Polarized hyperons and heavy quarks production in ep and pp scattering

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LHeC Workshop

Chavannes-de-Bogis

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Outline

Motivation: The "Spin Crisis" is far from over, the LHeC can help answering several open questions

1. Hyperons polarization phenomena (basic reaction mechanisms and observables in pp and ep → models
2. Gluon polarization from t tbar correlations
3. Charmed mesons production (transversity)

Work in preparation done mostly in collaboration with Gary Goldstein

Experimental analysis with Pasquale Di Nezza and Liliet Calero Diaz

Related Aurore Courtoy, Osvaldo Gonzalez Hernandez,
Kunal Kathuria, Abha Rajan

Main references:

arXiv:1310.5157 → OAM

Phys.Rev. D86 (2012) 036008 → deuteron
Phys.Rev. C88 (2013) 065206 → AM flavor separation

arXiv:1401.0438
arXiv:1311.0483
J.Phys. G, 39 (2012) 11500; arXiv:1201.6088
Phys. Rev. D79, 054014 (2009)

→ Pseudoscalar meson production and transversity

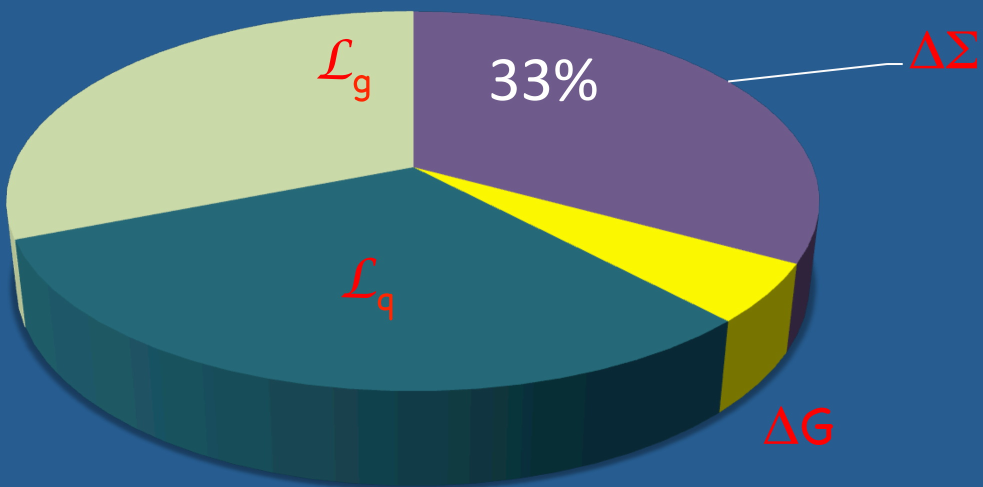
Spin Crisis far from over: open questions (and ramifications)

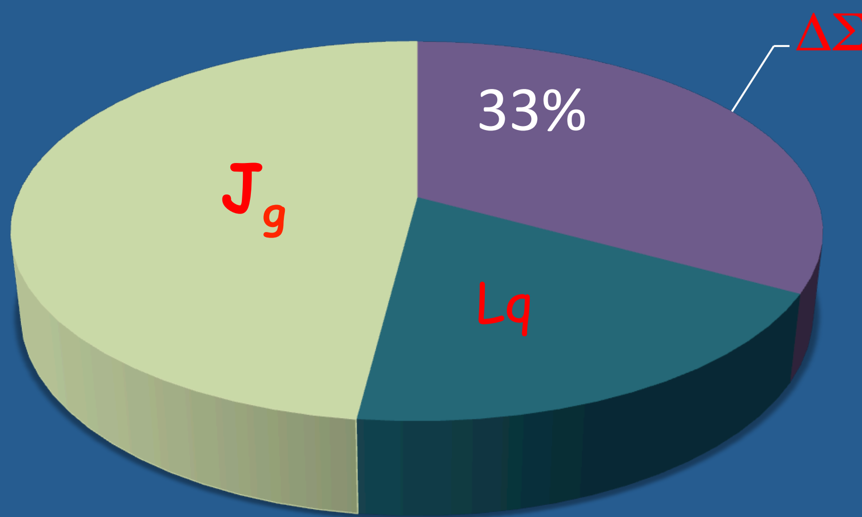
- ✓ Gluon spin contribution to the sum rule has a large error
- ✓ Role of Orbital Angular Momentum is being explored
- ✓ Transverse spin (sum rules…?)
- ✓ Existence of large Single Spin Asymmetries (SSA) in QCD: e.g. Polarized hyperon production
- ✓ The deuteron: new structure functions, b_1, b_2, and access to gluons OAM due to the cancellation of prton and neutron anomalous magnetic moments

The spin crisis in a "cartoon"

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$





Jaffe Manohar

Ji

Partonic picture:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \mathcal{L}_q + \Delta G + \mathcal{L}_g$$

- quark and gluon spin components are identified with the n=2 moments of spin dependent structure functions from DIS, ΔΣ and ΔG, and/or from DVCS, J_q and J_g.

$$M^{+12} = \frac{1}{2} q_+^\dagger \gamma^5 q_+ + \frac{1}{2} i q_+^\dagger (\vec{x}\times\partial)^3 q_+ + Tr(\varepsilon^{+-ij} F^{+j} A^j) + 2iTrF^{+j}(\vec{x}\times\partial)A^j$$

ΔΣ

L_q (new!)

arXiv:1310.5157

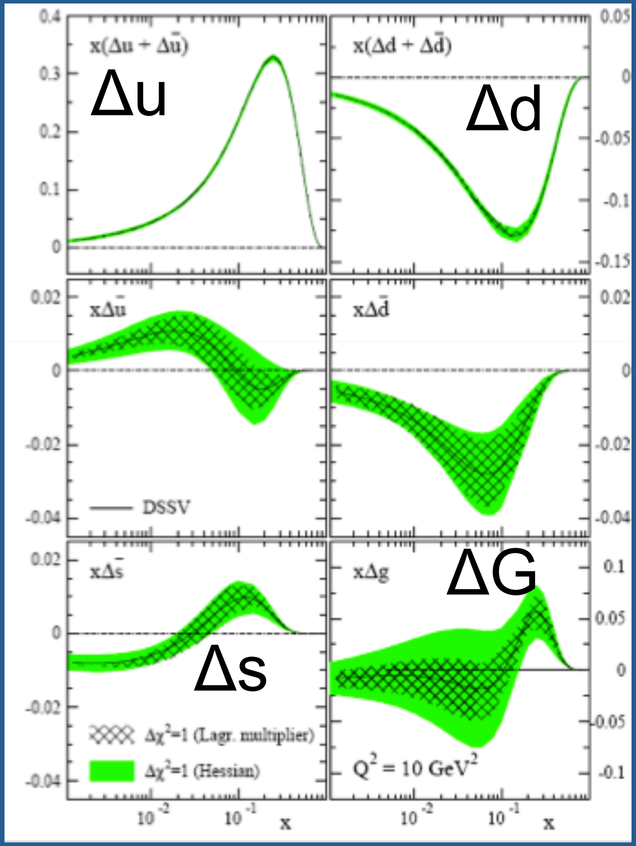
ΔG

L_g?

J_q

J_g ?

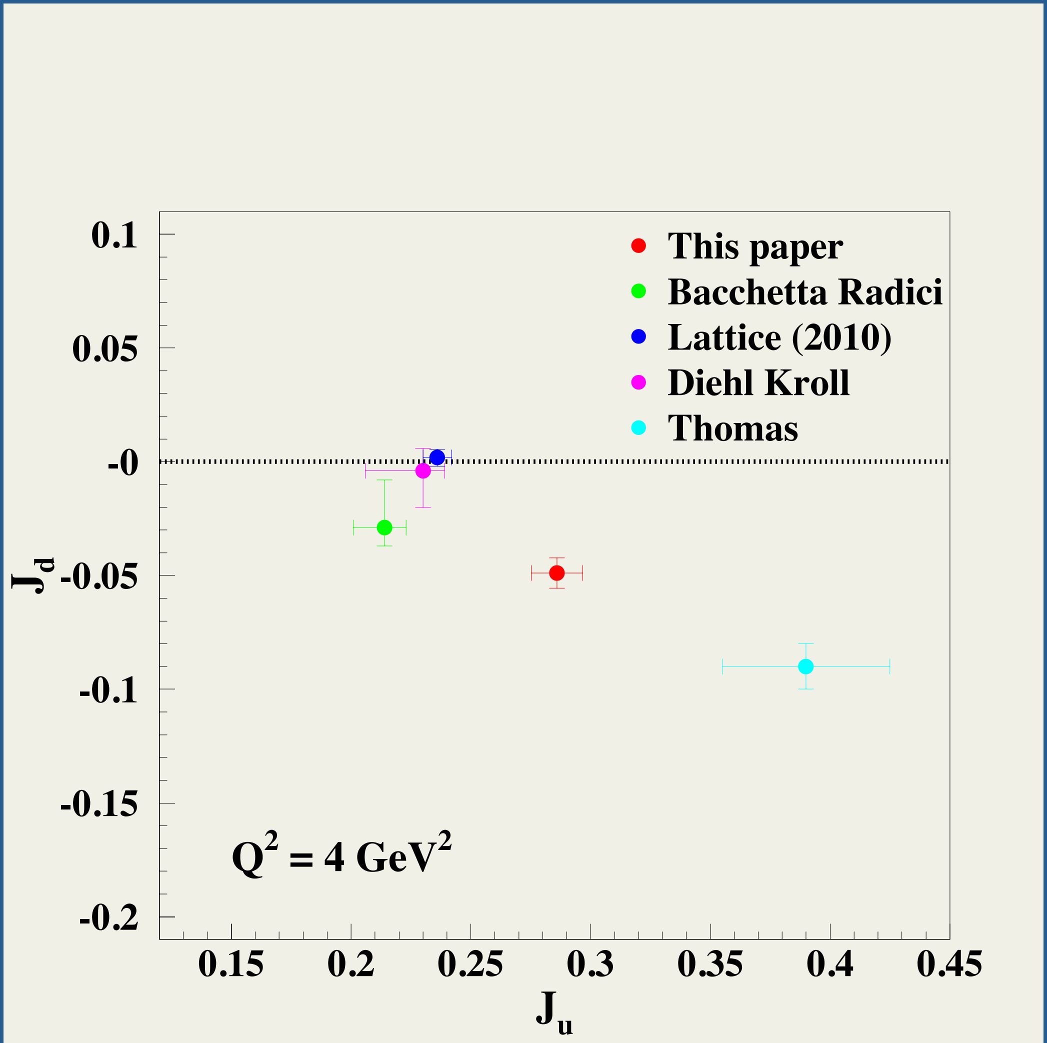
Observables: ΔΣ, ΔG



DSSV Global Analysis:

Phys. Rev. D 80, 034030 (2009)

Model dependent extractions of J_u and J_d



O. Gonzalez Hernandez et al., Phys. Rev. C88, 065206; arXiv:1206.1876

L_q (new!) arXiv:1310.5157

It was long believed that OAM could not be properly described in QCD (using the OPE)

Instead, OAM can be defined through the n=2 moment of a twist 3 term

$$\int dx\, x G_2 = -\frac{1}{2}\int dx\, x(H+E) + \frac{1}{2}\int dx\, \tilde{H}$$

Polyakov et al. (2000)
Hatta (2011)

$-L_q$ $\quad$ $-J_q$ $\quad$ S_q

$G_2 \rightarrow$ $\sigma_{ij}\Delta^j \Rightarrow \vec{S}_L \times \vec{\Delta}$

OAM is associated with a transverse spin component in the proton….

Courtoy et al., arXiv:1310.5157

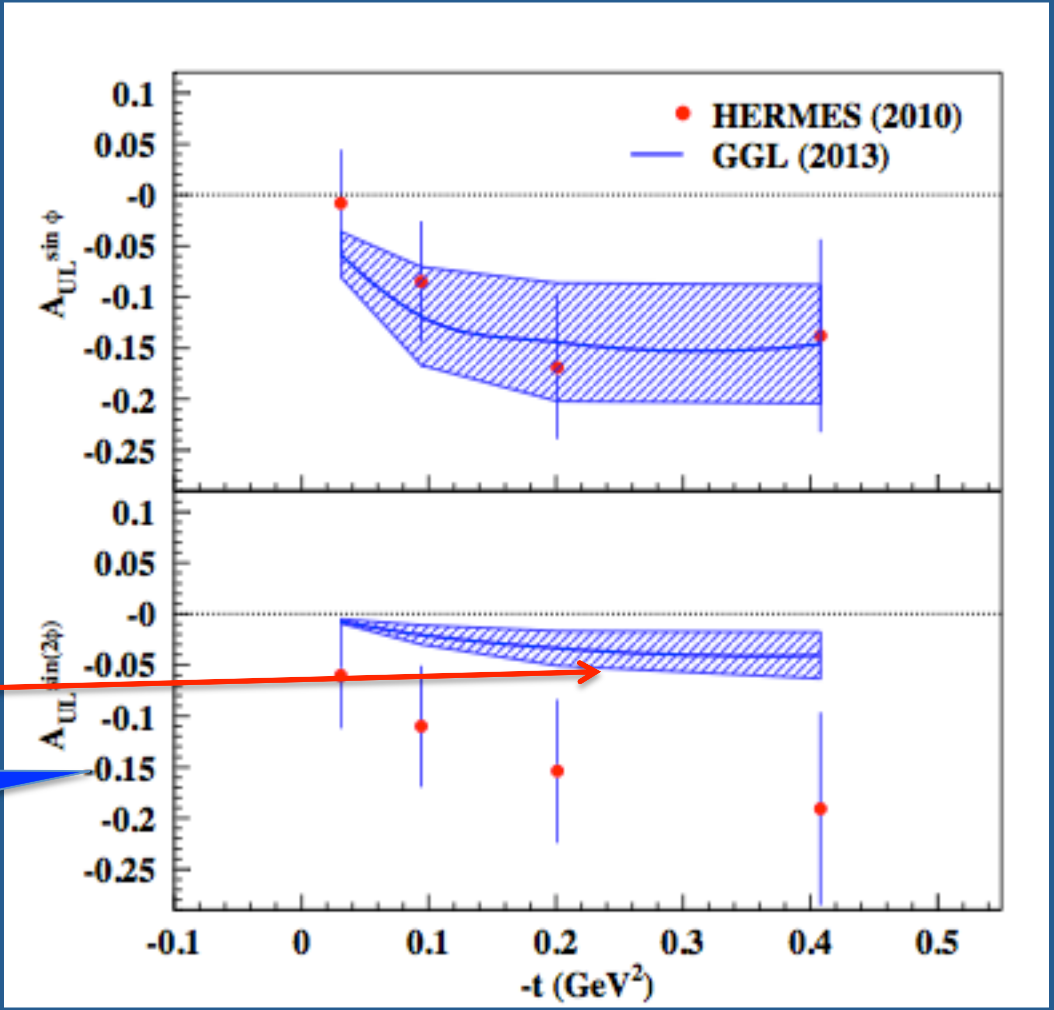
… and this can be looked at by singling out a tw 3 modulation in DVCS on a longitudinally polarized target

$$A_{UL,L} = \frac{N_{s_z=+} - N_{s_z=-}}{N_{s_z=+} + N_{s_z=-}} = \frac{\sqrt{2\epsilon(\epsilon+1)}\sin\phi F_{UL}^{\sin\phi}}{F_{UU,T} + \epsilon F_{UU,L}} + \frac{\epsilon \sin 2\phi F_{UL}^{\sin 2\phi}}{F_{UU,T} + \epsilon F_{UU,L}}$$

sin 2φ term is tw 3!

WW, small ξ

Jlab data in progress!
Avakian, S.Pisano, Biselli



In summary….

We extract ΔG from the double longitudinal asymmetry, A_{LL}, in various processes

We extract $\Delta\Sigma$ (sea quarks) from e.g. single longitudinal parity violating asymmetries in W production (RHIC).

We extract J_q from the single transverse asymmetry, A_{UT}, in DVCS

We measure L_q (OAM) through twist 3 contributions to the single longitudinal asymmetry, A_{UL}, in DVCS

We measure δq (transversity) through through exclusive pseudoscalar meson electroproduction

But .. To extract the gluon contribution to the spin sum rule and to understand the working of SSA's one needs a LHeC

Part 1. The "other" spin crisis: the longstanding puzzle of polarized hyperons production

Why is it important to understand SSA in QCD?

SSA in QCD,

$$\frac{d\sigma(qq \to q^{\uparrow}q) - d\sigma(qq \to q^{\downarrow}q)}{d\sigma(qq \to qq)} = \alpha(Q^2)\frac{m_q}{\sqrt{s}}f(\theta). \quad (1)$$

Kane, Pumplin, Repko, 70's

is predicted to be small, but ...

….. measurements showed high polarization values

MEASUREMENT OF POLARIZATION IN $\pi^- p \to \pi^0 n$ AND $\pi^- p \to \eta n$ *

D. D. Drobnis, J. Lales, R. C. Lamb, R. A. Lundy, A. Moretti, R. C. Niemann, T. B. Novey, J. Simanton, A. Yokosawa, and D. D. Yovanovitch
Argonne National Laboratory, Argonne, Illinois
(Received 13 November 1967)

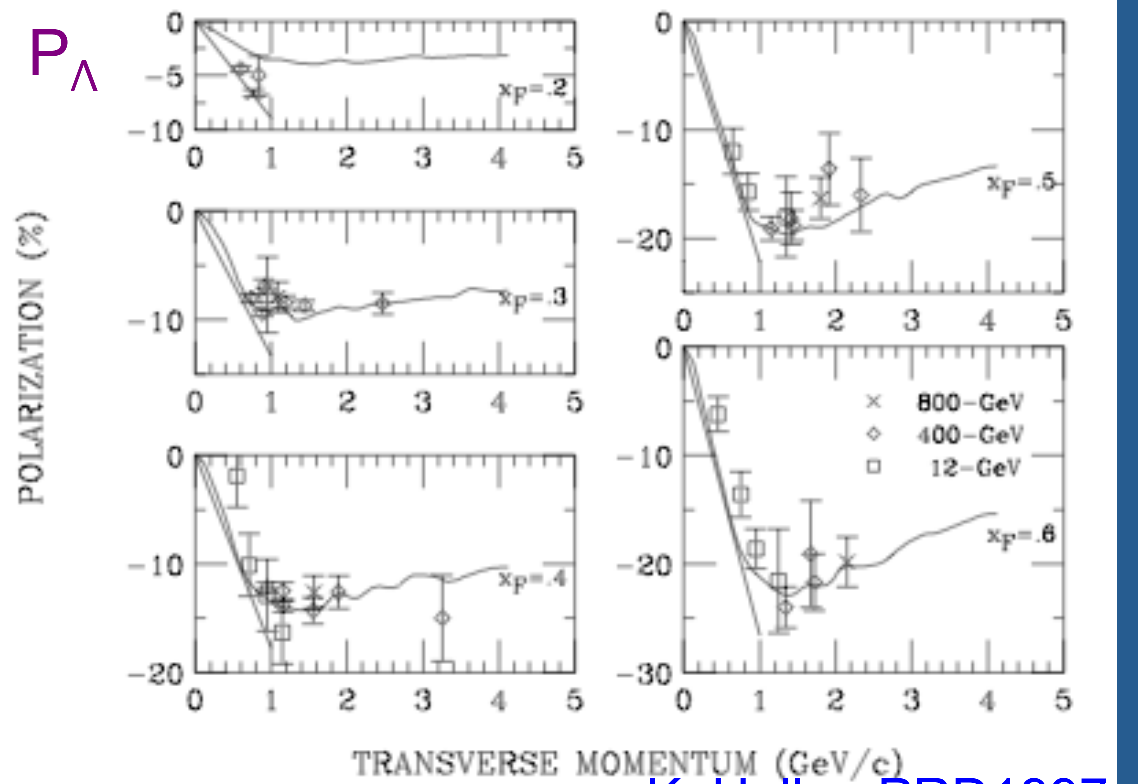
Polarization in $\pi^- p \to \pi^0 n$

2.07 GeV/c		2.50 GeV/c		2.72 GeV/c	
Momentum transfer interval $[\text{GeV}/c]^2$	Polarization %	Momentum transfer interval $[\text{GeV}/c]^2$	Polarization %	Momentum transfer interval $[\text{GeV}/c]^2$	Polarization %
.039 to .094	3 ± 7	.036 to .095	36 ± 8	.034 to .070	29 ± 14
.094 to .174	37 ± 9	.095 to .180	10 ± 6	.070 to .119	33 ± 10
.174 to .241	68 ± 14	.180 to .294	31 ± 7	.119 to .181	-3 ± 11
.241 to .362	32 ± 16	.294 to .387	41 ± 15	.181 to .256	17 ± 11
background	1 ± 1	background	3 ± 1	.256 to .395	10 ± 15
				background	-2 ± 1

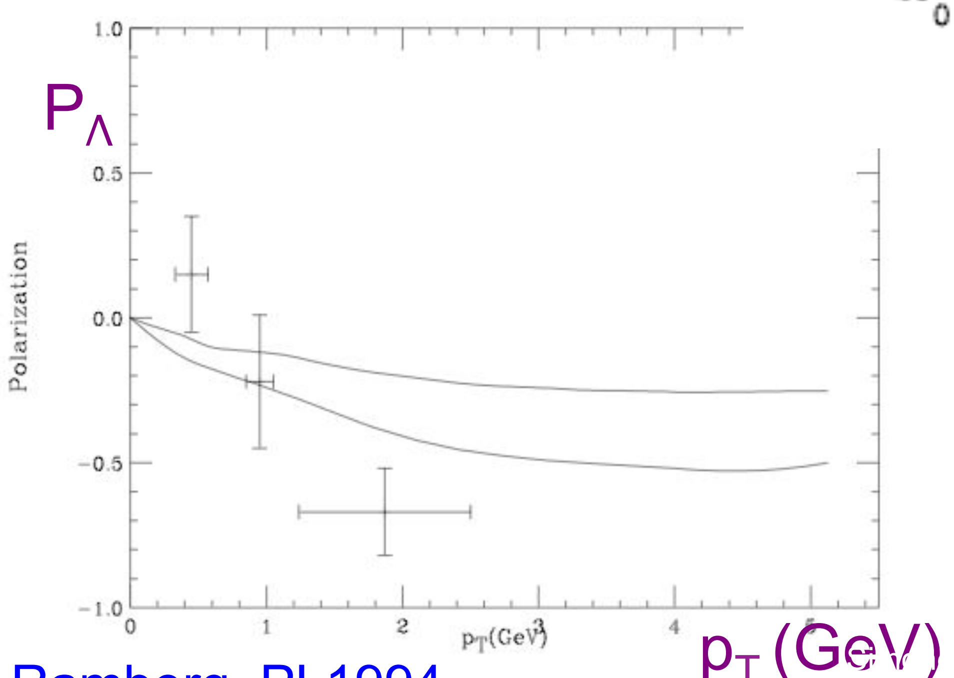
These data were the first evidence that spin was NOT "an inessential complication" in understanding strong interaction dynamics

…similarly, years later, and in QCD for hyperon production

$$pp \to \Lambda^{\uparrow}(\Lambda_c^{\uparrow})X$$

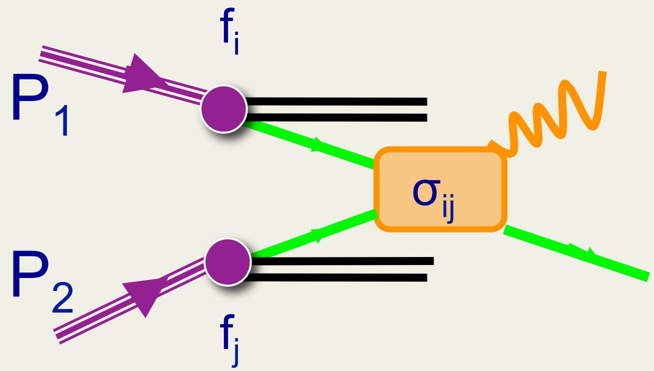


K. Heller, PRD1997



Ramberg, PL1994

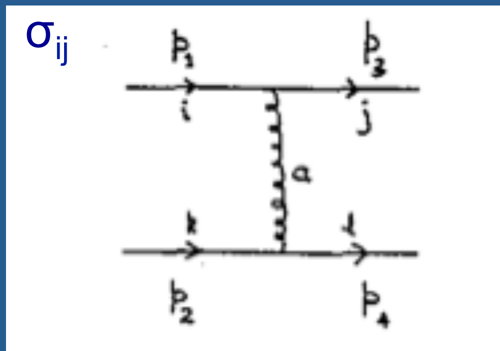
What can generate polarization (SSA) from initially unpolarized nucleons (…spontaneous polarization)?

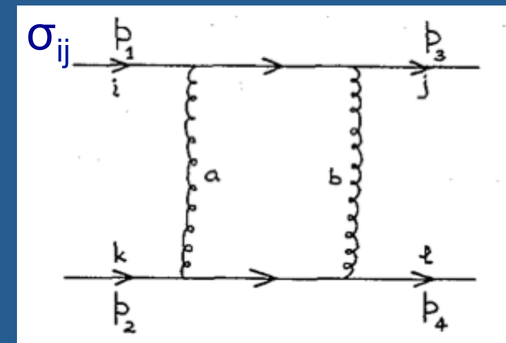


We know that factorization theorems are at work,

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

Dharmaratna and Goldstein, (PRD'90,'96)





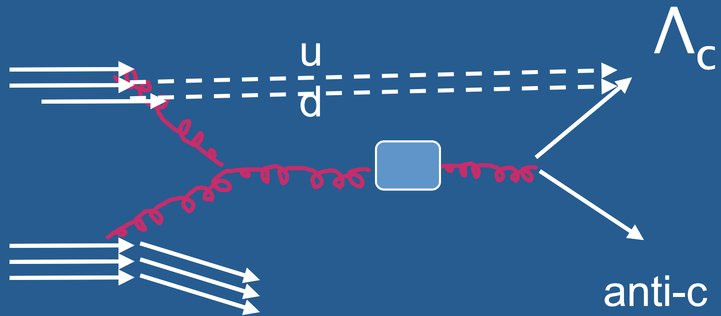
Need a loop in the process in order to generate a phase/imaginary part

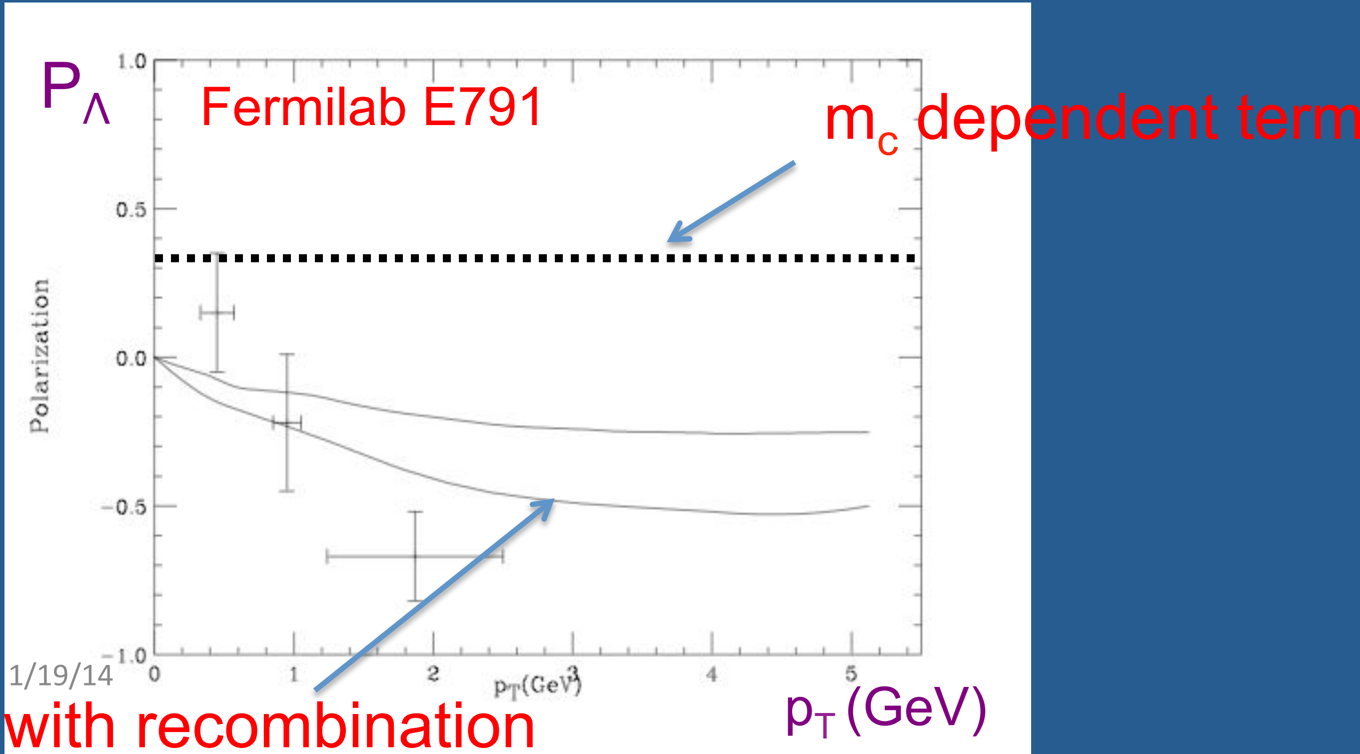
$$P_{\Lambda} = \frac{d\boldsymbol{\sigma}^{\uparrow} - d\boldsymbol{\sigma}^{\downarrow}}{d\boldsymbol{\sigma}^{\uparrow} + d\boldsymbol{\sigma}^{\downarrow}} = \frac{2\,\Im m(A_1^* A_5 - A_6^* A_2)}{\sum_{i=1}^{6} A_i^2}$$

$$A_1 = A_{++,++},\; A_2 = A_{++,--}, \ldots$$

D&G suggested NLO pQCD process, however…

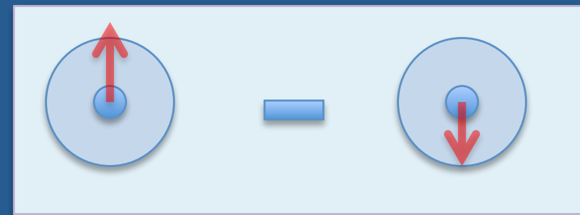
… they also made the observation that in order to reproduce the measured polarization a form of "recombination" should be present



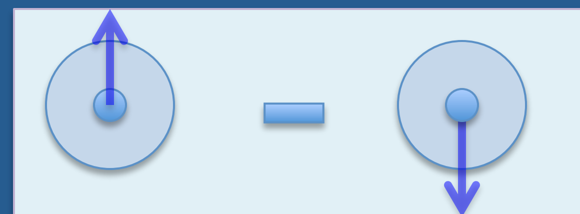


Ah ha! This is the same argument that allows us to observe the T-odd TMDs

$h_1^{\perp}$



$f_{1T}^{\perp}$



$f_{1T}^{\perp}$

S.J. Brodsky et al. / Physics Letters B 530 (2002) 99–107

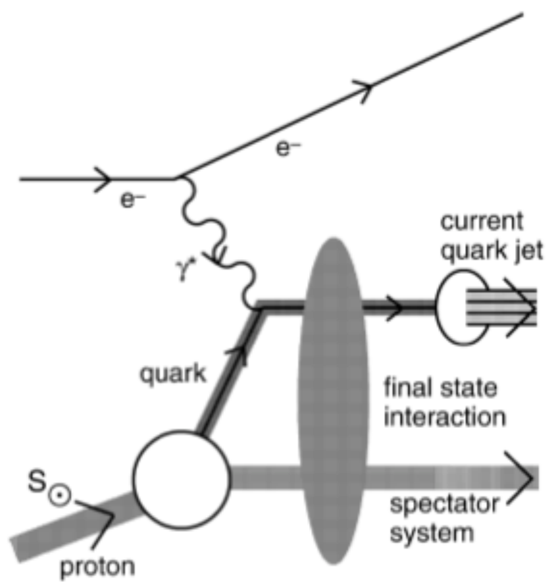
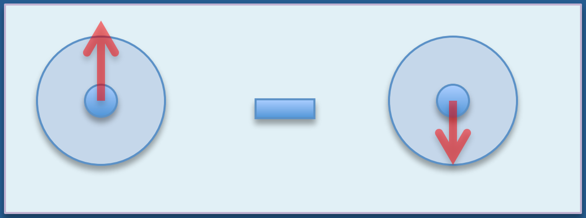


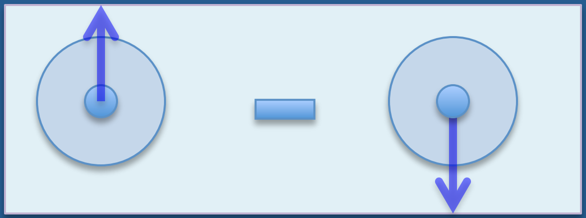
Fig. 1. The final-state interaction in the semi-inclusive deep inelastic lepton scattering $\ell p^{\uparrow} \to \ell' \pi X$.

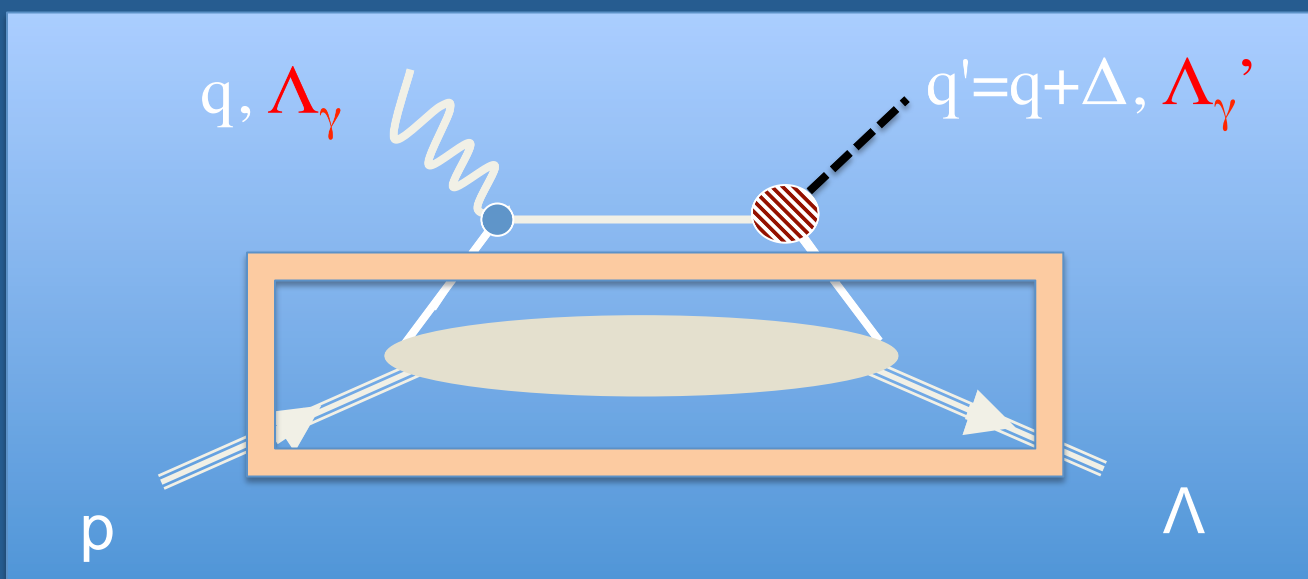
And that allows us to observe GPDs through Single Spin Asymmetries (SSA)

$$2\tilde{\mathrm{H}}_T + \mathrm{E}_T \leftrightarrow h_1^{\perp}$$

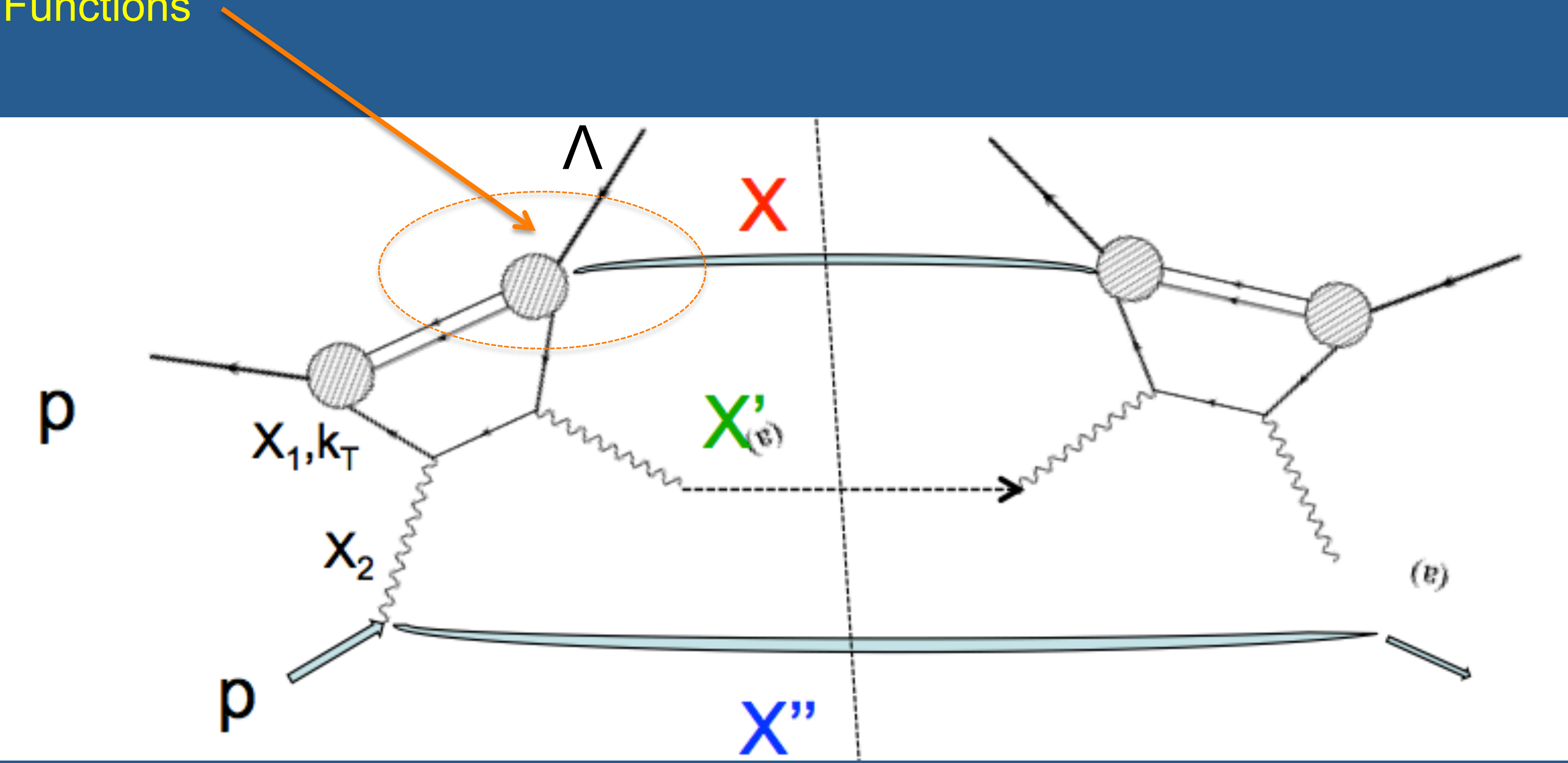


$$\mathrm{E} \leftrightarrow f_{1T}^{\perp}$$



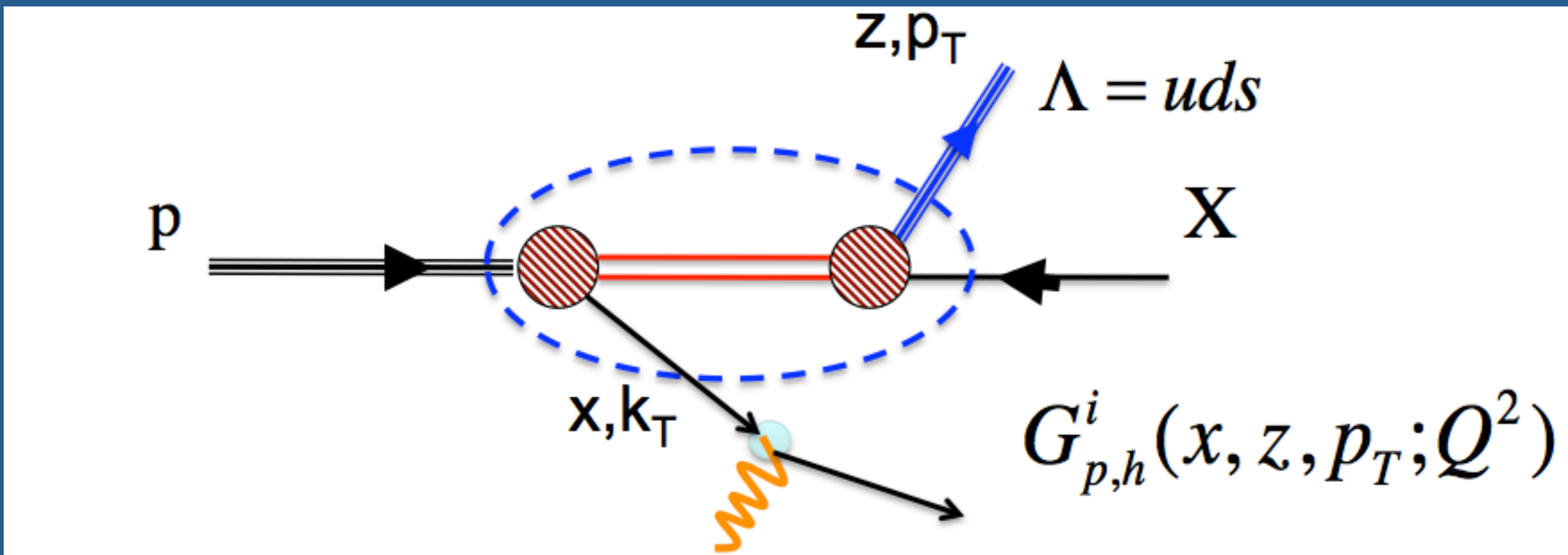


… similarly we can model Λ production through GPDs and Generalized Fracture Functions



Electroproduction (Jlab, HERMES regime)

Transverse Spin Asymmetries for Λ in Target Fragmentation region

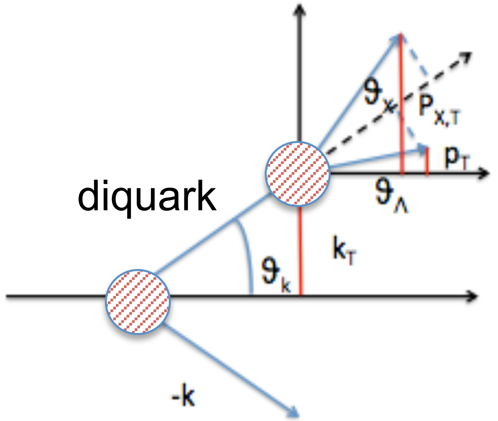


Fracture Function (Trentadue and Veneziano)

$$\mathcal{F}^{\lambda_q}_{\Lambda_N;\Lambda'_\Lambda,\Lambda_\Lambda}(x, k_T, z, p_T, Q^2) = \sum_{\Lambda_X} \int \frac{d^3P_X}{(2\pi)^3 2E_X} \int \frac{d^4\xi}{(2\pi)^4} e^{ik\cdot\xi}$$

$$\times \langle P, \Lambda_N \mid \bar{\psi}^{\lambda_q}(\xi) \mid P_h, \Lambda'_\Lambda; X\rangle \times \langle P_h, \Lambda_\Lambda; X \mid \psi^{\lambda_q}(0) \mid P, \Lambda_N\rangle.$$

In a diquark model



$$\mathcal{F}^{\lambda_q}_{\Lambda_N;\Lambda'_\Lambda,\Lambda_\Lambda}(x,k_T,z,p_T,Q^2) = A_{\Lambda_N,\lambda_q} \sum_{\Lambda_X} B^{\Lambda_\Lambda,\Lambda'_\Lambda}_{\Lambda_X}$$

where

$$A_{\Lambda_N,\lambda_q} = \mid \phi_{\lambda_q,\Lambda_N}(k,P) \mid^2,$$

with

$$\phi_{\Lambda_N,\lambda_q}(k,P) = \Gamma(k) \frac{\bar{u}(k,\lambda_q)U(P,\Lambda_N)}{(k^2-m^2)((P-k)^2-M^2_{diq})},$$

and

$$k = P - P_X - P_\Lambda \quad \Rightarrow k^2 = k^2(x,\mathbf{k}_T,z,\mathbf{p}_T)$$

whereas

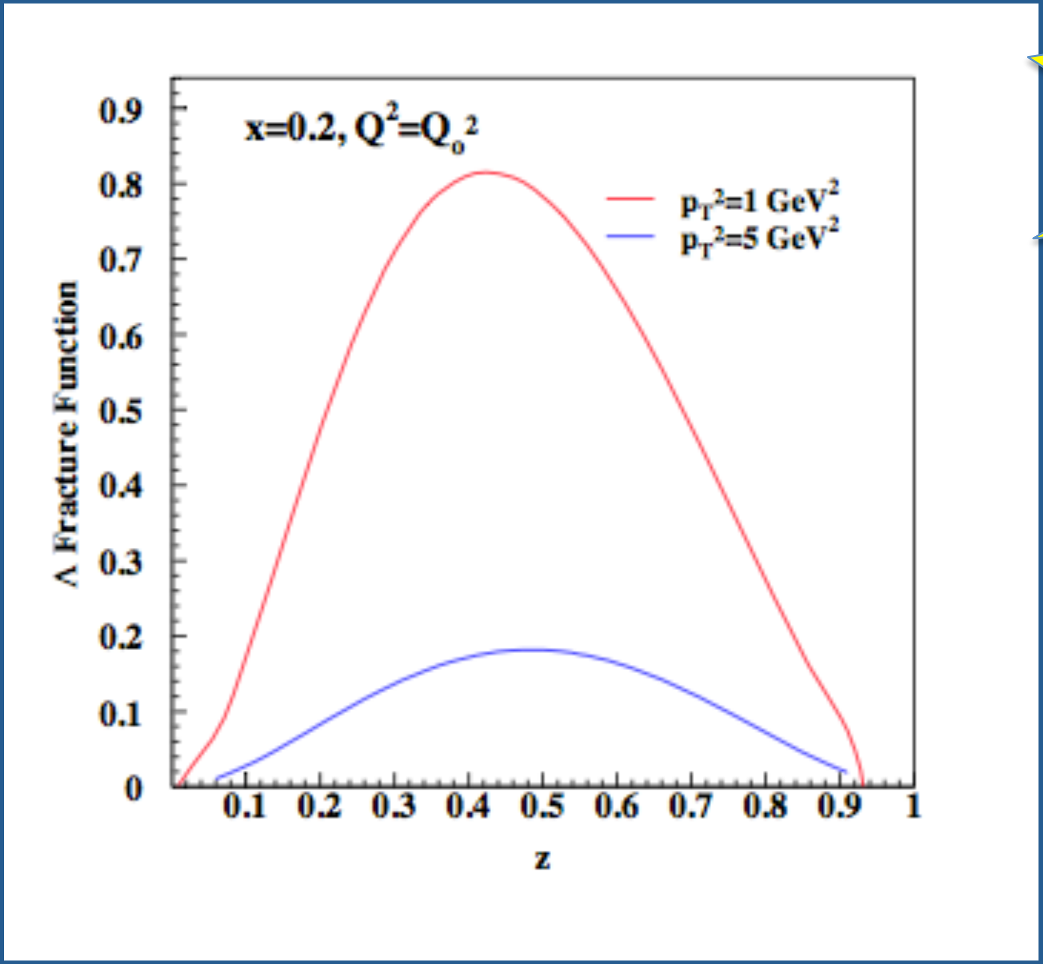
$$B^{\Lambda_\Lambda,\Lambda'_\Lambda}_{\Lambda_X} = \tilde{\phi}^*_{\Lambda_X,\Lambda'_\Lambda}(P_X,P_h)\tilde{\phi}_{\Lambda_X,\Lambda_\Lambda}(P_X,P_h), \qquad (4)$$

with

$$\tilde{\phi}_{\Lambda_X,\Lambda_\Lambda}(P_X,P_h) = \tilde{\Gamma}(P_X)\bar{v}(P_X,\Lambda_X)U(P_h,\Lambda_\Lambda)$$

defining the helicity structures at each soft vertex.

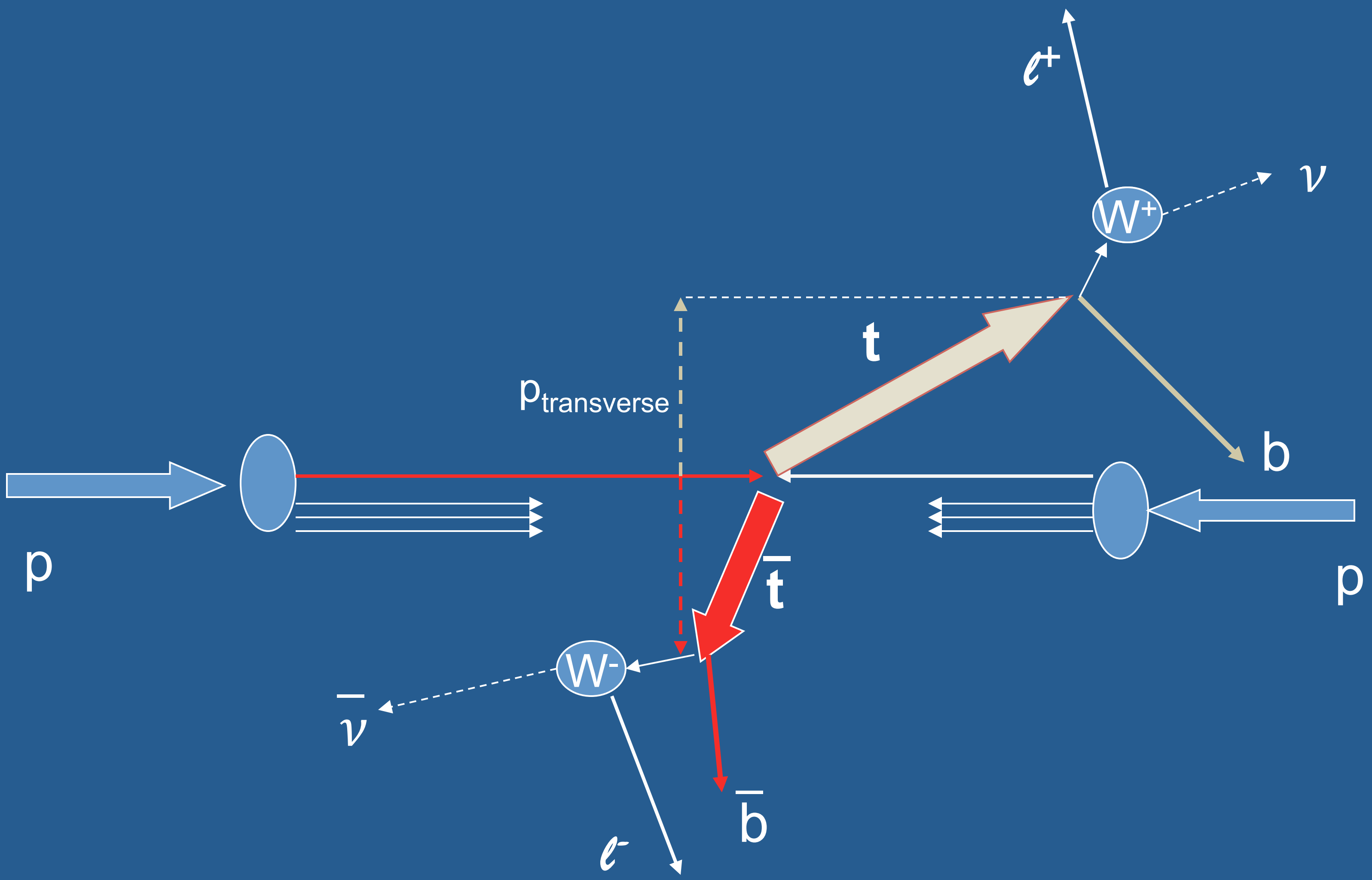
Status of theory



Plus preliminary data from ALICE
P. Di Nezza, L. Calero Diaz

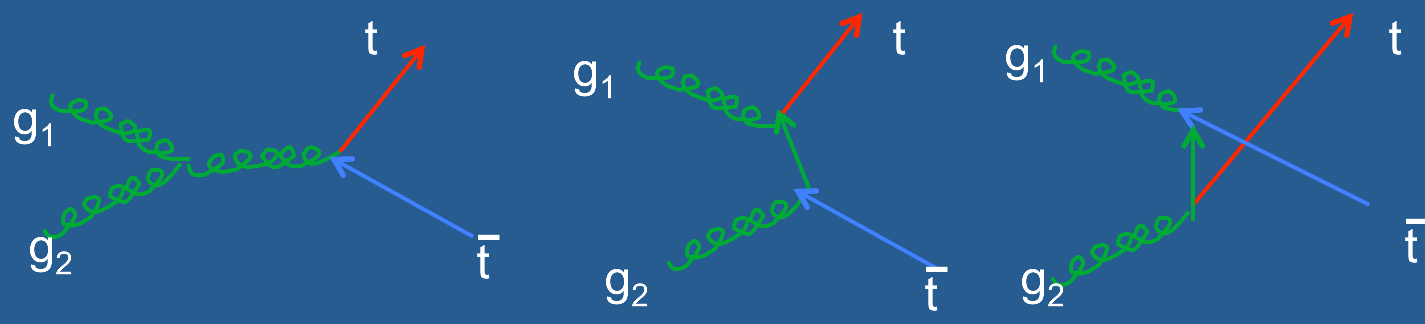
Part 2. Accessing polarized gluons from top anti-top spin correlations

Polarized top anti-top pairs production in pp collisions



At LHC:

Gluon fusion tree level mechanism
(Color gauge invariance)



g_1, g_2 carry helicity $\Lambda_1\ \Lambda_2 = \pm 1$

t, *t*-bar carry helicity $\lambda_t\ \lambda_{tbar} = \pm\ ½$

Introduced in:

G.R.Goldstein,``Spin Correlations in Top Quark Production and the Top Quark Mass'' in Proc. 12th Intl Symp. High Energy Spin Physics, Amsterdam, ed.C.W. deJager, et al., World Sci., Singapore (1997) p. 328.

R.H. Dalitz, G.R. Goldstein and R. Marshall, "Heavy Quark Spin Correlations in e+e- annihilations", Phys. Lett. B215, 783 (1988);

R.H. Dalitz, G.R. Goldstein and R. Marshall, "On the Helicity of Charm Jets", Zeits.f. Phys. C42, 441 (1989).

$$\rho_{t',\bar{t}';t,\bar{t}} \propto \sum_{all-helicities-not-tops} \bar{G}_{\bar{\Lambda}_N \bar{\Lambda}_g \bar{\Lambda}'_g} A^*_{\Lambda'_g \bar{\Lambda}'_g; t', \bar{t}'} A_{\Lambda_g \bar{\Lambda}_g; t, \bar{t}} G_{\Lambda_N \Lambda_g \Lambda'_g}$$

- The gluon spin correlations are transmitted to (determine the spin of) the decay products.
- The correlations between the lepton directions and the parent top spin (in the top rest frame) produce correlations between the lepton directions.
- The gluon fusion mechanism gives rise to a higher order (wrt quark antiquark) angular distribution due to the combination of two spin 1 gluons.

G.R.Goldstein,``Spin Correlations in Top Quark Production and the Top Quark Mass'' in Proc. 12th Intl Symp. High Energy Spin Physics, Amsterdam, ed.C.W. deJager, et al., World Sci., Singapore (1997) p. 328

Gluon linear polarization with like and unlike t-tbar helicities

$F \sim G_{XX}+G_{YY}$, $H \sim G_{XX}-G_{YY}$ or linear polarization

$\rho_{t',\bar{t}';t,\bar{t}}$	$\bar{F}\,F$	$\bar{H}\,H$	$\bar{F}\,H$	$\bar{H}\,F$
++;++	$\gamma^{-2}(1+\beta^2(1+\sin^4\theta))$	$\gamma^{-2}(-1+\beta^2(1+\sin^4\theta))$	$-2\dfrac{\beta^2}{\gamma^2}\sin^2\theta$	$-2\dfrac{\beta^2}{\gamma^2}\sin^2\theta$
+-;+-	$\beta^2\sin^2\theta(2-\sin^2\theta))$	$-\beta^2\sin^4\theta$	0	0

…also….Boer, Brodsky, C. Pisano (PRL 2012, JHEP2013) have considered the determination of polarized gluon distributions from azimuthal distributions of unpolarized t_tbar production in SIDIS and p+p.

However, we consider the polarization of the t-tbar as levers to differentiate between like pairs of gluon ploarizations and unlike pairs

Our method is more similar to Mahlon and Parke , PRD81, 074024 (2010) but with the gluon distributions being singled out (instead of just polarizations)

What about the LHeC?

The inclusive production of a particular single hadron (or t+tbar pair) at the LHC involves the convolution of the product of gluon distributions.

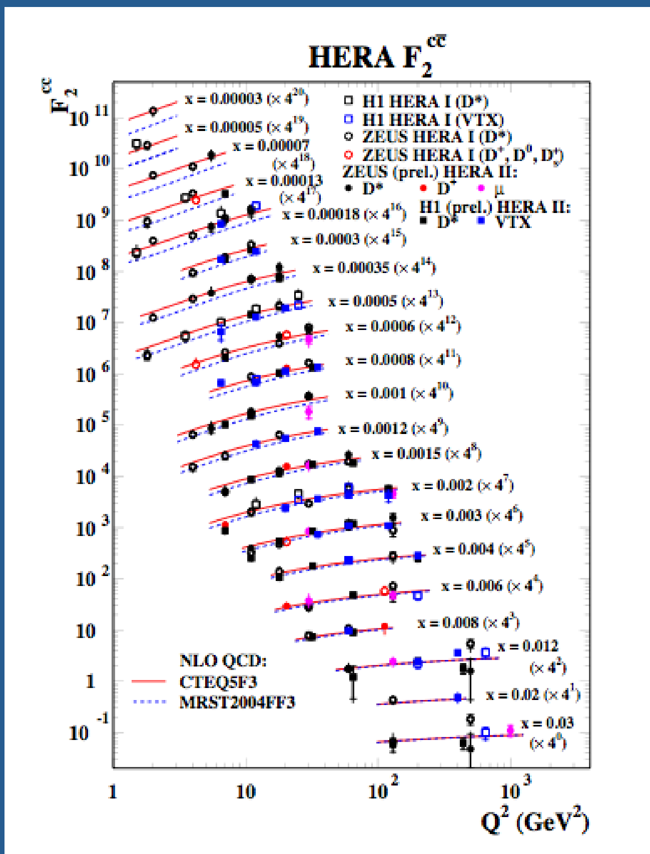
The corresponding electroproduction involves single gluon distributions, convoluted with fragmentation functions.

If factorization were exact, the extraction of the distributions would be universal.

To what extent that is not exact is one of the important questions in hadronic physics.

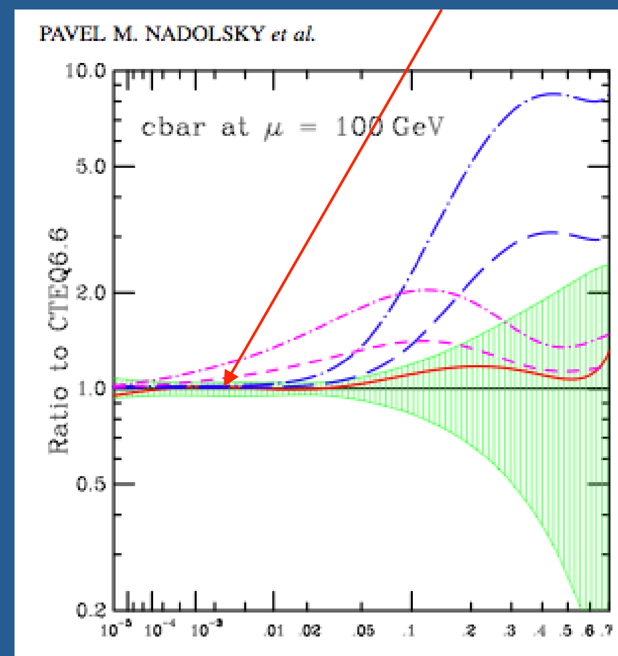
Part 3. Intrinsic strangeness and charm contribution to transversity from exclusive charmed mesons production

Outstanding issue in QCD (of extreme relevance for PDFs parametrizations) about the role of "non-perturbative/intrinsic strange and charm components"



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

IC/no-IC

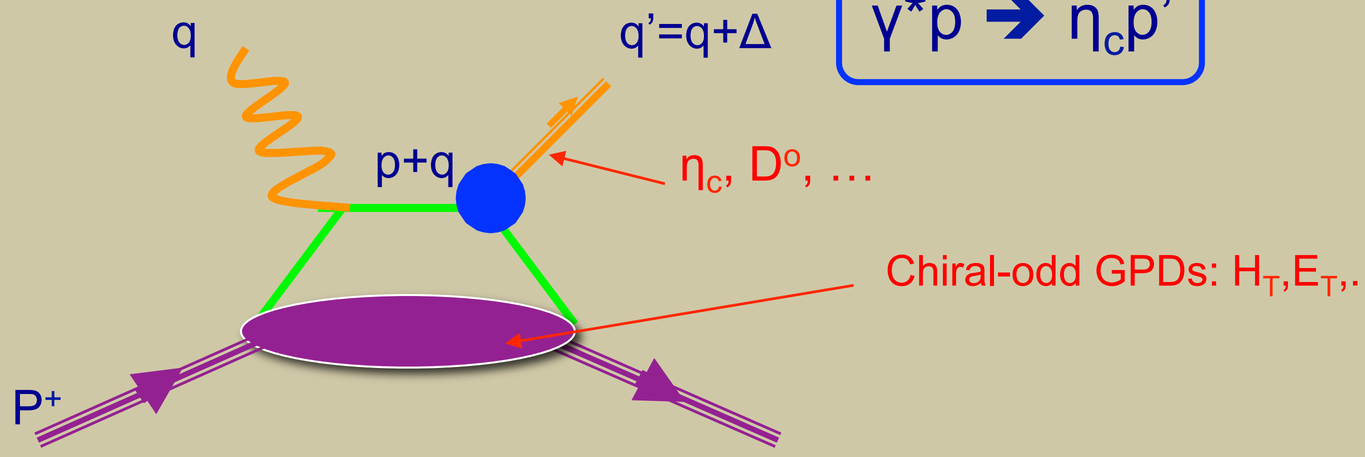


x

Why Exclusive Processes?

η_c, D^o, and $\bar{D}^o$ exclusive production is governed by chiral-odd GPDs which cannot evolve from gluons!

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

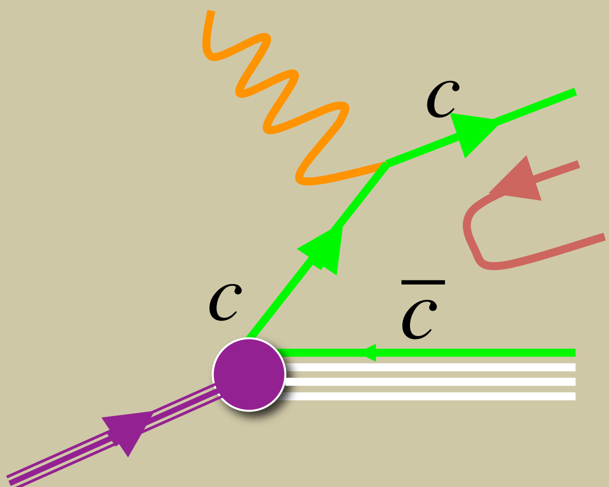


$\gamma^* p \rightarrow \eta_c p'$

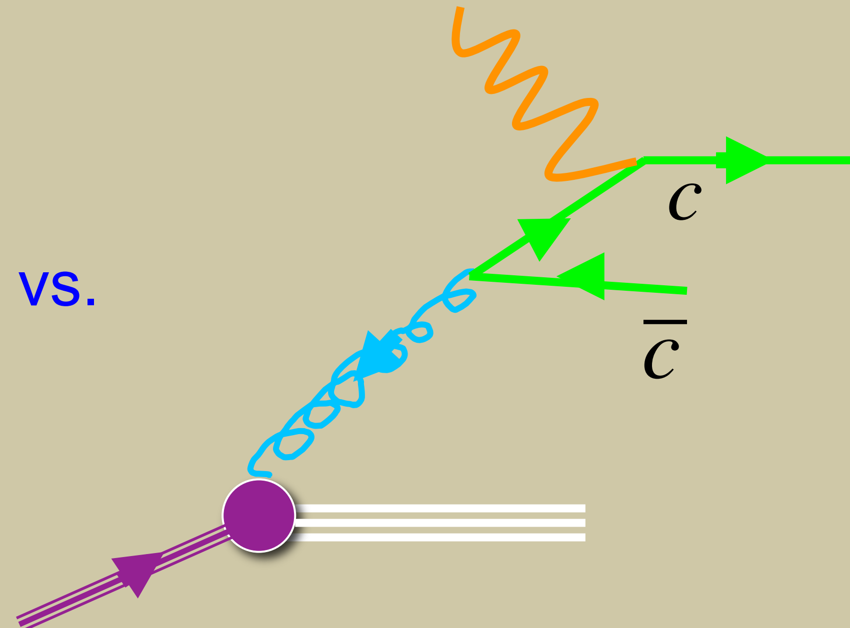
Windows into Heavy Flavor Production at the EIC

Inclusive Processes

Intrinsic Charm (IC)



vs.

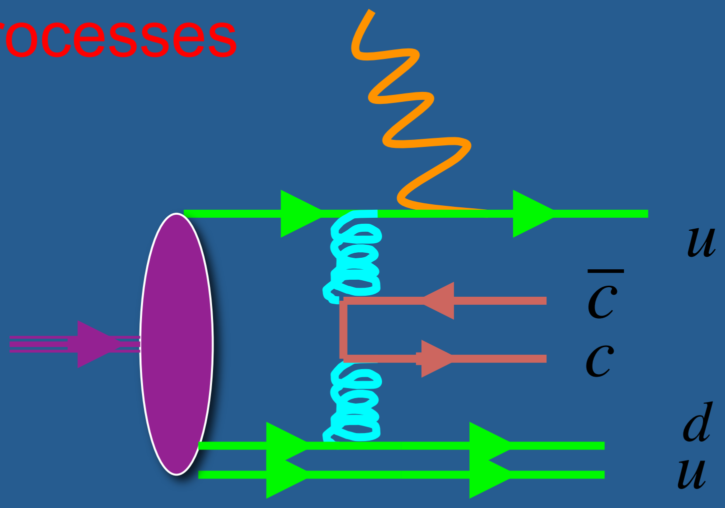


Gluon Fusion (GF)

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)

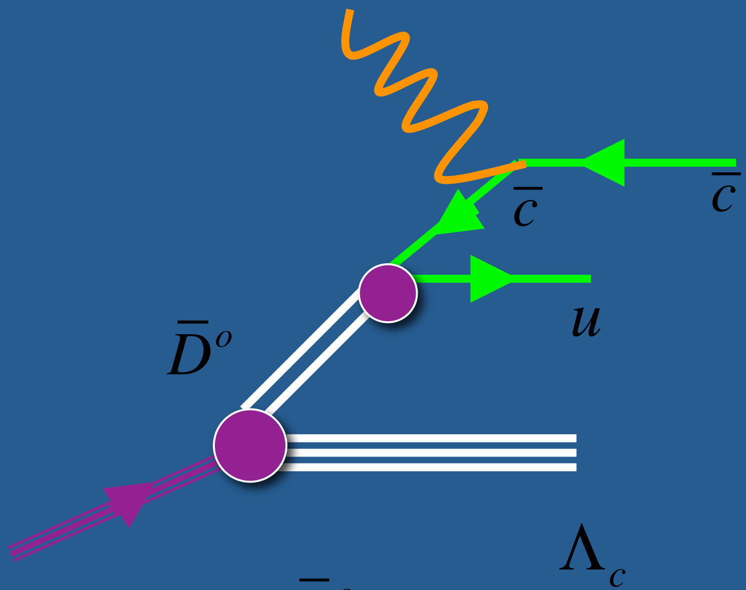
"Light Cone" based Processes



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

Brodsky, Gunion, Hoyer, R.Vogt, …

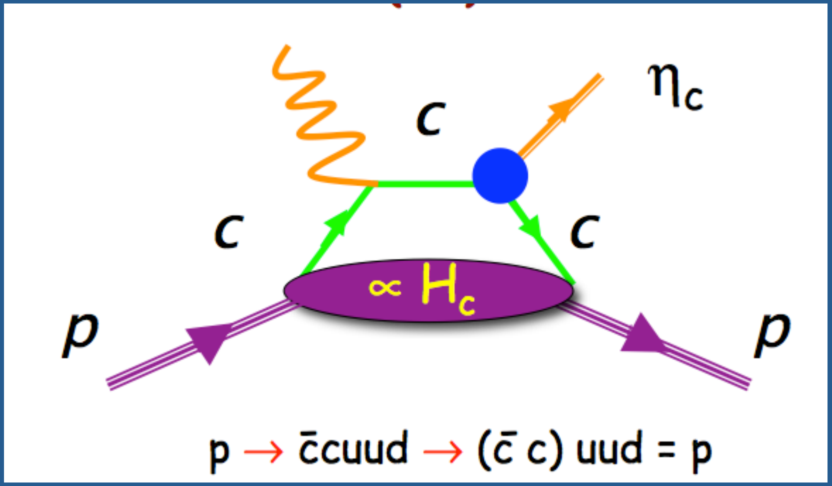
Hadronic Processes



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

Meson Cloud: Thomas, Melnichouk …

Exclusive Processes



… and related channels

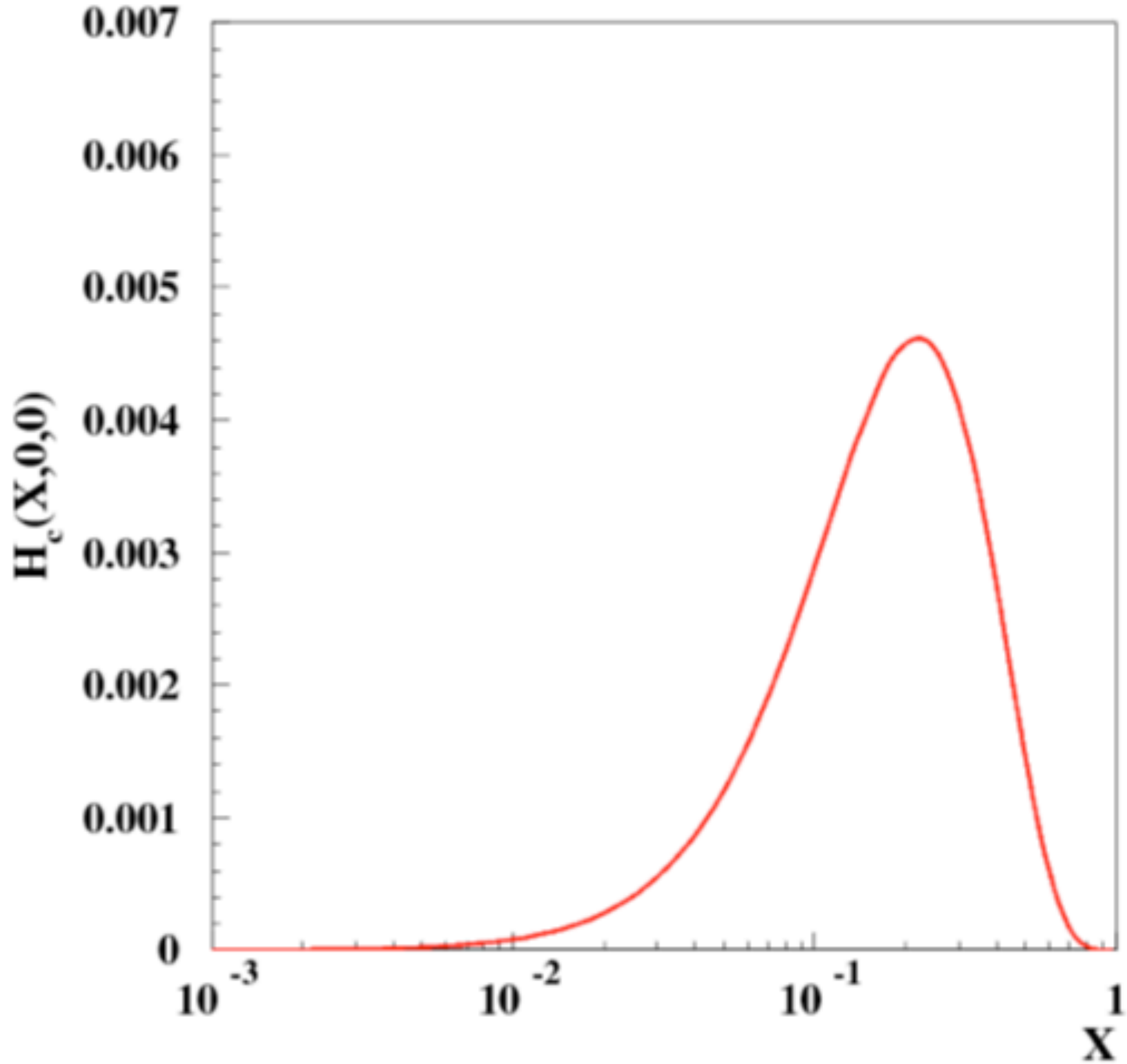
π^o,η_c electroproduction happens mostly in the chiral-odd sector

$\Rightarrow$it is governed by chiral-odd GPDs

$\Rightarrow$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”!

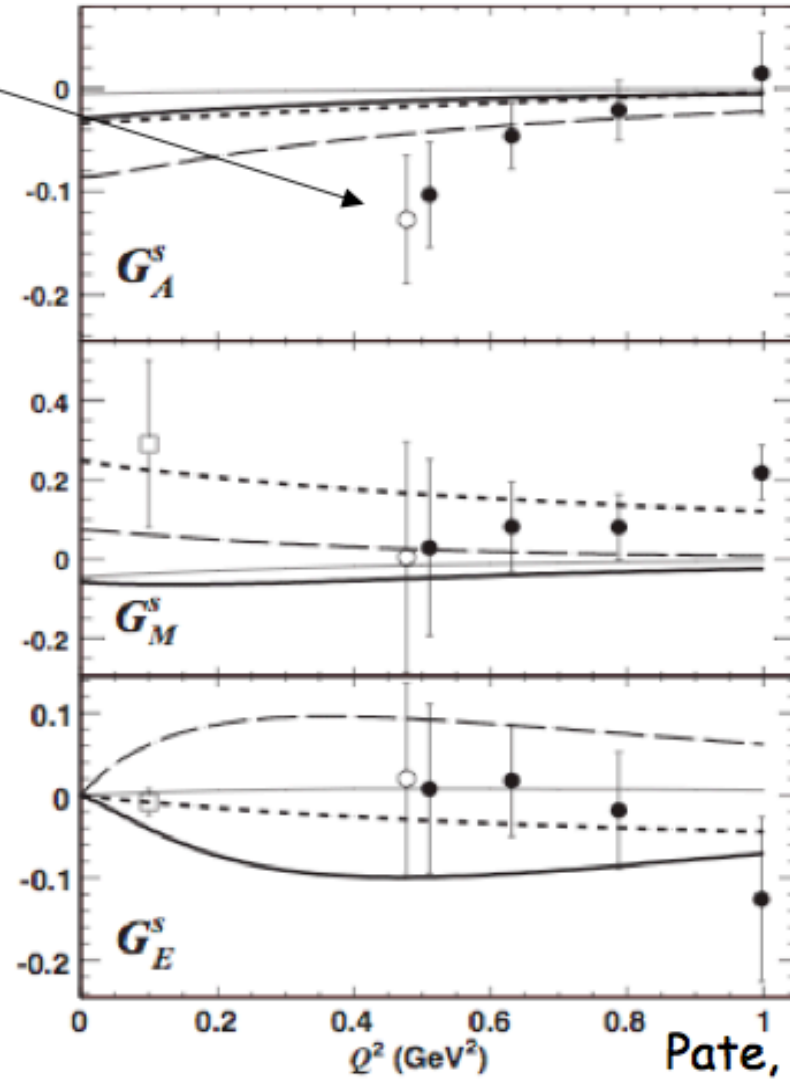
⇒ Replace PDF used for light quarks GPDs with NP charm based one



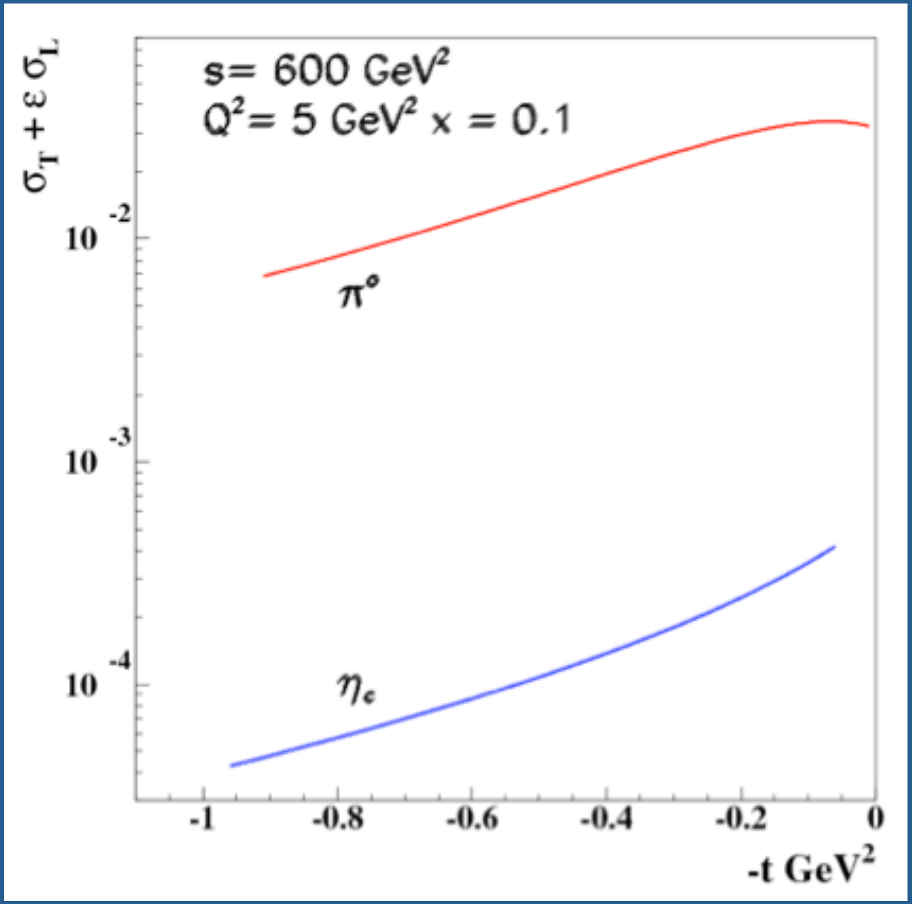
⇒ Replace FF used for light quarks GPDs with upper limit on charm based one

HAPPEx+E734

G0 + BNL E734



Pate, McKee, Papavissiliou,



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Conclusions and Outlook

- The solution to the spin problem in QCD resides in the gluonic components
- We have shown joint experimental and theoretical progress in determining the quark contributions (not there yet but a clear path exists)
- Hyperon polarization in pp collisions is yet another aspect of the spin problem and it is a manifestation of the same issues that affect TMDs
- Measurements at LHC will help clarify, but electron scattering experiments are crucial to explore the reaction mechanism (factorization and universality)
- We suggest developments in the formalism based on the concept of GPDs (generalized fracture functions) that can describe all spin phenomena from the multi-GeV to TeV regimes.
- Electron-ion colliders, the LHeC !, with an extended kinematical coverage (low to "larger" x_{Bj}) and wide Q^2 range will provide invaluable information on a range of hadronic properties related to spin: the nature of the proton charm content, quark and gluons spin, transversity
- Need to enter a quantitative phase specific to the LHeC (luminosities, …)

Back up

AM sum rule is obtained by connecting the quark matrix elements of n=2 term

$$\langle p' | \bar{\psi}(0)\gamma^{\mu} iD^{\nu}\psi(0) | p \rangle = \bar{U}(p',\Lambda')\gamma^{\mu}U(p,\Lambda)\bar{P}^{\nu} A_{20}(t) -$$

$$\bar{U}(p',\Lambda')\frac{i\sigma^{\alpha\mu}\Delta_{\mu}}{2M}U(p,\Lambda)\bar{P}^{\nu} B_{20}(t) + \frac{\Delta_{\mu}\Delta_{\nu}}{M}\bar{U}(p',\Lambda')U(p,\Lambda)C_{20}(t)$$

with the matrix elements of the energy momentum tensor

$$\langle p' | T_q^{\mu\nu} | p \rangle = \bar{U}(p',\Lambda')\left[\gamma^{(\mu}\bar{P}^{\nu)}A(t) - \bar{P}^{(\nu} i\sigma^{\mu)\alpha}\frac{\Delta_{\alpha}}{2M}B(t) + \frac{\Delta^{\mu}\Delta^{\nu} - g^{\mu\nu}\Delta^{2}}{M}C(t)\right]U(p,\Lambda)$$

$$\frac{1}{2}\int dx\, x\Big(H(x,0,0) + E(x,0,0)\Big) = J_z^{q,g}$$