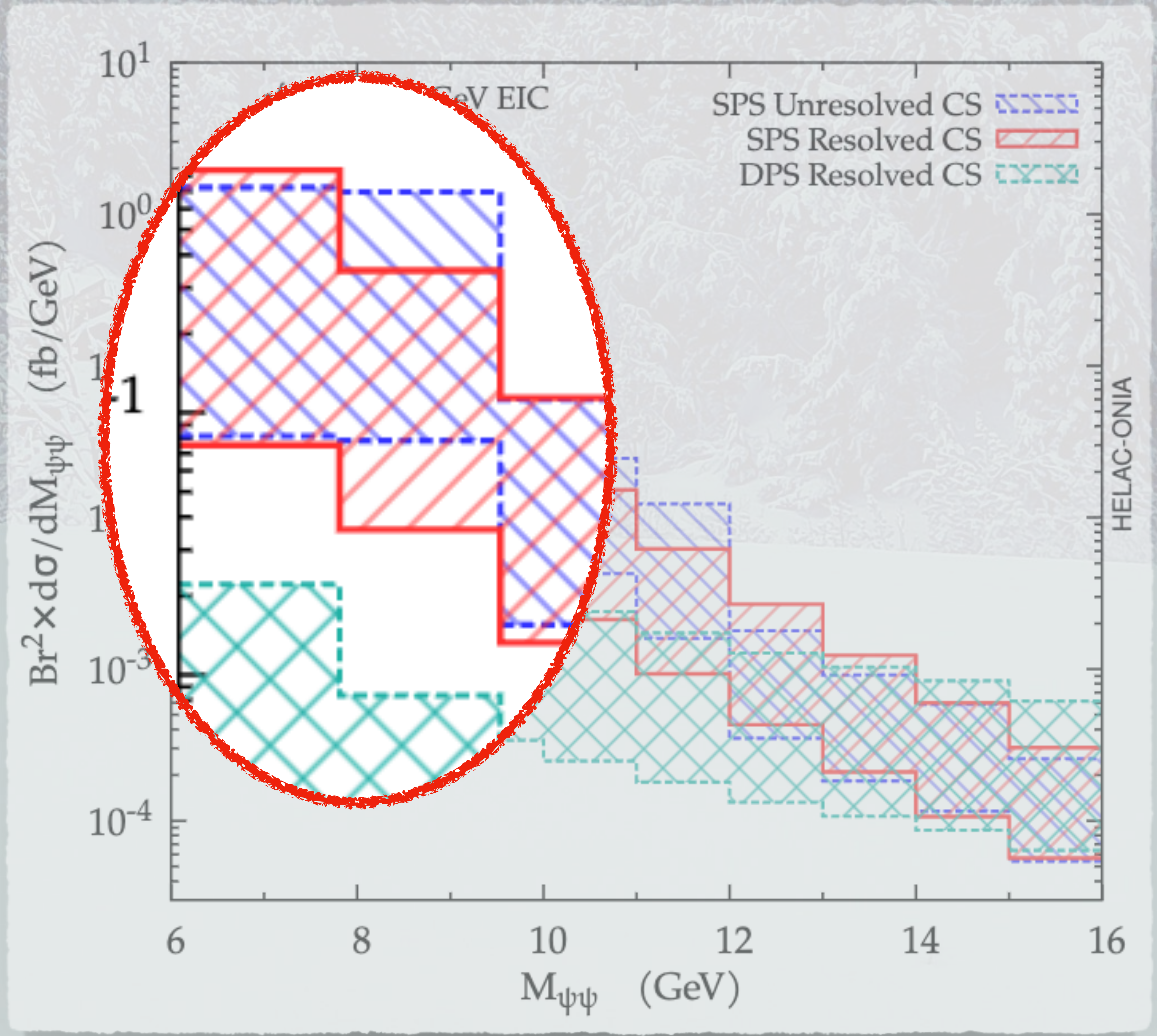
$\sqrt{s_{\gamma p}} = 100$ GeV



a) at low invariant mass:

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

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



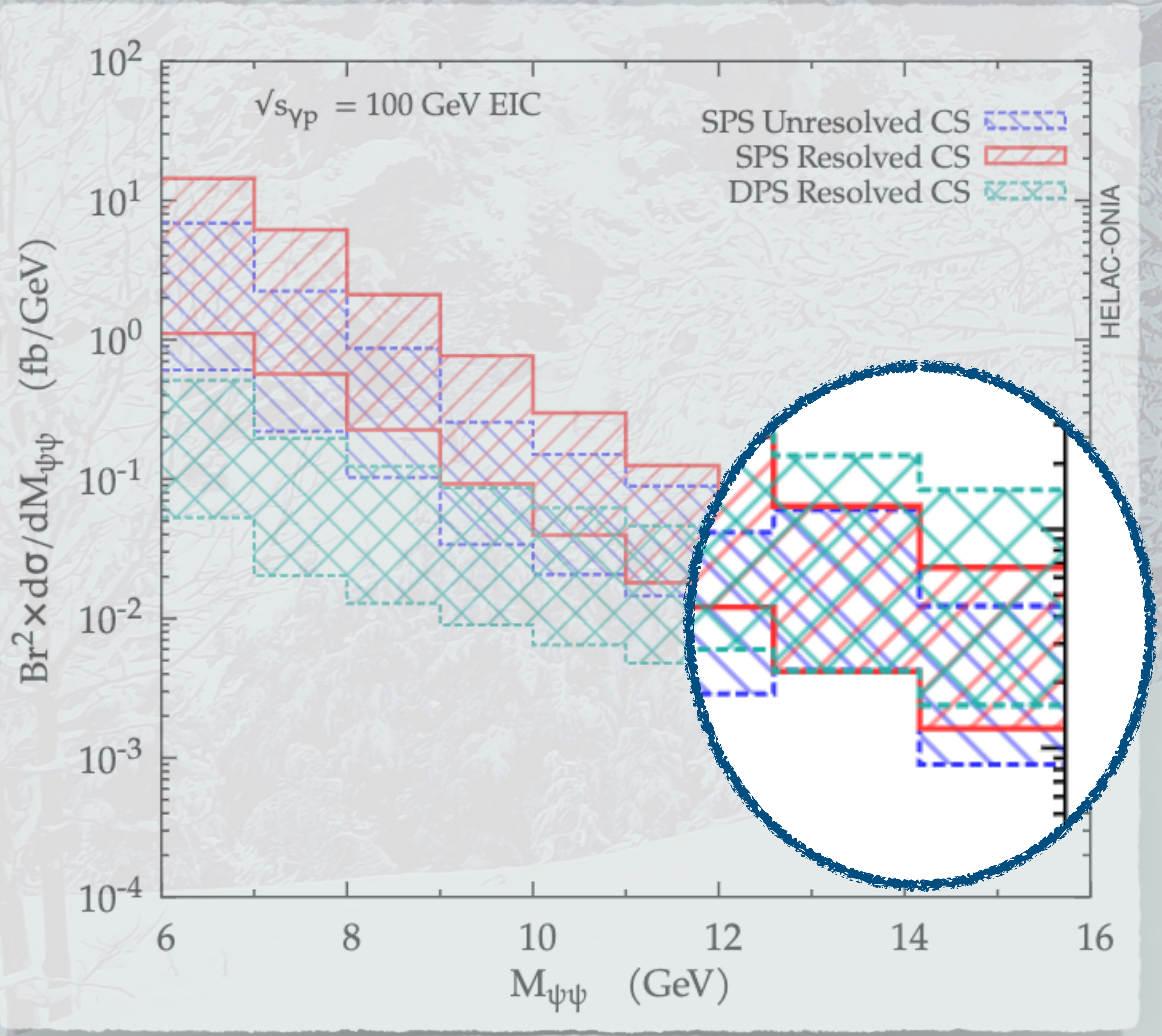
Numerical Results

PRELIMINARY

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

Invariant mass of the J/ψ pair

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



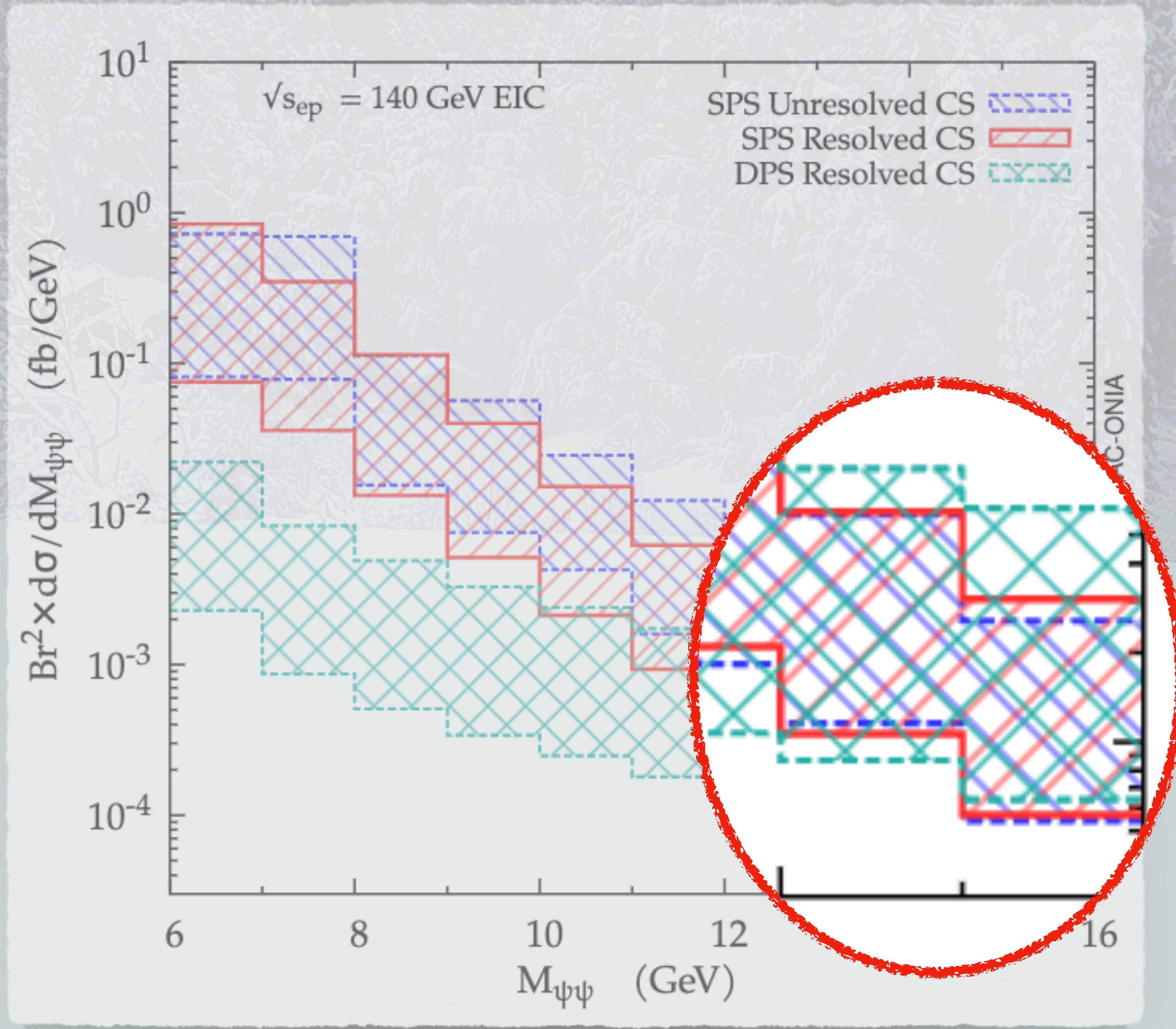
a) at low invariant mass:

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

b) at low invariant mass:

- DPS bigger then SPS
- DPS similar to SPS

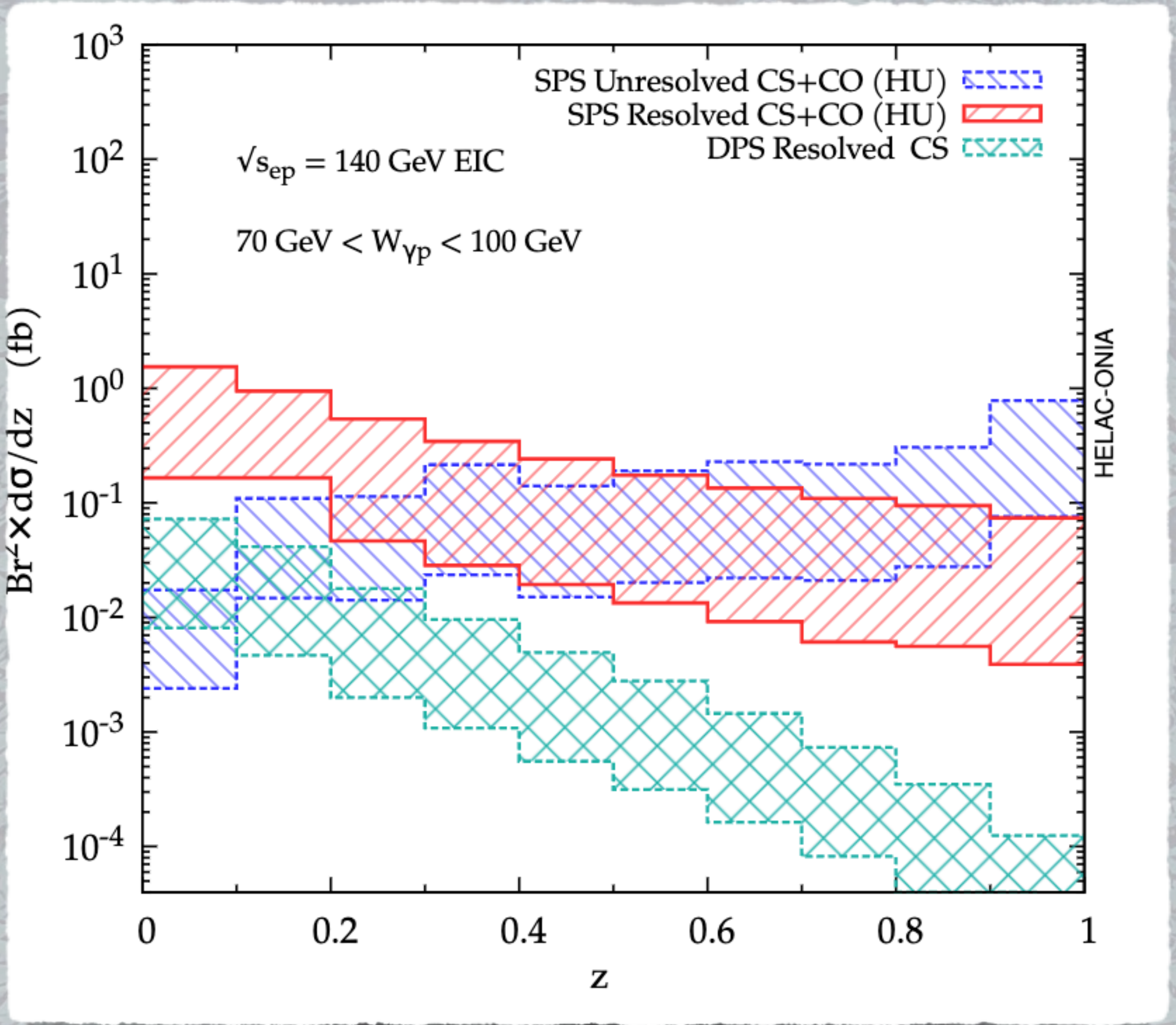
$\sqrt{s_{\gamma p}} = 140$ GeV

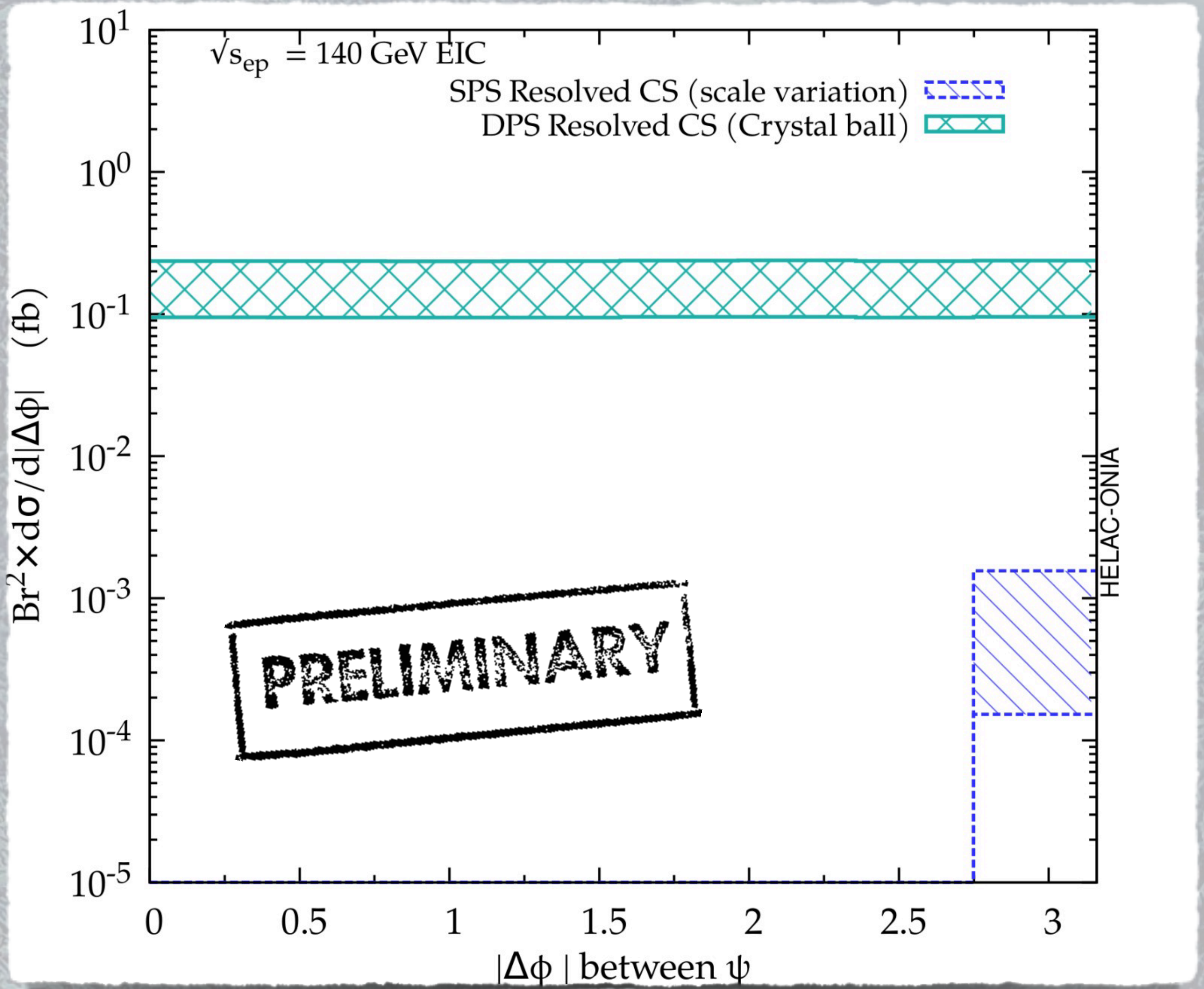


Numerical Results

PRELIMINARY

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



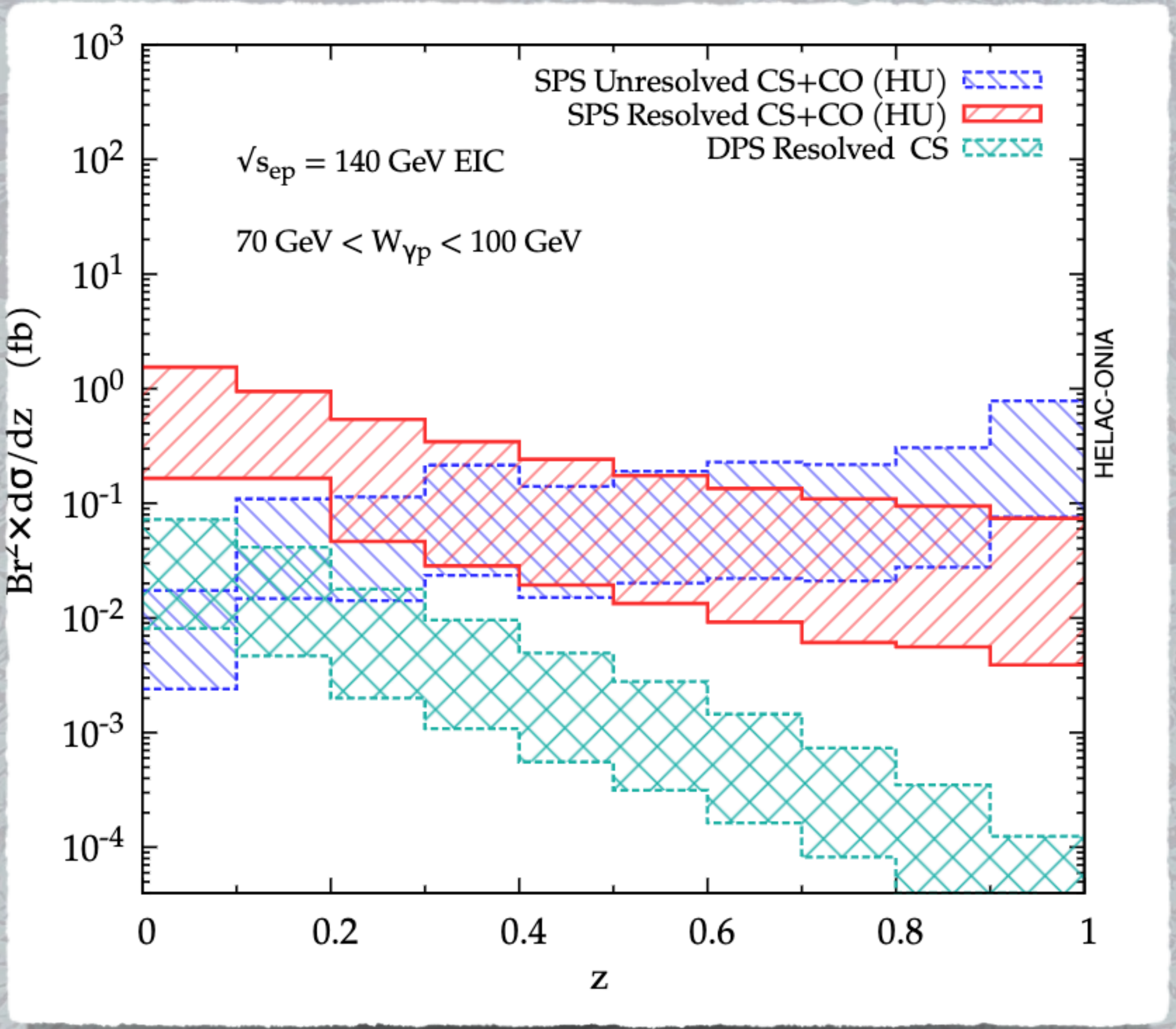


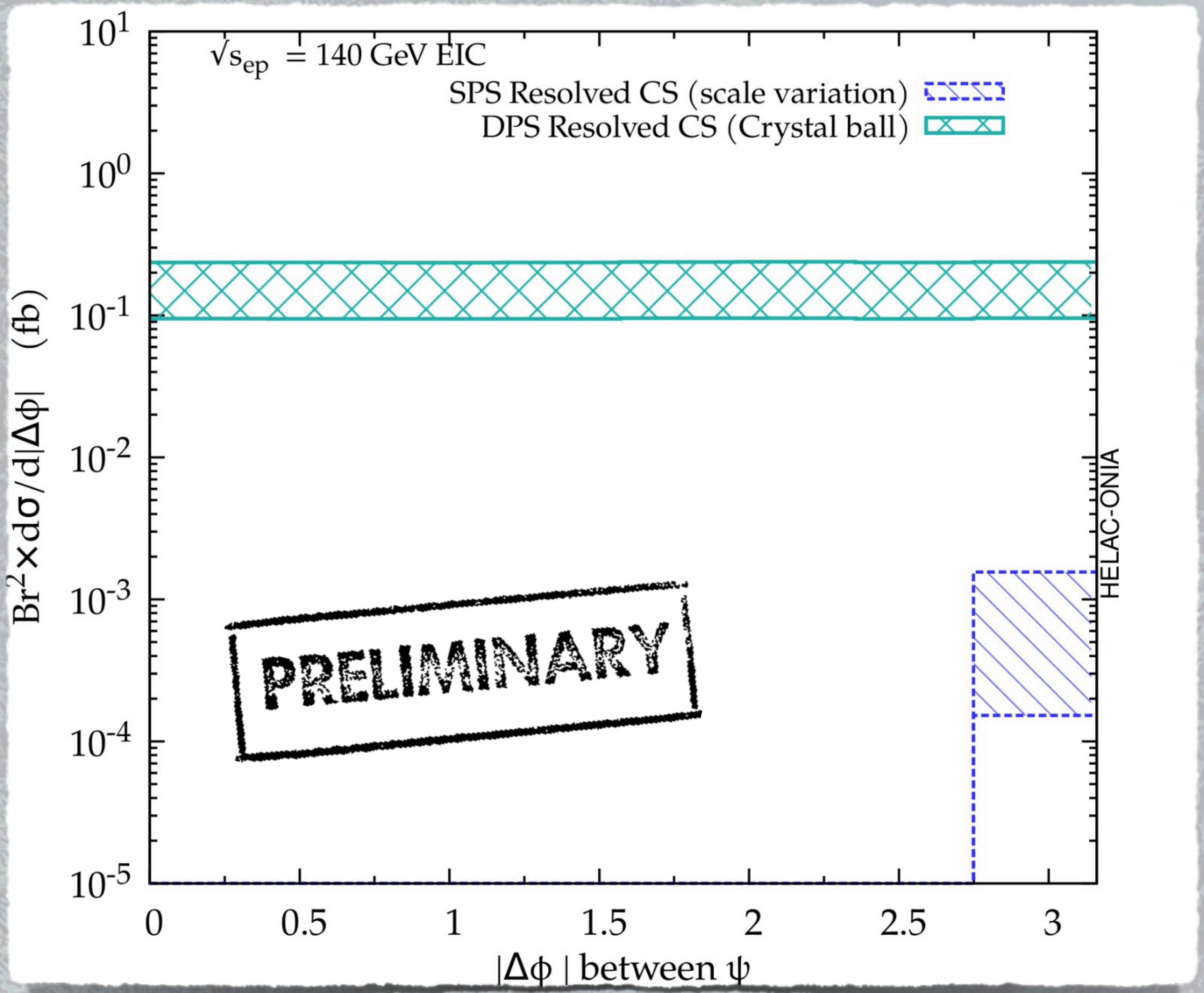
- for z<0.1, SPS resolved dominates → unique opportunity to investigate the PHOTON structure

Numerical Results

PRELIMINARY

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



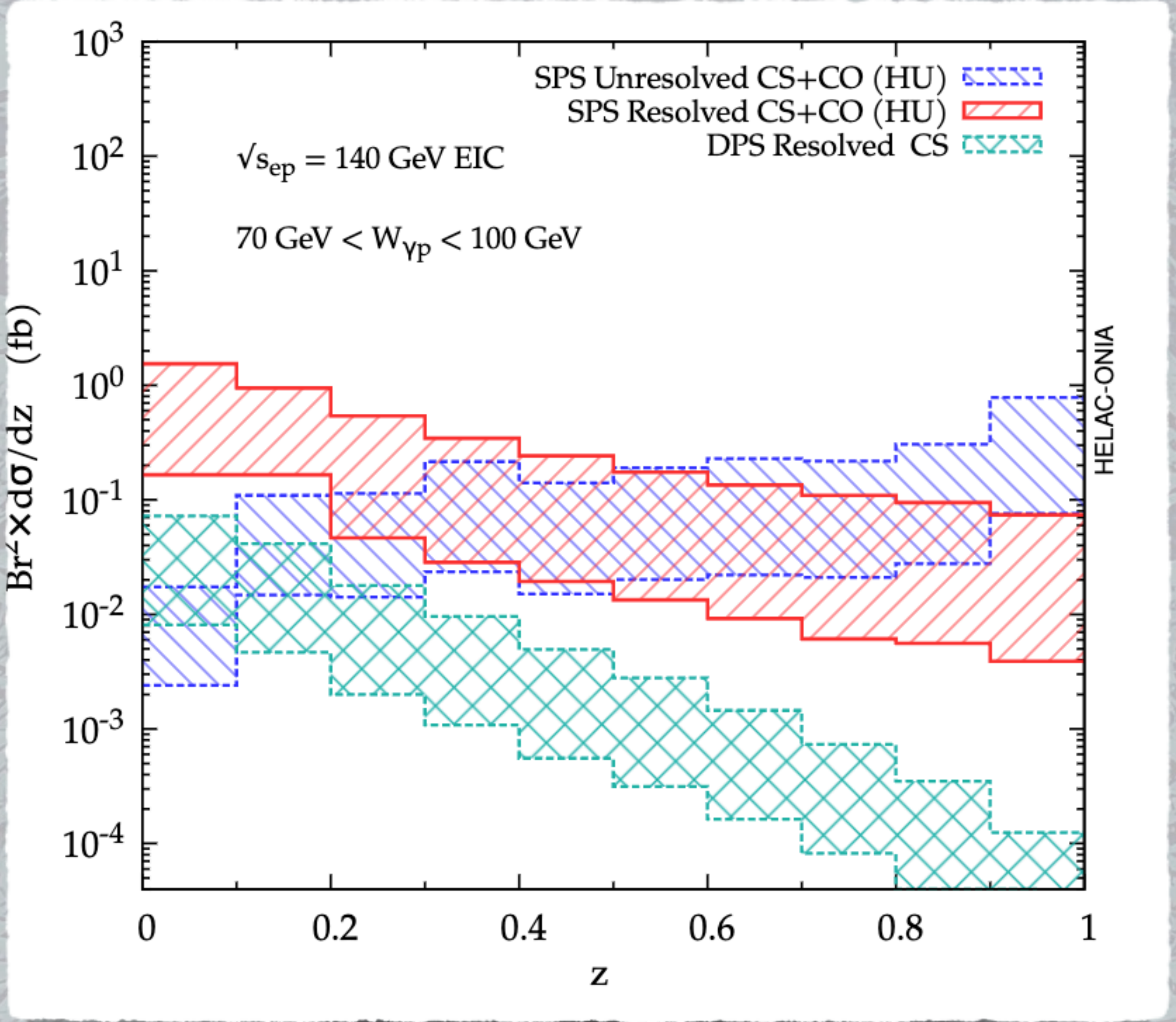


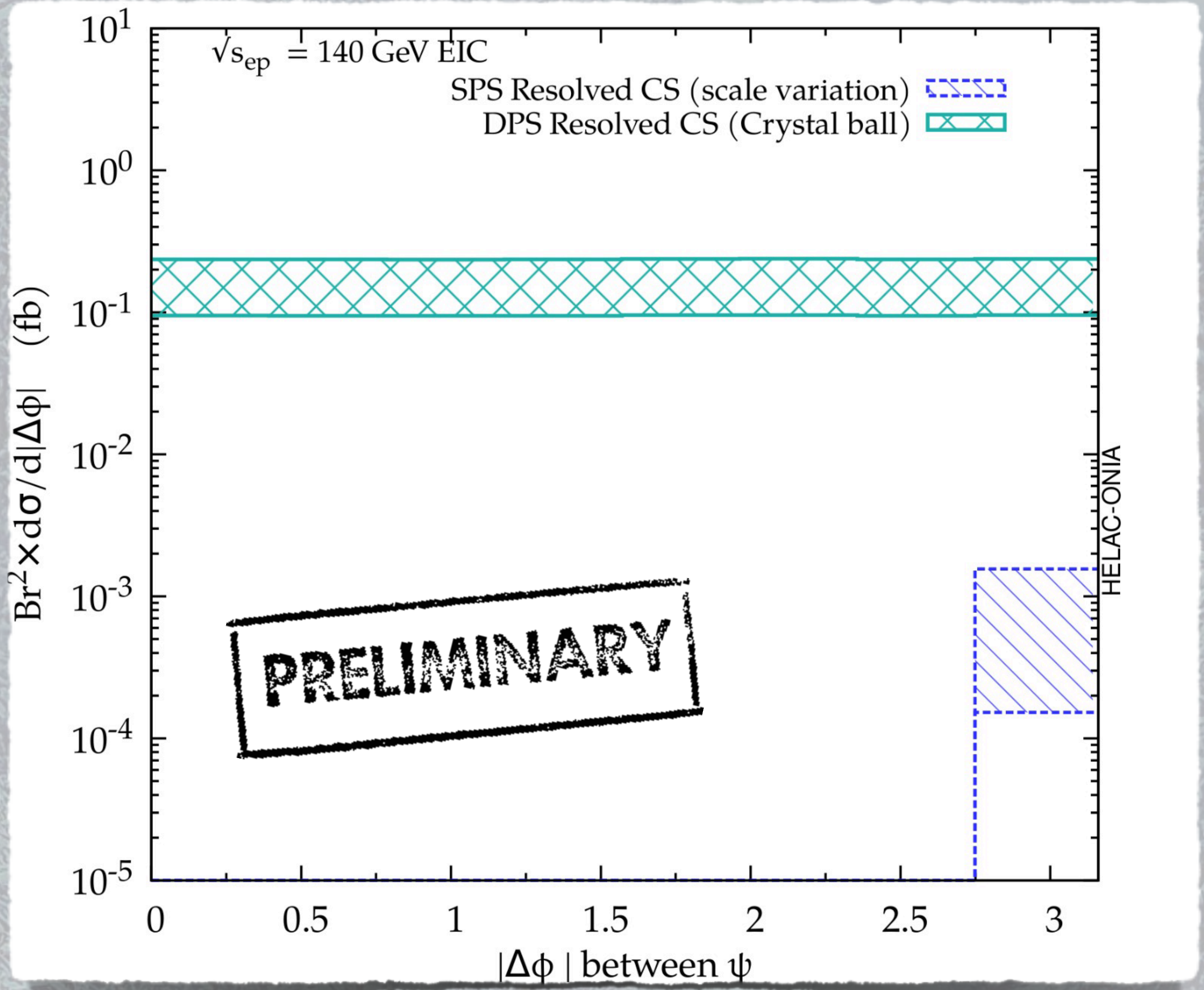
- for $z<0.1$, SPS resolved dominates → unique opportunity to investigate the PHOTON structure
- for high z, the direct SPS contribution dominates → we test the quarkonia production via direct photoproduction

Numerical Results

PRELIMINARY

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



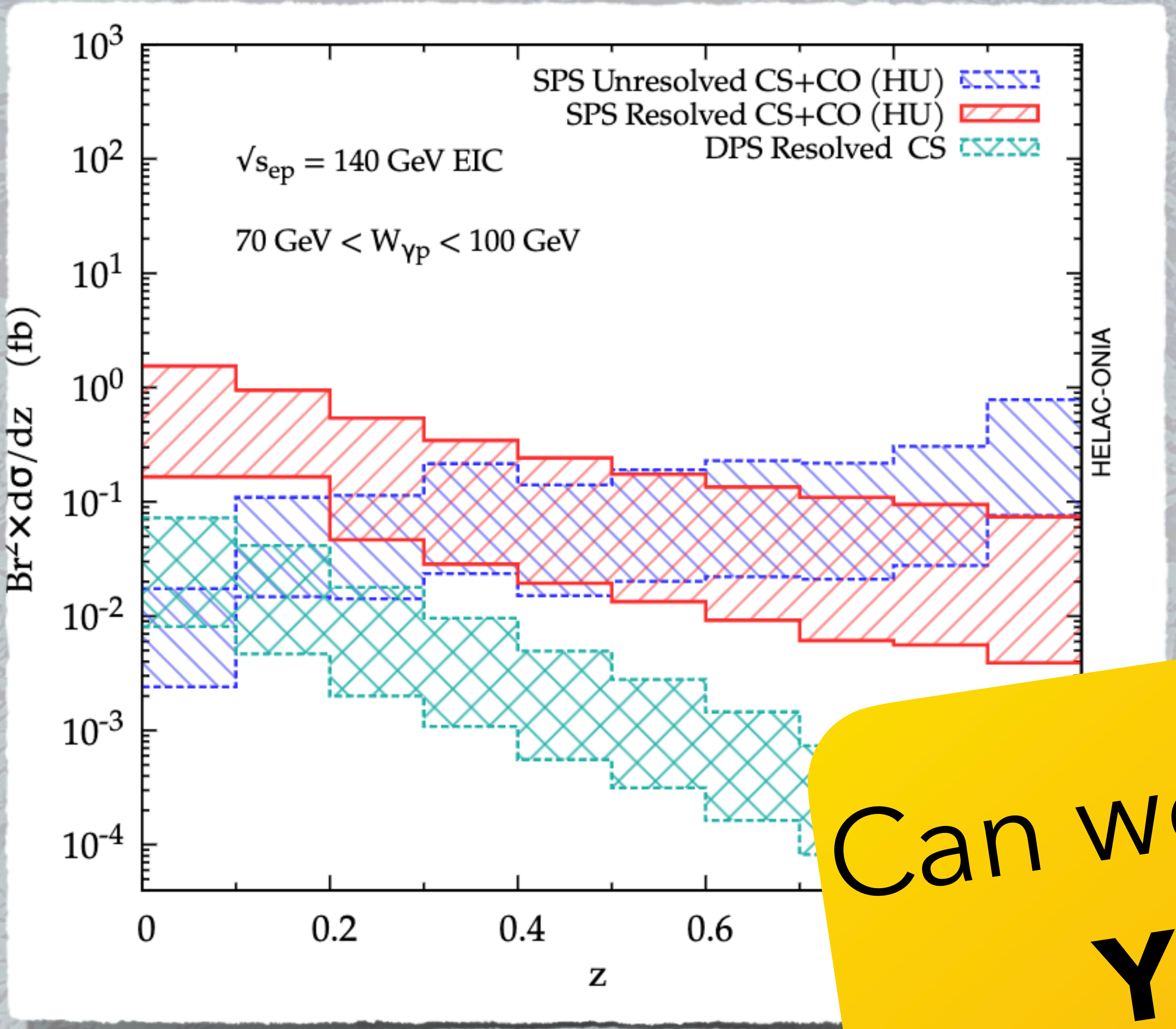


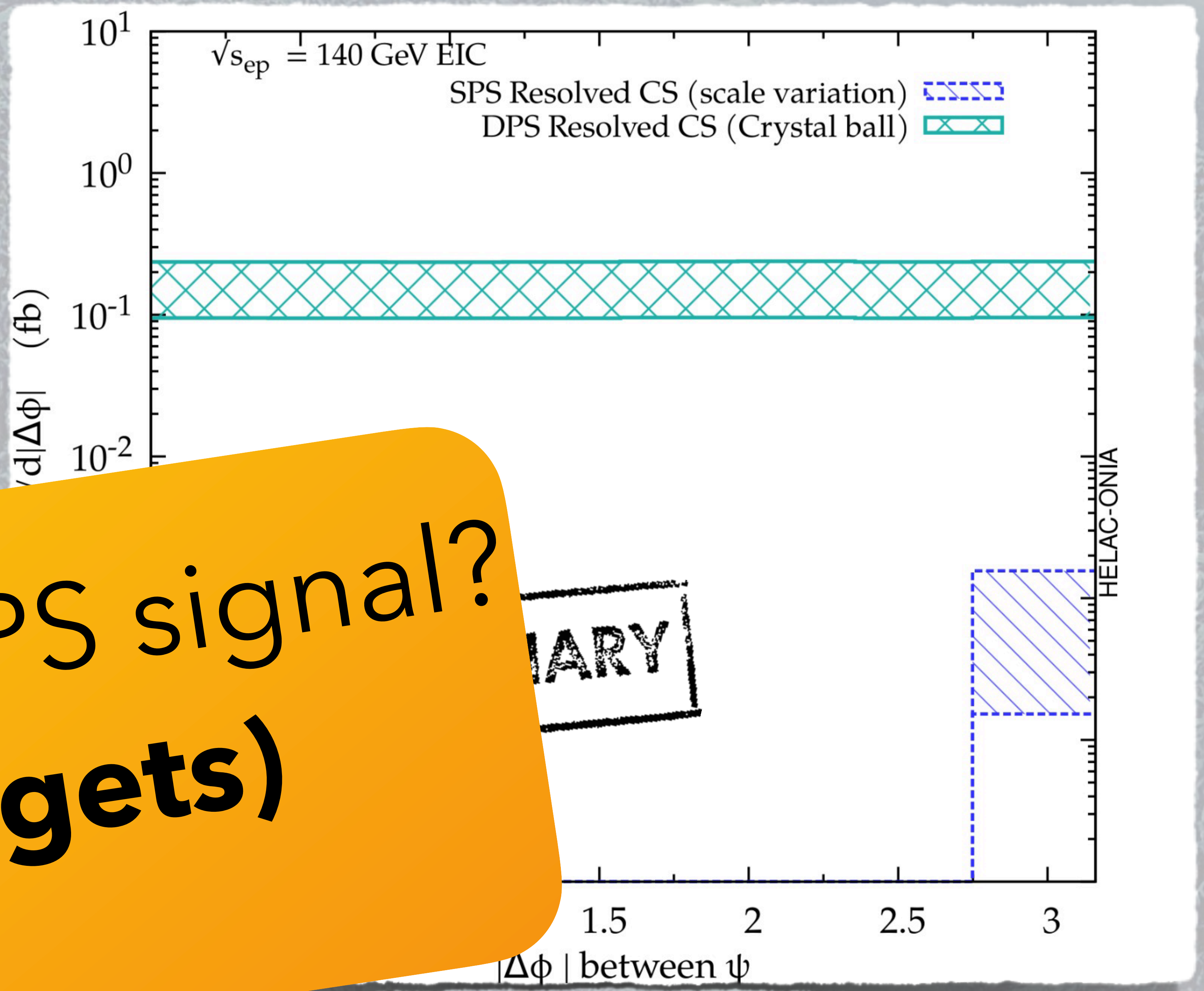
- for z<0.1, SPS resolved dominates → unique opportunity to investigate the PHOTON structure
- for high z, the direct SPS contribution dominates → we test the quarkonia production via direct photoproduction
- as for DPS studies @LHC, the cross-section dependence on the relative azimuthal angle is relevant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

Numerical Results

PRELIMINARY

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





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!

DPS in pA collisions

For DPS in pA and AA collisions the following references were missing:

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

and for TPS:

Triple-parton scatterings in proton–nucleus collisions at high energies
D. d'E. & A. Snigirev, EPJC 78 (2018) 5, 359

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:

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!

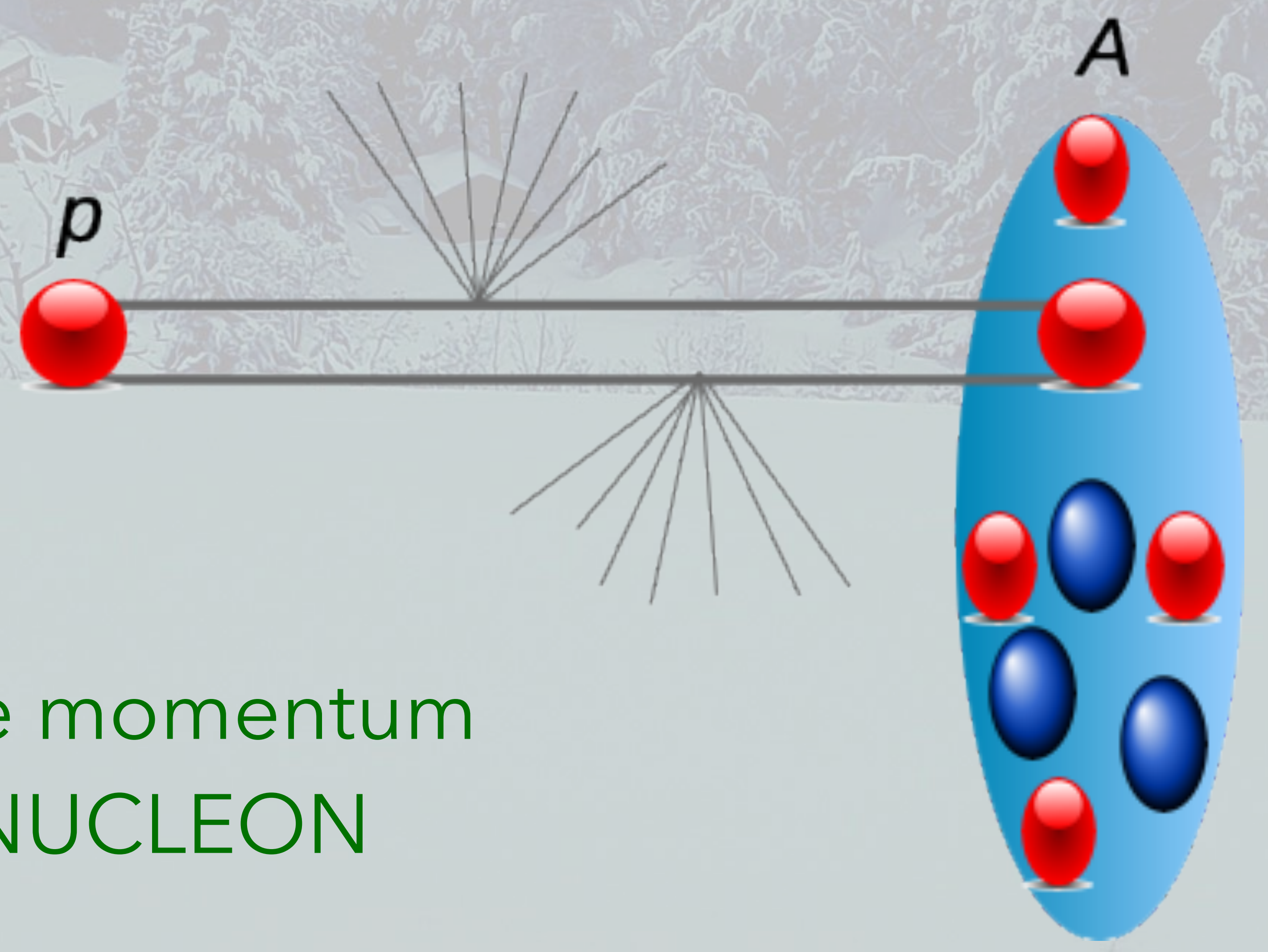
DPD of te nucleon inside the nucleus

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

Momentum fraction carried by a NUCLEON

Light-Cone Momentum Distribution

Transverse momentum of the NUCLEON



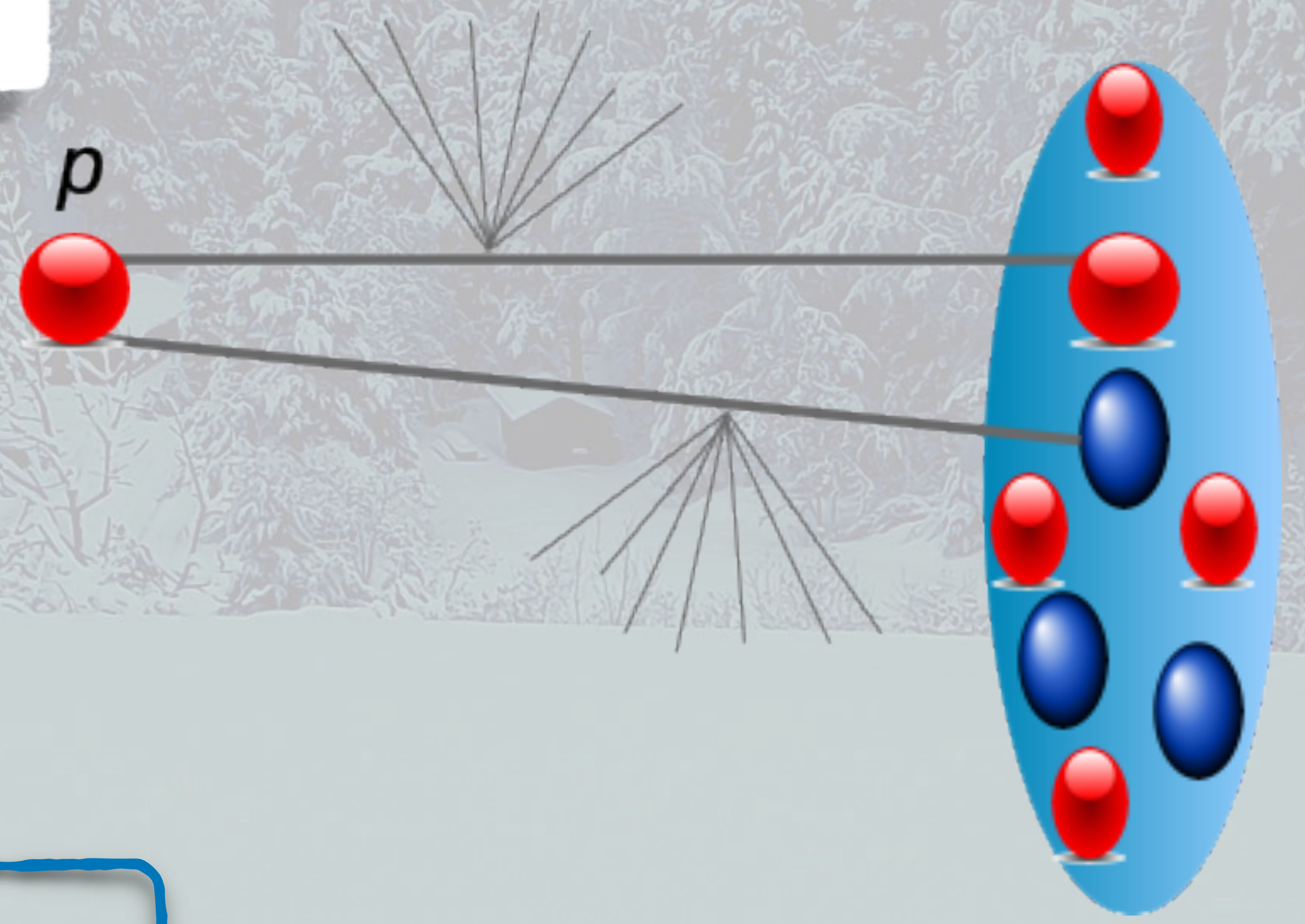
DPS in pA collisions

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

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!



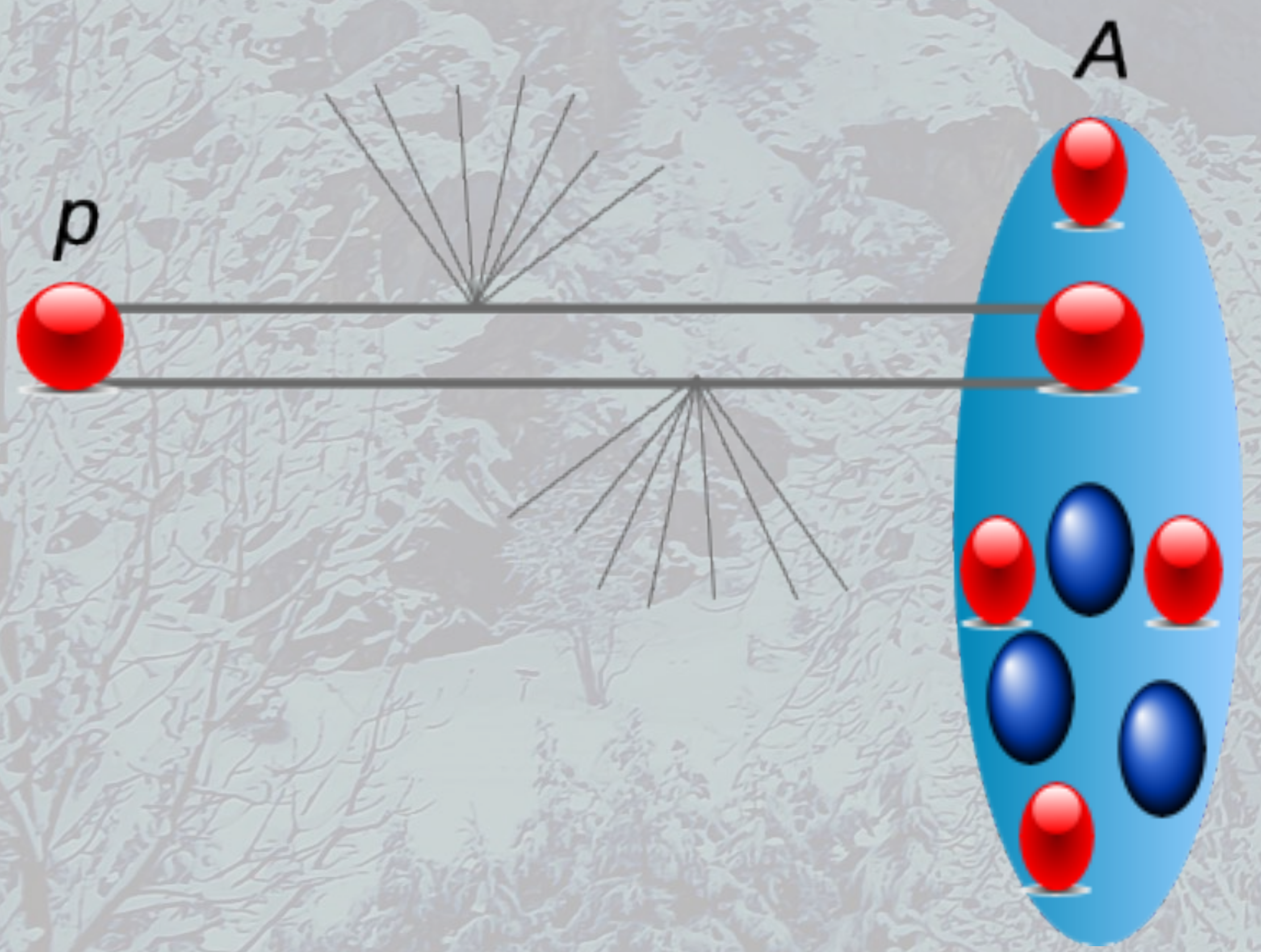
$$\tilde{F}^2_{a_1a_2}(x_1, x_2, \vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2 p_{ti}}{\xi_i} \delta\left(\sum_i \xi_i - A\right) \delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right) \psi_A^*(\xi_1, \xi_2, p_{t1}, p_{t2}, \ldots)$$

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

Nucleus wf

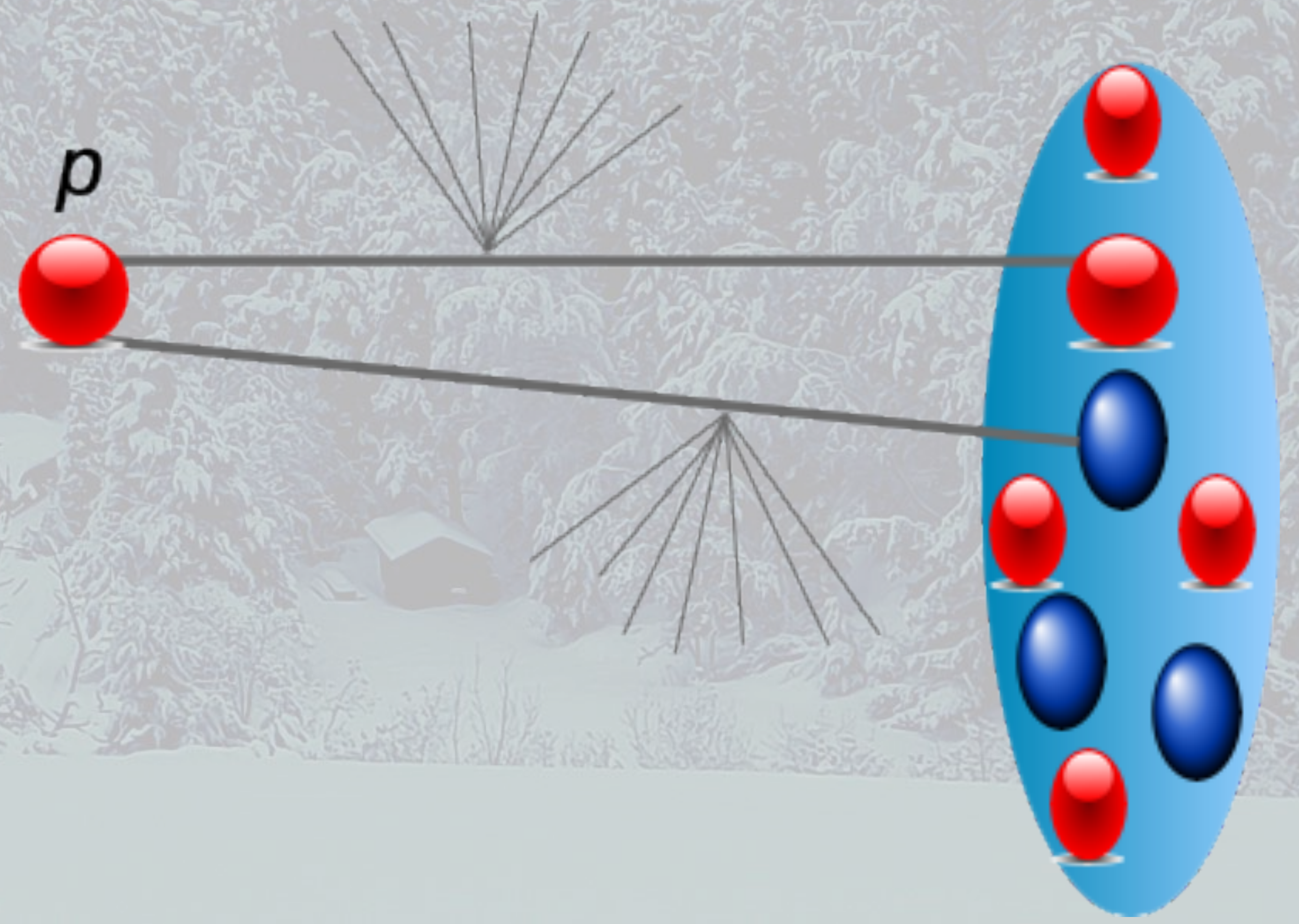
Nucleon GPD

DPS in pA collisions



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

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



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

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

DPS in γA collisions with light nuclei?

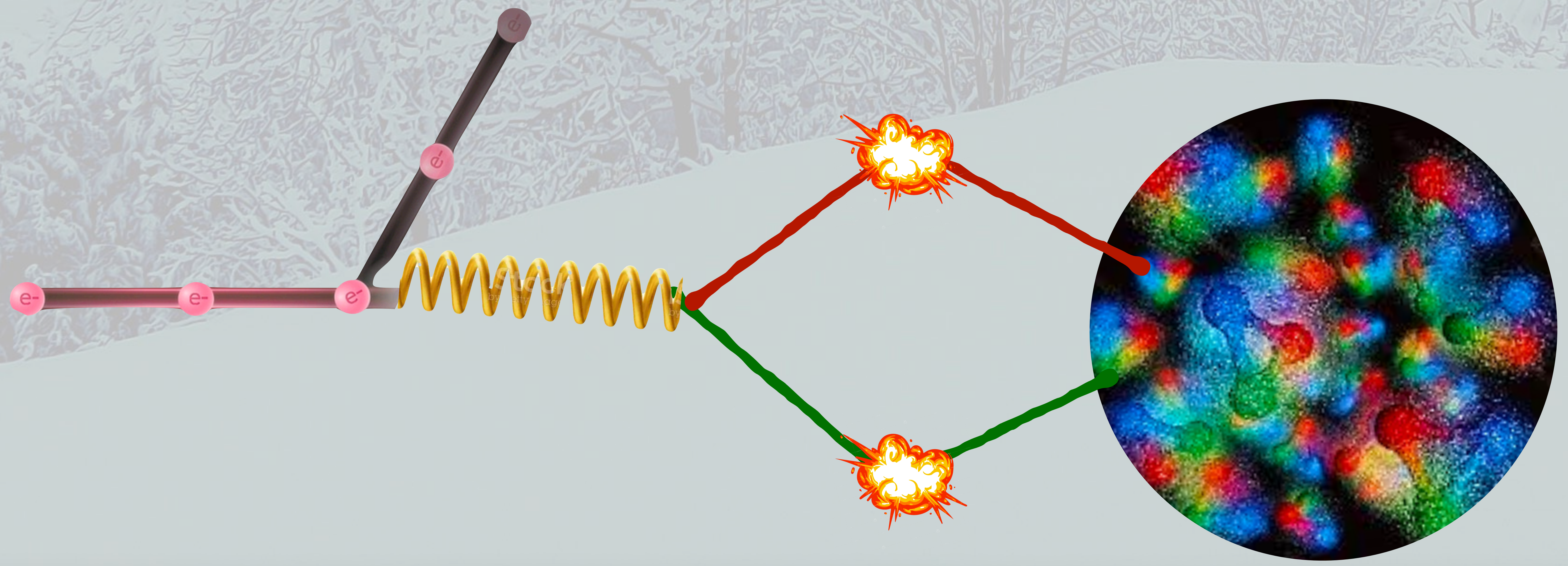
M.R. in progress

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

POSSIBLE SOLUTION?



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

POSSIBLE SOLUTION?

1) In γA the DPS2 will not contain any DPD of the proton → 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

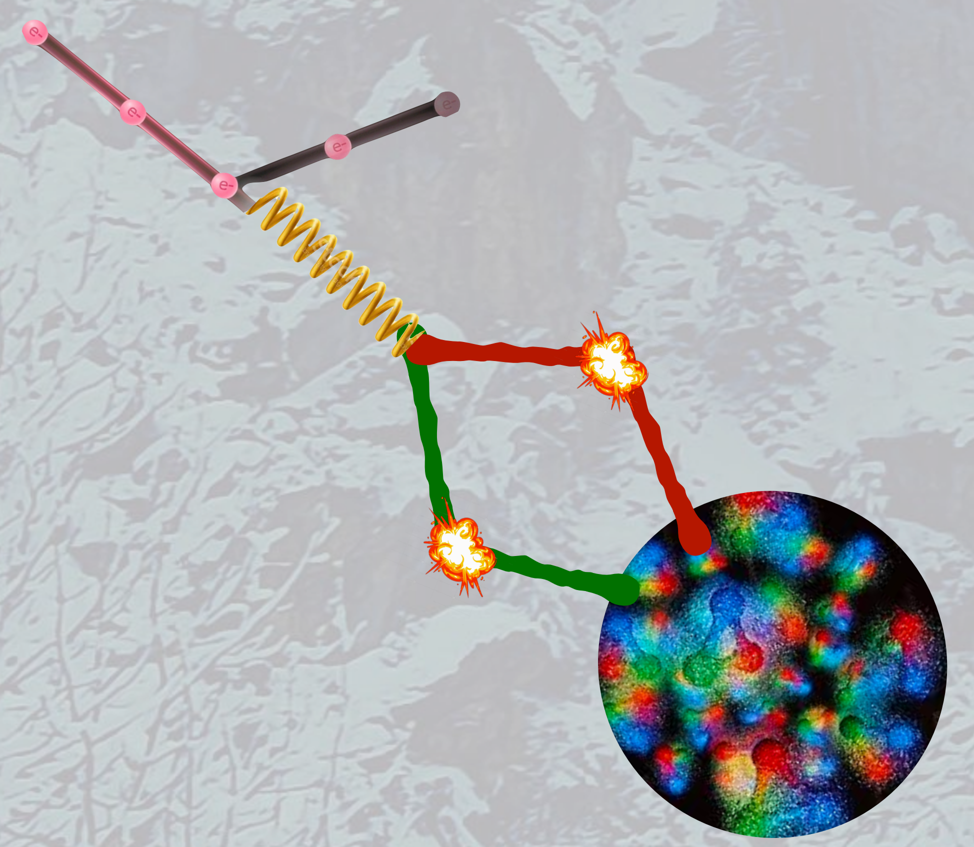
2) For light nuclei these calculations can be done starting from realistic wave-function (Av18 or chiral potential)!

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:



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

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

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

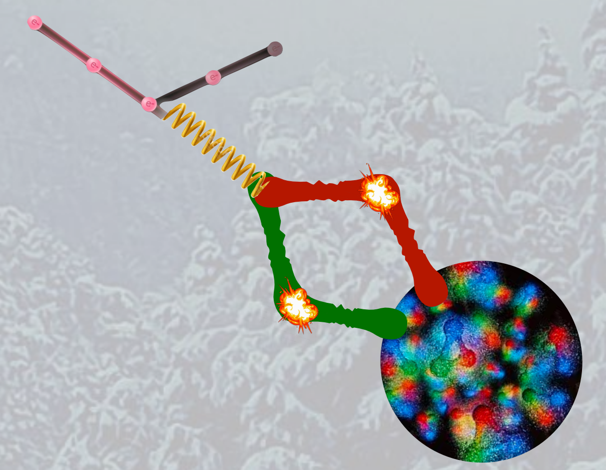
2) He^3 in e.g. **A. Del Dotto et al, PRC 95, 014001 (2017), M.R. et al, PLB 839 (2023), 137810**

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

For example in DPS1: $$\tilde{F}^{1}_{a_1a_2}(x_1,x_2,k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^{N}_{a_1a_2}\left(\frac{x_1}{\xi},\frac{x_2}{\xi},k_\perp\right) \rho_A^N(\xi,p_{t,N}) \frac{d\xi}{\xi} d^2p_{t,N}$$



Let us check sum rules:

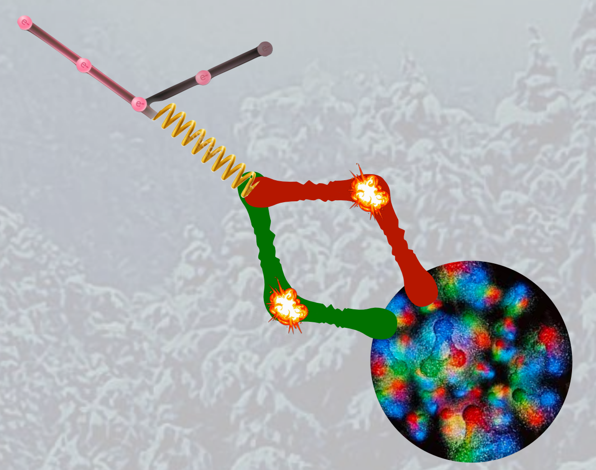
$$\int_0^1 dx_1 \int_0^{1-x_1} dx_2 F_{i_1i_2}(x_1,x_2,k_\perp=0) = \begin{cases} N_{i_1}N_{i_2} & \text{for } i_1 \neq i_2 \\ \left(N_{i_1}-1\right)N_{i_2} & \text{for } i_1 = i_2 \end{cases}$$

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



For example in DPS1: $$\tilde{F}^1_{a_1a_2}(x_1,x_2,k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi}\tilde{F}^N_{a_1a_2}\left(\frac{x_1}{\xi},\frac{x_2}{\xi},k_\perp\right) \rho^N_A(\xi,p_{t,N})\frac{d\xi}{\xi}d^2p_{t,N}$$

Let us check sum rules:

$$\int_0^1 dx_1 \int_0^{1-x_1} dx_2 F_{i_1i_2}(x_1,x_2,k_\perp=0) = \begin{cases} N_{i_1}N_{i_2} & \text{for } i_1 \neq i_2 \\ \left(N_{i_1}-1\right)N_{i_2} & \text{for } i_1 = i_2 \end{cases}$$

Gaunt's sum rules

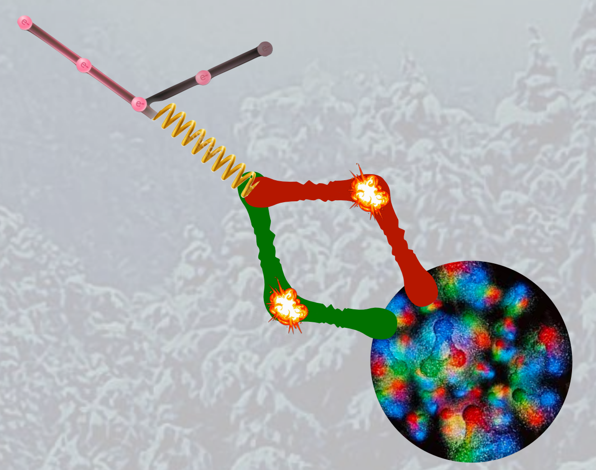
J. R. Gaunt and W. J. Stirling, JHEP 03, 005 (2010)

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

$$\int_0^1 dx_1 \int_0^{1-x_1} dx_2 F_{i_1i_2}(x_1,x_2,k_\perp=0) = \begin{cases} N_{i_1}N_{i_2} & \text{for } i_1 \neq i_2 \\ \left(N_{i_1}-1\right)N_{i_2} & \text{for } i_1 = i_2 \end{cases}$$

Gaunt's sum rules

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

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

$$\int_0^A dx_1 \int_0^{A-x_1} dx_2 \tilde{F}^{A,1}_{i_1i_2}(x_1,x_2,0) \sim \sum_{n=N,P} \int d\xi f^A_n(\xi) \begin{cases} \left(N^n_{i_1}-1\right)N^n_{i_2} & i_1 = i_2 \\ N^n_{i_1}N^n_{i_2} & i_1 \neq i_2 \end{cases}$$

Normalized to 1

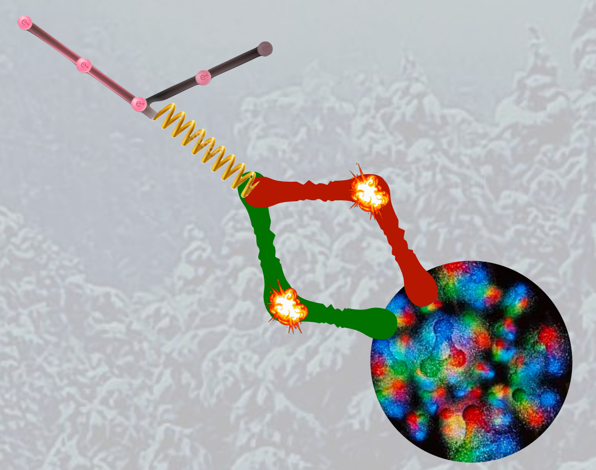
Gaunt's sum rules for the nucleon DPD: numbers of quarks with given flavor i in the nucleon n

DPS in γA collisions with light nuclei?

M.R. in progress

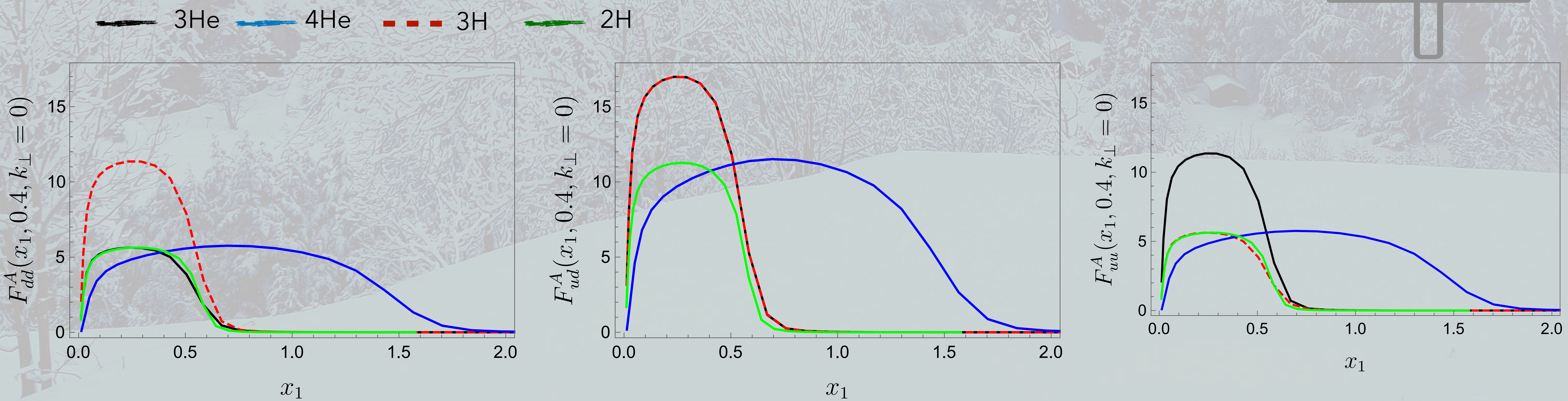
For example in DPS1:

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



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

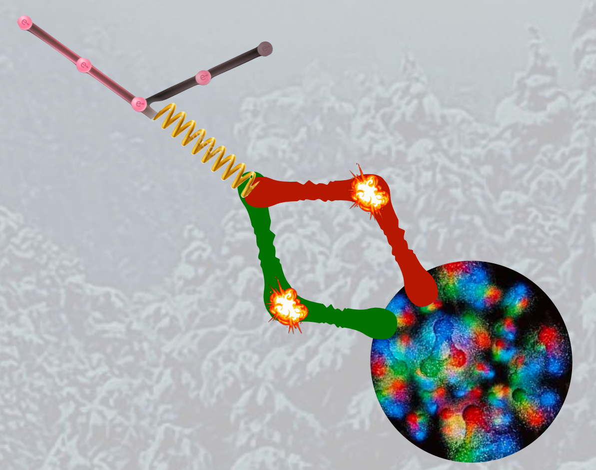
$0 < x_i < A$



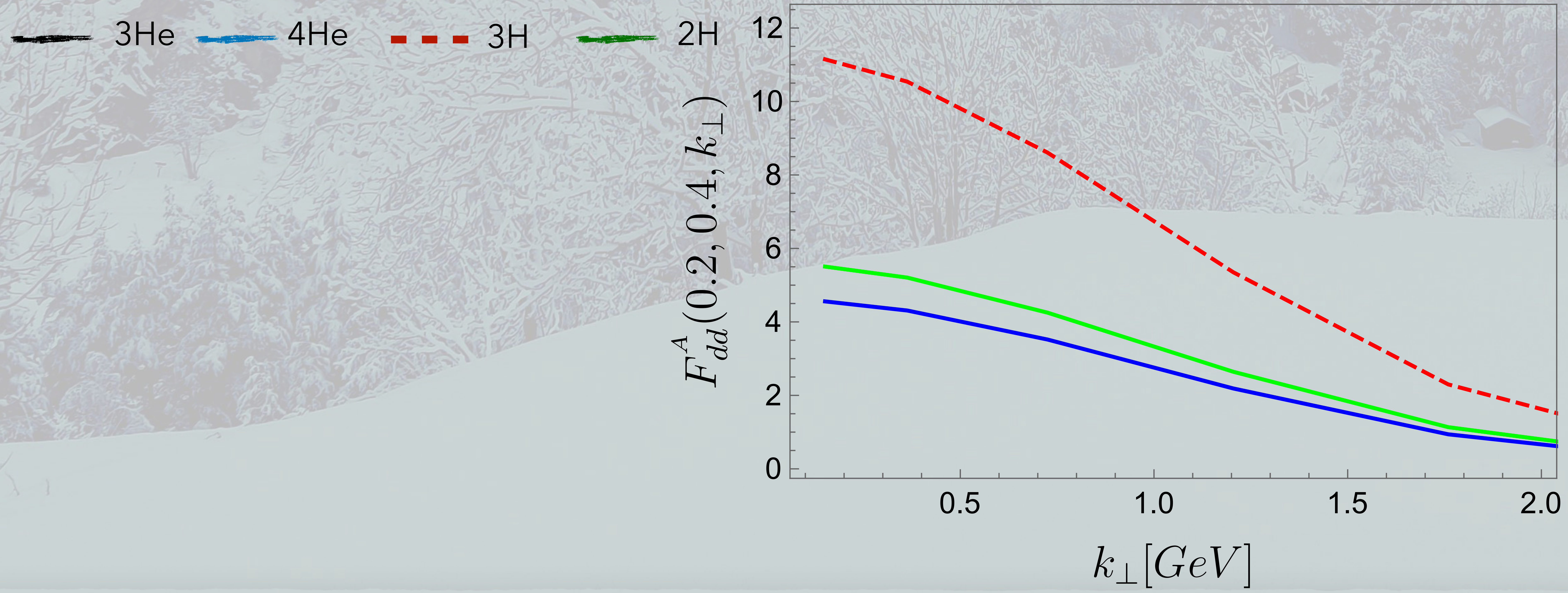
DPS in γA collisions with light nuclei?

M.R. in progress

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



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



DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS2:

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

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

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

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

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

DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS2:

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

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

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

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

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

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:

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

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

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

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

WE HAVE A LINK BETWEEN 2 DIFFERENT PROCESSES!

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

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

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

DPS in γA collisions with light nuclei?

M.R. in progress

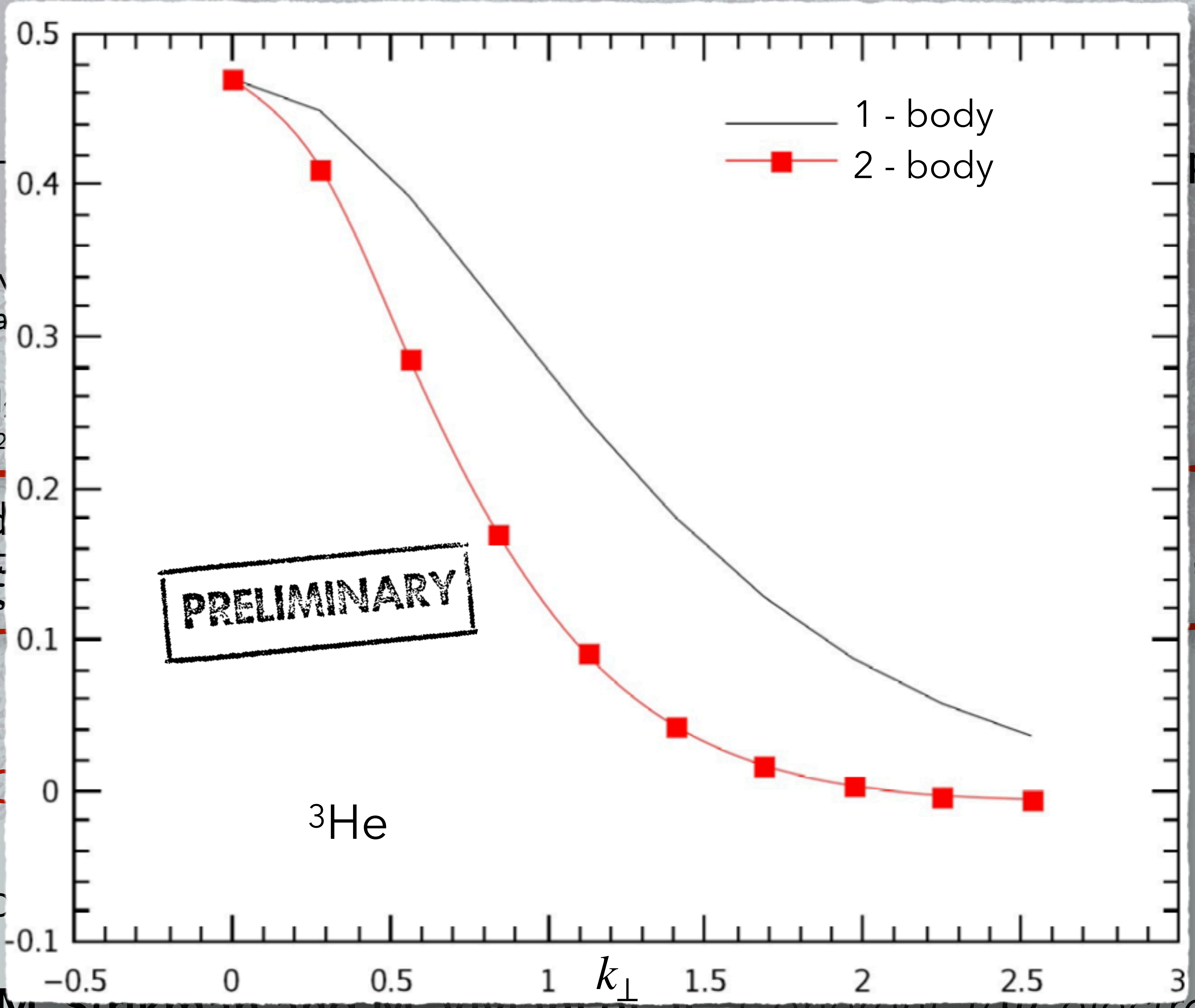
For example in DPS2:

$$\tilde{F}^2_{a_1 a_2}(x_1, x_2, \vec{k}_\perp) \propto \int \frac{1}{\xi_1 \xi_2} \prod_{i=1}^{i=A} \frac{d\xi_i d^2}{\xi_i} \quad \ldots \quad p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp \Big)$$

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

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

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



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

DPS in γA collisions with light nuclei?

M.R. in progress

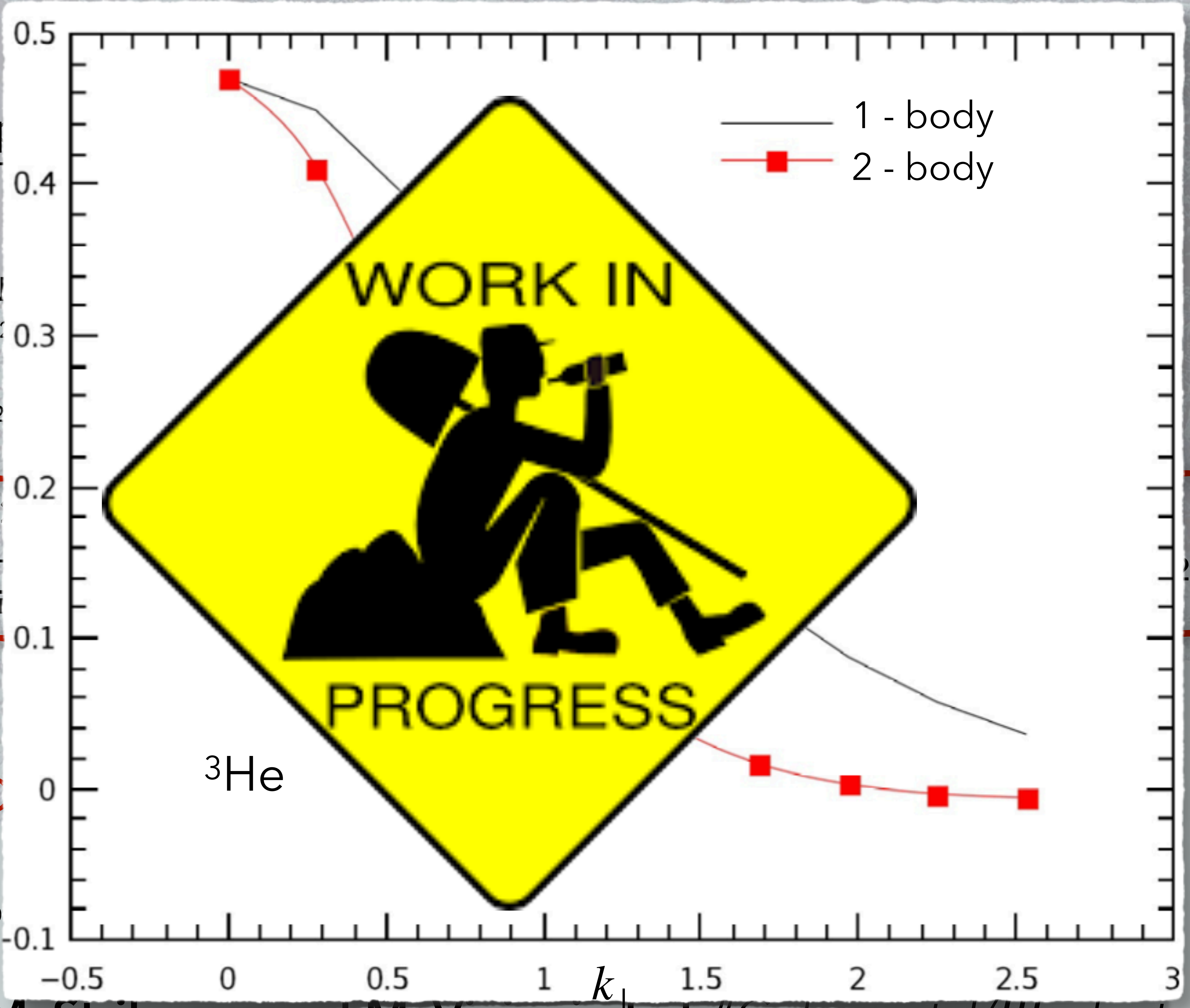
For example in DPS2:

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

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

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

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



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

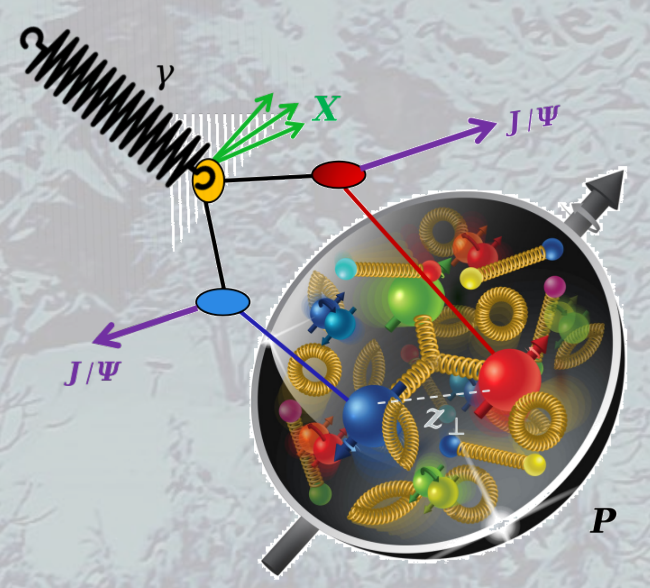
CONCLUSIONS

1) We demonstrated DPS represents a new way to access new information of hadrons

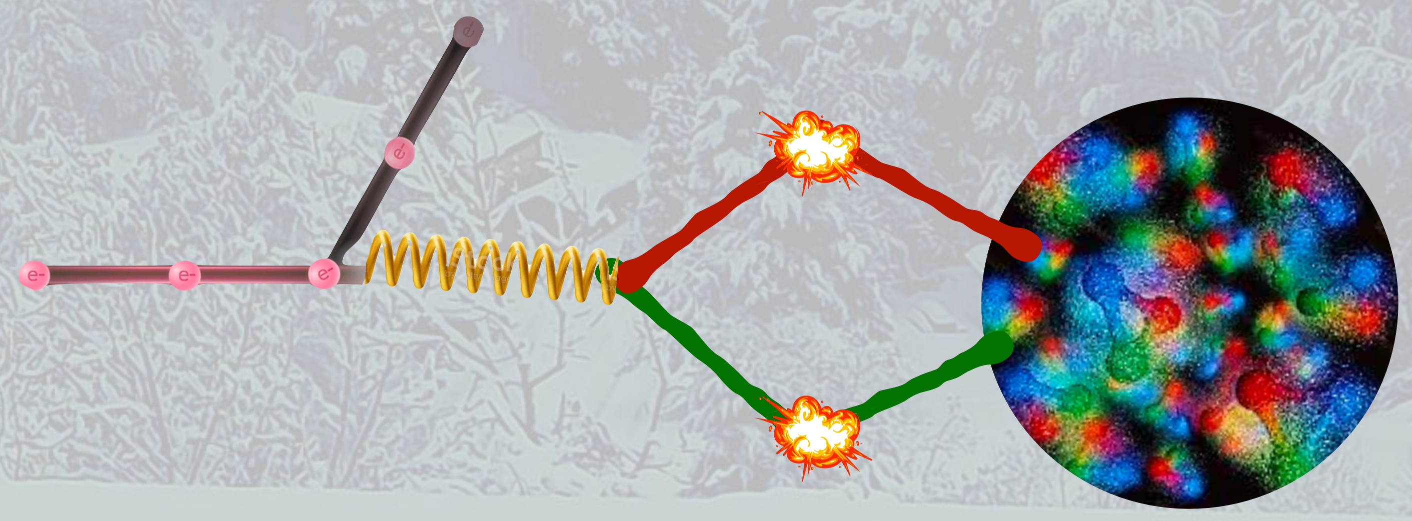
2) Several experimental analyses and theoretical developments are on going

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

a) DPS@EIC

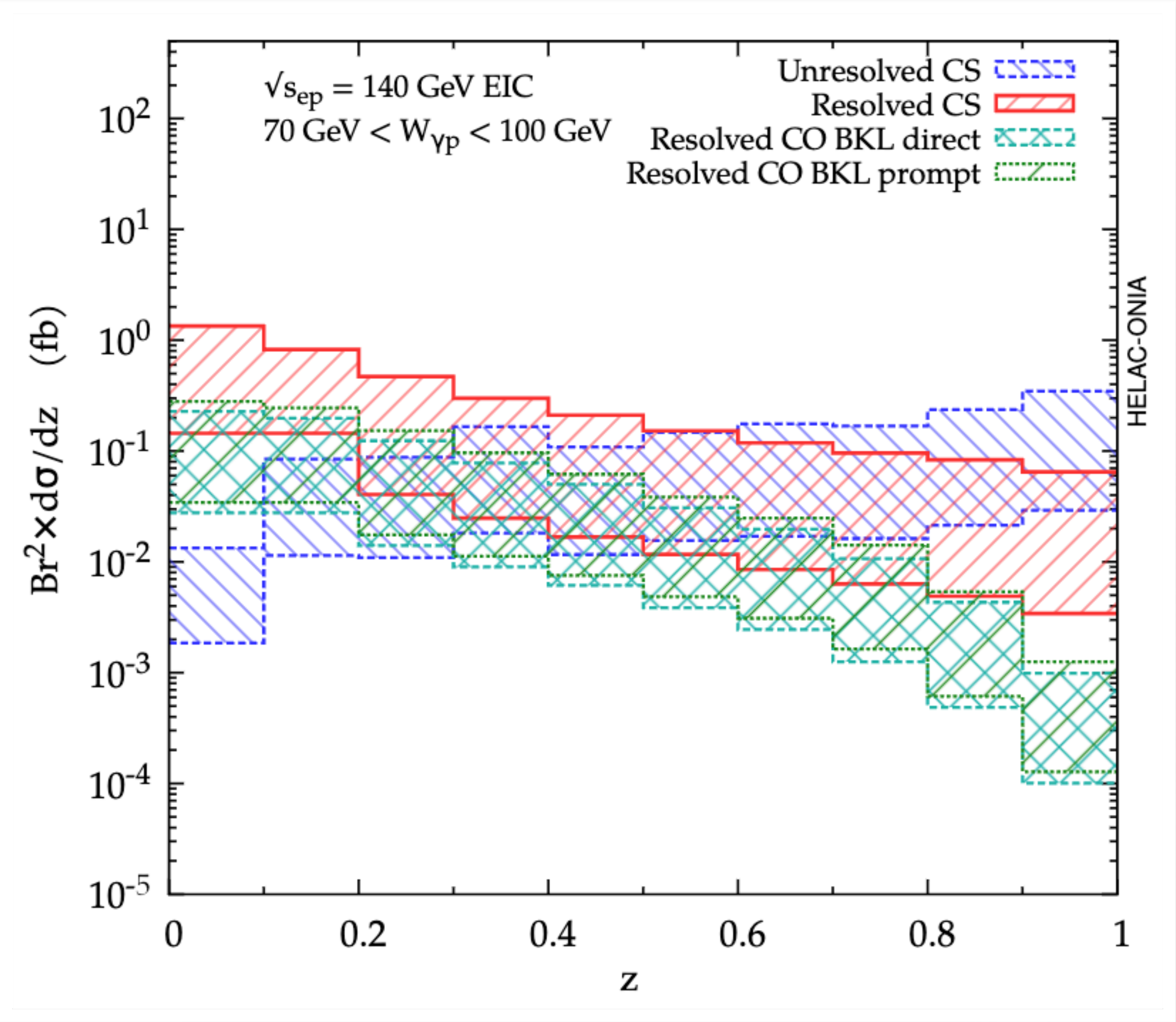


b) Nuclear DPS@EIC

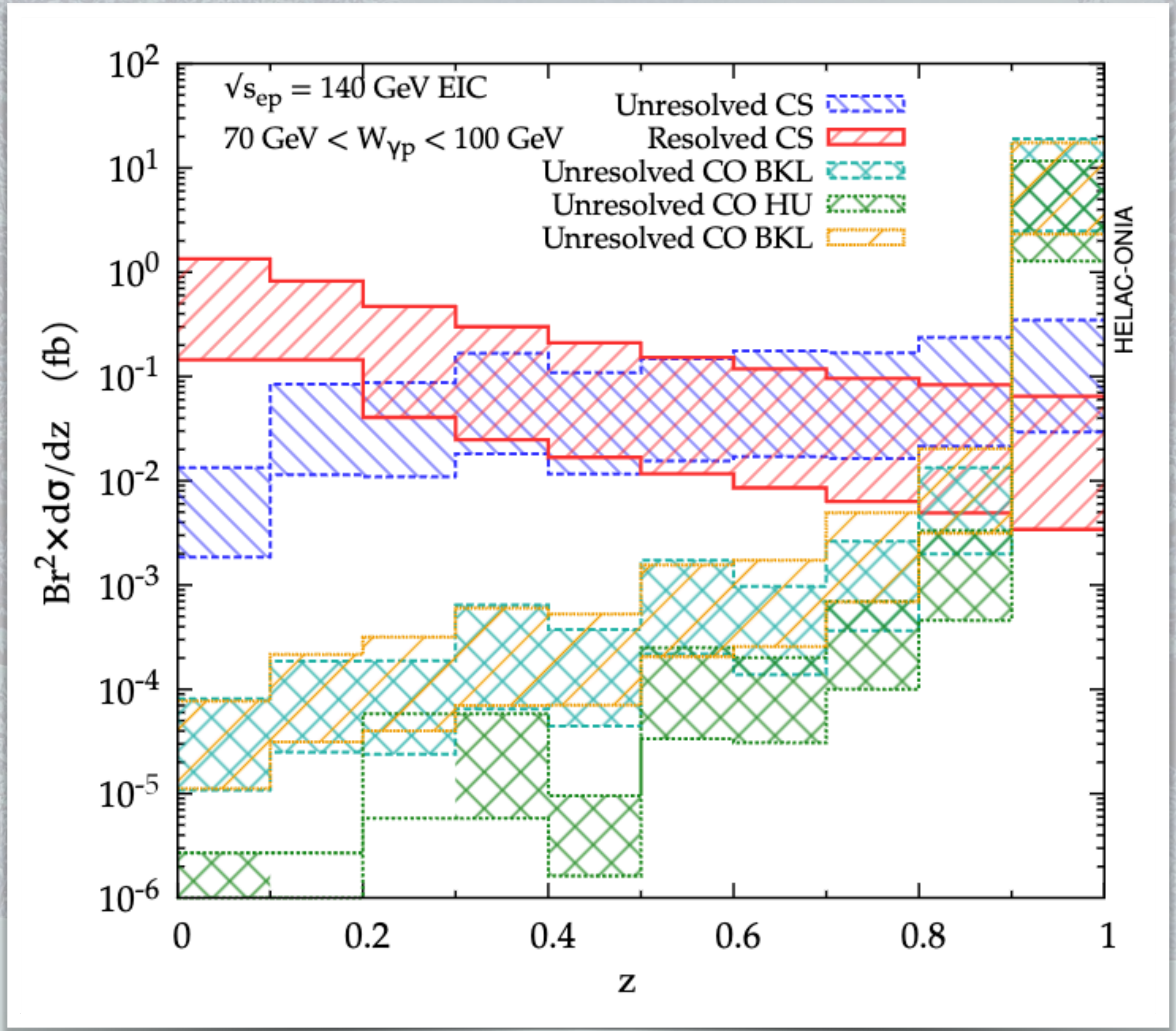


a) DPS contributes, in particular in the 4-jets photoproduction
b) We have estimated SPS and DPS cross sections for quarkonium-pair photoproduction at the EIC using the NRQC framework
c) The dependence of $\sigma_{\rm eff}^{\gamma p}(Q^2)$ on Q^2 can unveil the mean distance of partons in the proton
d) Quarkonium-pair photoproduction is a promising channel to probe the gluonic content of the photon structure

CONCLUSIONS



$$\mu_0 = \frac{H_T}{2} = \frac{\sum_i \sqrt{p_{Ti}^2 + m_i^2}}{2}$$



CO negligible if we cut z<0.9 (to be checked)

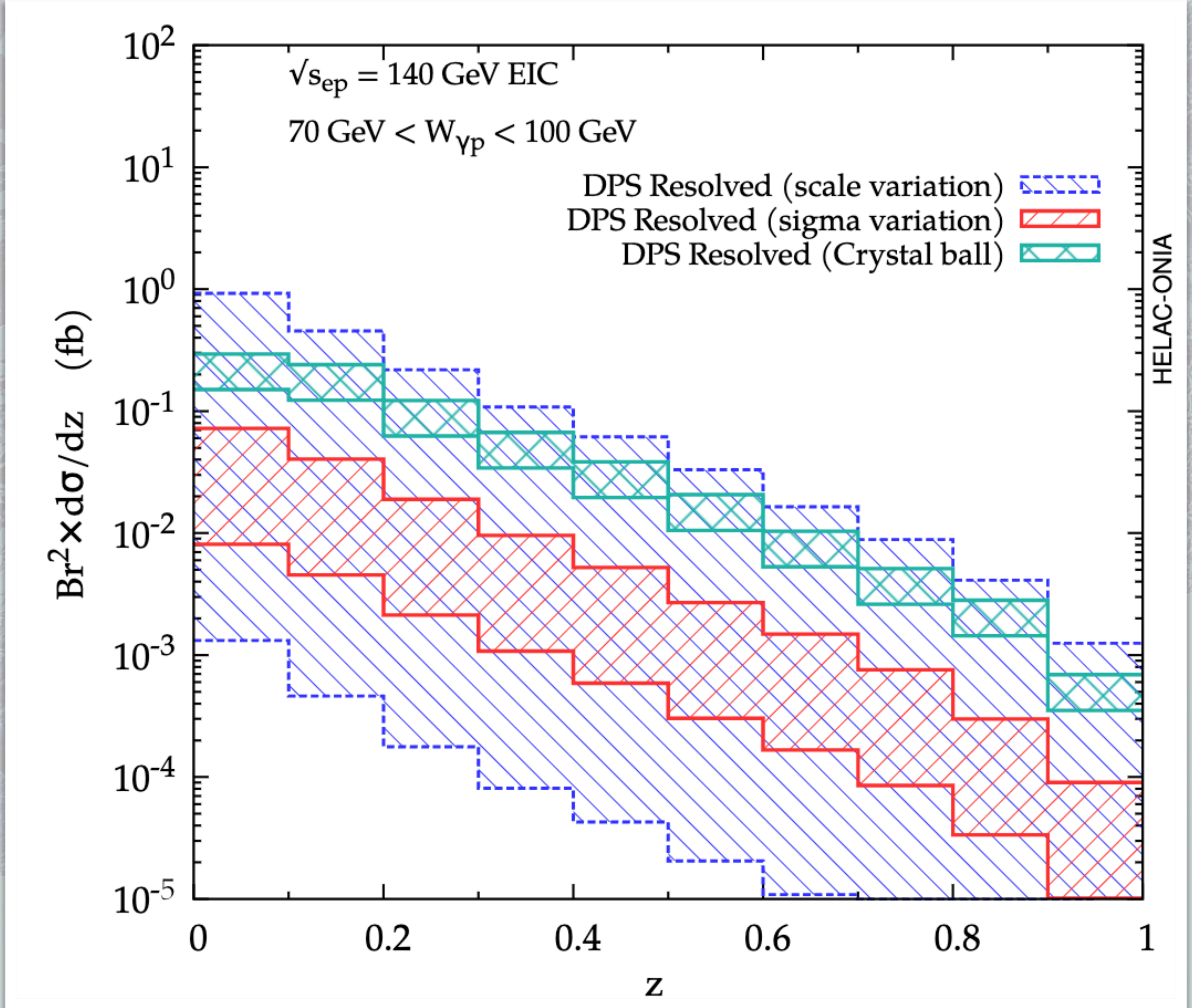
Numerical Results

PRELIMINARY

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

We also considered to use the Crystal Ball parametrization of the square of the amplitude $gg \longrightarrow \mathcal{Q} + X$

$$\begin{cases} \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \exp(-\kappa \frac{P_T^2}{M_{\mathcal{Q}}^2}) & \text{when } P_T \leq \langle P_T \rangle \\ \frac{\lambda^2 \kappa \hat{s}}{M_{\mathcal{Q}}^2} \exp(-\kappa \frac{\langle P_T \rangle^2}{M_{\mathcal{Q}}^2}) \left(1 + \frac{\kappa}{n} \frac{P_T^2 - \langle P_T \rangle^2}{M_{\mathcal{Q}}^2}\right)^{-n} & \text{when } P_T > \langle P_T \rangle \end{cases}$$



Backup - Luminosity I

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:

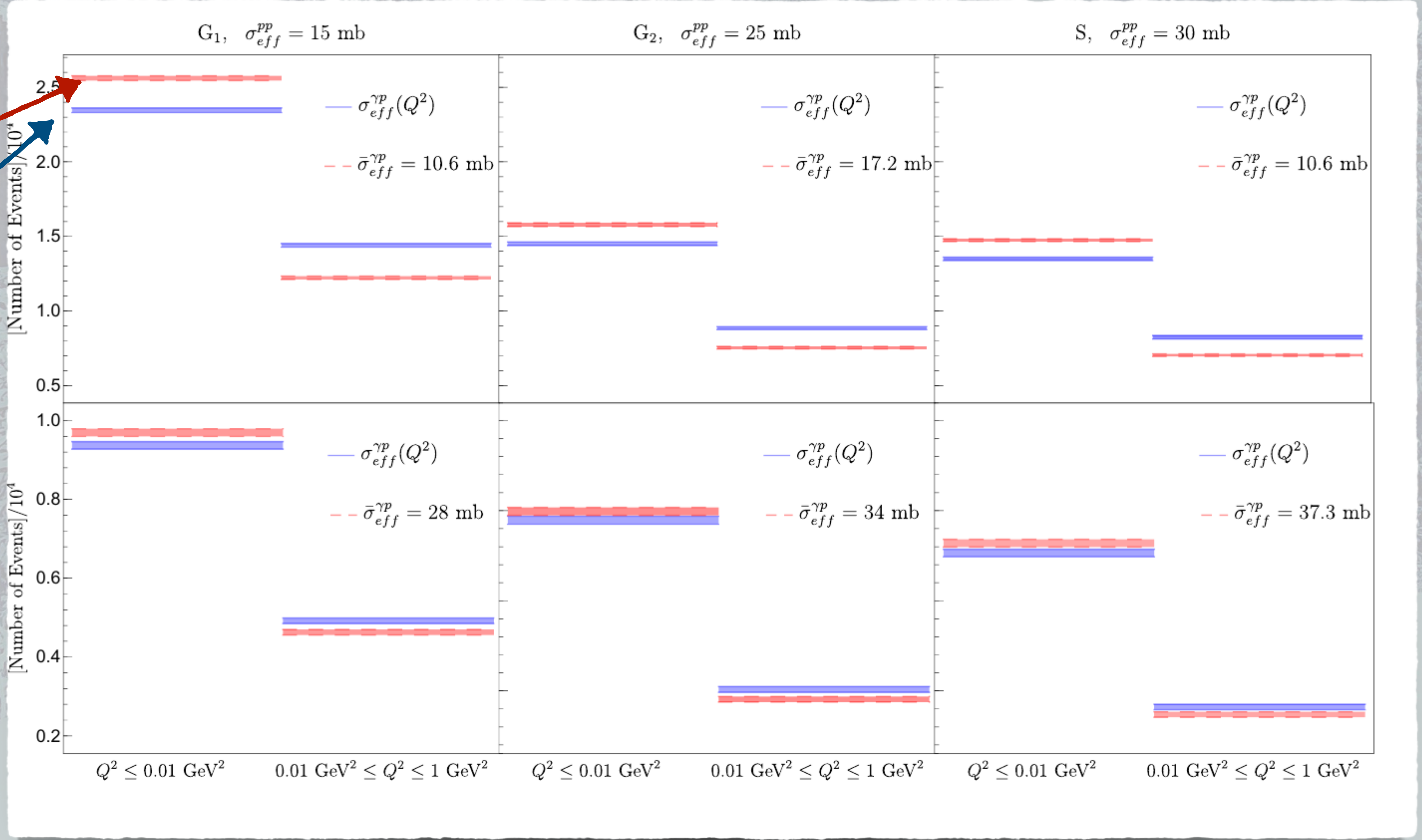
$$Q^2 \leqslant 10^{-2} \quad \text{and} \quad 10^{-2} \leqslant Q^2 \leqslant 1 \quad \mathrm{GeV}^2$$

2) We have estimated for each photon and proton models a constant effective cross section (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 $\sigma_{\rm eff}^{\gamma p}(Q^2)$

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

Backup - Luminosity II

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



Backup - $\sigma_{\text{eff}}^{\gamma p}(Q^2 \to \infty)$

1) 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:

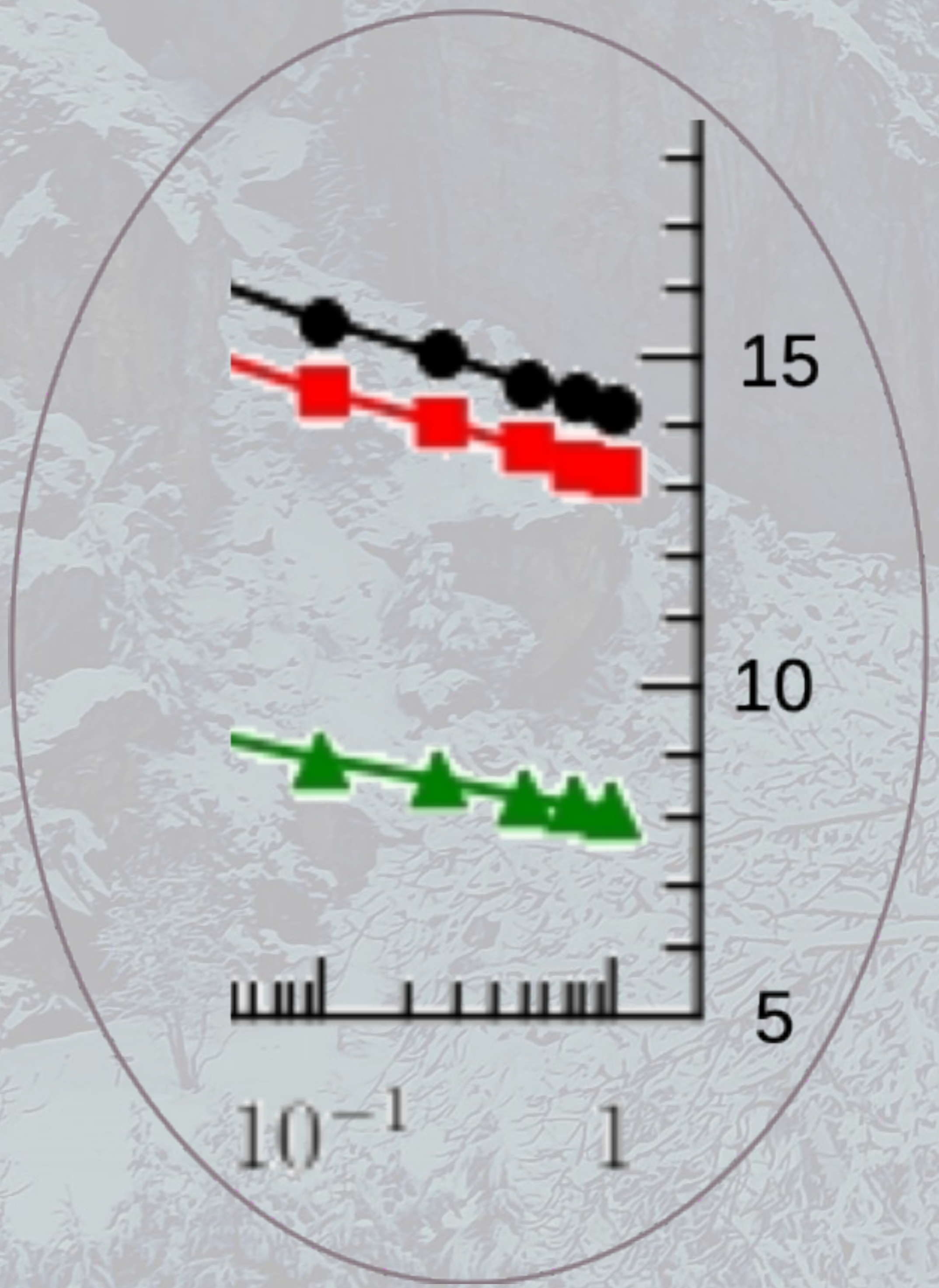
$$\frac{\pi}{2}\langle b^2 \rangle \leq \sigma_{eff}^{\gamma p}(Q^2 \to \infty) \leq 2\pi \langle b^2 \rangle$$

Being: $\sigma_{\text{eff}}^{\gamma p}(Q^2 \to \infty) = \sigma_{\text{eff}}^{2v1}$

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

Extracted from data

Backup - $\sigma_{\text{eff}}^{\gamma p}(Q^2 \to \infty)$



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

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

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

For the proton models we have used:

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

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

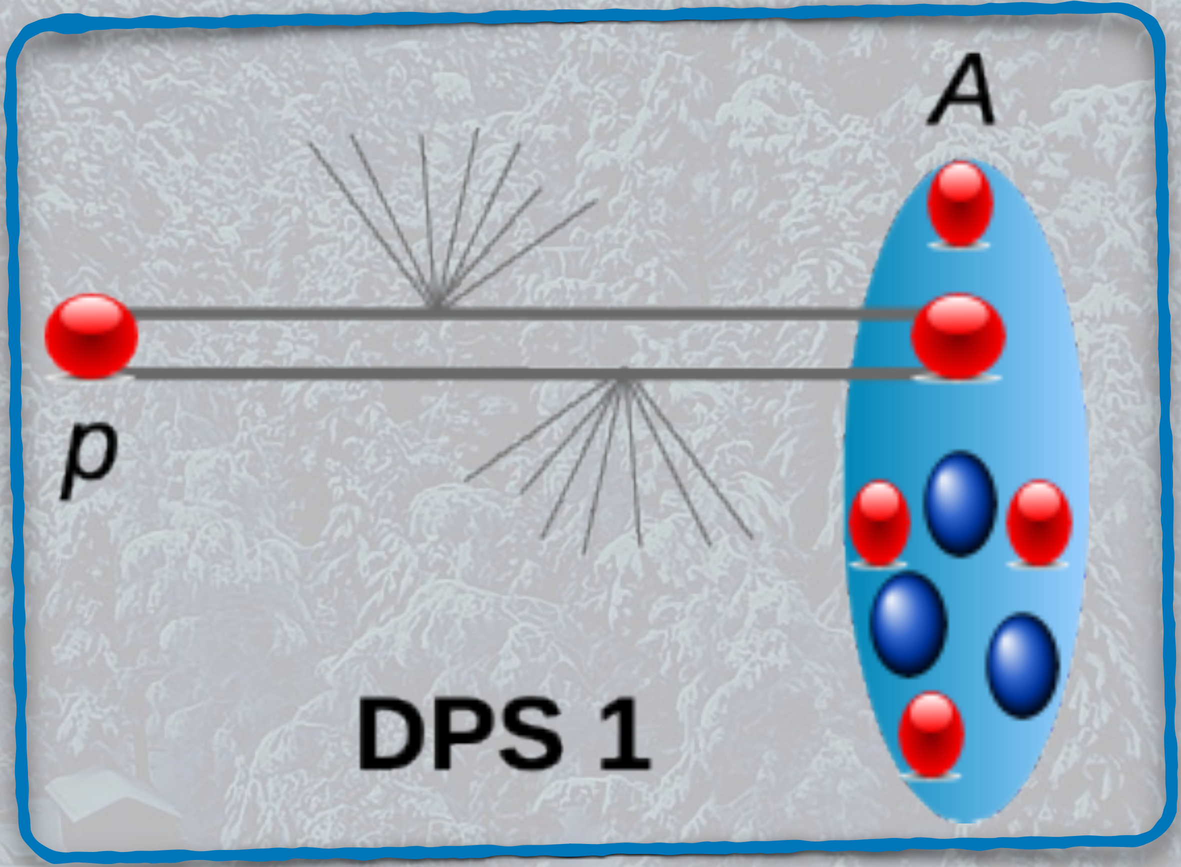
Thus for QED: $Q^2 >> 1 \text{ GeV}^2$ almost approximates the asymptotic

DPS in pA collisions

The DPS cross-section

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

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



the thickness function as a function of the impact parameter B

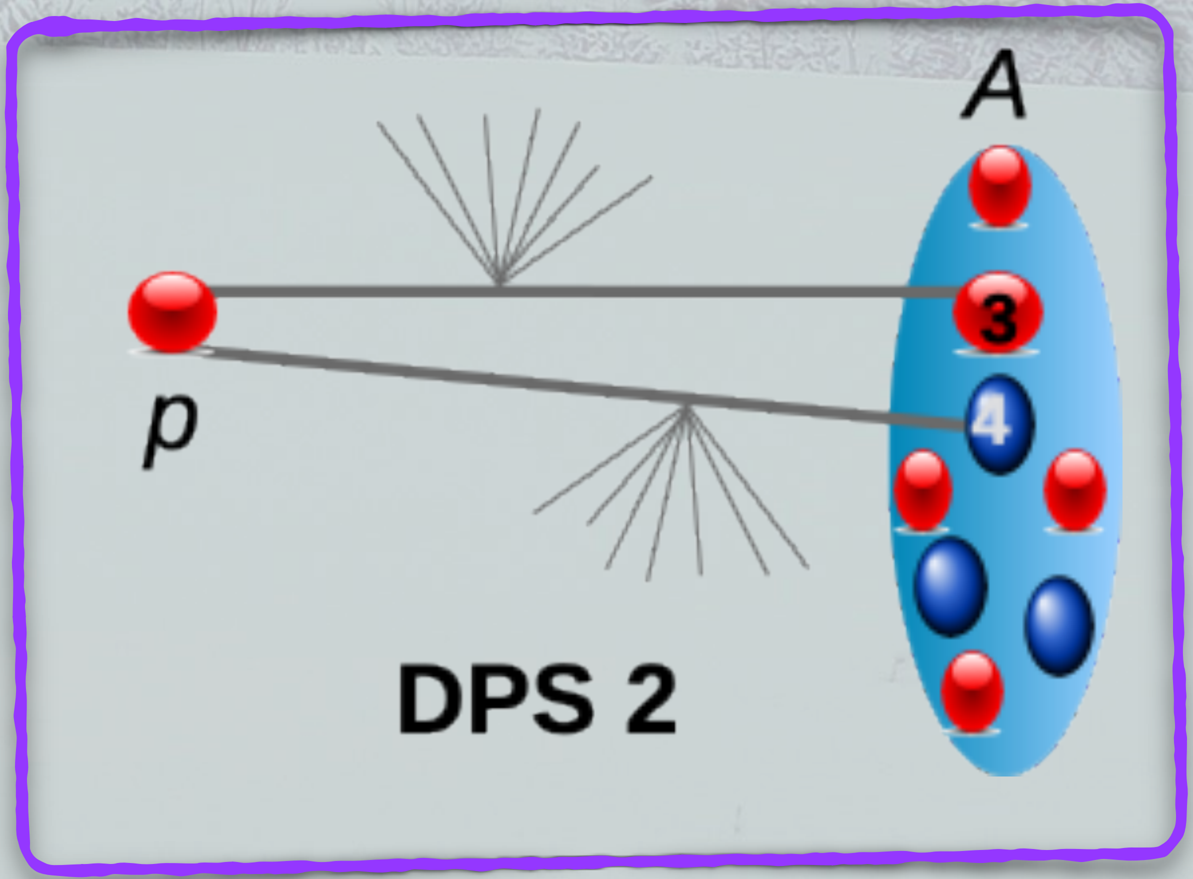
$$\bar{T}(\vec{b}_\perp + \vec{B}) \sim \bar{T}(\vec{B})$$

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

Wood-Saxon distribution for pb normalized to A

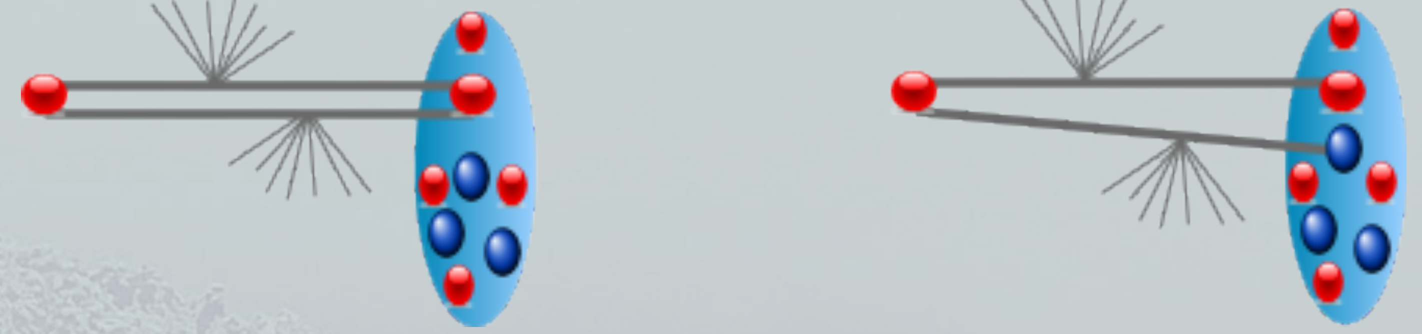
$$+$$

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



$$\Bigg\}$$

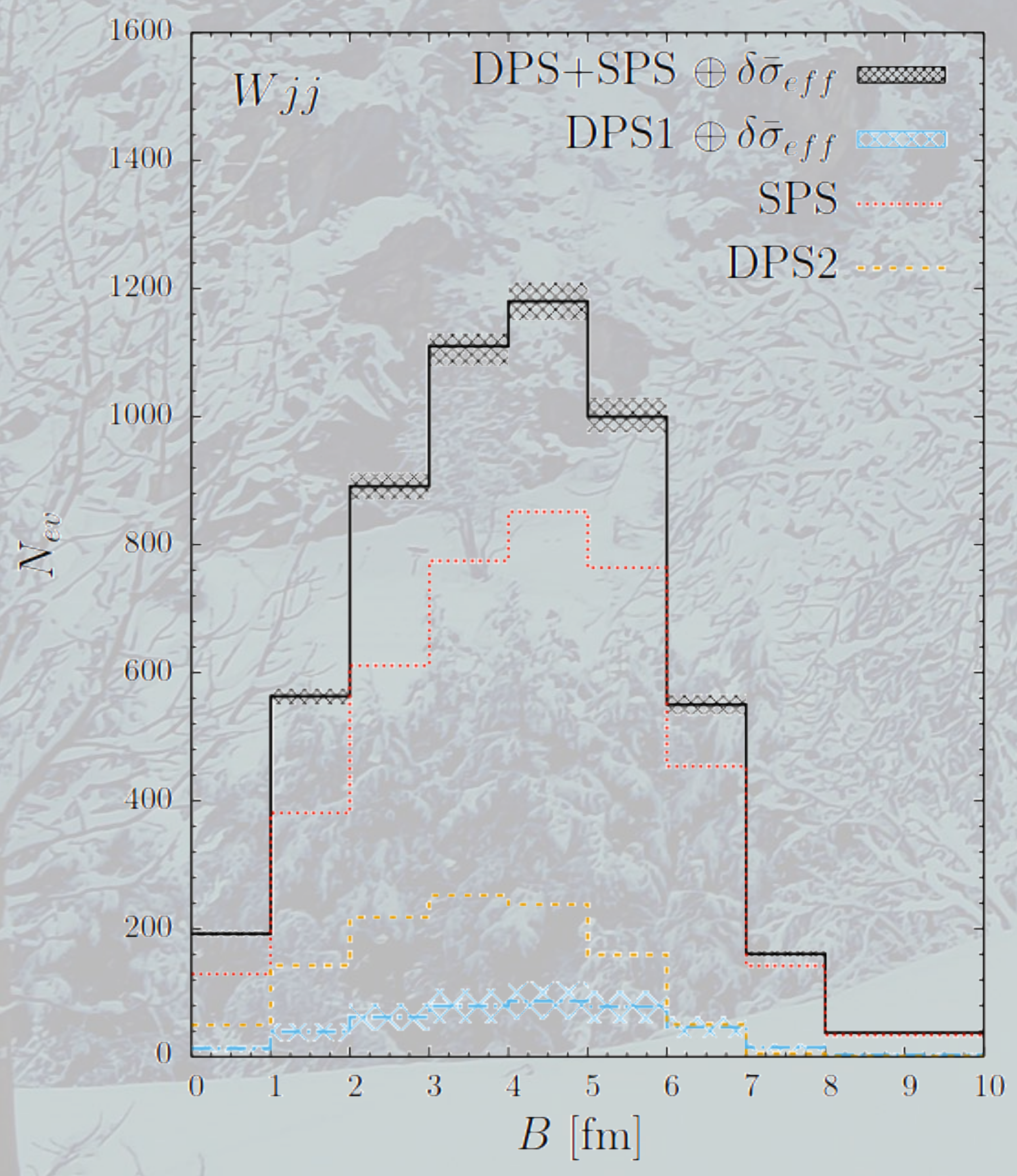
DPS in pA collisions



Some examples of predictions:

W+di-jets

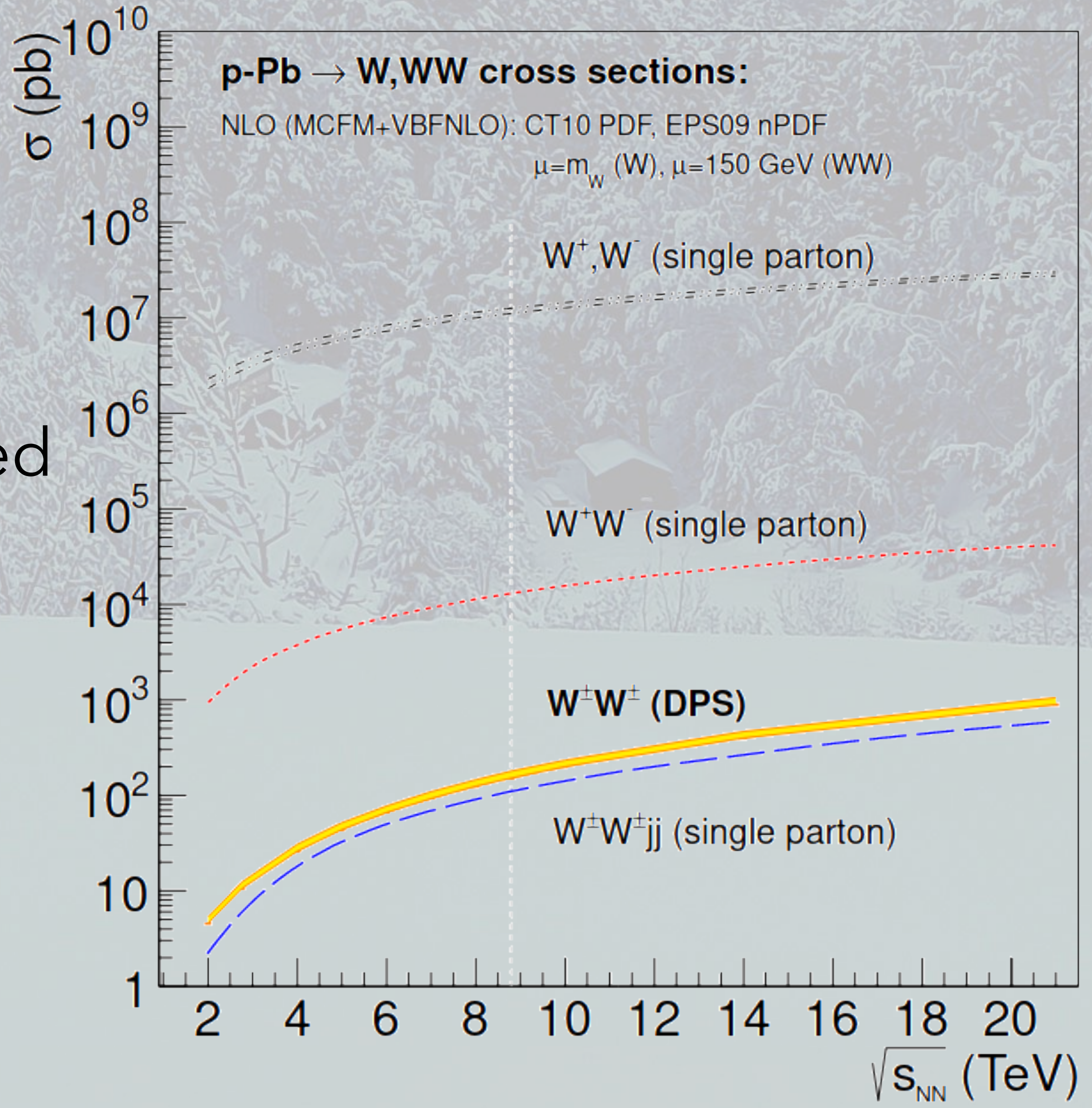
B. Blok and F. A. Ceccopieri EPJC (2020) 80, 278



- SPS dominant
- DPS2 bigger then DPS1 has expected

Same sign WW

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



DPS in γA collisions with light nuclei?

M.R. in progress

For example in DPS2:

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

if we approximate: $\xi_i \sim 1$ we get:

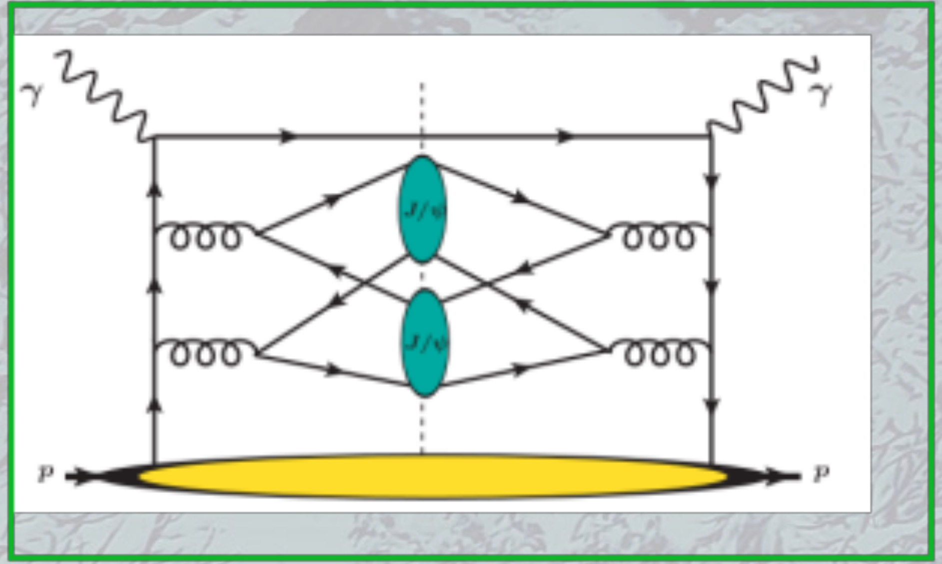
Di J/ψ photo-production@EIC

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

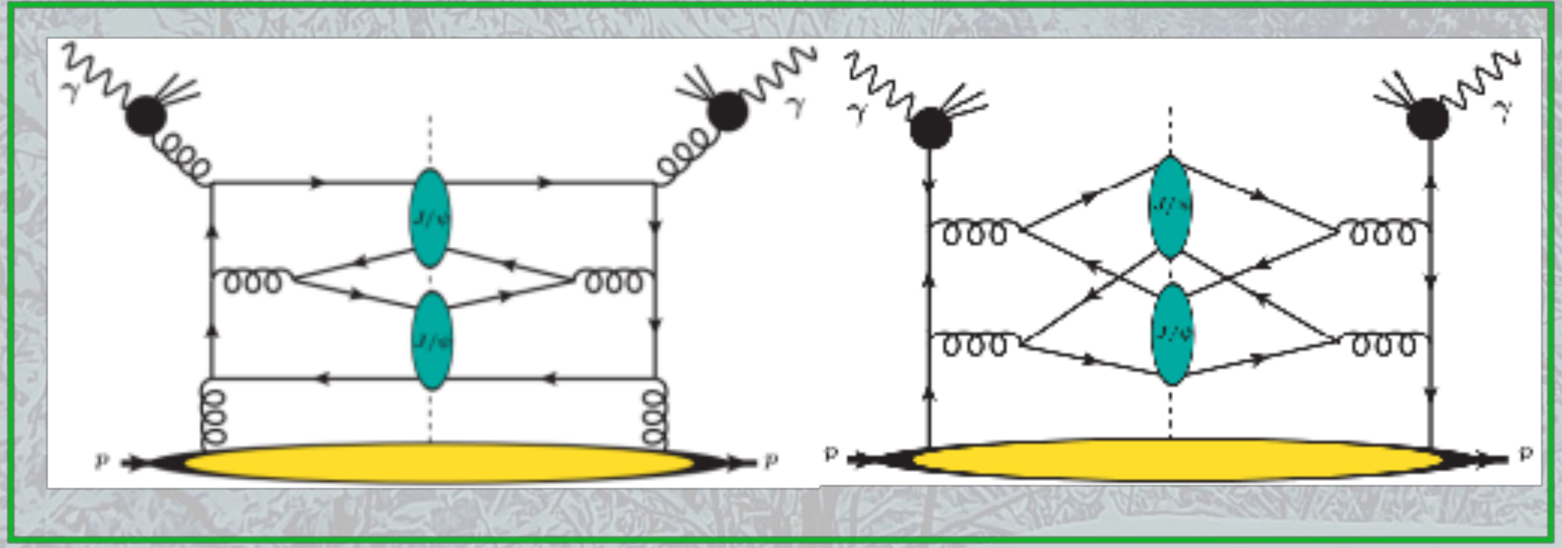
*Slide from R. Sangem

SPS → **Unresolved**, **Resolved**

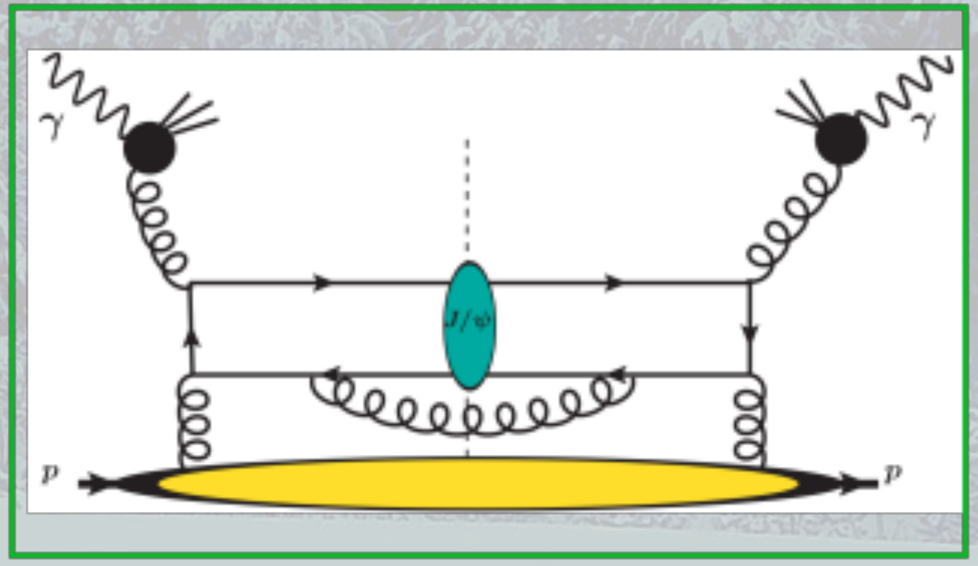
DPS → **Resolved**



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



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



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

Range of cross sections in CSM =100 GeV

$\sigma^{(J/\psi, J/\psi)}_{SPS} \times Br^2 = 4 - 30$ fb
$\sigma^{(J/\psi, J/\psi)}_{DPS} \times Br^2 = 0.2 - 5$ fb

(Resolved) $\sigma^{\gamma p}_{eff} = 10$ mb for DPS

$\sigma^{(J/\psi, J/\psi)}_{SPS} \times Br^2 = 2 - 12$ fb (Unresolved)

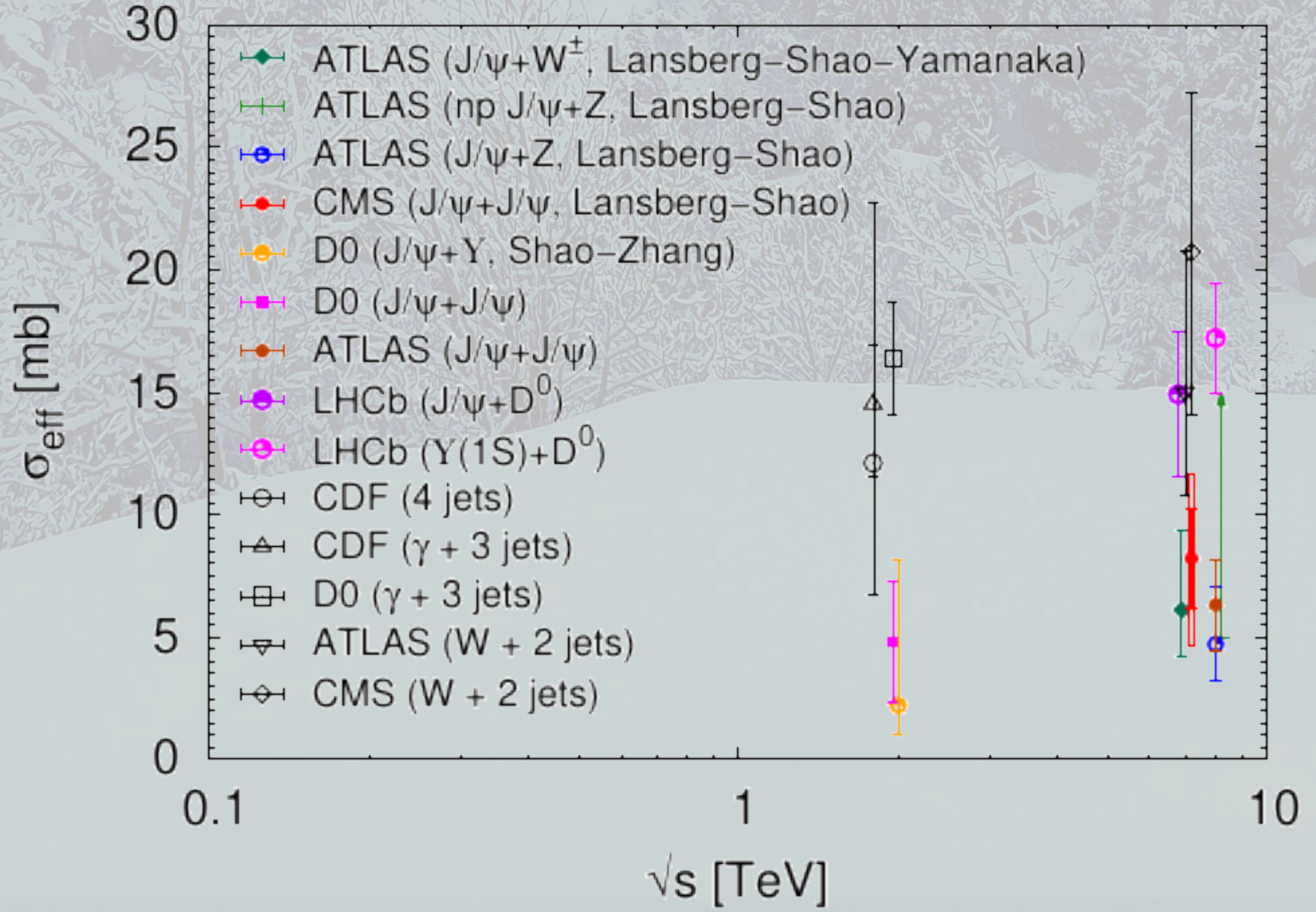
Some Data and Effective Cross Section

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

POCKET FORMULA

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

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



First observation of same sign WW via DPS:

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

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

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

Some Data and Effective Cross Section

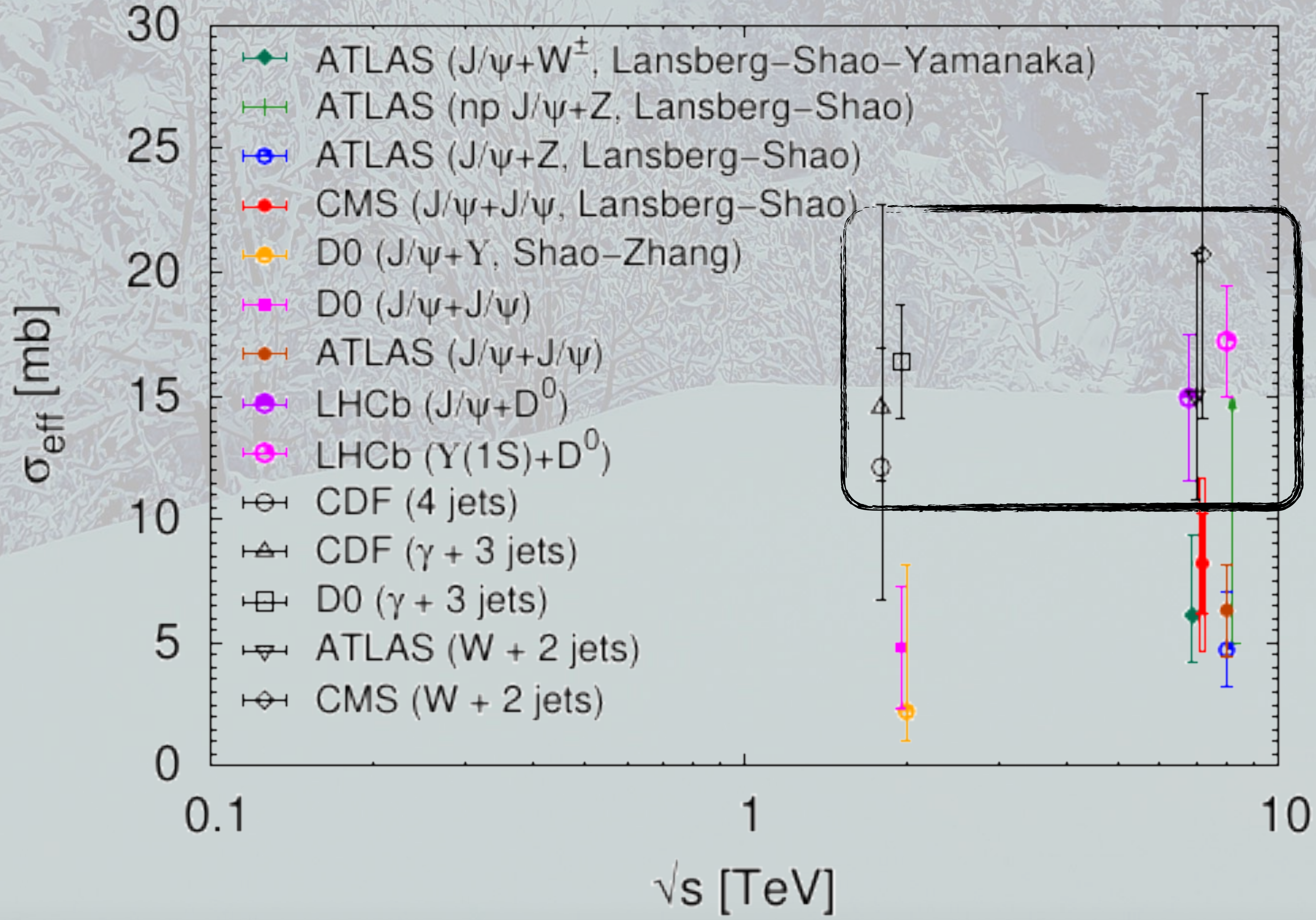
$$\sigma^{pp}_{eff} = \frac{m}{2}\frac{\sigma^{pp}_A \sigma^{pp}_B}{\sigma^{pp}_{DPS}}$$

POCKET FORMULA

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…



First observation of same sign WW via DPS:

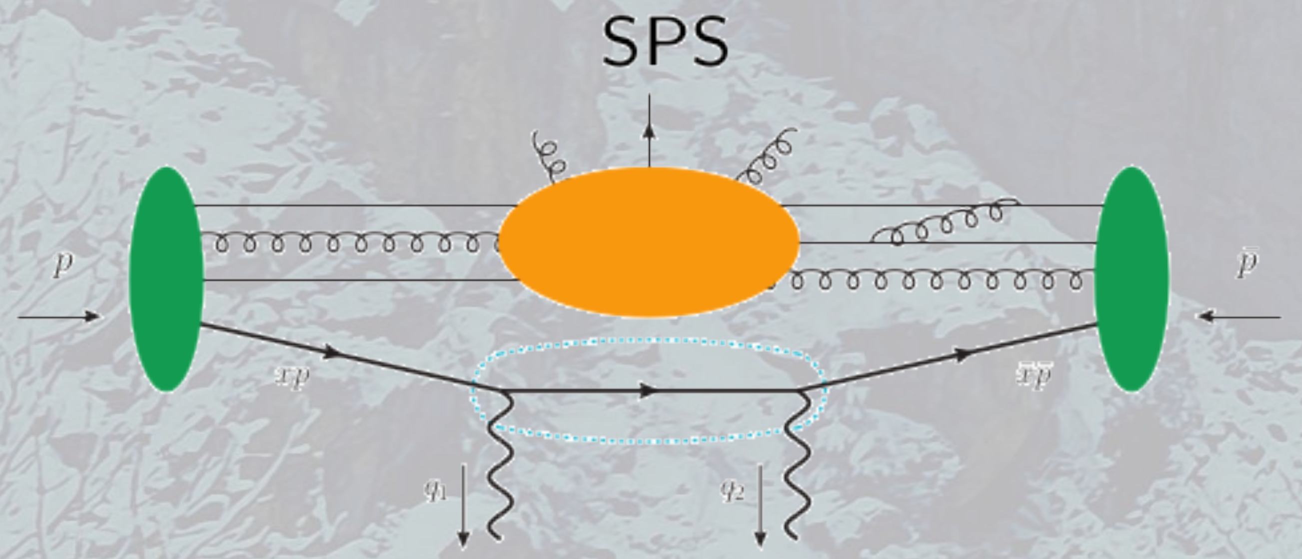
$$\sigma_{eff} = 12.2^{+2.9}_{-2.2} \text{ mb}$$

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

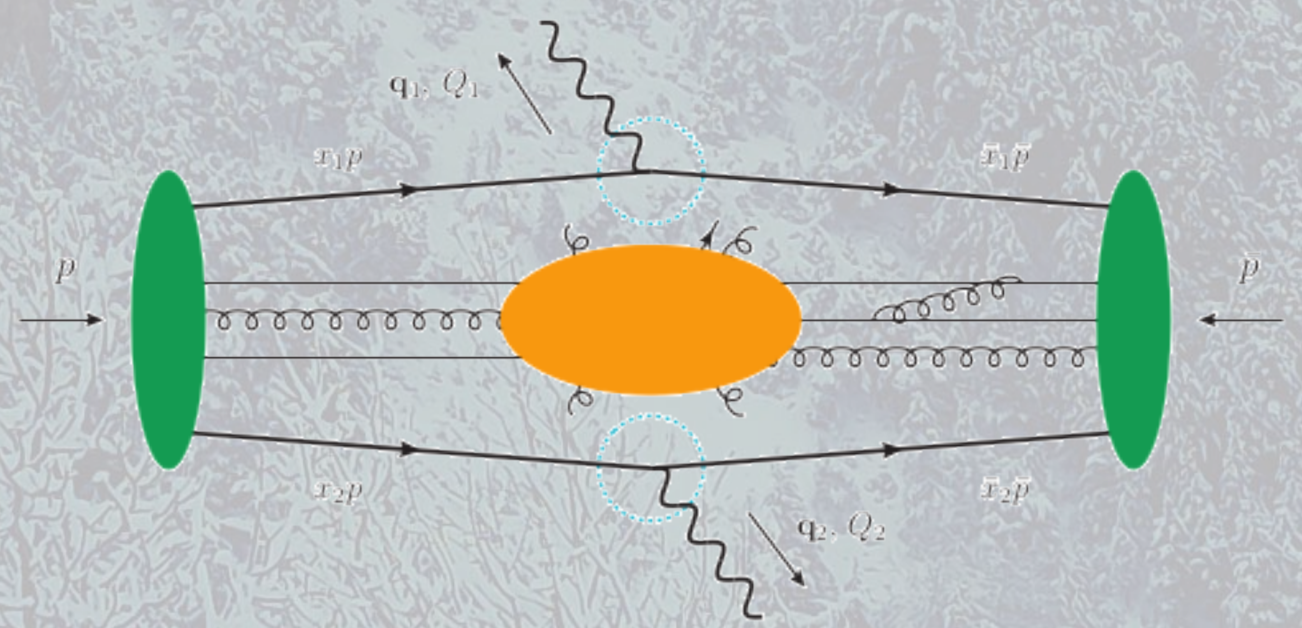
$$\sigma^{DPS} \sim 6.28 \text{ fb}$$

Double Parton Scattering scales

Scale analysis of SPS and DPS processes



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



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

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

Usually:

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

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

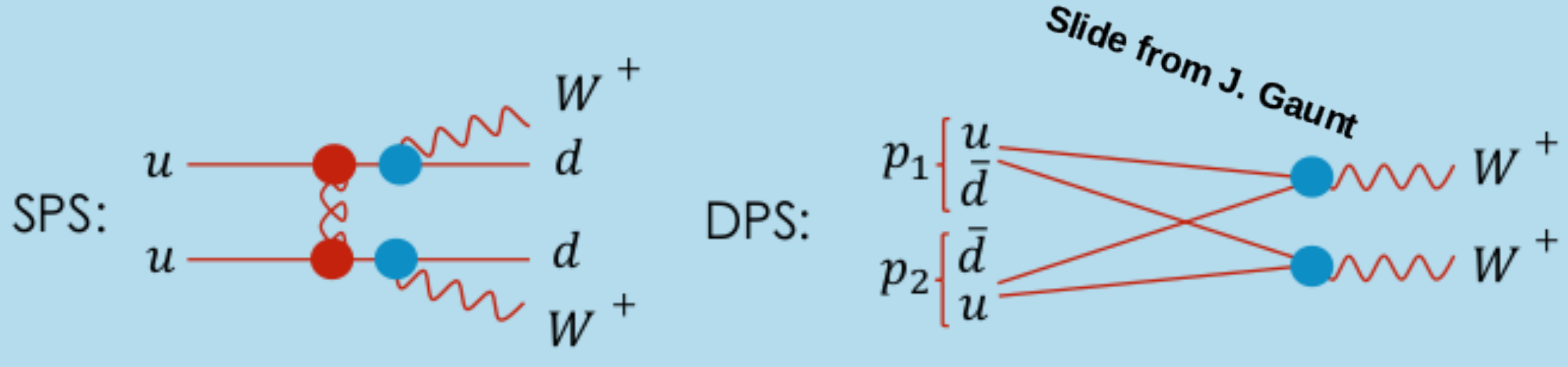
First appearance in theory studies:
Politzer
Paver, Treleani
Mekhfi

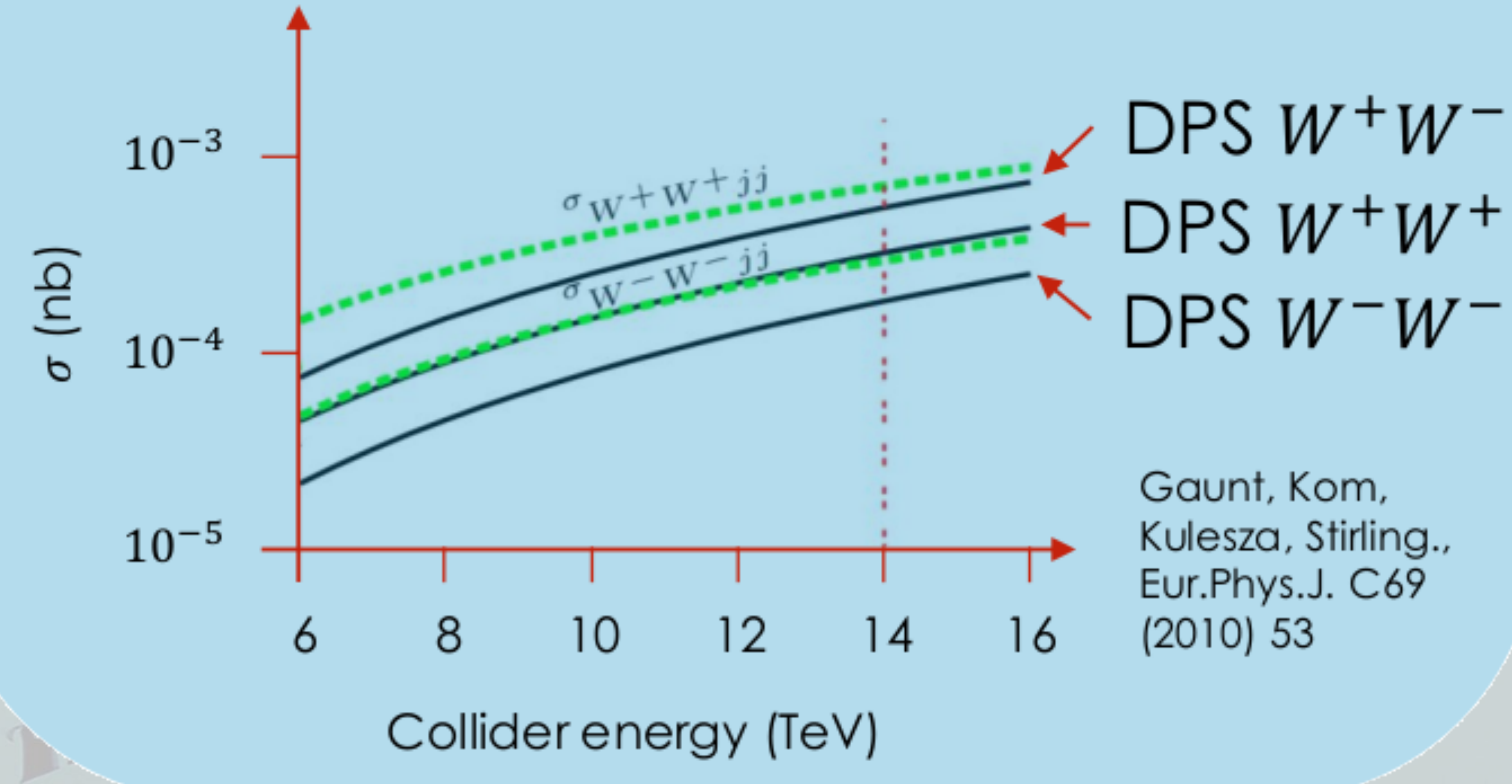
Other ground-setting works:
Gaunt, Stirling
Blok et al.
Diehl et al.
Manohar, Waalewijn
Ryskin, Snigierev
. . .

Nagar's slides MPI 2021

Where and Why DPS?

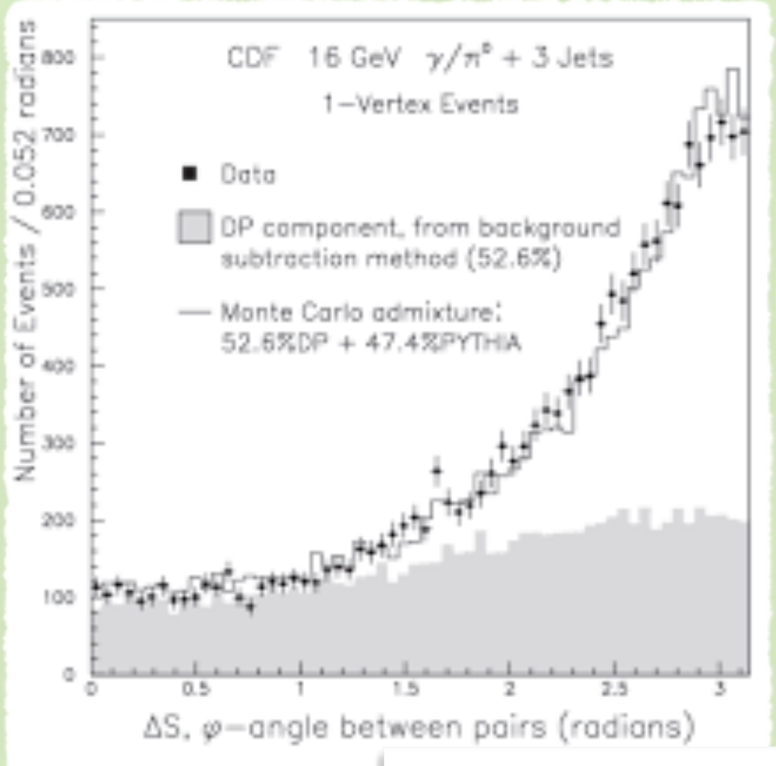
DPS can give a significant contribution to processes where SPS is suppressed by small/multiple coupling constants:



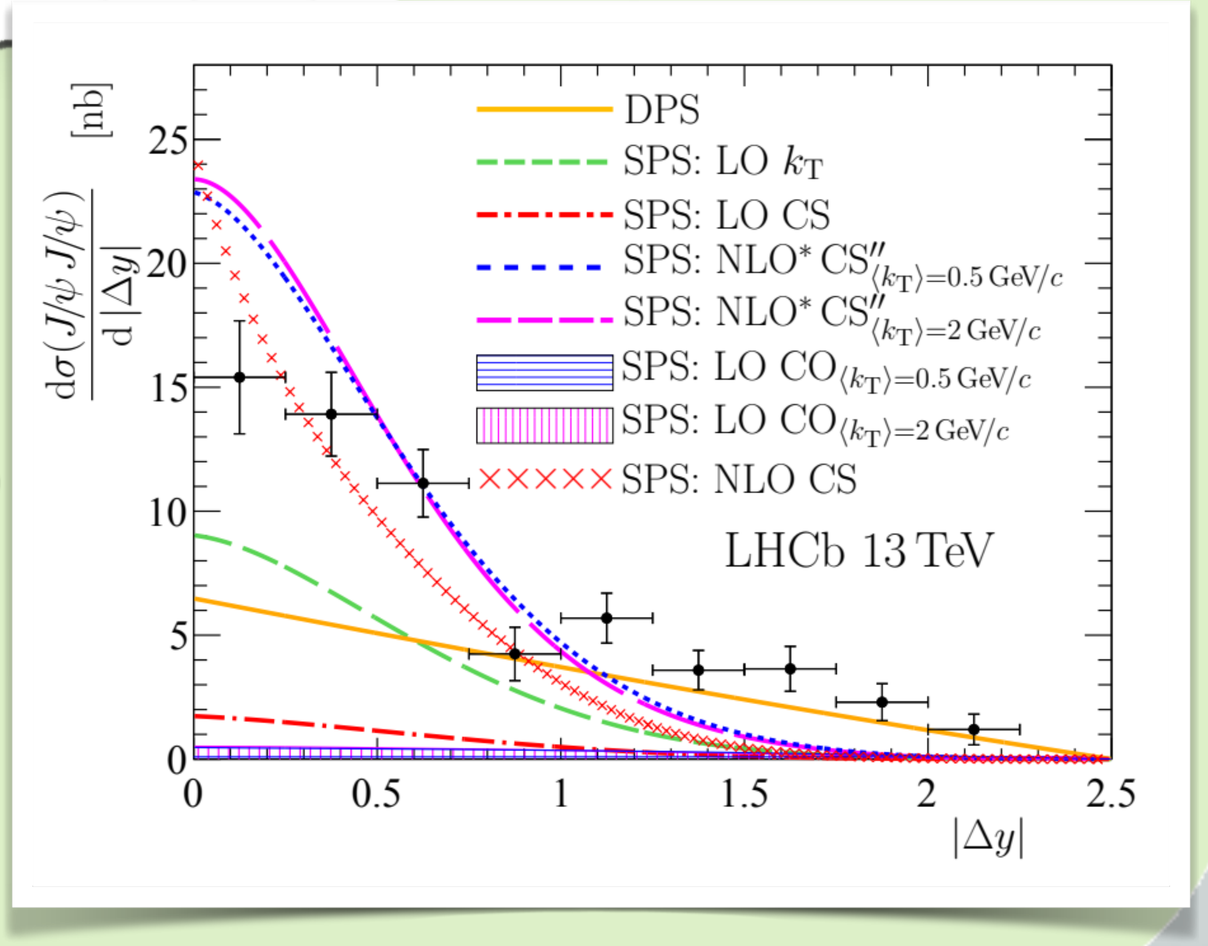


Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

...or in certain phase space regions



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

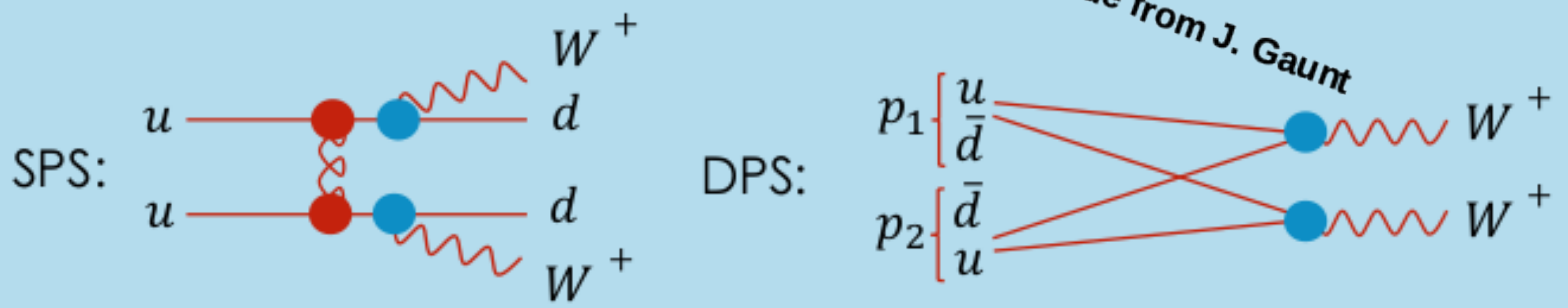


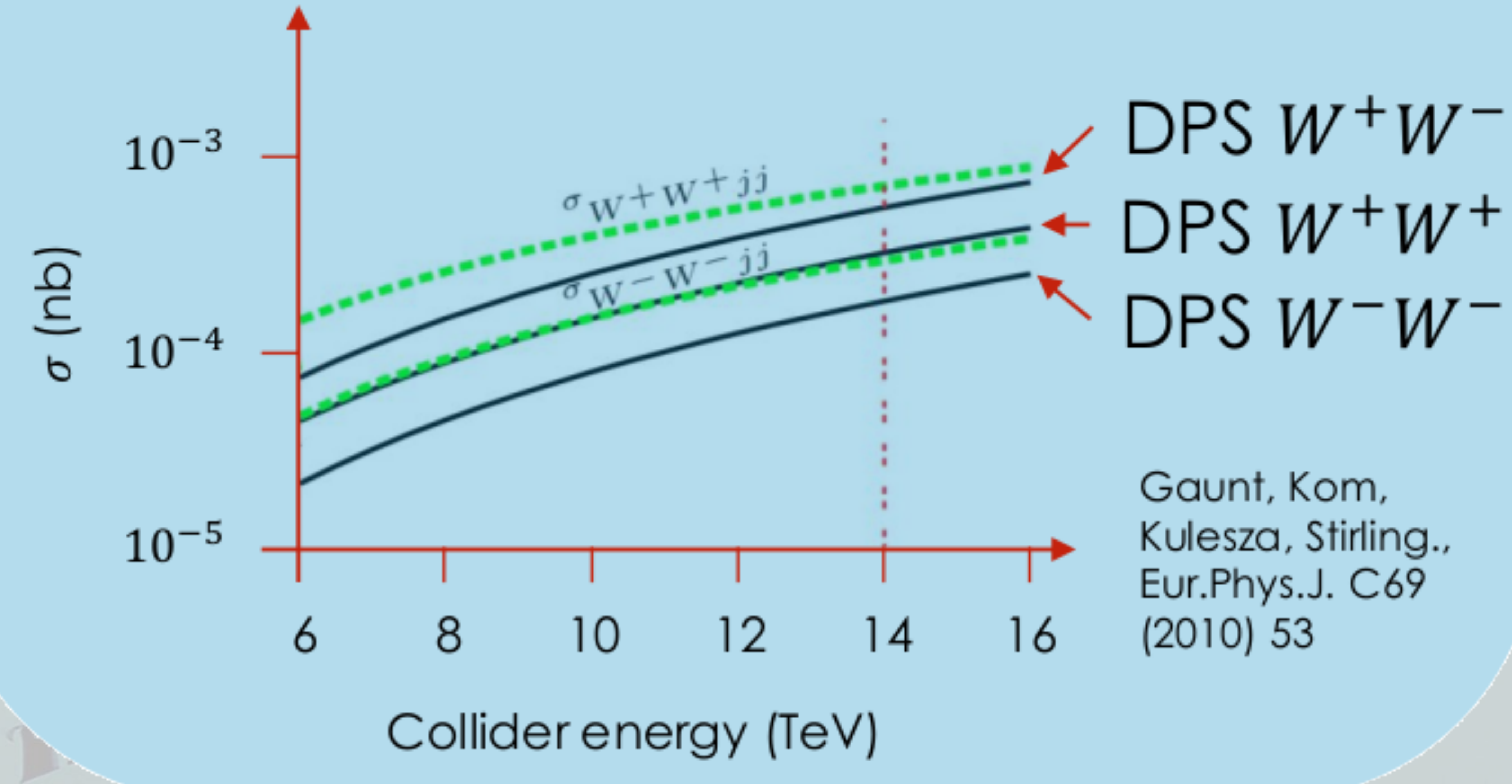
LHCb, double J/ψ, JHEP 06, 047, (2017)

Where and Why DPS?

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

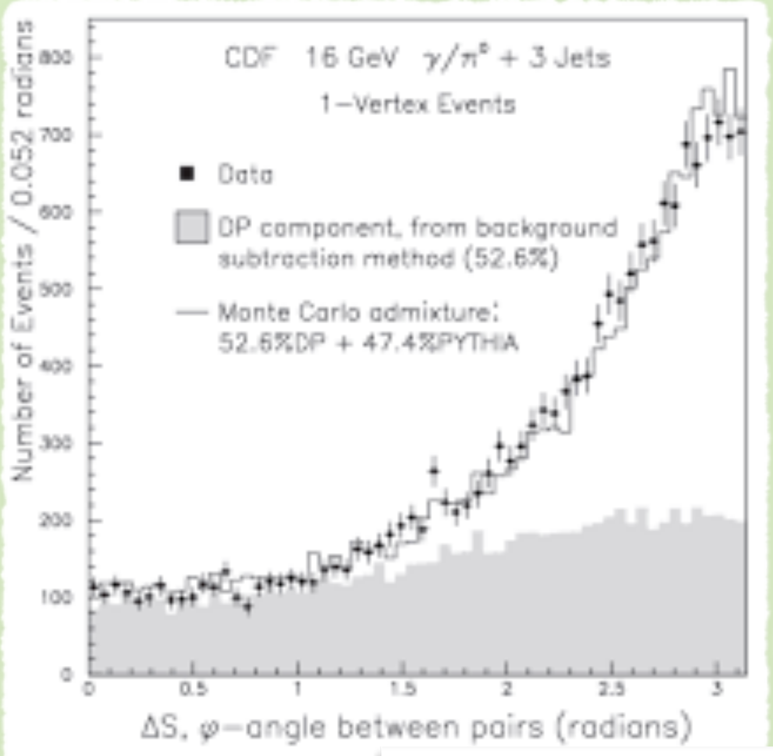
Slide from J. Gaunt





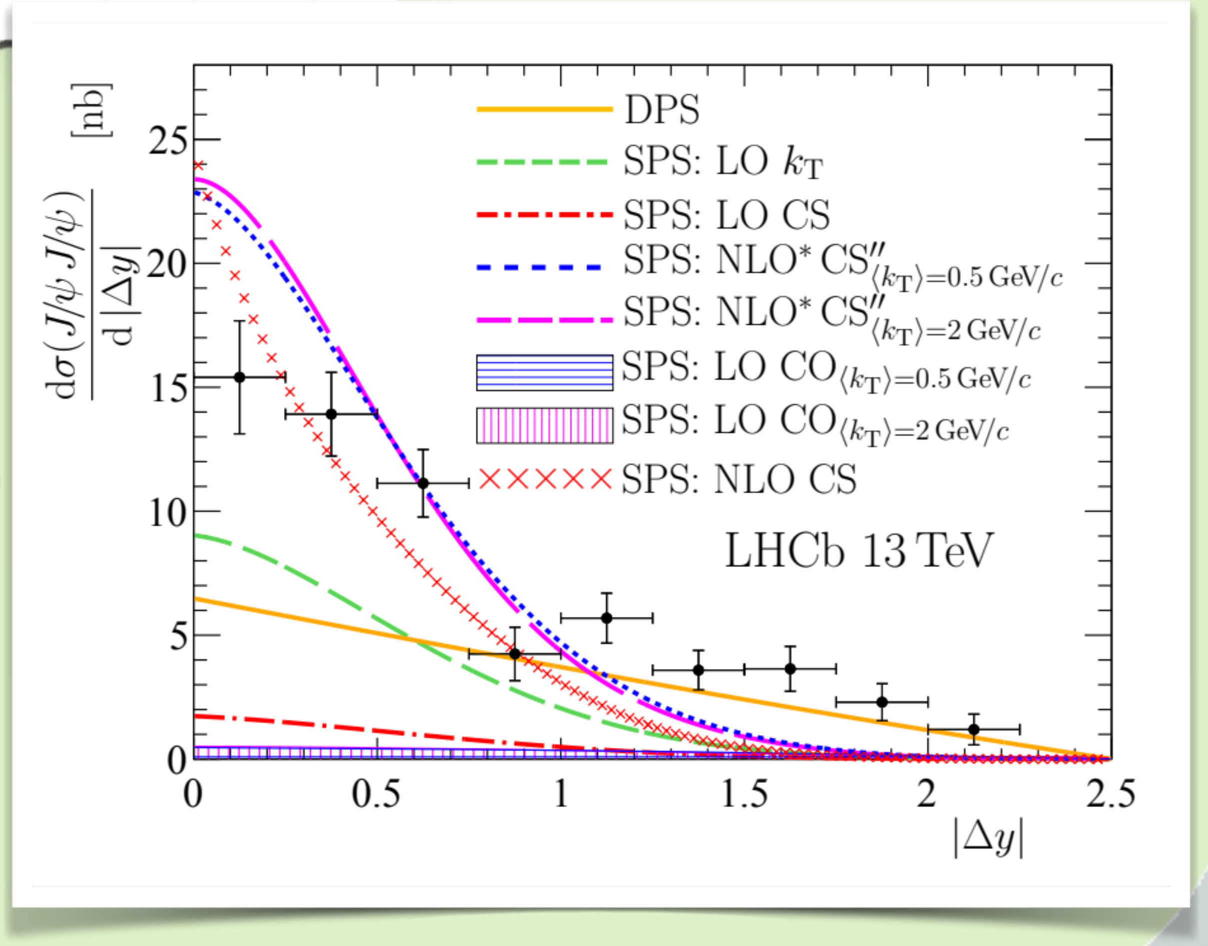
Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

...or in certain phase space regions

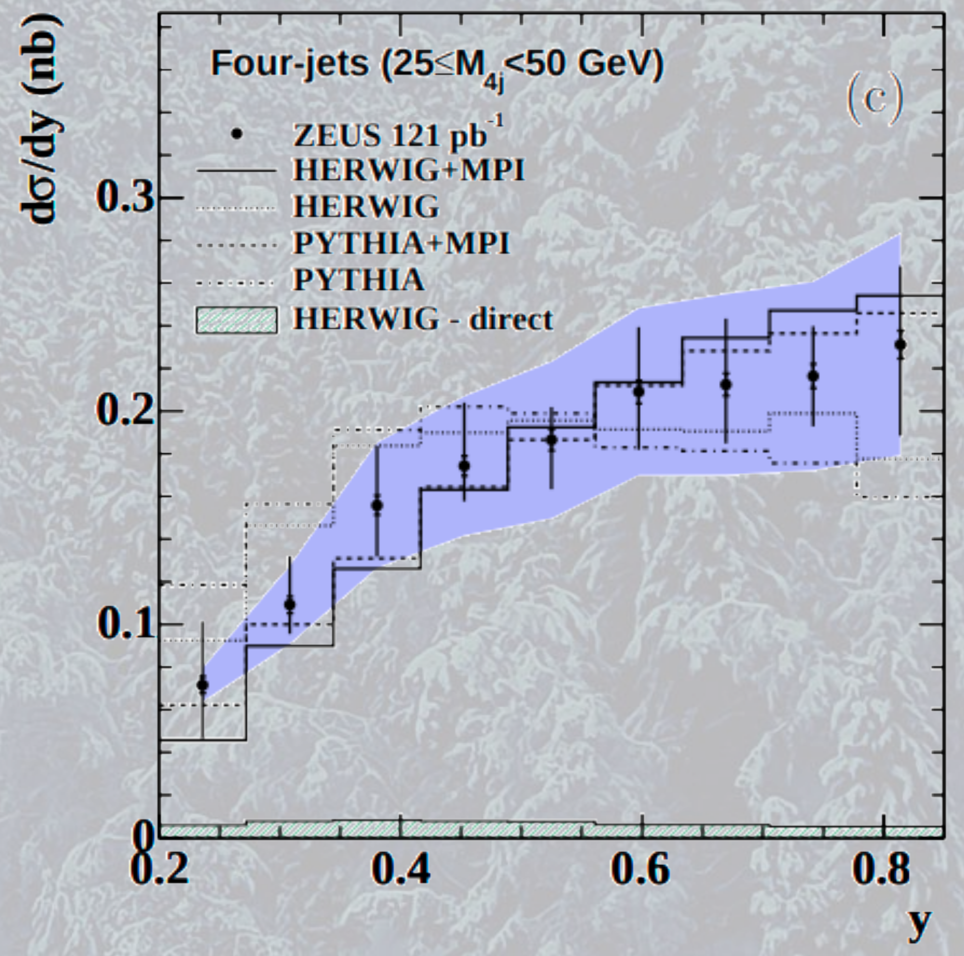


CDF, $\gamma + 3j$, Phys.Rev. D56 (1997) 3811-3832

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



in ep Colliders?



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