HADRON PHENOMENOLOGY IMPACT ON BSM TENSOR INTERACTION

RADPYC, MAY 2015

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How can hadronic physics help BSM search?

Hadronic observables extraction

Impact on β-decay observables

In collaboration with
Stefan Baessler (UVa)
Martín González Alonso (IPN, Lyon)
Simonetta Liuti (UVa)

ARXIV 1503.06814

OUTLINE

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

See, e.g.,

Plan Nacional de Investigación en Física de Altas Energías

Sección "Frontera de la Intensidad"

QCD FOR BSM

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

    HERE
  - ★ ...

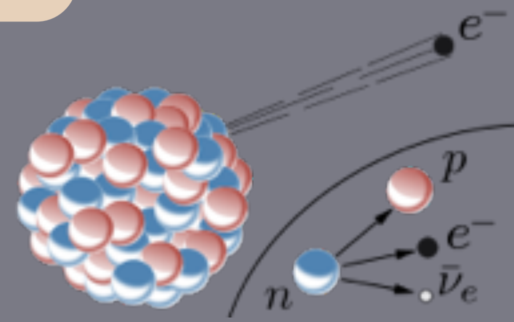
See, e.g.,

Plan Nacional de Investigación en Física de Altas Energías

Sección "Frontera de la Intensidad"

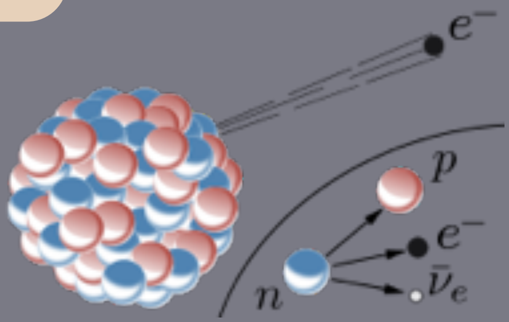
QCD FOR BSM

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



BETA DECAY IN SM

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

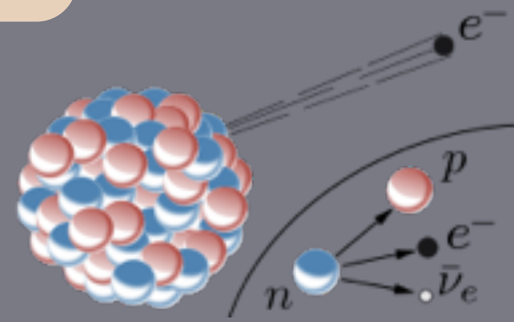


can be sketched as

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

BETA DECAY IN SM

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



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:

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

- 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)

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)

★ b=0 in SM

★ B ⊂ b_ν =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:**

$$d^3\Gamma = \frac{1}{(2\pi)^5}\frac{G_F^2|V_{ud}|^2}{2}p_e E_e\left(E_0 - E_e\right)^2 dE_e d\Omega_e d\Omega_\nu$$
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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)

- ★ b=0 in SM
- ★ B ⊂ b_ν =0 in SM

- sensitivity of neutron beta decay to new physics
- same for $0^+ \rightarrow 0^+$ processes: b_{0^+}

BETA DECAY OBSERVABLES

★ Neutron decay rate parameterized:

[Jackson et al., PR106]

[Lee & Yang, PR104]

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

★ b=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_{0^+}=0 in SM

➡ sensitivity of $0^+ \rightarrow 0^+$ proc to new physics

$$b_0^+ = 2\,\mathrm{Re}\left(\frac{C_\mathrm{S}}{C_\mathrm{V}}\right)$$

BETA DECAY OBSERVABLES

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

★ Neutron decay rate parameterized:

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

★ b_0^+=0 in SM

➡ sensitivity of $0^+ \to 0^+$ proc to new physics

$$b_0^+ = 2\,\mathrm{Re}\left(\frac{C_S}{C_V}\right)$$

Best constraints so far

$$C_S/C_V = -0.0014 \pm 0.0013$$

@1σ

[Hardy et al., PRC91]

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

@95%CL

[Pattie et al., PRC88]

BETA DECAY OBSERVABLES

New particles hints

- in loops
- mediators of interaction
- ...

New particles produced directly

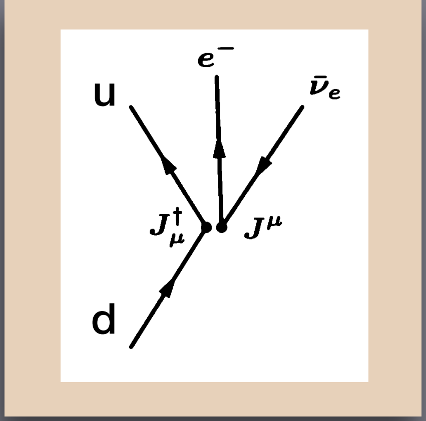
Low energy → **High energy**

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

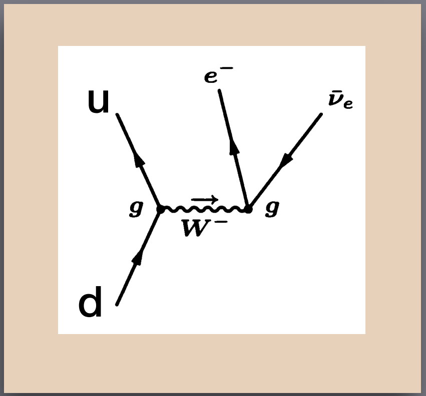
NEW FUNDAMENTAL INTERACTIONS

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

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



4-fermion interaction



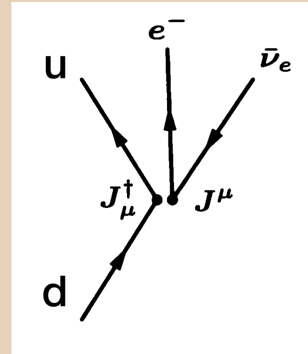
SM

BETA DECAY IN EFT

[Bhattarchaya et al., PRD85]

[Cirigliano et al., NPB 830]

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



4-fermion interaction

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

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

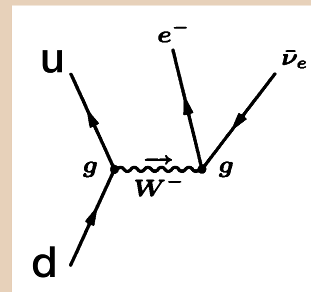
right

Tensor

$\varepsilon_T \equiv t_L$

Scalars

$\varepsilon_S \equiv s_L + s_R$



SM

BETA DECAY IN EFT

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

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

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

New LEC factorized into hadronic contribution & new EW interaction

LEC IN TERMS OF HADRONIC × NEW INT.

[Bhattarchaya et al., PRD85]
[Cirigliano et al., NPB 830]

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STANDARD MODEL

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

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

NEW BSM S & T INTERACTIONS

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STANDARD MODEL

$$C_S = \frac{G_F}{\sqrt{2}} V_{ud}\, g_S \epsilon_S$$

$$C_T = \frac{G_F}{\sqrt{2}} V_{ud}\, 4 g_T \epsilon_T$$

$$|g_S\epsilon_S| = 0.0014 \pm 0.0013 \quad @1\sigma$$

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

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

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

$$\Downarrow$$

FORM FACTORS

Neutron

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

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

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

MATCHING AT HADRONIC LEVEL

Proton

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

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Neutron

FORM FACTORS

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

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Isovector tensor FF

$t=(p_n-p_p)^2$

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

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

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Isovector tensor FF

When $t \rightarrow 0$, $g(0) \equiv$ 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

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

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

Exist in hadronic physics

When t→0, g(0)≡charge

$t=(p_n-p_p)^2$

Q^2 RGE scale

MATCHING AT HADRONIC LEVEL

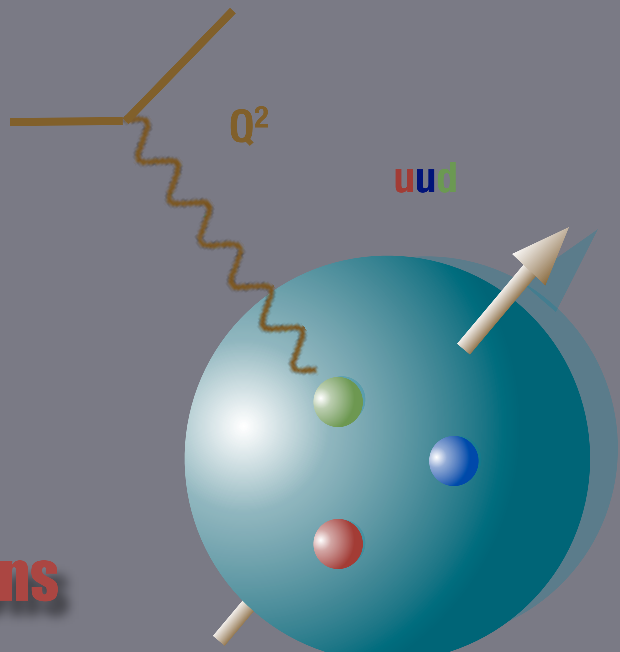
★ Nonlocal matrix element for proton structure

★ 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

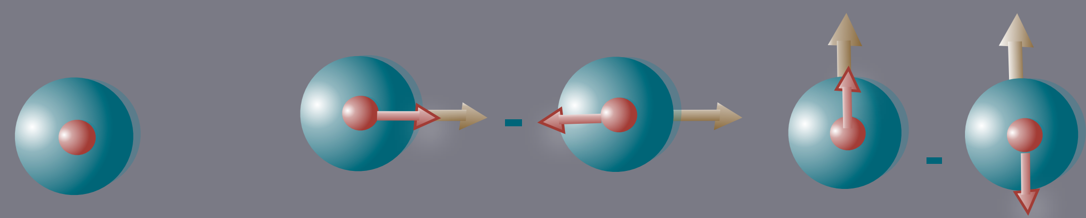
Lorentz structure
Discrete symmetries
Vectors at hand...

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

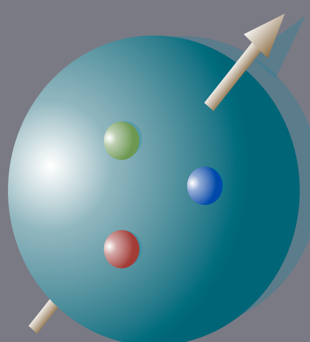
To leading *twist*:

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

Dirac operator $\Rightarrow$ Vector, Axial-vector, Tensor



PDF AT LEADING TWIST



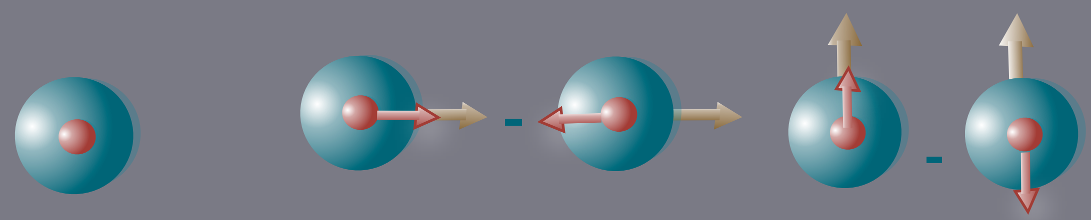
Lorentz structure
Discrete symmetries
Vectors at hand...

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

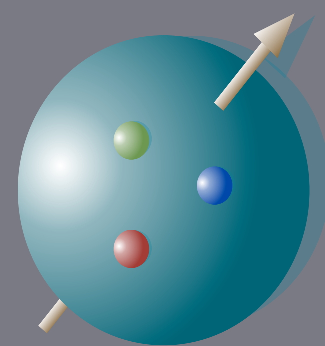
To leading *twist*:

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

Dirac operator ⇒ Vector Axial-vector Tensor



Charges ⇒ g_V, g_A, g_T



PDF AT LEADING TWIST

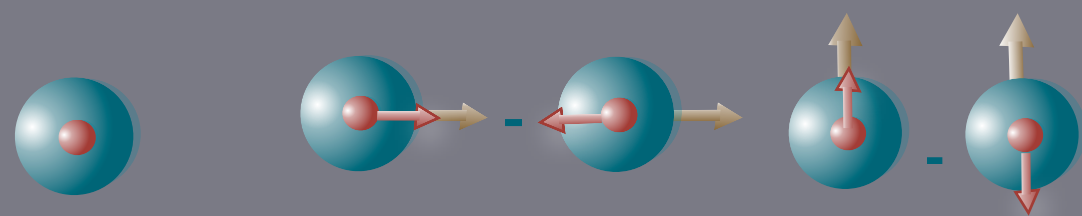
Lorentz structure
Discrete symmetries
Vectors at hand...

To leading *twist*:

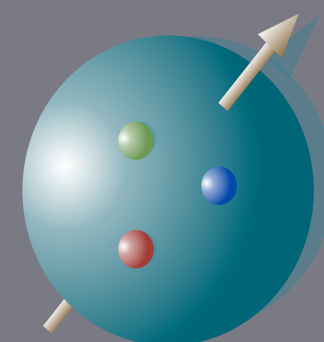
$$\int_{-1}^{1} dx\, h_1^{u_V - d_V}(x) = g_T$$

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

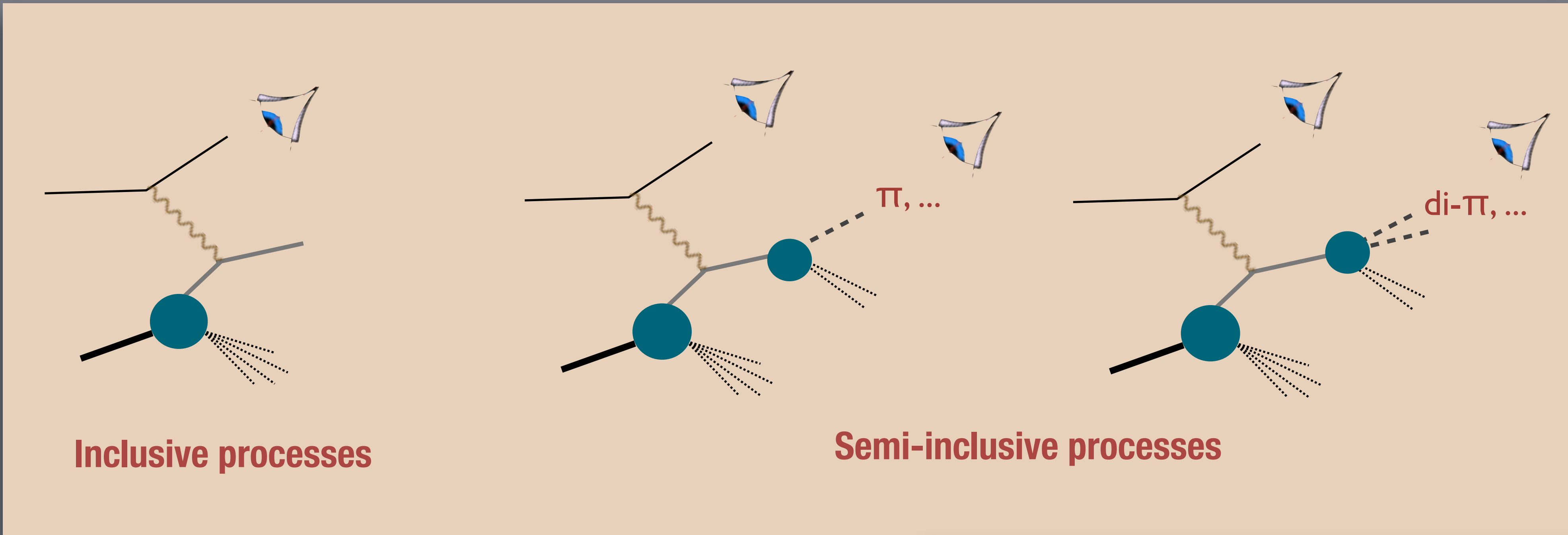
PDFs ⇒	$f_1^q(x)$,	$g_1^q(x)$,	$h_1^q(x)$
Dirac operator ⇒	Vector	Axial-vector	Tensor

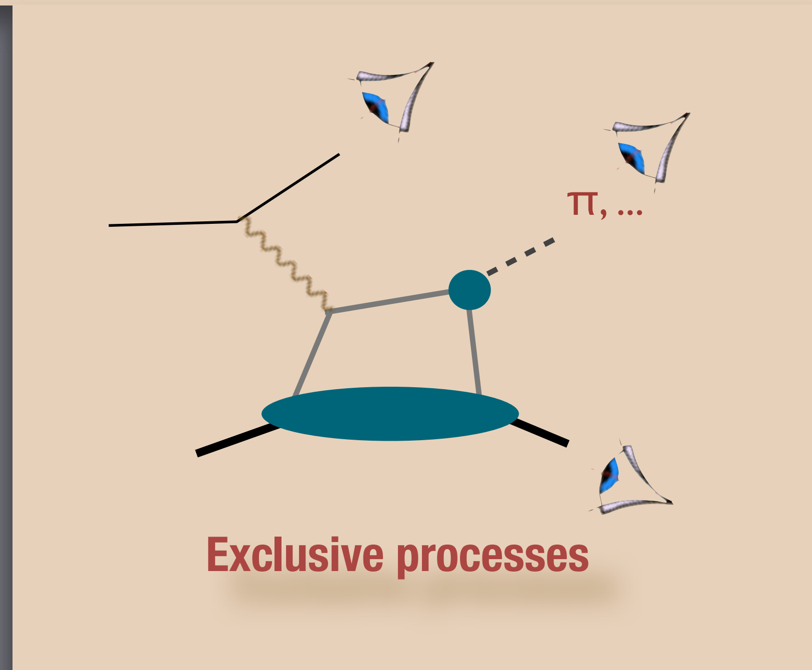


Charges ⇒	g_V,	g_A,	g_T

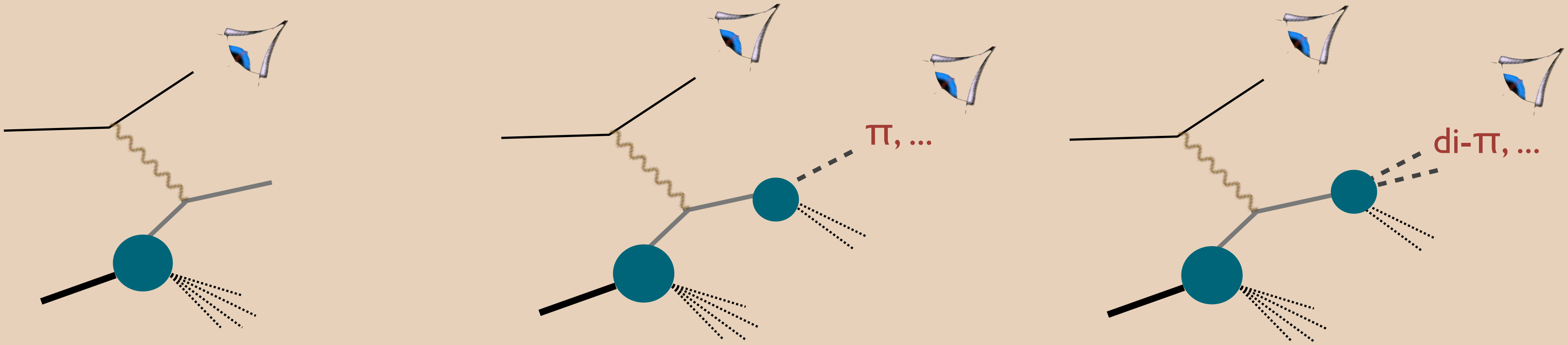


PDF AT LEADING TWIST



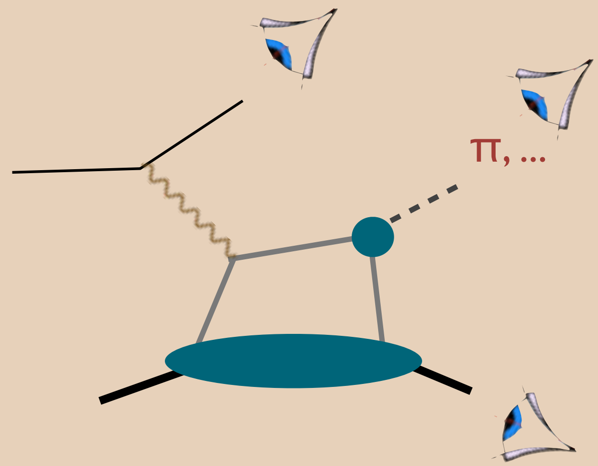


ACCESS TO DISTRIBUTION FUNCTIONS



Inclusive processes

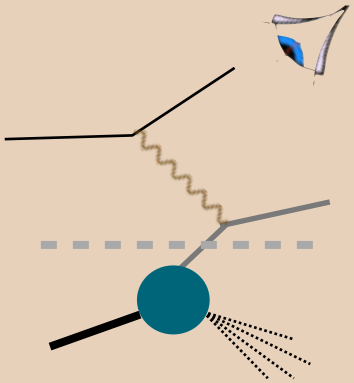
Semi-inclusive processes



Exclusive processes

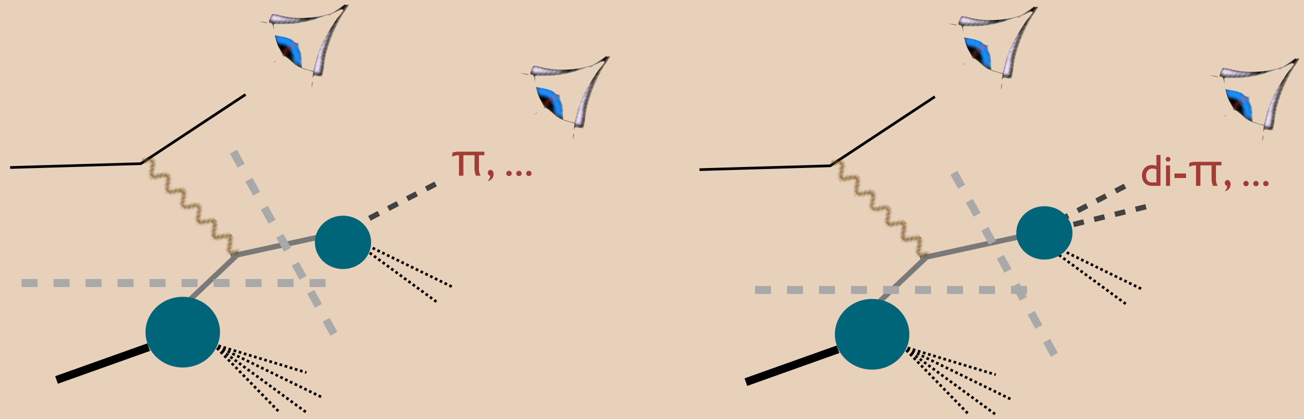
DEFINITION
AND
FACTORIZATION

ACCESS TO DISTRIBUTION FUNCTIONS



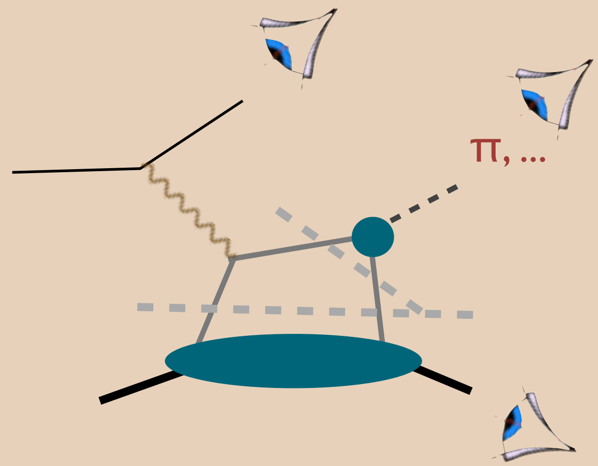
Inclusive processes

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



Semi-inclusive processes

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

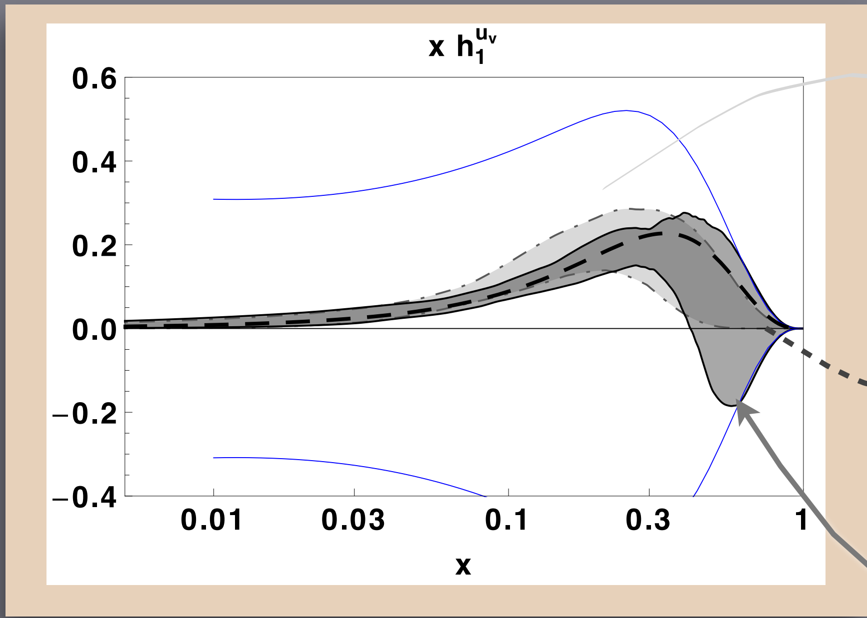


Exclusive processes

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

DEFINITION
AND
FACTORIZATION

ACCESS TO DISTRIBUTION FUNCTIONS



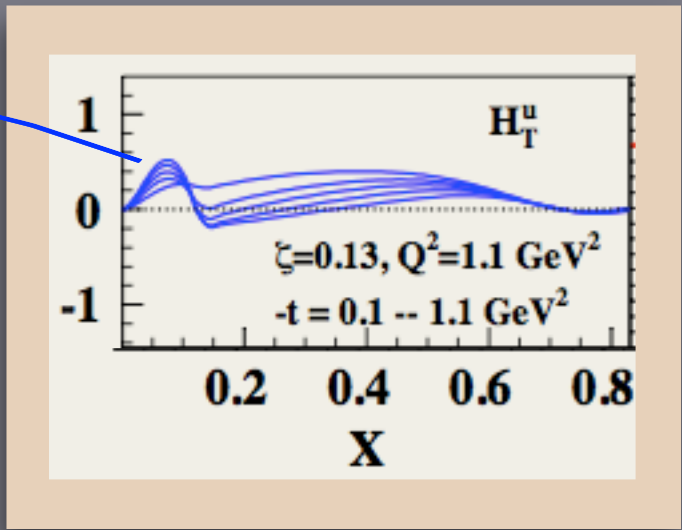
Torino 2013 @2.4 GeV^2

Kang et al central value

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

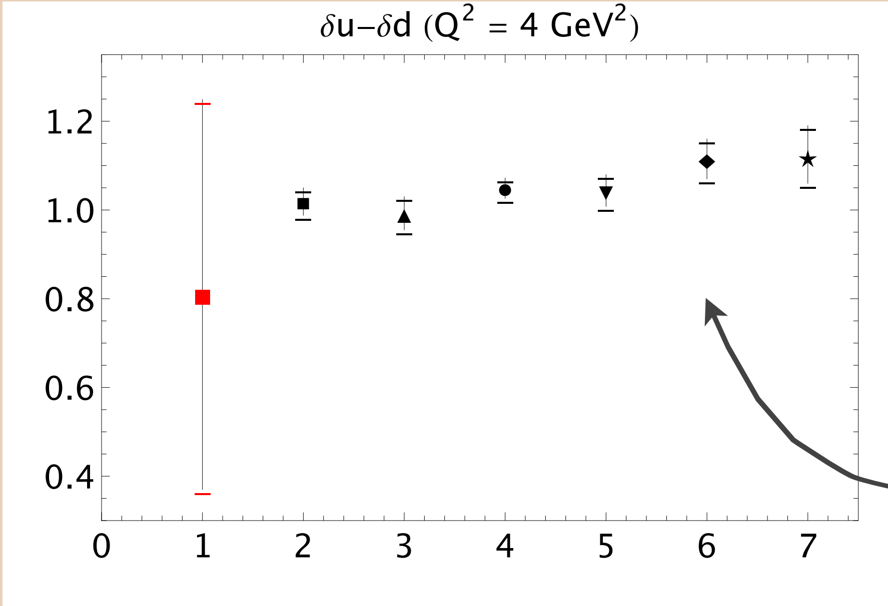
[Radici et al., JHEP 2015]

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



TRANSVERSITY PDF

[Goldstein et al, PRD 2015]



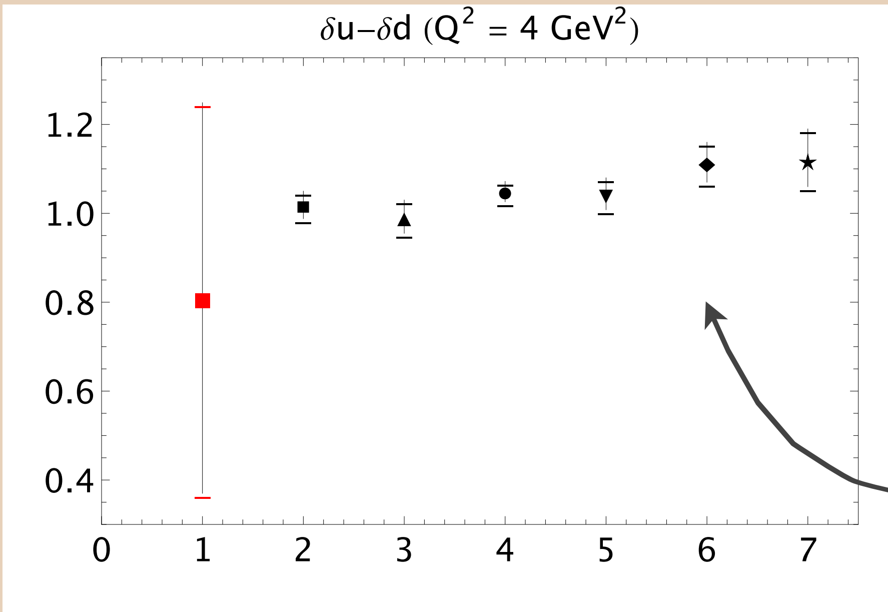
WITH MONTE CARLO LIKE FITTING

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

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

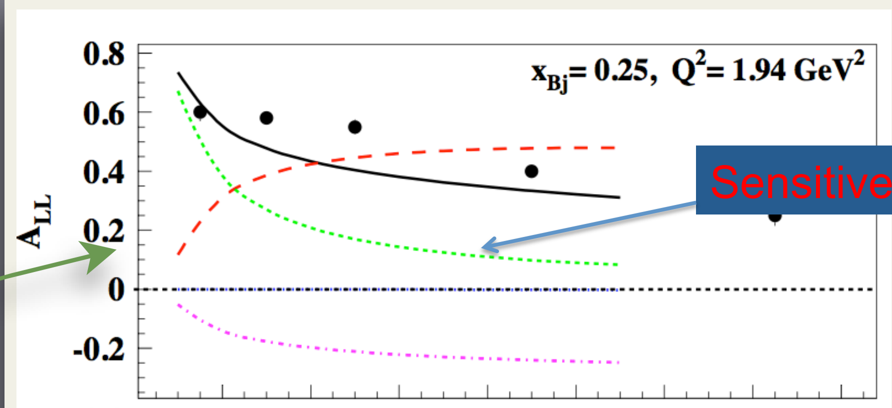
New Pavia flexible 0.125

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

HERE⇒TESTING GROUND FOR LATTICE QCD CALCULATIONS

ISOVECTOR TENSOR CHARGE

IMPACT OF FUTURE EXPERIMENTS

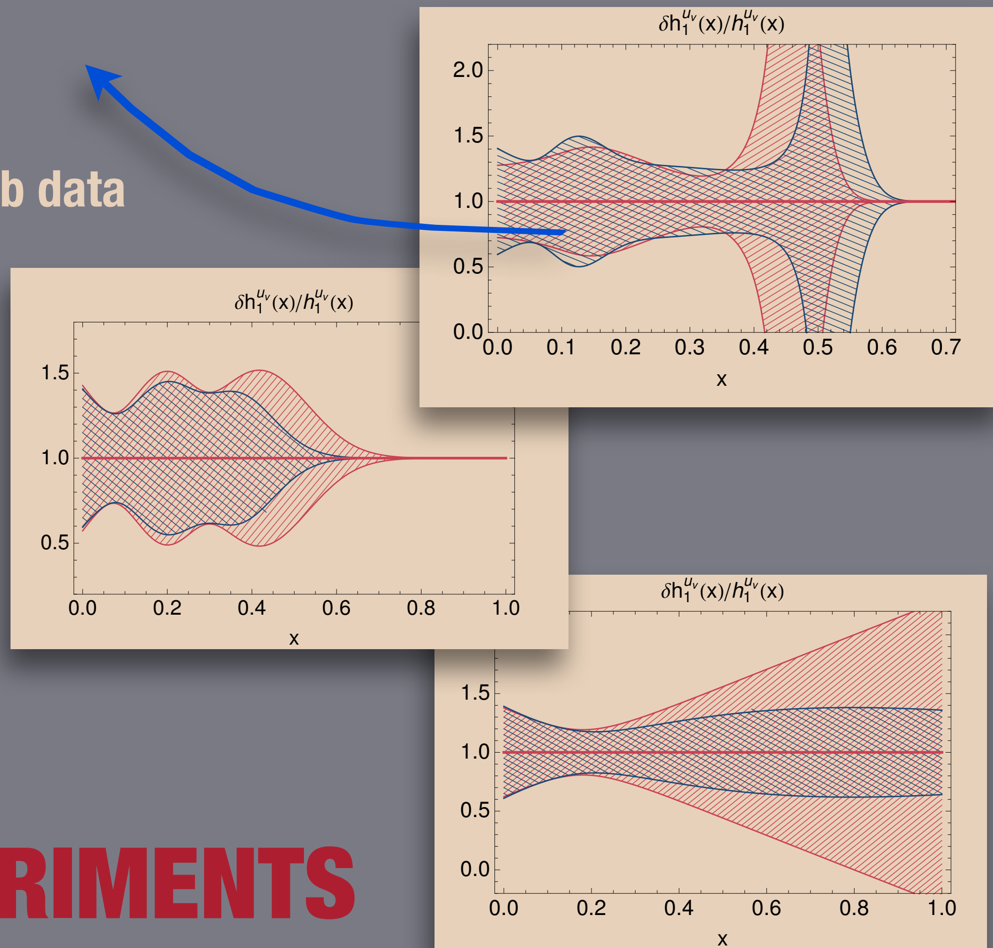


Andrey Kim, Harut Avakian et al., Jefferson Lab CLAS Collaboration

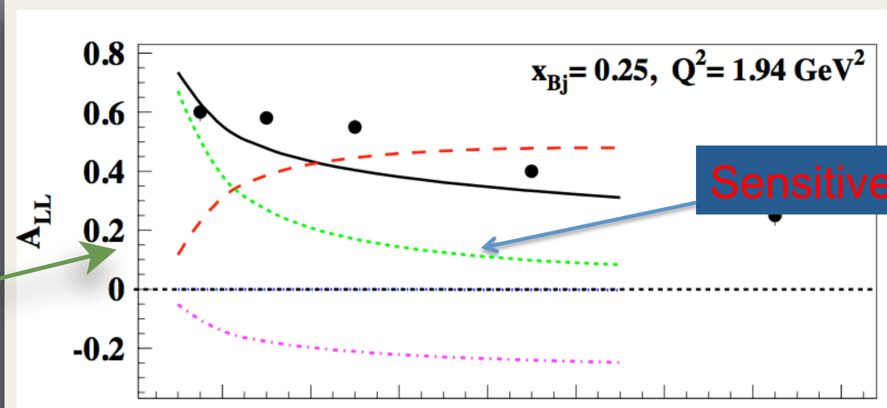
★ GGL depends on new JLab data

★ Pavia depends on new JLab data

★ Torino depends on TMD evolution +new JLab data



Jefferson Lab



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

- ★ **GGL depends on new JLab data**
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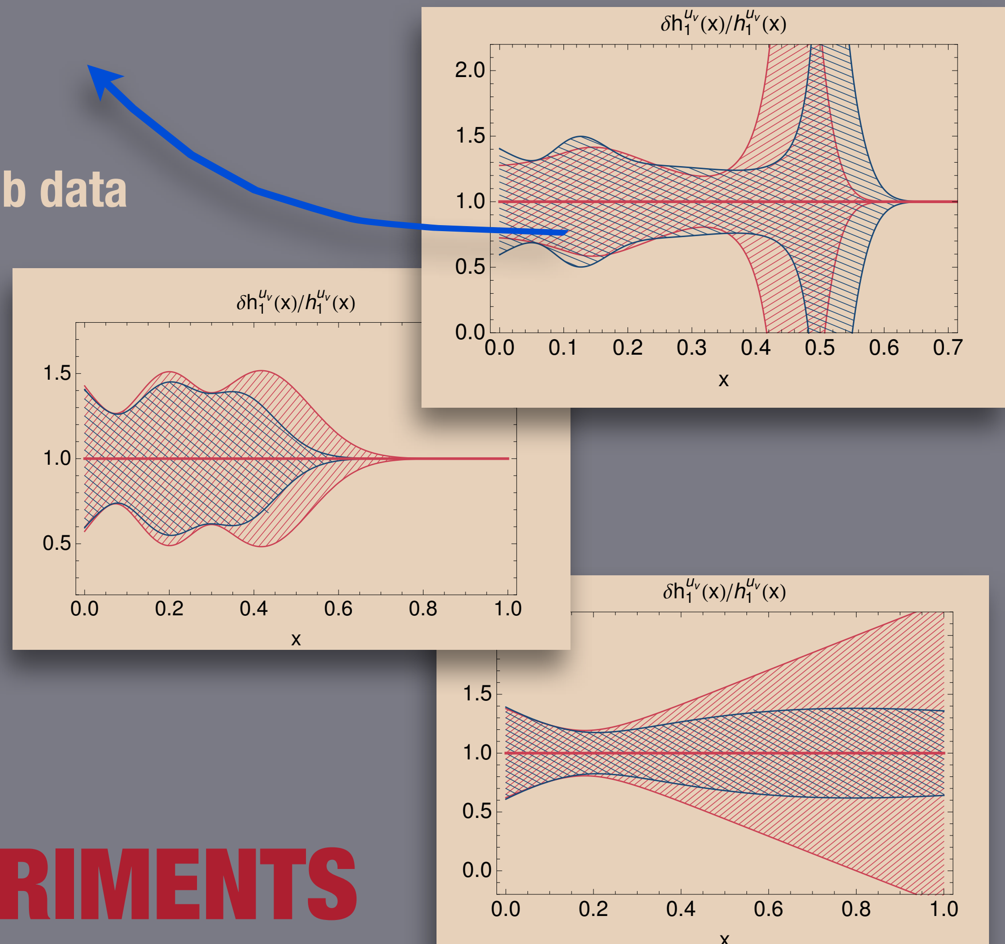
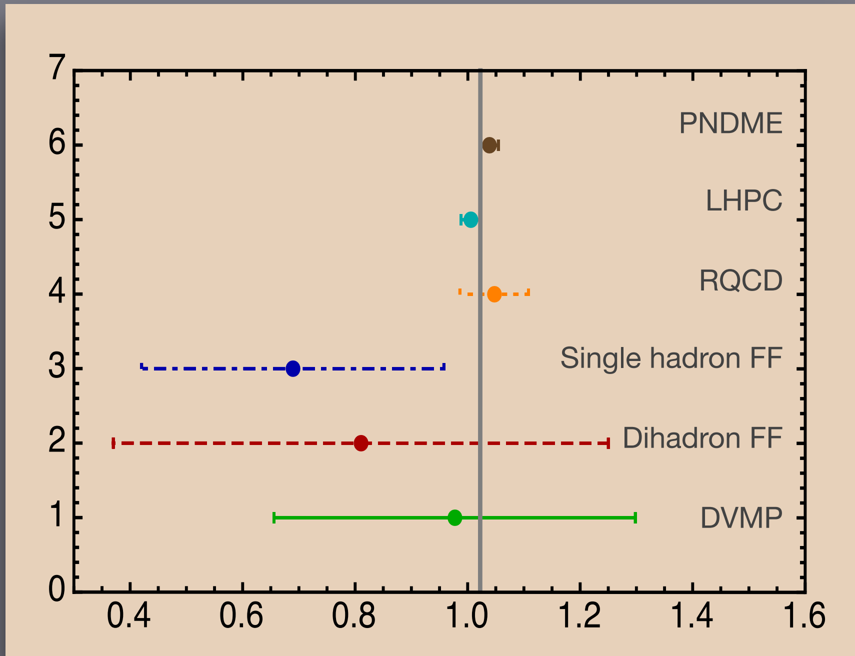


Transversities		$\delta g_T/g_T$	$(\delta g_T/g_T)^{\text{future}}$
Pavia	rigid	0.599	0.518
	flexible	0.696	0.639
	extra-flexible	1.007	0.865
Pavia average		0.767	0.674
GGL		0.329	0.115

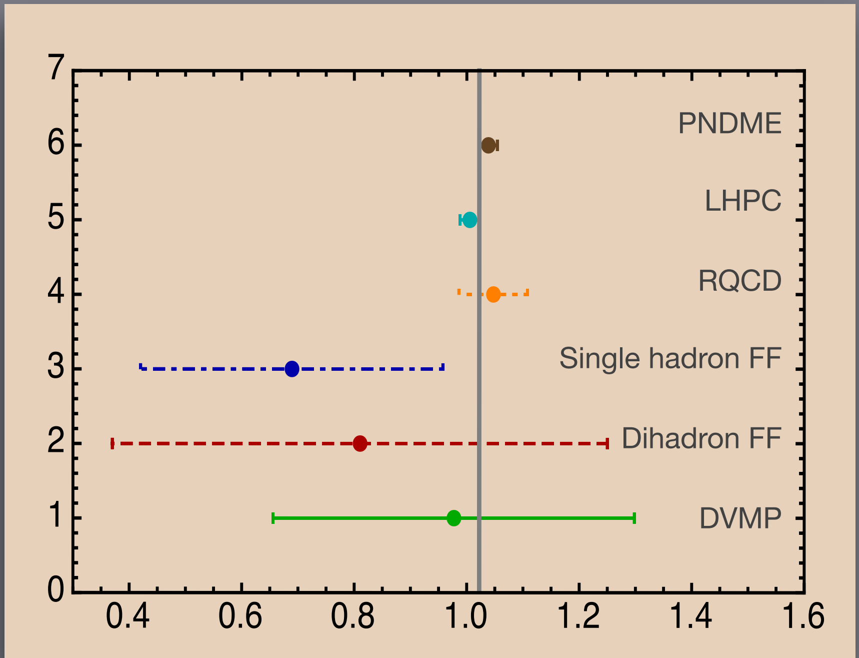
IMPACT OF FUTURE EXPERIMENTS



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

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

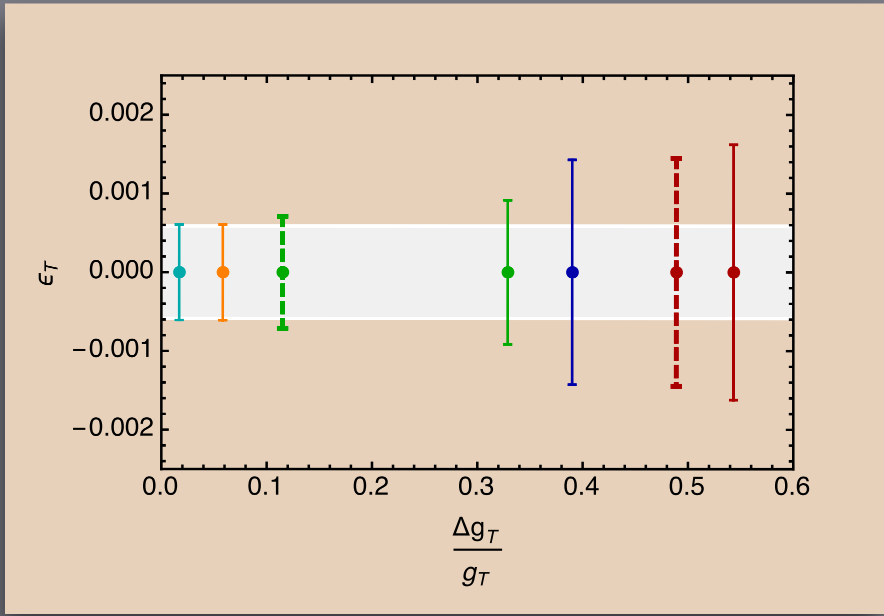
TENSOR INTERACTION AS OF NOW



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

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

we find....



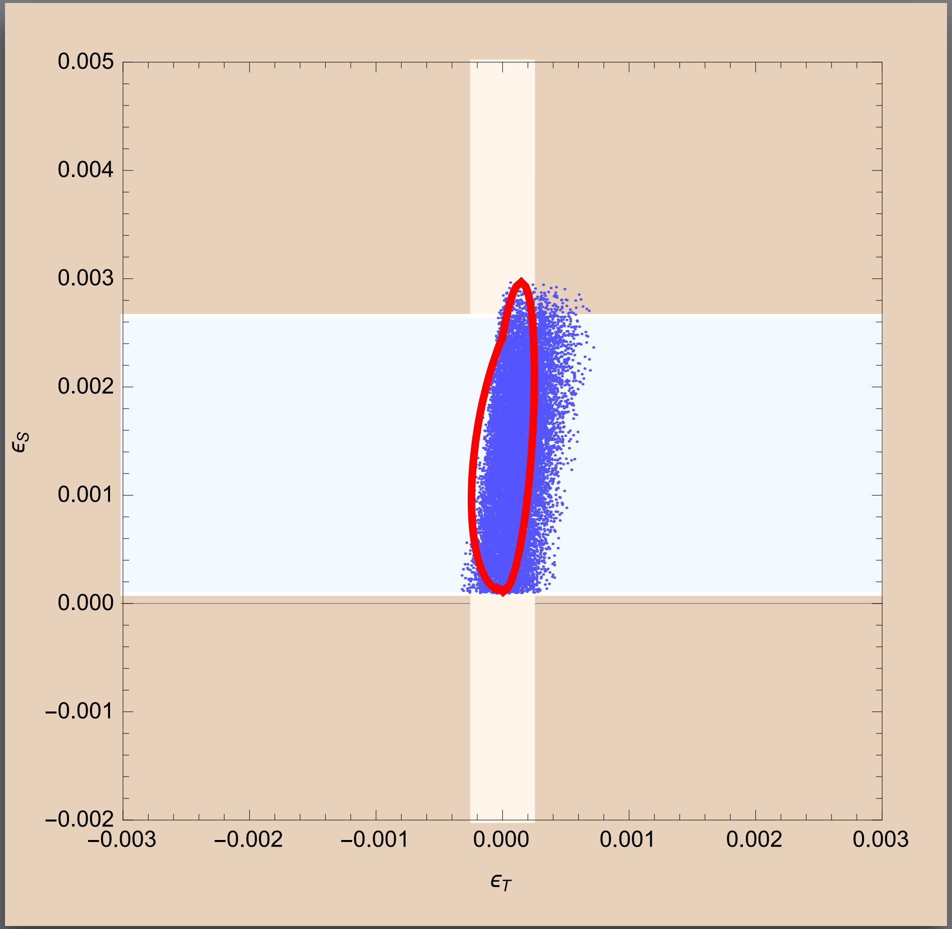
TENSOR INTERACTION AS OF NOW

ε_T vs. ε_S plane from b_0^+ and b

Warning: not a global fit

with g_S=1.02(11) at 90% CL from Gonzalez & Camalich, PRL112.

with $\langle g_T \rangle$=0.839(357) from GGL & Pavia new



1σ errors

- **Hessian in blue & pink**
- **Rfit method in red**
- **Scatter plot in blue**
- **MC 1D gives $\langle \varepsilon_T \rangle$ =0.0012**

NEW SCALAR-TENSOR

- ★ 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