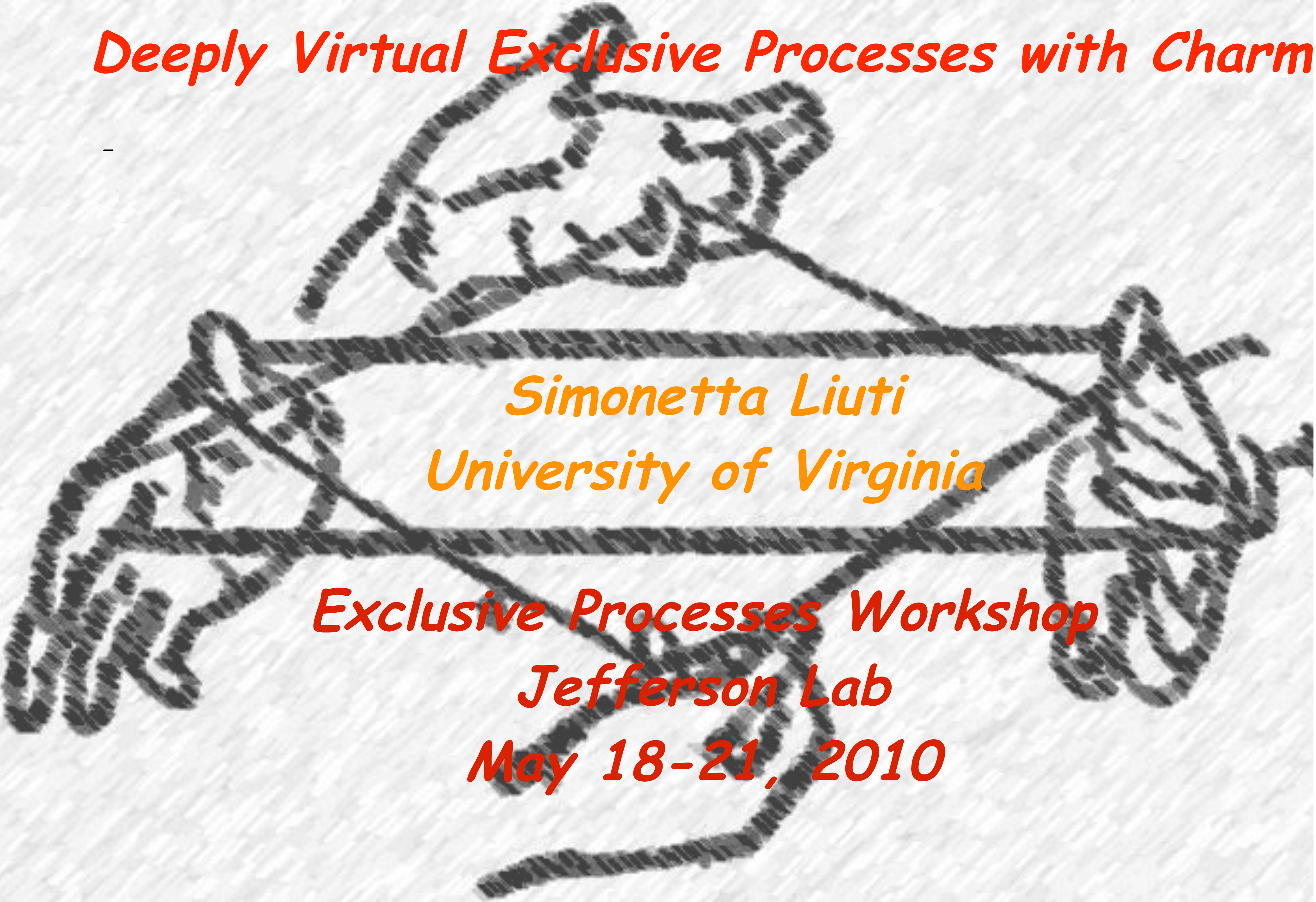
Deeply Virtual Exclusive Processes with Charm



Simonetta Liuti

University of Virginia

Exclusive Processes Workshop

Jefferson Lab

May 18-21, 2010

Outline

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

  ⇒ *A unique investigation of charm content of nucleons*

- ***From JLAB 6-12 GeV to EIC***

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

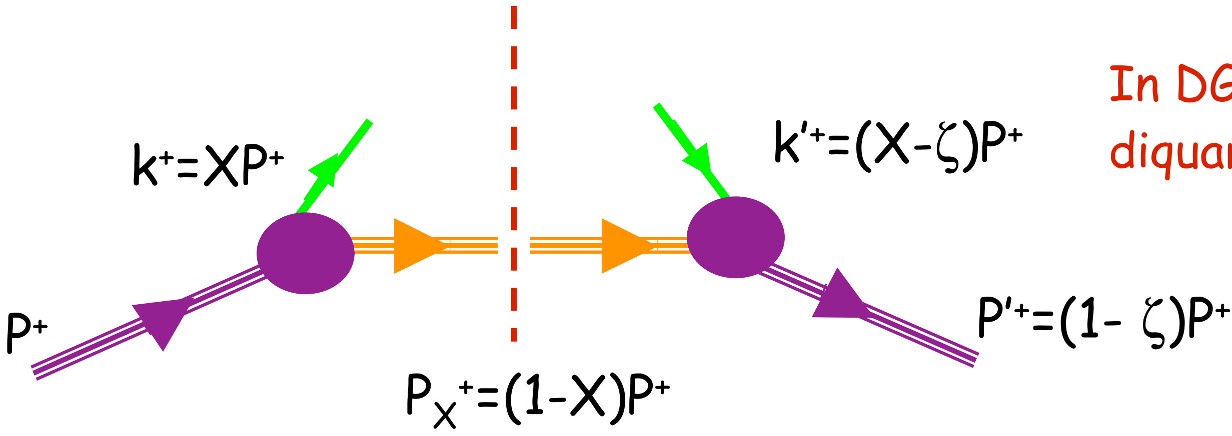
  (S. Ahmad, G. Goldstein, S.L., PRD79, 2008; G. Goldstein, S.L., hep-ph 2010)

- ***Conclusions/Outlook***

Partonic Interpretation of Generalized Parton Distributions (more at MENU)

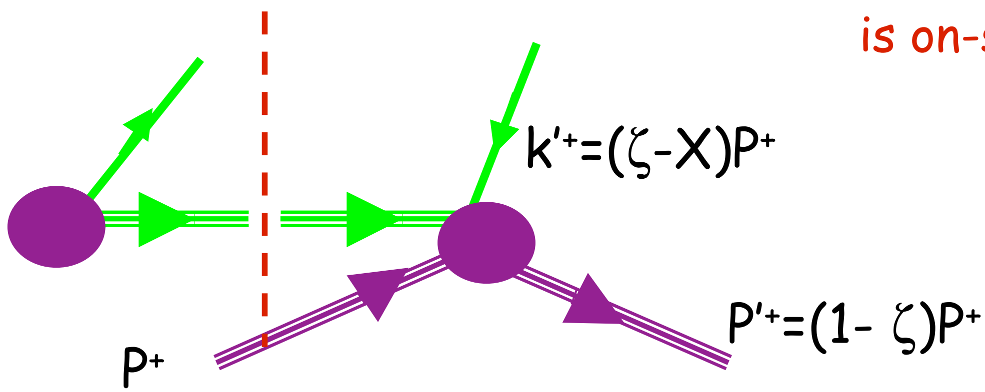
1. the support in X is defined by the region $| X | \leq 1$;
2. analytic properties of the partonic amplitude have to correspond to the emission and absorption of quarks/antiquarks via well defined on-mass shell intermediate hadronic states;
3. the quark-proton vertices have to be connected.

$$H(X,\zeta,t)=\sum_n \langle P'|\psi^+|n\rangle\langle n|\psi|P\rangle\,\delta\left[(X-\zeta)P^+ + p_n^+ - P'^+\right]$$



In DGLAP region spectator with diquark q. numbers is on-shell

See also Goldstein, S.L. PRD(2009)



In ERBL region struck quark, k, is on-shell

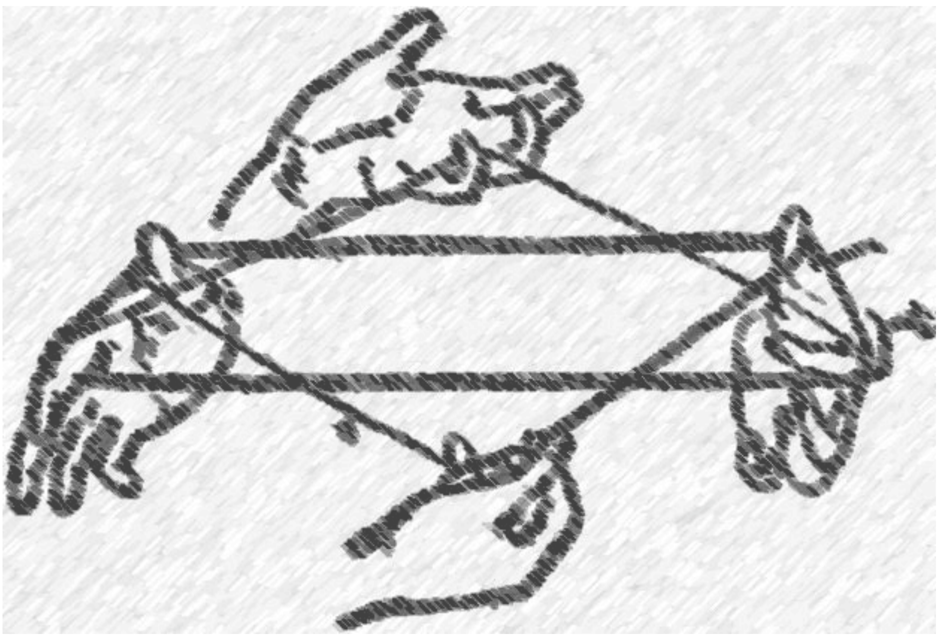
Can one give a partonic interpretation?

$$\langle P' \mid b^\dagger_\lambda\left((X-\zeta)\bar{P}^+, -\mathbf{k}_T+\mathbf{\Delta}_T\right)|n\rangle\langle n|\, d^\dagger_{-\lambda}\left(X\bar{P}^+, \mathbf{k}_T\right)|P\rangle$$
$$= \langle P' \mid b^\dagger_\lambda\left((X-\zeta)\bar{P}^+, -\mathbf{k}_T+\mathbf{\Delta}_T\right)|P,n\rangle\langle n|\, d^\dagger_{-\lambda}\left(X\bar{P}^+, \mathbf{k}_T\right)|0\rangle$$

No damn cat, and no damn cradle..

K. Vonnegut

"Cat's Cradle"

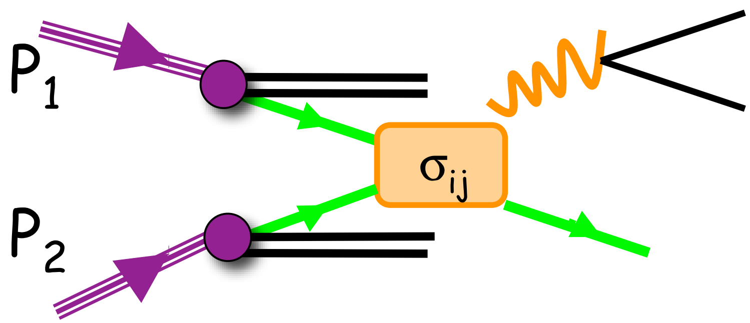


Introduction

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

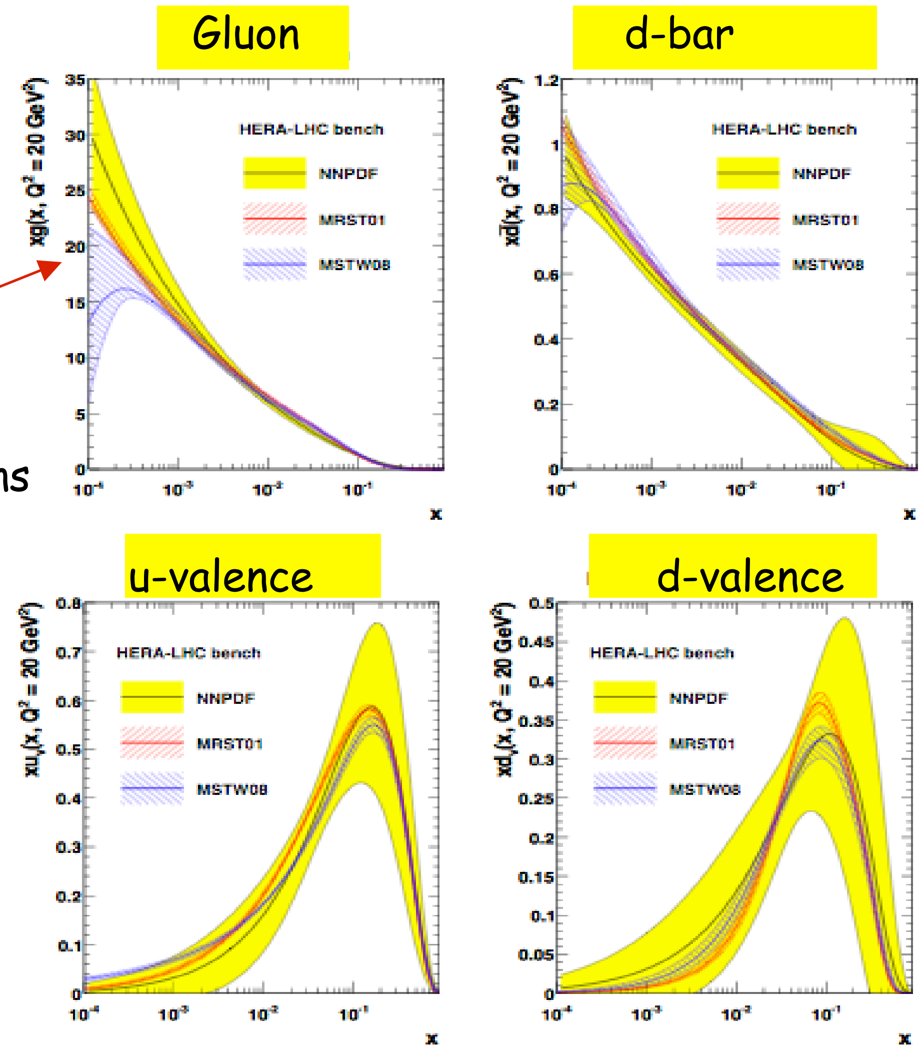
- QCD: A background for "beyond the SM discovery"
- Interesting dynamical questions for QCD at untested high energies

Most important points for EIC

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

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 L. Gamberg and G. Goldstein)

Study heavy quark components → charm, through hard exclusive processes

Why charm?

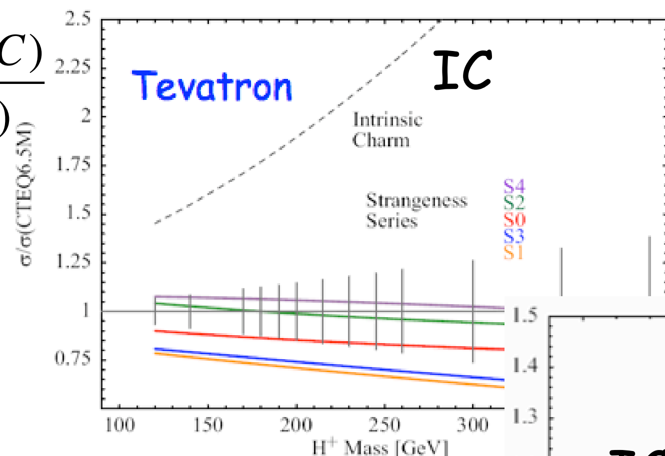
LHC processes are sensitive to charm content of the proton

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

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

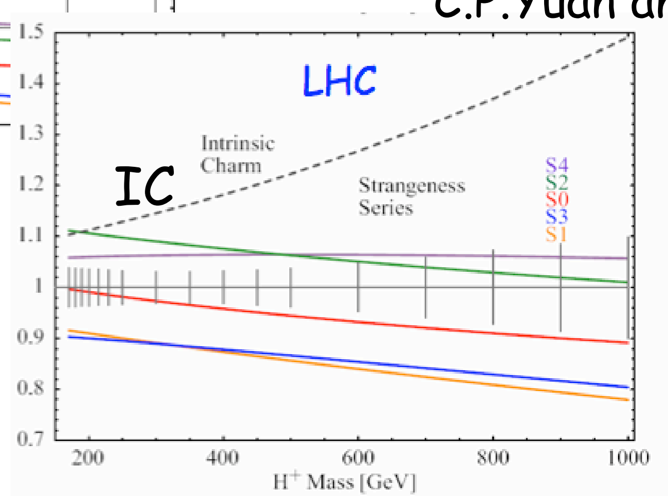
Impact of new CTEQ6.5(M,S,C) PDFs

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



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

C.P.Yuan and collaborators

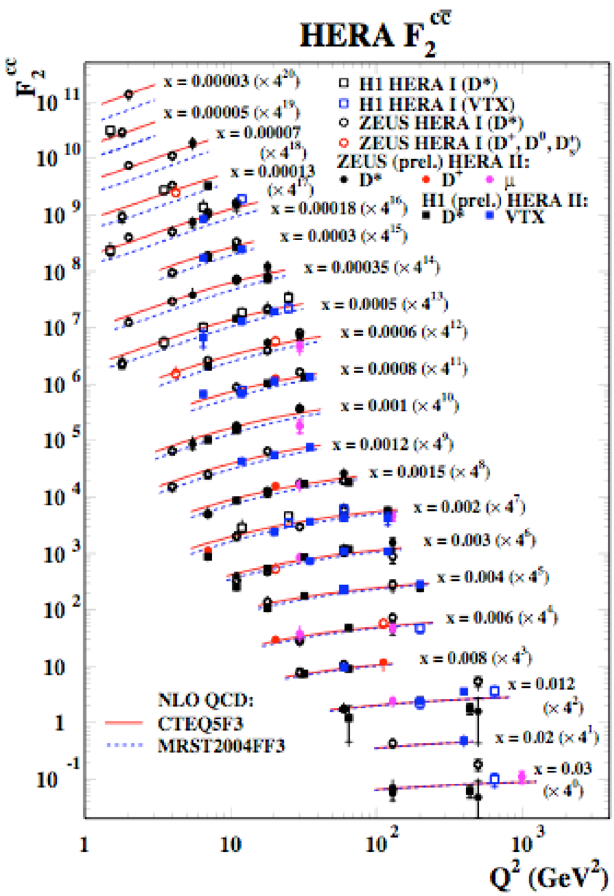


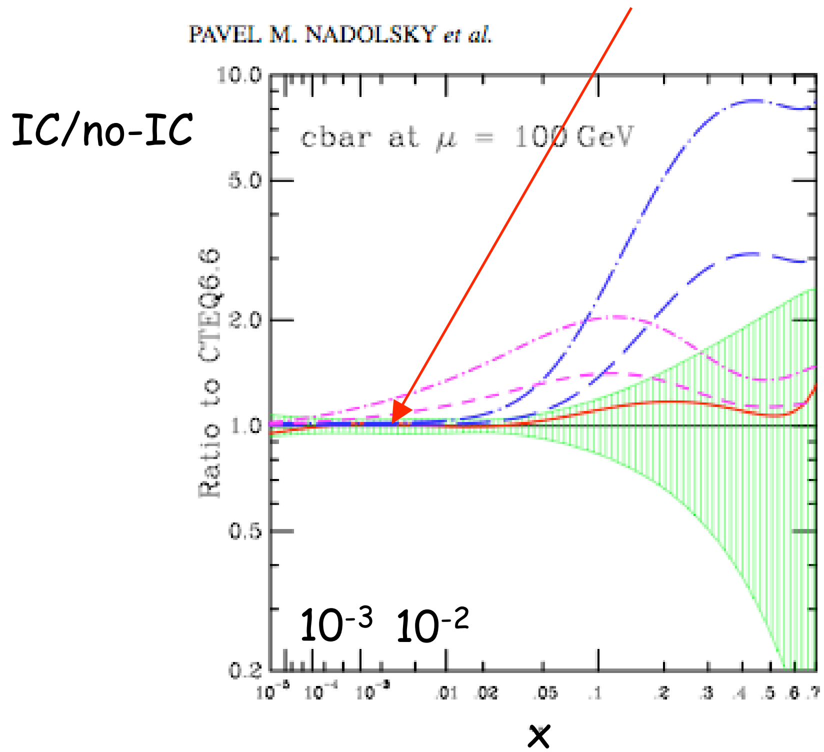
CTEQ 6.6

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

m_h (GeV)	$\Delta_{\rm GM}(\%)\vert\Delta_{\rm PDF}(\%)$													
	VBF		Z^0h		$Ah^{\pm}$		$gg \to h$		$c\bar{b} \to h^+$		$c\bar{s} \to h^+$		$c\bar{s} + c\bar{b} \to h^+$	
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**	**6.9**
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**	**5.4**
300	−1.6	2.8	−0.6	3	−0.4	5.3	2.3	2.7	1.9	4.3	**−14**	**7**	**−6.2**	**4.5**
400	−0.1	3.3	0	3.4	0.7	6.6	2.8	3.8	2	4.8	**−13**	**6.3**	**−5.6**	**4.4**
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**	**5.1**
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	6.4
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	8
800	2.3	3.5	1	4.8	2.8	13	4.9	7.8	4.1	12	**−8.7**	**9**	−2.4	10

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

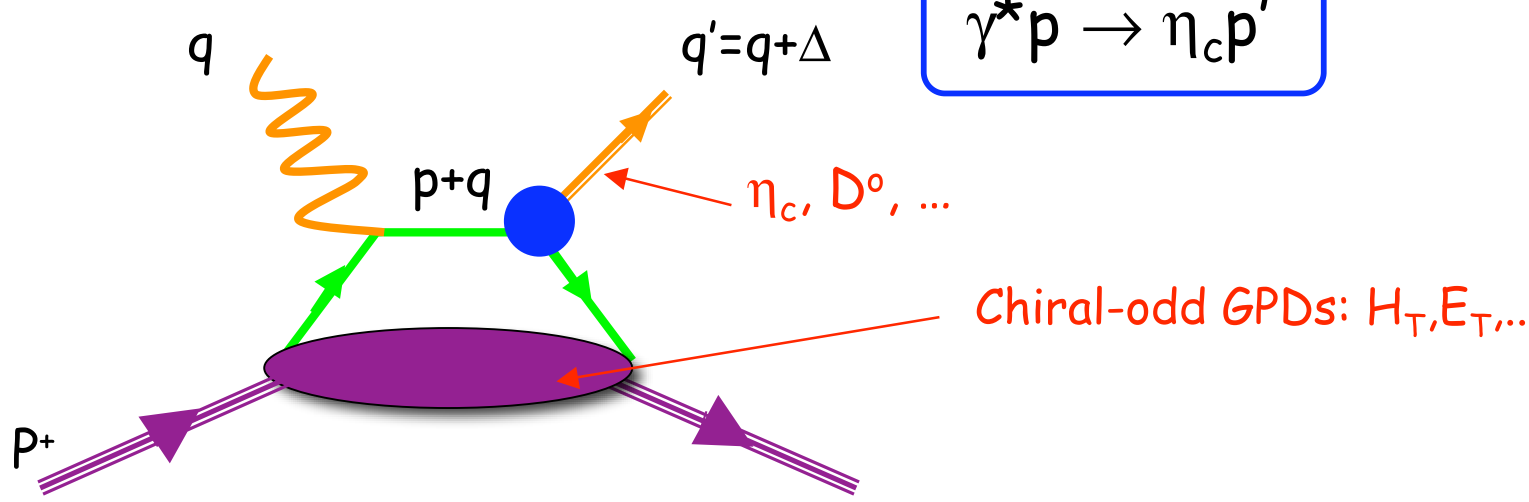




A window into heavy flavor production at the EIC

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"!

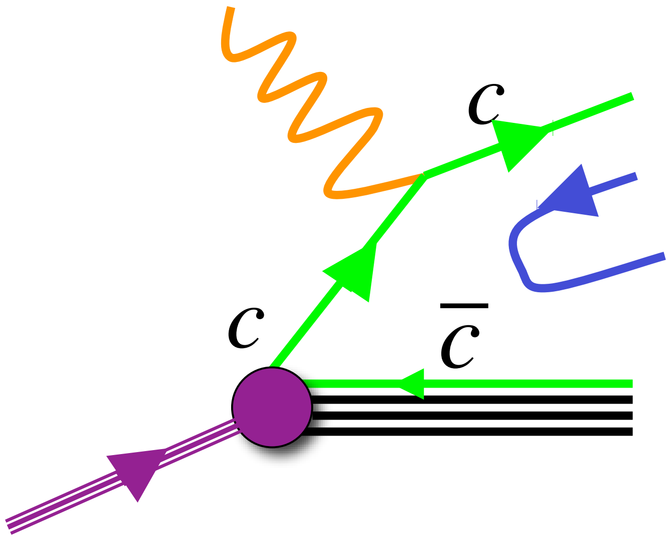


$$\gamma^* p \rightarrow \eta_c p'$$

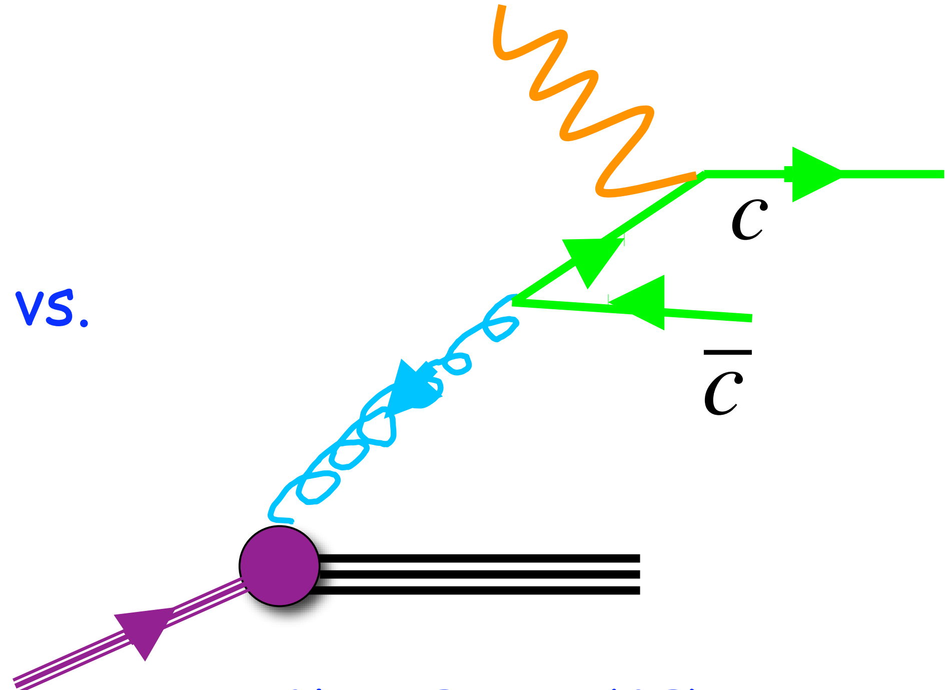
Windows into Heavy Flavor Production at the EIC

Inclusive

Intrinsic Charm (IC)



vs.

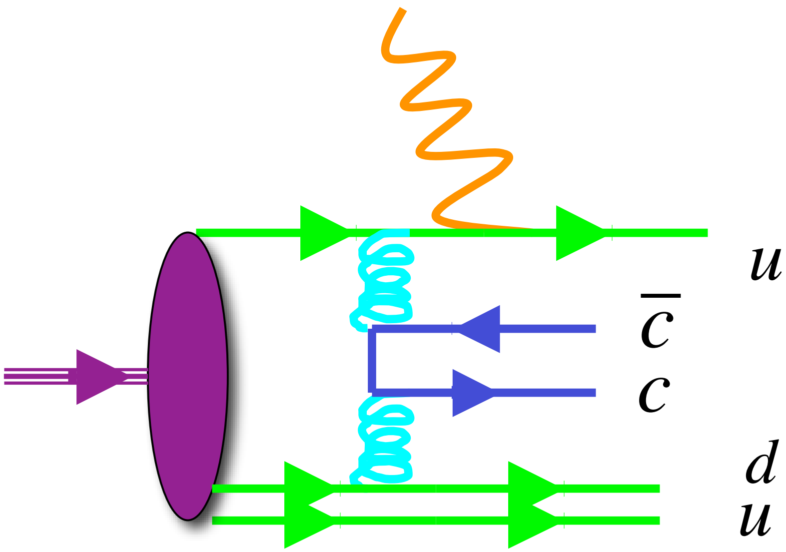


Gluon Fusion (GF)

IC content of proton can be large (up to 3 times earlier estimates) but PDF analyses are inconclusive (J.Pumplin, PRD75, 2007)

Intrinsic Charm (IC)

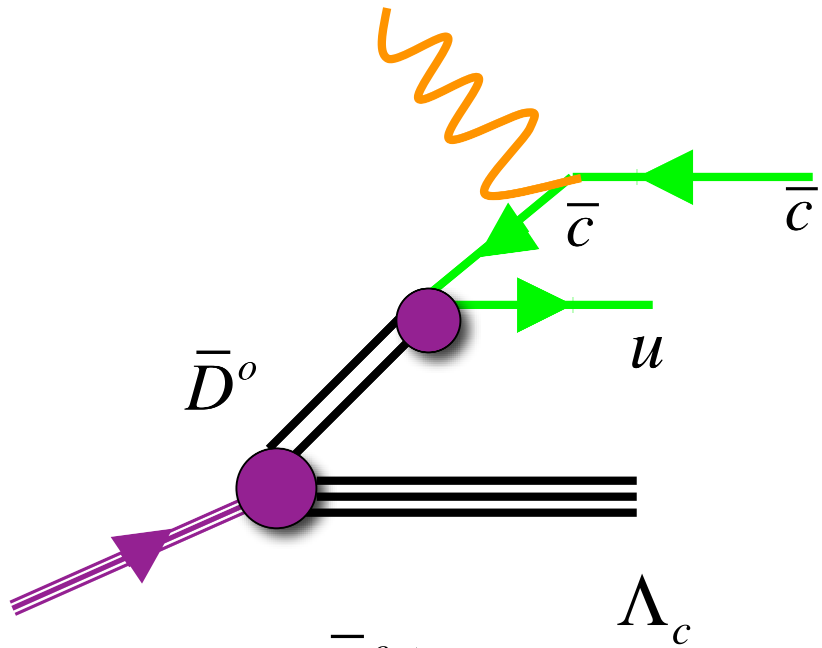
"Light Cone" based Processes



$$|p\rangle \rightarrow |uudc\bar{c}\rangle$$

Brodsky, Gunion, Hoyer, R.Vogt, ...

Hadronic Processes

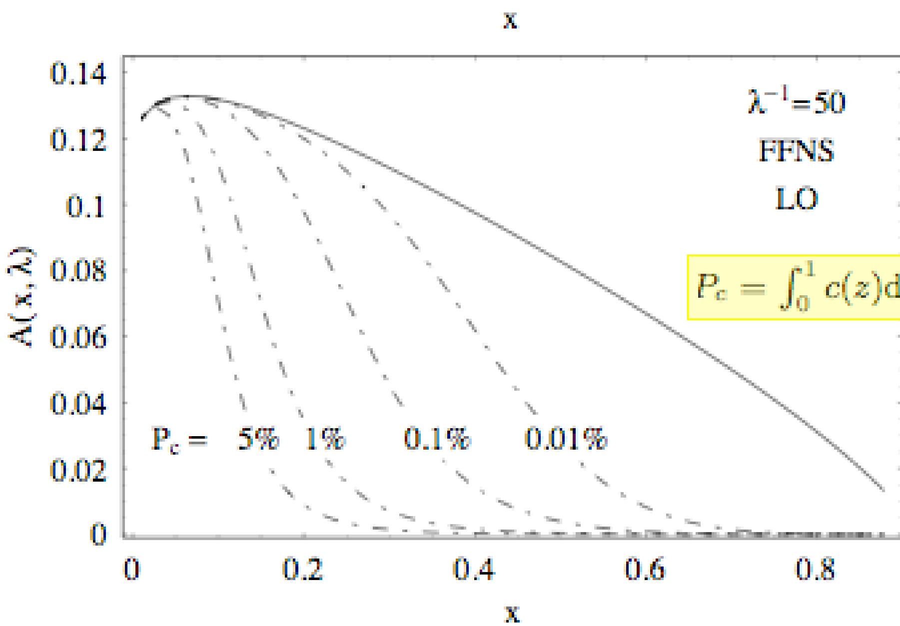


$$p \rightarrow \bar{D}^o \Lambda_c$$

Meson Cloud: Thomas, Melnichouk ...

Intrinsic Charm can be "partially" detected by looking at asymmetries in Inclusive Heavy Quark Jets Production

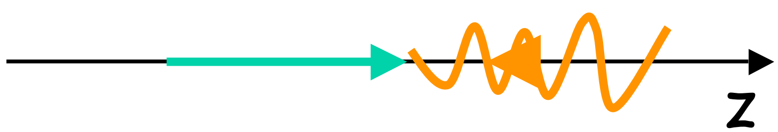
Ananikian and Ivanov, NPB (2008)



$$P_c = \int_0^1 c(z)\mathrm{d}z.$$

$$l(\ell) + N(p) \to l(\ell - q) + Q(p_Q) + X[\overline{Q}](p$$

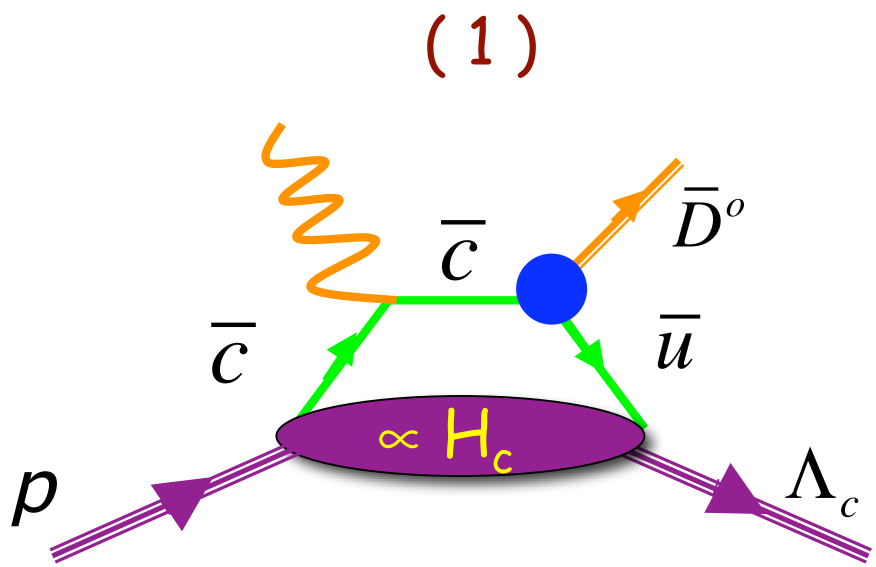
$$A_{2\varphi}(\rho, x, Q^2) = 2\langle\cos 2\varphi\rangle(\rho, x, Q^2) = \frac{\mathrm{d}^3\sigma_{lN}(\varphi = 0) + \mathrm{d}^3\sigma_{lN}(\varphi = \pi) - 2\mathrm{d}^3\sigma_{lN}(\varphi = \pi/2)}{\mathrm{d}^3\sigma_{lN}(\varphi = 0) + \mathrm{d}^3\sigma_{lN}(\varphi = \pi) + 2\mathrm{d}^3\sigma_{lN}(\varphi = \pi/2)}$$



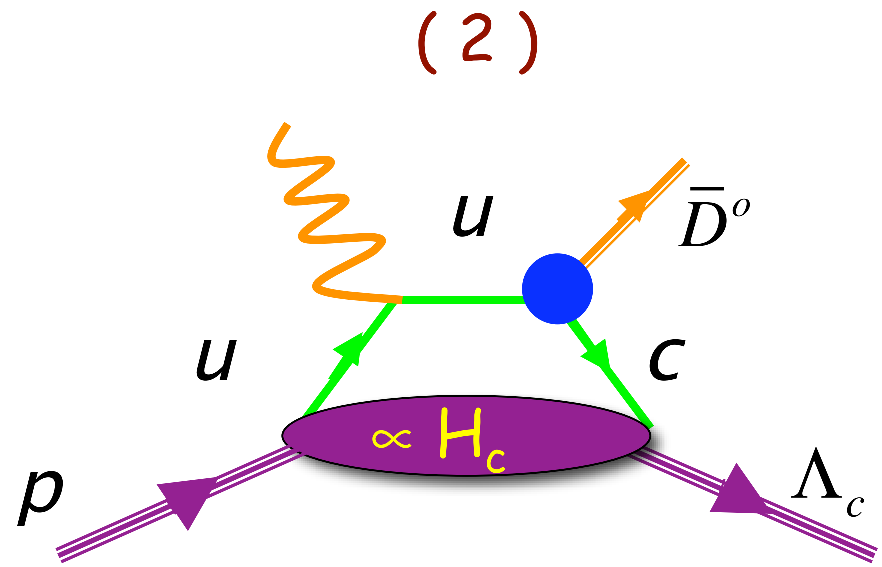
$A_{IC}^{LO} = 0$

What Observables?

Spin Asymmetries from Exclusive Heavy Quark Meson Production!



p → c̄cuud → (ūu) cud = Λ_c

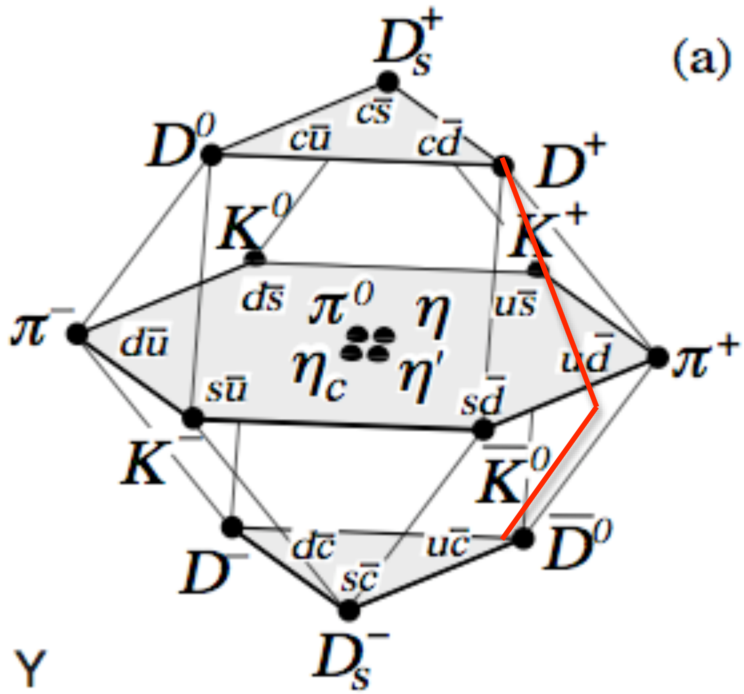


p → u + ud → cud = Λ_c

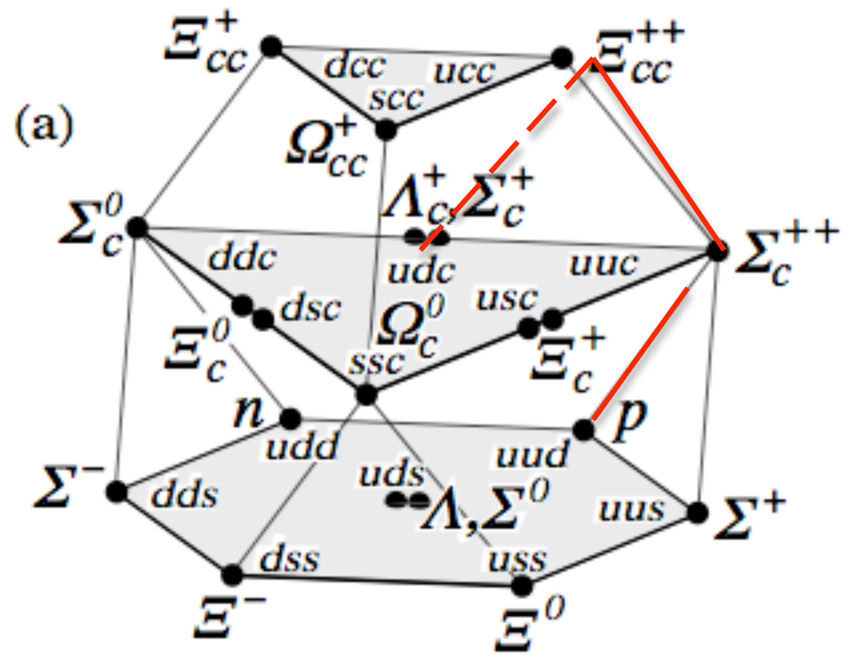
$\gamma^* p \rightarrow \bar{D}^o \Lambda_c^+ \Rightarrow 2H_u - H_d + H_c$
$\gamma^* p \rightarrow D^o \Sigma_c^+ \Rightarrow H_d - H_c$
$\gamma^* n \rightarrow \bar{D}^o \Sigma_c^o \Rightarrow H_u - H_c$

SU(4) relations allow one to extract H_c

SU(4) relations for GPDs

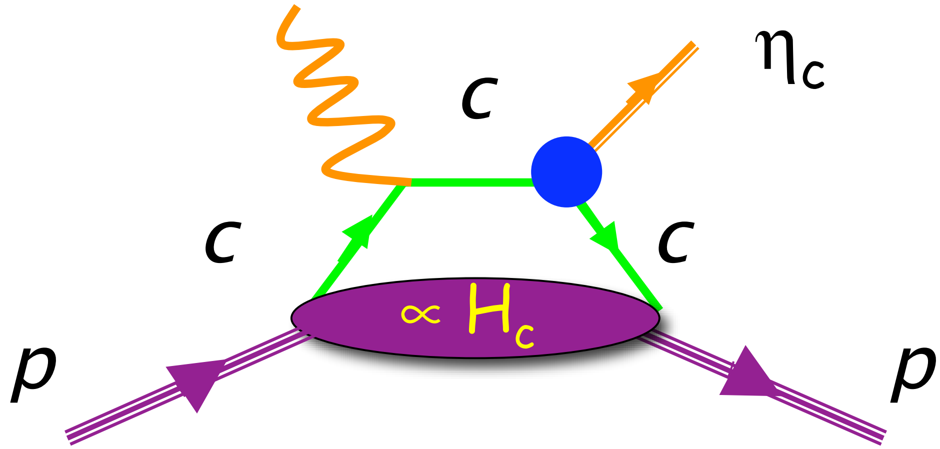


Y



Slice SU(4) weight diagrams to obtain SU(3) subgroup weight diagrams
This replaces u,d,s by u,d,c octet relations

(3)



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

EIC "golden plated signal"

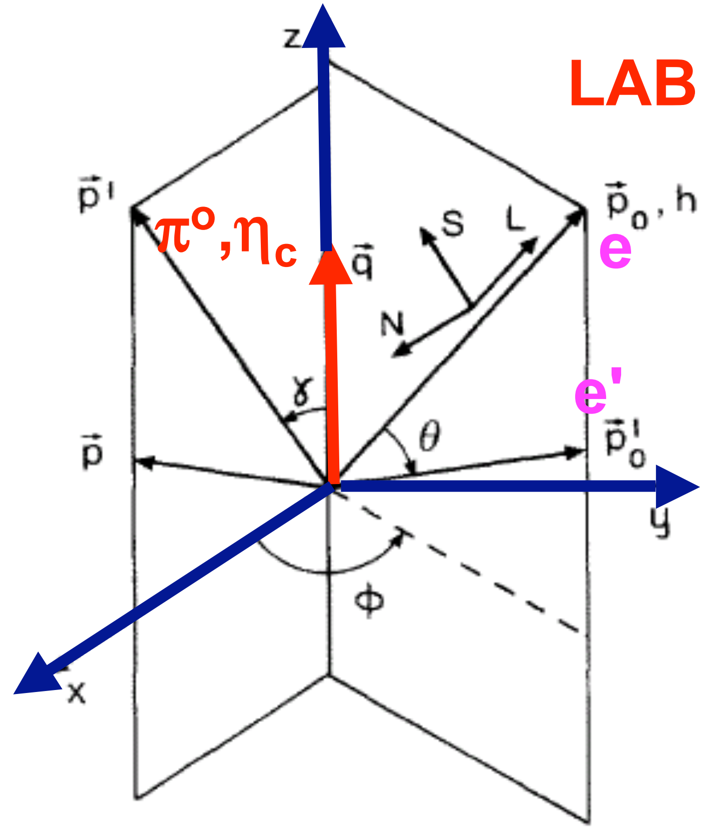
$\eta_c = c\bar{c} \rightarrow J^{PC} = 0^{-+}$

"But measuring η_c is very difficult"
Pavel Nadol Turonksi

Pseudoscalar Mesons Electroproduction and Chiral Odd GPDs

(S. Ahmad, G. Goldstein and S.L., PRD (2008))

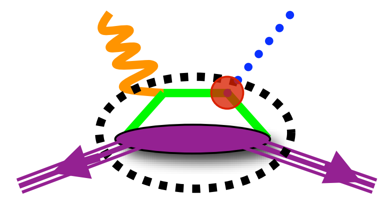
Unpolarized Cross Section



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

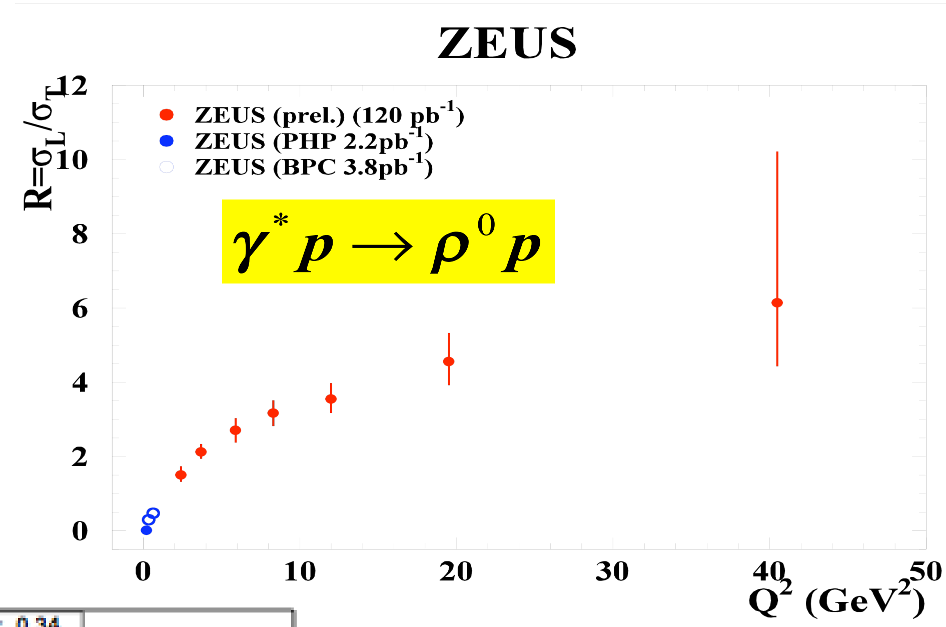
$$L_{\mu\nu}^{h=\pi^o} \approx \gamma^* \text{ polarization density matrix}$$

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

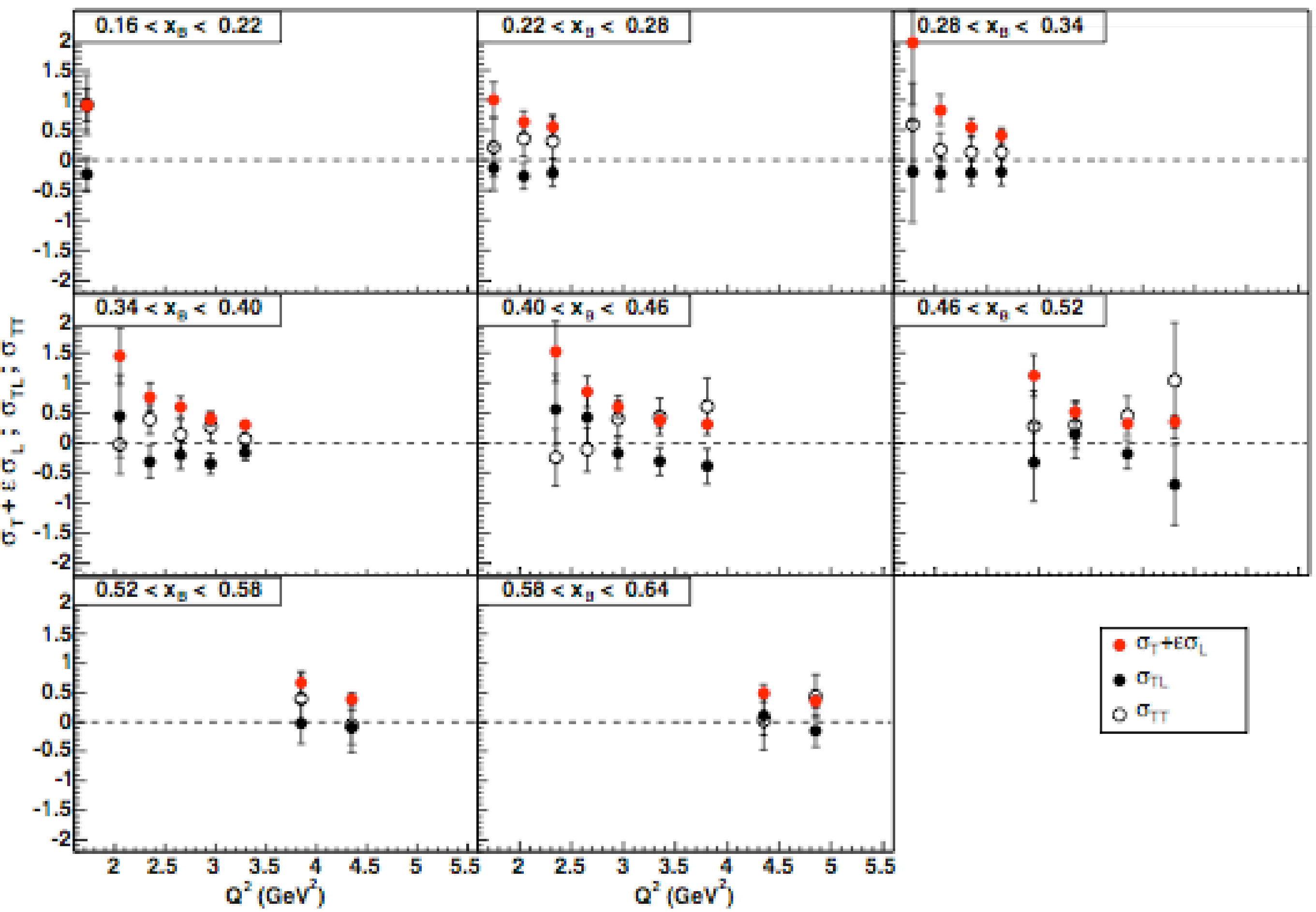


$$\frac{d\sigma}{dt\,d\phi} = \left(\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}\right) + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi$$

Q^2 dependence in exclusive meson production

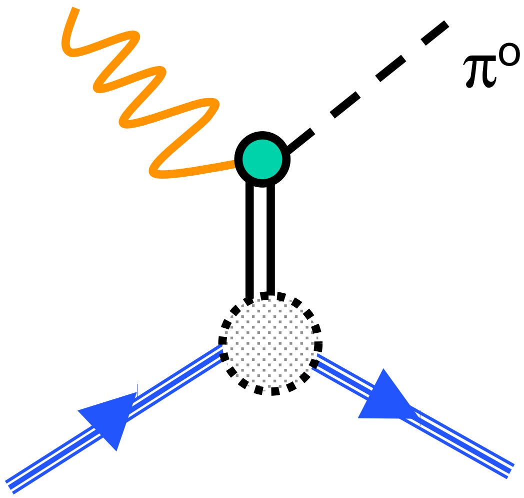


Jlab



Unexpected dominance of transverse components

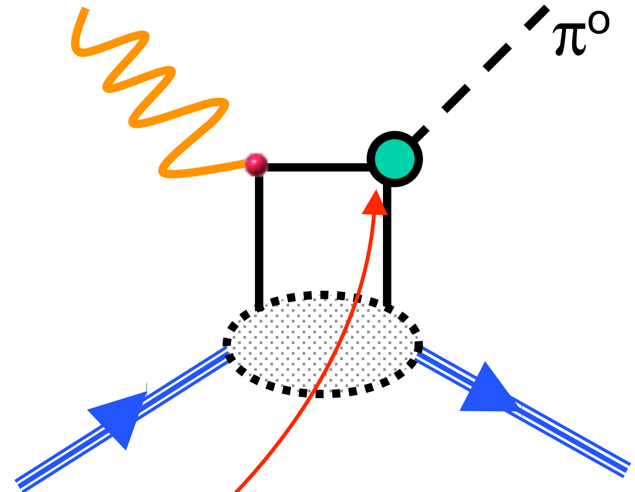
Q^2 dependence



"Regge factorization"

$J^{PC}=1^{--}$ γ, ρ, ω, ..

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



QCD factorization

chiral-even structure

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

GPDs: $\tilde{H}$, $\tilde{E}$,...

$\gamma_5 \rightarrow$

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

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

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

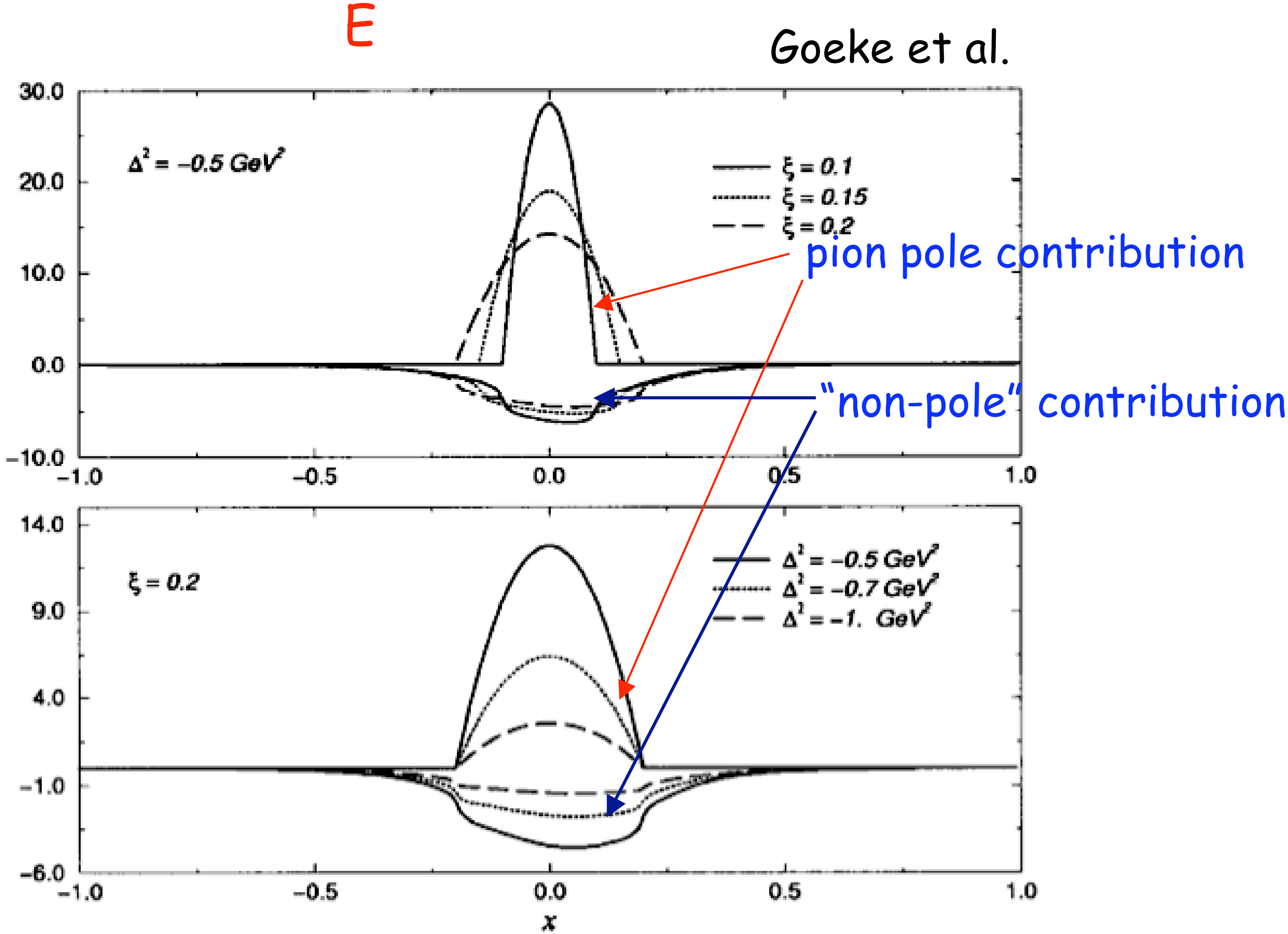
GPDs: $\tilde{H}$, $\tilde{E}$, and Weak Form factors

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

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

$g_P(t)$ = 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

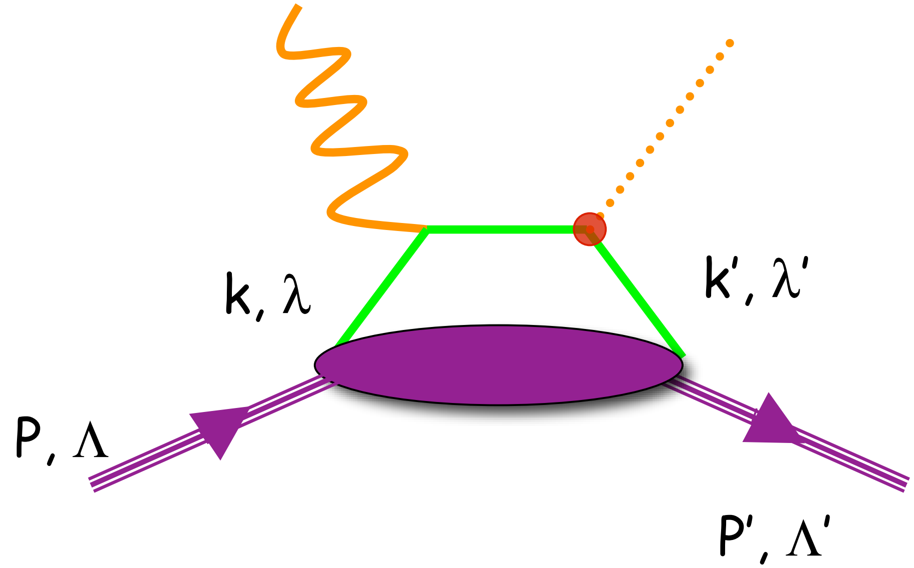
⇒issue overlooked in most recent literature on the subject

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

Helicity Amplitudes formalism

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

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



Factorized form

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

$g_{\Lambda_\gamma,\lambda;0,\lambda'}(X,\zeta,t,Q^2)$ → γ quark scattering amp.

$A_{\Lambda',\lambda';\Lambda,\lambda}(X,\zeta,t)$ → "quark-proton helicity amp."

6 "f" helicity amps

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

Rewrite helicity amps. expressions using new GFFs

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

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

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

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

elementary subprocess

Q^2 dependent pion vertex

GFFs

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

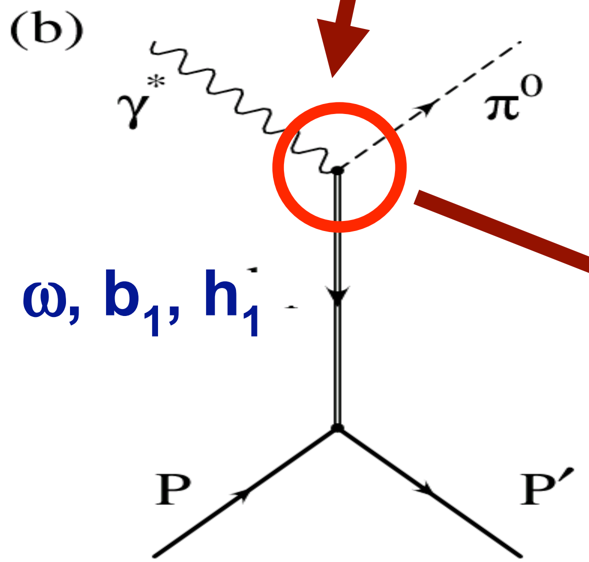
However…
$\Rightarrow$ suppression is not seen in experiments

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 (1996).

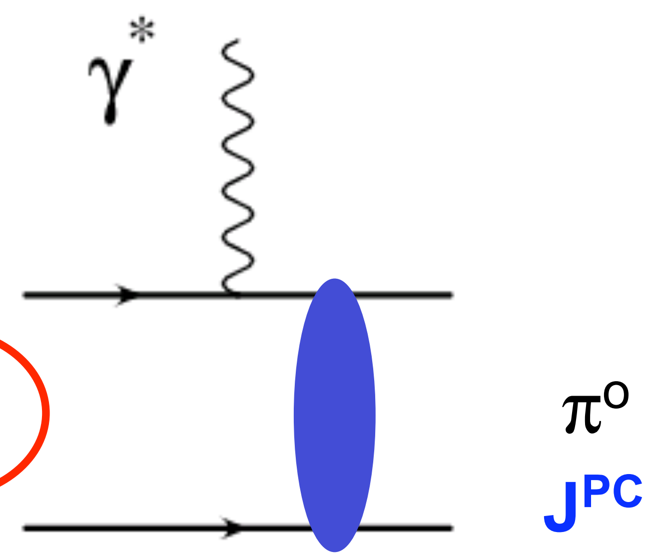
Q^2 dependence

t-channel exchange vertex



ρ, ω, b_1, h_1

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



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

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)exchanges

$J^{PC}=1^{--}$ → 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!

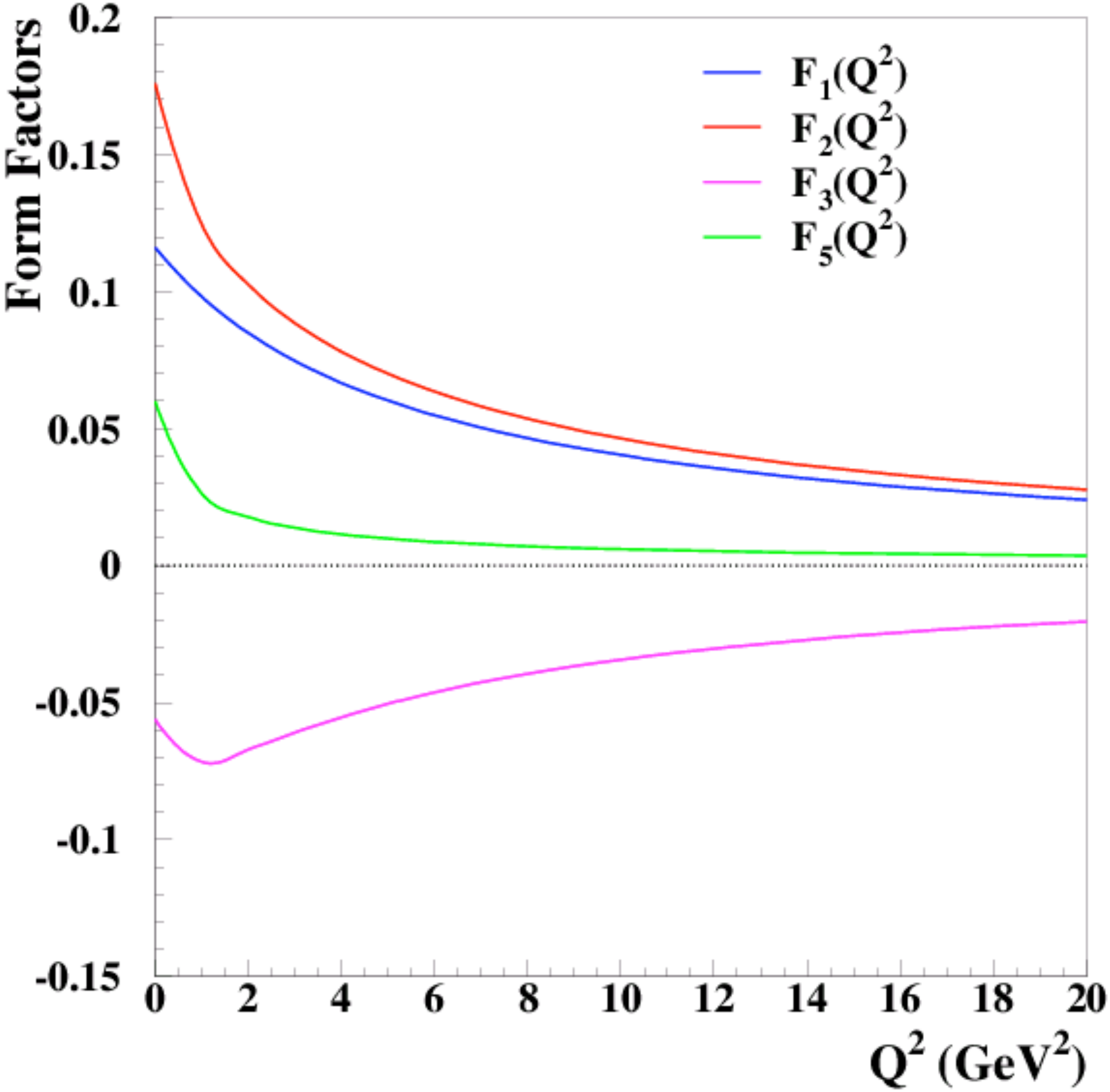
$$F_{\gamma^* V\pi^o} = \int dx_1 dy_1 \int d^2\mathbf{b}\, \psi_V(y_1,b)\, \mathcal{C} K_o(\sqrt{x_1(1-x_1)Q^2}b)\, \psi_{\pi^o}(x_1,b)\, exp(-S)$$

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

Because of OAM axial vector transition involves Bessel J_1

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

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



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

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

$R(X, \zeta, t)$ → "Regge"

$G(X, \zeta, t)$ → Quark-Diquark

+ Q^2 Evolution

Parameters from PDFs

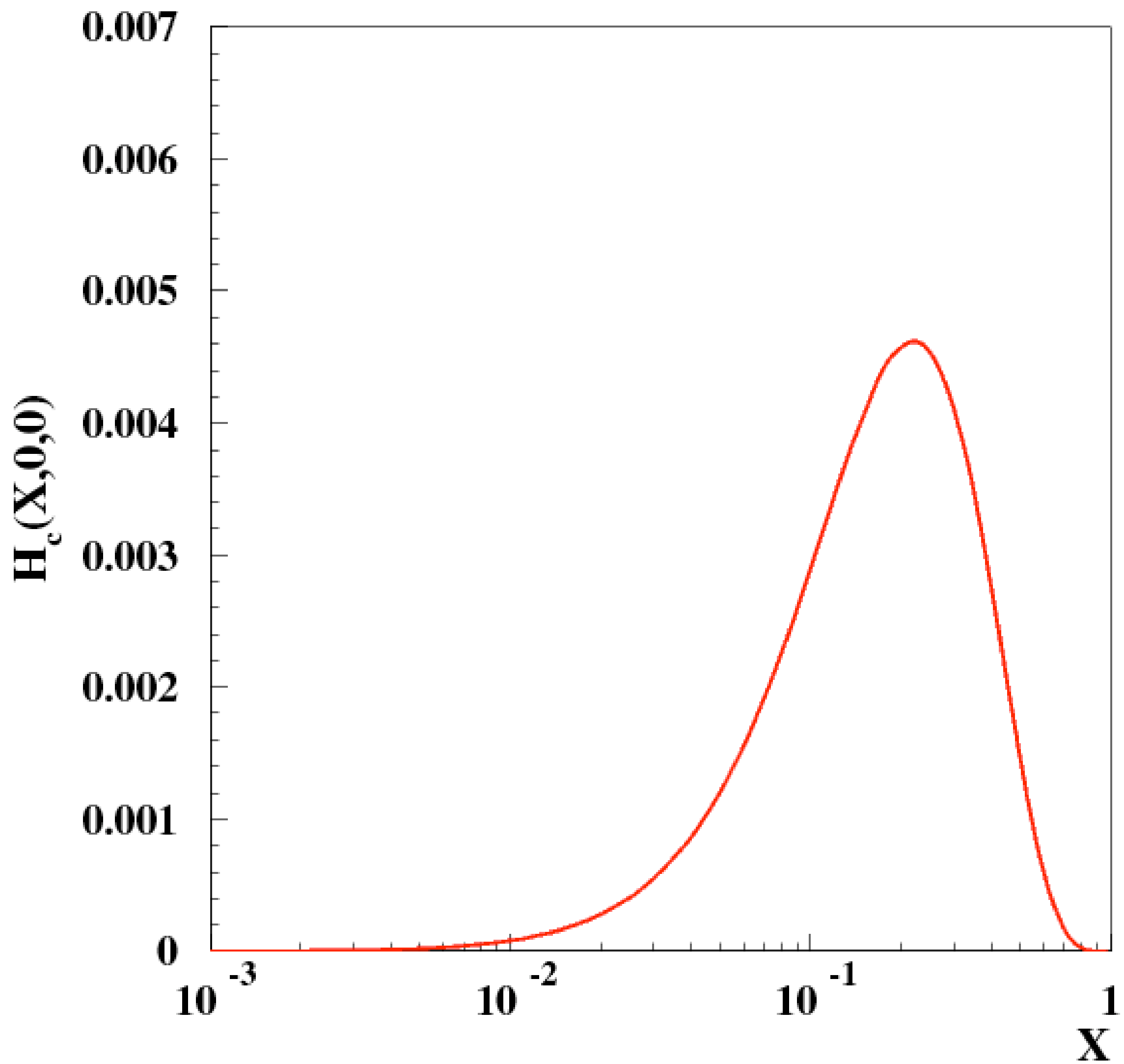
Flavor	M_X (GeV)	λ (GeV)	α
u	0.4972	0.9728	1.2261
d	0.7918	0.9214	1.0433

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 ± 0.031
d	1.5707 ± 0.0368	1.4316 ± 0.0440	0.720 ± 0.028	0.528 ± 0.031

Preliminary predictions for EIC

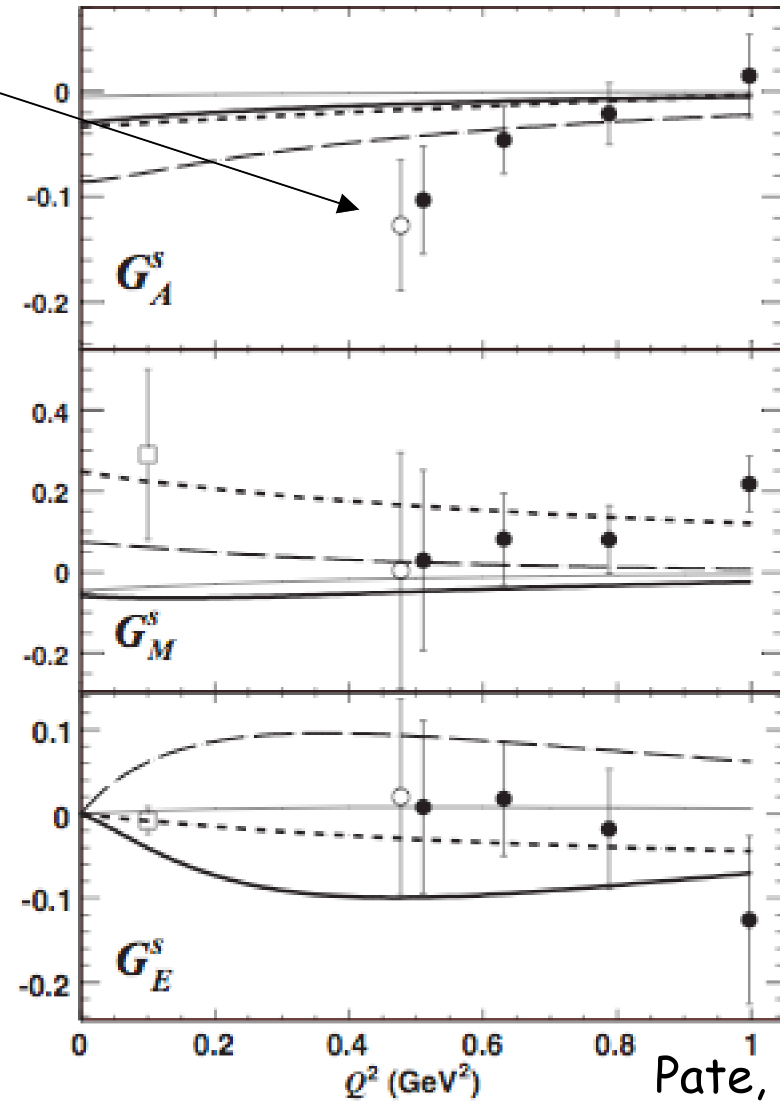
⇒ Replace PDF used for light quarks GPDs with NP charm based one



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

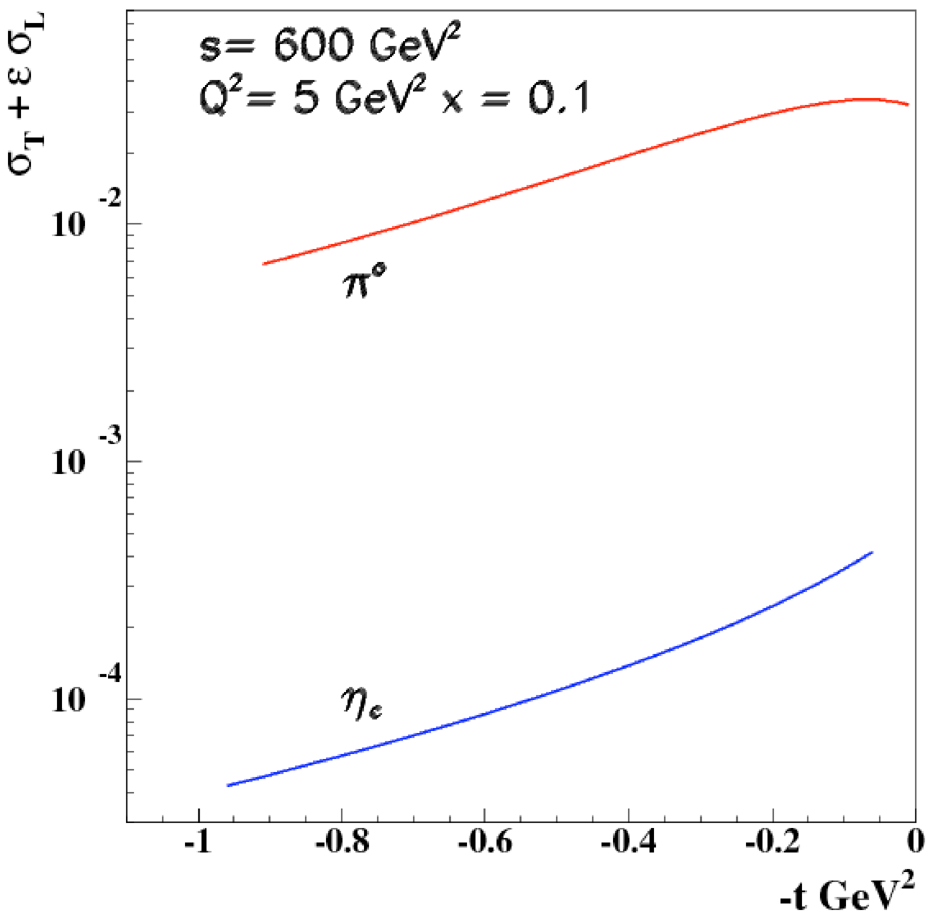
HAPPEx+E734

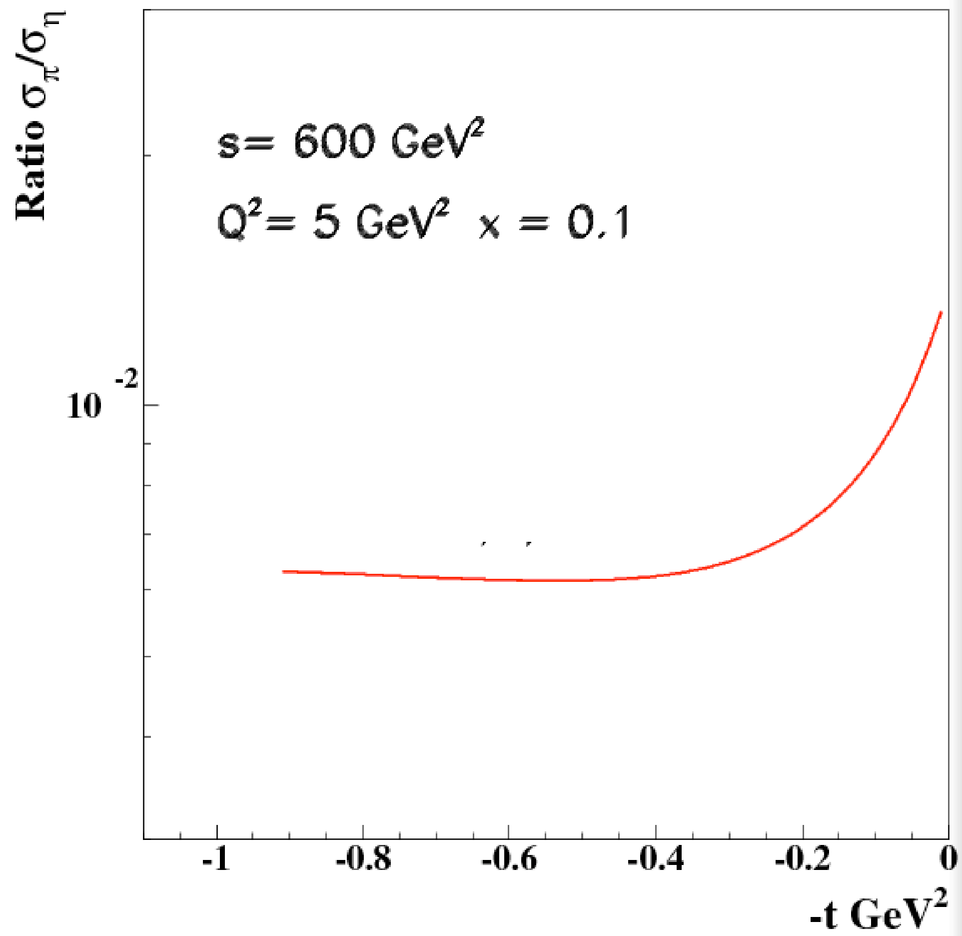
G0 + BNL E734



Pate, McKee, Papavissiliou, PRC78(2008)

Ratio η_c/π^o





G.Goldstein, S.L. (preliminary)

Finally, spin degrees of freedom

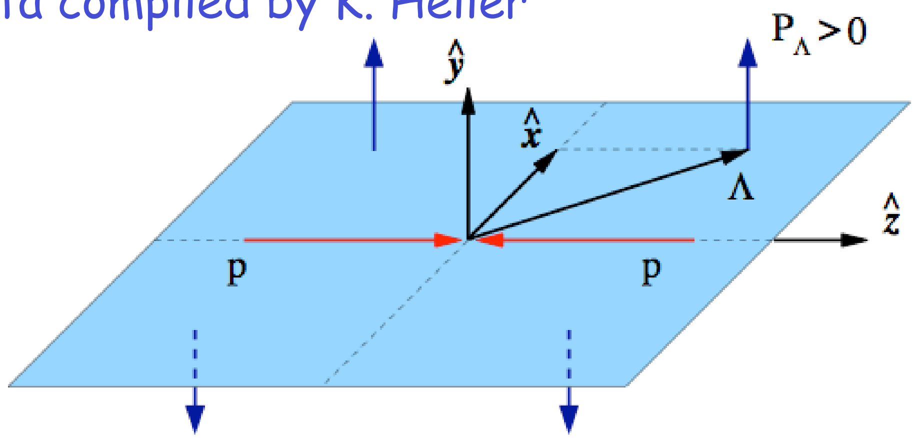
Transverse Λ polarization in unpolarized scattering

D. Boer, DIS 2010

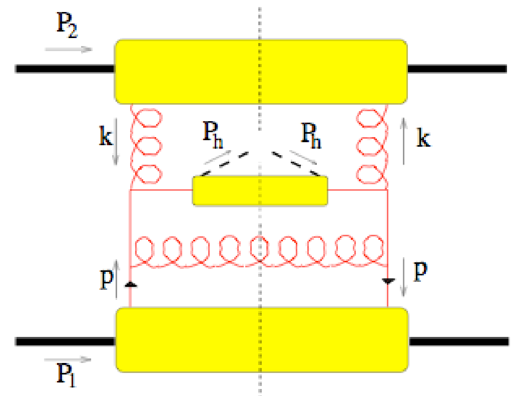
Large asymmetries have been observed in $p + p \to \Lambda^{\uparrow} + X$

G. Bunce *et al.*, PRL 36 (1976) 1113

Set of all data compiled by K. Heller



Outstanding puzzle!



Collinear Factorization

$$P_\Lambda \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg \to qg} \otimes ?$$

Non Collinear Factorization

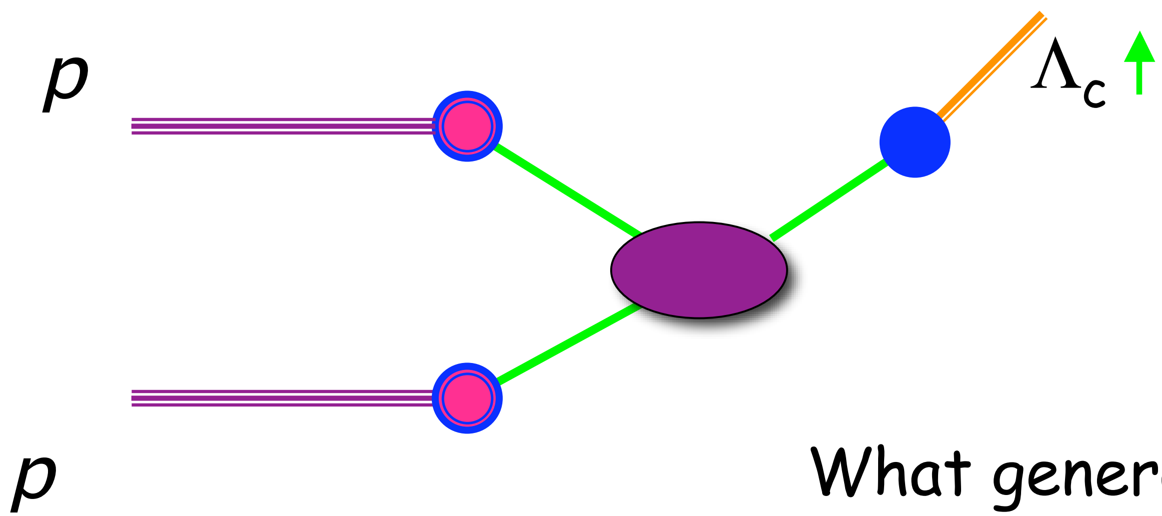
$D_{1T}^{\perp}$ has been extracted from fixed target $p + p(Be) \to \Lambda^{\uparrow}(\bar{\Lambda}^{\uparrow}) + X$ data

Anselmino, D.B., D'Alesio & Murgia, PRD 63 (2001) 054029

Polarizing Fragmentation Function

Spin: Problem of Polarization of Hyperons and Charmed Baryons in pp collisions

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

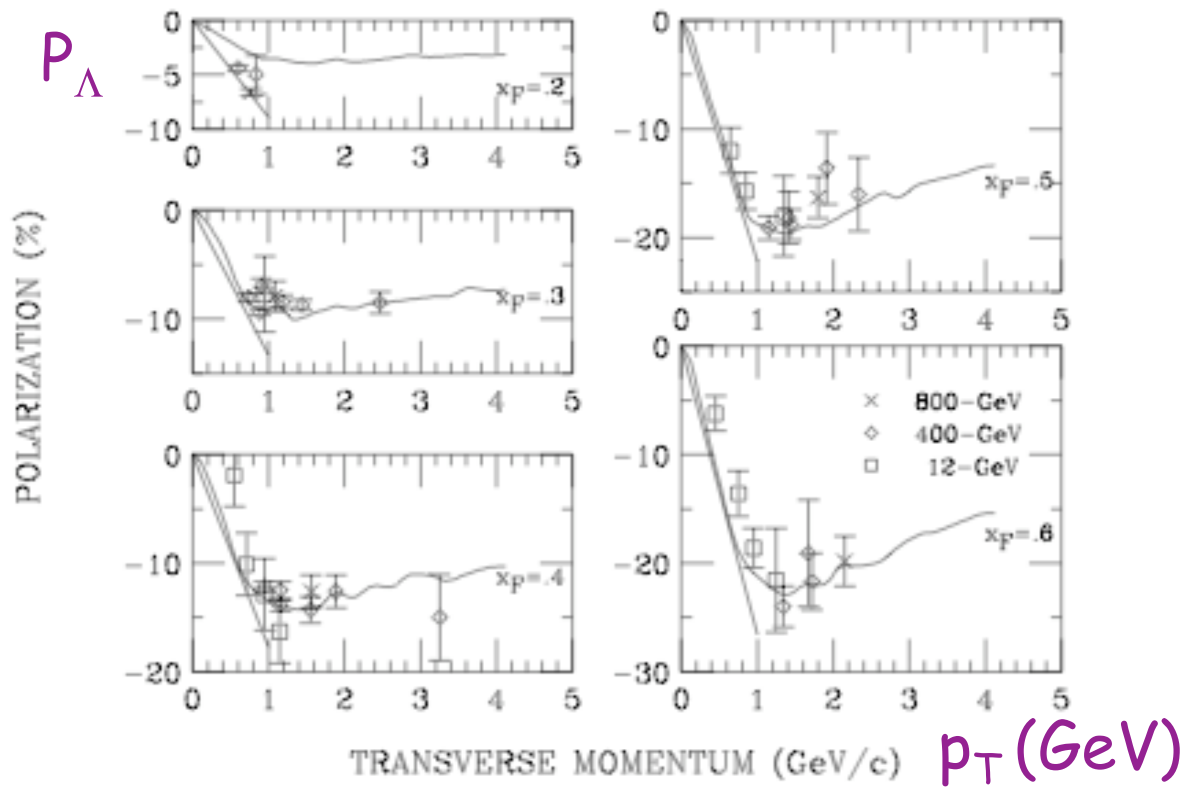


What generates polarization?

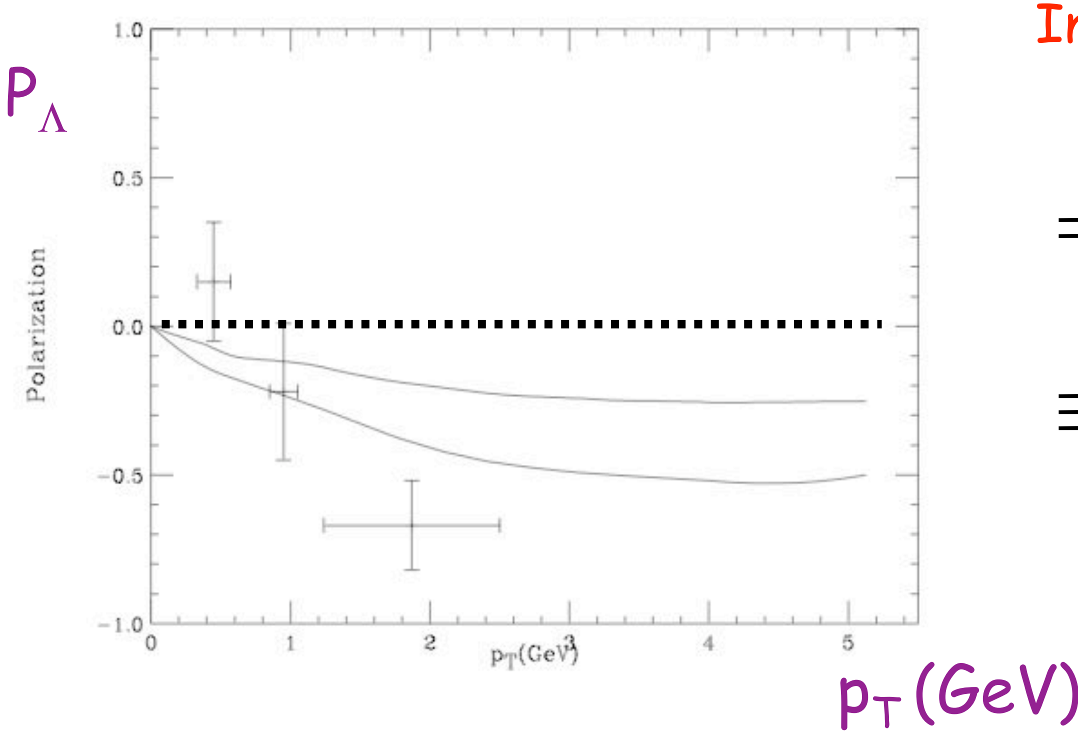
Model of hyperon polarization

Dharmaratna & GRG (1990,96,99)

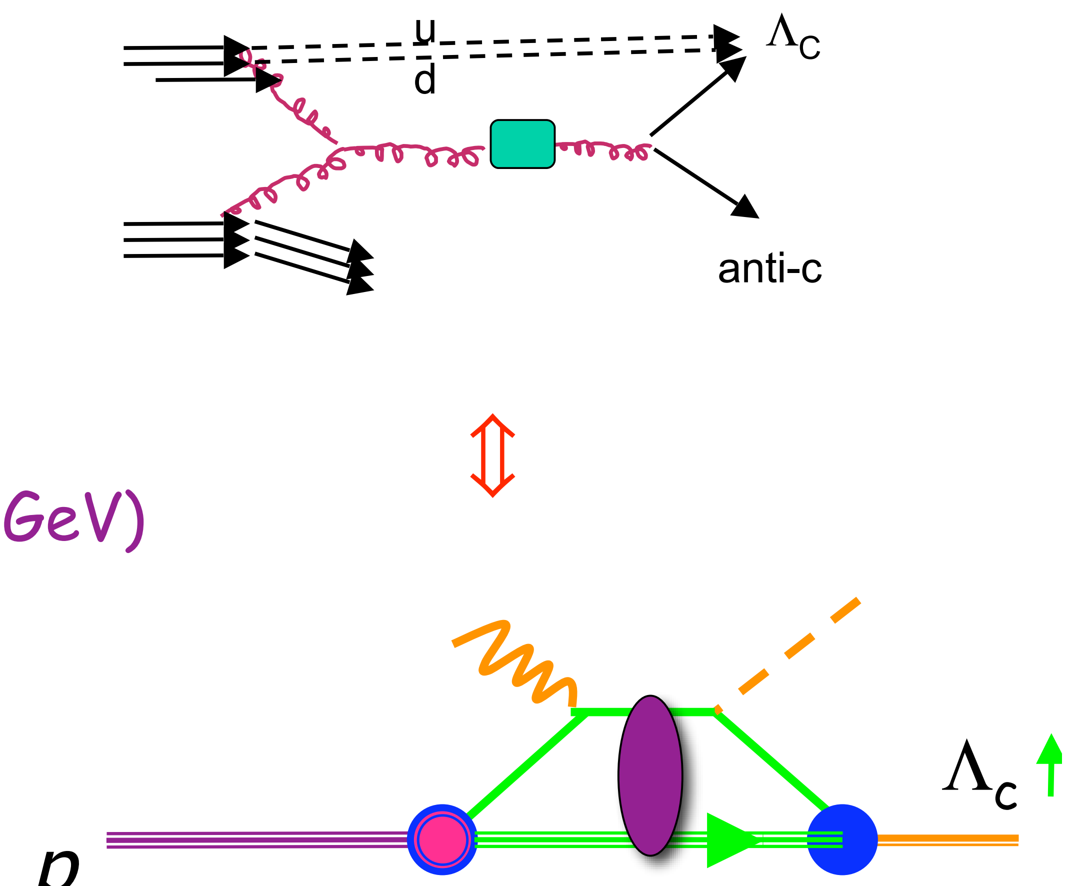
1.Gluon fusion dominant mechanism for producing polarized massive quark pair
2. Low p_T phenomenon
3. Recombination rules



Charmed hyperon polarization



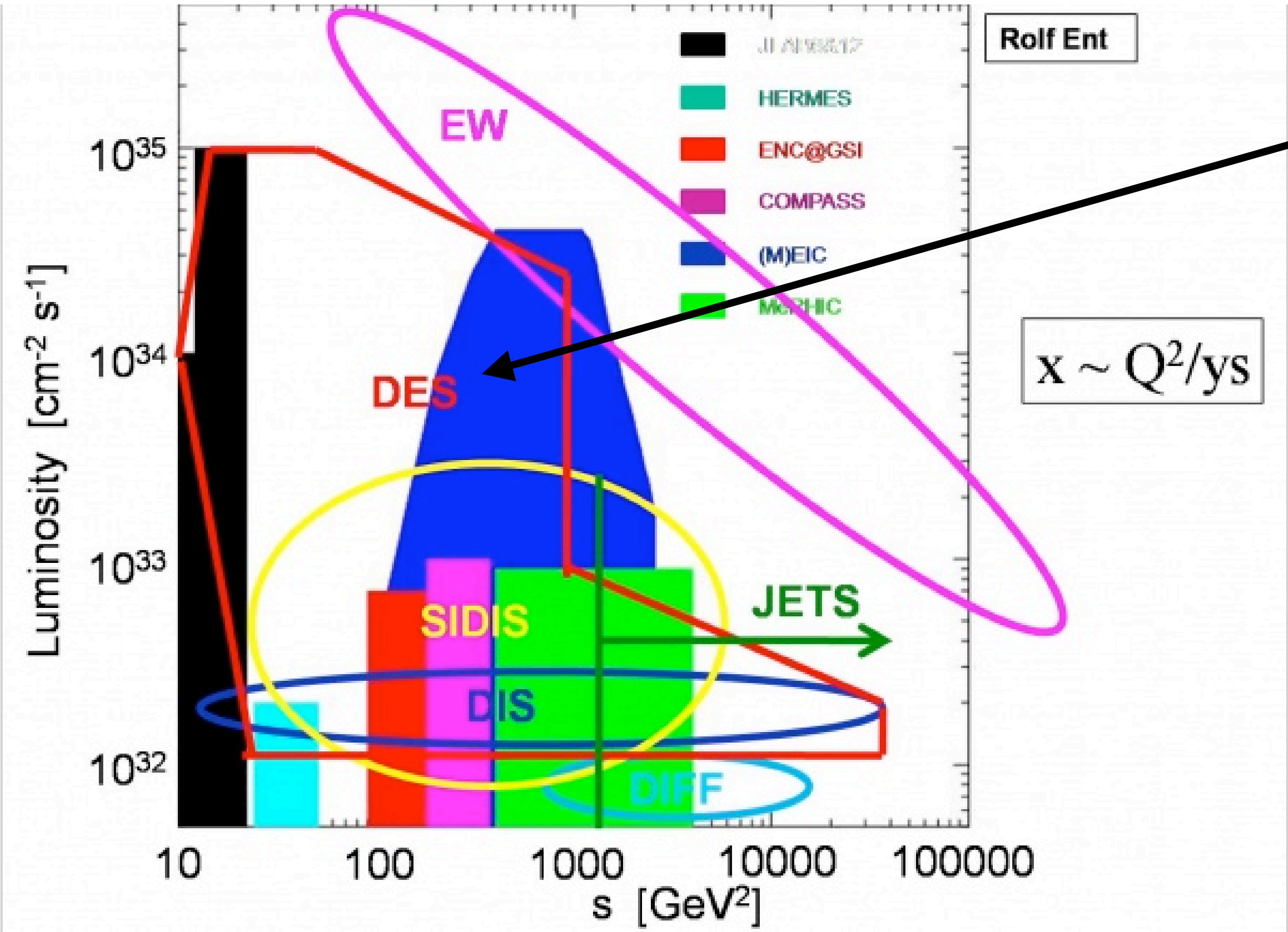
Interpretation in new language of GPDs



$\pi+p\to\Lambda_C+X$ Polzn(Λ_C) E791

$\Lambda_C^+\to p+\pi^++K^-$

Large mass scale



Region of 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