THE TENSOR AND THE SCALAR CHARGES OF THE NUCLEON: IMPACT ON NEW PHYSICS

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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
  - Beyond V-A interactions
  - ...

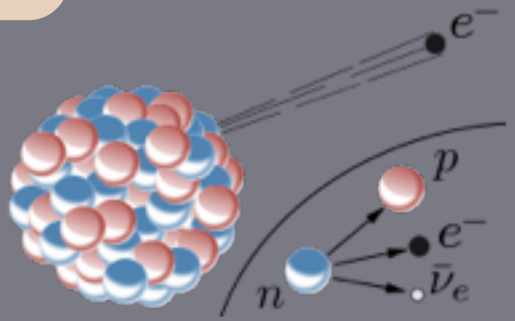
QCD FOR BSM

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

    HERE
  - ★ ...

QCD FOR BSM

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



BETA DECAY IN SM

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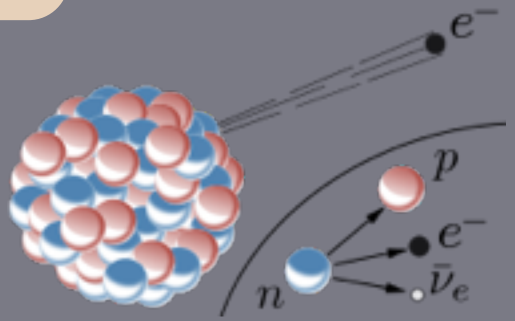

can be sketched as

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

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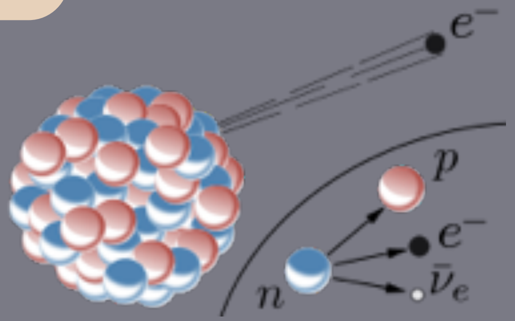

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Electroweak:
V-A

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

[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)**

Talk by Stefan Baessler

BETA DECAY OBSERVABLES

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★ 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)

Talk by Stefan Baessler

★ b=0 in SM

★ $B \subset b_\nu = 0$ in SM

- sensitivity of neutron beta decay to new physics

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

- **Neutron decay rate parameterized:**

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

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

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

$$b = \frac{2\sqrt{1-\alpha^2}}{1+3\lambda^2}\left[\mathrm{Re}\left(\frac{C_S}{C_V}\right) + 3\lambda^2 \mathrm{Re}\left(\frac{C_T}{C_A}\right)\right]$$

→ **b sensitive to scalar and tensor LEC**

→ **same for b_ν**

BETA DECAY OBSERVABLES

★ Extract LEC

$$\begin{aligned} C_V &= C_V^{\rm SM} + \delta C_V \\ C_V' &= C_V^{\rm SM} + \delta C_V' \\ C_A &= C_A^{\rm SM} + \delta C_A \\ C_A' &= C_A^{\rm SM} + \delta C_A' \\ C_S &= \delta C_S \\ C_S' &= \delta C_S' \\ C_T &= \delta C_T \\ C_T' &= \delta C_T'. \end{aligned}$$

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

Talk by Stefan Baessler

SCALAR & TENSOR INTERACTIONS

- Extract LEC

$$
\begin{aligned}
C_V &= C_V^{\rm SM} + \delta C_V \\
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C_S &= \delta C_S \\
C_S' &= \delta C_S' \\
C_T &= \delta C_T \\
C_T' &= \delta C_T'.
\end{aligned}
$$

NEW PHYSICS IN δ

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

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 & polarized
  - radiative pion decay

Talk by Stefan Baessler

SCALAR & TENSOR INTERACTIONS

New particles hints

- in loops
- mediators of interaction
- ...

New particles produced directly

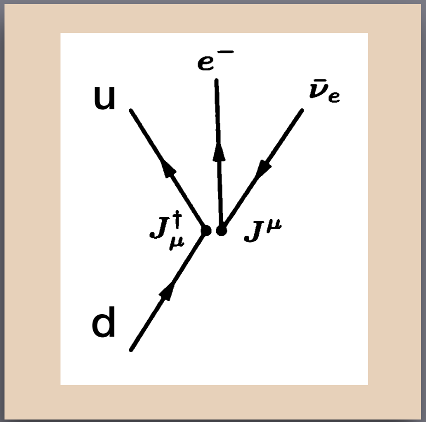
Low energy → **High energy**

- ★ **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**

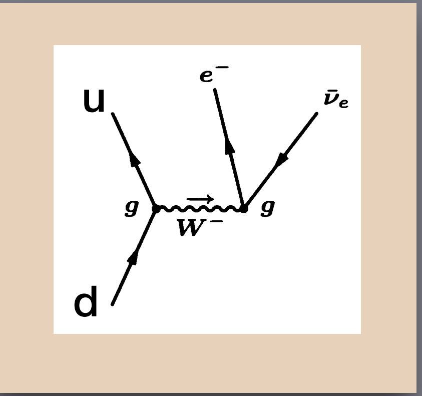
NEW FUNDAMENTAL INTERACTIONS

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

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



4-fermion interaction



SM

BETA DECAY IN EFT

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

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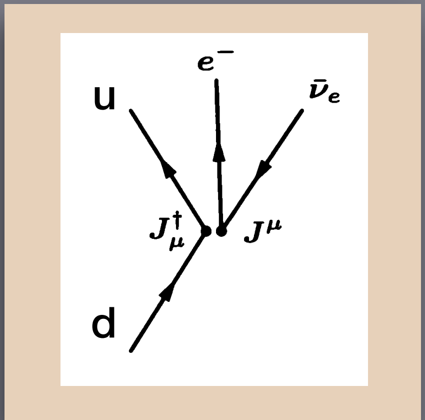

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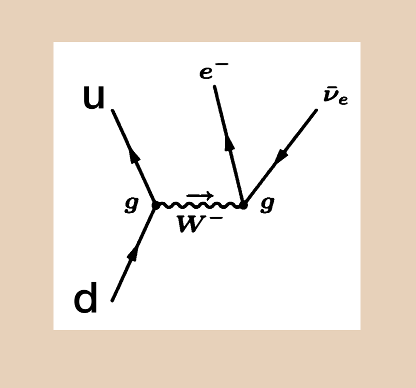

SM

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

right

Scalars

$\varepsilon_S \equiv s_L + s_R$

Tensor

$\varepsilon_T \equiv t_L$

BETA DECAY IN EFT

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

- ⋆ 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

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

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

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

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

LEC IN TERMS OF HADRONIC × NEW INT.

[Bhattarchaya et al., PRD85]

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NEW BSM S & T INTERACTIONS

New LEC factorized into hadronic contribution & new EW interaction

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

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

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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

Neutron

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

$$\Downarrow$$

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 $t \to 0$, $g(0) \equiv$ charge

$t=(p_n-p_p)^2$

Q^2 RGE scale

MATCHING AT HADRONIC LEVEL

Proton

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

$$\Downarrow$$

Neutron

FORM FACTORS

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Isovector tensor FF

Exist in hadronic physics

When t→0, g(0)≡charge

$t=(p_n-p_p)^2$

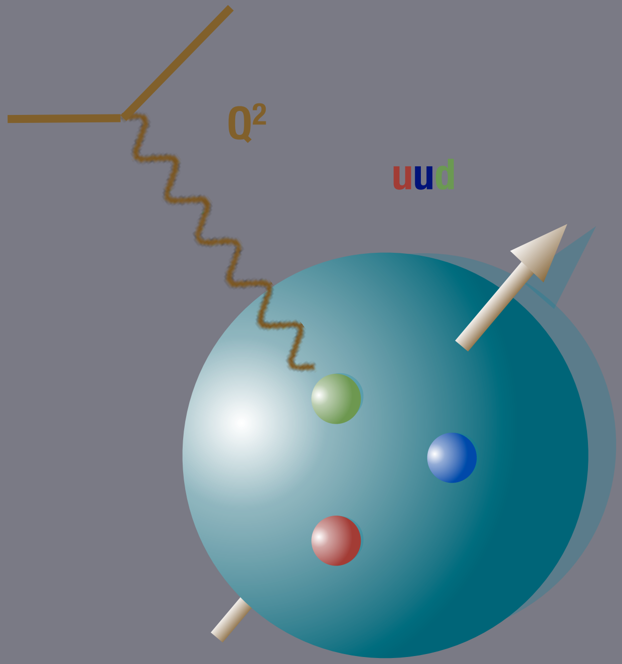
Q^2 RGE scale

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



HADRONIC STRUCTURE

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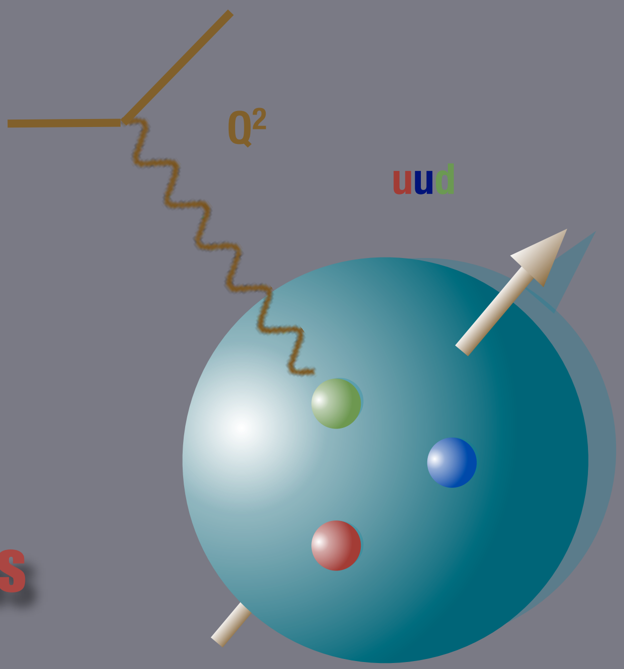


Scalar & tensor charge

accessible through sum rules of Parton Distributions

HADRONIC STRUCTURE

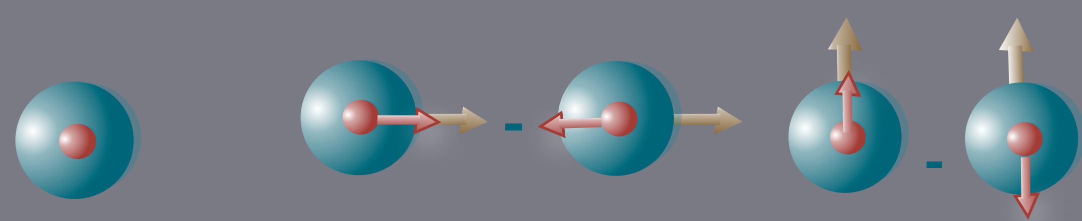
Lorentz structure
Discrete symmetries
Vectors at hand...

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

To leading *twist*:

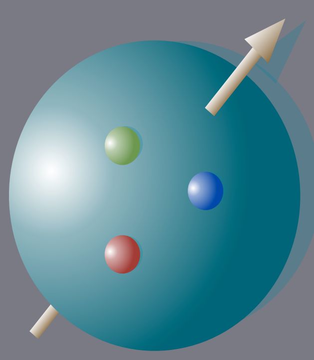
PDFs ⊠ $f_1^q(x)\,,\quad g_1^q(x)\,,\quad h_1^q(x)$

Dirac operator ⊠ Vector, Axial-vector, Tensor



Charges ⊠ g_V, g_A, g_T

PDF AT LEADING TWIST



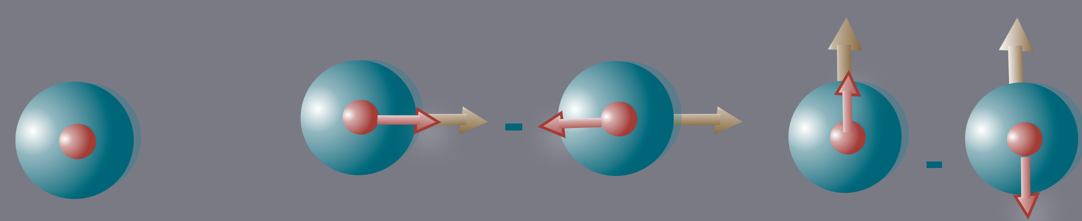
Lorentz structure
Discrete symmetries
Vectors at hand...

To leading *twist*:

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

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

PDFs ⊠	$f_1^q(x)$,	$g_1^q(x)$,	$h_1^q(x)$
Dirac operator ⊠	Vector	Axial-vector	Tensor



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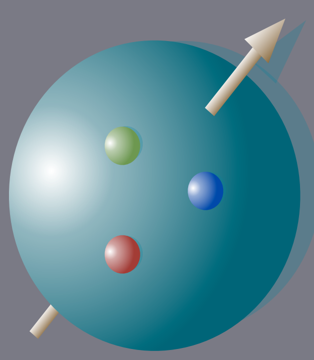
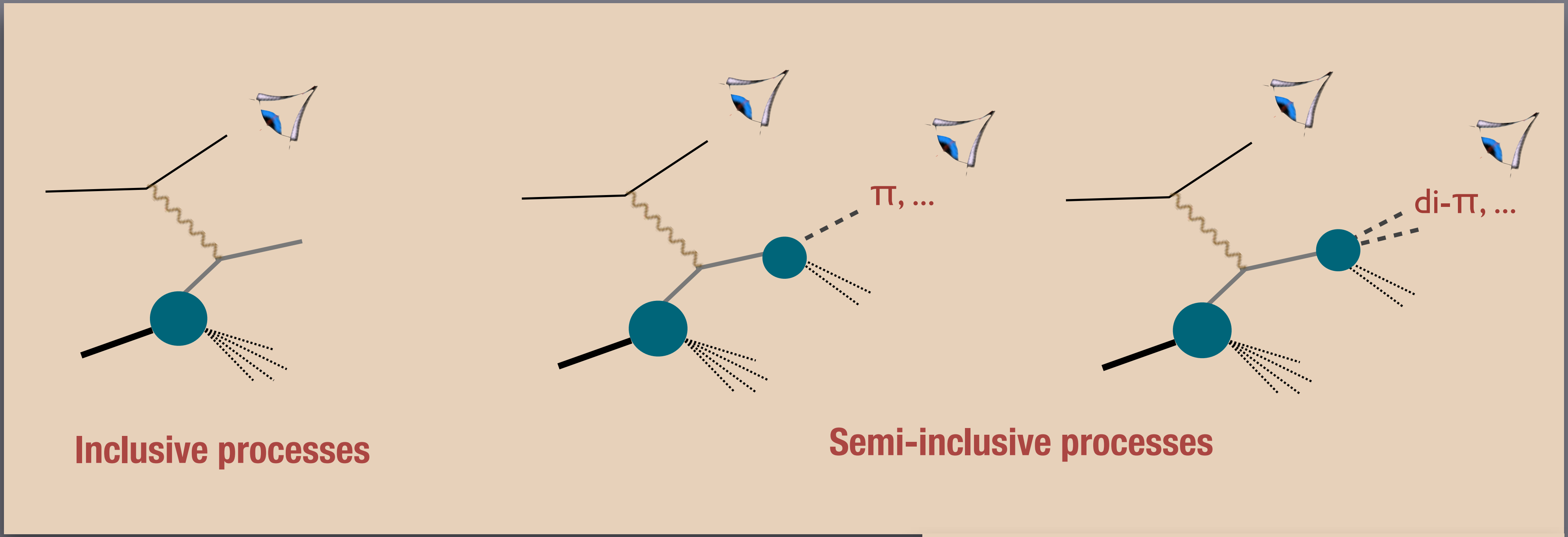
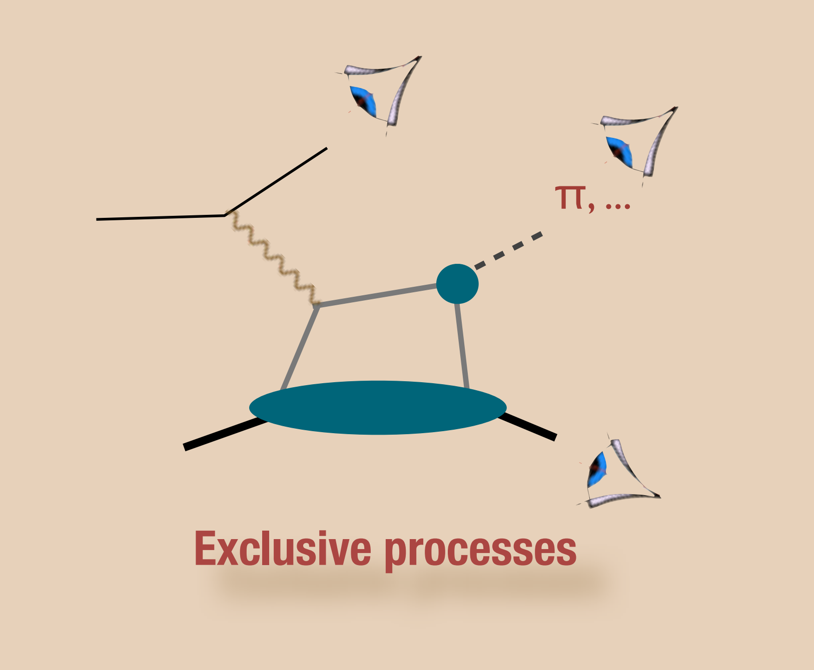
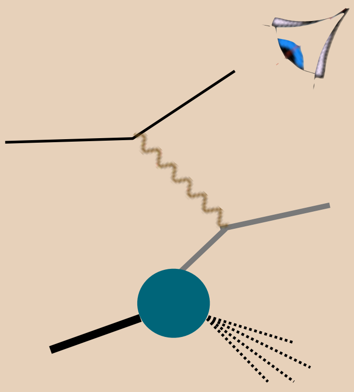


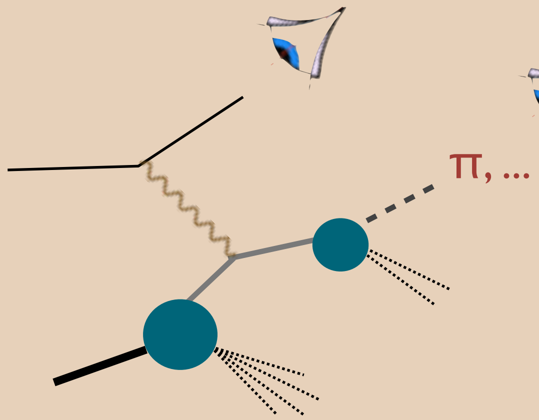


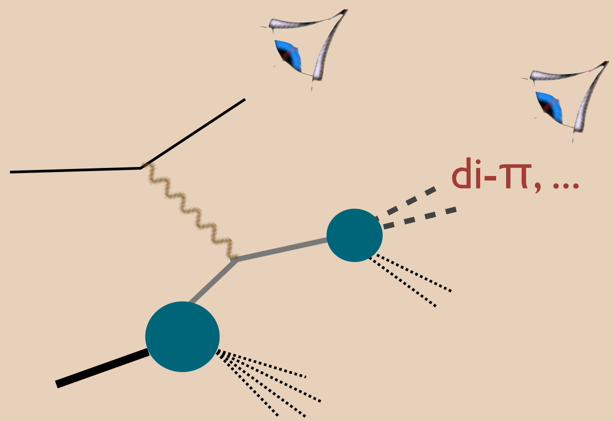


ACCESS TO DISTRIBUTION FUNCTIONS

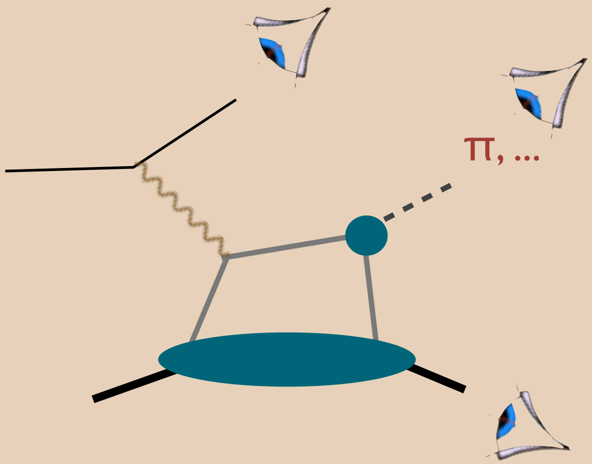


Inclusive processes





Semi-inclusive processes



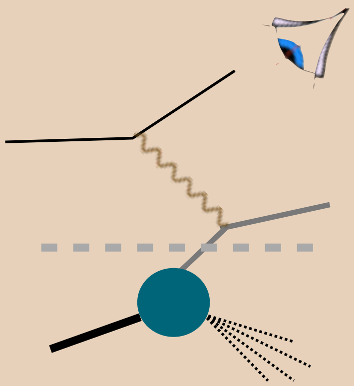
Exclusive processes

DEFINITION
AND
FACTORIZATION

ACCESS TO DISTRIBUTION FUNCTIONS

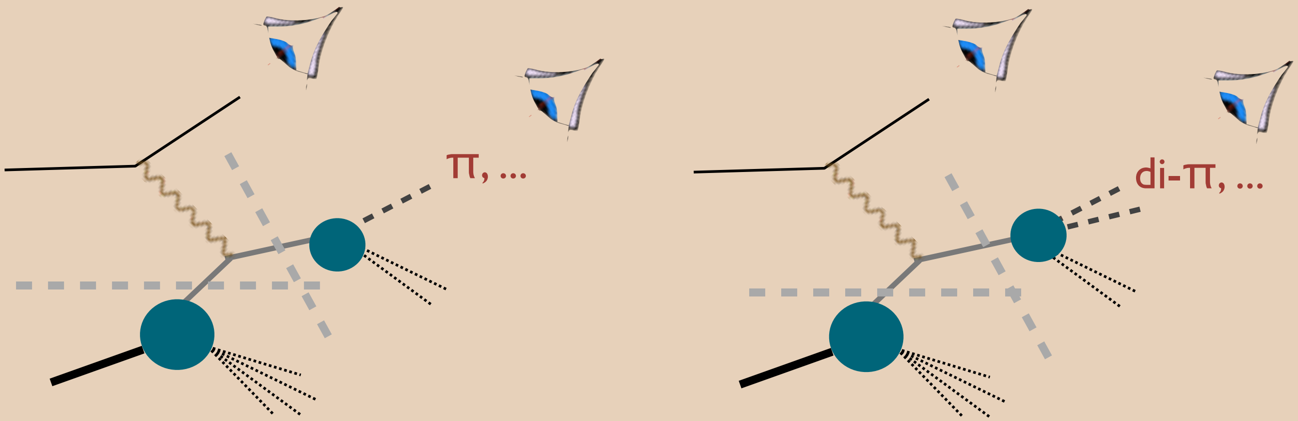
ACCESS TO DISTRIBUTION FUNCTIONS

DEFINITION
AND
FACTORIZATION



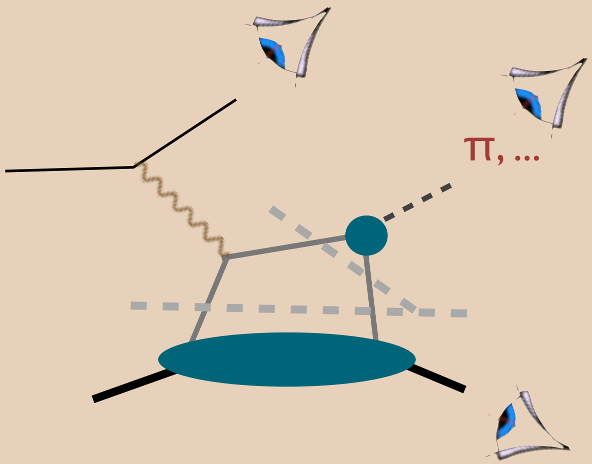
Inclusive processes

σ→ PDF×dσ



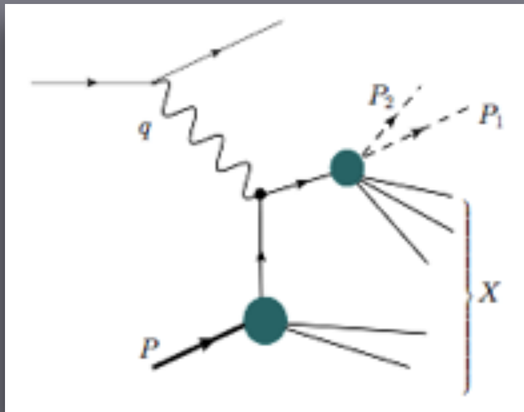
Semi-inclusive processes

σ→ PDF×dσ×Fragmentation Function



Exclusive processes

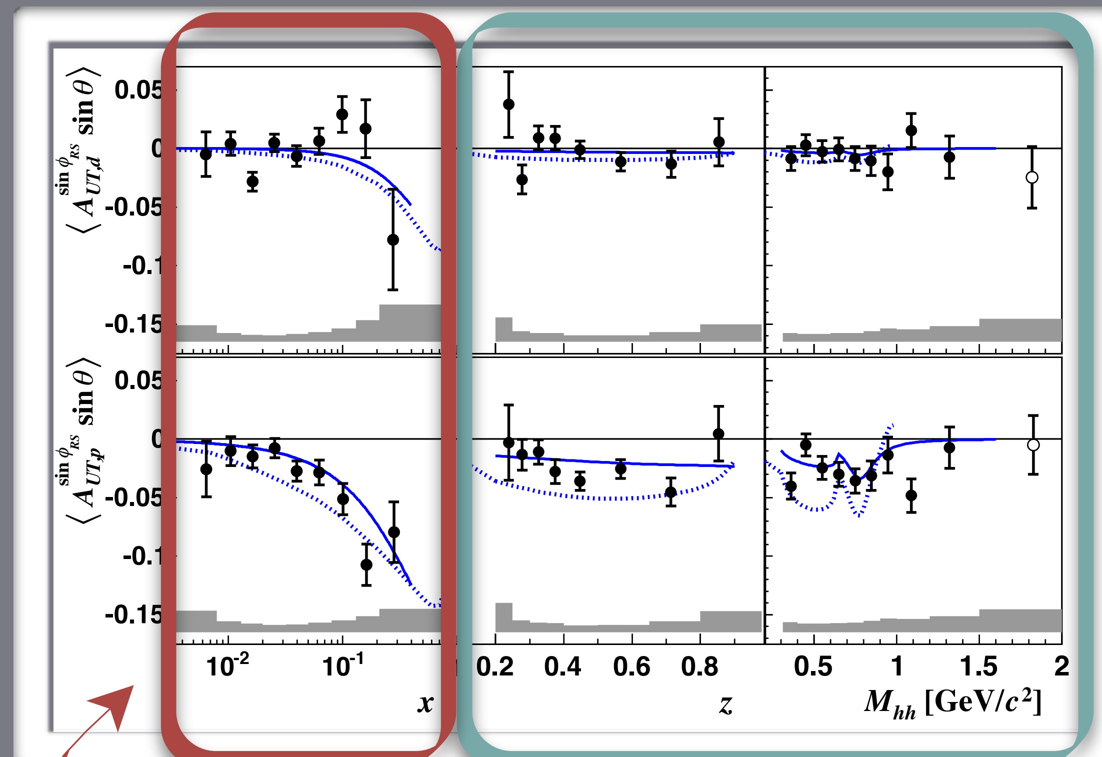
σ→ |Generalized PDF×H× Meson Amplitude|^2



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

2002-4 Deuteron Data

2007 Proton Data



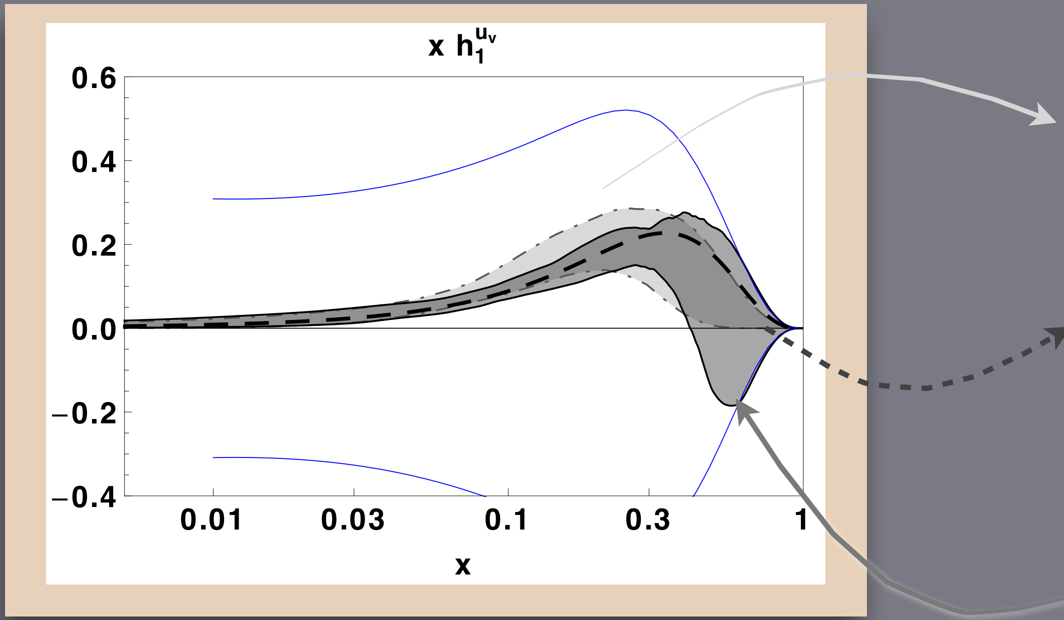
x-dependence only from Transversity
[A.C., et al, PRL 2012, JHEP 2013, 2015]

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

EXAMPLE OF DATA & EXTRACTION

- Semi-inclusive processes
  - $eN \rightarrow e\,\pi\,X$ Torino et al
  - $eN \rightarrow e\,(\pi\pi)\,X$ Pavia et al
- Exclusive: $eP \rightarrow e\,\pi^0\,P$ GGL

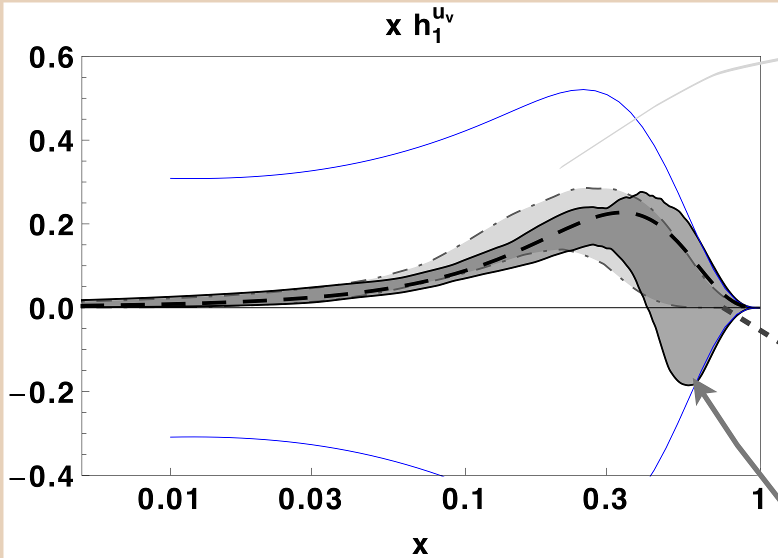
TRANSVERSITY PDF



[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

TRANSVERSITY PDF



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
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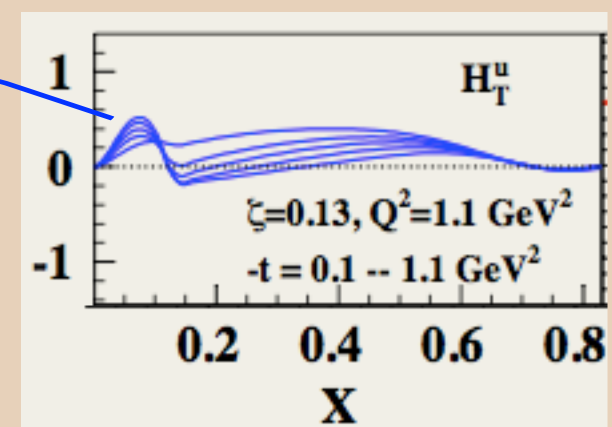
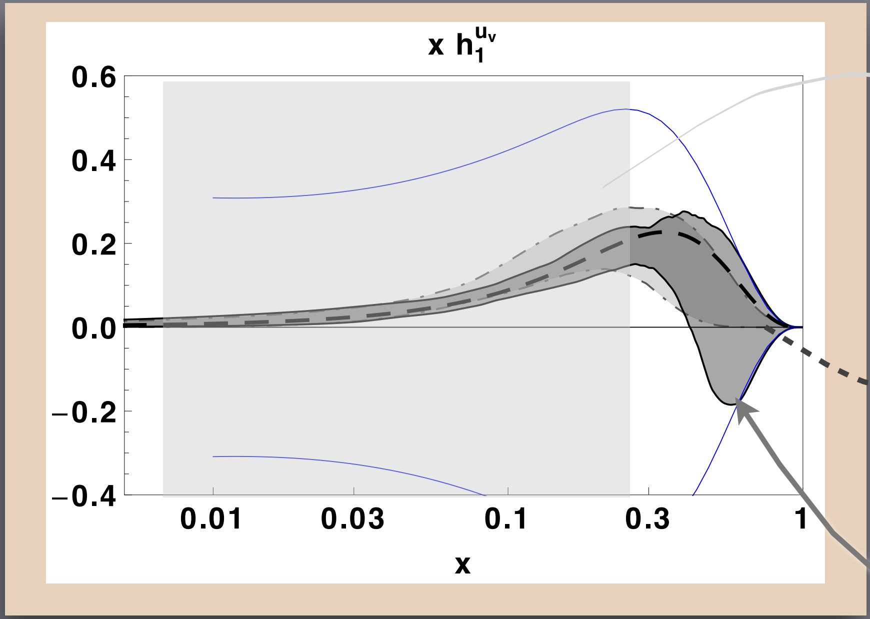


TRANSVERSITY PDF

[Goldstein et al, PRD 2015]



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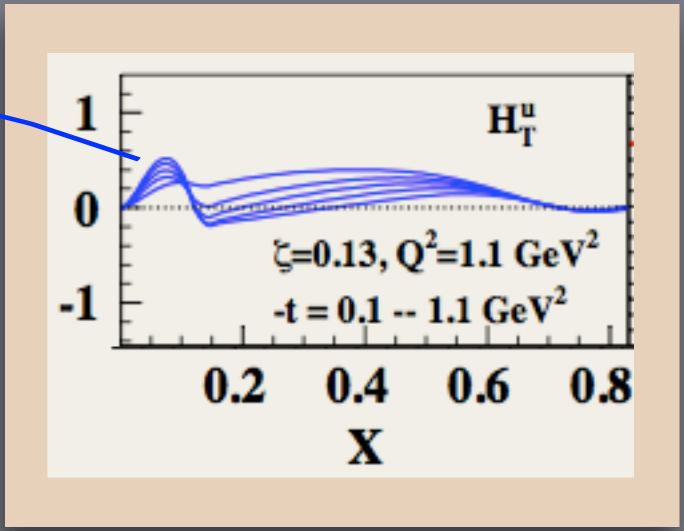
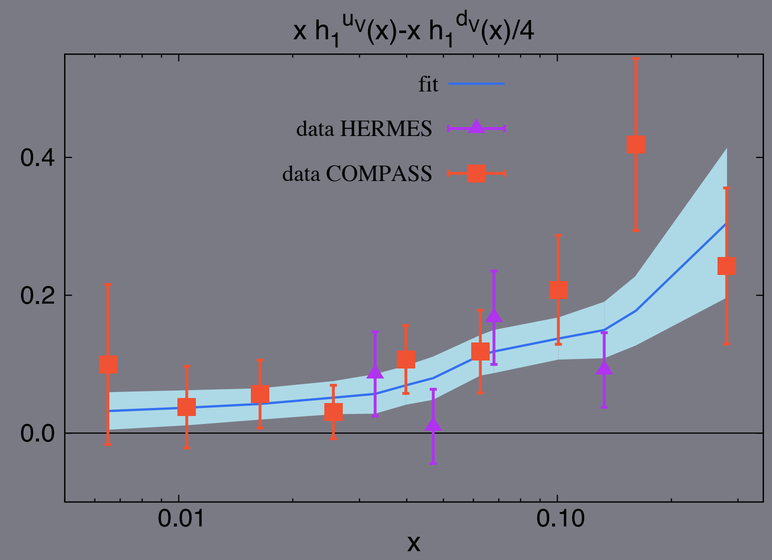


TRANSVERSITY PDF

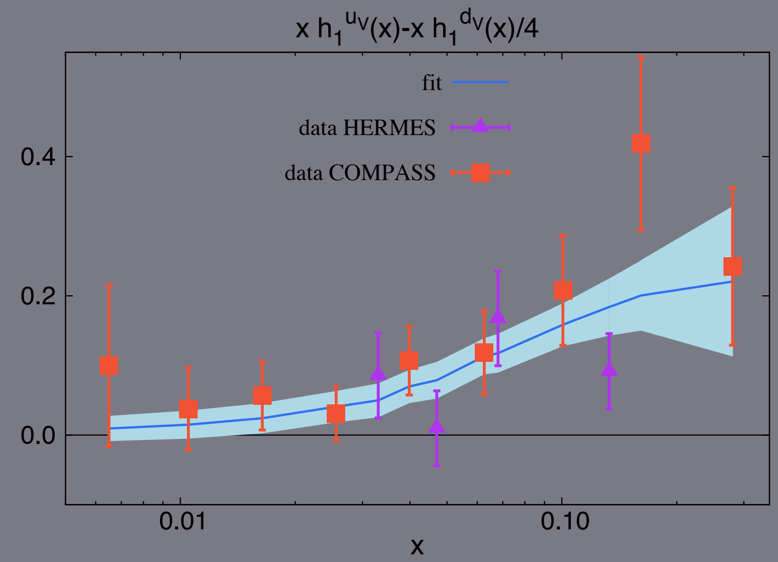
[Goldstein et al, PRD 2015]

ROLE OF FUNCTIONAL FORM FOR FIT

flexible functional form



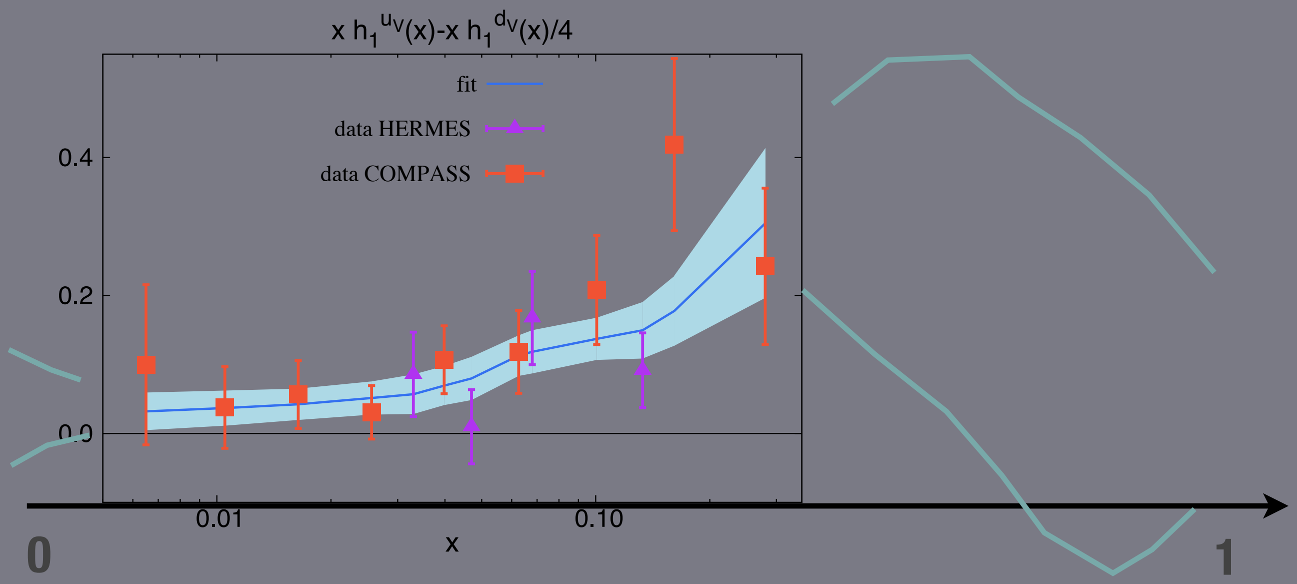
rigid functional form



UNCERTAINTY & DATA RANGE

ROLE OF FUNCTIONAL FORM FOR FIT

flexible functional form



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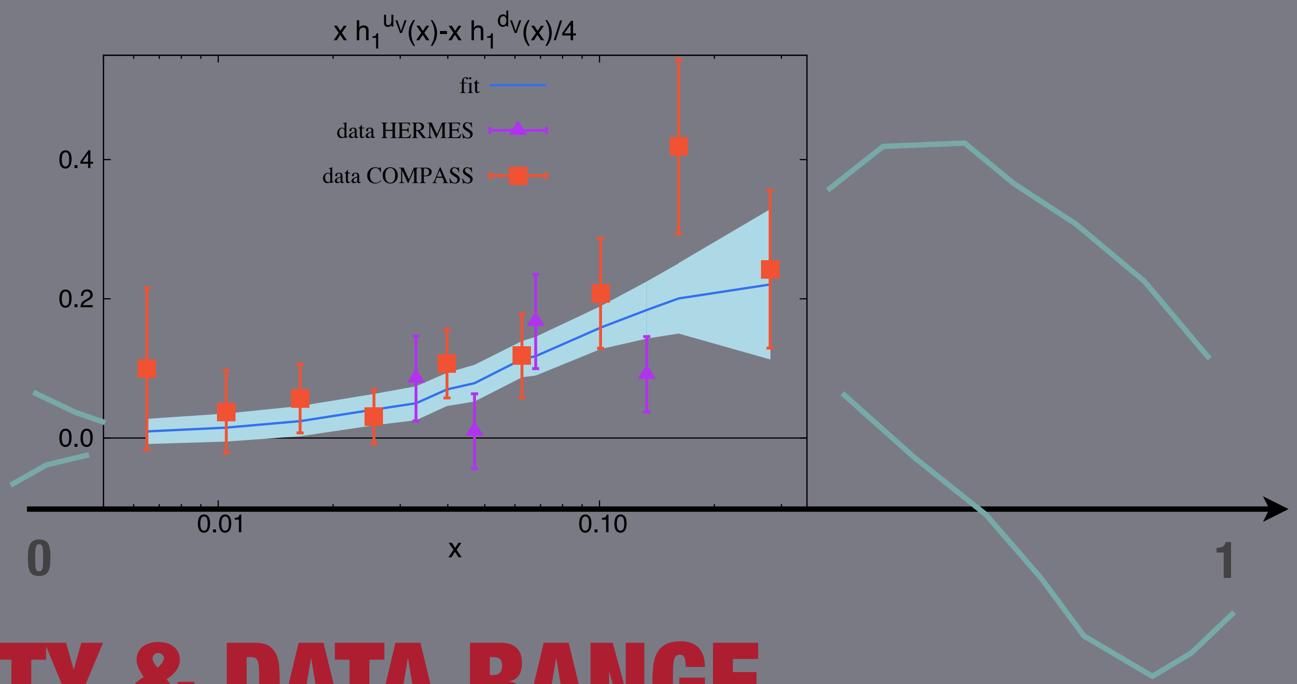

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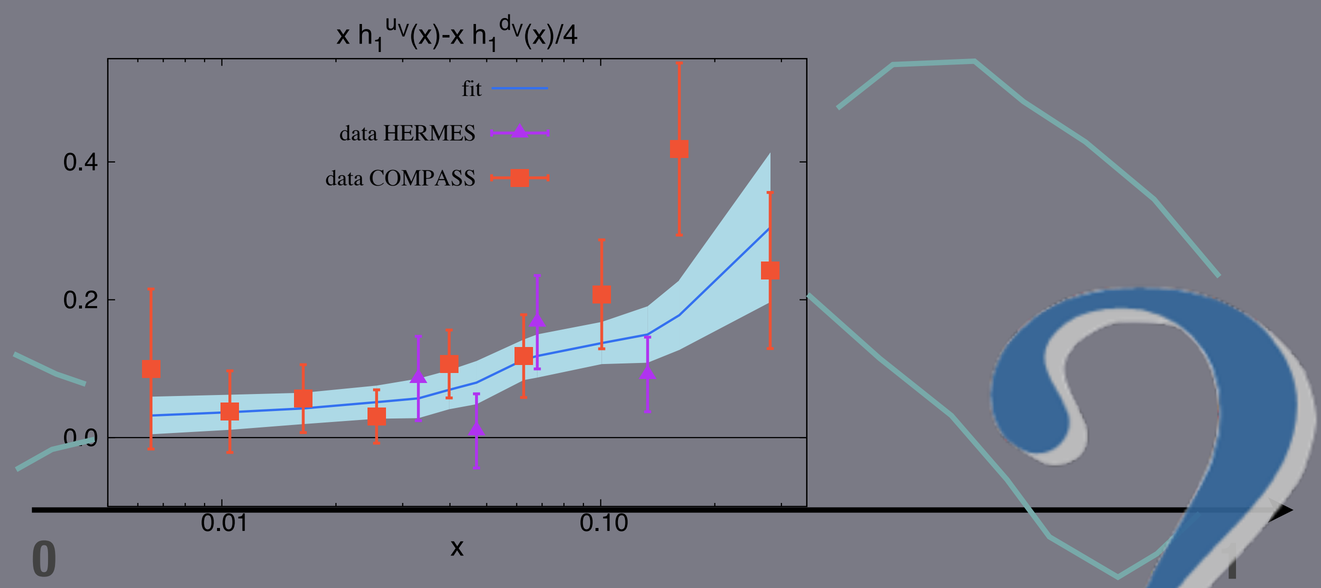
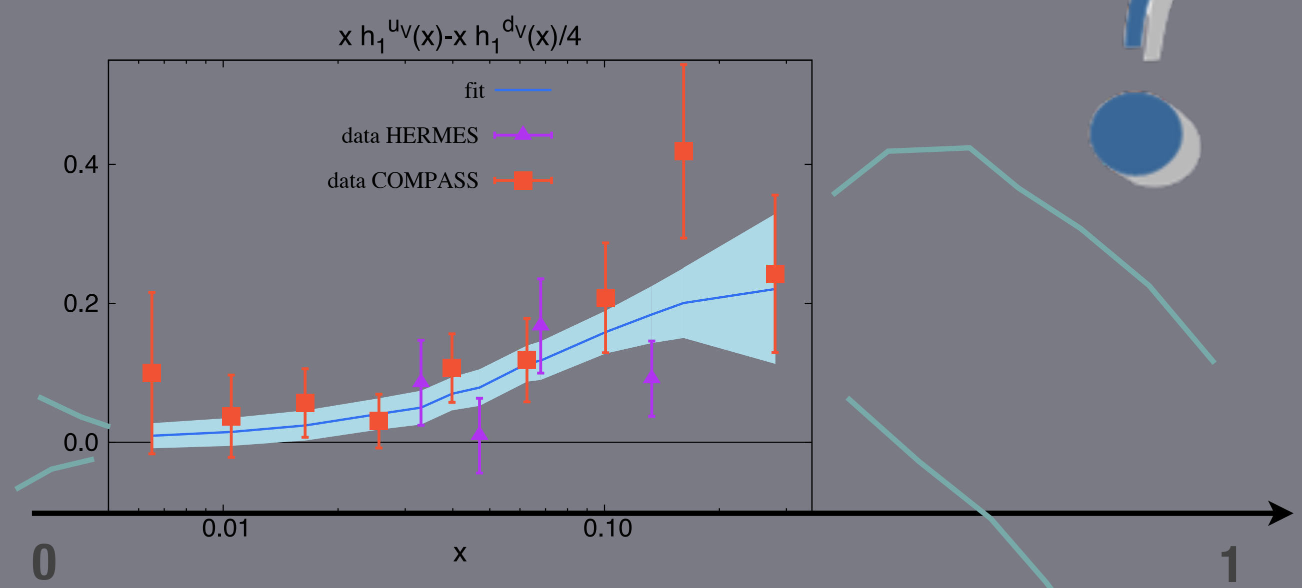


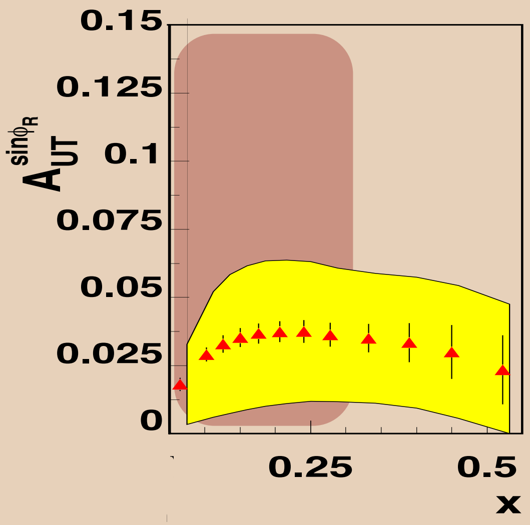
rigid functional form



Increase of uncertainty

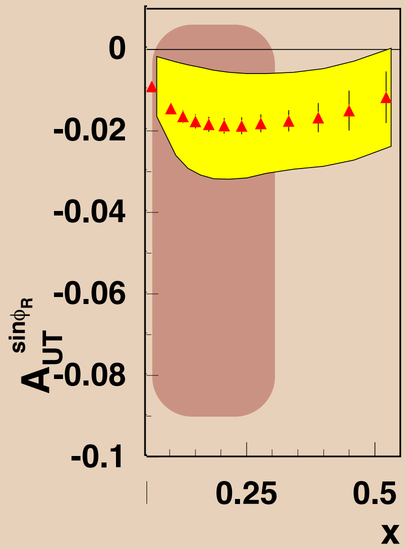
UNCERTAINTY & DATA RANGE

CLAS12 projection on proton target



0.007 < x < 0.53

SoLID projection on neutron target

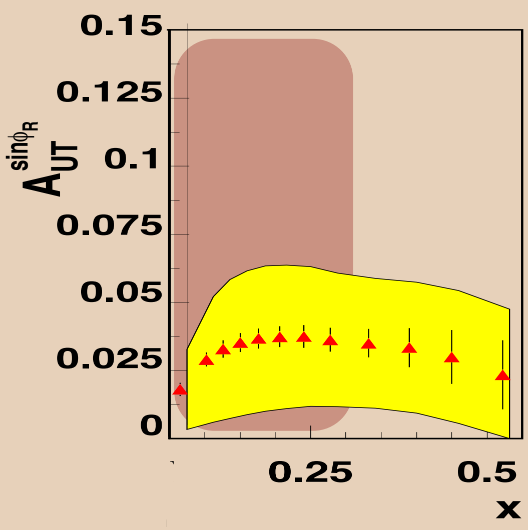


Jefferson Lab

MORE DATA

SOLUTIONS

CLAS12 projection on proton target



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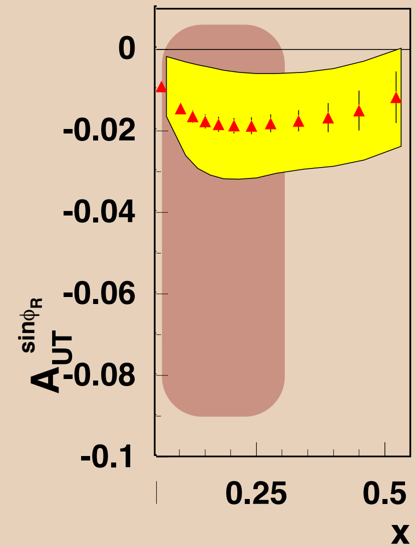
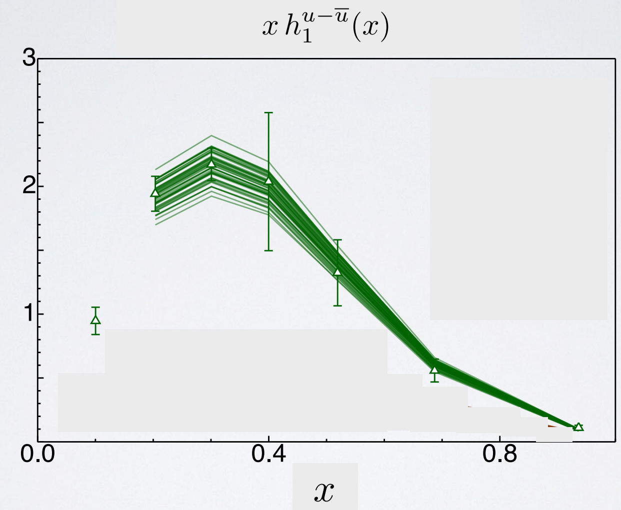


MORE DATA
+
MONTE CARLO LIKE FITTING

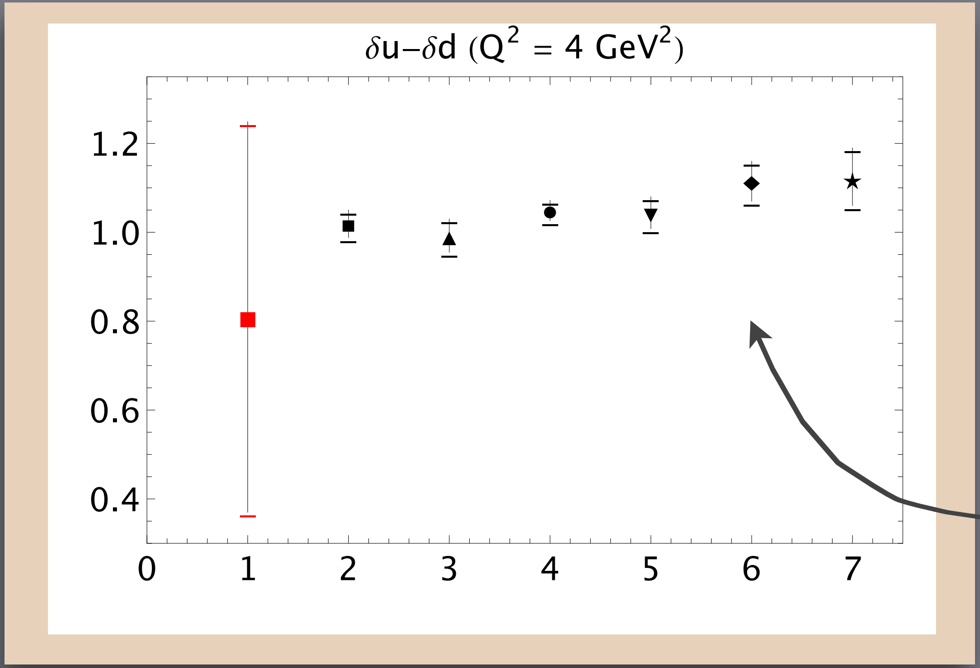


procedure repeated 100 times
(until reproduce mean and std. deviation of original data)

SOLUTIONS

Pavia 15
JHEP1505 (2015) 123

WITH MONTE CARLO LIKE FITTING



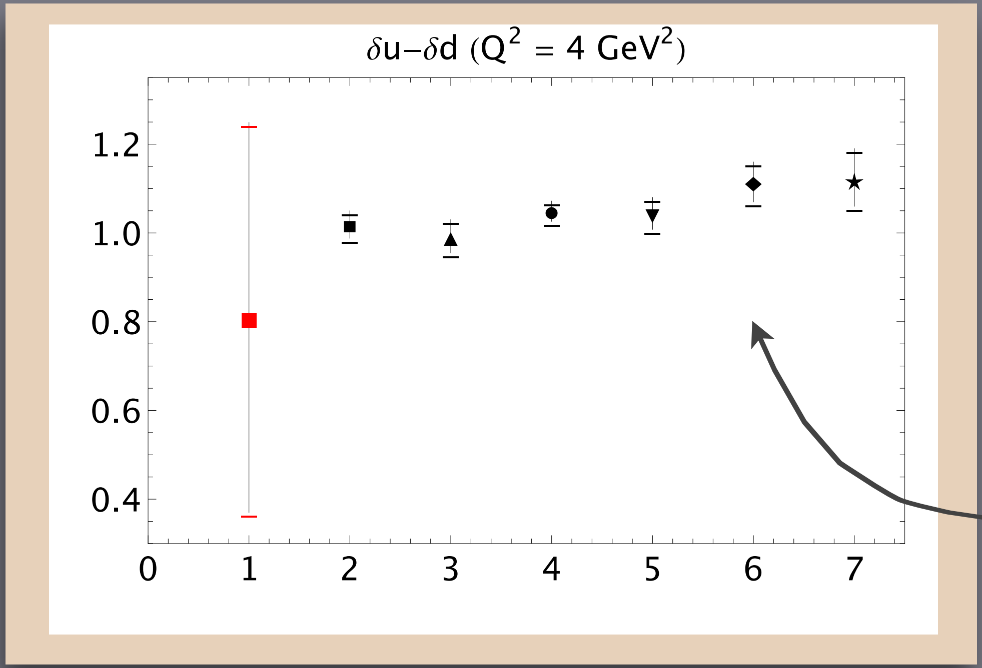
Various Lattice QCD results

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

New Pavia flexible 0.125

ISOVECTOR TENSOR CHARGE

WITH MONTE CARLO
LIKE FITTING



Various Lattice QCD results

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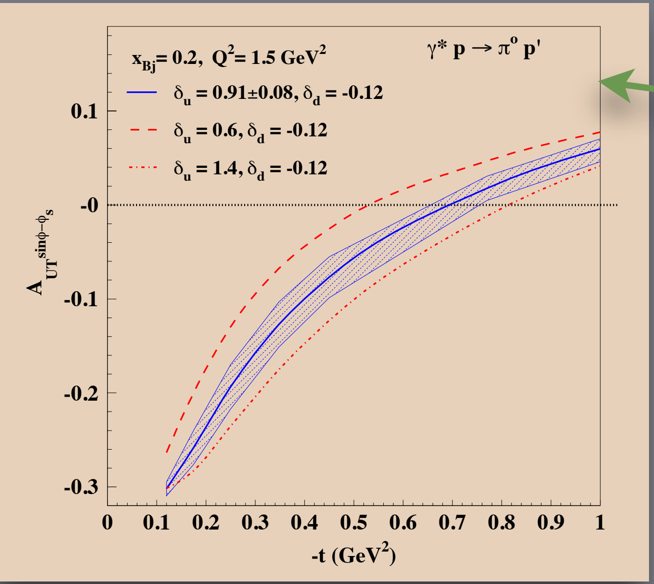
LATTICE RESULTS PRESENT TINY ERRORS W.R.T. HADRONIC EXTRACTIONS

HERE TESTING GROUND FOR LATTICE QCD CALCULATIONS

ISOVECTOR TENSOR CHARGE



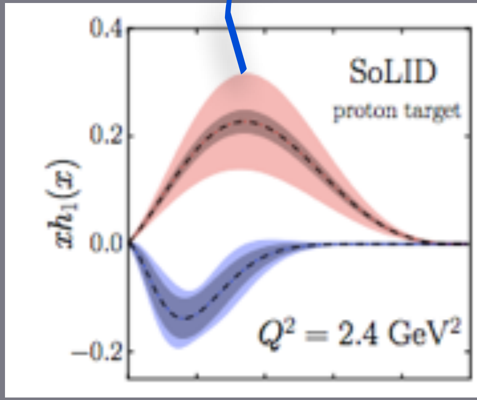
- ★ GGL depends on new JLab data

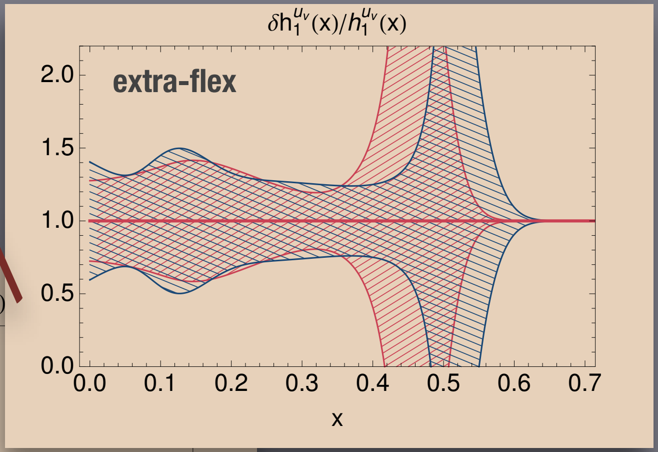
Courtoy et al, PRL 115

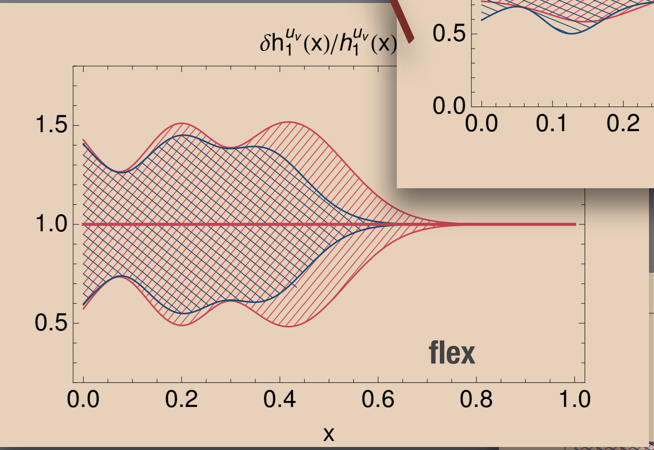
- ★ Pavia depends on new JLab data

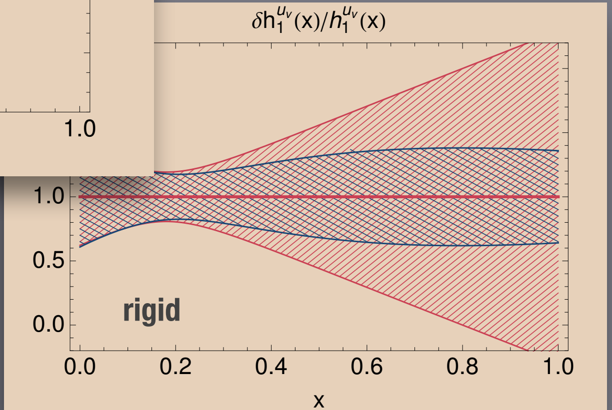
- ★ Torino depends on TMD evolution +new JLab data

Ye et al.,1609.02449

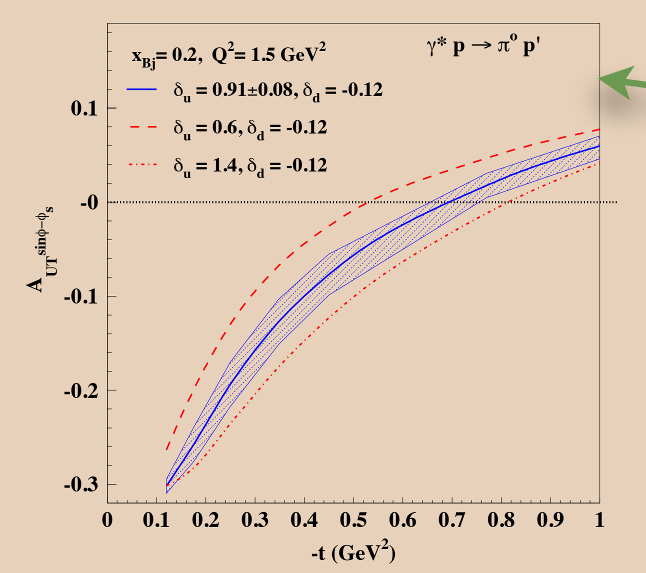








FUTURE



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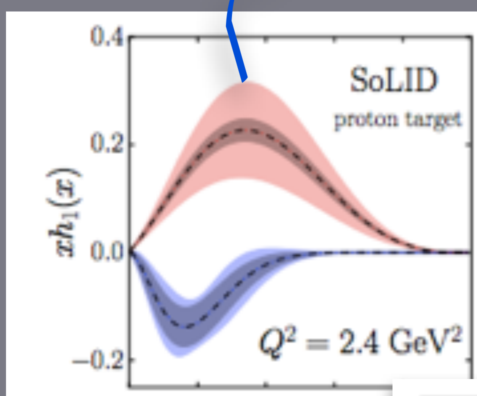
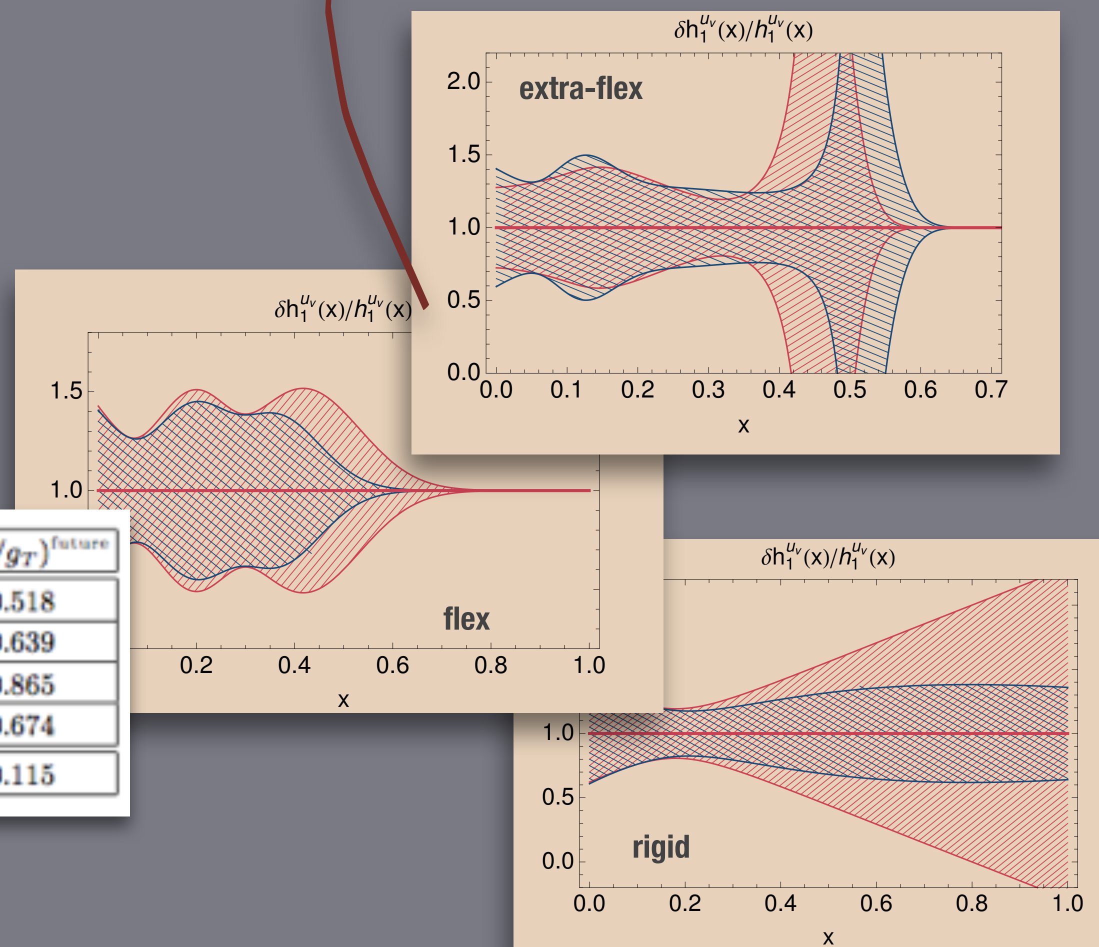
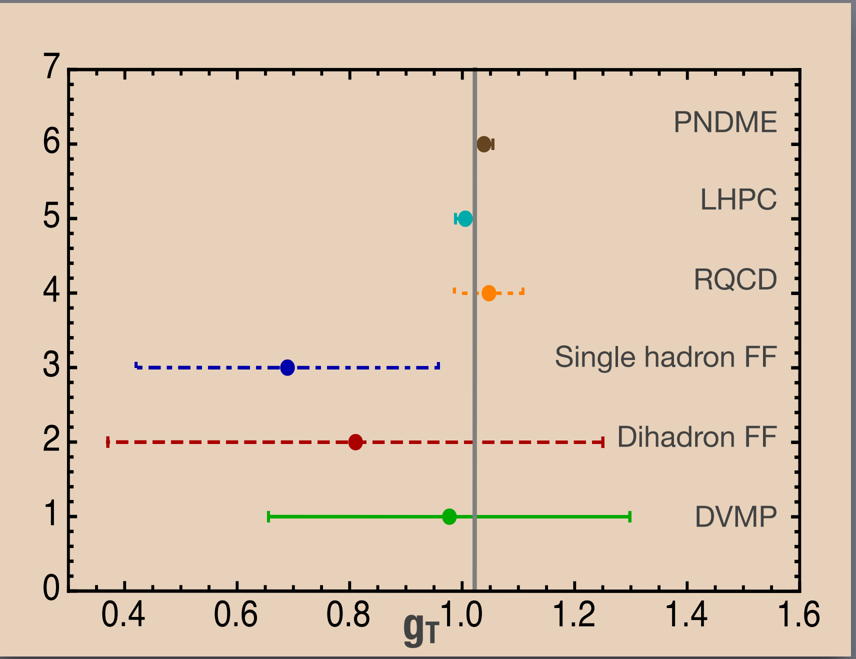




Transversities		$\delta g_T/g_T$	$(\delta g_T/g_T)^{\text{future}}$
Pavia	rigid	0.599	0.518
	flexible	0.696	0.639
	extra-flexible	1.007	0.865
Pavia average		0.767	0.674
GGL		0.329	0.115

FUTURE



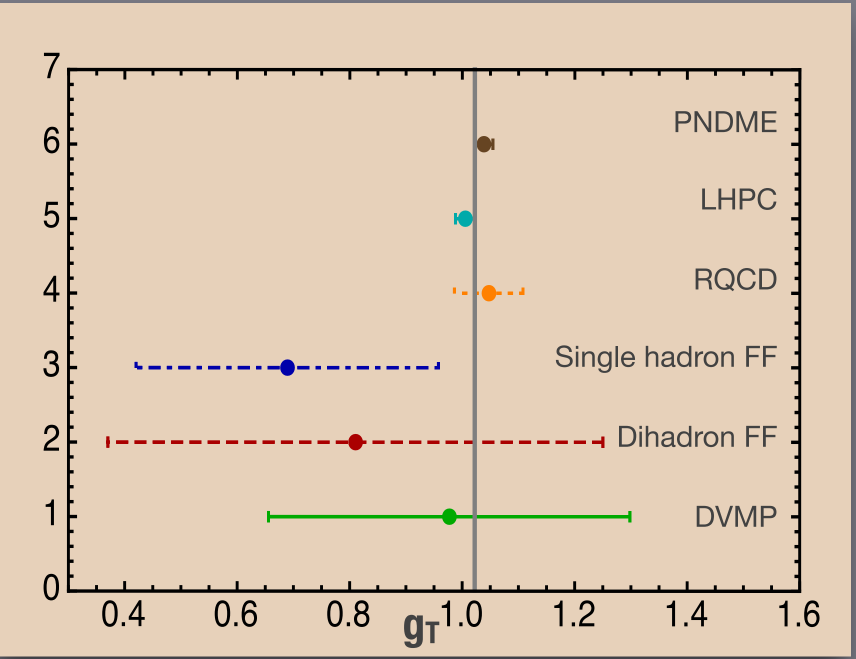
NOW WITH $g_T \pm \sigma_{gT}$

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

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



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

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we find....

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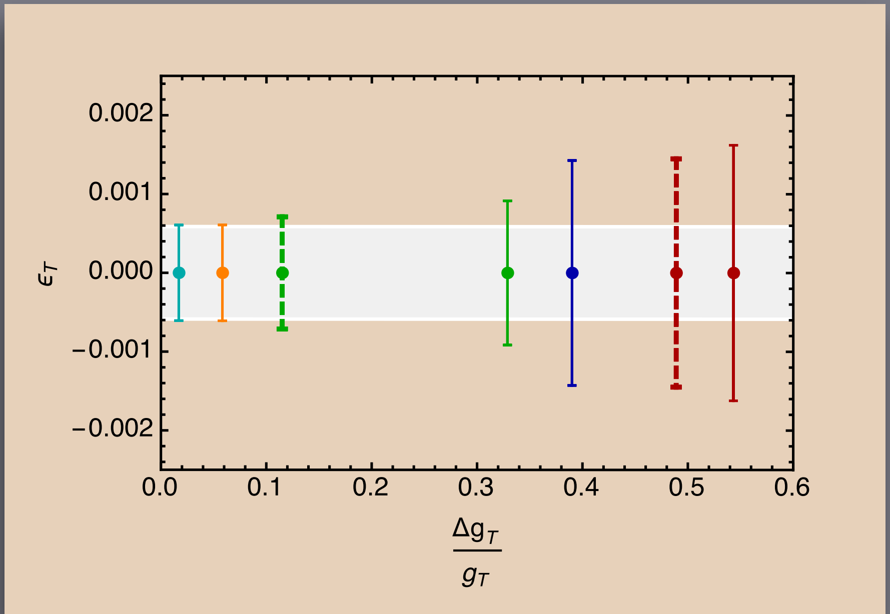


TENSOR INTERACTION AS OF NOW

★ **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**

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

★ **RFIT METHOD**

- Theoretical param anywhere within $[a-\sigma_a, a+\sigma_a]$ only
- other params as usual

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

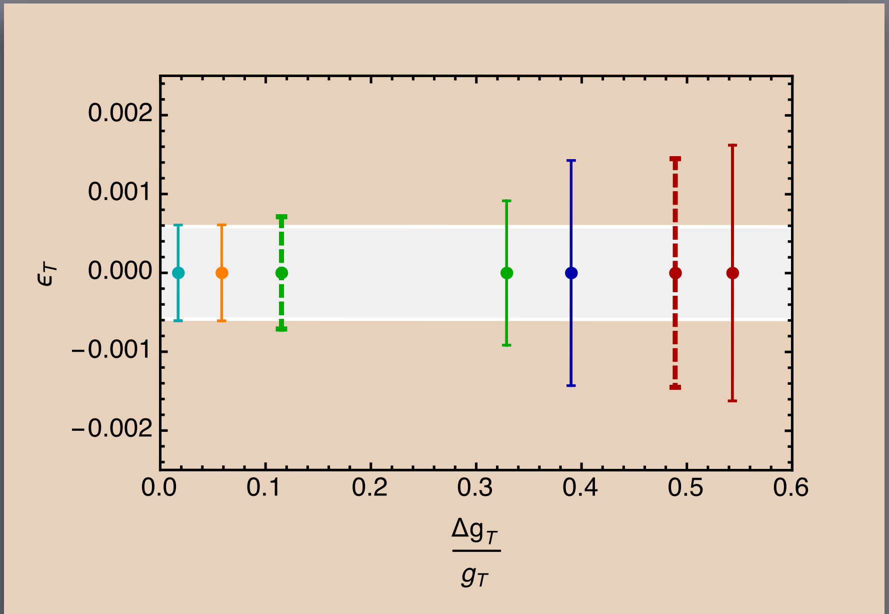
★ ...

ERROR TREATMENT

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

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

Rfit method:



Monte Carlo approach:

Pavia 2015 1D for $\langle\varepsilon_T\rangle$ only

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

TENSOR INTERACTION AS OF NOW

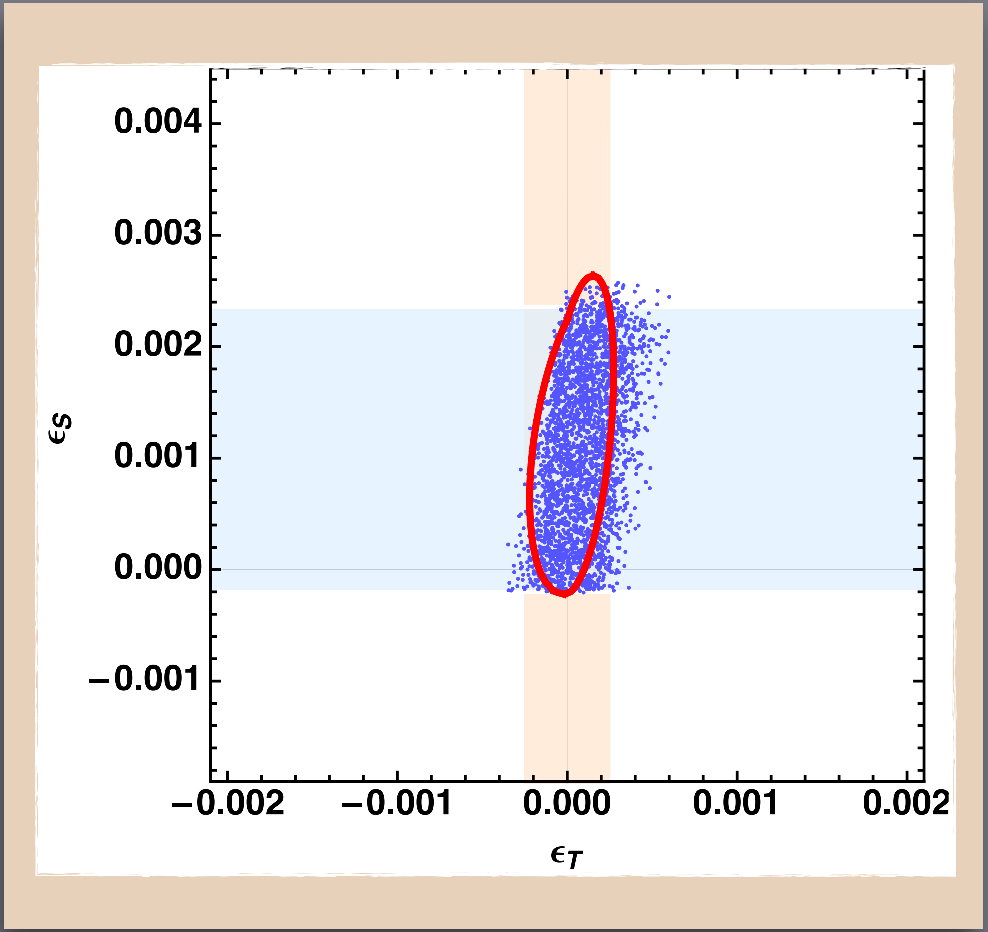
ε_T vs. ε_S plane from b_0^+ and b

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**



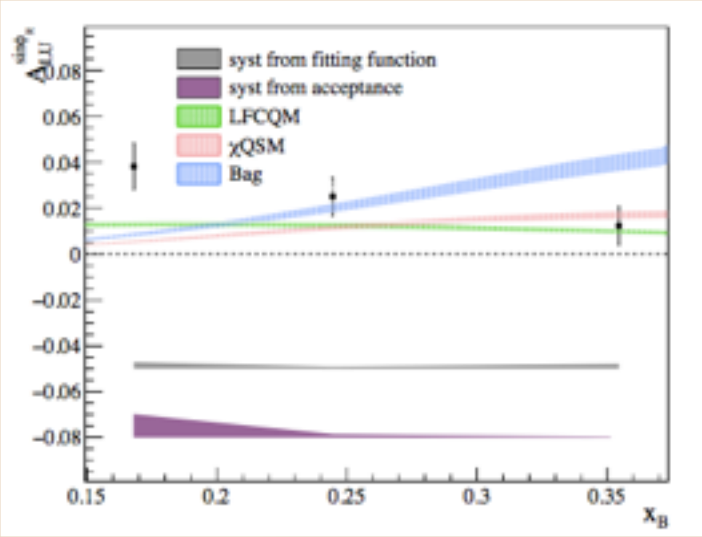
NEW SCALAR-TENSOR

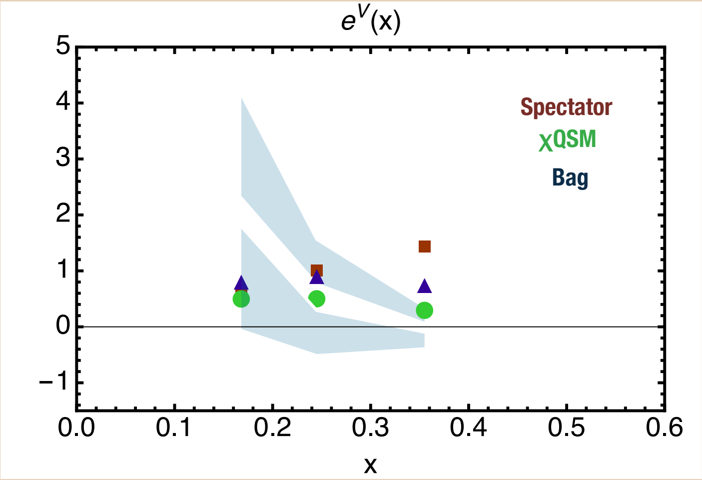
DIHADRON ASYMMETRY FOR UNPOLARIZED TARGET INVOLVING SCALAR PDF (subleading)

CLAS collaboration

S. Pisano et al., to be published

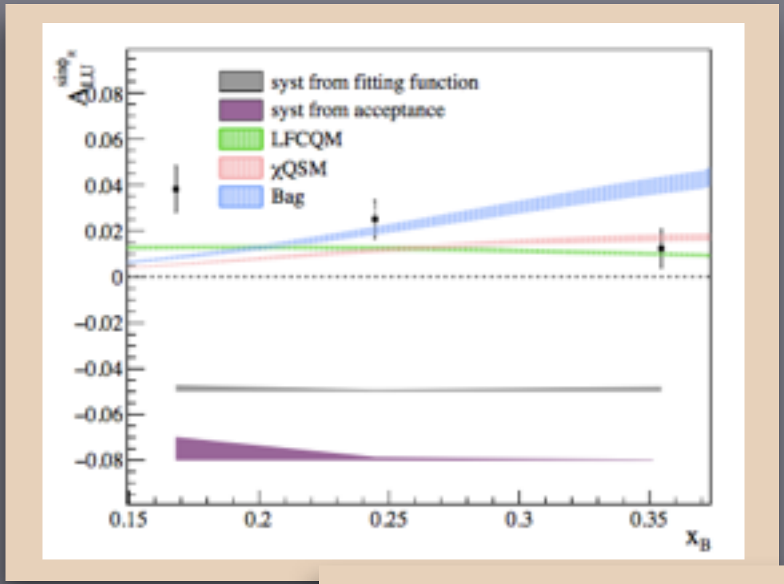
A.C. et al. 1405.7659





CAN WE DO THE SAME FOR SCALAR CHARGE?

DIHADRON ASYMMETRY FOR UNPOLARIZED TARGET INVOLVING SCALAR PDF (subleading)



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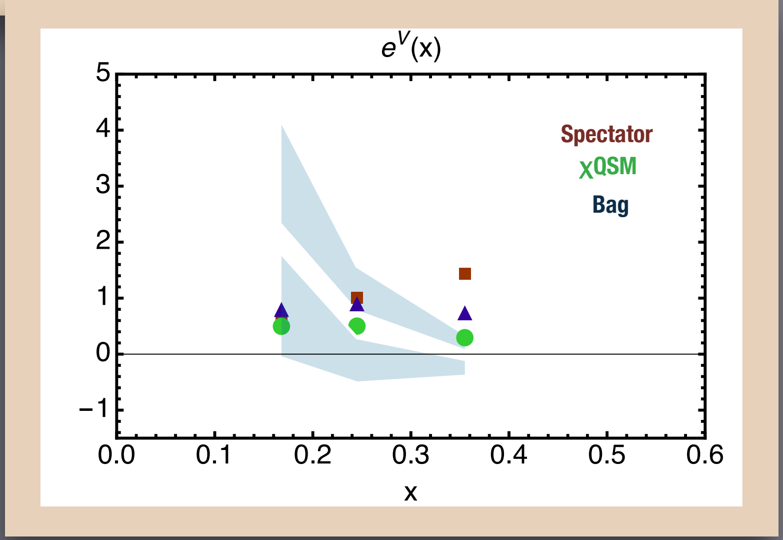

SCALAR CHARGE
related to e(x=0)

lots of things to think of...

CAN WE DO THE SAME FOR SCALAR CHARGE?

★ Neutron decay rate parameterized:

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

★ 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

* 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