Deeply Virtual Exclusive Processes with Charm*

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Graduate Students: Osvaldo Gonzalez Hernandez, Tracy McAskill

Outline

- *Introduction and Main Goal for an EIC*
- *Hard Exclusive Charmed Mesons Production*

    ⇒ *A unique investigation of charm content of nucleo*

- *From JLAB 6-12 GeV to EIC*

    ⇒ *Modeling the Q^2 dependence of neutral mesons electroproduction*

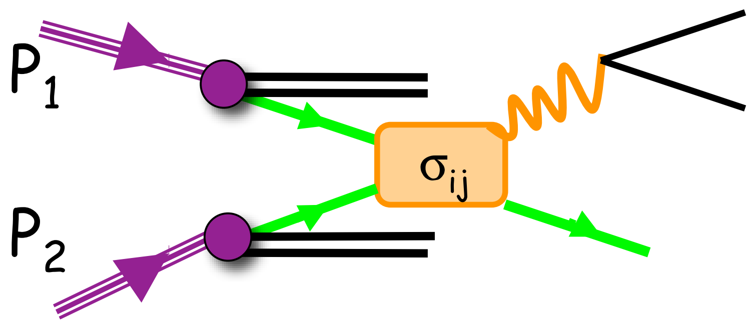
    (S. Ahmad, G. Goldstein, S.L., PRD79, 2008; G. Goldstein, S.L., hep 2010)

- *Conclusions/Outlook*

Introduction

The next decade…role of QCD at the LHC

- LHC results from multi-TeV CM energy collisions will open new horizons but many "candidate theories" will provide similar signatures of a departure from SM predictions…
- Precision measurements require QCD input



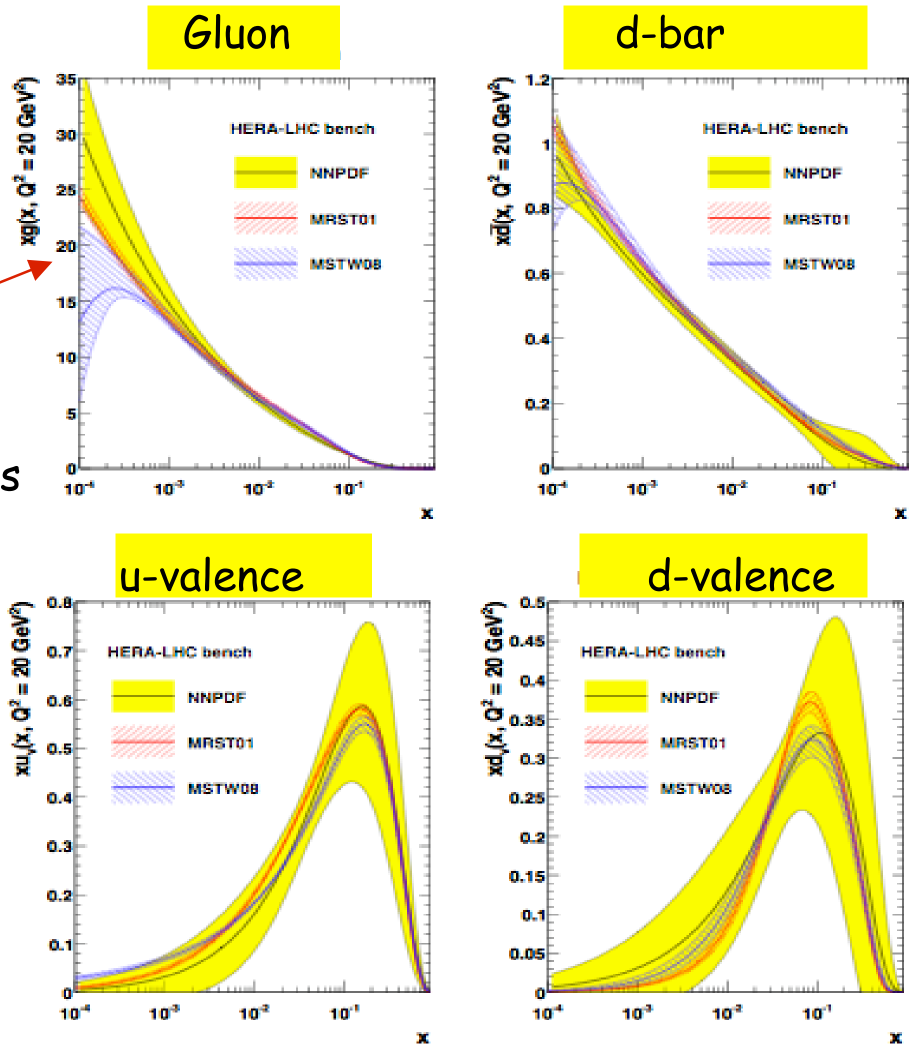
$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2\, f_i(x_1,\mu_F) f_j(x_2,\mu_F)\hat{\sigma}(x_1,x_2,\alpha_S(\mu_R),\mu_F)$$

Measured x-section — Parton distributions — Hard process x-section

- QCD: A background for "beyond the SM discovery"
- Interesting dynamical questions for QCD at untested high energies

Most important points for EIC

1) Our understanding of the structure of hadrons is … disconcertingly incomp



Uncertainties from different PDF evaluations/extractions (Δ_{PDF}) are smaller than the differences between the evaluations (Δ_G)

$\Delta_{PDF} < \Delta_G$

2) Rich dynamics of hadrons can only be accessed and tested at the desired accuracy level in lepton DIS

• Our contribution to EIC physics (S.L. with G. Goldstein and L. Gamberg)

Study heavy quark components → charm, through hard exclusive processe

Why charm?

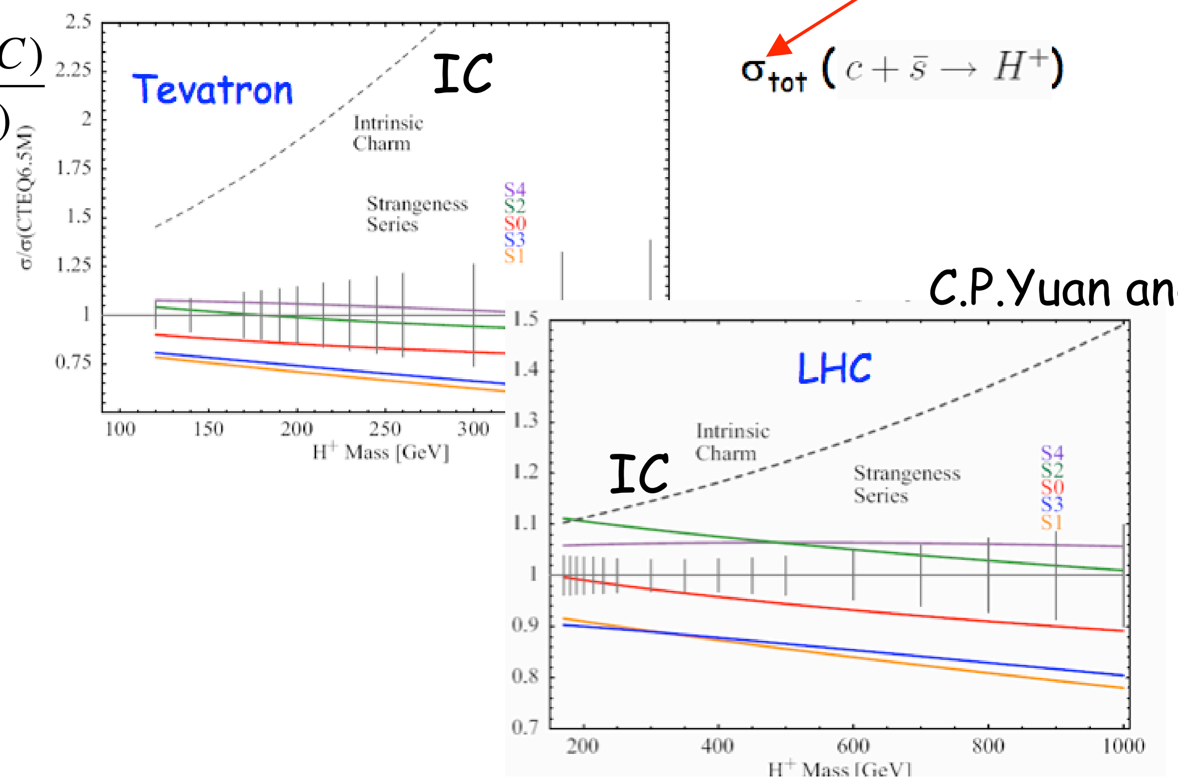
LHC processes are sensitive to charm content of the proton

⇒ Higgs production: SM Higgs, charged Higgs, $c\bar{s} \rightarrow H^+$

⇒ Precision physics (CKM matrix elements, V_{tb} ....): single top production

Impact of new CTEQ6.5(M,S,C) PDFs

$$\frac{\sigma(CTEQ, IC)}{\sigma(CTEQ)}$$



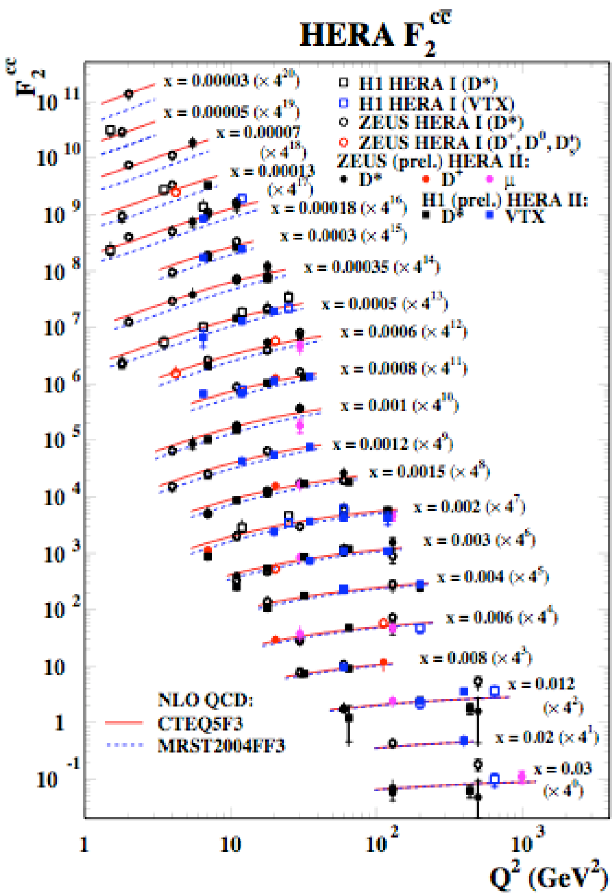
$\sigma_{tot}\,(c + \bar{s} \rightarrow H^+)$

C.P.Yuan and collaborators

CTEQ 6.6

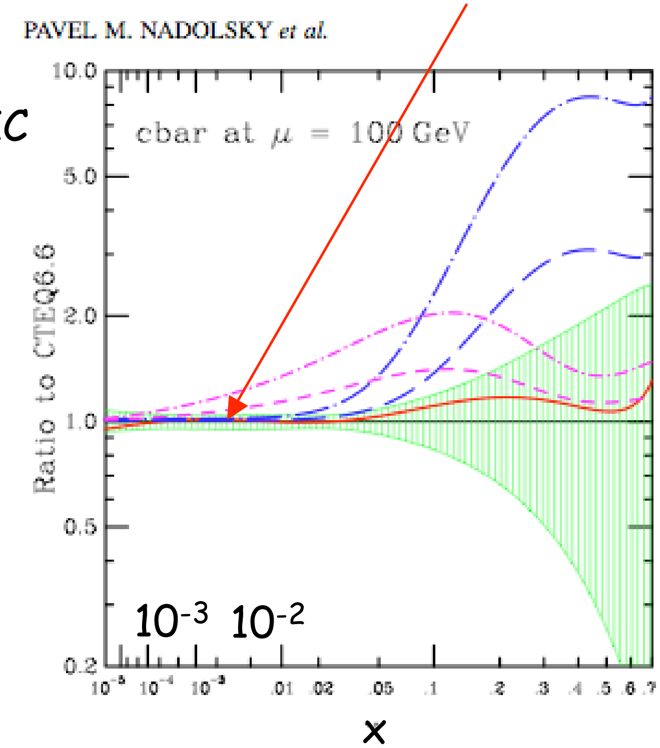
TABLE V. Relative differences $\Delta_{GM} \equiv \sigma_{6.1}/\sigma_{6.6} - 1$ between CTEQ 6.1 and CTEQ 6.6 cross sections for Higgs boson prod at the LHC listed at the beginning of Sec. IV, compared to the PDF uncertainties Δ_{PDF} in these processes. The $Ah^{\pm}$ cross section combined production of positively and negatively charged Higgs bosons, with m_h being the mass of the CP-odd boson (m_h = and $m_{h^{\pm}}$ given by $m^2_{h\pm} = m^2_A + M^2_W$.

m_h (GeV)	$\Delta_{GM}(\%) \vert \Delta_{PDF}(\%)$												
	VBF		Z^0h		$Ah^{\pm}$		$gg \rightarrow h$		$c\bar{b} \rightarrow h^+$		$c\bar{s} \rightarrow h^+$		$c\bar{s} + c\bar{b} \rightarrow$
100	**−3.8**	**3.1**	**−3.2**	**2.7**	**−3.2**	**4.3**	0.6	4.4	1.5	5.9	**−18**	**10**	**−8.4**
200	−1.8	2.8	−1.6	2.8	−1.9	4.3	1.7	3.2	2.1	4.7	**−16**	**8**	**−6.6**
300	−1.6	2.8	−0.6	3	−0.4	5.3	2.3	2.7	1.9	4.3	**−14**	**7**	**−6.2**
400	−0.1	3.3	0	3.4	0.7	6.6	2.8	3.8	2	4.8	**−13**	**6.3**	**−5.6**
500	0.2	2.8	0.4	3.7	1.1	7.6	3.3	3.9	2.3	6.1	**−12**	**6.3**	**−5**
600	−0.7	3.5	0.7	4.1	1.6	9.2	3.8	5.0	2.8	8	**−11**	**6.8**	−4.2
700	0.2	3.0	0.9	4.4	2.1	11	4.3	6.3	3.4	10	**−9.9**	**7.7**	−3.4
800	2.3	3.5	1	4.8	2.8	13	4.9	7.8	4.1	12	**−8.7**	**9**	−2.4



Data are at very low x where they canno
discriminate whether IC is there

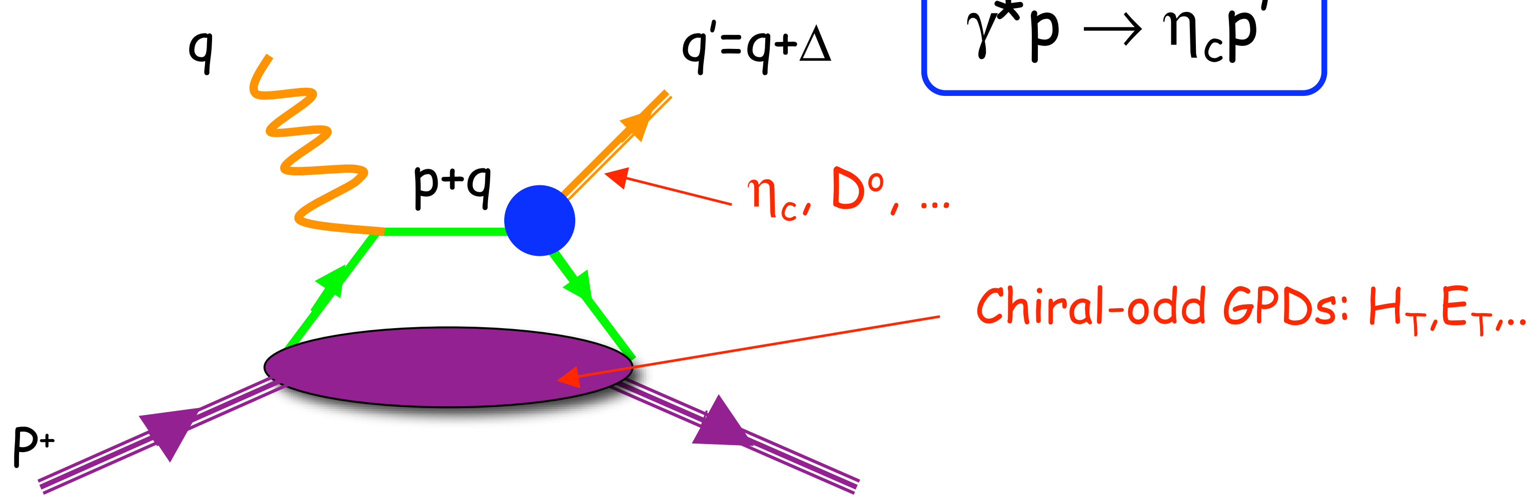
IC/no-IC



A window into heavy flavor production at the EIC

η_c, D^o, and $\bar{D}^o$ exclusive production is governed by chiral-odd soft matrix elements ($\Rightarrow$ Generalized Parton Distributions, GPDs) which cannot evolve from gluons!

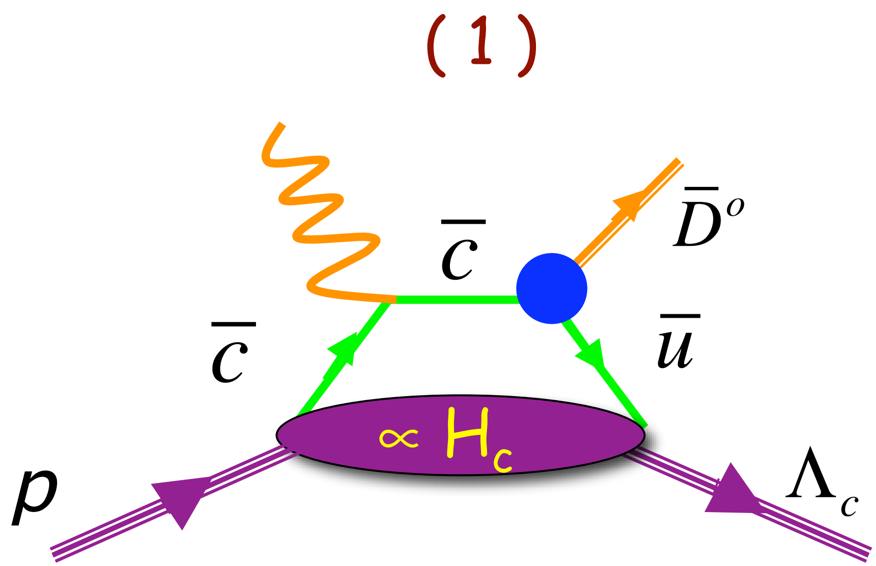
η_c, D^o, and $\bar{D}^o$ used as triggers of "intrinsic charm content"!



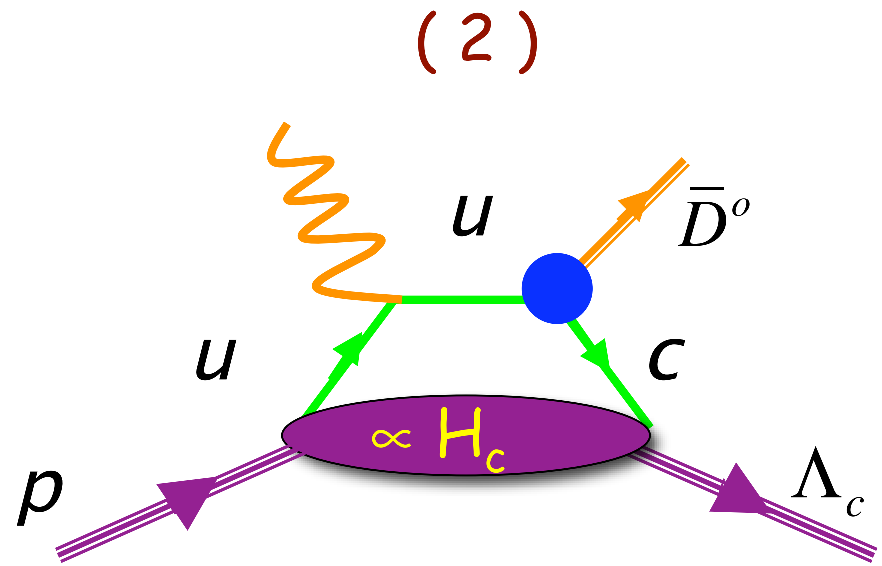
$\gamma^* p \rightarrow \eta_c p'$

What Observables?

Spin Asymmetries from Exclusive Heavy Quark Meson Production



$p \rightarrow \bar{c}cuud \rightarrow (\bar{u}\, u)\, cud = \Lambda_c$



$p \rightarrow u + ud \rightarrow cud = \Lambda_c$

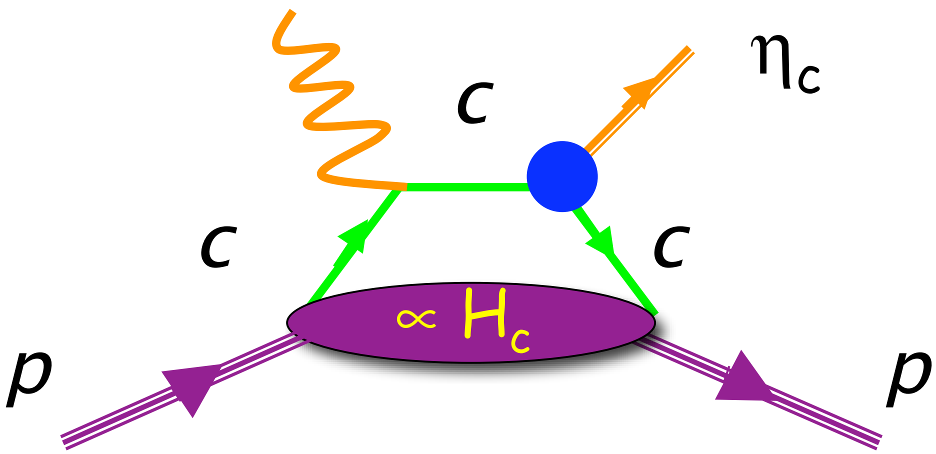
$\gamma^* p \rightarrow \bar{D}^o\, \Lambda_c^+ \Rightarrow 2H_u - H_d + H_c$

$\gamma^* p \rightarrow \bar{D}^o\, \Sigma_c^+ \Rightarrow H_d - H_c$

$\gamma^* n \rightarrow \bar{D}^o\, \Sigma_c^o \Rightarrow H_u - H_c$

SU(4) relations allow one to extract H_c

(3)

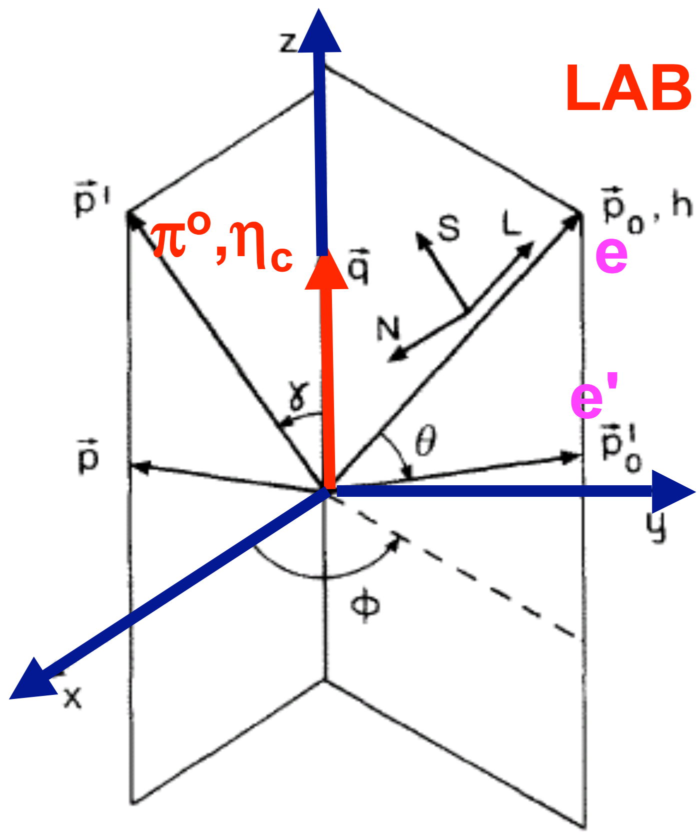


$p \rightarrow \bar{c}cuud \rightarrow (\bar{c}\,c)\,uud = p$

EIC "golden plated signal"

$\eta_c = c\bar{c} \rightarrow J^{PC} = 0^{-+}$

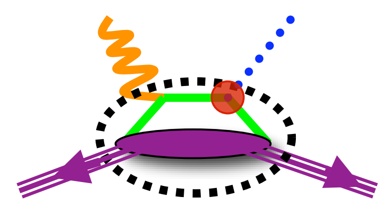
Unpolarized Cross Section



$$d\sigma \propto L_{\mu\nu}^{h=\pi^o} W_{\mu\nu}$$

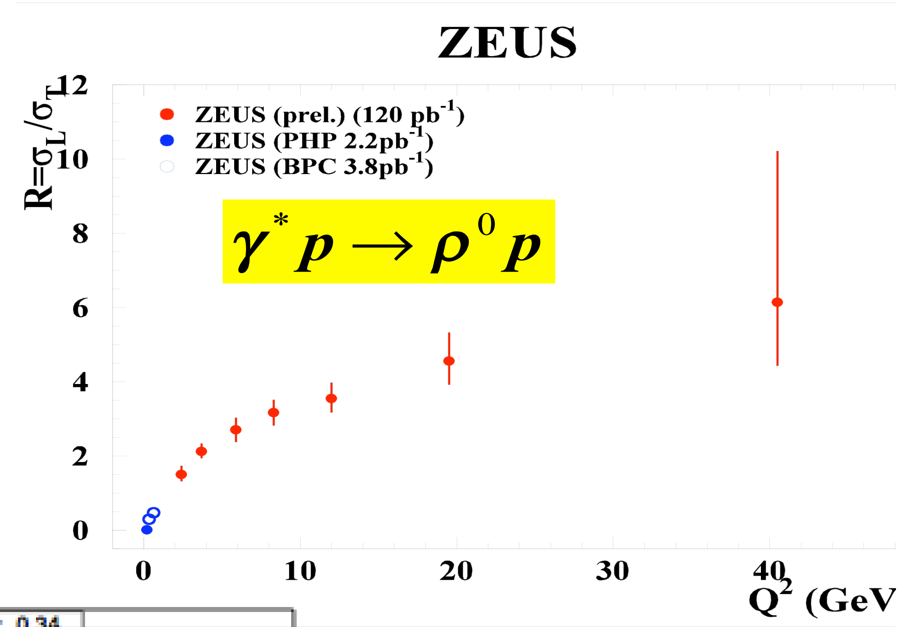
$$L_{\mu\nu}^{h=\pi^o} \approx \gamma^* \text{ polarization density matrix}$$

$$W_{\mu\nu} = \sum_f J_\mu J_\nu^* \delta(E_i - E_f) = \text{hadronic tensor}$$

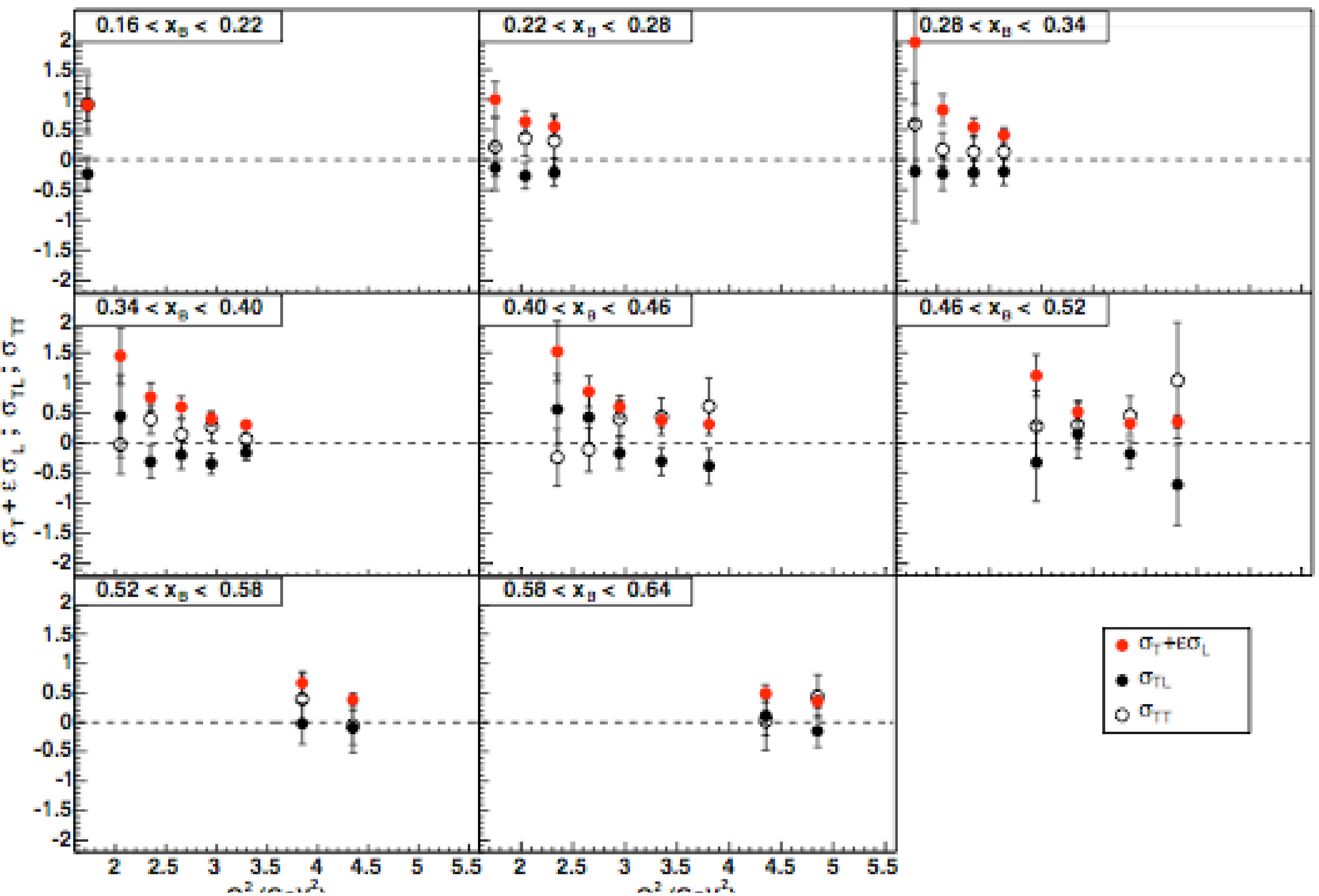


$$\frac{d\sigma}{dt\,d\phi} = \left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi$$

Q² dependence in exclusive meson production

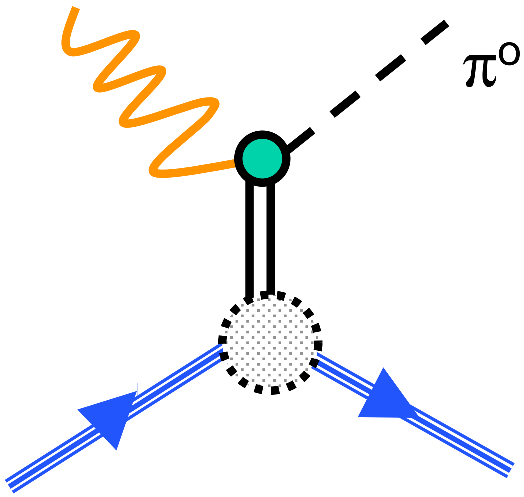


Jlab



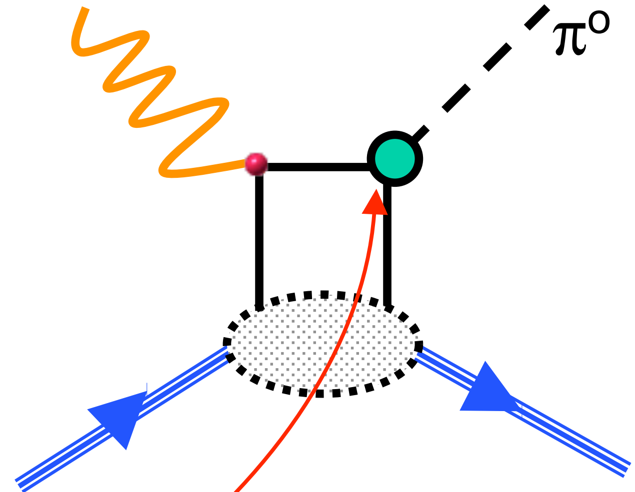
Unexpected dominance of transverse compone

Q^2 dependence



$J^{PC}=1^{--}$ γ, ρ, ω, ..

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



chiral-even stru

π^o vertex is described by current operators: γ_5 or $\gamma_\mu \gamma_5$

GPDs: $\tilde{H}$,

$\gamma_5 \rightarrow$

$$\gamma_5(\not{k}+\not{q})\gamma^\mu = (k_\nu + q_\nu)\frac{\gamma_5}{2}\left([\gamma^\nu,\gamma^\mu] + \{\gamma^\nu,\gamma^\mu\}\right) = (k_\nu + q_\nu)\gamma_5\,(i\sigma^{\mu\nu} + g^{\mu\nu})$$

$$\propto i\gamma_5\sigma^{\mu\nu}$$

chiral-odd structure

GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$...

Chiral Even Sector: M. Diehl and D. Ivanov (2008)

distribution	J^{PC}
$H^q(x,\xi,t) - H^q(-x,\xi,t)$	$0^{++}, 2^{++}, \ldots$
$E^q(x,\xi,t) - E^q(-x,\xi,t)$	$0^{++}, 2^{++}, \ldots$
$\widetilde{H}^q(x,\xi,t) + \widetilde{H}^q(-x,\xi,t)$	$1^{++}, 3^{++}, \ldots$
$\widetilde{E}^q(x,\xi,t) + \widetilde{E}^q(-x,\xi,t)$	$0^{-+}, 1^{++}, 2^{-+}, 3^{++}, \ldots$
$H^q(x,\xi,t) + H^q(-x,\xi,t)$	$1^{--}, 3^{--}, \ldots$
$E^q(x,\xi,t) + E^q(-x,\xi,t)$	$1^{--}, 3^{--}, \ldots$
$\widetilde{H}^q(x,\xi,t) - \widetilde{H}^q(-x,\xi,t)$	$2^{--}, 4^{--}, \ldots$
$\widetilde{E}^q(x,\xi,t) - \widetilde{E}^q(-x,\xi,t)$	$1^{+-}, 2^{--}, 3^{+-}, 4^{--}, \ldots$

Only combination good for π^o production

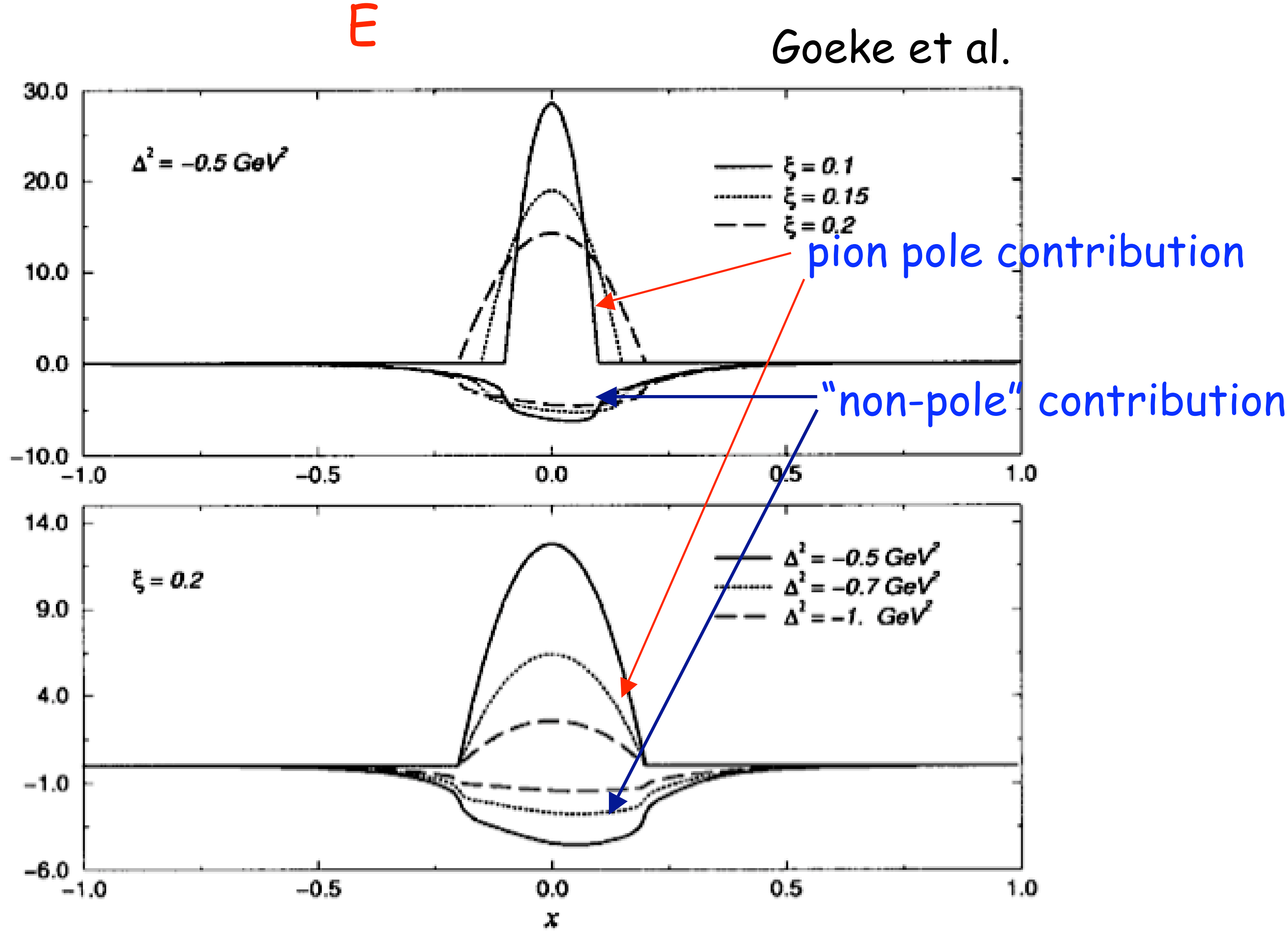
GPDs: $\tilde{H}$, $\tilde{E}$, and Weak Form factors

$$\langle N(p')\Lambda' | J_A^\nu | N(p)\Lambda \rangle = \overline{U}^{(\Lambda')}(p') \left[g_A(t)\gamma^\nu\gamma^5 + \frac{g_P(t)}{m_\mu}\Delta^\nu\gamma^5 \right] U^{(\Lambda)}(p)$$

$$g_P(t) = \frac{2m_\mu M}{m_\pi^2 - t} g_A(0)$$

$g_P(t)$ = pseudoscalar form factor → dominated by pion pole

$\tilde{E}$



1) For π^0 production the pion pole contribution is absent!

2) The non-pole contribution is very small!

π^o,η_c electroproduction happens mostly in the chiral-odd sector

⇒it is governed by chiral-odd GPDs

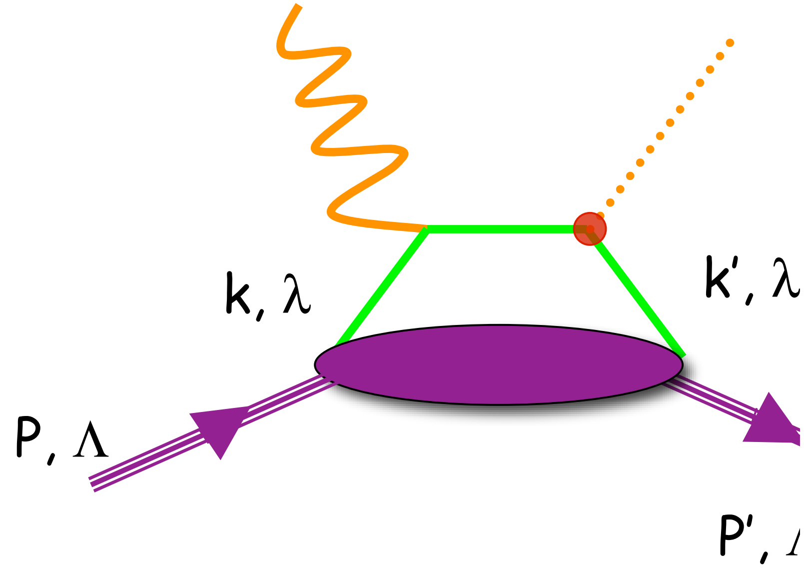
⇒issue overlooked in most recent literature on the subject

Since <u>chiral-odd</u> GPDs <u>cannot evolve from gluons</u> we have proven that η_c, D^o, and D^o uniquely single out the "intrinsic charm content"!

Helicity Amplitudes formalism

$$f_{\Lambda_\gamma,\Lambda;0,\ \Lambda'}$$

- Λ_γ → photon
- Λ → initial proton
- 0 → pion
- Λ' → final proton



Factorized form

$$f_{\Lambda_\gamma,\Lambda;0,\Lambda'} = \sum_{\lambda,\lambda'} \underline{g_{\Lambda_\gamma,\lambda;0,\lambda'}(X,\zeta,t,Q^2)} \otimes \underline{A_{\Lambda',\lambda';\Lambda,\lambda}(X,\zeta,t)},$$

γ quark scattering amp. "quark-proton helicity amp

6 "f" helicity amps

$$\frac{d\sigma_T}{dt} = \mathcal{N}\left(|\, f_{1,+;0,+}\,|^2 + |\, f_{1,+;0,-}\,|^2 + |\, f_{1,-;0,+}\,|^2 + |\, f_{1,-;0,-}\,|^2\right)$$
$$= \mathcal{N}\left(|\, \underline{f_1}\,|^2 + |\, \underline{f_2}\,|^2 + |\, \underline{f_3}\,|^2 + |\, \underline{f_4}\,|^2\right)$$
$$\frac{d\sigma_L}{dt} = \mathcal{N}\left(|\, f_{0,+;0,+}\,|^2 + |\, f_{0,+;0,-}\,|^2\right)$$
$$= \mathcal{N}\left(|\, \underline{f_5}\,|^2 + |\, \underline{f_6}\,|^2\right),$$

Rewrite helicity amps. expressions using new GFFs

$$f_1 = f_4 = \frac{g_2}{\mathcal{C}_q} F_V(Q^2) \frac{\sqrt{t_0 - t}}{2M} \left[\widetilde{\mathcal{H}}_T + \frac{1-\xi}{2} \mathcal{E}_T + \frac{1-\xi}{2} \widetilde{\mathcal{E}}_T \right]$$

$$f_2 = \frac{g_2}{\mathcal{C}_q} [F_V(Q^2) + F_A(Q^2)] \sqrt{1-\xi^2} \left[\mathcal{H}_T + \frac{t_0 - t}{4M^2} \widetilde{\mathcal{H}}_T - \frac{\xi^2}{1-\xi^2} \mathcal{E}_T + \frac{\xi}{1-\xi^2} \widetilde{\mathcal{E}} \right.$$

$$f_3 = \frac{g_2}{\mathcal{C}_q} [F_V(Q^2) - F_A(Q^2)] \sqrt{1-\xi^2} \frac{t_0 - t}{4M^2} \widetilde{\mathcal{H}}_T$$

$$f_5 = \frac{g_5}{\mathcal{C}_q} F_A(Q^2) \sqrt{1-\xi^2} \left[\mathcal{H}_T + \frac{t_0 - t}{4M^2} \widetilde{\mathcal{H}}_T - \frac{\xi^2}{1-\xi^2} \mathcal{E}_T + \frac{\xi}{1-\xi^2} \widetilde{\mathcal{E}}_T \right],$$

elementary subprocess

GFFs

Q^2 dependent pion vertex

Standard approach (Goloskokov and Kroll, 2009)

$\gamma_\mu\gamma_5 \Rightarrow$ leading twist contribution within OPE,
leads to suppression of transverse vs. longitudinal terms
$\gamma_5 \Rightarrow$ twist-3 contribution is possible

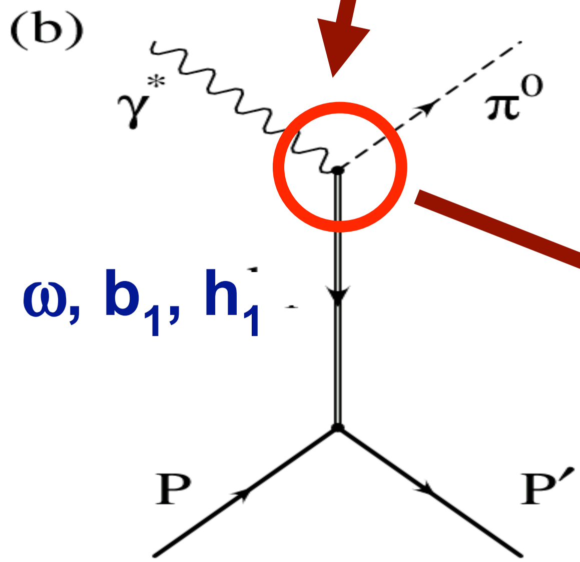
However…
$\Rightarrow$ suppression is not seen in experiments

Need to devise method to go beyond the collinear OPE: consider a mechanism that takes into account the breaking of rotational symmetry by the scattering plane in helicity flip processes (transverse d.o.f.)

See also T. Gousset, B. Pire and J.P. Ralston, Phys. Rev. D 53, 1202 (1

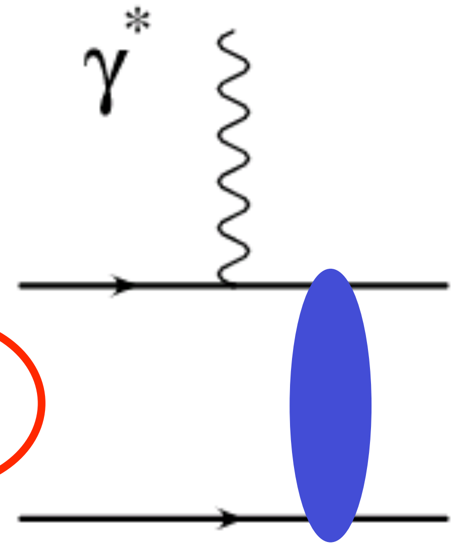
Q^2 dependence

t-channel exchange vertex



ρ, ω, b_1, h_1

modeled as $F_{p\gamma}$ (pseudoscalar-meson transition form factor)



π^o

J^{PC}=

ρ, ω | b_1, h_1

$J^{PC}=1^{--}$ ($^3S_1$)

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

mesons quark content: $\frac{1}{\sqrt{2}}\left(u\bar{u} \pm d\bar{d}\right)$

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

$J^{PC}=1^{--}$ ➞ transition from ω,ρ(S=1 L=0) to π^o(S=0 L=0) **ΔL =0**

$J^{PC}=1^{+-}$ ➞ transition from b_1,h_1 (S=0 L=1) to π^o(S=0 L=0) **ΔL =1**

“Vector” exchanges no change in OAM

“Axial-vector” exchanges change 1 unit of OAM!

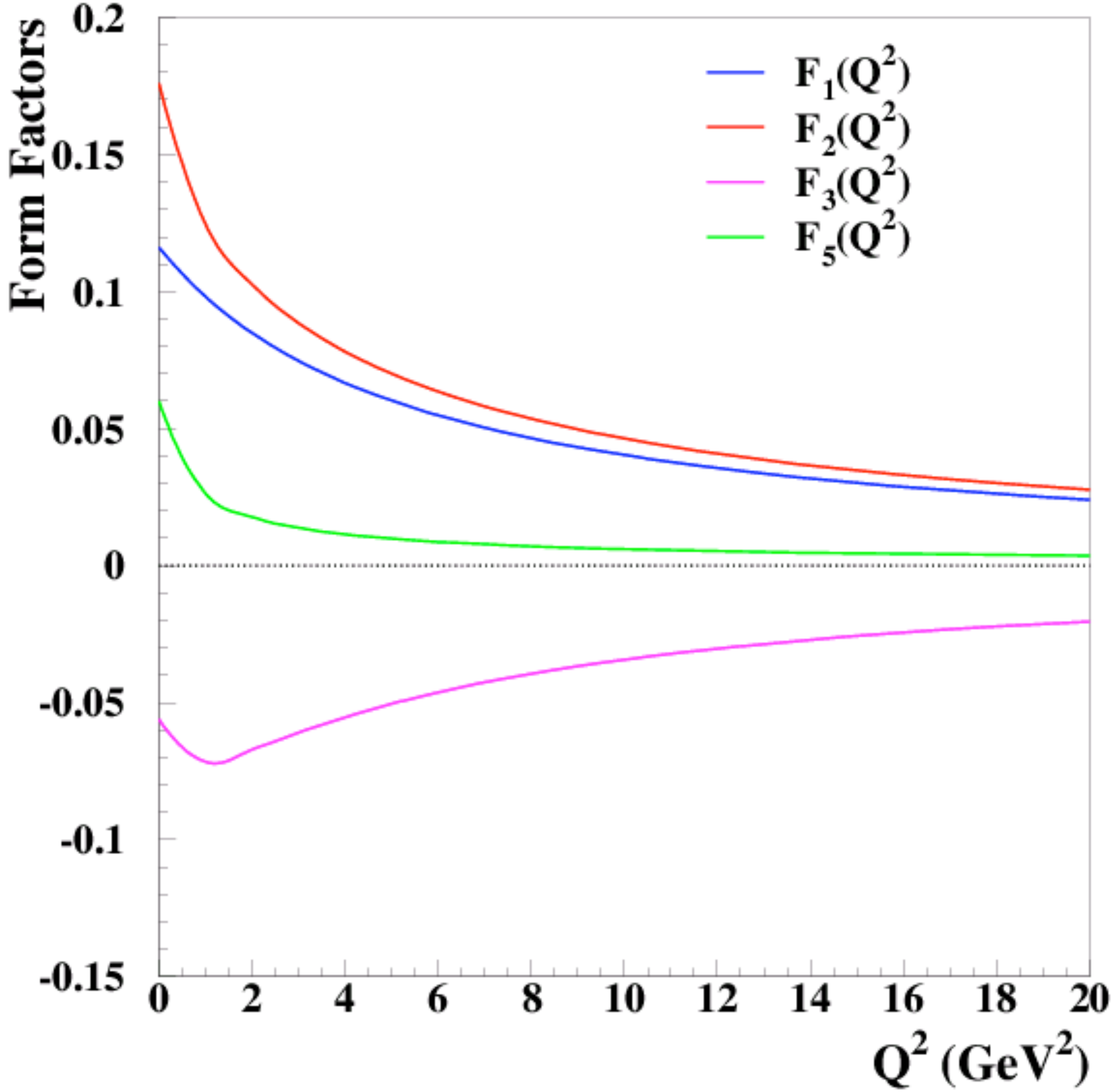
$$F_{\gamma^* V \pi^o} = \int dx_1 dy_1 \int d^2\mathbf{b}\, \psi_V(y_1, b) \mathcal{C} K_o(\sqrt{x_1(1-x_1)Q^2} b)\, \psi_{\pi^o}(x_1, b) exp(-S)$$

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

Because of OAM axial vector transition involves Bessel J_1

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

This yields configurations of larger “radius” in b space (suppressed with G



Form Factors
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
2
4
6
8
10
12
14
16
18
20
Q^2 (GeV^2)
F_1(Q^2)
F_2(Q^2)
F_3(Q^2)
F_5(Q^2)

Global parametrizations for GPDs...?

The name of the game: Devise a form combining essential dynamical elements with a flexible model that allows for a fully quantitative analysis constrained by the data

$$H_q(X, \zeta, t) = R(X, \zeta, t)\, G(X, \zeta, t)$$

"Regge"

Quark-Diquark

+ Q^2 Evolution

ζ=0,t=0

Parton Distribution Functions

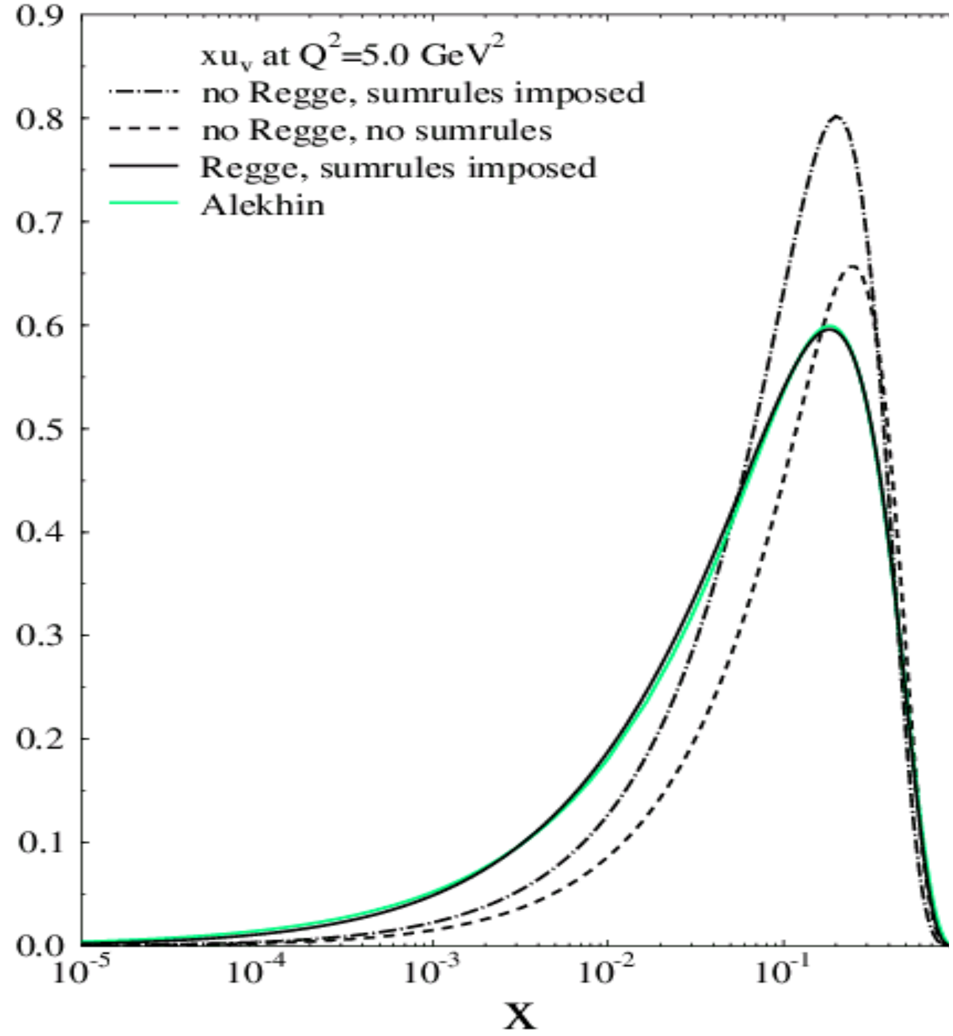
Notice! GPD parametric form is given at $Q^2=Q_o^2$ and evolved to Q^2 of data.

Notice! We provide a parametrization for GPDs that simultaneously fits the PDFs:

$$H_q(X,z,t) = R(X,z,t)\, G(X,z,t)$$

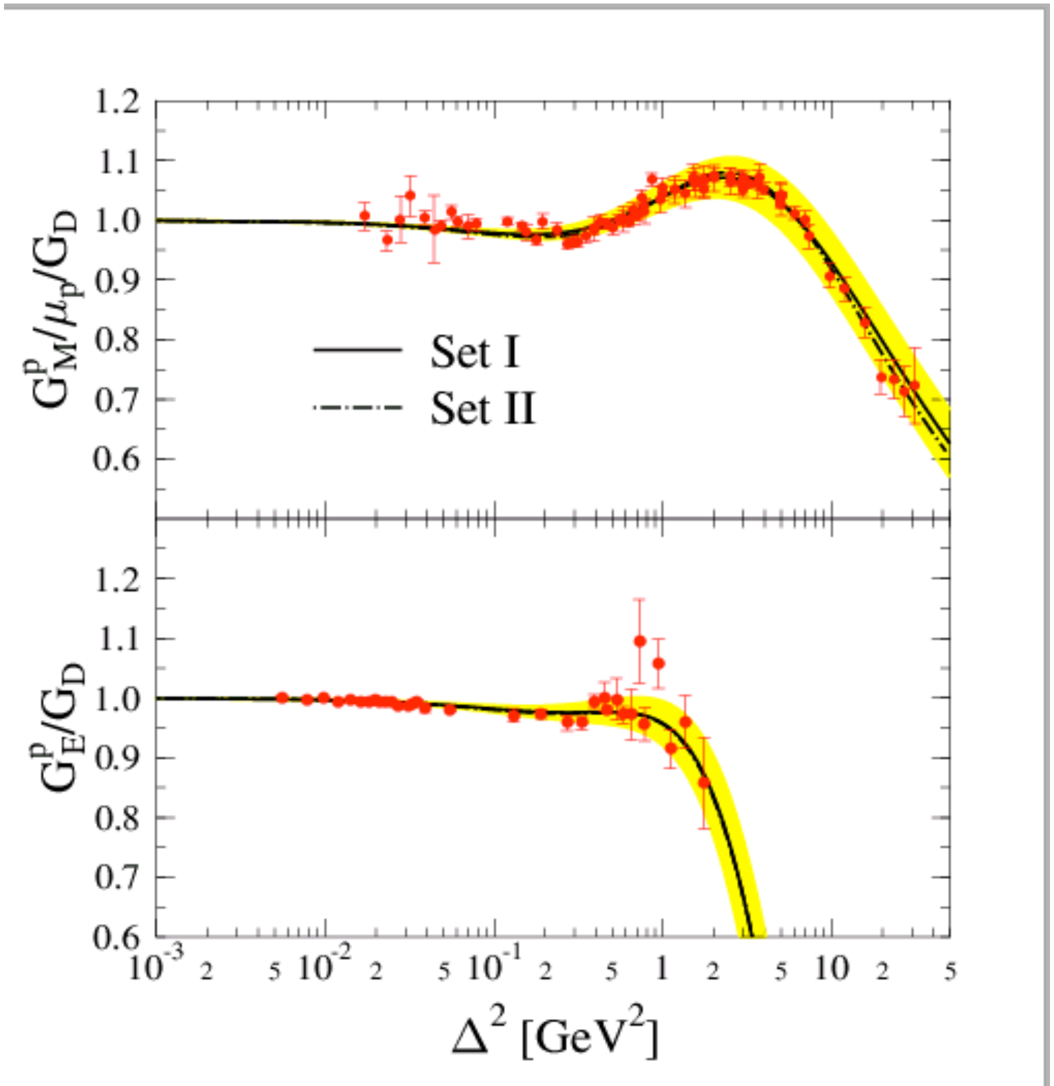
Regge

Quark-Diquark



$\zeta = 0, t \neq 0$

Nucleon Form Factors



$$\int_0^1 dX\, H^q(X,t) = F_1^q(t)$$

$$\int_0^1 dX\, E^q(X,t) = F_2^q(t),$$

Data Set	χ^2/N_{data} Set 1	χ^2/N_{data} Set 2	Data P
G_{E_p}	1.049	0.963	33
G_{M_p}	1.194	1.220	75
G_{E_p}/G_{M_p}	0.689	0.569	20
G_{E_n}	0.808	1.059	25
G_{M_n}	2.068	1.286	24
TOTAL	1.174	1.085	177

S. Ahmad, H. Honkanen, S. L., S.K. Taneja, PRD75:094003,2007

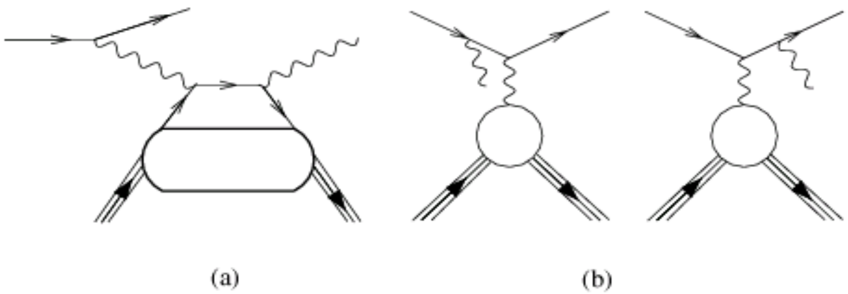
Parameters from PDFs

Flavor	M_X (GeV)	λ (GeV)	α
u	0.4972	0.9728	1.2261
d	0.7918	0.9214	1.0433

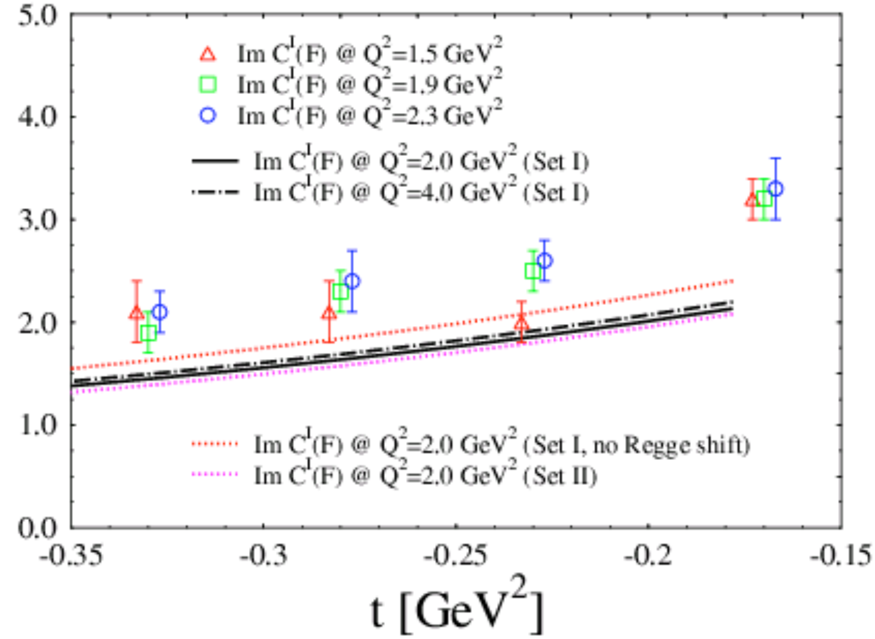
Parameters from FFs

Flavor	β_1 (GeV^{-2})	β_2 (GeV^{-2})	p_1	p_2
u	1.9263 ± 0.0439	3.0792 ± 0.1318	0.720 ± 0.028	0.528 ± 0.[illegible]
d	1.5707 ± 0.0368	1.4316 ± 0.0440	0.720 ± 0.028	0.528 ± 0.[illegible]

BSA data are predicted at this stage



Munoz Camacho et al., PRL(2006)

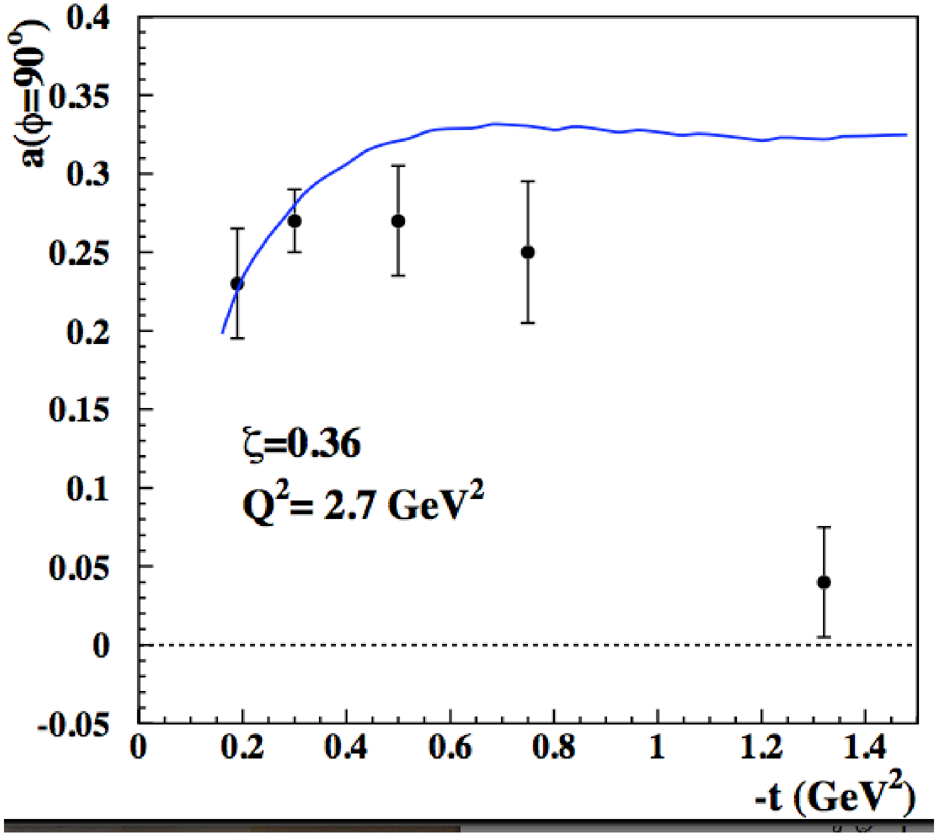


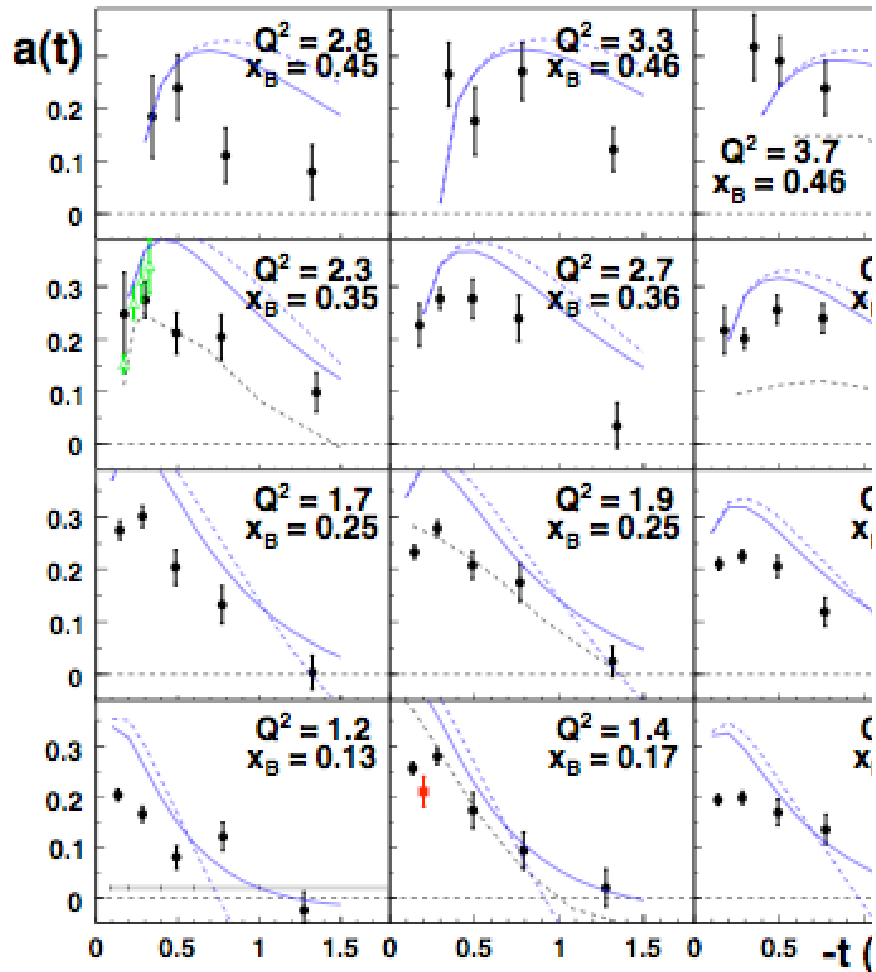
- Observable given by Interference Term between DVCS (a) and BH(b):

$$d\sigma^{\rightarrow} - d\sigma^{\leftarrow} \propto sin\phi \left[F_1(\Delta^2)\mathcal{H} + \frac{x}{2-x}(F_1+F_2)\widetilde{\mathcal{H}} + \frac{\Delta^2}{M^2}F_2(\Delta^2)\mathcal{E} \right]$$

$$\mathcal{H} = \sum_q e_q^2 (H(\xi,\xi,\Delta^2) - H(-\xi,\xi,\Delta^2))$$

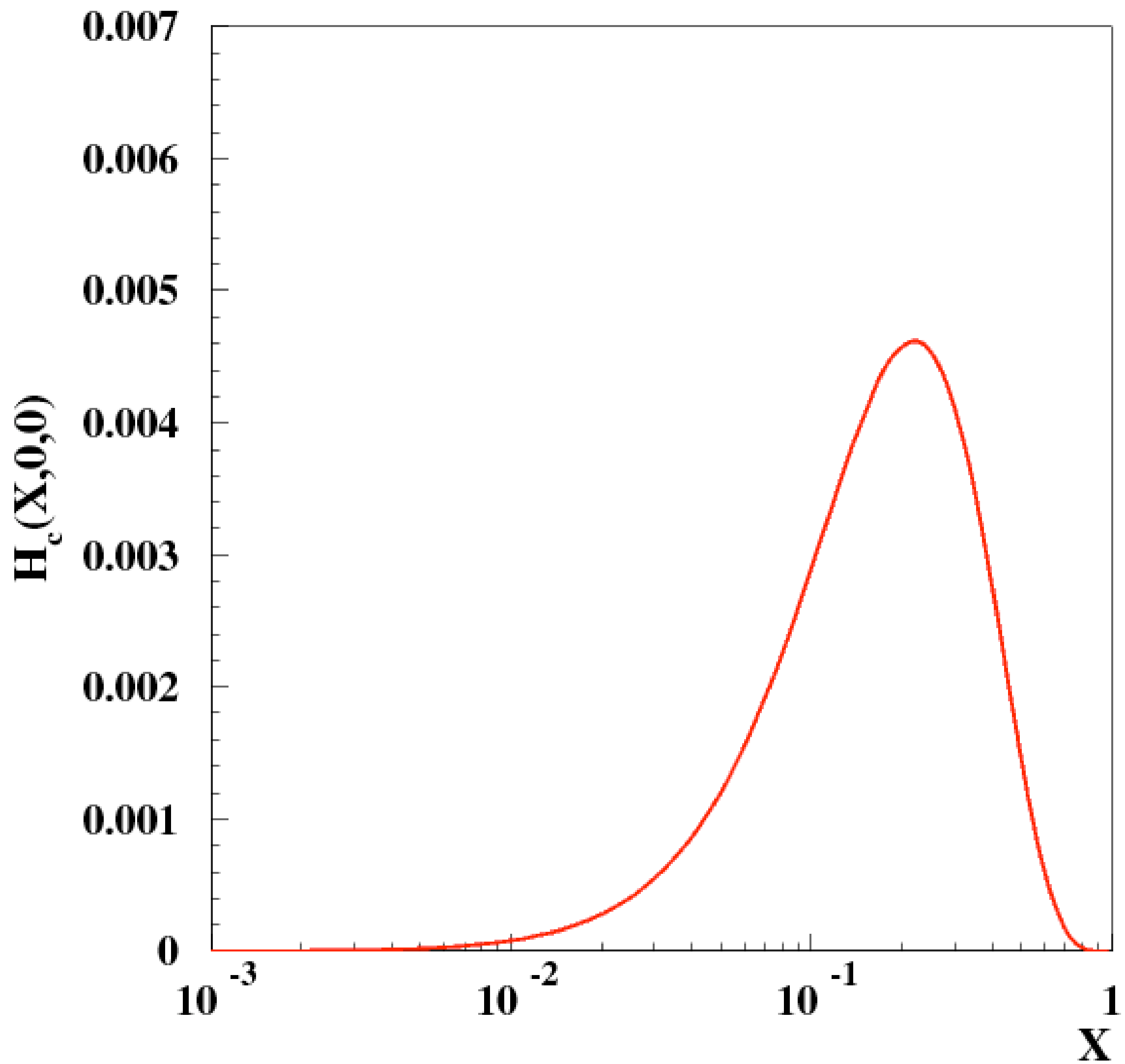
Hall B (one binning, 11 more)





Preliminary predictions for EIC

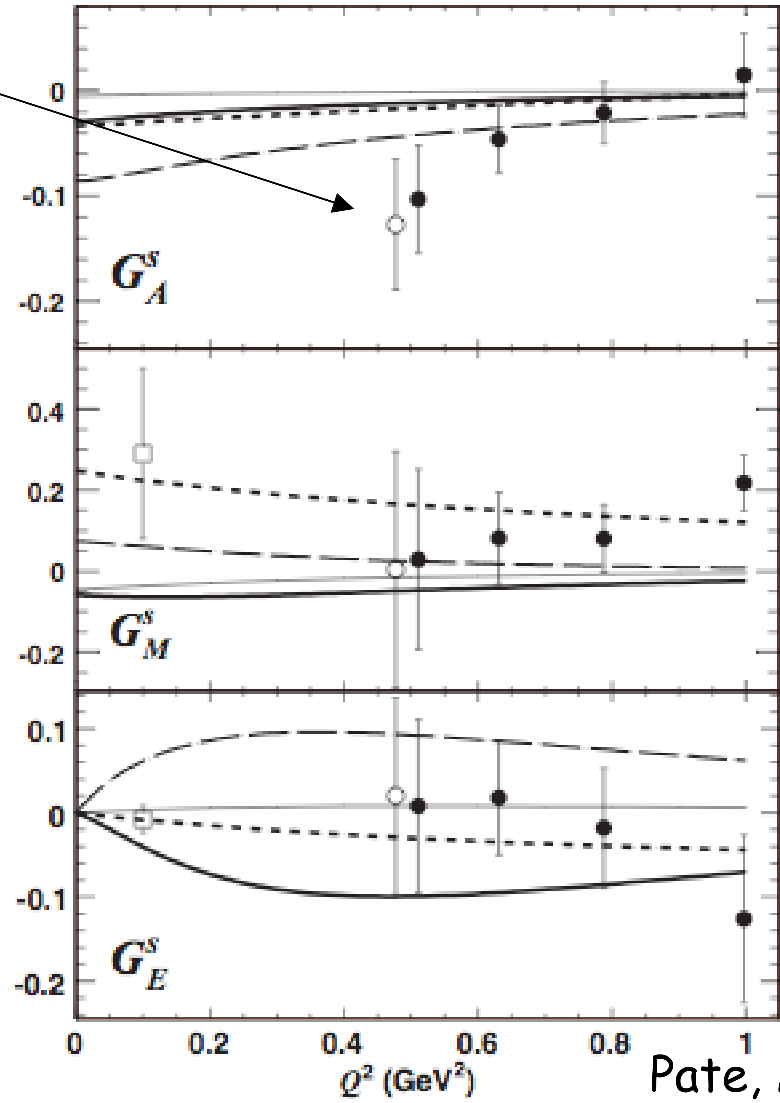
⟹ Replace PDF used for light quarks GPDs with NP charm based one



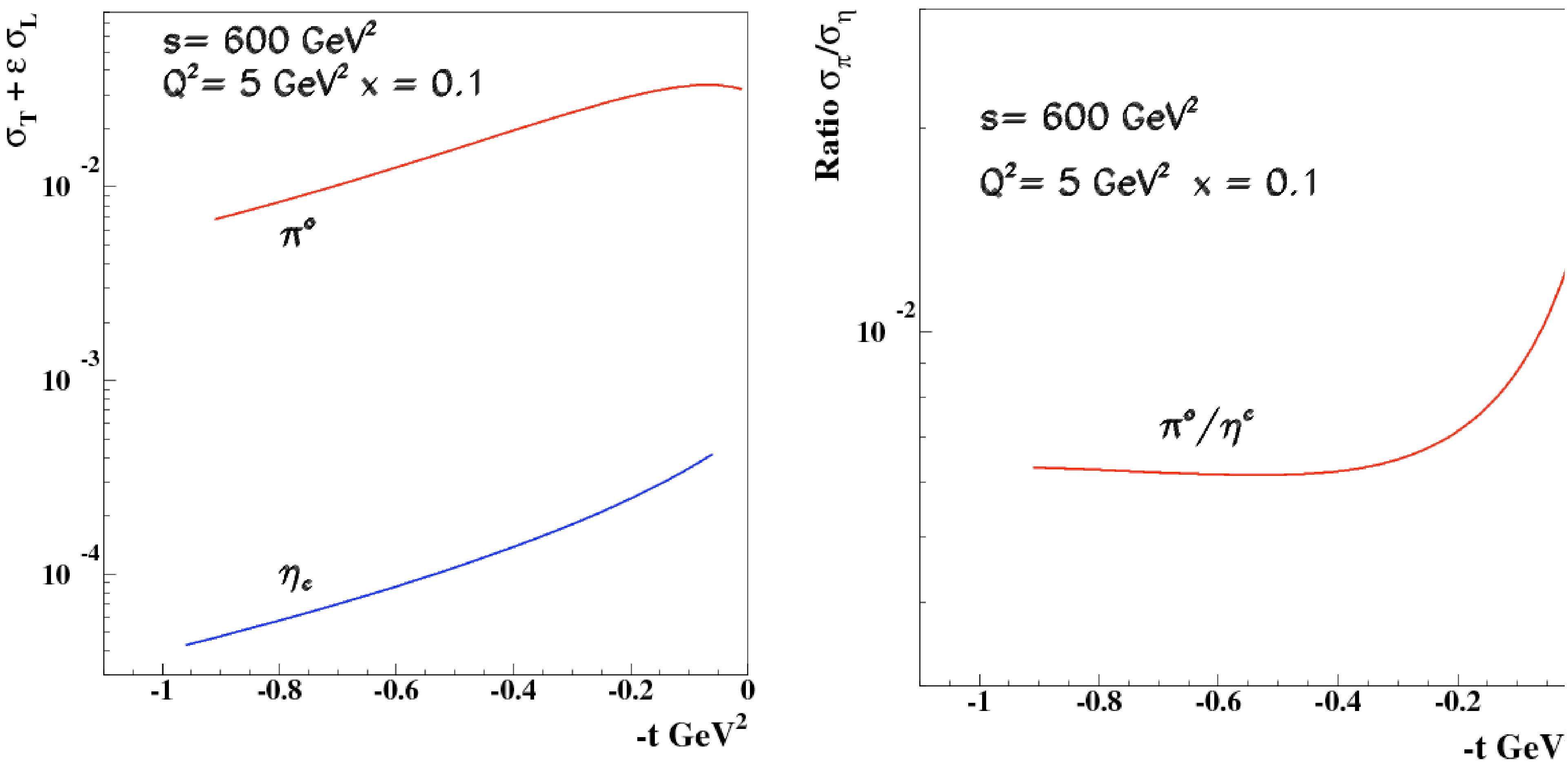
⟹ Replace FF used for light quarks GPDs with <u>upper limit</u> on charm based one

HAPPEx+E734

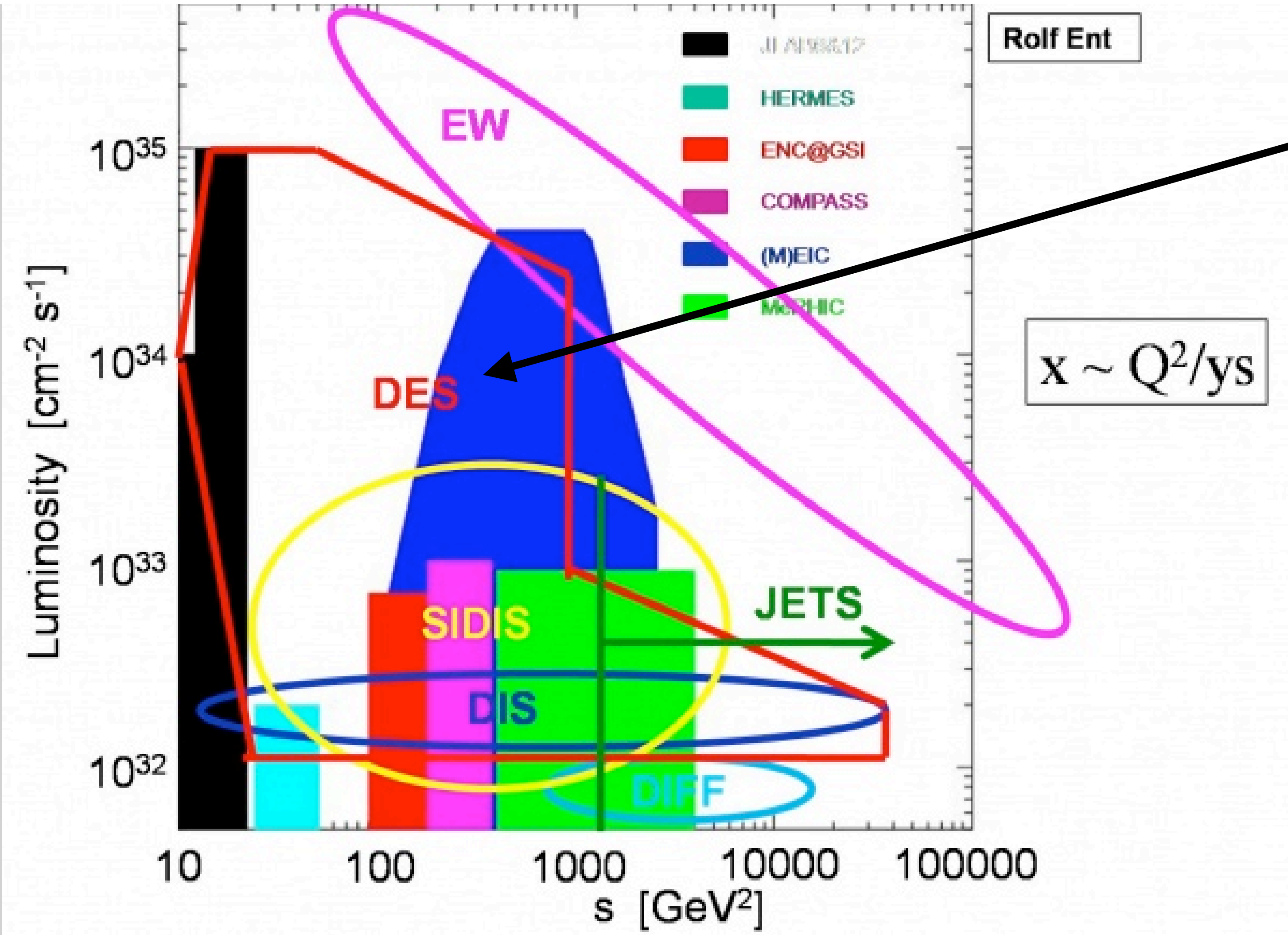
G0 + BNL E734



Pate, McKee, Papavissiliou, PRC78(2008)



G.Goldstein, S.L. (preliminary)



Region o
interest

Conclusions and Outlook

- EIC with an extended kinematical coverage (low to "larger" x_{Bj}) and wide Q^2 range will provide invaluable information on both pdfs (needed for LHC …!!), and basic hadronic properties: nature of charm content, quark and gluons spin, transversity…
- Through deeply virtual exclusive charmed mesons production we suggested a unique way of singling out the Intrinsic Charm (IC) content of the nucleon:
  - Transversity sensitive observables are key: they cannot evolve from gluons
  - Asymmetries for Pseudoscalar Charmed mesons production will establish a lower limit on the size of IC component