Spin Structure of the Nucleon: Experiment

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Content

- **Motivation**

  Precision measurements of the quark and gluon structure of the fundamental bound state of the strong interaction.

- **Helicity Structure**

- **Transverse Spin Structure**

Examples for:

Physics goals
Experimental needs
Required theory Input

A Fundamental and Old Question: What are Structure and Origin of Matter in the Universe?

Asked early: Leukipp and Demokrit (~ 450-400 BC)

→ atomic hypothesis !

There are small particles, atoms, of which all matter is made and which cannot be divided in smaller parts.

Some 80 generations later:

Modern experimental tools provide quantitative answers!

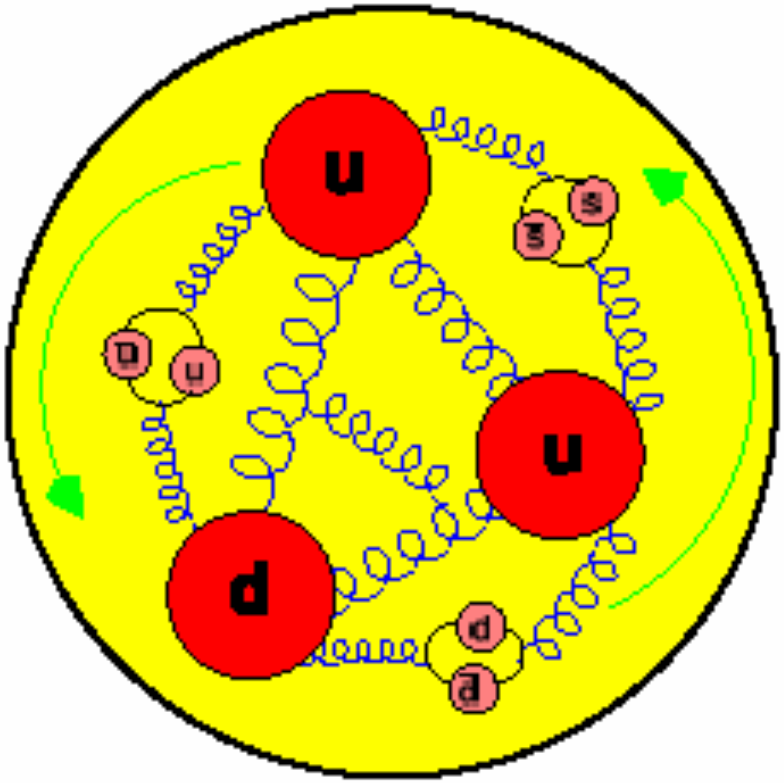
The Nucleon as QCD Laboratory

The proton is the fundamental bound state of QCD - quarks and gluons are the constituents:

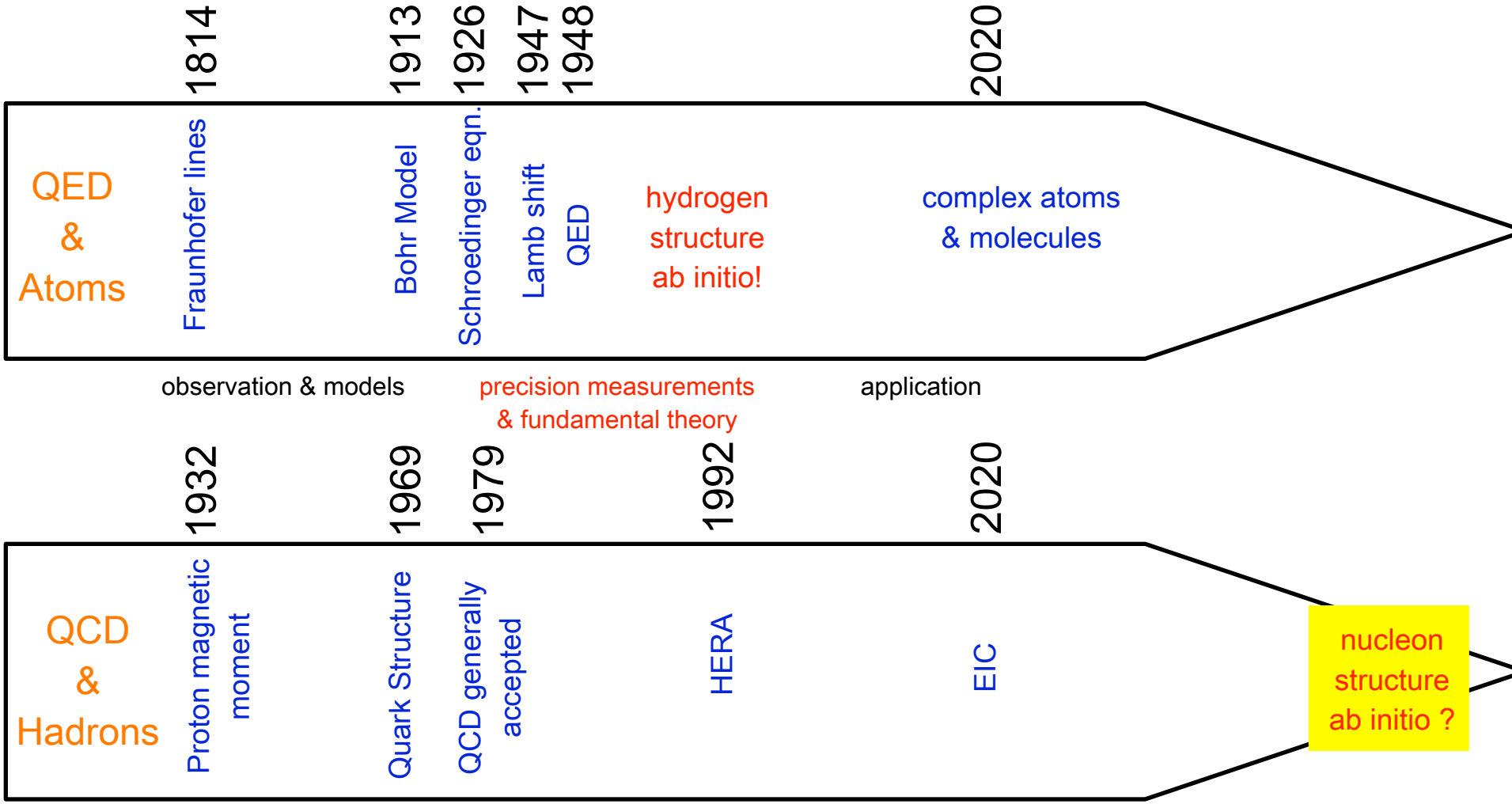
Can we understand the wave function of the nucleon from first principles QCD ?

Present (modest) status:

Description of proton in hard scattering processes with parton distribution functions (often model dependent!).



QED vs QCD


1814
1913
1926
1947
1948
2020
QED & Atoms
Fraunhofer lines
Bohr Model
Schroedinger eqn.
Lamb shift
QED
hydrogen structure ab initio!
complex atoms & molecules
observation & models
precision measurements & fundamental theory
application
1932
1969
1979
1992
2020
QCD & Hadrons
Proton magnetic moment
Quark Structure
QCD generally accepted
HERA
EIC
nucleon structure ab initio ?
observation & models
precision measurements & fundamental theory

Helicity Structure ➔ Goals

$$\frac{1}{2} = L_q + \frac{1}{2}\Delta\Sigma + L_G + \Delta G$$

Goals: (I) Precise measurements of **ΔΣ and ΔG and therefore total L_z**

present ΔΣ = 0.35 ∓ 0.06

➔ ∓ 0.01 ? (has a goal been quantified ?)

present ΔG = 0.01 ∓ 0.1 + extrapolation uncertainty

➔ ∓ 0.02 ? (has a goal been quantified ?)

QCD tests!

(II) Bjorken sumrule to 2% (factor 5 better than present) !

(III) g_1 evolution to 2%

(IV) Can L_z be directly accessed (in a model independent way)?

Helicity Structure ➔ Measurements

Inclusive:	g_1 (including evolution) and g_5 for proton and ^{3}He or d beams
Semi inclusive:	A_{LL} for identified charged pions and kaons
Exclusive:	DVCS
Jets:	A_{LL} for di-jets
Heavy flavor:	A_{LL} for D^0

➔Full acceptance detector with hadron pID capabilities, heavy flavor tagging, jet reconstruction, excellent momentum resolution, relative luminosity monitors and local polarimeters

Helicity Structure ➔ Needs & Input

Absolute polarimeter: < 2% (both beams)

Local polarimeters: < 2% (both beams)

Extrapolation uncertainties: < 2%

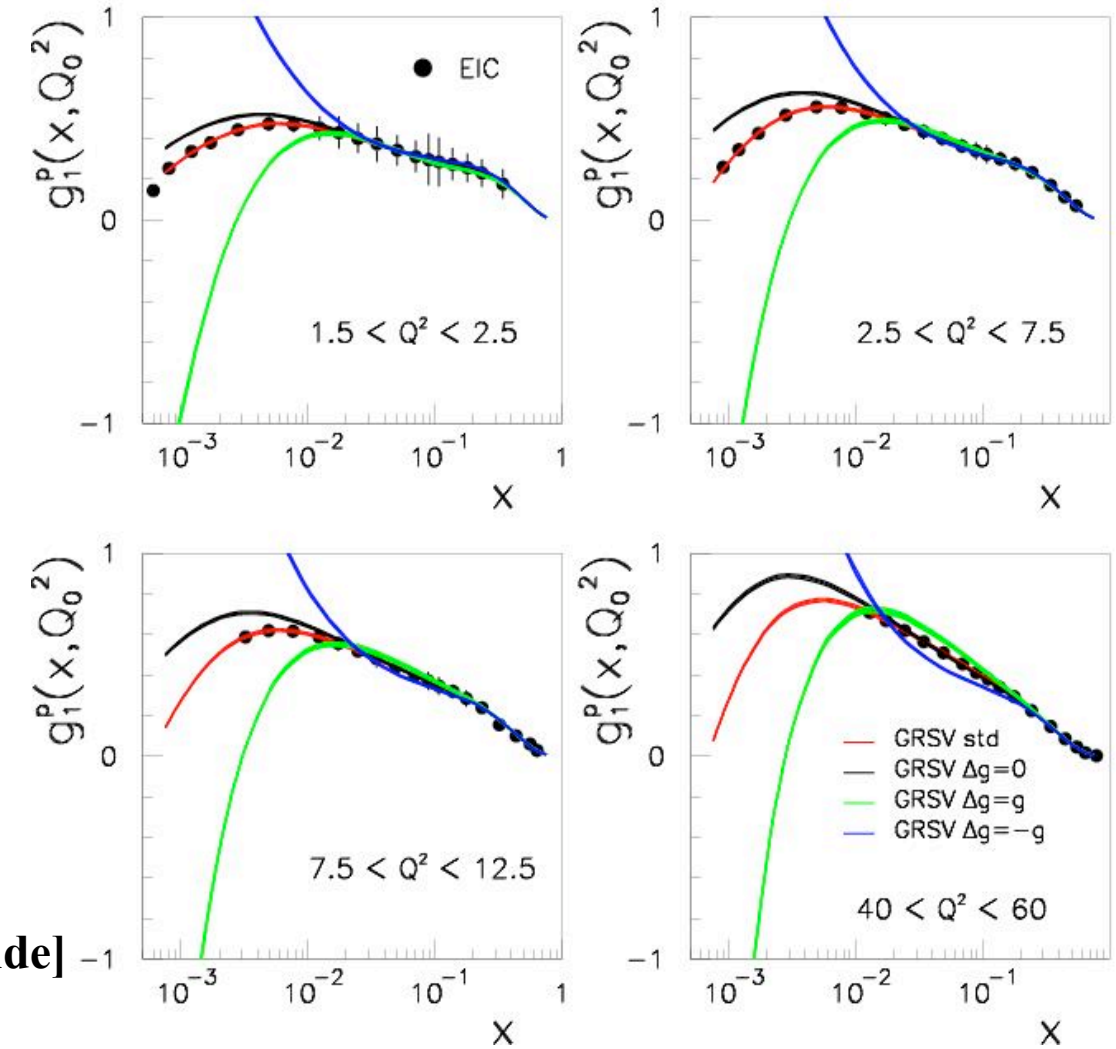
pQCD framework for PDF extraction: test with cross section
➔ normalization (luminosity) to < 2%

Fragmentation functions: need to be know to < 3%

Control of radiative corrections: < 2%

Helicity Structure ➔ g_1 at EIC

Excellent statistical resolution over a large region in Q^2 !

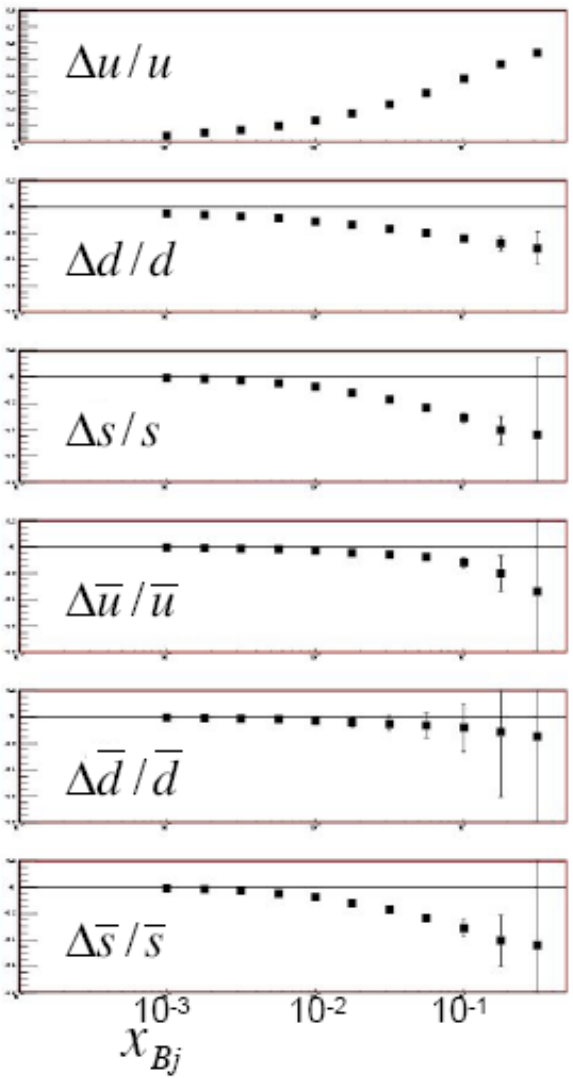


[Antje Bruell, Abhay Deshpande]

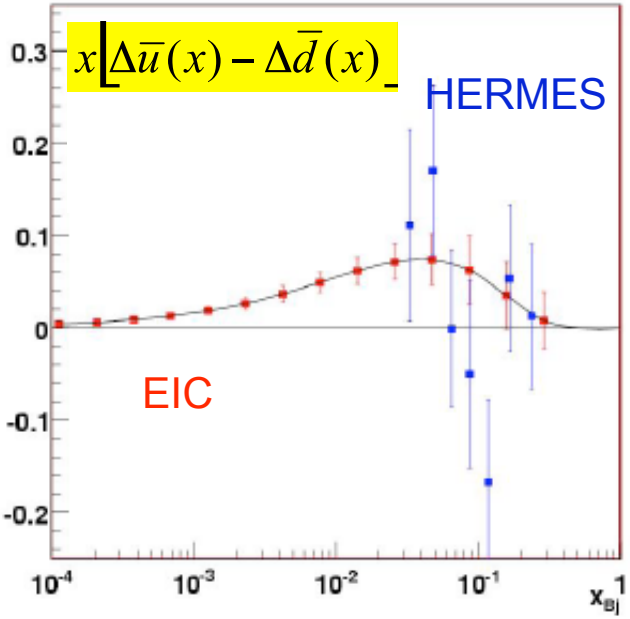
Helicity Structure ➔ SIDIS at EIC

p_e=5 GeV on p_p=50 GeV EIC projected data for 100 days at $10^{33}cm^{-2}s^{-1}$

[Ed Kinney, Joe Seele]



➔ enables study of flavor asymmetry for anti-quark helicity distributions



Excellent statistical resolution for all quark and anti-quark helicity distributions!

Fragmentation functions?

Need Hadron FFs for Studies of Quark-Gluon Structure in Hadron Production in pp and SIDIS

Example: extraction of the gluon helicity distribution from the QCD analysis of inclusive neutral pion production in polarized pp at RHIC:

$$A_{LL}^{\pi^0} \quad \text{in} \quad p^{\uparrow} + p^{\downarrow} \;®\; \pi^0 + X$$

From A_{LL} to ***ΔG(x)***

pQCD

$$A_{LL}^{\pi^0} \sim \frac{\Delta q(x_1)}{q(x_1)} \times \frac{\Delta G(x_2)}{G(x_2)} \times \hat{a}_{qg}^{qg} \times D_{q,g}^{\pi^0}(z)$$

PHENIX

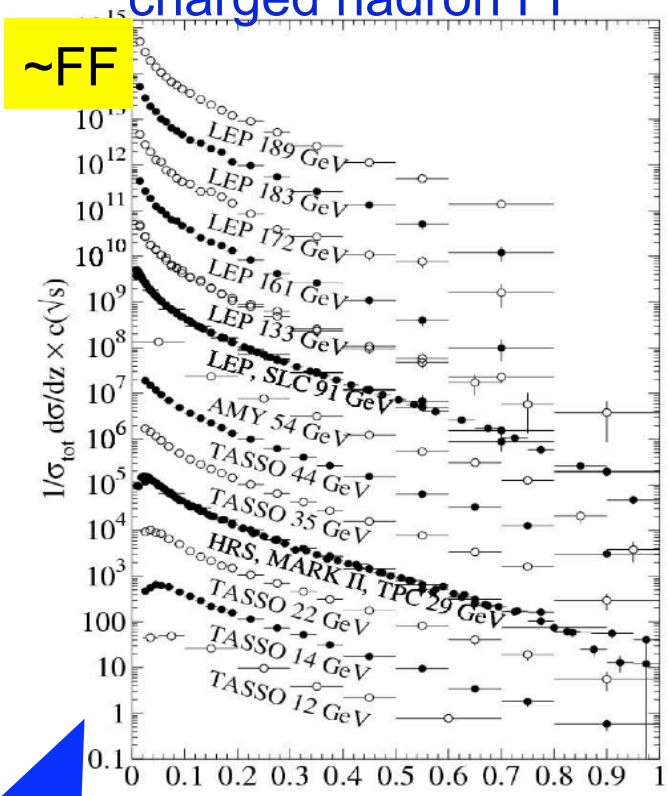
DIS

extract

FFs from e^+e^-

e^+e^- information on charged hadron FF-

~FF



$$z = \frac{E^h}{\sqrt{s}/2}$$

Need Hadron FFs for Studies of Quark-Gluon Structure in Hadron Production in pp and SIDIS

Example: extraction of the gluon helicity distribution from the QCD analysis of inclusive neutral pion production in polarized pp at RHIC:

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PHENIX

DIS

extract

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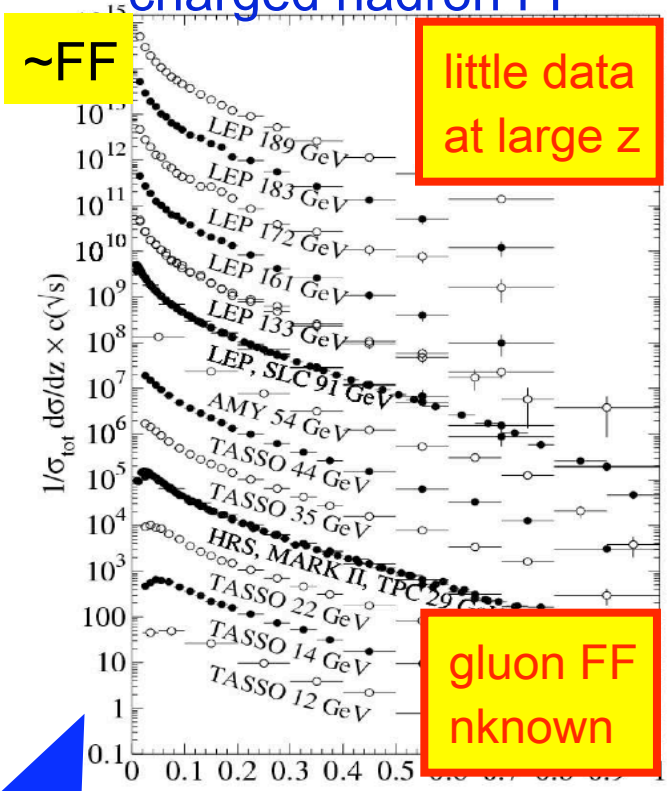
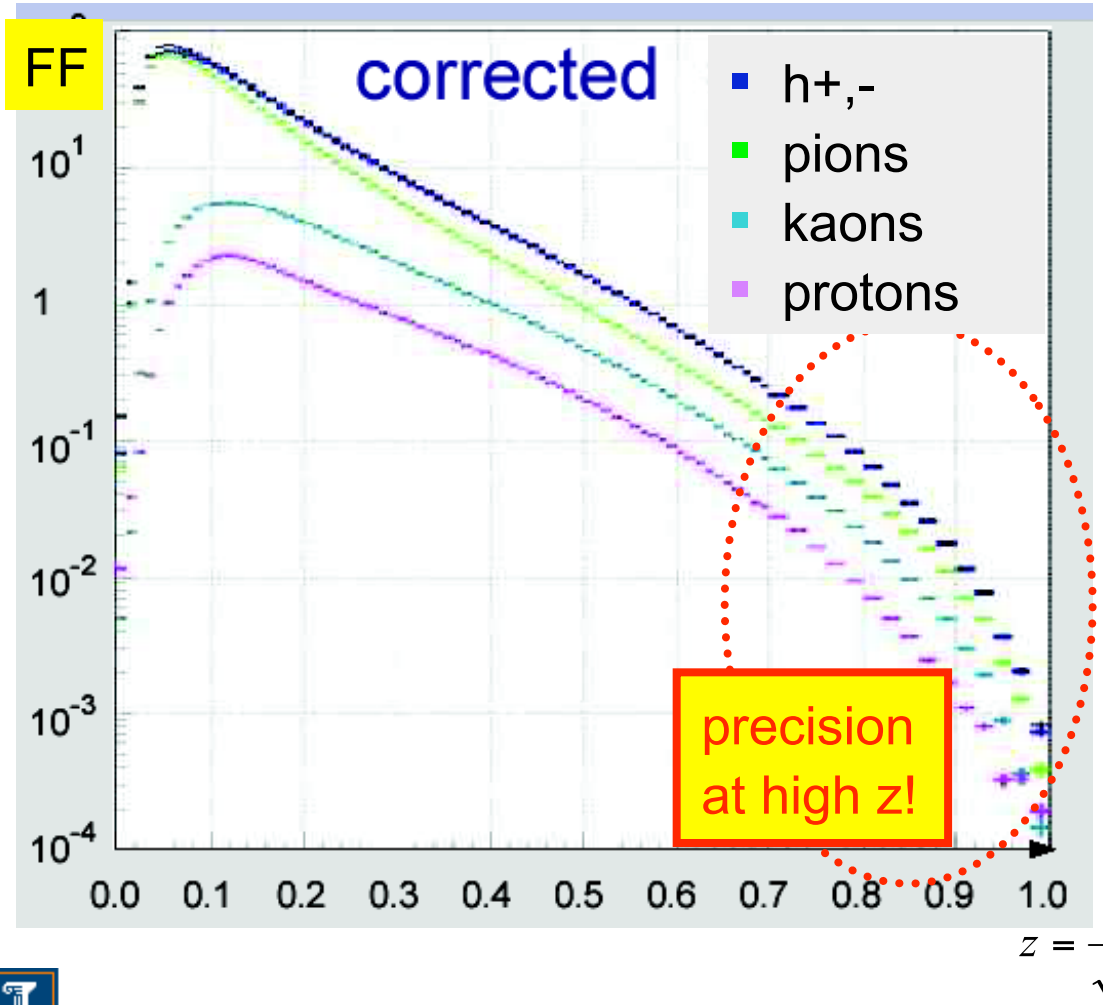
e^+e^- information on charged hadron FF-



$$z = \frac{E^h}{\sqrt{s}/2}$$

Possible Solution: Precision FF Information from e^+e^- in Belle:

Belle: Charged $h^{+/-}$, pions, kaons, protons



Belle sensitivities for identified charged hadron multiplicities (Monte Carlo projections)

$\sqrt{s}$=10.52 GeV

Inclusive hadrons
Pions
Kaons
Protons

Goal: early 2010 (UIUC/RBRC)

Helicity Structure ➔ ΔG from Charm at EIC

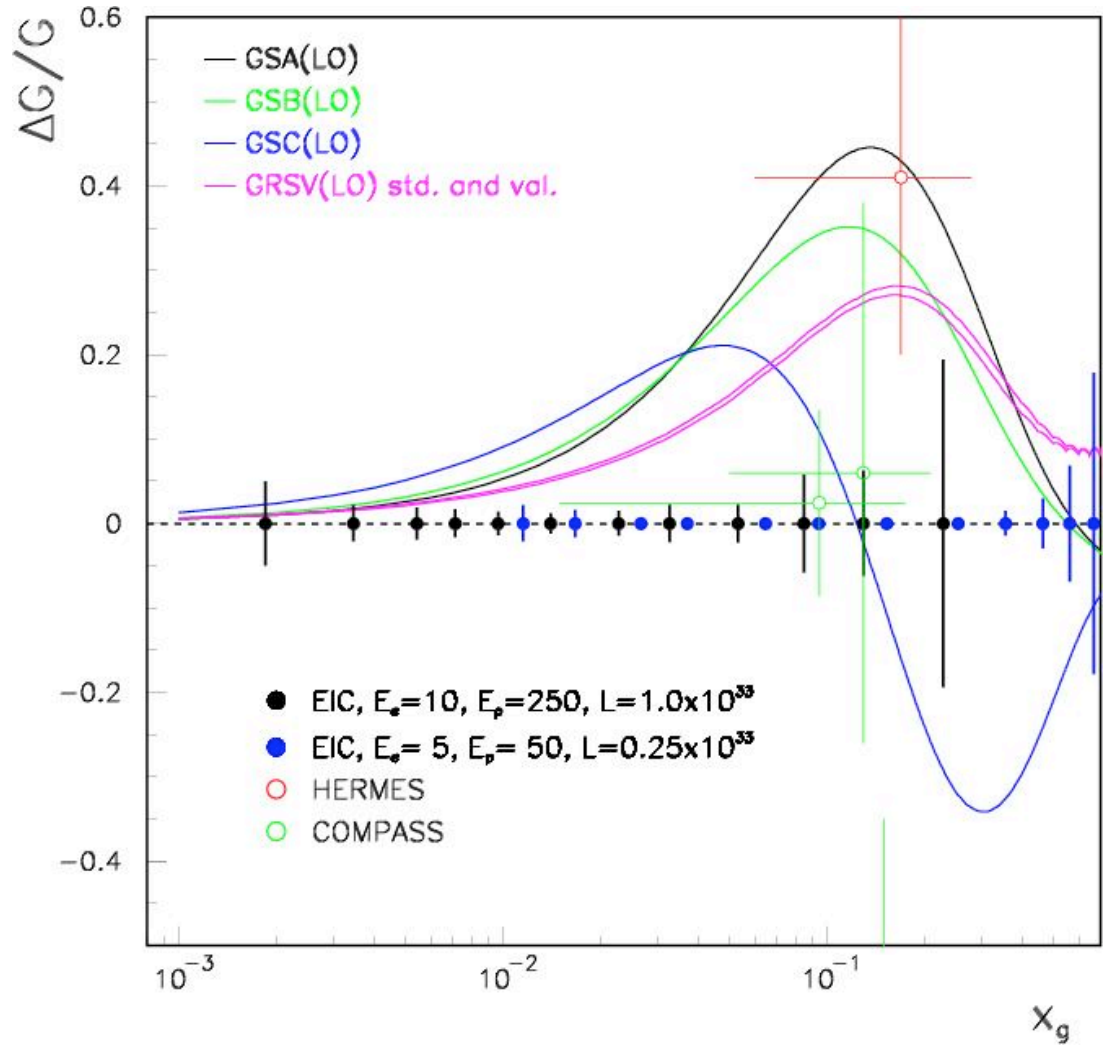
ΔG/G in e + p → D^0 + X

Requires displaced vertex resolution of 100 um

[Antje Bruell]

Excellent statistical resolution!

Also: g_1 evolution and di-jets



Sofar: Nucleon Spin Decomposition in the Infinite Momentum Frame ➔Jaffe-Manohar

$$M^{+12} = \frac{1}{2} q_+^\dagger (\vec{x} \times \vec{i}\partial)^3 q_+ + \frac{1}{2} q_+^\dagger \gamma_5 q_+ + 2\,\mathrm{Tr} F^{+j} (\vec{x} \times \vec{i}\partial) A^j + \mathrm{Tr}\epsilon^{+-ij} F^{+i} A^j$$

in $A^+ = 0$ gauge.

Each term here does have a partonic interpretation. The second term is the quark spin operator, responsible for Σ and equal to $\int_0^1 dx \Delta q(x, Q^2)$. The fourth term is the gluon spin operator in $A^+ = 0$ gauge where, remember, it is local, and it is equal to $\int_0^1 dx \Delta g(x, Q^2)$.

The other two are *convective* angular momentum in terms of the canonical quantum fields in null-plane quantum field theory.

$$\frac{1}{2} = \mathbb{L}_q + \frac{1}{2}\Sigma + \mathbb{L}_g + \Delta G$$

from Bob Jaffe, Urbana Workshop on Gluon Polariztn.

$$\frac{1}{2} = \int_0^1 dx \left\{ \mathbb{L}_q(x, Q^2) + \Delta q(x, Q^2) + \mathbb{L}_g(x, Q^2) + \Delta G(x, Q^2) \right\}$$

Alternative: Nucleon Spin Decompostion in the Rest Frame ➔ "Ji Sum Rule"

$$M^{012} = \frac{i}{2} q^\dagger (\vec{x} \times \vec{D})^3 q + \frac{1}{2} q^\dagger \sigma^3 q + 2\,\mathrm{Tr} E^j (\vec{x} \times \vec{D})^3 A^j + \mathrm{Tr}(\vec{E} \times \vec{A})^3 .$$

$$\frac{1}{2} = \hat{L}_q + \frac{1}{2}\Sigma + \hat{L}_g + \Delta\hat{G}$$

What do we learn by measuring the orbital angular momentum "here"?

from Bob Jaffe, Urbana Workshop on Gluon Polariztn.

- No parton representation for L_q, L_g, or $\Delta\hat{G}$.
- Σ is the integral of the helicity weighted quark distribution.
- But $\Delta\hat{G}$ is not the integral of the helicity weighted gluon distribution.
- L_g and L_q are not separately gauge invariant, so only the sum is meaningful.
- The "orbital angular momentum" terms are really interaction dependent quantities whose interpretation as OAM is dubious.

Generalized Parton Distributions to Access Orbital Angular Momentum …

GPDs H^u, H^d, E^u, E^d provide access to total quark contribution to proton angular momentum in exclusive processes $l + N \rightarrow l' + N + \gamma$

Proton spin sum

$$\frac{1}{2} = \underbrace{\frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q}_{J^q} + J_g$$

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Transverse Spin: Transversity vs Sivers vs Boer-Mulders

Transversity : Correlation between transverse proton spin and quark spin $\delta q(x)$

S_p– S_q – coupling

Sivers : Correlation between transverse proton spin and quark transverse momentum $\bar{f}_{1T}^{\perp q}(x, k_\perp^2)$

S_p-- L_q– coupling ?

Boer/Mulders: Correlation between transverse quark spin and quark transverse momentum $h_1^{\perp q}(x, k_\perp^2)$

S_q-- L_q– coupling ?

Transverse Spin ➔ Goals

$$\frac{1}{2} = L_q + \frac{1}{2}\int dx\left[\delta(x) + \delta\bar{q}(x)\right] + L_G$$

Bakker, Leader, Trueman

Goals: (I) Precise measurements of h_{1T} (transversity) and $f^{\perp}_{1T}$ (Sivers) to TBD%

(II) Tensor charge to TBD %

(III) h_{1T} evolution to TBD %

} (Lattice) QCD tests!

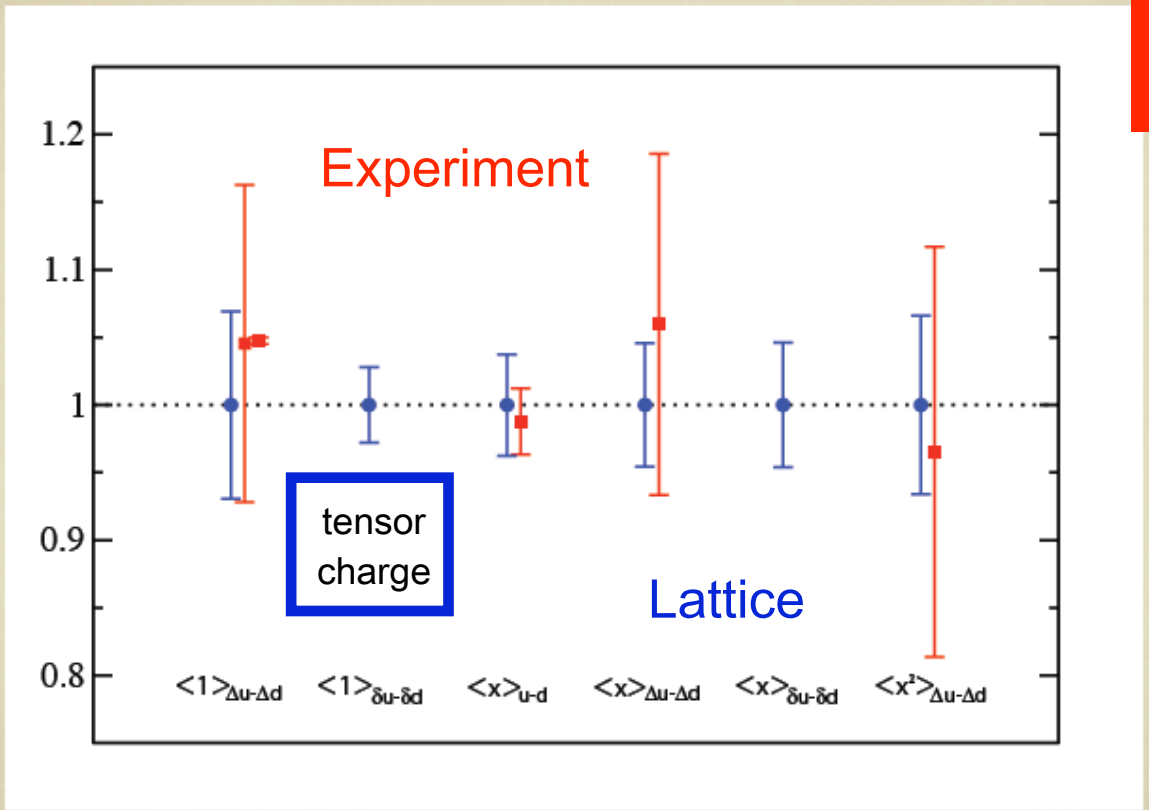
(IV) Can L_z be accessed through Sivers measurements?

Tensor Charge $g_T = \int dx\left[\delta(x) - \delta\bar{q}(x)\right]$

Lattice QCD Moments

Chiral Extrapolation of Moments

from John Negele at Urbana Workshop on Gluon Polarization



Gluon Polarization 6-16-08 J.W. Negele 38

Transverse Spin ➔ Measurements

Semi inclusive: A_{UT} Sivers, Collins and IFF asymmetries

➔Full acceptance detector with hadron pID capabilities, ~~heavy flavor tagging, jet reconstruction,~~ excellent momentum resolution, relative luminosity monitors and local polarimeters

Transverse Spin ➔ Needs & Input

Absolute polarimeter: < TBD (hadron beams)

Local polarimeters: < TBD (hadron beams)

Extrapolation uncertainties: < TBD

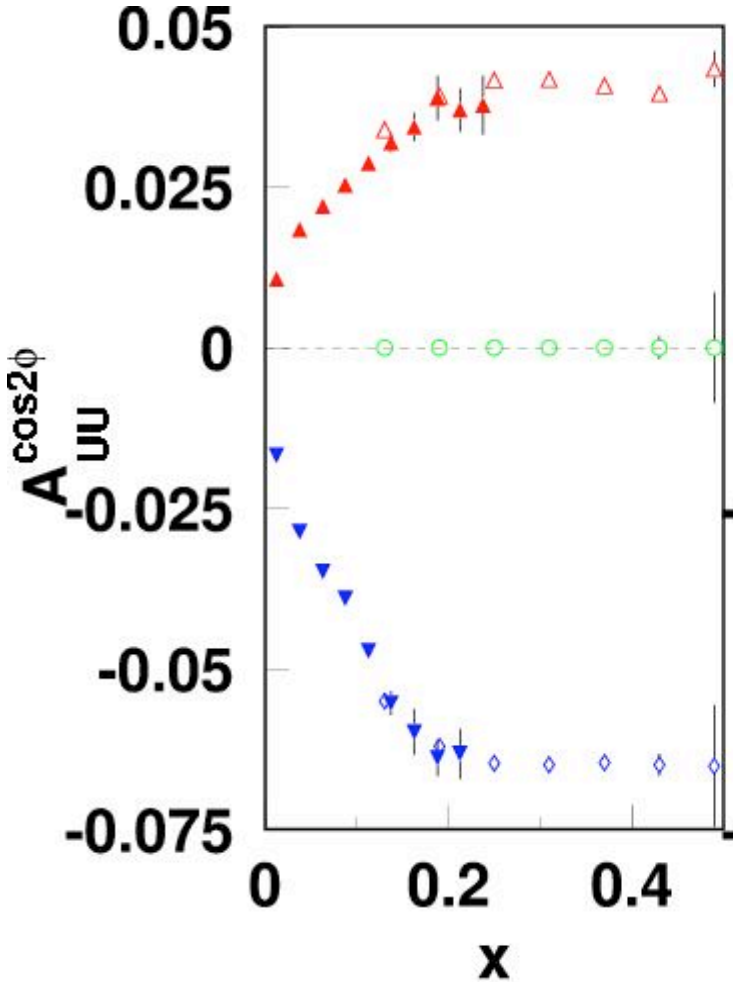
pQCD framework for PDF extraction: test with cross section
➔ normalization (luminosity) to < TBD

Fragmentation functions: need to be know to < TBD

Control of radiative corrections: < TBD

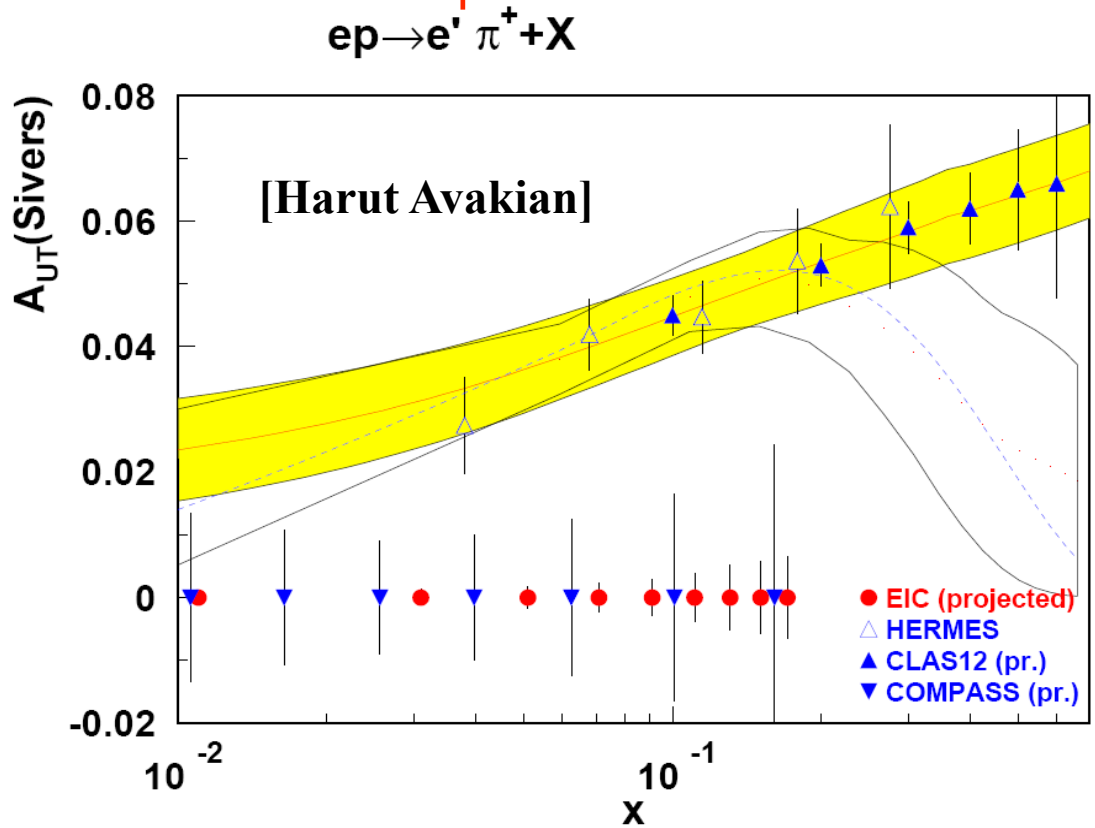
Boer Mulders $A_{UU}(\cos 2\Phi)$ and Sivers A_{UT} at EIC

[Harut Avakian, Antje Bruell]



High statistical resolution!

Link to orbital angular momentum is model dependent!



Transversity ➔ Collins A_{UT} at EIC

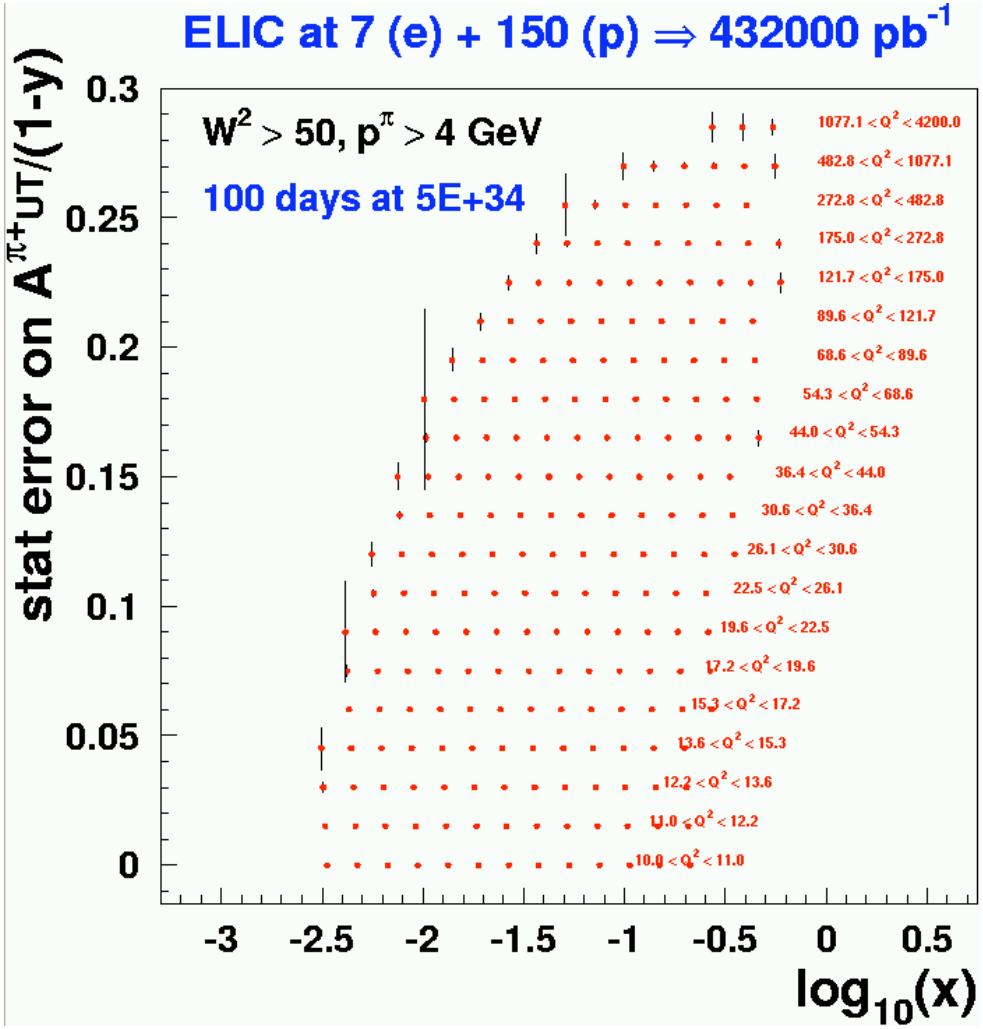
Excellent statistical resolution over a large region in Q^2 !

[Naomi Makins, Ralf Seidl]

A_{UT} ~ Transversity(x) x Collins(z)

With Collins from e^+e^- transversity can be extracted and the tensor charge can be calculated!

However, extraction relies on assumptions and alternative possibiities exist!



Plans for Transversity Extraction and

SIDIS $\Rightarrow$

transversity $\times$ Collins

SIDIS fixed target & EIC

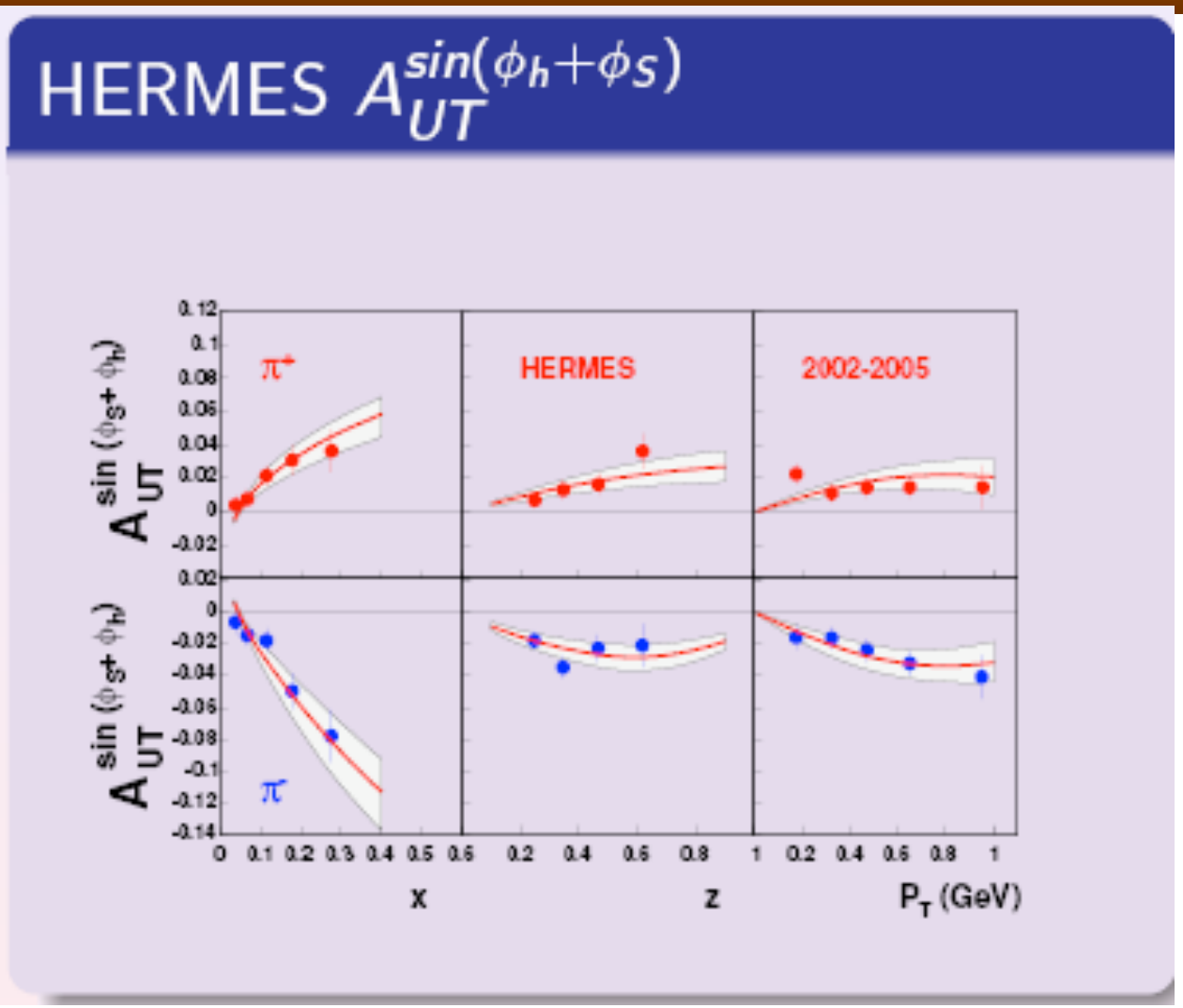
$e^+e^- \Rightarrow$ Collins FF from Belle

Theory

Transversity & Tensor Charge

Lattice QCD: Tensor Charge

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-

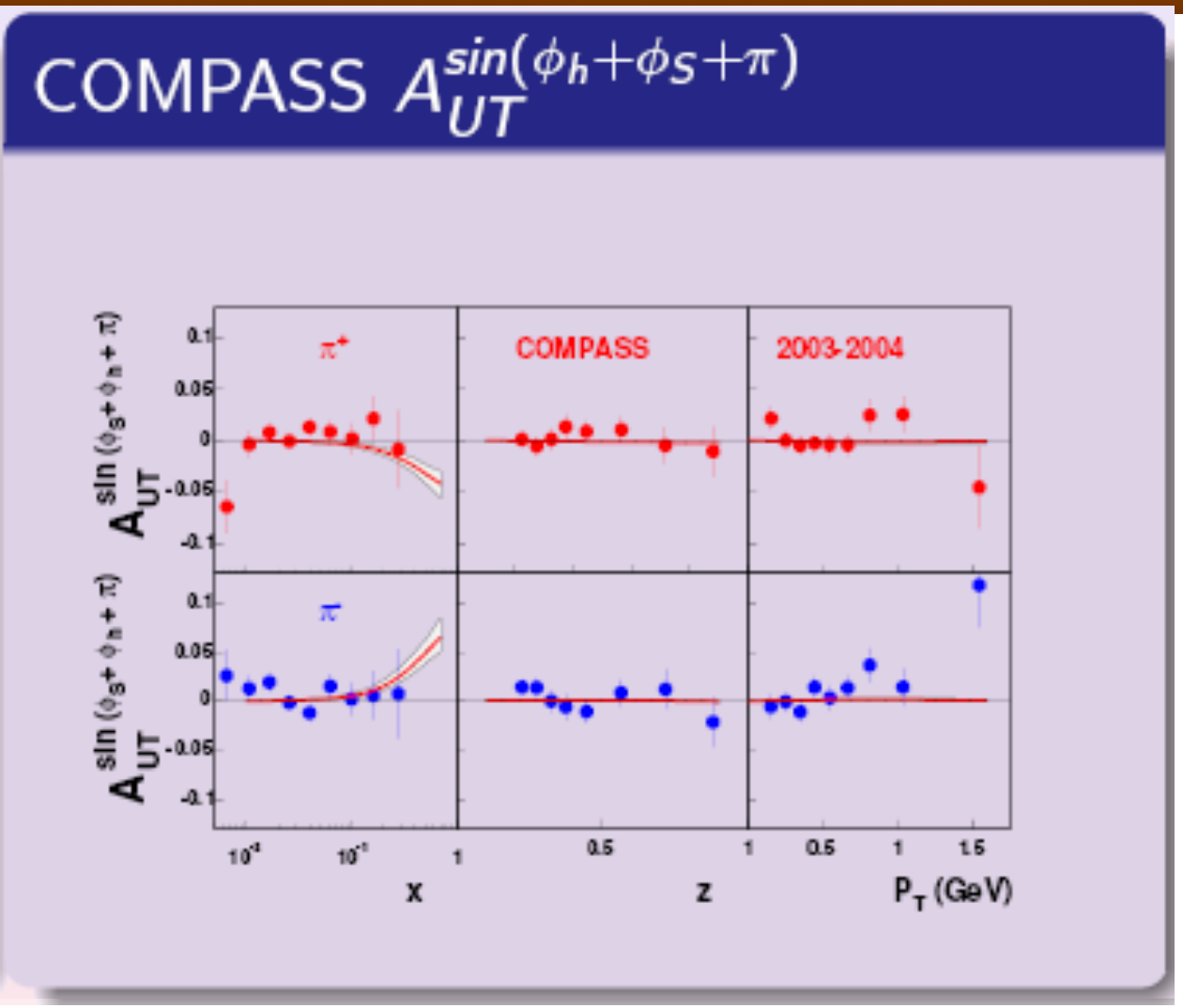


Fit includes:

HERMES SIDIS

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk and Melis at Transversity 2008, Ferrara. Previously: Phys. Rev. D75:05032,2007

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-



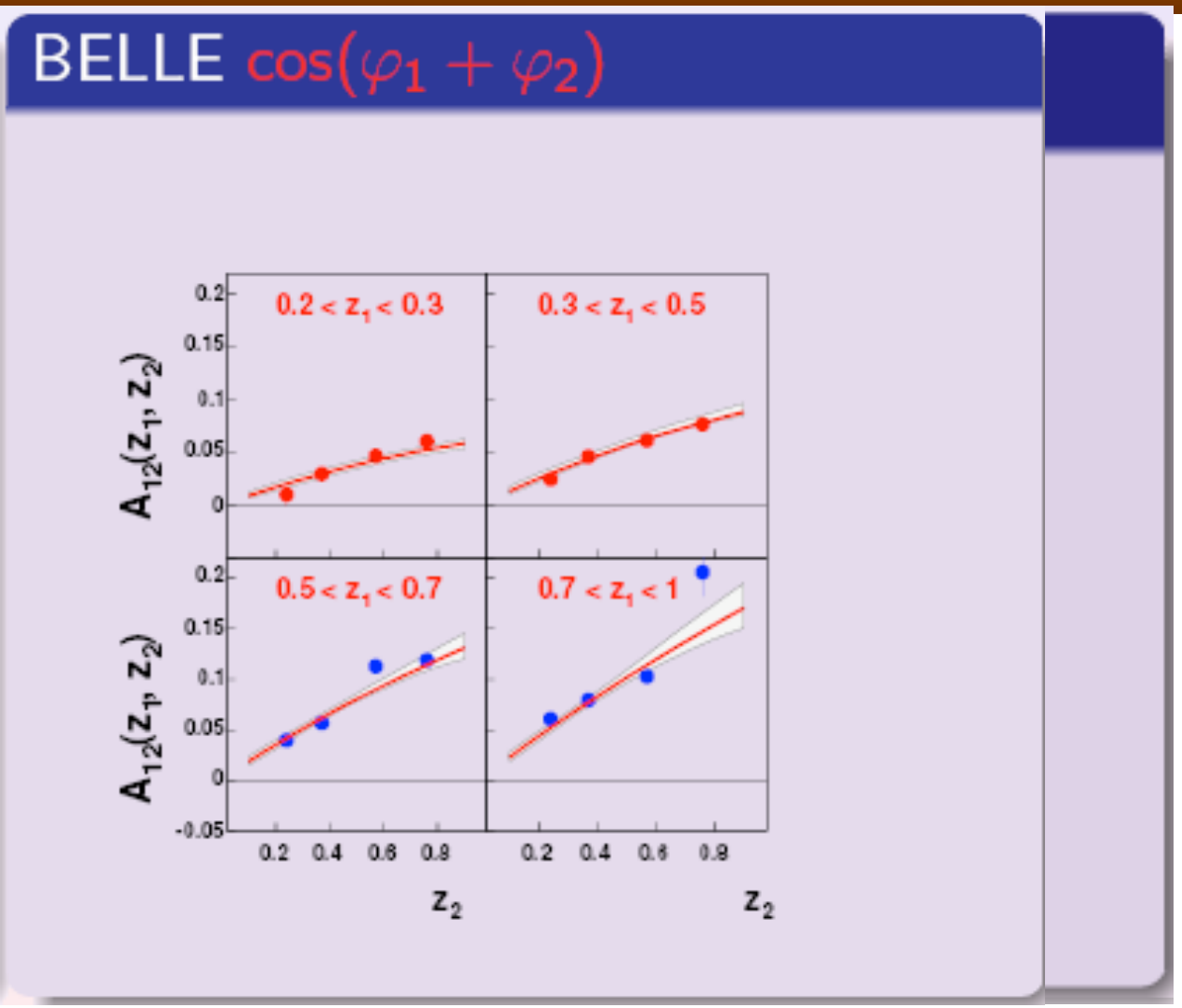
Fit includes:

HERMES SIDIS

+ COMPASS SIDIS

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk and Melis at Transversity 2008, Ferrara. Previously: Phys. Rev. D75:05032,2007

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-



Fit includes:

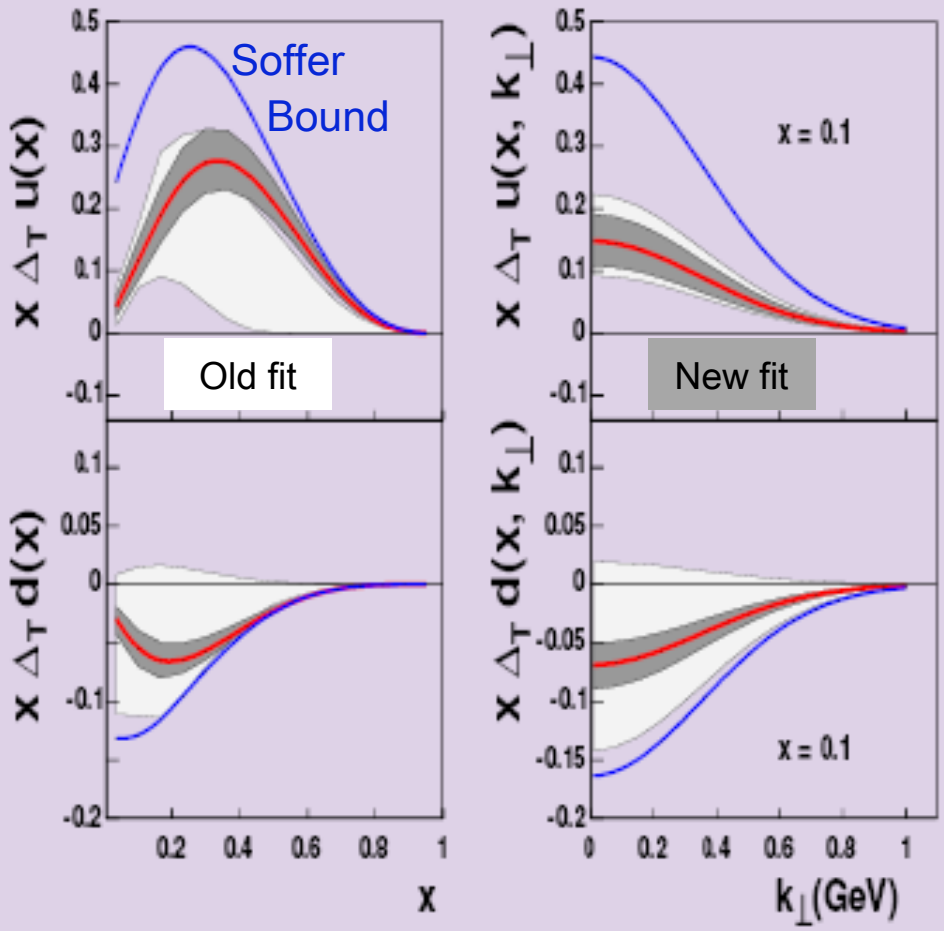
HERMES SIDIS

+ COMPASS SIDIS

+ Belle e^+e^-

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk and Melis at Transversity 2008, Ferrara. Previously: Phys. Rev. D75:05032,2007

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-



Fit includes:

HERMES SIDIS

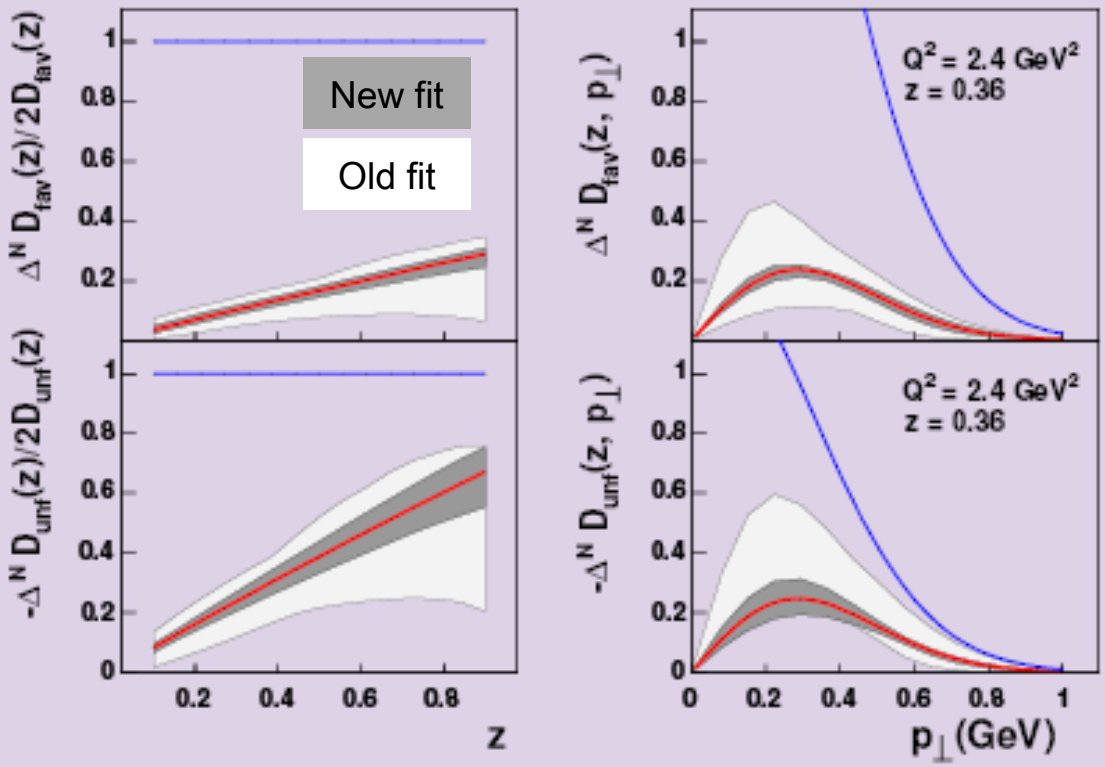
+ COMPASS SIDIS

+ Belle e^+e^-

→ transversity dist.

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk and Melis at Transversity 2008, Ferrara. Previously: Phys. Rev. D75:05032,2007

Extraction of Quark Transversity Distributions and Collins Fragmentation Functions SIDIS + e^+e^-



Fit includes:

HERMES SIDIS

+ COMPASS SIDIS

+ Belle e^+e^-

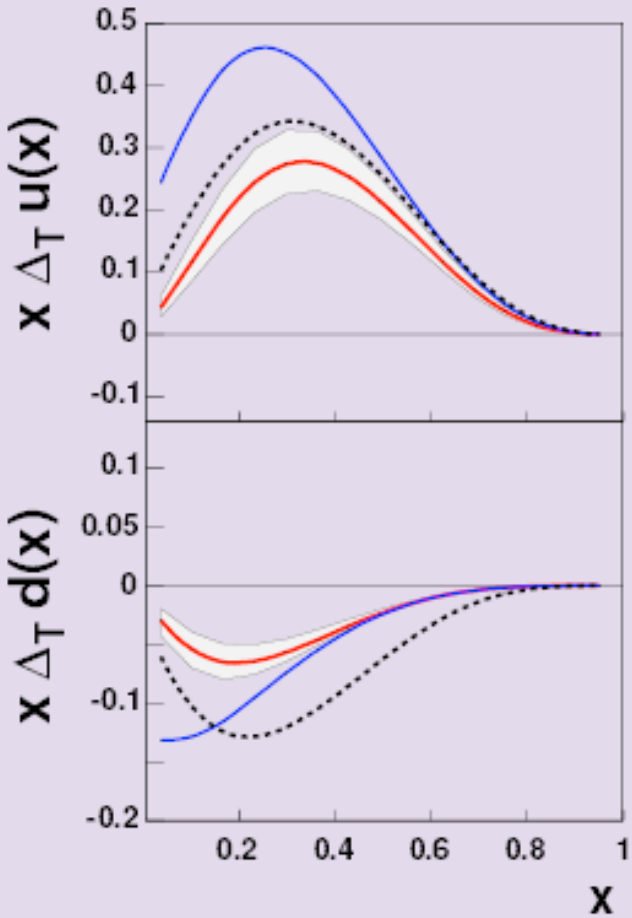
→ transversity dist.

+ Collins FF

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk and Melis at Transversity 2008, Ferrara. Previously: Phys. Rev. D75:05032,2007

Transversity vs. helicity

Prokudin et al. at Ferrara



1. Solid red line – transversity distribution

$$\Delta_T q(x)$$

this analysis at $Q^2 = 2.4$ GeV^2.

2. Solid blue line – Soffer bound

$$\frac{q(x) + \Delta q(x)}{2}$$

GRV98LO + GRSV98LO

3. Dashed line – helicity distribution

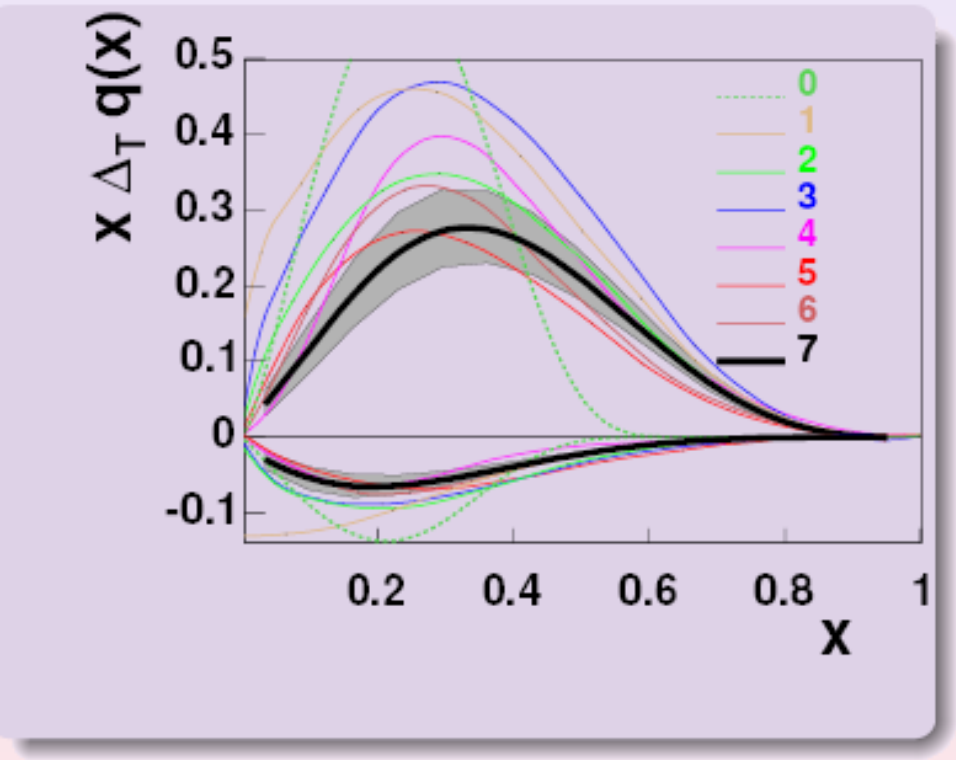
$$\Delta q(x)$$

GRSV98LO

Transversity, comparison with models

Prokudin et al. at Ferrara

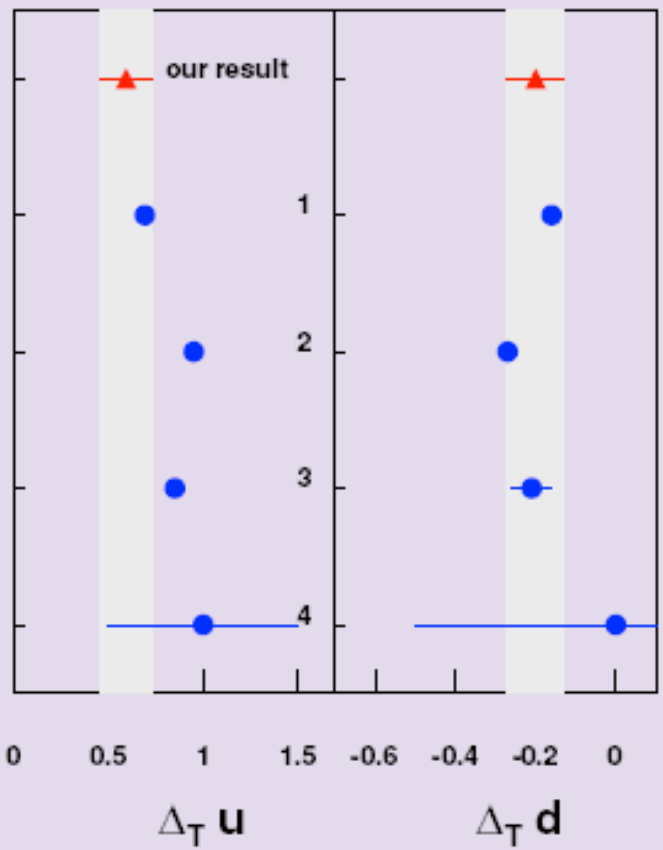
New extraction is close to most models.



0. Barone, Calarco, Drago PLB 390 287 (97)
1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 659 (08)
7. This analysis.

Tensor charges

$\Delta_T u = 0.59^{+0.14}_{-0.13}$, $\Delta_T d = -0.20^{+0.05}_{-0.07}$ at $Q^2 = 0.8$ GeV^2

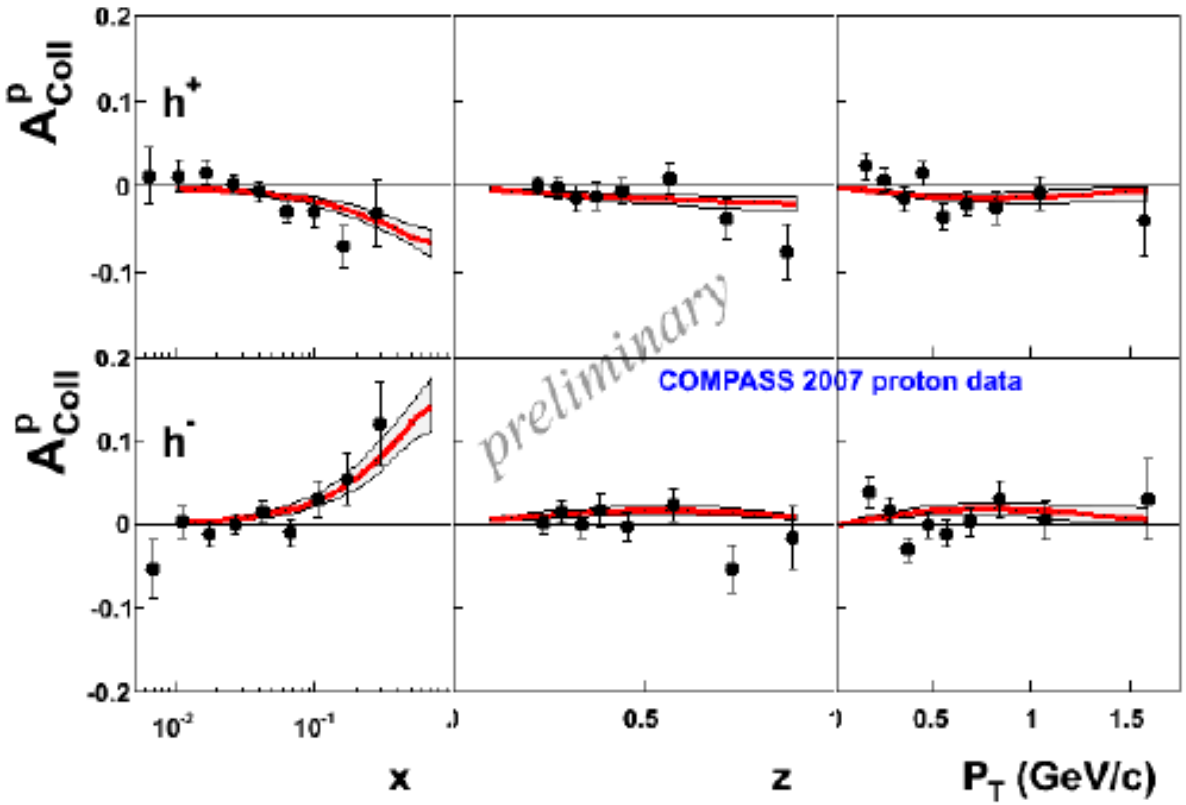


Prokudin et al. at Ferrara

1. Quark-diquark model:
   Cloet, Bentz and Thomas
   PLB **659**, 214 (2008), $Q^2 = 0.4$ GeV^2
2. CQSM:
   M. Wakamatsu, PLB B **653** (2007) 398
   $Q^2 = 0.3$ GeV^2
3. Lattice QCD:
   M. Gockeler et al.,
   Phys.Lett.B627:113-123,2005 , Q^2 =
   GeV^2
4. QCD sum rules:
   Han-xin He, Xiang-Dong Ji,
   PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2

Cross Checks with Different Target: Proton-Target at COMPASS

Preliminary COMPASS Collins Asymmetries for Proton Target vs predictions from Anselmino et al.



Good agreement of COMPASS proton data with preditions from fit to HERMES, Belle and COMPASS-d!

Collins Extraction of Transversity: Model Dependence from Transverse Momentum Dependences!

transversity

Collins FF

$$A_{UT}^{Collins} = \frac{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp \delta q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^{\perp}(z,p_\perp) \sin(\phi_S + \phi + \phi_q^h) \sin(\phi_S + \phi_h)}{\sum_q e_q^2 \int d\phi_S d\phi_h d^2k_\perp q(x,k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z,p_\perp)}$$

quark pdf

hadron FF

$k_\perp$ transverse quark momentum in nucleon

$p_\perp$ transverse hadron momentum in fragmentation

Anselmino, Boglione, D'Alesio, Kotzinian, Murgia, Prokudin, Turk Phys. Rev. D75:05032,2007

The transverse momentum dependencies are unknown and difficult to obtain experimentally!

Measurements of Transversity with Transverse Momentum Independent Functions !

$\bar{p}^{\uparrow} p^{\downarrow} \longrightarrow l + \bar{l} + X$ (PAX, FAIR) Drell Yan → req. polarized anti-protons

$\bar{p}^{\uparrow} p^{\downarrow} \longrightarrow jet + X$ (RHIC) need to improve systematics on rel. luminosity

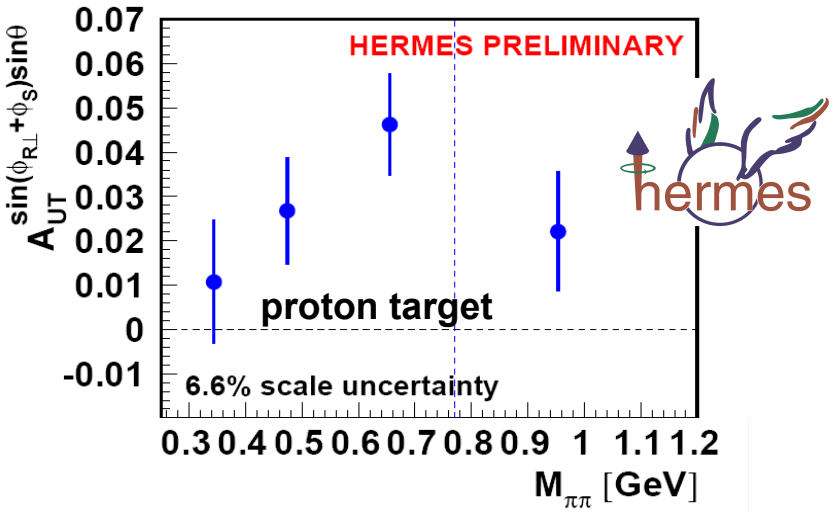
$ep^{\uparrow} \longrightarrow e' \Lambda^{\uparrow} + X$ (SIDIS, EIC) need Lambda-FF → e^+e^-

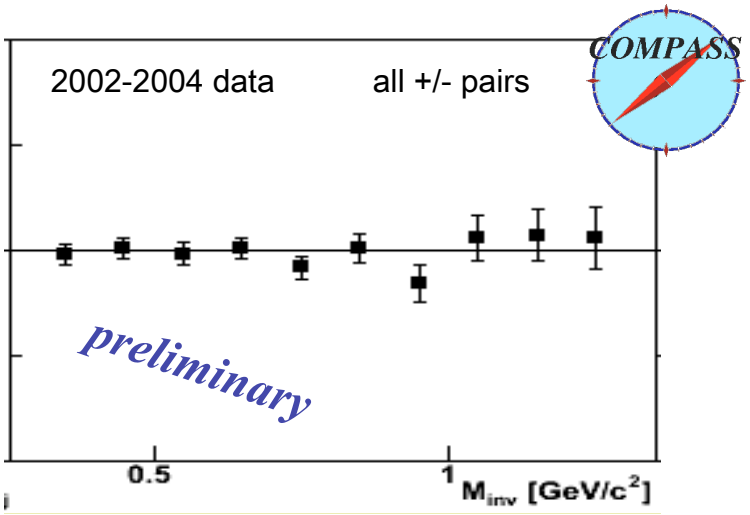
$pp^{\uparrow} \longrightarrow \Lambda^{\uparrow} + X$ (RHIC, JPARC) need Lambda-FF → e^+e^-

$ep^{\uparrow} \longrightarrow \pi^- + \pi^+ + X$ (SIDIS at JLab-12 GeV, EIC) need IFF → e^+e^-

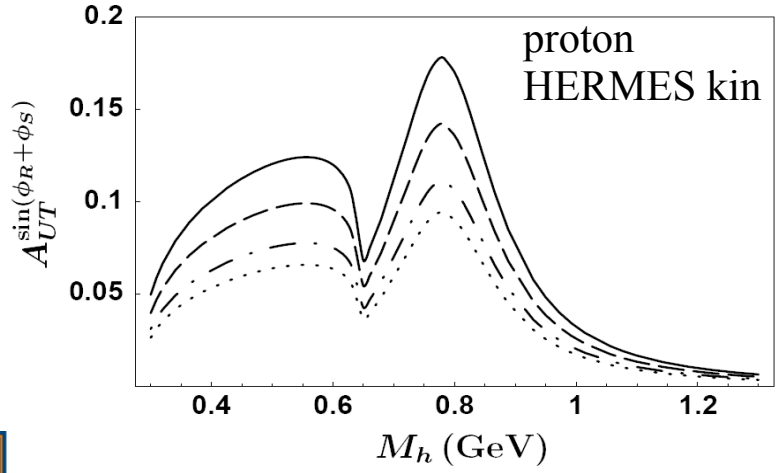
$pp^{\uparrow} \longrightarrow \pi^- + \pi^+ + X$ (RHIC, JPARC) need IFF → e^+e^-

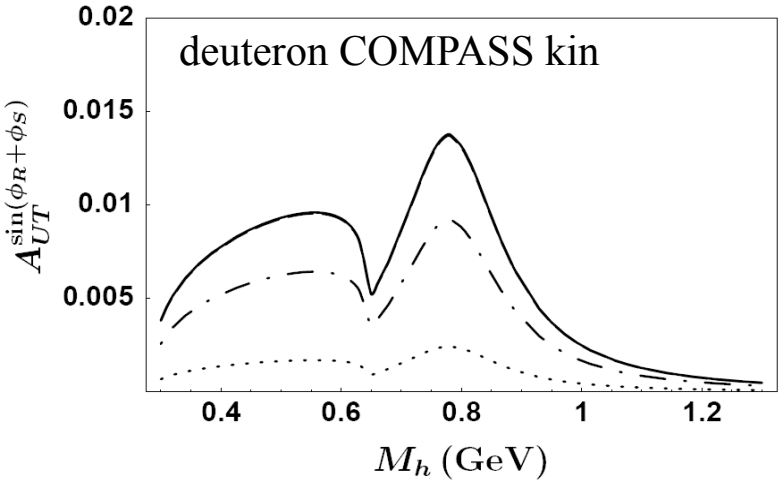
First IFF Asymmetries in Hermes and COMPASS



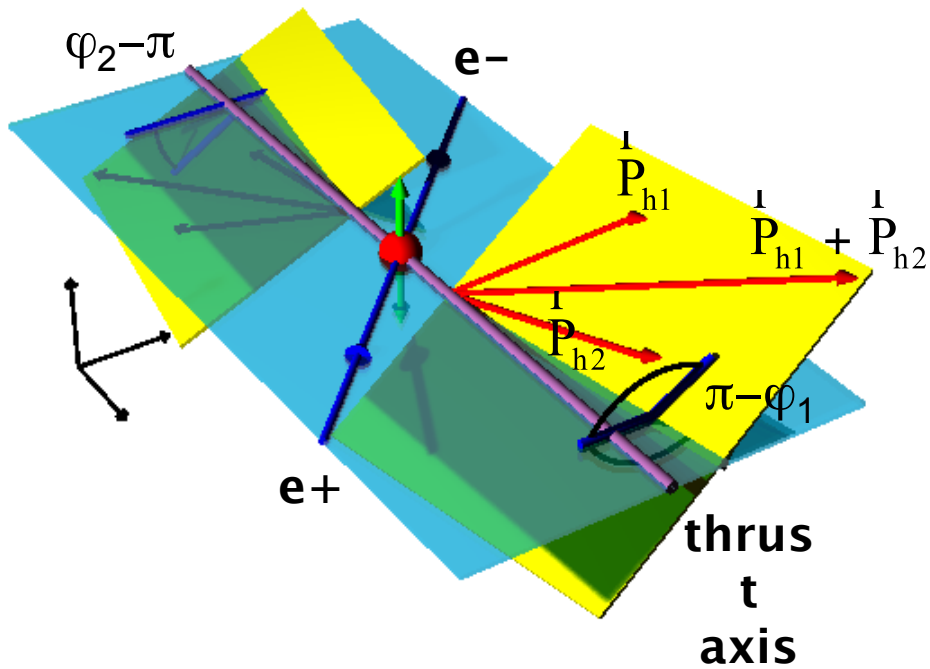


A. Bacchetta, M. Radici hep-ph/0608037 model calculations





Projections for IFF Measurement at BELLE



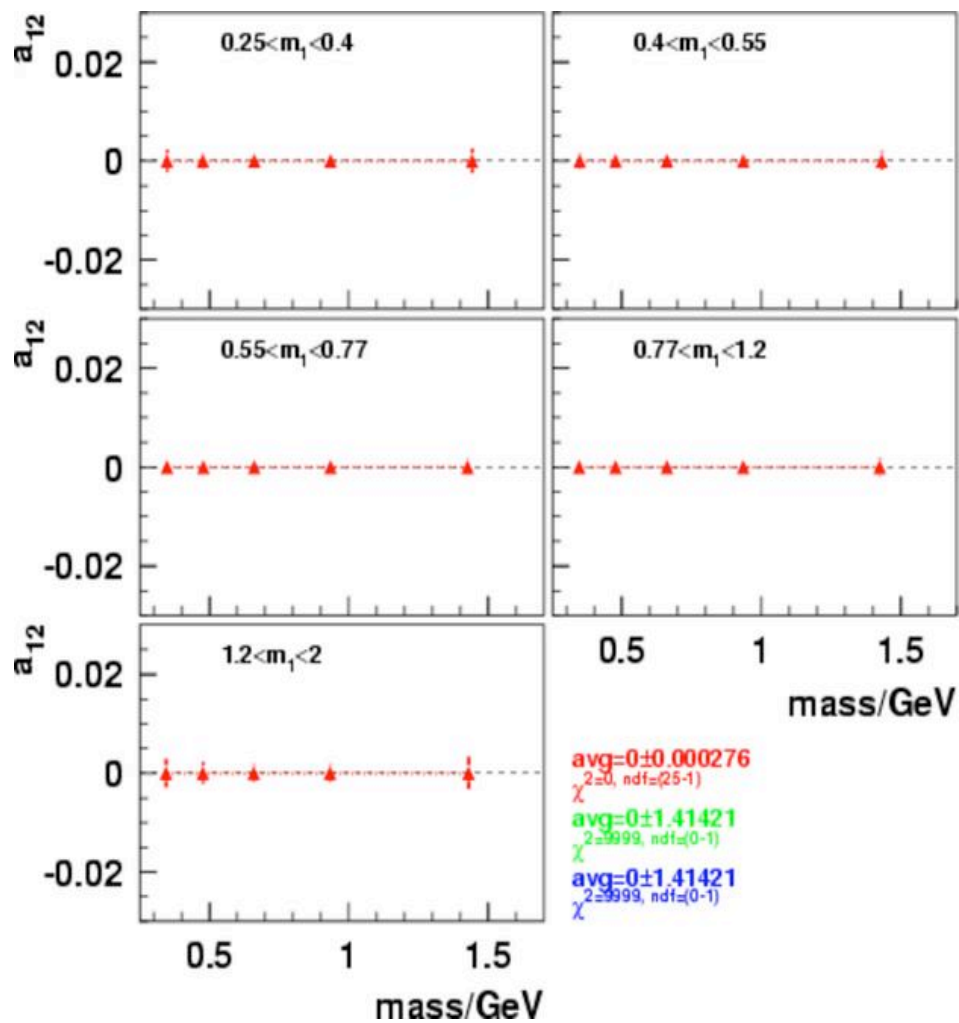
$$e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$$

$$A \propto H_1^S(z_1,m_1)H_1^S(z_2,m_2)\cos(\phi_1+\phi_2)$$

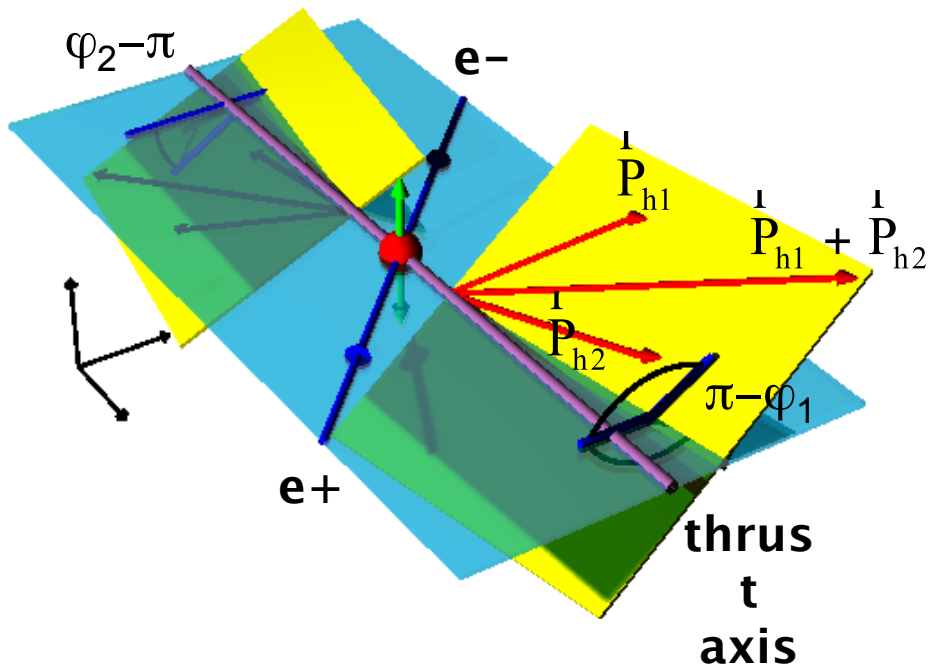
Artru and Collins, *Z. Phys. C69, 277 (1996)*

Boer, Jakob, and Radici, PRD67, 094003 (2003)

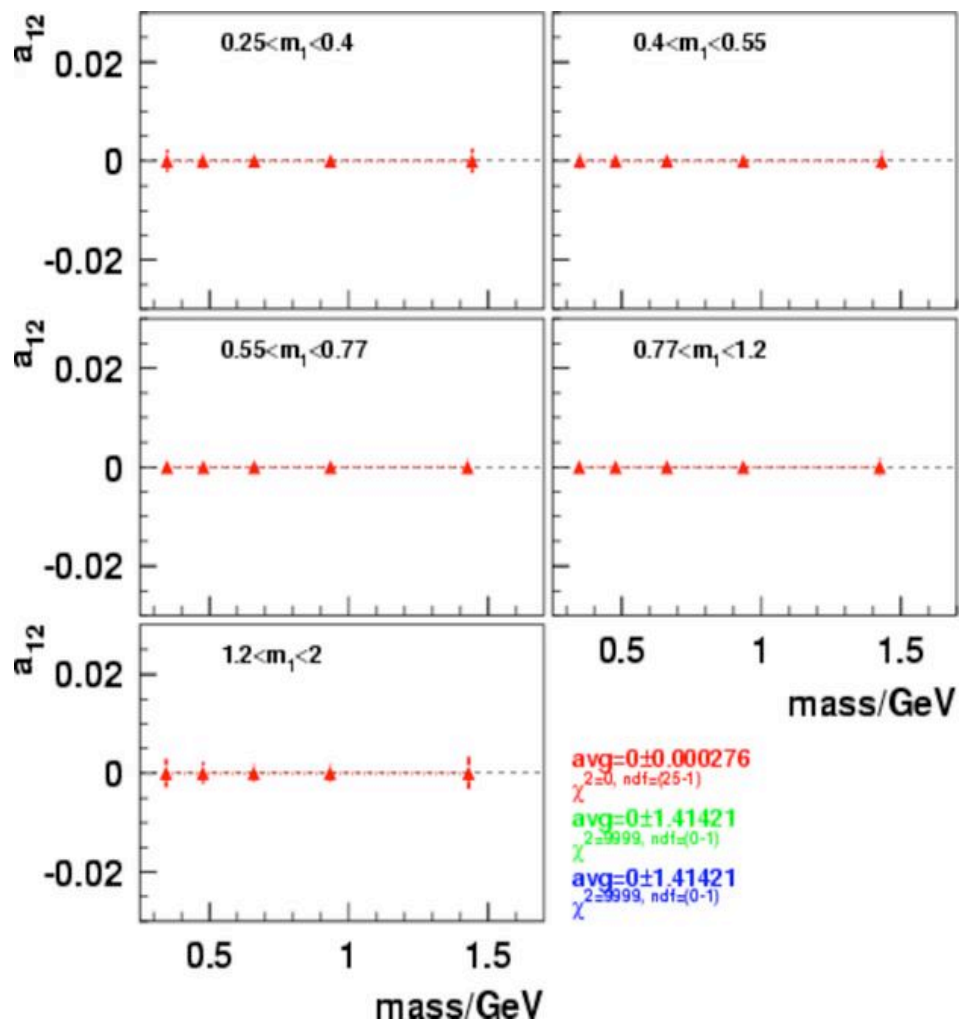
IFF sensitivity projection from data



Projections for IFF Measurement at BELLE



IFF sensitivity projection from data



e^+e^- ®

$A \propto H$

A

Boe

IFF provides clean access to transversity distributions and is an interesting alternative channel for EIC !

Summary

- EIC offers high luminosities and high center of mass energies for the study of nucleon structure.

- Precision measurements with clean theoretical interpretation will become possible:

  Helicity decomposition, transverse spin decompostion, Bjorken sumrule, tensor charge, precision tests of QCD evlolution of g_1 and h_{1T}.

- Significant effort and care will be needed to meet the experimental and theoretical challenges: high luminosity + polarization, high performance detector, precision polarimetery, tools for the clean pdf extraction.