Outline

- ✓ Motivation:
  - ✓ How do we detect quarks and gluons Orbital Angular Momentum (OAM)…
  - ✓ Is it an observable…
  - ✓ What are the observables…

- ✓ Introducing a procedure
  - ✓ Transverse Momentum Distributions and Generalized Parton Distributions: unraveling new multiparton correlations
  - ✓ Overview of the type of information one can extract
  - ✓ How reliably can GPDs be measured?
  - ✓ Towards a global fit: models, parameters, theoretical errors, resolution (GGL, PRD 2011)

  Can we understand flavor decomposition of Dirac and Pauli form factors?

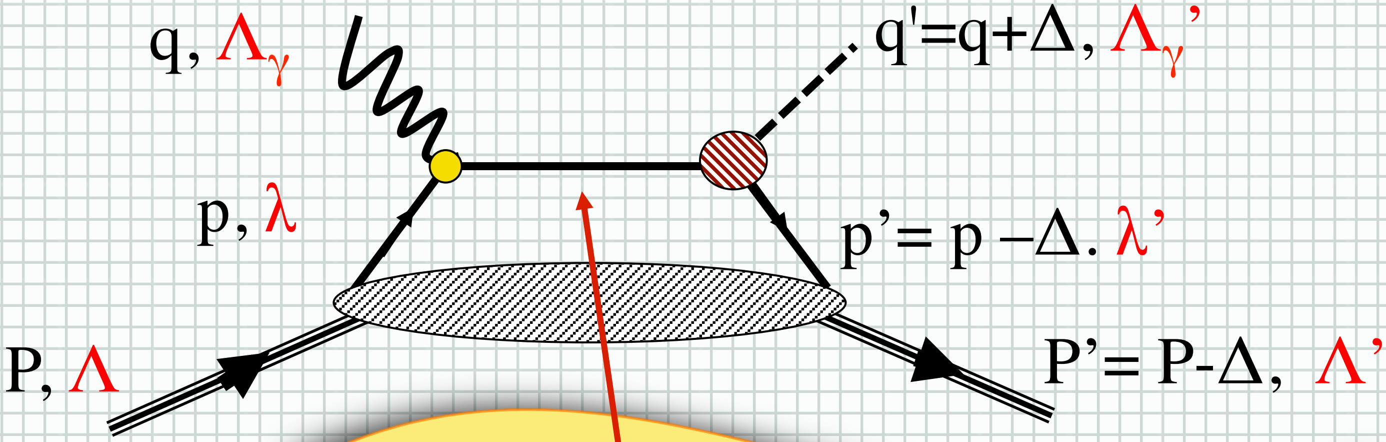
- ✓ Conclusions and Outlook

How do we detect quarks and gluons OAM?
(Is it an observable?)

A key observation for the detection of angular momentum

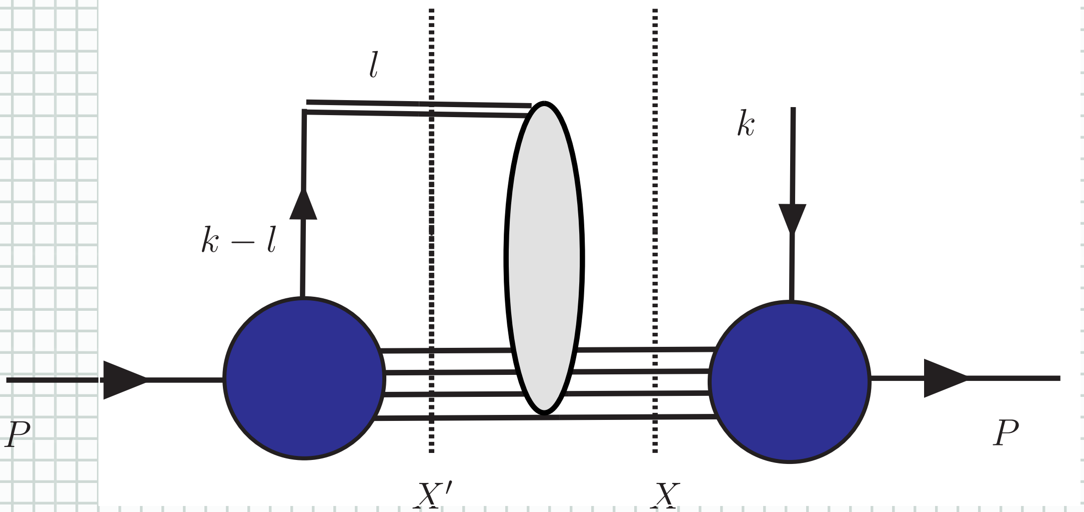
$$\gamma^* p \rightarrow \gamma(M) p'$$

GPDs



Loop directly in LO amplitude allows us to detect Single Spin Asymmetry (SSA)

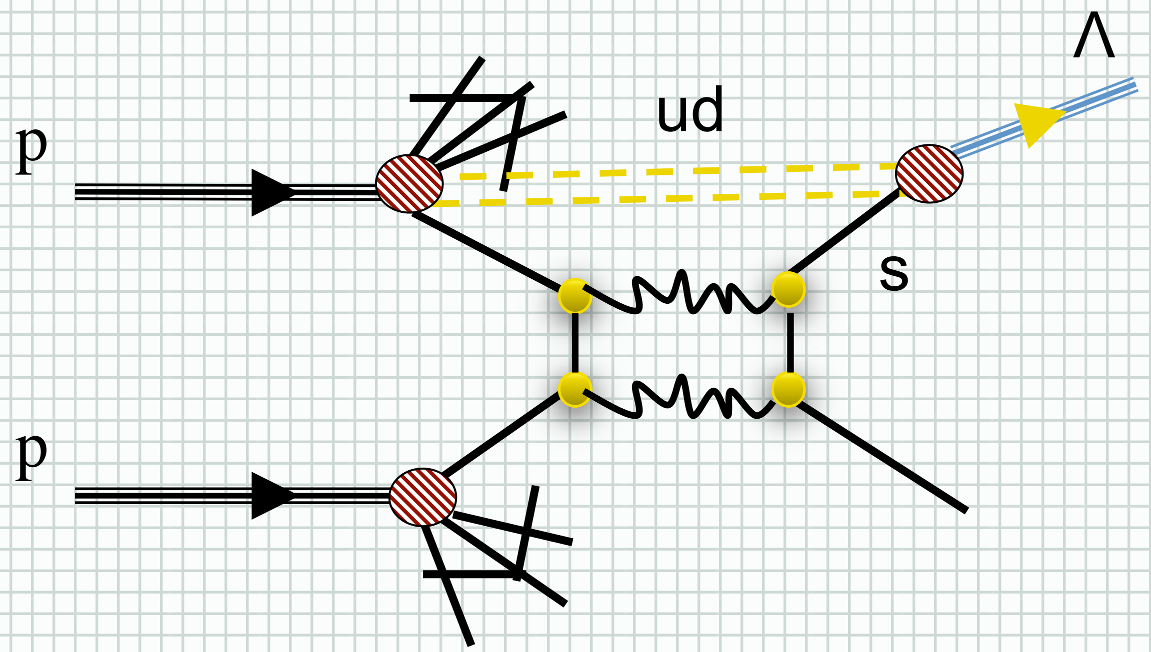
TMDs



$$h_1^{\perp}, f_{1T}^{\perp}$$

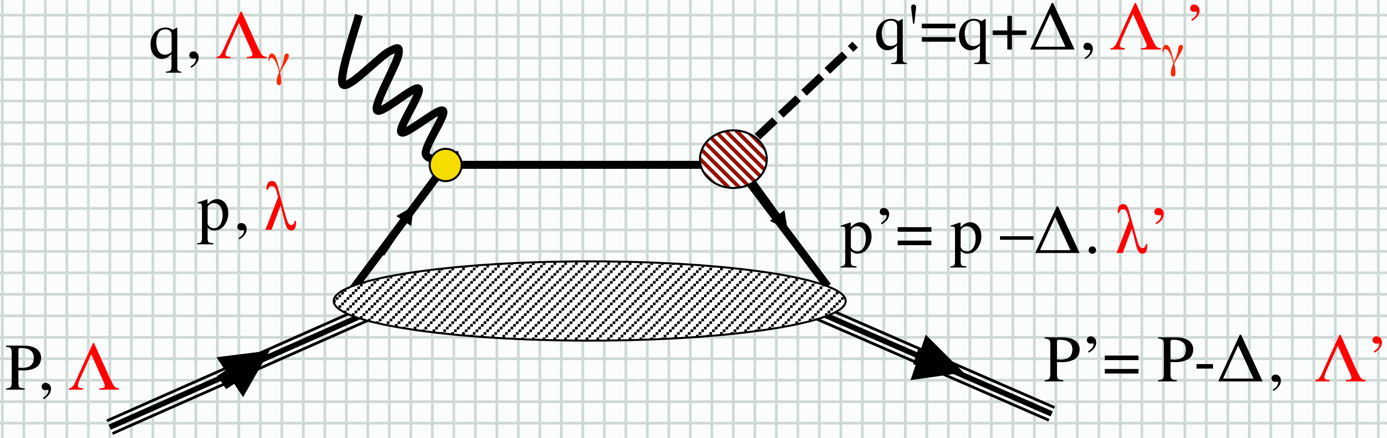
Brodsky, Hwang Schmidt, Ji and Yuan,…

Transverse Spin Asymmetries for Λ in pp scattering



Following Dharmaratna & Goldstein , 90's

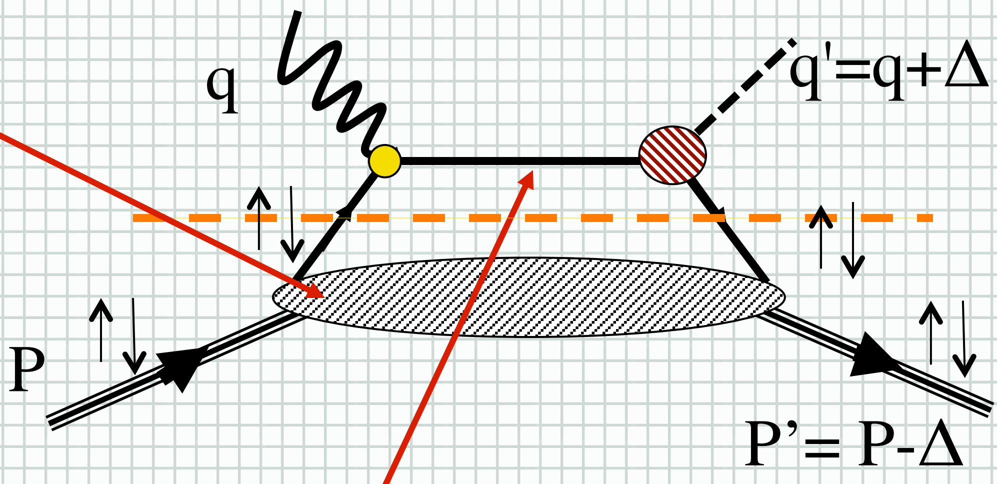
DVCS: Observables



$$f_{\Lambda_\gamma,\Lambda;\Lambda'_\gamma,\Lambda'} = \epsilon_\mu^{\Lambda_\gamma} T^{\mu\nu}_{\Lambda\Lambda'} \epsilon_\nu^{*\Lambda'_\gamma},$$

Factorization: Quark-Proton Helicity Amplitudes

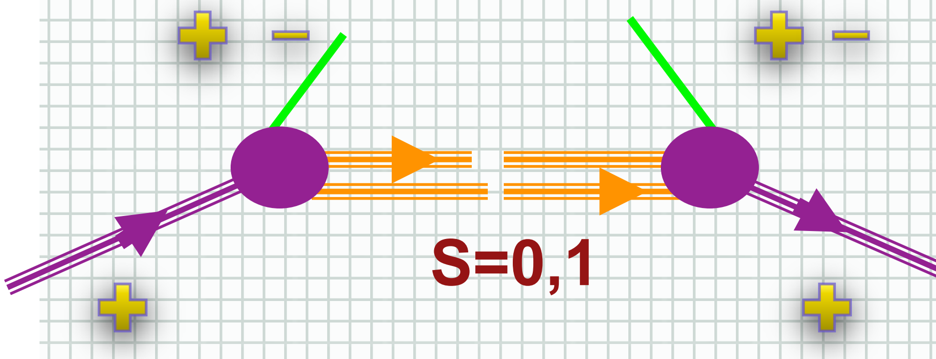
$$
\begin{aligned}
f^S_{++} &= f_{++,++} + f_{-+,-+} \\
&= g^S_{++} \otimes (A_{++,++} + A_{-+,-+}) \\
f^A_{++} &= f_{++,++} - f_{-+,-+} \\
&= g^A_{++} \otimes (A_{++,++} - A_{-+,-+}) \\
f^S_{+-} &= f_{++,+-} + f_{-+,--} \\
&= g^S_{++} \otimes (A_{-+,++} + A_{++,-+}) \\
f^A_{+-} &= f_{++,+-} - f_{-+,--} \\
&= g^A_{++} \otimes (A_{-+,++} - A_{++,-+})
\end{aligned}
$$



$$
g^{++}_{++} \pm g^{--}_{++} = \sqrt{X(X-\zeta)} \left(\frac{1}{X-\zeta+i\epsilon} \pm \frac{1}{X-i\epsilon} \right)
$$

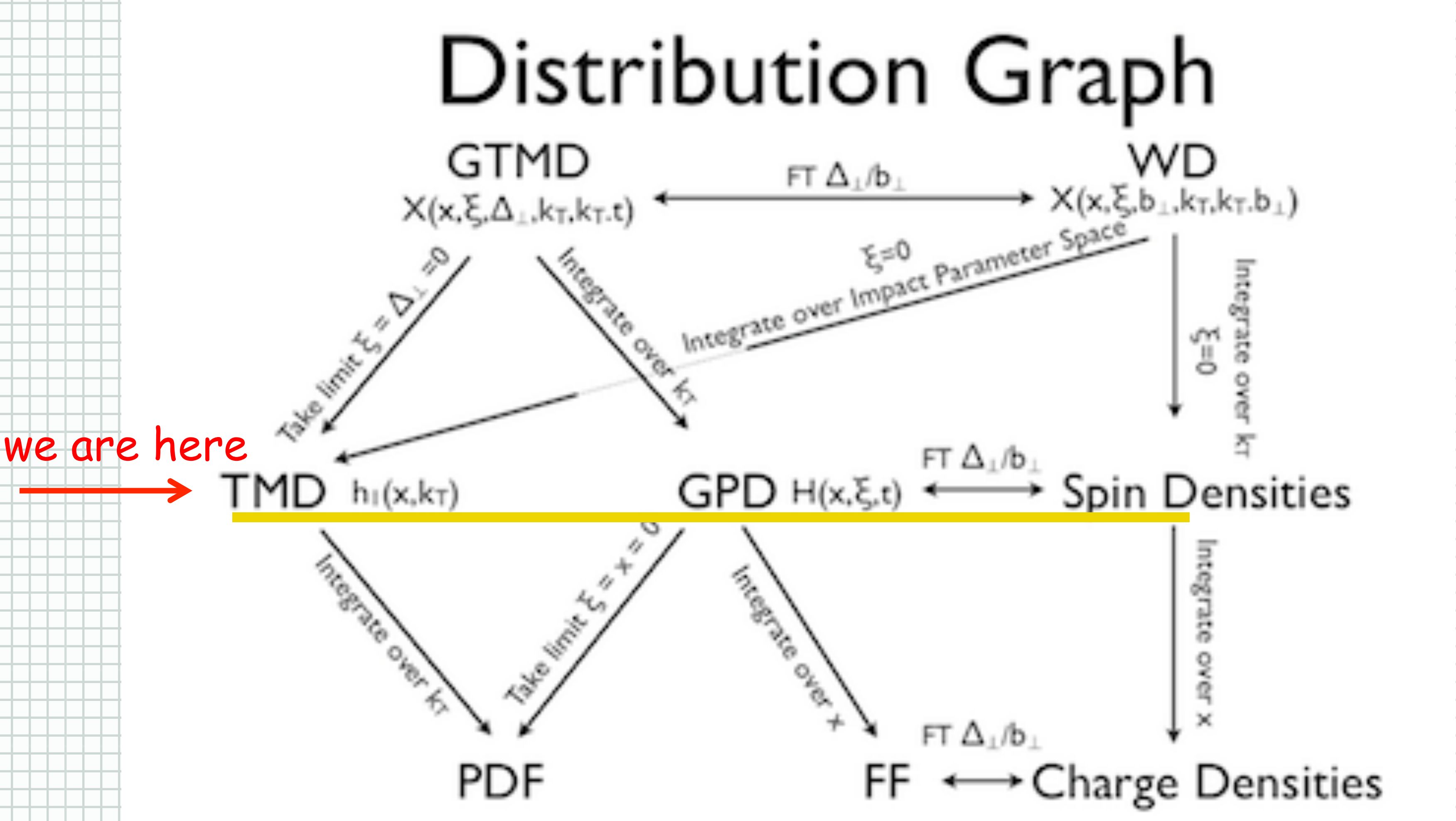
Helicity Amp. $A_{\Lambda'\lambda',\Lambda\lambda}$ in a Diquark Model

$$
\begin{aligned}
A_{++,++} &= \int d^2k_\perp \phi^*_{++}(k',P')\phi_{++}(k,P) \\
A_{+-,+-} &= \int d^2k_\perp \phi^*_{+-}(k',P')\phi_{+-}(k,P) \\
A_{-+,++} &= \int d^2k_\perp \phi^*_{-+}(k',P')\phi_{++}(k,P) \\
A_{++,-+} &= \int d^2k_\perp \phi^*_{++}(k',P')\phi_{-+}(k,P).
\end{aligned}
$$



$$
\begin{aligned}
\phi_{++} &= \mathcal{A}\,\bar{u}(k,+)u(P,+) = \mathcal{A}\langle k,+\mid P,+\rangle = \frac{\mathcal{A}}{\sqrt{X}}(m+Mx) \\
\phi_{--} &= \mathcal{A}\,\bar{u}(k,-)u(P,-) = \mathcal{A}\langle k,-\mid P,-\rangle = \frac{\mathcal{A}}{\sqrt{X}}(m+Mx) \\
\phi_{+-} &= \mathcal{A}\,\bar{u}(k,+)u(P,-) = \mathcal{A}\langle k,+\mid P,-\rangle = \frac{\mathcal{A}}{\sqrt{X}}(k_1-ik_2) \\
\phi_{-+} &= \mathcal{A}\,\bar{u}(k,-)u(P,+) = \mathcal{A}\langle k,-\mid P,+\rangle = -\frac{\mathcal{A}}{\sqrt{X}}(k_1+ik_2)
\end{aligned}
$$

What happens at the unintegrated level



M. Murray

Connection between "cartesian" and helicity bases

GTMDs (Metz et al, 2009)

$$W_{\lambda\lambda'}^{[\gamma^+]} = \frac{1}{2M}\,\bar{u}(p',\lambda')\left[F_{1,1} + \frac{i\sigma^{i+}k_T^i}{P^+}F_{1,2} + \frac{i\sigma^{i+}\Delta_T^i}{P^+}F_{1,3} + \frac{i\sigma^{ij}k_T^i\Delta_T^j}{M^2}F_{1,4}\right]u(p,\lambda),$$

$$W_{\lambda\lambda'}^{[\gamma^+\gamma_5]} = \frac{1}{2M}\,\bar{u}(p',\lambda')\left[-\frac{i\varepsilon_T^{ij}k_T^i\Delta_T^j}{M^2}G_{1,1} + \frac{i\sigma^{i+}\gamma_5 k_T^i}{P^+}G_{1,2} + \frac{i\sigma^{i+}\gamma_5\Delta_T^i}{P^+}G_{1,3} + i\sigma^{+-}\gamma_5\,G_{1,4}\right]u(p,\lambda),$$

GPDs

$$A_{++,++} = \frac{\sqrt{1-\zeta}}{1-\zeta/2}\left(\frac{H+\tilde{H}}{2} - \frac{\zeta^2/4}{1-\zeta}\frac{E+\tilde{E}}{2}\right)$$

$$A_{+-,+-} = \frac{\sqrt{1-\zeta}}{1-\zeta/2}\left(\frac{H-\tilde{H}}{2} - \frac{\zeta^2/4}{1-\zeta}\frac{E-\tilde{E}}{2}\right)$$

$$A_{++,-+} = -\frac{\Delta_1 - i\Delta_2}{2M}\left[E - \frac{\zeta/2}{1-\zeta/2}\tilde{E}\right]$$

$$A_{-+,++} = \frac{\Delta_1 + i\Delta_2}{2M}\left[E + \frac{\zeta/2}{1-\zeta/2}\tilde{E}\right]$$

These objects are at least twice as many and complex

Need to define a way of counting the number of independent objects

For form factors & gravitatomagnetic form factors use J^{PC} quantum numbers of crossed channel – NNbar states (Z.Chen and Ji, Hagler, GGL 2012)
(next slide)

Here we establish the criterion that we keep only the combinations of helicity amplitudes that are diagonal in a given spin basis: we are lead by the physical interpretation (physical quantities exist only if they can be tied to an observable)

By using Parity constraints on the Amps. we find a smaller number of GTMDs than in Metz et al.

General rule to count form factors: t-channel J^{PC} q. numbers

n	$J^{PC}(S;L)$				
0	0^{+-}	$1^{--}(1;0,2)$			
1	$0^{++}(1;1)$	1^{-+}	$2^{++}(1;1,3)$		
2	0^{+-}	$1^{--}(1;0,2)$	2^{+-}	$3^{--}(1;2,4)$	
3	$0^{++}(1;1)$	1^{-+}	$2^{++}(1;1,3)$	3^{-+}	$4^{++}(1;3,5)$
...	...				

TABLE III: J^{PC} of the vector operators with $(S;L,L')$ for the corresponding $N\bar{N}$ state. Where there are no $(S;L,L')$ values there are no matching quantum numbers for the $N\bar{N}$ system.

Haegler, PLB(2004)
Z.Chen&Ji, PRD(2005)

Nucleon

	$L=0$	1	2	3	4	...
$S=0$ J^{PC}	0^{-+}	1^{+-}	2^{-+}	3^{+-}	4^{-+}	
$S=1$	1^{--}	0^{++}	1^{--}	2^{++}	3^{--}	
		1^{++}	2^{--}	3^{++}	4^{--}	
		2^{++}	3^{--}	4^{++}	5^{--}	

TABLE I: J^{PC} of the $N\bar{N}$ states.

Deuteron

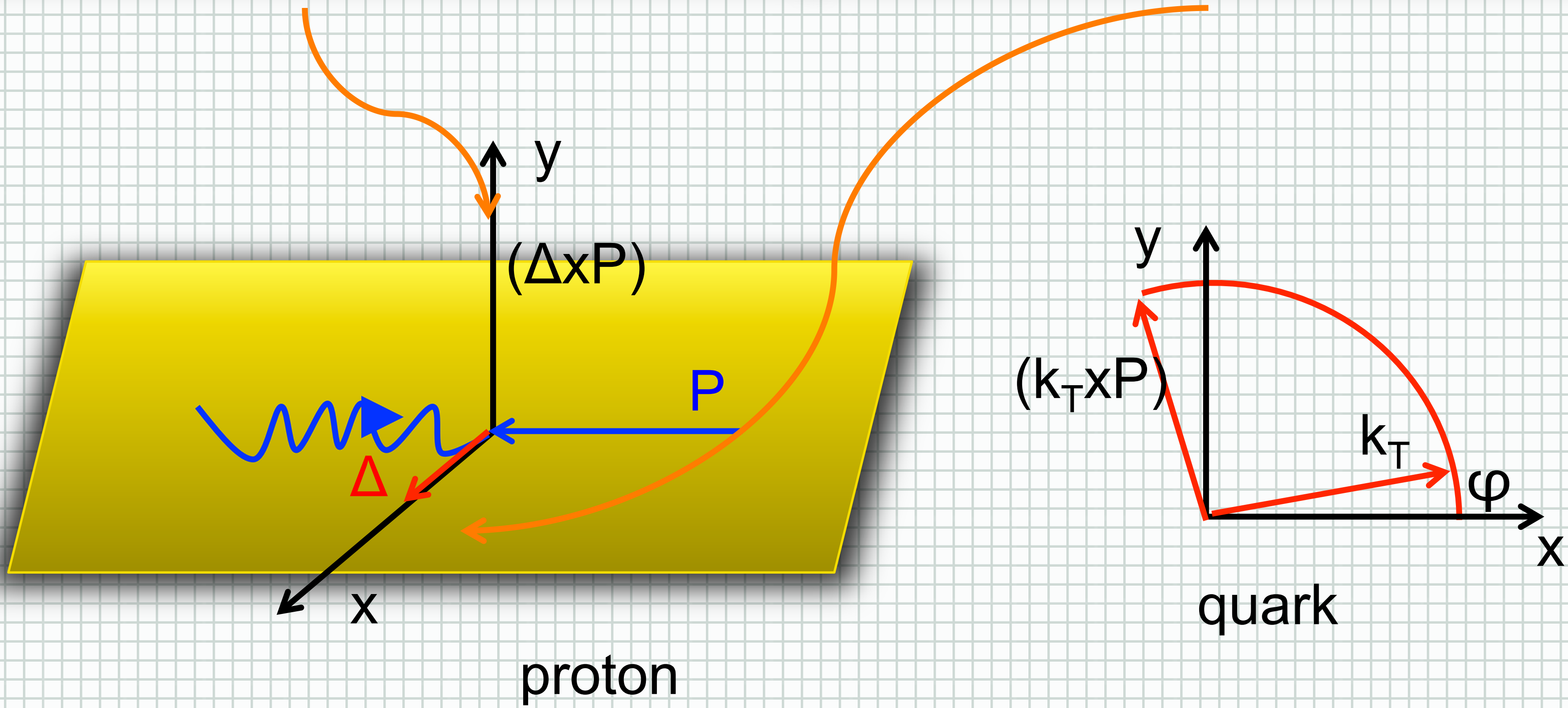
	$L=0$	1	2	3	4	...
$S=0$ J^{PC}	0^{++}	1^{--}	2^{++}	3^{--}	4^{++}	
$S=1$	1^{+-}	0^{-+}	1^{+-}	2^{-+}	3^{+-}	
		1^{-+}	2^{+-}	3^{-+}	4^{+-}	
		2^{-+}	3^{+-}	4^{-+}	5^{+-}	
$S=2$	2^{++}	1^{--}	0^{++}	1^{--}	2^{++}	
		2^{--}	1^{++}	2^{--}	3^{++}	
		3^{--}	2^{++}	3^{--}	4^{++}	
			3^{++}	4^{--}	5^{++}	
			4^{++}	5^{--}	6^{++}	

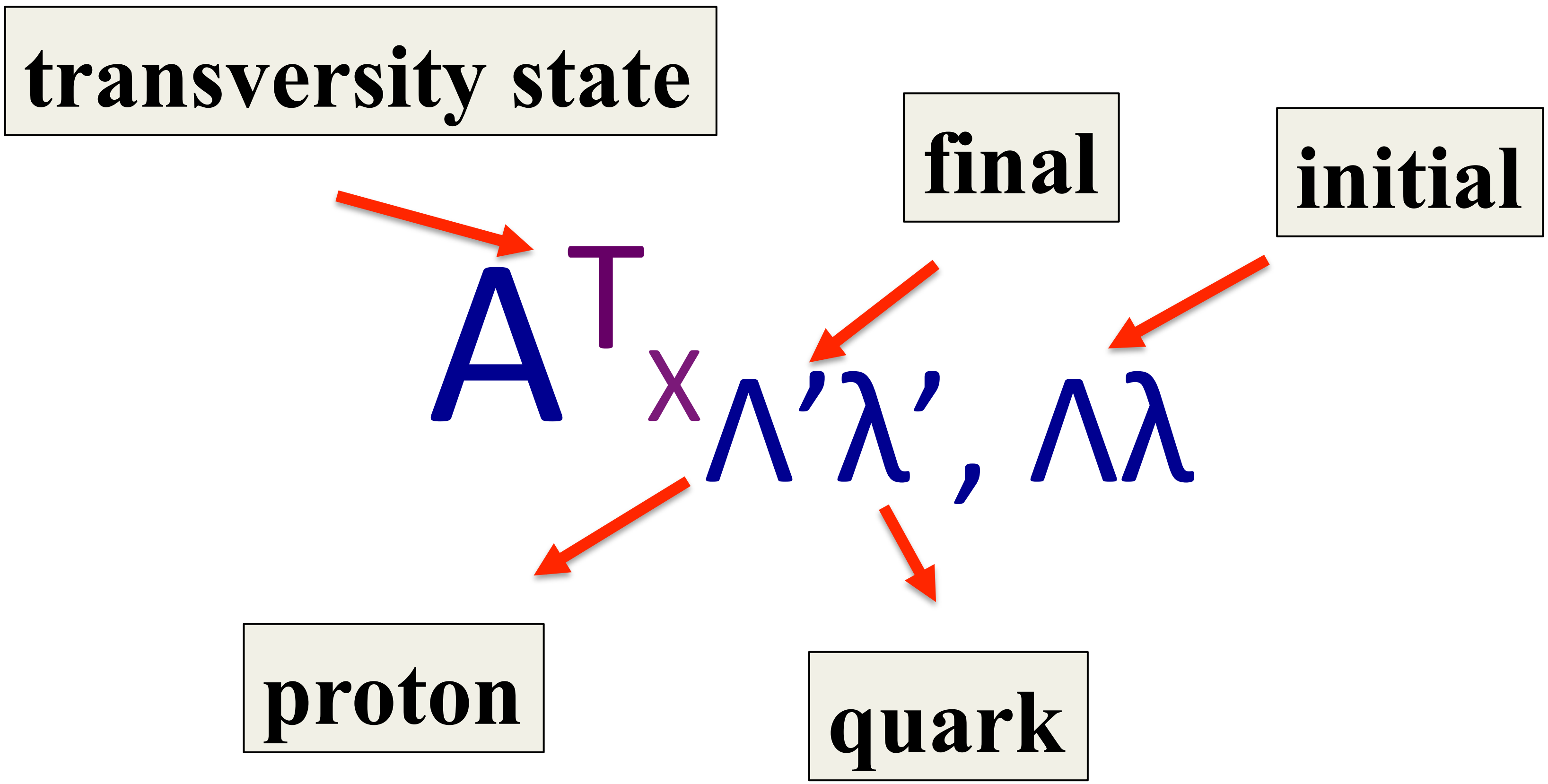
TABLE II: J^{PC} of the $d\bar{d}$ states.

Both S and L states considered (related to X.Ji's talk)

Transversity bases

Canonical	*Planar*
$\mid P,+(-)\rangle^{T_Y} = \frac{1}{\sqrt{2}}[\mid P,+\rangle + (-)i \mid P,-\rangle$	$\mid P,+(-)\rangle^{T_X} = \frac{1}{\sqrt{2}}[\mid P,+\rangle + (-) \mid P,-\rangle]$




transversity state
final
initial
$A^{T}_{\chi\,\Lambda'\lambda',\,\Lambda\lambda}$
proton
quark

Chiral Even Summary

L

$$2\widetilde{H}(X, k_\perp, 0, \Delta_\perp) = A_{++,++} - A_{+-,+-} + A_{--,--} - A_{-+,-+}$$

T_Y

$$-\frac{\Delta_1}{M} E(X, k_\perp, 0, \Delta_\perp) = -i(A^{T_Y}_{++,++} + A^{T_Y}_{+-,+-} - A^{T_Y}_{-+,-+} - A^{T_Y}_{--,--})$$

T_X

$$\xi \frac{\Delta_1}{M} \widetilde{E}(X, k_\perp, 0, \Delta_\perp) = (A^{L,T_Y}_{++,++} + A^{L,T_Y}_{+-,+-} - A^{L,T_Y}_{-+,-+} - A^{L,T_Y}_{--,--})$$

Chiral Odd Summary

T_Y

$$\tau \left[2\widetilde{H}_T(X, k_\perp, 0, \Delta_\perp) + E_T(X, 0, t)\right] = A^{T_Y}_{++,++} - A^{T_Y}_{+-,+-} + A^{T_Y}_{-+,-+} - A^{T_Y}_{--,--}$$

T_X

$$H_T(X, k_\perp, 0, \Delta_\perp) = A^{T_X}_{++,++} - A^{T_X}_{+-,+-} - A^{T_X}_{-+,-+} + A^{T_X}_{--,--}$$

$T_{Y,X}$

$$\tau^2 \widetilde{H}_T(X, k_\perp, 0, \Delta_\perp) = A^{T_Y}_{++,++} - A^{T_Y}_{+-,+-} - A^{T_X}_{-+,-+} + A^{T_X}_{--,--}$$

T_Y

$$\left[H_T(X, k_\perp, 0, \Delta_\perp) + \frac{1}{2}\tau^2 \widetilde{H}_T(X, k_\perp, 0, \Delta_\perp)\right] = A^{T_Y}_{++,++} - A^{T_Y}_{+-,+-} - A^{T_Y}_{-+,-+} + A^{T_Y}_{--,--}$$

… on to multi-parton distributions

Chiral Even Sector ➔ GPDs and TMDs with:

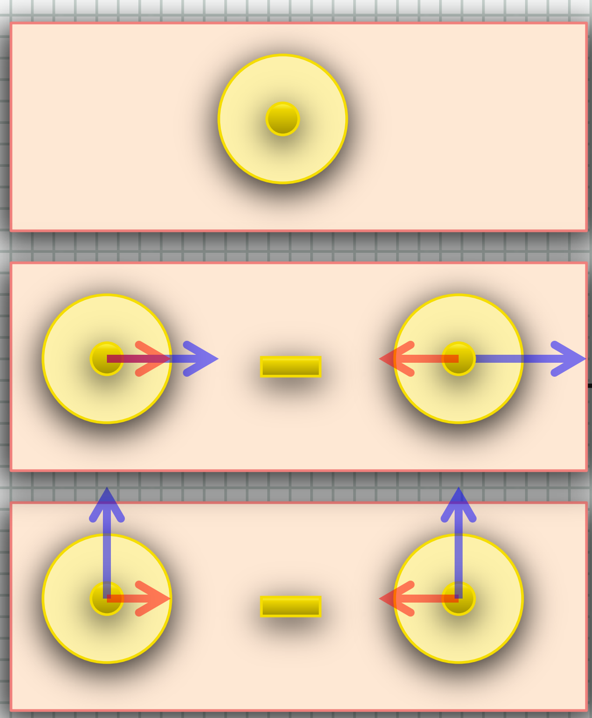
1. same helicity/transversity structure
2. Same parton correlations in a suitably defined forward limit

1

$$\mathrm{H} \leftrightarrow f_1$$

$$\tilde{\mathrm{H}} \leftrightarrow g_{1L}$$

$$\tilde{\mathrm{E}} \leftrightarrow g_{1T}$$



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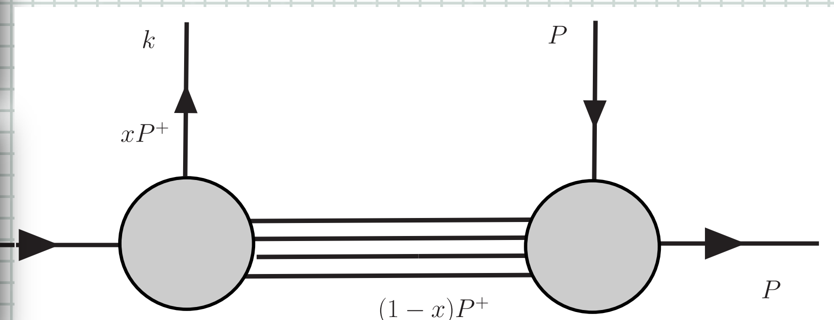
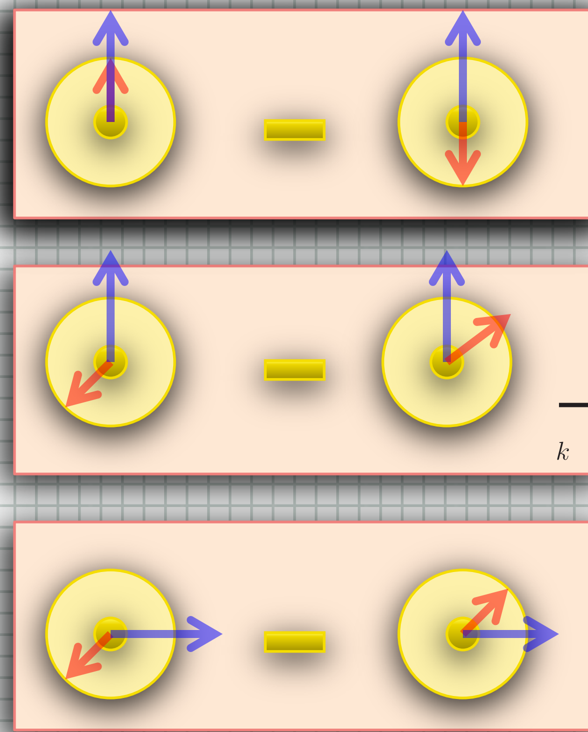


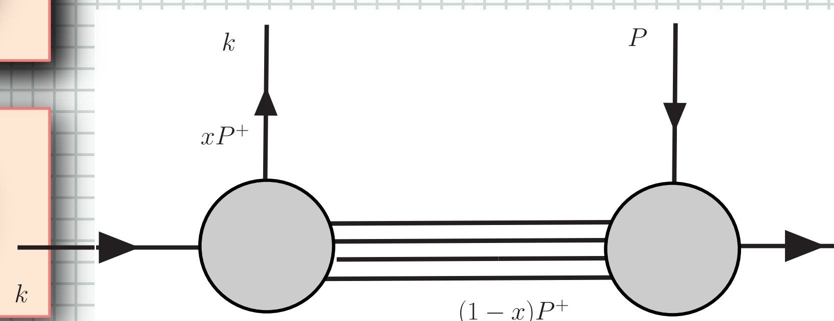
Chiral Odd Sector

$$\mathrm{H}_T \leftrightarrow h_1$$

$$-\boldsymbol{\tau}^2 \tilde{\mathrm{H}}_T \leftrightarrow h_{1T}^{\perp}$$

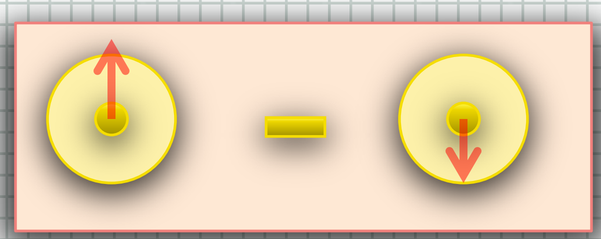
$$\boldsymbol{\tau} \tilde{E}_T \leftrightarrow h_{1L}^{\perp}$$



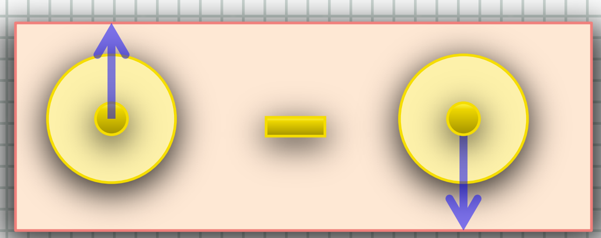


SSA Sector: GPDs and TMDs with same helicity/transversity structure

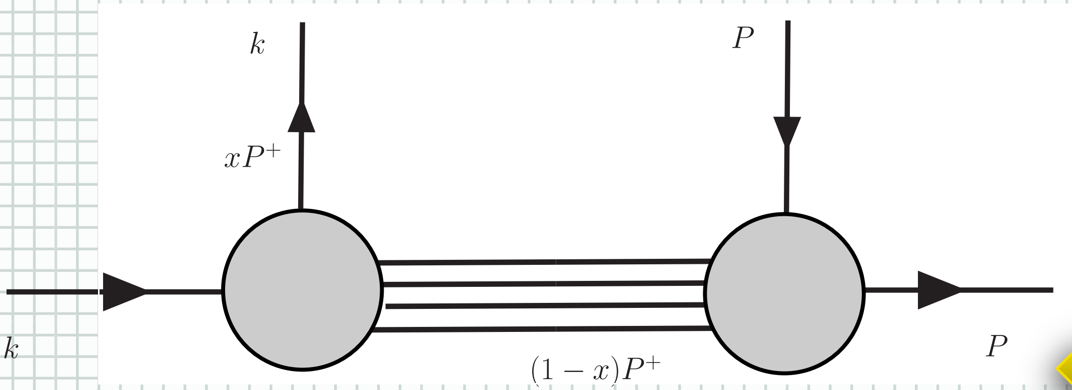
$$2\tilde{H}_T + E_T \leftrightarrow h_1^{\perp}$$



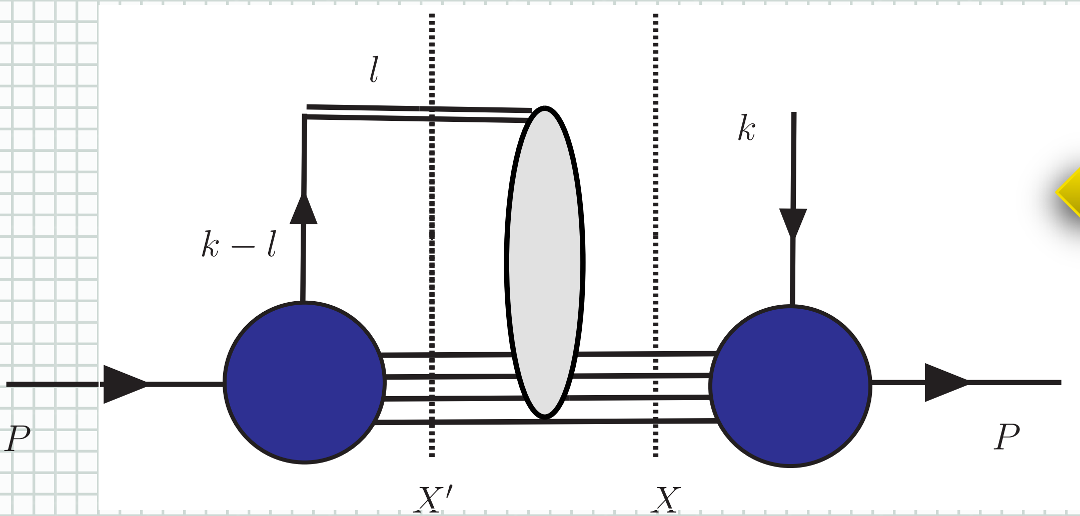
$$E \leftrightarrow f_{1T}^{\perp}$$



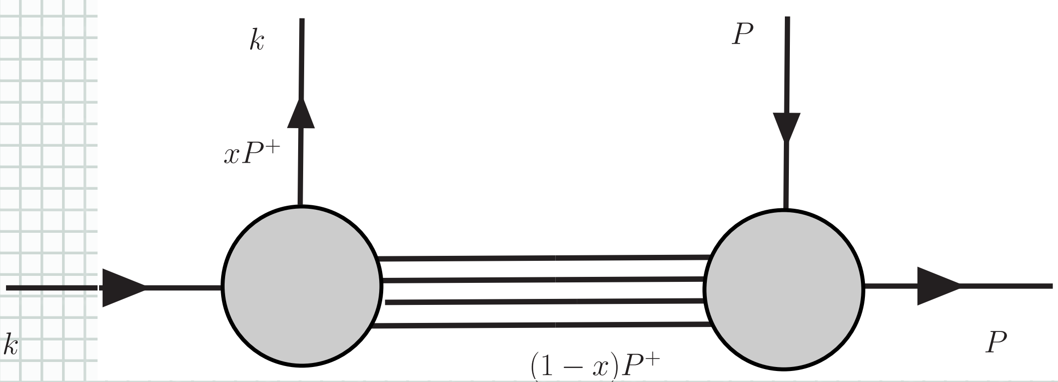
…but different multi-parton correlations in a suitably defined forward limit (aside from spin for a moment…)



$$2\tilde{H}_T + E_T, \; E$$



$$h_1^\perp, \, f_{1T}^\perp$$



Momentum Space: diagonal in x non diagonal in k_T

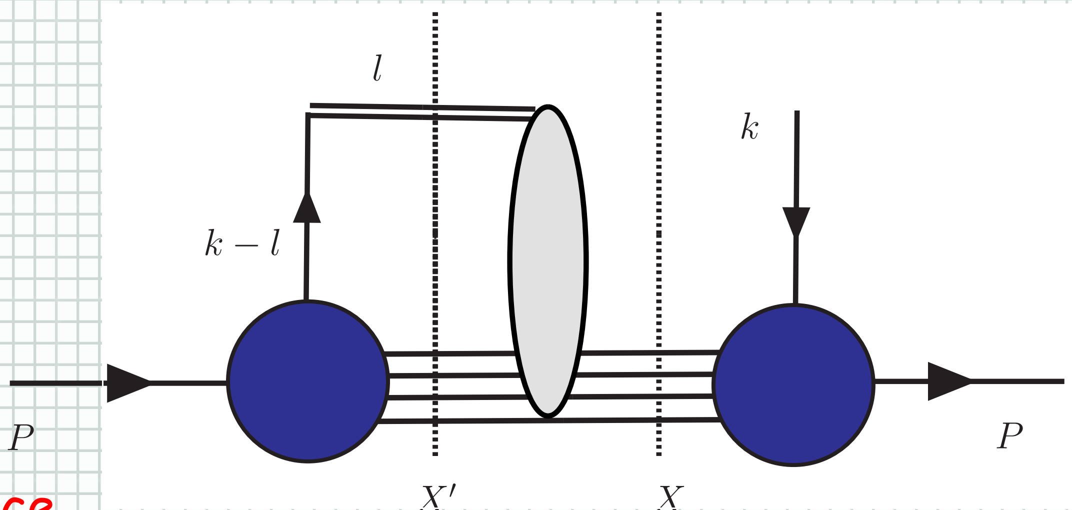
$$
\begin{aligned}
E(x,0,t) &= \int dz^- \exp^{ixP^+z^-} \langle P' \mid \bar{\psi}(0,z^-,0_T)\,\Gamma\,\psi(0,0,0_T) \mid P\rangle = \\
&= \sum_X \int dz^- \exp^{i(xP^+ - P'^+ + P_X^+)z^-} \langle P' \mid \bar{\psi}_+(0) \mid X\rangle\langle X \mid \psi_+(0,0,0_T) \mid P\rangle = \\
&= \int d^2k_T \phi^*(x, \underline{k_T - \Delta})\phi(x, \underline{k_T})
\end{aligned}
$$

Coordinate Space: diagonal in b

$$E(x,0,t) = \int d^2b \, e^{ib\cdot\Delta} \rho(x, \underline{b})$$

$t=\Delta^2$

GPDs and non SSA TMDs are one particle density distributions!



Momentum Space

$$\langle k_T^i(x)\rangle_{UT} = \int dz^- \exp^{ixP^+z^-} \langle P \mid \bar{\psi}(0,-z/2,0_T)\gamma^+ \left[\mathcal{W}(-z/2,z/2)I_q(z/2)\right] \psi(0,z/2,0_T) \mid P\rangle =$$

$$= \sum_{X,X'} \int dz^- \exp^{i(xP^+ - P^+ + P'^{(+)}_X)z^-} \langle P \mid \bar{\psi}_+(0) \mid X\rangle\langle X' \mid \psi_+(0) \mid P\rangle\langle X \mid \mathcal{W}(0,0)I_q(0) \mid X'\rangle =$$

$$= \int d^2k_T \int d^2l_T \phi^*(x,k_T)\phi(x,k_T - l_T, P) L(x,l_T)$$

FSI

This has the structure of an unintegrated GPD or GTMD

Coordinate Space

But careful! Although the correlator factorizes into a GTMD and FSI, it describes multiparton correlations which are different from the TMDs

$$\langle k_T^i(x)\rangle_{UT} = \int d^2b_1 d^2b_1' d^2b_2 \; \rho_2[(x,b_1),(0,b_2);(x,b_1'),(0,b_2)] I(b_1 - b_2)$$

semi-diagonal (in b) two-particle density distribution

The multiparticle densities scenario provides a necessary theoretical/formal context/background.

- We understand what makes diquark and quark target models "simple" in this context ➔ they are two component models, therefore all of the "complexity" of multiparton interactions is glossed over, FSI is a simple multiplicative factor.

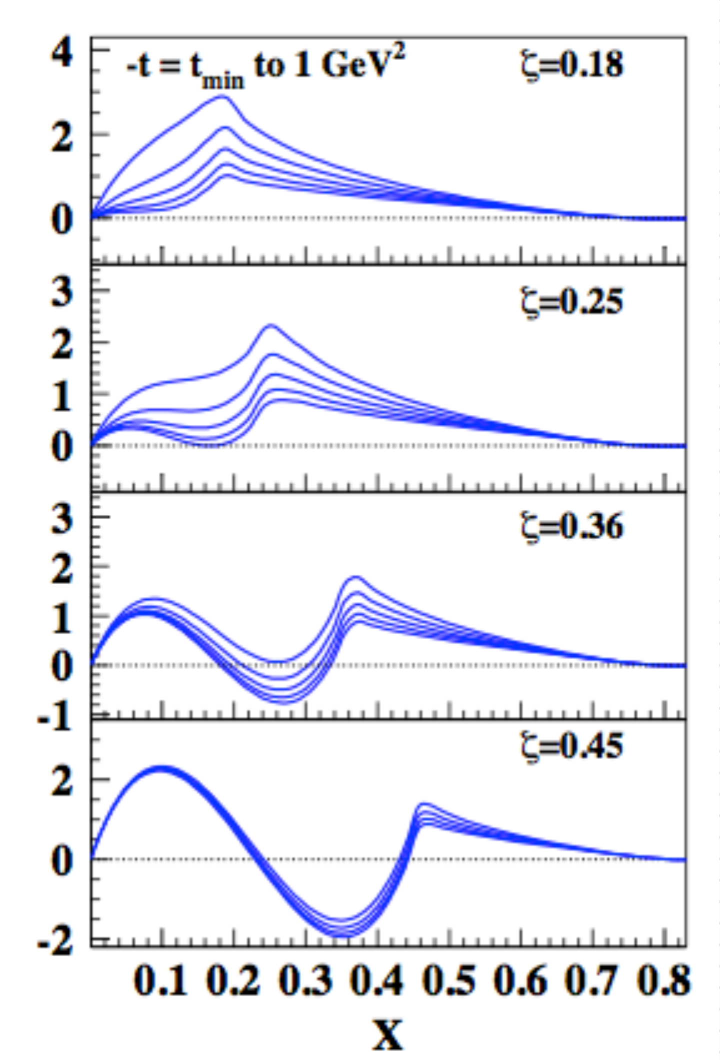
- More realistic diquark type models (with S and D wave spectators, see e.g. Goldstein and Liebl, PL1995; F.Gross and T. Peña, PRD 2011, or taking into account the internal momenta of the spectators, work in progress) could in principle give a very different answer

- Quark models could in principle give a very different answer (see e.g. A. Courtoy and S. Scopetta, PRD 2009)

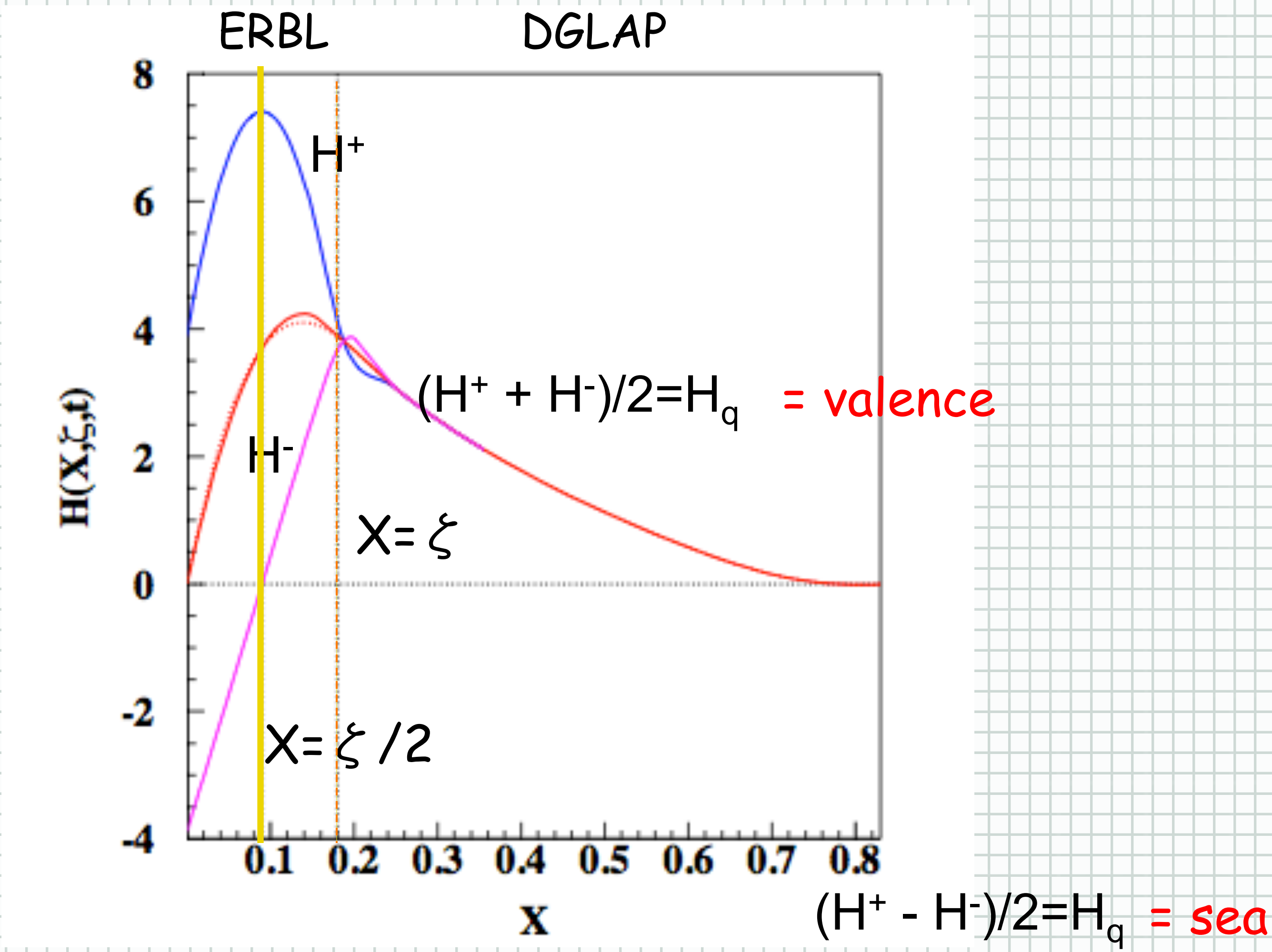
…on to physically motivated parametrization of data …

$H_q(X,\zeta,t)$

Goldstein et al. arXiv:1012.3776



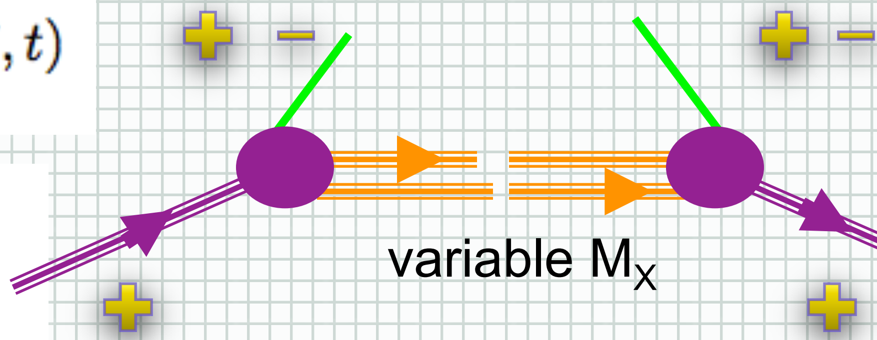
Crossing Symmetries



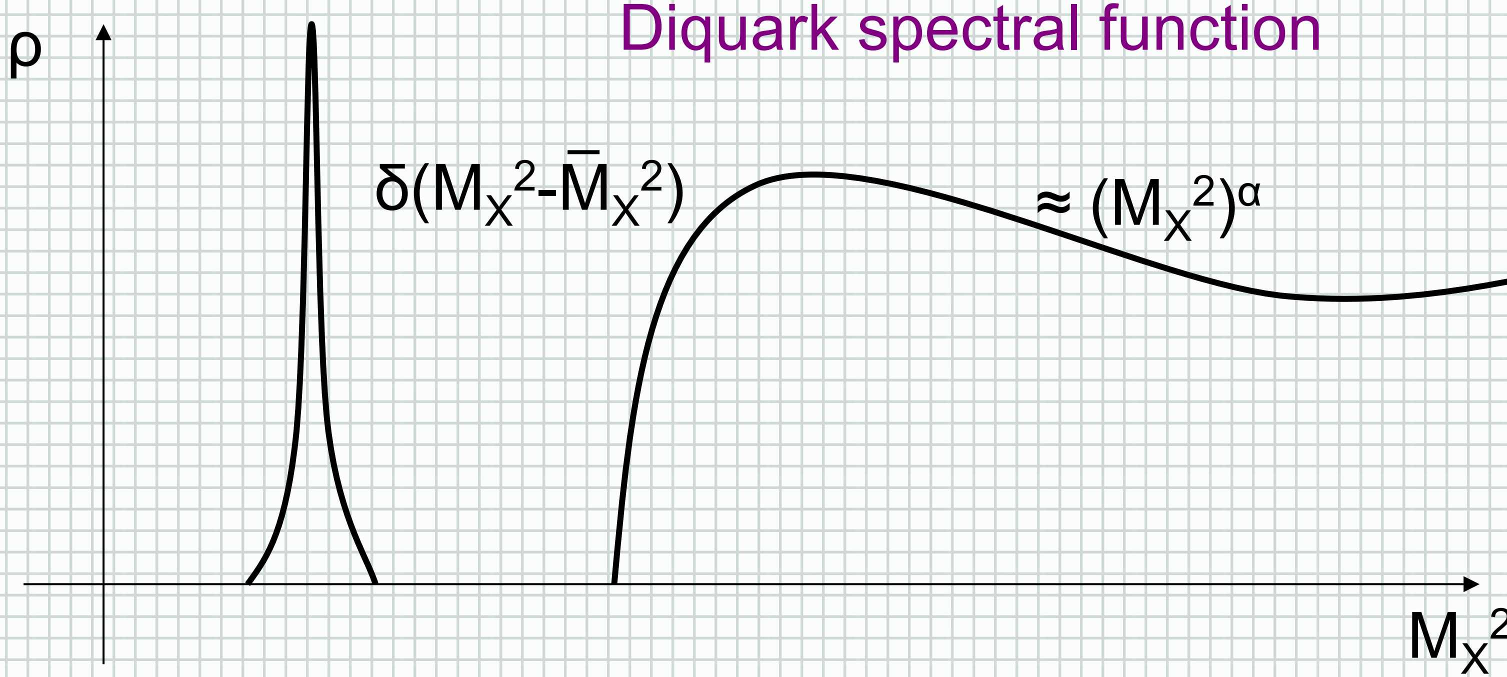
Parametric Form: Reggeized Diquark Model

$$F(X,\zeta,t) = \mathcal{N} G^{M_\Lambda}_{M_X,m}(X,\zeta,t)\, R_p^{\alpha,\alpha'}(X,\zeta,t)$$

$$\int_0^\infty dM_X^2 \rho_R(M_X^2) H(X,0,0) \sim X^{-\alpha(0)-1},$$



Diquark spectral function



Brodsky, Close, Gunion ➔ DIS ('70s)
Gorshteyn & Szczepaniak (PRD, 2010)
Brodsky, Llanes, Szczepaniak arXiv:0812.0395

$$F(X,\zeta,t) = \mathcal{N} G^{M_\Lambda}_{M_X,m}(X,\zeta,t)\, R_p^{\alpha,\alpha'}(X,\zeta,t)$$

$$H = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{\left[(m+MX)\left(m+M\frac{X-\zeta}{1-\zeta}\right)+\mathbf{k}_\perp\cdot\tilde{\mathbf{k}}_\perp\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2} + \frac{\zeta^2}{4(1-\zeta)}E,$$

$$E = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{-2M(1-\zeta)\left[(m+MX)\frac{\tilde{k}\cdot\Delta}{\Delta_\perp^2}-\left(m+M\frac{X-\zeta}{1-\zeta}\right)\frac{k_\perp\cdot\Delta}{\Delta_\perp^2}\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2}$$

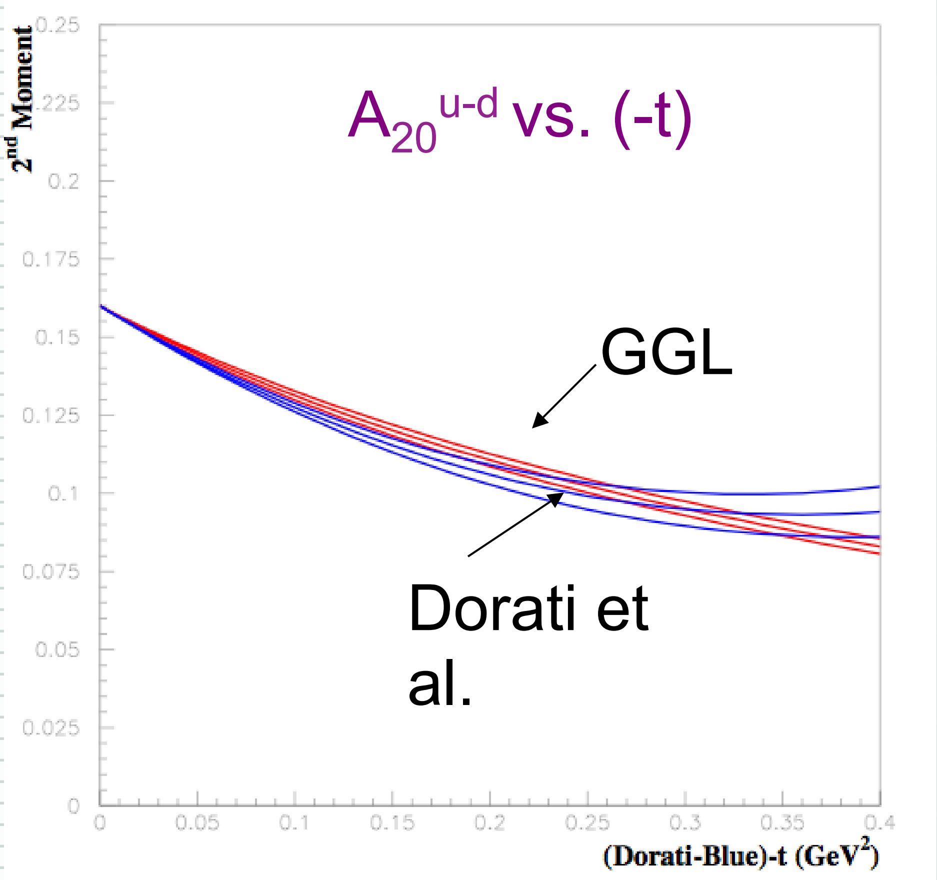
$$\widetilde{H} = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{\left[(m+MX)\left(m+M\frac{X-\zeta}{1-\zeta}\right)-\mathbf{k}_\perp\cdot\tilde{\mathbf{k}}_\perp\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2} + \frac{\zeta^2}{4(1-\zeta)}\widetilde{E}$$

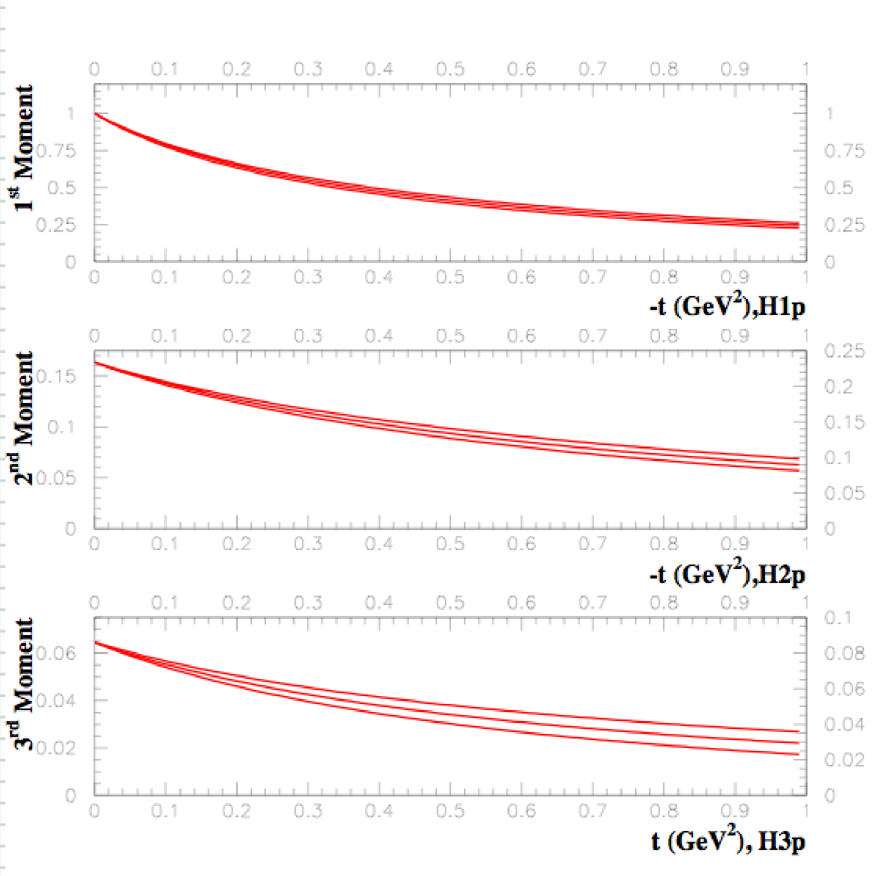
$$\widetilde{E} = \mathcal{N}\frac{1-\zeta/2}{1-X}\int d^2k_\perp \frac{-\frac{4M(1-\zeta)}{\zeta}\left[(m+MX)\frac{\tilde{k}\cdot\Delta}{\Delta_\perp^2}+\left(m+M\frac{X-\zeta}{1-\zeta}\right)\frac{k_\perp\cdot\Delta}{\Delta_\perp^2}\right]}{(k^2-M_\Lambda^2)^2(k'^2-M_\Lambda^2)^2}$$

We asked the question: "What is the minimal number of parameters necessary to fit X and t ?" Can be addressed with Recursive Fit

Parameters	H	E	$\widetilde{H}$	$\widetilde{E}$
m_u (GeV)	0.420	0.420	2.624	2.624
M_X^u (GeV)	0.604	0.604	0.474	0.474
M_Λ^u (GeV)	1.018	1.018	0.971	0.971
α_u	0.210	0.210	0.219	0.219
α'_u	2.448 ± 0.0885	2.811 ± 0.765	1.543 ± 0.296	5.130 ± 0.101
p_u	0.620 ± 0.0725	0.863 ± 0.482	0.346 ± 0.248	3.507 ± 0.054
$\mathcal{N}_u$	2.043	1.803	0.0504	1.074
χ^2	0.773	0.664	0.116	1.98
m_d (GeV)	0.275	0.275	2.603	2.603
M_X^d (GeV)	0.913	0.913	0.704	0.704
M_Λ^d (GeV)	0.860	0.860	0.878	0.878
α_d	0.0317	0.0317	0.0348	0.0348
α'_d	2.209 ± 0.156	1.362 ± 0.585	1.298 ± 0.245	3.385 ± 0.145
p_d	0.658 ± 0.257	1.115 ± 1.150	0.974 ± 0.358	2.326 ± 0.137
$\mathcal{N}_d$	1.570	-2.800	-0.0262	-0.966
χ^2	0.822	0.688	0.110	1.00

Comparison with lattice

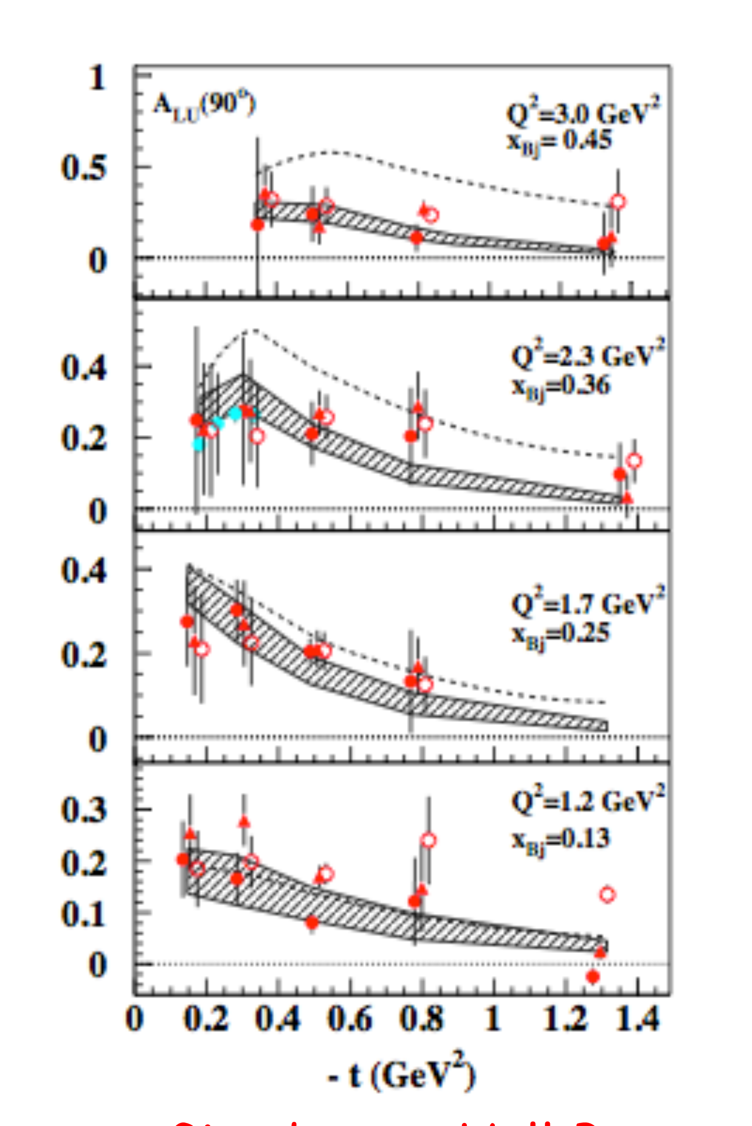




Implementing DVCS data…

$$R = X^{-[\alpha+\alpha'(X)t+\beta(\zeta)t]},$$

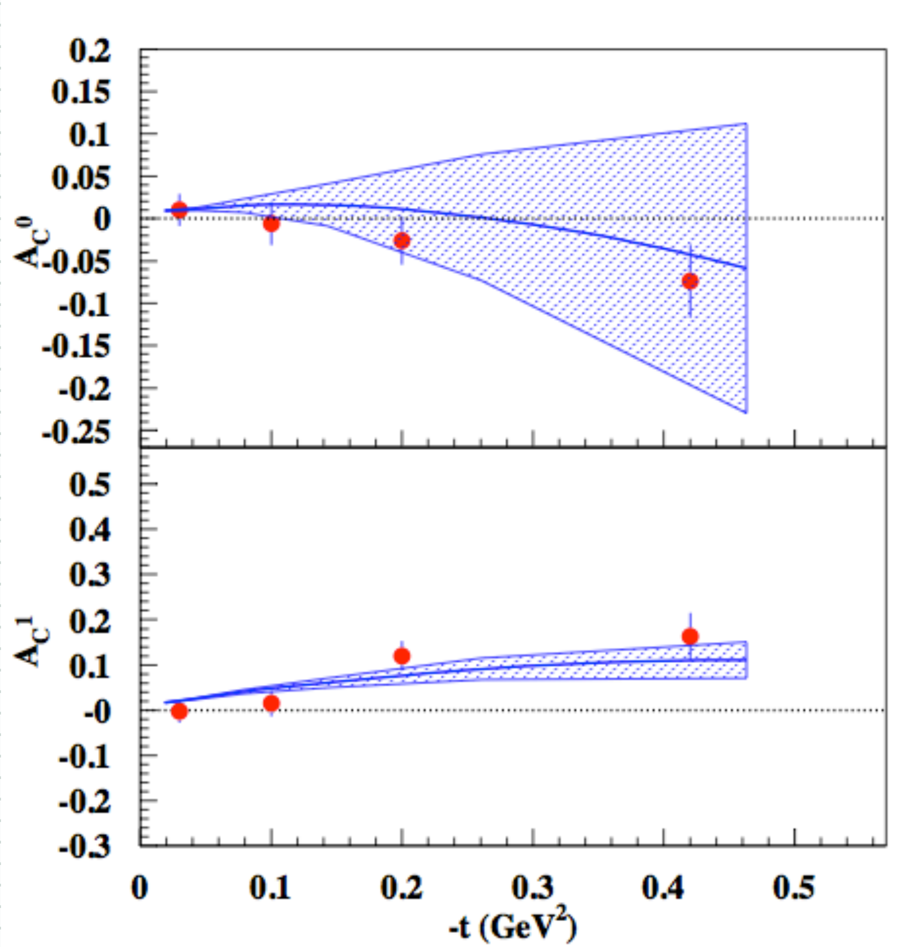
extra term

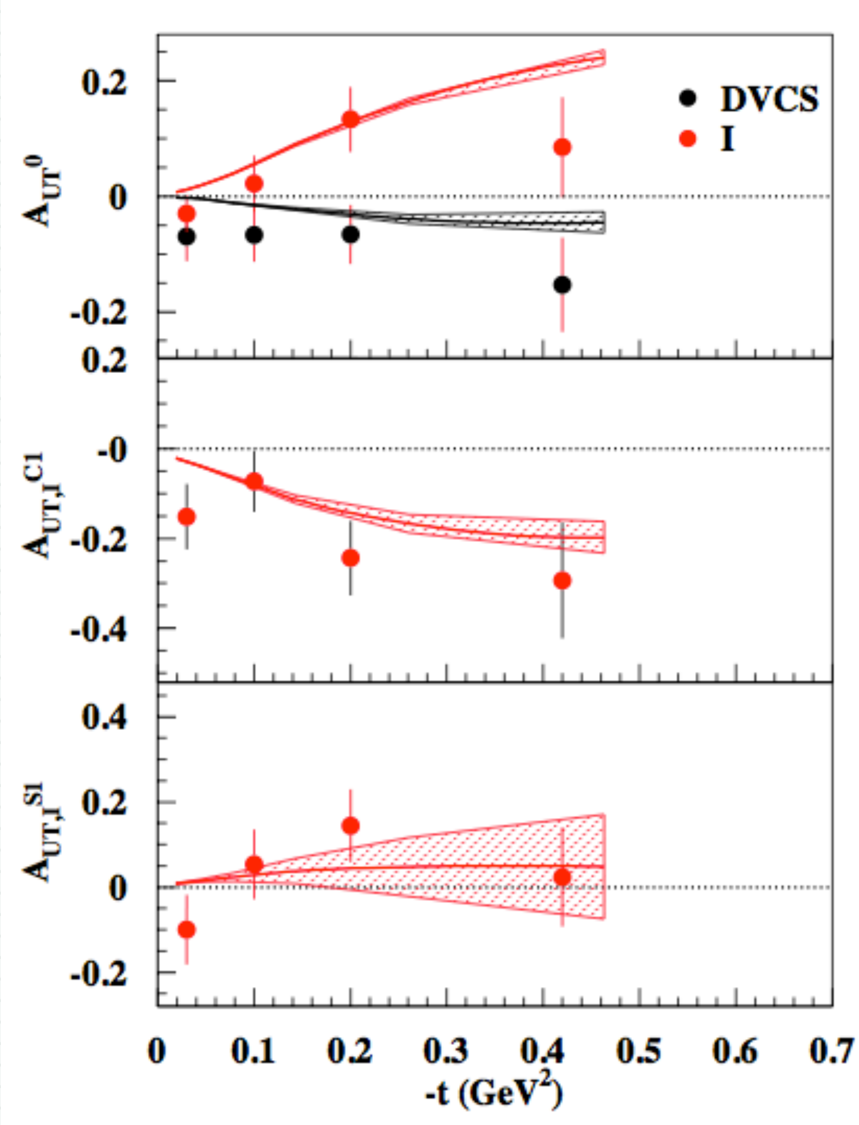


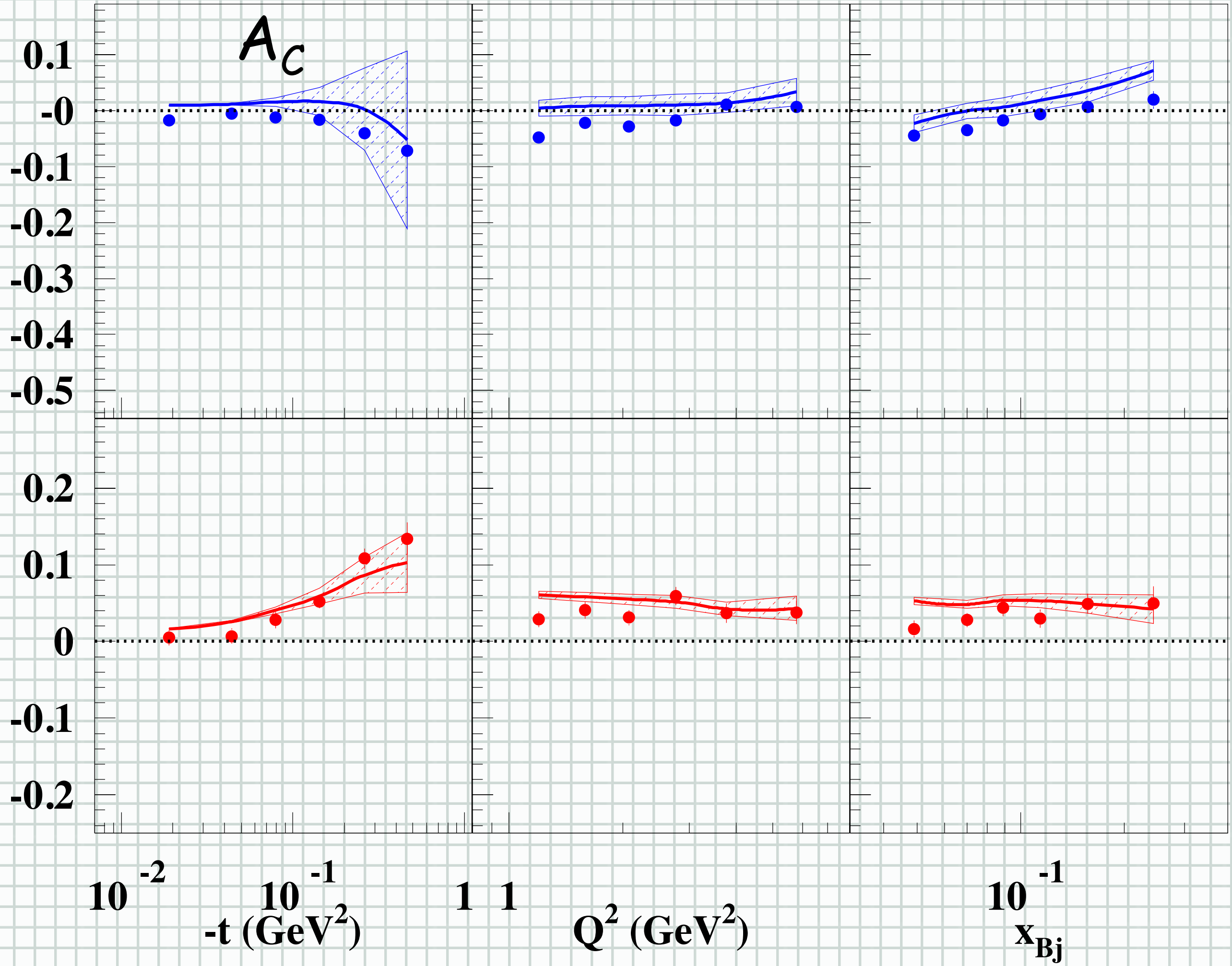
Girod et a., Hall B

Having fitted Jlab data, we predict Hermes

Goldstein et al. arXiv:1012.3776



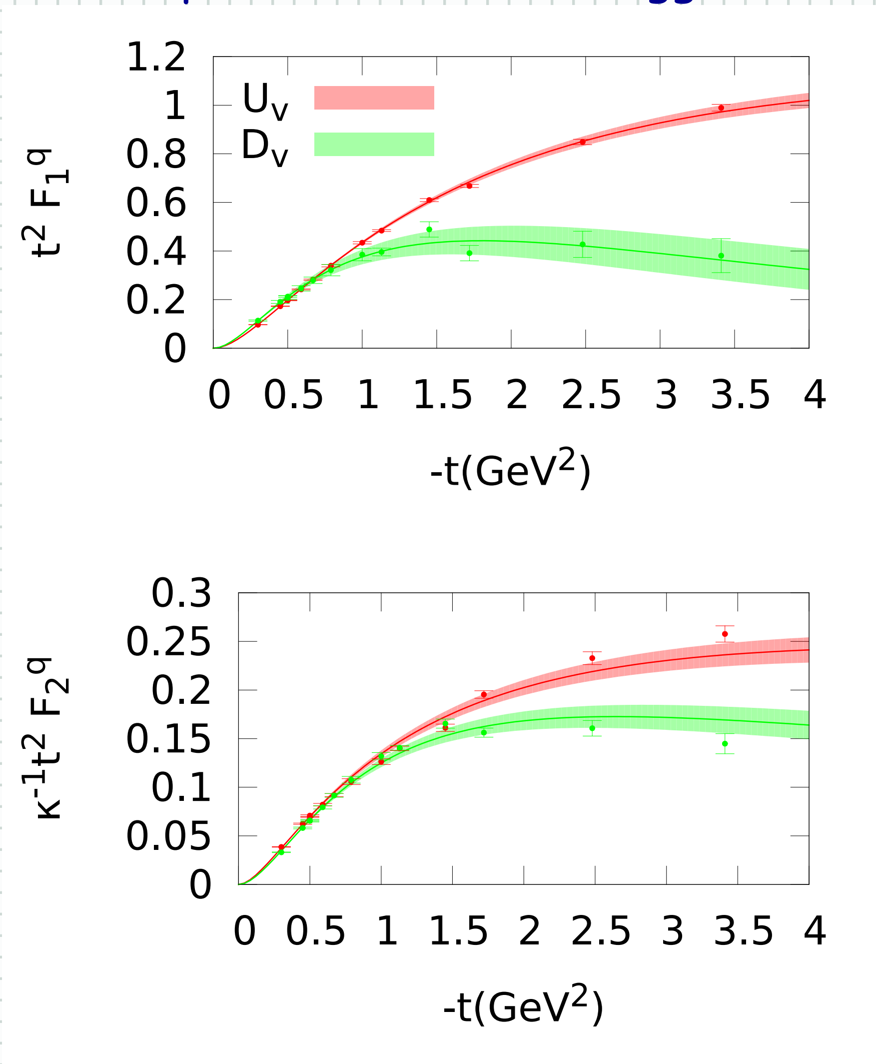




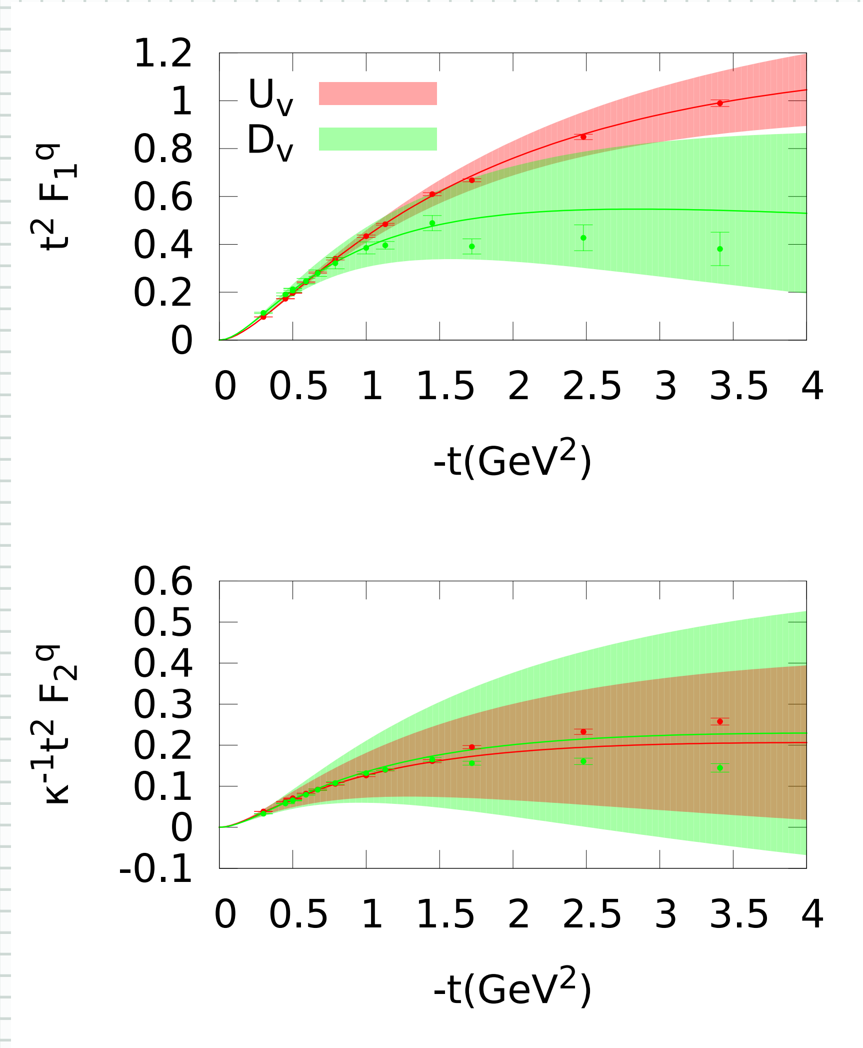
A_C
0.1
-0
-0.1
-0.2
-0.3
-0.4
-0.5
0.2
0.1
0
-0.1
-0.2
10^{-2}
10^{-1}
1
1
10^{-1}
-t (GeV^2)
Q^2 (GeV^2)
x_{Bj}

New flavor separated data on form factors (G.Cates et al., PRL 2011)

Interpretation? We believe it is not a simple model (pointlike diquark excluded), but can explain it in terns of reggeized diquark model



After



…Before

Gonzalez, S.L., Goldstein, Katuria, arXiv, June 2012

Chiral Odd Sector

Using Parity relations with scalar (S=0) and axial vector (S=1) diquarks we can predict all GPDs

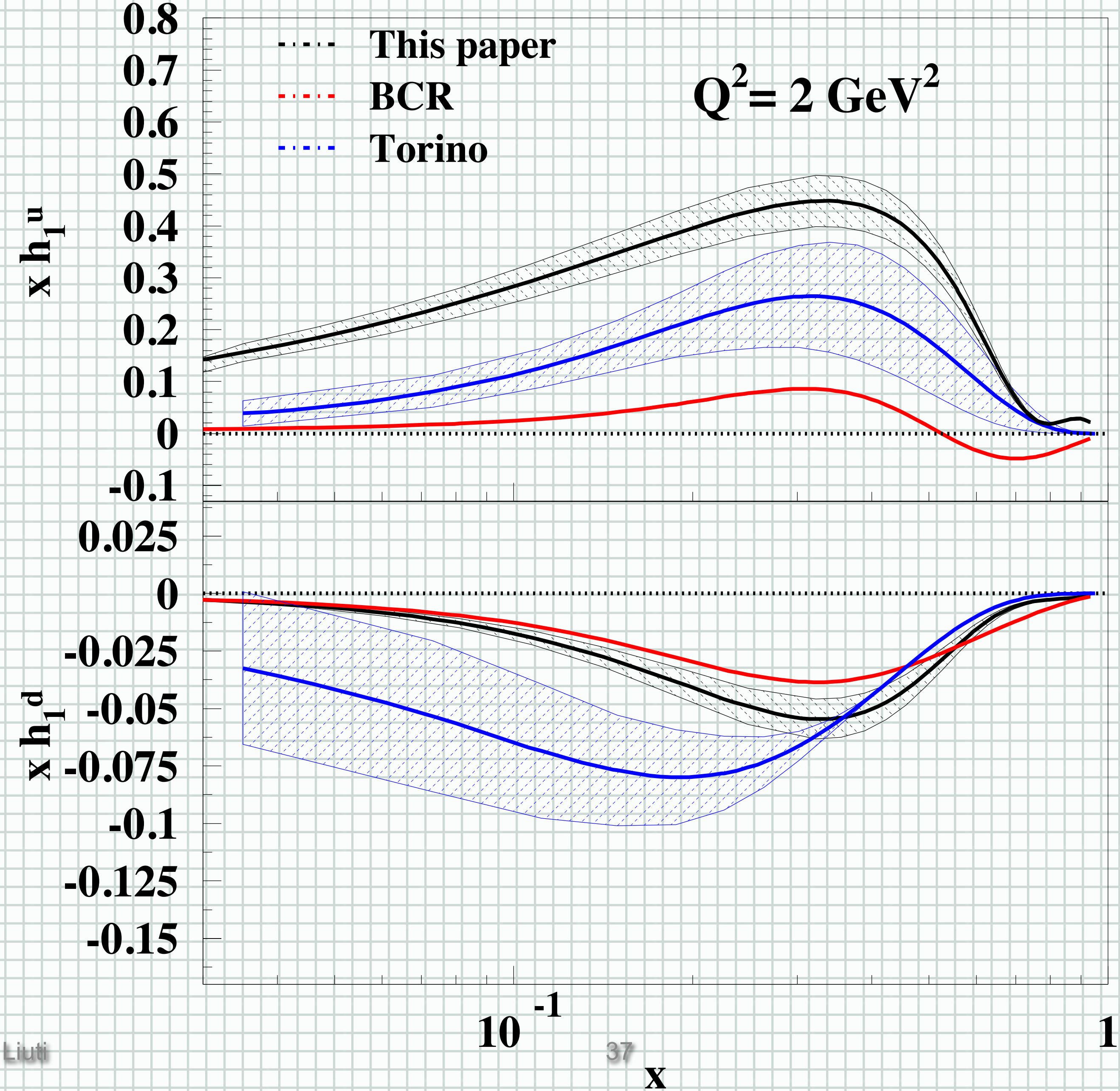
$S = 0$

$$\begin{aligned}
\widetilde{H}_T^{(0)} &= -\frac{M(1-x)}{m+Mx} E^{(0)} \\
E_T^{(0)} &= 2\left(1+\frac{M(1-x)}{m+Mx}\right) E^{(0)} \\
\widetilde{E}_T^{(0)} &= 0 \\
H_T^{(0)} &= \frac{H^{(0)}+\widetilde{H}^{(0)}}{2} - \frac{t_0-t}{4M^2}\frac{M(1-x)}{m+Mx} E^{(0)}
\end{aligned}$$

$S = 1$

$$\begin{aligned}
\widetilde{H}_T^{(1)} &= 0 \\
E_T^{(1)} &= 2E^{(1)} \\
\widetilde{E}_T^{(1)} &= 0 \\
H_T^{(1)} &= -\frac{2x}{1+x^2}\frac{H^{(1)}+\widetilde{H}^{(1)}}{2}
\end{aligned}$$

Extraction of transversity using DVCS data

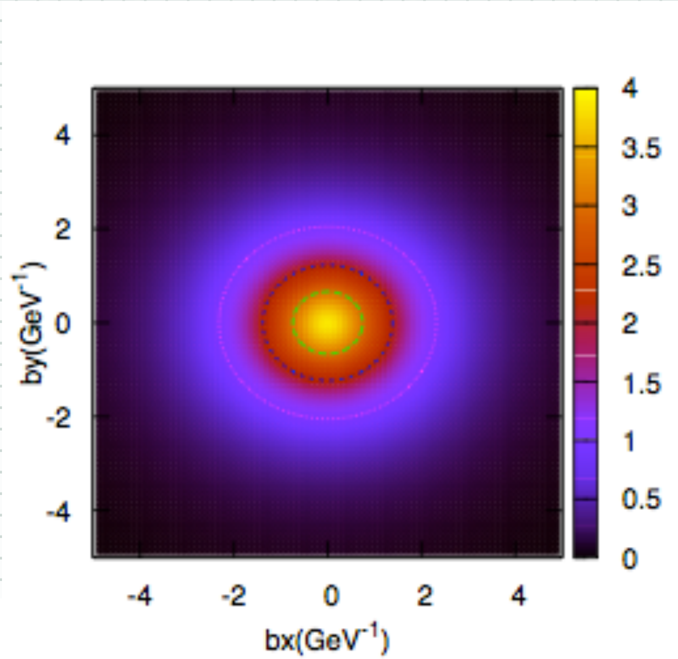


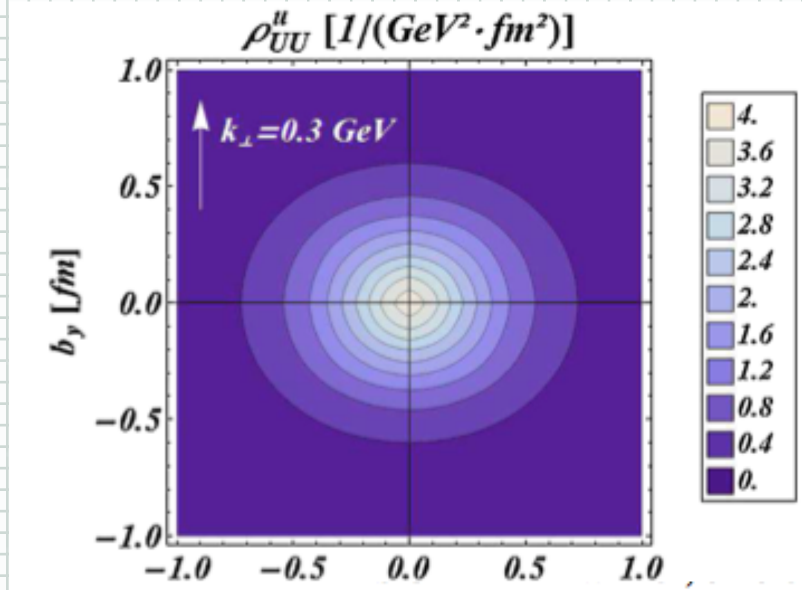
Wigner distribution studies

Gonzalez, Goldstein, S.L., R-Diquark Model   Lorce, Pasquini, (2011) LCCQM

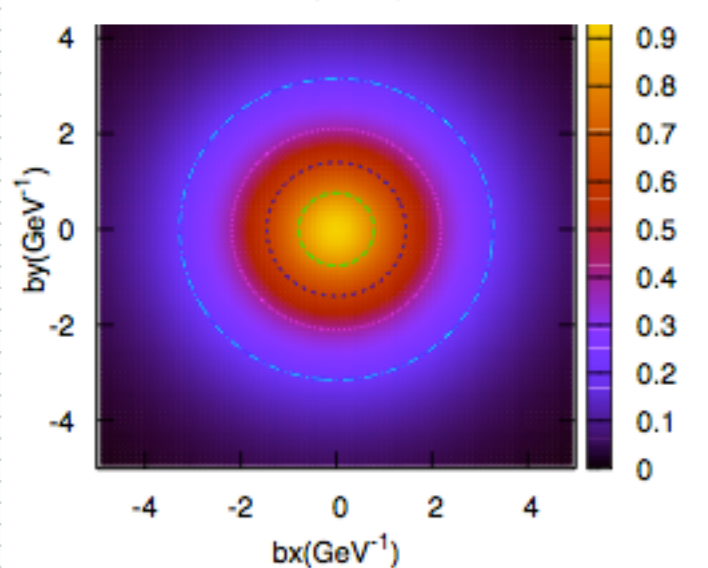
H

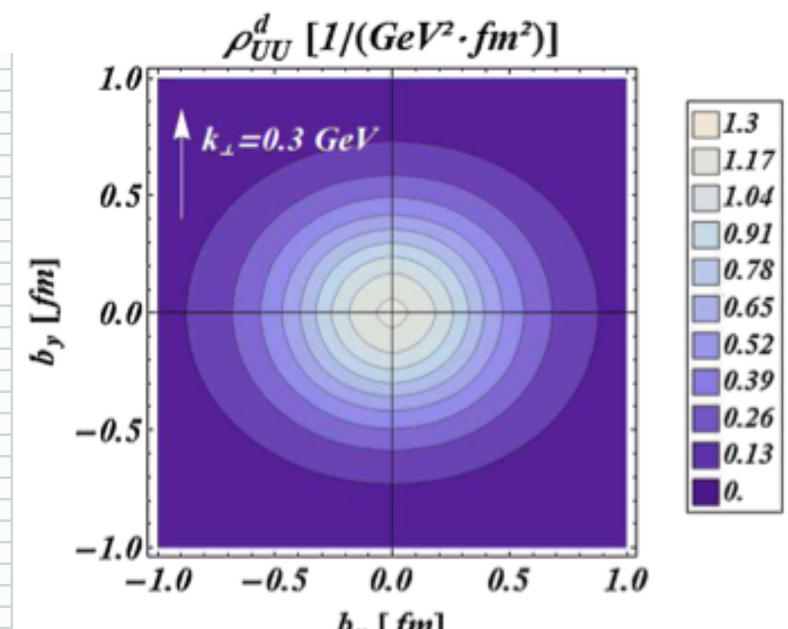
H_u [1/GeV^4]



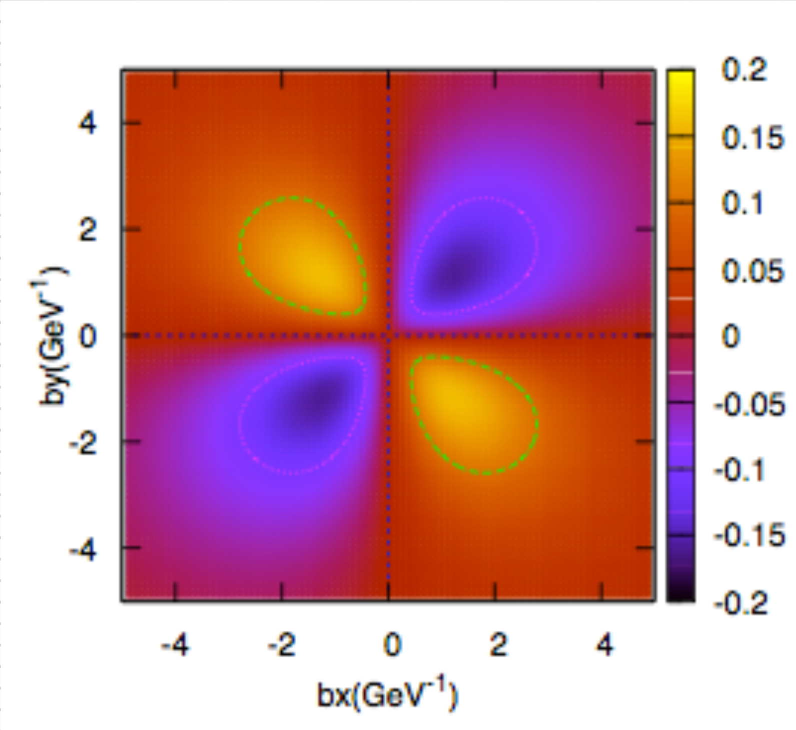


H_d [1/GeV^4]





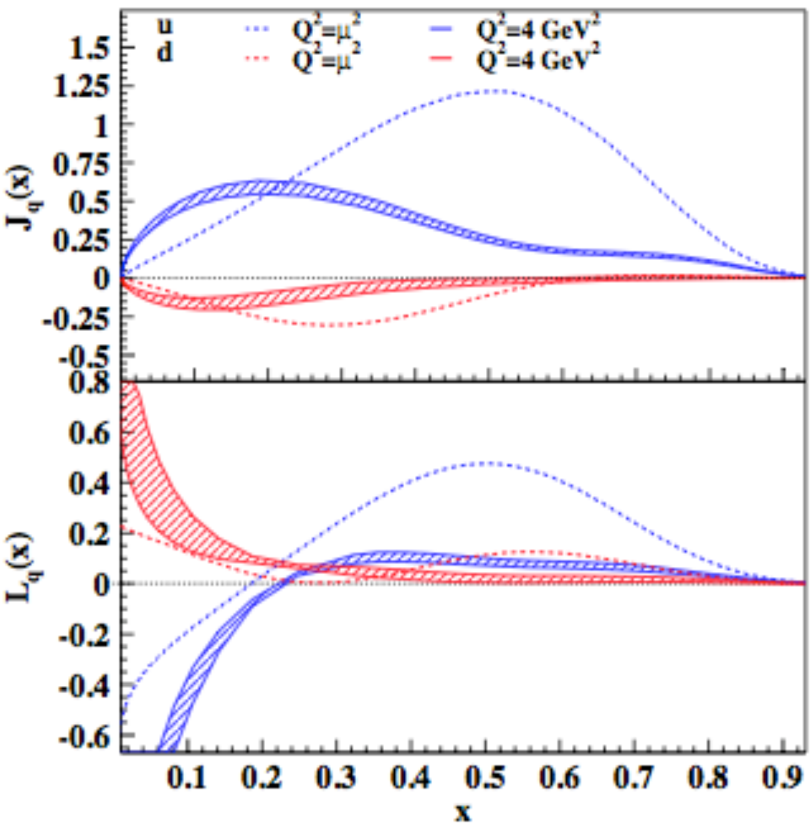
E



ρ_{TU}?

…finally, a way to explore gluon OAM !!

Orbital Angular Momentum in the Deuteron



New sum rule for spin 1 system ➔deuteron

$$J_q = \frac{1}{2}\int dx\, x\,[H_q(x,0,0) + E_q(x,0,0)]\,,$$

$$J_q = \frac{1}{2}\int dx\, x\, H_2^q(x,0,0),$$

+ H.O.

$F_1+F_2= G_M$

G_M

Taneja, Kathuria, S.L., Goldstein, arXiv:1101.0581, Phys.Rev.D, 2012

Additional interest in Spin 1 targets: deuterium, ^{6}Li, …

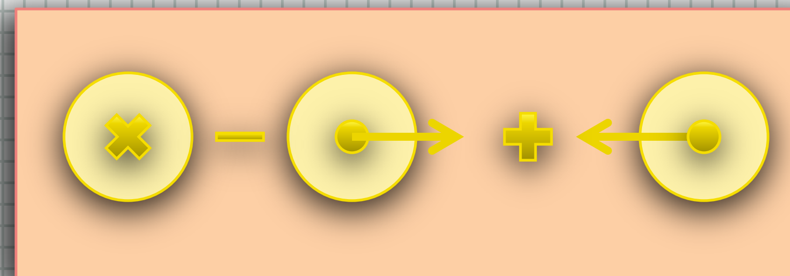
✓ In DIS: Unique possibility to study how the deep inelastic structure of nuclei differs from a system of free nucleons.

➔ One more distribution w.r.t. spin 1/2

Tensor Structure Function

Hoobhoy, Jaffe, Manohar (1989)

$$b_1(x) = \frac{1}{2}\left[2q_\uparrow^0 - \left(q_\uparrow^1 + q_\downarrow^1\right)\right]$$



$b_1(x) \to 0$ for free nucleons

$b_1(x) \neq 0$ in bound systems

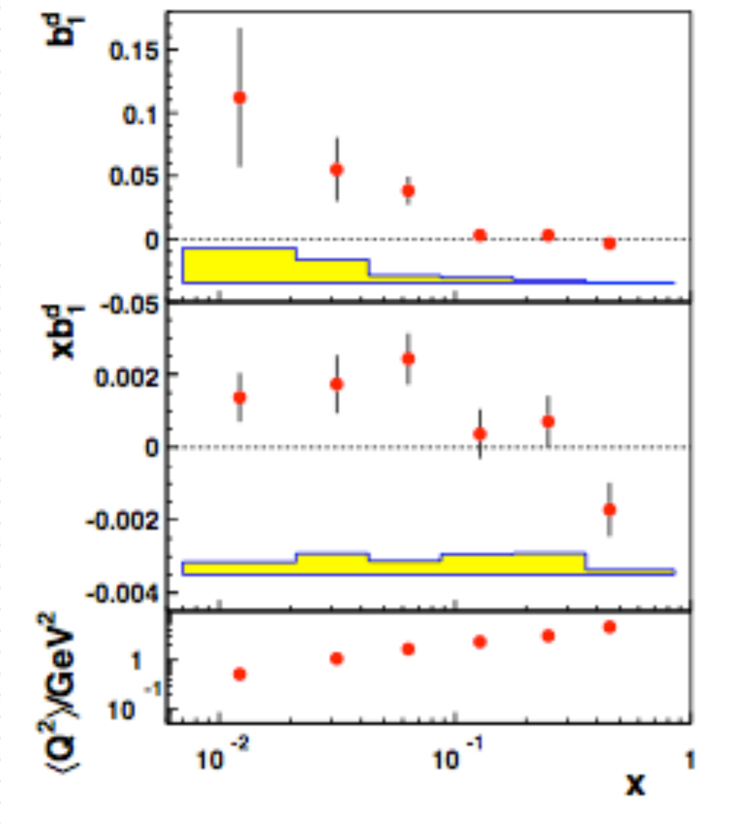
➔ Role of D wave!

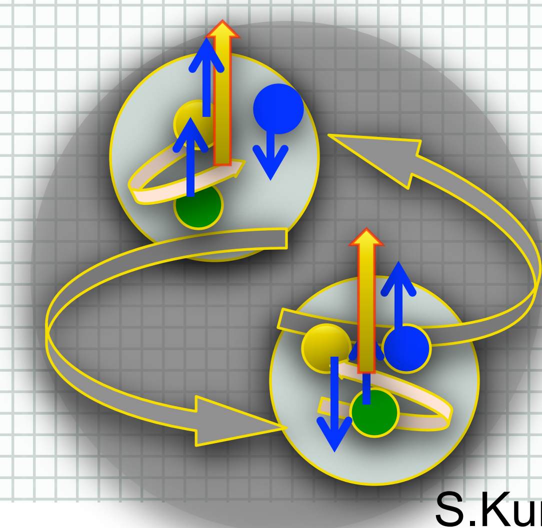
Sum Rule

$$\int b_1(x)\,dx = \frac{1}{9}\int\left\{4\left[\bar{u}_\uparrow^0 - \left(\bar{u}_\uparrow^1 + \bar{u}_\downarrow^1\right)\right] + \left[\bar{d}_\uparrow^0 - \left(\bar{d}_\uparrow^1 + \bar{d}_\downarrow^1\right)\right] + \left[\bar{s}_\uparrow^0 - \left(\bar{s}_\uparrow^1 + \bar{s}_\downarrow^1\right)\right]\right\}dx$$

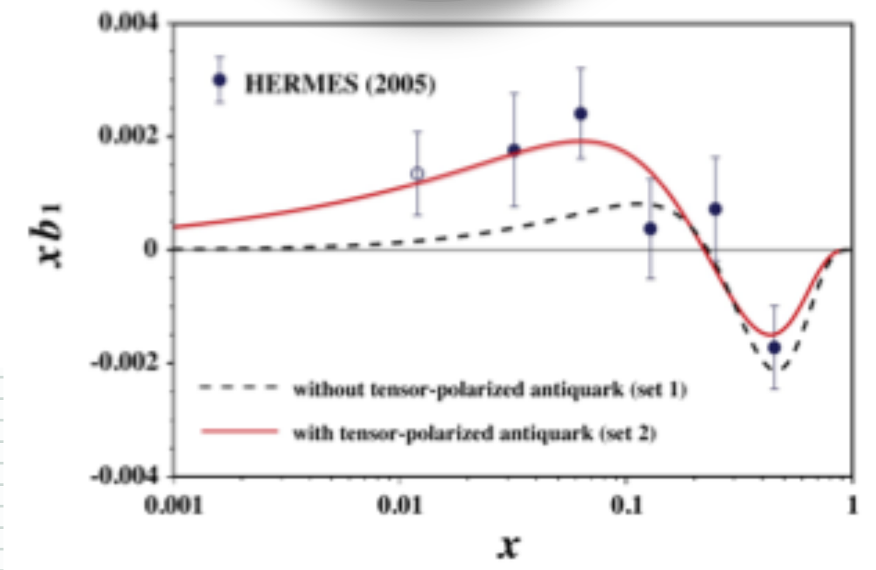
Close and Kumano (1990)

Hermes 2005

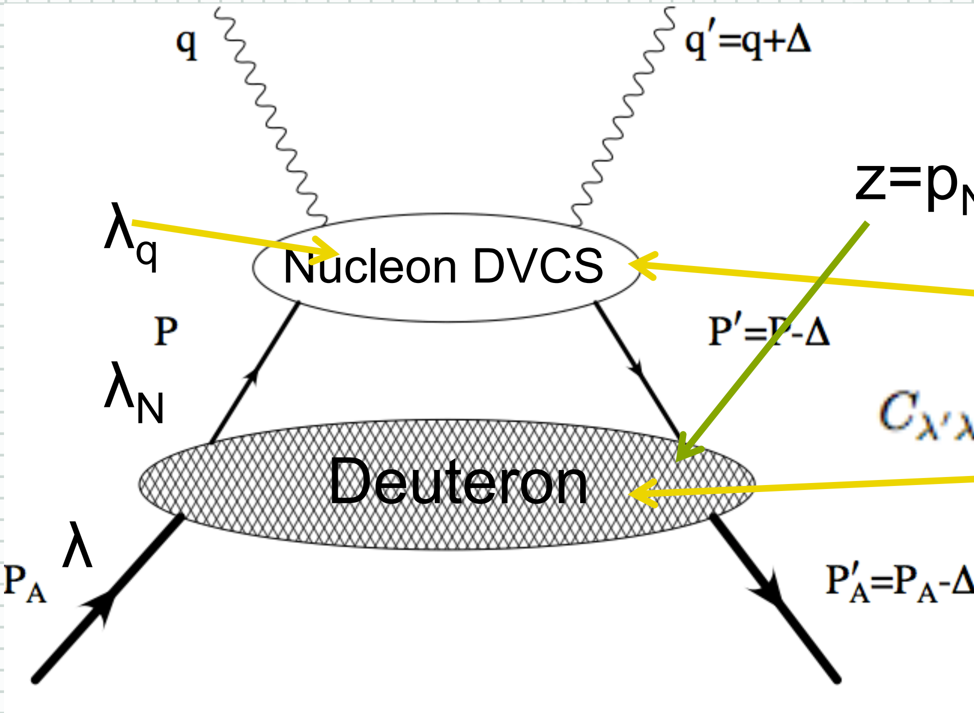




S.Kumano PRD82,2010



What are the quark and gluon angular momenta in the deuteron?



$z = p_N^+/P^+_D$

$$C_{\lambda'\lambda'_q,\lambda\lambda_q} = \sum_{\lambda_N,\lambda'_N} B_{\lambda'\lambda'_N,\lambda\lambda_N} \otimes A_{\lambda'_N\lambda'_q,\lambda_N\lambda_q}$$

$$\sqrt{\frac{t_0 - t}{2M^2}} H_2(x,0,0) = 2\left[\left(C_{1+,1+} + C_{1-,1-}\right) - \left(C_{1+,0+} + C_{1-,0-}\right)\right]$$

$$\Rightarrow H_2 \approx \int_x^{M_D/M_N} dz \left[f^{++}(z) H_{ISO}(x/z,0,0) + f^{0+}(z) E_{ISO}(x/z,0,0) \right]$$

$H_{ISO} = H_u + H_d \quad E_{ISO} = E_u + E_d$

Deuteron LC Momentum distribution

$$f^{++}(z) = 2\pi M \int_{p_{min}(z)}^{\infty} dp\, p \sum_{\lambda_N} \chi_+^{*\,\lambda'_{N_1}\lambda_{N_2}}(z,p)\,\chi_+^{\lambda_{N_1}\lambda_{N_2}}(z,p) \tag{14}$$

$$f^{0+}(z) = 4\pi M \int_{p_{min}(z)}^{\infty} dp\, p \sum_{\lambda_N} \chi_0^{*\,\lambda'_{N_1}\lambda_{N_2}}(z,p)\,\chi_+^{\lambda_{N_1}\lambda_{N_2}}(z,p). \tag{15}$$

$z = p_N^+ / P^+_D$

$\lambda_N = \{\lambda_{N1}, \lambda'_{N1}\lambda_{N2}\}$

Deuteron w.f. (momentum space)

$$\chi_\lambda^{\lambda_{N_1},\lambda_{N_2}}(z,p) = \mathcal{N} \sum_{L,m_L,m_S} \begin{pmatrix} j_1 & j_2 & 1 \\ \lambda_{N_1} & \lambda_{N_2} & m_S \end{pmatrix} \begin{pmatrix} L & S & J \\ m_L & m_S & \lambda \end{pmatrix} \times Y_{L\,m_L}\left(\frac{\mathbf{p}}{p} = \frac{M(1-z)-E}{p}\right) u_L(p),$$

Mixture of S and D components , L=0,2

If $f^{++}(z) = f^{+0}(z) = \delta(1-z)$ then $H_2 = H + E$

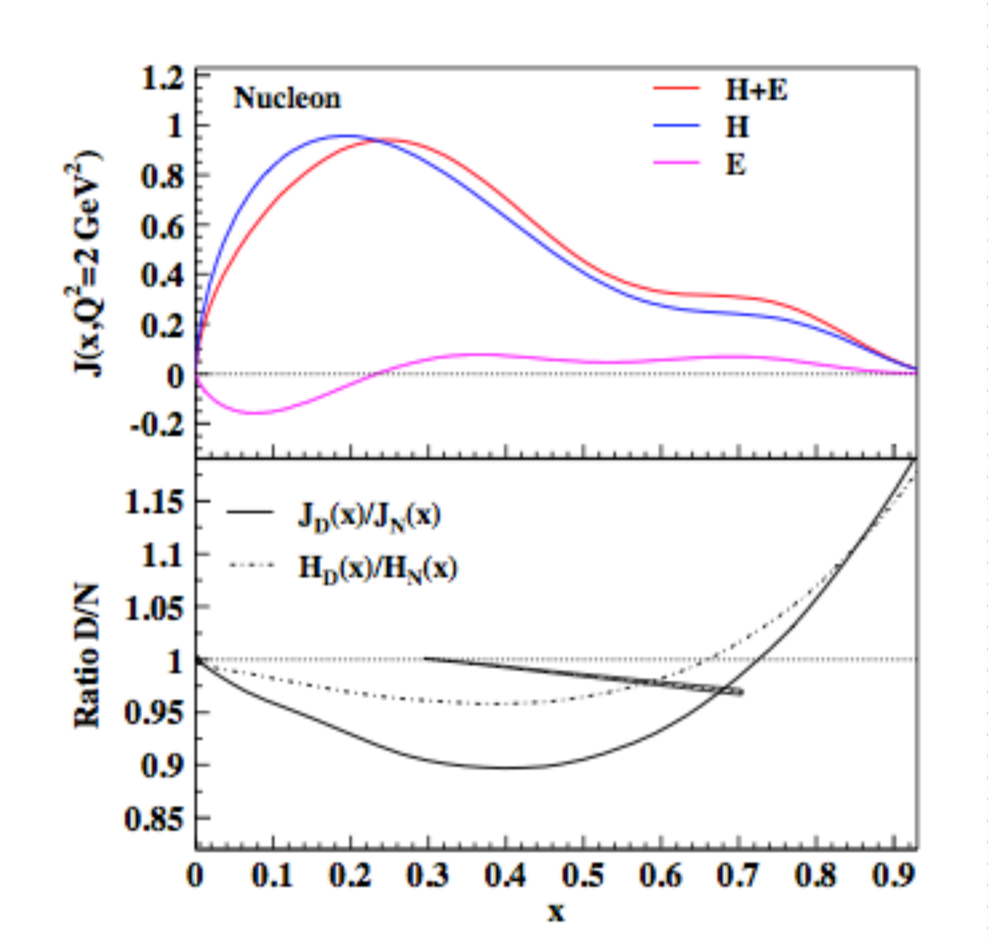
$$J_q = \frac{1}{2}\int dx\, x\left[H_q(x,0,0) + E_q(x,0,0)\right],$$

→

$$J_q = \frac{1}{2}\int dx\, x\, H_2^q(x,0,0),$$

$F_1 + F_2 = G_M$

G_M



Observable sensitive to gluon OAM

$$A_{UT} \approx -\frac{4\sqrt{D_0}}{\Sigma} \Im m \left[\mathcal{H}_1^* \mathcal{H}_5 + \left(\mathcal{H}_1^* + \frac{1}{6}\mathcal{H}_5^* \right) (\mathcal{H}_2 - \mathcal{H}_4) \right]$$

subleading

Conclusions

- GPDs can be extracted from data (once the questions addressed in this talk are considered)
- We have a well tested parametrization that satisfies all constraints – including form factor normalization – for the valence and sea quarks distributions. Work in progress to include gluon component.
- Many open questions on the interpretation of GTMDs and their connection to observables: issue of "observability" of OAM
- Deuteron is an important target: access to gluons
- All of these questions call for new analysis methods (Neural Network and Self Organizing Maps Approaches are the future)
- All of these questions can be addressed in a systematic way at an EIC