PHENOMENOLOGY OF DIHADRON FRAGMENTATION FUNCTIONS AT CLAS12

Aurore Courtoy
CINVESTAV/CONACyT (Mexico)

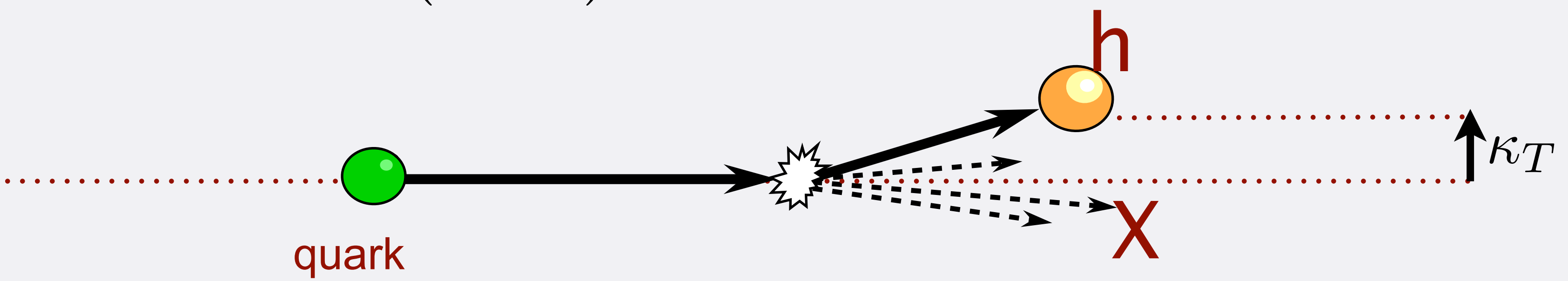
OUTLINE

Dihadron Fragmentation Functions

- Fragmentation
  - ➡ Asymmetries at Belle
  - ➡ Multiplicities at CLAS12
- SIDIS with Dihadron
- Confinement
  - ➡ Transversity
  - ➡ Higher-twist PDFs

HADRONIZATION

$$D_1^{q\to h}\left(z,\kappa_T^2\right)$$



Hadronization of the quark into a hadron h

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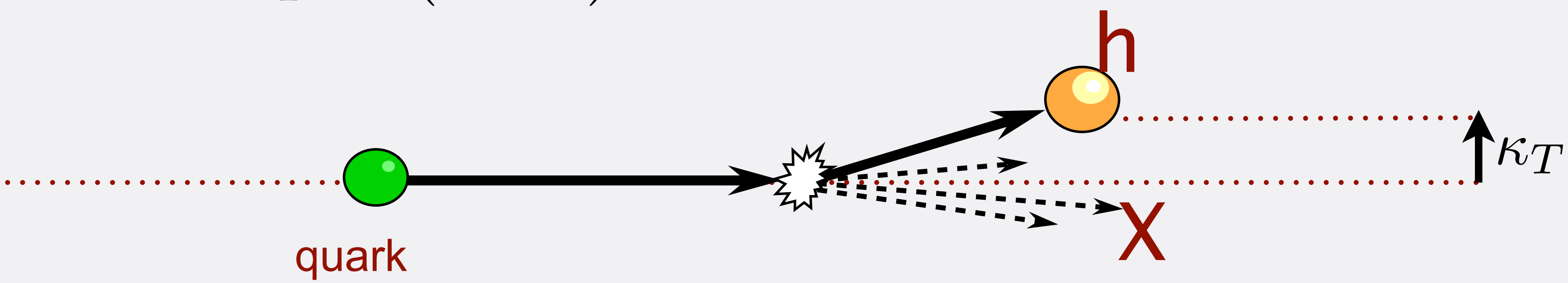

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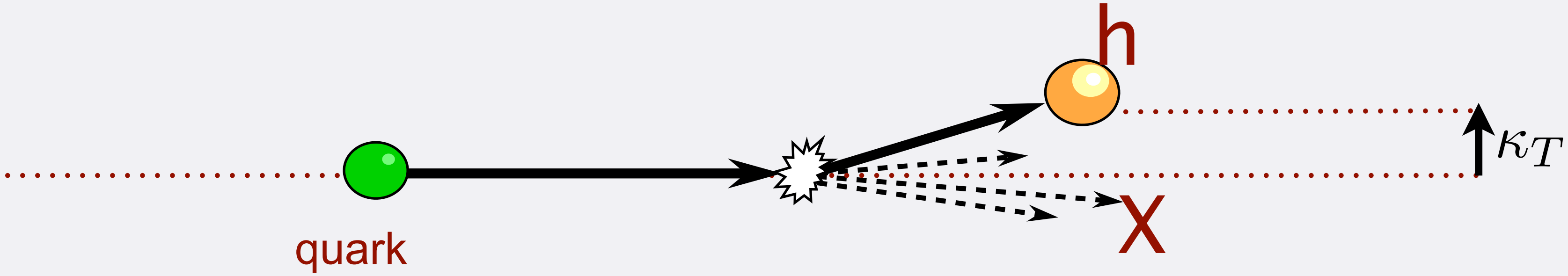
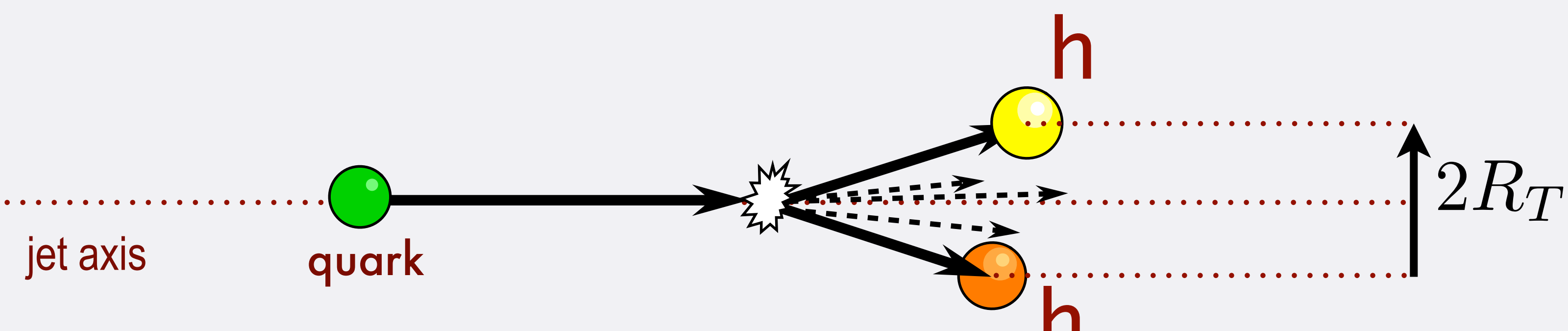


$$D_1^{q\to h_1 h_2}\left(z_1,z_2,R_T^2\right)$$



Hadronization of the quark into a hadron h

SINGLE-HADRON & DIHADRON SIDIS

Transverse mmt dep.

$$d\sigma \propto \sum_q \left[\mathrm{PDF}^q \otimes \mathrm{FF}^q\right] \left(x, z, P_{h\perp}^2\right)$$

Collinear

$$d\sigma \propto \sum_q \mathrm{PDF}^q(x) \times \mathrm{DiFF}^q\left(z, M_h\right)$$

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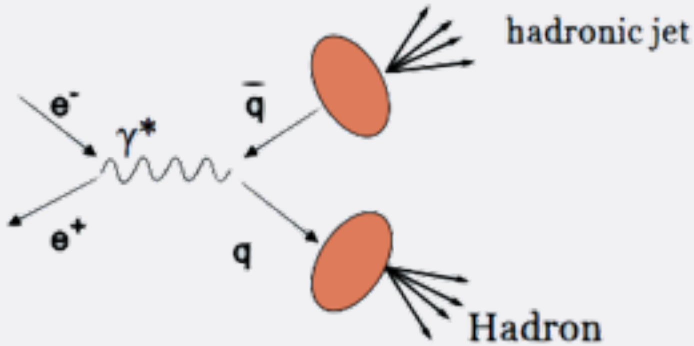
- Collinear Distribution functions
- Simple product
- 1D ``tomography"
- 2pion physics

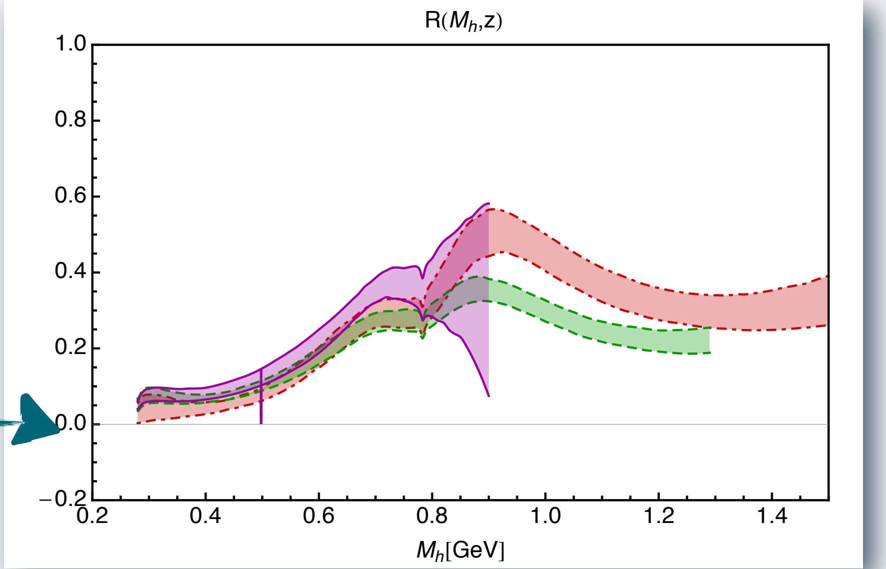
SI PION PAIRS PRODUCTION @ BELLE

[Belle Collaboration, PRL107]



$$A_{e^+e^-}(z, M_h^2, \bar{z}, \bar{M}_h^2) \propto \frac{\sum_q e_q^2 H_{1,\,sp}^{q\to\pi^+\pi^-}(z, M_h^2)\bar{H}_{1,\,sp}^{\bar{q}\to\pi^+\pi^-}(\bar{z}, \bar{M}_h^2)}{\sum_q e_q^2 D_1^{q\to\pi^+\pi^-}(z, M_h^2)\bar{D}_1^{\bar{q}\to\pi^+\pi^-}(\bar{z}, \bar{M}_h^2)}$$

$$R(z, M_h) = \frac{|\mathbf{R}|}{M_h}\,\frac{H_{1,sp}^{\sphericalangle u}(z, M_h; Q_0^2)}{D_1^u(z, M_h; Q_0^2)}$$



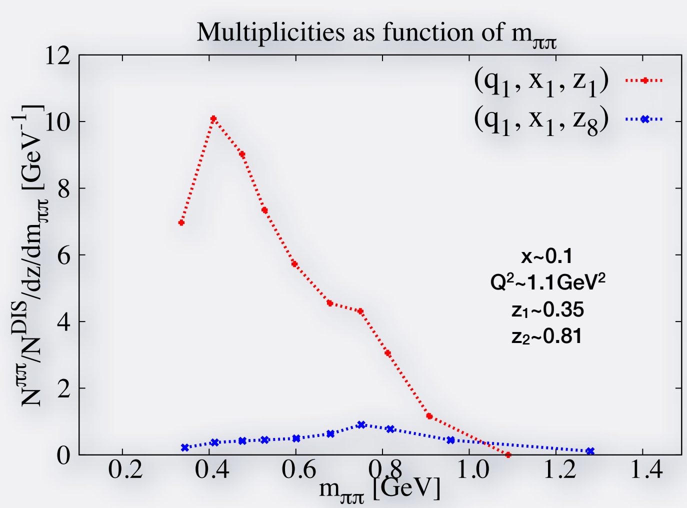
[A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]
[Radici, A.C., Bacchetta, Radici, Guagnelli, JHEP 1505]

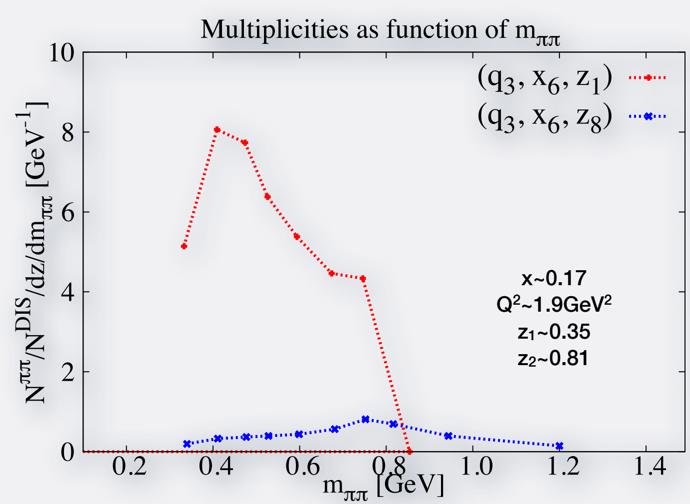
MULTIPLICITIES

Improve knowledge on Dihadron FF

➜ think reduce uncertainty

$$M^h(z, m_{\pi\pi}, x; Q^2) = \frac{\sum_q e_q^2 f_1^q(x; Q^2) D_1^q(z, m_{\pi\pi}; Q^2)}{\sum_q e_q^2 f_1^q(x; Q^2)}$$





- exp. input at lower Q^2
- test PWE & higher twists
- better knowledge on (z, M_h)-dpdence

Based on [A.C., Bacchetta, Radici, Bianconi, Phys.Rev. D85]

MULTIPLICITIES

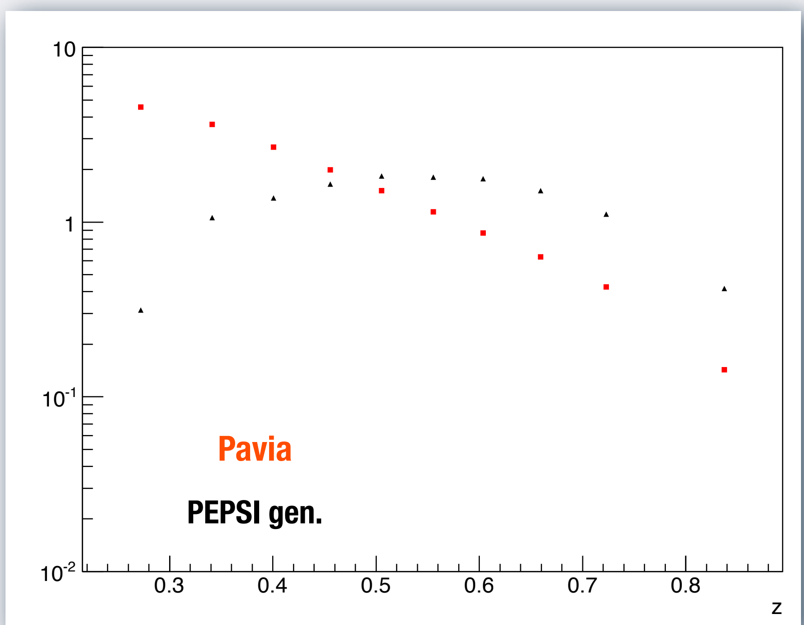
Analysis Proposal for CLAS12

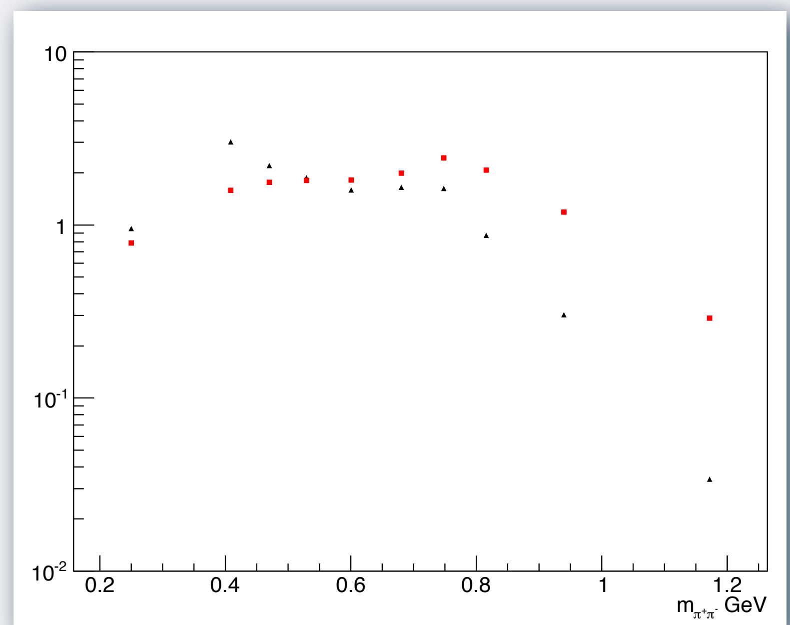
$$M(Q^2, x_B, z, m_{\pi^+\pi^-}) = \frac{N^{DH}/\Delta x_B \Delta Q^2 \Delta z \Delta m_{\pi^+\pi^-}}{N^{DIS}/\Delta x_B \Delta Q^2}$$

Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium

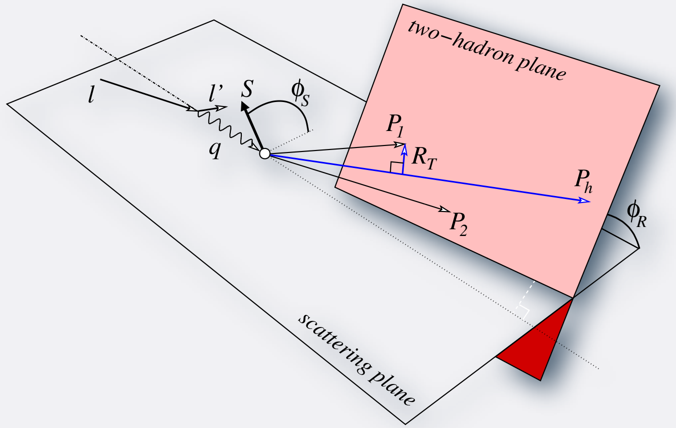
A 12 GeV Research Proposal to Jefferson Lab (PAC 42)

E12-06-112B
Silvia Pisano & A.C.





DIHADRON SIDIS



- **A_{UT}**

$$A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,y,z,M_h;Q) = -\frac{B(y)}{A(y)}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q\, e_q^2\, h_1^q(x;Q^2)\, H_{1,sp}^{\sphericalangle\, q}(z,M_h;Q^2)}{\sum_q\, e_q^2\, f_1^q(x;Q^2)\, D_1^q(z,M_h;Q^2)}$$

[Jaffe, Jin, Tiang, PRL 80]
[Radici, Jakob & Bianconi, PRD65]

- **A_{LU}**

$$A_{LU}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{W(y)}{A(y)}\,\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q\, e_q^2\left[x e^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\, f_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q\, e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

[Bacchetta & Radici, PRD69]

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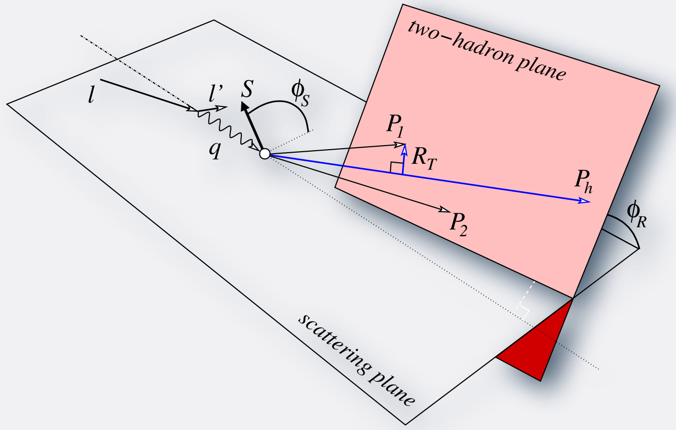

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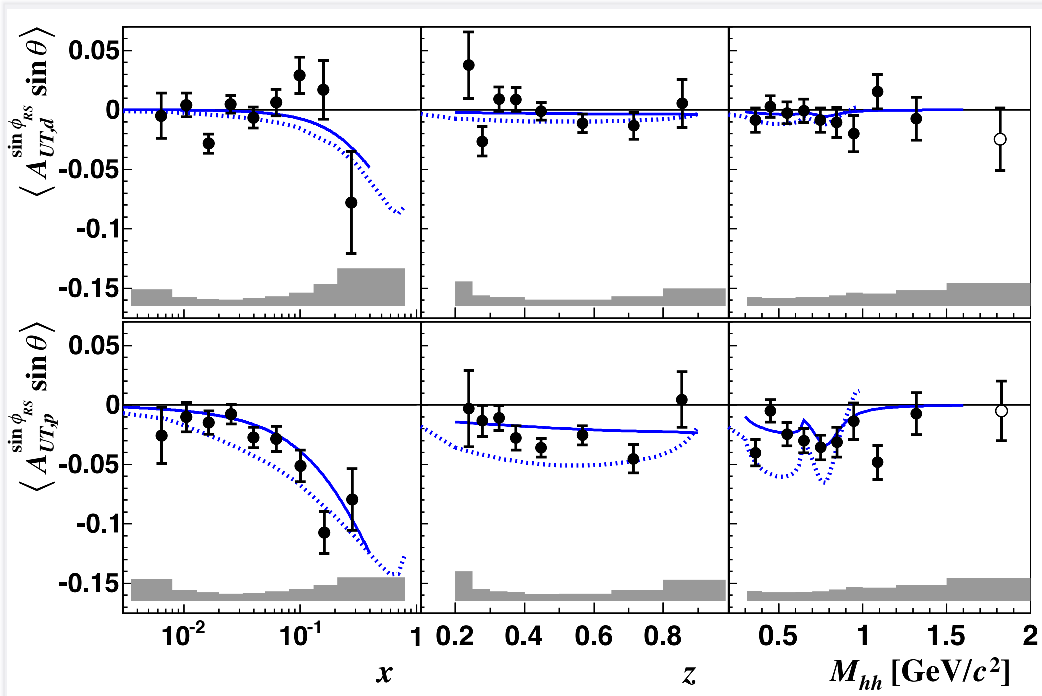
DIHADRON SIDIS ON PROTON & DEUTERON

2002-4 Deuteron Data

2007 Proton Data



$$A_{\mathrm{DIS}}(x,z,M_h^2,Q^2) = -C_y \frac{\sum_q e_q^2\, h_1^q(x,Q^2)\, \frac{|\bar{R}|}{M_h}\, H_{1,sp}^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}{\sum_q e_q^2\, f_1^q(x,Q^2) \quad D_1^{q\to\pi^+\pi^-}(z,M_h^2,Q^2)}$$

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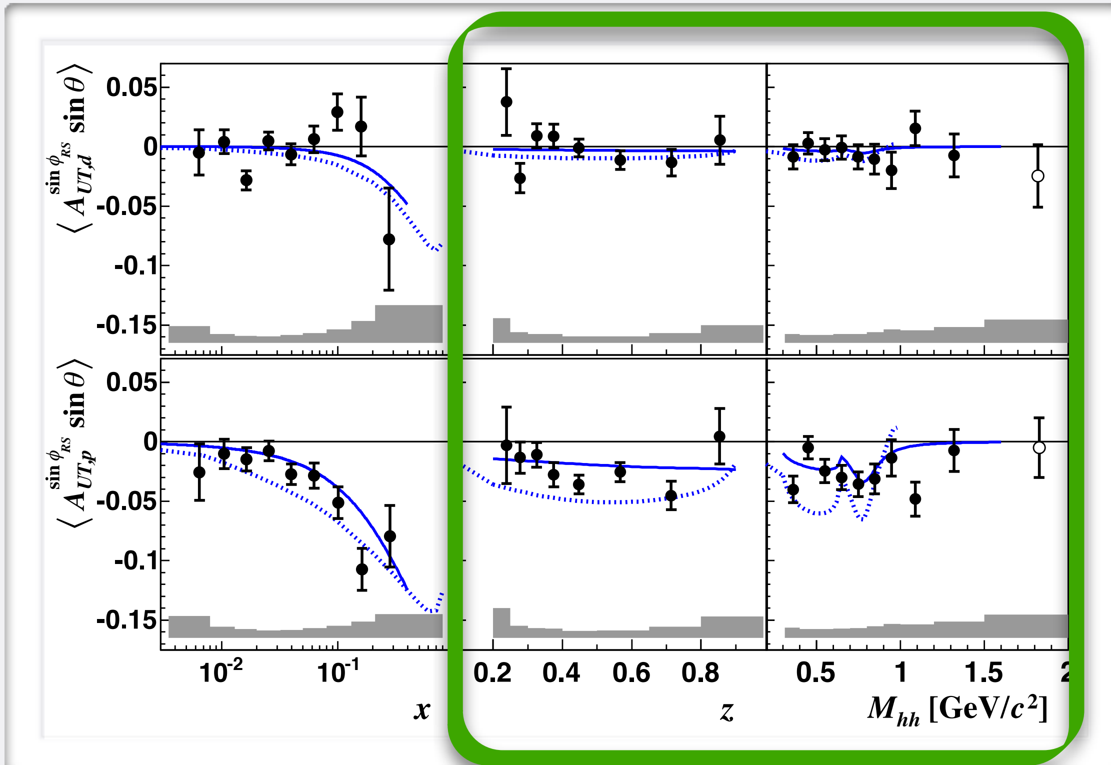

(z, M_h)-dpdence determined by DiFF from Belle

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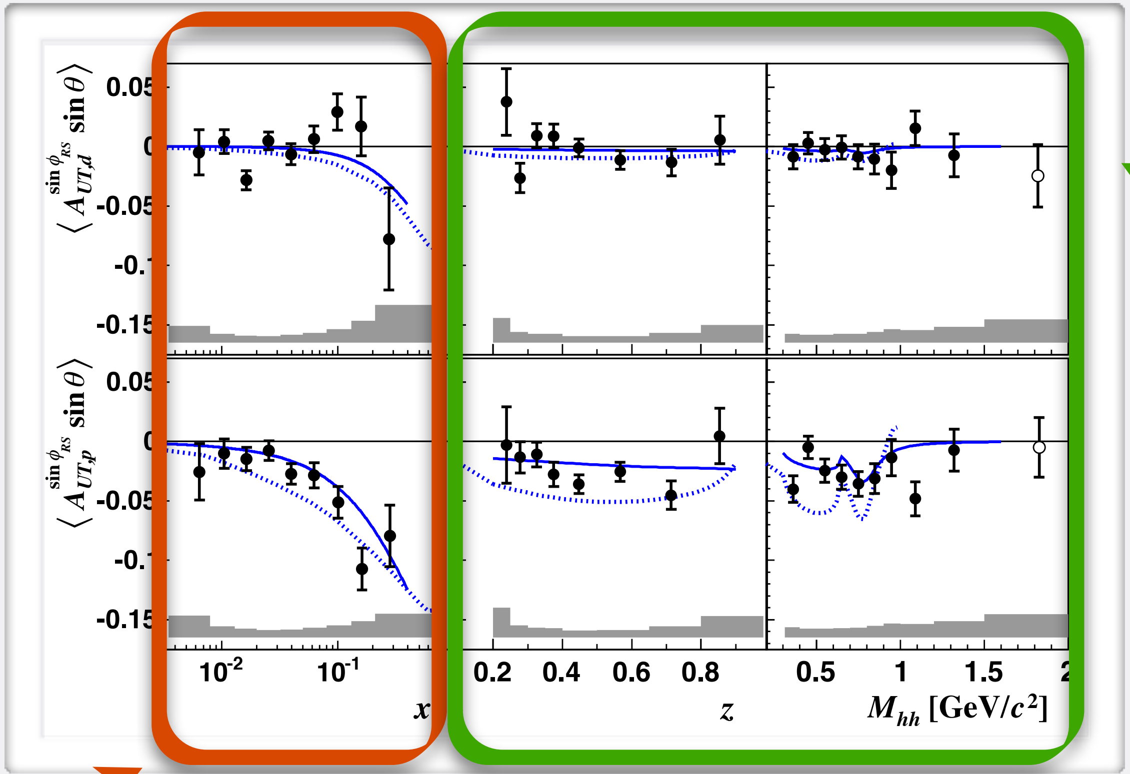

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x-dependence only from Transversity

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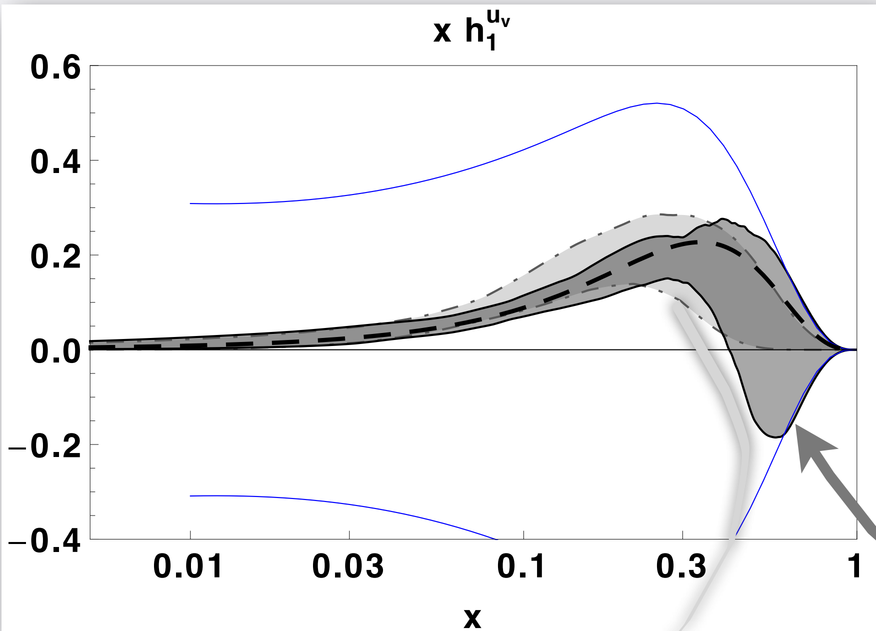
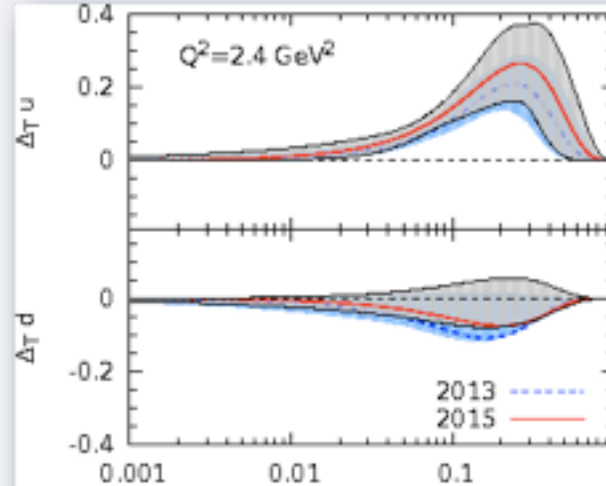
STATE-OF-THE-ART TRANSVERSITY

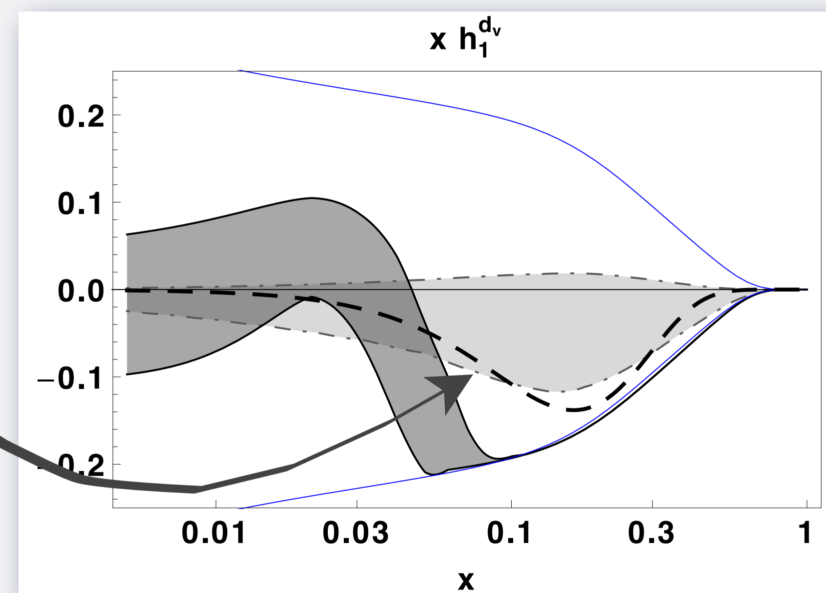




[Anselmino et al., 1510.05389]

Pavia @2.4 GeV^2 flexible-0.125

Torino 2013 @2.4 GeV^2



Kang et al central value

Discrepancy in the d distribution

New proton data don't change that!

[Radici, A.C., Bacchetta, Radici, Guagnelli, JHEP 1505]

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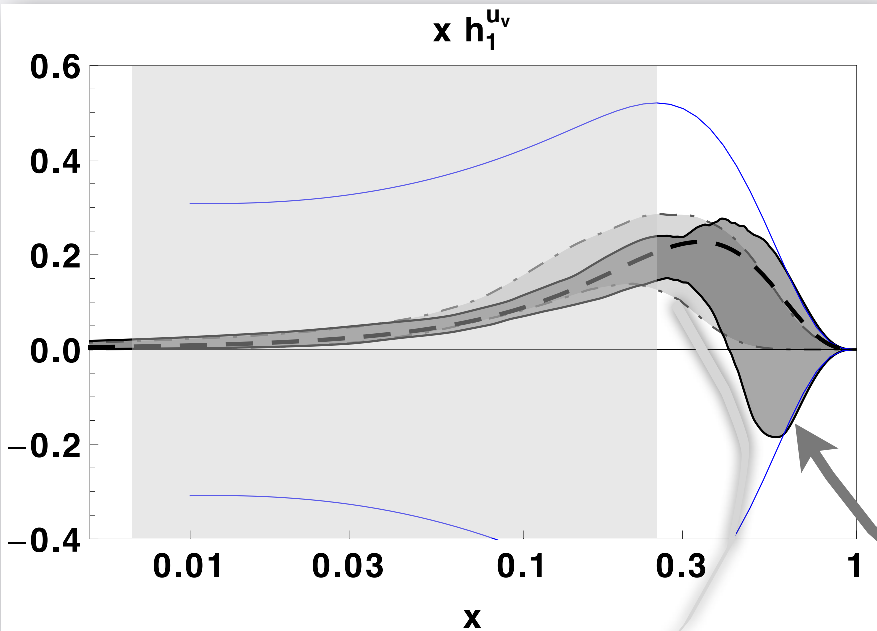

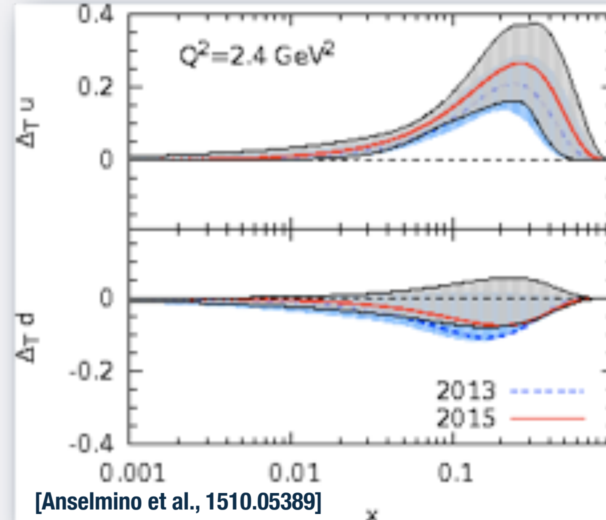

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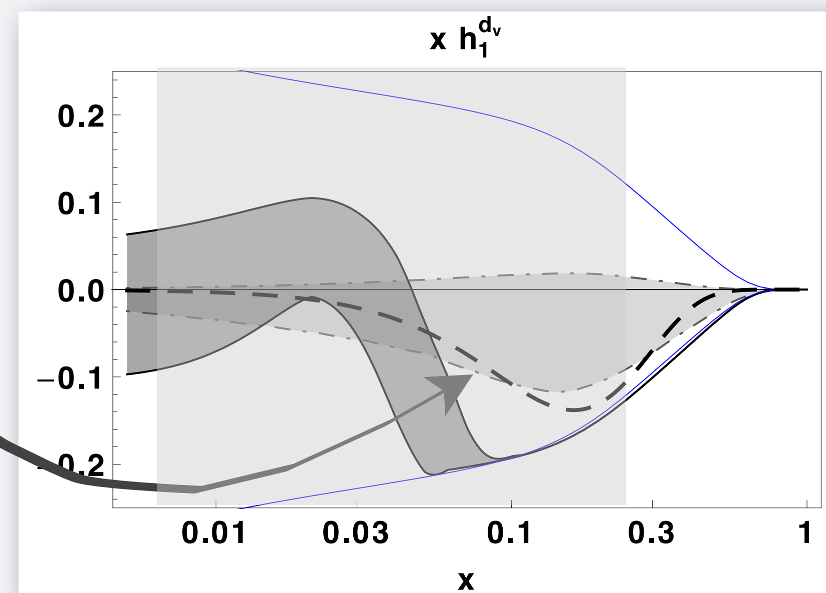

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FUTURE OF THE TRANSVERSITY

Proposal for CLAS12 PR12-12-009

A 12 GeV Research Proposal to Jefferson Lab (PAC 39)

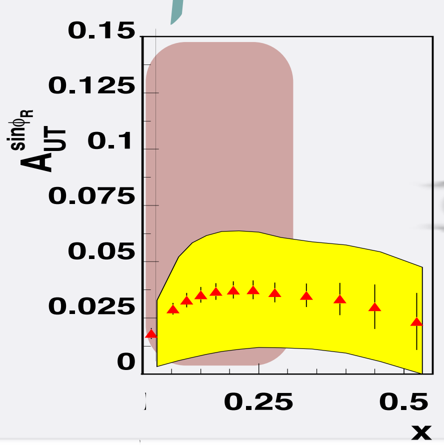
Measurement of transversity with dihadron production in SIDIS with transversely polarized target

Analysis Proposal for SoLID

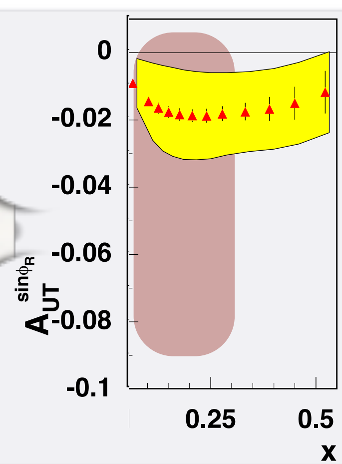
Dihadron Electroproduction in DIS with Transversely Polarized ^{3}He Target at 11 and 8.8 GeV

June 2, 2014

(A Proposal to Jefferson Lab (PAC 42))



0.007 < x < 0.53



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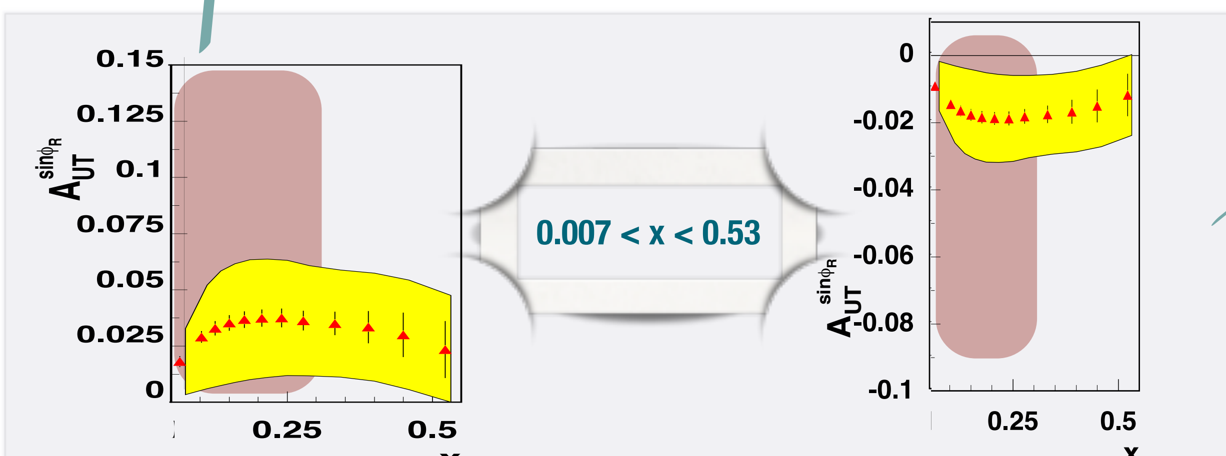

Improve determination of tensor charge!

$$\int_0^1 dx\, h_1^{q_V}(x) = \delta q$$

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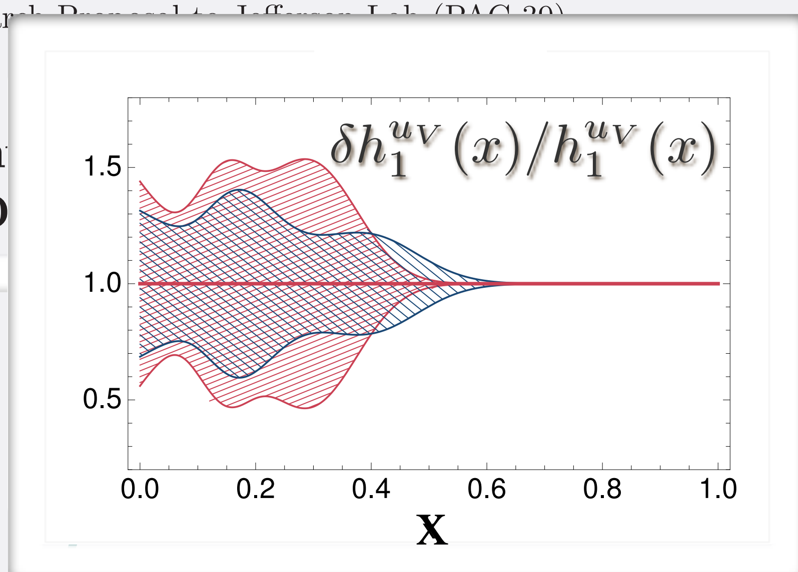
Proposal for CLAS12 PR12-12-009

A 12 GeV Resear

Measuremen … oduction
in SID … get



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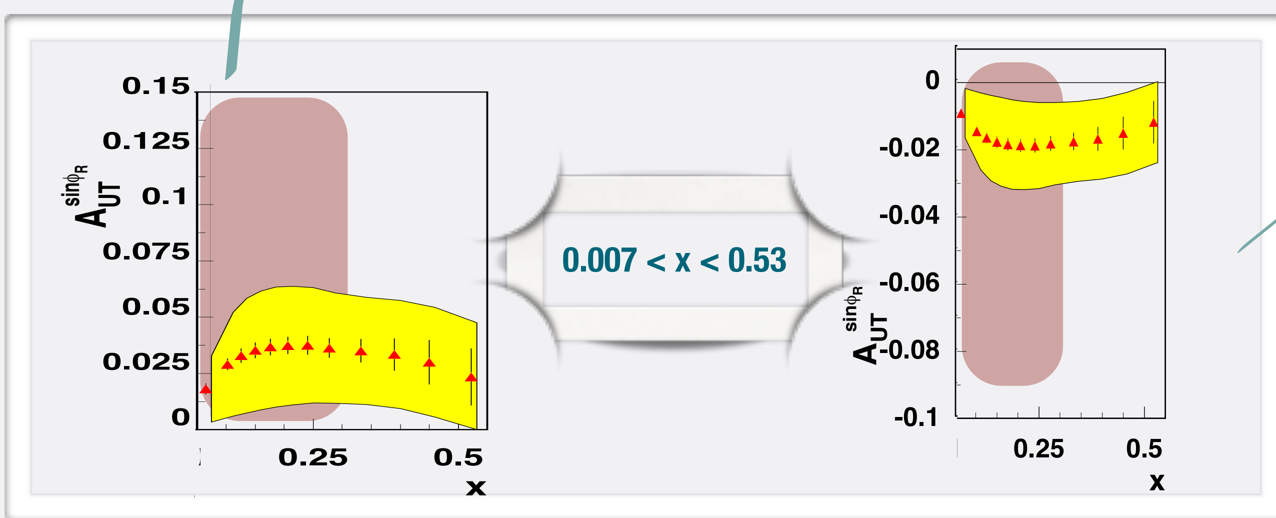

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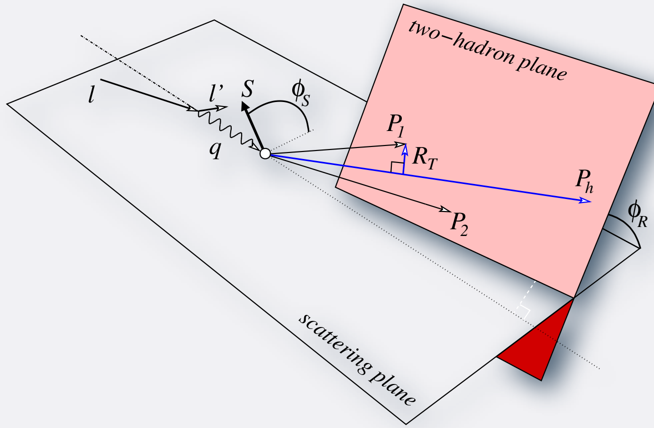

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@ CLAS12 & SoLID

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[Jaffe, Jin, Tiang, PRL 80]
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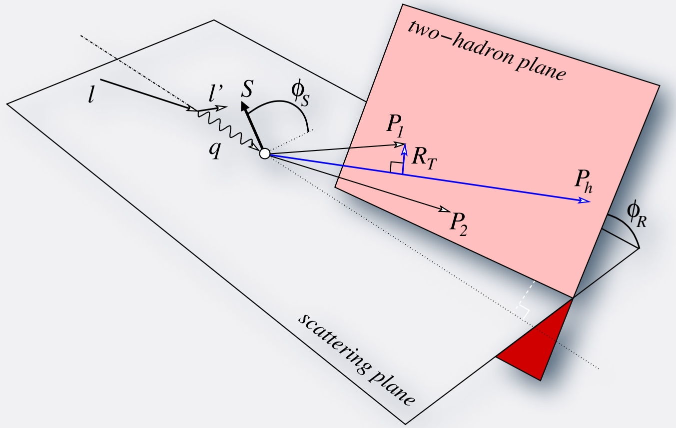
DIHADRON SIDIS



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@ CLAS12 & SoLID

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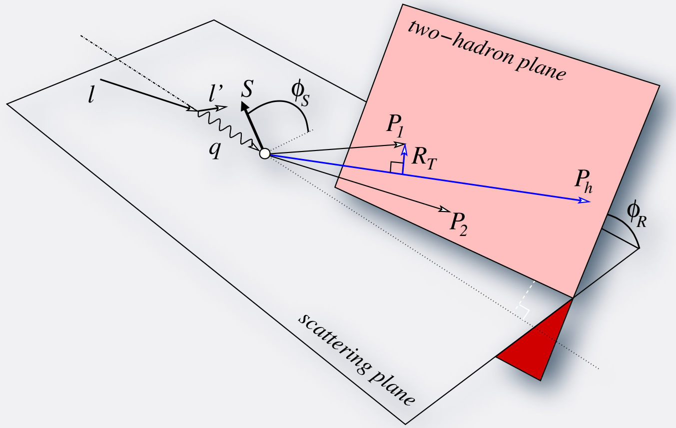
[Bacchetta & Radici, PRD69]

☑ **A$_{UL}$ @CLAS**

$$A_{UL}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{V(y)}{A(y)}\,\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q e_q^2\left[x h_L^q(x)\, H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\, g_1^q(x)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q e_q^2\, f_1^q(x)\, D_{1,ss+pp}^q(z,M_h)}$$

DIHADRON SIDIS



☑ A_{UT} @ HERMES & COMPASS
@ CLAS12 & SoLID

$$A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,y,z,M_h;Q) = -\frac{B(y)}{A(y)}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q e_q^2\,h_1^q(x;Q^2)\,H_{1,sp}^{\sphericalangle\,q}(z,M_h;Q^2)}{\sum_q e_q^2\,f_1^q(x;Q^2)\,D_1^q(z,M_h;Q^2)}$$

[Jaffe, Jin, Tiang, PRL 80]
[Radici, Jakob & Bianconi, PRD65]

☑ A_{LU} @CLAS & CLAS12

$$A_{LU}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{W(y)}{A(y)}\,\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q e_q^2\left[x e^q(x)\,H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\,f_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q e_q^2\,f_1^q(x)\,D_{1,ss+pp}^q(z,M_h)}$$

[Bacchetta & Radici, PRD69]

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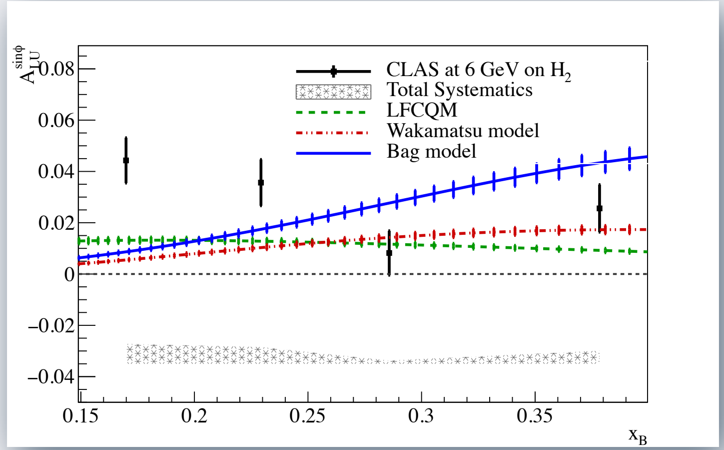
$$A_{UL}^{\sin\phi_R\,\sin\theta}(x,y,z,M_h,Q) = -\frac{V(y)}{A(y)}\,\frac{M}{Q}\,\frac{1}{2}\,\frac{|\mathbf{R}|}{M_h}\,\frac{\sum_q e_q^2\left[x h_L^q(x)\,H_{1,sp}^{\sphericalangle,q}(z,M_h) + \frac{M_h}{zM}\,g_1^q(x)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,M_h)\right]}{\sum_q e_q^2\,f_1^q(x)\,D_{1,ss+pp}^q(z,M_h)}$$

BEAM SPIN ASYMMETRY@CLAS

GOAL: extract e(x)

$$A_{LU}^{\sin\phi_R}(x, z, m_{\pi\pi}; Q, y) = -\frac{W(y)}{A(y)}\frac{M}{Q}\frac{|\mathbf{R}|}{m_{\pi\pi}}\frac{\sum_q e_q^2\left[x e^q(x,Q^2)\, H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi},Q^2) + \frac{m_{\pi\pi}}{zM} f_1^q(x,Q^2)\, \tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi},Q^2)\right]}{\sum_q e_q^2 f_1^q(x,Q^2)\, D_{1,ss+pp}^q(z,m_{\pi\pi},Q^2)}$$

...from CLAS data



Silvia Pisano's analysis e1-f

BEAM SPIN ASYMMETRY@CLAS

higher-twist PDF e(x) unknown

GOAL: extract e(x)

$$A_{LU}^{\sin\phi_R}(x,z,m_{\pi\pi};Q,y) = -\frac{W(y)}{A(y)}\frac{M}{Q}\frac{|\mathbf{R}|}{m_{\pi\pi}}\frac{\sum_q e_q^2\left[x e^q(x,Q^2)\,H_{1,sp}^{\sphericalangle,q}(z,m_{\pi\pi},Q^2)+\frac{m_{\pi\pi}}{zM}\,f_1^q(x,Q^2)\,\tilde{G}_{sp}^{\sphericalangle,q}(z,m_{\pi\pi},Q^2)\right]}{\sum_q e_q^2\,f_1^q(x,Q^2)\,D_{1,ss+pp}^q(z,m_{\pi\pi},Q^2)}$$

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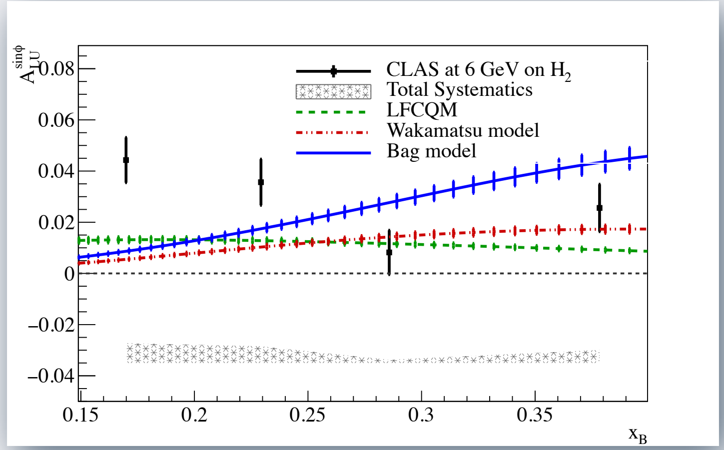

Silvia Pisano's analysis e1-f

BEAM SPIN ASYMMETRY@CLAS

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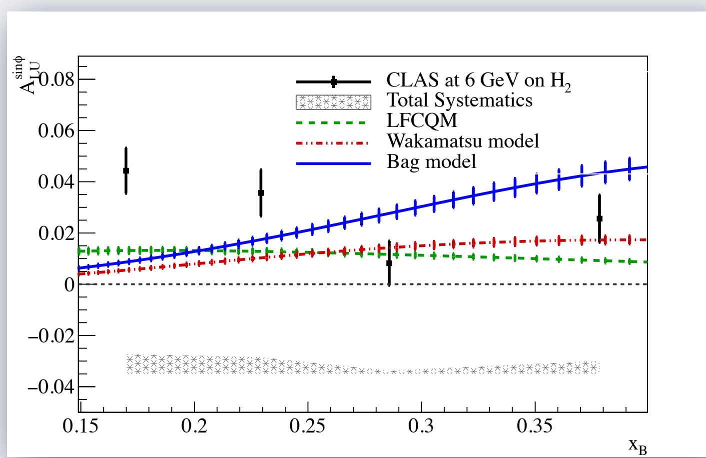
leading-twist DiFFs
known

...from CLAS data



Silvia Pisano's analysis
e1-f

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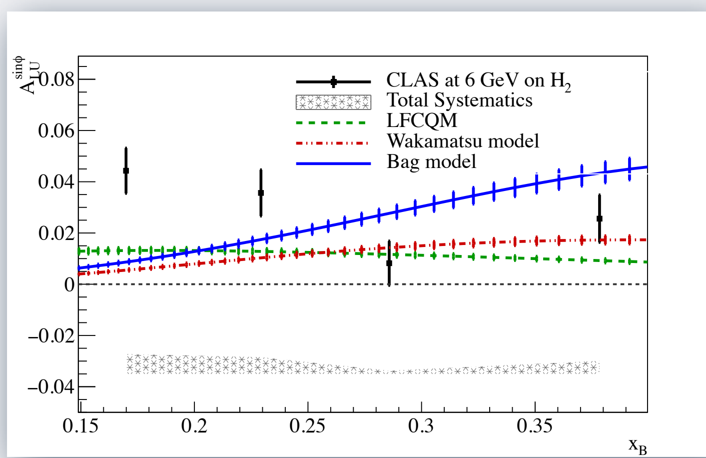
leading-twist DiFFs known

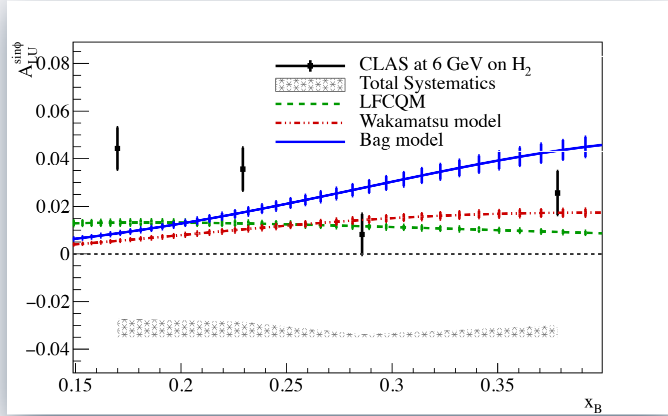
...from CLAS data

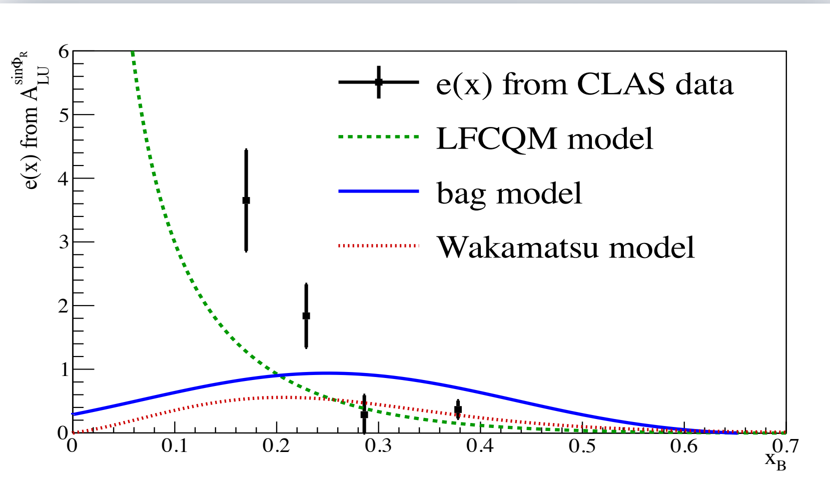


Silvia Pisano's analysis e1-f

FIRST TRY EXTRACTION

Assume no dynamical higher-twist in the fragmentation part





leading-twist DiFFs known from PAVIA fit

$$A_{LU}^{\sin\phi_R}(x_i, m_{\pi\pi\,i},, z_i; Q_i, y_i) = -\frac{W(y_i)}{A(y_i)}\,\frac{M}{Q_i}\,\frac{x_i\left[\frac{4}{9}e^{u_V}(x_i, Q_i^2) - \frac{1}{9}e^{d_V}(x_i, Q_i^2)\right]\, n_{u,i}^{\uparrow}(Q_i^2)}{\sum_{q=u,d,s} e_q^2\, f_1^q(x_i, Q_i^2)\, n_{q,i}(Q_i^2)}$$

[AC et al, arXiv:1405.7659]

TWIST-3 PDF @CLAS12

Analysis Proposal for CLAS12

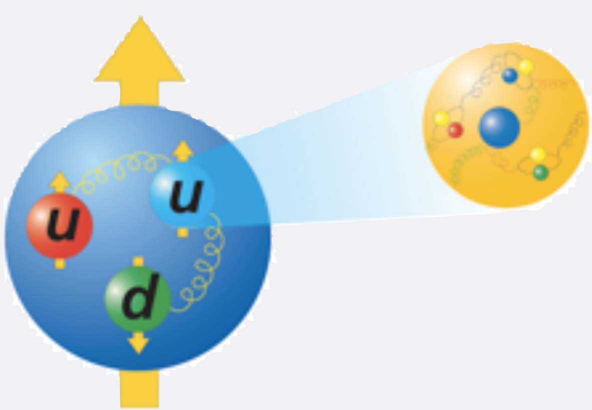
Higher-twist collinear structure of the nucleon through di-hadron SIDIS on unpolarized hydrogen and deuterium

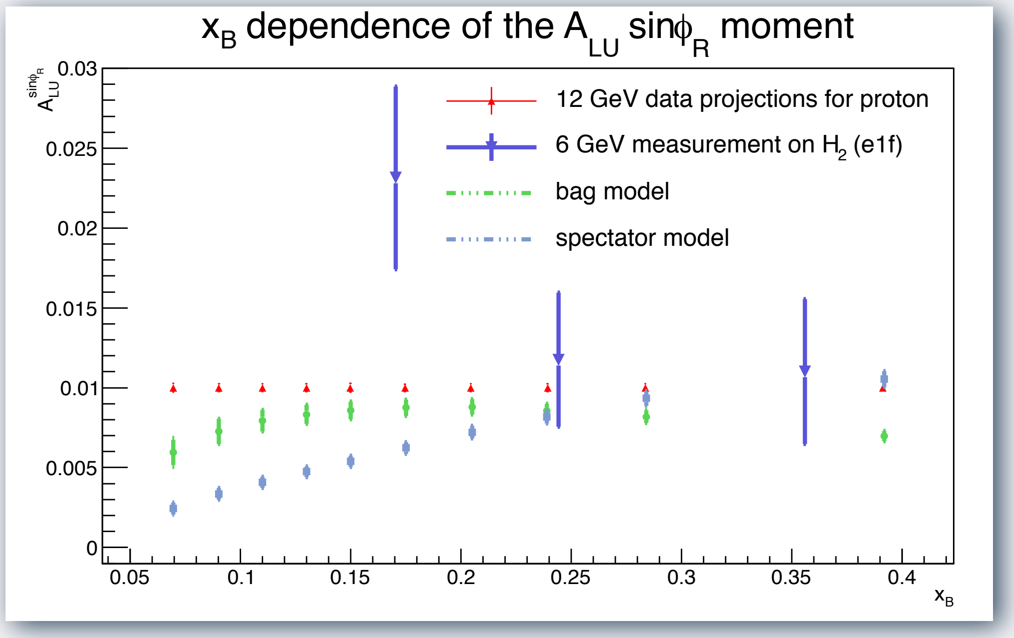
A 12 GeV Research Proposal to Jefferson Lab (PAC 42)

E12-06-112B
Silvia Pisano & A.C.

e(x)

- related to the scalar charge
- quark-gluon correlation
- quark mass term





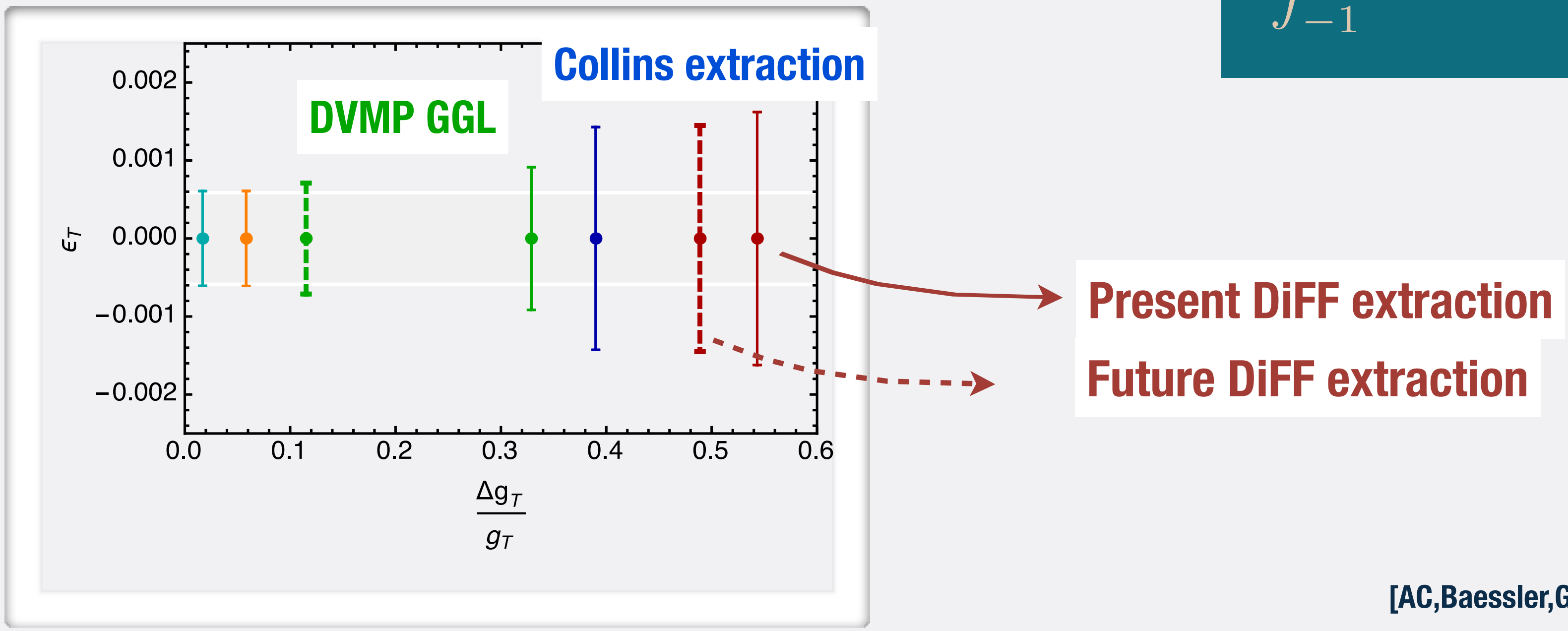
BSM FUNDAMENTAL INTERACTIONS?

Example: New fundamental interaction from beta decay?

$$\Delta\mathcal{L}_{eff} = G_F V_{ud}\sqrt{2}\,\epsilon_S g_S\,\bar{p}n\cdot\bar{e}(1-\gamma_5)\nu_e$$
$$-4G_F V_{ud}\sqrt{2}\,\epsilon_T g_T\,\bar{p}\sigma_{\mu\nu}n\cdot\bar{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e$$

[Cirigliano et al., NPB 830]

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



[AC,Baessler,Gonzalez-Alonso,Liuti, PRL 115]

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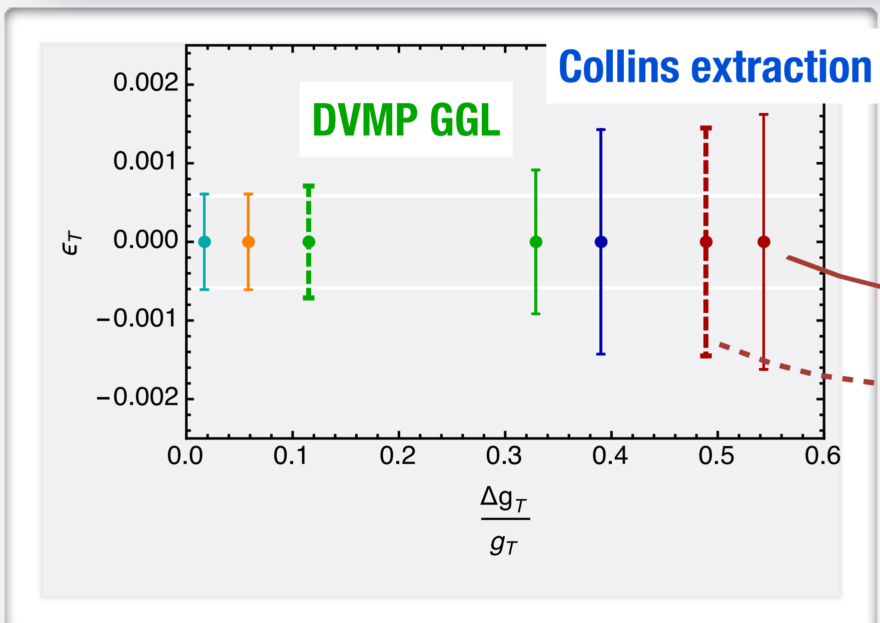
[Cirigliano et al., NPB 830]

Could we do the same with g_S?

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



Present DiFF extraction

Future DiFF extraction

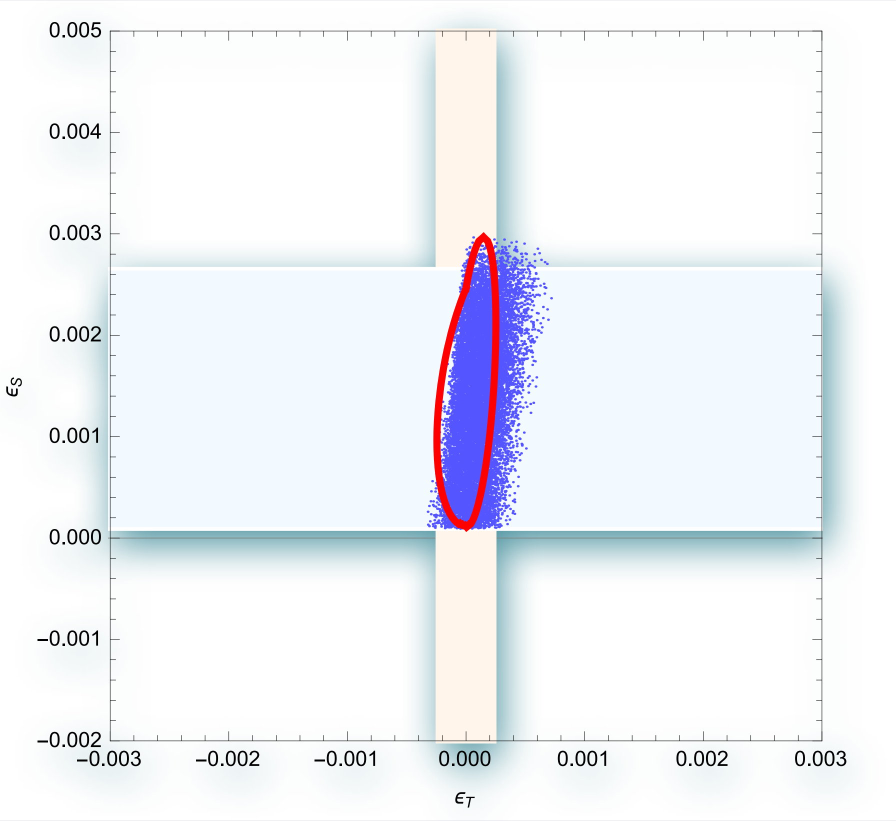
[AC,Baessler,Gonzalez-Alonso,Liuti, PRL 115]

BSM FUNDAMENTAL INTERACTIONS?

ε_T vs. ε_S plane from beta decay observables

with ε_S**=0.0011(21)** at 90% CL from Gonzalez & Camalich, PRL112.

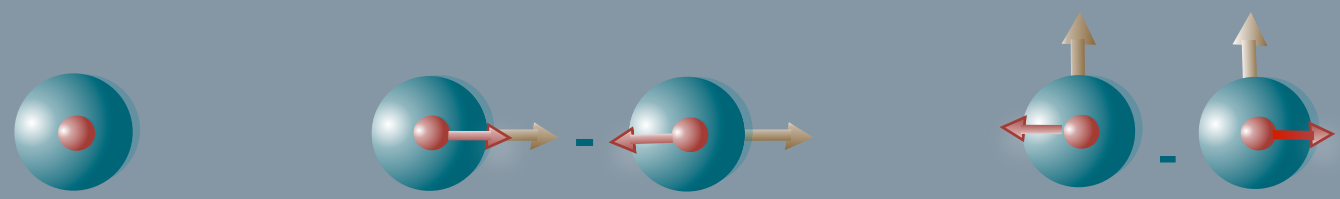
with **<g_T>=0.839(357)** from GGL & Pavia new



- **1σ errors**
- **Hessian in blue & pink**
- **Rfit method in red**
- **Scatter plot in blue**
- **MC 1D gives <ε_T> =0.0012**

[AC,Baessler,Liuti, in progress]

CONCLUSIONS



✓ Vector, axial OK from first principles

- Dihadron SIDIS is a good tool to
    - access to scalar, tensor structures
    - glimpse of quark-gluon correlations
- Get more info on DiFF from CLAS12 as well

BACK UP

Proposal

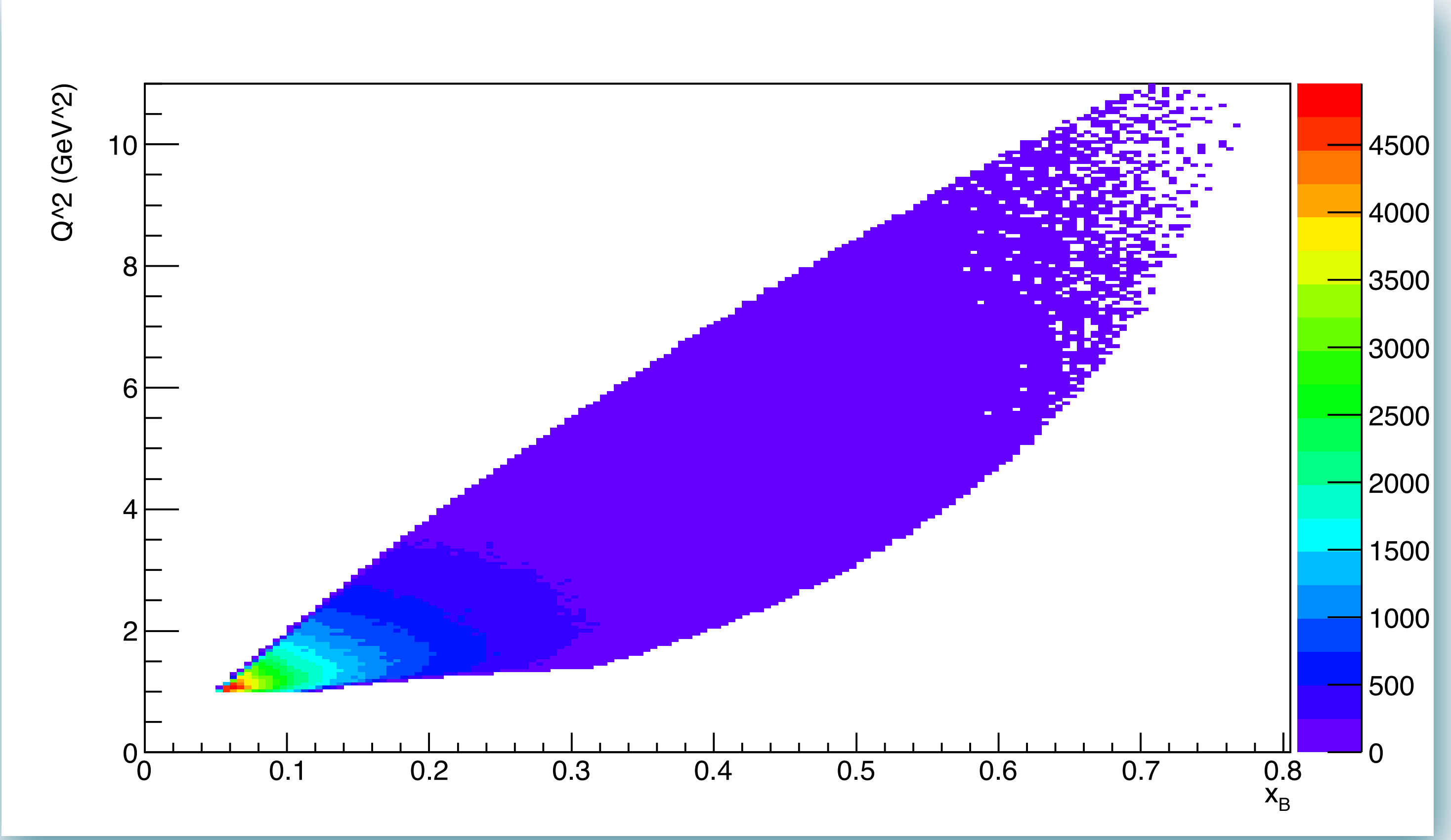


Figure 14: Q^2 vs. x_B for the final di-hadron sample.

SIDIS CROSS SECTION

$$\frac{d\sigma}{dx\,dy\,dz\,d^2\mathbf{P}_{h\perp}} \propto \frac{4\pi\alpha_{elm}^2 s}{Q^4} \sum_a e_a^2 x \left\{ \cdots + (1-y) \frac{|\mathbf{P}_{h\perp}|}{M_h} |\mathbf{S}_\perp| \sin(\phi_S + \phi_h)\, h_1(x) H_1^\perp(z, \mathbf{P}_{h\perp}^2) + \cdots \right\}$$

1 process
a convolution

↔

2 nonperturbative functions

- **h_1 for the parton distribution**
- **$H_1^\perp$ for the fragmentation**

No clean extraction of DISTRIBUTION part without INDEPENDENT process for the FRAGMENTATION PART!!

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1 process
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⟷

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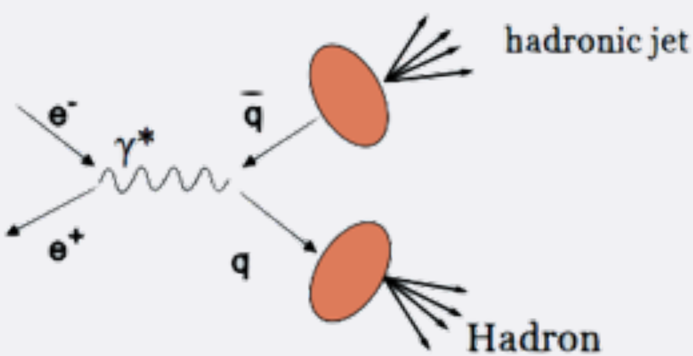
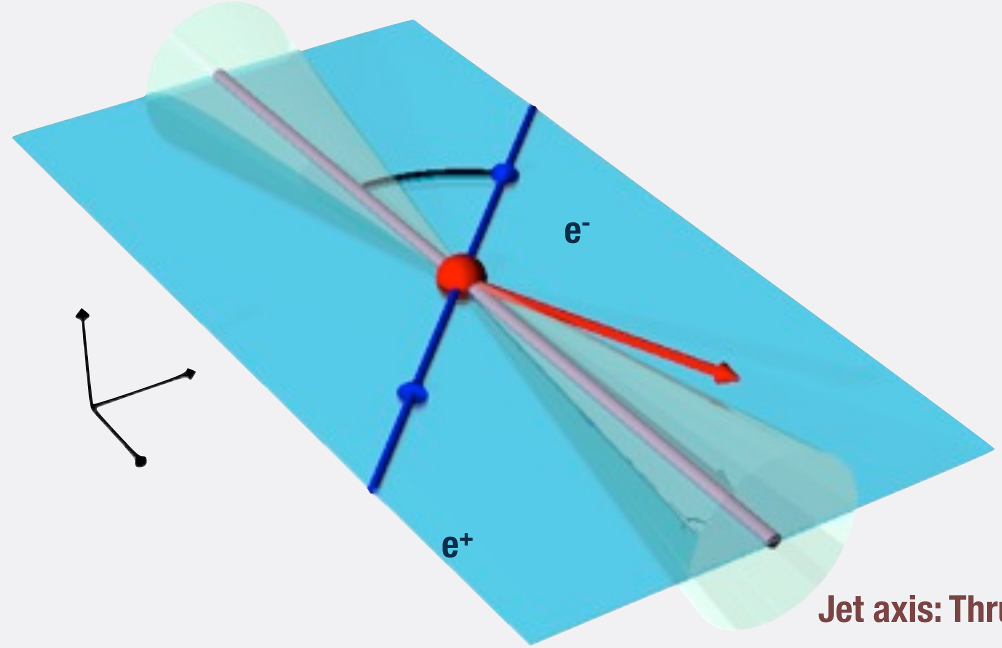


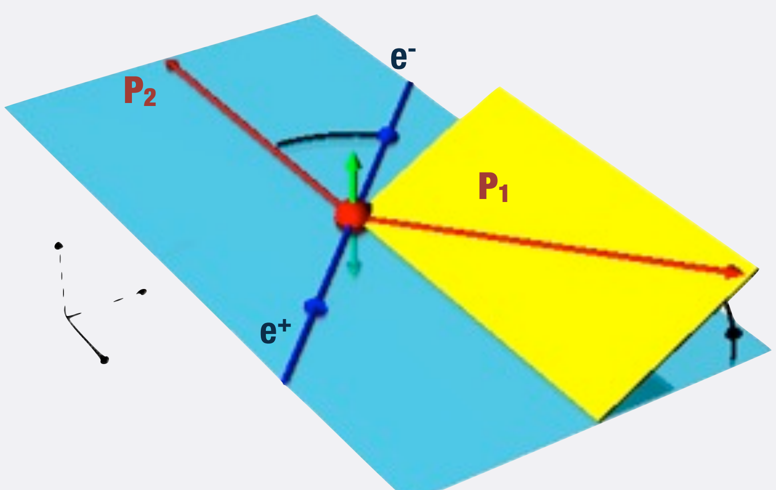
FRAGMENTATION FUNCTIONS are accessed in e+e- annihilation

FRAGMENTATION IN ELECTRON-POSITRON ANNIHILATION



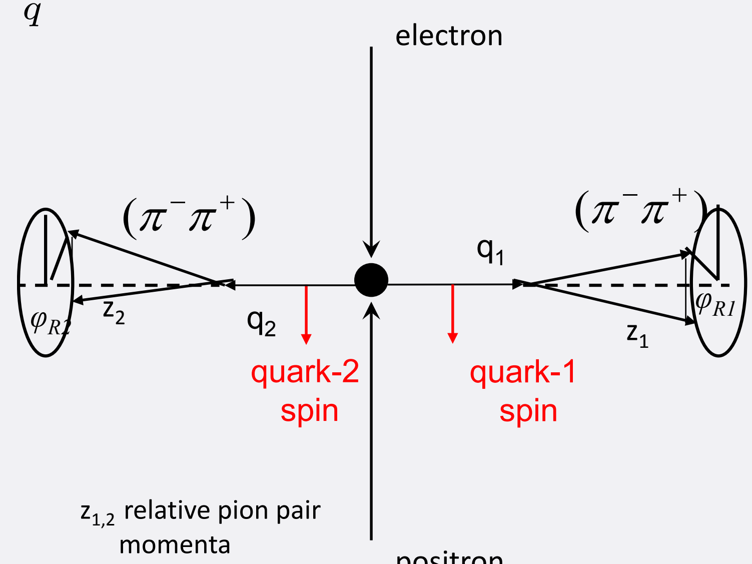
Transverse mmt dep.

$$d\sigma \propto \sum_q \left[\mathrm{FF}^q \otimes \mathrm{FF}^{\bar{q}}\right](z_1, z_2, \mathbf{P}_{1\perp}, \mathbf{P}_{2\perp})$$



Collinear

$$d\sigma \propto \sum_q \mathrm{FF}^q(z_1, M_{h1}) \otimes \mathrm{FF}^{\bar{q}}(z_2, M_{h2})$$

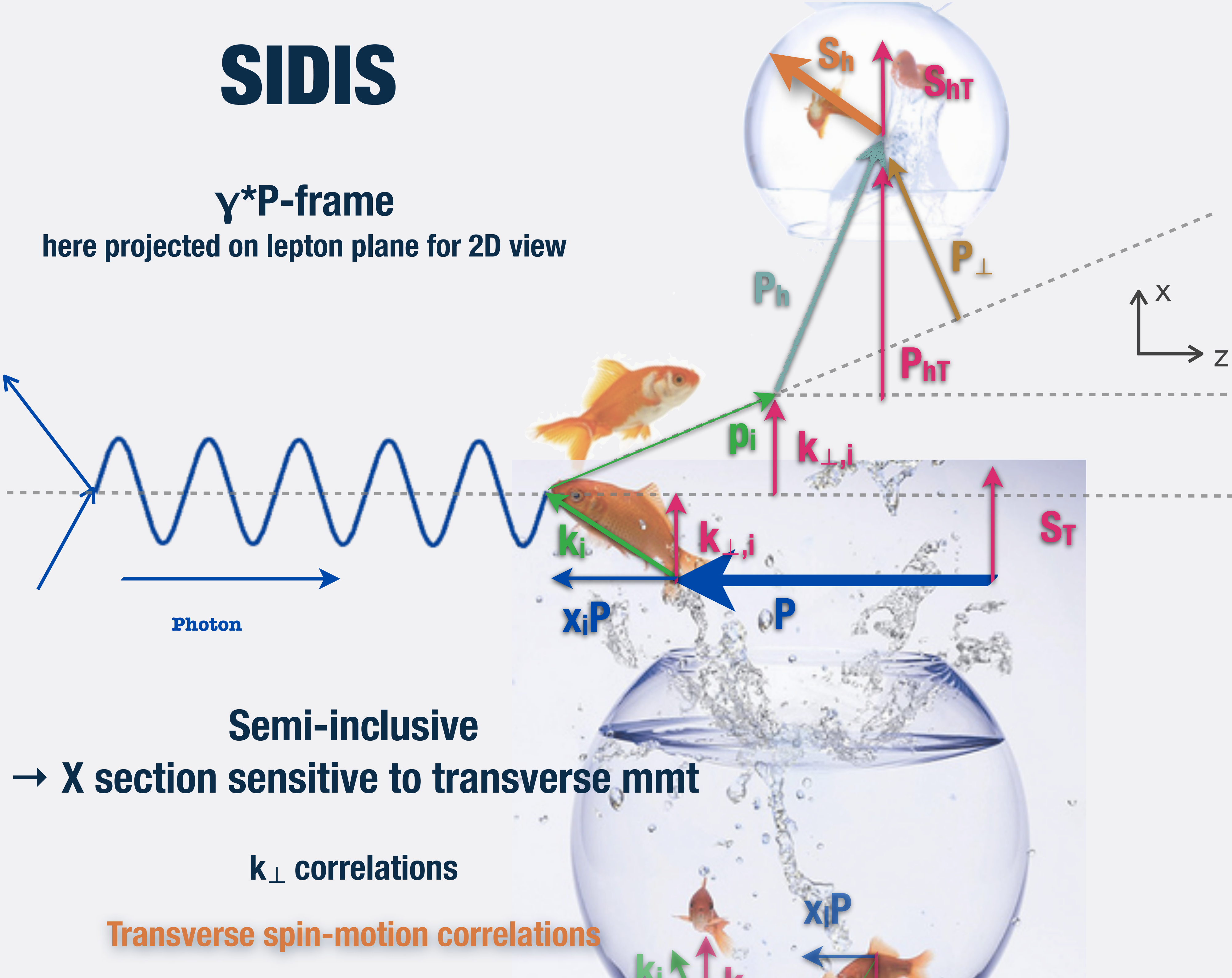


Courtesy of Anselm Vossen

SIDIS

γ*P-frame

here projected on lepton plane for 2D view



Semi-inclusive

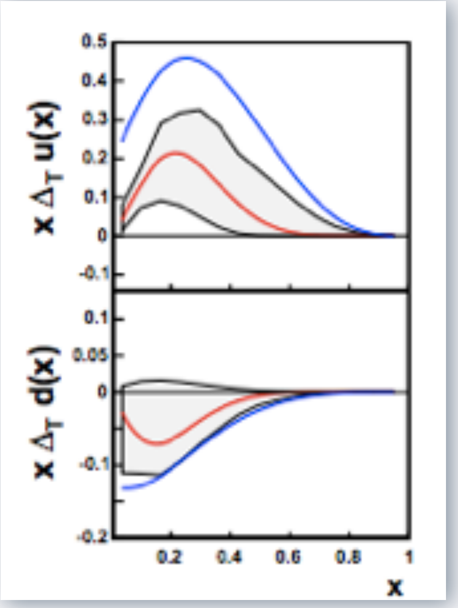
→ X section sensitive to transverse mmt

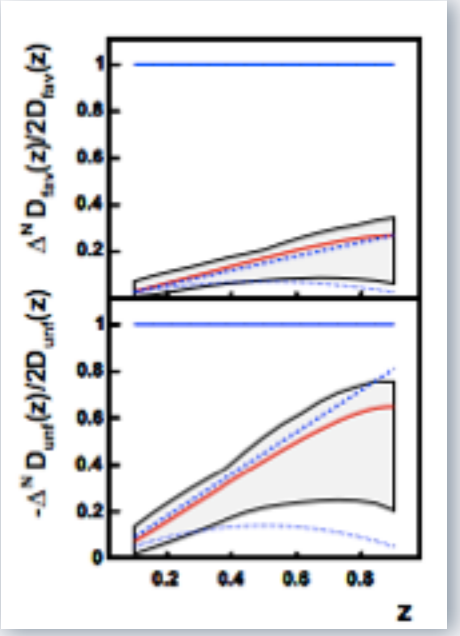
$k_\perp$ correlations

Transverse spin-motion correlations

INTERPLAY & COLLABORATION BETWEEN TWO FIELDS

- **2007:** first success of a great collaboration
- First global fit including a CHIRAL-ODD PDF
- Anselmino et al. "*Transversity and Collins functions from SIDIS and e⁺ e⁻ data*"





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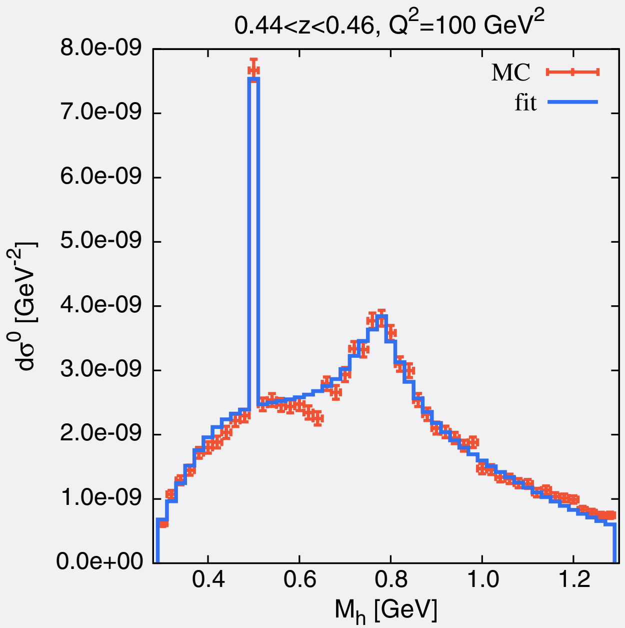
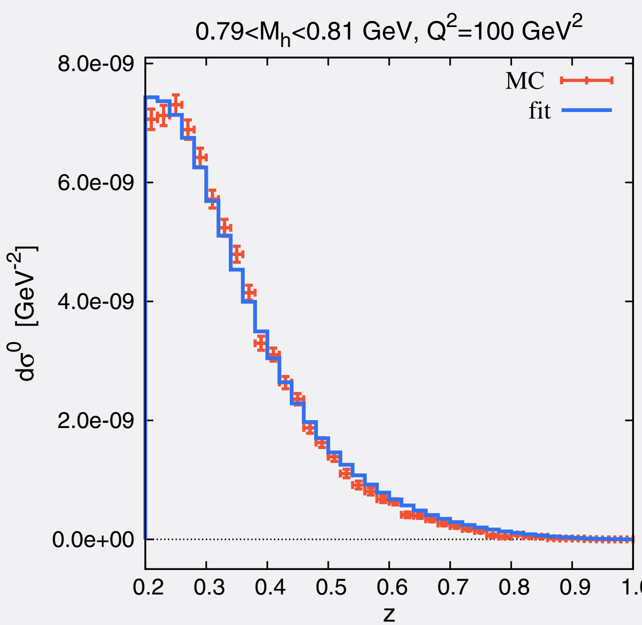
- We had to make up for the lack of hadron multiplicities...

- **2011:** we manage to fit the unpolarized FF





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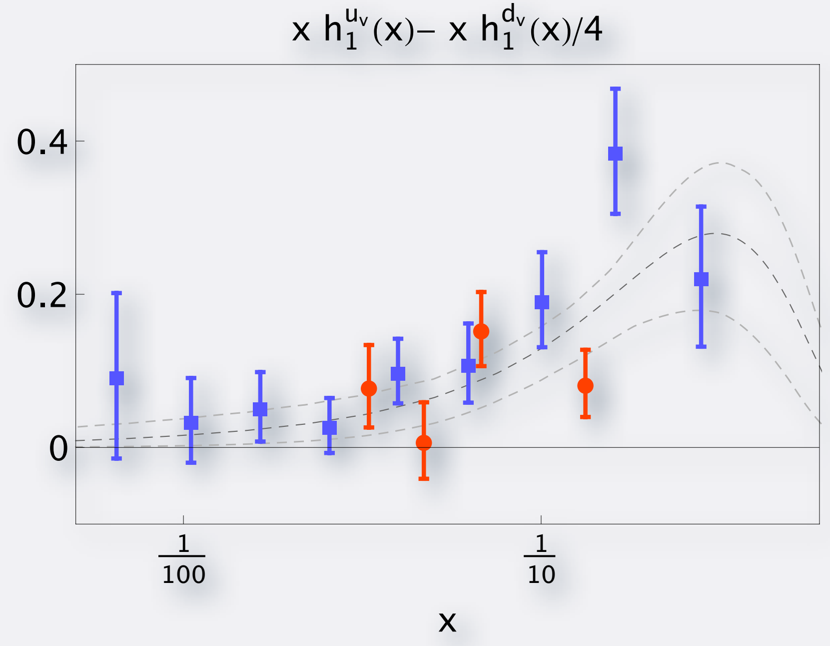
- **2011-now:** fits for valence distributions, improvement of statistical techniques, proposals for more measurements, ...



[Bacchetta,AC,Radici, PRL107]

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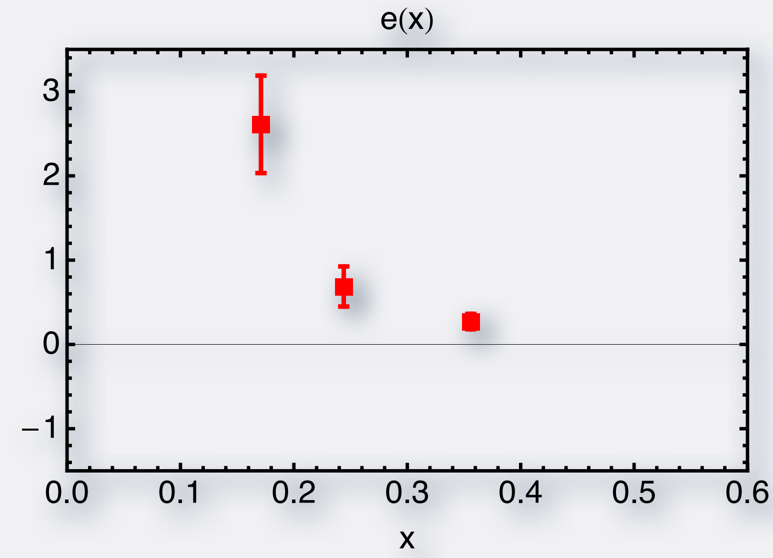

[AC,Avakian,Mirazita,Pisano, arXiv:1405.7659]

- **2013-now:** subleading-twist
- first EXTRACTION of a subleading PDF
- e(x) related to the nuclear SCALAR CHARGE & Sigma pion-nucleon

- **2015-6?:** publish CLAS analysis & extraction!

MANPOWER LIMITING PROGRESS

- Very FEW Belle members dedicated to hadronic physics (~5-6)
- Same for BaBar (~1-2)

- Lack of interest from the e^+e^- community

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Study of Fragmentation Functions in e^+e^- Annihilation

Mauro Anselmino,[1] Harut Avakian,[2] Alessandro Bacchetta,[3] Aurore Courtoy,[4] Abhay Deshpande,[5] Renee Fatemi,[6] Leonard Gamberg,[7] Haiyan Gao,[8] Matthias Grosse Perdekamp,[9] Zhong-Bo Kang,[10] Sebastian Kuhn,[11] John Lajoie,[12] Hrayr Matevosyan,[13] Andreas Metz,[14] Zein-Eddine Meziani,[14] Akio Ogawa,[15] Silvia Pisano,[16] Alexei Prokudin,[2] Marco Radici,[17] Ted Rogers,[18] Patrizia Rossi,[2] Ami Rostomyan,[19] Peter Schweitzer,[20] Anselm Vossen,[21] and Feng Yuan[22]

NSAC white paper

SCALAR CHARGE

Theoretically and experimentally chalenging

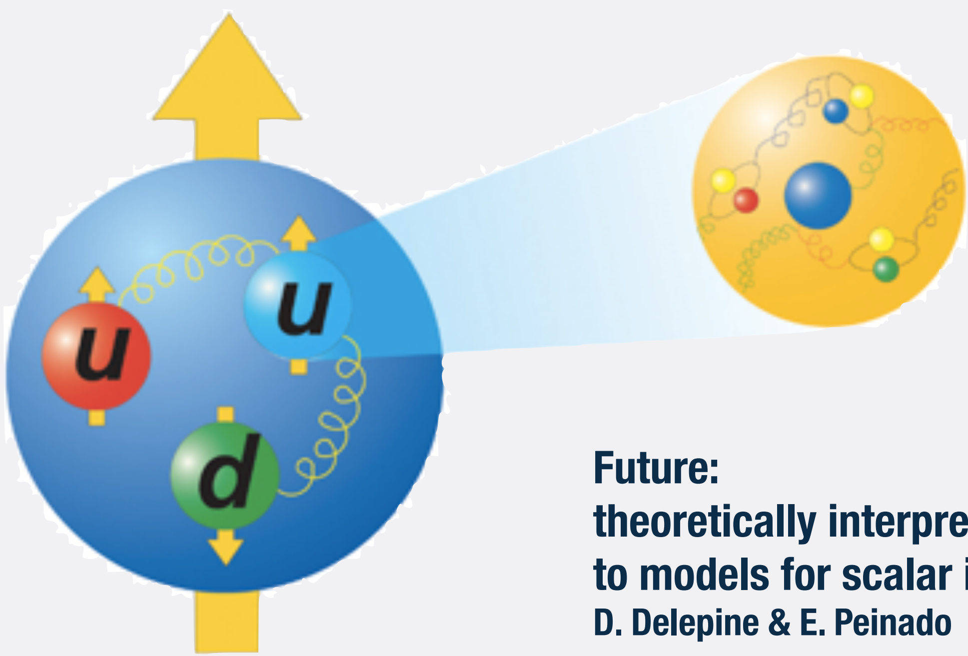
$$\int_{-1}^{1} dx\, e^q(x,Q^2) = \int_{-1}^{1} dx\, e^q_{\rm loc}(x,Q^2) = \frac{1}{2M}\langle P|\bar{\psi}_q(0)\psi_q(0)|P\rangle(Q^2) = \sigma_q(Q^2)$$

$$\sigma_u(Q^2) + \sigma_d(Q^2) \equiv \frac{\sigma_{\pi N}}{\left(m_u(Q^2)+m_d(Q^2)\right)/2}$$

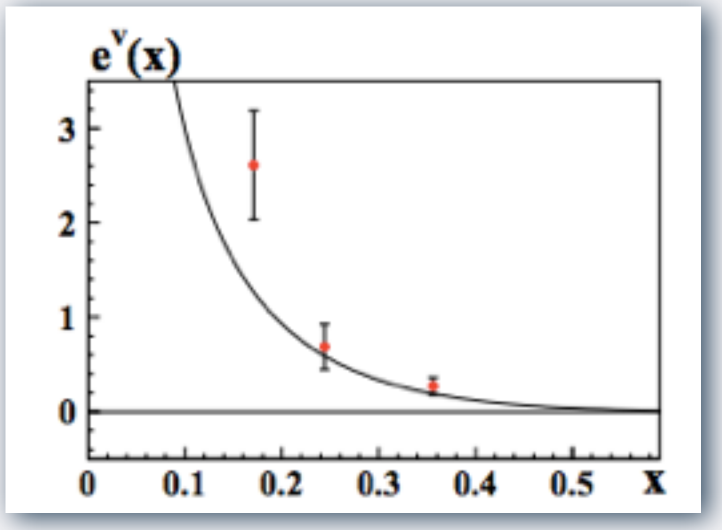
pion-nucleon sigma-term

$$\sigma_{\pi N} = \Sigma_{\pi N}(=79\pm 7\text{MeV}) - 15\text{MeV}$$

GWU (2002) result

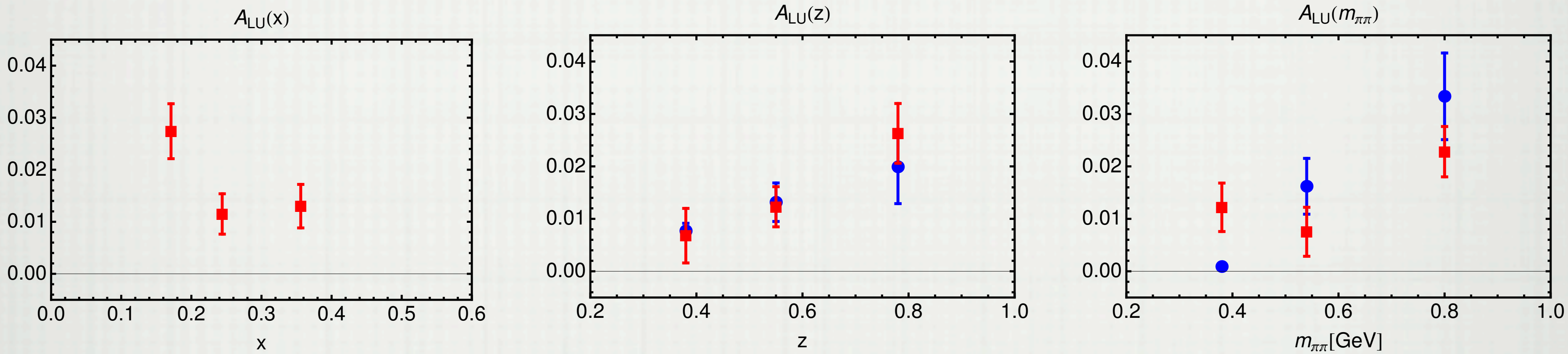


Future:
theoretically interpret & apply
to models for scalar interactions!
D. Delepine & E. Peinado



LFCQ model : Lorcé et al. [arXiv:1411.2550]

TRIPTIC OF BSA EXTRACTION



CHECK for DiFFs in z and $m_{\pi\pi}$

$$A_{LU,\text{fit}}^{\sin\phi_R}(x_i, m_{\pi\pi,i}, z_i; Q_i, y_i) = -\frac{W(y_i)}{A(y_i)}\frac{M}{Q_i}\, n_x \frac{\int_{z_{\min,i}}^{z_{\max,i}} dz \int_{(m_{\pi\pi,\min})_i}^{(m_{\pi\pi,\max})_i} \frac{|\mathbf{R}|}{m_{\pi\pi}} H_1^{\sphericalangle,u}(z, m_{\pi\pi}, Q_i^2)}{\int_{z_{\min,i}}^{z_{\max,i}} dz \int_{(m_{\pi\pi,\min})_i}^{(m_{\pi\pi,\max})_i} D_1^u(z, m_{\pi\pi}, Q_i^2)}$$

integral of x dependence guessed here~0.2

leading-twist DiFFs known from PAVIA fit

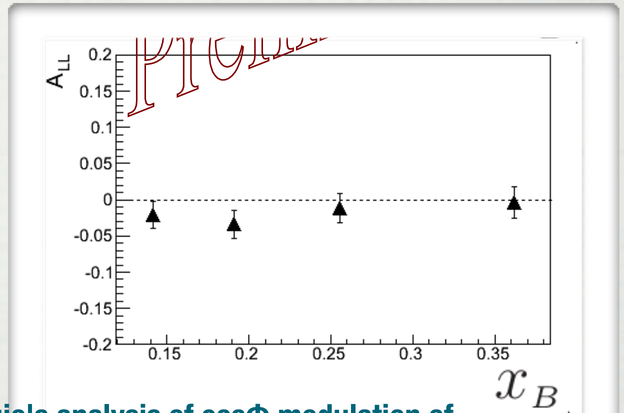
BEYOND WW

$$A_{LU}^{\sin\phi_R}\left(x_i, m_{\pi\pi\,i,}, z_i; Q_i, y_i\right) = -\frac{W(y_i)}{A(y_i)}\,\frac{M}{Q_i}\,\frac{x_i\left[e^V(x_i,Q_i^2)\right] n_{u,i}^{\uparrow}(Q_i^2) + \left[f_1^V(x_i,Q_i^2)\right]/z_i\; n_{u,i}^{\tilde G^{\triangleleft}}(Q_i^2)}{\sum_{q=u,d,s} e_q^2\, f_1^q(x_i,Q_i^2)\, n_{q,i}(Q_i^2)}$$

Twist-3 DiFFs from DSA?

$$F_{LL}^{\cos\phi_R} = -\sum_q e_q^2\, x \frac{|R|\sin\theta}{Q}\,\frac{1}{z}\, g_1^q(x)\, \widetilde{D}^{\triangleleft\, q}\left(z, \cos\theta, m_{hh}\right)$$

$$\boxed{n_u^{\widetilde{G}^{\triangleleft}}(Q_i^2) \overset{\text{assump.}}{\equiv} n_u^{\widetilde{D}^{\triangleleft}}(Q_i^2) \cong \kappa\, n_u^{\uparrow}(Q_i^2)}$$



Sergio's analysis of cosΦ modulation of DSA

From DSA we estimate an upper limit with κ=0.2

- **PDF part /z~0.7**
- **Q x D_1 part~1.**
- **$H_1^{\sphericalangle}$ part~0.2**

BEYOND WW

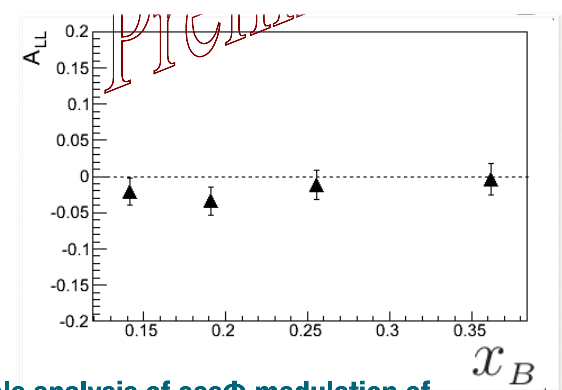
$$A_{LU}^{\sin\phi_R}(x_i, m_{\pi\pi\,i}, z_i; Q_i, y_i) = -\frac{W(y_i)}{A(y_i)}\,\frac{M}{Q_i}\,\frac{x_i\left[e^V(x_i,Q_i^2)\right] n_{u,i}^{\uparrow}(Q_i^2) + \left[f_1^V(x_i,Q_i^2)\right]/z\; n_{u,i}^{\tilde{G}^{\sphericalangle}}(Q_i^2)}{\sum_{q=u,d,s} e_q^2\, f_1^q(x_i,Q_i^2)\, n_{q,i}(Q_i^2)}$$

higher-twist DiFFs unknown

Twist-3 DiFFs from DSA?

$$F_{LL}^{\cos\phi_R} = -\sum_q e_q^2\, x\frac{|R|\sin\theta}{Q}\,\frac{1}{z}\, g_1^q(x)\, \widetilde{D}^{\sphericalangle\, q}(z,\cos\theta, m_{hh})$$

$$\boxed{n_u^{\widetilde{G}^{\sphericalangle}}(Q_i^2) \overset{\text{assump.}}{\equiv} n_u^{\widetilde{D}^{\sphericalangle}}(Q_i^2) \cong \kappa\, n_u^{\uparrow}(Q_i^2)}$$

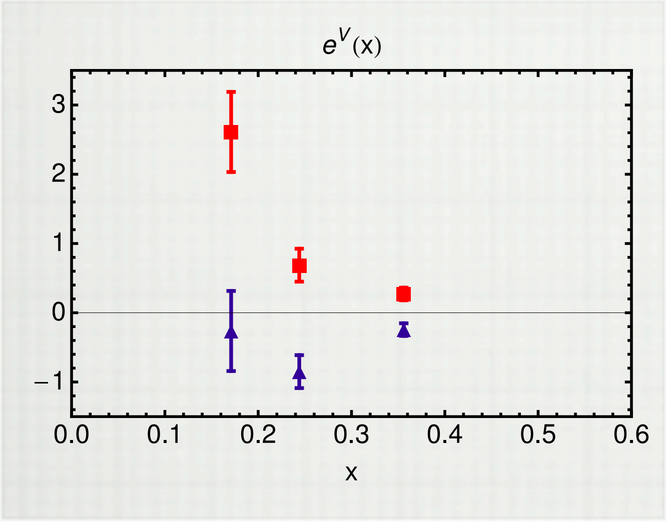


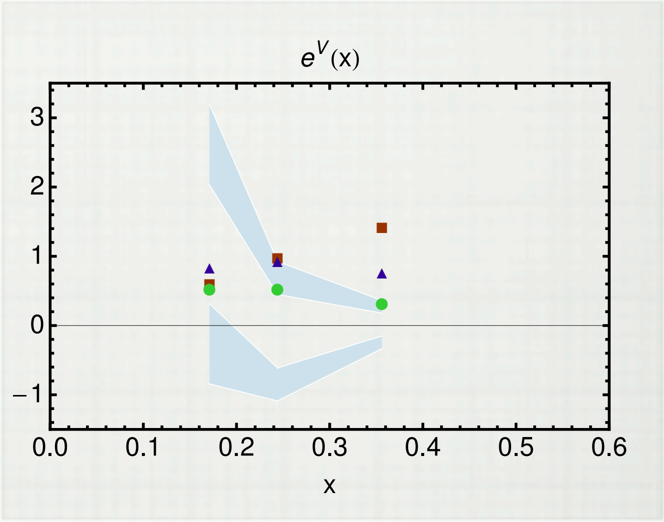
Sergio's analysis of cosΦ modulation of DSA

From DSA we estimate an upper limit with κ=0.2

- PDF part /z~0.7
- Q x D_1 part~1.
- $H_1^{\sphericalangle}$ part~0.2

BEYOND WW





- **WW**
- **second scenario**

$$A_{LU,\text{leading}}^{\sin\phi_R}(x_i, m_{\pi\pi,i}, z_i; Q_i, y_i) = -\frac{W(y_i)}{A(y_i)}\frac{M}{Q_i}\frac{\left[x_i e^V(x_i,Q_i^2) + \kappa f_1^V(x_i,Q_i^2)/z_i\right]\, n_{u,i}^{\uparrow}(Q_i^2)}{\sum_{q=u,d,s} e_q^2\, f_1^q(x_i,Q_i^2)\, n_{q,i}(Q_i^2)}$$