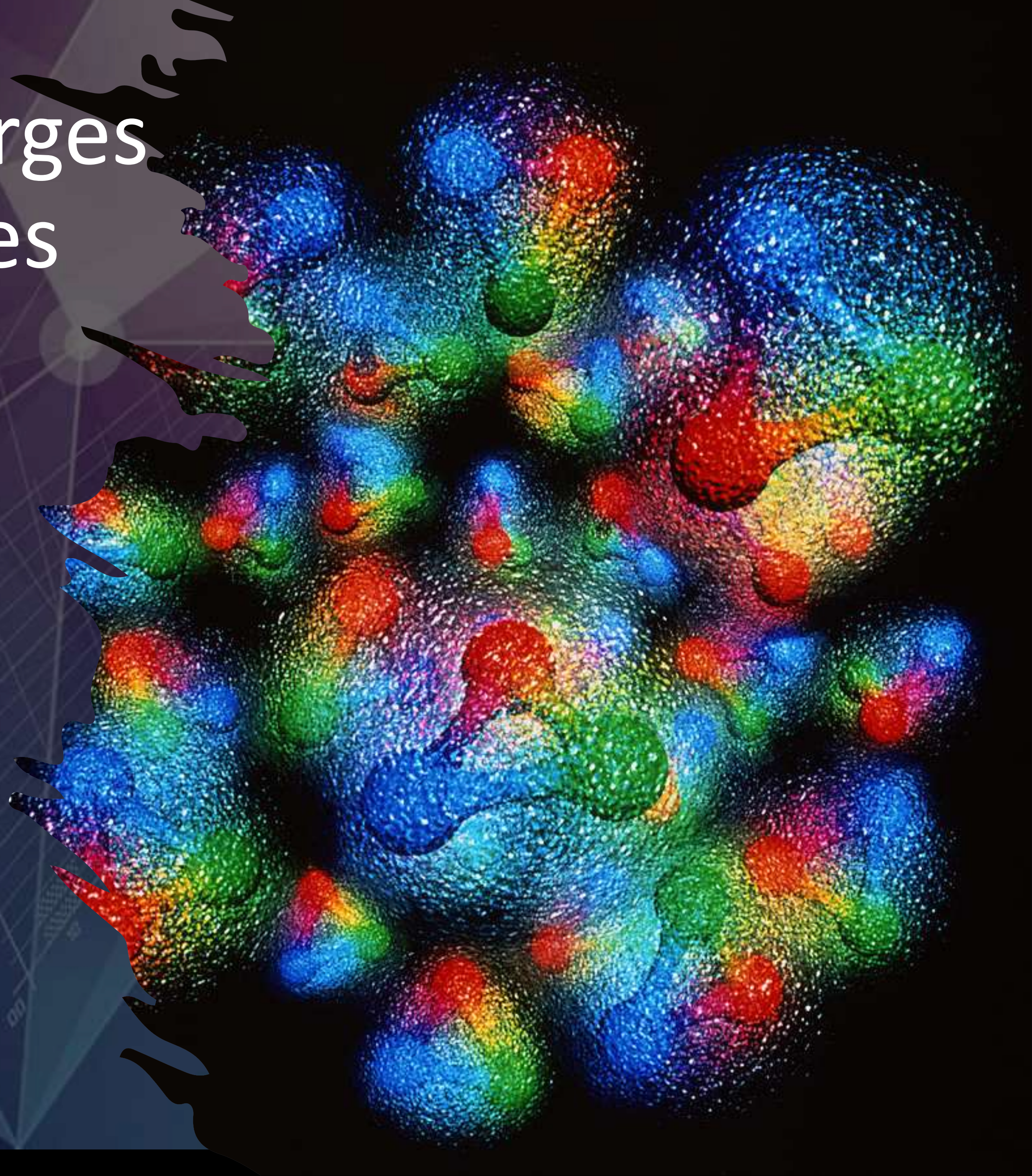
Tensor and Scalar Charges Searches and exclusives detection at EIC

Simonetta Liuti



CENTER for NUCLEAR FEMTOGRAPHY

Outline

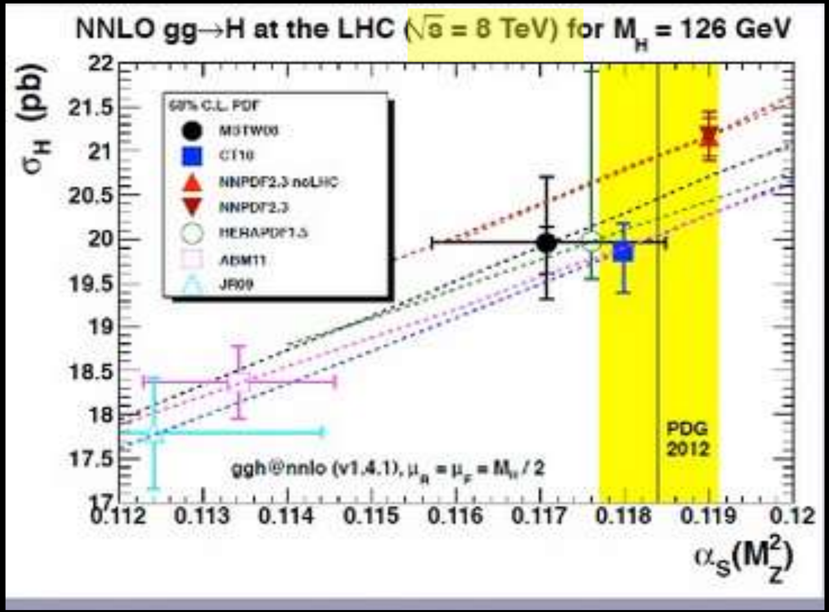
1. Introduction
2. Role of spin dependent observables in low energy processes (neutron beta decay, EDM)
3. Chiral Odd GPDs
4. Extraction from experiment: role of EIC
5. Impact on BSM searches
6. Conclusions and Outlook

1. Introduction

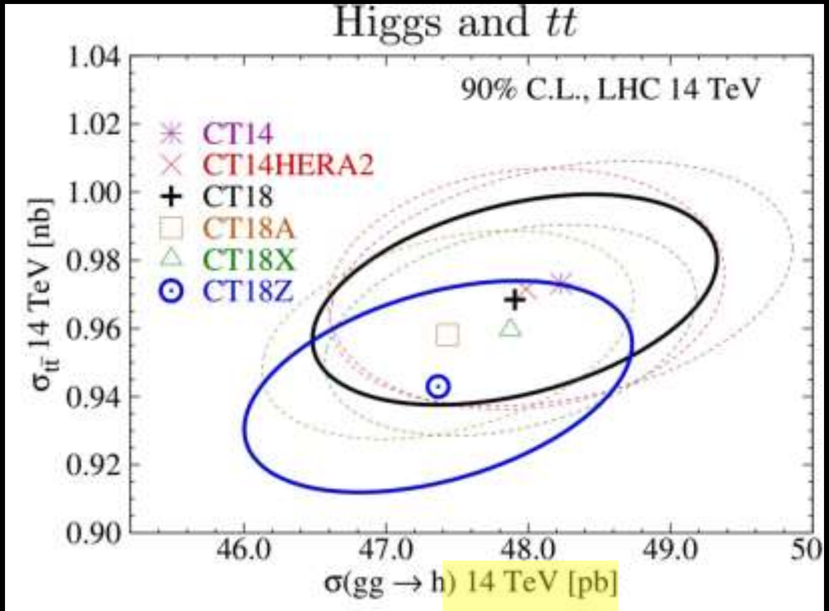
QCD impacts the extraction of several of the 19 (28) fundamental parameters in the SM

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
9. The fine structure constant α (1)

At high energy the proton pdfs uncertainties govern the theoretical errors on crucial processes



Example: Higgs production



T. Hobbs, this workshop

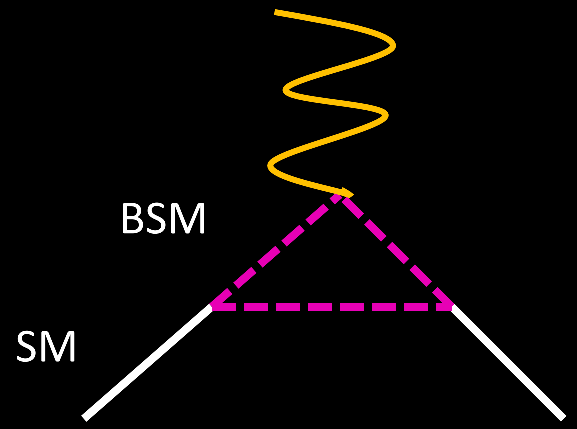
QCD affects also the low-energy regime in the indirect search for BSM physics:

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. …..

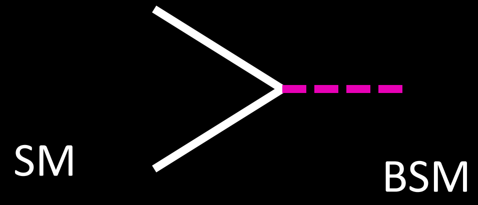
Low Energy << 1 GeV

High Energy ≈ Λ_{BSM}> "N" TeV

BSM particles appear in loops



BSM particles are produced directly

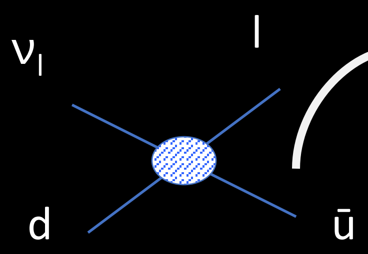


BSM Effective Lagrangian

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

$$e_{L,R,S,P,T} » \frac{m_W^2}{L^2_{BSM}}$$

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



Vector	$\bar{u}\, g^m u$
Axial-Vector	$\bar{u}\, g^m g^5 u$
Pseudoscalar	$\bar{u}\, g^5 u$
Scalar	$\bar{u}\, u$
Tensor	$\bar{u} s^m u$

2. Role of spin dependent observables

Differential decay distribution for polarized neutron decay

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

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

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

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

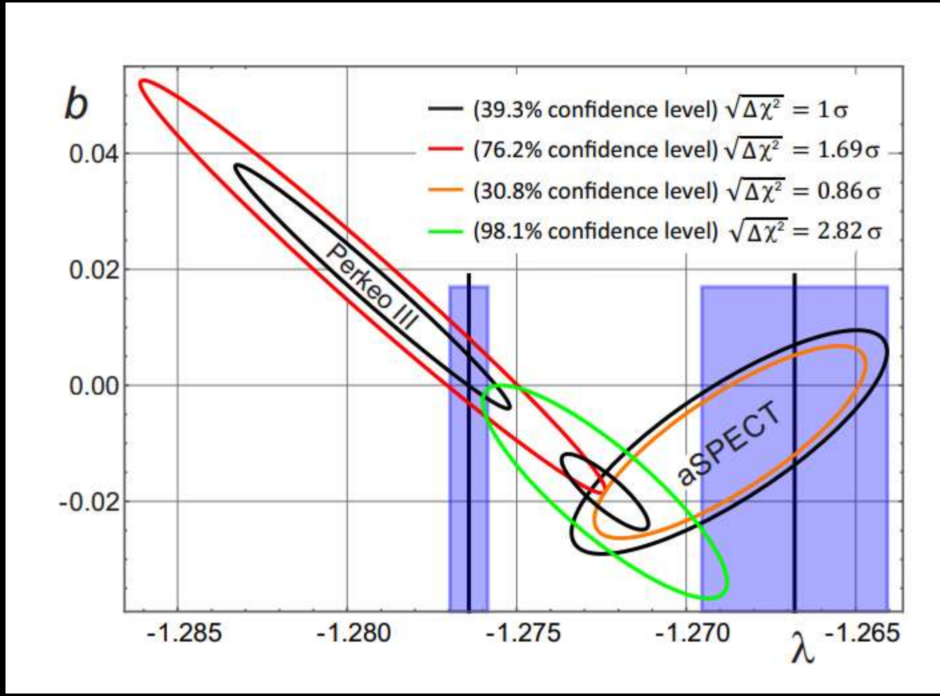
Fierz term

These terms can contain tensor corrections

Reanalysis of aSpect experiment

M. Beck, W. Heil, Ch. Schmidt, S. Baeßler, F. Gluck, G. Konrad, and U. Schmidt: arXiv 2308.16170 (accepted in PRL)

Correlated analysis of Fierz term and $\lambda = {}^{g_A}/_{g_V}$



b is found to be non-zero

b decomposition in terms of tensor and scalar components

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

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 (ε_S) can be measured depends on the uncertainty on g_T (g_S)
- The observable is always the product of the fundamental coupling times a hadronic matrix element

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

- Polarized hard scattering processes at Jlab @12 GeV and at EIC can provide the hadronic matrix elements to extract the BSM tensor, scalar and pseudo-scalar effective couplings entering the neutron beta decay cross section

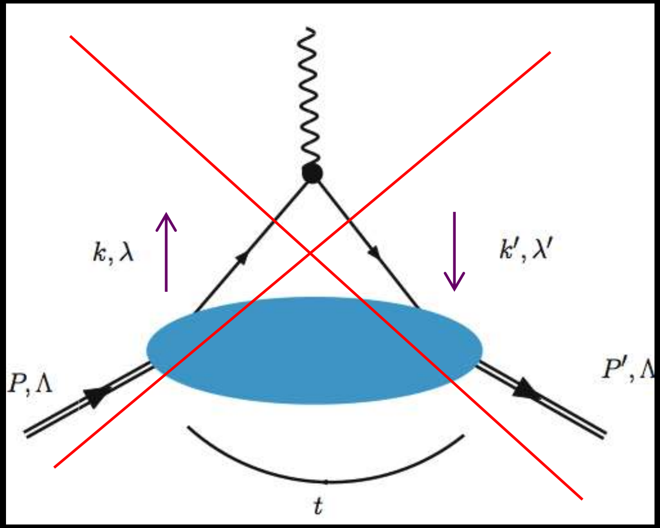
- The most general form of gauge interactions with the exchange of a spin-1 particle is a linear combination of **VECTOR** and **AXIAL-VECTOR**

- The tensor charge is not "fundamental" in the SM

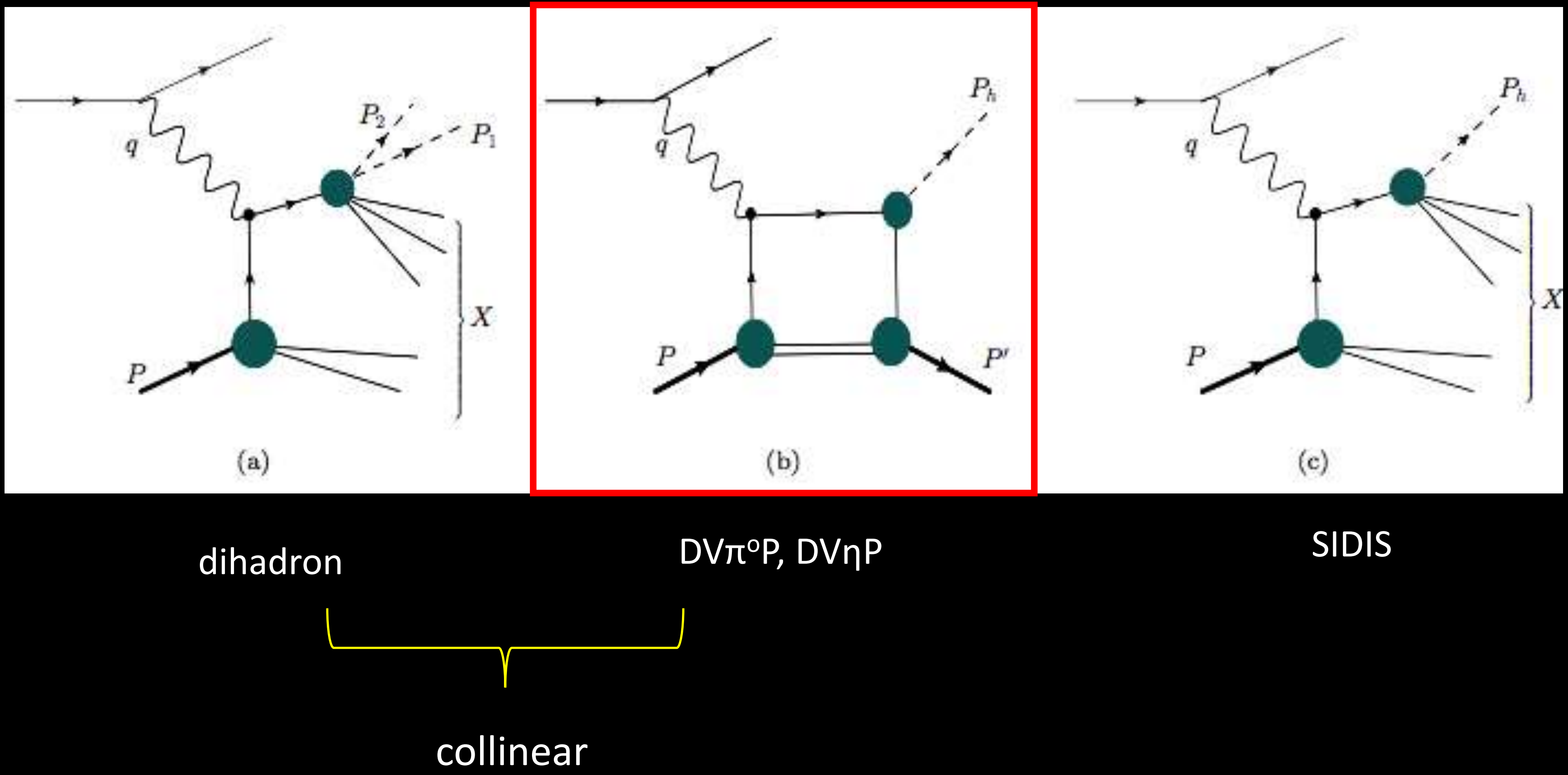
- A "tensor form factor" cannot be measured in elastic scattering processes mediated by either one or two photons

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

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



To detect chiral odd distributions we need another distinct hadronic blob

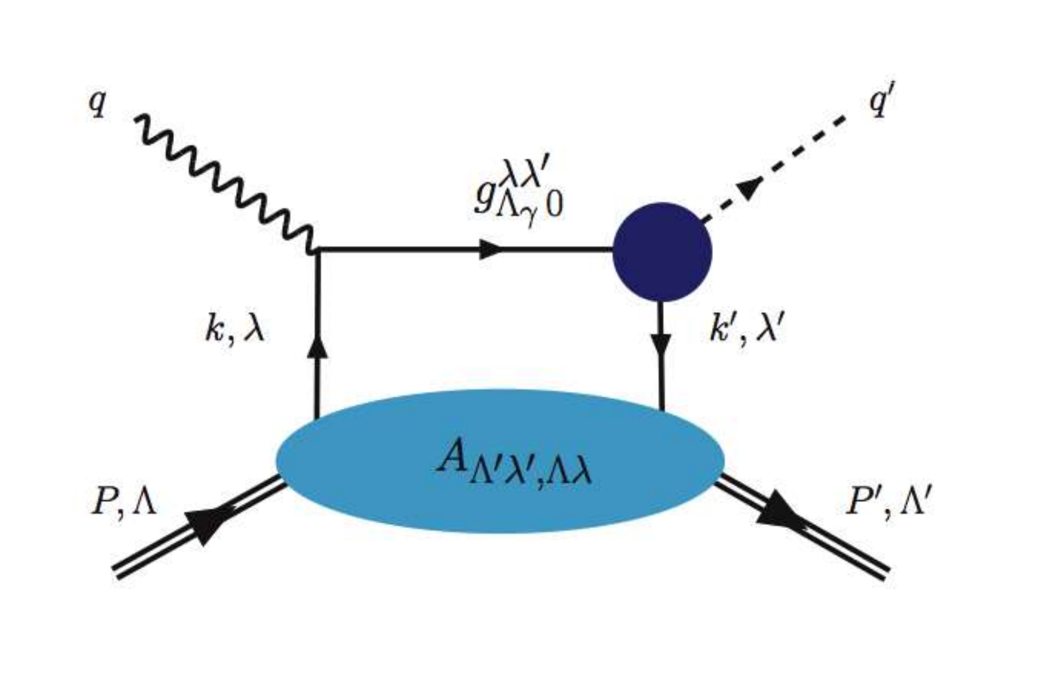


3. Chiral odd GPDs

Deeply virtual pseudoscalar meson production $e\,p \to e' p' \pi^o$

process first suggested in S. Ahmad, G. Goldstein and SL, Phys.Rev. D79 (2009) 054014

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

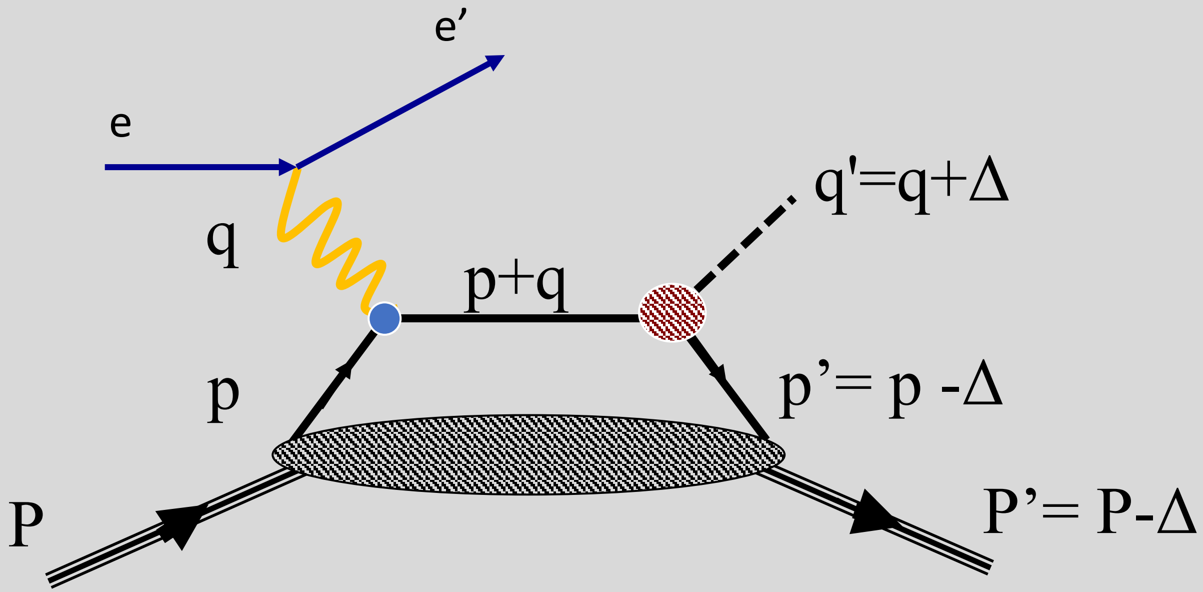


Consequences of having loop at amplitude level

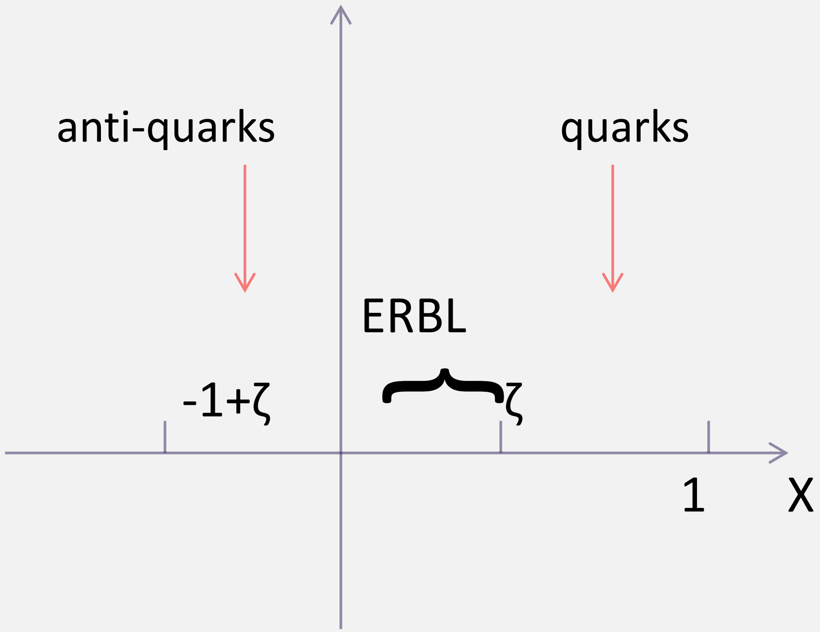
- Δ is an observable (Δ^2 =t), p is not
- Both *Re* and *Im* parts are present:

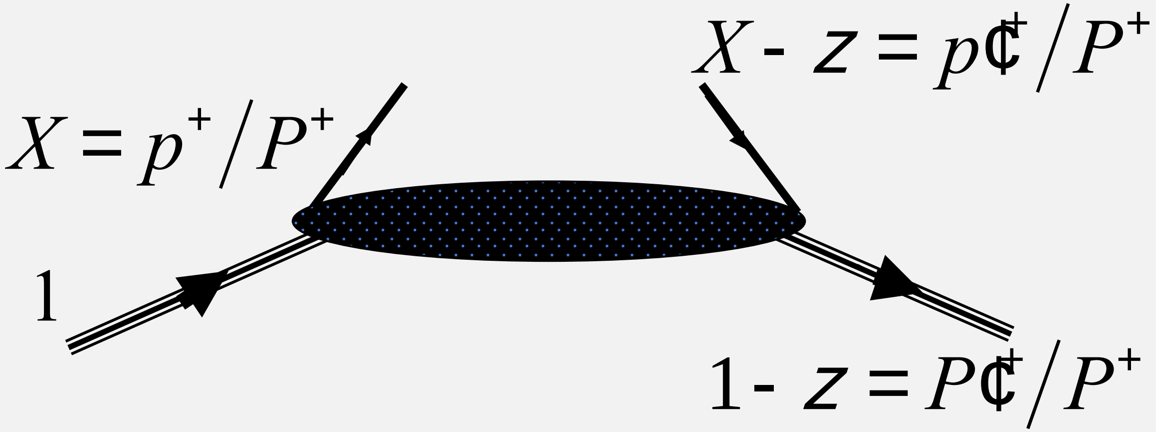
$$\frac{1}{(p+q)^2 - m^2 + i\epsilon} = PV\frac{1}{(p+q)^2 - m^2} - i\pi\delta((p+q)^2 - m^2)$$

- Quark momenta and spins on LHS can be different from the RHS



Light Cone Variables





Asymmetry in kinematics on LHS and RHS of diagram

Quark correlator in the chiral odd sector: four GPDs

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

One to one relation with helicity amplitudes

proton flip

$$A_{++,--} = \frac{\sqrt{1-\zeta}}{1-\zeta/2}\left[H_T + \frac{t_0 - t}{4M^2}\widetilde{H}_T + \frac{\zeta^2/4}{1-\zeta}E_T + \frac{\zeta/2}{1-\zeta}\widetilde{E}_T\right]$$

$$A_{+-,-+} = -\frac{\sqrt{1-\zeta}}{1-\zeta/2}\,\frac{t_0 - t}{4M^2}\,\widetilde{H}_T$$

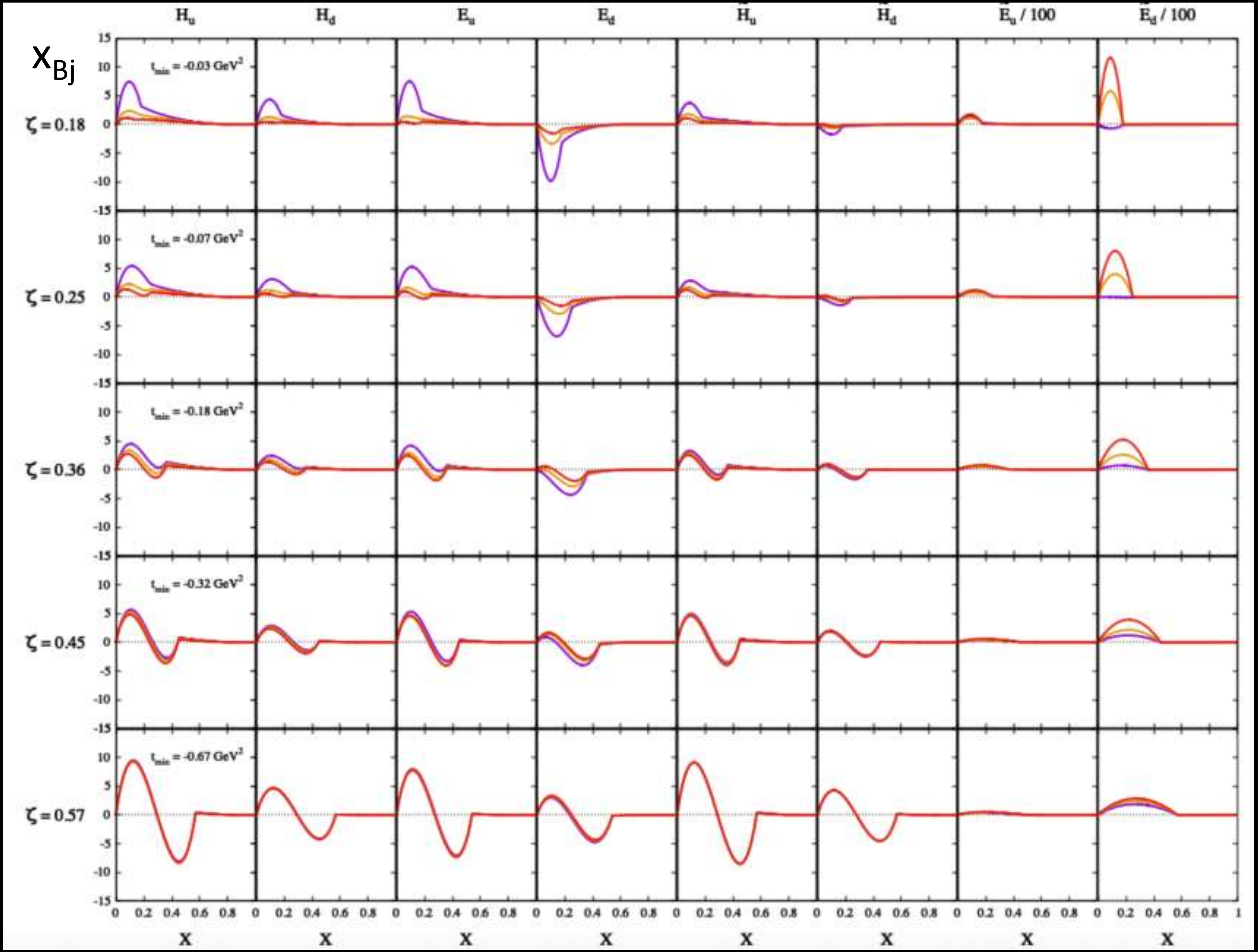
proton non-flip

$$A_{++,+-} = \frac{\sqrt{t_0 - t}}{2M}\left[\widetilde{H}_T + \frac{1-\zeta}{2-\zeta}E_T + \frac{1-\zeta}{2-\zeta}\widetilde{E}_T\right],$$

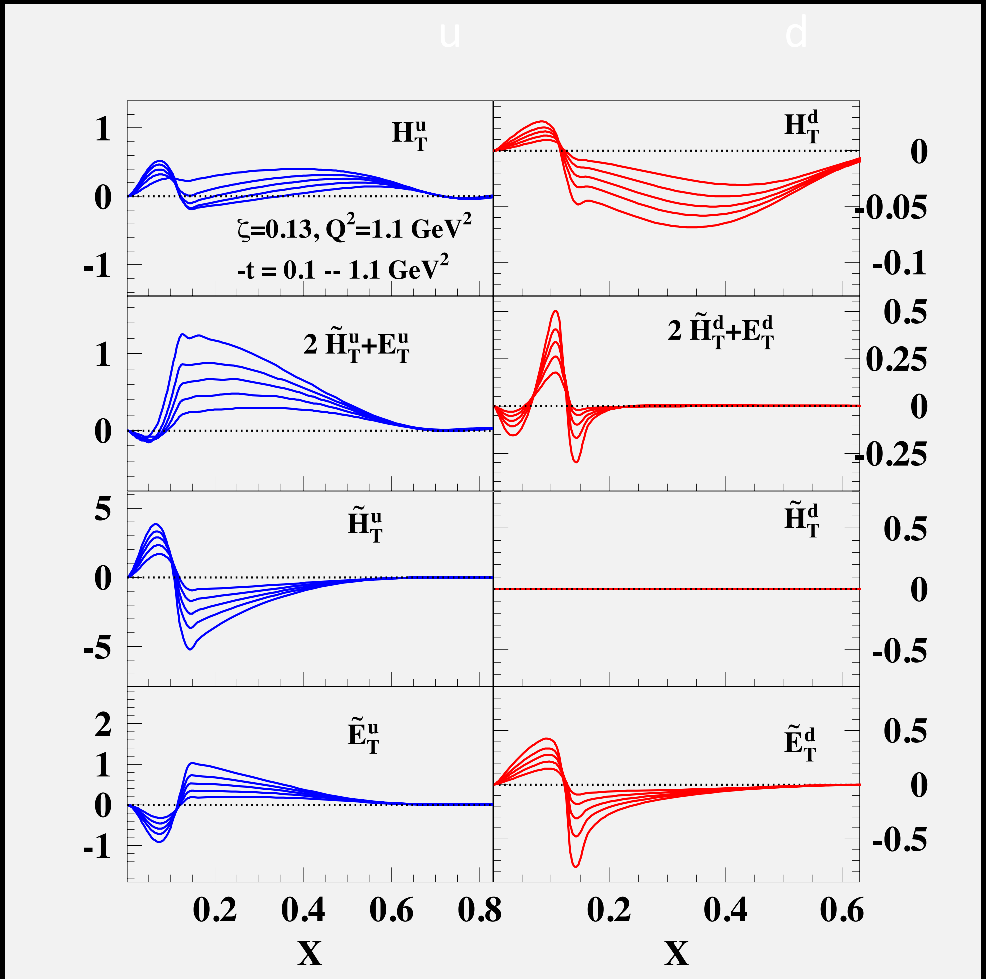
$$A_{-+,--} = \frac{\sqrt{t_0 - t}}{2M}\left[\widetilde{H}_T + \frac{1}{2-\zeta}E_T + \frac{1}{2-\zeta}\widetilde{E}_T\right].$$

Chiral even GPDs

B. Kriesten, P. Velie, E. Yeats, F. Y. Lopez and S. Liuti, *Phys. Rev D 105 (2022)*



Chiral Odd GPDs



tensor charge

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

tensor anomalous magnetic moment

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

?

?

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

4. Extraction from experiment

Cross Section Formulation

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

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

GPDs
in helicity
amplitudes

$$F_{UU,T} = \mathcal{N}\left[|\, f_{10}^{++}\,|^2 + |\, f_{10}^{+-}\,|^2 + |\, f_{10}^{-+}\,|^2 + |\, f_{10}^{--}\,|^2\right]$$

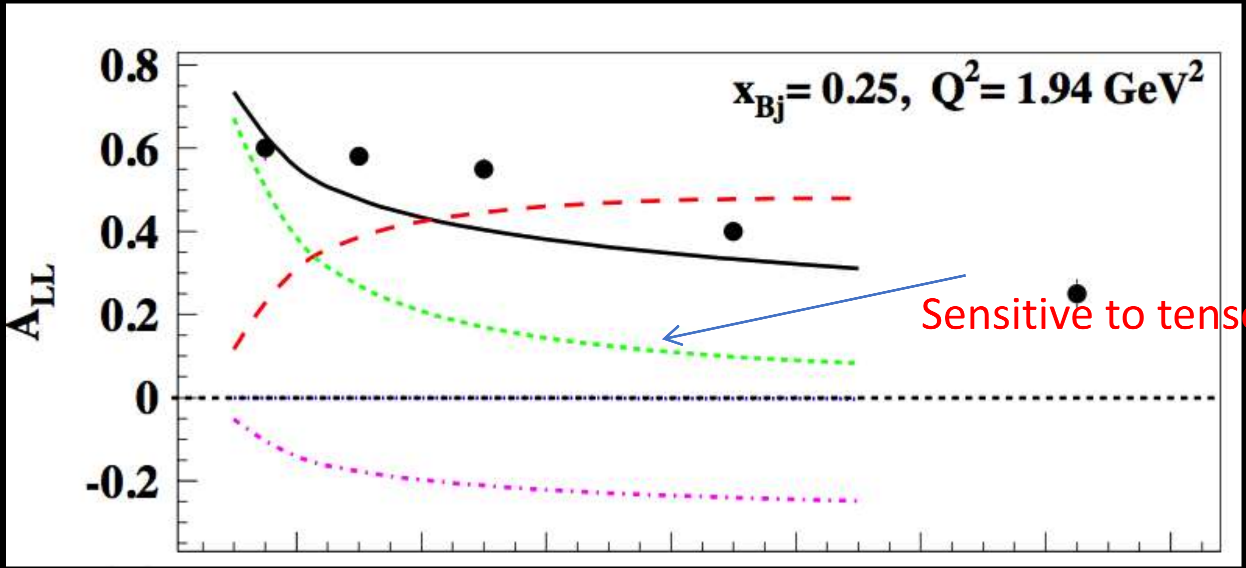
$$F_{UU,L} = \mathcal{N}\left[|\, f_{00}^{++}\,|^2 + |\, f_{00}^{+-}\,|^2\right]$$

$$F_{UU}^{\cos 2\phi} = -\mathcal{N}\, 2\Re e\left[(f_{10}^{++})^*(f_{10}^{--}) - (f_{10}^{+-})^*(f_{10}^{-+})\right]$$

$$F_{UU}^{\cos\phi} = -\mathcal{N}\Re e\left[(f_{00}^{+-})^*(f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} - f_{10}^{--})\right]$$

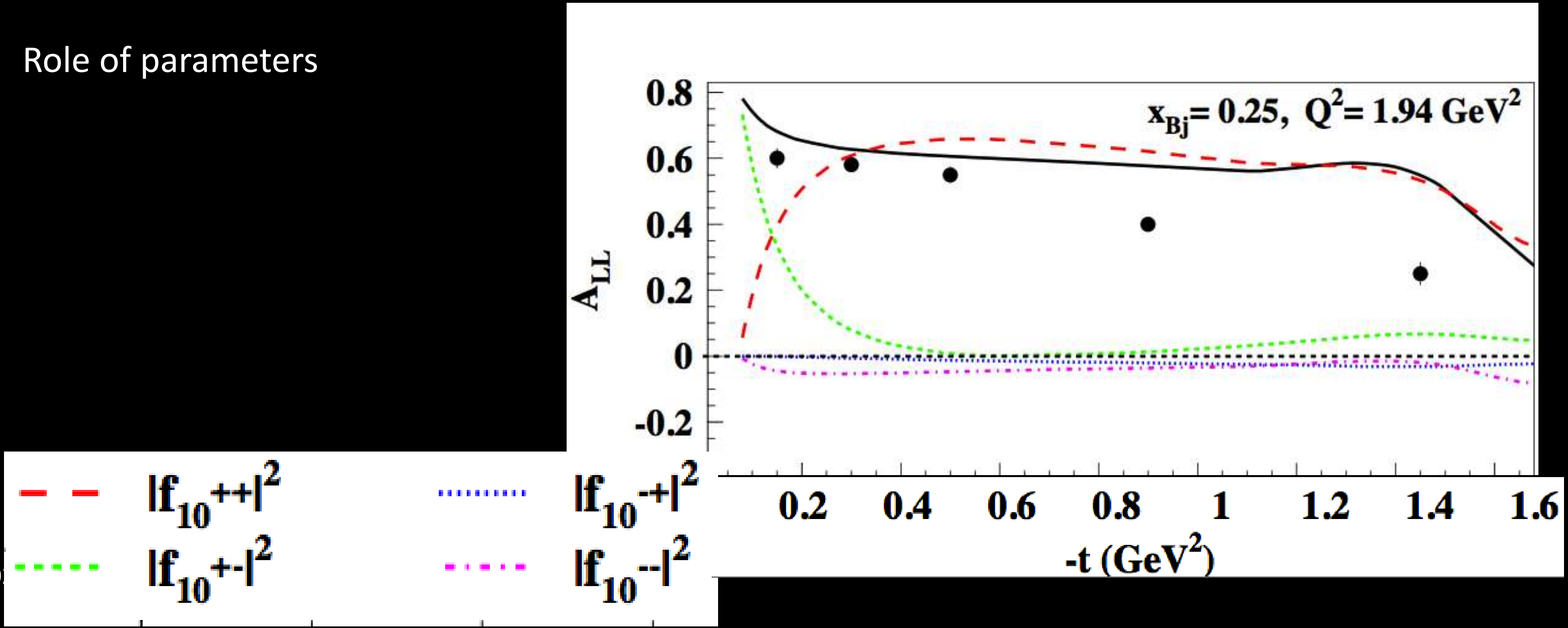
$$F_{LU}^{\sin\phi} = \mathcal{N}\Im m\left[(f_{00}^{+-})^*(f_{10}^{+-} + f_{10}^{-+}) + (f_{00}^{++})^*(f_{10}^{++} - f_{10}^{--})\right]$$

Example

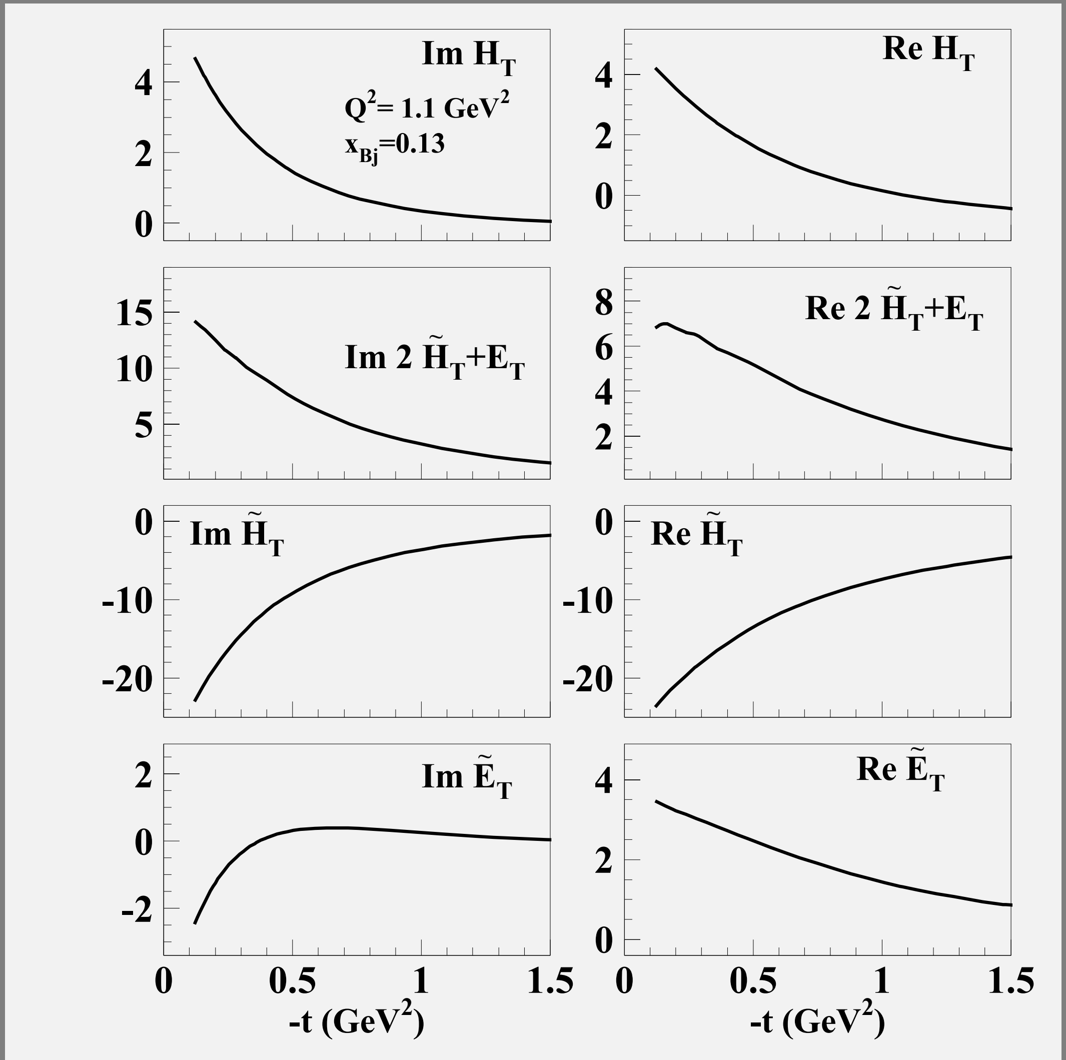


Andrey Kim et al., Jefferson Lab CLAS Collaboration

Role of parameters

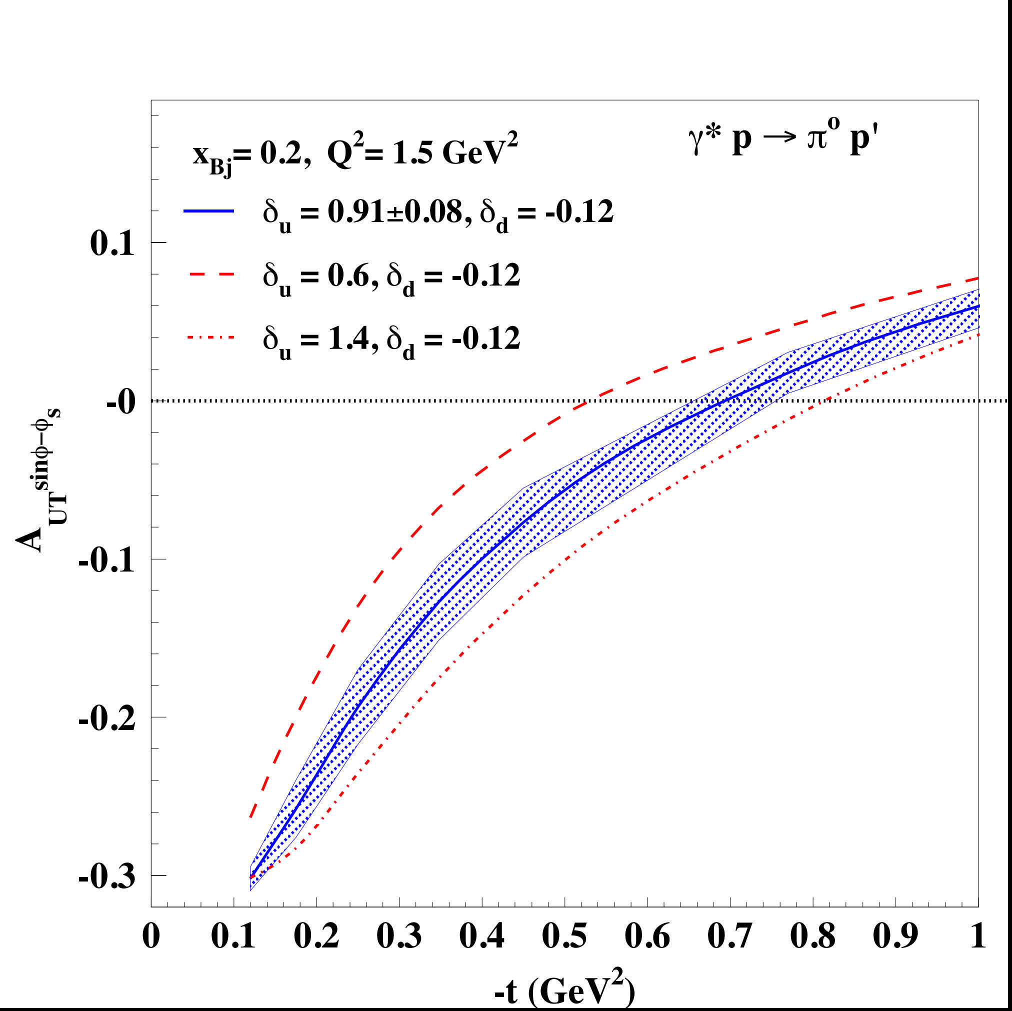


Chiral Odd Compton Form Factors

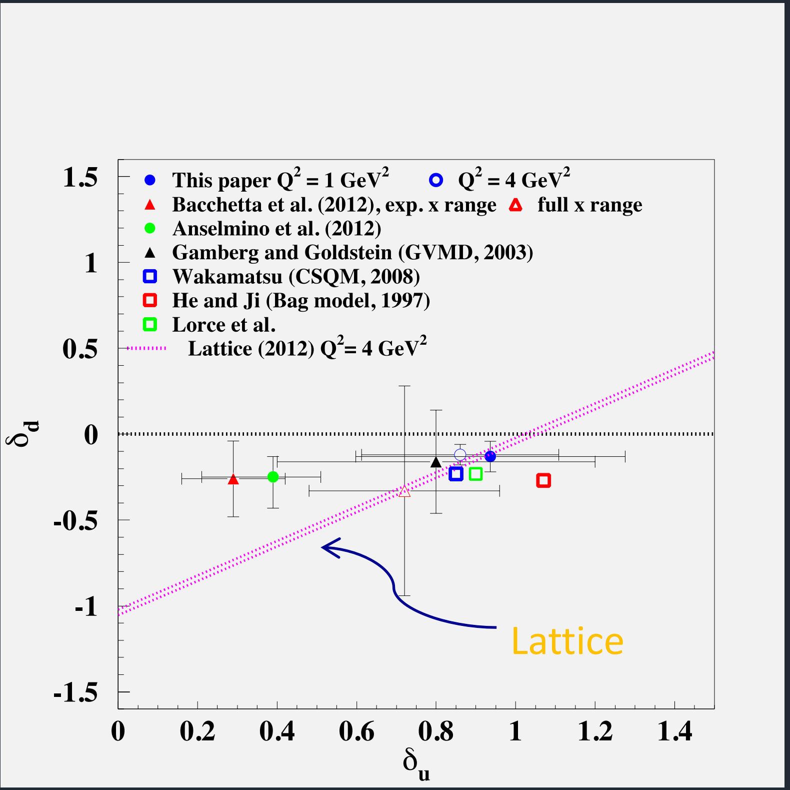


G. Goldstein, O. Gonzalez-Hernandez, SL, PRD(2015) arXiv:1311.0483

Projections for a transverse polarized target

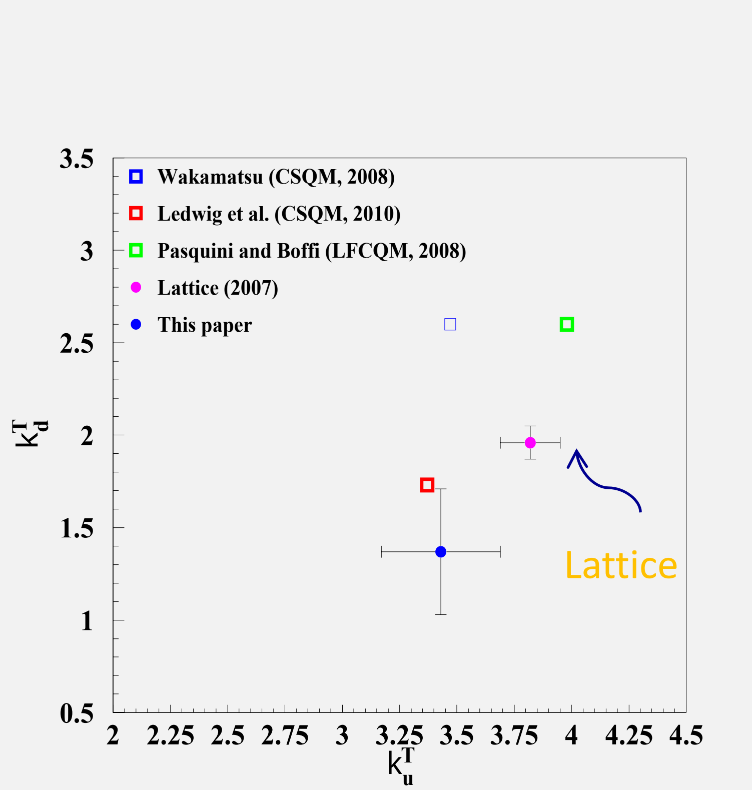


Flavor separated tensor charge



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)

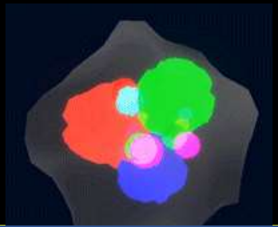
Tensor anomalous magnetic moment



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

Us: arXiv:1401.0438 [hep-ph]

The EXCLAIM project (EXCLusives with Artificial Intelligence and Machine learning)



OUR PEOPLE

Computer Science/Machine Learning: Douglas Adams, Tareq Alghamdi, GiaWei Chern, Brandon Kriesten (10%), Yaohang Li, Saraswati Pandey, RA2

Experiment: Marie Boer, Debaditya Biswas, Postdoc

Lattice QCD: Michael Engelhardt, Huey Wen Lin, Postdoc

Phenomenology/Theory: Joshua Bautista, Marija Cuic, Andrew Dotson, Gary Goldstein, Carter Gustin, Adil Khawaja, SL, Zaki Panjsheeri, Kiara Ruffin, Matt Sievert, Dennis Sivers, RA2 NMSU

OUR PLAN

EXCLAIM is developing ***physics aware*** networks by using ***theory constraints*** in ***deep learning*** models (not PINN)

1. ML is not treated as a set of “black boxes” whose working is not fully controllable

2. Utilize concepts in *information theory and quantum information theory* to interpret the working of ML algorithms necessary to extract information from data

3. At the same time, use ML methods as a testing ground for the working of quantum information theory in a large class of deeply virtual scattering processes

Does one need AI/ML for the analysis?

Draw from expertise on Global Analyses of Parton Distribution Functions (PDFs) from inclusive scattering experiments

- A major component is in the role played by Uncertainty Quantification

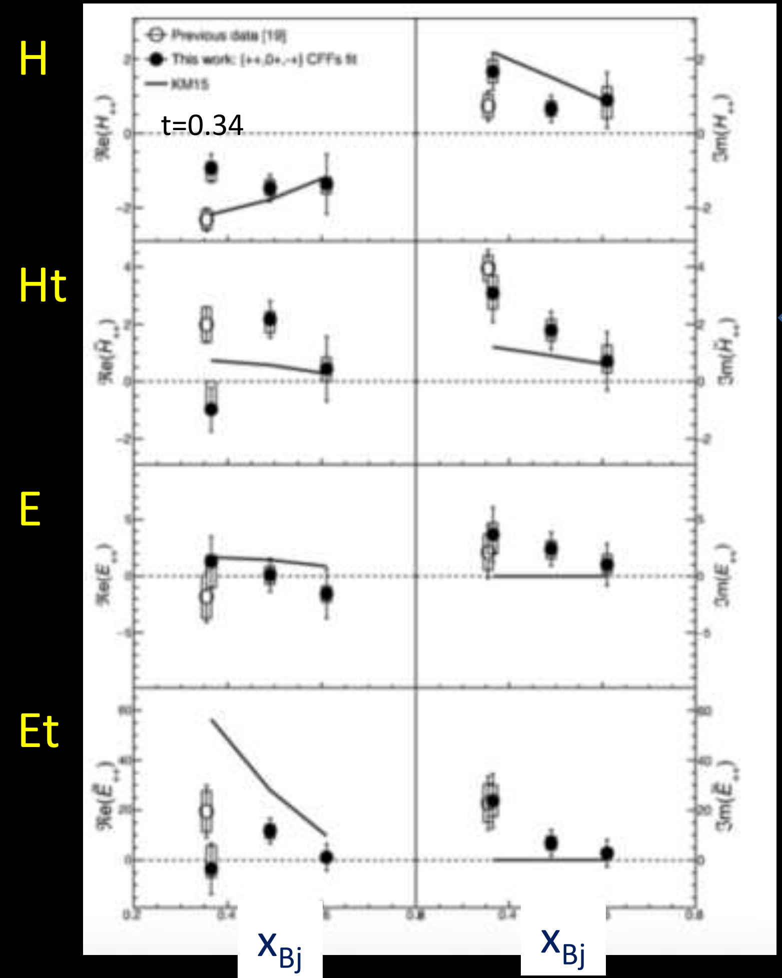
- Epistemic and aleatoric uncertainty

- Moreover, the learning methods using ML allow us to obtain "more" from the analysis

- "More" >>>>> access to latent space

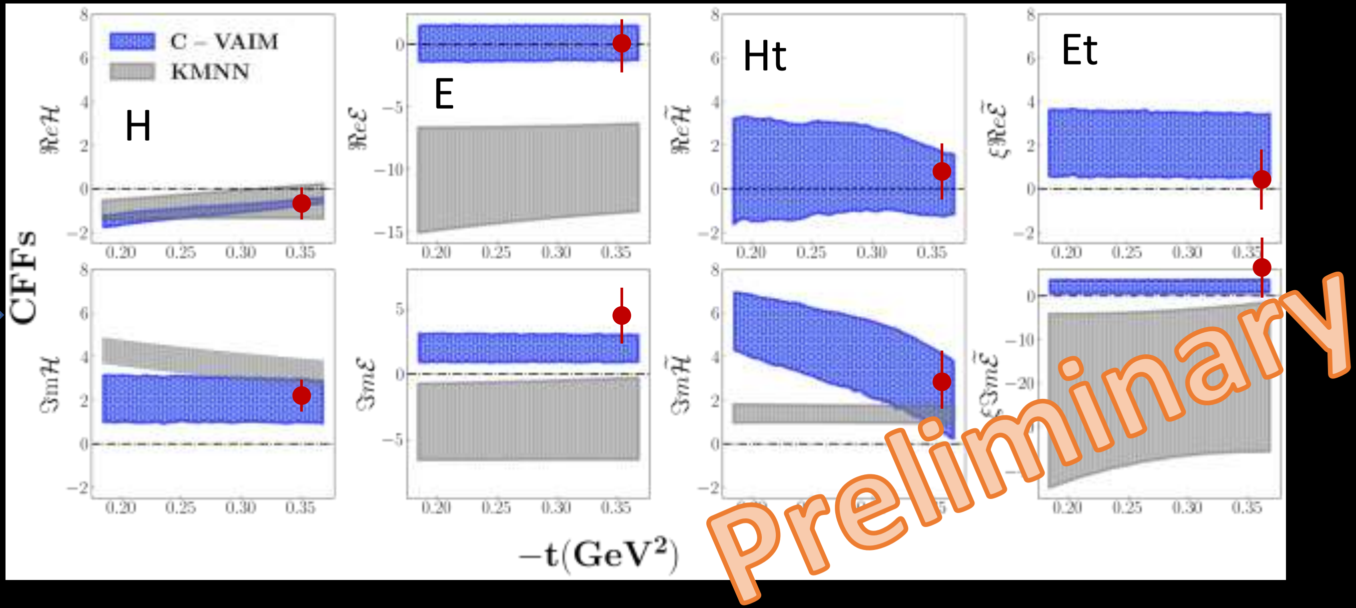
Compton form factors

Hessian based

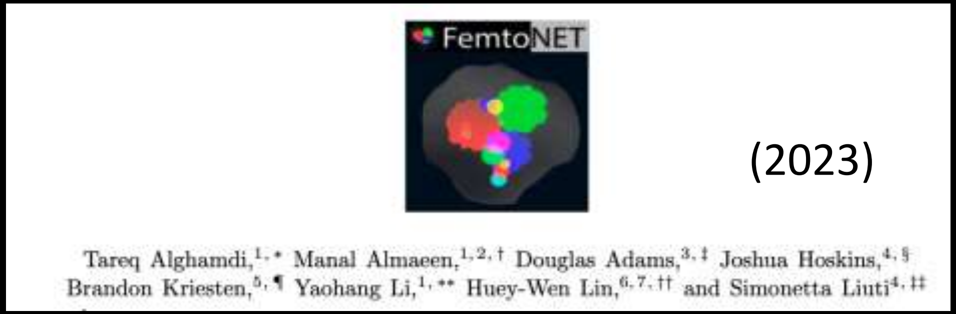


Hall A, https://arxiv.org/pdf/2201.03714.pdf

ML based



- KMNN, Cuic, Kumericki, Schaefer, https://arxiv.org/abs/2007.00029
- C-VAIM -: **A variational autoencoder inverse mapper solution to Compton form factor extraction from deeply virtual exclusive reactions**

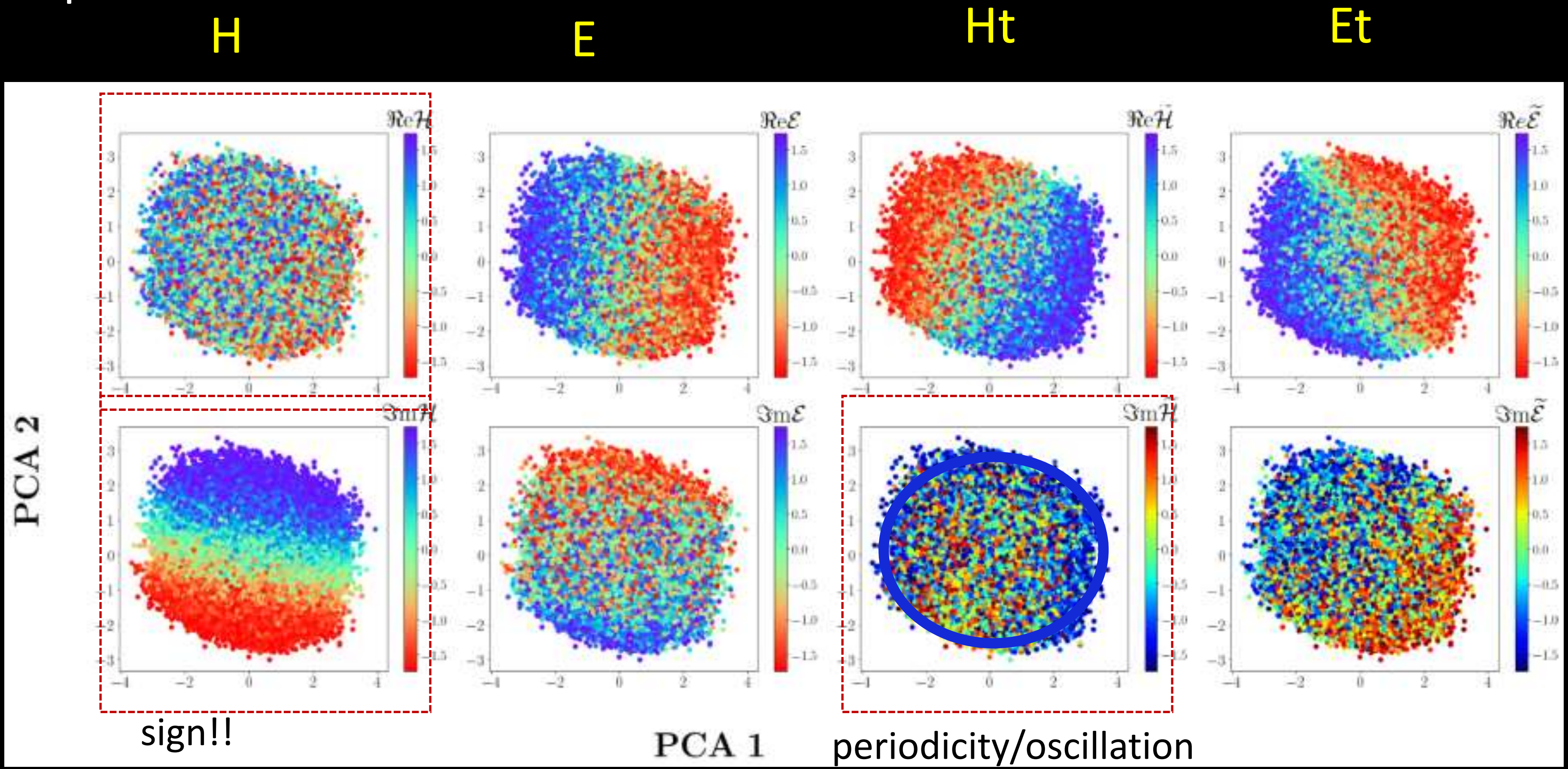


Searching for the PDFs, CFFs, GPDs, … in hadronic physics is an Inverse Problem

Forward problem many parameters → 1 observable $y = f(x, \alpha, \beta, \gamma, \delta, \ldots)$

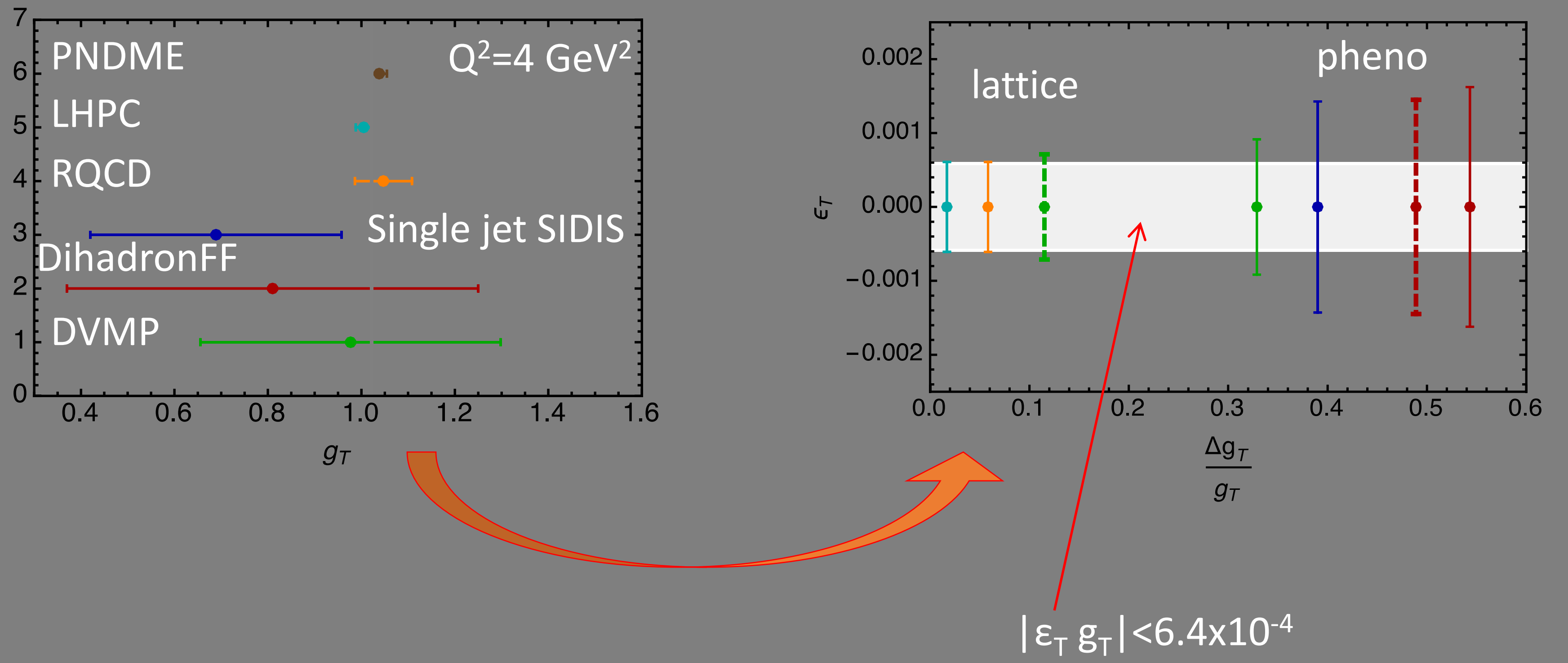
Inverse problem 1 observable → many parameters

The latent space of CFFs



5. Impact on BSM searches

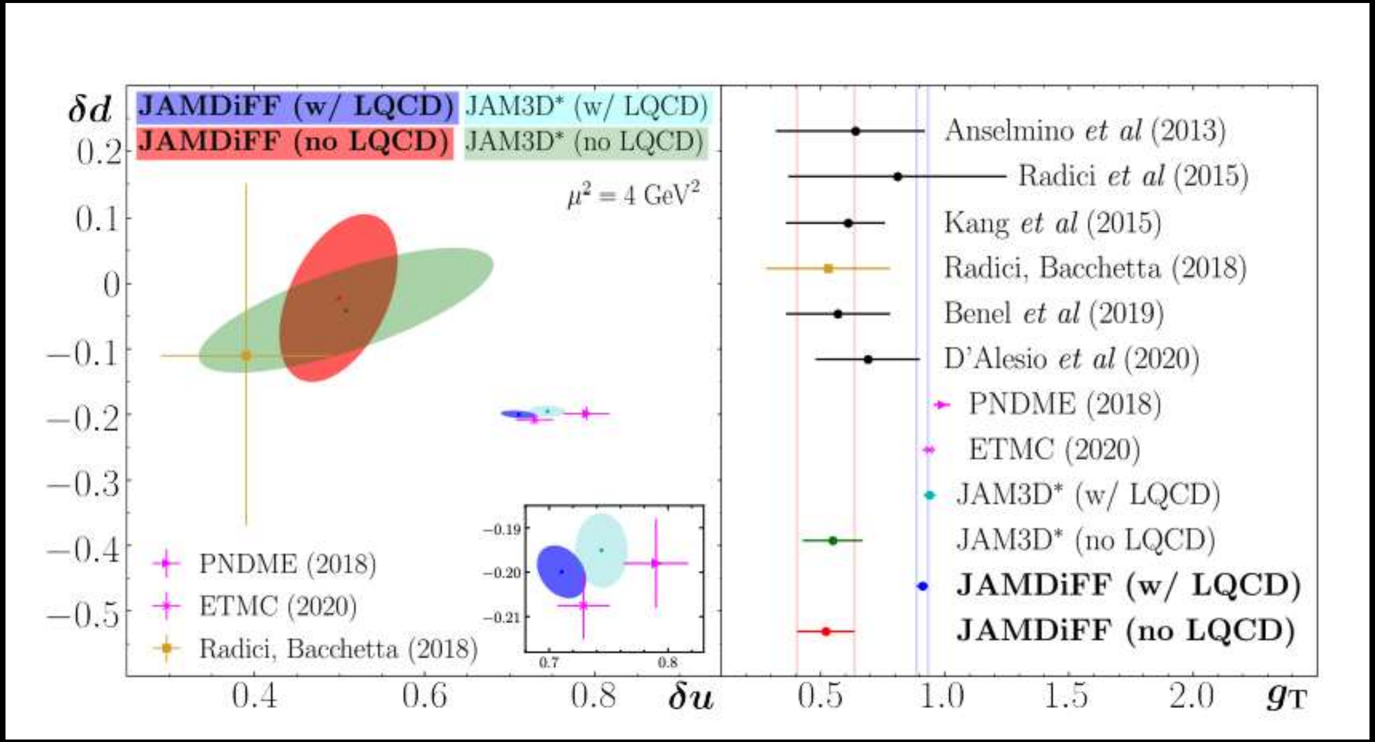
Impact on BSM searches…



superseded now: Pattie et al, PRC88 (2013)

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

Present



JAM Collaboration, Cocuzza et al.,

- 2306.12998

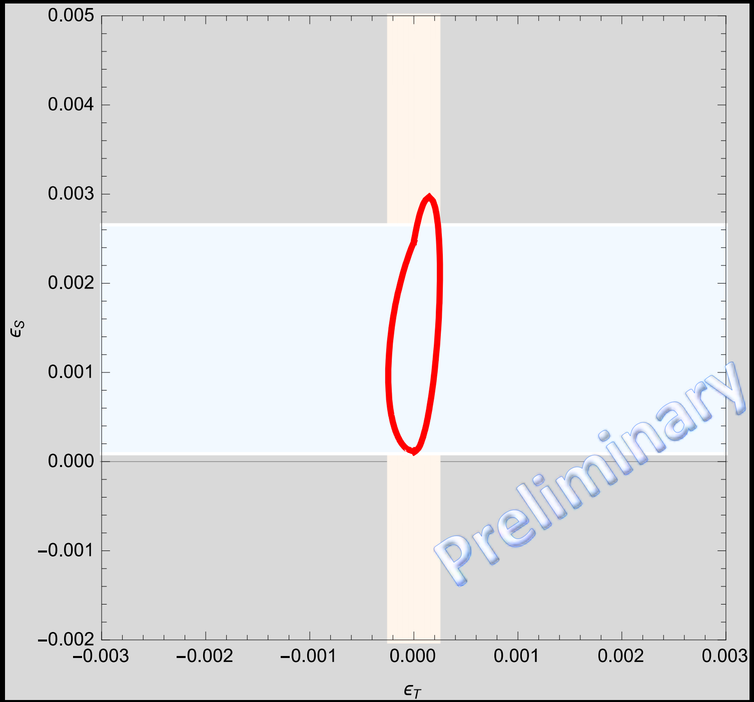
*Our work is systematically either not quoted, or quoted improperly in graphs shown by the JAM collaboration

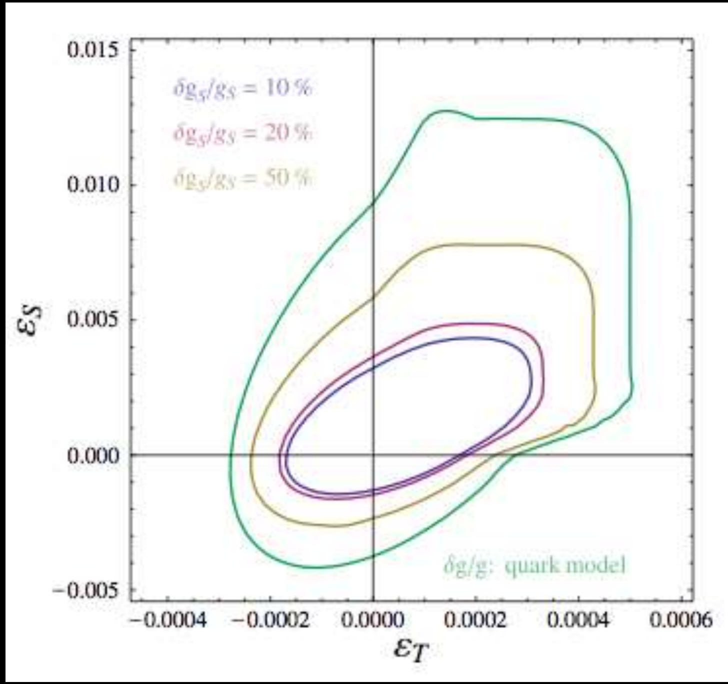
Future Analysis

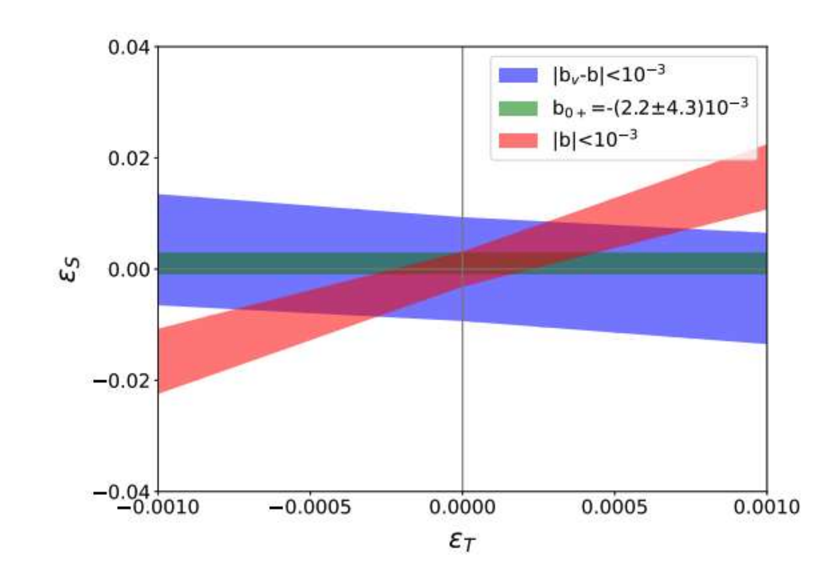
Combined 90% confidence level in ε_S-ε_T plane

ε_S

Lattice Extraction







R.E. Smail et al.., arXiv 2304.02866

T. Bhattacharya et al., PRD85 (2012)

ε_T

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

… all of these analyses will have to be redone at the light of the new aSpect result!

Future Analysis

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

- Study the additional non-forward currents connection with new chiral-odd GPDs
- Potential impact/correlations with axial vector sector (initial study by S. Gardner and B.Plaster, PRC87(2013))
- Impact on EDM measurement, other observables
- In depth study of scalar charge…

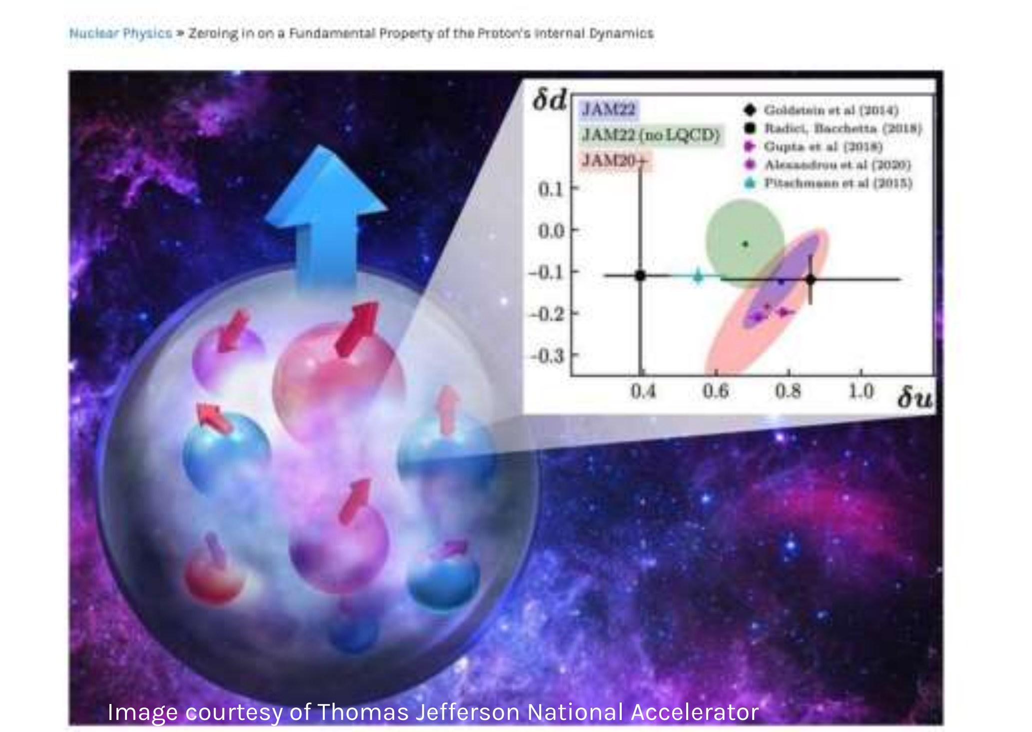


Image courtesy of Thomas Jefferson National Accelerator Facility

https://www.energy.gov/science/np/articles/zeroing-fundamental-property-protons-internal-dynamics

This work was supported by the Department of Energy Office of Science, Nuclear Physics program under the Coordinated Theoretical Approach to Transverse Momentum Dependent Hadron Structure in QCD (TMD Topical Collaboration)

Gamberg, L., *et al.* (JAM Collaboration), **Electron-Ion Collider impact study on the tensor charge of the nucleon.** *Physics Letters B* **816**, 136255 (2021). [DOI: 10.1016/j.physletb.2021.136255]

You have to answer for men's bad behavior, which is insane, but if you point that out, you're accused of complaining. You're supposed to stay pretty for men, but not so pretty that you tempt them too much or that you threaten other women because you're supposed to be a part of the sisterhood.

But always stand out and always be grateful. But never forget that the system is rigged. So find a way to acknowledge that but also always be grateful.

You have to never get old, never be rude, never show off, never be selfish, never fall down, never fail, never show fear, never get out of line. It's too hard! It's too contradictory and nobody gives you a medal or says thank you! And it turns out in fact that not only are you doing everything wrong, but also everything is your fault.

America Ferrera’s Monologue, Barbie (2023)

In conclusion: Why is the tensor charge interesting? (summary)

- ✓ It describes a specific response of the nucleon to polarization but it is not a fundamental object ➔ composite structure
- ✓ It evolves in PQCD but it does not couple to gluons (valence-like structure)
- ✓ Because the anomalous dimensions do not vanish for the first Mellin moment, the tensor charge evolves with Q^2
- ✓ These studies are of interest for both the “BSM” and “hadronic” communities

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

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.

More precise measurements of "features" of the structure of hadrons give insight on:

1) *longitudinal and transverse spin structure*, role of *orbital angular momentum*, QCD factorization

2) *strongly coupled gauge theories* from high energy (models of dark matter)
to low energy description of lattices with QCD symmetry from cold atoms, Wigner distributions at the femtoscale…

sl4y@virginia.edu