Spin Azimuthal Asymmetries in Semi-Inclusive DIS at JLAB

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- Nucleon spin & transverse momentum of partons
- Transverse-momentum dependent distributions
- Spin-azimuthal asymmetries
- Experimental status of single-spin asymmetries
- Projections for JLab at 12 GeV
- Summary & Outlook

PAC meeting, Jan 17, JLab

Physics Motivation

Orbital Angular Momentum (OAM) in the focus.

Transverse momentum of quarks is a key to OAM.

Parton Distribution Functions generalized to contain information not only on longitudinal, but also on the transverse distribution of partons:

Complementary sets of non-perturbative functions sensitive to different aspects of transverse distributions

- Generalized Parton Distributions (GPD) H, E ...
- Transverse-momentum dependent (TMD) parton distributions

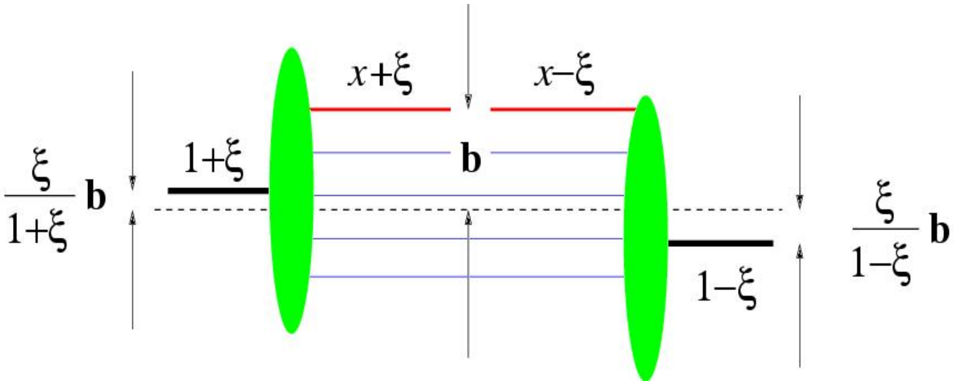
TMD distributions contain direct information about the quark orbital motion

GPDs and TMDs

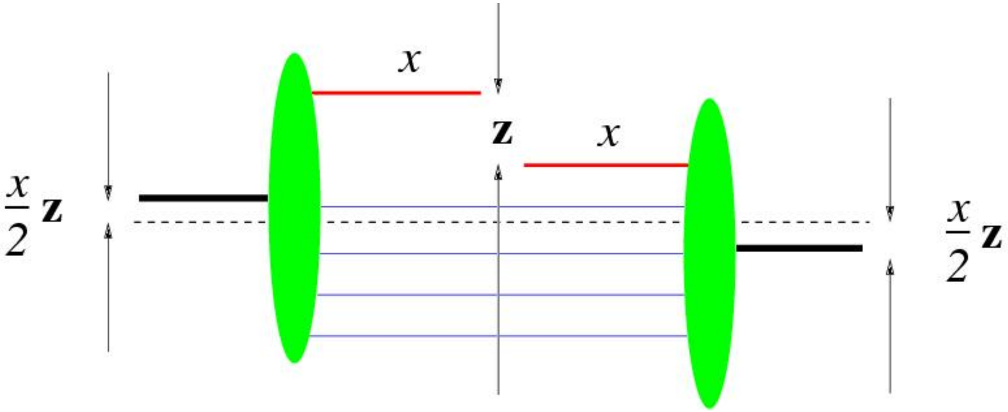
In impact parameter space: partons described by their longitudinal momentum fraction **x**, transverse distance **b** from proton center and transfer of longitudinal momentum ξ.

(M.Diehl hep-ph/0205208)

GPDs: correlate hadronic wave functions with both different momentum fractions and different transverse positions of the partons.



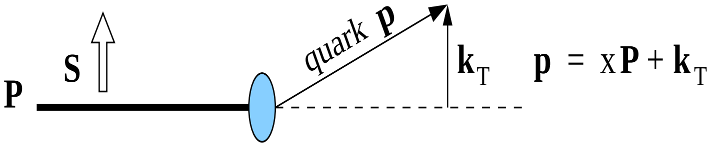
TMDs: correlation in transverse position of a single quark. The struck quark has a different transverse location relative to the spectator partons in the initial and final state



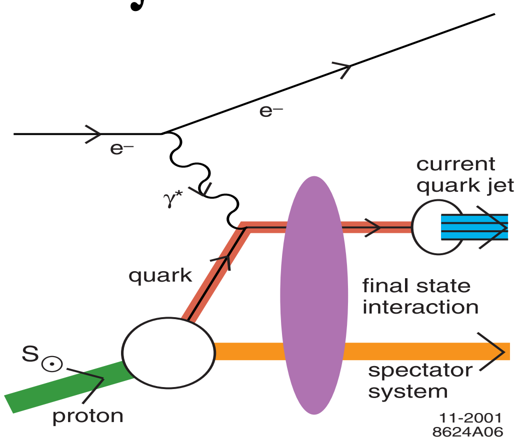
k_T- Dependent Parton Distributions

Twist-2 PDFs $f_1^u(x) \equiv u(x),\ g_1^u(x) \equiv \Delta u(x),\ h_1^u(x) \equiv \delta u(x)$

f_1, g_1 studied for decades:
h_1 essentially unknown



$$f_1(x) = \int d^2k_T f_1(x, k_T)$$

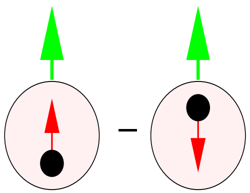


FSI from Brodsky et al. used in gauge invariant definition of TMDs by Collins, Ji et al. 2002

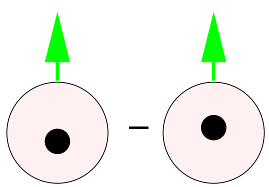
Distribution functions		Chirality even	Chirality odd
Twist-2	U	f_1	$h_1^\perp$
	L	g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$, g_{1T}	h_1, $h_{1T}^\perp$
Twist-3	U	$f^\perp$	e
	L	$g_L^\perp$	h_L
	T	g_T, $g_T^\perp$	h_T, $h_T^\perp$

Classification of PDF by Mulders et al.

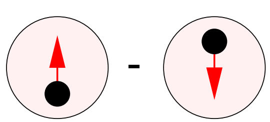
Novel Distributions

$h_1 =$ 

Transversity: probes relativistic nature of quarks, does not mix with gluons. First moment - tensor charge: $\delta\Sigma = \sum_f \int_0^1 dx(\delta q_f - \delta\bar{q}_f)$= 0.56+/-0.09 ($Q^2$=2)

$f_{1T}^{\perp} =$ 

Sivers function: describes unpolarized quarks in transversely polarized nucleon. A non-zero T-odd $f_{1T}^{\perp}$, requires final state interactions + interference between different helicity states
(Brodsky et al., Collins, Ji et al. 2002)

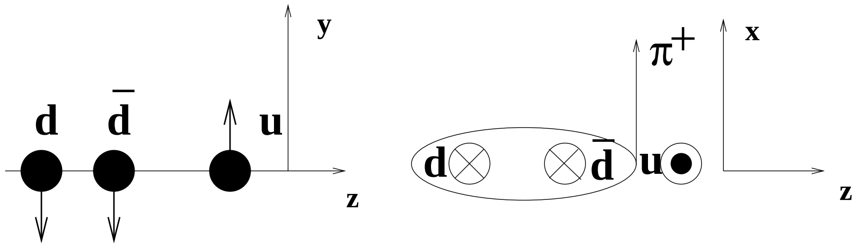
$H_1^{\perp} =$ 

Collins function: describes fragmentation of transversely polarized quarks into unpolarized hadrons. Physics mechanisms to generate non-zero T-odd $H_1^{\perp}$ by Collins 1993, Bacchetta et al. 2002

Semi-Classical Models

Collins effect:

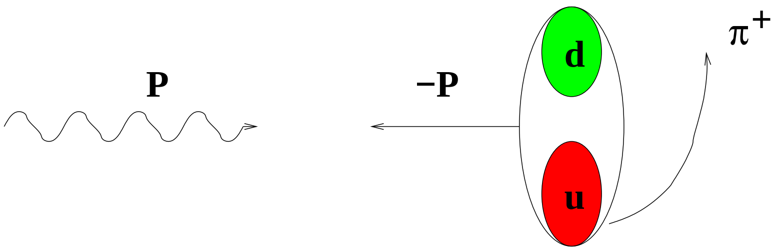
asymmetric fragmentation



Orbital momentum generated in string breaking and $q\bar{q}$ pair creation produces left-right asymmetry from transversely polarized quark fragmentation (Artru-hep-ph/9310323).

Sivers effect:

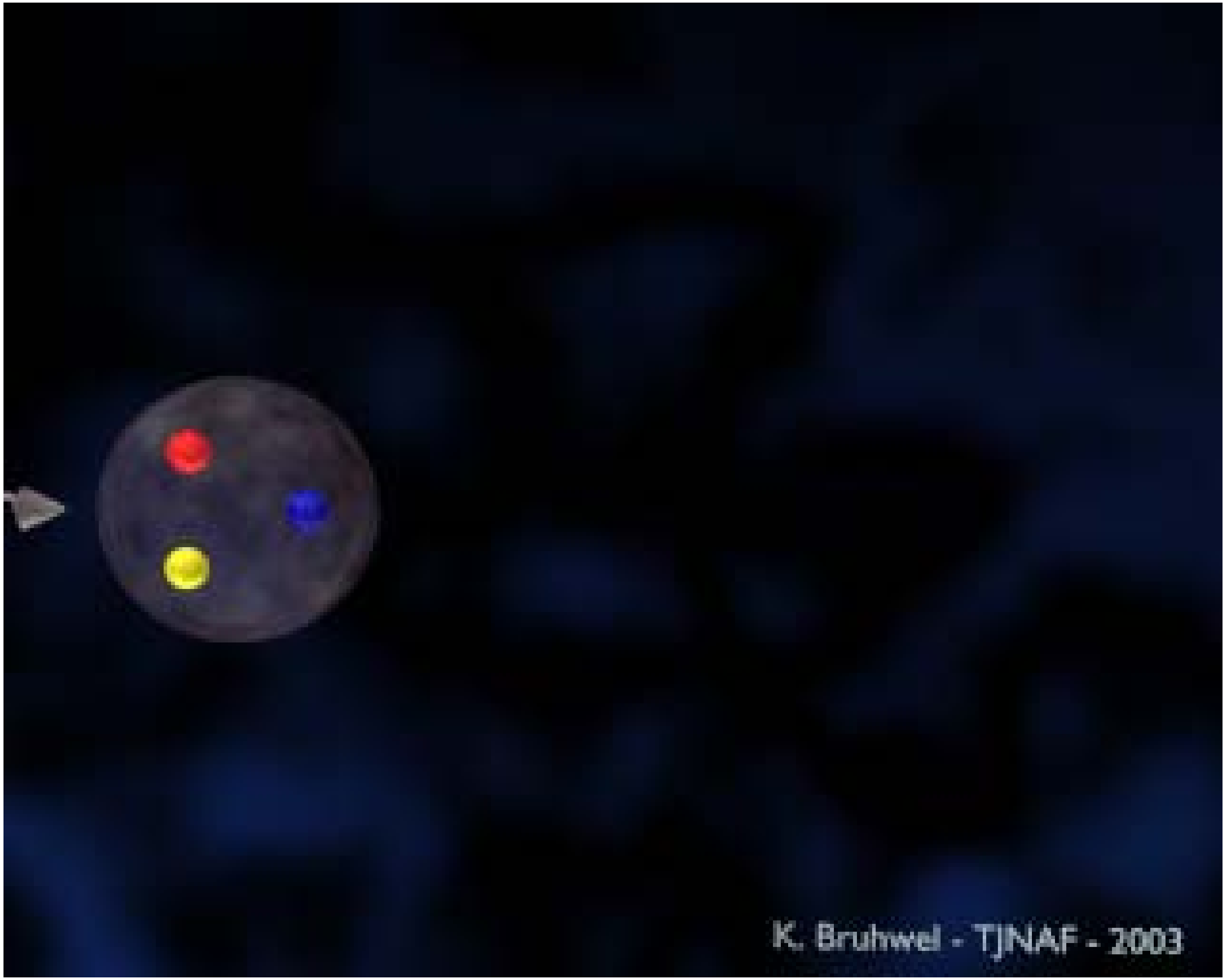
asymmetric distribution



In the transversely polarized proton **u** quarks are shifted down and **d** quark up giving rise to SSA (Burkardt-hep-ph/02091179).

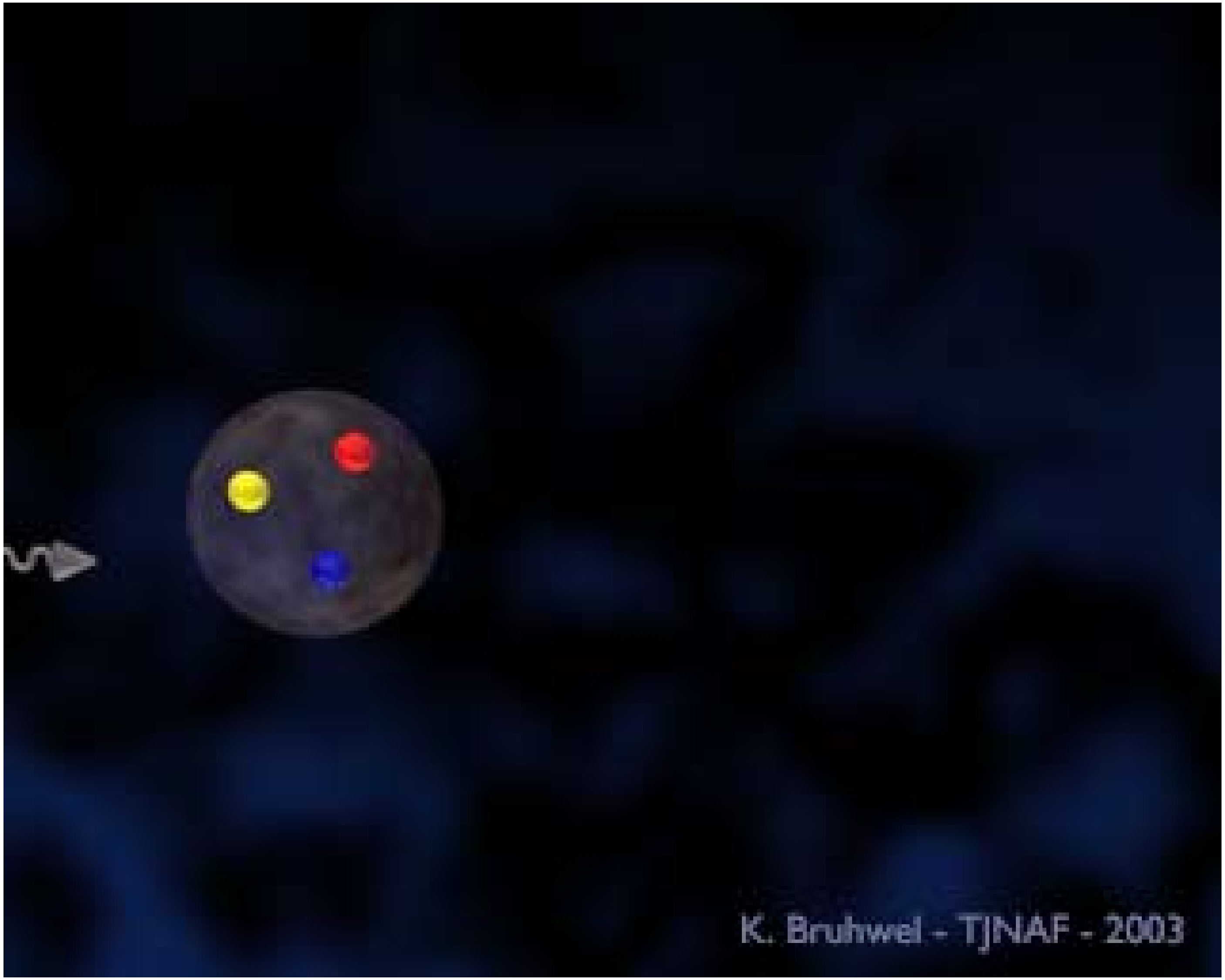
The shift (~ 0.4 fm) is defined by spin-flip GPD **E** and anomalous magnetic moment of proton.

Collins Effect:



Left-right asymmetry in the fragmentation of transversely polarized quarks

Sivers Effect:



Left-right asymmetry in the distribution function

Transverse Momentum of Partons

Non-zero transverse momenta of partons are accessible in measurements of azimuthal distributions of final state hadrons.

Azimuthal Asymmetries in electroproduction:

- clean test of QCD (Georgi, Politzer 1978)
- intrinsic transverse momentum of partons (Cahn 1979)
- final state interactions (Berger 1980)

The DIS data from EMC (1987) and Fermilab (1993) are most consistent with intrinsic parton transverse momentum squared, k_T^2 of ~ 0.25 GeV^2

Spin-Azimuthal Asymmetries

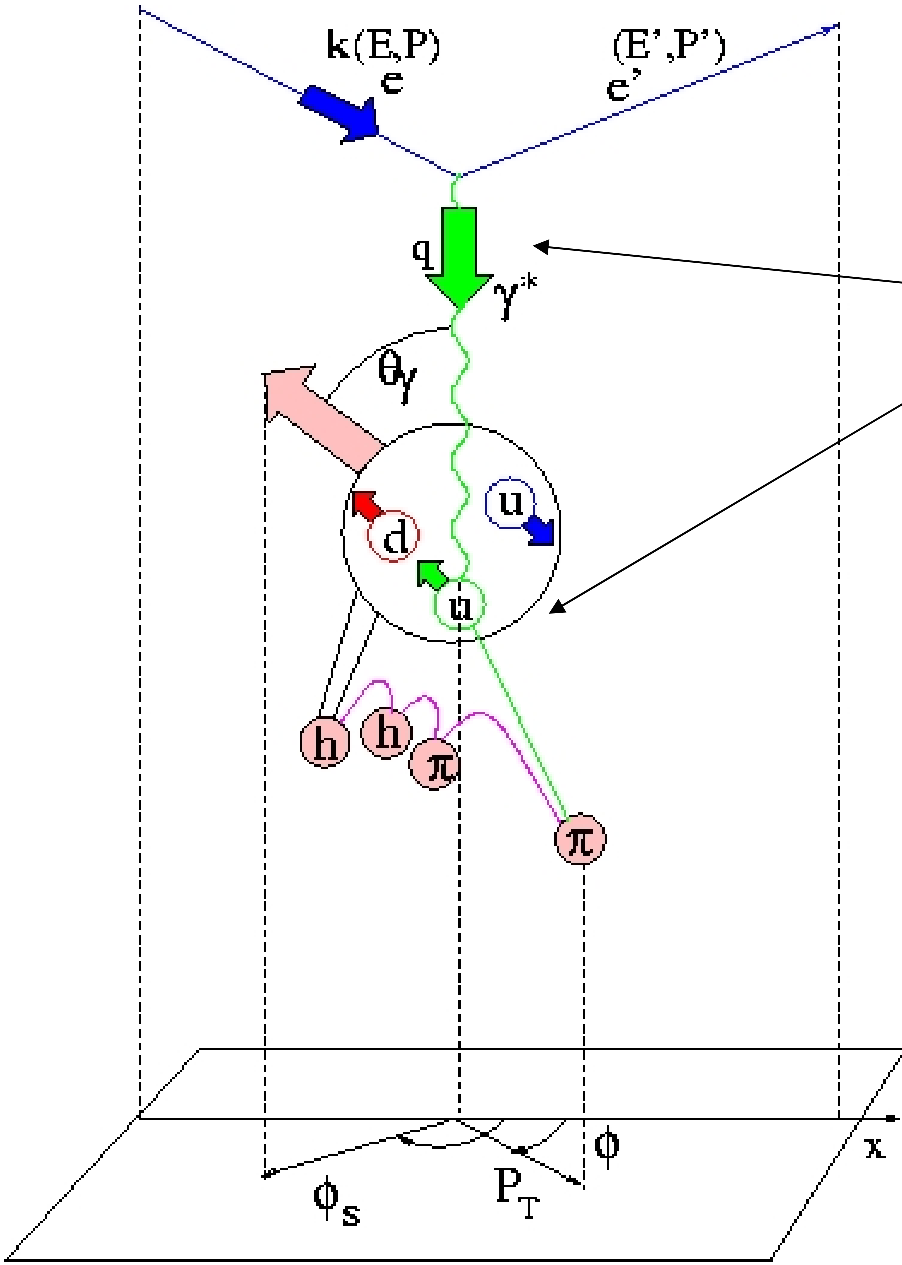
Spin asymmetries + azimuthal dependence ⟶ new class of DIS measurements Spin-Azimuthal Asymmetries:

Significant progress made recently in studies of Single-Spin Azimuthal Asymmetries (SSA) with longitudinally polarized target (HERMES), transversely polarized target (SMC), and polarized beam (CLAS).

- SSA are sensitive to the orbital momentum of quarks.
- provide a window to the physics of partonic final and initial state interactions
- model calculations indicate that SSA are not affected significantly by a wide range of corrections.
- Good agreement in SSAs measured in a wide energy range in electroproduction and **pp** scattering.

SSAs: appropriate observable at JLAB beam energies and $\mathbf{Q^2}$

Polarized Semi-Inclusive DIS



Cross section defined by scale variables **x,y,z**

$$
\begin{aligned}
x &= Q^2/2ME_\gamma \\
y &= E_\gamma/E \\
z &= E_h/E_\gamma \\
\sin\theta_\gamma &\approx \frac{2Mx}{Q}\sqrt{1-y} \\
\sin\phi &= \frac{[\vec{q}\times\vec{k}]\vec{P}_\perp}{|\vec{q}\times\vec{k}||P_\perp|}
\end{aligned}
$$

Hadron-Parton transition: by distribution function $f_1^u(x)$: probability to find a **u**-quark with a momentum fraction **x**

Parton-Hadron transition: by fragmentation function $D_{1u}^{\pi+}(z)$: probability for a **u**-quark to produce a π^+ with a momentum fraction **z**

Contributions to σ in ep→e'πX

σ for longitudinally polarized leptons scattering off unpolarized protons:

$$\frac{d\sigma_{UU}}{dx_B\,dy\,dz\,d^2P_\perp} = \frac{4\pi\,\alpha^2\,s}{Q^4}\,x_B\Big\{\Big(1-y+\frac{1}{2}y^2\Big)\mathcal{H}_T + (1-y)\,\mathcal{H}_L - (2-y)\sqrt{1-y}\,\cos\phi\,\mathcal{H}_{LT} + (1-y)\,\cos 2\phi\,\mathcal{H}_{TT}\Big\},$$

$$\frac{d\sigma_{LU}}{dx_B\,dy\,dz\,d^2P_\perp} = \lambda_e\,\frac{4\pi\,\alpha^2\,s}{Q^4}\,x_B\,y\sqrt{1-y}\,\sin\phi\,\mathcal{H}'_{LT}$$

Different structure functions can be extracted as **azimuthal moments** of the total cross section.

$$\longrightarrow \quad \frac{1}{2}A_{LU}^{\sin\phi} = \langle\sin\phi\rangle = \frac{1}{P^{\pm}N^{\pm}}\sum_{i=1}^{N^{\pm}}\sin\phi_i$$

Contributions to σ in Polarized SIDIS

$$\sigma_{UU} \propto (1-y+y^2/2)\sum_{a,\bar{a}} e_a^2 x f_1^a(x) D_1^a(z)$$

$$\sigma_{UU}^{\cos 2\phi} \propto (1-y)\cos 2\phi \sum_{a,\bar{a}} e_a^2 x h_1^{\perp}(x) H_1^{\perp a}(z)$$

$$\sigma_{LL} \propto \lambda_e S_L y(2-y)\sum_{a,\bar{a}} e_a^2 x g_1^a(x) D_1^a(z)$$

$$\sigma_{LT}^{\cos\phi} \propto \lambda_e S_T y(2-y)\cos(\phi-\phi_S)\sum_{a,\bar{a}} e_a^2 x g_{1T}(x) D_1^a(z)$$

$$\sigma_{UL}^{\sin 2\phi} \propto S_L 2(1-y)\sin 2\phi \sum_{a,\bar{a}} e_a^2 x h_{1L}^{\perp}(x) H_1^{\perp a}(z)$$

$$\sigma_{UT}^{\sin\phi} \propto S_T(1-y)\sin(\phi+\phi_S)\sum_{a,\bar{a}} e_a^2 x h_1^a(x) H_1^{\perp a}(z)$$

$$\sigma_{UT}^{\sin\phi} \propto S_T(1-y)\sin(\phi-\phi_S)\sum_{a,\bar{a}} e_a^2 x f_{1T}^{\perp}(x) D_1^a(z)$$

$$\sigma_{LU}^{\sin\phi} \propto \lambda_e \sin\phi\, y\sqrt{1-y}\frac{M}{Q}\sum_{a,\bar{a}} e_a^2 x^2 e^a(x) H_1^{\perp a}(z)$$

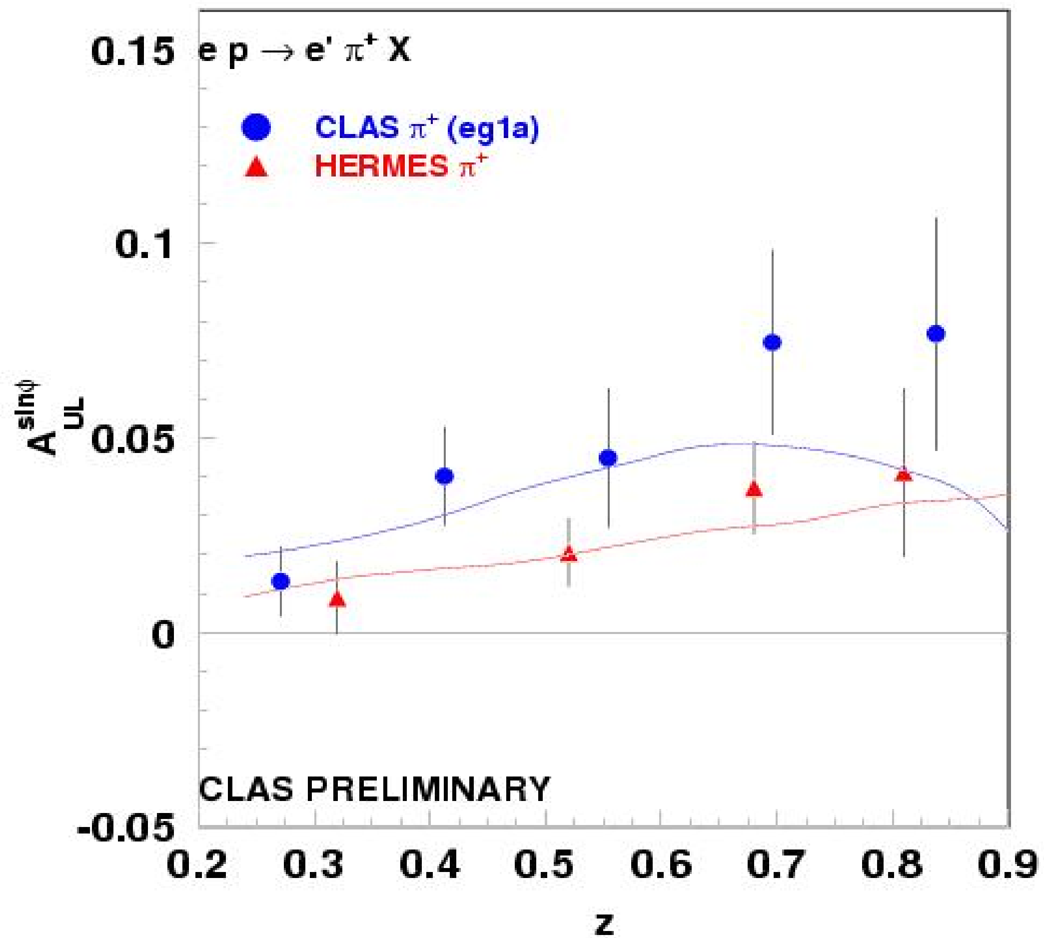
λ_e, S_L, S_T electron and proton long. and trans. pol.

$\sum_{a,\bar{a}} \rightarrow$ sum over quarks and anti-quarks.

Long. Pol Target SSA for π+

A_{UL} are consistent both in magnitude and sign with predictions based on Collins mechanism

Target SSA: CLAS (4.3 GeV) is consistent with HERMES (27.5 GeV)
Curves for Sivers effect from BHS-2002.

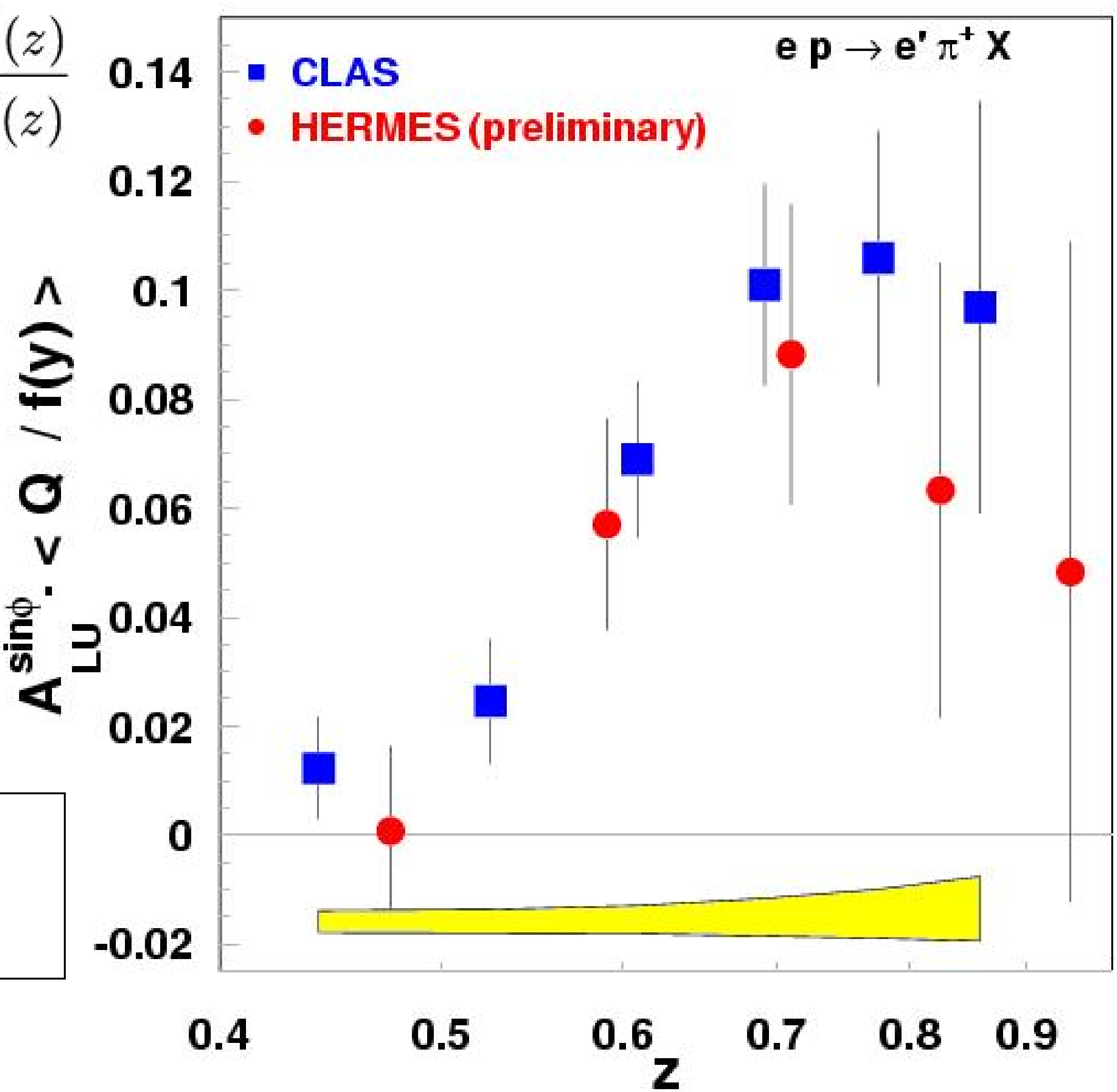


$$A_{UL} \propto \sin\theta_\gamma \times A_{UT} \propto \sin\theta_\gamma \frac{f_{1T}^{\perp u}(x)}{u(x)}$$

Beam SSA: sinφ Moment

$$A_{LU} \propto \lambda_e f(y) \frac{M}{Q} \frac{H_1^{u,\pi^+}(z)}{D_1^{u,\pi^+}(z)}$$

Beam SSA A_{LU} from CLAS at 4.3GeV and HERMES (SPIN-2002) at 27.5 GeV



Beam SSA measurements for different beam energies are consistent.

First Extraction of e(x) from CLAS Data

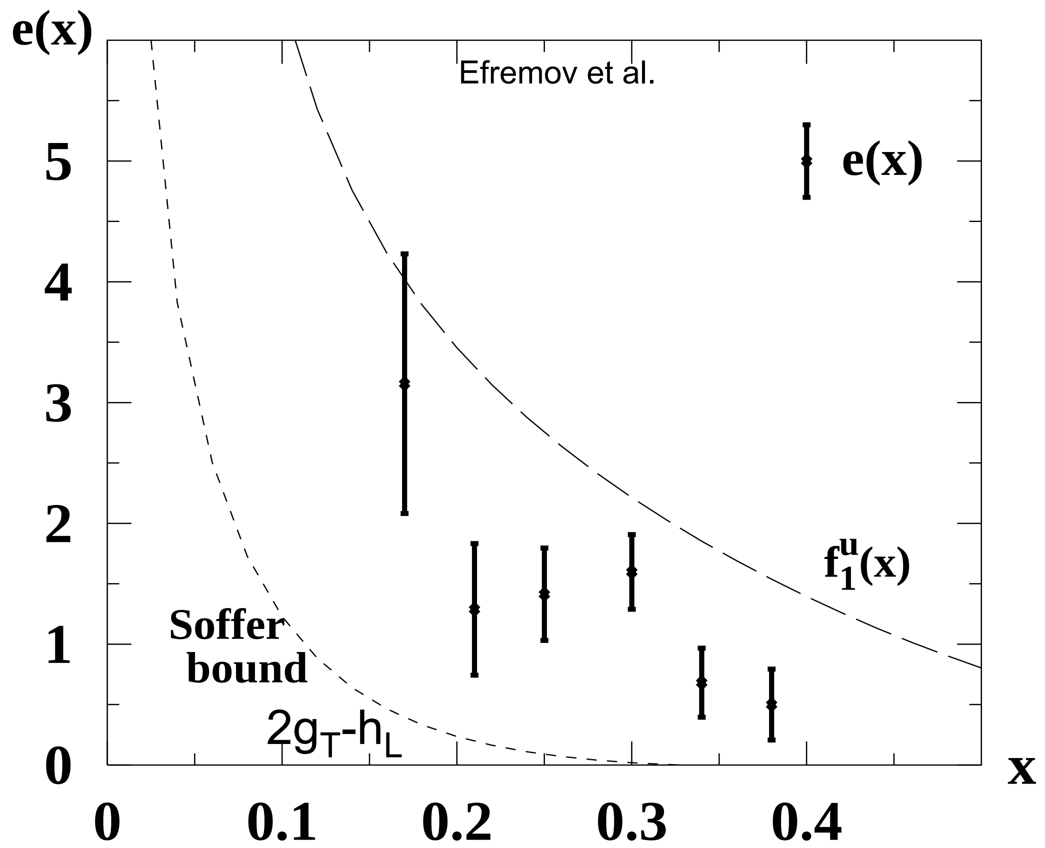
SSA analyzed in terms of the fragmentation effect

x-dependence of CLAS beam SSA (A_{LU})

+

z-dependence of HERMES target SSA (A_{UL})

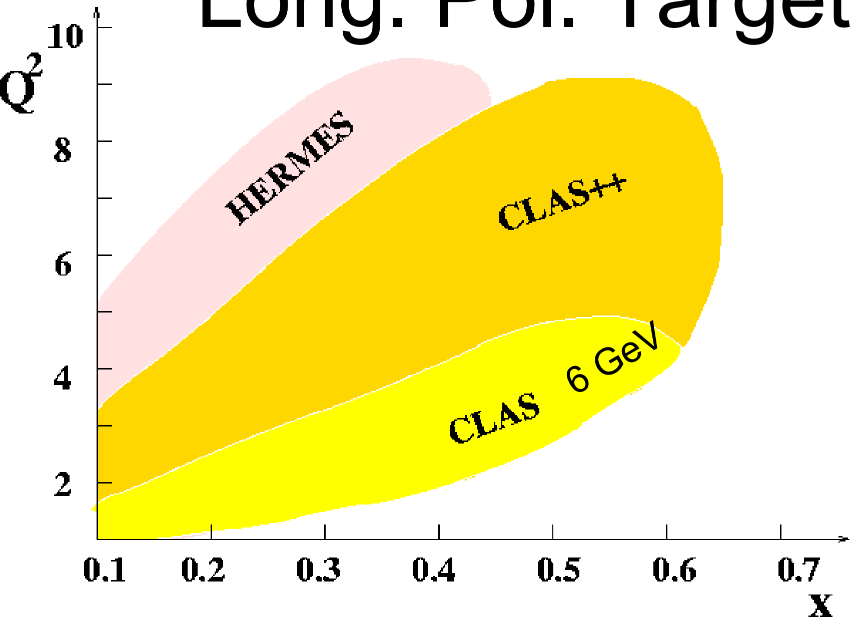
First glimpse of Twist-3 e(x)



$$\int_0^1 e(x) = \frac{2\sigma_{\pi N}}{m_u + m_d}$$

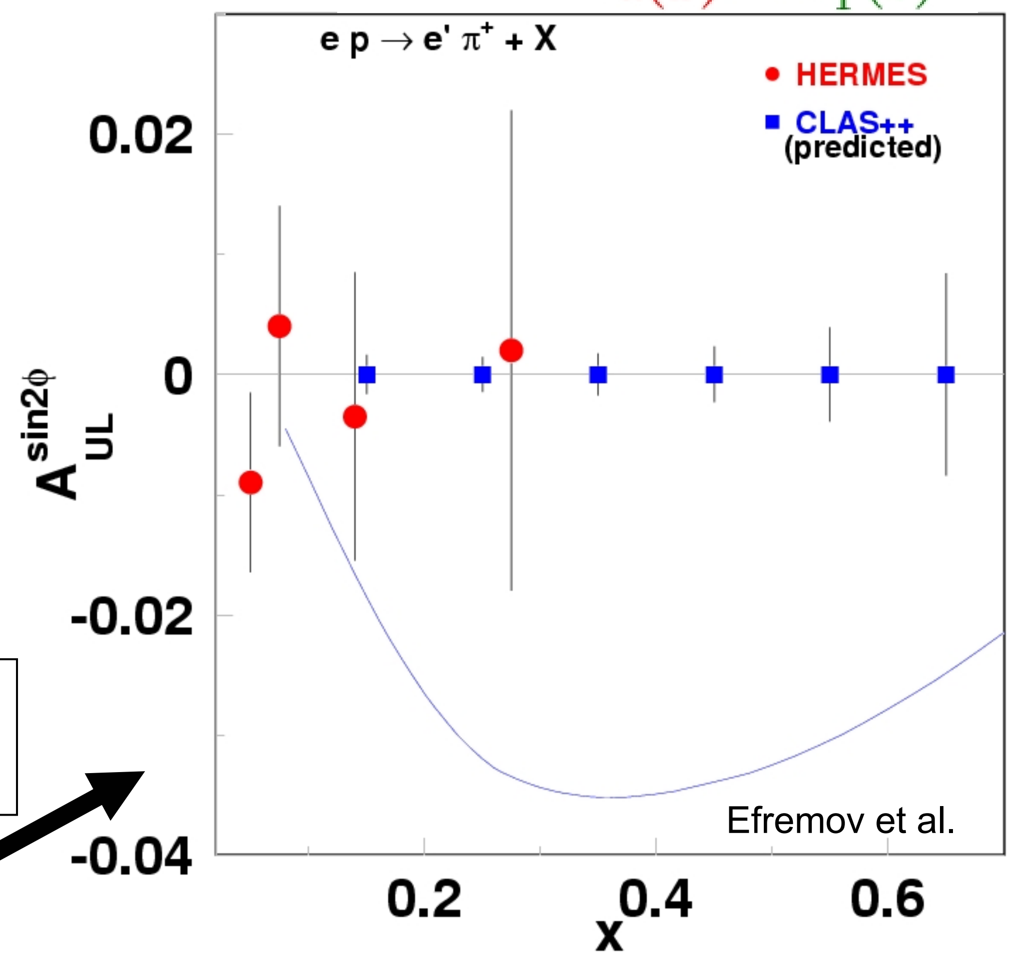
Jaffe,Ji 1992

Long. Pol. Target SSA for π^+ at 12GeV



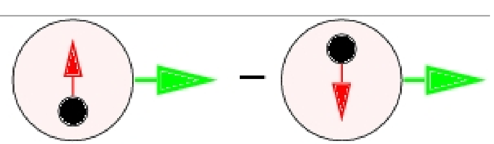
large x + high luminosity

$$A_{UL}^{\sin 2\phi} \propto \frac{h_{1L}^{\perp u}(x)}{u(x)} \frac{H_1^{\perp u}(z)}{D_1^u(z)}$$



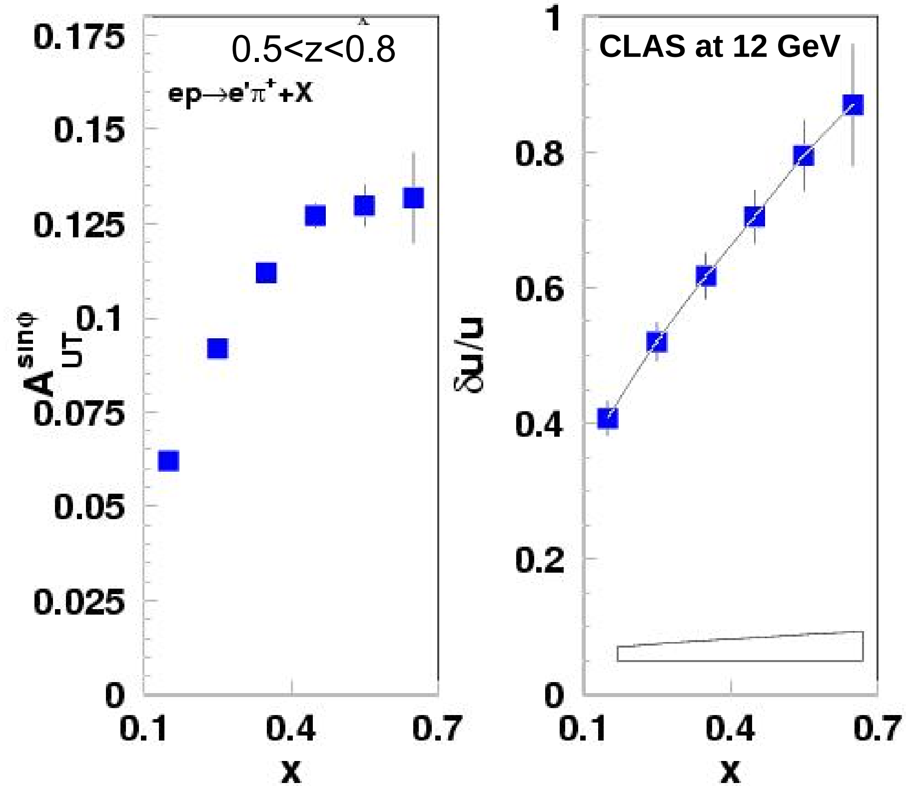
The sin 2ϕ asymmetry for 2000 h of projected CLAS++ data.

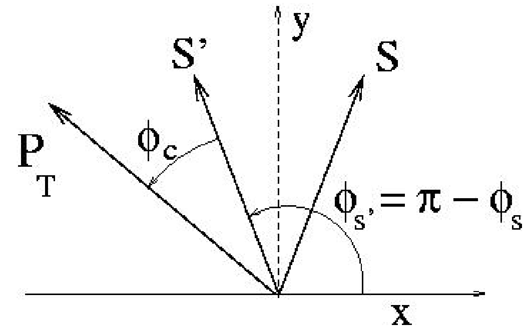
Direct measurement of k_T dependent leading-twist distribution function

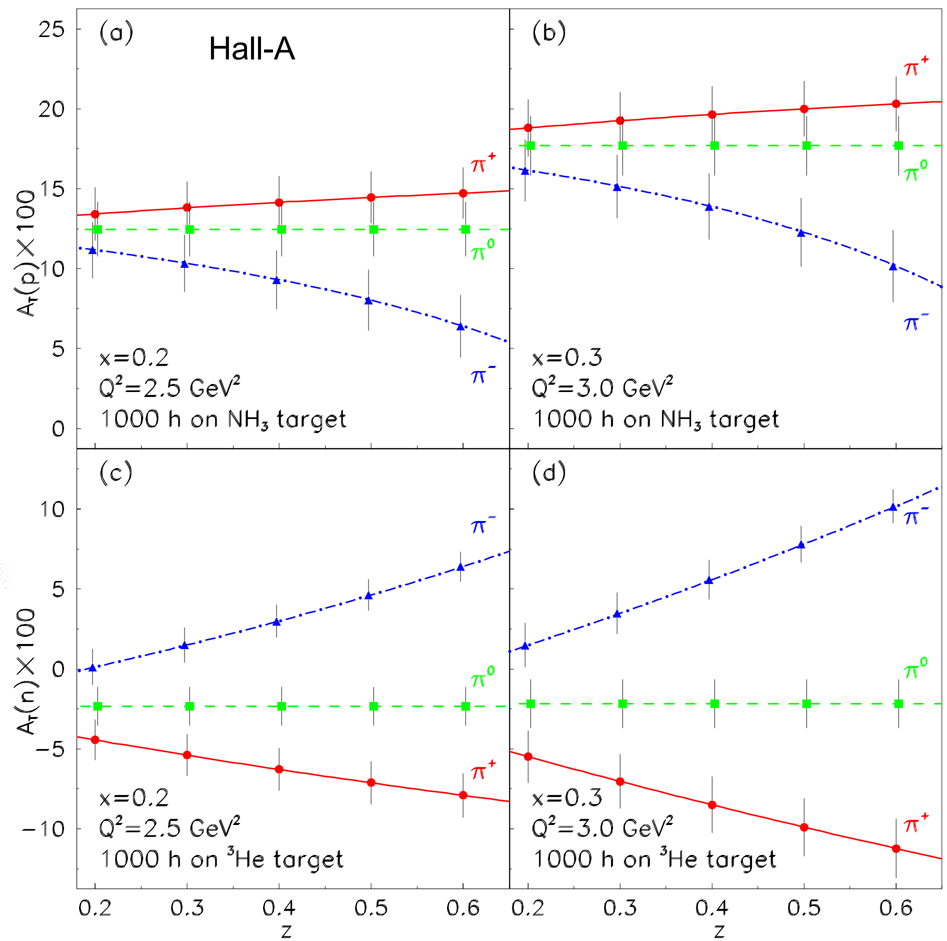
$h_{1L}^{\perp}$ = 

Transverse Target SSA at 12GeV

$$A_{UT} \propto \sin\phi_c \frac{h_1^u(x)}{u(x)} \frac{H_1^u}{D_1^u}$$





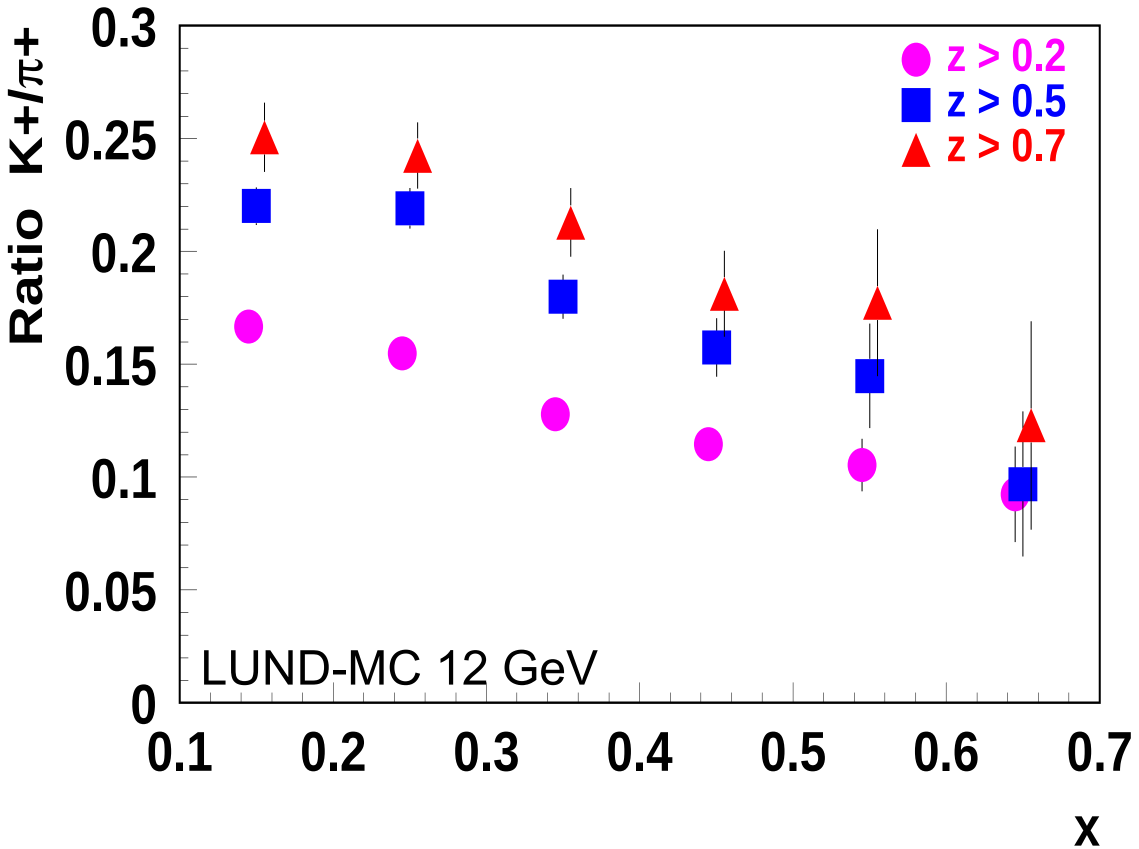


Expected precision of the A_{UT} and extracted δu/u from transverse spin asymmetry

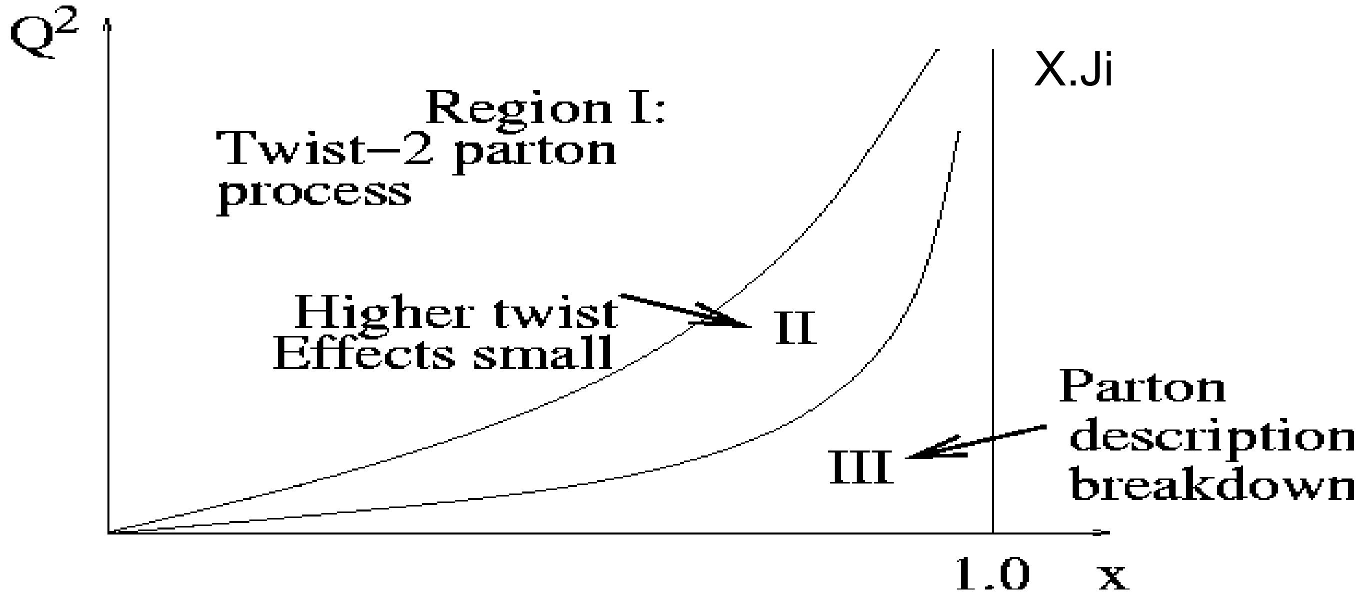
Other Flavors

More hadrons (K+, ρ ..) allow studies of:

- **x/z** factorization
- **u**-quark dominance
- flavor dependence
- universality property of factorization



Semi-inclusive DIS at JLab



Key goal: study the transition between the nonperturbative and perturbative regimes of QCD utilizing JLab's advantages:

- High luminosity
- Full coverage in azimuthal angle (separate all contributions)
- Wide kinematic range (test factorization, measure HT)
- Good particle ID (compare different final state particles)

Summary

- Transverse Momentum Dependent distributions of partons contain direct information about the quark Orbital Angular Momentum. They are accessible in measurements of spin-azimuthal asymmetries

- Current data are consistent with a partonic picture, and can be described by a variety of theoretical models.

- Significantly higher statistics of JLab data at 12 GeV, in a wide kinematical range will provide a full set of data needed to constrain relevant distribution (transversity,Sivers,Collins,…) functions.

- Upgraded Jlab will play a leading role in studies of quark orbital motion, providing fundamental insights into important physics quantities like spin, flavor, and multi-parton correlations.

SIDIS tests at JLAB

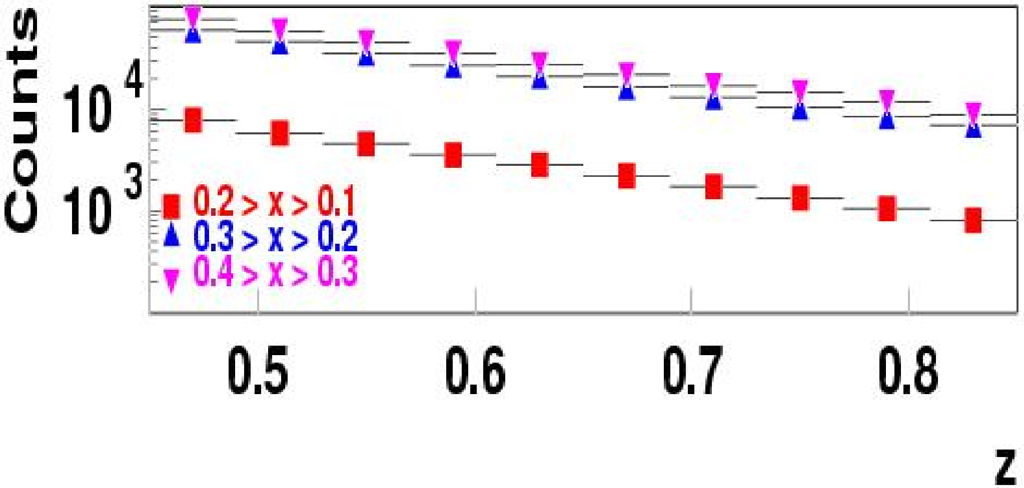
Open issues

- factorization
- separation of current fragmentation

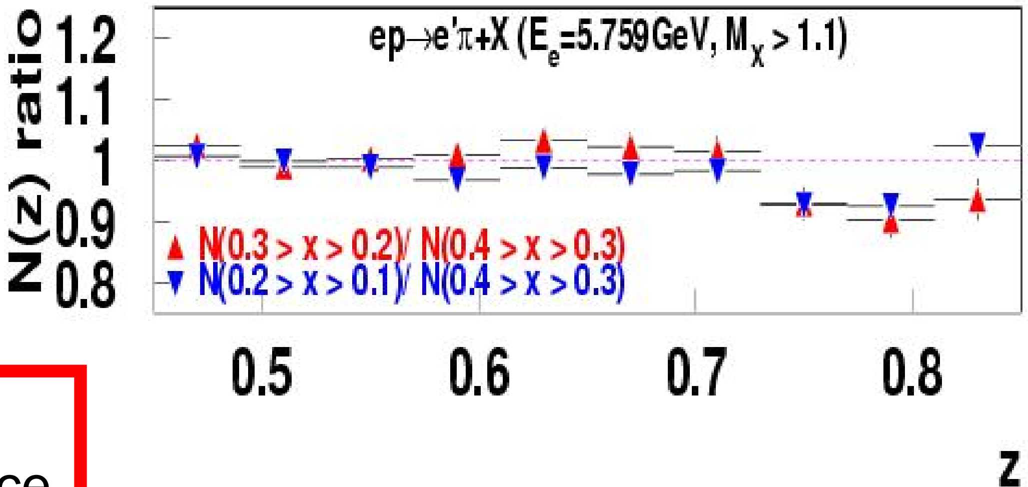
Proposed tests to make sure simple parton picture work (SIDIS workshop in April 2002):

- x and z factorization
- Ratio of charged pions
- Ratios of pion yields for proton/neutron
- Pion production asymmetries

x,z Factorization



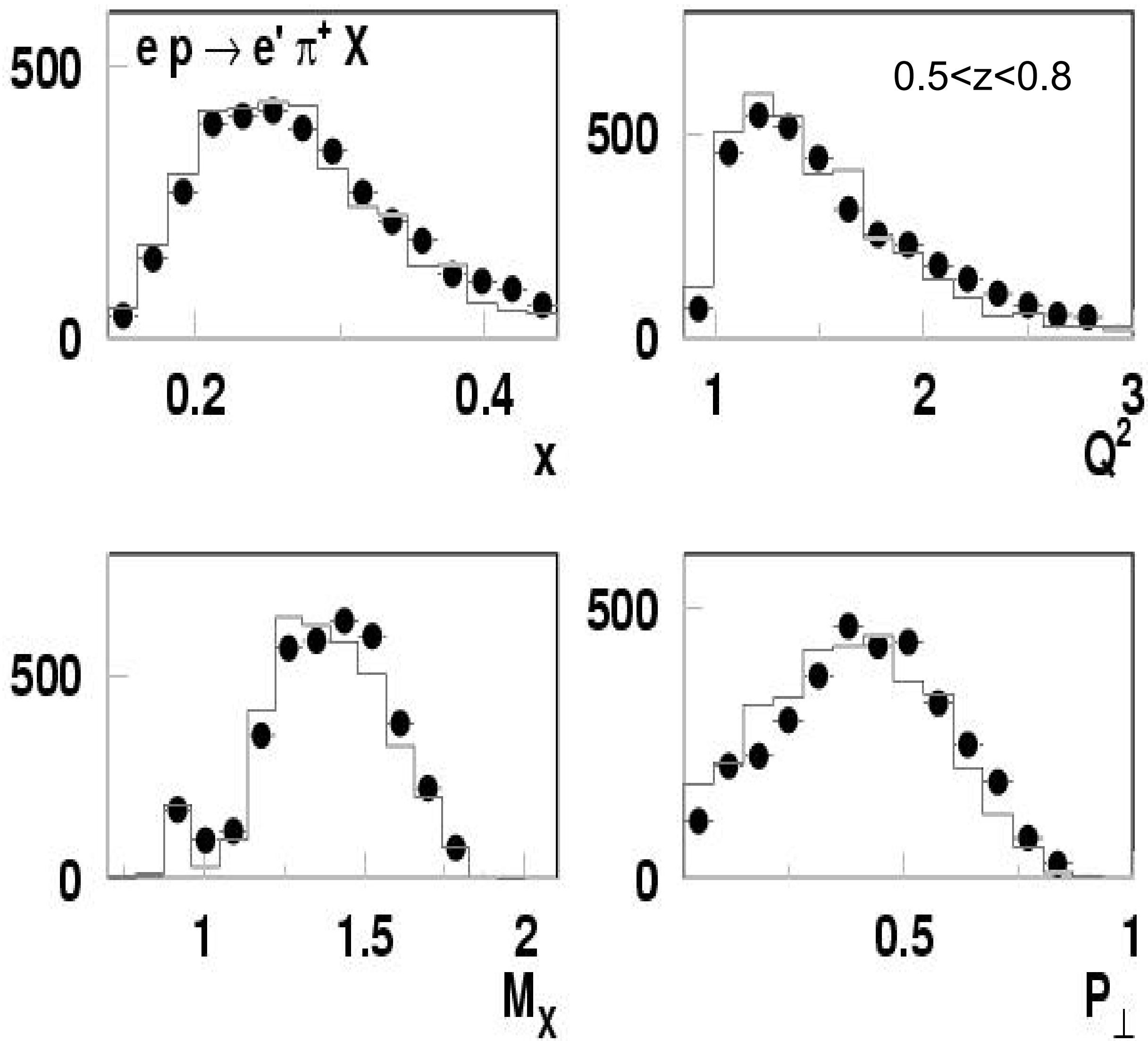
The **z** distribution for different ranges of Bjorken **x**



No significant variation observed in **z** dependence for different **x** ranges.

CLAS data vs LUND-MC

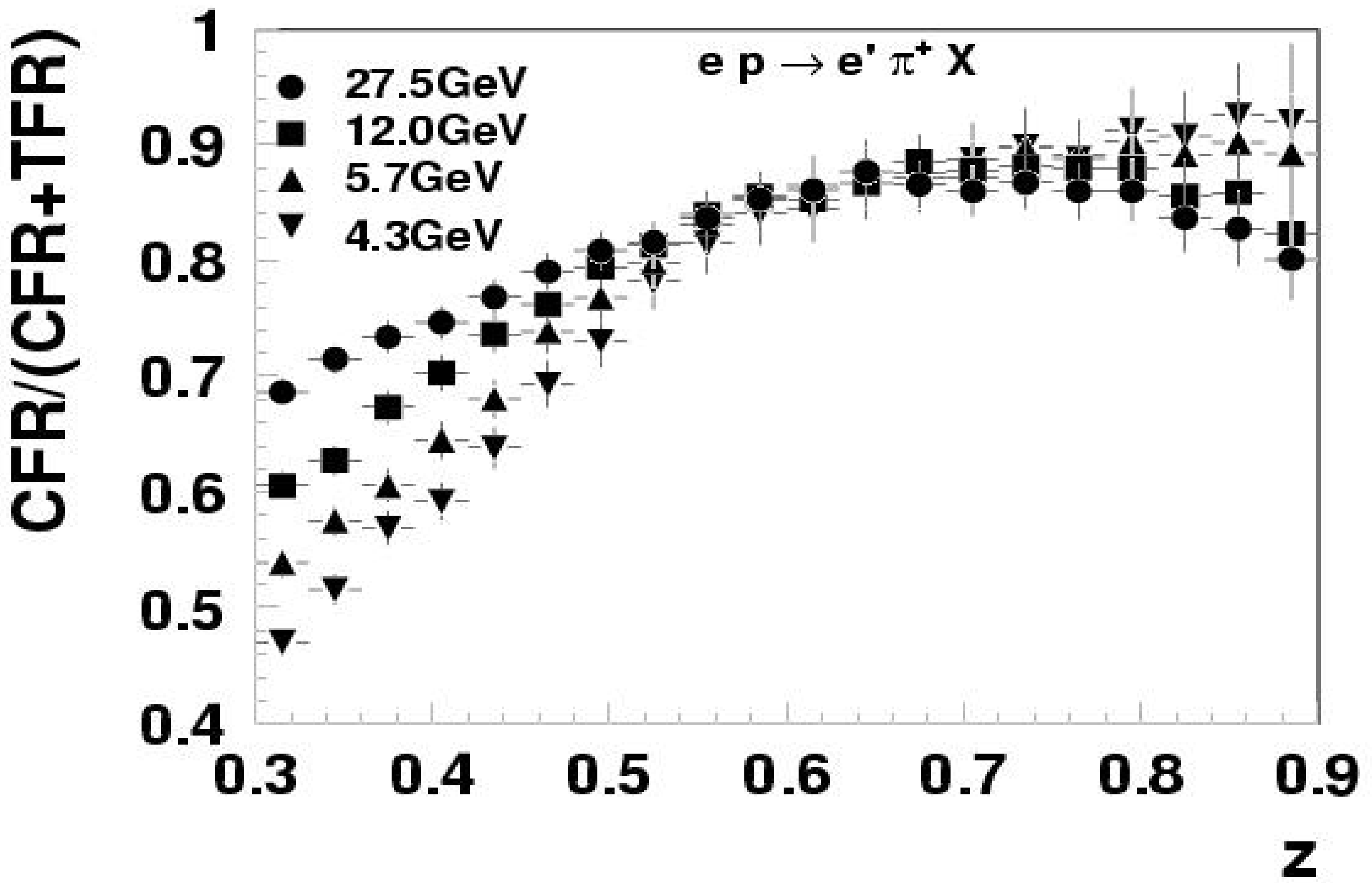
CLAS data (4.3GeV)
and LUND-MC
comparison



LUND-MC
tuned at higher
energies

Current Fragmentation Region at CLAS

DIS:
$Q^2>1$
$W^2>4$
$y<0.85$



The separation of CFR with $0.5<z<0.8$ is not changing significantly with beam energy.