From deep inelastic scattering to double parton scattering off light nuclei

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INFN section of Perugia

In collaboration with:

Sergio Scopetta (Perugia, Italy)
Michele Viviani (Pisa, Italy)
Emanuele Pace (Roma, Italy)
Giovanni Salmè (Roma, Italy)
Filippo Fornetti (Perugia, Italy)
Eleonora Proietti (Pisa, Italy)

INFN PERUGIA
Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

STRONG 2020

Outline

- Presentation of NINPHA IS activity
- EMC effect of light-nuclei
- Coherent J/ψ electro-production on light-nuclei and multiparticle effects
- Double parton scattering on light-nuclei @EIC

Conclusions

NINPHA National Initiative on the Physics of Hadrons

Genova
Local PI: E. Santopinto
Staff: A. Pilloni (Unime)
Associate: P. Saracco

Cagliari
National PI: F. Murgia
Local PI: U. D'Alesio
Staff: G. Bozzi, C. Pisano
Post-doc: C. Flore (M. Curie)
PhD: S. Anedda, N. Kato

5 units
34 people
29.8 FTE

Perugia
Local PI: M. Rinaldi
Staff: M. Alvioli, S. Pacetti, S. Scopetta
Associate: G. Salmè
PhD: F. Fornetti, F. Rosini

Pavia
Local PI: M. Radici
Staff: A. Bacchetta, B. Pasquini [S. Rodini]
Post-doc: F. Delcarro
PhD: A.C. Alvaro, L. Polano, A. Schiavi

Torino
Local PI: M. Boglione
Staff: V.C. Barone, E.R. Nocera, P.G. Ratcliffe (Insubria)
A. Signori
Post-doc: T. Giani, J.O. Gonzalez-Hernandez,
J. Rittenhouse-West, Y. Zhou
PhD: T. Sharma

NINPHA - Research activity and topics

Development of a full three-dimensional picture of the nucleon
Transverse-momentum-dependent (TMD) formalism
TMD Factorization theorems & TMD CSS evolution
DIS, SIDIS, Drell-Yan, e+e- annihilations
TMD PDFs and FFs, GPDs, GTMDs, proton spin
quark & gluon orbital angular momentum
em & gravitational nucleon form factors
Hadron and meson light-cone wave functions and distribution amplitudes
Collinear PDFs and FFs
State-of-the-art global fits of TMDs and collinear PDFs

Cagliari, Pavia, Torino

Relativistic nonpert. description of light nuclei & hadron ynamics
3D tomography of light nuclei and hadrons
Light-front Hamiltonian dynamics
Minkowskian continuum-QCD formalism
Holographic approaches to hadron spectroscopy
Double parton interactions and distributions
Quantum computing tools

Perugia

QCD Spectroscopy & Nonperturbative models for (excited) heavy and light hadrons
Charmonium and Bottomonium new states, exotics
Molecular and diquark/multiquark bound states
Effective field theory approaches
Relativistic Bethe-Salpeter equation in Minkowski space
Nucleon polarizabilities & dispersion relation techniques

Genova, Perugia, Pavia

PRIN 2022 ProtoTaste
Tasting the flavor of the proton in its full dimensions
Cagliari, Pavia, Torino

NINPHA - Productivity results (2024)

40 papers in refereed journals

20 published proceedings

69 talks at nat. and int. conferences

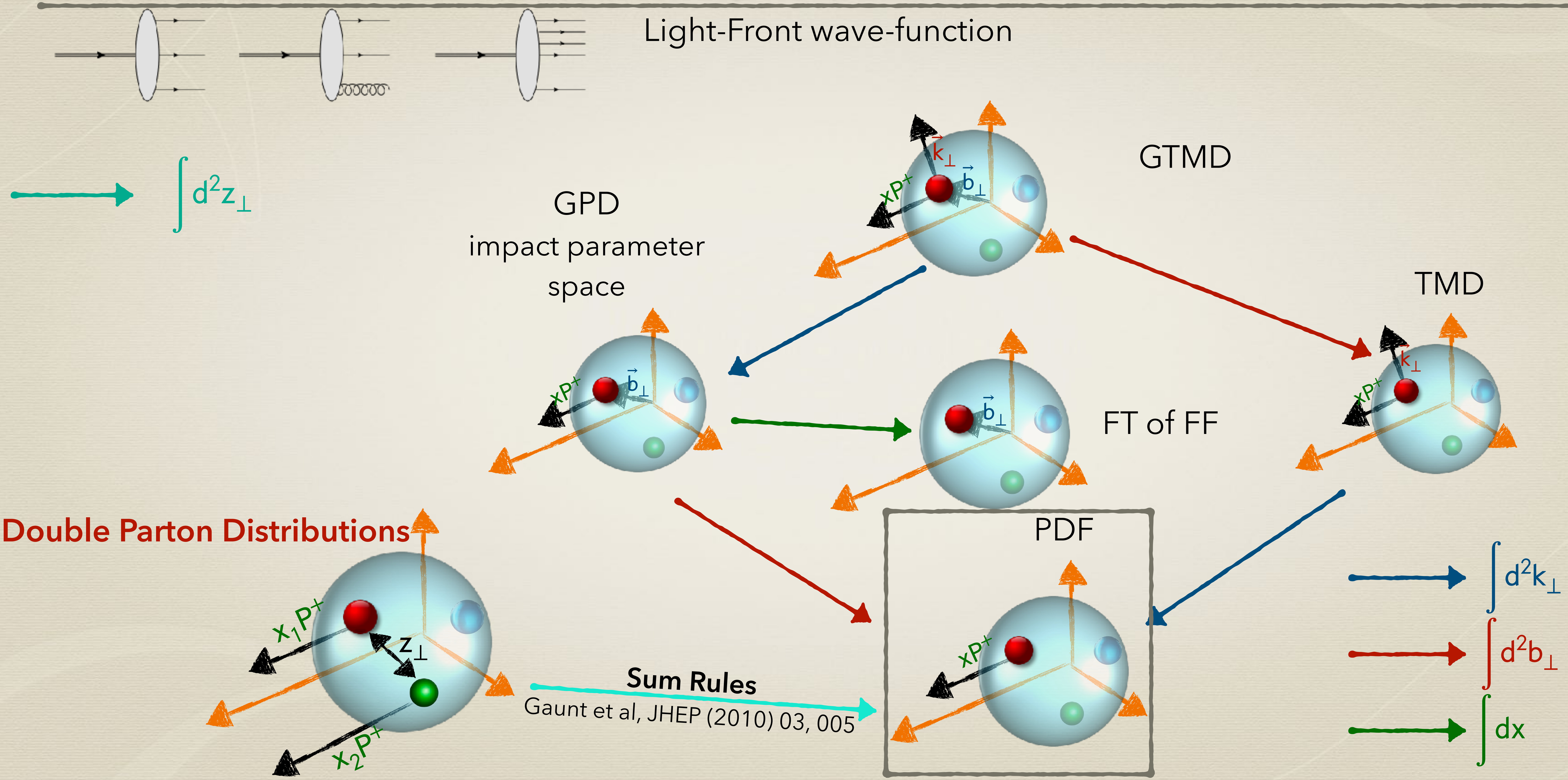
12 Bachelor theses

8 Master theses

1 PhD thesis

Some (good) News:
Giuseppe Bozzi from RTDB to associate professor in 2024 [CA];
Simone Rodini got an RTT position (just in these days!) [PV]
Emanuele Nocera & Andrea Signori from RTDB to associate professors (September 2025) [TO]

Multidimensional picture of hadrons

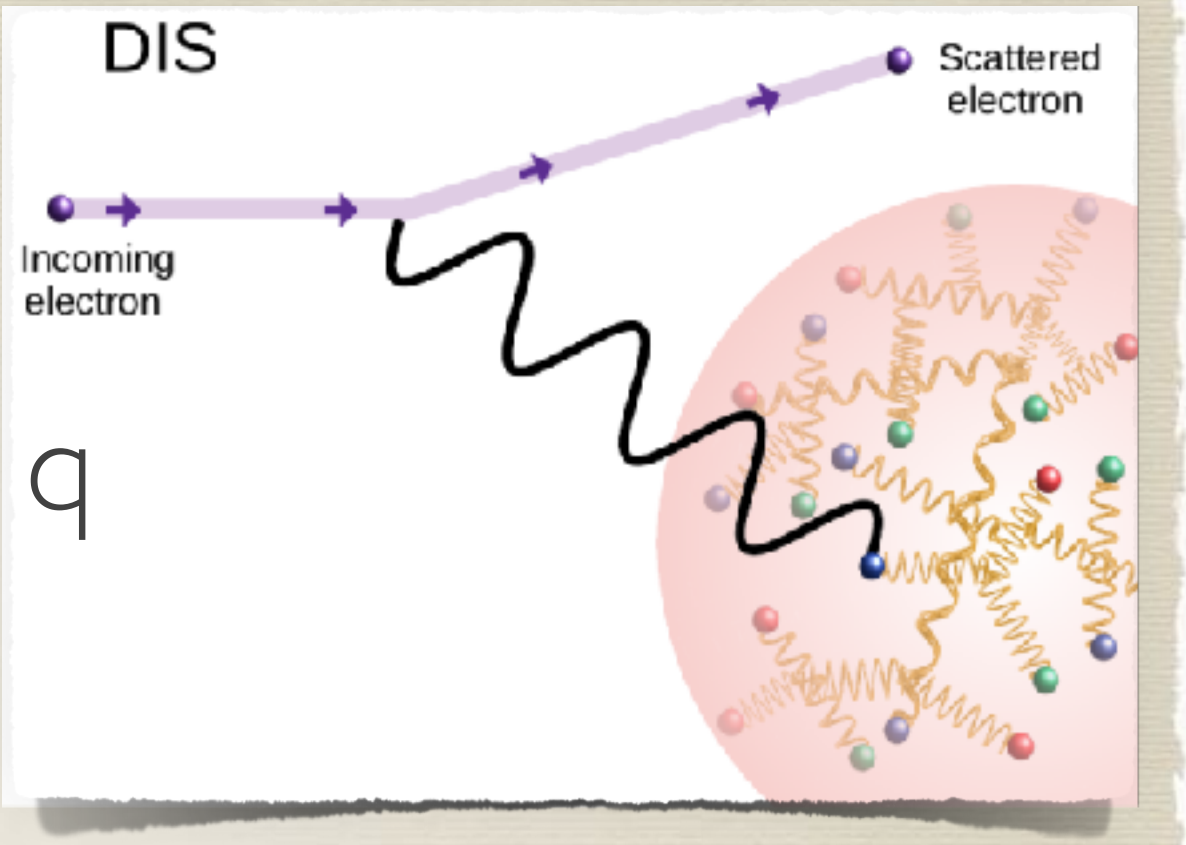


The EMC effect

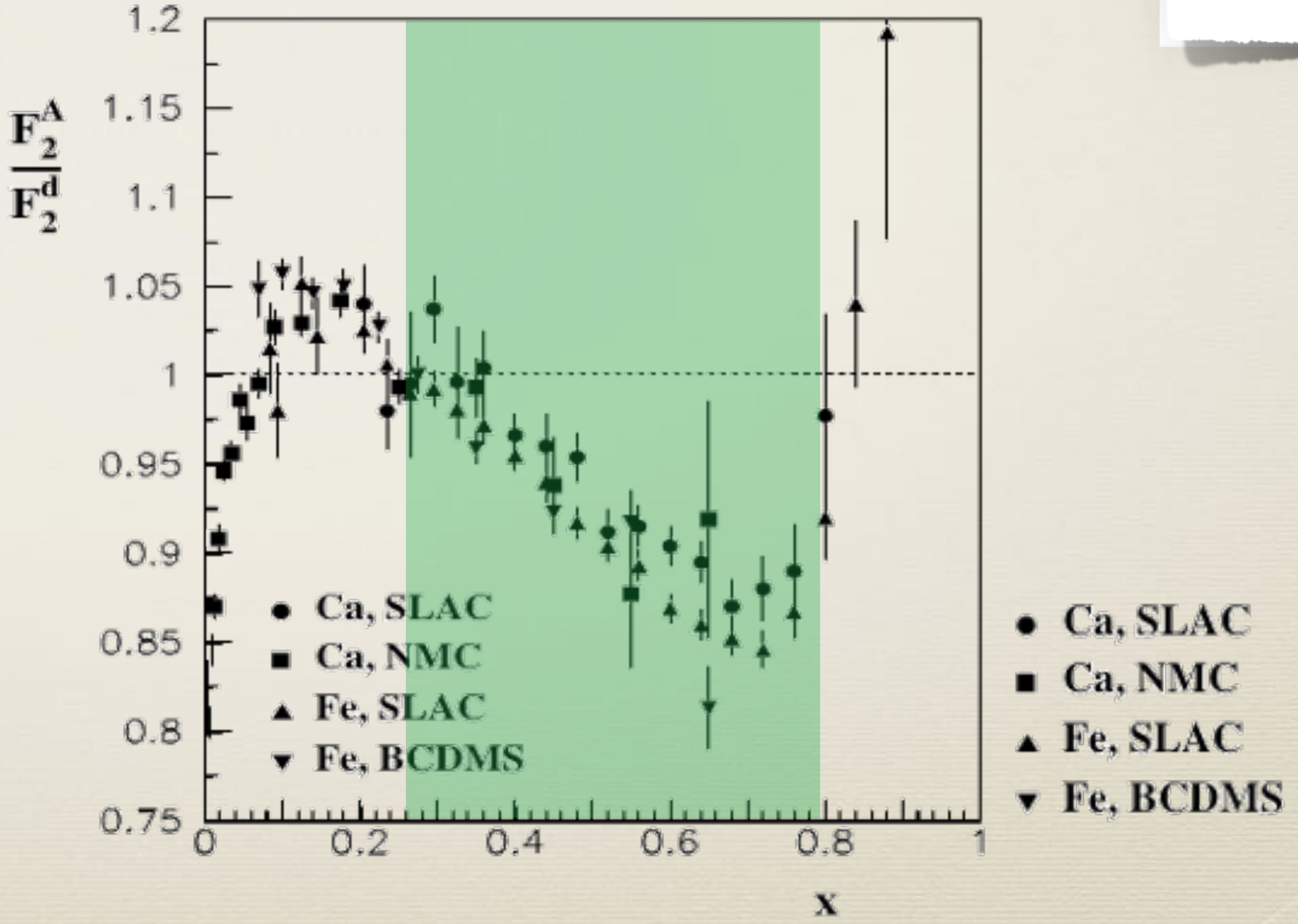
In DIS off a nuclear target with A nucleons:

$$0 \leq x = \frac{Q^2}{2M\nu} \leq \frac{M_A}{M} \simeq A$$

$$\frac{d\sigma}{d\Omega dE'} \propto F_2^A(x)$$



0.2 ≤ x ≤ 0.8 "EMC (binding) region":
mainly valence quarks involved



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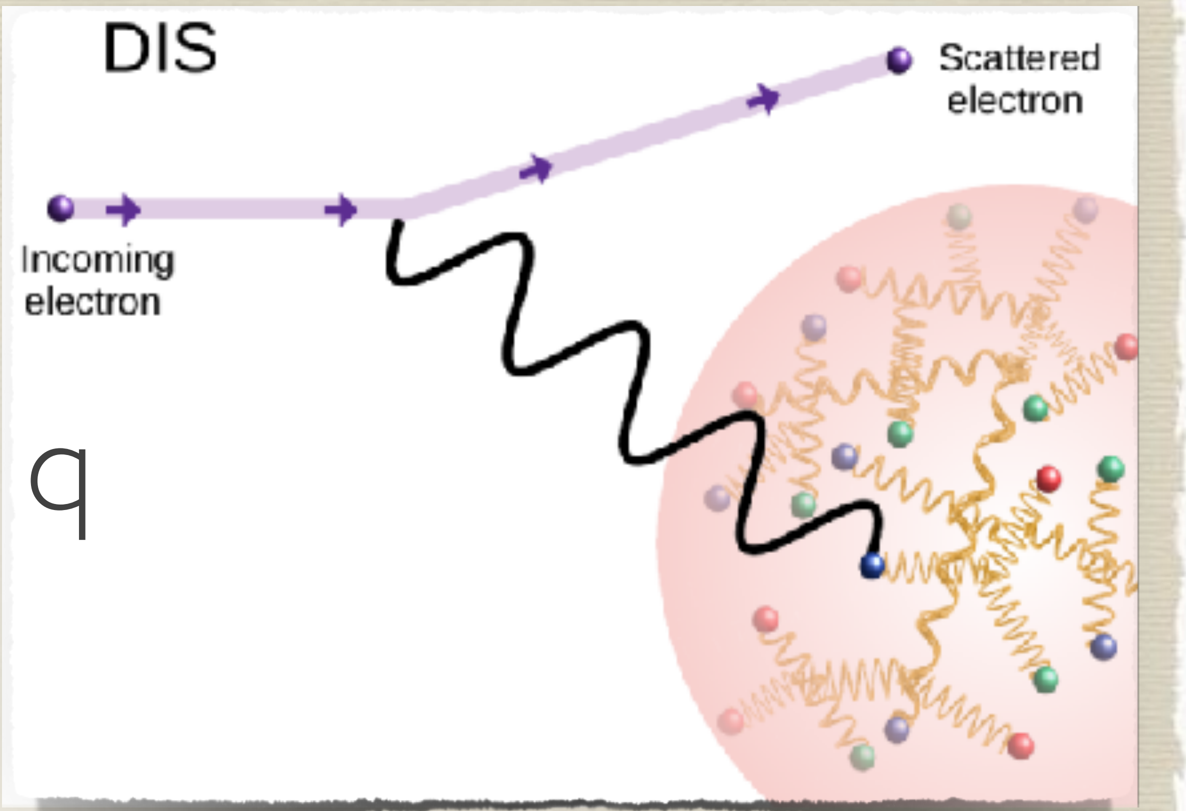
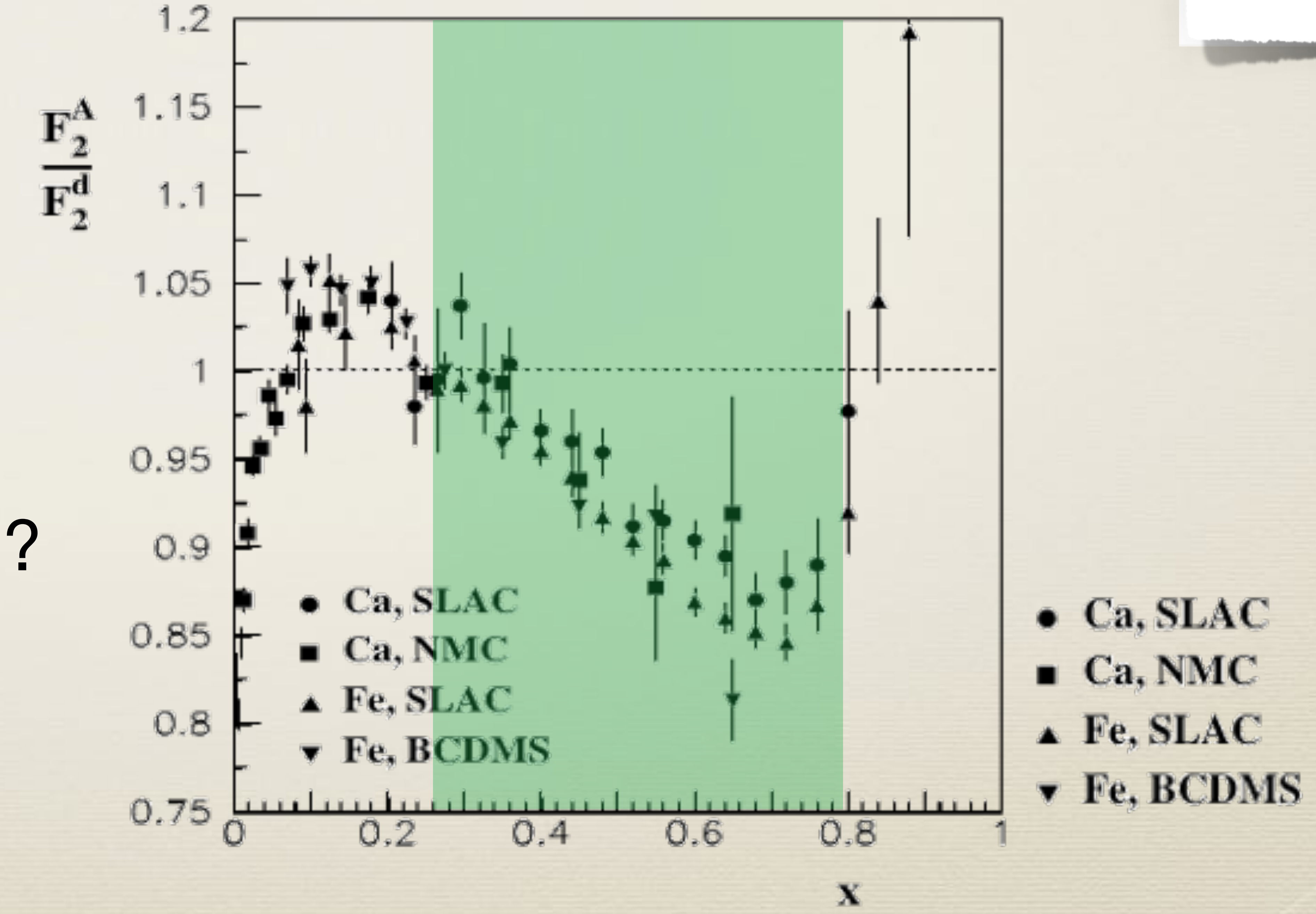


0.2 ≤ x ≤ 0.8 "EMC (binding) region":
mainly valence quarks involved

Naive parton model interpretation:

"Valence quarks, in the bound nucleon, are in average slower that in the free nucleon"

Is the bound proton bigger than the free one??



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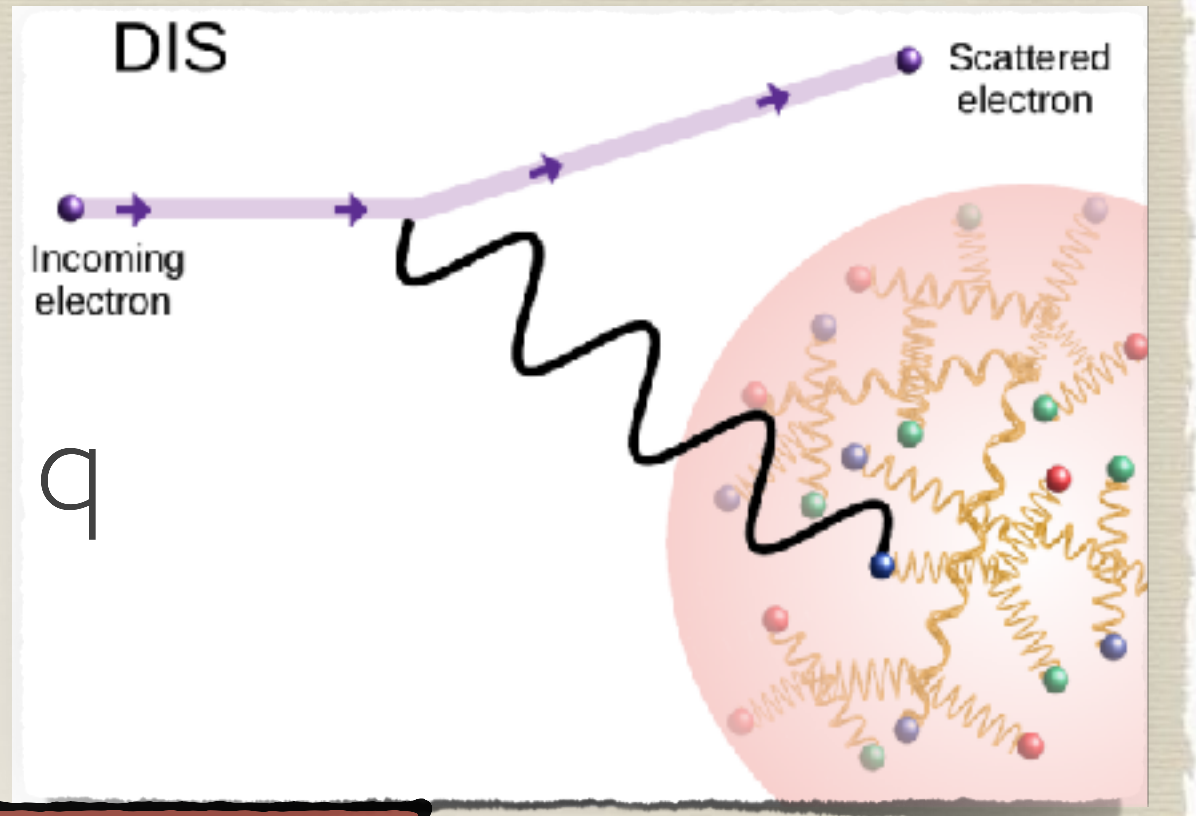
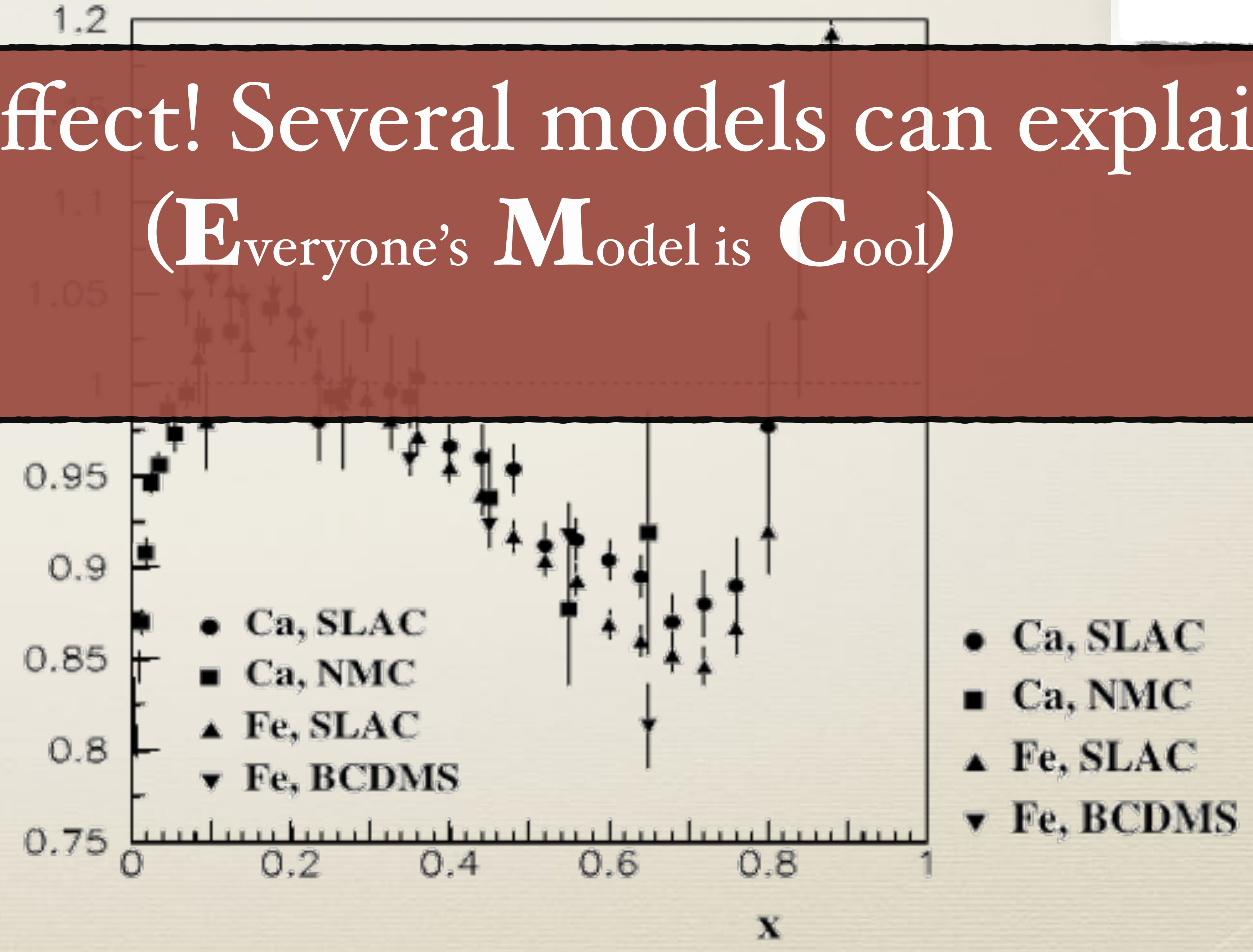


$0.2 \leq x \leq 0.8$ "EMC (binding) region": mainly valence quarks involved

Small effect! Several models can explain it
(Everyone's Model is Cool)



Explanation (exotic) advocated: confinement radius bigger for bound nucleons, quarks in bags with 6, 9,..., 3A **quark, pion cloud effects... Alone or mixed with conventional ones...**

Nuclear SFs and EMC ratio

To calculate the EMC ratio $R^A_{EMC}(x) = \dfrac{F_2^A(x)}{F_2^d(x)}$ for any nucleus A, we need the nuclear SFs.

Within our approach we have:

$$F_2^A(x) = \sum_N \int_{\xi_{min}}^1 d\xi \; F_2^N\left(\frac{mx}{\xi M_A}\right) \; f_A^N(\xi)$$

$^*\xi$ = longitudinal momentum fraction carried by a nucleon in the nucleus

1) in the Bjorken limit we have the LCMD: $f_1^N(\xi) = \sum\!\!\!\!\!\!\int d\epsilon \int \dfrac{d\kappa_\perp}{(2\pi)^3} \dfrac{1}{2\kappa^+} P^N(\tilde{\kappa}, \epsilon) \dfrac{E_s}{1-\xi}$

Unpolarized LF spectral function: $P^N(\tilde{\kappa}, \epsilon) = \dfrac{1}{2j+1} \sum_{\mathcal{M}} P^N_{\sigma\sigma}(\tilde{\kappa}, \epsilon, \mathbf{S}, \mathcal{M})$

Since our approach **fulfill both macro-locality and Poincaré covariance** the LC momentum distribution satisfies 2 essential sum rules at the same time:

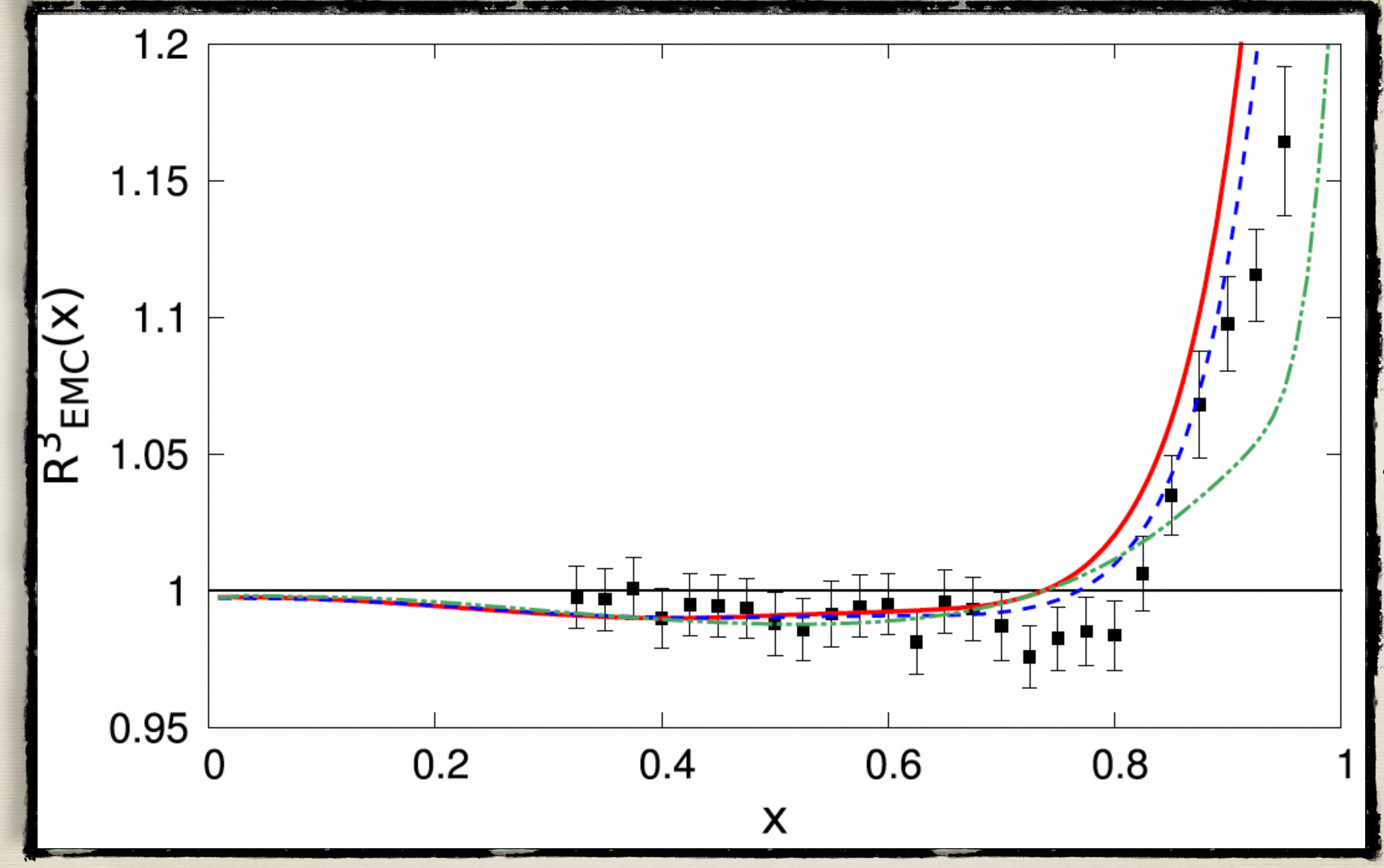
$A = \int_0^1 d\xi [Z f_1^p(\xi) + (A-Z) f^n(\xi)]$: **Baryon number SR**;

$1 = Z < \xi >_p + (Z-N) < \xi >_n \,;\, < \xi >_N = \int_0^1 d\xi \, \xi \, f_1^N(\xi)$: **Momentum SR (MSR)**

The EMC effect for ^{3}He E.Pace, M.R. G.Salmè and S.Scopetta, Phys. Lett. B 839(2023) 127810

[1] J. Arrington, et al, **Phys. Rev. C 104 (6) (2021) 065203**

[2] S. A. Kulagin and R. Petti, **Phys. Rev. C 82, 054614 (2010)**



Solid line: Av18/UIX + SMC*
Dashed line:Av18 + SMC*
Dotted-dashed: Av18/UIX +CJ15**

Full squares: JLab data from experiment E03103 [1] **as reanalyzed in** [2]

[B. Adeva, et al., Phys. Lett. B 412 (1997) 414–424.]

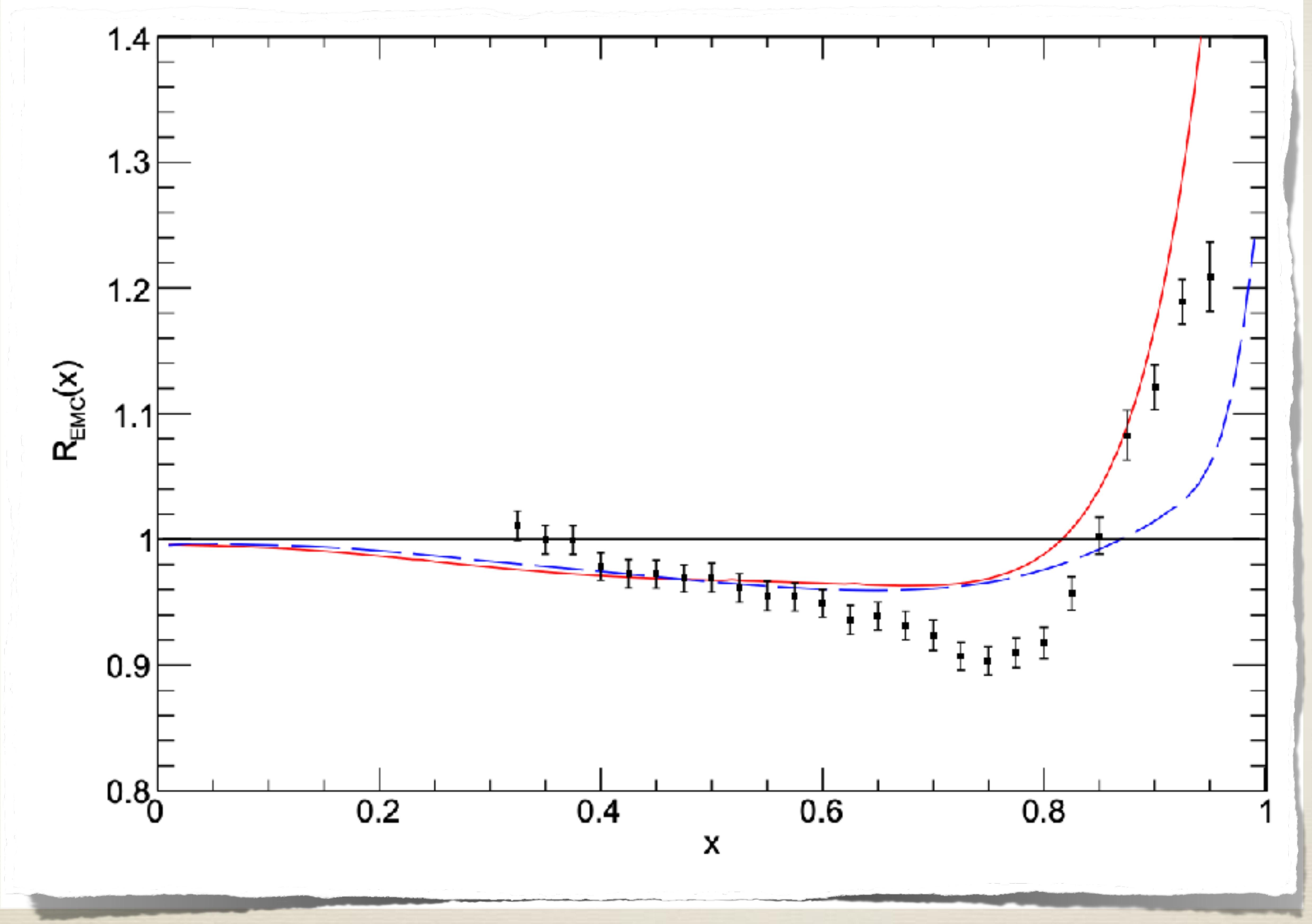
****[A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, N. Sato, Phys. Rev. D 93 (11) (2016) 114017]**

Small but **solid** effect, comparable to the experimental data

The EMC effect for ^{4}He

F.Fornetti, E.Pace, M.R., G.Salmè, S.Scopetta and M.Viviani, **Phys.Lett.B** 851 (2024) 138587

Full squares: JLab data from experiment E03103



Both lines calculated with Av18/UIX

Solid line: SMC parametrization of F_2^p *

Dashed line: CJ15 +TMC Parametrization of F_2^p**

F_2^n extracted from MARATHON data

[B. Adeva, et al., Phys. Lett. B 412 (1997) 414–424.]

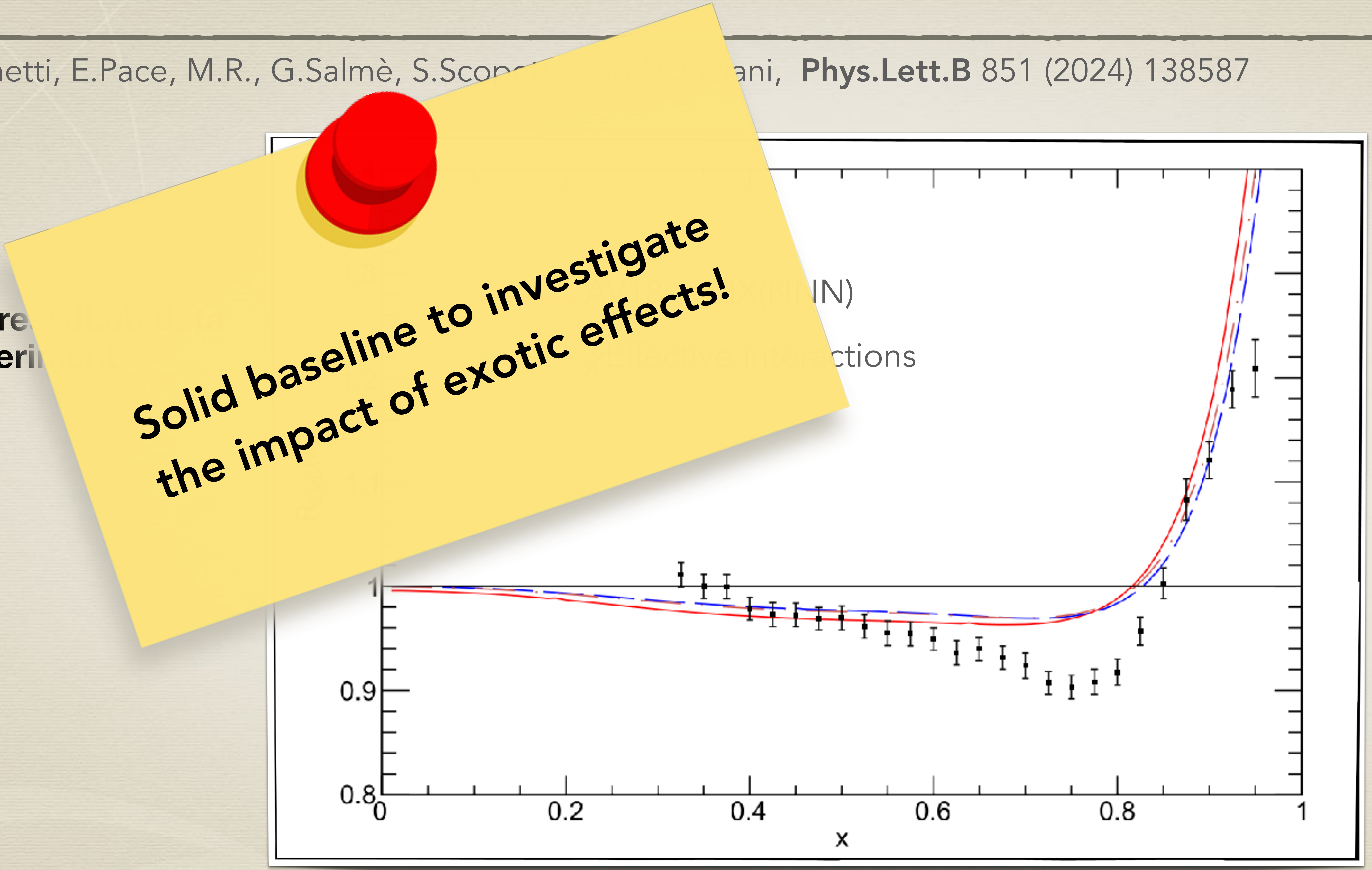
**[A. Accardi, L. T. Brady, W. Melnitchouk, J. F. Owens, N. Sato, Phys. Rev. D 93 (11) (2016) 114017]

The dependence on the choice of the **free nucleon SFs** is largely under control in the **properly EMC region**

The EMC effect for ^{4}He

F.Fornetti, E.Pace, M.R., G.Salmè, S.Scop... ...ani, **Phys.Lett.B** 851 (2024) 138587

Full square... from experi... E03103



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*[B. Adeva, et al., Phys. Lett. B 412 (1997) 414–424.]

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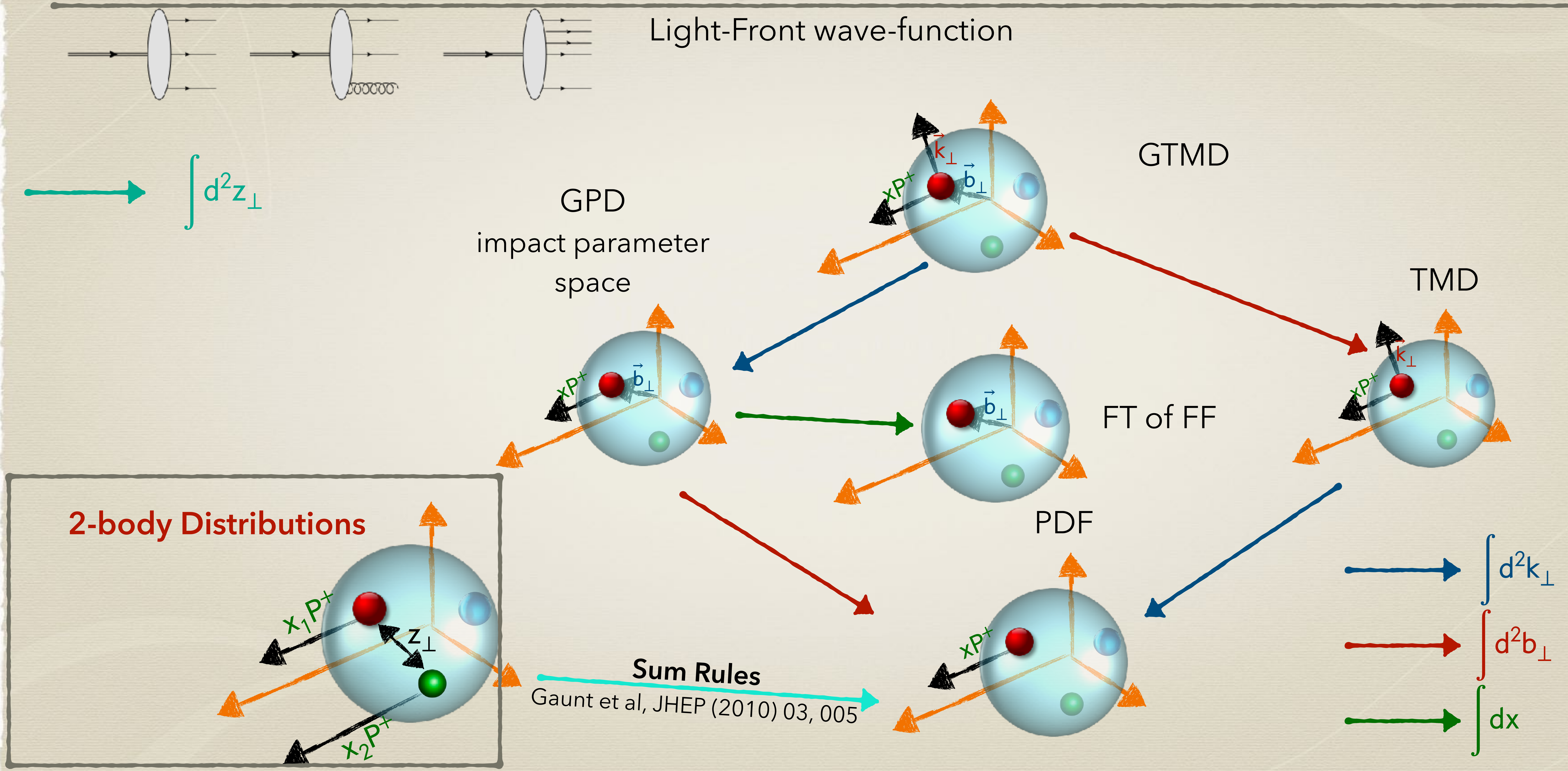


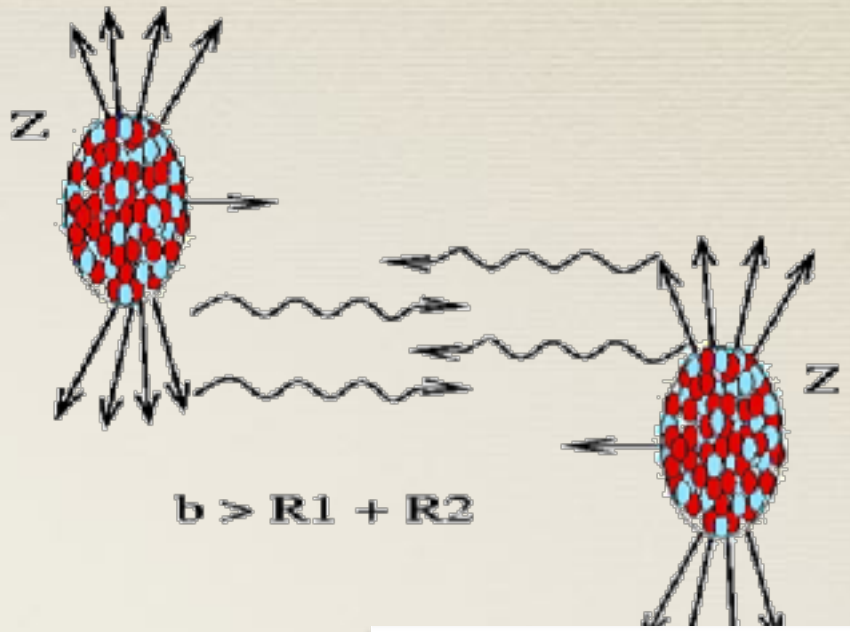
J/ψ electroproduction on light-nuclei

Gluon shadowing in UPC collisions @ LHC

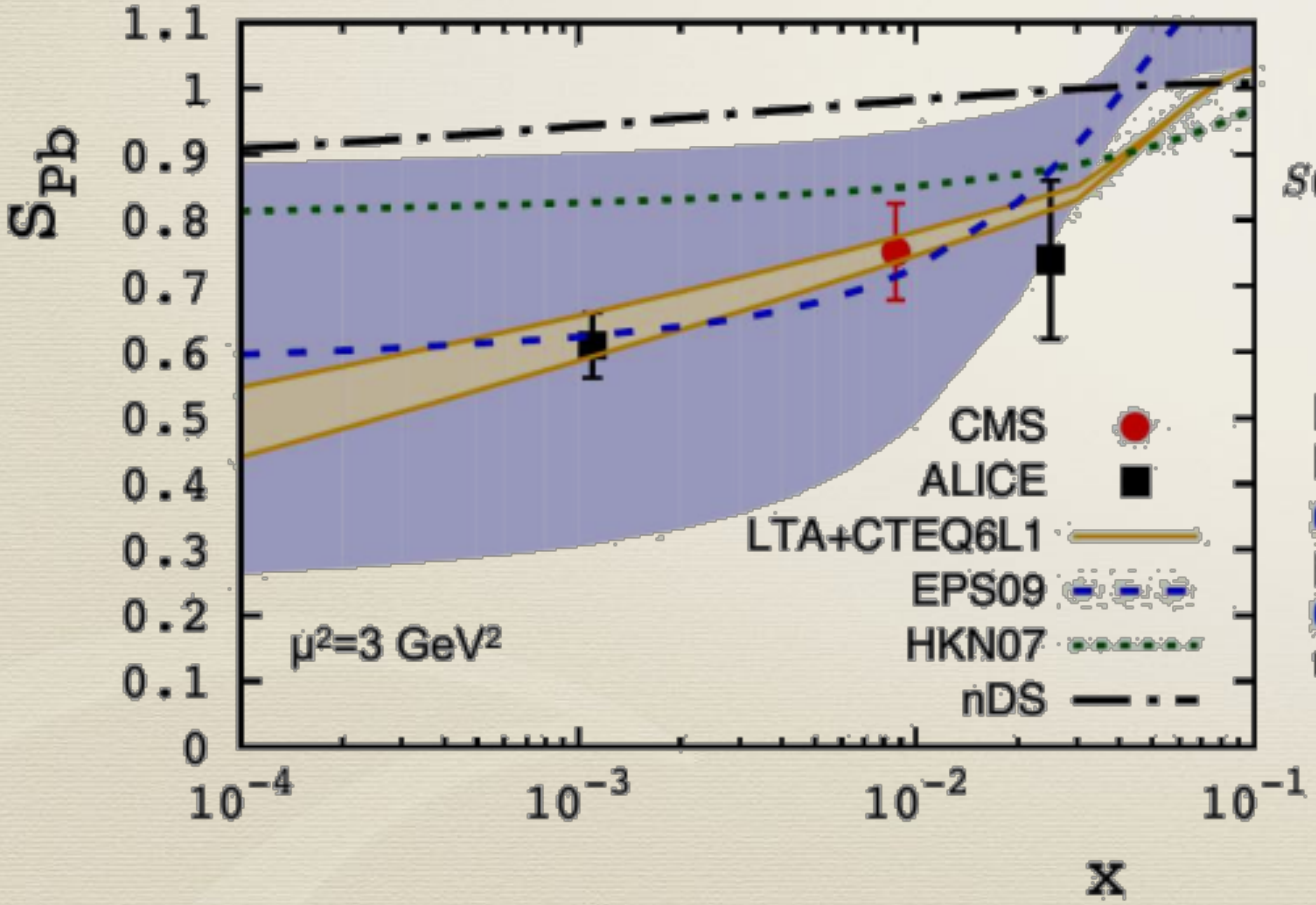
Large (up to 40%) Leading twist (LT) shadowing in:

$\gamma + Pb/Au \to \rho(J/\Psi) + Pb/Au$ Explained/predicted

(**Frankfurt, Guzey, Strikman Phys. Rep. 512 (2012) 255**)



Abbas *et al.* [ALICE], EPJ C 73 (2013) 2617; CMS Collab., PLB 772 (2017) 489 ⟶ suppression factor S_{Pb}



$$S(W_{\gamma p}) = \left[\frac{\sigma_{\gamma Pb \to J/\psi Pb}}{\sigma^{IA}_{\gamma Pb \to J/\psi Pb}}\right]^{1/2} = \kappa_{A/N}\frac{G_A(x,\mu^2)}{AG_N(x,\mu^2)}$$

Introduction. Studies of nuclear shadowing have a long history [1–5]. In quantum mechanics and in the eikonal limit, it is manifested in the total hadron-nucleus cross section being smaller than the sum of individual hadron-nucleon cross sections. In essence, this is due to simultaneous interactions of the projectile with $k \geq 2$ nucleons of the nuclear target, leading to a reduction (shadowing) of the total cross section. In this frame-

LTA: Guzey, Zhalov JHEP 1310 (2013) 207
EPS09: Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065
HKN07: Hirai, Kumano, Nagai, PRC 76 (2007) 065207
nDS: de Florian, Sassot, PRD 69 (2004) 074028

J/ψ electroproduction on light-nuclei

- Problem:
  @ EIC/LHC it is challenging to measure coherent scattering at $t \neq 0$ for $A \simeq 200$; Large coherence length: information on interactions with many nucleons, in average

- Solution:
  use the lightest nuclei, especially ^3He and ^4He, to study coherent effects for interactions with exactly 2 nucleons in the range of $0 < -t < 0.5$ GeV2 .

Complementary measurements with light ion beams @ the EIC:

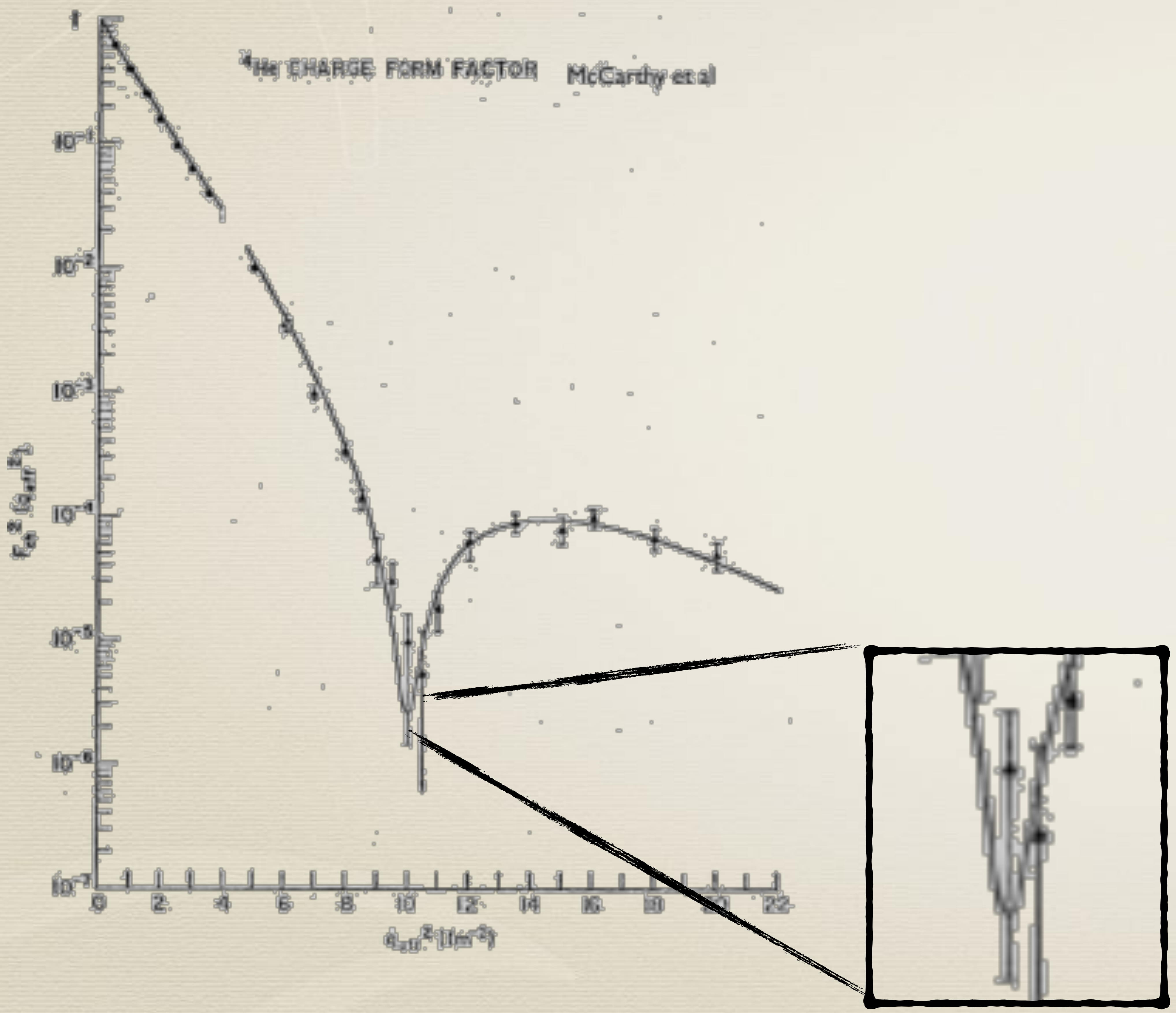
- Scattering off 2 and 3 nucleons can be separately probed
- no excited states -> easy to select coherent events

Here:

Results on J/Ψ diffractive electro-production off ^3He – ^4He

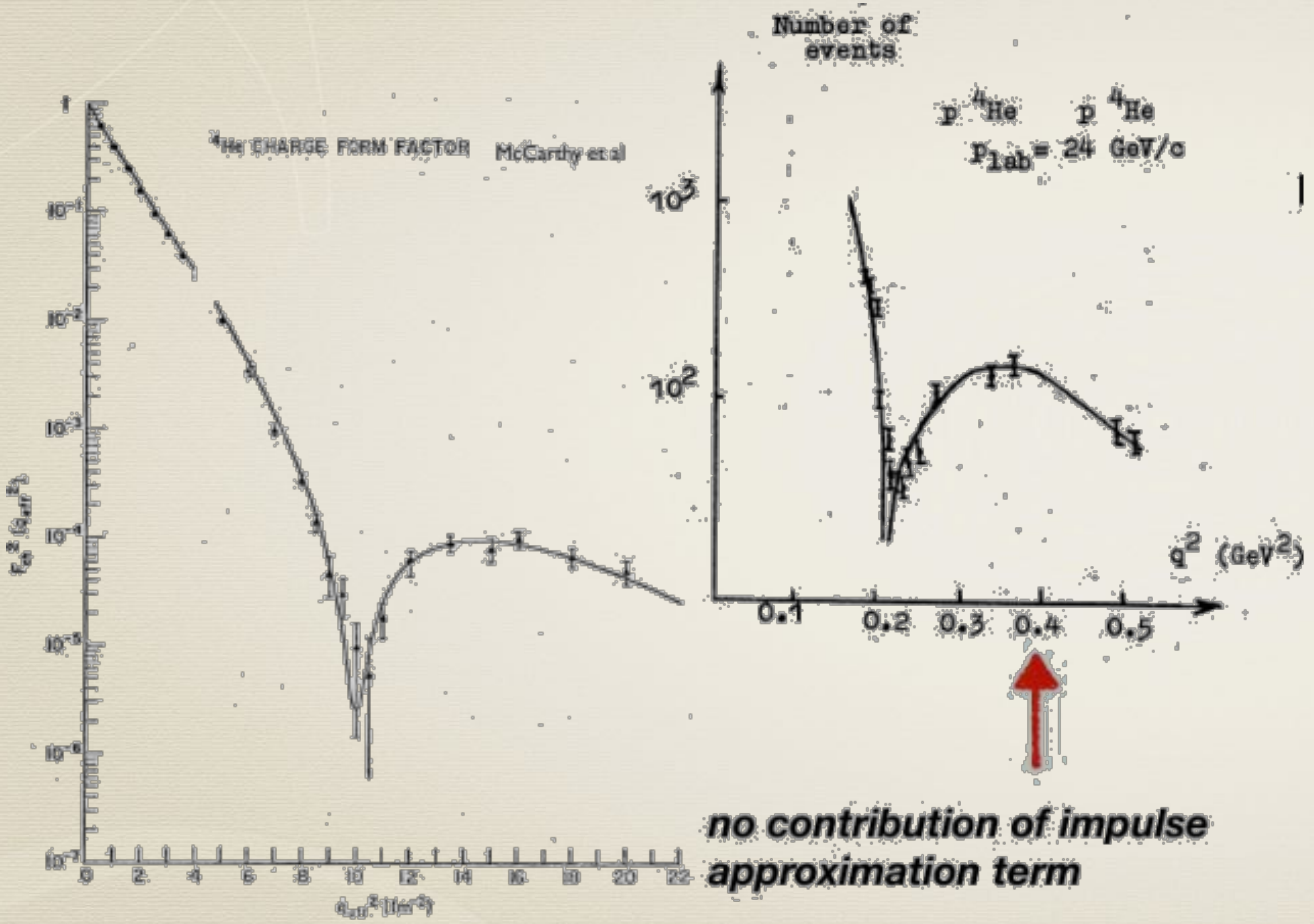
V. Guzey, M. R., S. Scopetta, M. Strikman and M. Viviani, PRL 129 (2022) 24, 24503

J/ψ electroproduction on light-nuclei



- ^{4}He charge FF, dominated by one-body dynamics (IA) presents the first diffraction minimum at: $-t \simeq 0.4$ GeV^2

J/ψ electroproduction on light-nuclei



no contribution of impulse approximation term

- ^{4}He charge FF, dominated by one-body dynamics (IA) presents the first diffraction minimum at: $-t \simeq 0.4$ GeV^2
- around this value of t, the cross section in p +^{4}He -> p +^{4}He is dominated by effects beyond IA: multinucleon interactions, gluon shadowing for hard processes

J/ψ electroproduction on light-nuclei

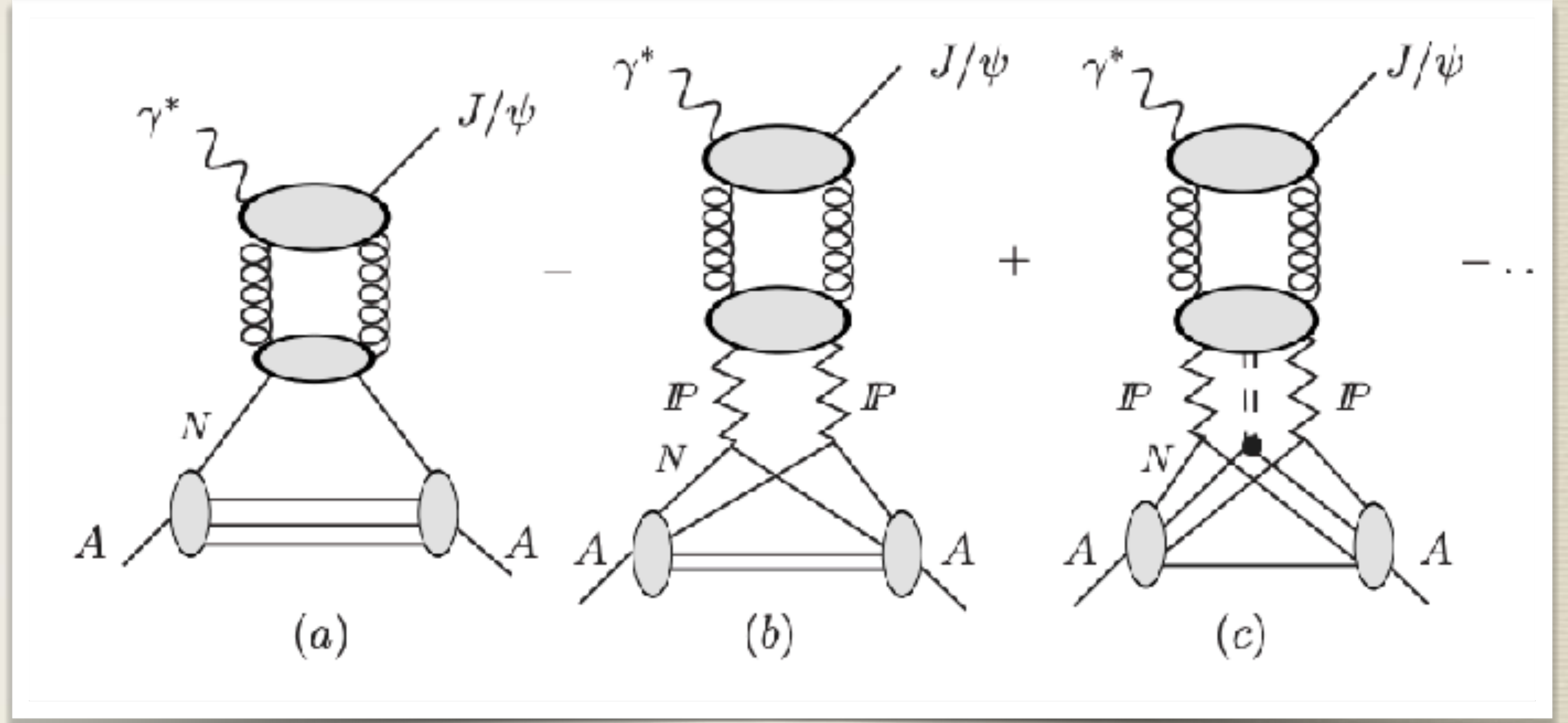
$$\frac{d\sigma_{\gamma^* A \to VA}}{dt} = \frac{d\sigma_{\gamma^* N \to VN}}{dt}(t=0)\left|F_1(t)e^{(B_o/2)t} + \sum_{k=2}^{4} F_k(t)\right|^2$$

$$F_k(q) = \left(\frac{i}{8\pi^2}\right)^{k-1} C_n^k\, A_k \int \prod_{l=1}^{k} d^2 q_l\, f(q_l)\Phi_k(q, q_l)\,\delta\left(\sum_l q_l - q\right) \quad k = 2,3,4$$

$$F_1(q) = 4\Phi_1(q) \qquad f(q_l) = scattering\ amplitude\ for\ J/\Psi N \to J/\Psi N$$

$$A_{k>1} = \frac{<\sigma^k>}{<\sigma>}\frac{(1-i\eta)^k}{1-i\eta_0};\ the\ \ same\ used\ in\ UPC\ studies!$$

LT parton shadowing for J/Ψ coherent production off He (gluon GPDs in He)
(**Frankfurt, Guzey, Strikman Phys. Rep. 512 (2012) 255**)



Parameters:

- B_0
- η (η_0)=Re(f)/Im(f) for $\gamma p \to J/\psi p$ ($J/\psi p \to J/\psi p$)

- moments < σ^i > chosen for the specific final state and the specific kinematics **(Guzey et al. PRC 93 (2016) 055206).**

The model has been tested in J/Ψ photoproduction in Pb-Pb UPCs at the LHC(**V. Guzey and M. Zhalov, JHEP 10, 207 (2013)**)

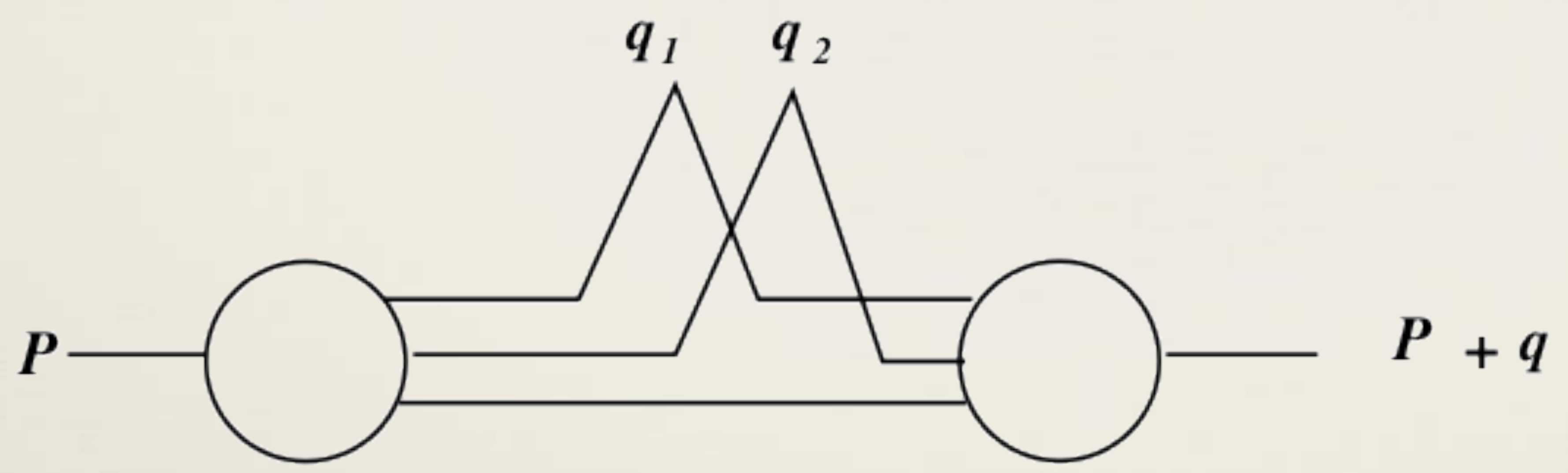
- Φ_k "k-body form factor", is the nuclear input

J/ψ electroproduction on light-nuclei

$$\Phi_k(\vec{q}_1,\dots\vec{q}_k) = \int \prod_{i=N}^{4} \left\{ \frac{d\vec{p}_i}{(2\pi)^3} \right\} \psi^*_{P'}(\vec{p}_1+\vec{q}_1,\dots\vec{p}_k+\vec{q}_k,\dots,\vec{p}_N)\,\psi_P(\vec{p}_1,\dots,\vec{p}_k,\dots\vec{p}_N)\,\delta\left(\sum_{i=1}^{N}\vec{p}_i\right)$$

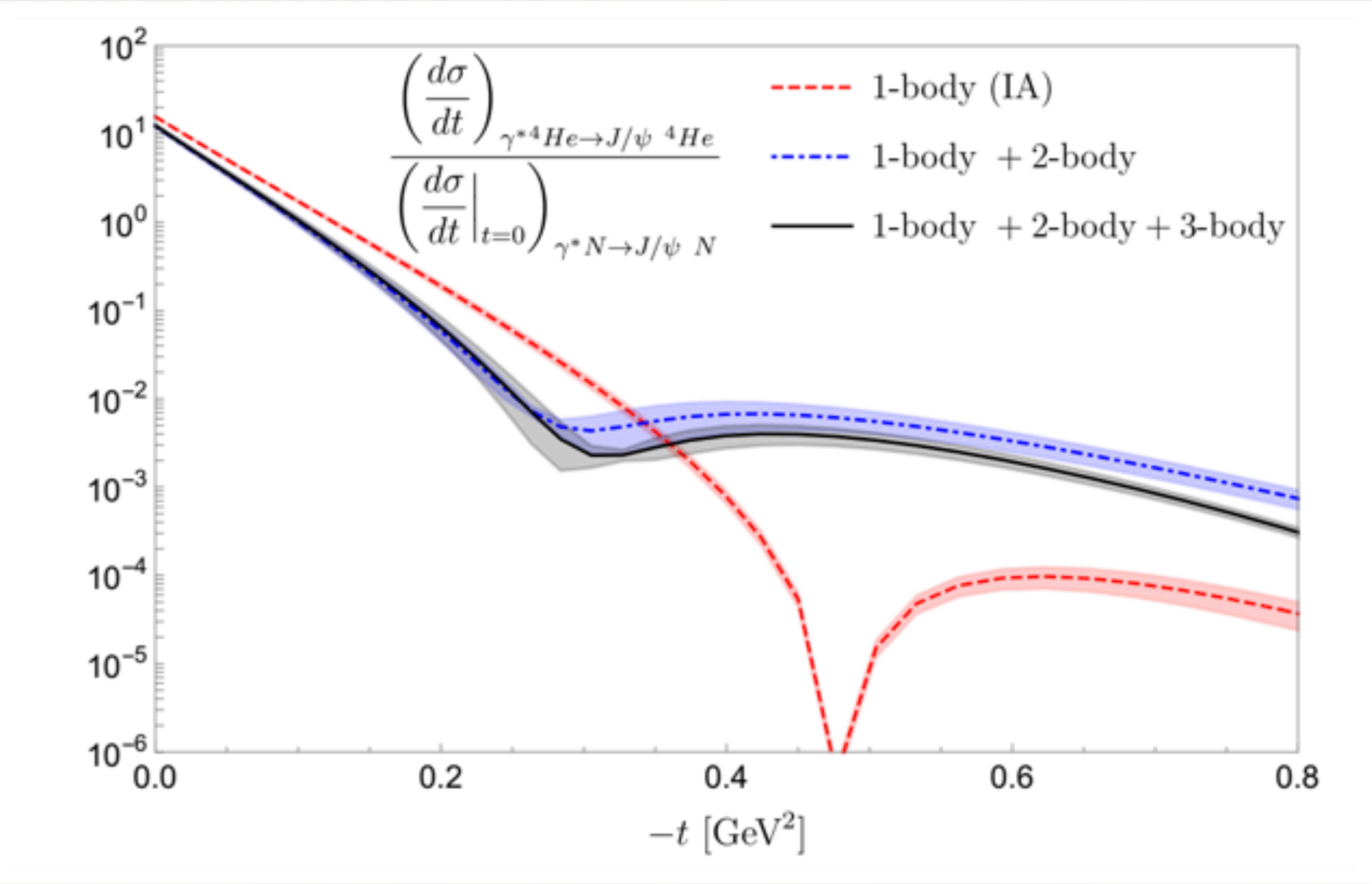
- Φ_1 (IA, very important here), Φ_2 and Φ_3 evaluated using the realistic w. f. obtained by the Pisa group using: *a)* Av18 for ^{3}He *b)* the N4LO chiral potential (D. R. Entem, R. Machleidt, Y. Nosyk, Phys. Rev. C 96, 024004 (2017)) for ^{4}He

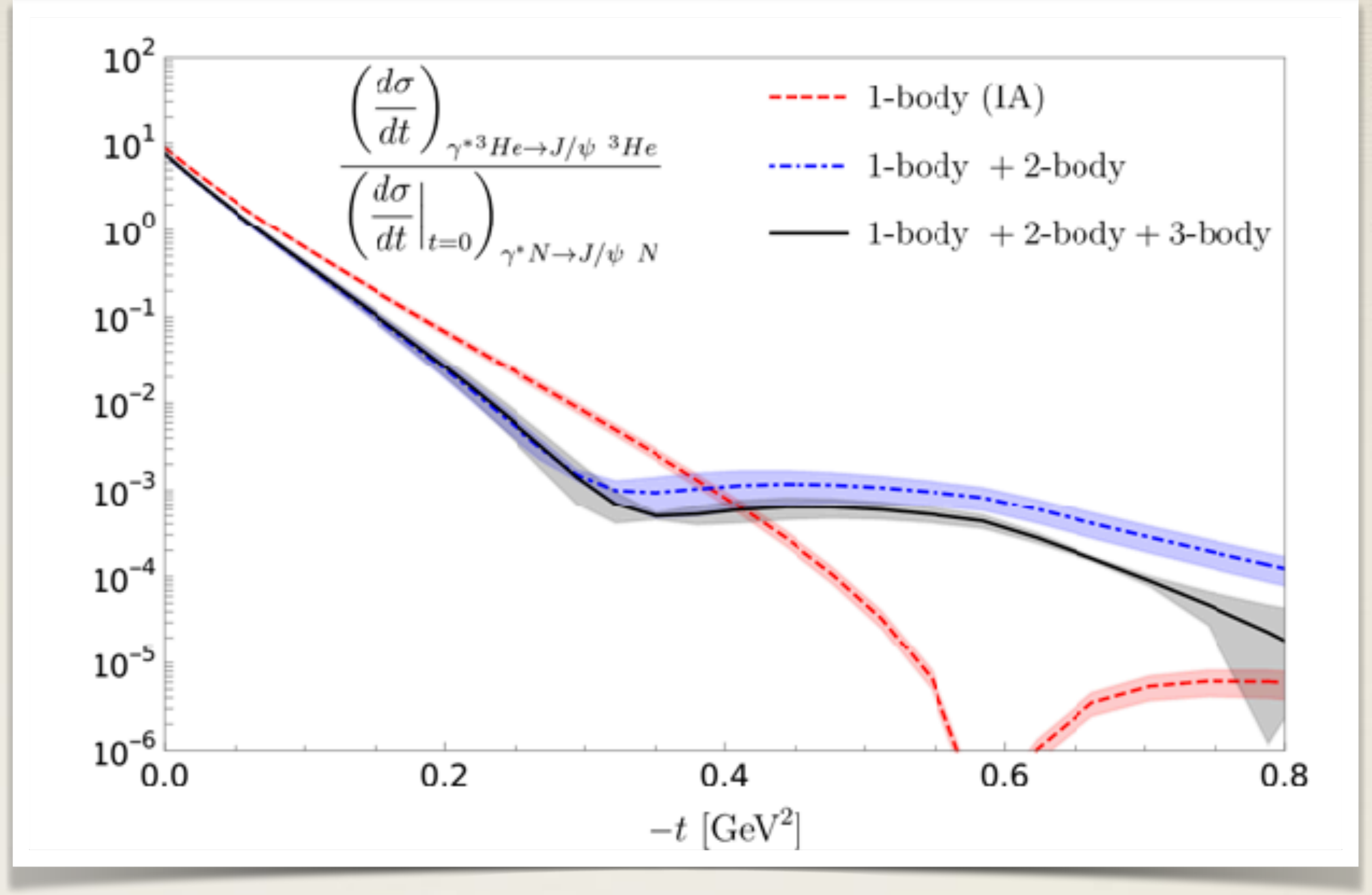
- Example of Φ_2 :



- we remark that $\Phi_2(k_\perp, -k_\perp)$ is the same quantity appearing in the double parton scattering

J/Ψ exclusive production @EIC: xB ≈ 10-3





Error bars account:

-10% of variation for B_0

-15 of variation in < σ^2 >

✔ 1-body + 2-body re-scatterings dominate the cross-sections shift of the minimum due to 2-body dynamics

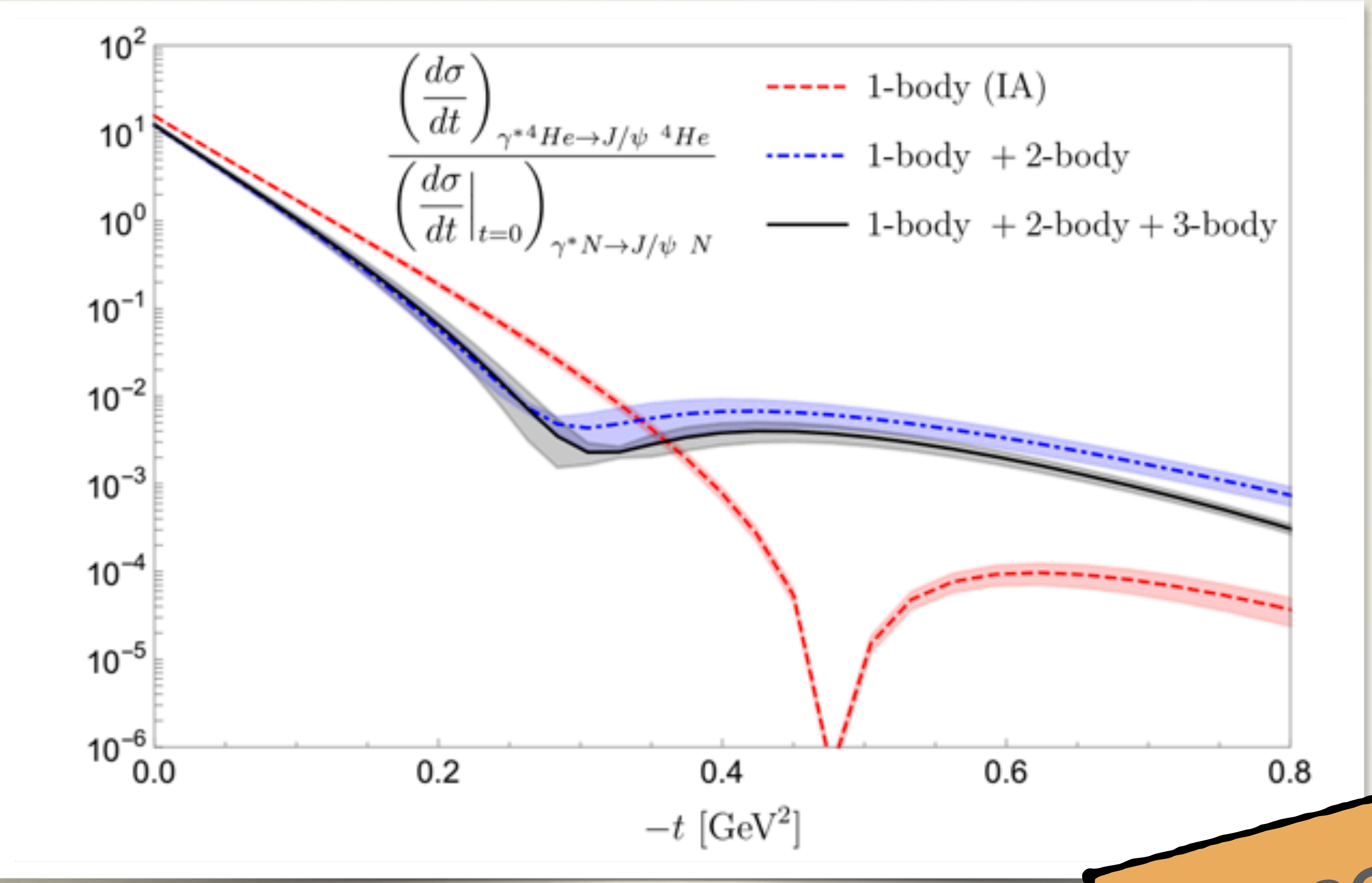
✔ 1-body dynamics under theoretical control: very good chances to disentangle

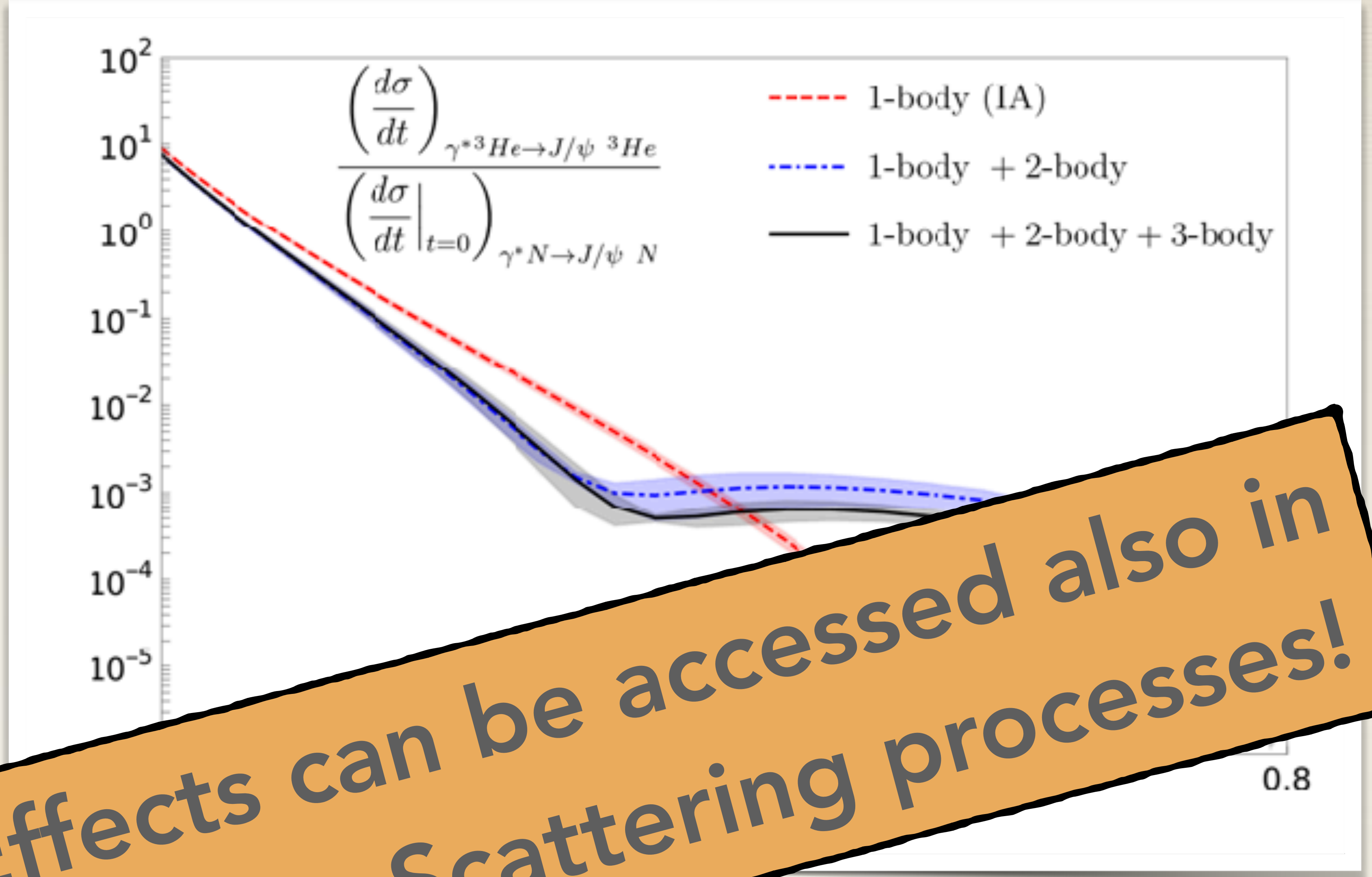
✔ 2-body dynamics (LT gluon shadowing)

✔ unique opportunity to access the real part of the scattering amplitudes in a wide range of t

✔ The position of the minimum is extremely sensitive to dynamics and the structure!

J/Ψ exclusive production @EIC: xB ≈ 10-3





These Effects can be accessed also in Double Parton Scattering processes!

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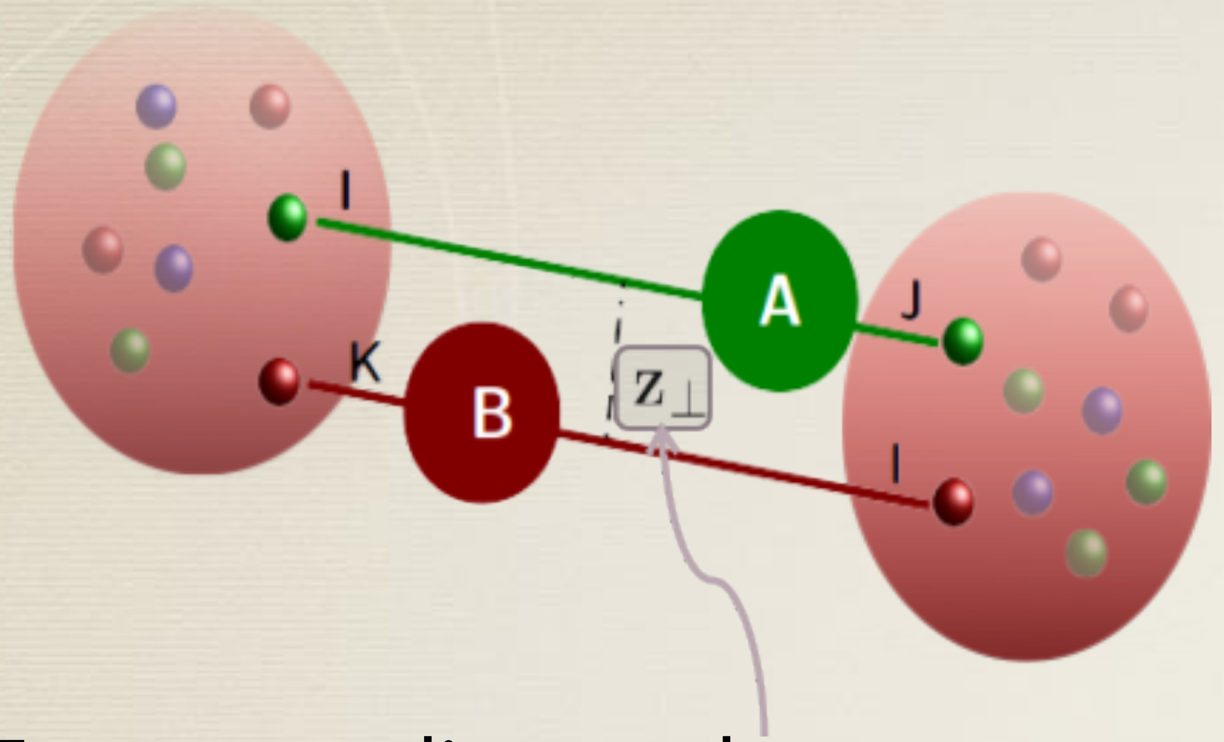
Double Parton Scattering

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



Transverse distance between two partons

$$d\sigma \propto \int d^2z_\perp \, F_{ij}(x_1, x_2, z_\perp, \mu_A, \mu_B) F_{kl}(x_3, x_4, z_\perp, \mu_A, \mu_B)$$

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

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

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

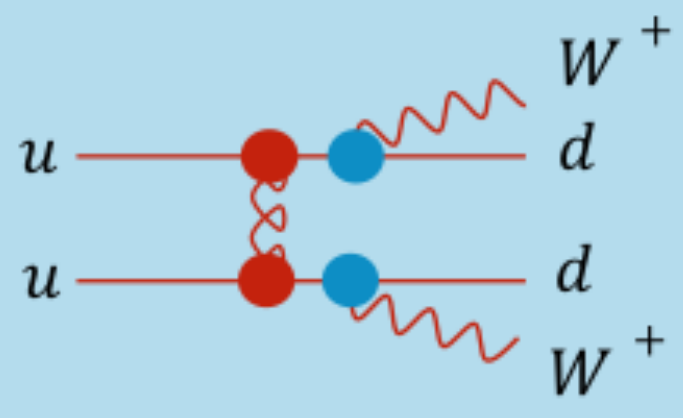
$$\hat{O}(\lambda_k) = \frac{\not{n}}{2}\frac{1 + \lambda_k\gamma_5}{2} \,.$$

Where and Why DPS?

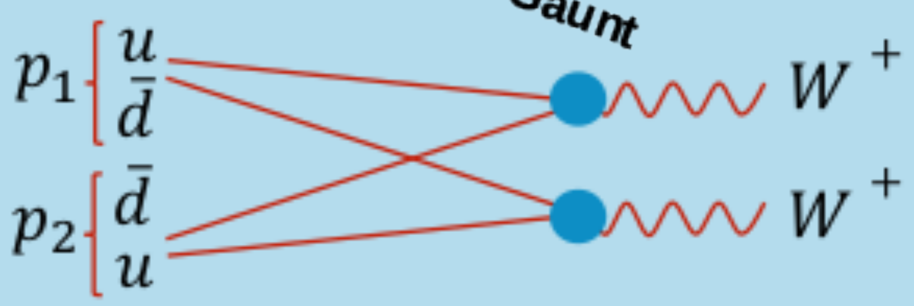
DPS can give a significant contribution to processes where SPS is suppressed by small/multiple coupling constants:

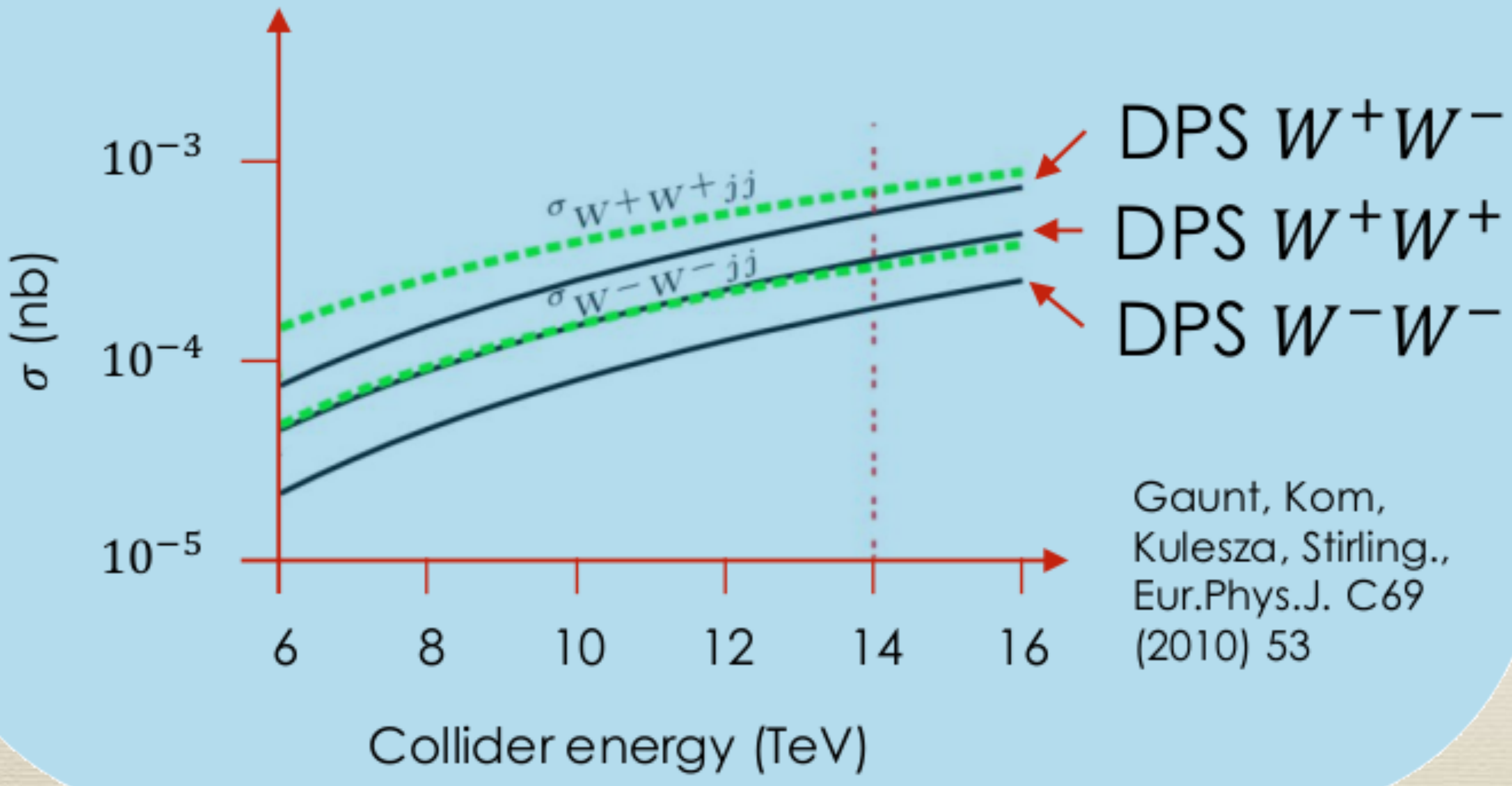
Slide from J. Gaunt

SPS:



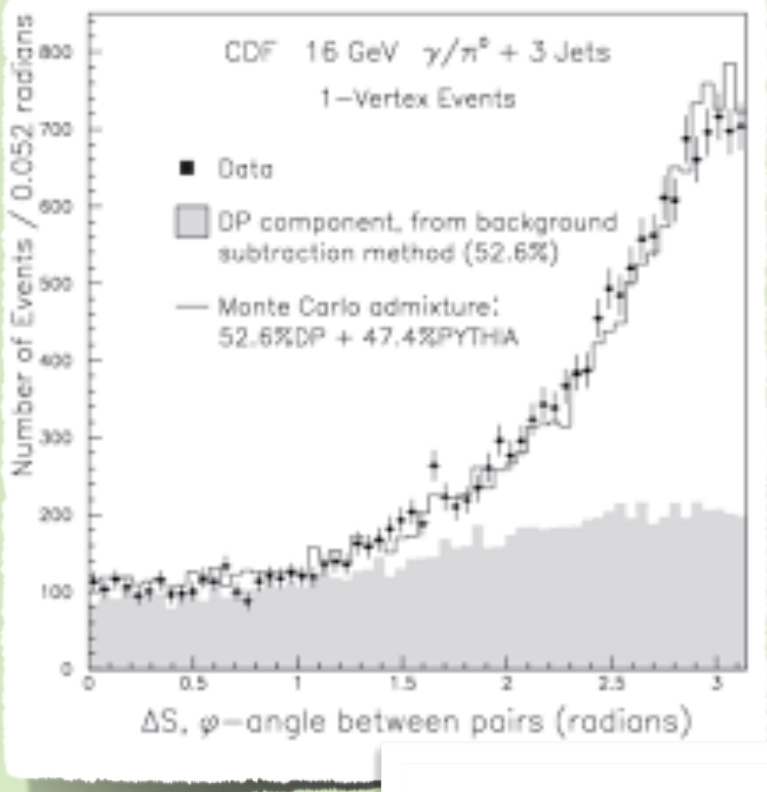
DPS:





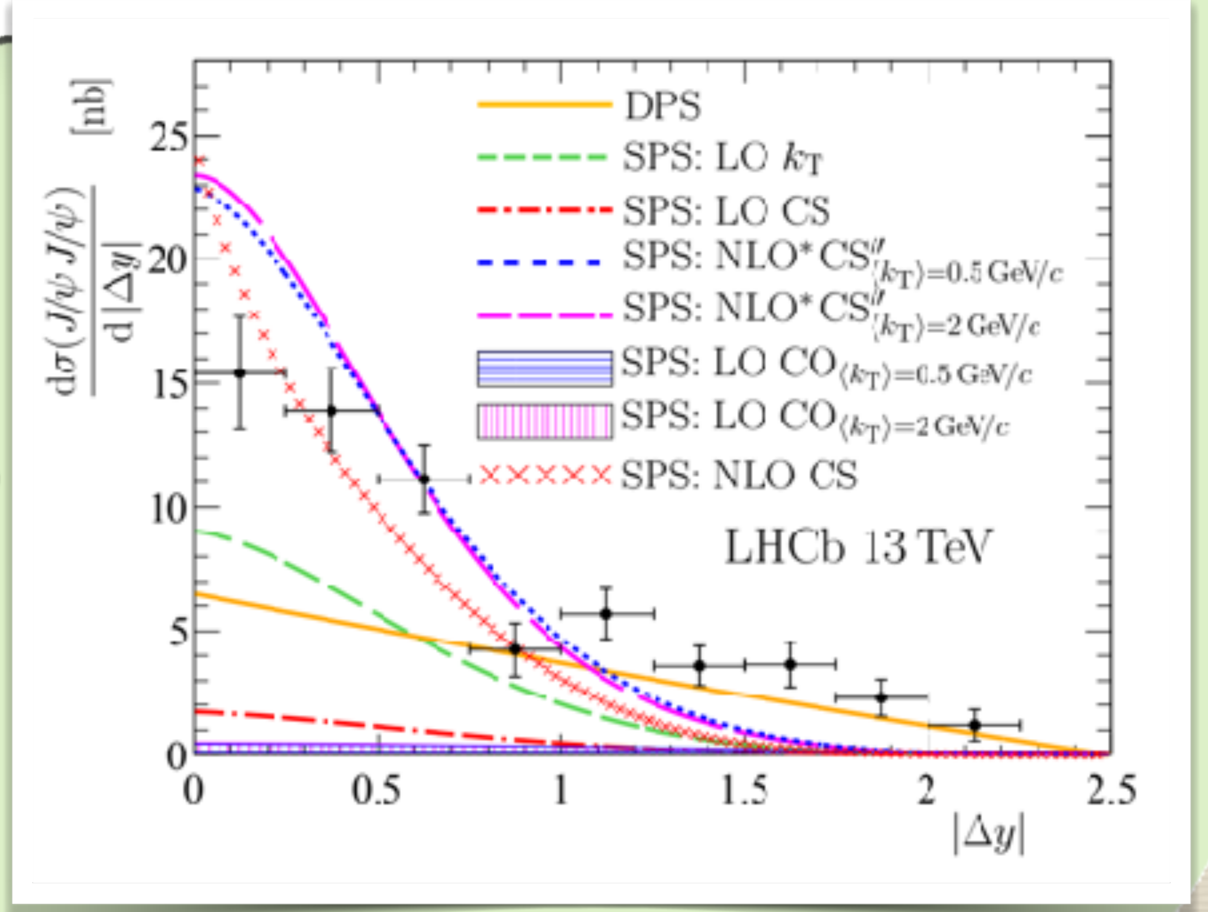
Gaunt, Kom, Kulesza, Stirling., Eur.Phys.J. C69 (2010) 53

…or in certain phase space regions

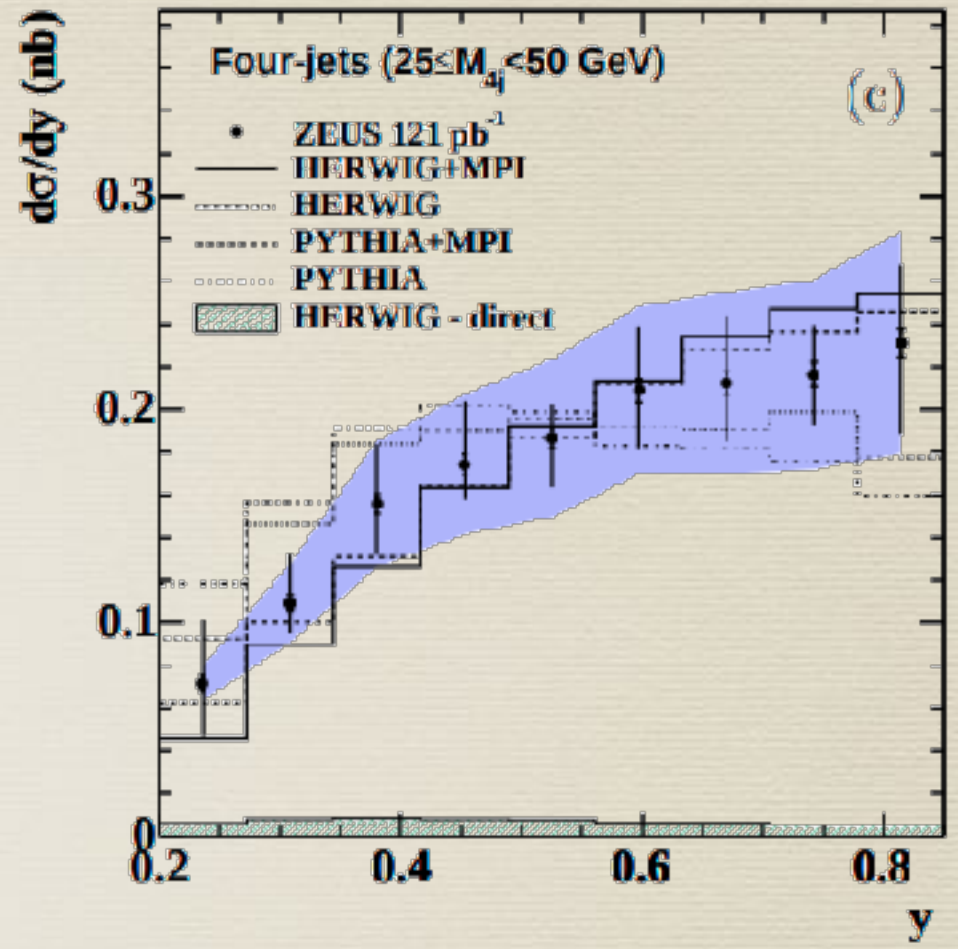


CDF, $\gamma + 3j$, Phys.Rev. D56 (1997) 3811-3832

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**

Some Data and Effective Cross Section

If DPDs factorize in terms of PDFs then

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

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

POCKET FORMULA

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

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

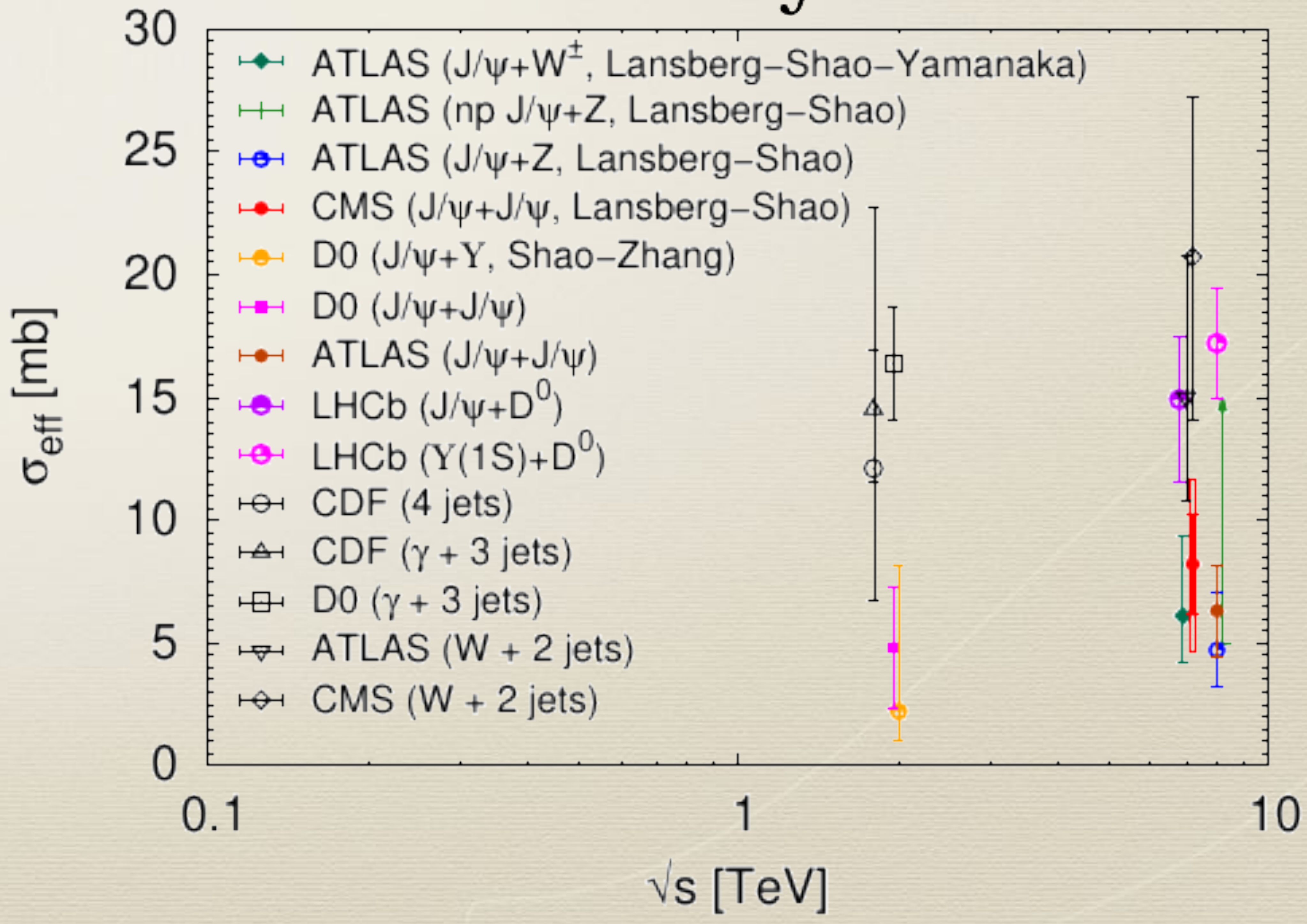
As for the standard FF:

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

From the asymptotic behavior we got the following relation:

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

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



Some Data and Effective Cross Section

If DPDs factorize in terms of PDFs then

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

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

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

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

POCKET FORMULA

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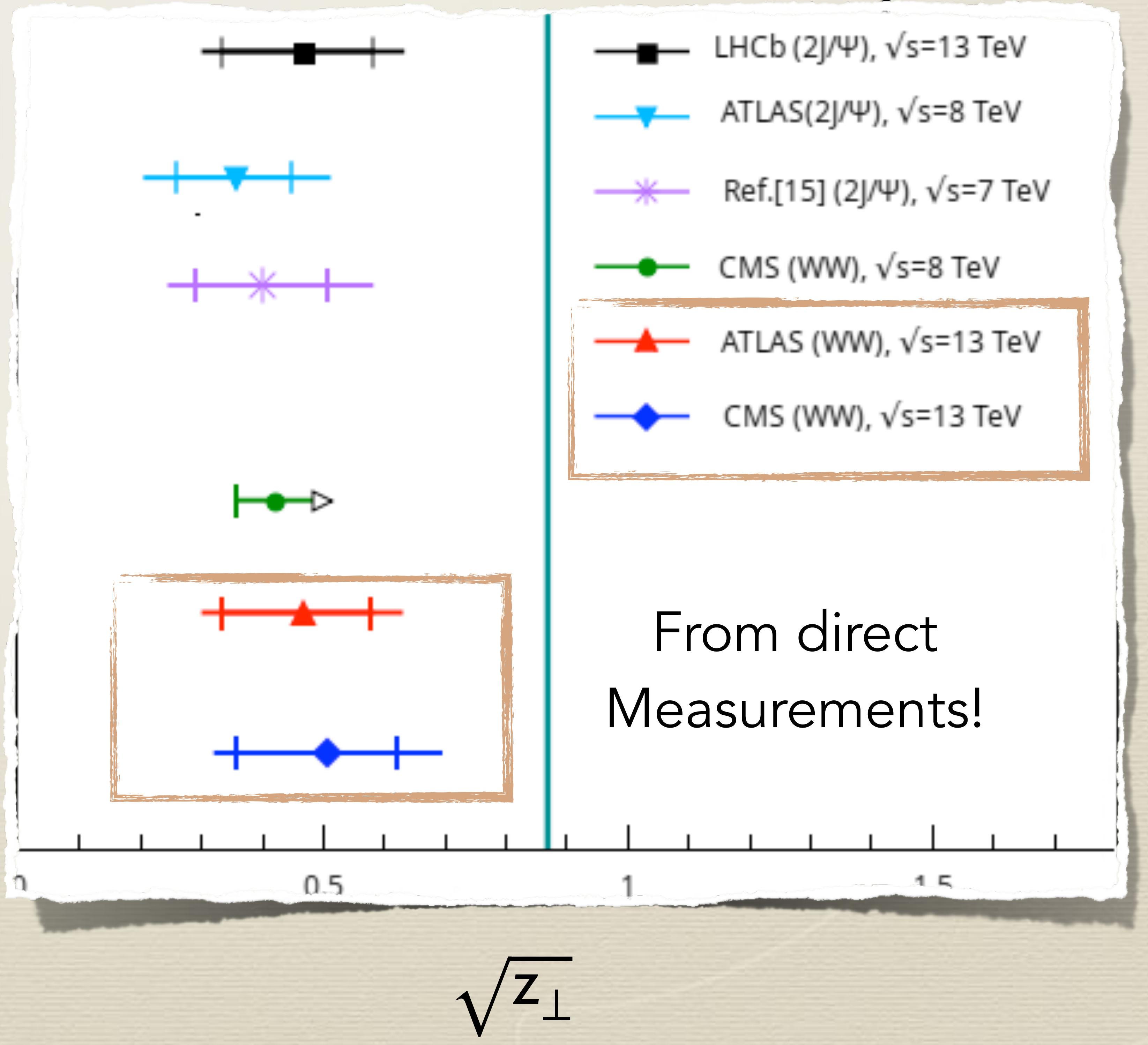
M. R. and F. A. Ceccopieri, PRD 97, no. 7, 071501 (2018)



Some Data and Effective Cross Section

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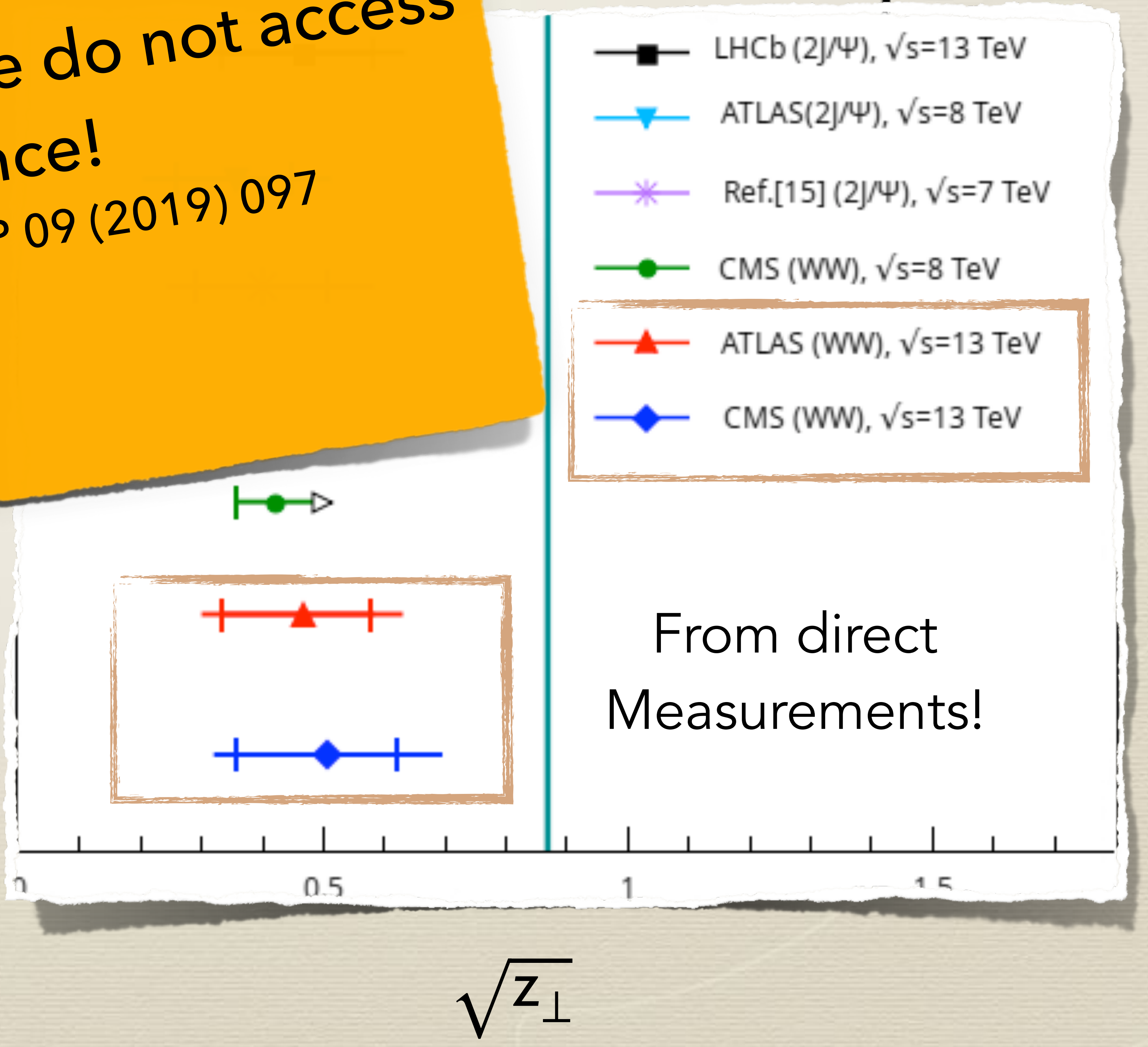
From the asymptotic behavior w

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

In hadron-hadron collisions we do not access directly the distance!

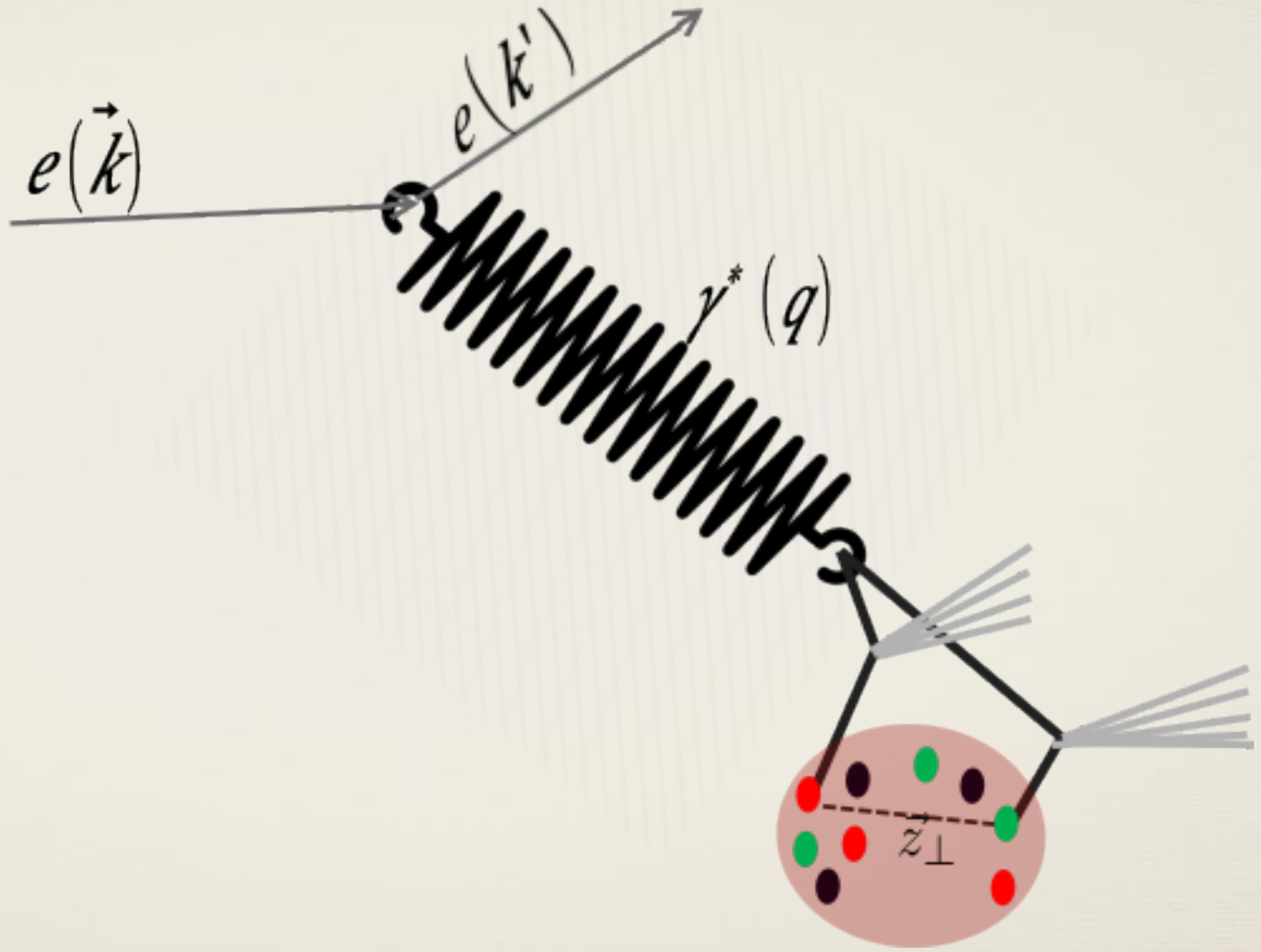
M.R. and F. A. Ceccopieri, JHEP 09 (2019) 097

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



DPS in $\gamma - p$ interactions

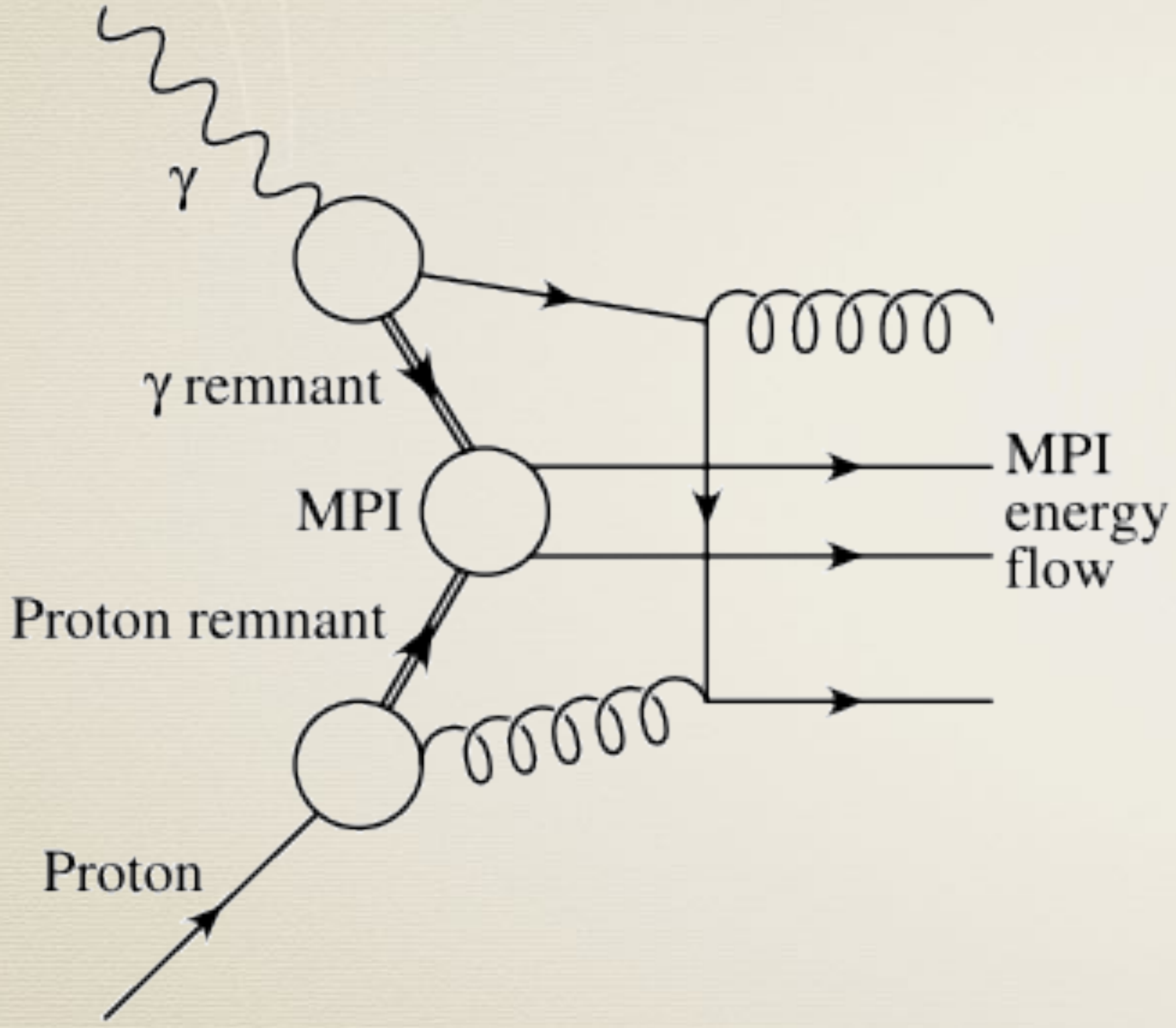
We consider the possibility offered by a DPS process involving a photon FLACTUATING in a quark-antiquark pair interacting with a proton:

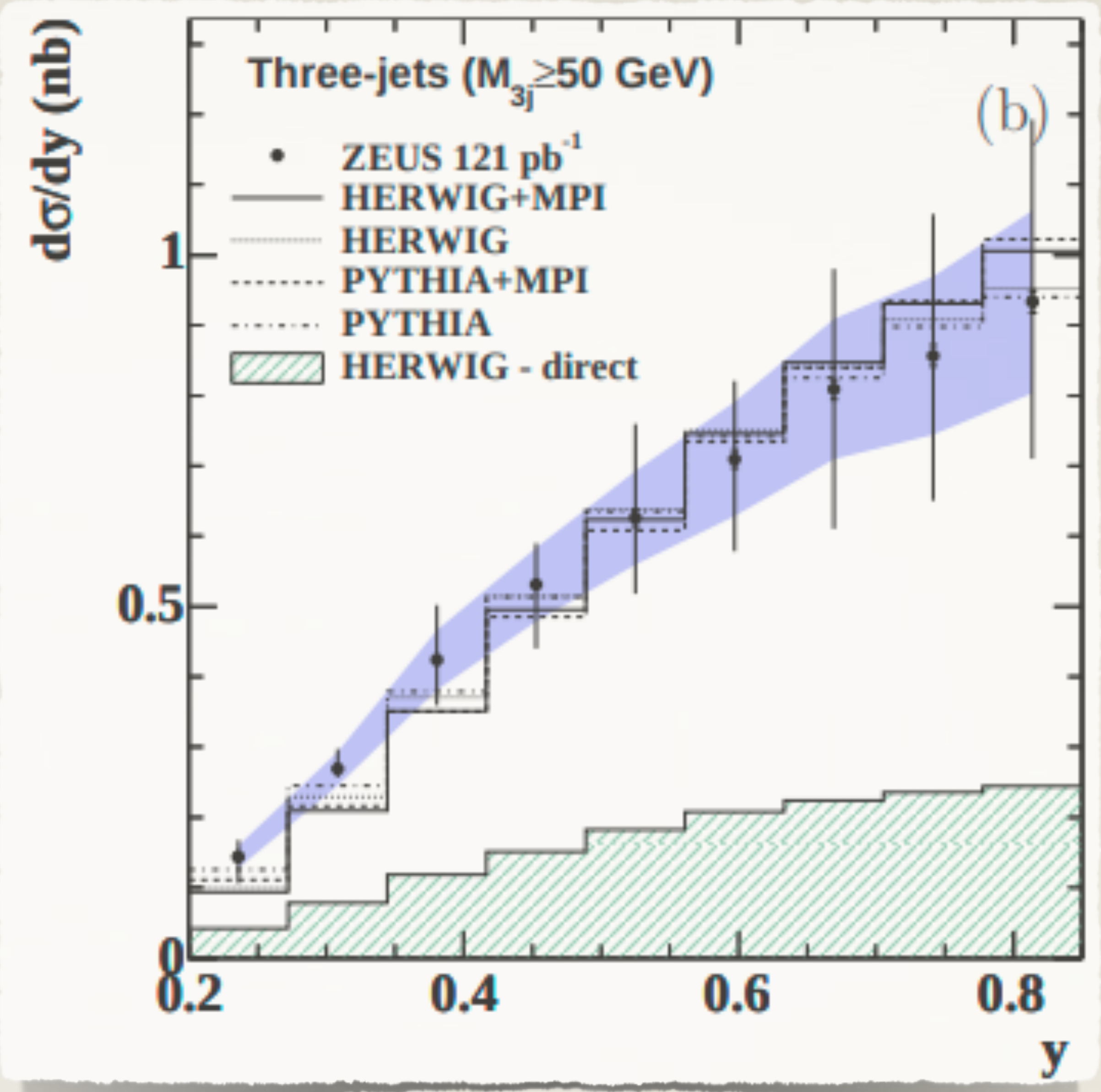


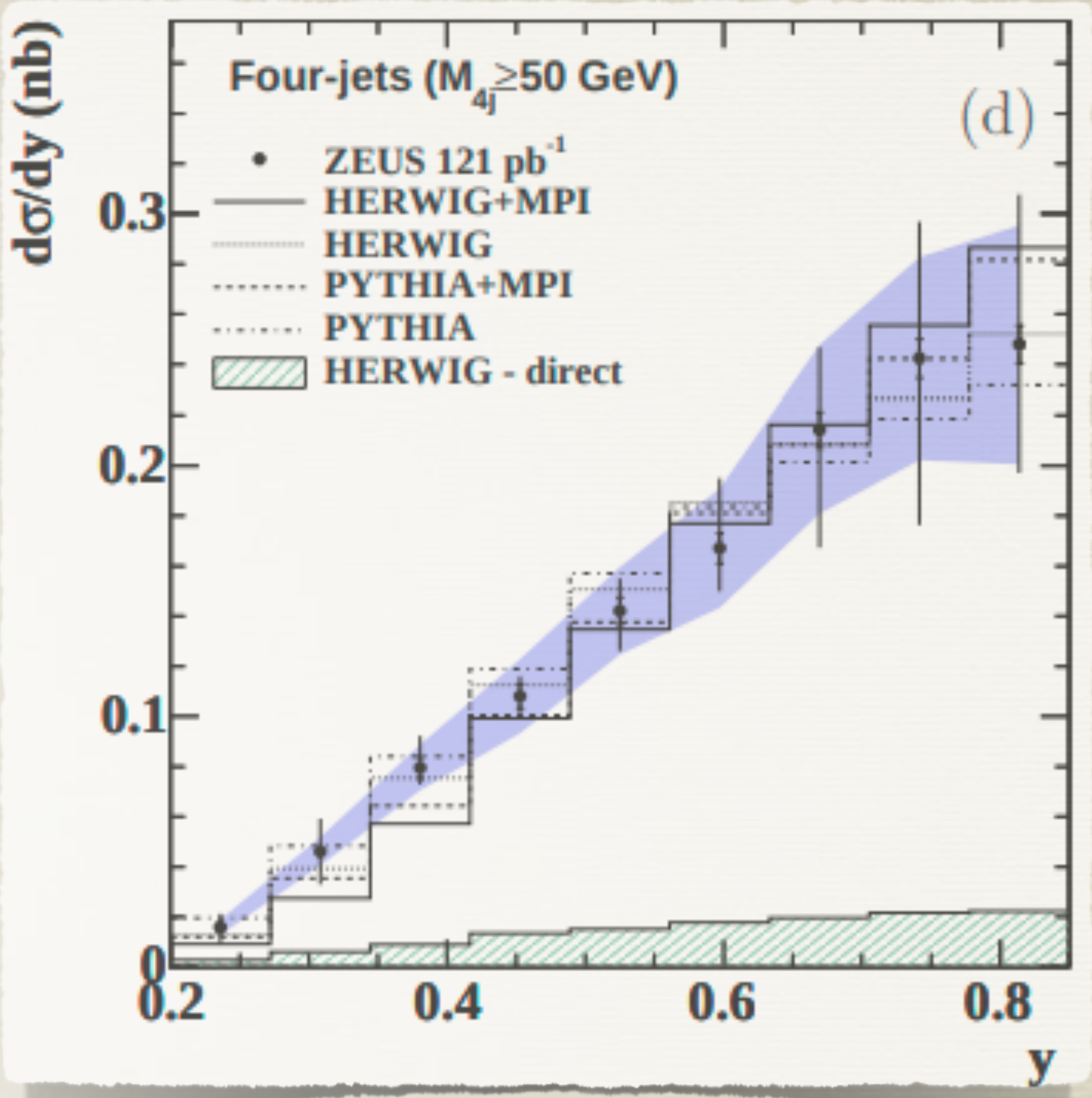
M. R. and F. A. Ceccopieri, PRD 105 (2022) L011501

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)

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:

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

$^*\tilde{F}_2^A(z_\perp) =$ prob. distr. of finding two partons at given transverse distance

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

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

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

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

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

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

In this case we have two mechanisms that contribute:

F. A. Ceccopieri, F. Fornetti, E. Pace, M. Rinaldi, G. Salmè and N. Iles, ``Theoretical insights on nuclear double parton distributions", EPJC accepted, [arXiv:2507.02495 [nucl-th]].

DPS in pA collisions

F. A. Ceccopieri, F. Fornetti, E. Pace, M.R., G. Salmè and N. Iles, [arXiv:2507.02495 [nucl-th]]

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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!

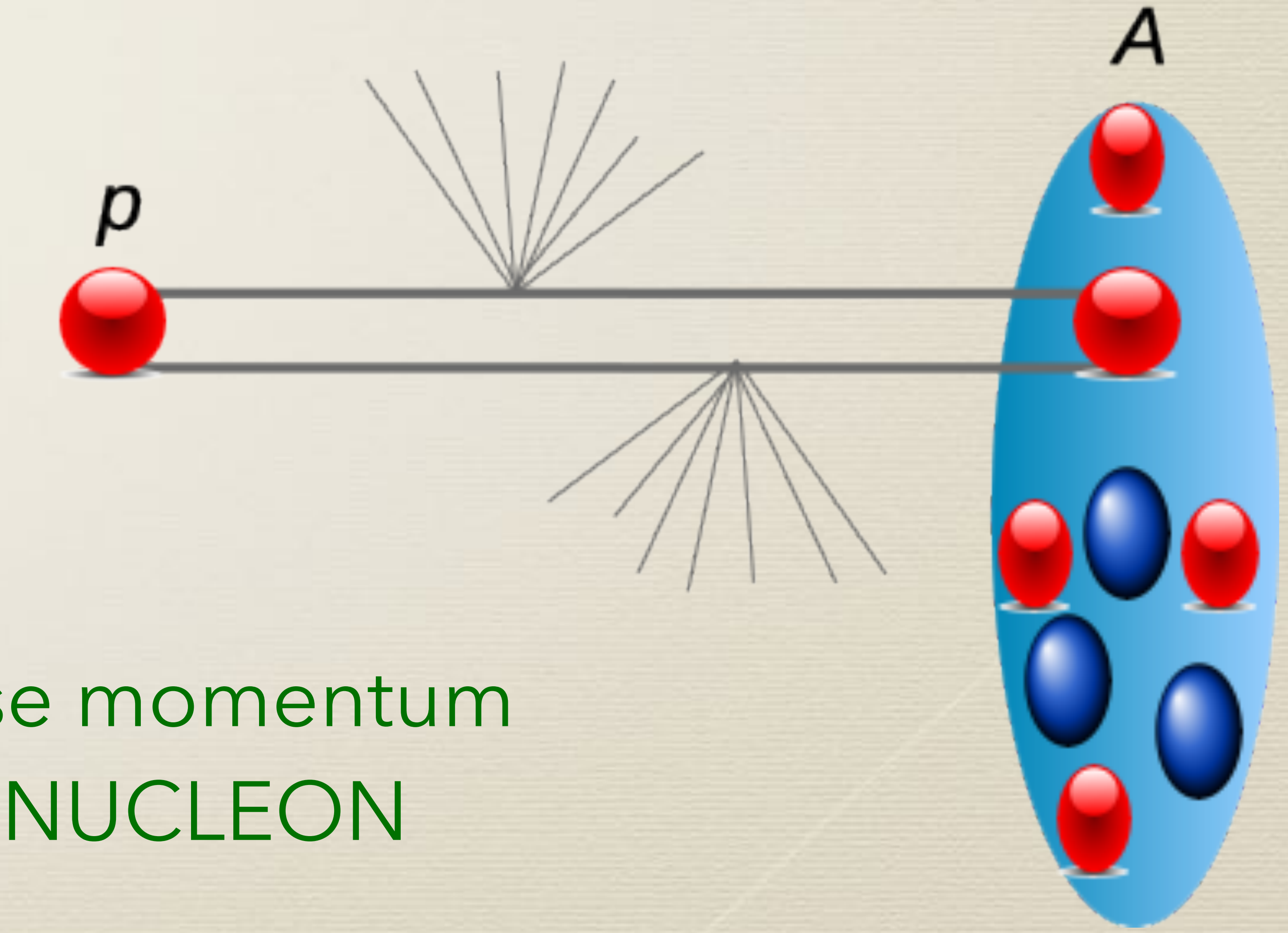
DPD of te nucleon inside the nucleus

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

Momentum fraction carried by a NUCLEON

Light-Cone Momentum Distribution

Transverse momentum of the NUCLEON



DPS in pA collisions

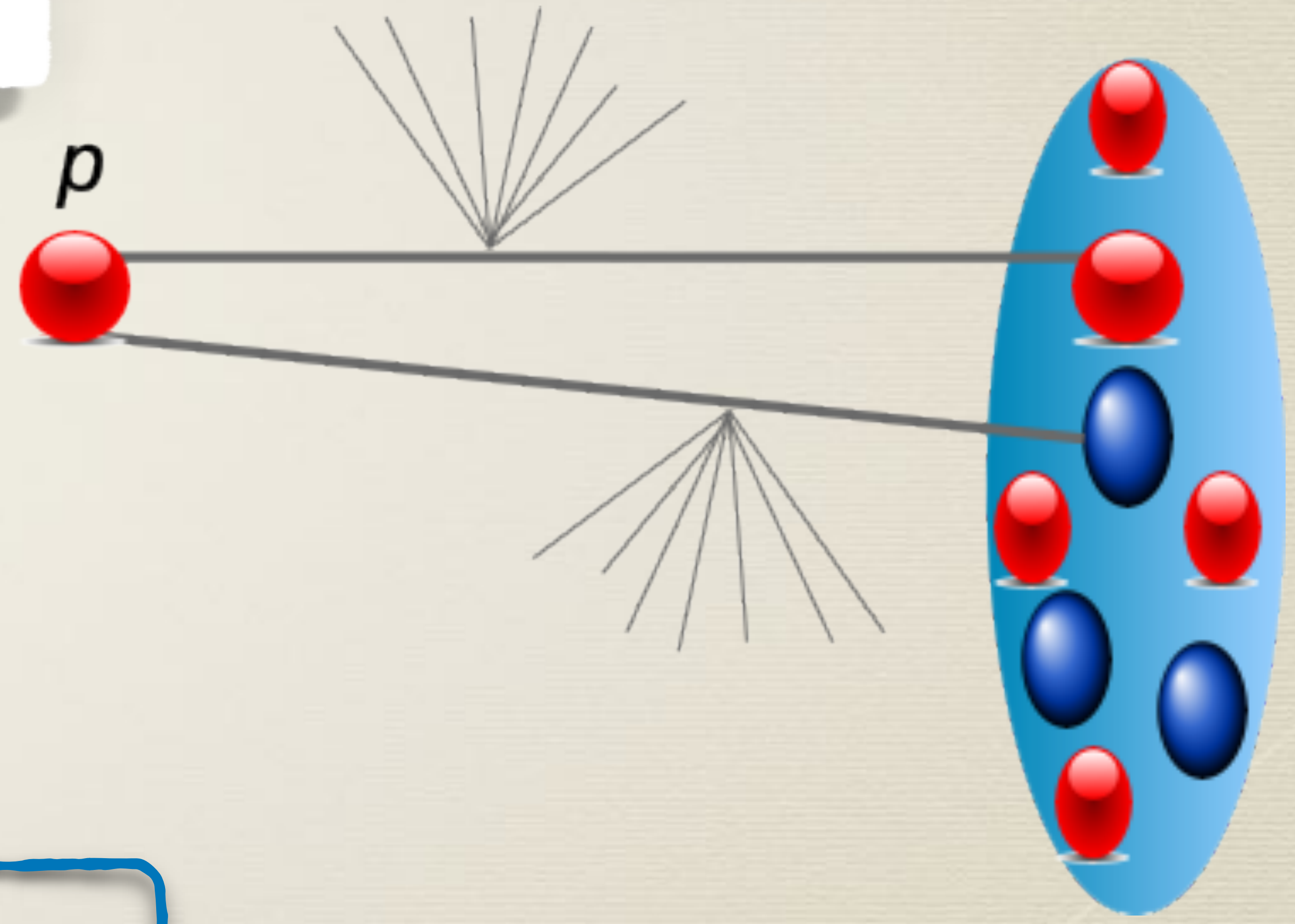
F. A. Ceccopieri, F. Fornetti, E. Pace, M.R., G. Salmè and N. Iles, [arXiv:2507.02495 [nucl-th]]

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

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!



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

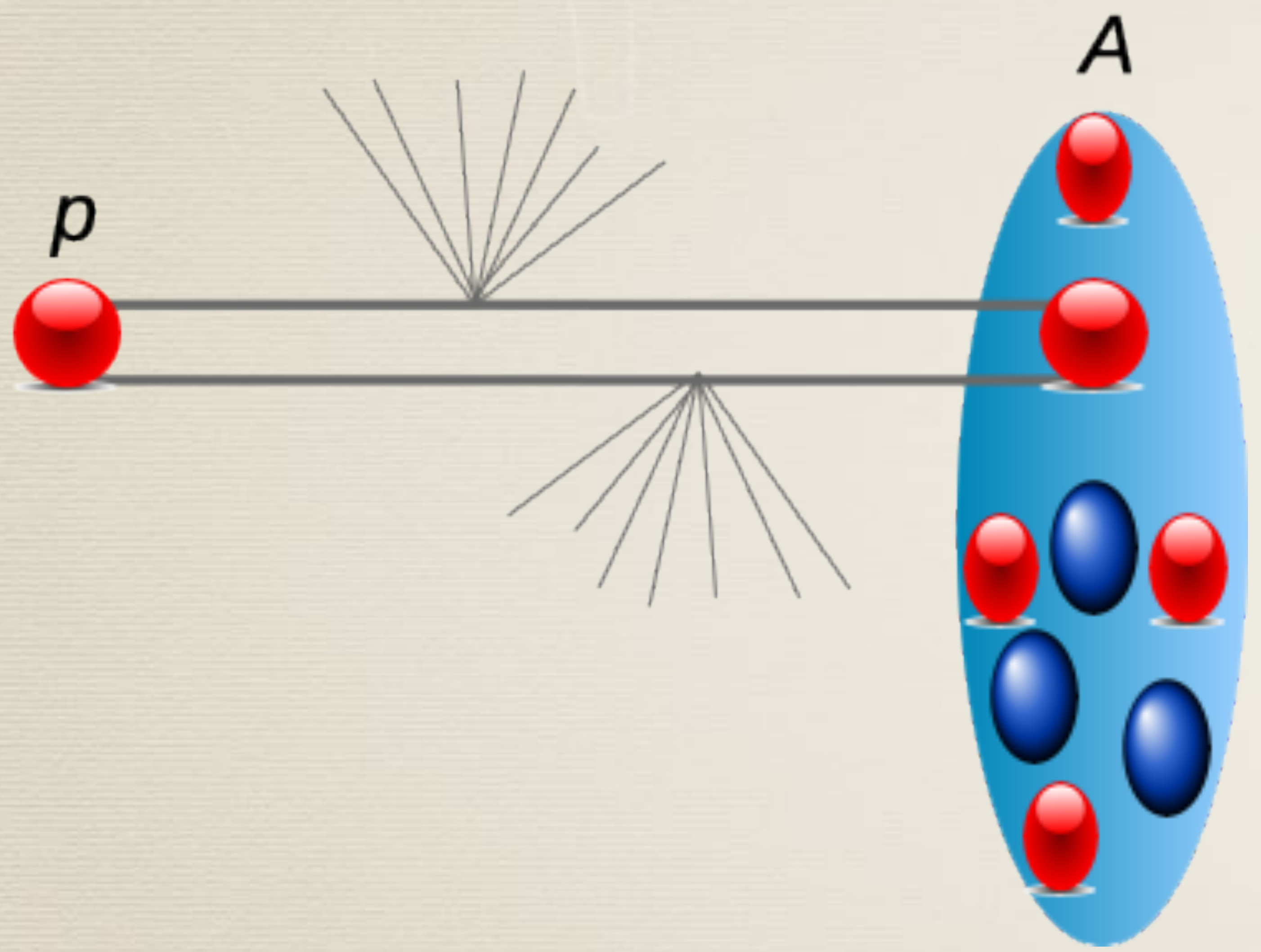
$$\times \psi_A\left(\xi_1, \xi_2, p_{t1} + \vec{k}_\perp, p_{t2} - \vec{k}_\perp, \ldots\right) G_{a_1}^{N_1}\left(x_1/\xi_1, |\vec{k}_\perp|\right) G_{a_2}^{N_2}\left(x_2/\xi_2, |\vec{k}_\perp|\right)$$

Nucleus wf

Nucleon GPD

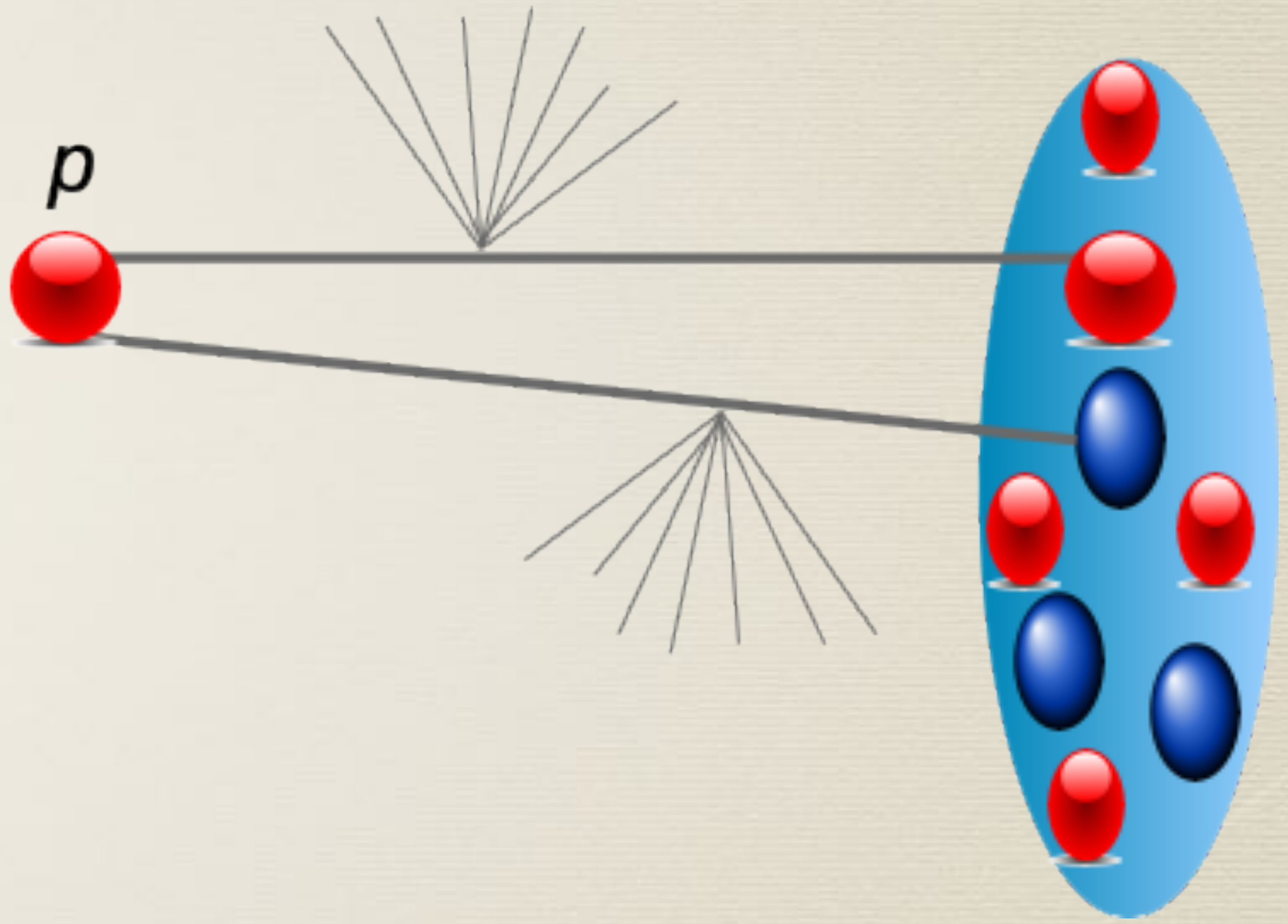
DPS in pA collisions

F. A. Ceccopieri, F. Fornetti, E. Pace, M.R., G. Salmè and N. Iles, [arXiv:2507.02495 [nucl-th]]



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

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



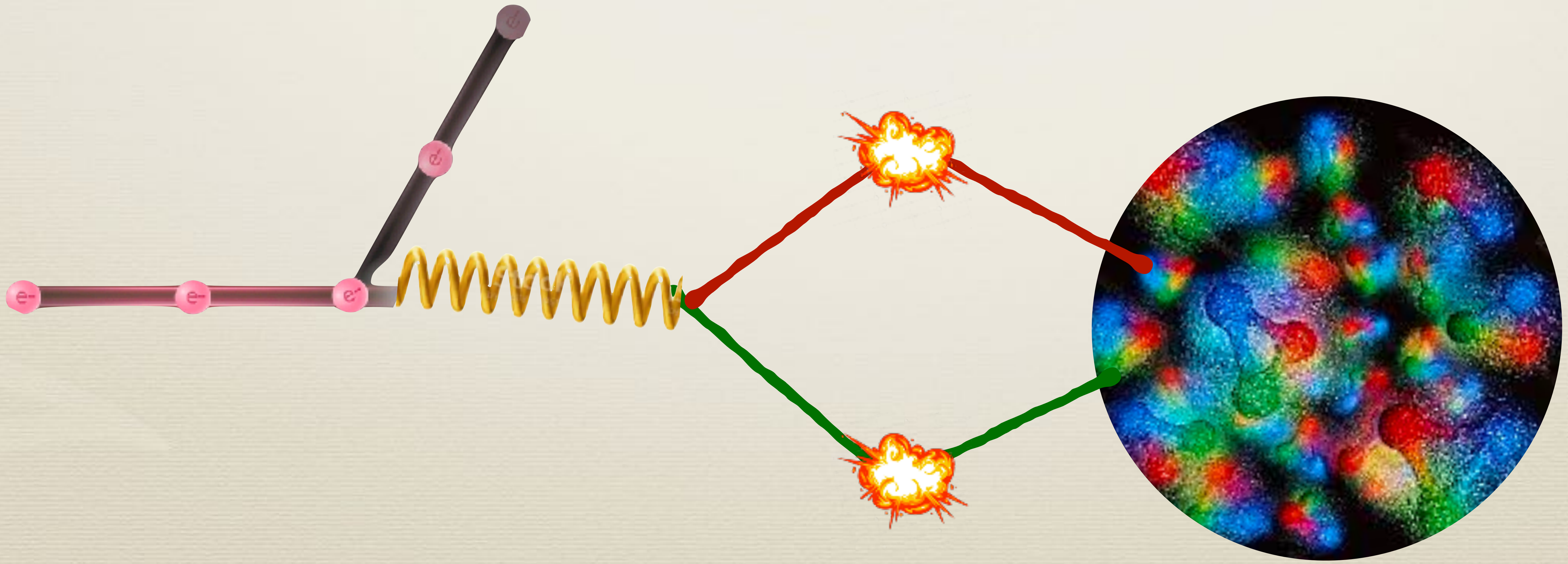
DPS in γA collisions with light nuclei?

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?



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POSSIBLE SOLUTION?

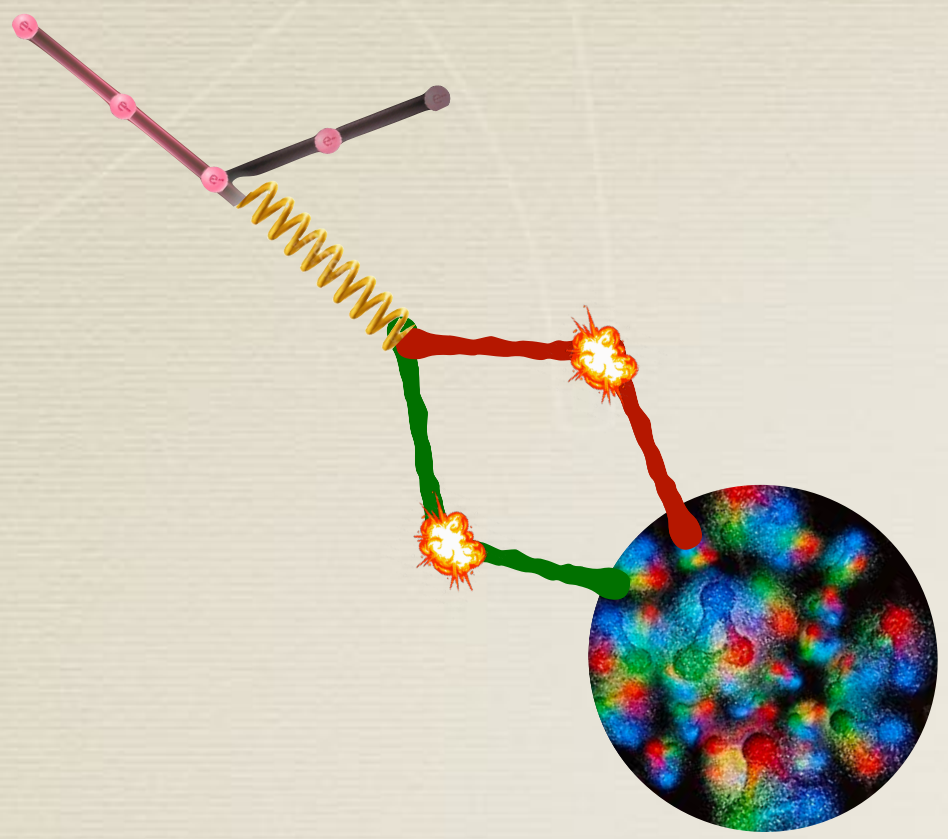
1) In γA the DPS2 will not contain any DPD of the proton ⇒ this mechanism can now be viewed as a background that can be evaluated if we properly treat the photon (as previously discussed) and the Nuclear geometry

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?

DPS1 in γA collisions with light nuclei

For example in DPS1:



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

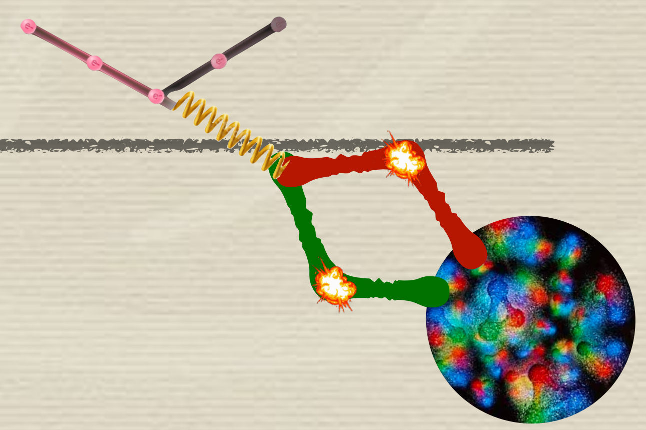
The nuclear light-cone distribution can be evaluated with realistic wave-function (from Av18 +UIV potential) in a fully relativistic and Poincaré covariant approach for:

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**

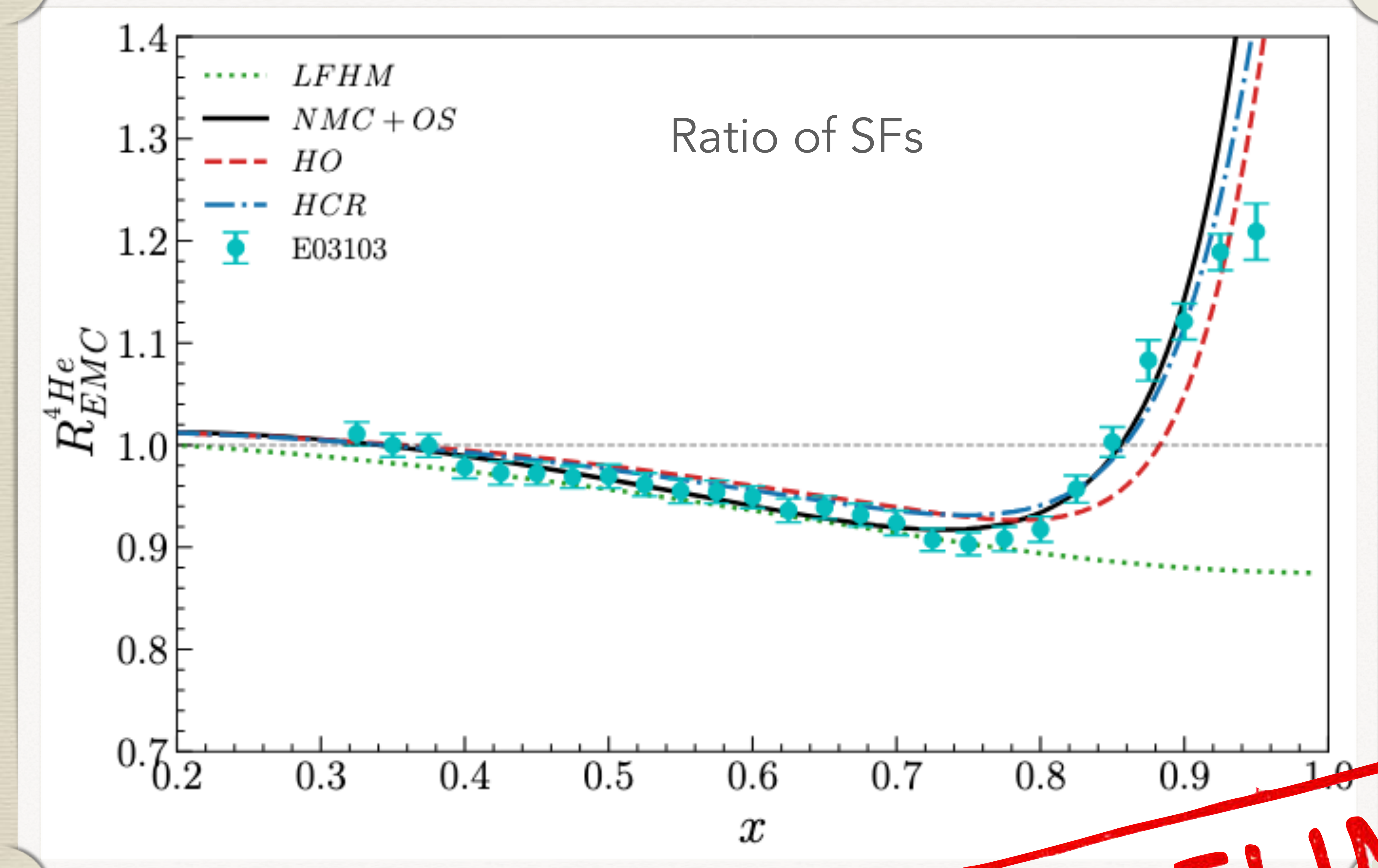
3) ^4He from **F. Fornetti, E. Pace, M. R., G. Salmé, S. Scopetta and M. Viviani, PLB 851 (2024), 138587**

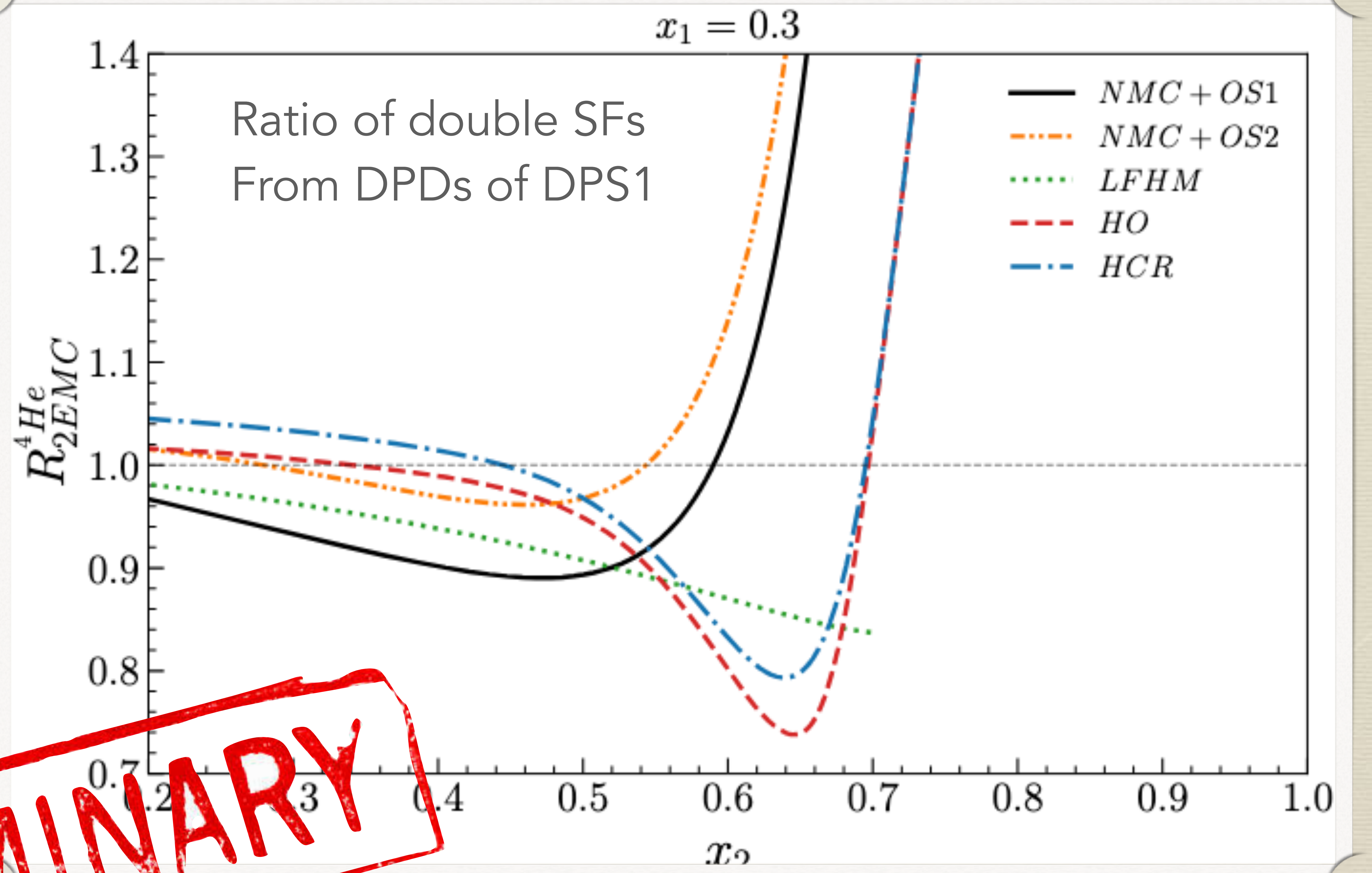
DPS1 in γA collisions with light nuclei



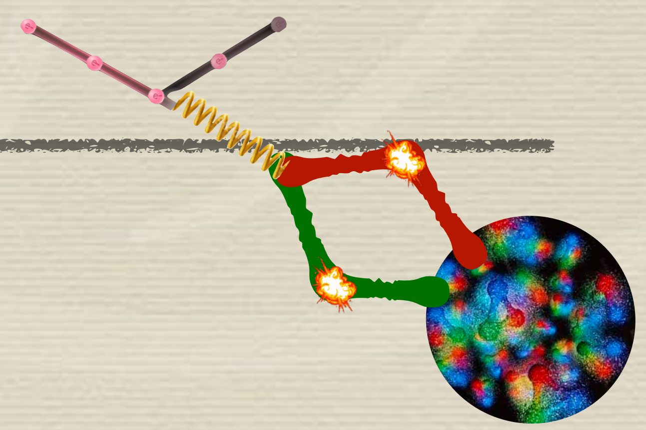
For example in DPS1: $\tilde{F}^1_{a_1 a_2}(x_1, x_2, k_\perp) = \sum_{N=p,n} \int \frac{1}{\xi} \tilde{F}^N_{a_1 a_2}\left(\frac{x_1}{\xi}, \frac{x_2}{\xi}, k_\perp\right) \rho^N_A(\xi, p_{t,N}) \frac{d\xi}{\xi} d^2 p_{t,N}$

Possible solution to the EMC effect. In fact:





DPS1 in γA collisions with light nuclei



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

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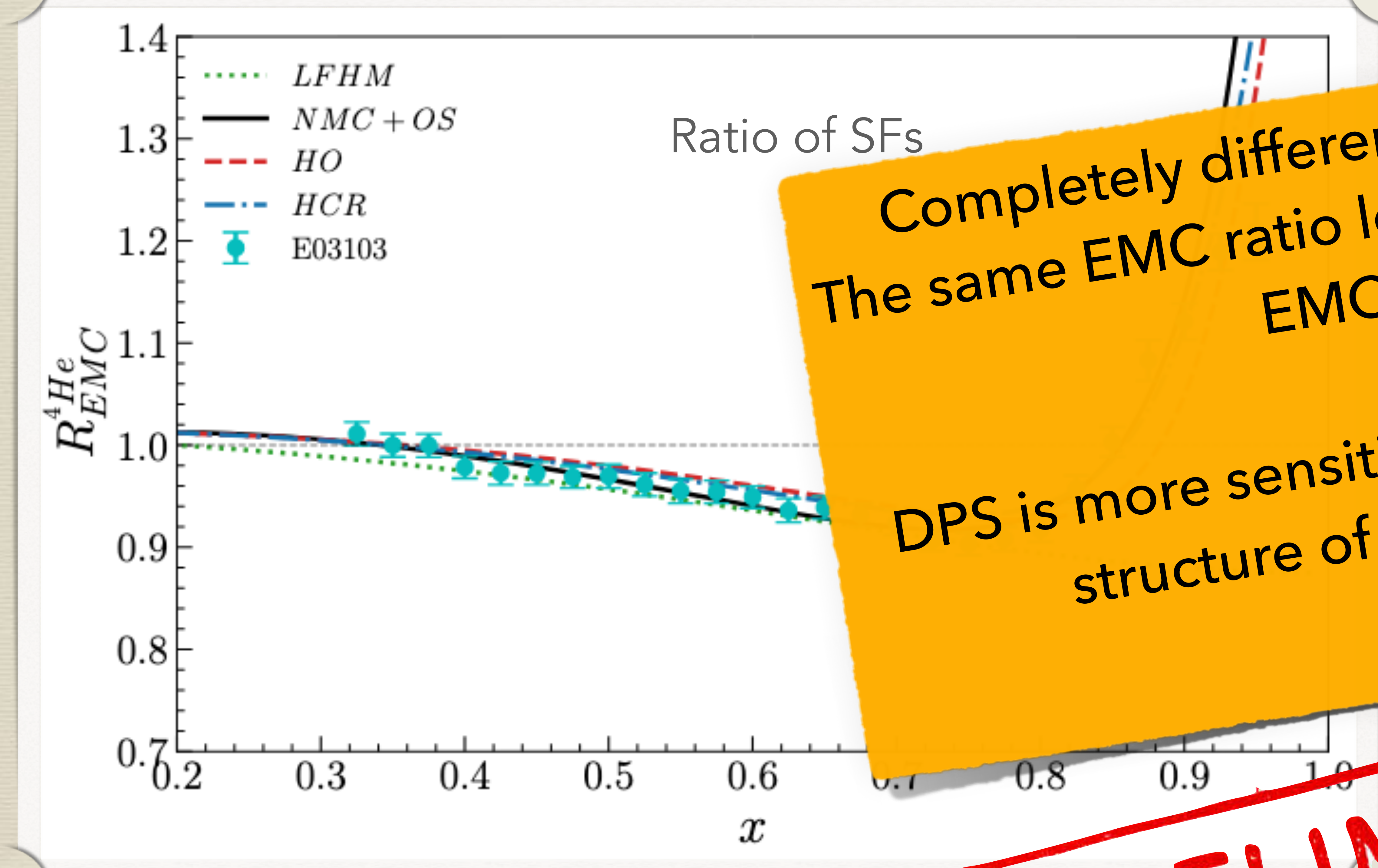
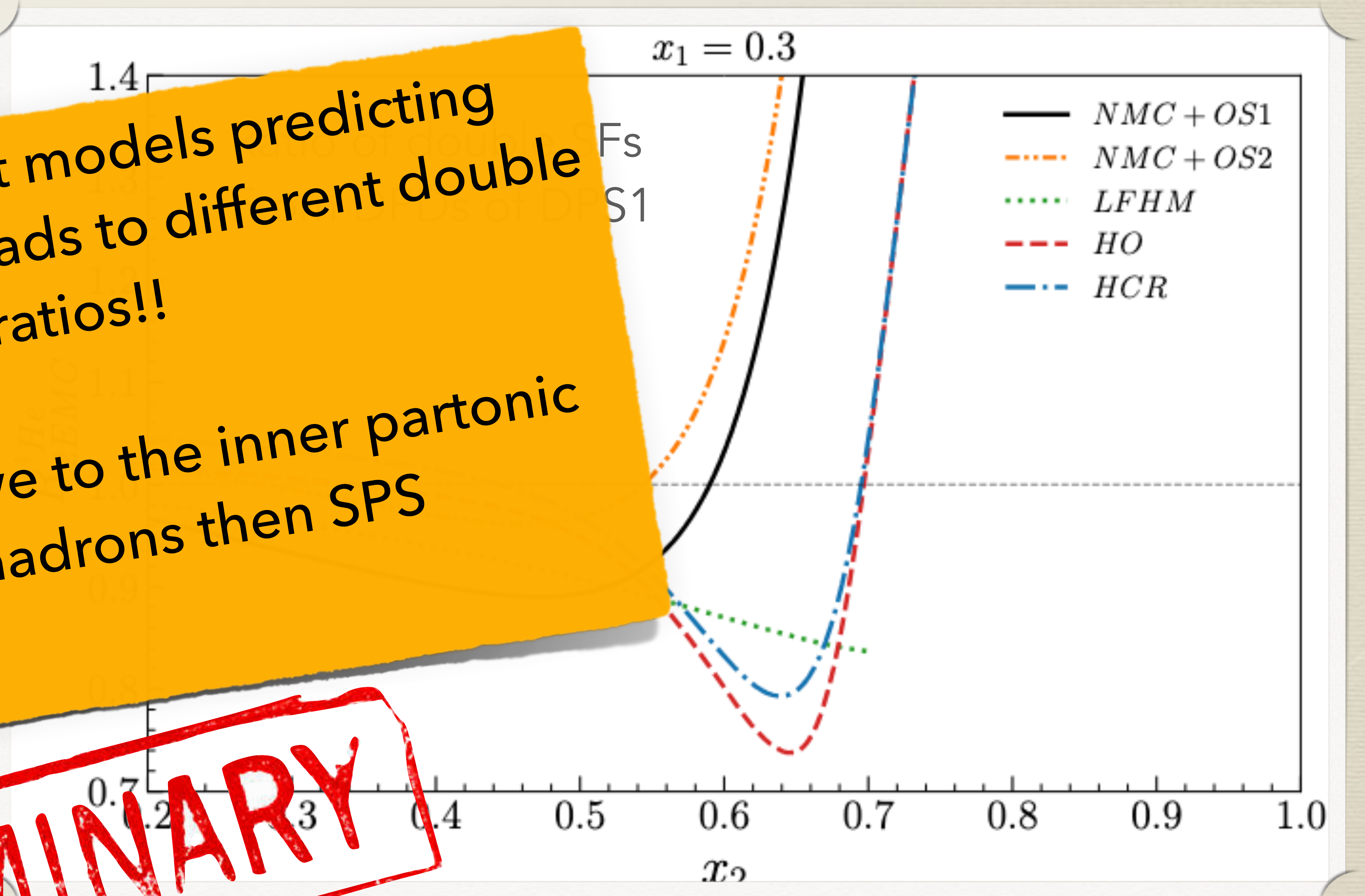


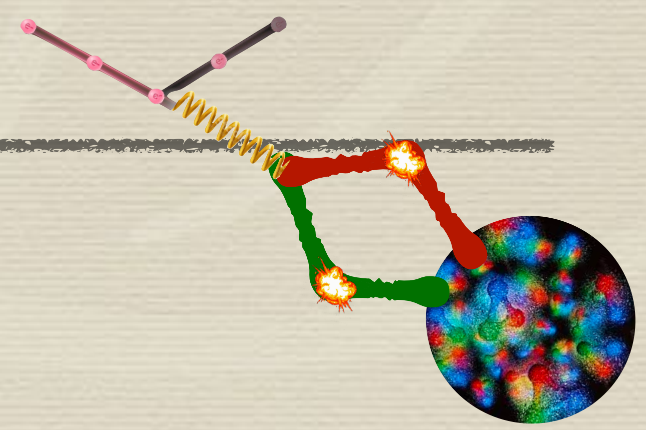


Completely different models predicting
The same EMC ratio leads to different double
EMC ratios!!

DPS is more sensitive to the inner partonic
structure of hadrons then SPS

PRELIMINARY

DPS2 in γA collisions with light nuclei



F. A. Ceccopieri, F. Fornetti, E. Pace, M.R., G. Salmè and N. Iles, [arXiv:2507.02495 [nucl-th]]

For example in DPS2:

$$D_{ij}^{A,2}(x_1, x_2, \mathbf{k}_\perp) = A(A-1) \sum_{\tau_1,\tau_2=n,p} \sum_{\lambda_1,\lambda_2} \sum_{\lambda_1',\lambda_2'} \int d\xi_1 \, \frac{\xi}{\xi_1} \int d\xi_2 \, \frac{\xi}{\xi_2} \, \rho^A_{\tau_1\tau_2}(\xi_1, \xi_2, \mathbf{k}_\perp, \lambda_1, \lambda_2, \lambda_1', \lambda_2')$$
$$\times \, \Phi^{\tau_1,i}_{\lambda_1,\lambda_1'}\left(x_1 \frac{\bar{\xi}}{\xi_1}, 0, \mathbf{k}_\perp\right) \Phi^{\tau_2,j}_{\lambda_2,\lambda_2'}\left(x_2 \frac{\bar{\xi}}{\xi_2}, 0, -\mathbf{k}_\perp\right) \, .$$

DPS2 in γA collisions with light nuclei

F. A. Ceccopieri, F. Fornetti, E. Pace, M.R., G. Salmè and N. Iles, [arXiv:2507.02495 [nucl-th]]

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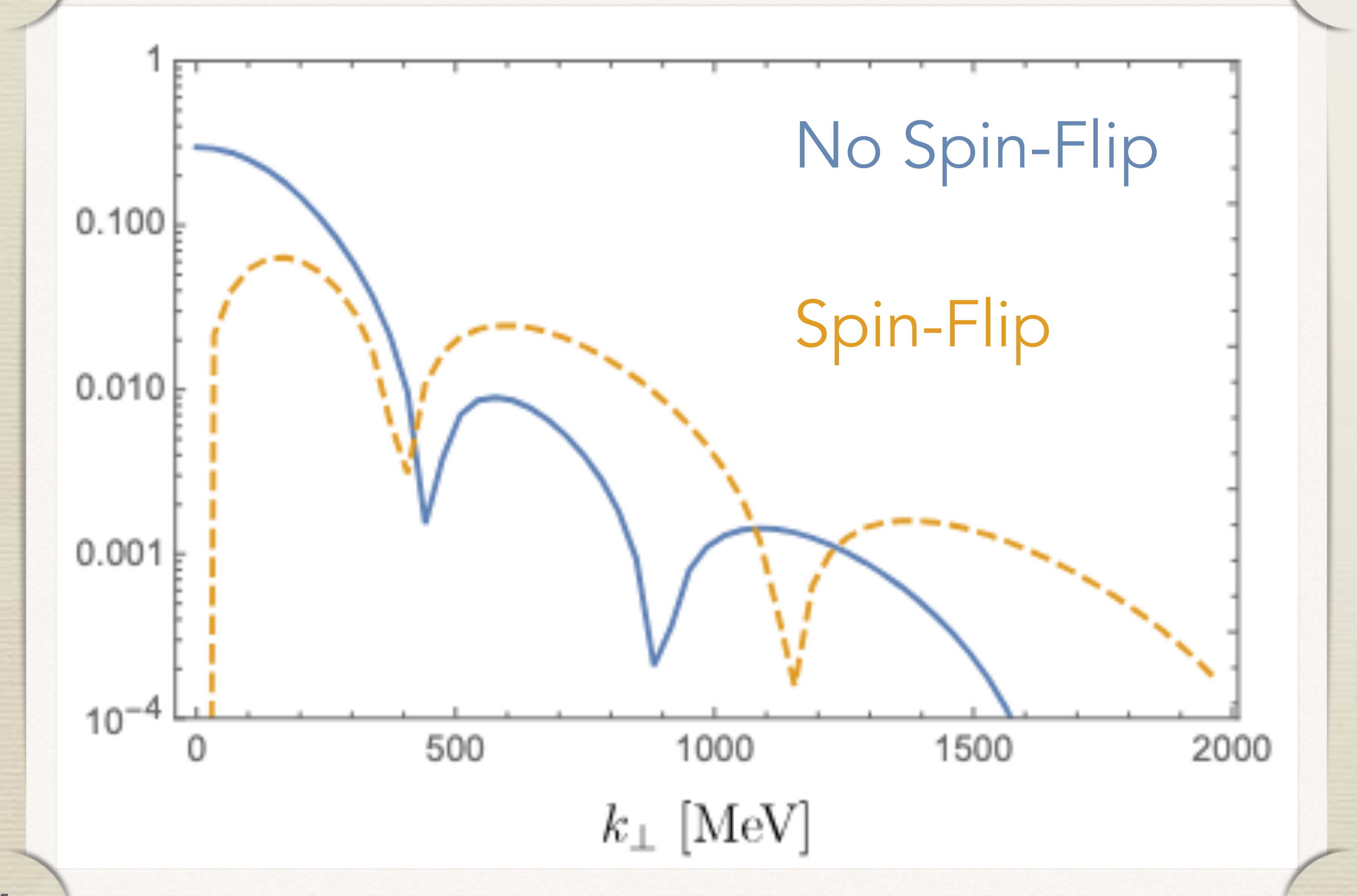
$$D_{ij}^{A,2}(x_1,x_2,\mathbf{k}_\perp) = A(A-1)\sum_{\tau_1,\tau_2=n,p}\sum_{\lambda_1,\lambda_2}\sum_{\lambda_1',\lambda_2'}\int d\xi_1\,\frac{\xi}{\xi_1}\int d\xi_2\,\frac{\xi}{\xi_2}\,\rho^A_{\tau_1\tau_2}(\xi_1,\xi_2,\mathbf{k}_\perp,\lambda_1,\lambda_2,\lambda_1',\lambda_2')$$
$$\times\,\Phi^{\tau_1,i}_{\lambda_1,\lambda_1'}\left(x_1\frac{\bar{\xi}}{\xi_1},0,\mathbf{k}_\perp\right)\Phi^{\tau_2,j}_{\lambda_2,\lambda_2'}\left(x_2\frac{\bar{\xi}}{\xi_2},0,-\mathbf{k}_\perp\right).$$

Off-forward LC momentum distribution

Standard LC correlator parametrized by GPDs

We address the possible role of nucleon spin-flip effects for the first time!



We have:

1) the Off-forward LCMDs which depends of the deuteron obtained within the Av18 Potential + LF approach to properly fulfill the Poincaré covariance

2) the role of spin effects could be important to make Realistic predictions

DPS in γA collisions with light nuclei

Finally:

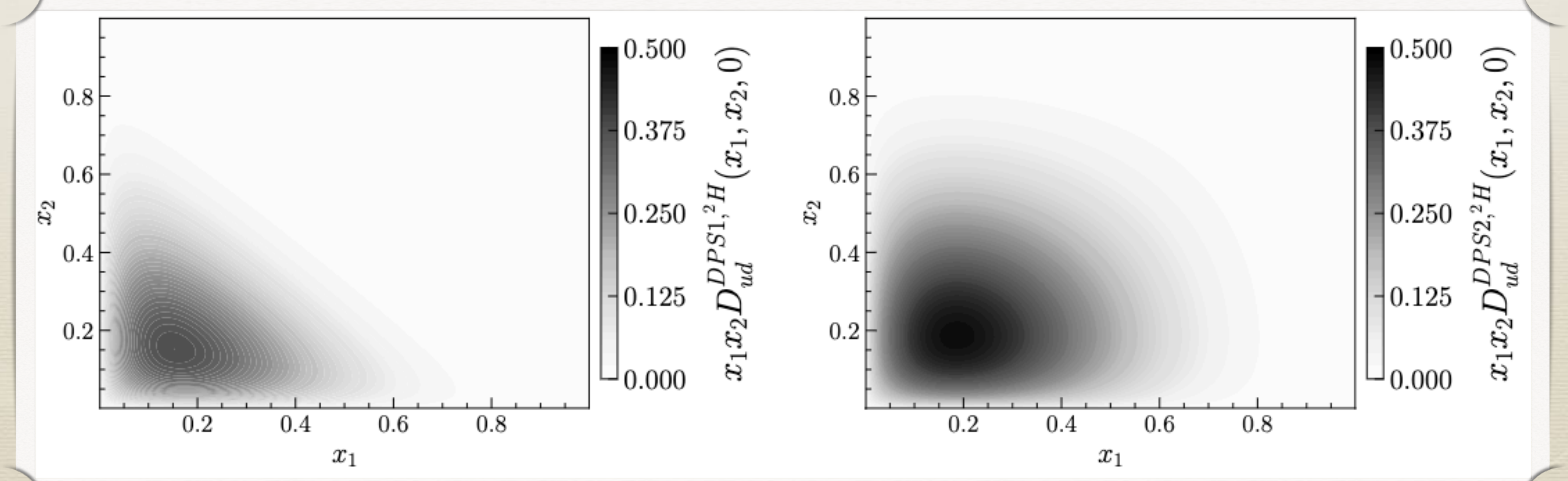
$$D_{ij}^{A,1}(x_1,x_2,\mathbf{k}_\perp) = \int d^2y_\perp \; e^{-i\mathbf{k}_\perp\cdot\mathbf{y}_\perp}\,\tilde{D}_{ij}^{A,1}(x_1,x_2,\mathbf{y}_\perp) = A\sum_{\tau=n,p}\int d\xi\;\frac{\bar{\xi}^2}{\xi^2}\;\rho_\tau^A(\xi)\;D_{ij}^\tau\left(x_1\frac{\bar{\xi}}{\xi},x_2\frac{\bar{\xi}}{\xi},\mathbf{k}_\perp\right)$$

$$D_{ij}^{A,2}(x_1,x_2,\mathbf{k}_\perp) = A(A-1)\sum_{\tau_1,\tau_2=n,p}\sum_{\lambda_1,\lambda_2}\sum_{\lambda_1',\lambda_2'}\int d\xi_1\;\frac{\bar{\xi}}{\xi_1}\int d\xi_2\;\frac{\bar{\xi}}{\xi_2}\;\rho_{\tau_1\tau_2}^A(\xi_1,\xi_2,\mathbf{k}_\perp,\lambda_1,\lambda_2,\lambda_1',\lambda_2')$$
$$\times\;\Phi_{\lambda_1,\lambda_1'}^{\tau_1,i}\left(x_1\frac{\bar{\xi}}{\xi_1},0,\mathbf{k}_\perp\right)\Phi_{\lambda_2,\lambda_2'}^{\tau_2,j}\left(x_2\frac{\bar{\xi}}{\xi_2},0,-\mathbf{k}_\perp\right)\;.$$

1) For DPS1 we used the product of PDFs as phenomenological nucleon DPDs (standard strategy)

2) For DPS2 we used the Goloskokv-Kroll model for the nucleon GPDs

Full deuteron DPDs at $k_\perp = 0$:



DPS in γA collisions with light nuclei

Before closing let us mention that the integral over ξ_1 and ξ_2 yields the nuclear two-body form factor:

$$F^{double}_{A,\tau_1,\tau_2}(\mathbf{k}_\perp) = \int \frac{d\xi_1}{\xi_1} \int \frac{d\xi_2}{\xi_2} \; \bar{\xi}^2 \bar{\rho}^A_{\tau_1,\tau_2}(\xi_1, \xi_2, \mathbf{k}_\perp)$$

Nuclear 2-body form factor

Calculated 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

Conclusions

- **EMC of light-nuclei within a Poincaré covariant LF approach**
  - ☑ We developed a rigorous formalism for the calculation of nuclear SFs, TMD LCMDs, spin-dependent SFs and DPDs involving only nucleonic DOF with the conventional nuclear physics
  - ☑ For ^{3}He we obtain results in agreement with experimental data for the EMC effect.
  - ☑ For the deviations from experimental data could be ascribed to genuine QCD effects: **our results provide a reliable baseline to study exotic phenomena**
  - ☑ The approach has been successfully applied to the calculation of spin-dependent SFs
- **NR calculations**
  - ☑ Calculation of the ^{4}He GPDs which are in good agreement with data (both for coherent and incoherent) channels
  - ☑ Calculation of the ^{3}He GPDs and predictions for asymmetries for the positron beam JLab upgrade
  - ☑ Calculation of the J/ψ electro-production of ^{3}He and ^{4}He including effects beyond IA
- **To do next**
  - ☐ Application of the approach to calculate the EMC effect of heavier nuclei (^{6}Li starting project)
  - ☐ Calculate the Double Parton Scattering cross-section of light-nuclei

The EMC effect

Conventional (NR) calculations:

✔ Qualitative agreement

No fulfillment of both particle and momentum sum rules ✘

In general, the lack of the **Poincarè covariance** and **macroscopic locality*** generates **biases for the study of genuine QCD effects** (nucleon swelling, exotic quark configurations …)

Macroscopic locality (= **cluster separability** (relevant in nuclear physics)): i.e. observables associated to different space-time regions must commute in the limit of large space like separation (i.e. causally disconnected).

In this way, when a system is separated into disjoint subsystems by a sufficiently large space like separation, then the subsystems behave as independent systems

B.D.Keister and W.N.Polyzou, Adv.Nucl.Phys. 20 (1991), 225-479

LF approach in pills

Poincaré covariance → Find 10 generators:

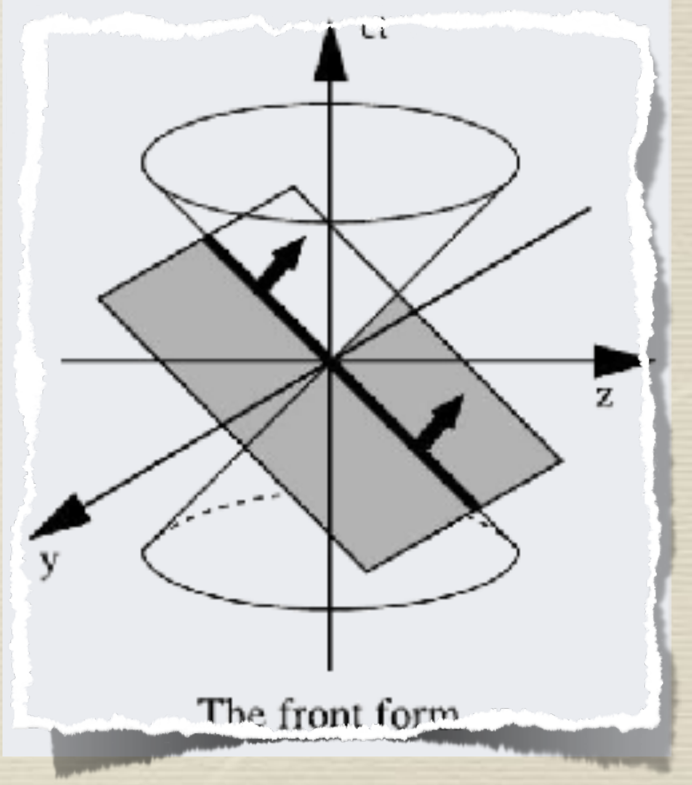
$P^\mu \to 4D$ displacements and $M^{\nu\mu} \to$ Lorentz transformation, that fulfill:

$$[P^\mu, P^\nu] = 0; [M^{\mu\nu}, P^\rho] = -i(g^{\mu\rho}P^\nu - g^{\nu\rho}P^\mu)$$
$$[M^{\mu\nu}, M^{\rho\sigma}] = -i(g^{\mu\rho}M^{\nu\sigma} + g^{\nu\sigma}M^{\mu\rho} - g^{\mu\sigma}M^{\nu\rho} - g^{\nu\sigma}M^{\mu\sigma})$$

Such a goal can be achieved in different equivalent ways depending on the initial conditions

IF → $t = x^0 = 0$

LF → $x^+ = x^0 + x^3 = 0$ ✓



- **7 Kinematical generators** (max n°): i) 3 LF boosts (in instant form they are dynamical!) ; $\tilde{P} = (P^+ = P^0 + P^3, \mathbf{P}_\perp)$; iii) Rotation around the z-axis
- The LF boosts have a subgroup structure: **trivial separation of intrinsic and global motion, as in the NR case**
- $P^+ \geq 0 \to$ meaningful Fock expansion, once massless constituents are absent
- **The infinite-monentum frame (IMF) description of DIS is easily included**

LF + Bakamjian-Thomas construction

BT properly constructed the 10 Poincaré operators in presence of interactions following this scheme:

i) Only the mass operator M contains the interaction

ii) It generates the dependence of the 3 dynamical generators (P^- and LF transverse rotations)

iii) The eigenvalue equation $M^2|\psi> = s|\psi>$ is formally equivalent to the Schrödinger equation

Free mass

For a nucleus A: $M_{BT}[1,2,3,\dots,A] = M_0[1,2,3,\dots,A] + V(\mathbf{k}^2; \mathbf{k}\cdot\mathbf{k}_i; \mathbf{k}_j\cdot\mathbf{k}_i)$

2 & 3 body forces operator

$$M_0[1,2,3,\dots,A] = \sum_i^A \sqrt{m^2 + \mathbf{k}_i^2}$$

$$\sum_{i=1}^A \mathbf{k}_i = 0$$

From this construction:

1) The commutation rules impose to V **invariance for translations and rotations** as well as independence on the total momentum, as it occurs for V^{NR}

2) One can assume $M_{BT}[1,2,\dots,A] \sim M^{NR}$

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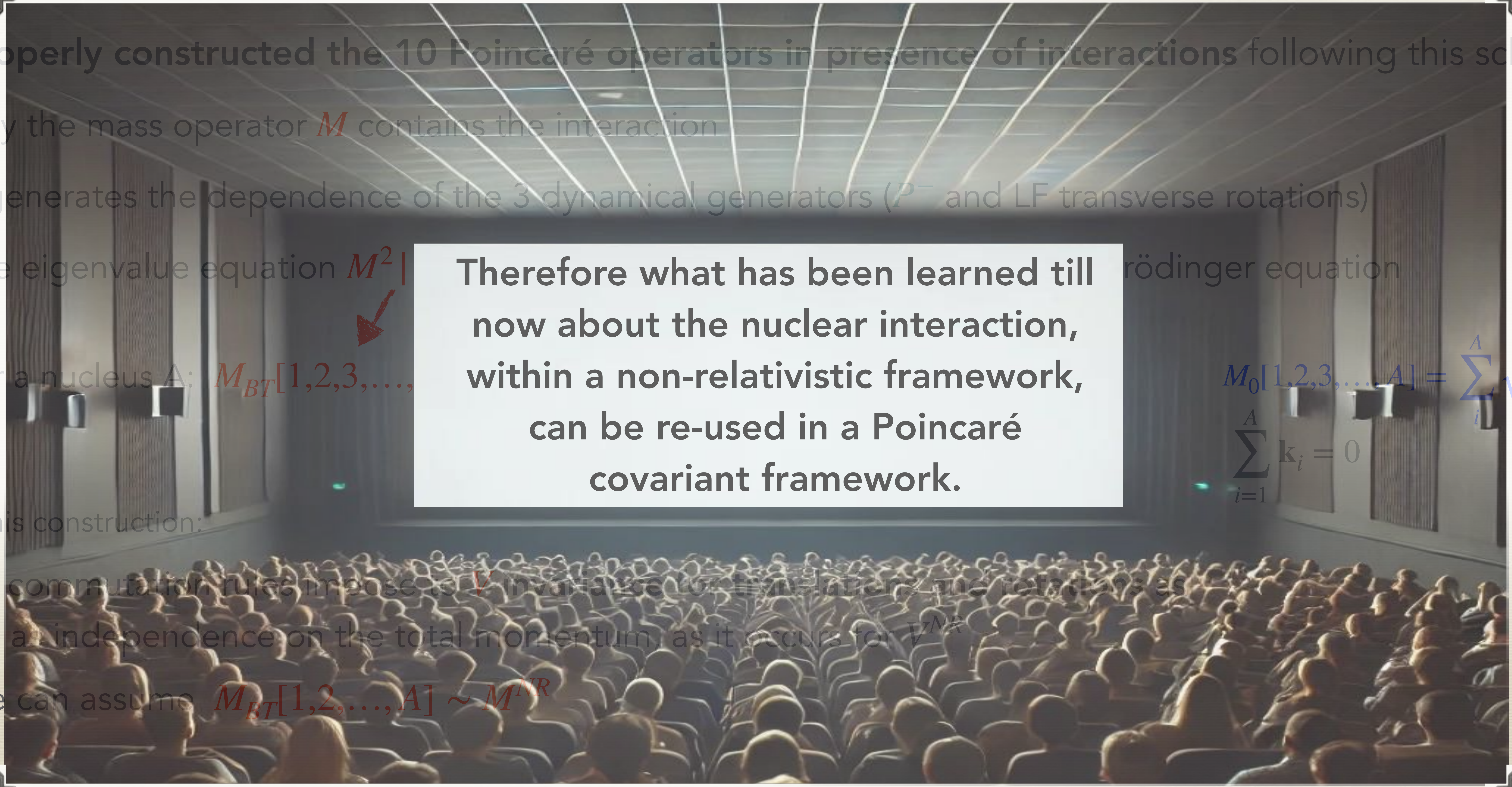
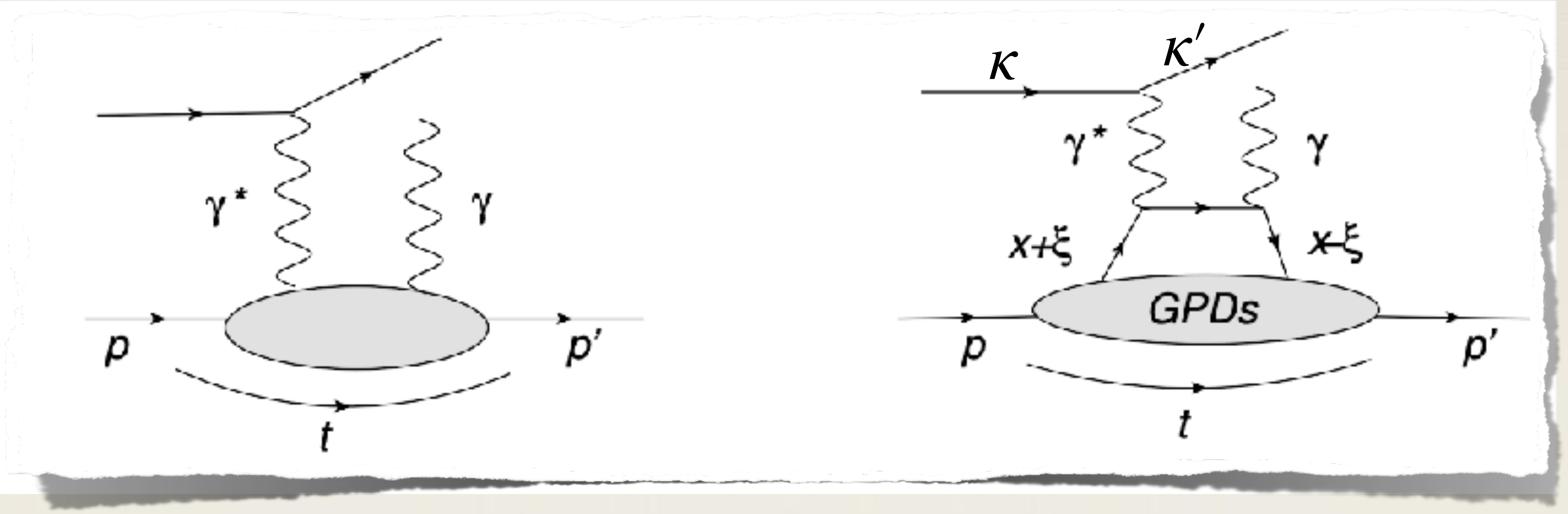


Deeply Virtual Compton Scattering

Exclusive electro-production of real photon: access to GPDs:



$$\bar{p}^\mu = \frac{p^\mu + p'^\mu}{2}$$

$$a^\pm = a^0 \pm a_z$$

Light-Cone coordinates

GPDs depend on:

$$\Delta^\mu = (p' - p)^\mu$$

- $t = \Delta^2$
- $x = \frac{\bar{k}^+}{\bar{p}^+}$
- $\xi = \frac{\Delta^+}{2\bar{p}^+}$
- $Q^2 = (\kappa' - \kappa)^2$

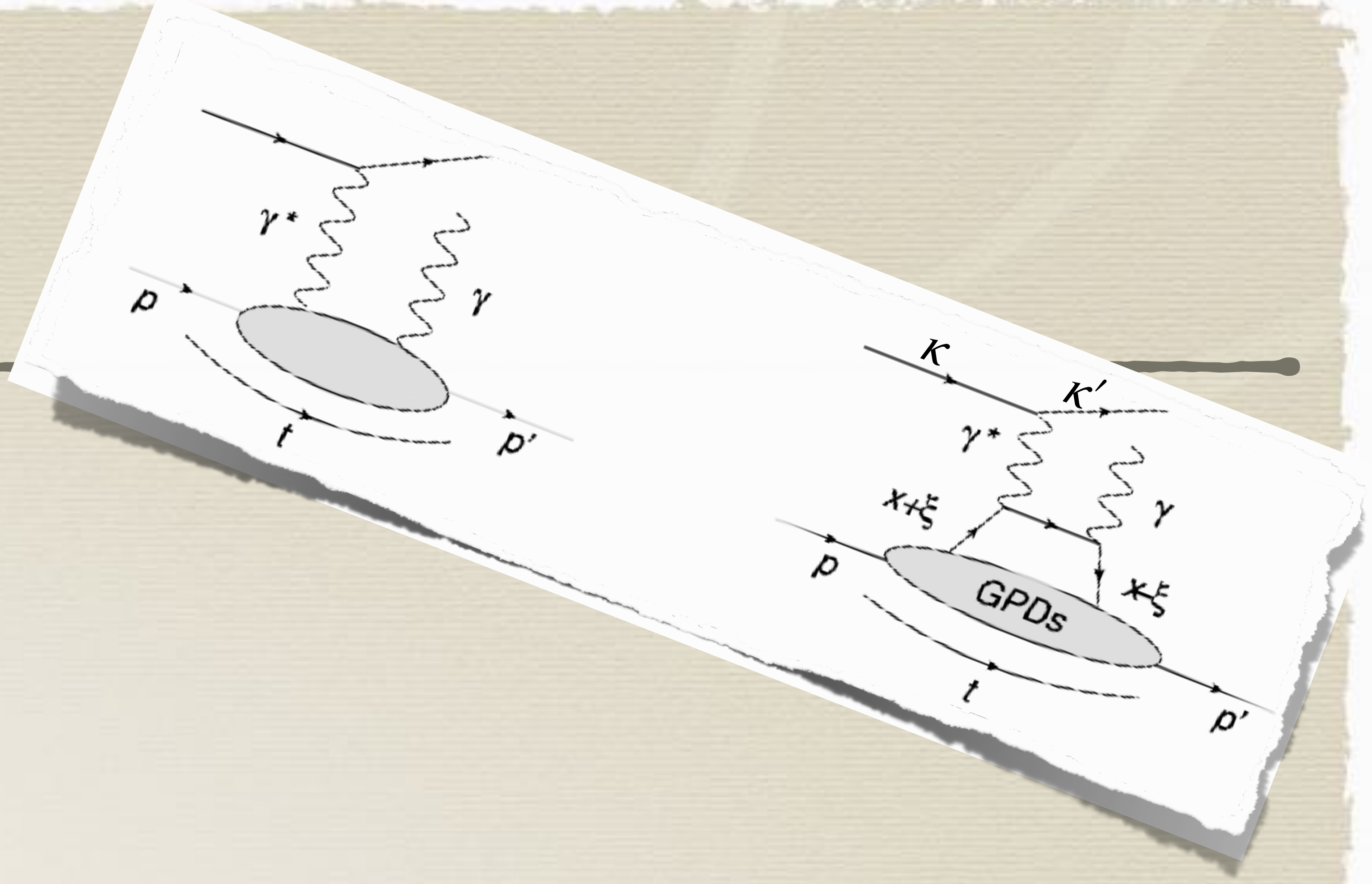
GPDs are defined from non-local matrix elements

$$F^q_{\lambda,\lambda'}(x,\xi,t) = \int \frac{dz^-}{4\pi} e^{ix\bar{p}^+z^-} \langle p',\lambda' | \bar{\psi}(-z/2)\gamma^+\psi(z/2) | p,\lambda\rangle |_{z^+=\mathbf{z}_\perp=0} =$$

$$\frac{1}{2\bar{p}^+}\left[H_q(x,\xi,t)\bar{u}(p',\lambda')\gamma^+u(p,\lambda) + E_q(x,\xi,t)\bar{u}(p',\lambda')\frac{i\sigma^{+\nu}\Delta_\nu}{2M}u(p,\lambda)\right]$$

at leading twist and for 1/2 spin target (the scale dependence is omitted)

GPDs properties



- Forward limit: $\Delta^\mu = 0$

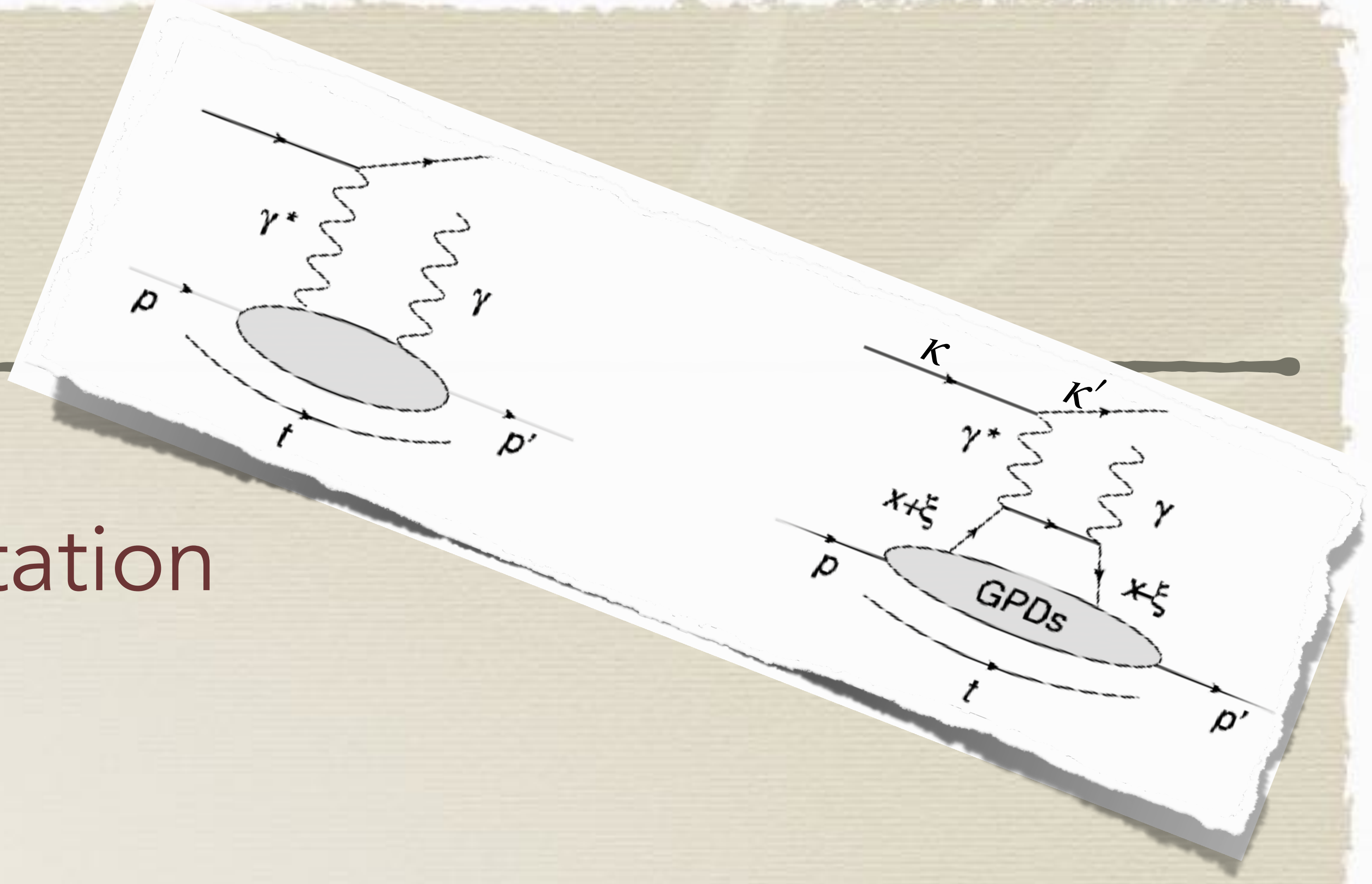
$$H(x, \xi, t) \xrightarrow[\Delta^\mu \to 0]{} f(x) \qquad f(x) = \text{Parton Distribution Function (PDF)}$$

- First moment: relations between GPDs and form factors

$$\int_{-1}^{1} dx\, H_q(x, \xi, t) = F_1^q(t) \qquad \int_{-1}^{1} dx\, E_q(x, \xi, t) = F_2^q(t)$$

ξ-independence is a consequence of Lorentz invariance

GPDs properties



- The Fourier Transform of GPDs at $\xi = 0$ have a probabilistic interpretation

$$\rho_q(x, \vec{b}_\perp) = \int \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\vec{\Delta}_\perp \cdot \vec{b}_\perp} H_q(x, 0, t) + \ldots$$

Hadron tomography

- Moments of GPDs $\int dx\ x^n \mathrm{GPDs}$ are related to **gravitational form factors**

Mechanical properties of hadrons

- Ji's sum rule:

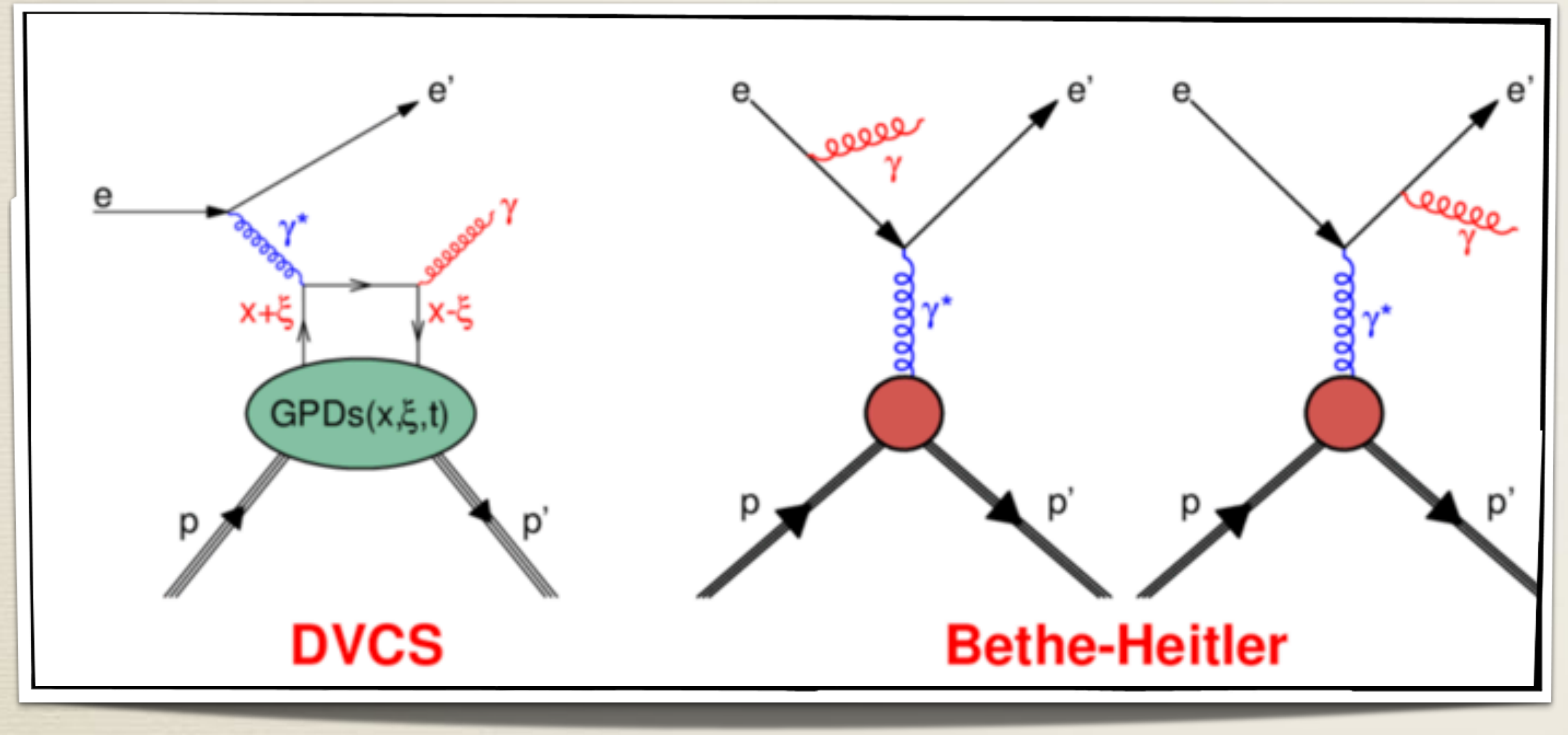
$$\langle J_q \rangle = \int_{-1}^{1} dx\ x \left[H_q(x, \xi, 0) + E(x, \xi, 0) \right]$$

Solution to the proton spin crisis?

GPDs meet experiments

There are several GPDs (for quarks and gluons) depending on the spin of the target hence we need several observable from different processes: DVCS, double DVCS, DVMP (double virtual meson production)

We need to take into account the Bethe-Heitler contribution to the final state:



$$\sigma \propto \mathcal{T}^2_{DVCS} + \mathcal{T}^2_{BH} + \mathcal{I}_{DVCS-BH}$$

with

GPD = H, E,...

$\mathcal{T}_{DVCS}$ function of $\mathcal{F}_{q(g)}(\xi, t) = \int_{-1}^{1} \mathrm{d}x \, \frac{F_{q(g)}(x, \xi, t)}{x \pm \xi + i\varepsilon}$

Compton Form Factors (CFFs)

GPDs meet experiments

There are several GPDs (for quarks and gluons) depending on the spin of the target hence we need several observable from different processes: DVCS, double DVCS, DVMP (double virtual meson production)

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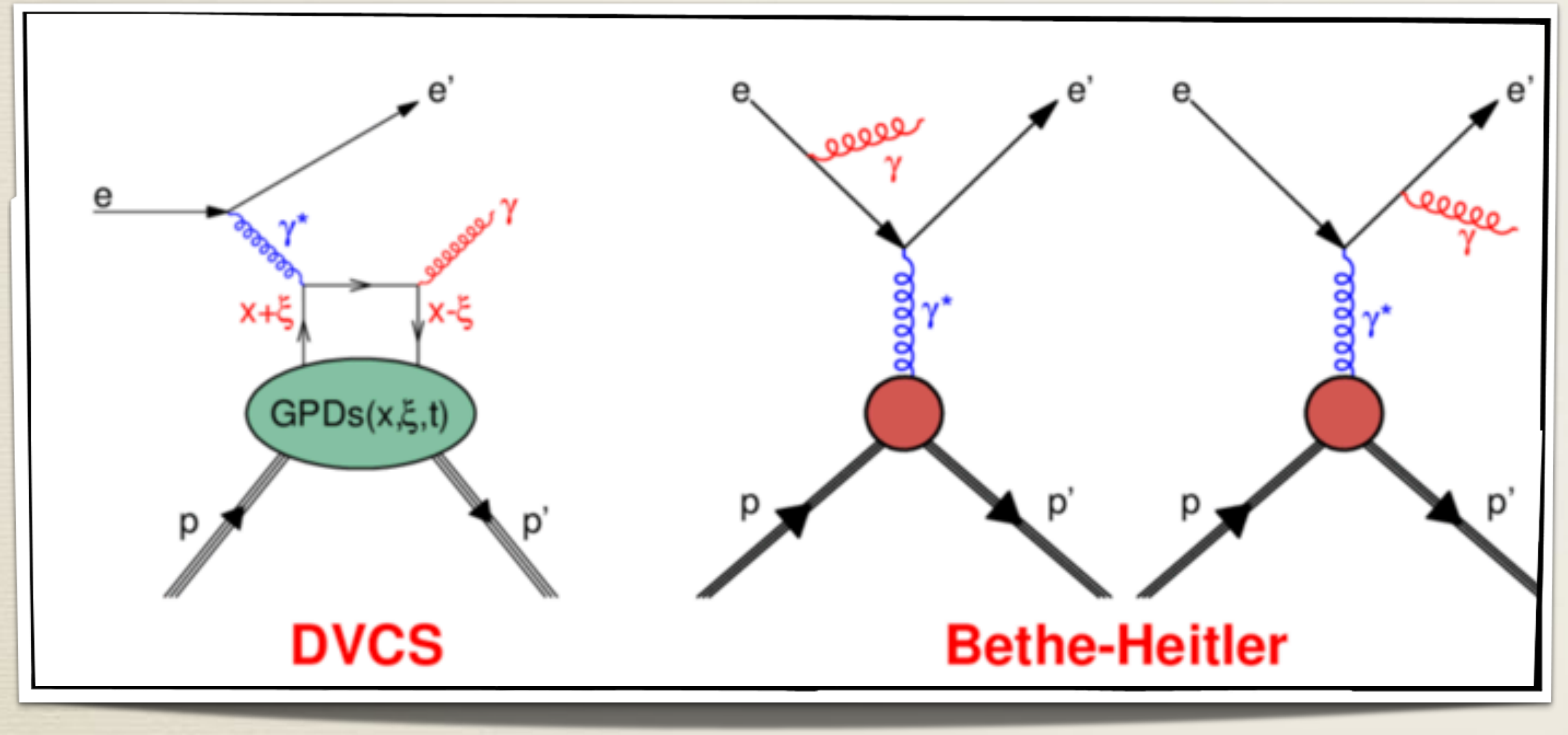


$$\sigma \propto \mathcal{T}^2_{DVCS} + \mathcal{T}^2_{BH} + \mathcal{I}_{DVCS-BH}$$

Asymmetries are fundamental to disentangle the real and imaginary parts of different CFFs.

- **B**eam **C**harge **A**symmetry: $\dfrac{\mathrm{d}\sigma^+ - \mathrm{d}\sigma^-}{\mathrm{d}\sigma^+ - \mathrm{d}\sigma^-} \sim \Re e \mathcal{F}$

- **B**eam **S**pin **A**symmetry: $\dfrac{\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow}{\mathrm{d}\sigma^\uparrow - \mathrm{d}\sigma^\downarrow} \sim \Im m \mathcal{F}$

Why light nuclear targets?

Several reasons. For example:

To access the **neutron** GPDs **Light nuclear targets** play a special role! ^2H and ^3He are well known and nuclear effects can be properly taken into account thanks to the realistic wave functions available.

→ To get a complete **flavor decomposition** of GPDs

→ To study the neutron **spin structure**

- CLAS data demonstrate that measurements for ^4He are possible, separating coherent and incoherent channels;
- **Realistic microscopic calculations are necessary**

Nuclear tomography!

why is it important?

GPDs as solution to the EMC effect?

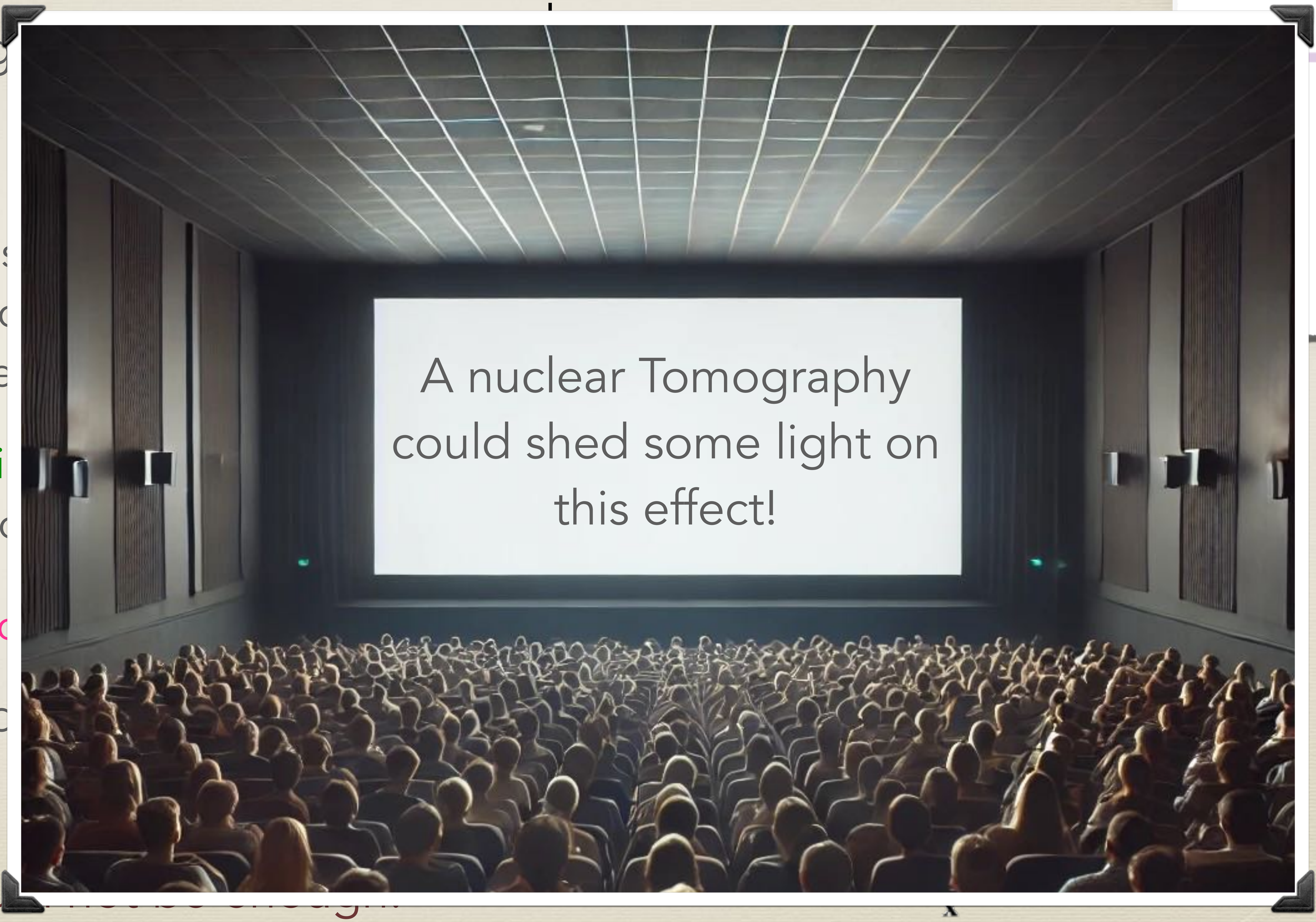
In DIS off a nuclear targ

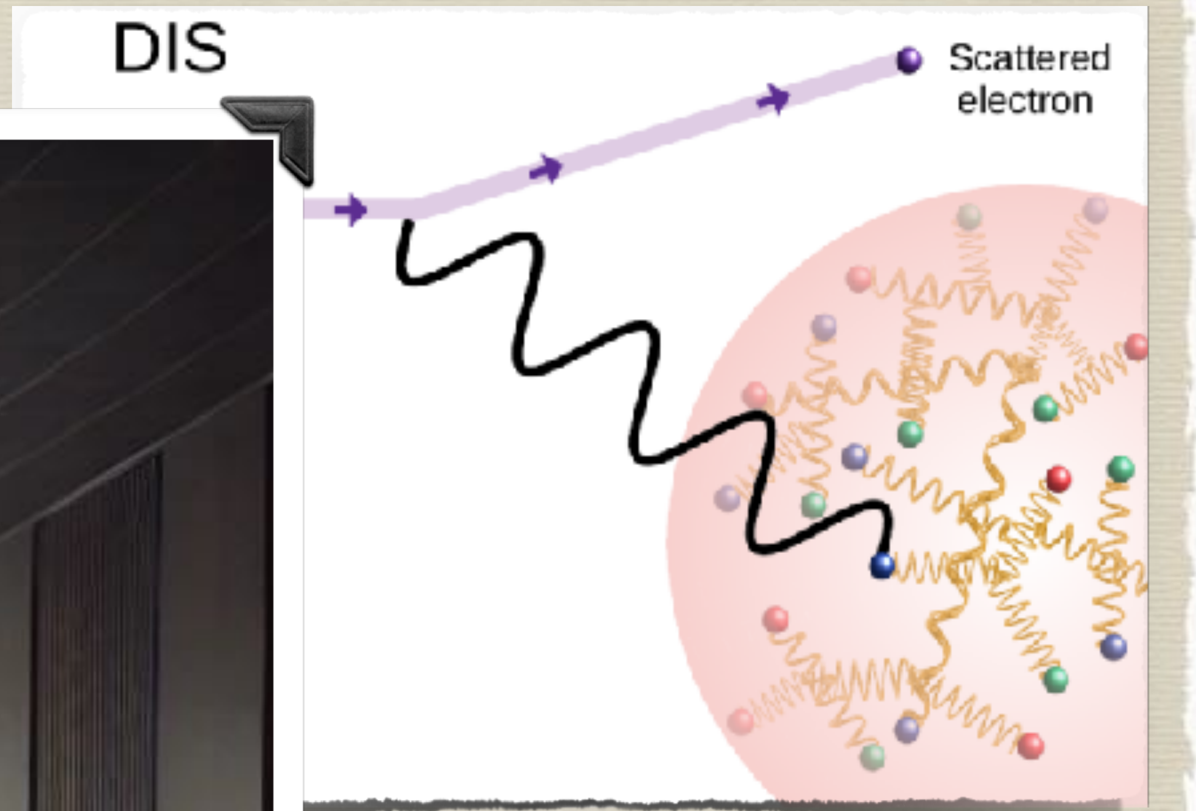
$$0 \le x = \frac{Q^2}{2M\nu} \le \frac{M_A}{M} \simeq A$$

- $x \le 0.3$ "Shadowing, anti-s coherence effects, the pho partons belonging to diffe
- $0.2 \le x \le 0.8$ "EMC (bindi mainly valence quarks invo
- $0.8 \le x \le 1$ "Fermi motio

Small effect! Several moc (**E**veryone's **M**odel is **C**ool)

Collinear information cou

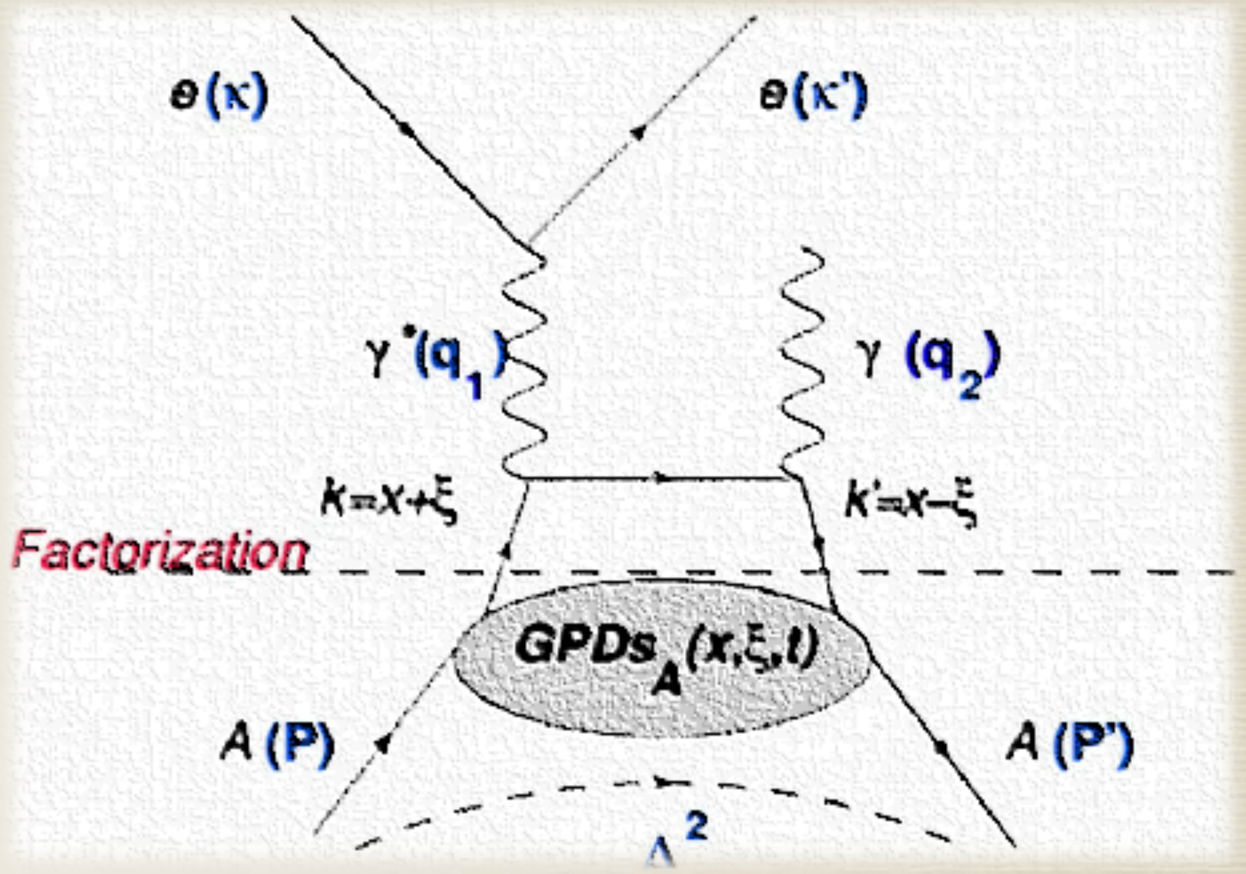




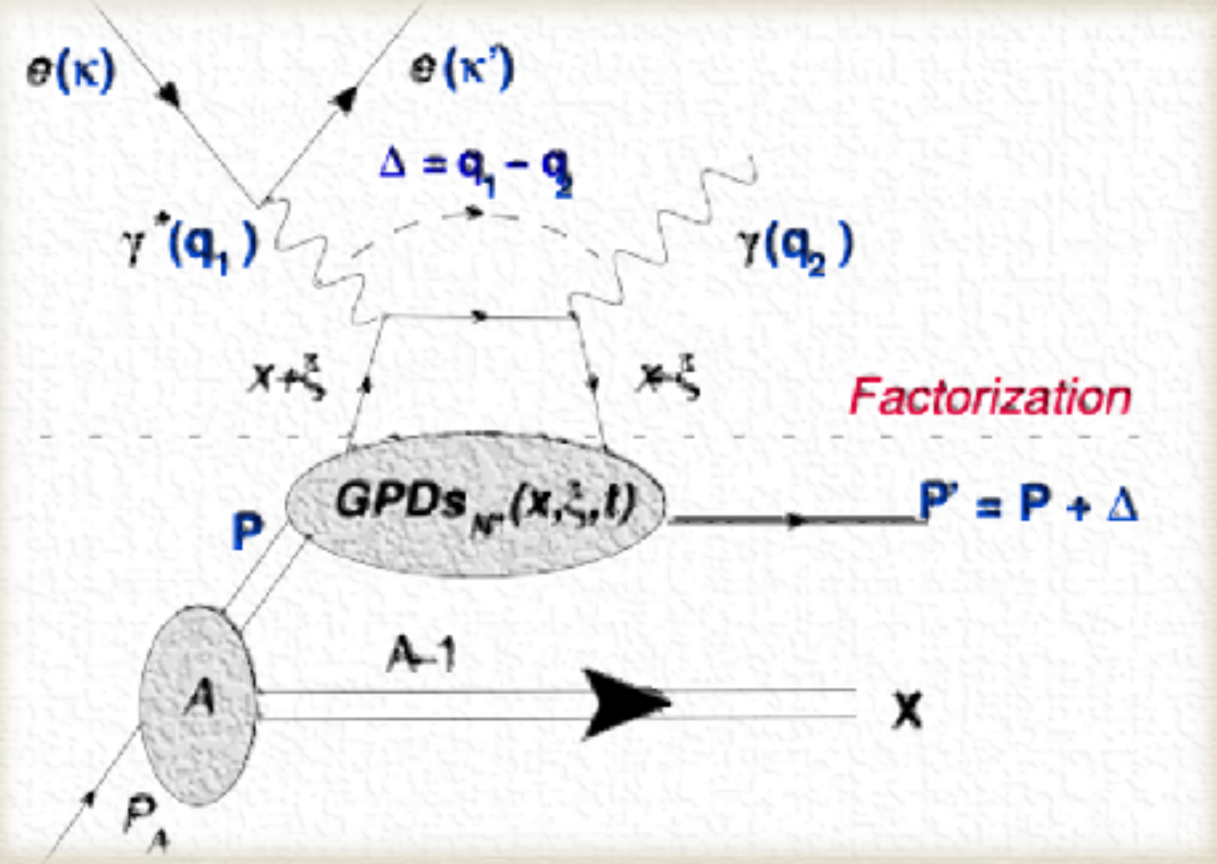
Nuclear DVCS

In the nuclear case we have two channels:

Coherent channel → we access the GPDs of the nucleus
Tomography of the nucleus



Incoherent channel → we access the GPDs of the bound nucleons
Same distribution of the free one?
Tomography of the bound nucleon



Some Data and Effective Cross Section

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

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: $pp \longrightarrow A + B + X$

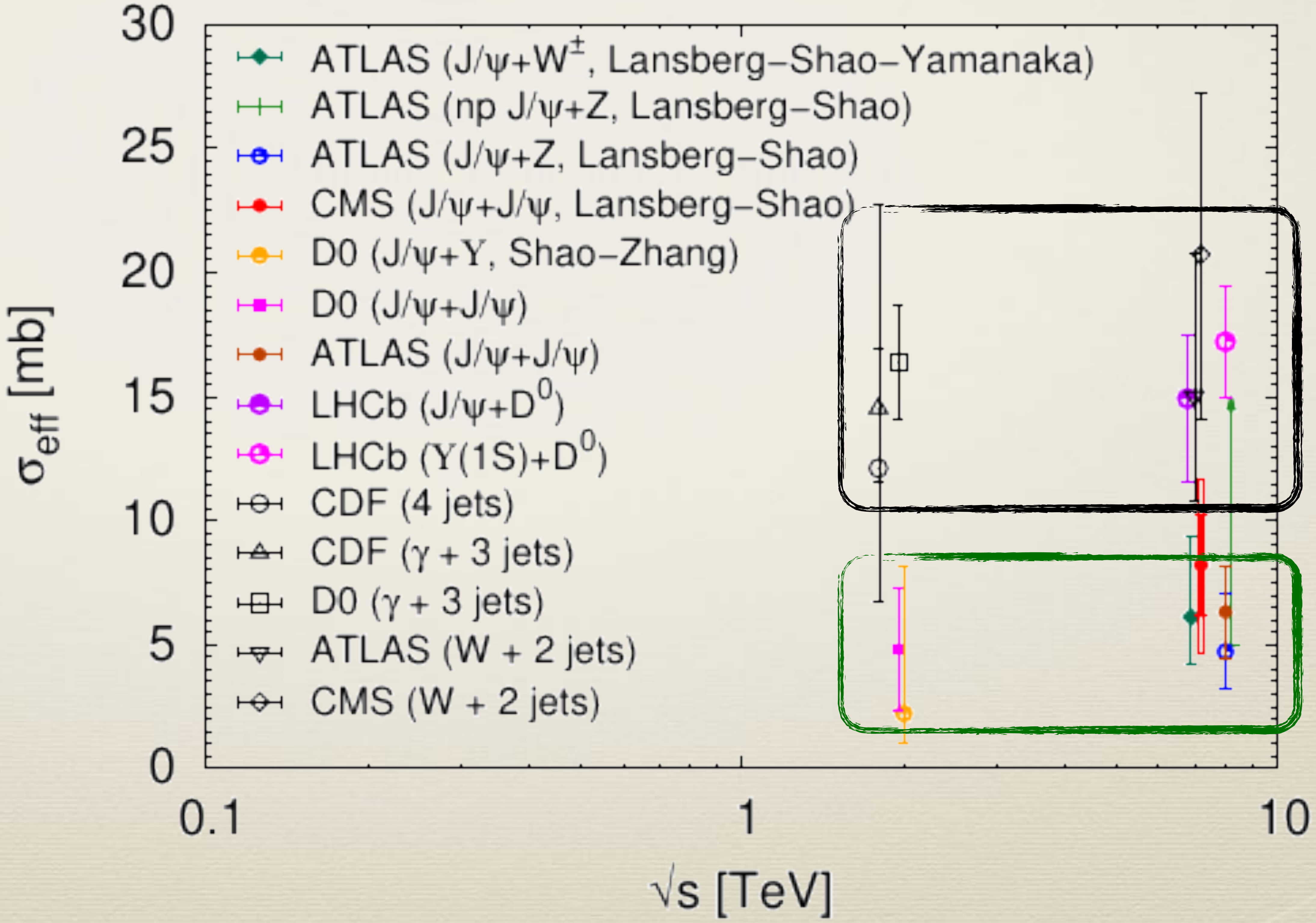
Results for W, Jet productions…

Results for quarkonium productions

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:

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

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

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

New analysis of same sign WW via DPS:

$$\sigma_{\text{eff}} = 10.6 \pm 1.8 \text{ mb}$$

[ATLAS coll], arXiv:2505.08313

NINPHA - PG

1) Matteo Rinaldi (RL) (ricercatore, INFN sezione di PG, 100%)
2) Simone Pacetti (PA, INFN sezione di PG, 70%)
3) Francesco Rosini (Ph.D., INFN sezione di PG, 70%)
4) Sergio Scopetta (PA, INFN sezione di PG, 100%)
5) Massimiliano Alvioli (ricercatore CNR, 25%)

6) Giovanni Salmè (senior, INFN sezione di Roma 1)
7) Filippo Fornetti (dottorando)