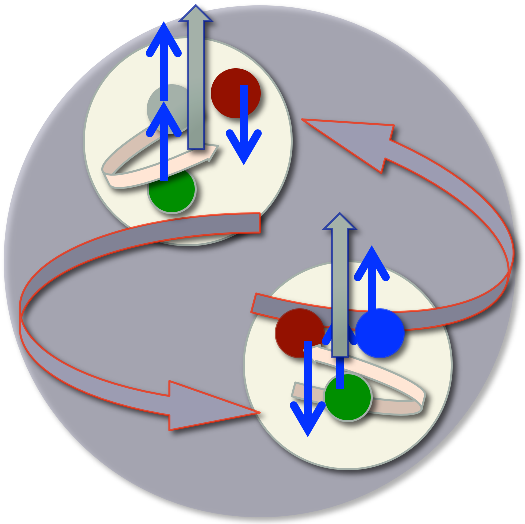
BSM INTERACTIONS AND HADRON PHENOMENOLOGY

EICUG MEETING
JEFFERSON LAB, DECEMBER 19, 2017

Simonetta Liuti
University of Virginia



Based on

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees Search Press

Beyond-Standard-Model Tensor Interaction and Hadron Phenomenology

Aurore Courtoy, Stefan Baeßler, Martín González–Alonso, and Simonetta Liuti

Phys. Rev. Lett. **115**, 162001 – Published 15 October 2015

…and a newly formed group

Baessler, Liuti (Virginia)	Experiment/Phenomenolgy
Bacchetta, Radici (Pavia)	Phenomenolgy
Courtoy (UNAM, Mexico)	Phenomenolgy
Engelhardt (NMSU)	Lattice

Outline

1. Introduction
2. Role of spin dependent observables in low energy processes (neutron beta decay, EDM)
3. Chiral Odd GPDs
4. Extraction from experiment: role of EIC
5. Impact on BSM searches
6. Conclusions and Outlook

1. INTRODUCTION

ROLE OF QCD PHENOMENOLGY IN SEARCHES FOR NEW PHYSICS

We live in interesting times….

…*rising new questions and challenges* trigger future developments for strong-interaction physics/QCD in the "post-discovery of the Higgs boson era" at the LHC.

QCD impacts the extraction of several of the 19 (28) fundamental parameters in the SM

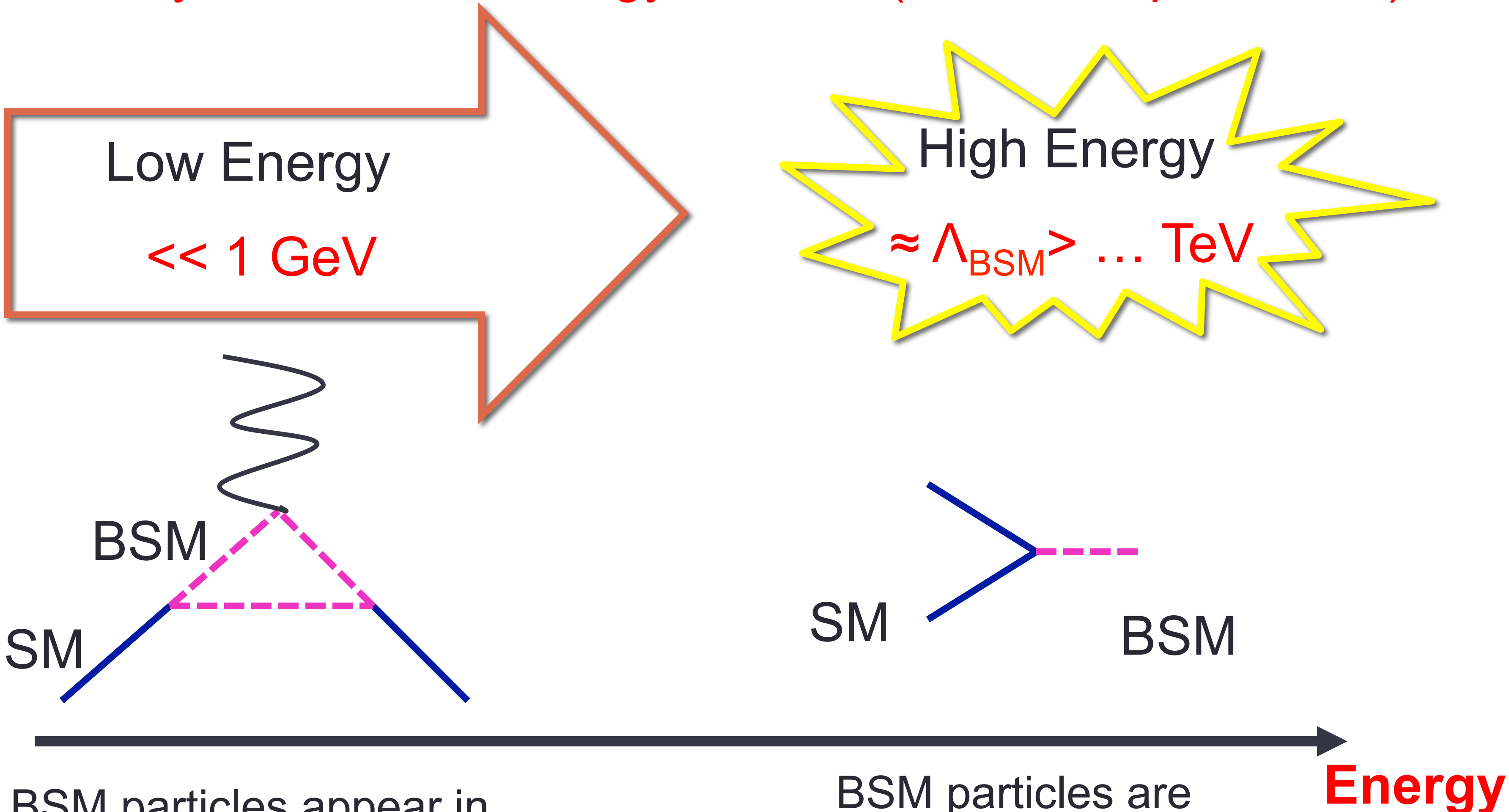
1. The Weinberg angle or weak mixing angle θ_W
2. The strong interaction coupling constant α_S
3. The electroweak symmetry breaking energy scale (or the Higgs potential vacuum expectation value, v.e.v.) v
4. The Higgs potential coupling constant λ /the Higgs mass m_H
5. The three mixing angles θ_{12}, θ_{23} and θ_{13} and the CP-violating phase δ_{13} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix
6. The Yukawa coupling constants that determine the masses of the 6 quarks.
7. … + 3 charged leptons
8. Strong CP parameter

Impact of QCD on indirect searches for BSM physics

1. CP violation in *B* mesons decays
2. Permanent Electric Dipole Moment (EDM) in hadrons and nuclei
3. Anomalous magnetic moment of the muon
4. Neutrino physics
5. PVDIS
6. Non V-A contributions in nuclear, neutron and pion beta decay
7. …..

Intensity Frontier

Intensity Frontier vs. Energy Frontier (collider experiments)

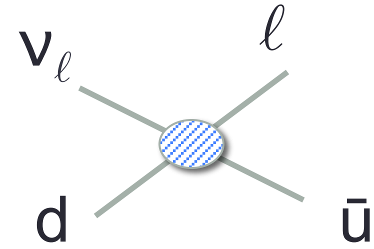


BSM particles appear in loops

BSM particles are produced directly

BSM Effective Lagrangian

V. Cirigliano et al., Prog.Nuc.Part. Phys. (2013)



$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)$$
$$\times[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}[\gamma^\mu - (1-2\epsilon_R)\gamma^\mu\gamma_5]d$$
$$+\bar{\ell}(1-\gamma_5)\nu_\ell \cdot \bar{u}[\epsilon_S - \epsilon_P\gamma_5]d$$
$$+\epsilon_T\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d] + \text{H.c.},$$

$$\varepsilon_{L,R,S,P,T} \approx \frac{m_W^2}{\Lambda_{BSM}^2}$$

Vector	$\bar{u}\gamma^\mu u$
Axial-Vector	$\bar{u}\gamma^\mu\gamma^5 u$
Pseudoscalar	$\bar{u}\gamma^5 u$
Scalar	$\bar{u}u$
Tensor	$\bar{u}\sigma^{\mu\nu}u$

The "strong interactions issues" in all of these examples are outstanding questions that stimulate a deeper understanding of the structure of hadrons

1. Spin structure: longitudinal and transverse spin, spin crisis, role of orbital angular momentum.
2. Running of α_S
3. Transverse Momentum Distributions: QCD factorization for quark and gluons
4. …

At the same time … understanding these issues gives us insights into strongly coupled gauge theories

- ✓ … from the high energy end: models for dark matter, BSM Higgs mechanism…
- ✓ … to the low energy end: description of lattices with QCD symmetry from cold atoms, Wigner distributions at the femtoscale…

2. ROLE OF SPIN DEPENDENT OBSERVABLES

A. Courtoy, S. Baessler, M. Gonzalez-Alonso and S. Liuti, arXiv: 1503.06814 [hep-ph], Phys ReV. Lett (2015).

Differential decay distribution for polarized neutron decay

$$n \to p + e^- + \bar{\nu}$$

T.D. Lee, Chen-Ning Yang, Phys. Rev. 104 (1956)

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{(G_F^{(0)})^2 |V_{ud}|^2}{(2\pi)^5}(1 + 2\epsilon_L + 2\epsilon_R) \times (1 + 3\tilde{\lambda}^2) \cdot w(E_e) \cdot D(E_e, \mathbf{p}_e, \mathbf{p}_\nu, \boldsymbol{\sigma}_n),$$

$$D(E_e, \mathbf{p}_e, \mathbf{p}_\nu, \boldsymbol{\sigma}_n) = 1 + c_0 + c_1 \frac{E_e}{M_N} + \boxed{\frac{m_e}{E_e}\bar{b}} + \bar{a}(E_e)\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \bar{A}(E_e)\frac{\boldsymbol{\sigma}_n \cdot \mathbf{p}_e}{E_e} + \boxed{\bar{B}(E_e)}\frac{\boldsymbol{\sigma}_n \cdot \mathbf{p}_\nu}{E_\nu} + \bar{C}_{(aa)}(E_e)\left(\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu}\right)^2 + \bar{C}_{(aA)}(E_e)\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu}\frac{\boldsymbol{\sigma}_n \cdot \mathbf{p}_e}{E_e} + \bar{C}_{(aB)}(E_e)\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu}\frac{\boldsymbol{\sigma}_n \cdot \mathbf{p}_\nu}{E_\nu}, \quad (9)$$

Fierz term

These terms can contain tensor corrections

A more specific look…

$$b = \frac{2}{1+3\lambda^2}\left[g_S\epsilon_S - 12\boxed{g_T\epsilon_T}\lambda\right]$$
$$b_\nu = \frac{2}{1+3\lambda^2}\left[g_S\epsilon_S\lambda - 4\boxed{g_T\epsilon_T}(1+2\lambda)\right],$$

g_T and g_S are the flavor non-singlet/isovector hadronic matrix elements

$$\langle p_p, S_p|\,\bar{u}d\,|p_n, S_n\rangle = g_S(-t)\,\overline{U}(p_p, S_p)U(p_n, S_n) \quad ,$$
$$\langle p_p, S_p|\,\bar{u}\sigma_{\mu\nu}d\,|p_n, S_n\rangle = g_T(-t)\,\overline{U}(p_p, S_p)\sigma_{\mu\nu}U(p_n, S_n),$$

… or by using isospin symmetry:

$$\langle p_p', S_p|\,\bar{u}u - \bar{d}d\,|p_p, S_p\rangle = g_S(-t)\,\overline{U}(p_p', S_p)U(p_p, S_p) \quad ,$$
$$\langle p_p', S_p|\,\bar{u}\sigma_{\mu\nu}u - \bar{d}\sigma_{\mu\nu}d\,|p_p, S_p\rangle = g_T(-t)\,\overline{U}(p_p', S_p)\sigma_{\mu\nu}U(p_p, S_p),$$

The precision with which ε_T can be measured depends on the uncertainty on g_T

The observable is always the product of the fundamental coupling times a hadronic matrix element

$$\boxed{C_T = \frac{G_F}{\sqrt{2}} V_{ud} g_T \varepsilon_T}$$

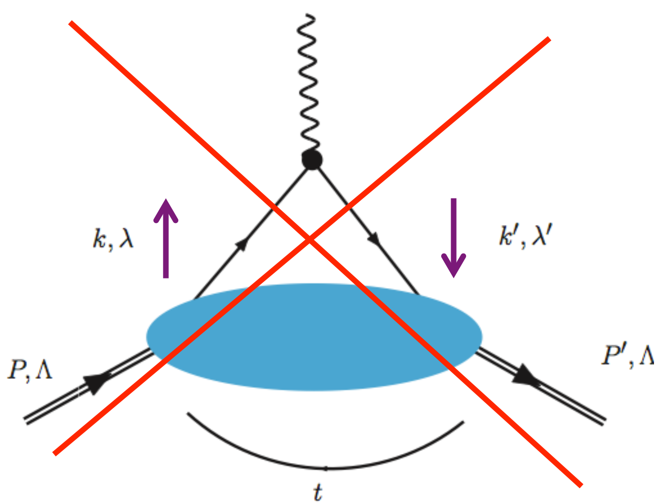
Lee-Yang effective coupling

Polarized hard scattering processes measurable at Jlab @12 GeV and at Electron Ion Collider (EIC) provide the hadronic matrix elements which are necessary to extract the possible BSM tensor, scalar and pseudo-scalar effective couplings entering the neutron beta decay cross section

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

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

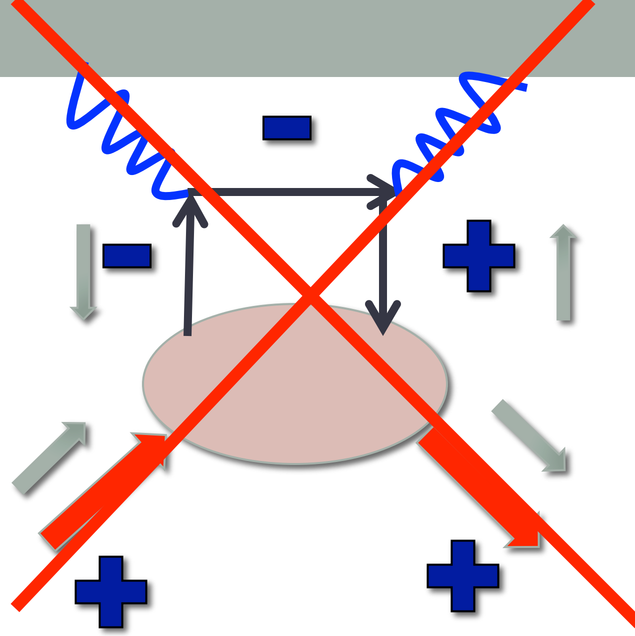
- ✓ The tensor charge is not "fundamental"
- ✓ A "tensor form factor" cannot be measured in elastic scattering type processes mediated by either one or two photons

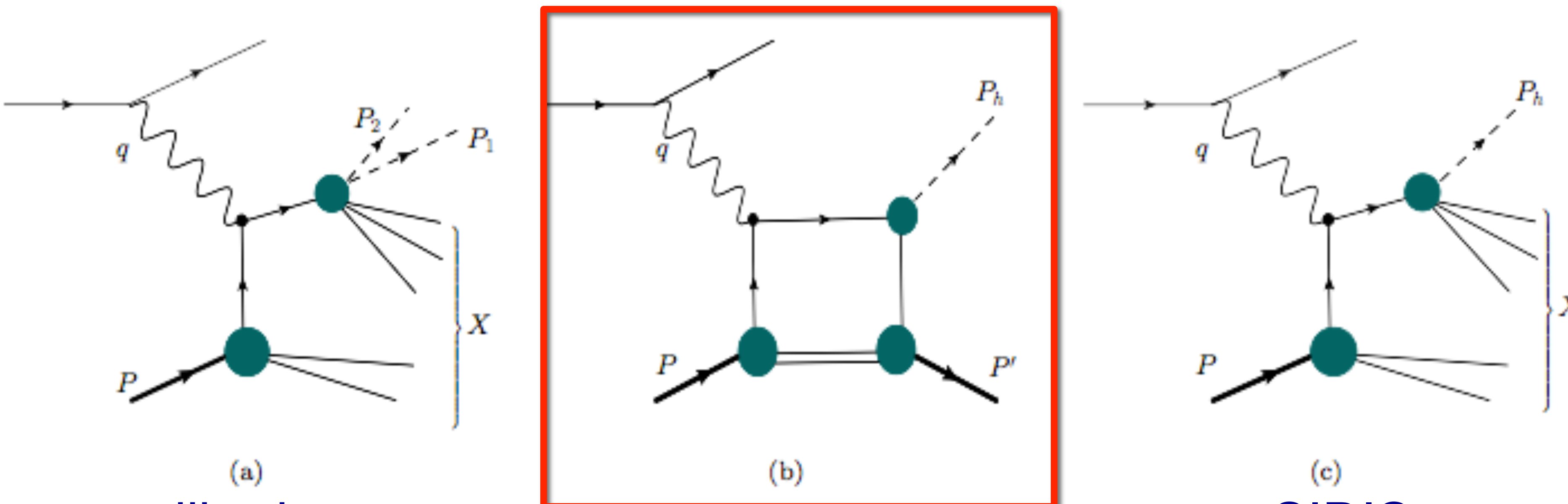


$$\langle p', \Lambda' \mid \pm i\bar{\psi}(0)\,\underbrace{\left(\sigma^{+1} \pm i\sigma^{+2}\right)\psi(0)}\mid p, \Lambda\rangle$$

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

To detect chiral odd
distributions we need
another
distinct hadronic blob





dihadron

DVπ°P, DVηP

SIDIS

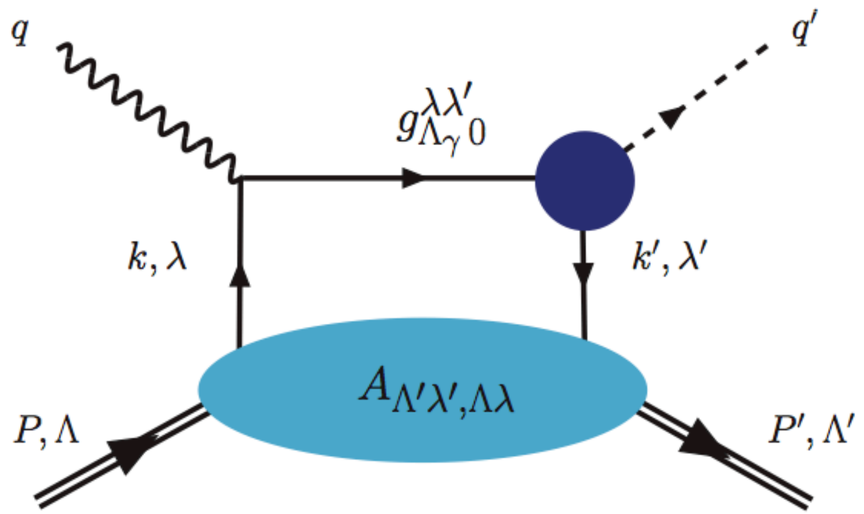
collinear

3. CHIRAL ODD GPD'S

$$\boxed{e\,p \to e'p'\pi^o}$$

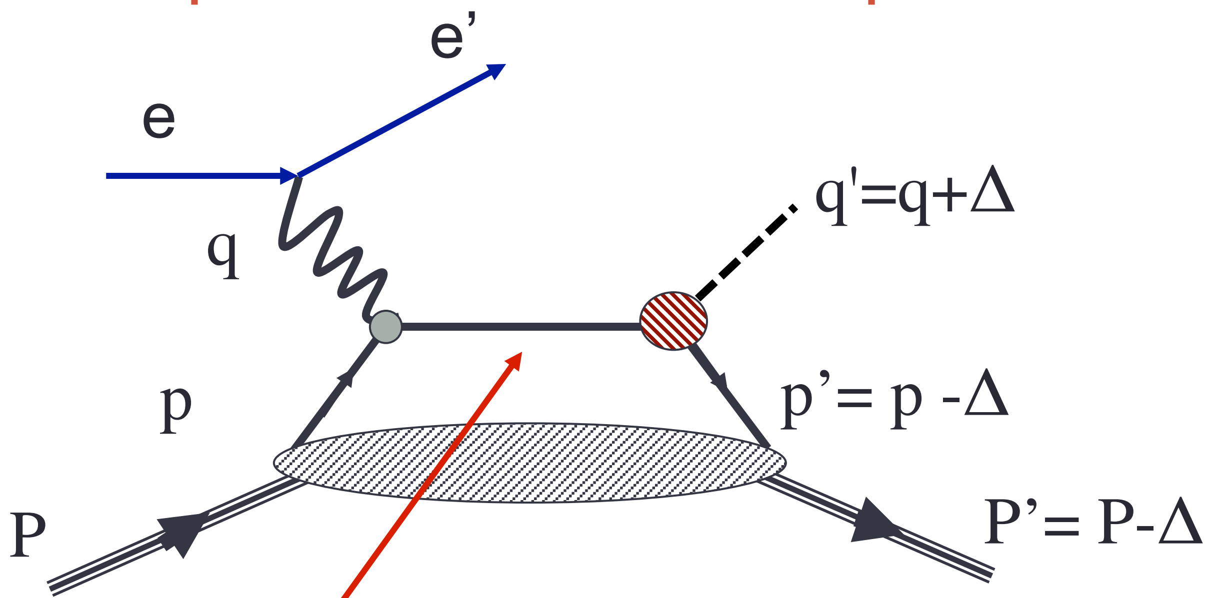
The non-local matrix elements probed are

$$\boxed{\langle P'|\bar{u}(\xi)\sigma_{\mu\nu}\,u(0)|P\rangle}$$



Ahmad et al. Phys.Rev. D79 (2009) 054014

Deeply virtual pseudoscalar meson production



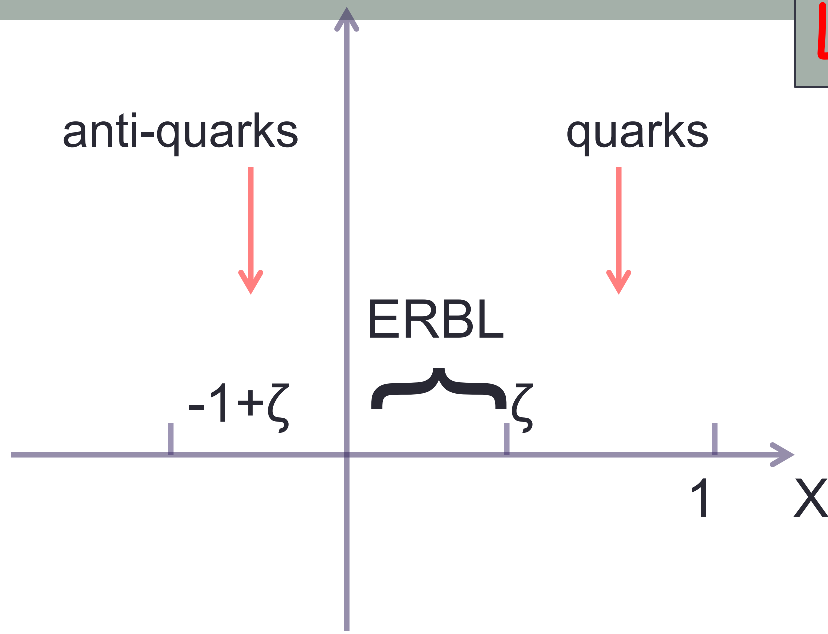
Loop directly in LO amplitude

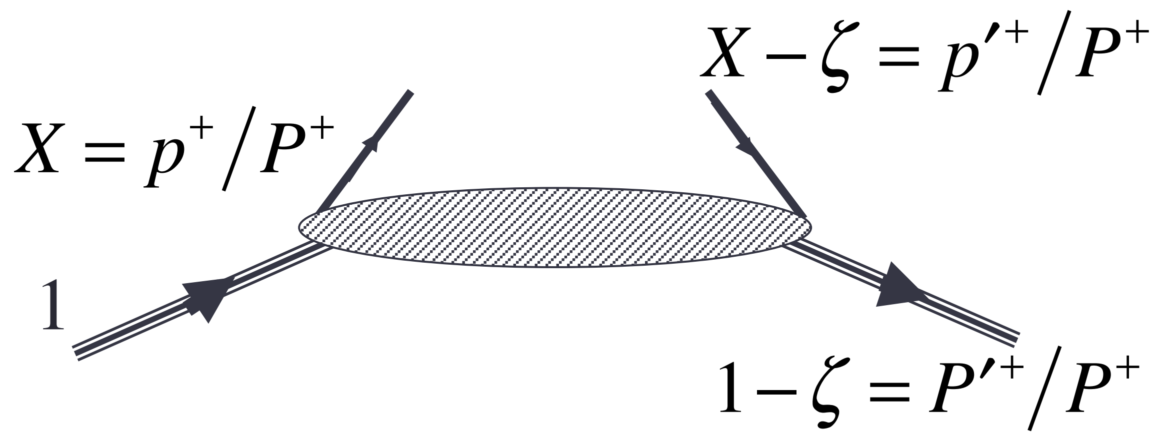
(1) $$\frac{1}{(p+q)^2-m^2+i\varepsilon}=PV\frac{1}{(p+q)^2-m^2}-i\pi\delta((p+q)^2-m^2)$$

Both Re and Im parts are present

(2) Quarks momenta and spins on LHS can be different from the RHS

Light Cone Variables

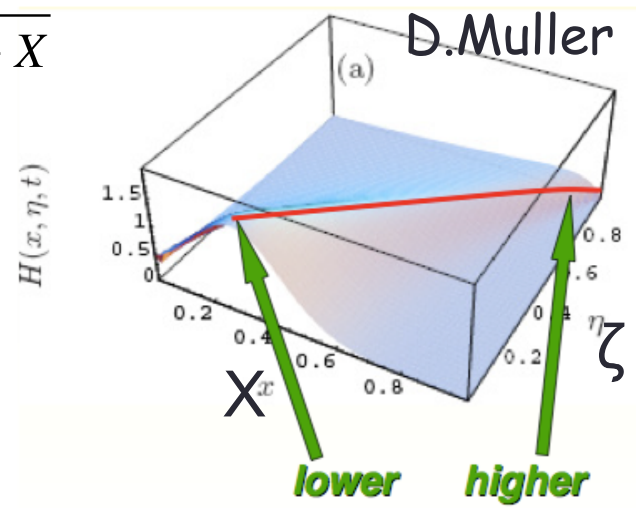




Asymmetry in kinematics on LHS and RHS of diagram

$$\frac{1}{(p+q)^2 - m^2 + i\varepsilon} = PV\frac{1}{(p+q)^2 - m^2} - i\pi\delta((p+q)^2 - m^2)$$

$$\rightarrow \frac{1}{-Q^2 + 2(pq) + i\varepsilon} \rightarrow \frac{1}{-Q^2/2(Pq) + (pq)/(Pq)} = \frac{1}{-\zeta + X}$$



Amplitude

$$\mathcal{F}_q = \boxed{P.V.\int_{-1+\zeta} dX\, F_q(X,\zeta,t)\left[\frac{1}{\zeta - X} - \frac{1}{X}\right]} + i\boxed{\pi e_q^2 F_q(\zeta,\zeta,t)}$$

GPD

Comptom Form Factor

GPD on “ridge”

Quark correlator in the chiral odd sector

$$
\boxed{\begin{aligned}
W_{\Lambda',\Lambda}^{[i\sigma^{i+}\gamma_5]}(x,\xi,t) = {}& \overline{U}(P',\Lambda')\left(i\sigma^{+i} H_T(x,\xi,t) + \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2M} E_T(x,\xi,t) \right. \\
& \left. + \frac{P^+\Delta^i - \Delta^+P^i}{M^2}\widetilde{H}_T(x,\xi,t) + \frac{\gamma^+P^i - P^+\gamma^i}{2M}\widetilde{E}_T(x,\xi,t)\right) U(P,\Lambda)
\end{aligned}}
$$

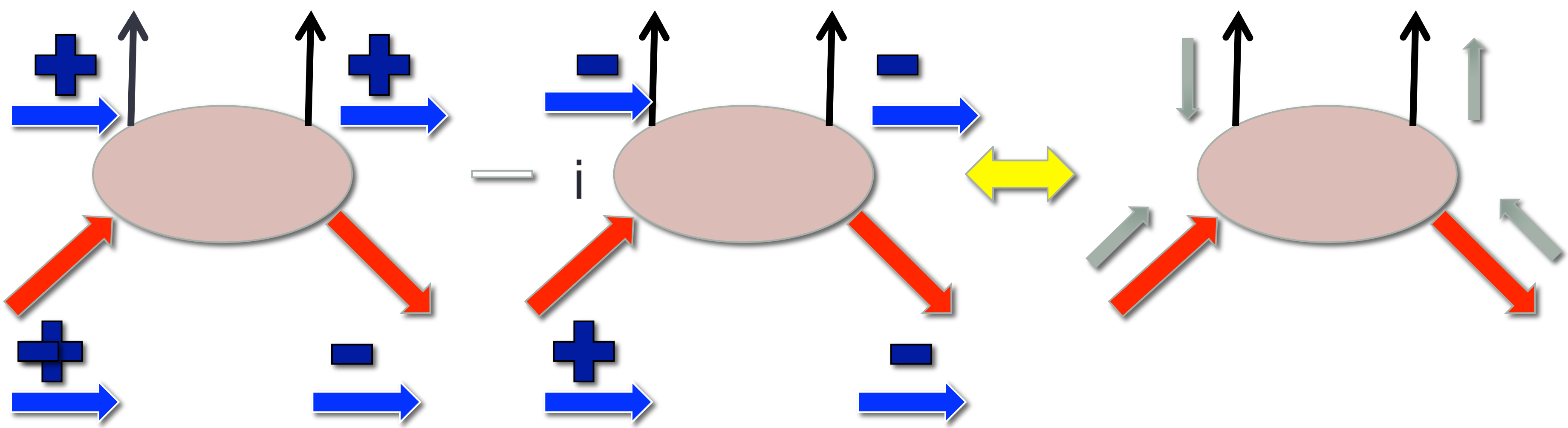
Transversity and the Tensor Charge/Tensor Form Factor

Net transverse polarization of a quark in transversely polarized proton:

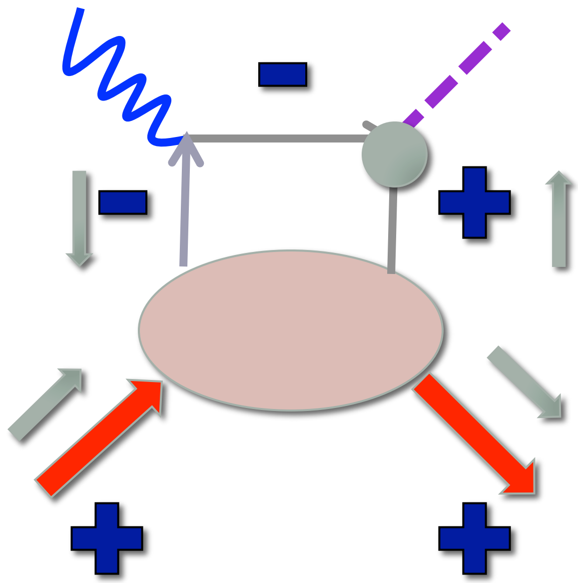
$$\boxed{h_1\left(x,Q^2\right) \Rightarrow \int_0^1 dx\, h_1\left(x,Q^2\right) = \delta(Q^2)}$$

$$\left|\uparrow\downarrow\right\rangle_Y = \left|\rightarrow\right\rangle \pm i\left|\leftarrow\right\rangle$$

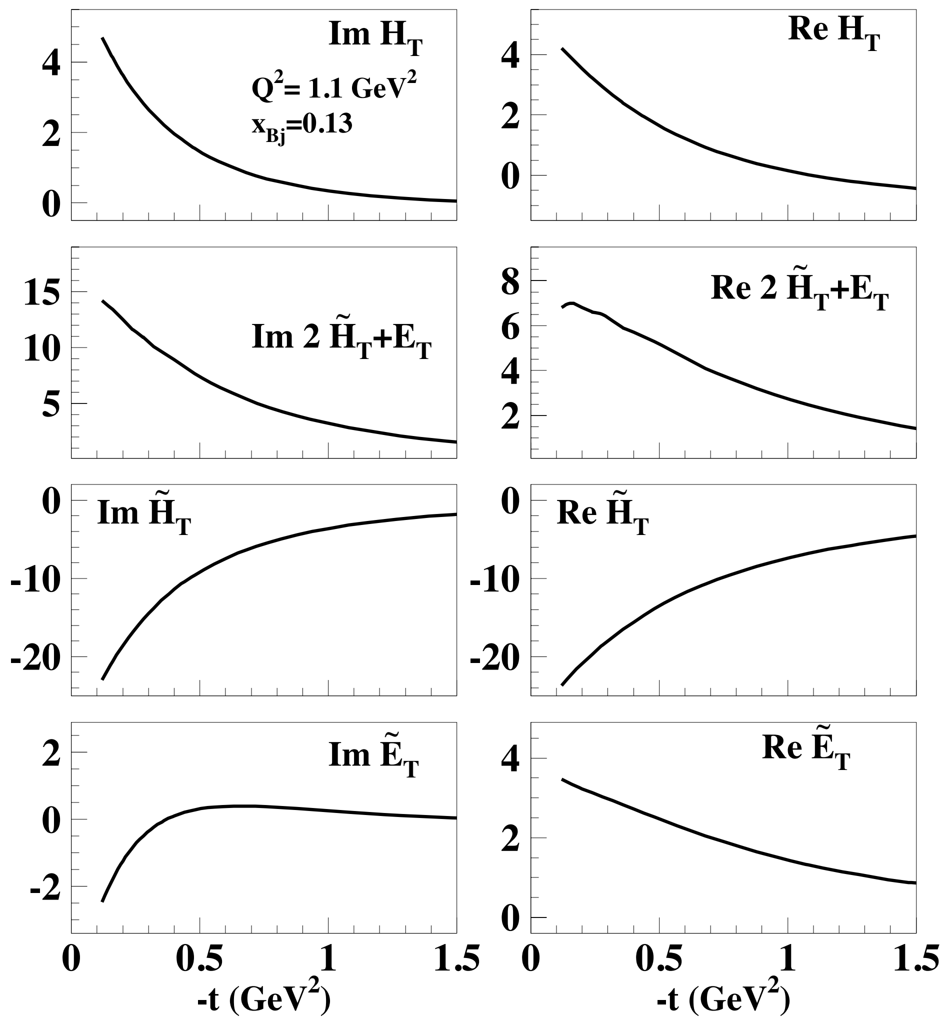
$$A_{\Lambda'\pm,\Lambda\mp} \Leftrightarrow H_T, E_T, \tilde{H}_T, \tilde{E}_T$$



Tensor Anomalous Magnetic Moment

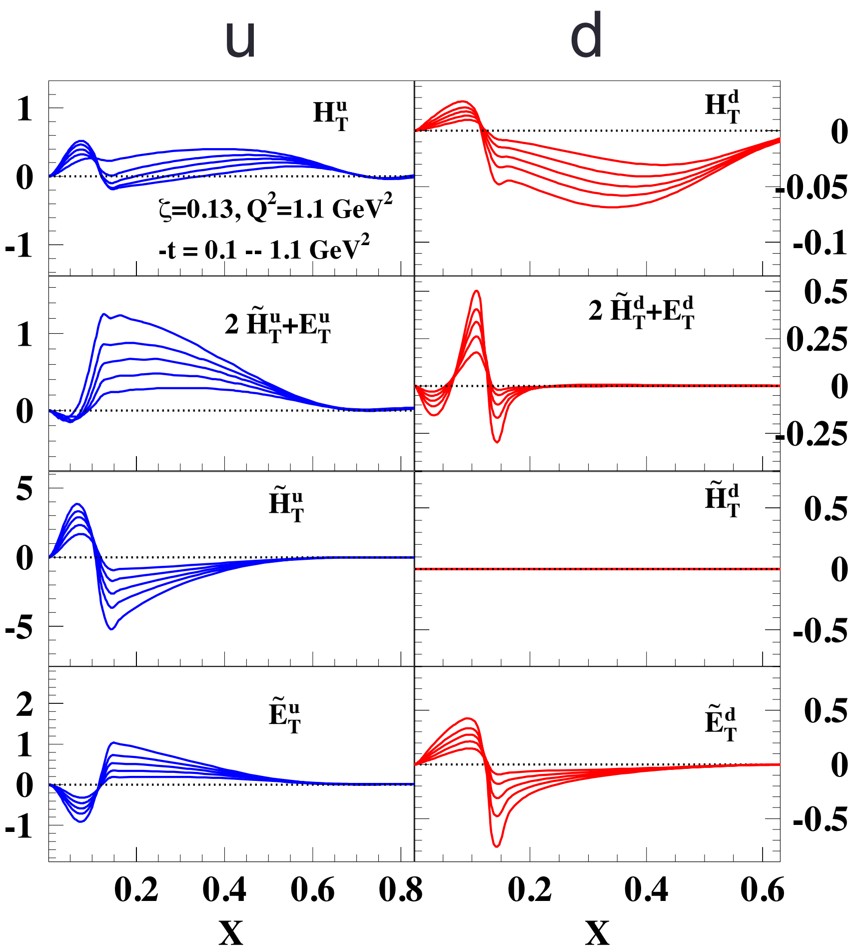


$A_{+-,++}$ $\Rightarrow$ $2\tilde{H}_T + E_T$



Im H_T
Q^2= 1.1 GeV^2
x_{Bj}=0.13
Re H_T
Im 2 $\tilde{H}_T$+E_T
Re 2 $\tilde{H}_T$+E_T
Im $\tilde{H}_T$
Re $\tilde{H}_T$
Im $\tilde{E}_T$
Re $\tilde{E}_T$
-t (GeV^2)
-t (GeV^2)

The Chiral Odd sector is vastly unexplored



G. Goldstein, O. Gonzalez-Hernandez, S.L., PRD(2015) arXiv:1311.0483

tensor charge

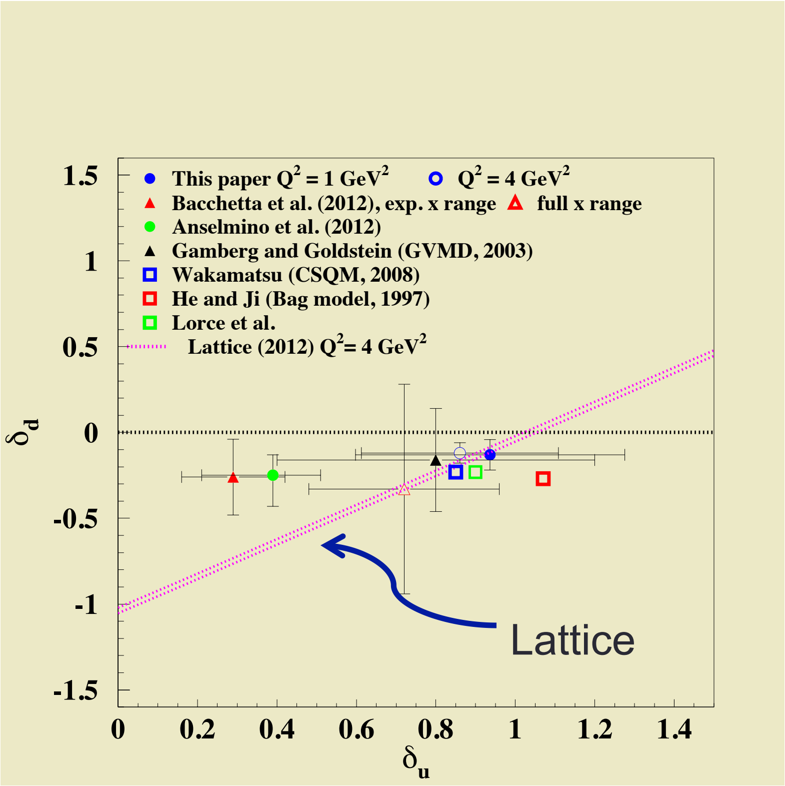
$$\int dx\, H_T^q(x,\zeta,t,Q^2) = \delta_q(t,Q^2)$$

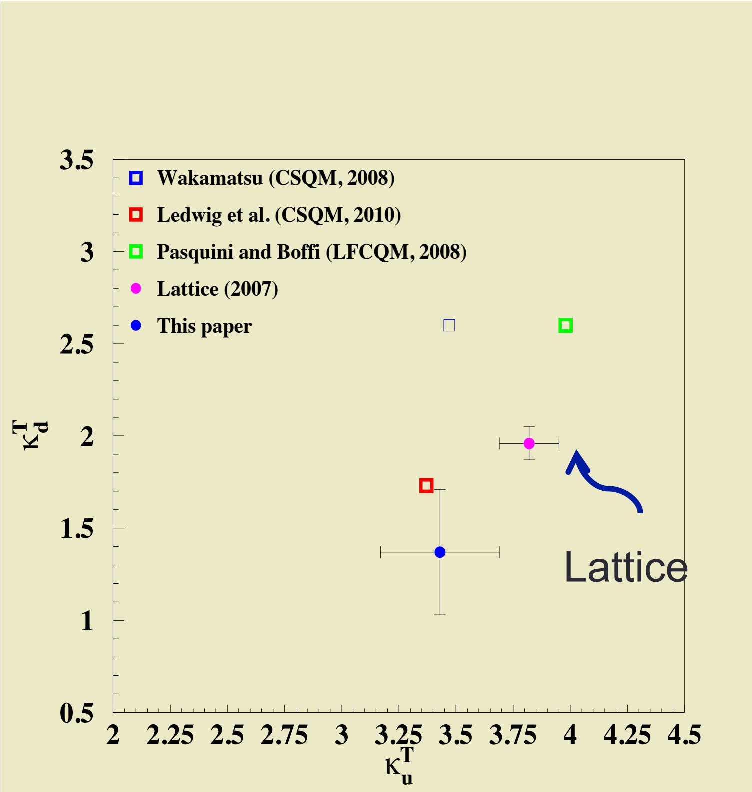
tensor anomalous magnetic moment

$$\int dx\, [2\tilde{H}_T^q(x,\zeta,t,Q^2) + E_T^q(x,\zeta,t,Q^2)] = \kappa_q(t,Q^2)$$

(M. Burkardt, PRD66, 114005 (2002))

arXiv:1401.0438 [hep-ph]





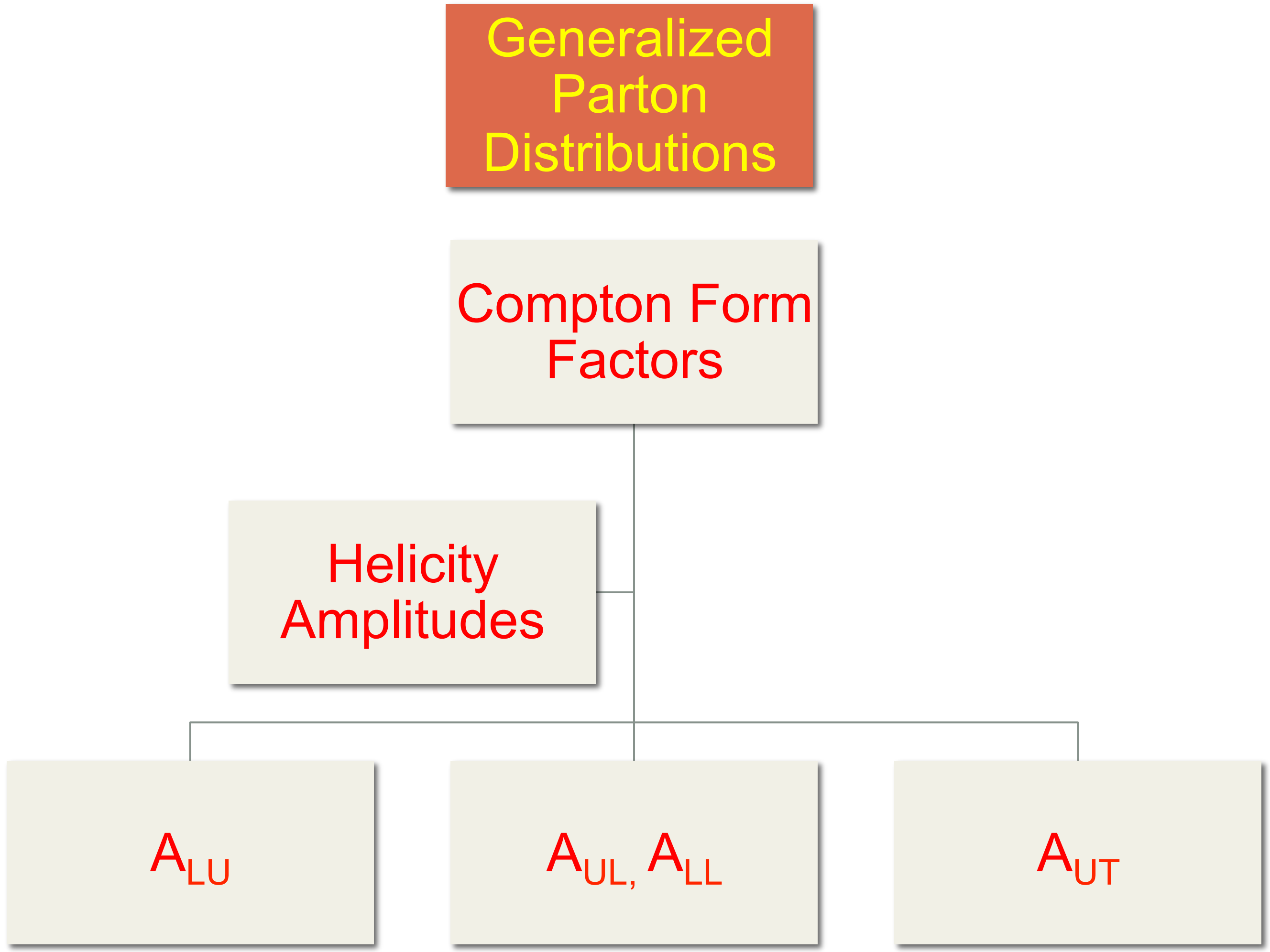
J.~R.~Green, J.~W.~Negele, A.~V.~Pochinsky, S.~N.~Syritsyn, M.~Engelhardt and S.~Krieg,
%``Nucleon Scalar and Tensor Charges from Lattice QCD with Light Wilson Quarks,''
Phys.\ Rev.\ D {\bf 86}, 114509 (2012)

M. Gockeler et al. [QCDSF and UKQCD Collaborations], Phys. Rev. Lett. 98, 222001 (2007)

4. EXTRACTION FROM EXPERIMENT

Experiment: DVπ°P, DVηP

(Hall A and B, K. Joo, M. Defurne)



Cross Section Formulation

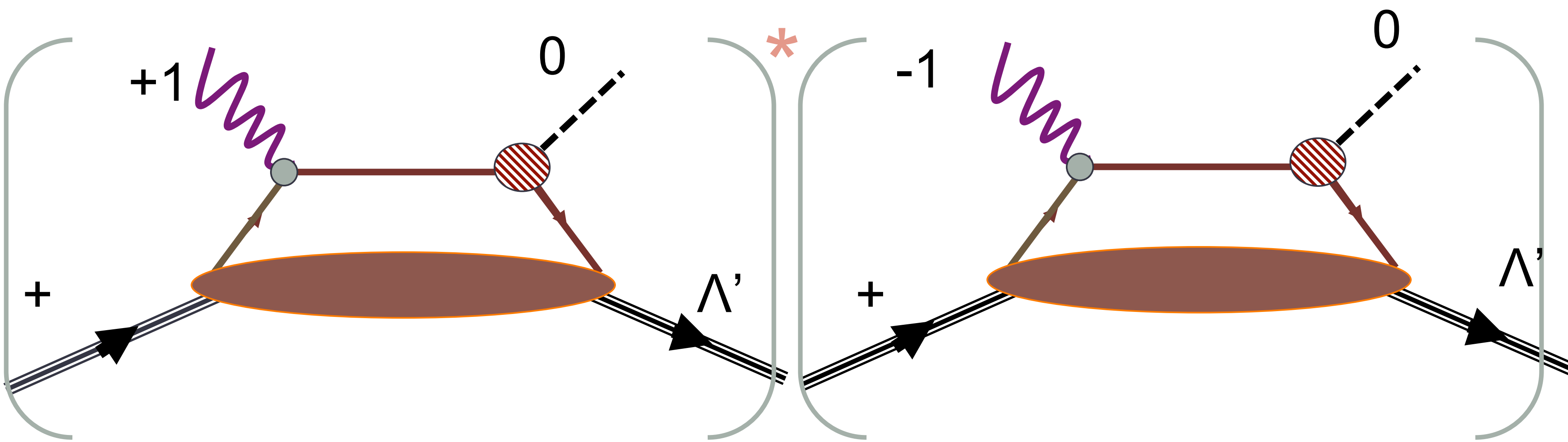
Goldstein, Gonzalez Hernandez, S.L. Phys.Rev. D91 (2015)

$$
\begin{aligned}
\frac{d^4\sigma}{dx_{Bj}dyd\phi dt} = \Gamma \Big\{ & \boxed{F_{UU,T} + \epsilon F_{UU,L} + \epsilon \cos 2\phi F_{UU}^{\cos 2\phi} + \sqrt{2\epsilon(\epsilon+1)} \cos\phi F_{UU}^{\cos\phi} + h\sqrt{2\epsilon(1-\epsilon)}\, \sin\phi F_{LU}^{\sin\phi} \Big]} \\
& + S_{||} \Big[\sqrt{2\epsilon(\epsilon+1)} \sin\phi F_{UL}^{\sin\phi} + \epsilon \sin 2\phi F_{UL}^{\sin 2\phi} + h \Big(\sqrt{1-\epsilon^2}\, F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\, \cos\phi\, F_{LL}^{\cos\phi} \Big) \Big] \\
& + S_{\perp} \Big[\sin(\phi-\phi_S) \Big(F_{UT,T}^{\sin(\phi-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi-\phi_S)} \Big) + \epsilon \Big(\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \Big) \\
& + \sqrt{2\epsilon(1+\epsilon)} \Big(\sin\phi_S F_{UT}^{\sin\phi_S} + \sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)} \Big) \Big] \\
& + S_{\perp} h \Big[\sqrt{1-\epsilon^2} \cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \Big(\cos\phi_S F_{LT}^{\cos\phi_S} + \cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)} \Big) \Big] \Big\}
\end{aligned}
$$

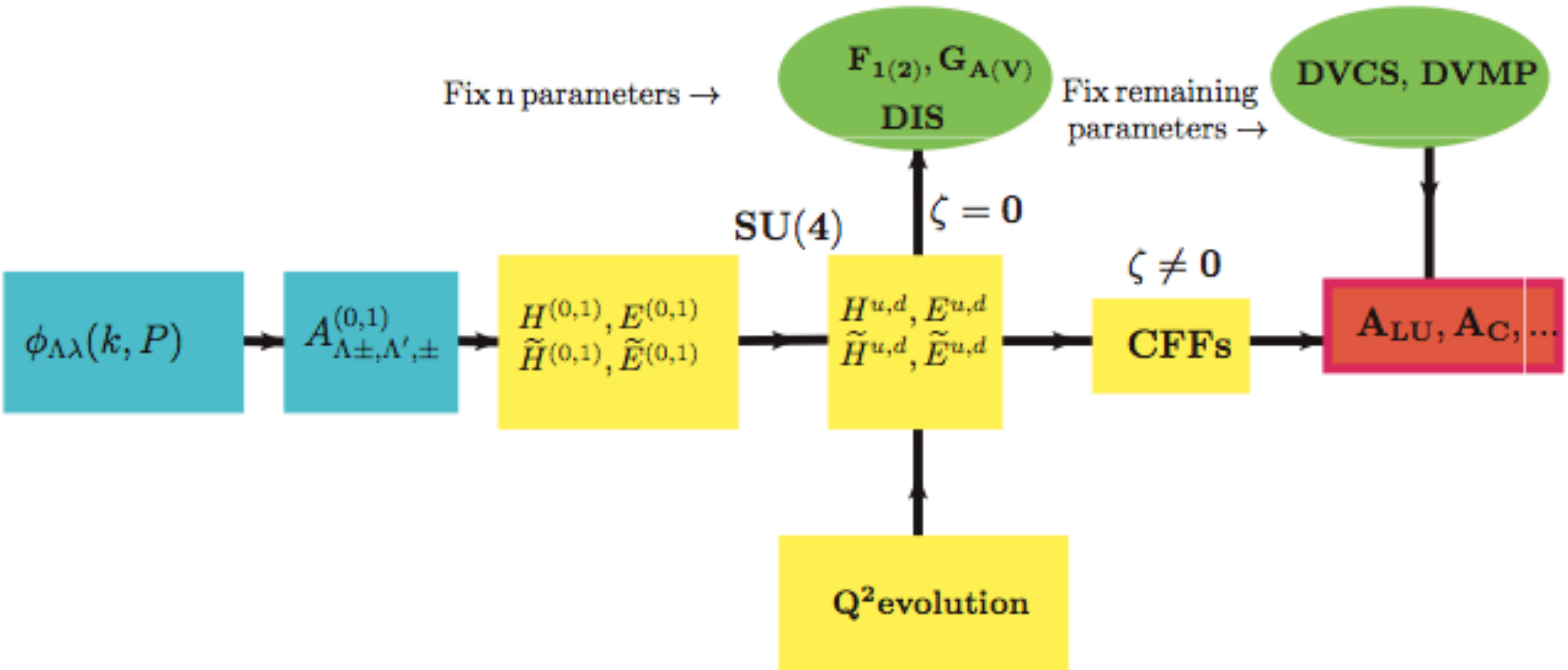
GPDs
in helicity
amplitudes

$$
\begin{aligned}
F_{UU,T} &= \mathcal{N} \left[|\, f_{10}^{++}\, |^2 + |\, f_{10}^{+-}\, |^2 + |\, f_{10}^{-+}\, |^2 + |\, f_{10}^{--}\, |^2 \right] \\
F_{UU,L} &= \mathcal{N} \left[|\, f_{00}^{++}\, |^2 + |\, f_{00}^{+-}\, |^2 \right] \\
F_{UU}^{\cos 2\phi} &= -\mathcal{N}\, 2\Re e \left[(f_{10}^{++})^* (f_{10}^{--}) - (f_{10}^{+-})^* (f_{10}^{-+}) \right] \\
F_{UU}^{\cos\phi} &= -\mathcal{N} \Re e \left[(f_{00}^{+-})^* (f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^* (f_{10}^{++} - f_{10}^{--}) \right] \\
F_{LU}^{\sin\phi} &= \mathcal{N} \Im m \left[(f_{00}^{+-})^* (f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^* (f_{10}^{++} - f_{10}^{--}) \right]
\end{aligned}
$$

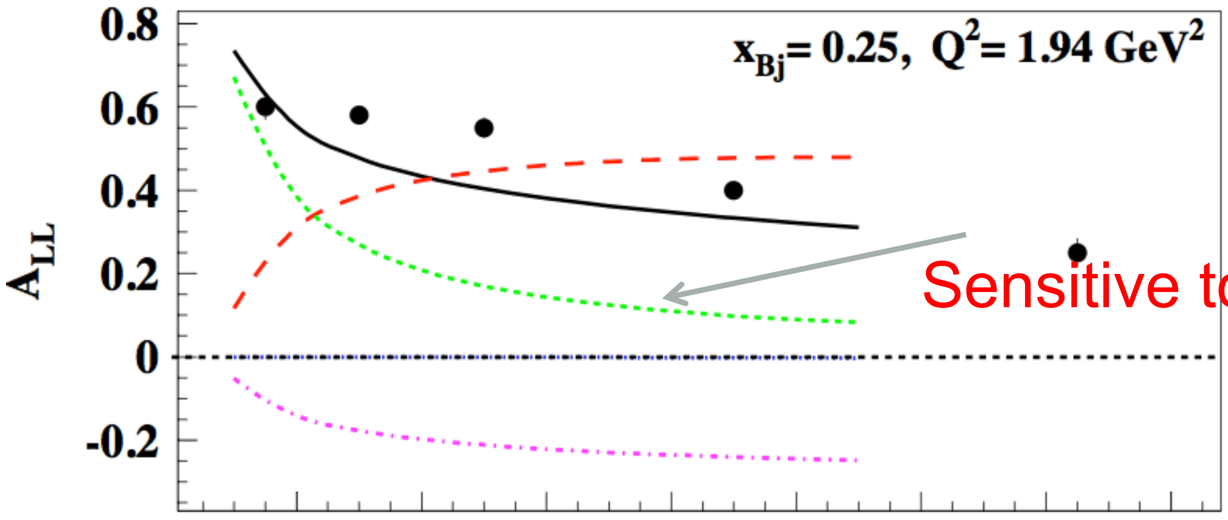
General form of structure function of a chiral odd term:



helicity amplitudes $$F^{++}_{1,-1} = \sum_{\Lambda'} \left(f_{10}^{+\Lambda'} \right)^* \left(f_{-10}^{+\Lambda'} \right)$$



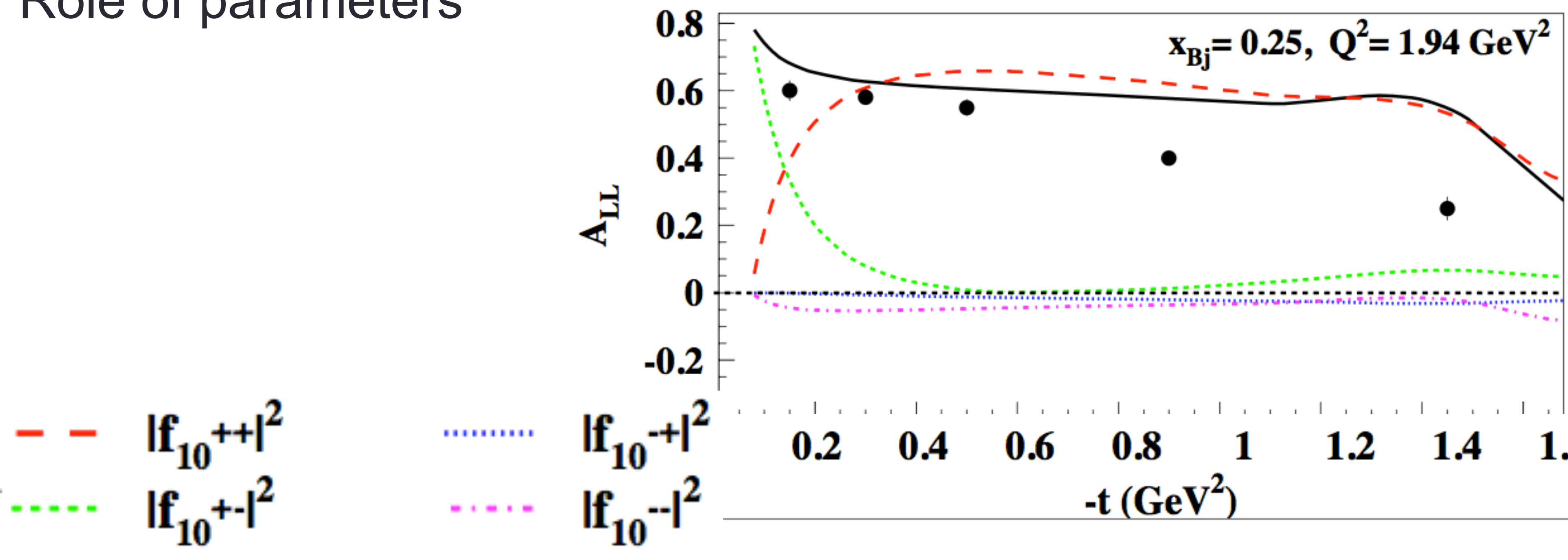
Goldstein, Gonzalez Hernandez, S.L. Phys.Rev. D91 (2015)



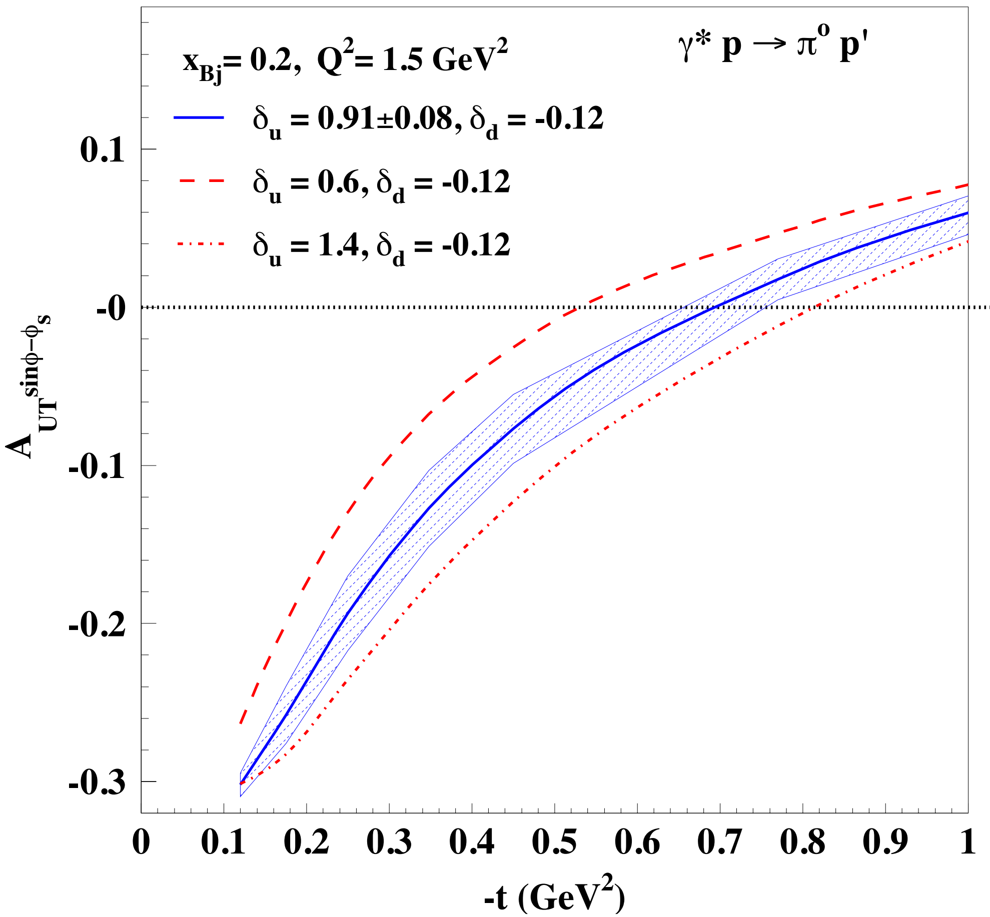
Andrey Kim, Harut Avakian et al., Jefferson Lab CLAS Collaboration

Sensitive to tensor charge

Role of parameters

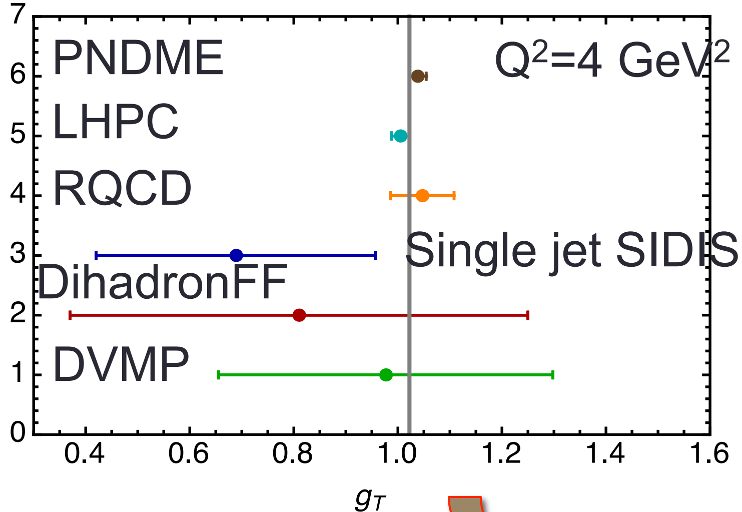


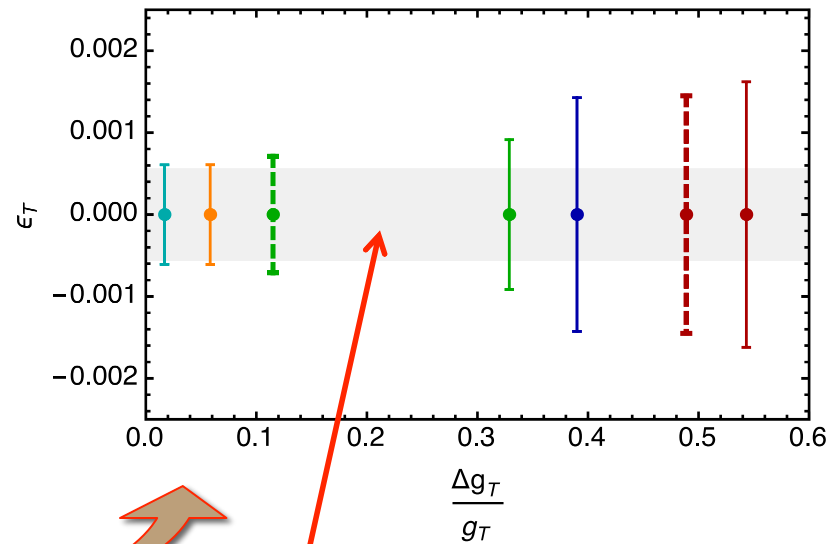
Projections for transverse polarized target



5. IMPACT ON BSM SEARCHES

Impact on BSM searches…



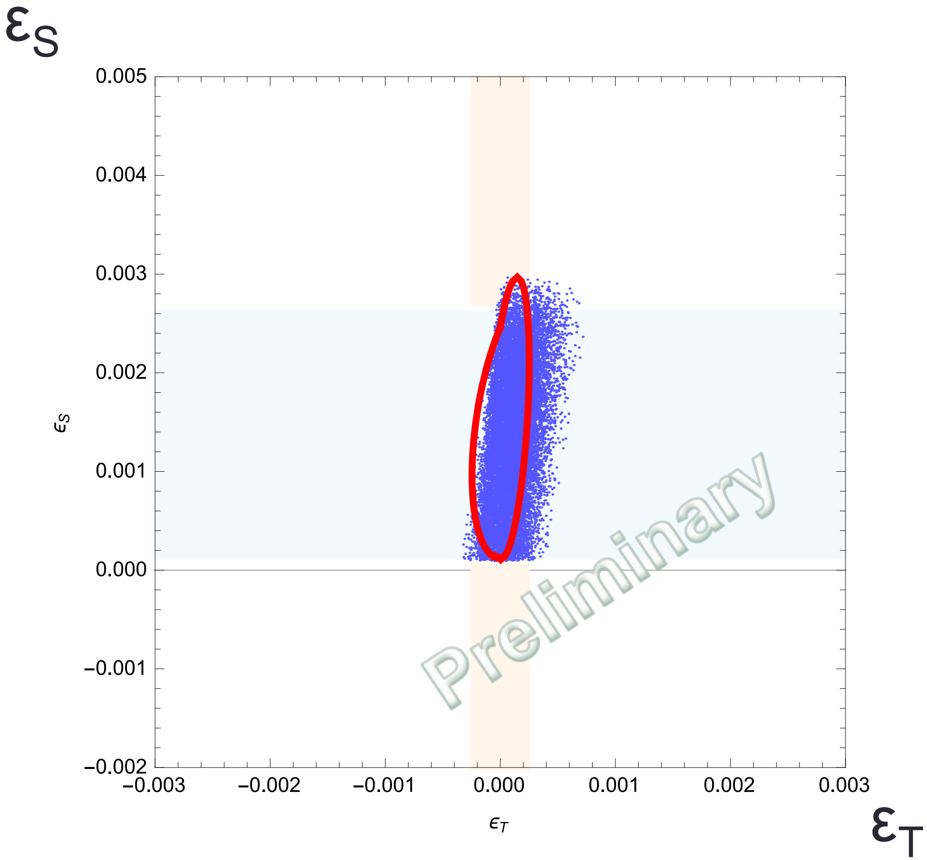


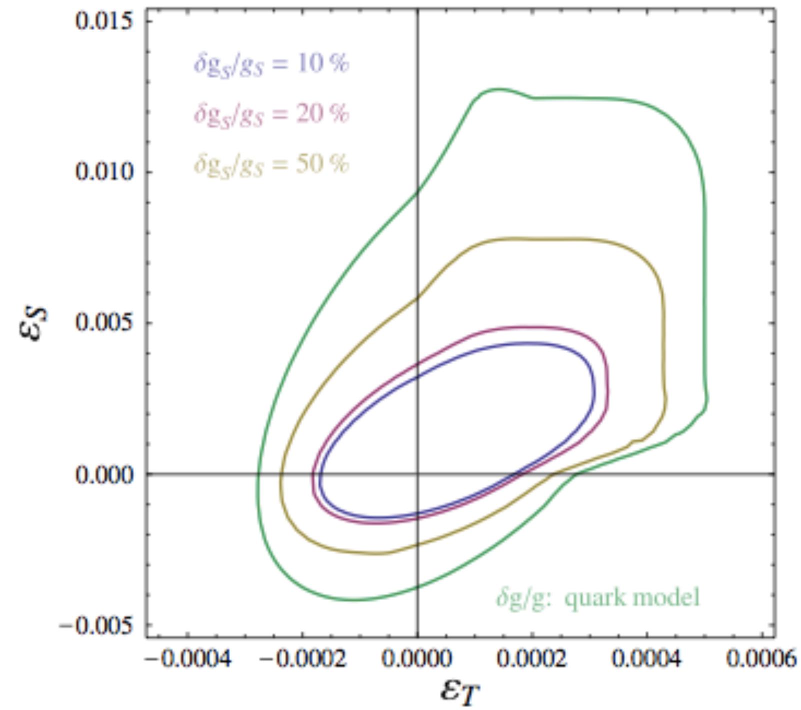
$|\varepsilon_T\, g_T| < 6.4 \times 10^{-4}$

Pattie et al, PRC88 (2013)

A. Courtoy, S.Baessler, M. Gonzalez-Alonso, S.L, arXiv:1503.06814

New Analysis (Pavia, UNAM, NMSU, Virginia)





Lattice Extraction

Bhattacharya et al., PRD85 (2012)

g_S from J. Martin-Camalich + M. Gonzalez-Alonso, PRL (2014)

Combined 90% confidence level in ε_S-ε_T plane

Future developments

$$\langle p(p')|\bar{u}\sigma_{\mu\nu}d|n(p)\rangle \equiv \bar{u}_p(p')[g_T(q^2)\sigma^{\mu\nu} + g_T^{(1)}(q^2)(q^\mu\gamma^\nu - q^\nu\gamma^\mu) + g_T^{(2)}(q^2)(q^\mu P^\nu - q^\nu P^\mu) + g_T^{(3)}(q^2)(\gamma^\mu \not{q}\gamma^\nu - \gamma^\nu\not{q}\gamma^\mu)]u_n(p),$$

Study the additional currents

- Potential impact in axial vector sector studied by S. Gardner and B.Plaster, PRC87(2013)
- Connection with new chiral-odd GPDs
- Impact on EDM measurements
- More…

Conclusions and outlook

The possibility of obtaining the scalar and tensor form factors and charges directly from experiment with sufficient precision, gives an entirely different leverage to neutron beta decay searches

We outlined an approach to extract the tensor charge from measurements of hard electron proton scattering processes (DVMP, Dihadron electroproduction, single jet SIDIS). This program can be developed at the EIC!!!!

The hadronic matrix element is the same which enters the DIS observables measured in precise semi-inclusive and deeply virtual exclusive scattering off polarized targets

However, the error on ε_T , depends on both the central value of g_T as well as on the relative error, $\Delta g_T / g_T$, therefore, independently from the theoretical accuracy that can be achieved, experimental measurements are essential since they simultaneously provide a testing ground for lattice QCD calculations.

sl4y@virginia.edu