TENSOR CHARGE AND PHYSICS BEYOND THE STANDARD MODEL

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How can hadronic physics help BSM search?

Hadronic observables extraction

Impact on β-decay observables

in collaboration with S. Liuti, S. Baessler, M. González Alonso, A. Bacchetta and M. Radici

Creation of a working group on
Theory and Experiment Analysis of Hadronic Matrix elements (TEAHM)

OUTLINE

- ★ Direct search
  - ★ Large-x PDF
  - ★ α_s
- ★ Indirect search
  - ★ Parity Violating DIS
  - ★ Beyond V-A interactions
  - ★ ...

QCD FOR BSM

- ★ Direct search
  - ★ Large-x PDF
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  - ★ Parity Violating DIS
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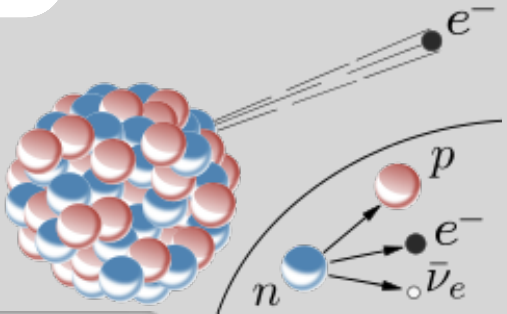
HERE

  - ★ ...

QCD FOR BSM

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



can be sketched as

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

BETA DECAY IN SM

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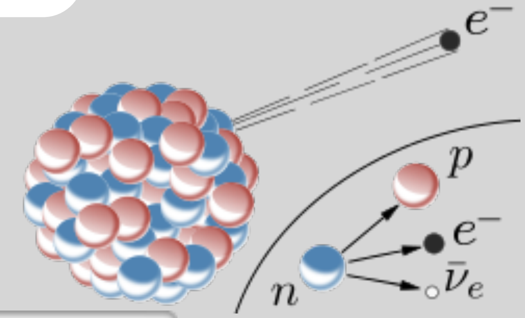

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Electroweak:
V-A

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

BETA DECAY OBSERVABLES

[Jackson et al., PR106]
[Lee & Yang, PR104]

- ⋆ **Neutron decay rate parameterized:**

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

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

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

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

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- ★ **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

★ from various processes

- ★ decay rate for super allowed $0^+ \to 0^+$
- ★ decay rate for beta decay (total, angular correlation in unpolarized & polarized parts)
- ★ radiative pion decay

SCALAR & TENSOR INTERACTIONS

- ⋆ **Extract LEC**

$$C_V = C_V^{SM} + \delta C_V$$
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NEW PHYSICS IN δ

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

λ→pretty well known

Best constraints so far

$$C_S/C_V = 0.0014(13)$$

@1σ

[Hardy et al., PRC91]

$$-0.0026 < C_T/C_A < 0.0024$$

@95%CL

[Pattie et al., PRC88]

- ⋆ **from various processes**
  - ⋆ decay rate for super allowed $0^+ \to 0^+$
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SCALAR & TENSOR INTERACTIONS

New particles hints

- in loops
- mediators of interaction
- ...

New particles produced directly

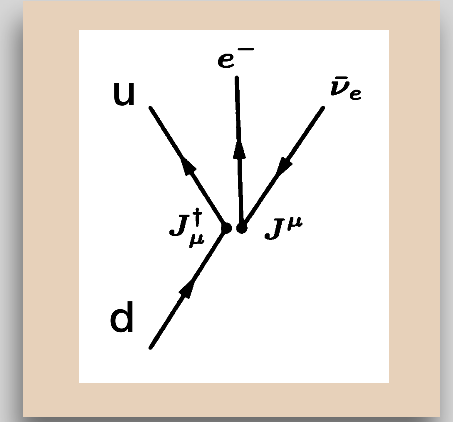
Low energy → **High energy**

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

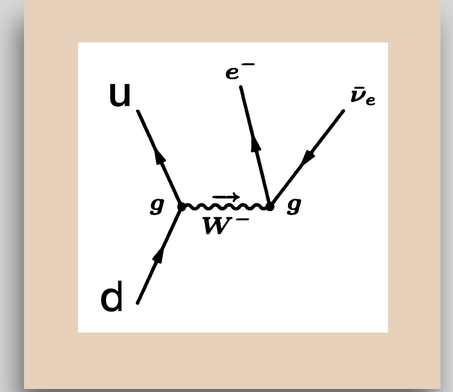
NEW FUNDAMENTAL INTERACTIONS

EFT AT THE QUARK LEVEL $d_j \to u_i l^- \nu_l$

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



4-fermion interaction



SM

BETA DECAY IN EFT

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

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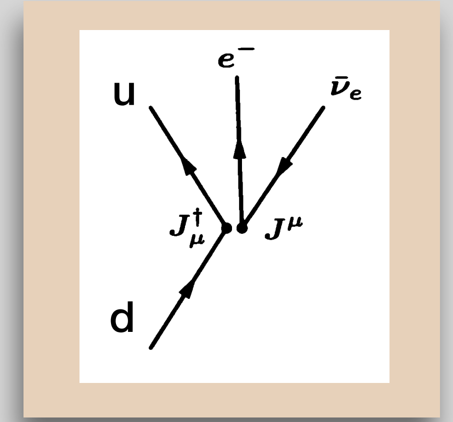


4-fermion interaction

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

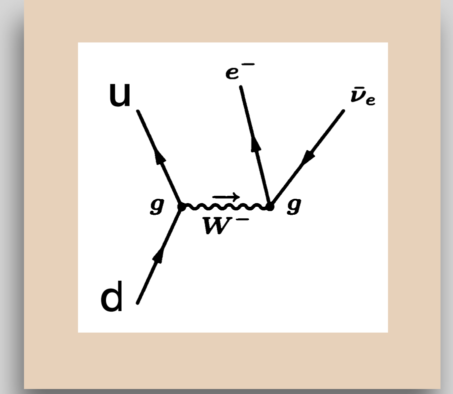
right

Scalars

$\varepsilon_S \equiv s_L + s_R$

Tensor

$\varepsilon_T \equiv t_L$



SM

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$$C_{\rm SM} = \frac{G_F}{\sqrt{2}} V_{ud}\,(g_V - g_A)$$

STANDARD MODEL

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

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

NEW BSM S & T INTERACTIONS

[Pattie et al, Phys.Rev. C88]
[Wauters et al, Phys.Rev. C89]

LEC IN TERMS OF HADRONIC × NEW INT.

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New LEC factorized into hadronic contribution & new EW interaction

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$$|g_S \epsilon_S| = 0.0014 \pm 0.0013 \quad \text{@1σ}$$

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

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NEW BSM S & T INTERACTIONS

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

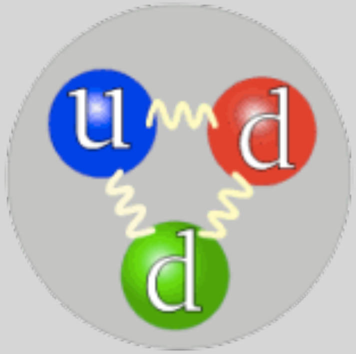
New LEC factorized into hadronic contribution & new EW interaction

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

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

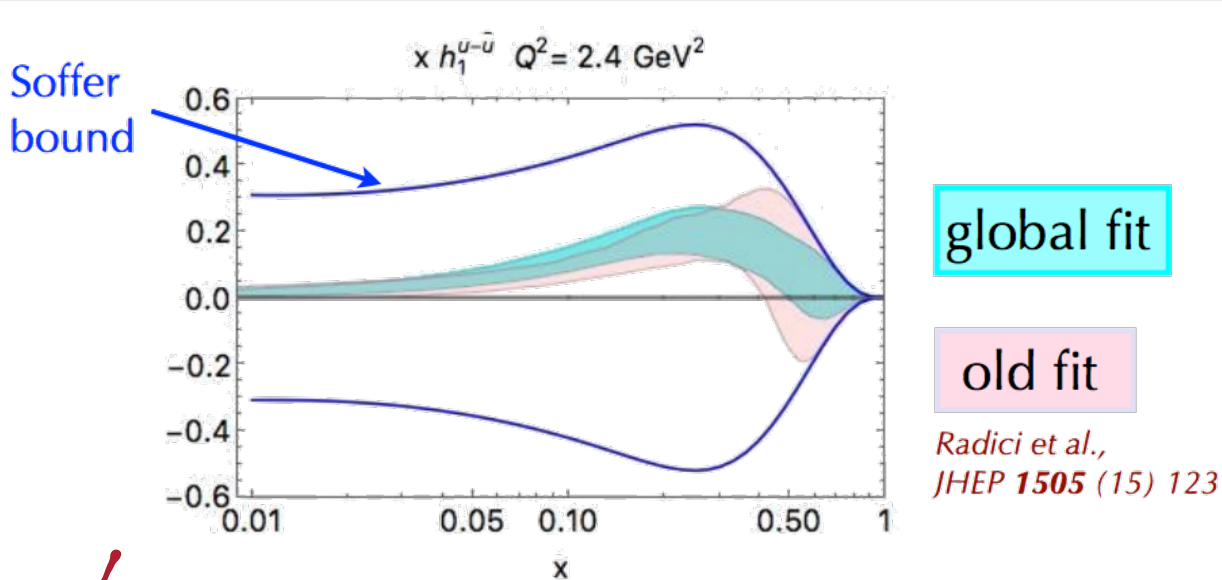
Isovector tensor FF

When t→0, g(0)≡charge

$t=(p_n-p_p)^2$

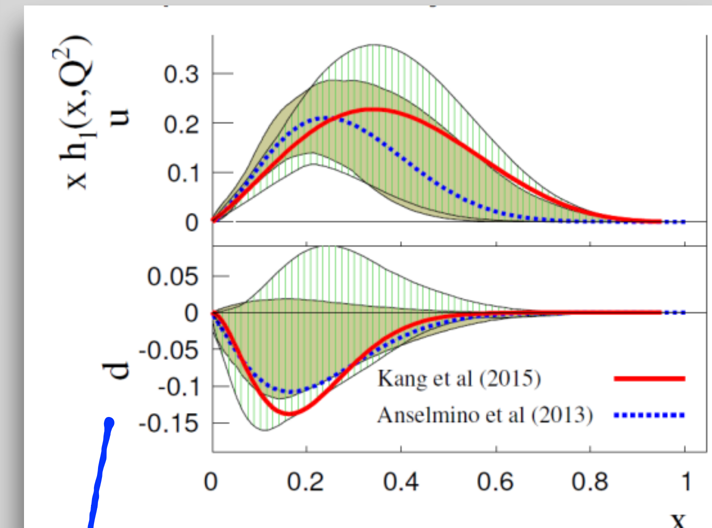
Q^2 RGE scale

MATCHING AT HADRONIC LEVEL

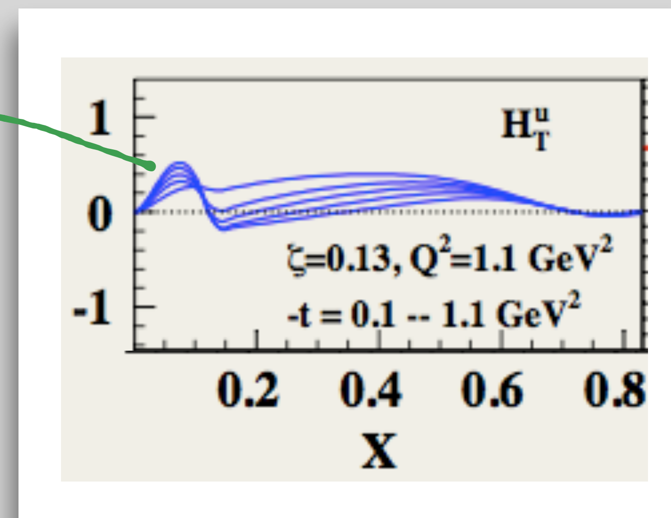


From Radici's talk

From Prokudin's talk

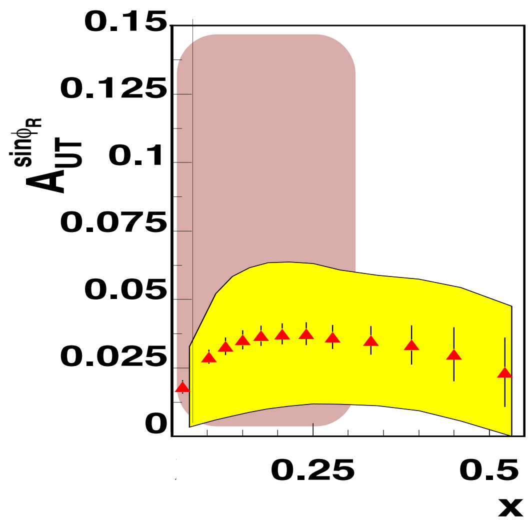


- ⋆ Semi-inclusive processes
  - ⋆ eN→e π X **Torino et al**
  - ⋆ eN→e (ππ) X **Pavia et al**
- ⋆ Exclusive: eP→e π^0 P **GGL**



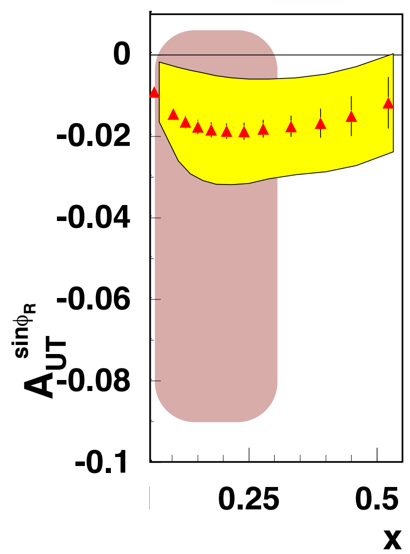
TRANSVERSITY PDF

CLAS12 projection on proton target



0.007 < x < 0.53

SoLID projection on neutron target

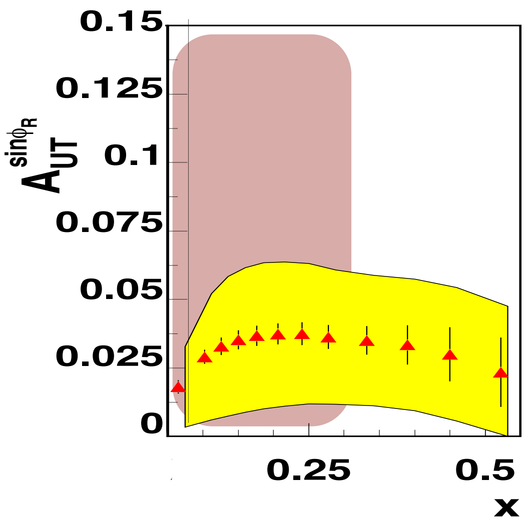


Jefferson Lab

FUTURE DATA

Jefferson Lab

CLAS12 projection on proton target



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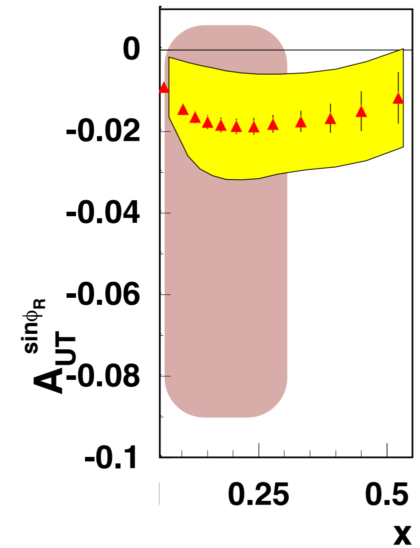
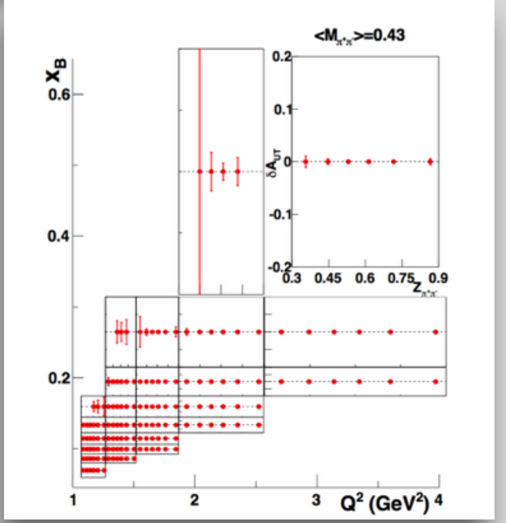


SoLID: about 1000 unprojected bins on 3He target



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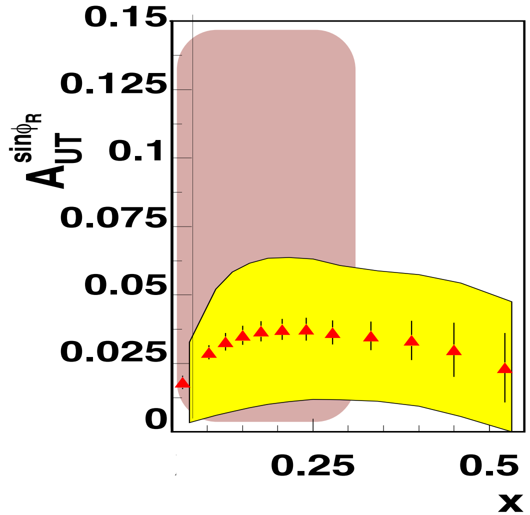

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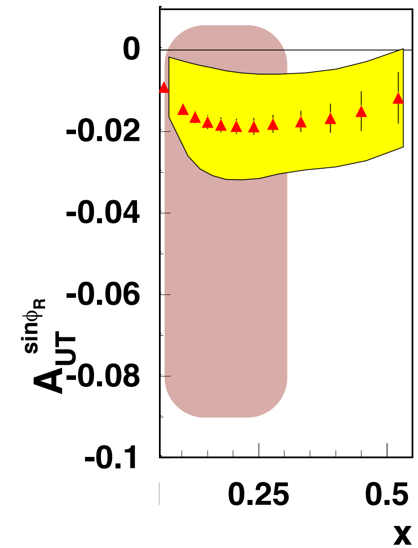

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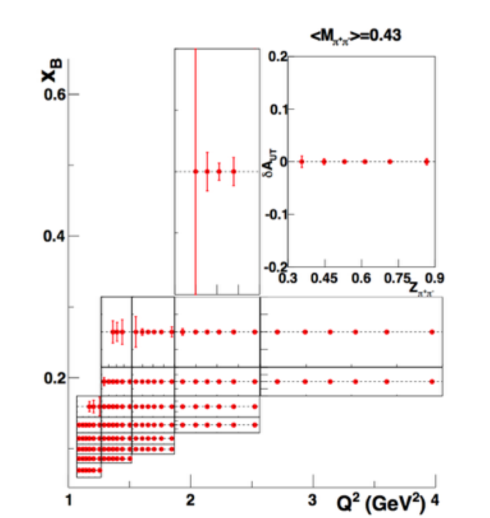
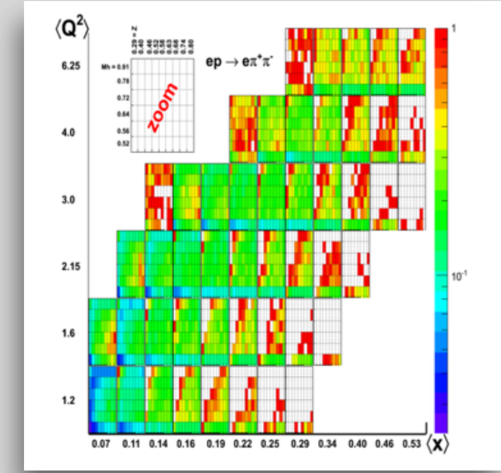
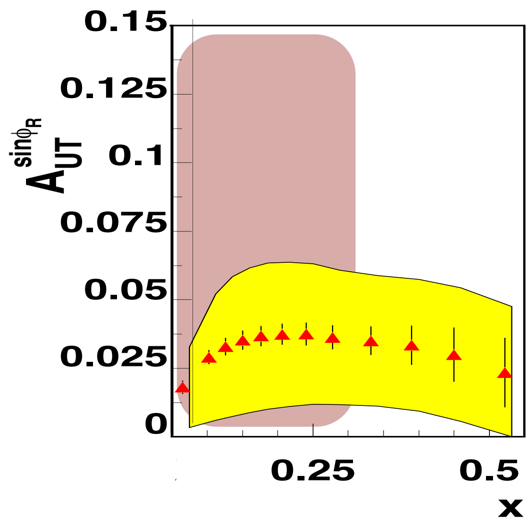


CLAS12: about 1000 unprojected bins on 1H target



FUTURE DATA

CLAS12 projection on proton target



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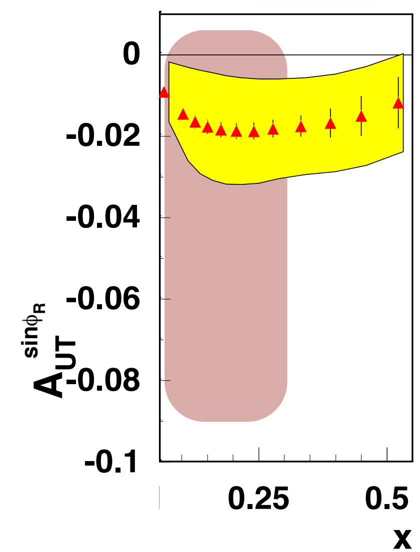
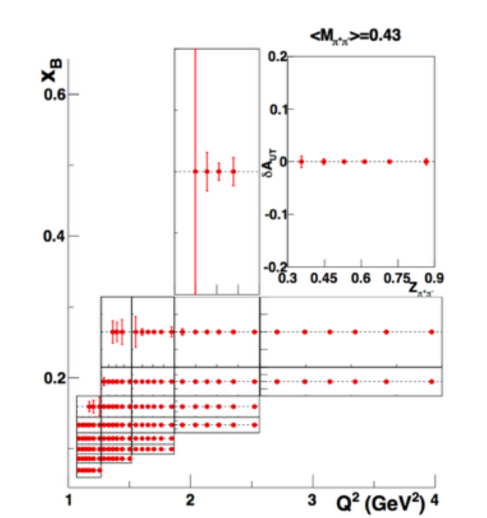
SoLID projection on neutron target



?

SoLID: about 1000 unprojected bins on 3He target



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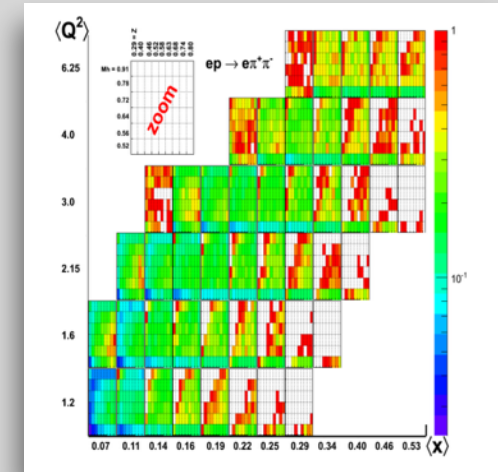

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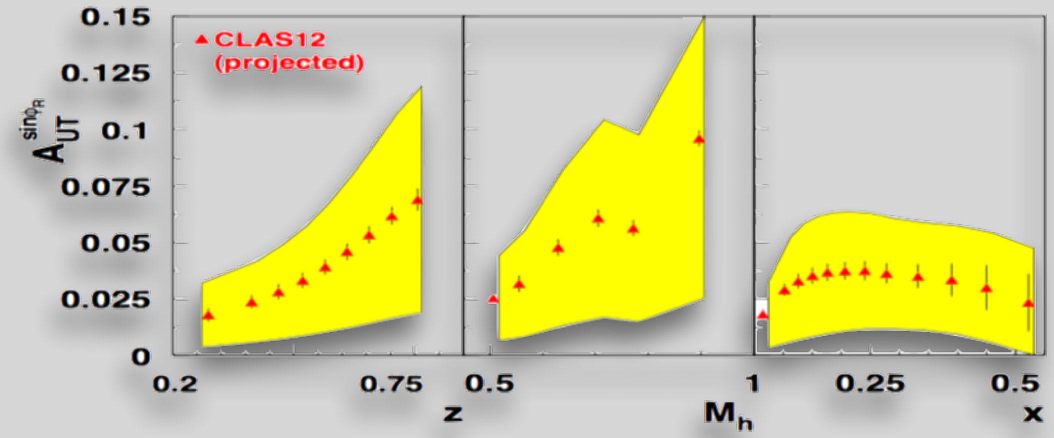
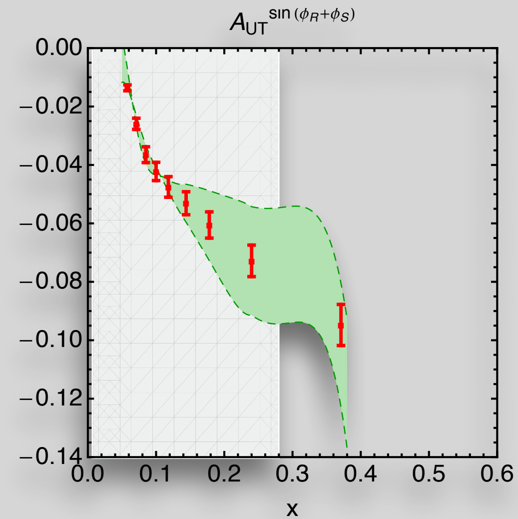
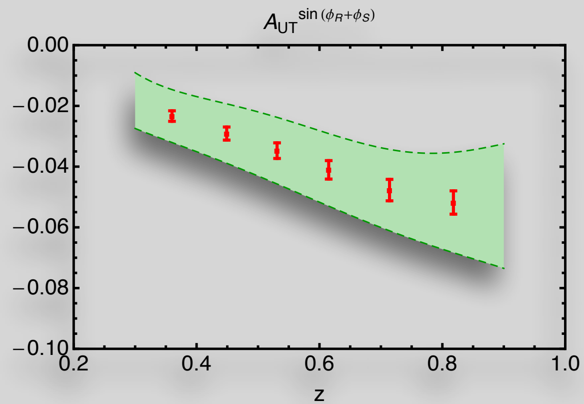
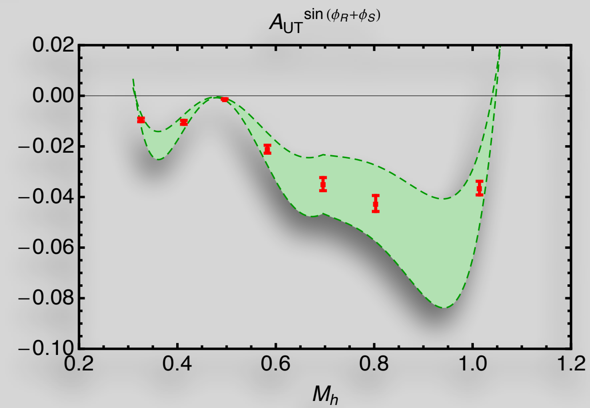


CLAS



SoLID





TRIPTIC PROJECTIONS

JLAB12 IMPROVEMENT

Courtoy, Baessler, González-Alonso and Liuti, PRL 115 (2015)

functional forms using the replica method for the error analysis. As for future extractions, the dihadron SIDIS will be studied in CLAS12 at JLab on a proton target and in SoLID on a neutron target [21] that will give both an improvement of ~10% in the ratio $\Delta g_T/g_T$ thanks to a wider kinematical coverage and better measurement of the contribution of the d quark. The results from this extraction are shown in Fig. 1.

- ★ GGL with new JLab data
- ★ Pavia with on new JLab data from both CLAS12 & SoLID

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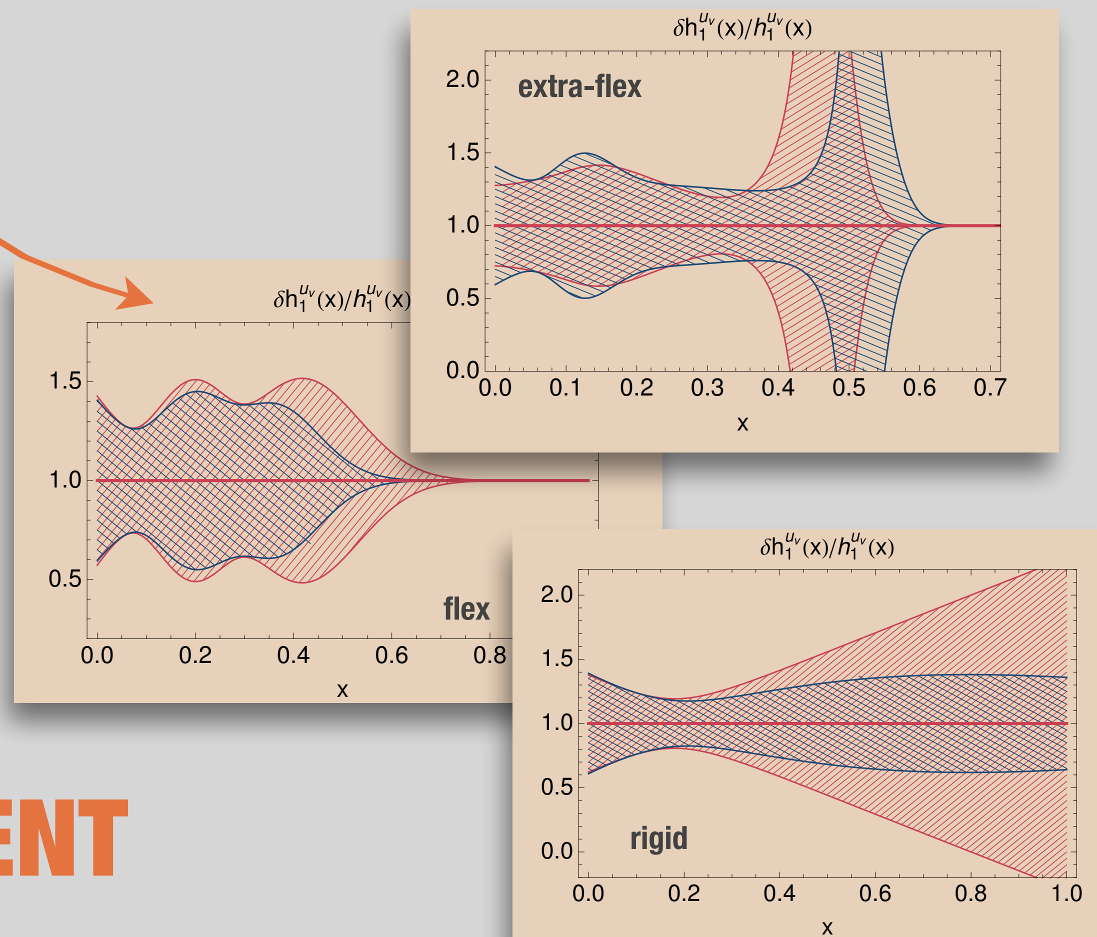
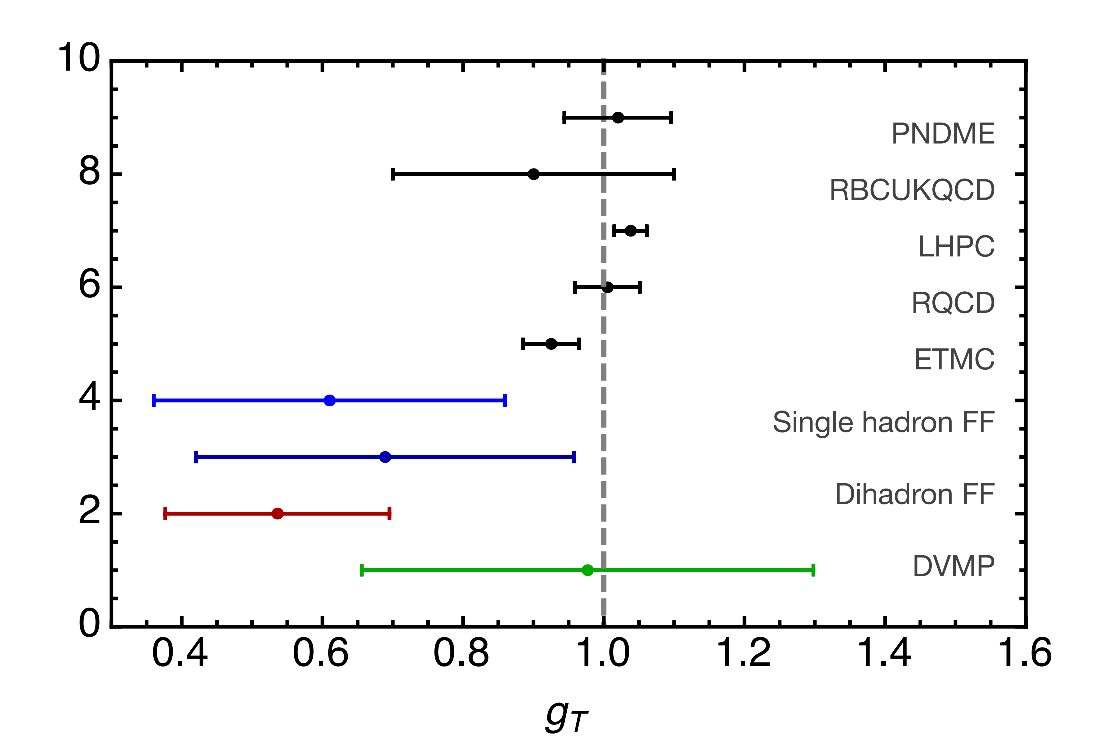
- ★ **Pavia with on new JLab data from both CLAS12 & SoLID**

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



JLAB12 IMPROVEMENT

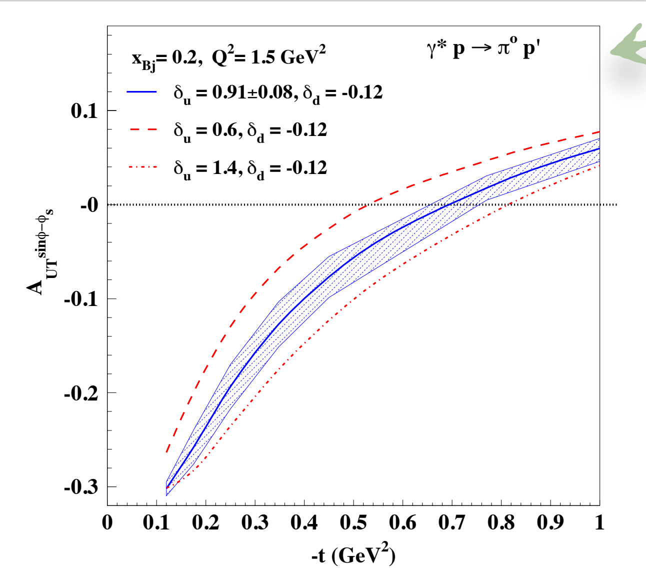
$$\int_{-1}^{1} dx\, h_1^{u_V - d_V}(x) = g_T$$



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

HERE TESTING GROUND FOR LATTICE QCD CALCULATIONS

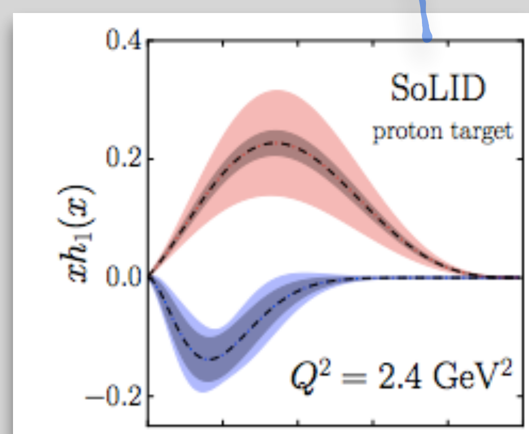
ISOVECTOR TENSOR CHARGE

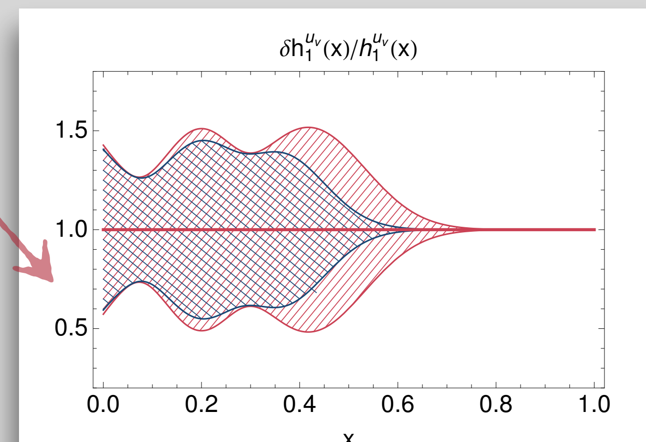


★ GGL relies on DVMP data

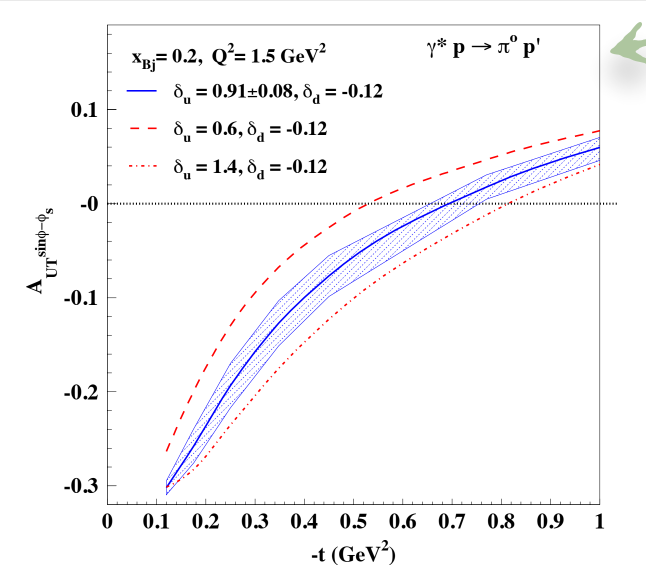
★ Pavia relies on SIDIS, e^+e^- & hadron-hadron data

★ Torino depends on TMD evo. + SIDIS & e^+e^- data





FUTURE



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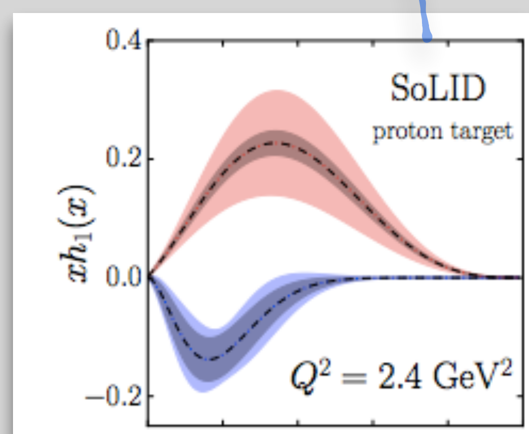

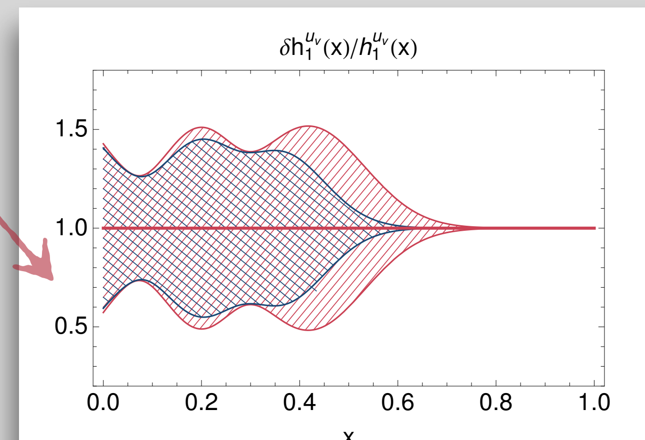

Transversities		$\delta g_T/g_T$	$(\delta g_T/g_T)^{\text{future}}$	Improvement
Pavia	rigid	0.599	0.518	
	flexible	0.696	0.639	
	extra-flexible	1.007	0.865	
Pavia average		0.767	0.674	12%
GGL		0.329	0.115	65%
Kang et al				90%

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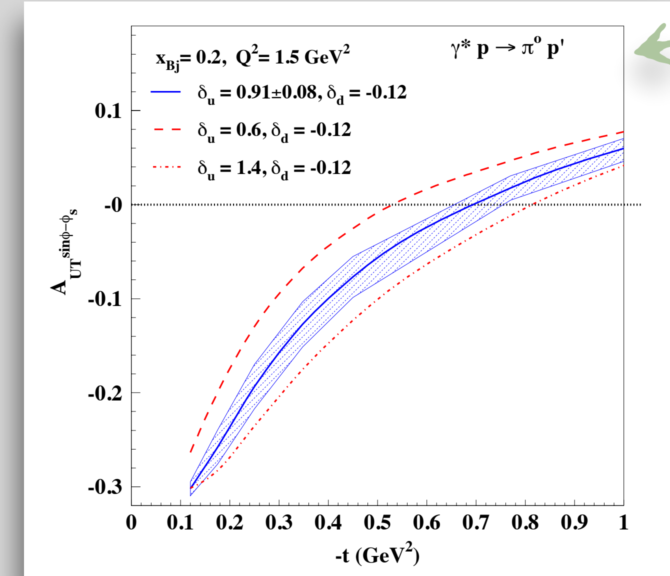

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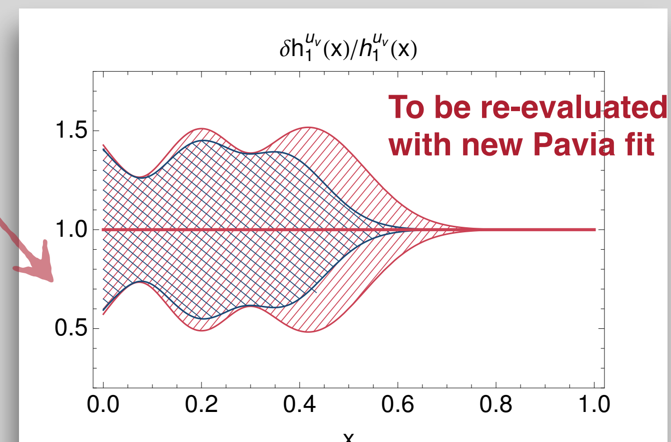

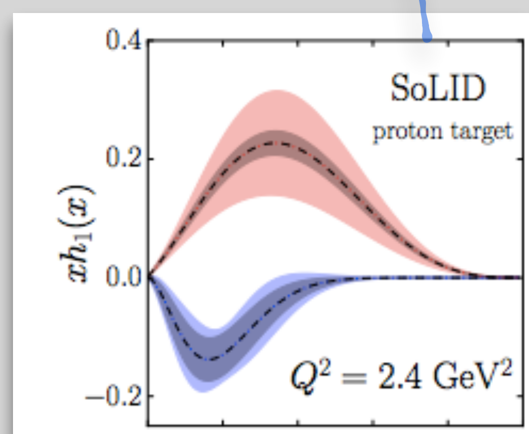

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FUTURE

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

@95%CL

EXOTIC TENSOR INTERACTION

★ **HESSIAN PROPAGATION**

- Usual error propagation

$$\sigma_f^2 = \sum_{a,b\,\in\,\text{params}} \frac{\partial f}{\partial a}\,\text{cov}_{ab}\,\frac{\partial f}{\partial b}$$

with here $\Delta\chi^2 = 1$

★ **MONTE CARLO APPROACH**

- N replicas of data within xσ gaussian noise

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

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

★ **SCATTER PLOT**

- 1+ 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

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

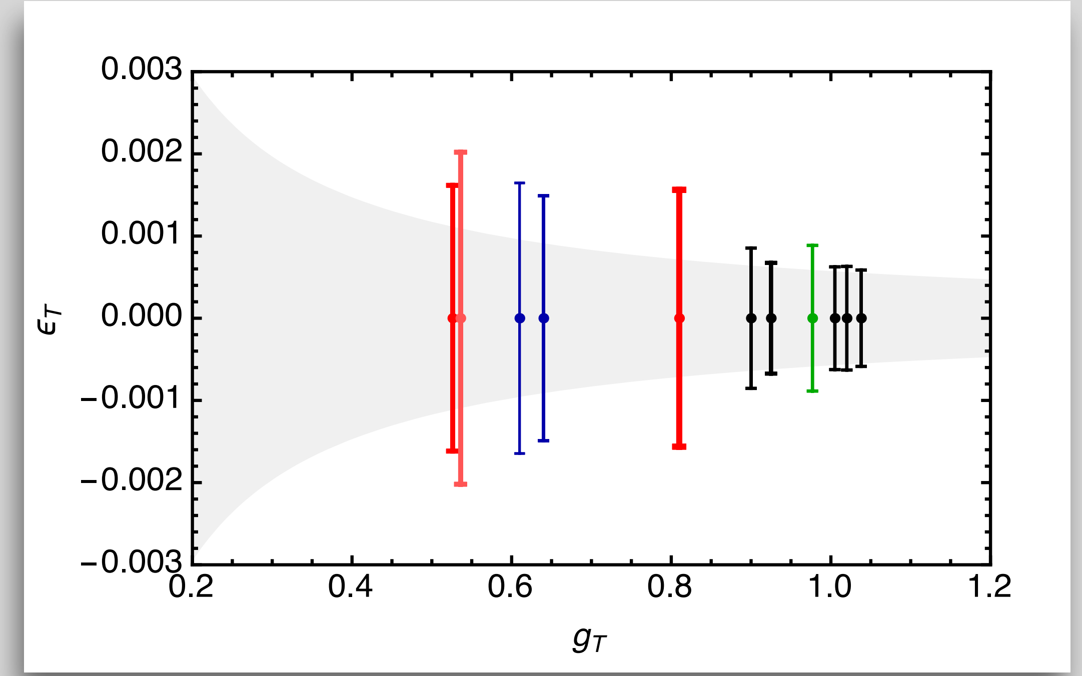
★ ...

ERROR TREATMENT

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

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

scatter plot evaluation



Pavia 1sigma
2sigma
2015

Kang et al
Anselmino et al

GGL

Lattice results

TENSOR INTERACTION 2017

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

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

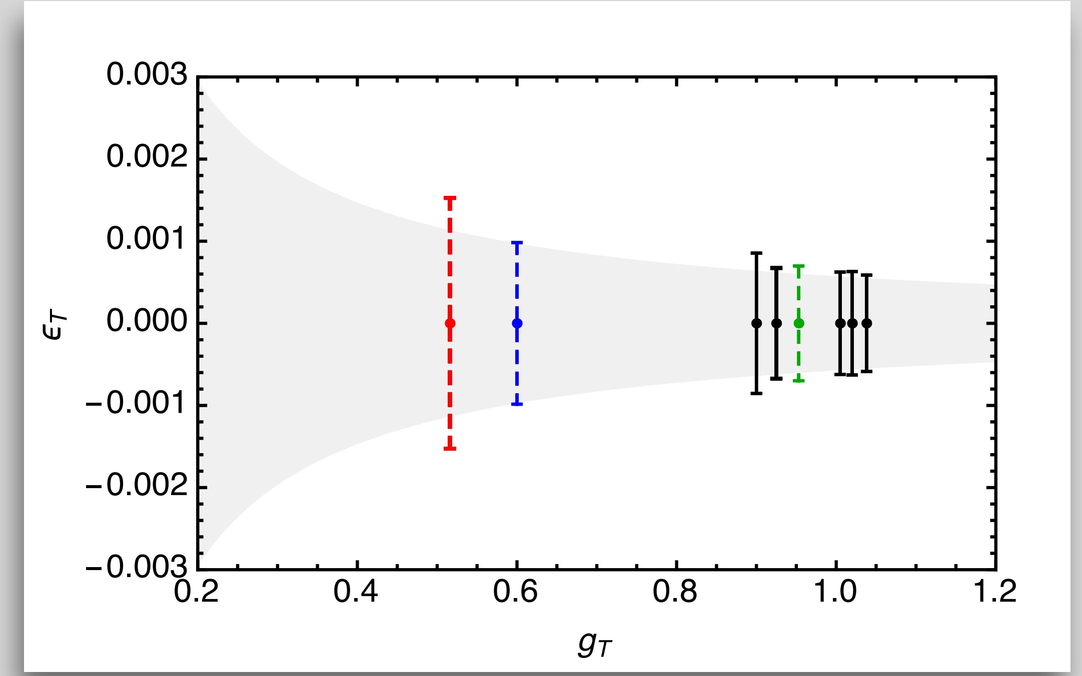
scatter plot evaluation

Dihadron estimated after Jlab12

Single-hadron after SoLID

GGL after JLab12

Lattice results

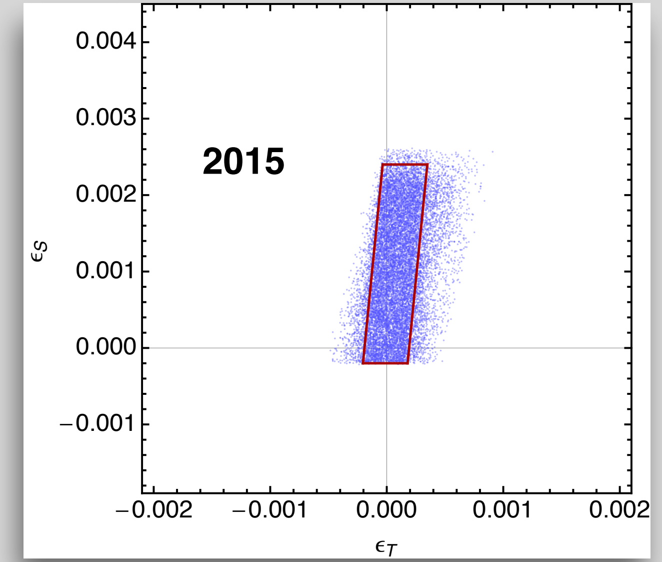


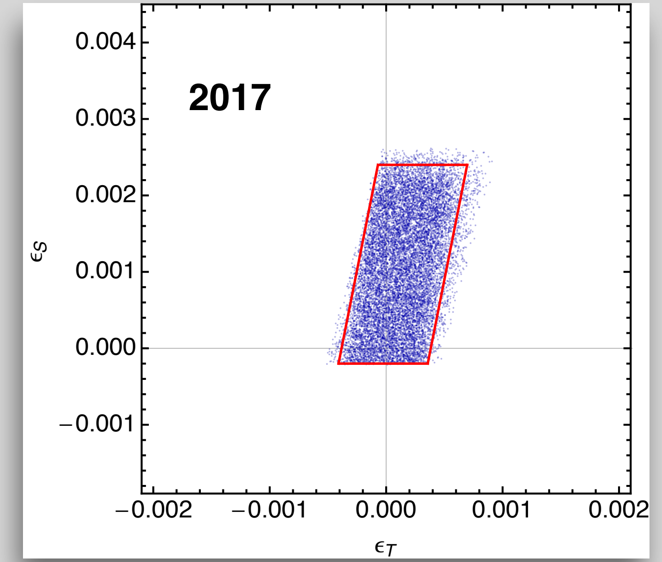
TENSOR INTERACTION IN THE NEXT YEARS

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
- gT from Pavia 2015 vs. 2017





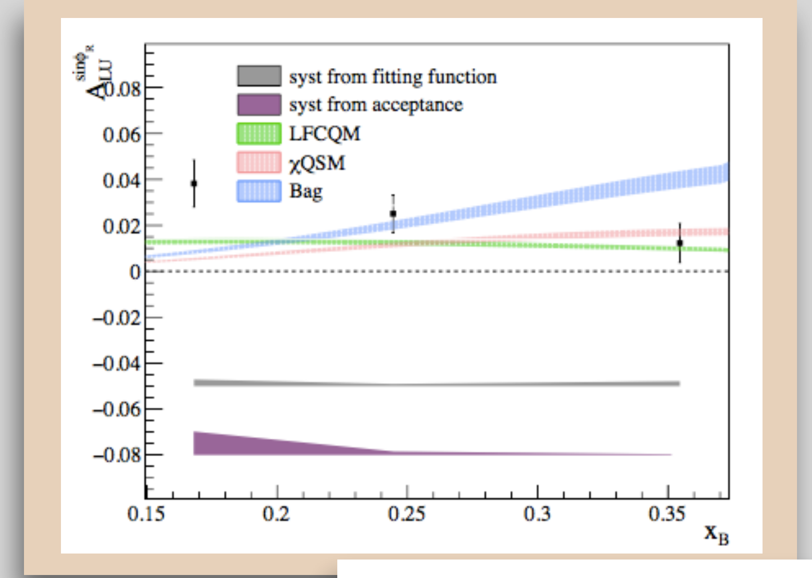
1σ errors

- **Limit given central value red**
- **Scatter plot in blue**

NEW SCALAR-TENSOR

DIHADRON ASYMMETRY FOR UNPOLARIZED TARGET INVOLVING SCALAR PDF (subleading)

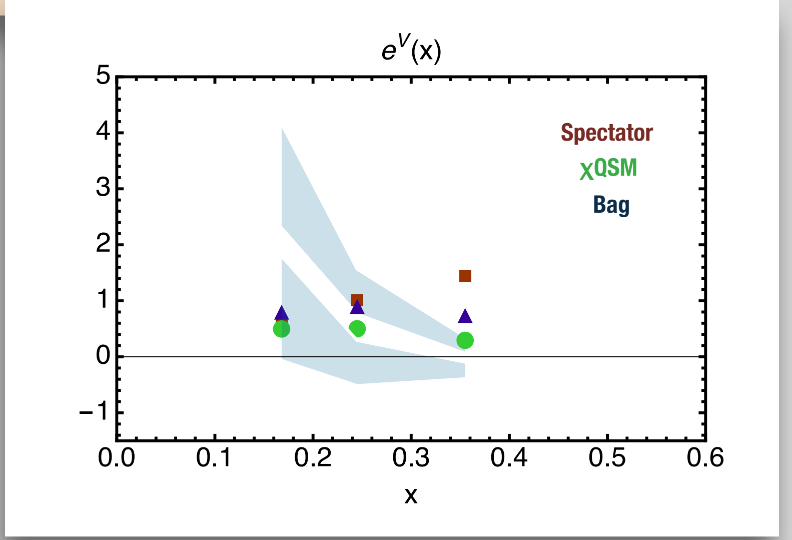
Jefferson Lab



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

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