SIMONETTA LIUTI
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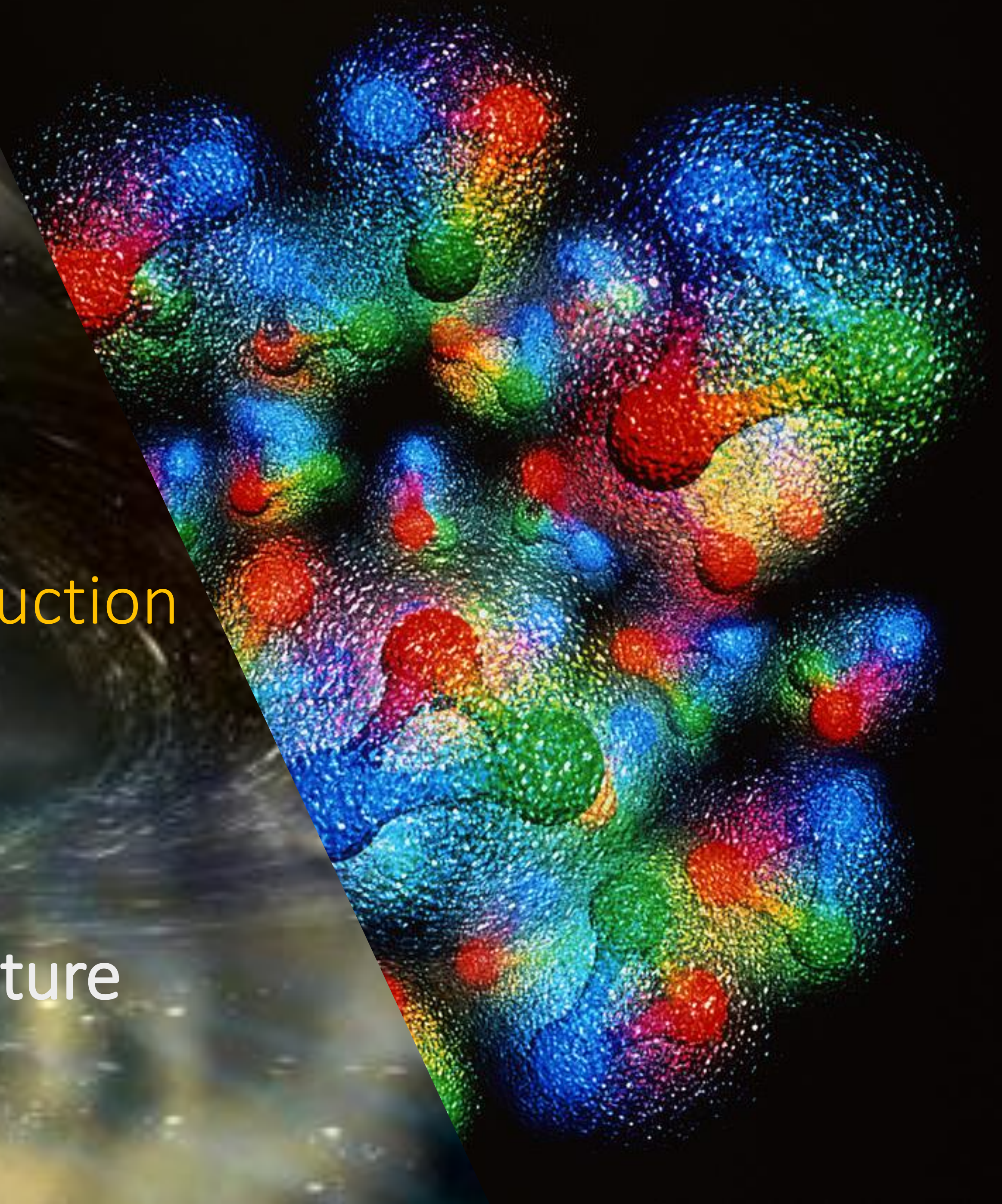
Selected topics in exclusive meson production



International Workshop on Hadron Structure and Spectroscopy
CERN, August 29^{th} 31^{st} 2022

Outline

- Brief Overview

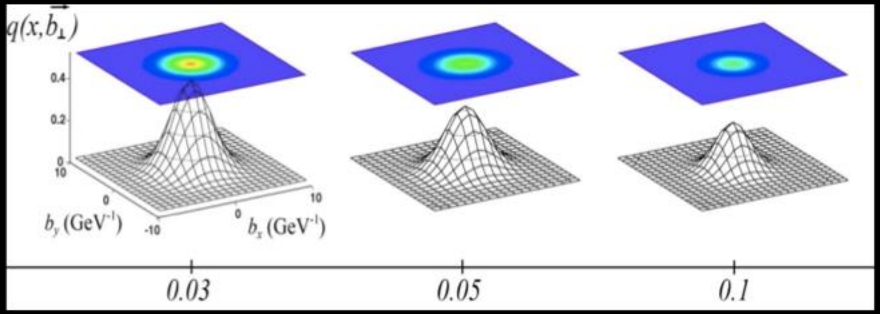
- Selected topics:
    - Pseudoscalar meson production
    - toward higher CoM energies: charmed mesons
    - Scale dependence

- What I will not cover:
    - Specifics of vector mesons
    - Nuclear targets
    - FemtoNET

a framework with benchmarks for ML and DNN analyses of deeply virtual exclusive scattering cross sections

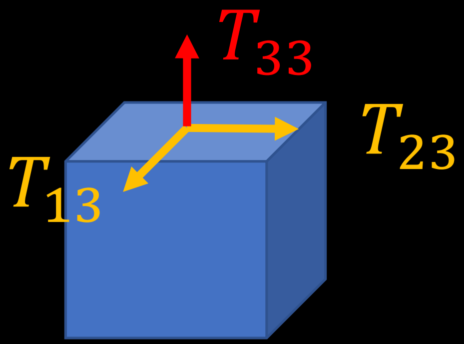
M.Almaeen, J.Grigsby, J.Hoskins, B.Kriesten, Y. Li, H. W. Lin and SL, arXiv:2207.10766

- Quark and Gluon Imaging

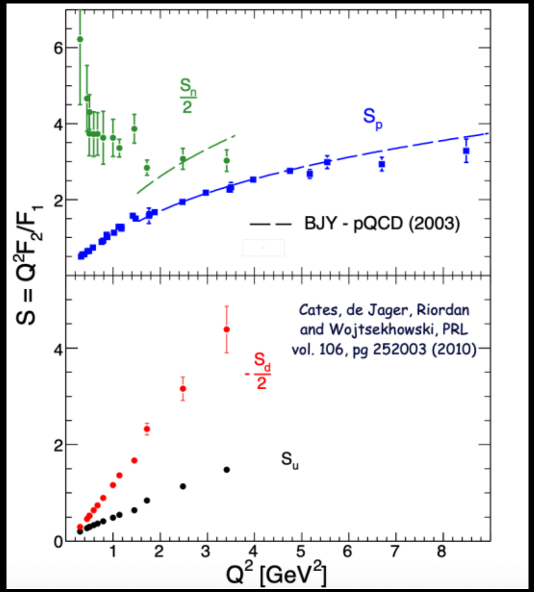


M. Defurne

- What generates the proton spin, mass and its internal forces (dynamics)

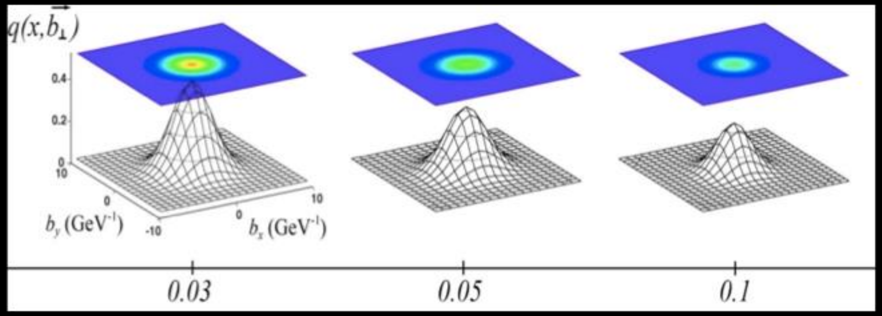


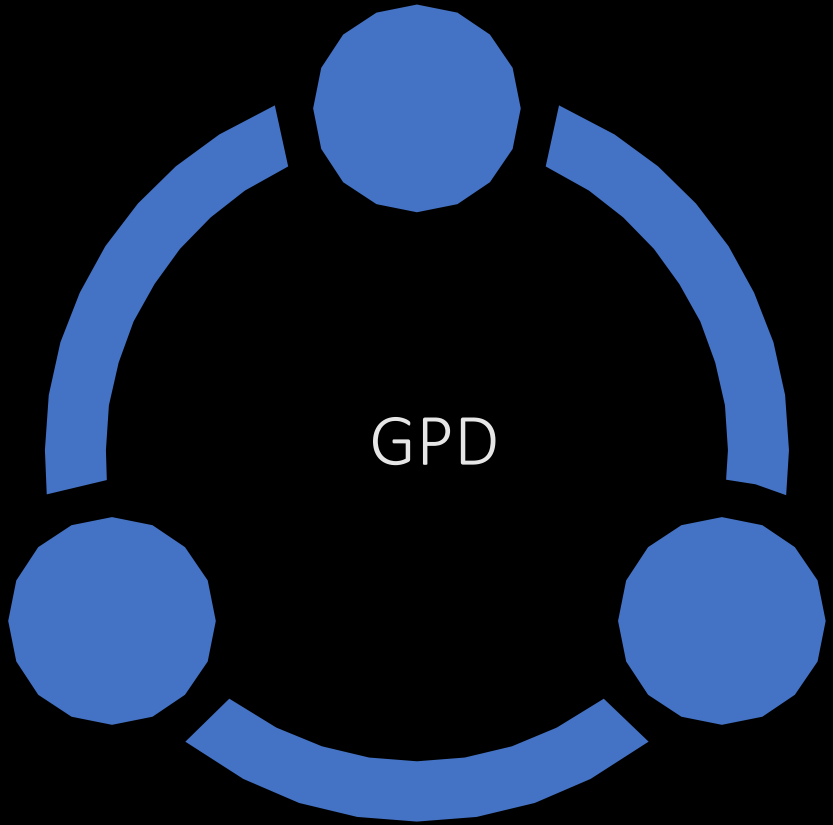
- Mechanisms of flavor dependence in nucleons and nuclei and BSM explorations

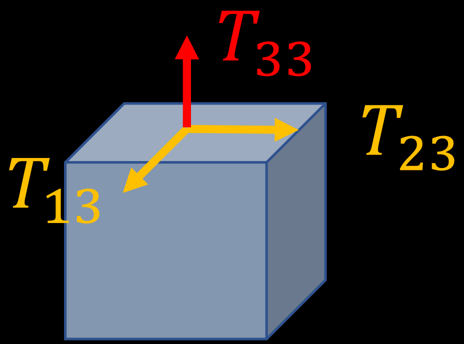


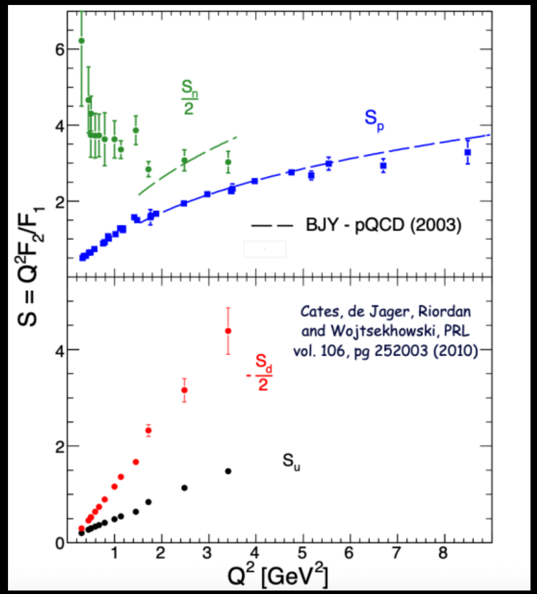
G. Cates et al. (2010)

Common thread

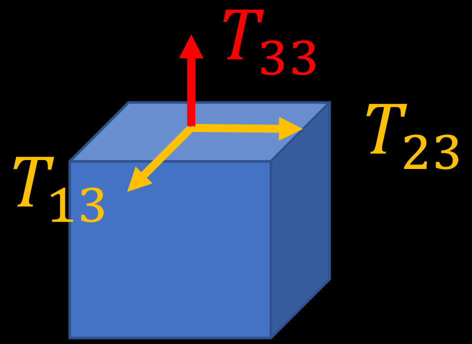




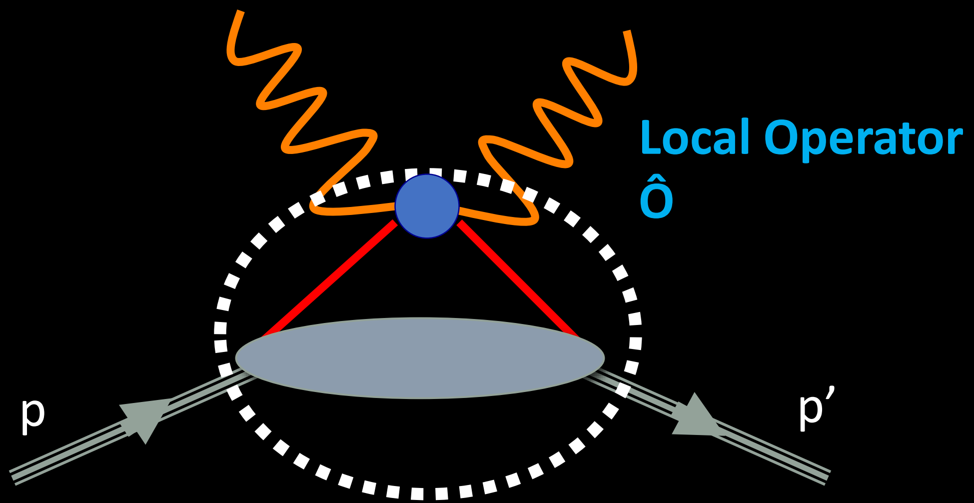




Proton spin: quark longitudinal angular momentum, J_z^q



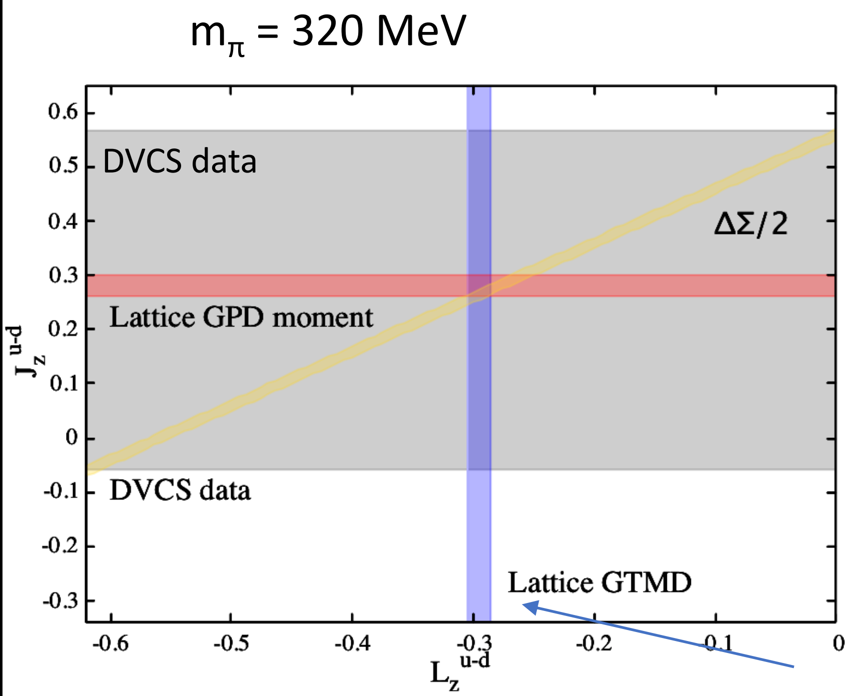
$$J_z^q = \int_0^1 dx\, x\left(H_q + E_q\right)$$



GPD Moments → EMT Form Factors

X. Ji (1997)

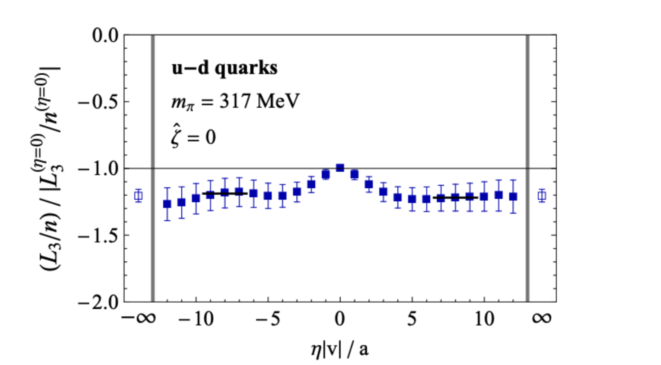
What we know from measurements and lattice



Engelhardt et al., Phys. Rev. D102, (2020)

q=u-d

$$J_q = L_q + \frac{1}{2}\Delta\Sigma_q$$



- Do we need to measure a GTMD to learn about OAM?

Connecting the two pictures using **QCD Equations of Motion** and **Lorentz symmetry**

$$
\begin{aligned}
J_L &= L_L + S_L \\
\frac{1}{2}\int dx\, x(H+E) &= \int dx\, x(\widetilde{E}_{2T} + H + E) + \frac{1}{2}\int dx\, \widetilde{H} \\
&= -\int dx\, F_{14}^{(1)} + \frac{1}{2}\int dx\, \widetilde{H}
\end{aligned}
$$

- A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016)
- A. Rajan, M. Engelhardt, S.L., PRD (2018)

*Twist 3 GPD notation from Meissner, Metz and Schlegel, JHEP(2009)

Quark Spin Orbit: $L \cdot S$

$$\frac{1}{2}\int dx\, x\widetilde{H} + \frac{m_q}{2M}\kappa_T^q = \int dx\, x(2\widetilde{H}'_{2T} + E'_{2T} + \widetilde{H}) + \frac{1}{2}e_q$$

$J_z S_z$ $\qquad$ $L_z S_z$ $\qquad$ $S_z S_z$

- A. Rajan, A. Courtoy, M. Engelhardt, S.L., PRD (2016)
- A. Rajan, M. Engelhardt, S.L., PRD (2018)

*Twist 3 GPD notation from Meissner, Metz and Schlegel, JHEP(2009)

A closer look to $J_z S_z$

$$2(J_z S_z)_q \equiv 2[(J \cdot S)_q - (J_T \cdot S_T)_q] = \frac{1}{2}\int dx x \widetilde{H} + \frac{m_q}{2M}\kappa_T^q$$

$$\kappa_T^q = \int dx \left(E_T + 2\widetilde{H}_T\right) , \qquad e_q = \int dx \, H$$

Quark transverse anomalous magnetic moment
(M. Burkardt, PRD72 (2005)

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Quark transverse anomalous magnetic moment
(M. Burkardt, PRD72 (2005)

Transverse Angular Momentum Sum Rule

O. Alkassasbeh, M. Engelhardt, SL and A. Rajan, (2022) soon on arXiv

$$\underbrace{\frac{1}{2}\int dx x(H+E) - \frac{1}{2}\int dx\, \mathcal{M}_T}_{J_T} = \underbrace{\int dx x\big(\widetilde{E}_{2T} + H + E + \frac{H_{2T}}{\xi}\big)}_{L_T} + \underbrace{\frac{1}{2}\int dx\, g_T - \frac{1}{2}\int dx\, x\mathcal{A}_T}_{S_T}$$

Twist 3 GPDs Physical Interpretation

GPD	$P_q P_p$	TMD	Ref. 1
$H^{\perp}$	UU	$f^{\perp}$	$2\widetilde{H}_{2T} + E_{2T}$
$\widetilde{H}_L^{\perp}$	LL	$g_L^{\perp}$	$2\widetilde{H}'_{2T} + E'_{2T}$
$H_L^{\perp}$	UL	$f_L^{\perp\,(*)}$	$\widetilde{E}_{2T} - \xi E_{2T}$
$\widetilde{H}^{\perp}$	LU	$g^{\perp\,(*)}$	$\widetilde{E}'_{2T} - \xi E'_{2T}$
$H_T^{(3)}$	UT	$f_T^{(*)}$	$H_{2T} + \tau \widetilde{H}_{2T}$
$\widetilde{H}_T^{(3)}$	LT	g'_T	$H'_{2T} + \tau \widetilde{H}'_{2T}$

1/Q correction to H

1/Q correction to $\widetilde{\mathrm{H}}$ $\quad L \cdot S$

NEW!! OAM L_z

NEW!!

1/Q correction to E: OAM, L_T

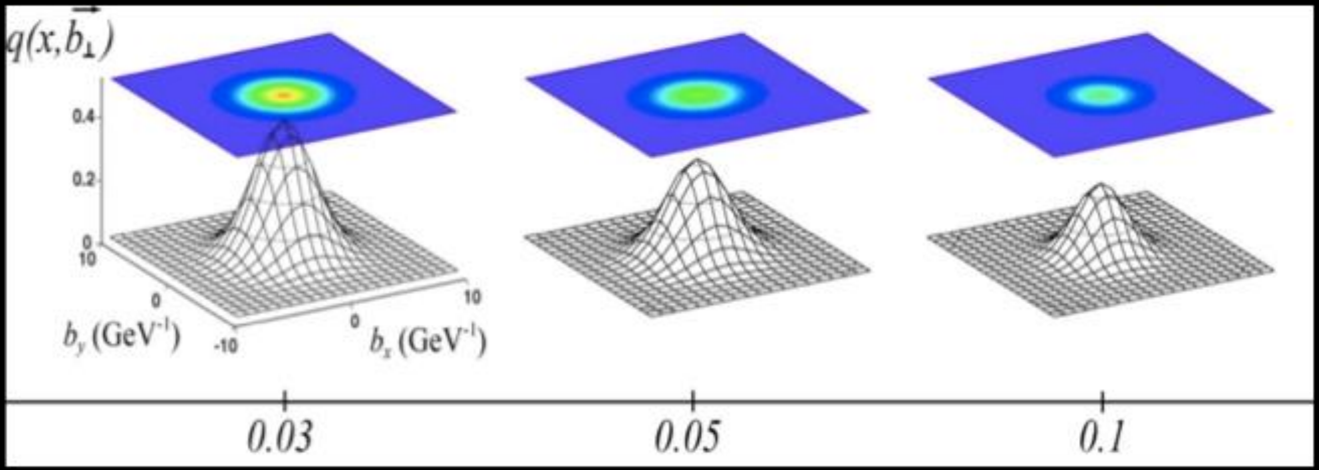
1/Q correction to $\widetilde{\mathrm{E}}$

(*) T-odd

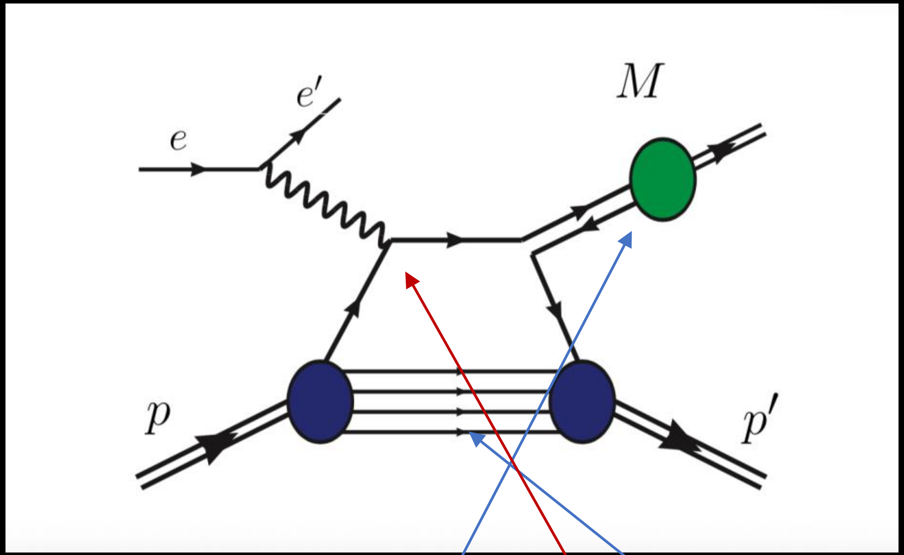
[1] Meissner, Metz and Schlegel, JHEP(2009)

Measuring All This:

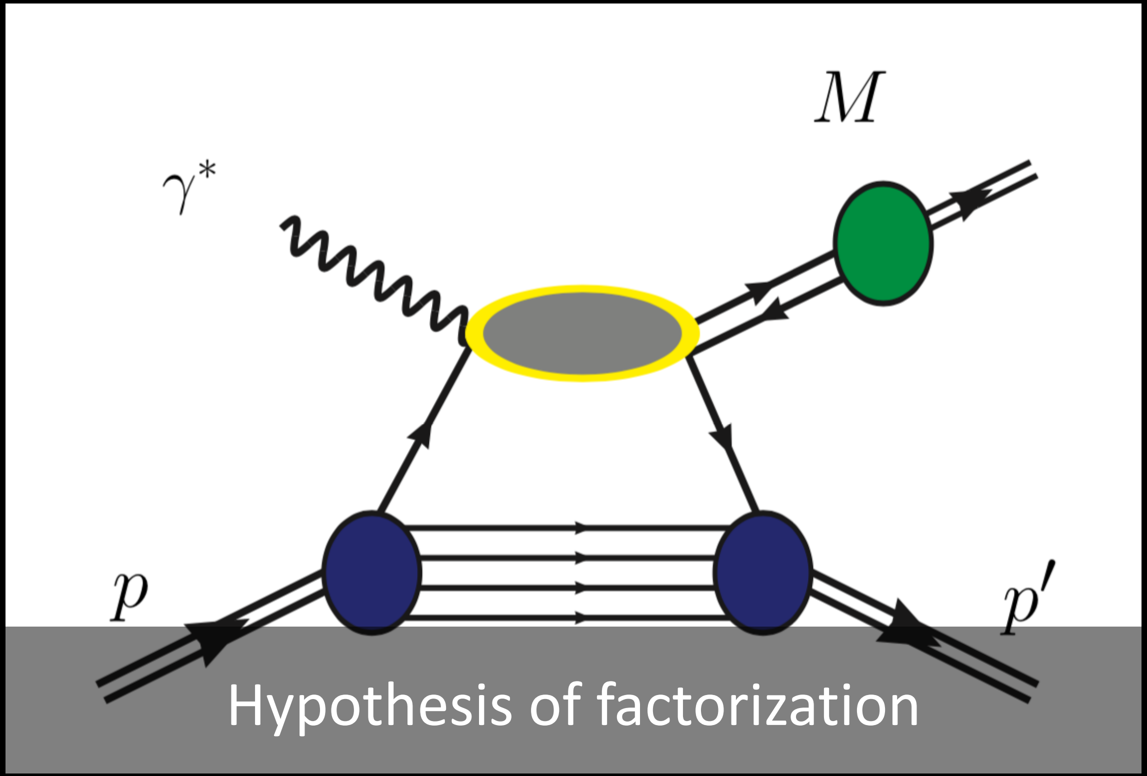
from Jlab@12 GeV, **Jlab@12+ GeV**, COMPASS to the EIC

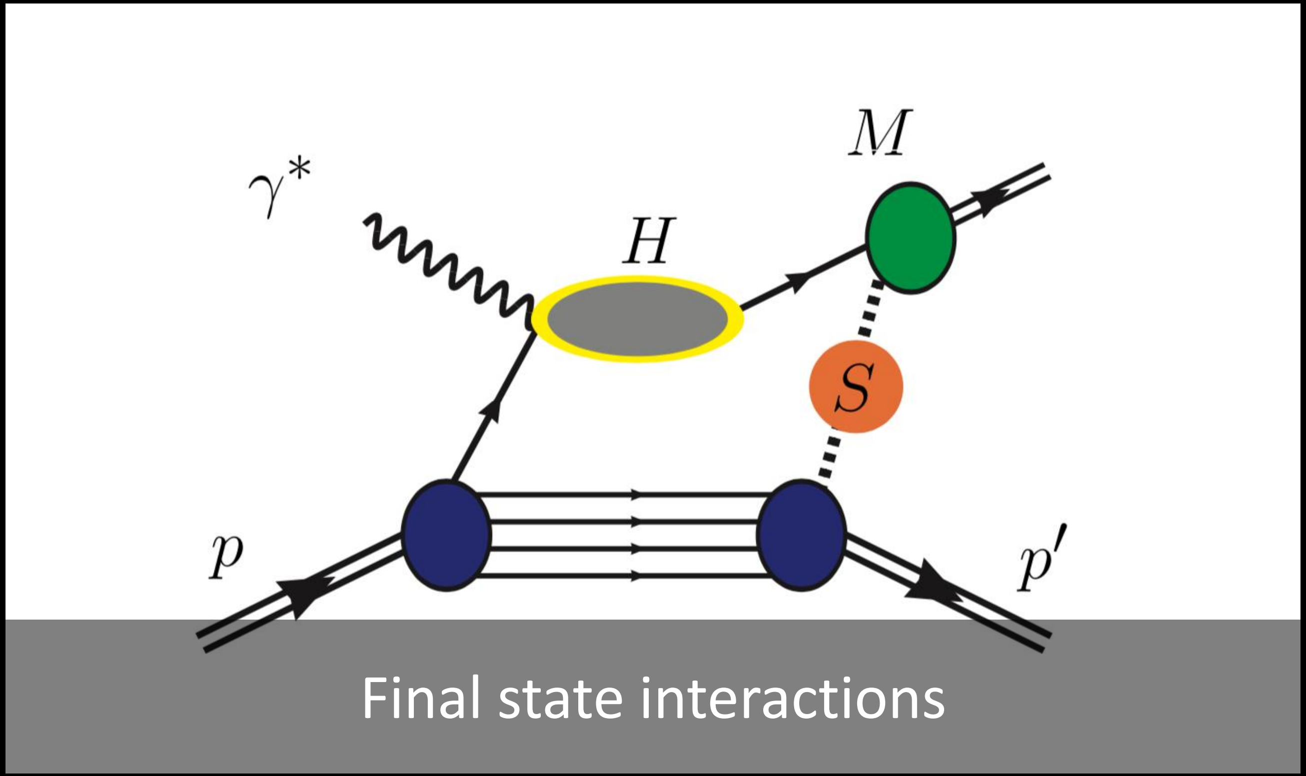


Role of meson production



$$A = \int_0^1 dz\,(DA)\int_{-1}^{1} dx\,(PQCD)(GPD)$$


M
γ^*
p
p'
Hypothesis of factorization


M
γ^*
H
S
p
p'
Final state interactions

Factorization Theorem for meson production

Collins, Frankfurt & Strikman (PRD, 1997)

1) When the virtual photon is longitudinally polarized the end-point contributions in the meson wave function are power suppressed.

(Due to helicity conservation polarization transfers directly from the photon to the produced vector meson)

3) γ^*_L singles out small size configurations compared to γ^*_T.

4) “Non small size” configurations are less likely to factorize and are power suppressed.

This is the underlying physics idea that has all to be proven!

In this working hypothesis ...

$$\rho_L^0 \to \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right] (e_u H_u - e_d H_d)$$

$$\rho_L^+ \to \int_{-1}^{1} dx \left[\frac{e_u}{x-\xi+i\epsilon} + \frac{e_d}{x+\xi+i\epsilon} \right] (H_u - H_d)$$

$$\omega_L \to \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi+i\epsilon} \right] (e_u H_u + e_d H_d)$$

$$\pi^0 \to \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi-i\epsilon} \right] (e_u \widetilde{H}_u - e_d \widetilde{H}_d)$$

$$\pi^+ \to \int_{-1}^{1} dx \left[\frac{e_u}{x-\xi+i\epsilon} + \frac{e_d}{x+\xi+i\epsilon} \right] (\widetilde{H}_u - \widetilde{H}_d)$$

$$\eta \to \frac{1}{\sqrt{6}} \int_{-1}^{1} dx \left[\frac{1}{x-\xi+i\epsilon} + \frac{1}{x+\xi+i\epsilon} \right] (e_u \widetilde{H}_u + e_d \widetilde{H}_d - 2e_s \widetilde{H}_s)$$

Beyond longitudinally polarized photon

- G. R. Goldstein, J. O. Gonzalez Hernandez and S. Liuti,
  [arXiv:1401.0438 [hep-ph]].
- Courtoy, S. Baessler, M. Gonzalez-Alonso and S. Liuti,
  Phys. Rev. Lett. 115 , 162001 (2015)
- G.R. Goldstein, J. O. Gonzalez Hernandez and S. Liuti,
  Phys. Rev. D 91114013 (2015)
- G. R. Goldstein, J. O. Gonzalez Hernandez and S. Liuti,
  J. Phys. G 39, 115001 (2012)
- S. Liuti and G. R. Goldstein,
  [arXiv:1009.1334 [hep-ph]].
- S. Ahmad, G. R. Goldstein and S. Liuti,
  Phys. Rev. D 79, 054014 (2009)

SAEED AHMAD, GARY R. GOLDSTEIN, AND SIMONETTA LI

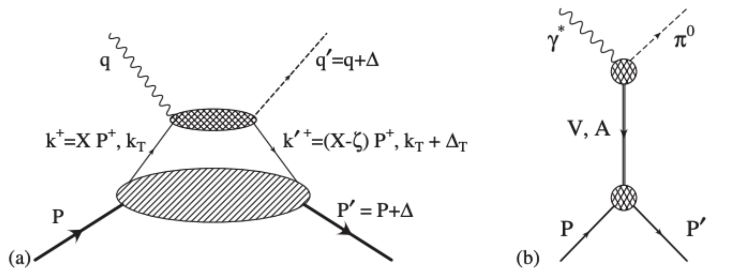


FIG. 1. π^o electroproduction. Left: partonic degrees of freedom interpretation; Right: t-channel exchange diagram.

Focus on pseudoscalar mesons

Pseudoscalar meson production gives access to:

- the tensor charge, g_T
- the tensor anomalous magnetic moment, κ_T

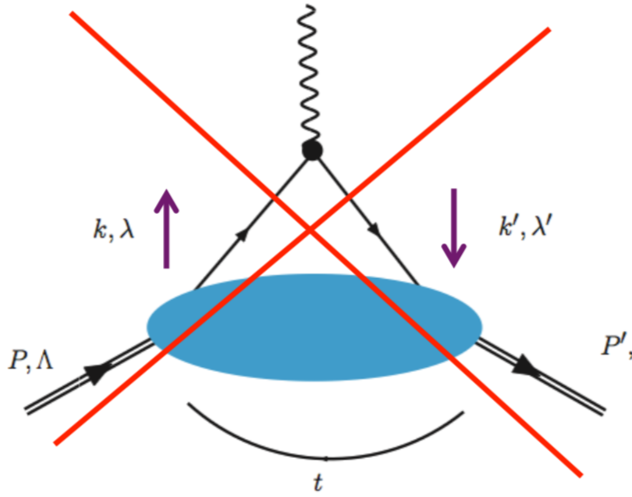
Opportunity for BSM studies

Courtoy, Baessler, Gonzalez Alonso, Liuti (PRL, 2015)

The most general form of gauge interactions with the exchange of a spin-1 particle is a linear combination of

VECTOR $\bar{\Psi}\gamma_\mu\Psi$ and **AXIAL-VECTOR** $\bar{\Psi}\gamma_\mu\gamma_5\Psi$

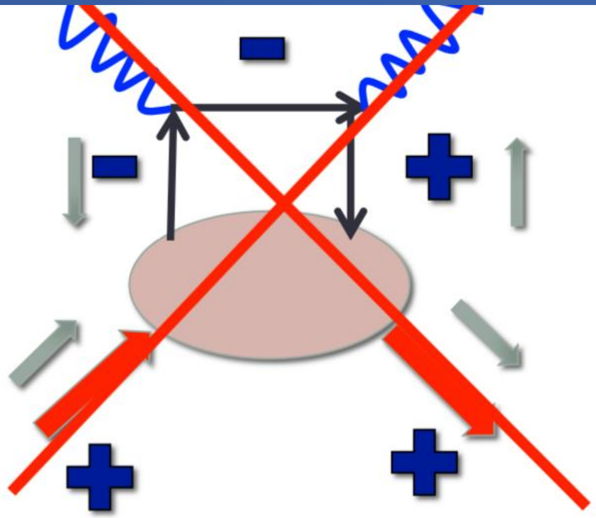
- ✓ The tensor charge is not “fundamental”
- ✓ A “tensor form factor” cannot be measured in elastic scattering type processes mediated by either one or two photons

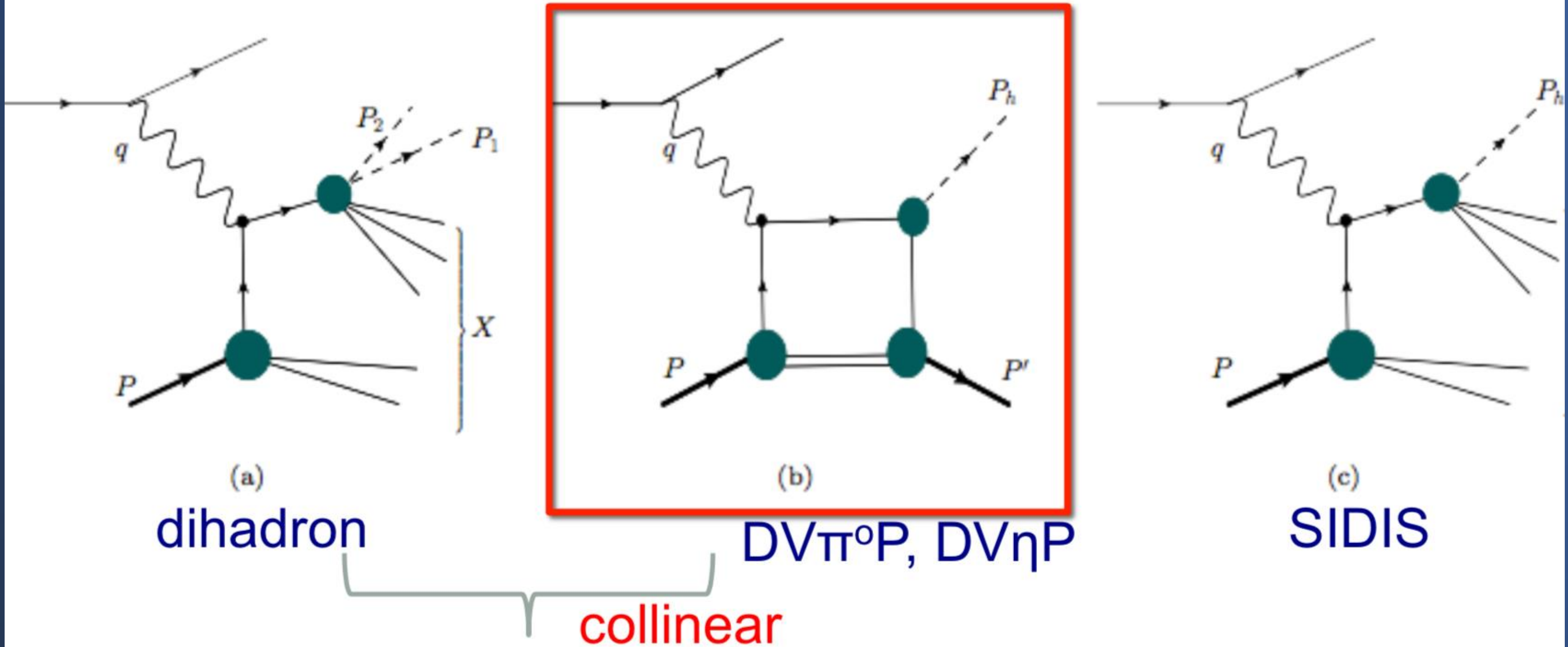


$$\langle p', \Lambda' \mid \pm i\bar{\psi}(0)\left(\sigma^{+1} \pm i\sigma^{+2}\right)\psi(0) \mid p, \Lambda\rangle$$

The operator is chiral-odd: only connects quarks with opposite helicity

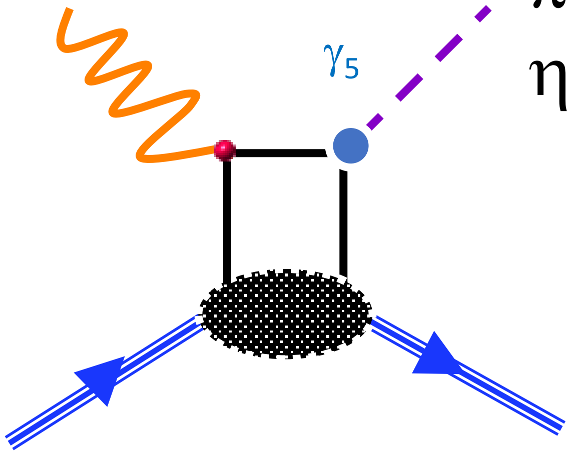
To detect chiral odd distributions we need another
distinct hadronic blob





$J^{PC}=1^{--}$ γ, ρ, ω, ..

$J^{PC}=1^{+-}$ b_1, h_1



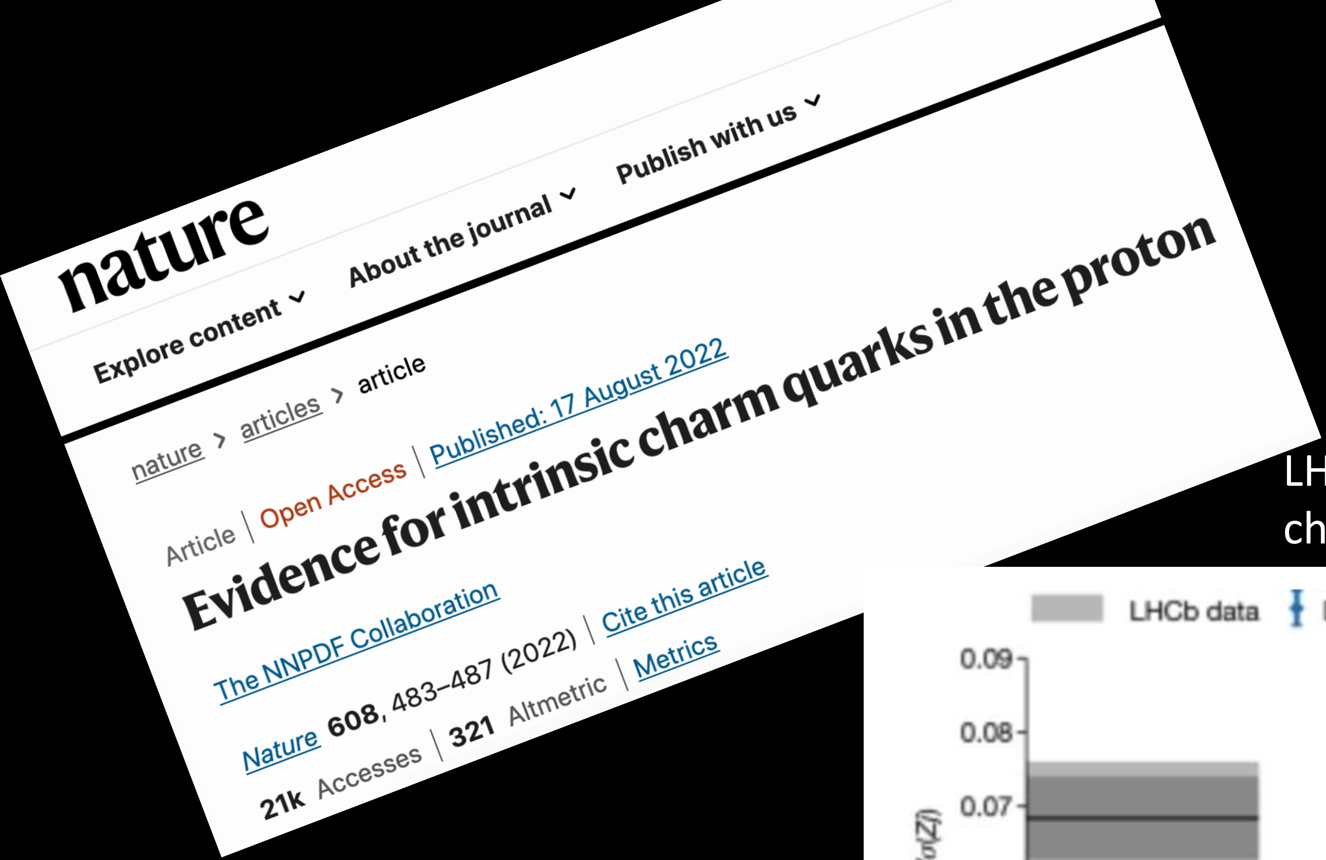
π^0 D^0

η η_c

New! Charmed mesons

chiral-odd structure

$$\gamma_5(\not{k}+\not{q})\gamma^\mu = (k_\nu+q_\nu)\frac{\gamma_5}{2}\left([\gamma^\nu,\gamma^\mu]+\{\gamma^\nu,\gamma^\mu\}\right) = (k_\nu+q_\nu)\gamma_5\,(i\sigma^{\mu\nu}+g^{\mu\nu})$$
$$\propto\ i\gamma_5\sigma^{\mu\nu}$$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Article | Open Access | Published: 17 August 2022

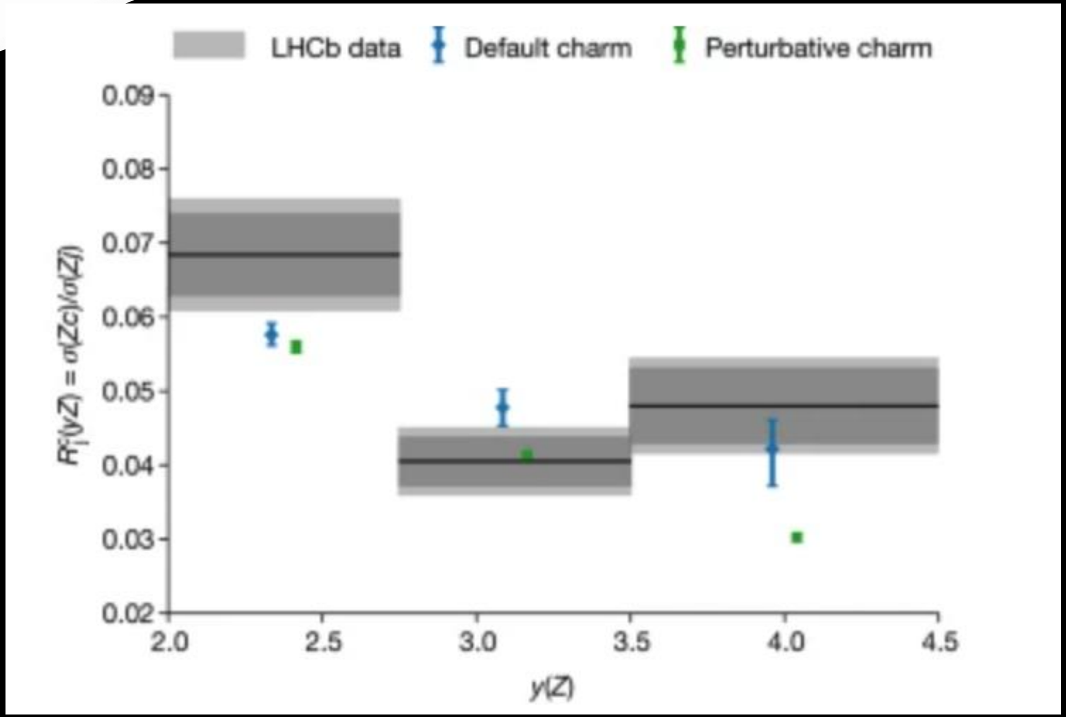
Evidence for intrinsic charm quarks in the proton

The NNPDF Collaboration

Nature **608**, 483–487 (2022) | Cite this article

21k Accesses | **321** Altmetric | Metrics

LHCb measurement of *Z*-boson production in association with charm-tagged jets

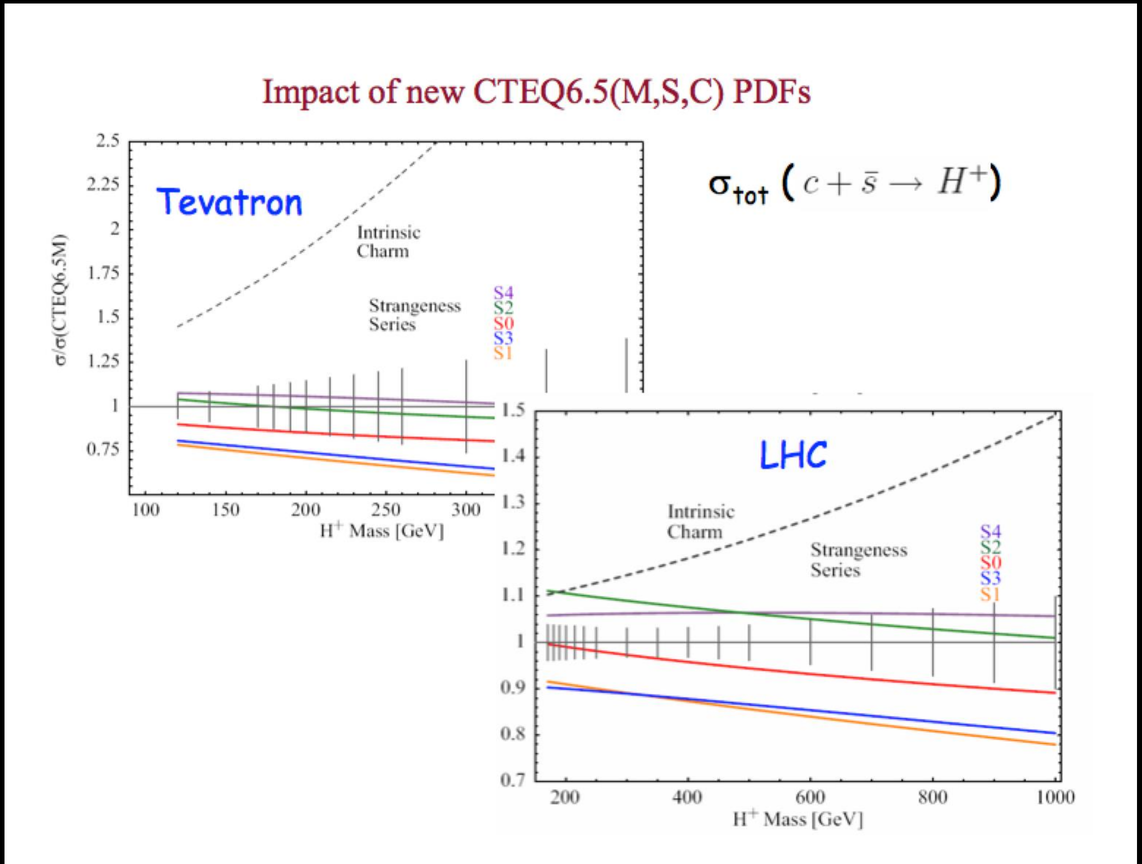


Heavy quark pseudoscalar meson exclusive electroproduction to access **intrinsic charm**

LHC processes are sensitive to charm content of the proton

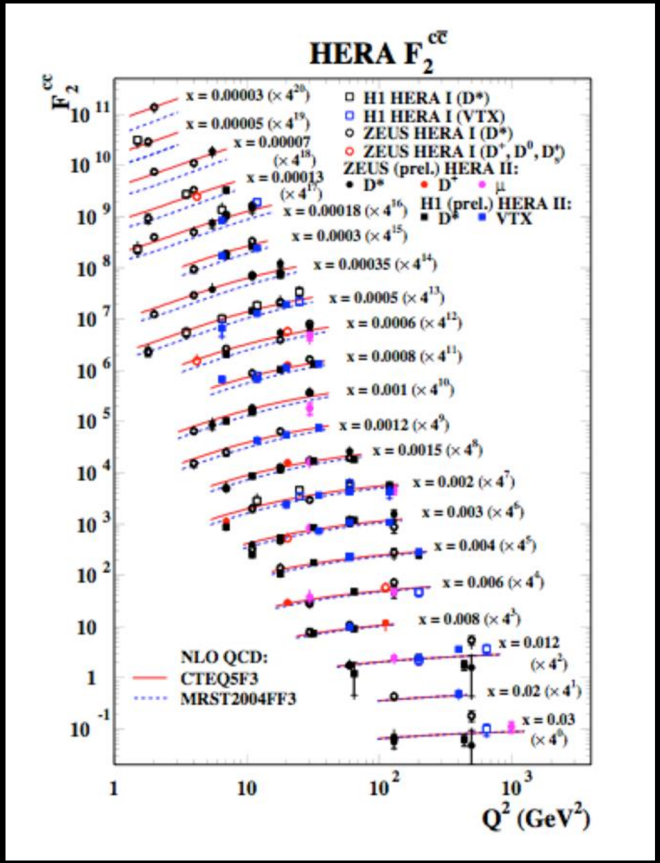
$\Rightarrow$ Higgs production: SM Higgs, charged Higgs,

$\Rightarrow$ Precision physics (CKM matrix elements, V_{tb} ….): single top production, …

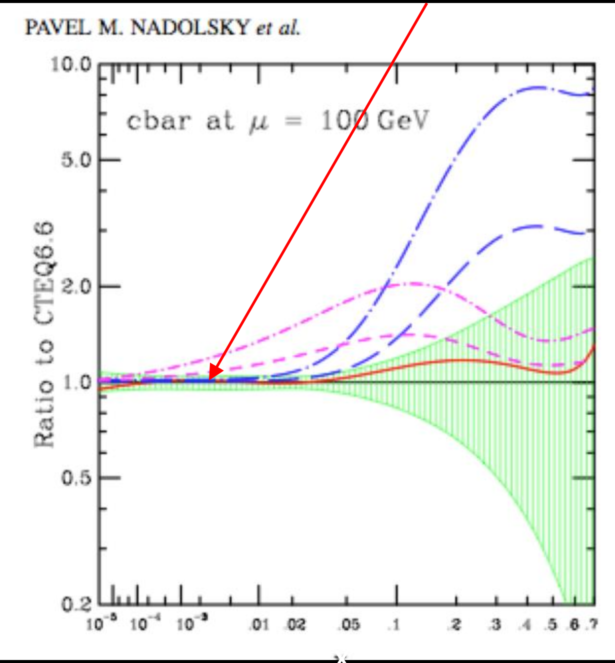


C.P Yuan et al. (2010)

Most data are at very low x where they cannot discriminate whether IC is there



IC/no-IC



x

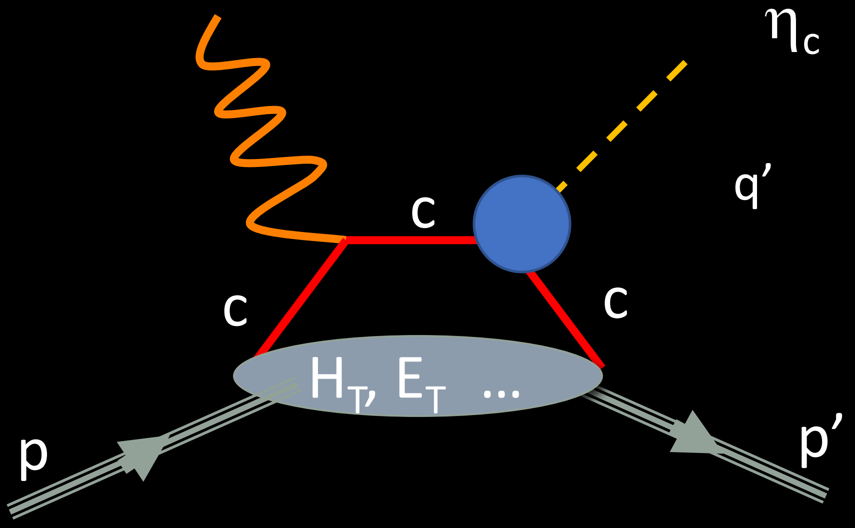
(see also P. Di Nezza's talk)

In exclusive electroproduction η_c, D^o, and $\bar{D}^o$ is governed by chiral-odd soft matrix elements which cannot evolve from gluons

η_c, D^o, and $\bar{D}^o$ can be used as triggers of “intrinsic charm content”

Gold plated signal: η_c exclusive production

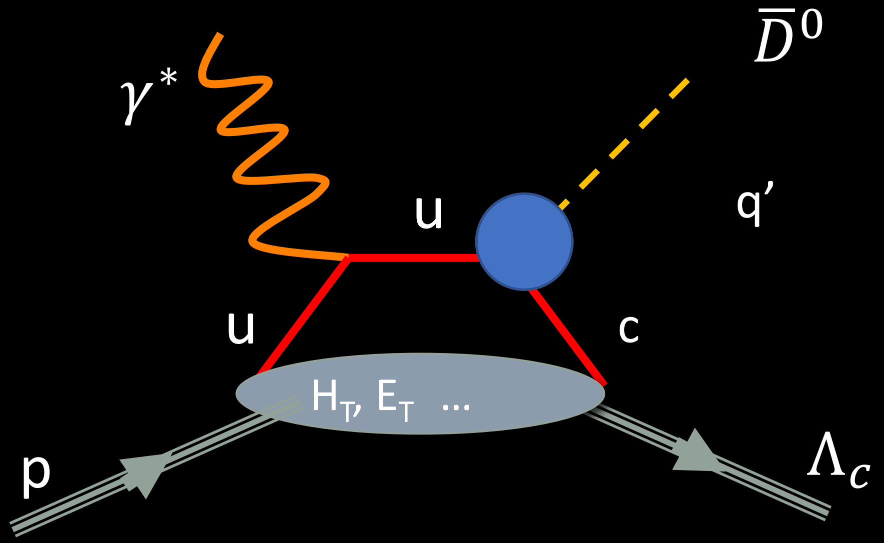
$\gamma^* \ p \rightarrow \eta_c \ p$



flavor content of string

p → c + (c-bar uud) + c → p

Other interesting channel $\gamma^* \; p \; \rightarrow \; \bar{D}^0 \, \Lambda_c$



flavor content of string   p → u + (ud) + c → Λ_c

Cross Section

G.R. Goldstein, J. O. Gonzalez Hernandez and SL, Phys. Rev. D 91114013 (2015)

$$\frac{d^4\sigma}{dx_{Bj}dyd\phi dt} = \Gamma\Big\{ \Big[F_{UU,T} + \epsilon F_{UU,L} + \epsilon\cos 2\phi F_{UU}^{\cos 2\phi} + \sqrt{2\epsilon(\epsilon+1)}\cos\phi F_{UU}^{\cos\phi} + h\sqrt{2\epsilon(1-\epsilon)}\,\sin\phi F_{LU}^{\sin\phi}\Big]$$

$$+ S_{||}\Big[\sqrt{2\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi} + \epsilon\sin 2\phi F_{UL}^{\sin 2\phi} + h\Big(\sqrt{1-\epsilon^2}\,F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\,\cos\phi\, F_{LL}^{\cos\phi}\Big)\Big]$$

$$+ S_{\perp}\Big[\sin(\phi-\phi_S)\Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)}\Big) + \epsilon\Big(\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\Big)$$

$$+ \sqrt{2\epsilon(1+\epsilon)}\Big(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\Big)\Big]$$

$$+ S_{\perp}h\Big[\sqrt{1-\epsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)}\Big(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\Big)\Big]\Big\}$$

Helicity amplitudes

$$F_{UU,T} = \mathcal{N}\left[|\, f_{10}^{++}\,|^2 + |\, f_{10}^{+-}\,|^2 + |\, f_{10}^{-+}\,|^2 + |\, f_{10}^{--}\,|^2\right]$$

$$F_{UU,L} = \mathcal{N}\left[|\, f_{00}^{++}\,|^2 + |\, f_{00}^{+-}\,|^2\right]$$

$$F_{UU}^{\cos 2\phi} = -\mathcal{N}\, 2\Re e\left[(f_{10}^{++})^*(f_{10}^{--}) - (f_{10}^{+-})^*(f_{10}^{-+})\right]$$

$$F_{UU}^{\cos\phi} = -\mathcal{N}\Re e\left[(f_{00}^{+-})^*(f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} - f_{10}^{--})\right]$$

$$F_{LU}^{\sin\phi} = \mathcal{N}\Im m\left[(f_{00}^{+-})^*(f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} - f_{10}^{--})\right]$$

κ_T

$$f_{10}^{++} \propto \Delta\left(2\widetilde{\mathcal{H}}_T + (1-\xi)\mathcal{E}_T - (1-\xi)\widetilde{\mathcal{E}}_T\right)$$

g_T

$$f_{10}^{+-} \propto \mathcal{H}_T + \frac{t_0 - t}{4M^2}\widetilde{\mathcal{H}}_T + \frac{\xi^2}{1-\xi^2}\mathcal{E}_T + \frac{\xi}{1-\xi^2}\widetilde{\mathcal{E}}_T$$

$$f_{10}^{-+} \propto \Delta^2\,\widetilde{\mathcal{H}}_T$$

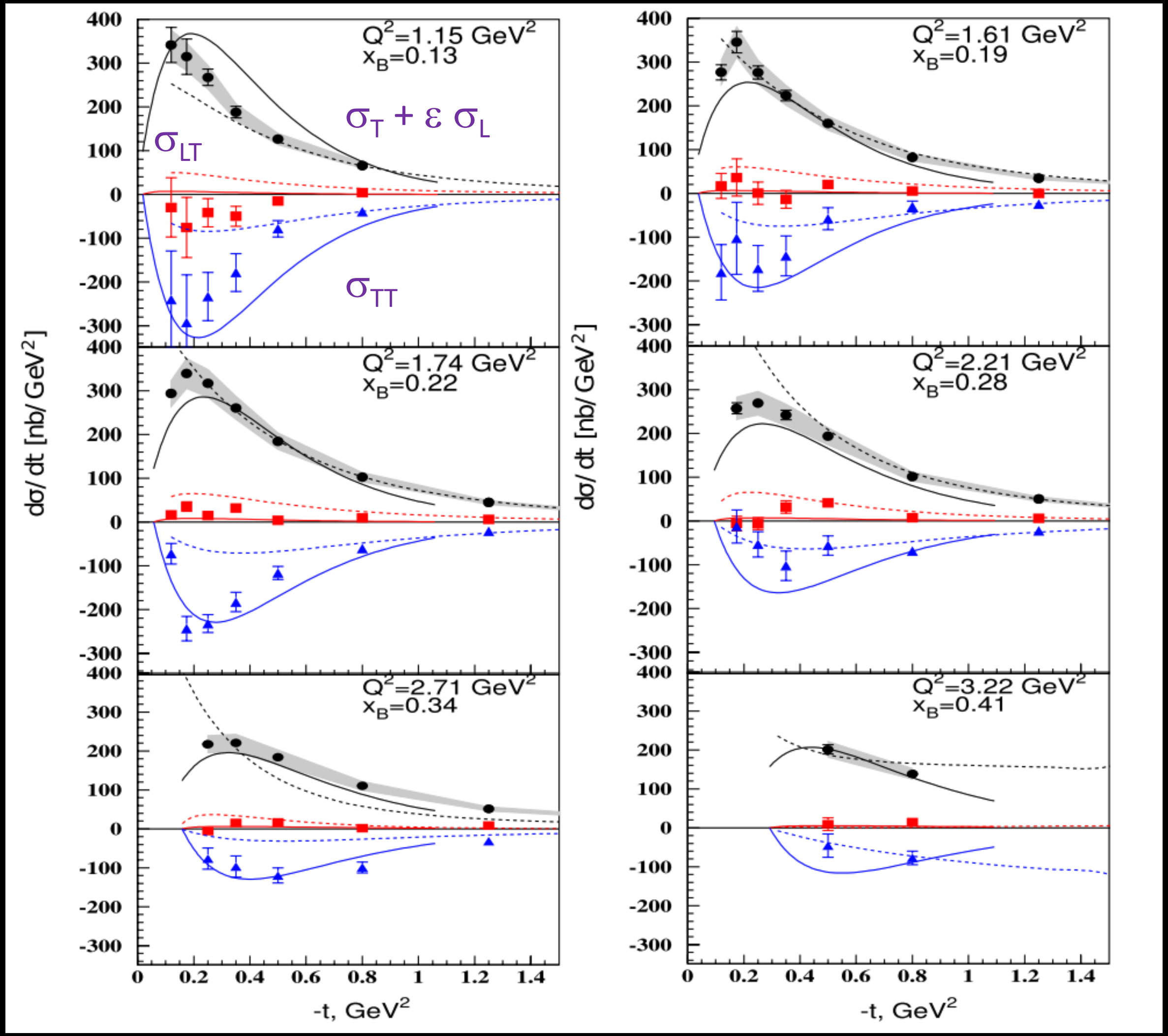
κ_T

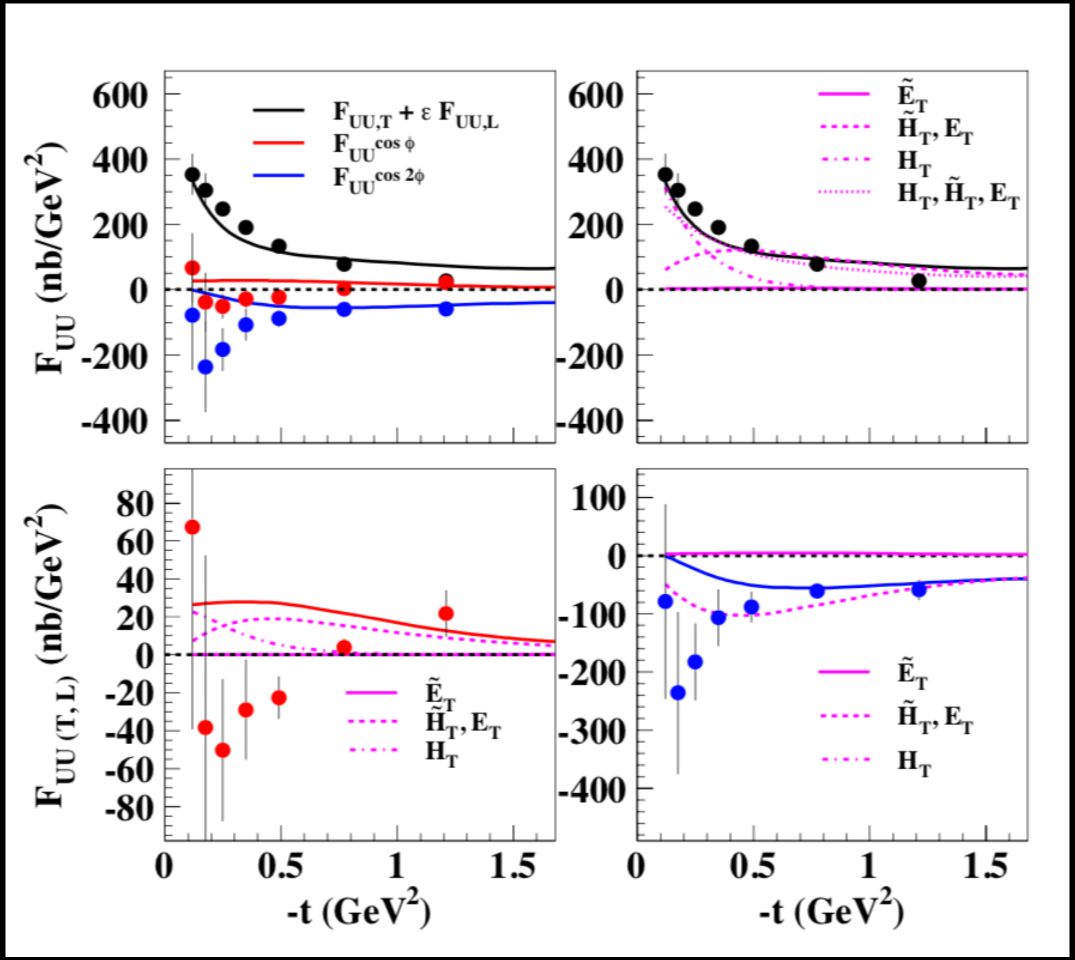
$$f_{10}^{--} \propto \Delta\left(2\widetilde{\mathcal{H}}_T + (1+\xi)\mathcal{E}_T + (1+\xi)\widetilde{\mathcal{E}}_T\right),$$

Unpolarized Cross Section initial data

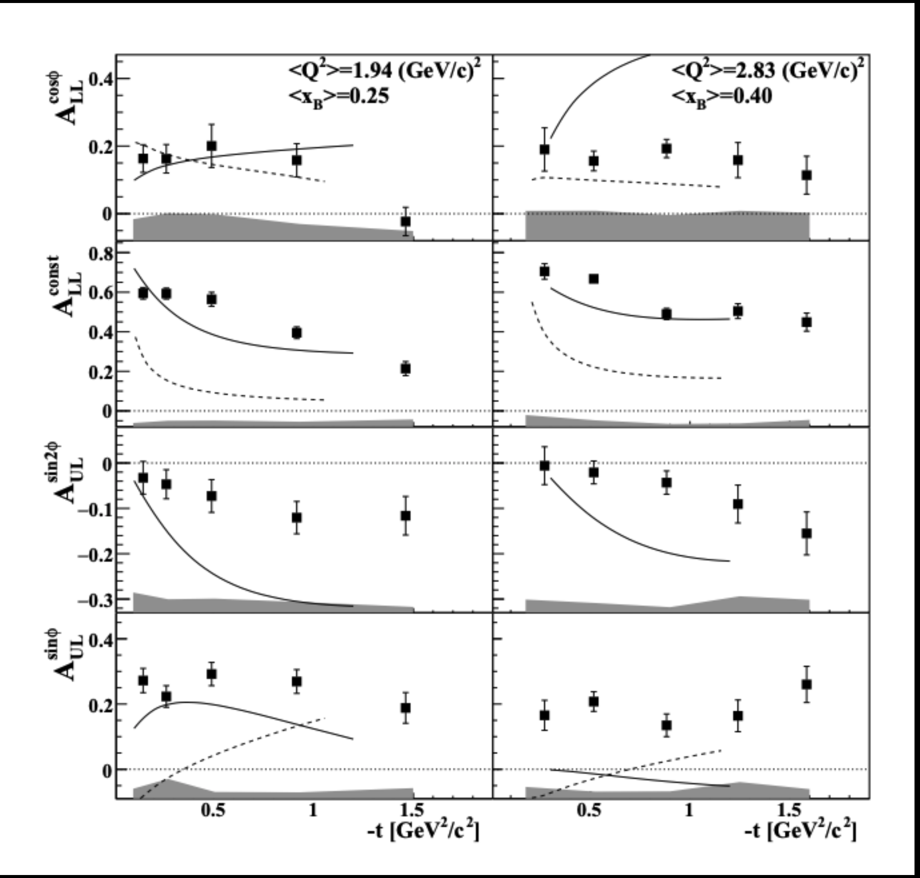
G. Goldstein, O. Gonzalez-Hernandez, SL

Phys.Rev.D 91 (2015)



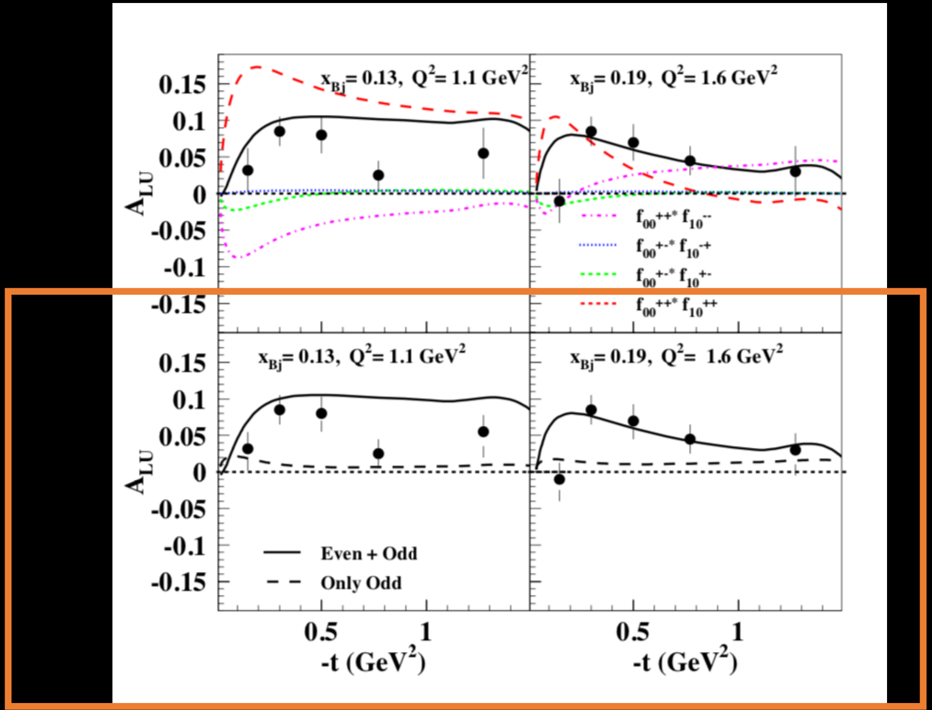


Asymmetries for Longitudinally polarized beam/target



A. Kim, A. Avakian et al, *Phys.Lett.B* 768 (2017)

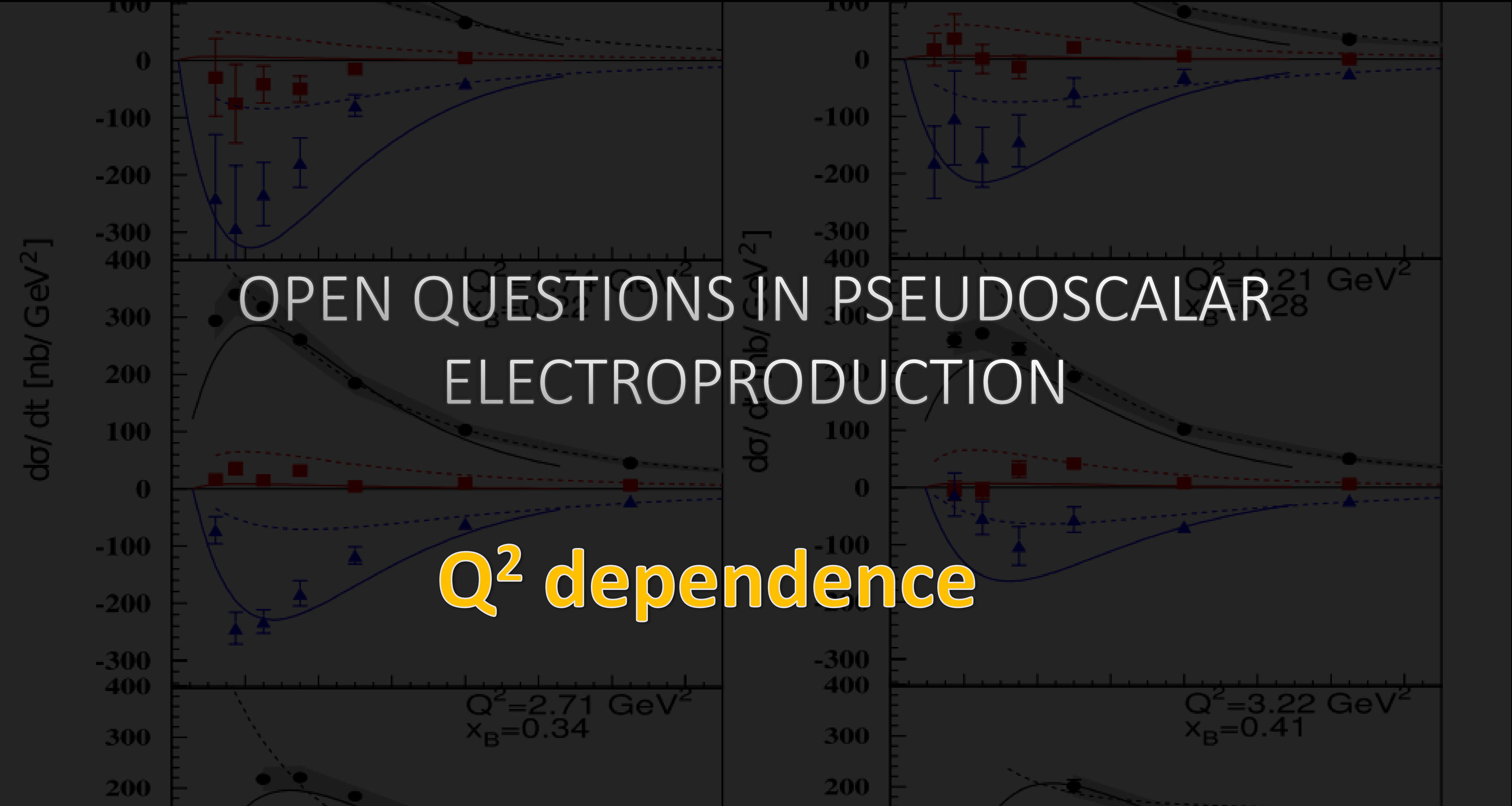
Compounded chiral odd and even effects



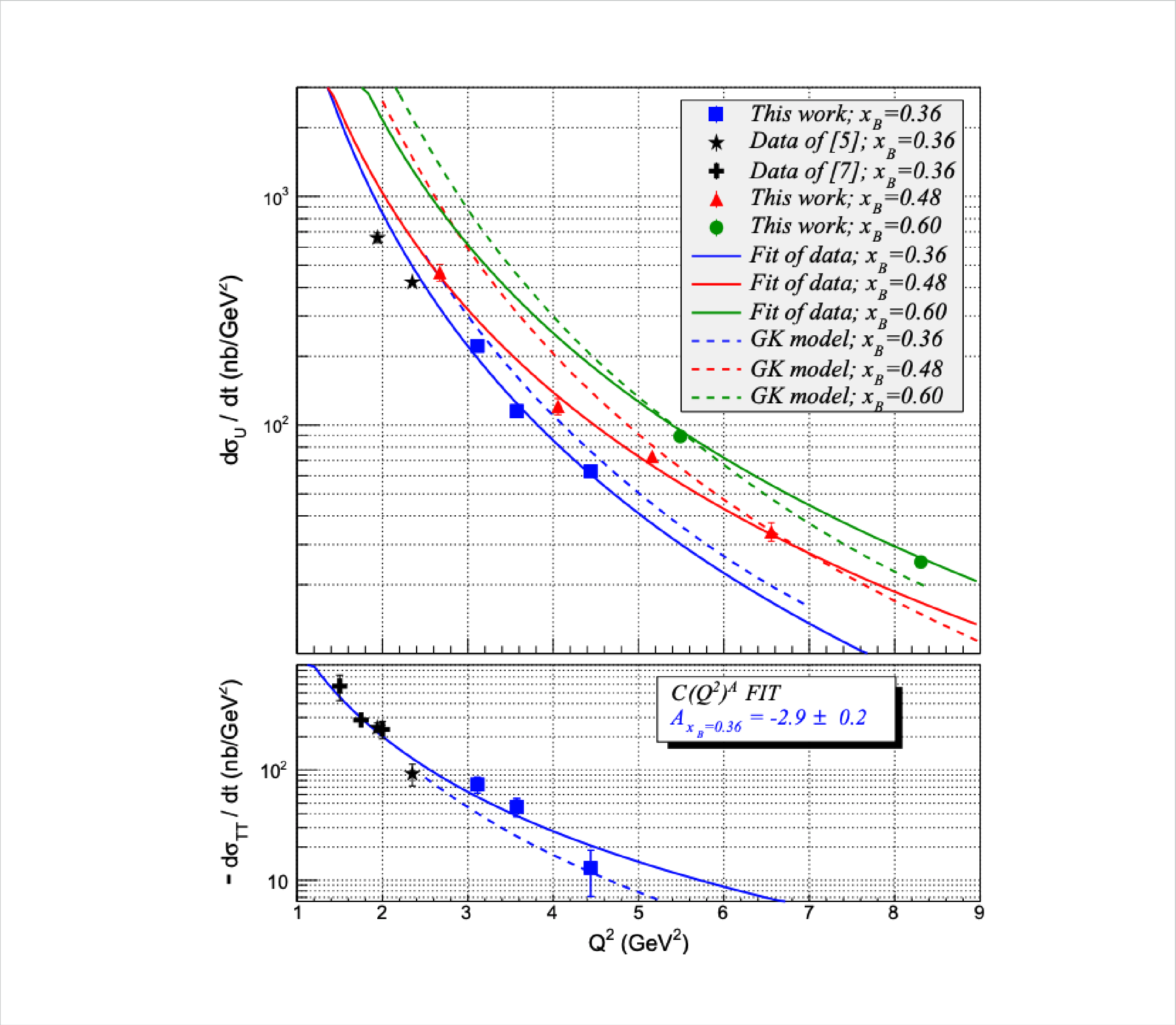
G.Goldstein, J. O. Gonzalez Hernandez and SL
Phys. Rev. D 91114013 (2015)

OPEN QUESTIONS IN PSEUDOSCALAR ELECTROPRODUCTION

Q^2 dependence

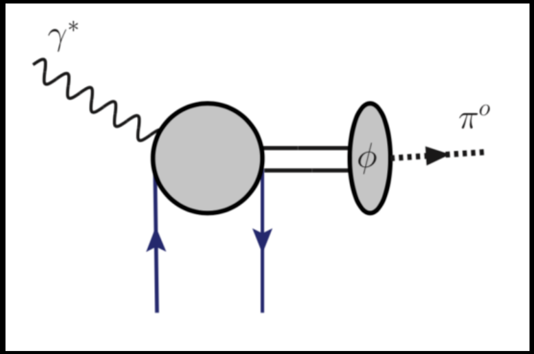


- New data from Hall A seem to indicate that the “standard” Q^2 dependence picture does not fit the data



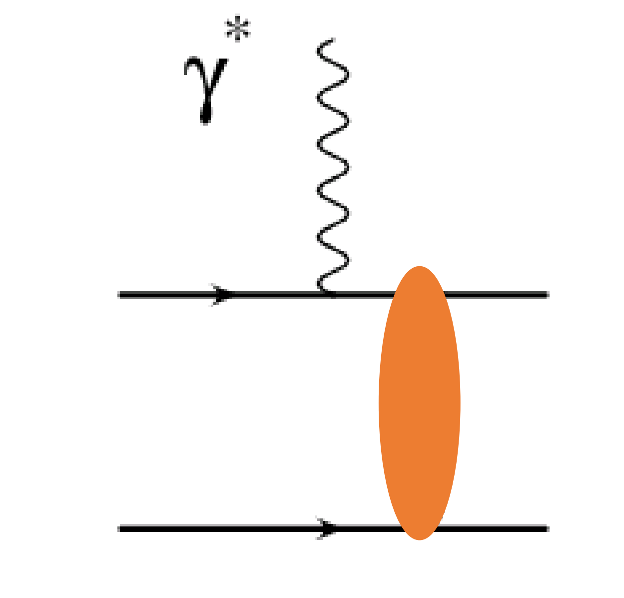
M. Dlamini et al. [Jefferson Lab Hall A], Phys. Rev. Lett. 127, 152301 (2021)

View DVMP vertex as pseudoscalar-meson transition form factor



$J^{PC}=1^{--}$ $(^3S_1)$ ρ, ω

$J^{PC}=1^{+-}$ $(^1P_1)$ b_1, h_1



π^o

$J^{PC}=0^{-+}$

Distinction between ω,ρ (vector) and b_1,h_1 (axial-vector)exchanges

$J^{PC}=1^{--}$ → transition from ω,ρ(S=1 L=0) to π^0(S=0 L=0) $\Delta L = 0$

$J^{PC}=1^{+-}$ → transition from b_1,h_1 (S=0 L=1) to π^0(S=0 L=0) $\Delta L = 1$

"Vector" exchanges no change in OAM

"Axial-vector" exchanges change 1 unit of OAM!

$$F_{\gamma^* V \pi^o} = \int dx_1 dy_1 \int d^2\mathbf{b}\, \psi_V(y_1, b)\, \mathcal{C} K_o(\sqrt{x_1(1-x_1)Q^2}b)\, \psi_{\pi^o}(x_1, b)\, exp(-S)$$

$$F_{\gamma^* A \pi^o} = \int dx_1 dy_1 \int d^2\mathbf{b}\, \psi_A^{(1)}(y_1, b)\, \mathcal{C} K_o(\sqrt{x_1(1-x_1)Q^2}b)\, \psi_{\pi^o}(x_1, b)\, exp(-S)$$

Because of OAM axial vector transition involves Bessel J_1

$$\psi_A^{(1)}(y_1, b) = \int d^2k_T J_1(y_1 b)\psi(y_1, k_T),$$

This yields configurations of larger “radius” in b space (suppressed with Q^2)

Helicity Amplitudes

Hard scattering

$$f_1 = f_4 = \int_{-1+\zeta}^{1} dX\, g_2(X,\zeta,t,Q^2)\, F_V(Q^2)\, A_{++,+-}(X,\zeta,t)$$

$$f_2 = \int_{-1+\zeta}^{1} dX\, g_2(X,\zeta,t,Q^2)\, [F_V(Q^2) + F_A(Q^2)]\, A_{--,++}(X,\zeta,t)$$

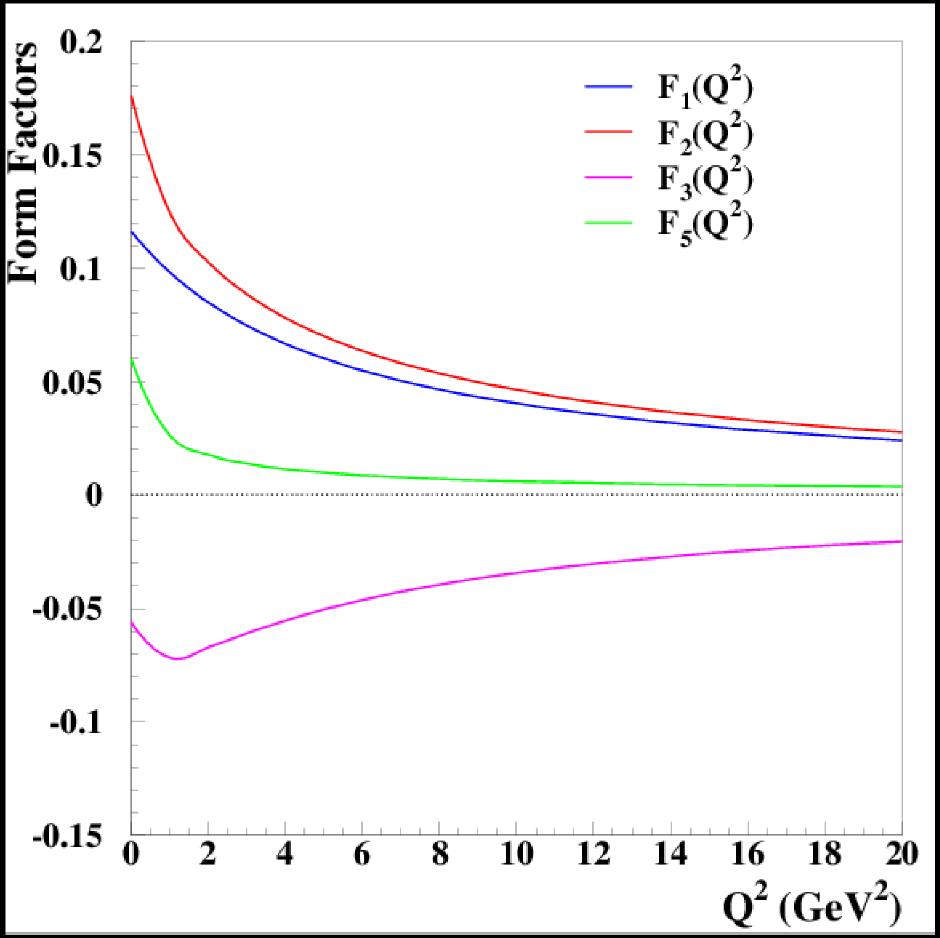
$$f_3 = \int_{-1+\zeta}^{1} dX\, g_2(X,\zeta,t,Q^2)\, [F_A(Q^2) - F_V(Q^2)]\, A_{+-,-+}(X,\zeta,t)$$

$$f_5 = \int_{-1+\zeta}^{1} dX\, g_5(X,\zeta,t,Q^2)\, F_A(Q^2)\, A_{--,++}(X,\zeta,t)$$

Q^2 dependence at pion vertex

These are the form factors for the different configurations

Quantitative calculations are in progress



Conclusions

- Pseudoscalar and vector meson production are both essential channels to pin down chiral even and chiral odd GPDs
- There is lots of interesting physics to keep discovering (Q2 dependence, BSM, charm …)
- More synergy between theory and experiment!