THE TENSOR AND THE SCALAR CHARGES OF THE NUCLEON FROM HADRON PHENOMENOLOGY

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How can hadronic physics help BSM search?

Hadronic observables extraction

Impact on β-decay observables

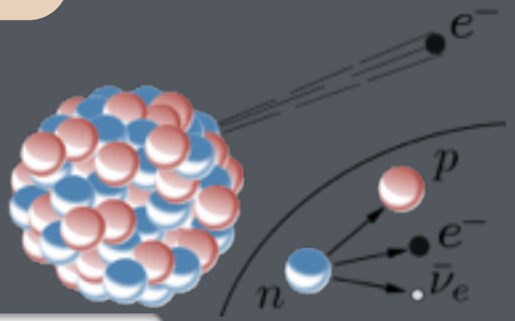
partially based on Phys.Rev.Lett. 115 (2015) 162001

OUTLINE

- Direct search
  - Large-x PDF
  - α_s
- Indirect search
  - Parity Violating DIS
  - $\boxed{\text{Beyond V-A interactions}}$ HERE
  - ...

QCD FOR BSM

$$N(p_n) \longrightarrow P(p_p) e^-(p_e) \bar{\nu}_e(p_\nu)$$



can be sketched as

$$\text{“} \left[d \xrightarrow{\Gamma} u\, e^-(p_e) \bar{\nu}_e(p_\nu) \right] \otimes \left[\langle P | \bar{u}\, \Gamma\, d | N \rangle \right] \text{”}$$

Electroweak:
V-A

Proton structure:
g_V & g_A

$$M = -i \frac{G_F}{\sqrt{2}} \bar{u}_e \gamma_\mu \left(1 - \gamma^5\right) v_\nu \langle p | \bar{u} \gamma^\mu \left(1 - \gamma^5\right) d | n \rangle \cos\theta_c$$

BETA DECAY IN SM

[Jackson et al., PR106]

[Lee & Yang, PR104]

- Neutron decay rate parameterized:

$$\mathrm{d}^3\Gamma = \frac{1}{(2\pi)^5}\frac{G_F^2|V_{ud}|^2}{2} p_e E_e \left(E_0 - E_e\right)^2 \mathrm{d}E_e \mathrm{d}\Omega_e \mathrm{d}\Omega_\nu$$
$$\times\xi\left[1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \mathbf{s}_n\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + \dots\right)\right]$$

- Effective Hamiltonian for β-decay
  - Lorentz low energy constants $C_{S,P,V,A,T}$
  - SM 1param $\boxed{\lambda=-C_A/C_V}$
  - a(λ), A (λ), B (λ)

- b=0 in SM
- $B \subset b_\nu = 0$ in SM

- sensitivity of neutron beta decay to new physics

BETA DECAY OBSERVABLES

[Jackson et al., PR106]

[Lee & Yang, PR104]

- **Neutron decay rate parameterized:**

$$\mathrm{d}^3\Gamma = \frac{1}{(2\pi)^5}\frac{G_F^2|V_{ud}|^2}{2}p_eE_e\left(E_0-E_e\right)^2\mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$
$$\times\xi\left[1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m_e}{E_e}+\mathbf{s}_n\left(A\frac{\mathbf{p}_e}{E_e}+B\frac{\mathbf{p}_\nu}{E_\nu}+\ldots\right)\right]$$

- **b=0 in SM**
- **B ⊂ b_ν =0 in SM**

- **sensitivity of neutron beta decay to new physics**

$$b=\frac{2\sqrt{1-\alpha^2}}{1+3\lambda^2}\left[\mathrm{Re}\left(\frac{C_\mathrm{S}}{C_\mathrm{V}}\right)+3\lambda^2\mathrm{Re}\left(\frac{C_\mathrm{T}}{C_\mathrm{A}}\right)\right]$$

- **b sensitive to scalar and tensor LEC**
- **same for b_ν**

BETA DECAY OBSERVABLES

- ★ **Extract LEC**

$$C_V = C_V^{\rm SM} + \delta C_V$$
$$C'_V = C_V^{\rm SM} + \delta C'_V$$
$$C_A = C_A^{\rm SM} + \delta C_A$$
$$C'_A = C_A^{\rm SM} + \delta C'_A$$
$$C_S = \delta C_S$$
$$C'_S = \delta C'_S$$
$$C_T = \delta C_T$$
$$C'_T = \delta C'_T.$$

NEW PHYSICS IN δ

$$C_V^{\rm SM} = g_V$$
$$C_A^{\rm SM} = -g_A$$

λ→pretty well known

Best constraints so far

$$\mathrm{C_S/C_V} = 0.0014(13)$$

@1σ

[Hardy et al., PRC91]

$$-0.0026 < \mathrm{C_T/C_A} < 0.0024$$

@95%CL

[Pattie et al., PRC88]

- ★ **from various processes**
  - ★ decay rate for super allowed $0^+ \to 0^+$
  - ★ decay rate for beta decay (total, angular correlation in unpolarized &
  - ★ radiative pion decay

SCALAR & TENSOR INTERACTIONS

New particles hints

- in loops
- mediators of interaction
- ...

New particles produced directly

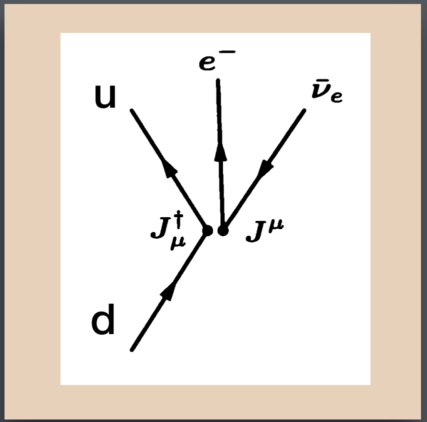
Low energy → High energy

- ★ **Effective field theories for low energy**
  - ➡ **New (heavy) dof integrated out**
- ★ **Consider all Dirac bilinears for EW interactions**
  - ➡ $1, \quad \gamma_5, \quad \gamma_\mu(1+\gamma_5), \quad \sigma_{\mu\nu}$
  - ➡ **Define ``*Wilson coefficient*" for new interaction**

NEW FUNDAMENTAL INTERACTIONS

EFT AT THE QUARK LEVEL $d_j \to u_i l^- \bar{\nu}_l$

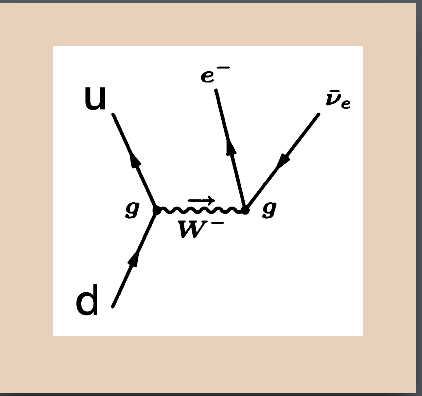
$$\mathcal{L}^{(\mathrm{eff})} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i$$



4-fermion interaction

$$\mathcal{L}_{d_j\to u_i\ell^-\bar{\nu}_\ell} = \frac{-g^2}{2m_W^2}V_{ij}\Big[\big(1+[v_L]_{\ell\ell ij}\big)\bar{\ell}_L\gamma_\mu\nu_{\ell L}\bar{u}^i_L\gamma^\mu d^j_L + [v_R]_{\ell\ell ij}\bar{\ell}_L\gamma_\mu\nu_{\ell L}\bar{u}^i_R\gamma^\mu d^j_R$$
$$+ [s_L]_{\ell\ell ij}\bar{\ell}_R\nu_{\ell L}\bar{u}^i_R d^j_L + [s_R]_{\ell\ell ij}\bar{\ell}_R\nu_{\ell L}\bar{u}^i_L d^j_R$$
$$+ [t_L]_{\ell\ell ij}\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L}\bar{u}^i_R\sigma^{\mu\nu}d^j_L\Big] + \mathrm{h.c.},$$

right



Scalars

$\varepsilon_S \equiv s_L + s_R$

SM

Tensor

$\varepsilon_T \equiv t_L$

BETA DECAY IN EFT

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

$$\text{“}\left[d \xrightarrow{\Gamma} u\, e^-(p_e)\bar{\nu}_e(p_\nu) \right] \otimes \left[\langle P | \bar{u}\, \Gamma\, d | N \rangle \right]\text{”}$$

$$C_{\rm SM} = \frac{G_F}{\sqrt{2}} \ldots$$ STANDARD MODEL

$$|g_S \epsilon_S| = 0.0014 \pm 0.0013$$ @1σ

$$|g_T \epsilon_T| < 6 \cdot 10^{-4}$$ @95%CL

$$C_{\rm S} = \frac{G_F}{\sqrt{2}} V_{ud}\, g_S \epsilon_S$$

$$C_{\rm T} = \frac{G_F}{\sqrt{2}} V_{ud}\, 4\, g_T \epsilon_T$$

NEW BSM S & T INTERACTIONS

Precision with which the NEW COUPLINGS can be measured depend on the knowledge of hadronic charges

New LEC factorized into hadronic contribution & new EW interaction

LEC IN TERMS OF HADRONIC × NEW INT.

Proton

$$\langle P(p_p, S_p)|\bar{u}\Gamma d|N(p_n, S_n)\rangle$$

$$\Downarrow$$

Neutron

FORM FACTORS

$$\langle P(p_p, S_p)|\bar{u}\gamma_\mu d|N(p_n, S_n)\rangle = g_V\,(t)\;\bar{u}_P\gamma_\mu u_N + \mathcal{O}(\sqrt{t}/M)$$

Isovector vector FF

$$\langle P(p_p, S_p)|\bar{u}\sigma_{\mu\nu} d|N(p_n, S_n)\rangle = g_T\,(t, Q^2)\;\bar{u}_P\sigma_{\mu\nu} u_N$$

Isovector tensor FF

Exist in hadronic physics

When t→0, g(0)≡charge

$t=(p_n-p_p)^2$

Q^2 RGE scale

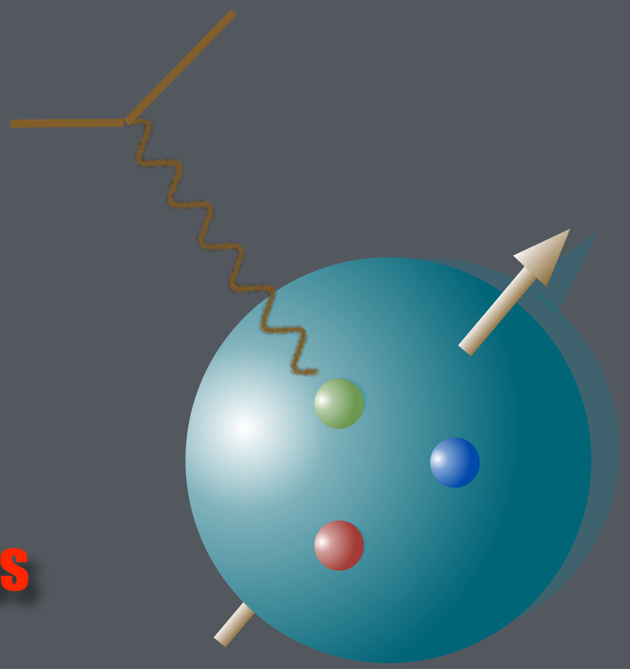
MATCHING AT HADRONIC LEVEL

- ★ Nonlocal matrix element for proton structure
  - ★ Parton Distribution Functions

- built from Lorentz symmetry from vectors at hand
- defined in Bjorken scaling
- nonperturbative objects
- 1st principle related to ``charges"

Fundamental charges for γ_μ & $\gamma_\mu\gamma_5$ only

Structural charges for the others



Scalar & tensor charge

accessible through sum rules of Parton Distributions

HADRONIC STRUCTURE

Lorentz structure
Discrete symmetries
Vectors at hand...

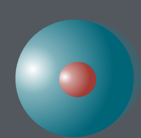
Kinematics of the Bjorken scaling
$Q^2 \to \infty$
$p.q \to \infty$
$Q^2/2p.q \equiv x = \text{finite}$

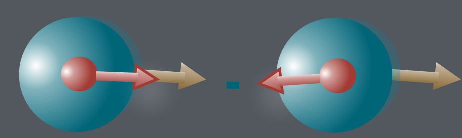
To leading twist:

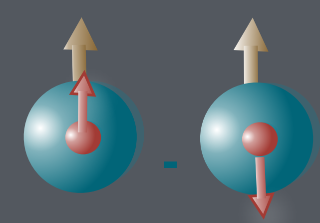
$$\int_{-1}^{1} dx\, h_1^{u_V - d_V}(x) = g_T$$

PDFs ⇒ $f_1^q(x)\,,\qquad g_1^q(x)\,,\qquad h_1^q(x)$

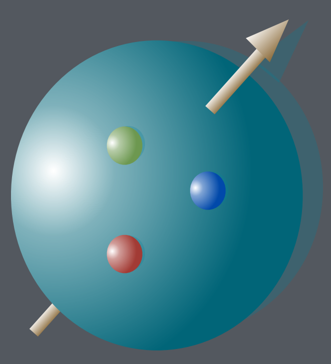
Dirac operator ⇒ Vector | Axial-vector | Tensor







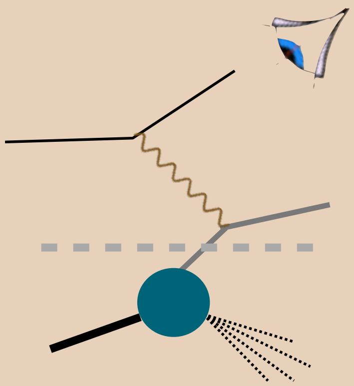
Charges ⇒ g_V, g_A, g_T



PDF AT LEADING TWIST

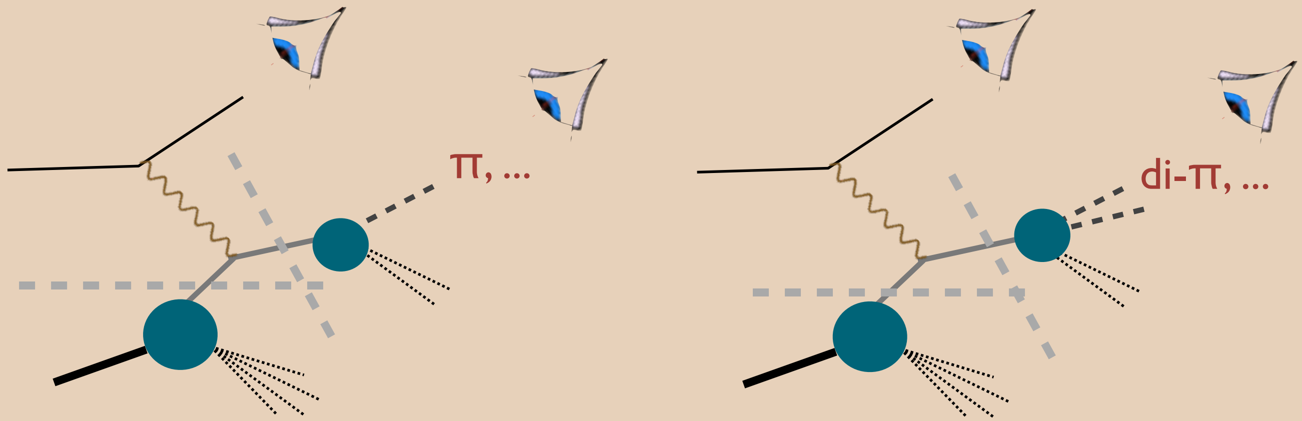
ACCESS TO DISTRIBUTION FUNCTIONS

DEFINITION
AND
FACTORIZATION



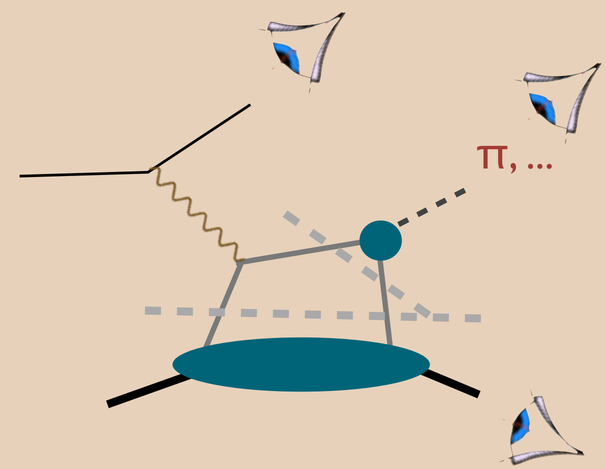
Inclusive processes

$\sigma \rightarrow$ PDF$\times d\sigma$



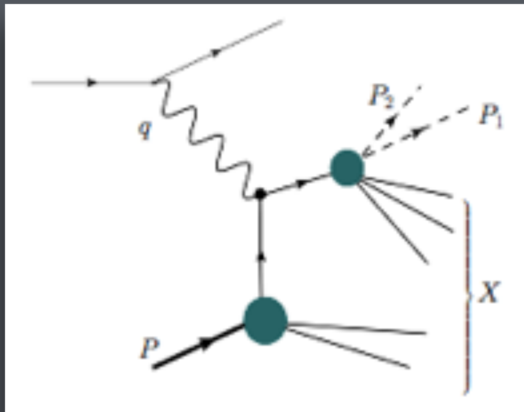
Semi-inclusive processes

$\sigma \rightarrow$ PDF$\times d\sigma \times$Fragmentation Function



Exclusive processes

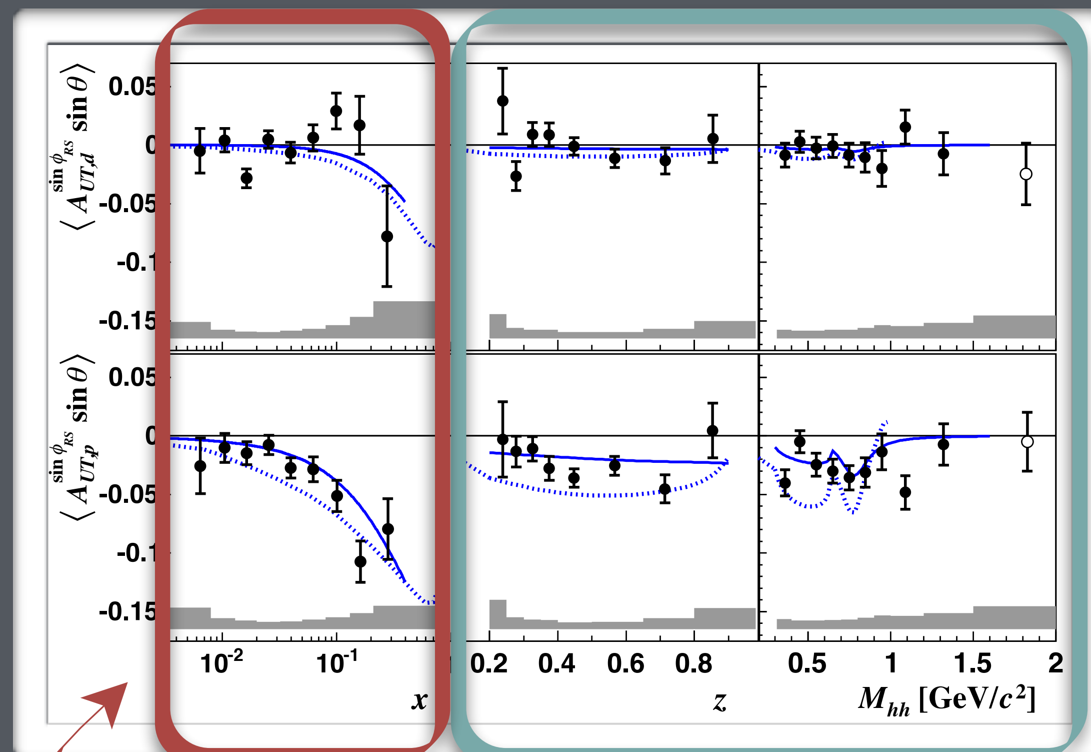
$\sigma \rightarrow |\text{Generalized PDF} \times H \times \text{ Meson Amplitude}|^2$



TRIPTIC OF TARGET SPIN ASYMMETRY
SIDIS PRODUCTION OF PION PAIRS @ COMPASS & HERMES

2002-4 Deuteron Data

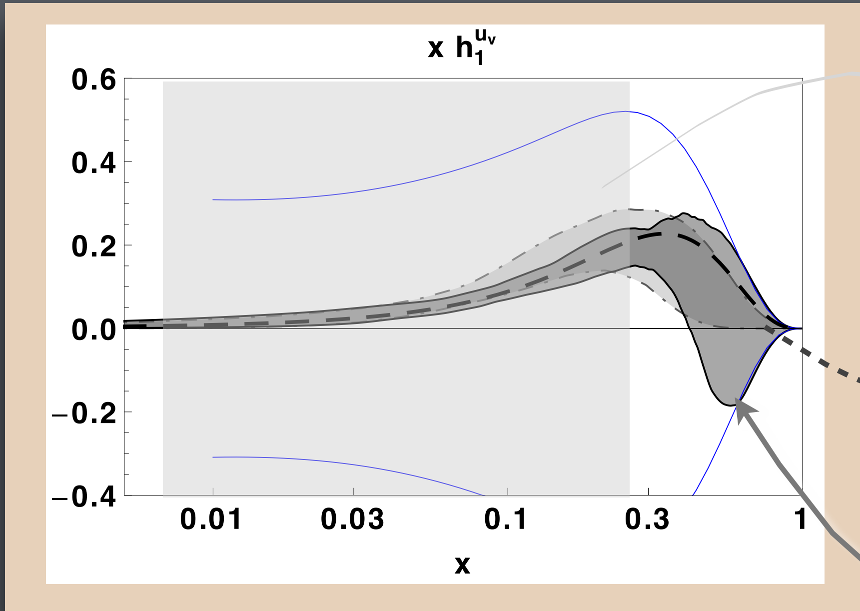
2007 Proton Data



x-dependence only from Transversity
[A.C., et al, PRL 2012, JHEP 2013, 2015]

(z, M_h)-dpdence determined by DiFF from Belle
[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

EXAMPLE OF DATA & EXTRACTION



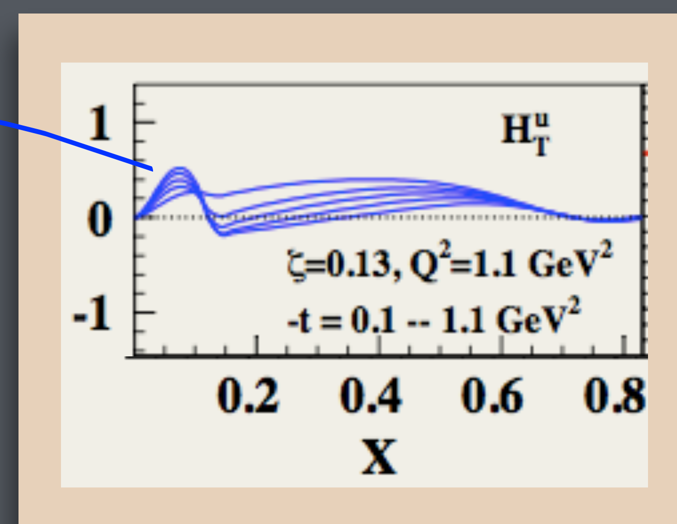
Torino 2013 @2.4 GeV^2

Kang et al central value

1σ error band from replicas @2.4 GeV^2 PAVIA

[Radici et al., JHEP 2015]

- ⋆ Semi-inclusive processes
  - ⋆ eN→e π X Torino et al
  - ⋆ eN→e (ππ) X Pavia et al
- ⋆ Exclusive: eP→e π^0 P GGL

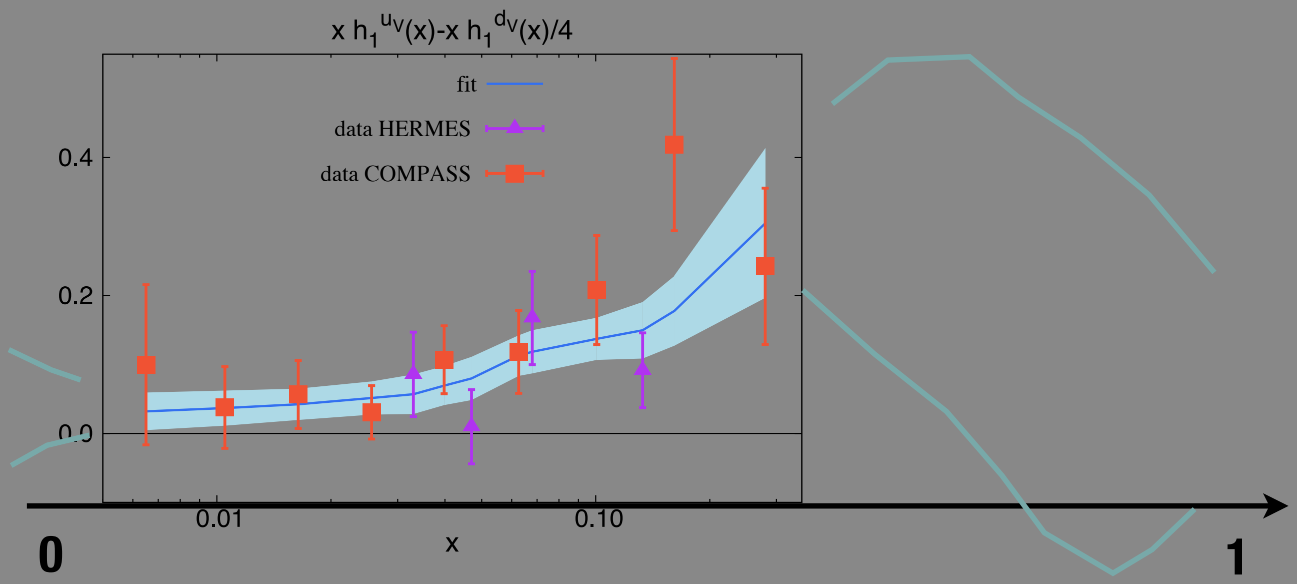


[Goldstein et al, PRD 2015]

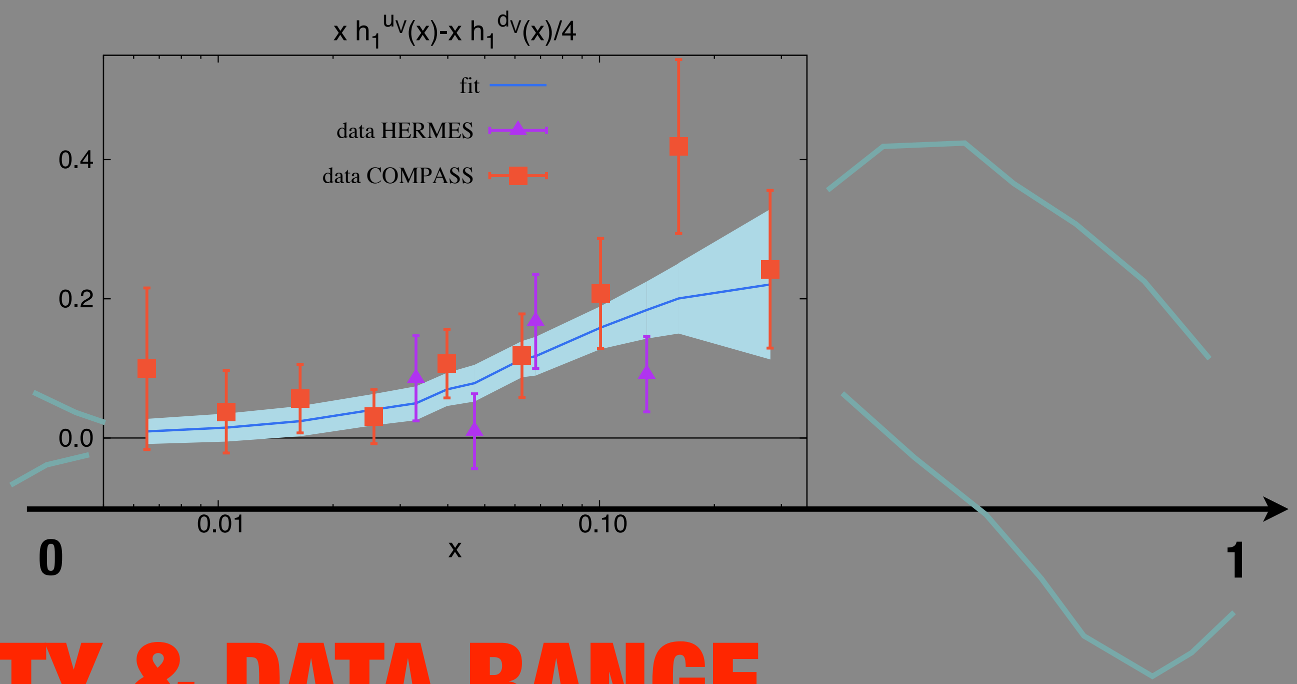
TRANSVERSITY PDF

ROLE OF FUNCTIONAL FORM FOR FIT

flexible functional form

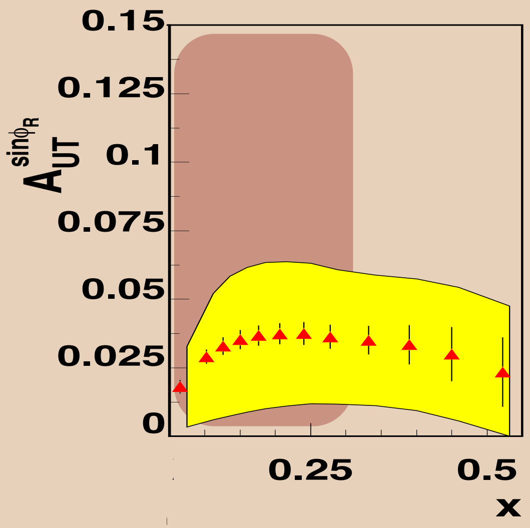


rigid functional form



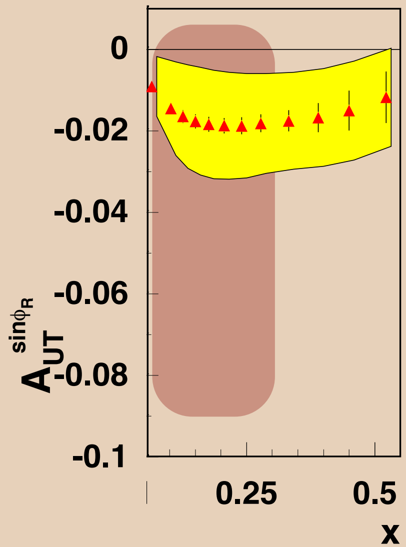
UNCERTAINTY & DATA RANGE

CLAS12 projection on proton target



0.007 < x < 0.53

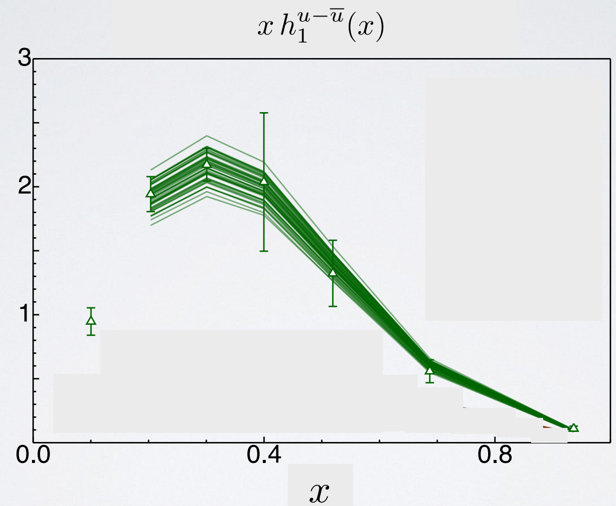
SoLID projection on neutron target



Jefferson Lab

?

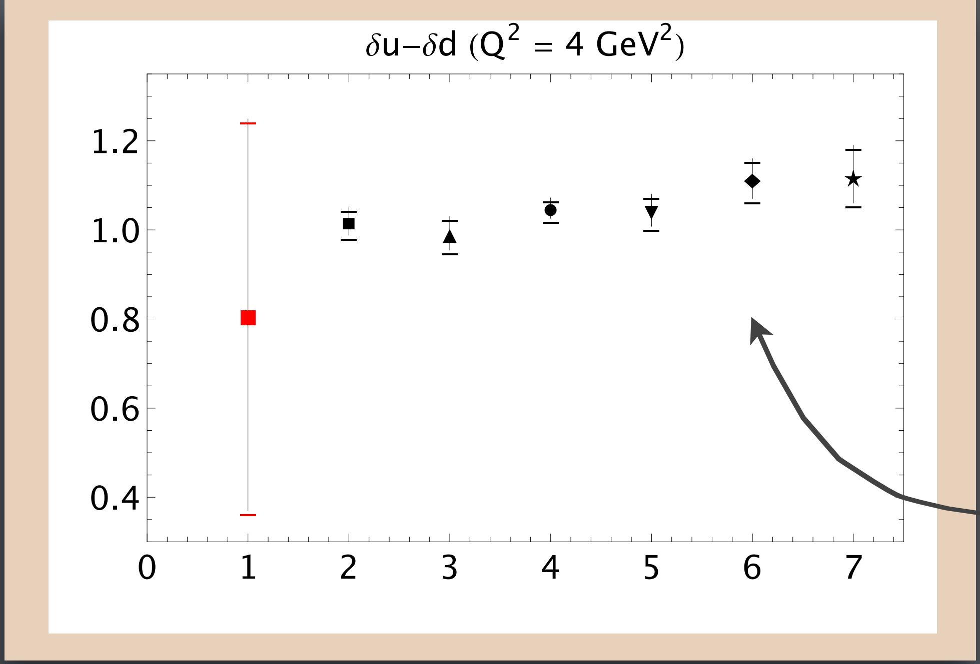
MORE DATA
+
MONTE CARLO LIKE FITTING



procedure repeated 100 times
(until reproduce mean and std. deviation of original data)

SOLUTIONS

Pavia 15
JHEP1505 (2015) 123



WITH MONTE CARLO
LIKE FITTING

Various Lattice QCD results

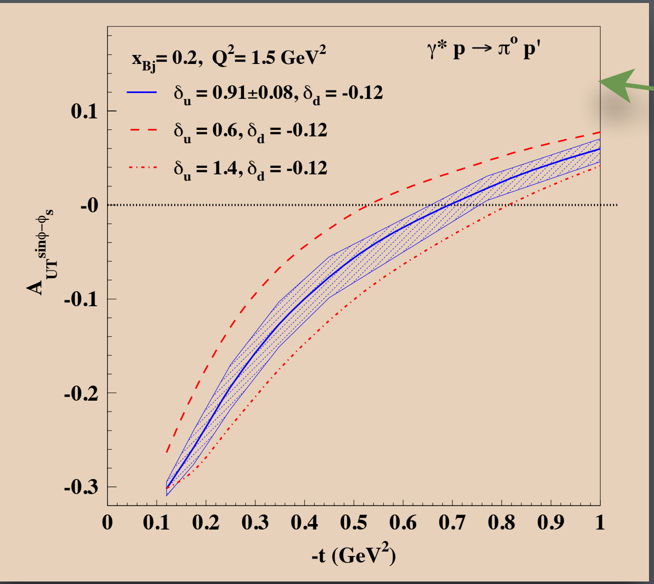
$$\boxed{g_T = 0.81 \pm 0.44 \quad \text{at } Q^2 = 4 \text{ GeV}^2}$$

Pavia flexible 0.125

LATTICE RESULTS PRESENT TINY ERRORS W.R.T. HADRONIC EXTRACTIONS

HERE TESTING GROUND FOR LATTICE QCD CALCULATIONS

ISOVECTOR TENSOR CHARGE

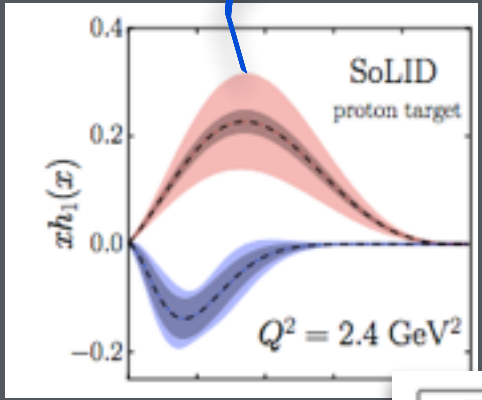


- ★ **GGL depends on new JLab data**

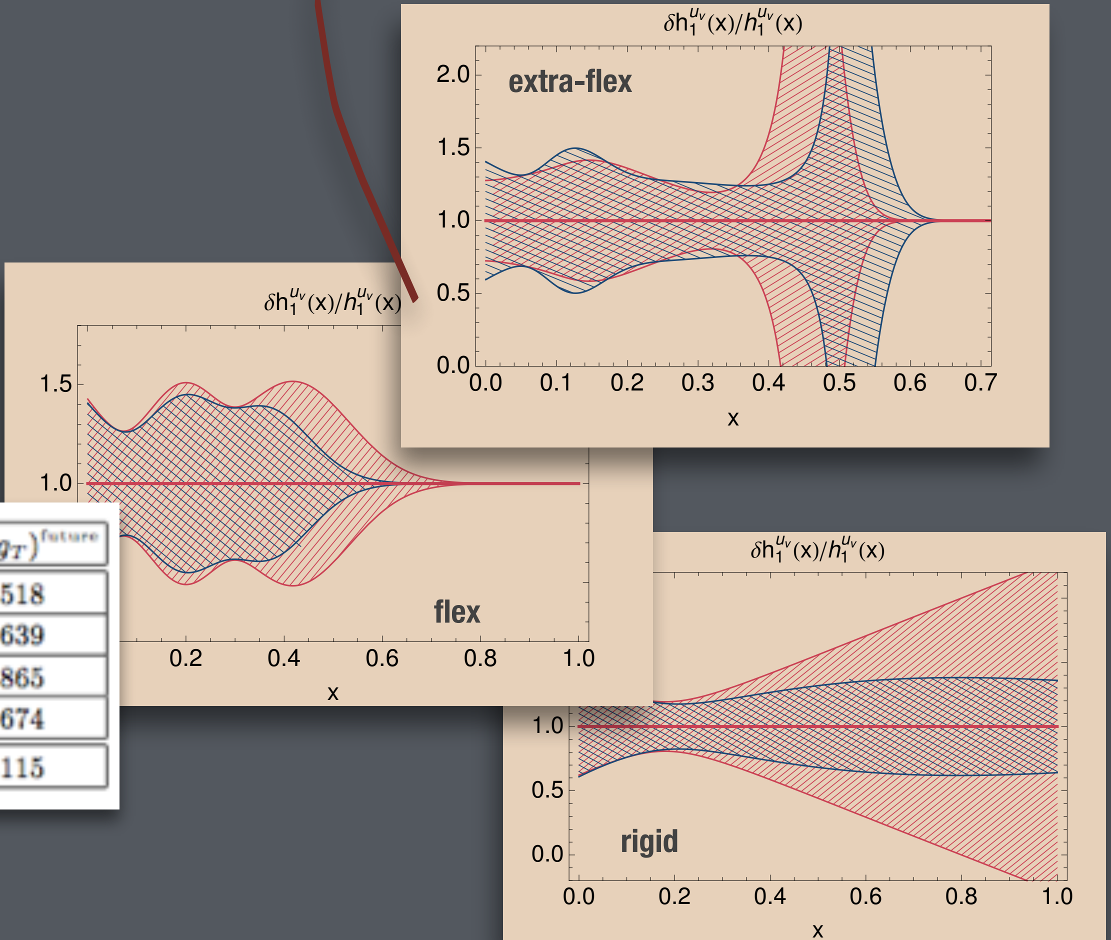
Courtoy et al, PRL 115

- ★ **Pavia depends on new JLab data**
- ★ **Torino depends on TMD evolution +new JLab data**

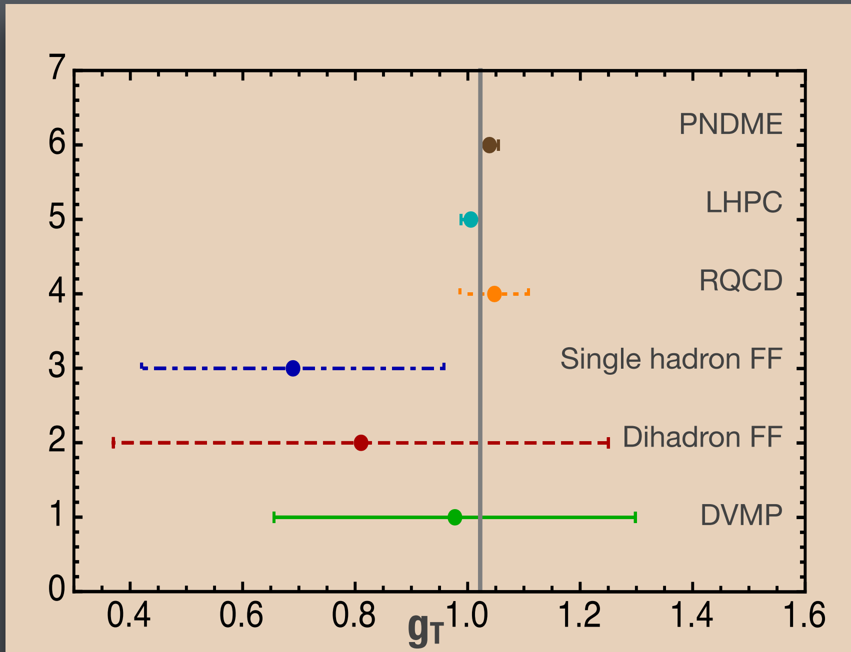
Ye et al.,1609.02449



Transversities		$\delta g_T/g_T$	$(\delta g_T/g_T)^{\text{future}}$
Pavia	rigid	0.599	0.518
	flexible	0.696	0.639
	extra-flexible	1.007	0.865
Pavia average		0.767	0.674
GGL		0.329	0.115



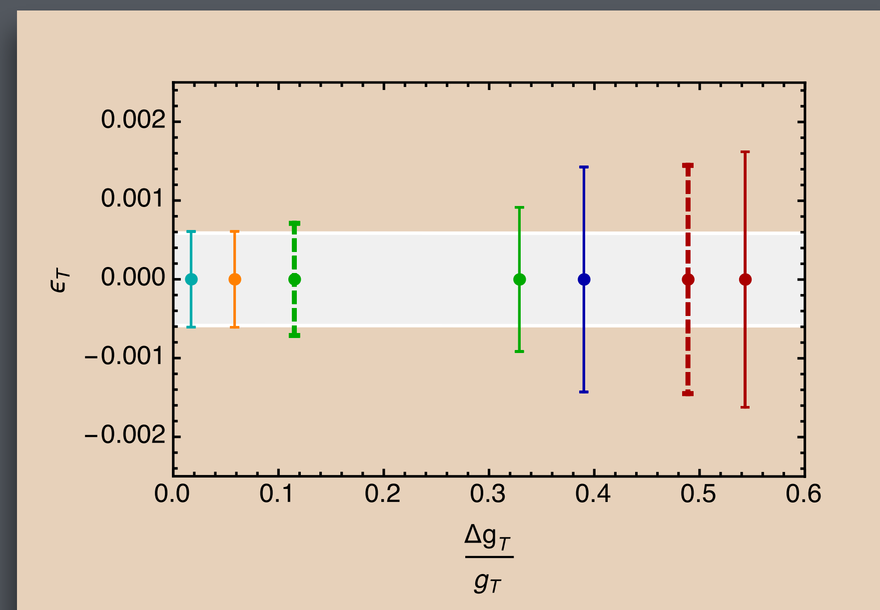
FUTURE



NOW WITH $g_T \pm \sigma_{g_T}$

AND $|g_T \epsilon_T| < 6 \cdot 10^{-4}$

we find....



New PNDME: g_T =0.987(51)(20) [PRD94]
NME compatible results [1611.07452]

Ye et al.: g_T =0.64±0.021 (Q^2=2.4GeV^2)

TENSOR INTERACTION AS OF NOW

★ **HESSIAN PROPAGATION**

- Usual error propagation

$$\sigma_f^2 = \sum_{a,b\,\in\,\mathrm{params}} \frac{\partial f}{\partial a}\,\mathrm{cov}_{ab}\,\frac{\partial f}{\partial b}$$ with here $$\Delta\chi^2 = 1$$

★ **MONTE CARLO APPROACH**

- N replicas of data within xσ gaussian noise

$$f \pm \sigma_f = X\%\mathrm{CL} \times f_i, \qquad i = 1, \cdots N$$

$$X = 68, 90, 95, \ldots$$

★ **SCATTER PLOT**

- 2+ D
- Random generation of allowed values within xσ

★ **RFIT METHOD**

- Theoretical param anywhere within [a-σ_a, a+σ_a] only
- other params as usual

$$-2\ln\mathcal{L}_{\mathrm{calc}}(\{y_{\mathrm{calc}}\}) \equiv \begin{cases} 0, & \forall\, y_{\mathrm{calc},i} \in [y_{\mathrm{calc},i} \pm \delta y_{\mathrm{calc},i}] \\ \infty, & \text{otherwise} \end{cases}$$

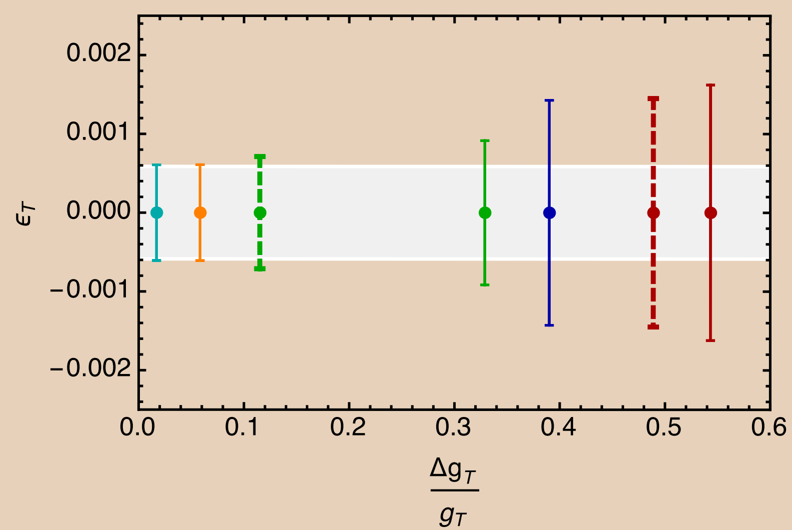
★ ...

ERROR TREATMENT

NOW WITH $g_T \pm \sigma_{gT}$

AND $|g_T \epsilon_T| < 6 \cdot 10^{-4}$

Rfit method:



Monte Carlo approach:

Pavia 2015 1D for $<\varepsilon_T>$ only

- present: $|\varepsilon_T| < 0.00162$
- compared to
  Naviliat-Cuncic & González-Alonso: $|\varepsilon_T| < 0.0013$

TENSOR INTERACTION AS OF NOW

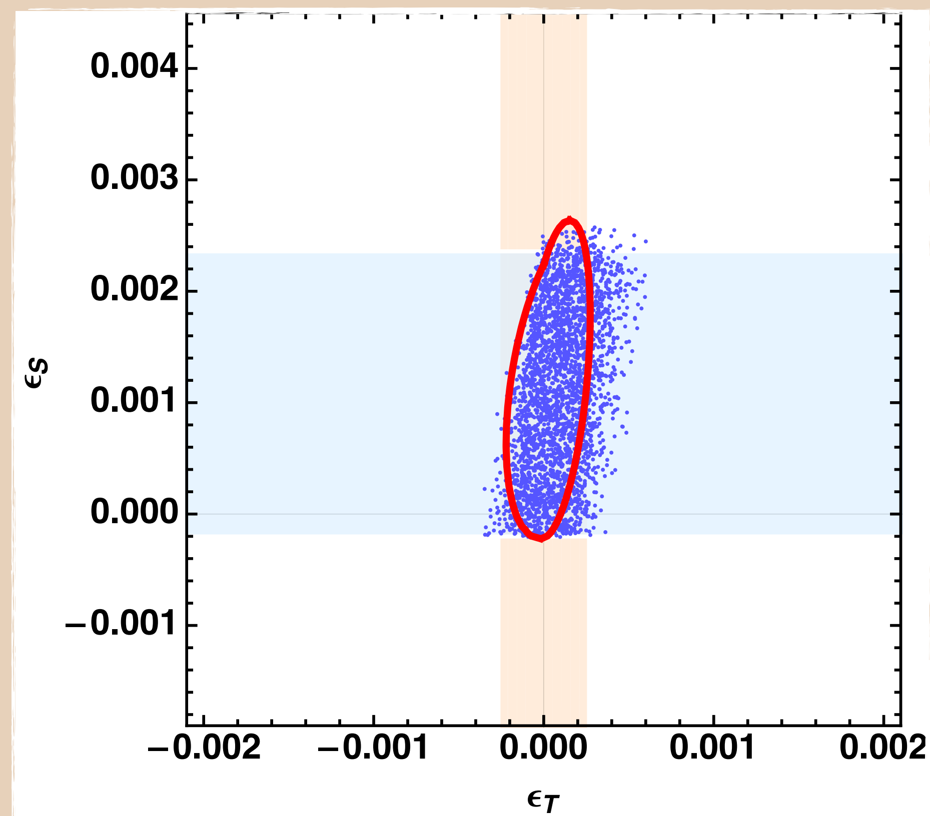
ε_T vs. ε_S plane from b_0^+ and b

Warning: not a global fit

- with $g_S = 1.02 \pm 0.11$
  from González-Alonso and Martin Camalich, PRL 112
- with $g_T = 0.81 \pm 0.44$
  from Pavia 15
- to be compared to $\langle g_T \rangle = 0.839(357)$
  from GGL & Pavia 15

1σ errors

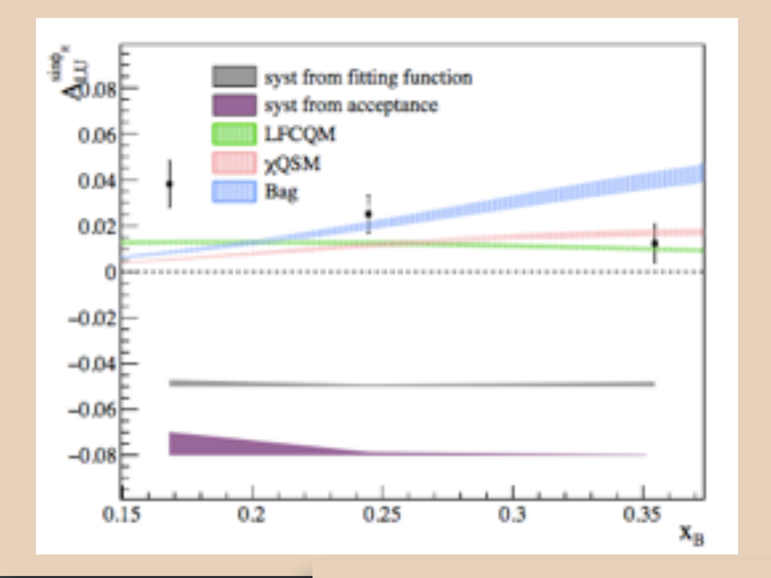
- **Hessian in blue & pink**
- **Rfit method in red**
- **Scatter plot in blue**



NEW SCALAR-TENSOR

DIHADRON ASYMMETRY FOR UNPOLARIZED TARGET INVOLVING SCALAR PDF (subleading)

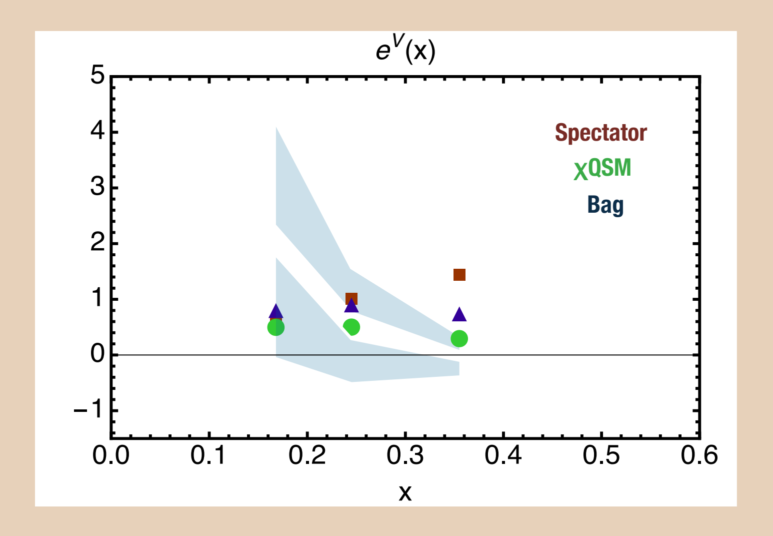
Jefferson Lab



CLAS collaboration

S. Pisano et al., to be published

A.C. et al. 1405.7659



SCALAR CHARGE related to e(x=0)

lots of things to think of...

CAN WE DO THE SAME FOR SCALAR CHARGE?

* Evaluation of bounds for BSM tensor interaction
  - from hadronic matrix elements extracted from experiments
  - as opposed to lattice calculations
* Hadronic uncertainties are still very large
* However, competitive results expected from future hadronic experiments
* Complementarity +testing of lattice results

WORTH MENTIONING

HADRONIC MATRIX ELEMENTS RELATED TO OUTSTANDING QCD QUESTIONS

STRUCTURE OF HADRONS→CONFINEMENT, CHIRAL SYMMETRY,...

CONCLUSIONS

- Neutron decay rate parameterized:

$$\mathrm{d}^3\Gamma = \frac{1}{(2\pi)^5}\frac{G_F^2|V_{ud}|^2}{2}p_e E_e\left(E_0 - E_e\right)^2 \mathrm{d}E_e\mathrm{d}\Omega_e\mathrm{d}\Omega_\nu$$
$$\times\xi\left[1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \mathbf{s}_n\left(A\frac{\mathbf{p}_e}{E_e} + B\frac{\mathbf{p}_\nu}{E_\nu} + \dots\right)\right]$$

- Nab collaboration plans to measure b, term sensitive to C_S and C_T with precision of 10^-3

- abBA collaboration (and others) plans to measure A and B angular coefficients for polarized neutrons, B is also sensitive to C_S and C_T with precision of 10^-3

FUTURE OF BETA DECAY OBSERVABLES

- ⋆ **Redefinition of "new" scale**
- ⋆ **effective coupling (rescaled)** $\epsilon_i \propto m_W^2/\Lambda_i^2$

  where m_W enters through $G_F = g^2/(4\sqrt{2}m_W^2)$

- ⋆ **but underlying mechanism not known**

SCALE OF NEW PHYSICS