Topics

- Introduction to GPDs:

  1. Open questions in nuclear high-energy physics: Proton spin crisis and EMC effect
  2. Introduction to DVCS and GPDs
  3. Forward limit and first moment of GPDs
  4. Tomography
  5. Momentum and Ji's sum rule
  6. Cross-section and Asymmetries
  7. Multi-dimensional picture of hadrons

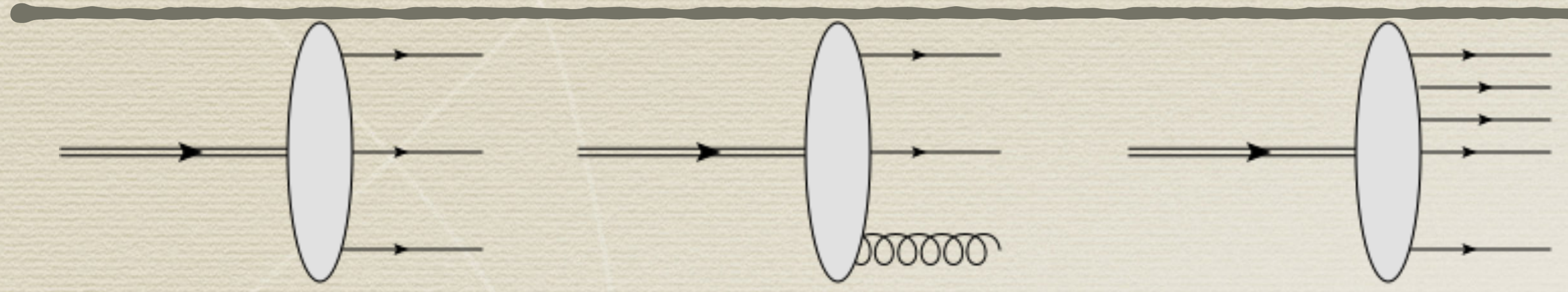
- Nuclear GPDs:

  1. Why nuclear GPDs and DVCS in IA: the ^{3}He case
  2. Coherent DVCS on spin 1/2 nuclei in IA and NR limit
  3. Some Numerical results
  4. Some experiments

- Examples:

  1. Megnetic FF
  2. Fock expansion for hadronic states
  3. Use of the Fock expansion as a tool to evaluate nuclear distributions in IA. The case of PDFs.
  4. If I will have time also Double Parton Distributions.

Multidimensional picture of hadrons

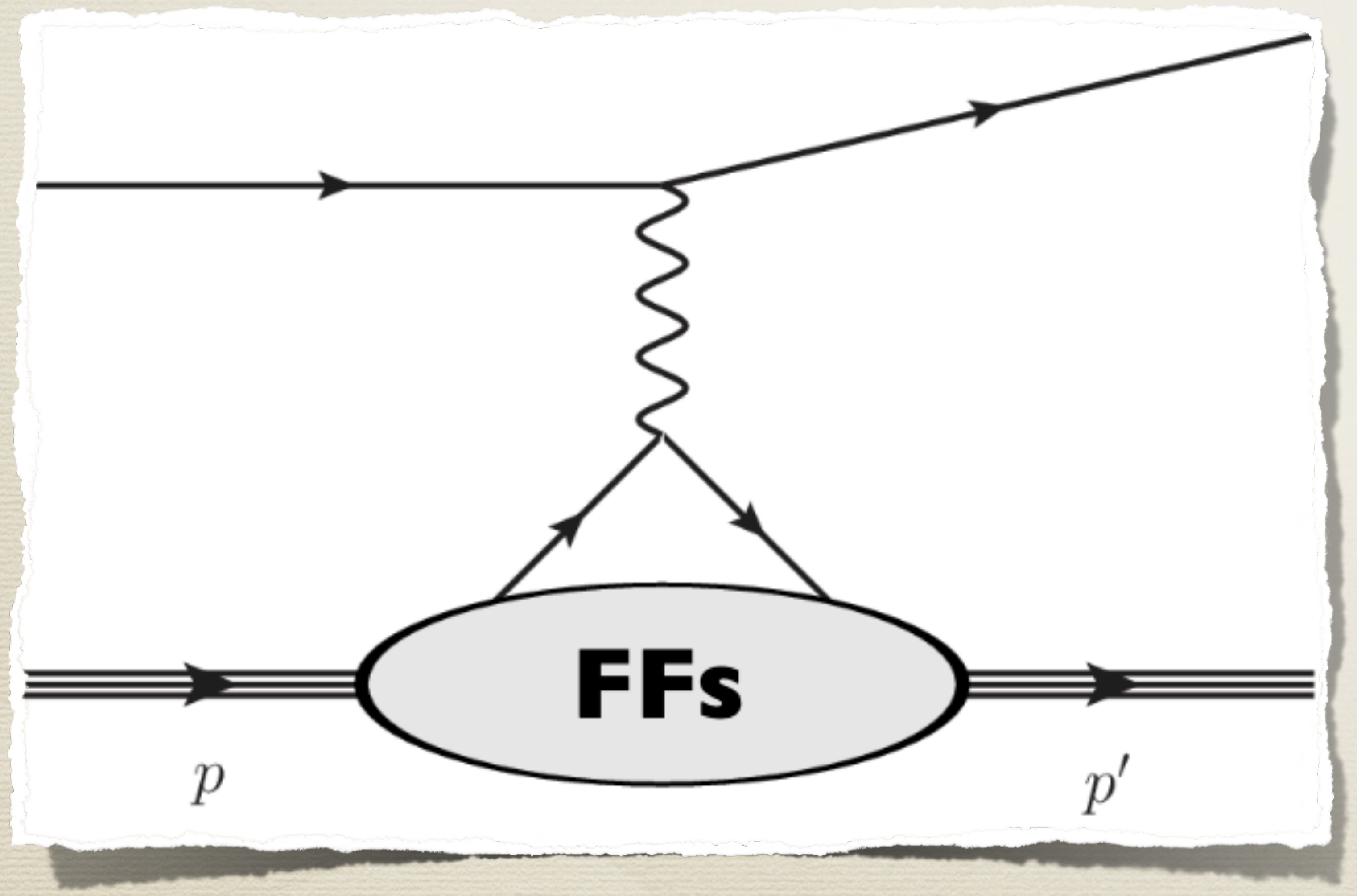


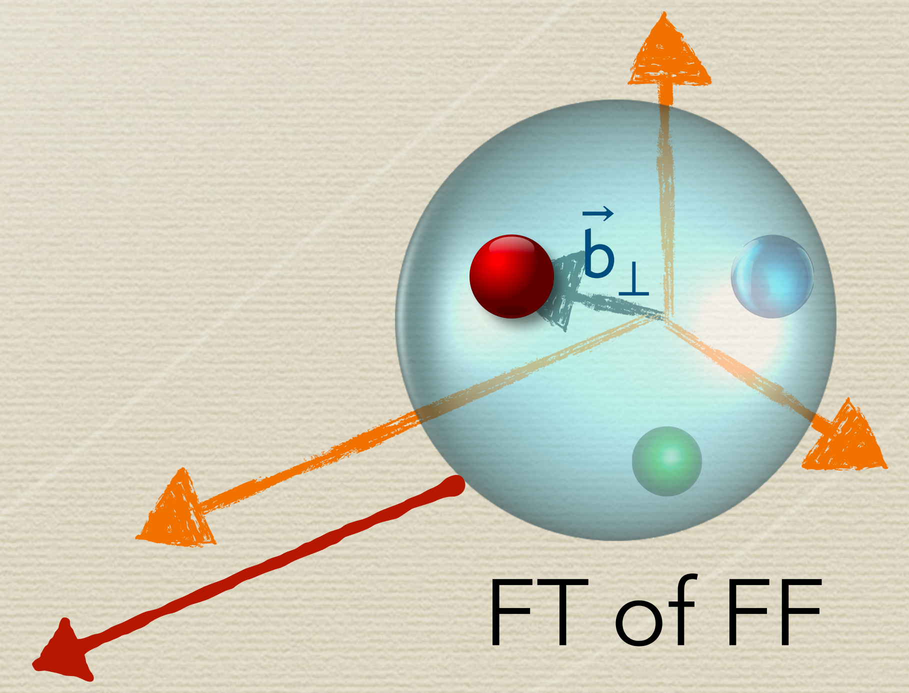
Light-Front wave-function

$\longrightarrow \int d^2 b_\perp$

$$\langle P + \frac{\Delta}{2} | \bar{\psi}_q(0) \gamma^+ \psi_q(0) | P - \frac{\Delta}{2} \rangle$$

Elastic Scattering

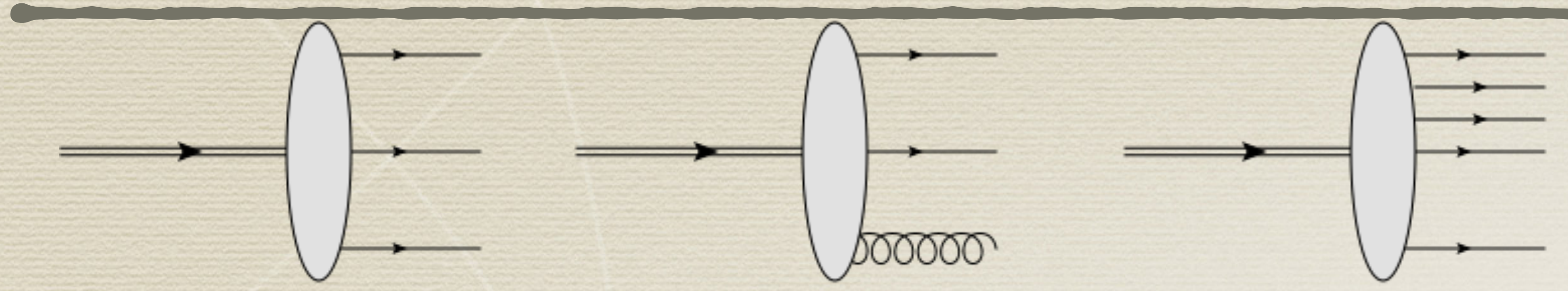




FT of FF

Charge

Multidimensional picture of hadrons



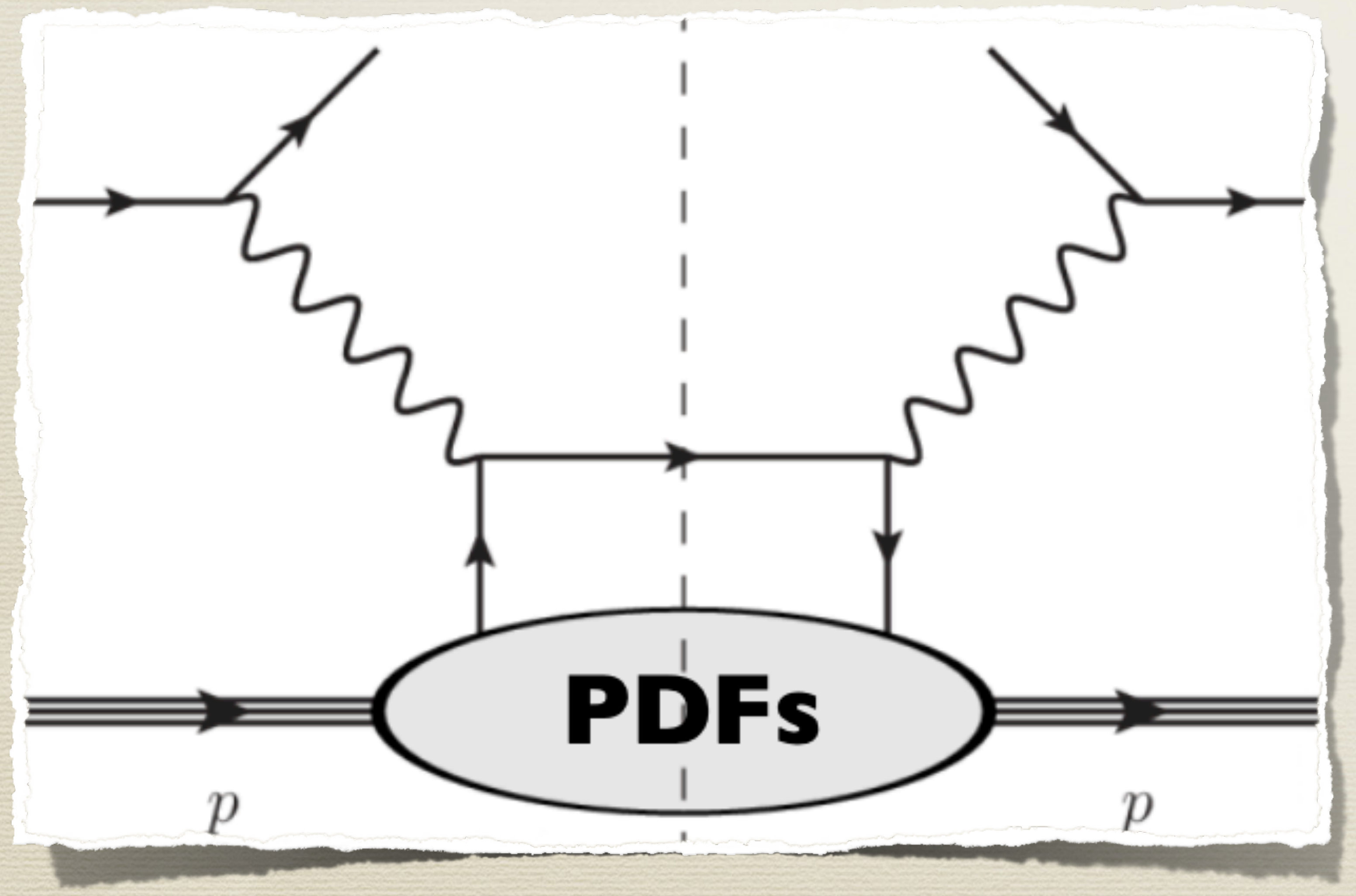
Light-Front wave-function

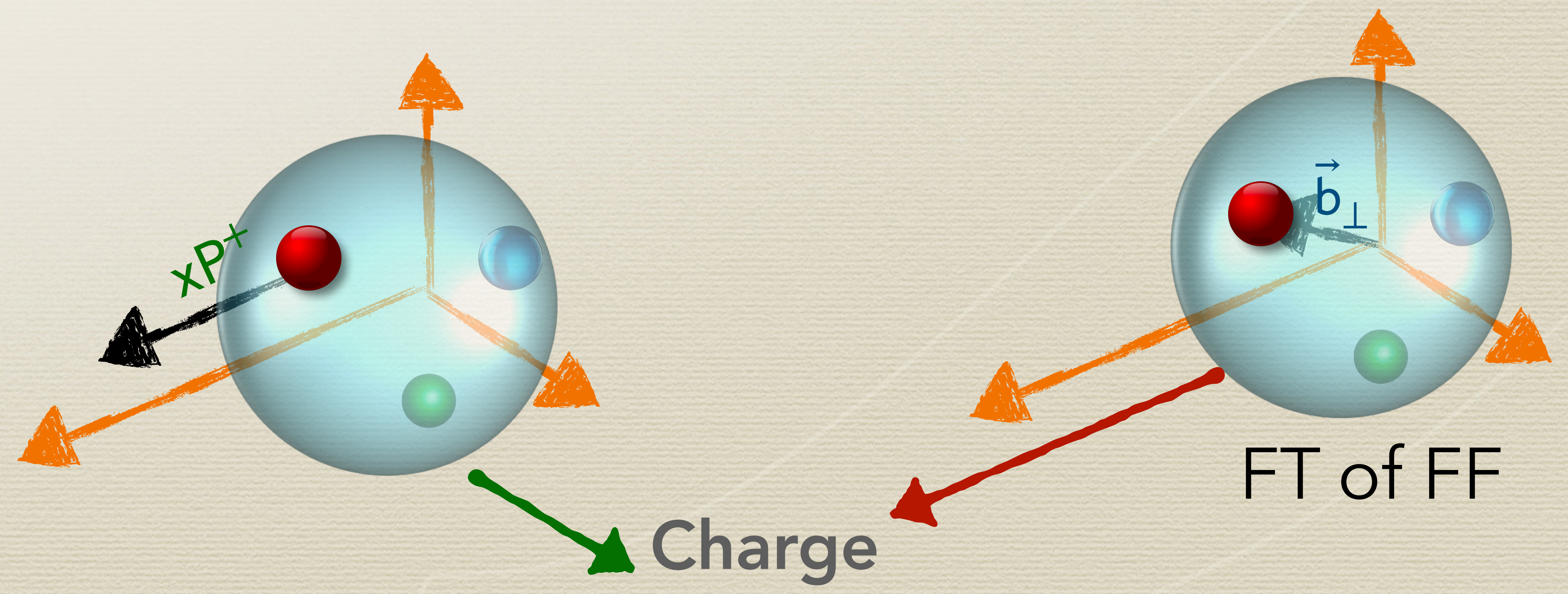
$\longrightarrow \int d^2 b_\perp$

$\longrightarrow \int dx$

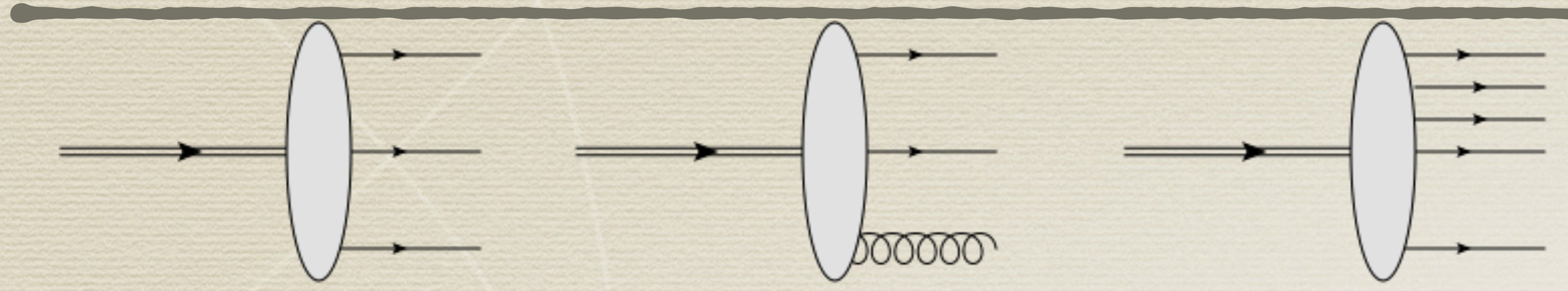
$$\int \frac{dz^-}{4\pi} e^{xP^+z^-} \langle P|\bar{\psi}_q(0)\gamma^+\psi_q(z^-)|P\rangle$$

Deep Inelastic Scattering





Multidimensional picture of hadrons



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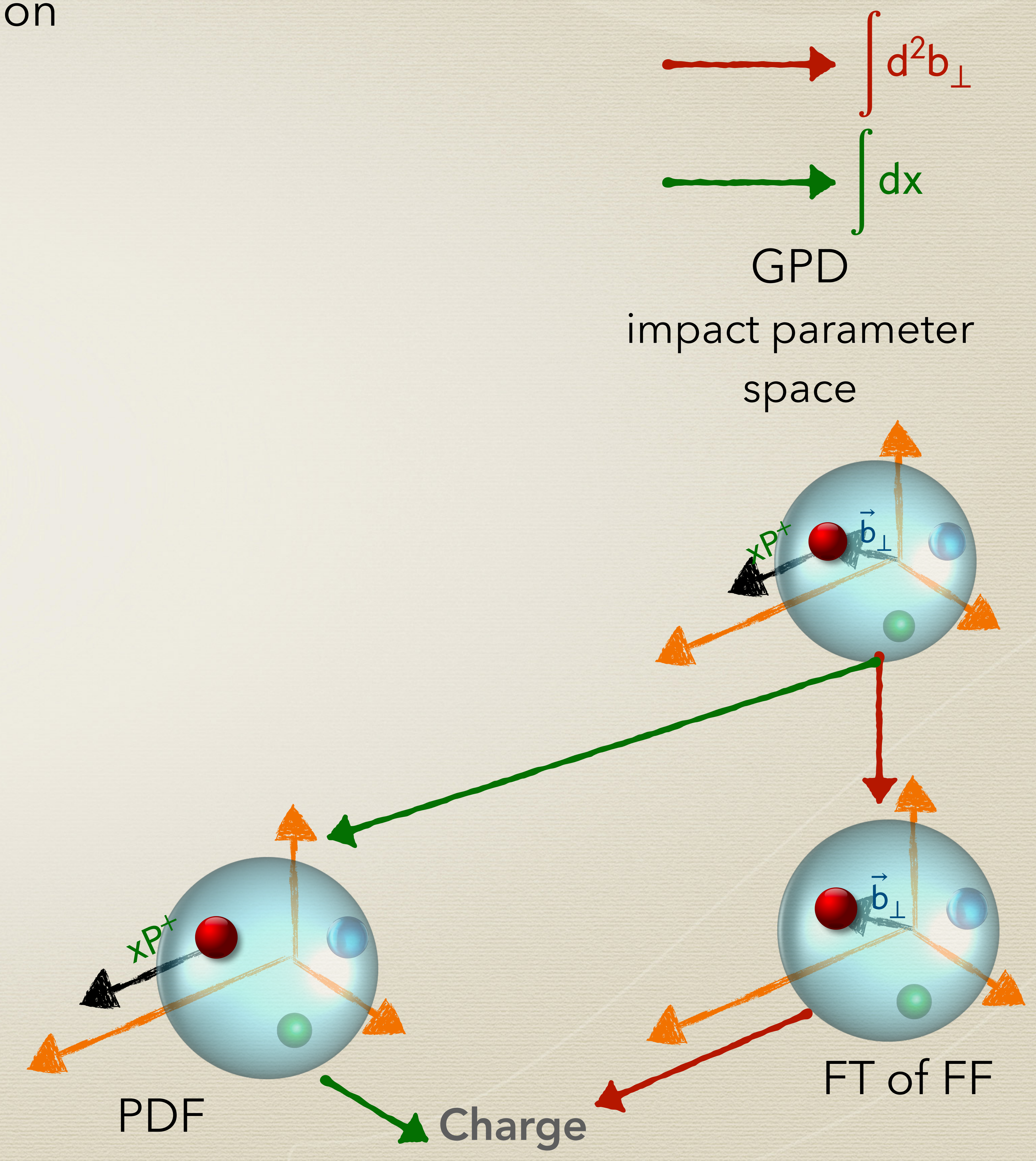
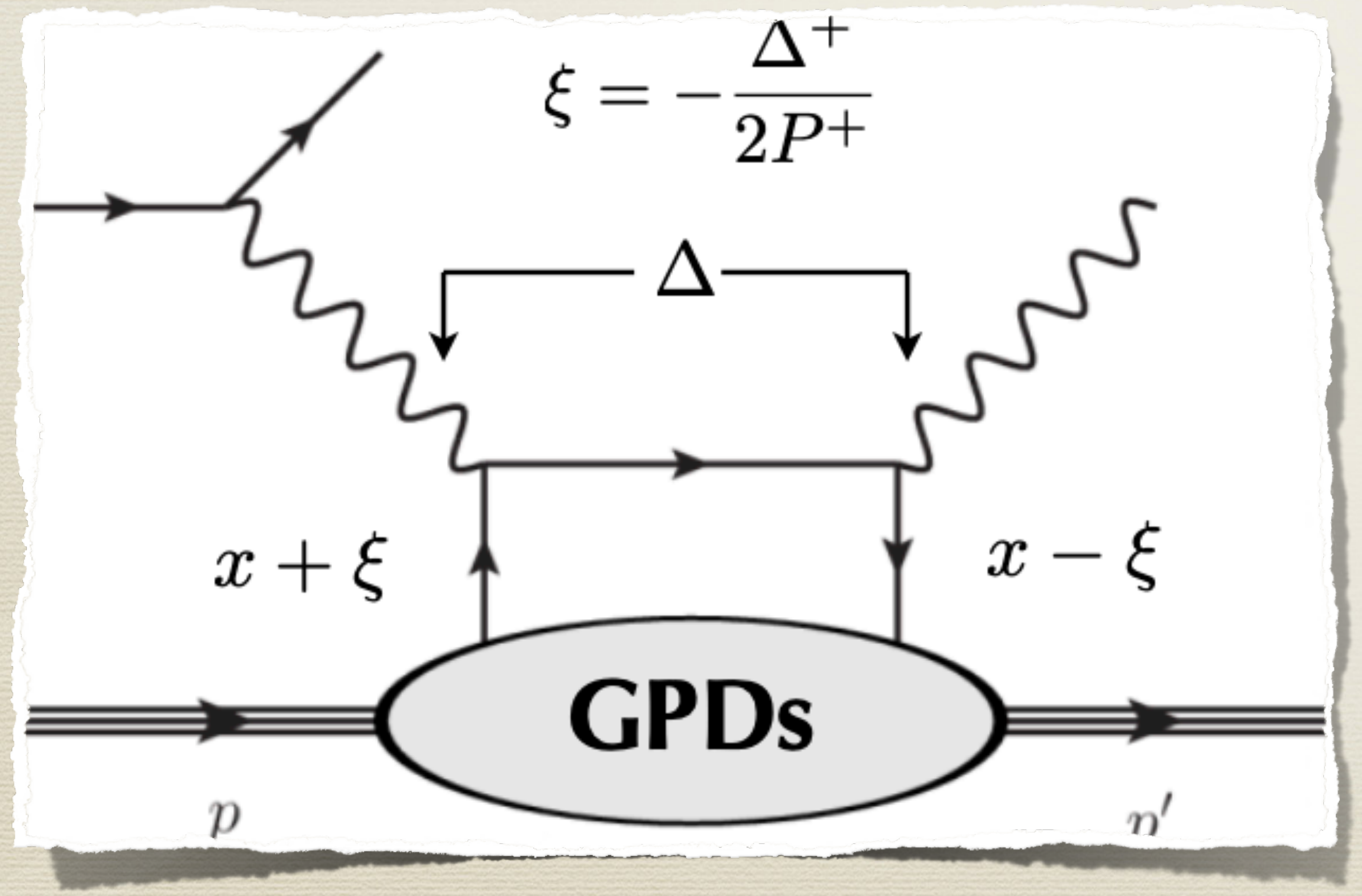
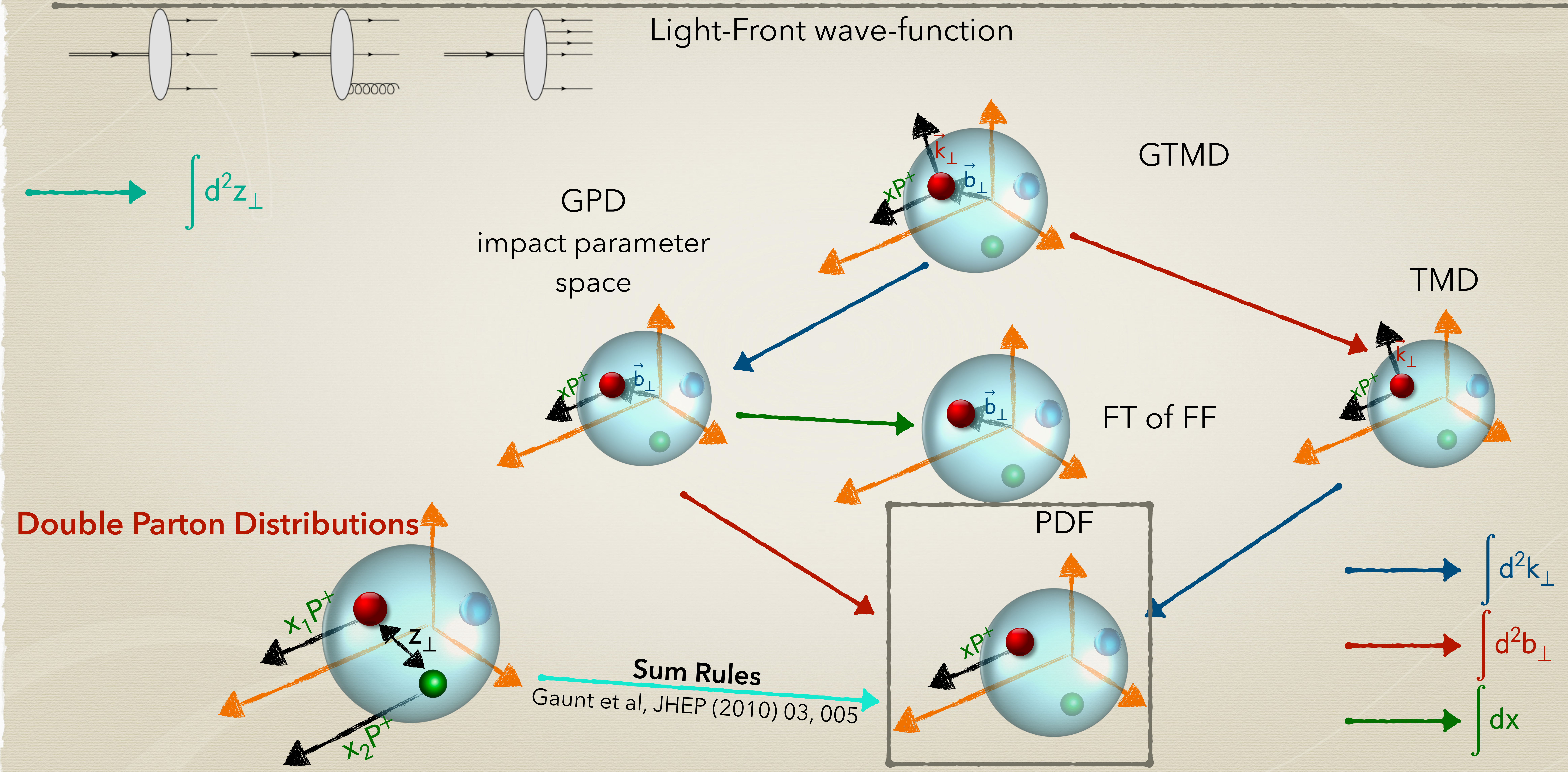


Deeply Virtual Compton Scattering



Multidimensional picture of hadrons



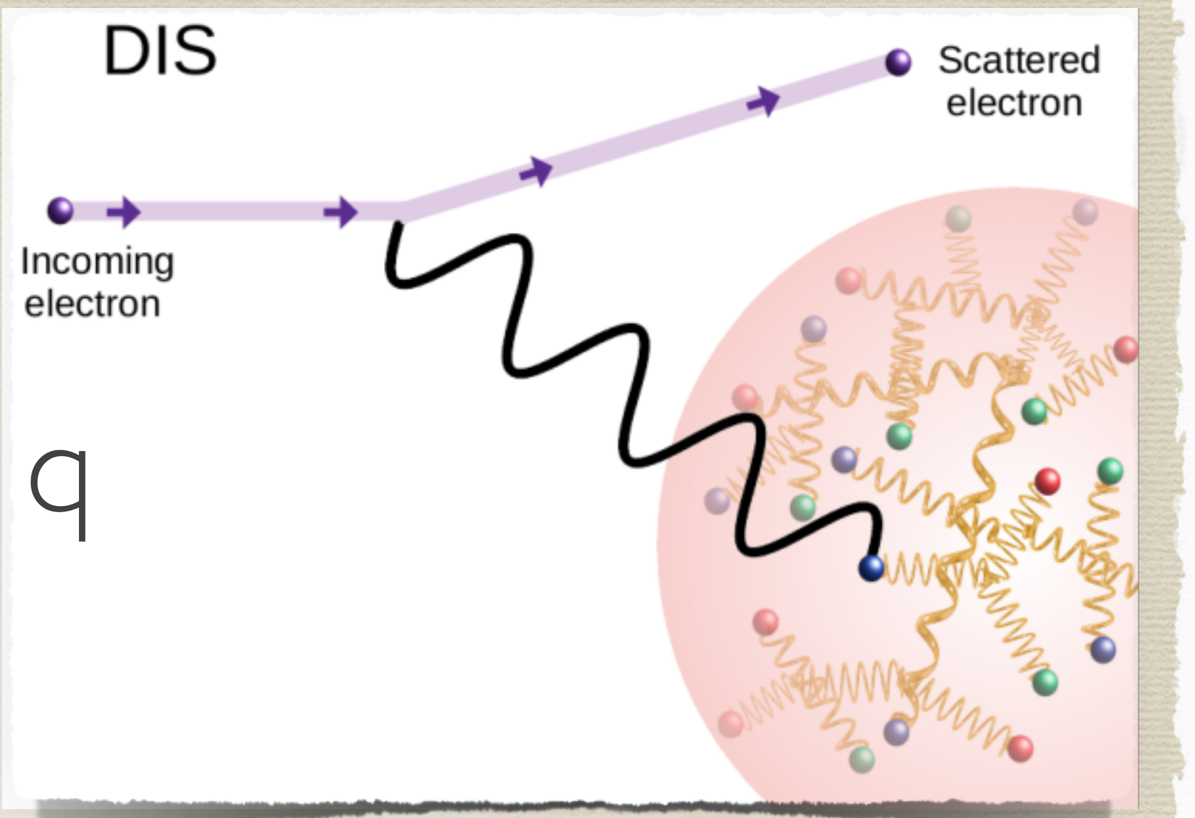
The EMC effect

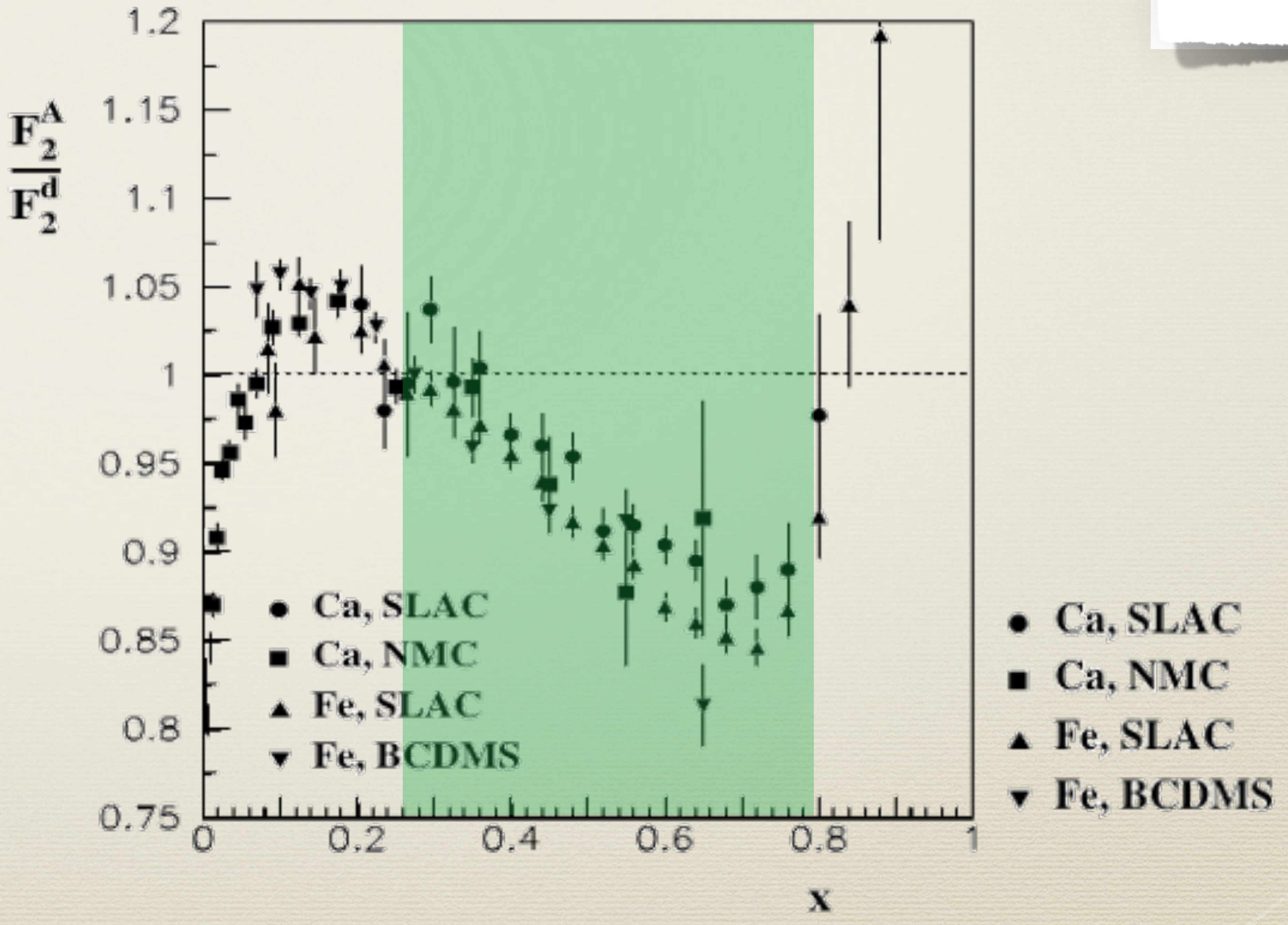
In DIS off a nuclear target with A nucleons:

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

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

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





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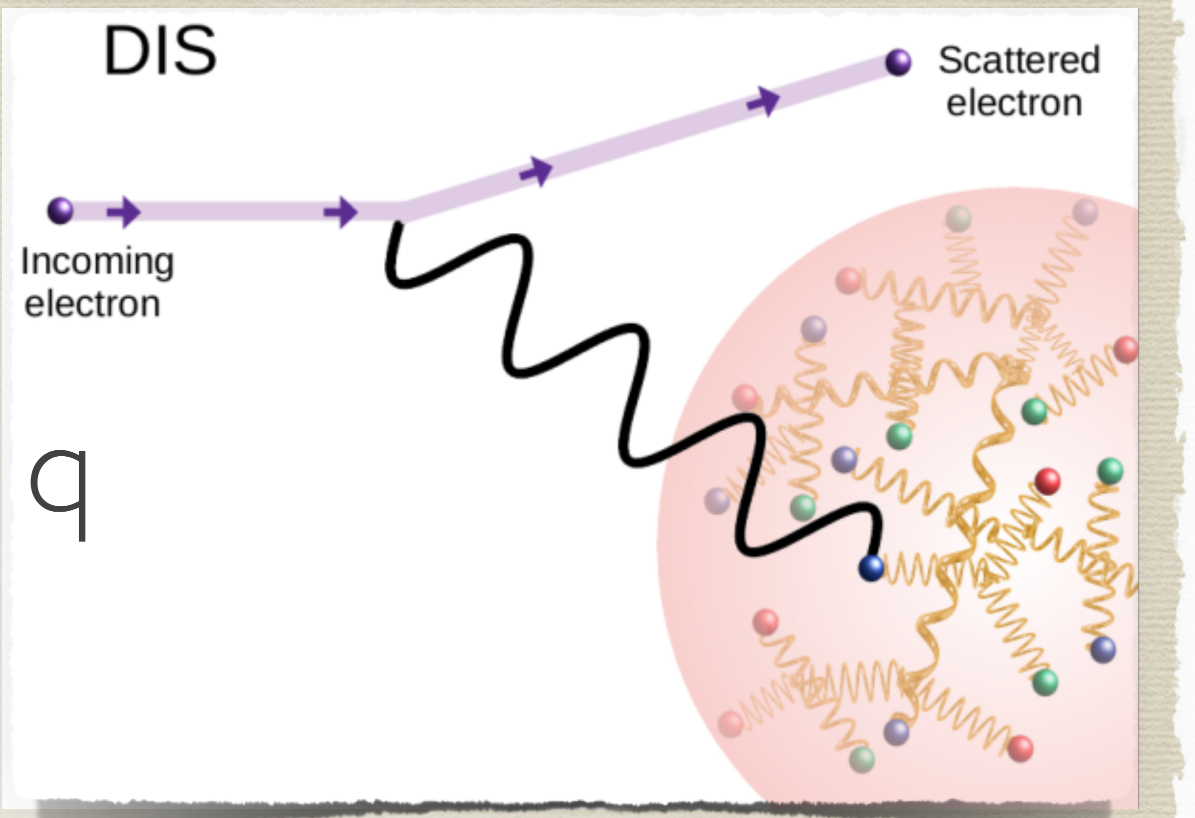

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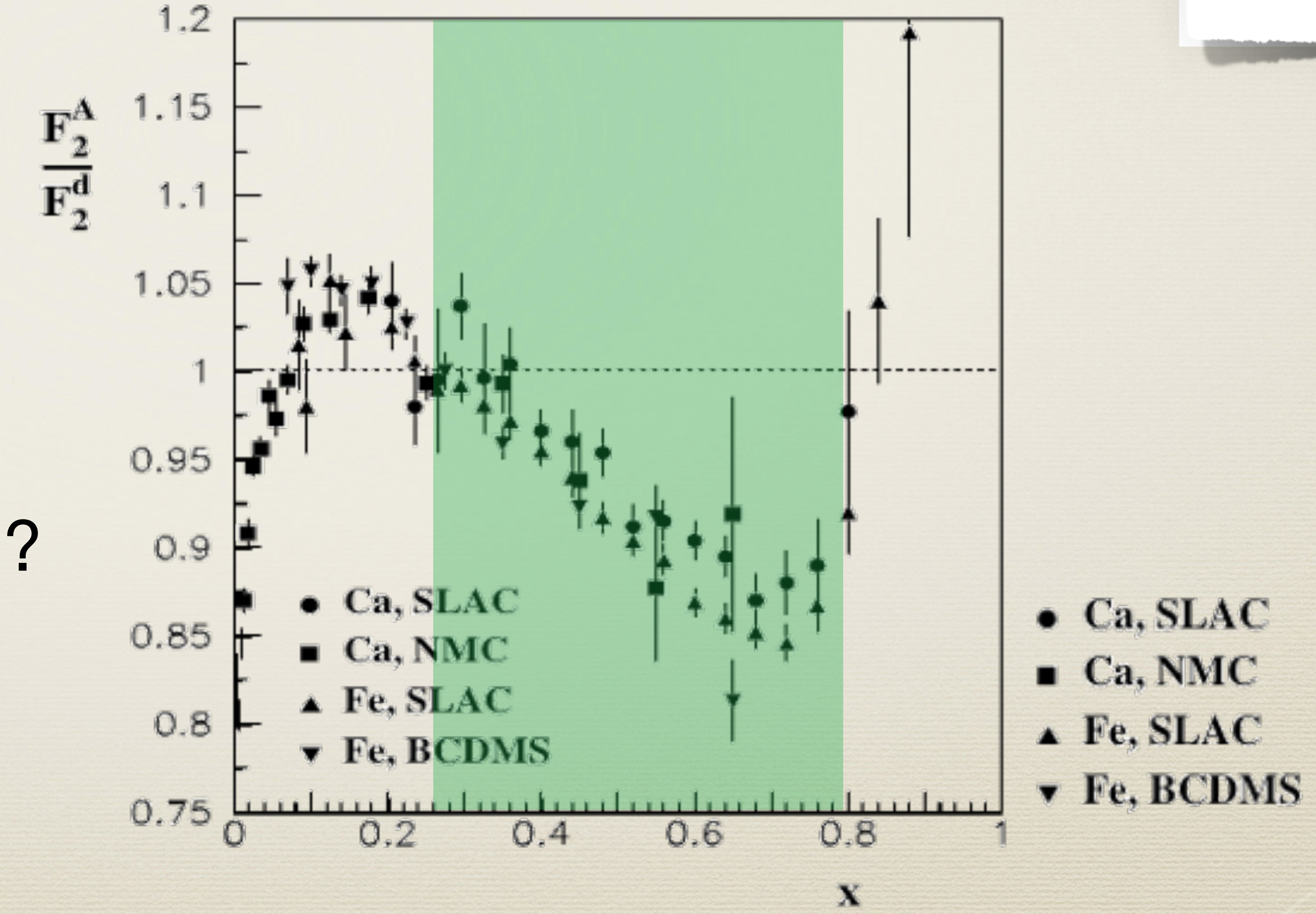
Naive parton model interpretation:

"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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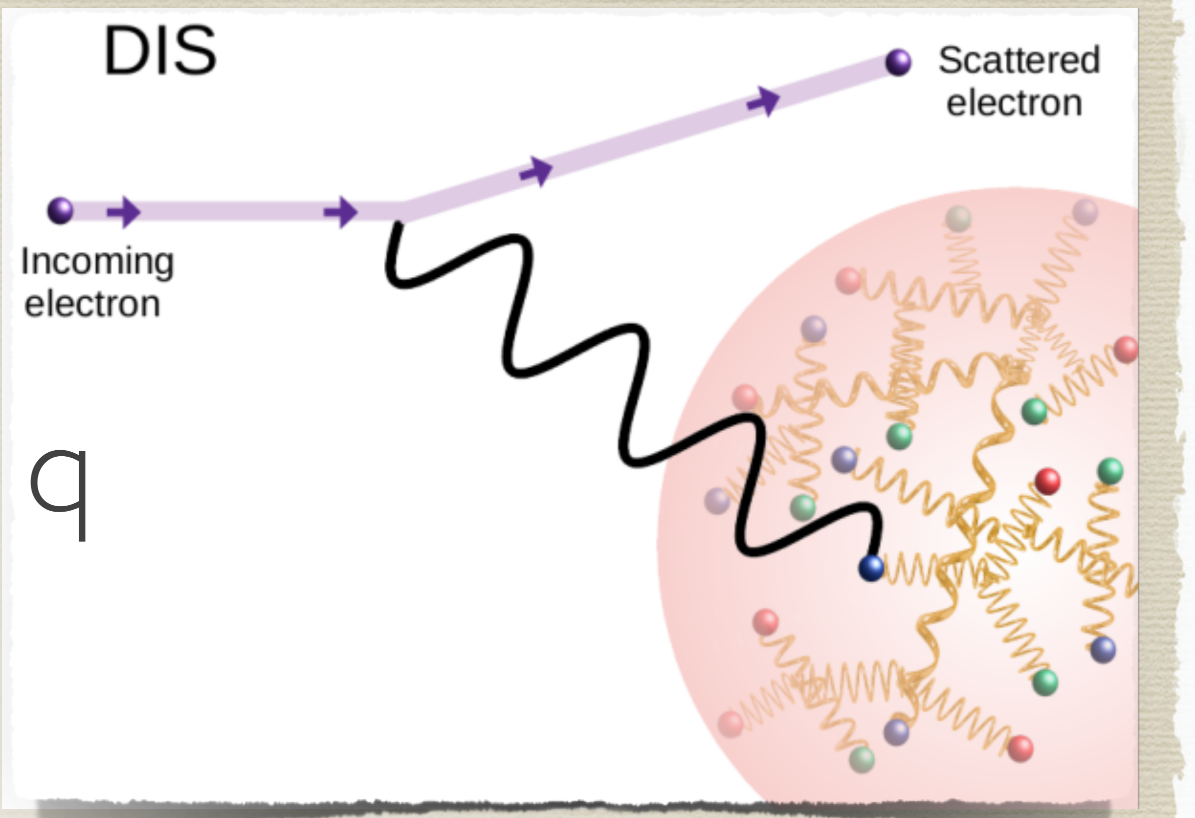

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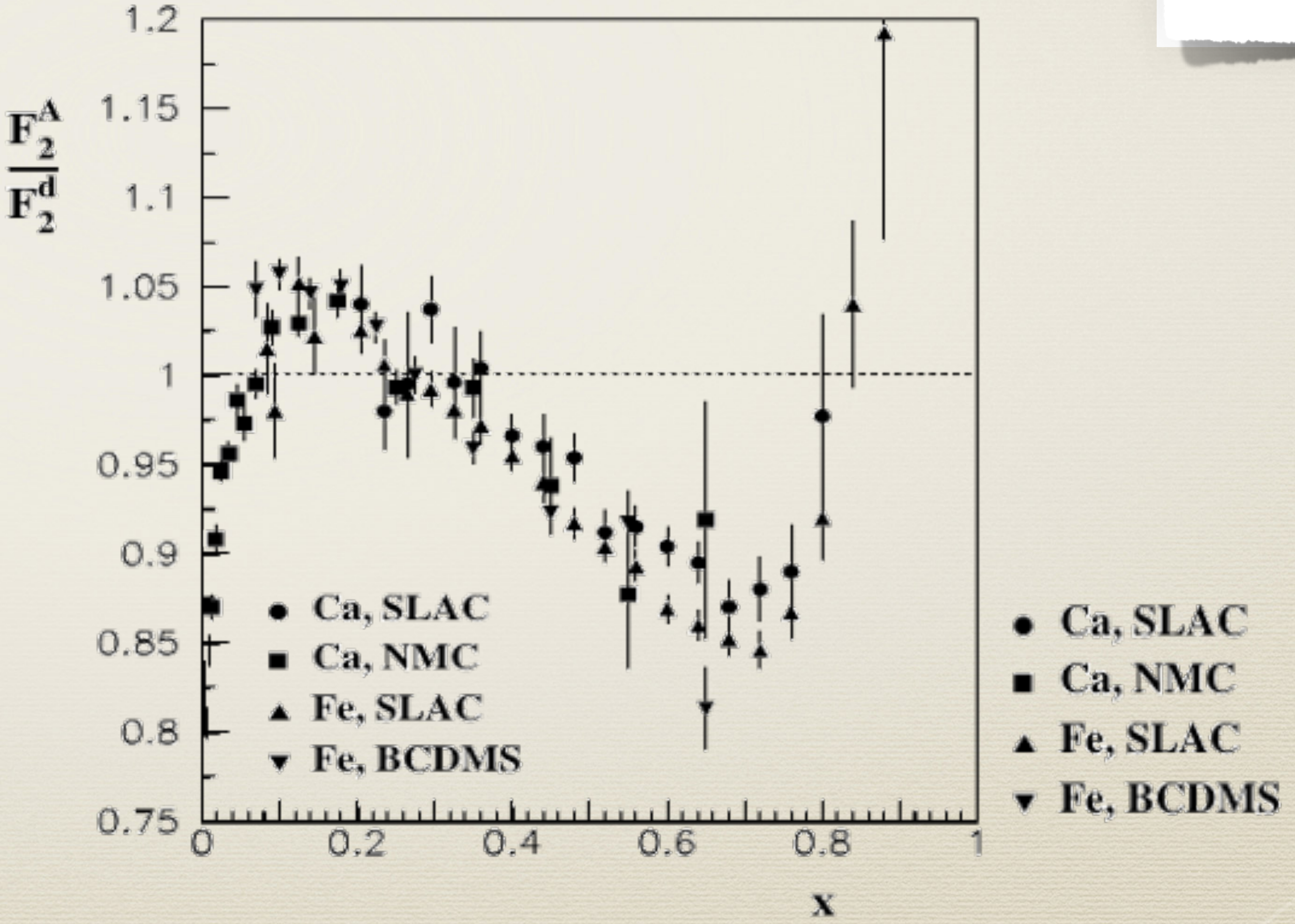


Explanation (exotic) advocated: confinement radius bigger for bound nucleons, quarks in bags with 6, 9,..., 3A
quark, pion cloud effects... Alone or mixed with conventional ones...

Nuclear SFs and EMC ratio

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

Within our approach we have:

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

*ξ = longitudinal momentum fraction carried by a nucleon in the nucleus

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

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

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

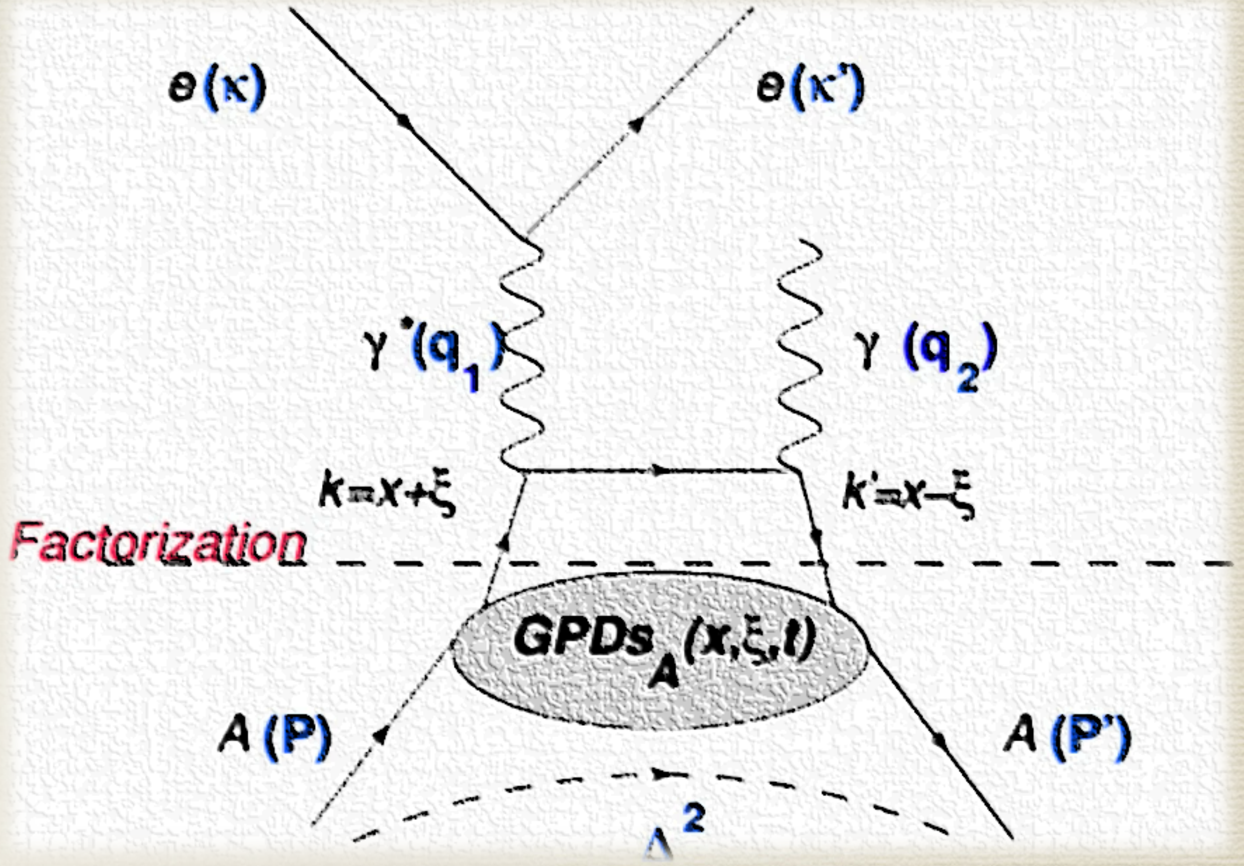
$A = \int_0^1 d\xi [Z f_1^p(\xi) + (A-Z) f^n(\xi)]$: **Baryon number SR**;

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

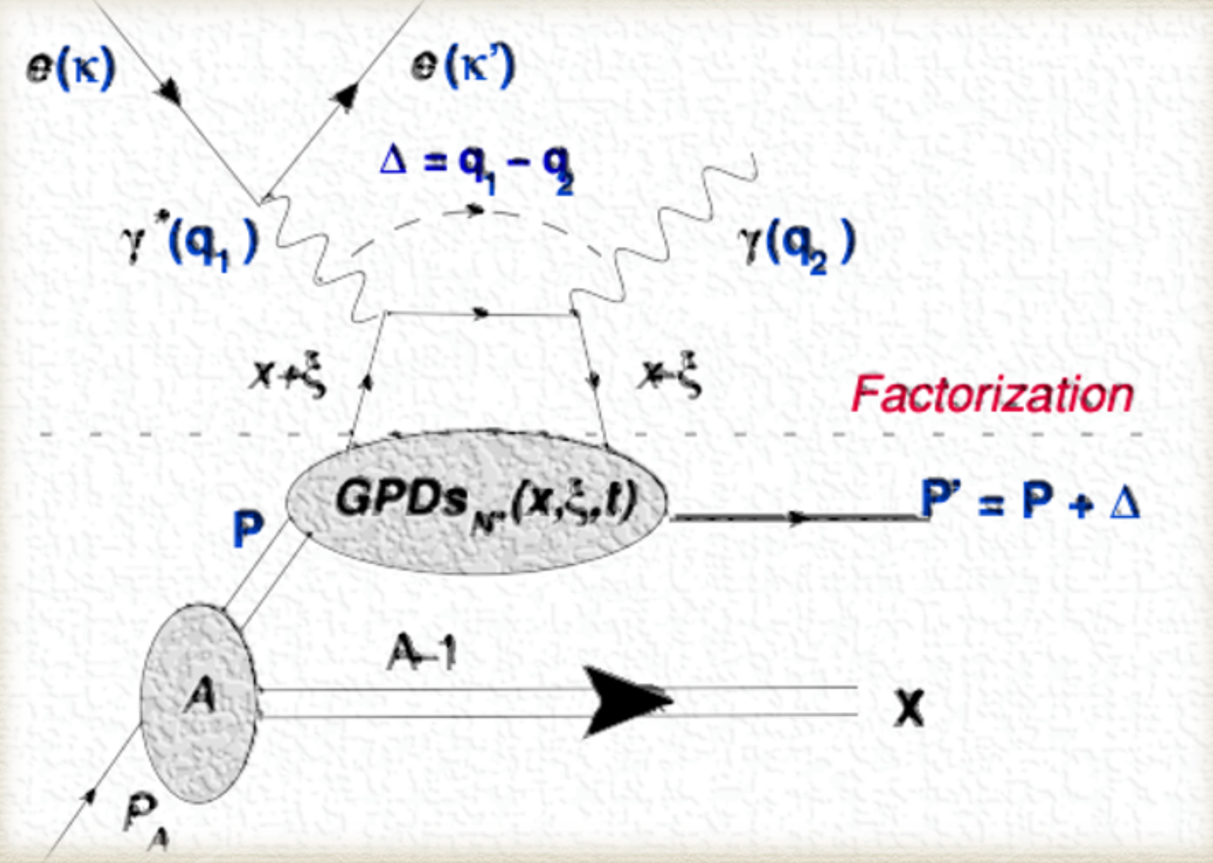
Nuclear DVCS

In the nuclear case we have two channels:

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

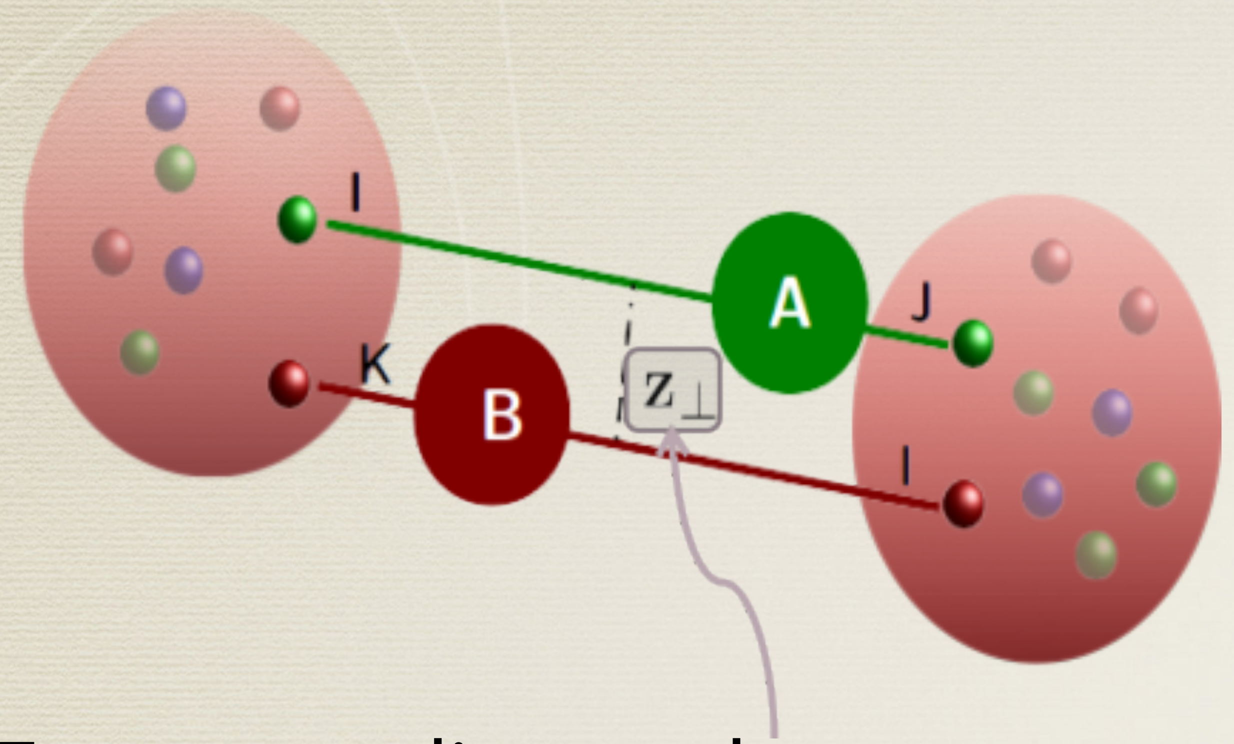


Incoherent channel → we access the GPDs of the bound nucleons
Same distribution of the free one?
Tomography of the bound nucleon



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

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

$$\hat{0}_i^k(z,z') = \bar{q}_i(z)\hat{O}(\lambda_k)q_i(z')$$

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

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:

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

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

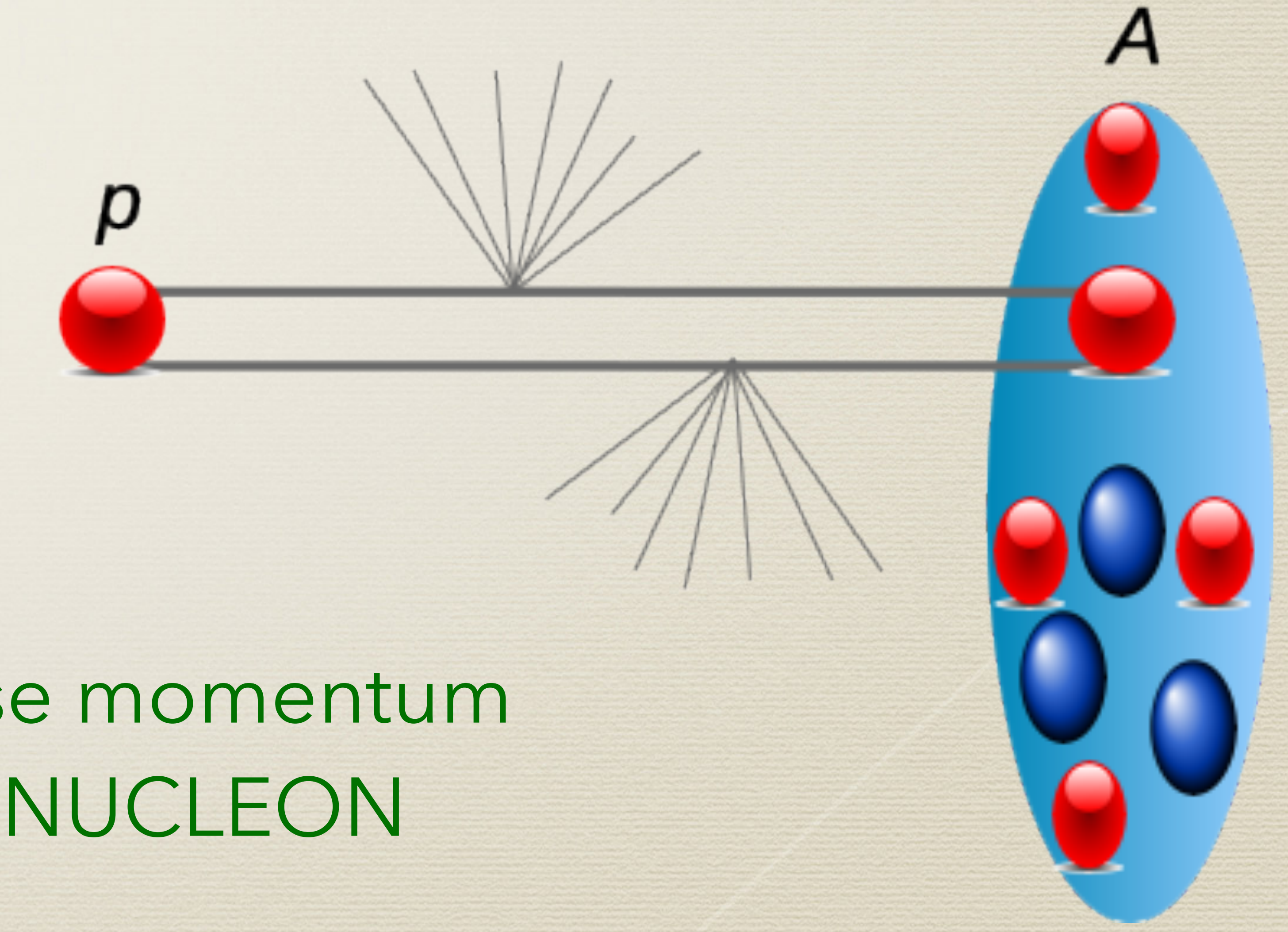
DPD of te nucleon inside the nucleus

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

Momentum fraction carried by a NUCLEON

Light-Cone Momentum Distribution

Transverse momentum of the NUCLEON



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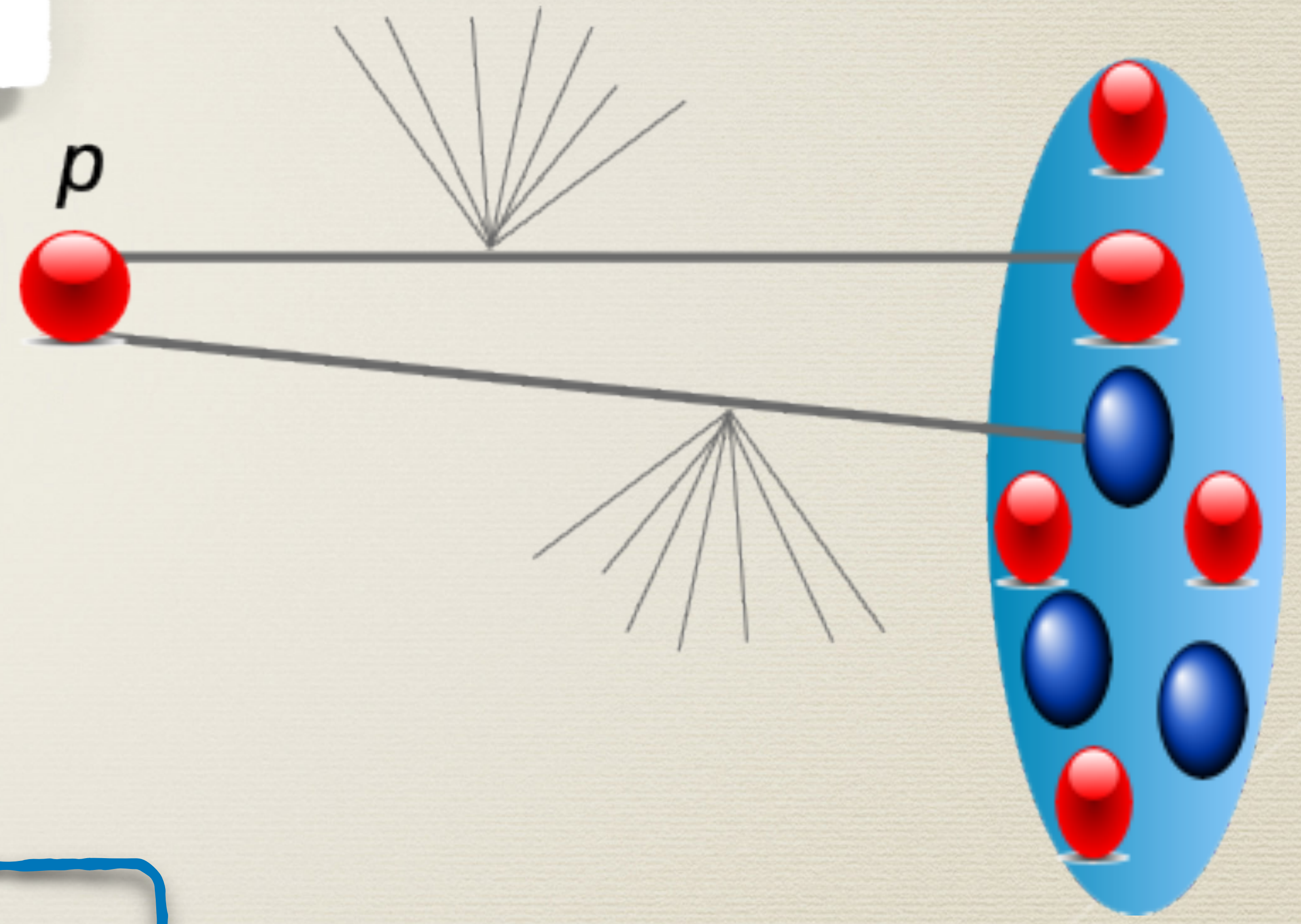
B. Blok et al, EPJC (2013) 73:2422

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

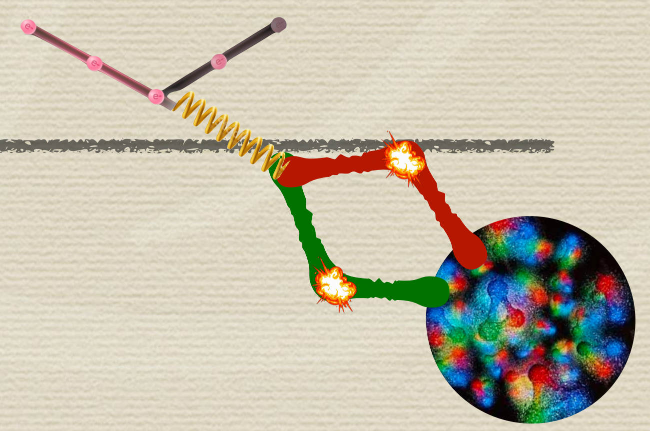


$$\tilde{F}^2_{a_1a_2}(x_1,x_2,\vec{k}_\perp) \propto \int \frac{1}{\xi_1\xi_2}\prod_{i=1}^{i=A}\frac{d\xi_i d^2p_{ti}}{\xi_i}\delta\left(\sum_i \xi_i - A\right)\delta^{(2)}\left(\sum_i \mathbf{p}_{ti}\right)\psi_A^*(\xi_1,\xi_2,p_{t1},p_{t2},\dots) \times \psi_A\left(\xi_1,\xi_2,p_{t1}+\vec{k}_\perp,p_{t2}-\vec{k}_\perp,\dots\right)G_{a_1}^{N_1}\left(x_1/\xi_1,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

Nucleus wf

Nucleon GPD

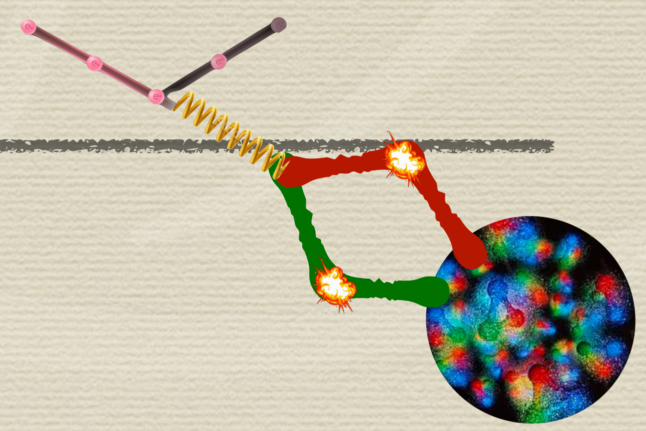
DPS2 in γA collisions with light nuclei



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



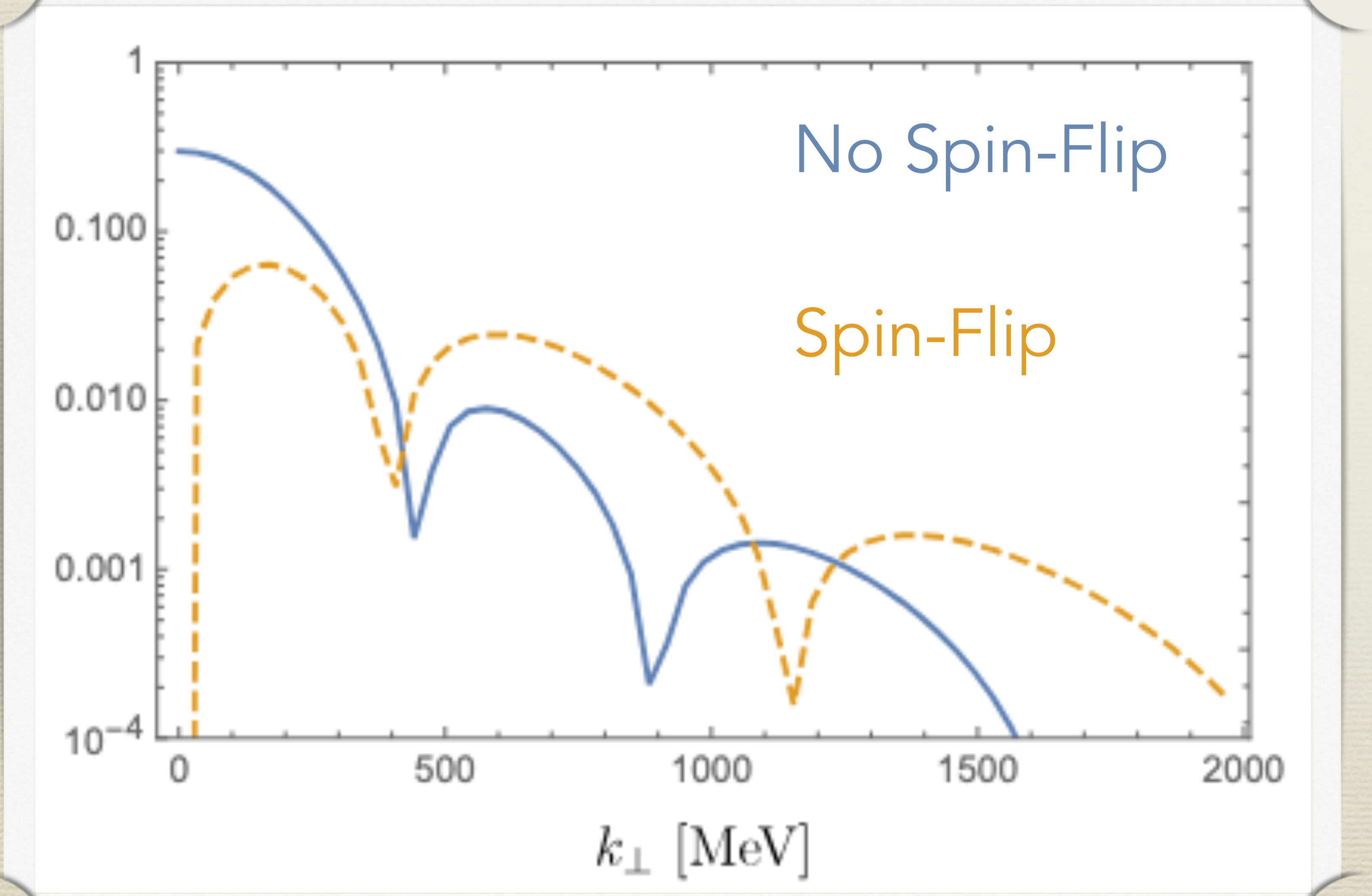
For example in DPS2:

$$D^{A,2}_{ij}(x_1,x_2,\mathbf{k}_\perp) = A(A-1)\sum_{\tau_1,\tau_2=n,p}\;\sum_{\lambda_1,\lambda_2}\;\sum_{\lambda'_1,\lambda'_2}\int d\xi_1\,\frac{\bar{\xi}}{\xi_1}\int d\xi_2\,\frac{\bar{\xi}}{\xi_2}\,\rho^A_{\tau_1\tau_2}(\xi_1,\xi_2,\mathbf{k}_\perp,\lambda_1,\lambda_2,\lambda'_1,\lambda'_2)$$
$$\times\,\Phi^{\tau_1,i}_{\lambda_1,\lambda'_1}\left(x_1\frac{\bar{\xi}}{\xi_1},0,\mathbf{k}_\perp\right)\Phi^{\tau_2,j}_{\lambda_2,\lambda'_2}\left(x_2\frac{\bar{\xi}}{\xi_2},0,-\mathbf{k}_\perp\right)\,.$$

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!

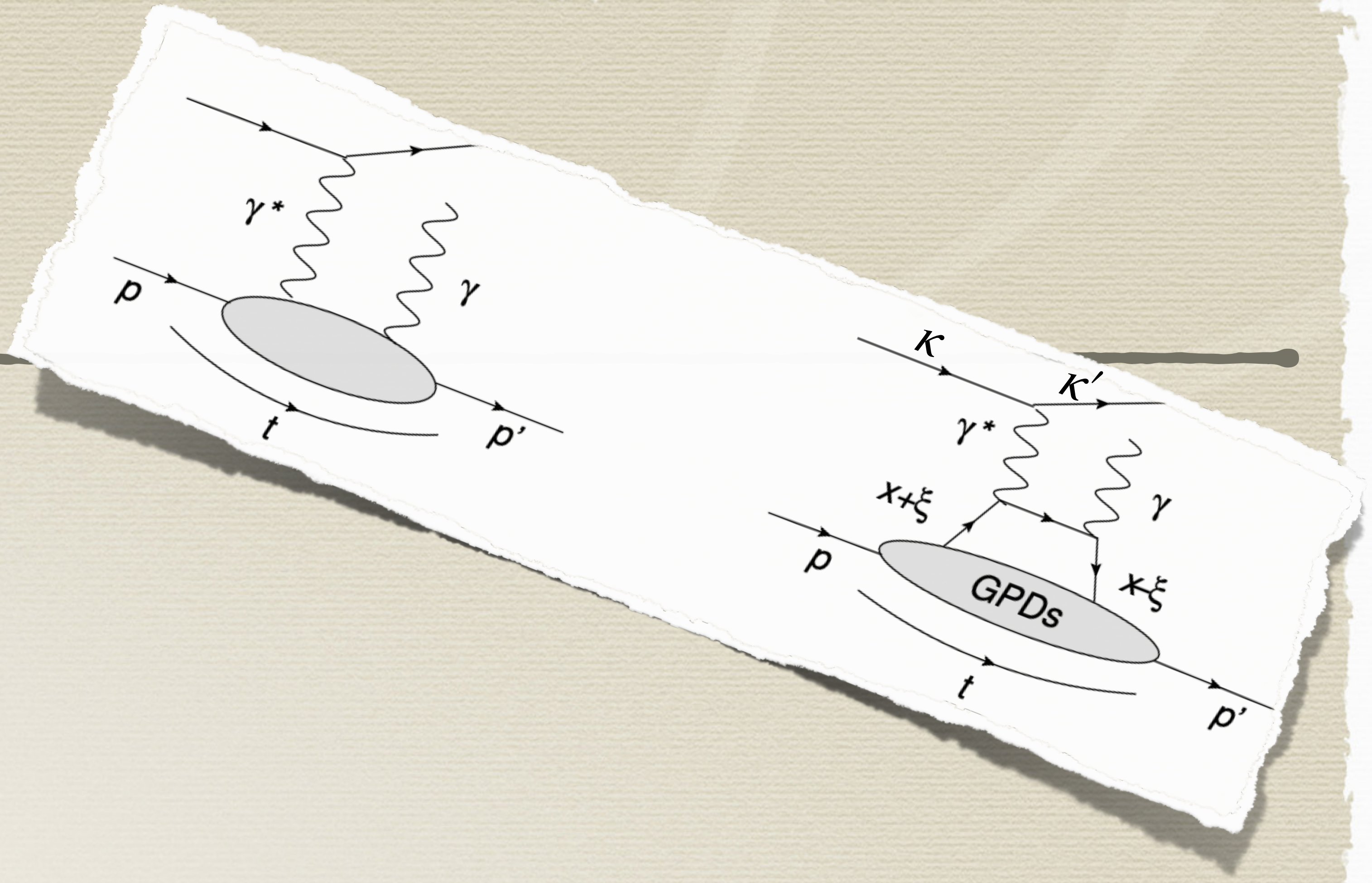


We have:

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

GPDs properties



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

$$H(x, \xi, t) \xrightarrow[\Delta^\mu \to 0]{} f(x)$$

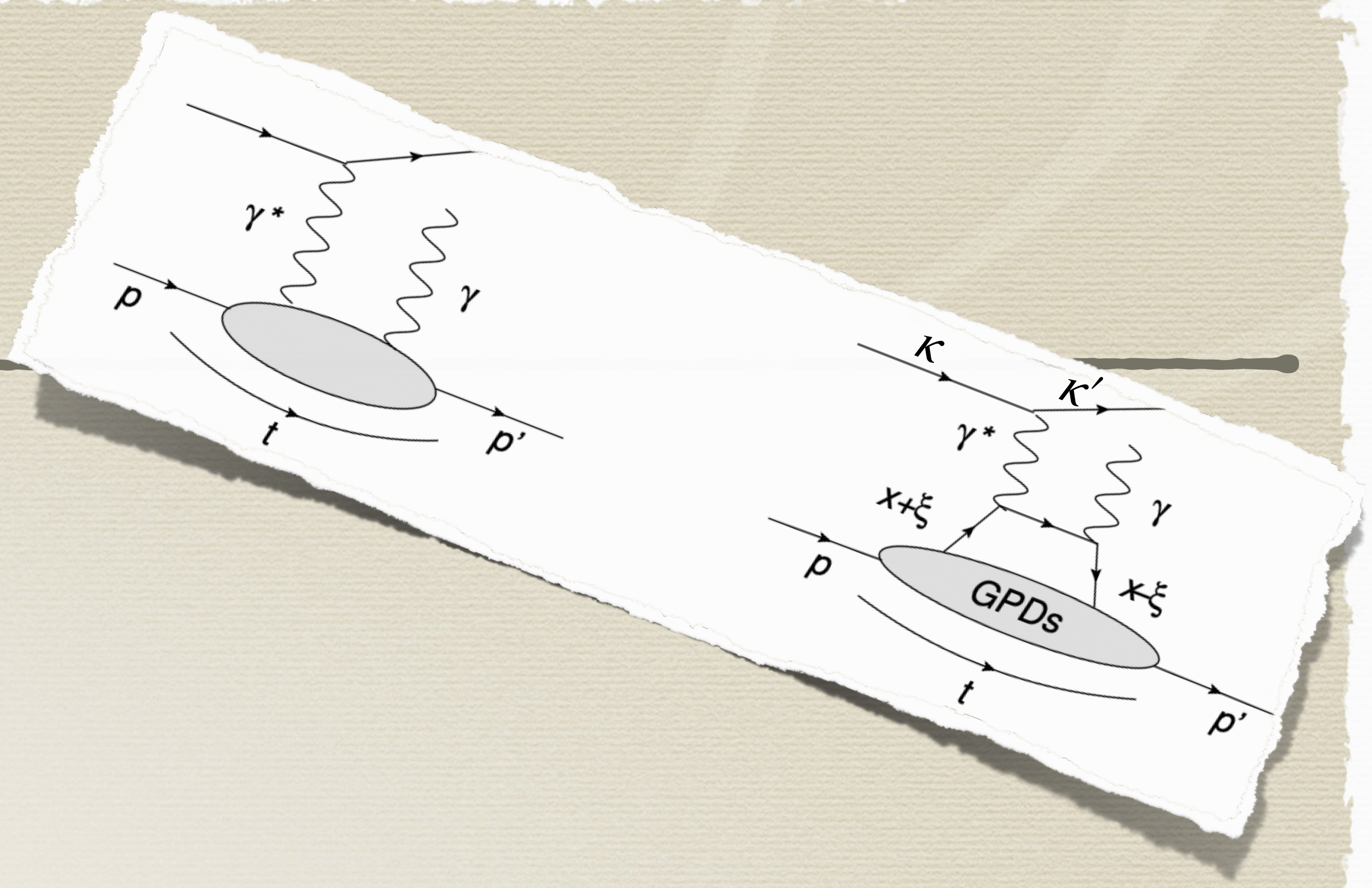
f(x) = Parton Distribution Function (PDF)

- 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



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

$$H(x, \xi, t) \underset{\Delta^\mu \to 0}{\longrightarrow} f(x)$$

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- First moment: relations between GPDs and form factors

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

- Lorentz invariance implies **polynomiality**:

$$\int_{-1}^{1} dx\, x^n H^q(x,\xi,t) = \sum_{\substack{i=0 \\ \text{even}}}^{n} (2\xi)^i A^q_{n+1,i}(t) + \mathrm{mod}(n,2)\,(2\xi)^{n+1} C^q_{n+1}(t),$$

$$\int_{-1}^{1} dx\, x^n E^q(x,\xi,t) = \sum_{\substack{i=0 \\ \text{even}}}^{n} (2\xi)^i B^q_{n+1,i}(t) - \mathrm{mod}(n,2)\,(2\xi)^{n+1} C^q_{n+1}(t).$$