Perspective of TMD Measurements At Jefferson Lab (6 and) 11 GeV

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June 15, 2007@Trento, Italy.

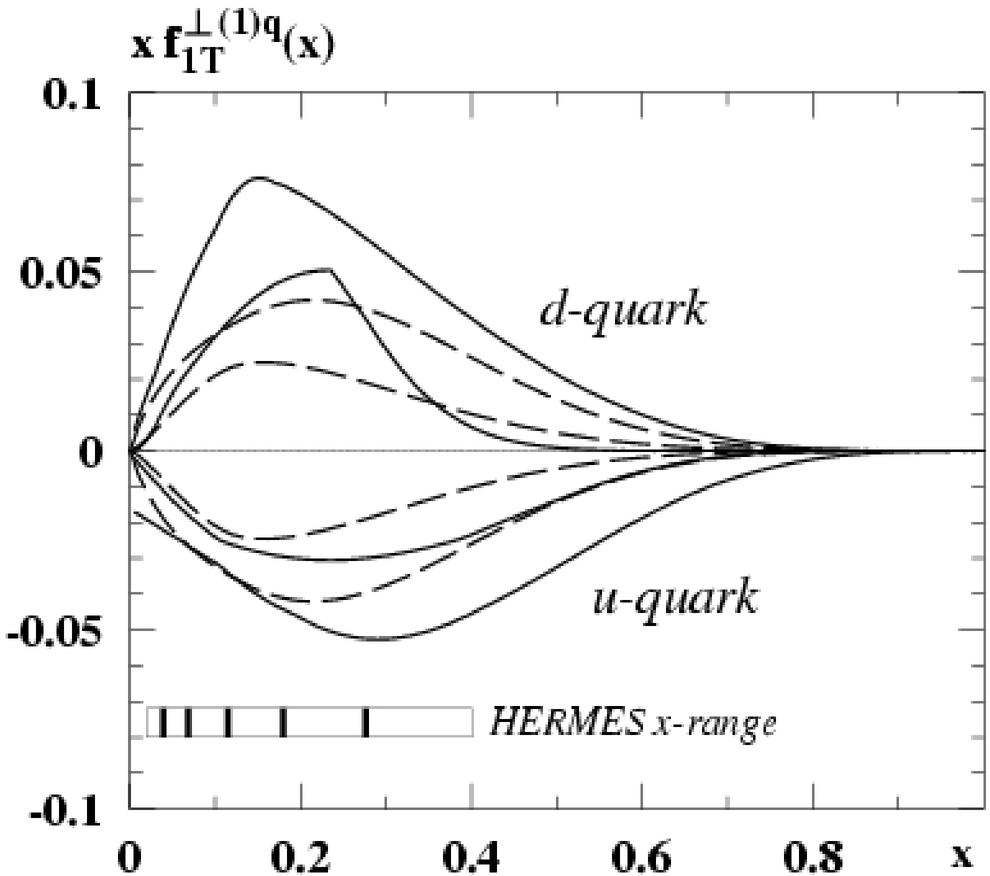
1. A_{UT} 6 GeV measurement with a polarized ^{3}He target.

2. A_{LT} 6 GeV measurement with a polarized proton target.

3. Perspective of 11 GeV TMD measurements.

4. How do we know we hit a quark (at 11 GeV) ?

If d-quark Sivers function is large ...



M. Anselmino et al., hep-ph/0511017.

Fit to data.

- Sivers function: correlation between quark transverse momentum and nucleon's transverse spin.

Consistent with a bag model calculation (F. Yuan).
d-quark's angular momentum is opposite to u-quark's.

Target single-spin asymmetries on a neutron can not be small

Neutron

Proton:	u	u	d	Notation: $d = u_n$			
e_q^2:	$\frac{4}{9}$	$\frac{4}{9}$	$\frac{1}{9}$				
Neutron:	d_n	d_n	u_n	$\Rightarrow$	u	u	d
e_q^2:	$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$		$\frac{1}{9}$	$\frac{1}{9}$	$\frac{4}{9}$

Charged pion

$\pi^+(u\bar{d})$ $\pi^-(d\bar{u})$

$$D^{fav} = D_u^{\pi^+} = D_d^{\pi^-} \qquad D^{unfav} = D_u^{\pi^-} = D_d^{\pi^+}$$

$$\sigma_n^{\pi^+} \propto 4d \cdot D^{fav} + u \cdot D^{unfav} \qquad \sigma_n^{\pi^-} \propto 4d \cdot D^{unfav} + u \cdot D^{fav}$$

$n(e, e'\pi^+)$ is sensitive to d-quark. $n(e, e'\pi^-)$ is more sensitive to u-quark.

- Two JLab 6 GeV transverse spin experiments.

Experiment E06-010 and E06-011: neutron $A_{UT}^{n\pi-}$ and $A_{UT}^{n\pi+}$

Approved with "A" rating and 29 days of beam time. These two experiments, scheduled to take data in mid 2008, will provide the first neutron data on the transverse target single-spin asymmetries in semi-inclusive DIS.

- Access information on quark distribution in semi-inclusive DIS.
- High luminosity experiment on a polarized ^{3}He target, valence quark effect at high-x.

Experiment E06-010/E06-011 at Jefferson Lab Hall A

California State Univ., Duke Univ., Florida International. Univ., Univ. Illinois, JLab, Univ. Kentucky, Univ. Maryland, Univ. Massachusetts, MIT, Old Dominion Univ., Rutgers Univ., Temple Univ., Penn State Univ., Univ. Virginia, College of William & Mary, Univ. Sciences & Tech, China Inst. Of Atomic Energy, Beijing Univ., Seoul National Univ., Univ. Glasgow, INFN Roma and Univ. Bari, St. Mary's Univ., Univ. of Ljubljana, Tel Aviv Univ.

Collaboration

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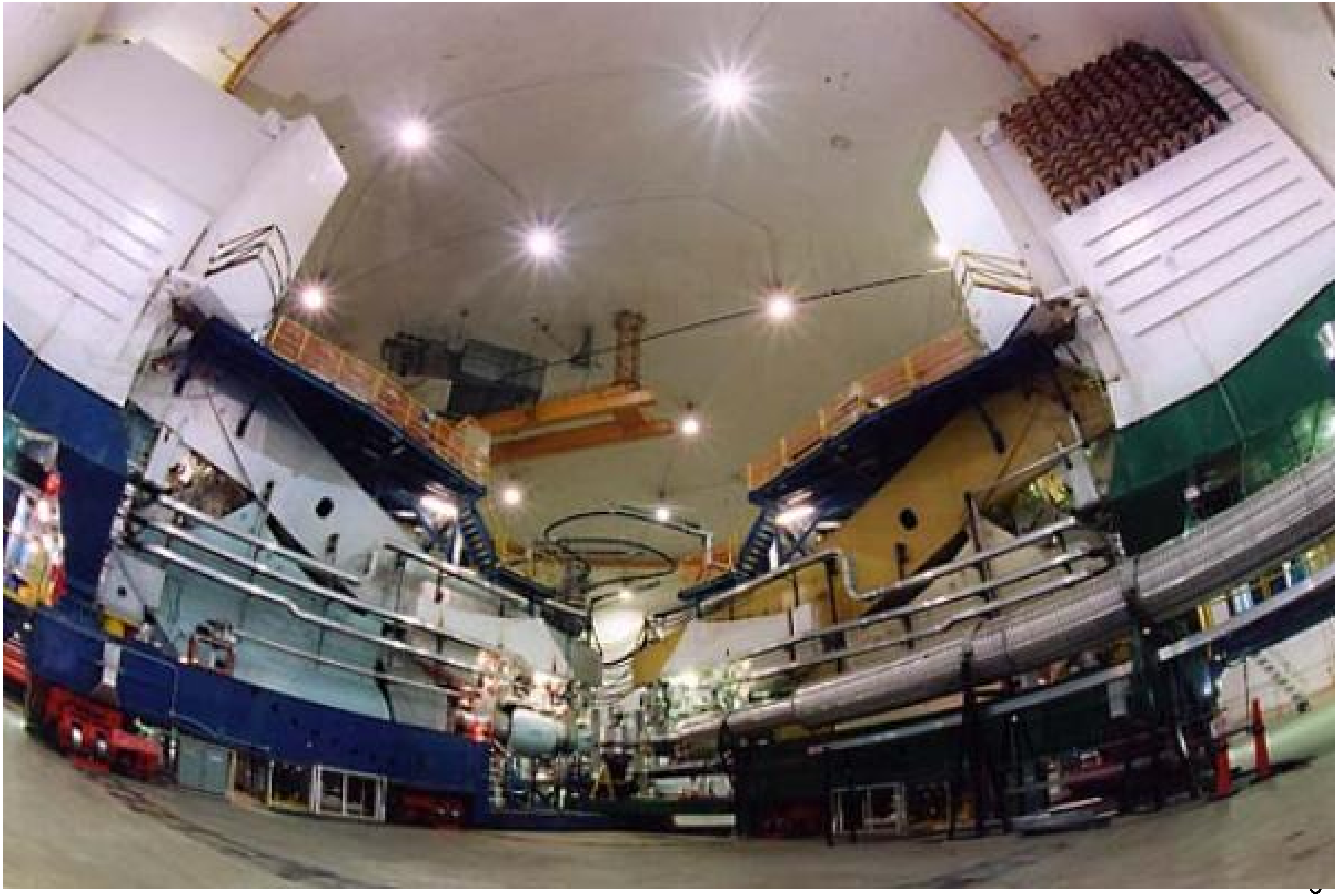
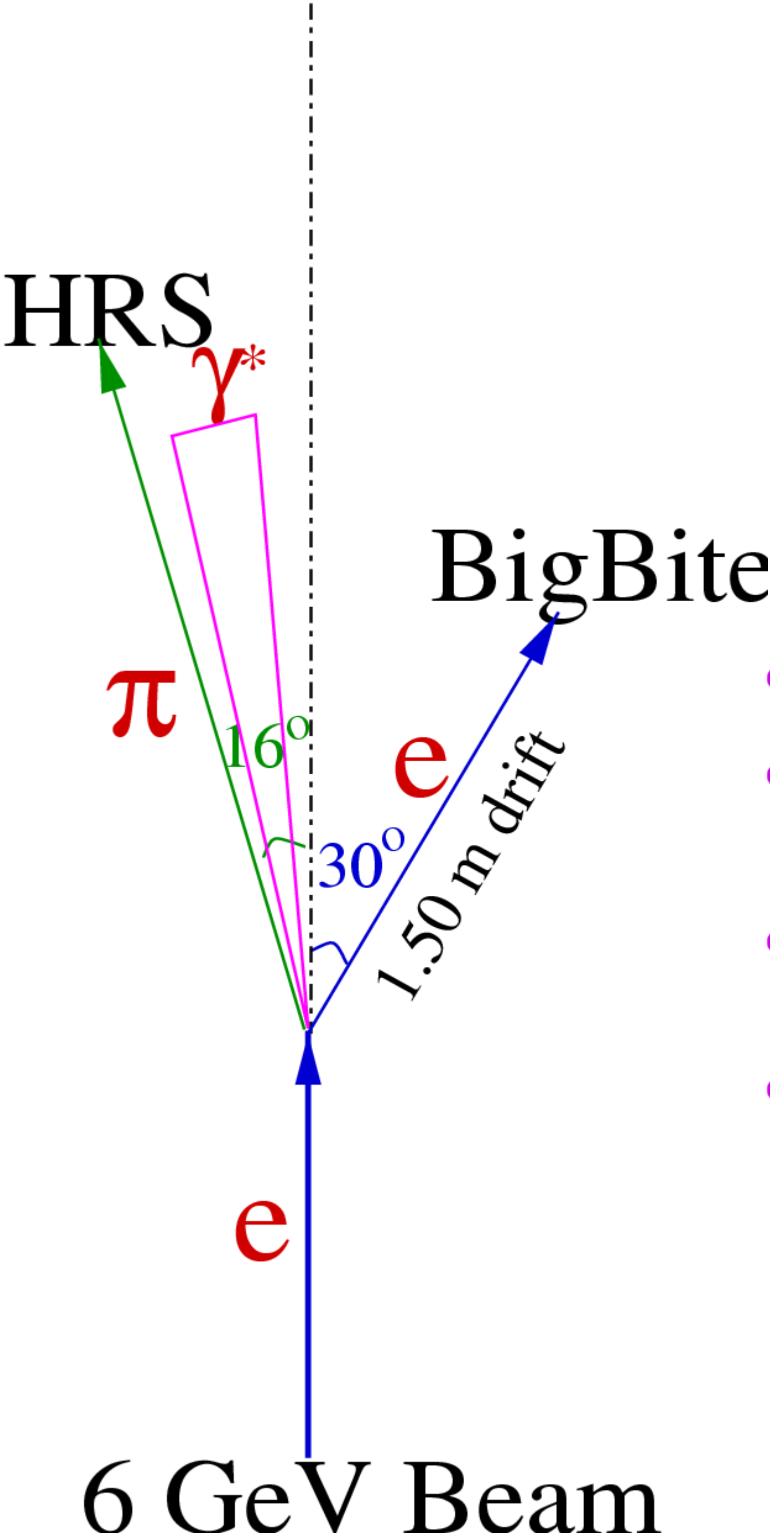
Jefferson Lab Hall A



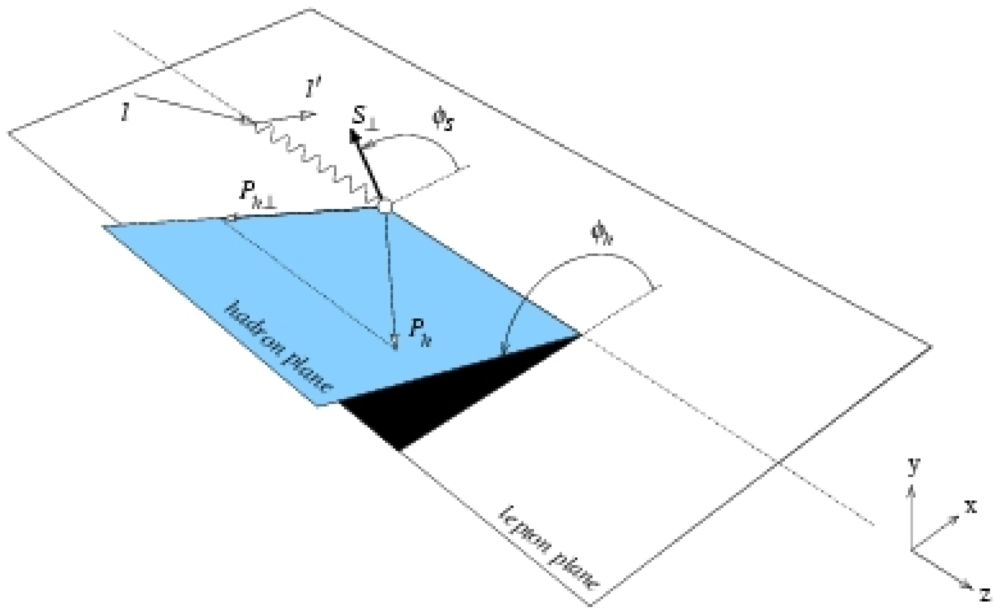


E06-010 and E06-011

- Use existing equipments in Hall A.
- Polarized ^{3}He target, 10 atm pressure.
  $\mathcal{L}(\vec{n}) = 10^{36}$ cm^{-2}s^{-1}.
- HRS$_L$ at 16° as h-arm ($\pi^{+/-}$ or $K^{+/-}$ with RICH for PID.).
  $p_h = 2.4$ GeV/c, $z = 0.5$.
- BigBite spectrometer at 30° as e-arm. $\Delta\Omega = 64$ msr.

Separation of Collins and Sivers effects through angular dependence

$$A_{UT}(\phi_h^l, \phi_S^l) = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

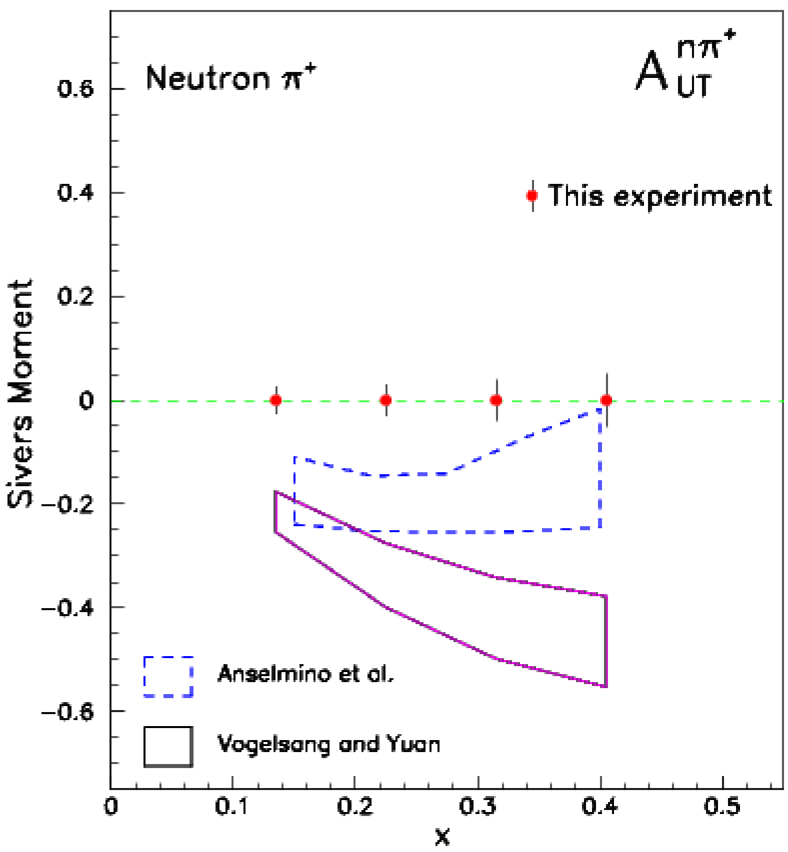


$$\sigma_{UT} \quad \propto \quad S_T(1-y)\frac{P_{h\perp}}{zM_h}\,\sin(\phi_h^\ell + \phi_S^\ell) \cdot \sum e_q^2\, h_1^q(x) \otimes H_{1q}^{\perp h}(z, P_{h\perp}^2)$$

$$+ \quad S_T(1-y+\frac{y^2}{2})\frac{P_{h\perp}}{zM_N}\,\sin(\phi_h^\ell - \phi_S^\ell) \cdot \sum e_q^2\, f_{1T}^{\perp q}(x) \otimes D_{1q}^h(z_h, P_{h\perp}^2)$$

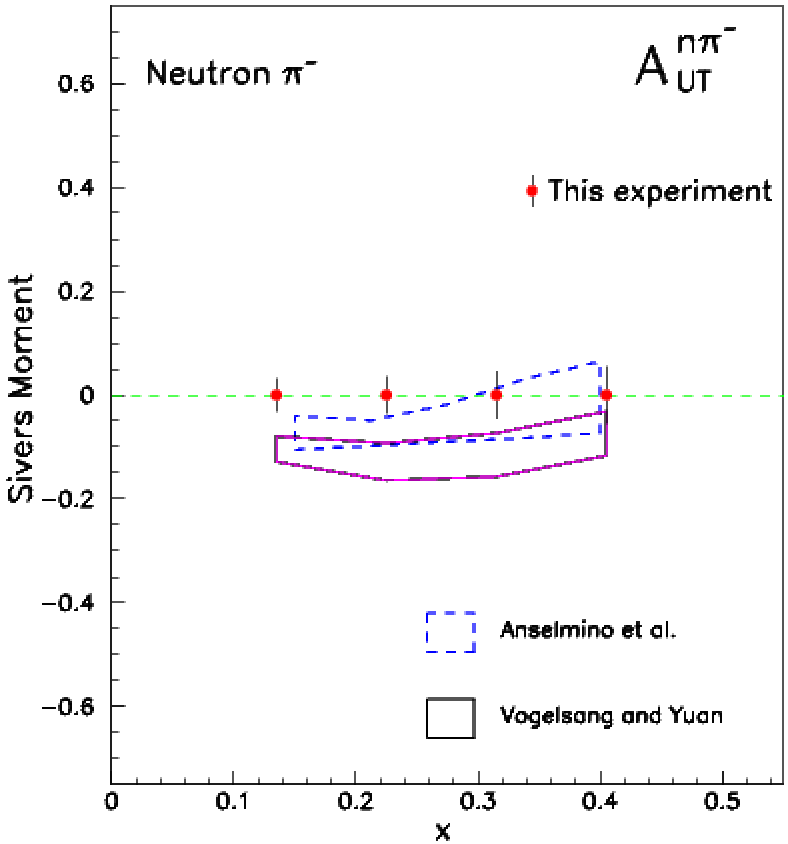
Freedom in target spin orientation: easy separation of Collins and Sivers asymmetries.

Sivers Asymmetry $A_{UT}^{n\pi^+}$ Compared with Expectations



- Sivers π^+ asymmetry is large and negative ?
- $f_{1T}^{\perp d} \approx f_{1T}^{\perp u}$? d-quark carries opposite angular momentum compared to u-quark ?

Sivers Asymmetry $A_{UT}^{n\pi^-}$



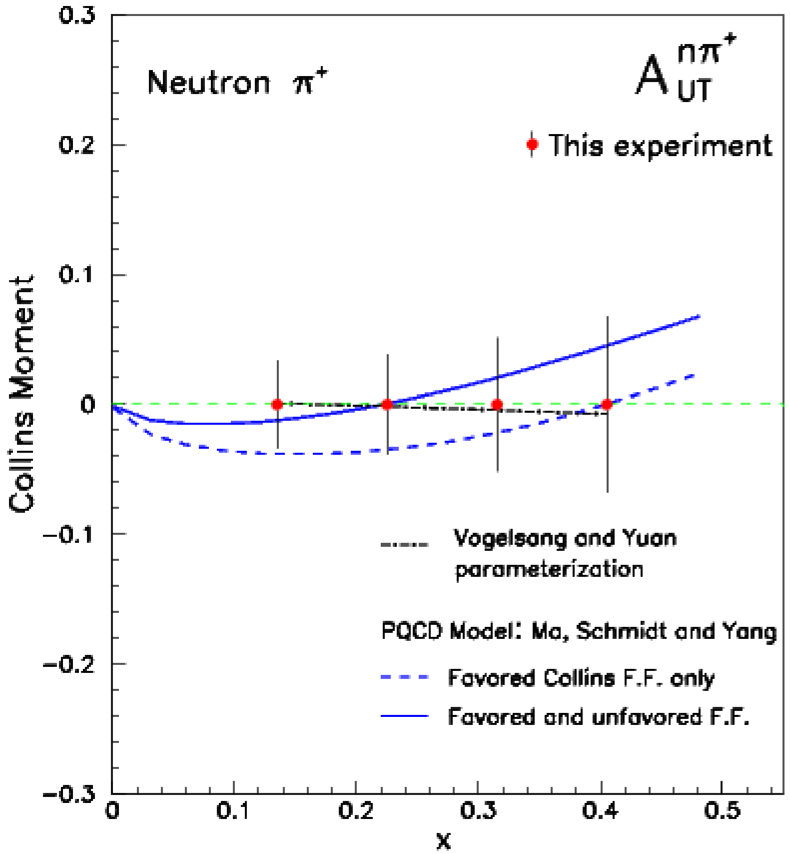
JLab neutron data allows an independent extraction of u and d-Sivers function to cross check with HERMS and COMPASS extracted Sivers functions.

JLab neutron Sivers:

$$A_{UT}^{n\pi^+} \propto 4 f_{1T}^{\perp d} \cdot D_1^{fav} + f_{1T}^{\perp u} \cdot D_1^{unfav}$$

$$A_{UT}^{n\pi^-} \propto 4 f_{1T}^{\perp d} \cdot D_1^{unfav} + f_{1T}^{\perp u} \cdot D_1^{fav}$$

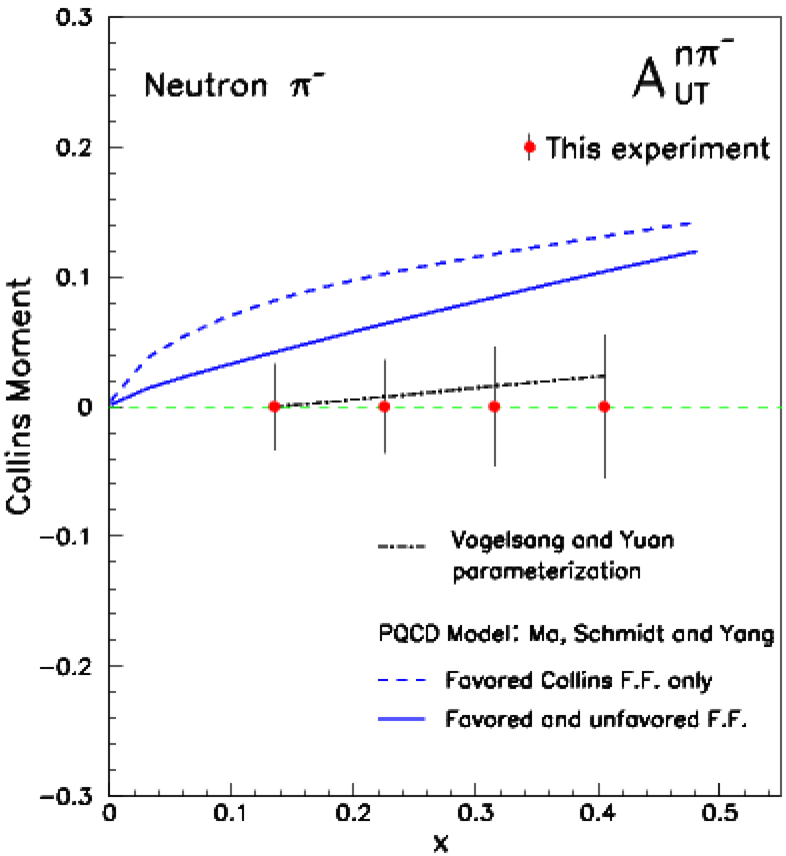
Collins Asymmetry $A_{UT}^{n\pi^+}$ Compared with Expectations



- Collins π^+ asymmetry is expected to be small ?
- Cancellations between δu and δd ?
- Collins F.F. $H_1^{\perp unfav} \approx -H_1^{\perp fav}$?

Ma *et al.* assumed: $\frac{H_1^{\perp unfav}}{H_1^{\perp fav}} = \frac{D_1^{unfav}}{D_1^{fav}}$.

Collins Asymmetry $A_{UT}^{n\pi^-}$



- Collins π^- asymmetry is expected to be non-vanishing ?

A combined analysis with HERMES proton data and $A_{UT}^{n\pi^-}$ allows a solution of four unkowns:

HERMES proton Collins:

$$A_{UT}^{p\pi^+} \propto 4\delta u \cdot H_1^{\perp fav} + \delta d \cdot H_1^{\perp unfav}$$

$$A_{UT}^{p\pi^-} \propto 4\delta u \cdot H_1^{\perp unfav} + \delta d \cdot H_1^{\perp fav}$$

JLab neutron Collins:

$$A_{UT}^{n\pi^+} \propto 4\delta d \cdot H_1^{\perp fav} + \delta u \cdot H_1^{\perp unfav}$$

$$A_{UT}^{n\pi^-} \propto 4\delta d \cdot H_1^{\perp unfav} + \delta u \cdot H_1^{\perp fav}$$

A_{LT} at 6 GeV: JLab proposal PR07-015

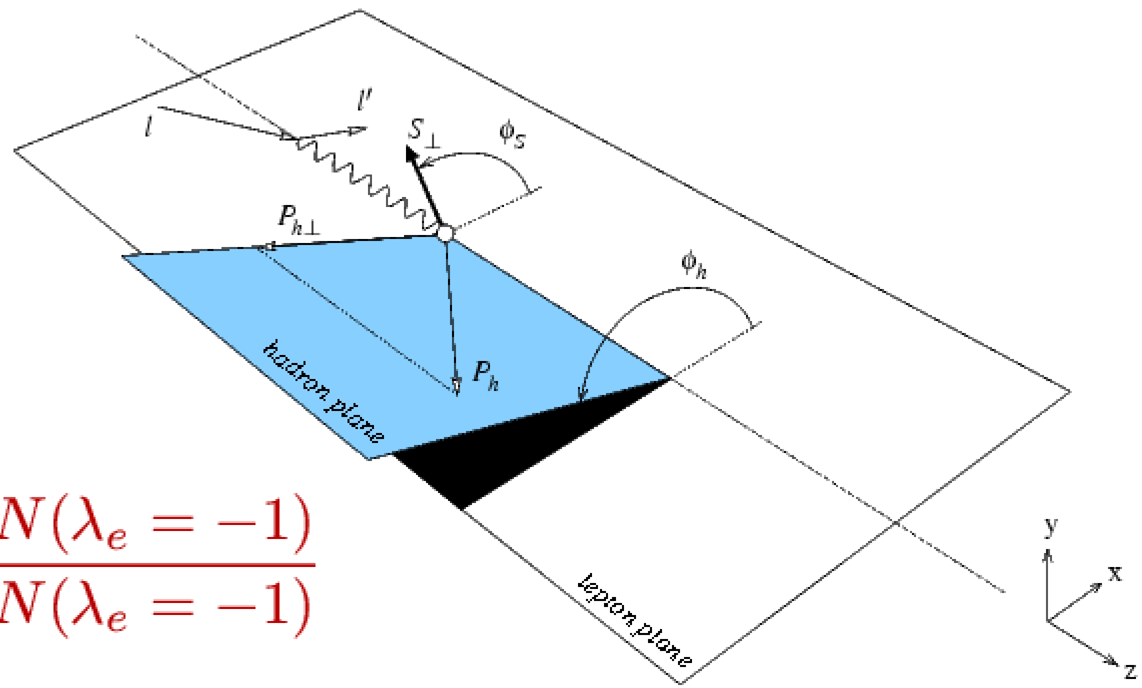
X. Jiang et al. Jan. 2007.

Goal: to clearly establish $\mathcal{A}_{LT} \neq 0$ through $p^{\uparrow}(\vec{e}, e'\pi^{+})X$ reaction, and make the first extraction of u-quark transverse-momentum dependent (TMD) parton distribution $g_{1T}(x, Q^2)$.

- A non-zero $\mathcal{A}_{LT}$ arises from a non-zero g_{1T}^{q}, which is a direct result of quark's transverse motion (thus its angular momentum).
- A non-zero $\mathcal{A}_{LT}$ has never been established. Models predict $\mathcal{A}_{LT} \approx 5 \sim 10\%$. g_{1T}^{q} can be linked to other parton distributions through Lorentz Invariance relation and Equation of Motion.

NOT APPROVED:
1. Limitation on beam time (500 hours).
2. Lack of a strong physics motivation.
3. Limited Pt coverage (0.0-0.5 GeV/c).
4. Extraction of g_{1T} is model dependent (Pt shape).

Transverse Target Asymmetry $\mathcal{A}_{LT}$ in $p^{\uparrow}(\vec{e}, e'\pi^{+})$

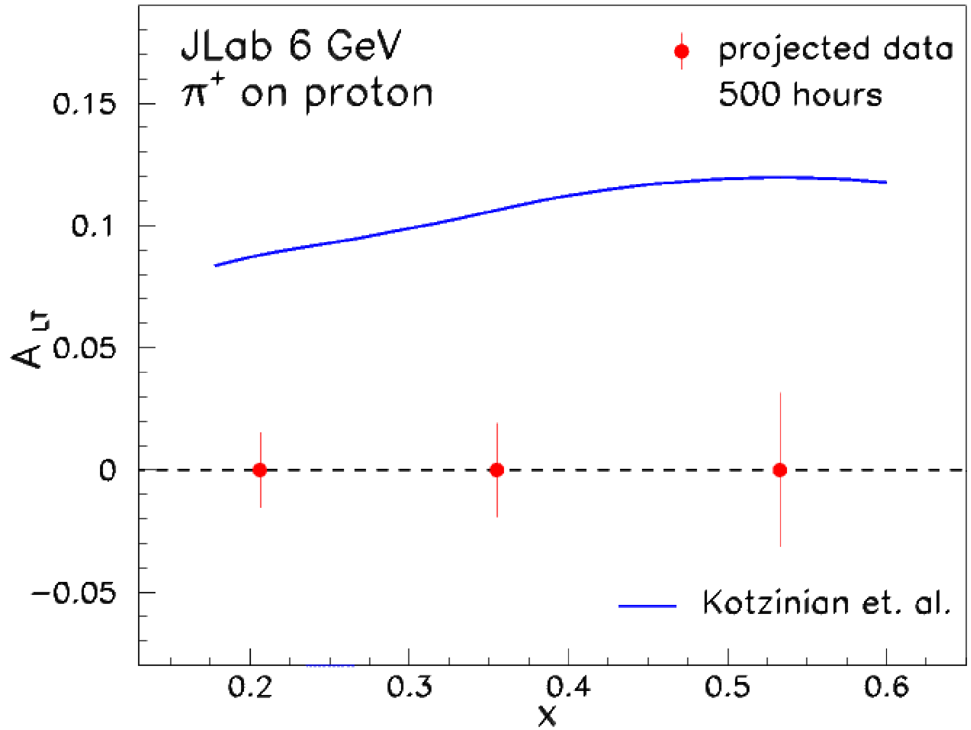


$$\mathcal{A}_{LT} = \frac{N(\lambda_e = +1) - N(\lambda_e = -1)}{N(\lambda_e = +1) + N(\lambda_e = -1)}$$

$$\sigma_{LT} = \lambda_e S_{\perp} \cdot \cos(\phi_h^{\ell} - \phi_S^{\ell}) \sum_q e_q^2 \, g_{1T}^q(x) \otimes D_{1q}^h(z, P_{h\perp}^2)$$

u-quark dominance: (twice as much)$\cdot e_q^2 \cdot$ (favored F.F.) $\Rightarrow \mathcal{A}_{LT}^{\pi^+}(p) \propto \frac{g_{1T}^{u(1)}}{f_1^u}$.

This experiment: identical setup as in SANE$_{\perp}$, add HMS spectrometer at 14° to take coincidence triggers. $\phi_S^{\ell} \approx 180^{\circ}, 0^{\circ}$, $\phi_h^{\ell} \approx 180^{\circ} \Rightarrow \cos(\phi_h^{\ell} - \phi_S^{\ell}) \approx +1$ or -1.



- First data to establish $\mathcal{A}_{LT} \neq 0$.

New data on a new spin observable will stimulate more theory activities.

Surprises might be around the corner:

- $\mathcal{A}_{LT}$ end up too large or too small ?
- $\mathcal{A}_{LT}$ end up with the wrong sign ?

How much is the Lorentz Invariance relation violated ?

$$g_2^q(x) = \frac{d}{dx} g_{1T}^{q(1)}(x)$$

Constraint from QCD Equation of Motion

An exact relation (Mulders and Tangerman 1996):

$$x(g_1^q + g_2^q) = g_{1T}^{q(1)} + \frac{m_q}{M} h_1^q + x\tilde{g}_T$$

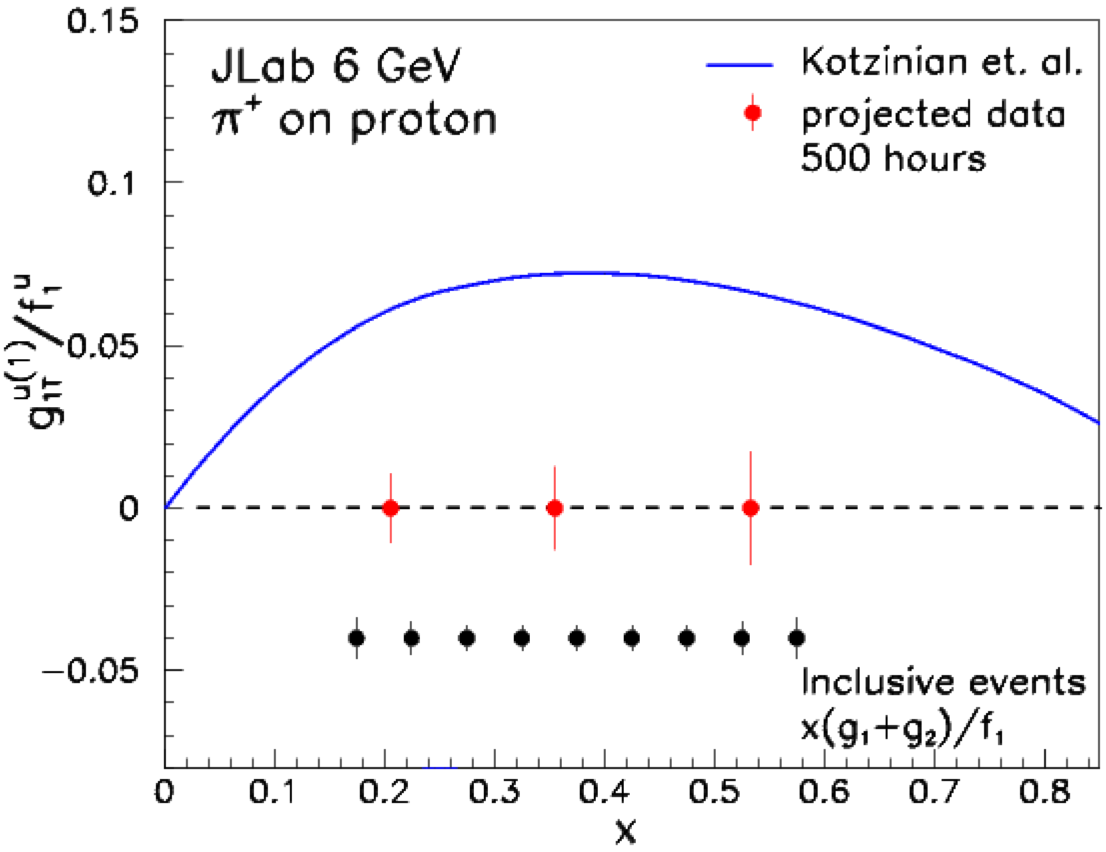
If ignore higher twist $\tilde{g}_T$ (Wandzura-Wilczek) and quark mass m_q:

$$x\left(g_1^q + g_2^q\right) = g_{1T}^{q(1)}, \quad i.e.\ A_2 \propto \mathcal{A}_{LT}.$$

A relation can be explicitly tested within the same data set since:

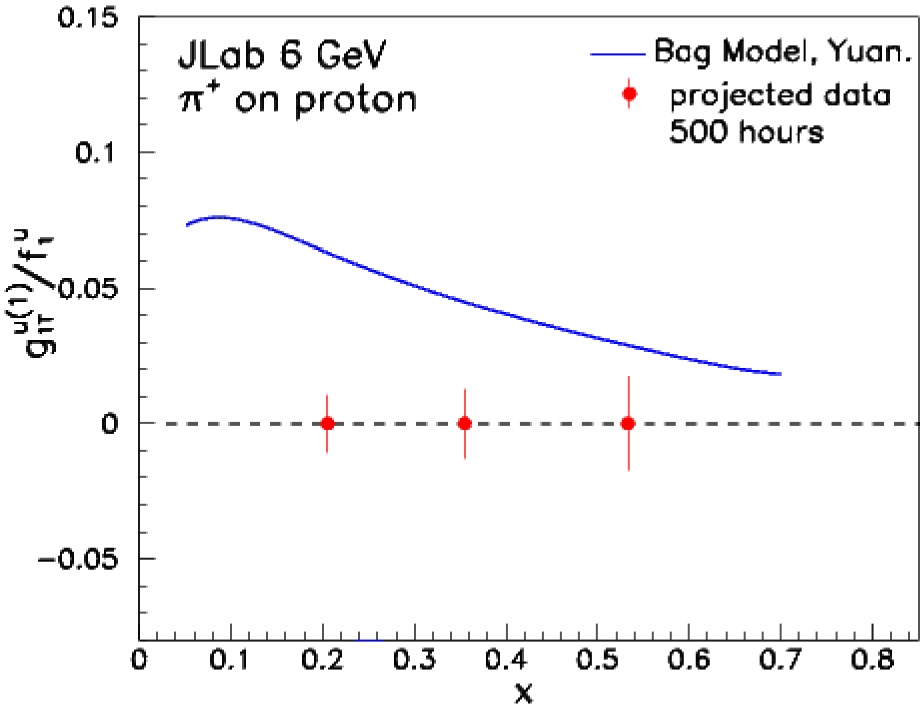
$$A_2(x,Q^2) = \frac{\gamma\left[g_1(x,Q^2) + g_2(x,Q^2)\right]}{F_1(x,Q^2)}, \quad \gamma^2 = \frac{(2Mx)^2}{Q^2}.$$

Inclusive asymmetries can be obtained at the same time



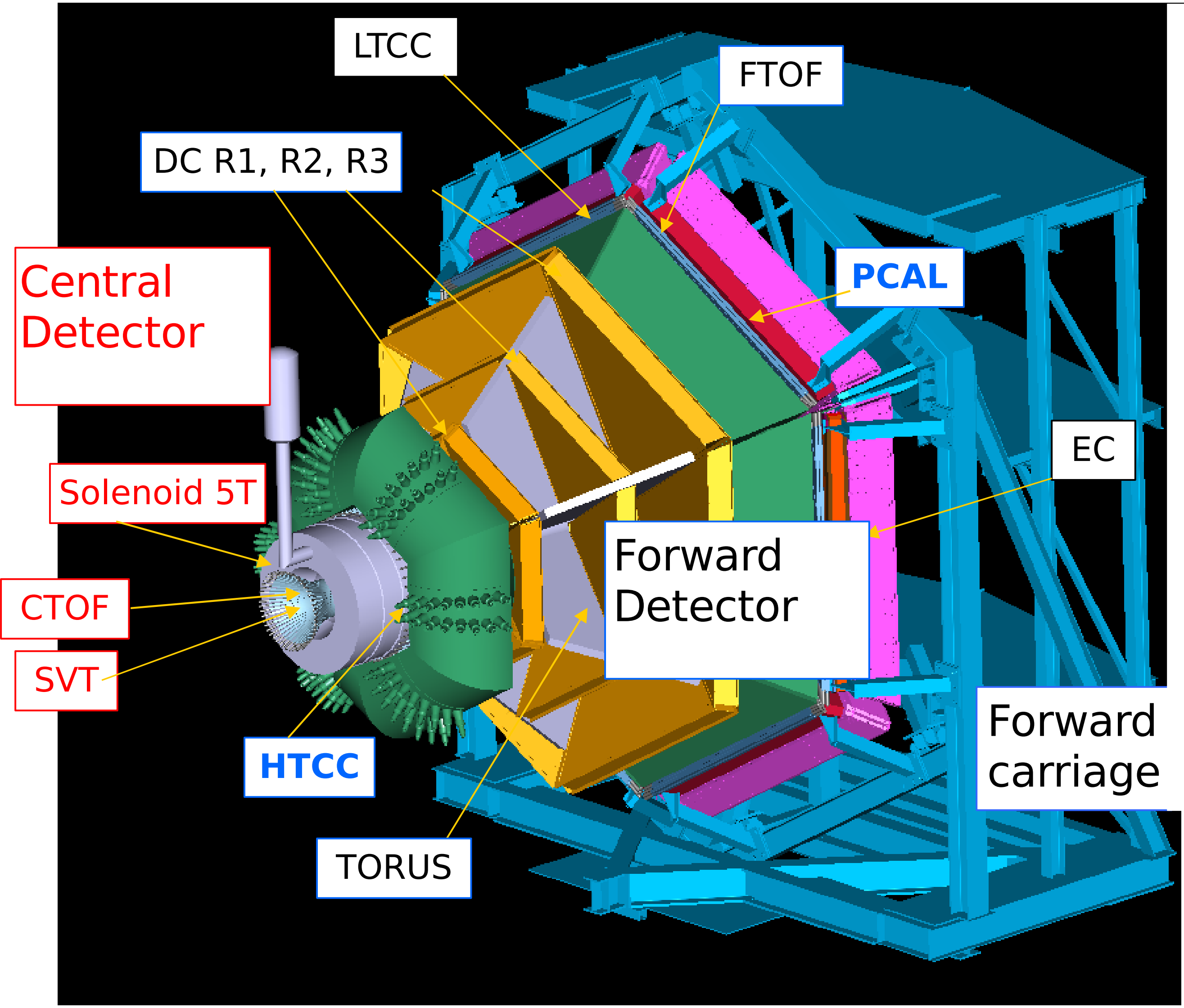
- High statistics.
- Common systematics in $P_B P_T$.

... and compare with Bag Model calculation



- g_{1T}^u has the same sign as Δu ?

After the JLab 12 GeV upgrade: CLAS12

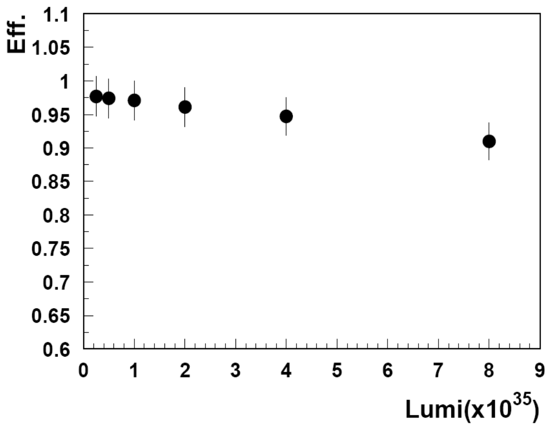


Wide detector and physics acceptance (current/target fragmentation)

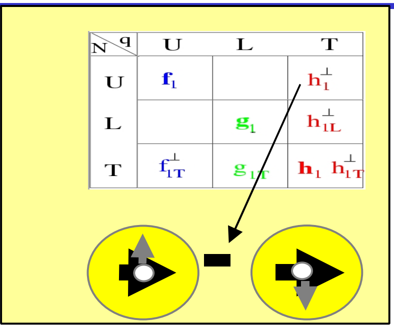
High beam polarization 85%

High target polarization 85%

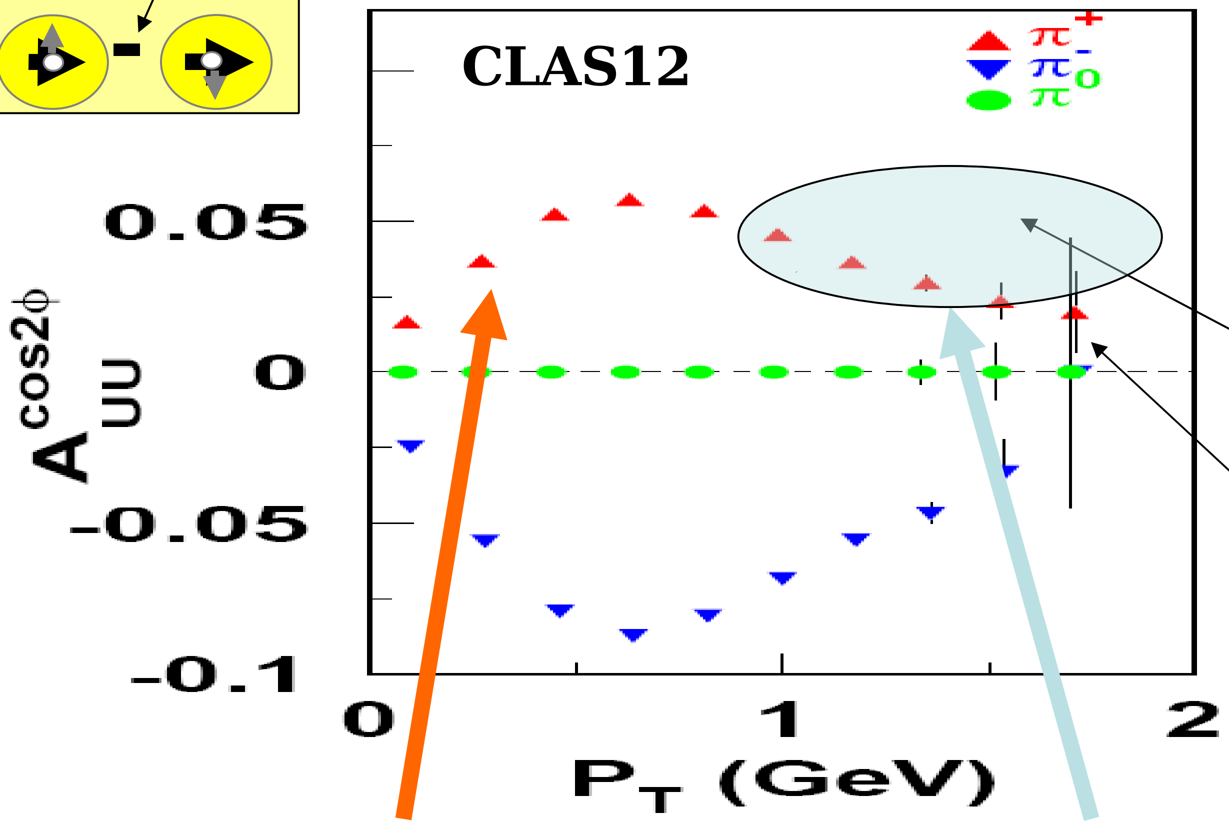
Lumi = $10^{35}cm^{-1}s^{-1}$



Collins asymmetry & Boer-Mulders Effect



$$A_{UU}^{\cos 2\phi} \propto h_1^\perp H_1^\perp$$



Transversely polarized quarks in the unpolarized nucleon

$\mathbf{s_T(p\times k_T)} \leftrightarrow h_1^\perp$

$\sin(\phi_C) = \cos(2\phi_h)$

In the perturbative limit $1/P_T^2$ behavior expected (F.Yuan)

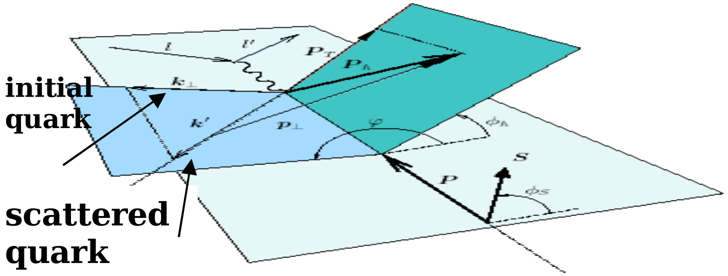
quark-scalar diquark model (L.Gamberg)

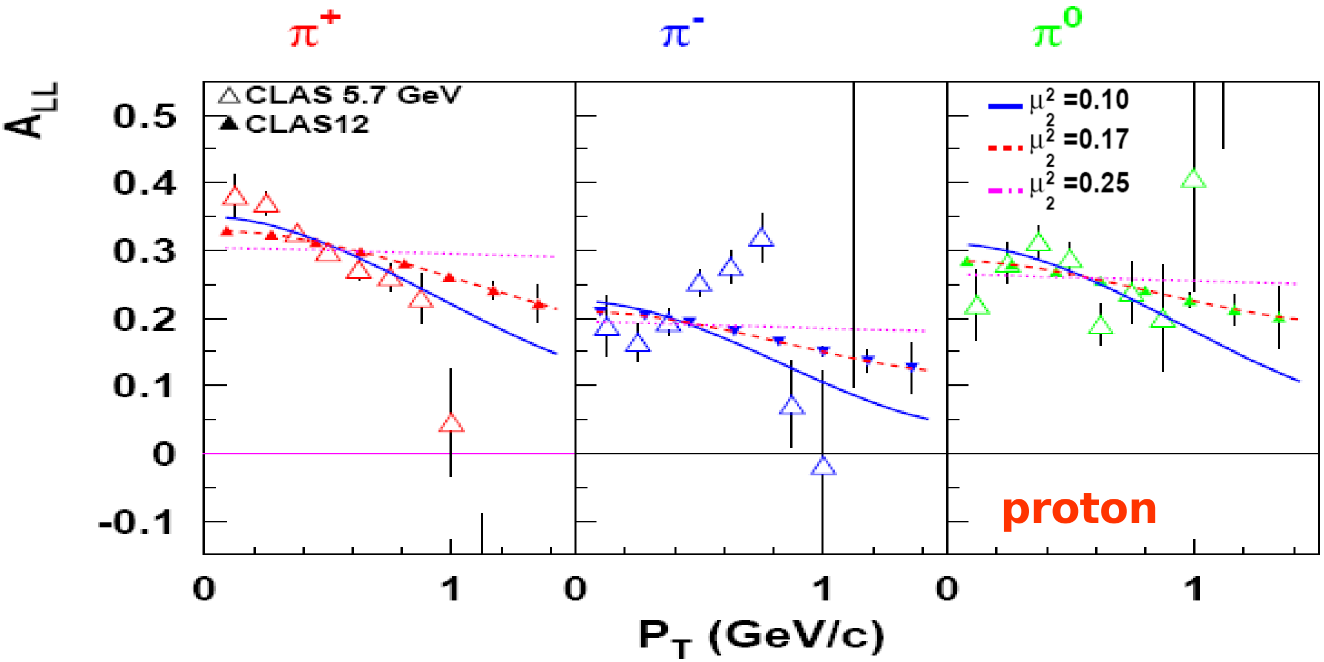
$4<Q^2<5$ (2000h @ 11 GeV with $10^{35} sec^{-1}cm^{-2}$)

Non-perturbative TMD **Perturbative region** $\Lambda_{QCD} \ll P_T \ll Q$

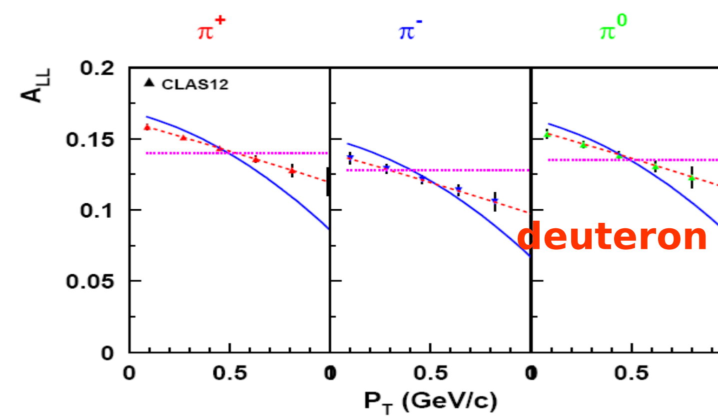
- BM cos2ϕ moment, sensitive to spin-orbit correlations: the only leading twist azimuthal moment for unpolarized target
- $\mathbf{P_T}$-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).
- More info will be available from SIDIS (HERMES,COMPASS,ZEUS,EIC) and DY (RHIC,GSI)

A_{LL}-P_T-dependence





hep-ph/0608048
μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2



$$\sigma_0 = \frac{1+(1-y)^2}{xy^2}\frac{1}{\mu_D^2+z^2\mu_0^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_0^2}\right)\sum_q e_q^2 f_1^q(x)\, D_q^h(z)$$

$$\Delta\sigma_{LL} = \frac{y(2-y)}{xy^2}\frac{1}{\mu_D^2+z^2\mu_2^2}\exp\left(-\frac{P_{hT}^2}{\mu_D^2+z^2\mu_2^2}\right)\sum_q e_q^2 g_1^q(x)\, D_q^h(z)$$

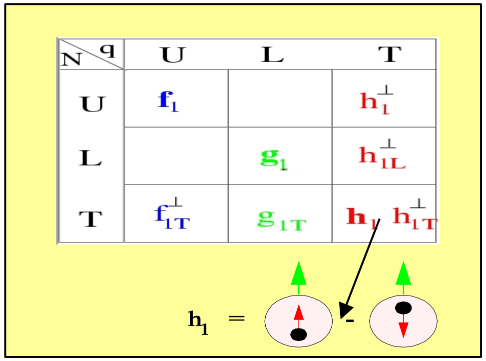
$$f_1^q(x,k_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_\perp^2}{\mu_0^2}\right),$$

$$D_q^h(z,p_\perp) = D_q^h(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_\perp^2}{\mu_D^2}\right)$$

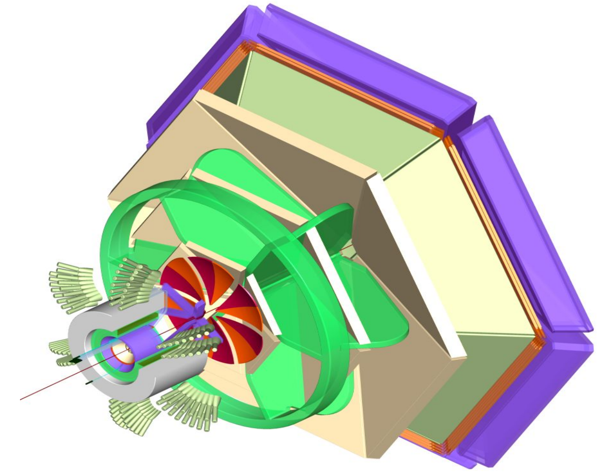
$$g_1^q(x,k_\perp) = g_1^q(x)\frac{1}{\pi\mu_2^2}exp(-\frac{k_\perp^2}{\mu_2^2})$$

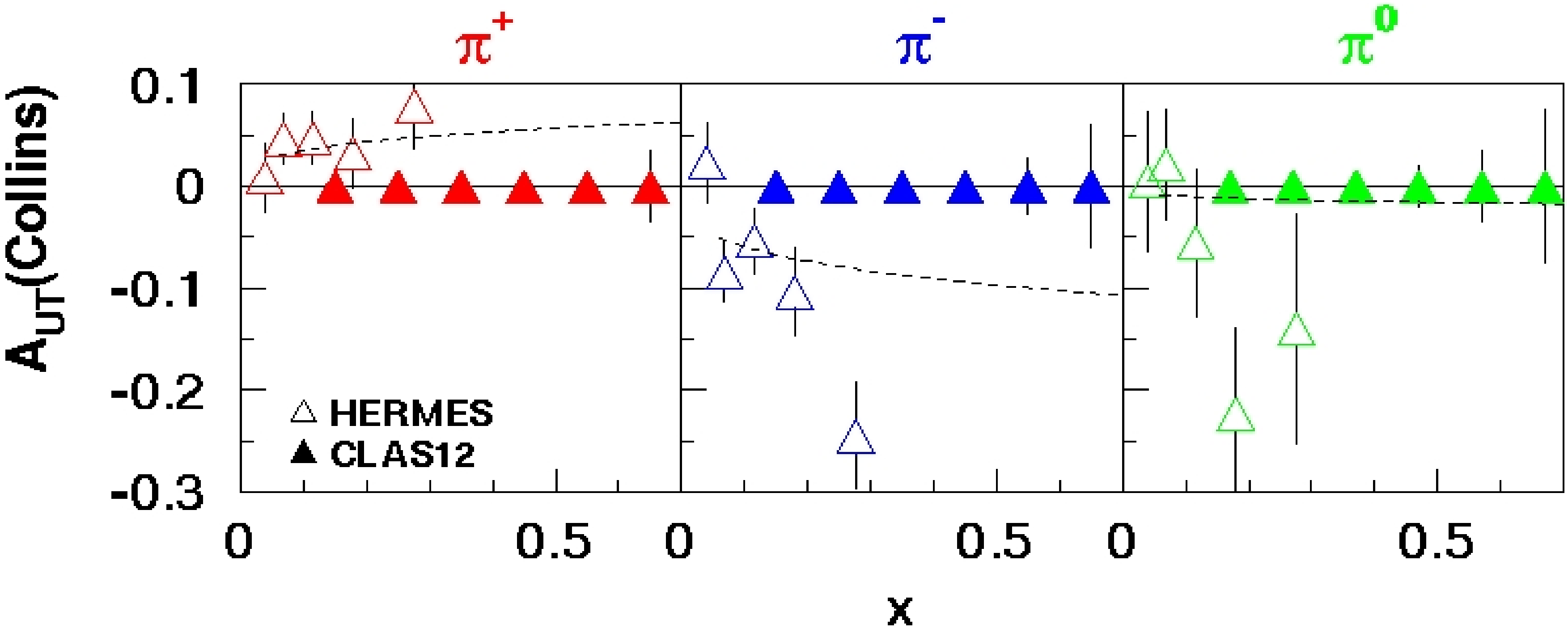
P_T-dependence of double spin asymmetries provide access to difference in k_T-distributions of quarks with spin orientations along and opposite to the proton spin.

Collins Effect



$$\sigma_{UT}^{Collins} \sim (1-y)\, h_1 H_1^\perp$$





Study the Collins fragmentation for all 3 pions with a **transversely polarized target** and measure the transversity distribution function.

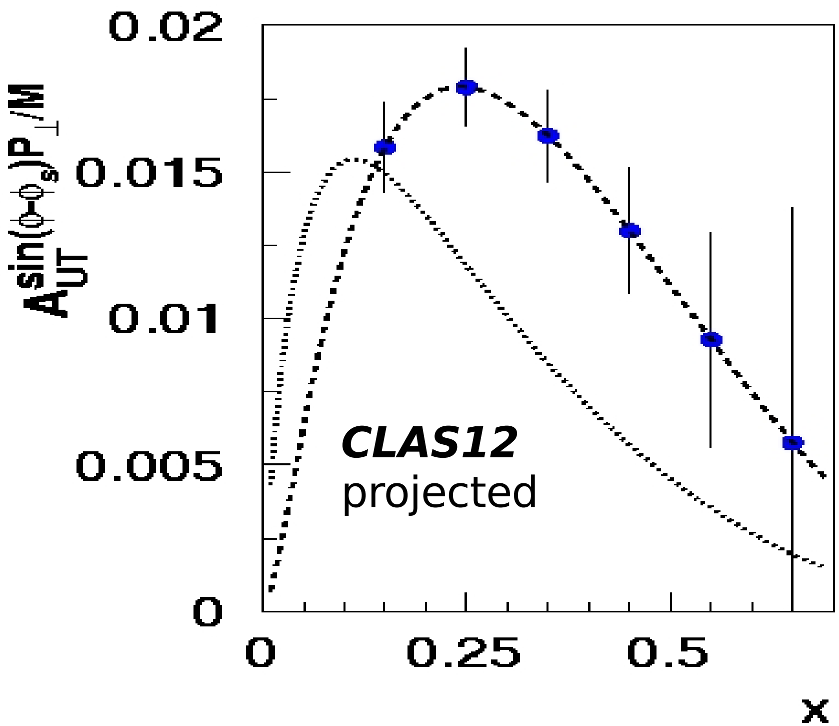
CLAS12: Sivers effect projections

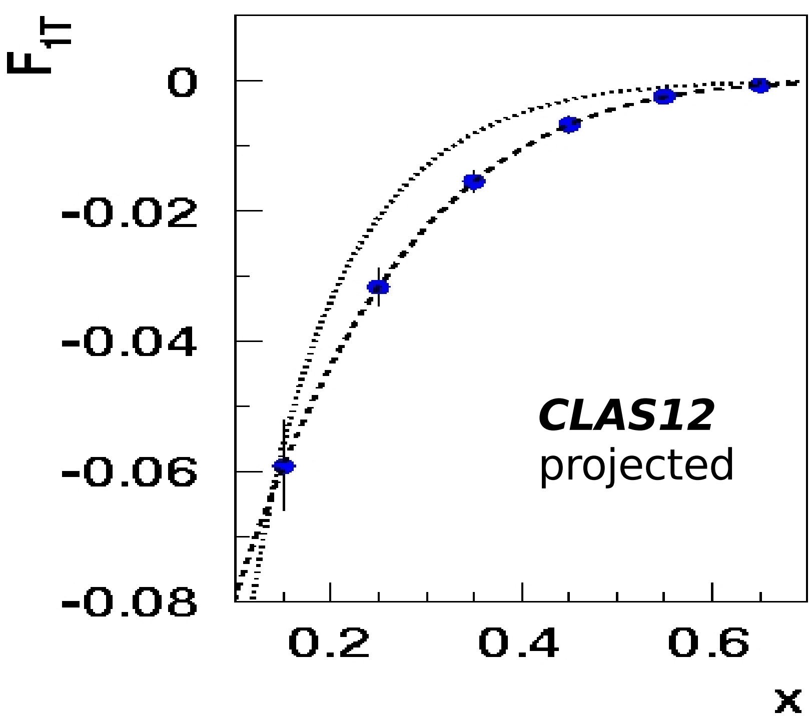
In large Nc limit:
$f_{1T}^{u} = -f_{1T}^{d}$

$$f_{1T}^{\perp}(x) D_1(z)$$

Efremov et al
(large x_B behavior of f_{1T} from GPD E)

$$F_{1T}=\sum_q e_q^2 f_{1T}^{\perp q}$$





Sivers function extraction from A_{UT} (π^0) does not require information on fragmentation function. It is free of HT and diffractive contributions.

A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.

A Solenoid in Hall A

- Program on spin structure with polarized target(s) and a solenoid
  - highest polarized luminosity: ~10^{36}
  - **A solenoid magnet with detector package (GEM, Lead-glass+ Cherenkov)**

    large acceptance: ~700 msr for polarized

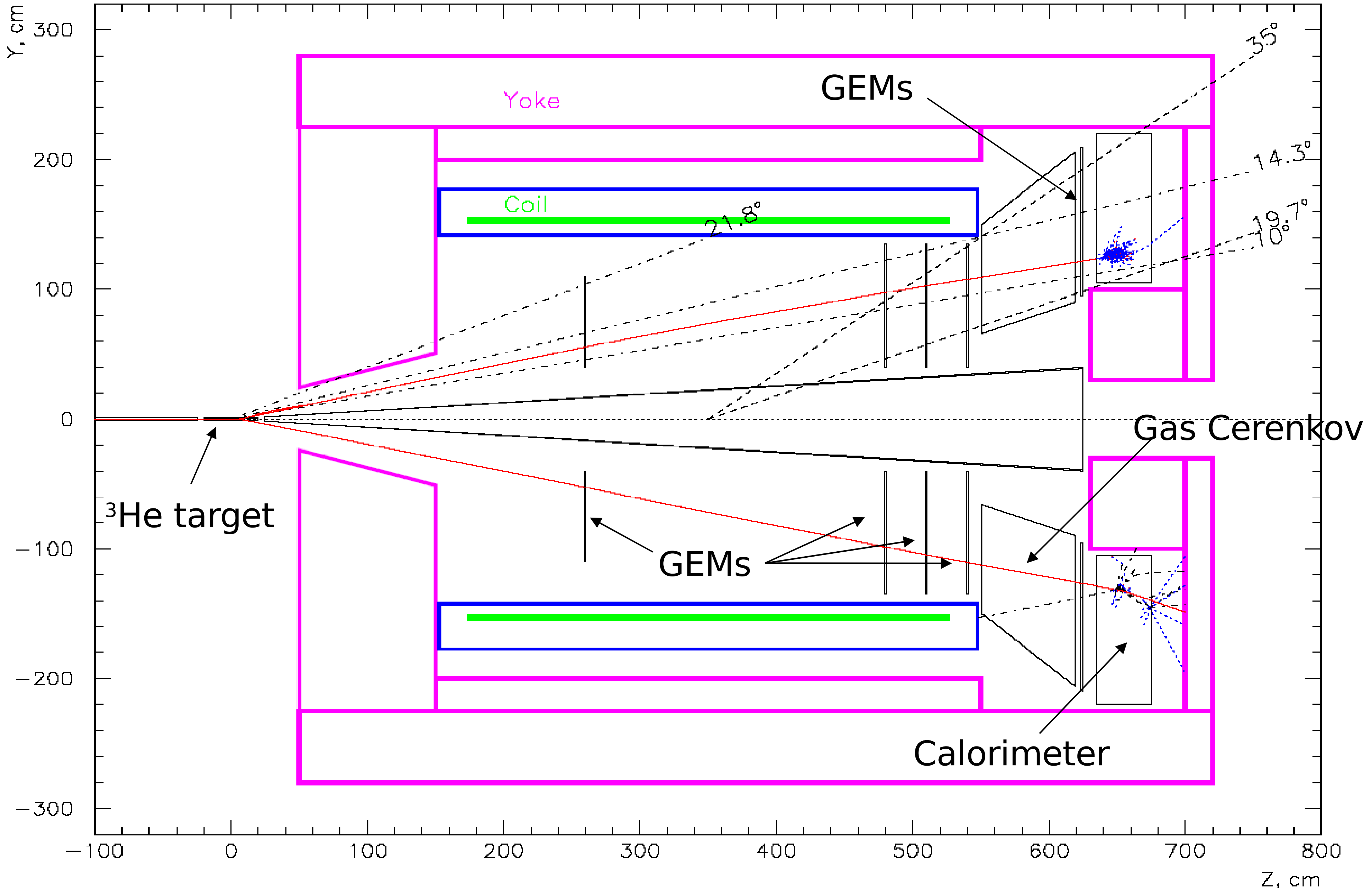
  → high luminosity and large acceptance
  - **Inclusive DIS: improve by a factor of 10-100**

    A_1 at high-x: 200 hours, high precision
  - **SIDIS: improve by a factor of 100-1000**

    spin-flavor decomposition (~2 orders improvement)

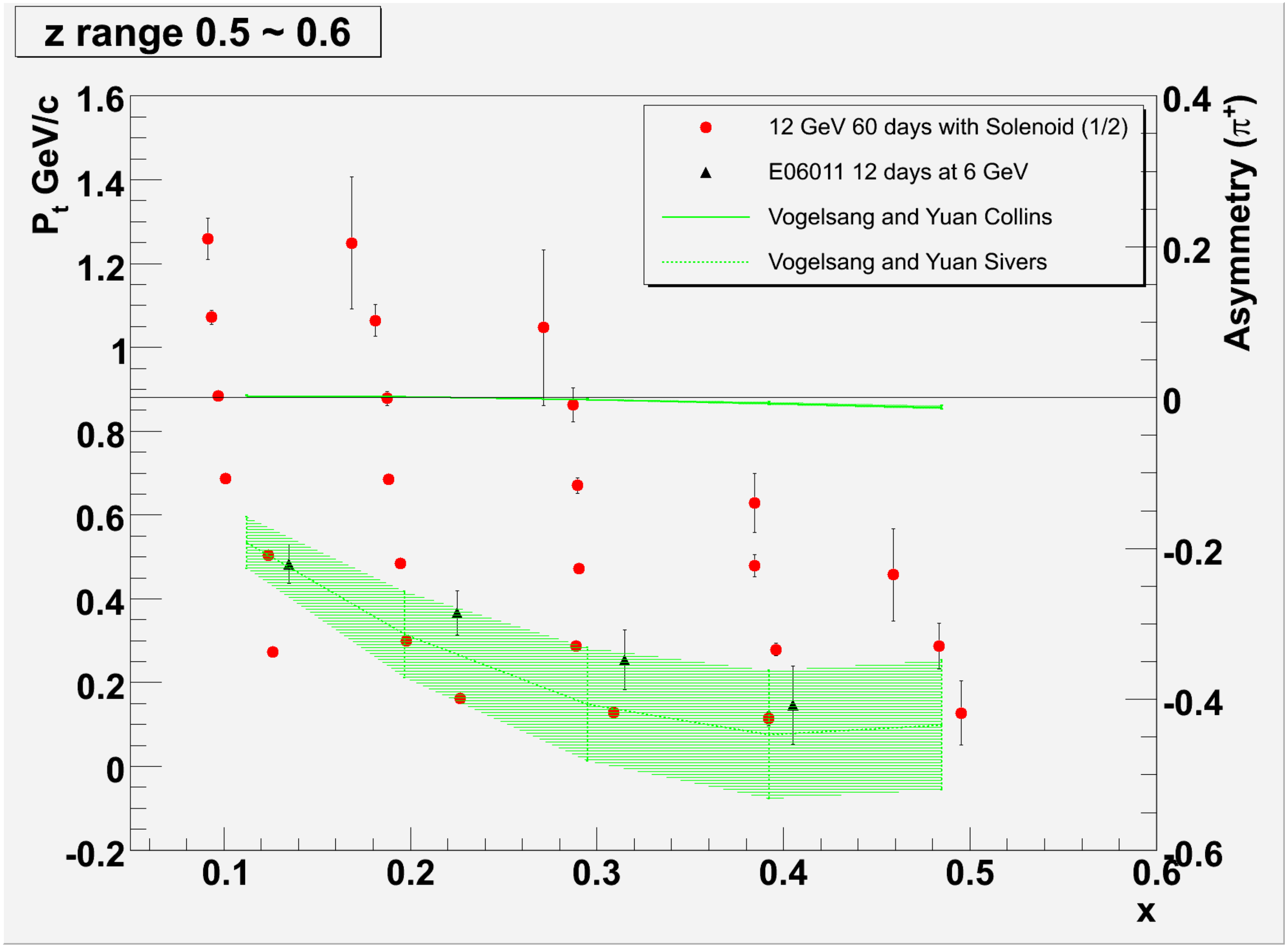
    transversity and TMDs,

Solenoid detector for (SI)DIS



Projection of Collins/Sivers Asymmetries vs P_T and x for π+ (60 days)

- For one z bin (0.5-0.6)
- Will obtain 4 z bins (0.3-0.7)
- Also π- at same time
- With upgraded PID for K+ and K-



Interpretation Issues of SIDIS Reaction at 11 GeV

- How do we know that we hit a quark ?
- Is the information of the struck quark well-preserved when it fragment into a hadron ?
- What is the kinematic region over which SIDIS reactions at 11 GeV can be interpretated in terms of parton PDFs and quark Frag. Func.

Do we understand SIDIS multiplicities, the x-, Q2- and z-dependencies,
and the relative relations between different hadrons ?

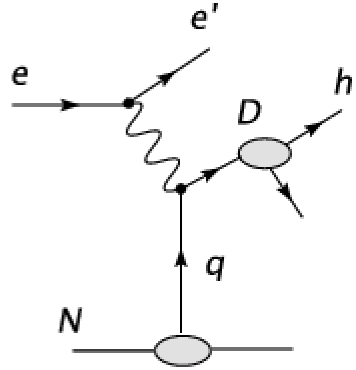
Do we understand the SIDIS cross sections ?

to the Next-to-Leading Order.

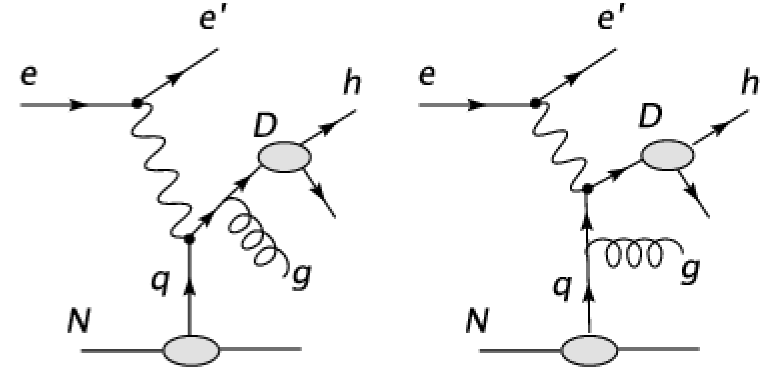
H.-J. Lu and X. Jiang et al. June 2007.

At the Next-to-Leading Order

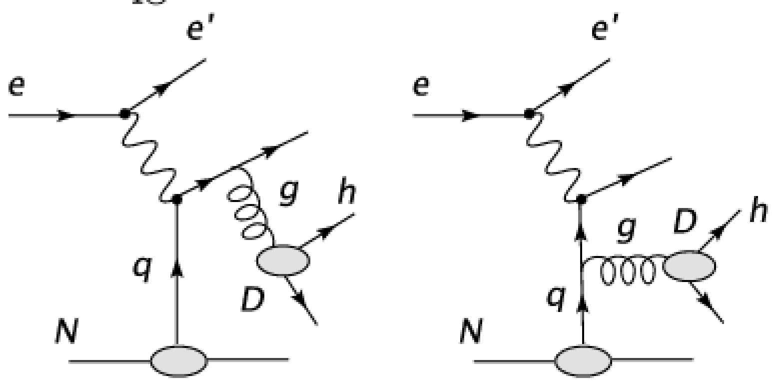
LO:



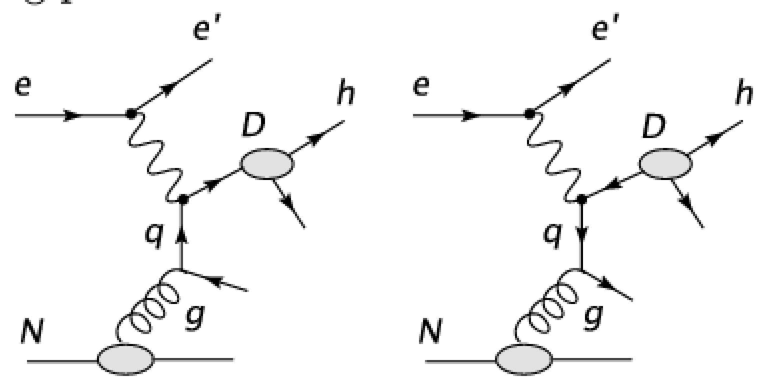
NLO-qq:



NLO-qg:



NLO-gq:



$$\sigma^h(x,z) = \sum_f e_f^2 q_f \left[1 + \otimes \frac{\alpha_s}{2\pi} \mathcal{C}_{qq} \otimes \right] D_{q_f}^h$$
$$+ \left(\sum_f e_f^2 q_f \right) \otimes \frac{\alpha_s}{2\pi} \mathcal{C}_{qg} \otimes D_G^h + G \otimes \frac{\alpha_s}{2\pi} \mathcal{C}_{gq} \otimes \left(\sum_f e_f^2 D_{q_f}^h \right)$$

NLO Global Fits

D. de Florian, R. Sassot and M. Stratmann (2007).

included: all LEP, SLD, TASSO, TPC e^+e^- data w/o "flavor tagging"
[other (= older e^+e^-) data have no impact on the fit]

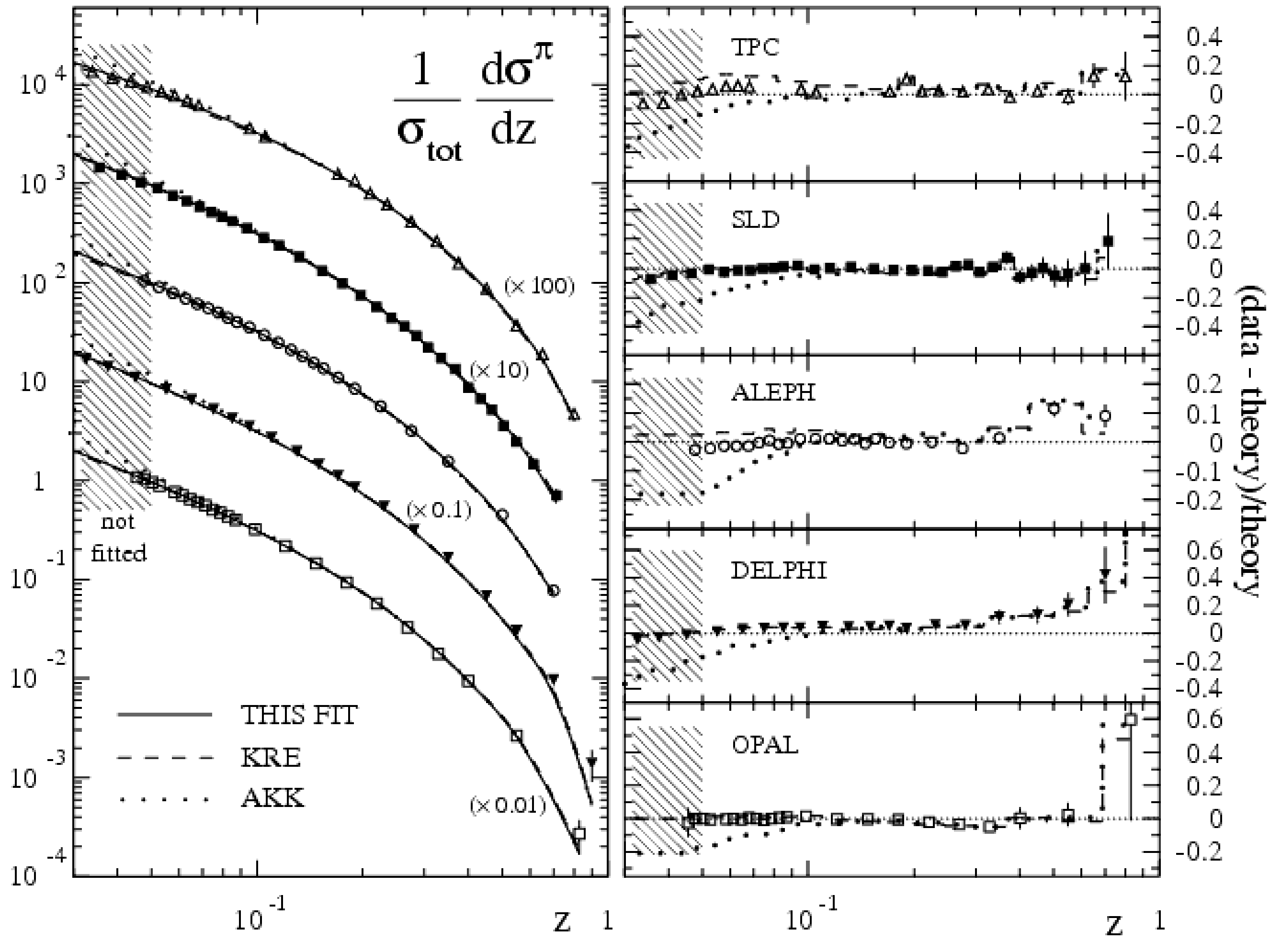
HERMES SIDIS ep data

BRAHMS, PHENIX, and STAR pp data

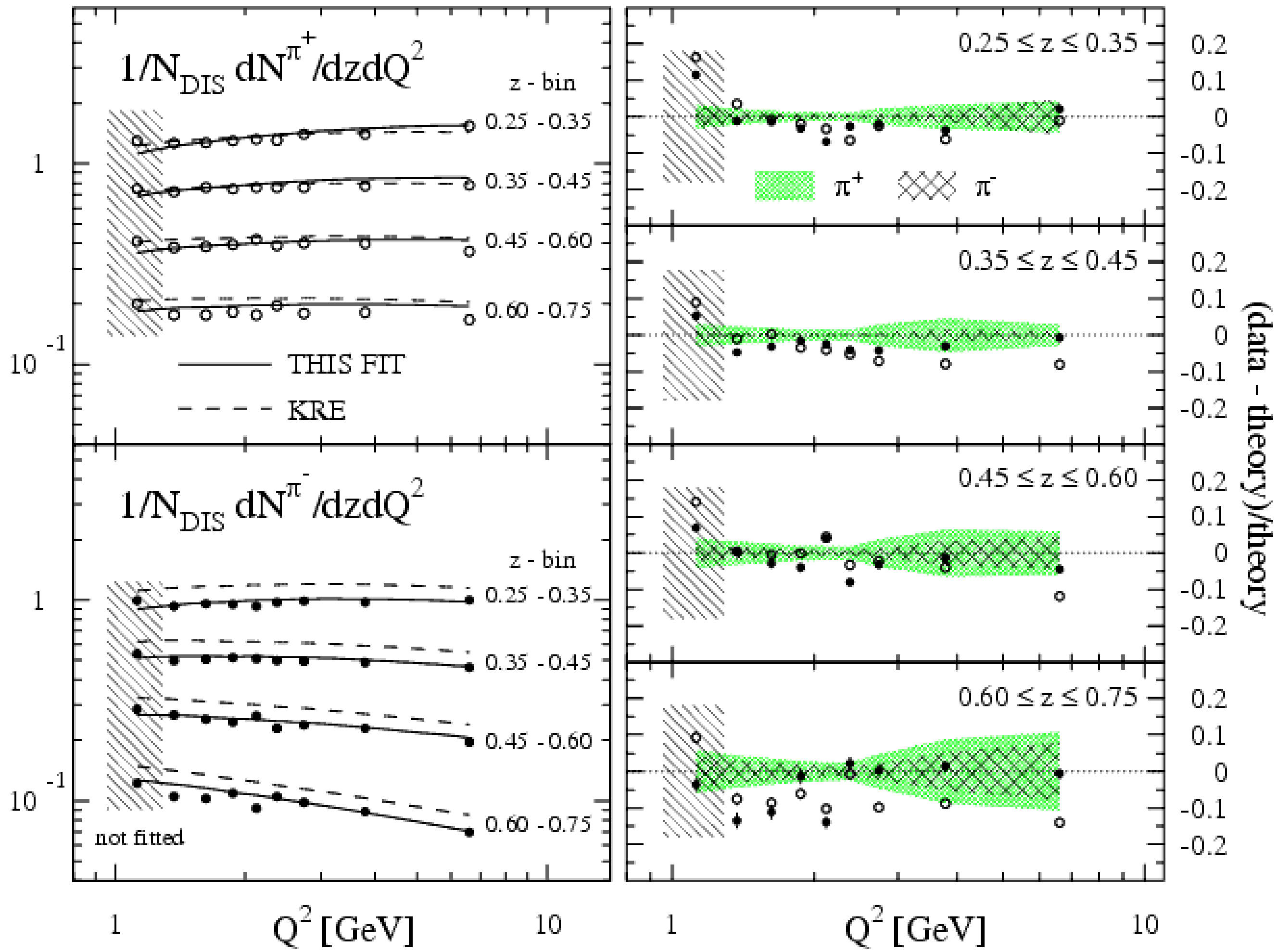
- good description of e^+e^-, ep, and pp data
- pion fragmentation well determined; kaons less
- new data sets can be straightforwardly included

Make predictions (with error band) for JLab 11 GeV kinematics.

NLO fit compared with e^+e^- data



NLO fit compared with HERMES data

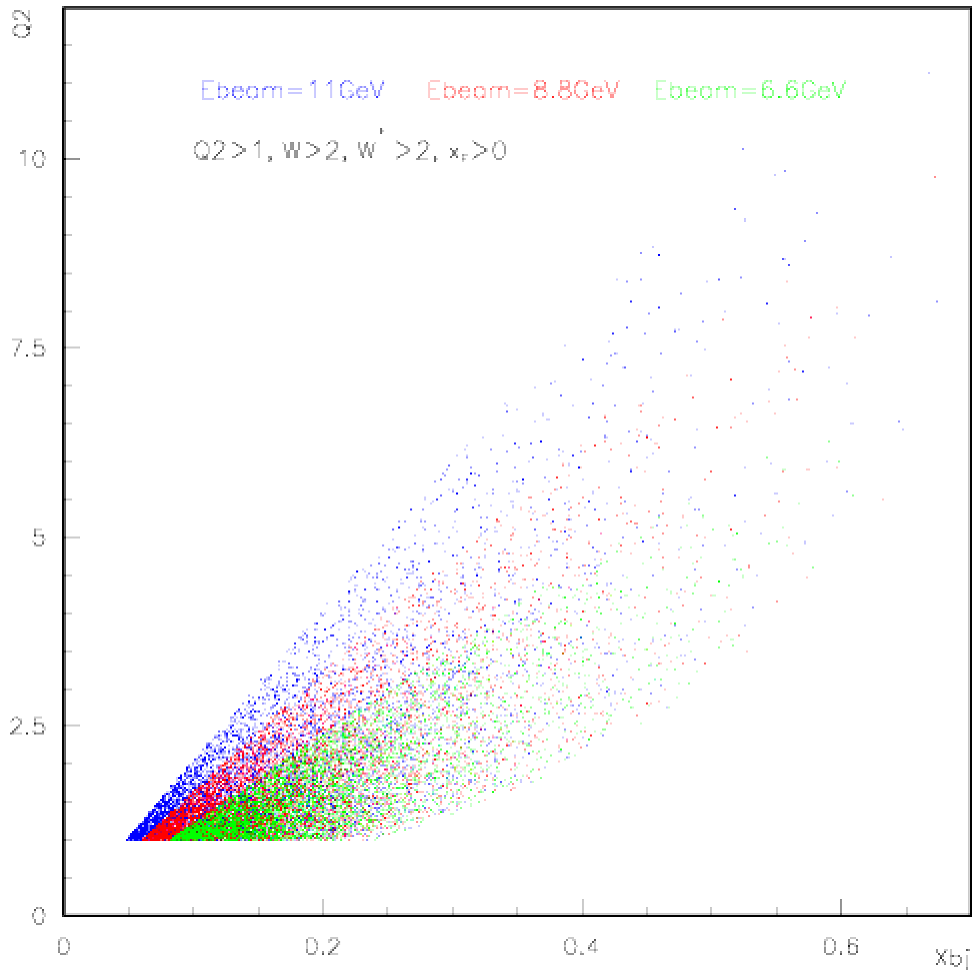


A Detailed Study of SIDIS Pion Productions on Unpolarized Proton and Deuteron Target with the CLAS12 Detector

- E0=11 (8.8 and 6.6) GeV.
- CLAS12 forward detector ($5^o \sim 30^o$).
- Unpolarized proton and deuteron targets.
- Luminosity=10^{35} cm^{-2} s^{-1}. 1000h (250h).
- High precision data over a large 3D (x,Q^2,z) dense-grid to compare with NLO predictions.

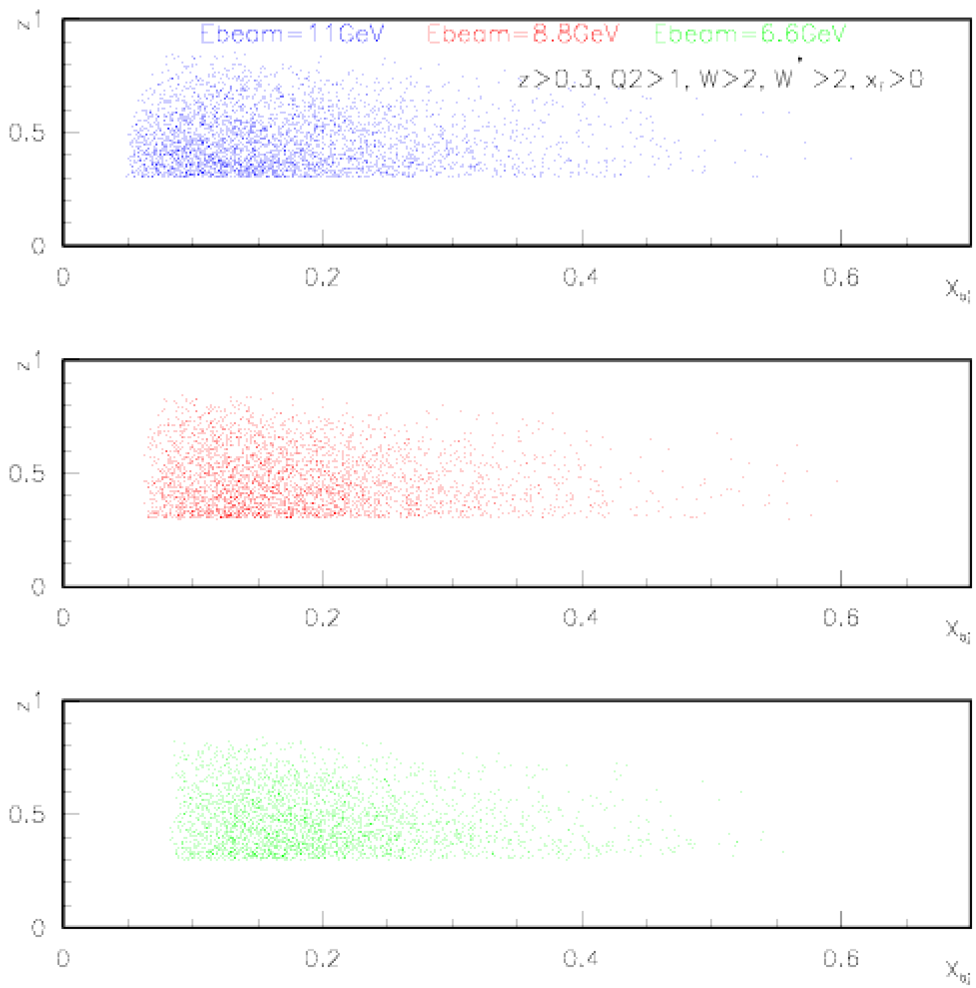
H.-J. Lu and X. Jiang et al. June 2007.

Kinematic Coverage Q2 vs x

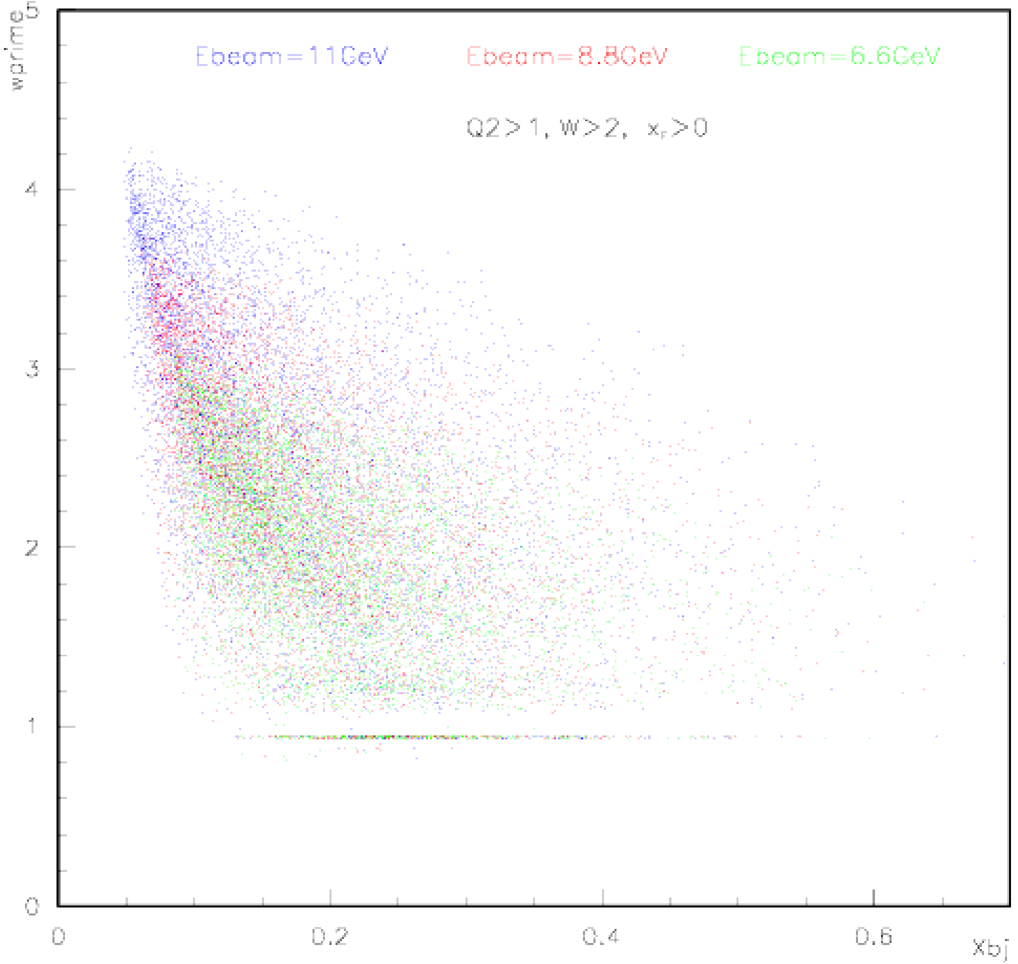


Plot density not scaled with number of events.

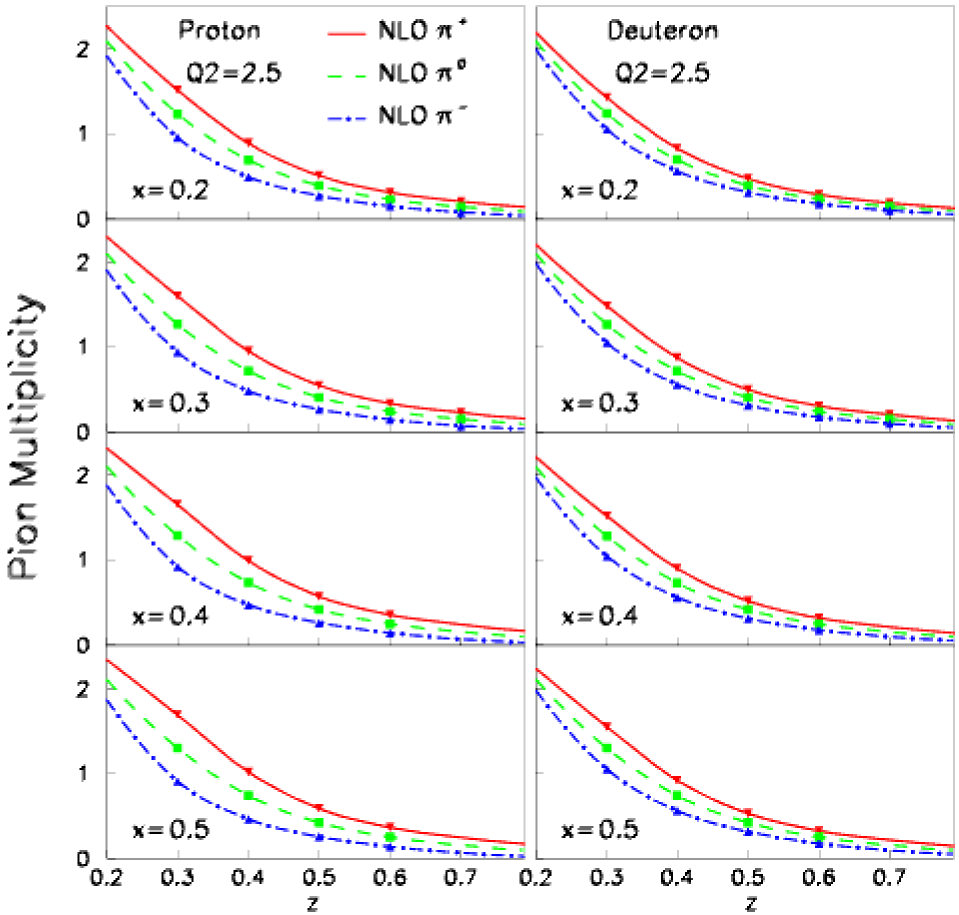
Kinematic Coverage z vs x



Kinematic Coverage W' vs x



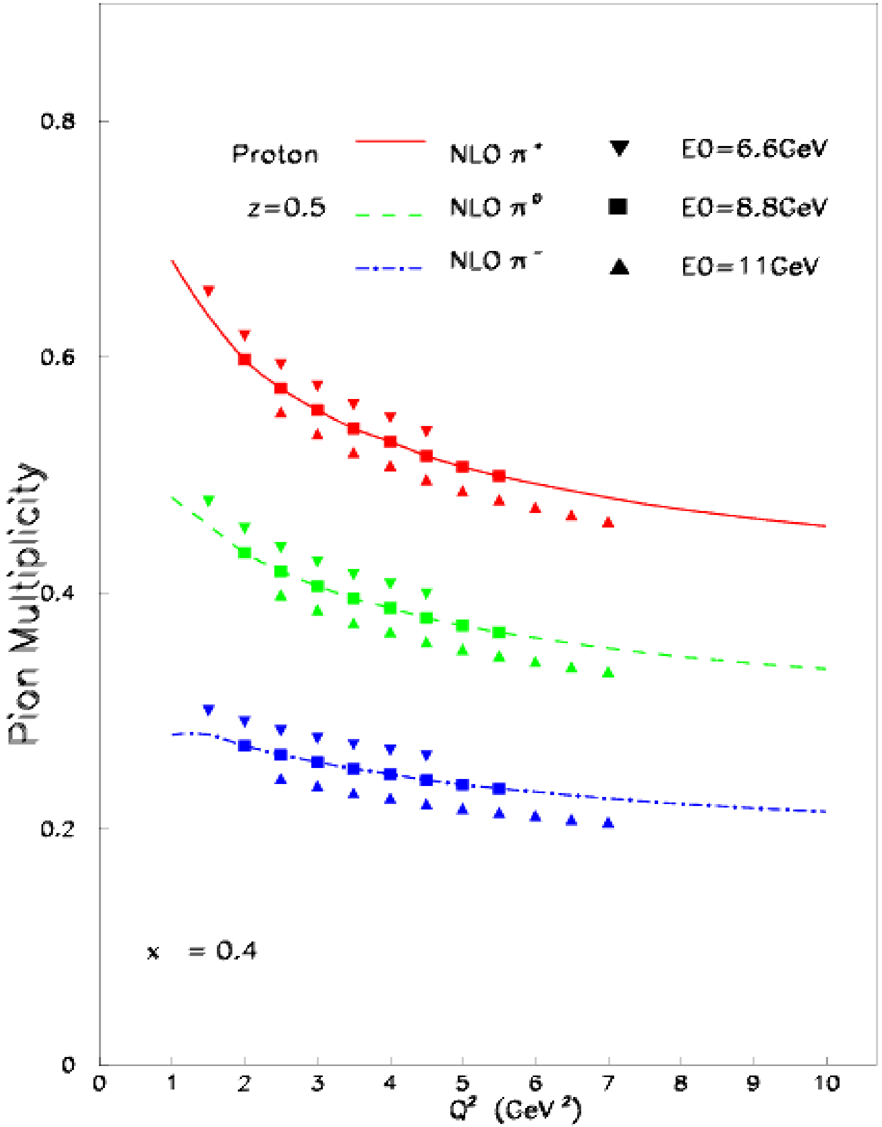
Pion Multiplicities



Theory “error” band: +/- 4 %.

Plotted for only one Q2 bin.

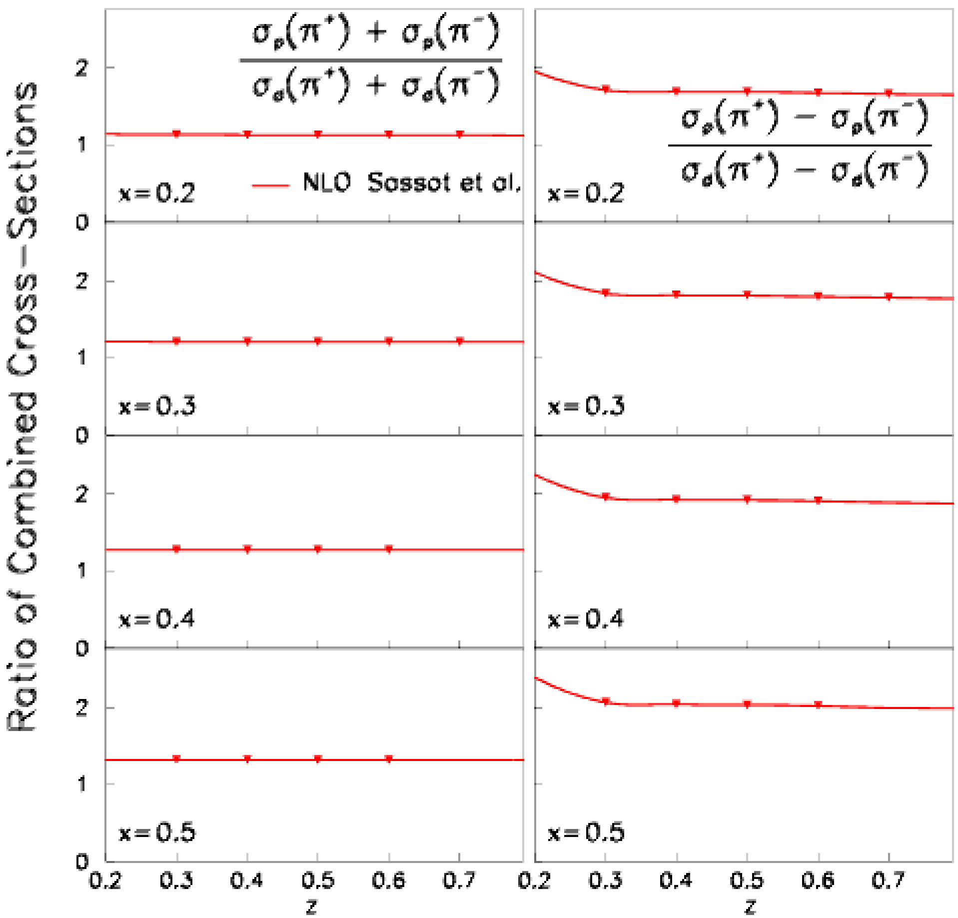
A high precision check of Q^2 dependencies



Cover a large Q2 range for the same (x, z) bin.

Plotted for only one bin: x=0.4, z=0.5.

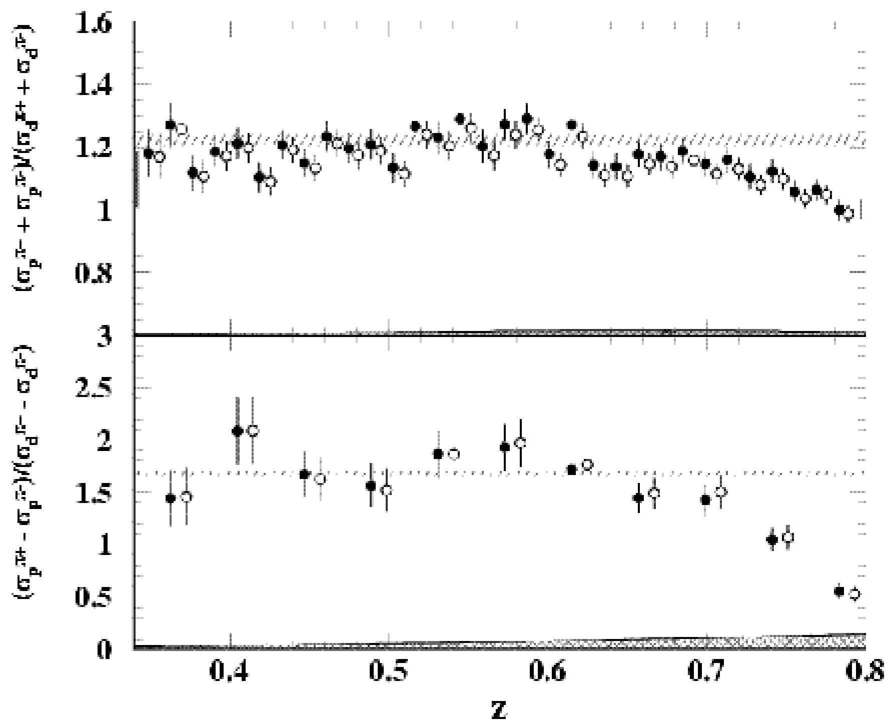
Ratios of the Combined Cross Sections



Plotted for only one Q^2-bin: Q^2=2.5 GeV^2.

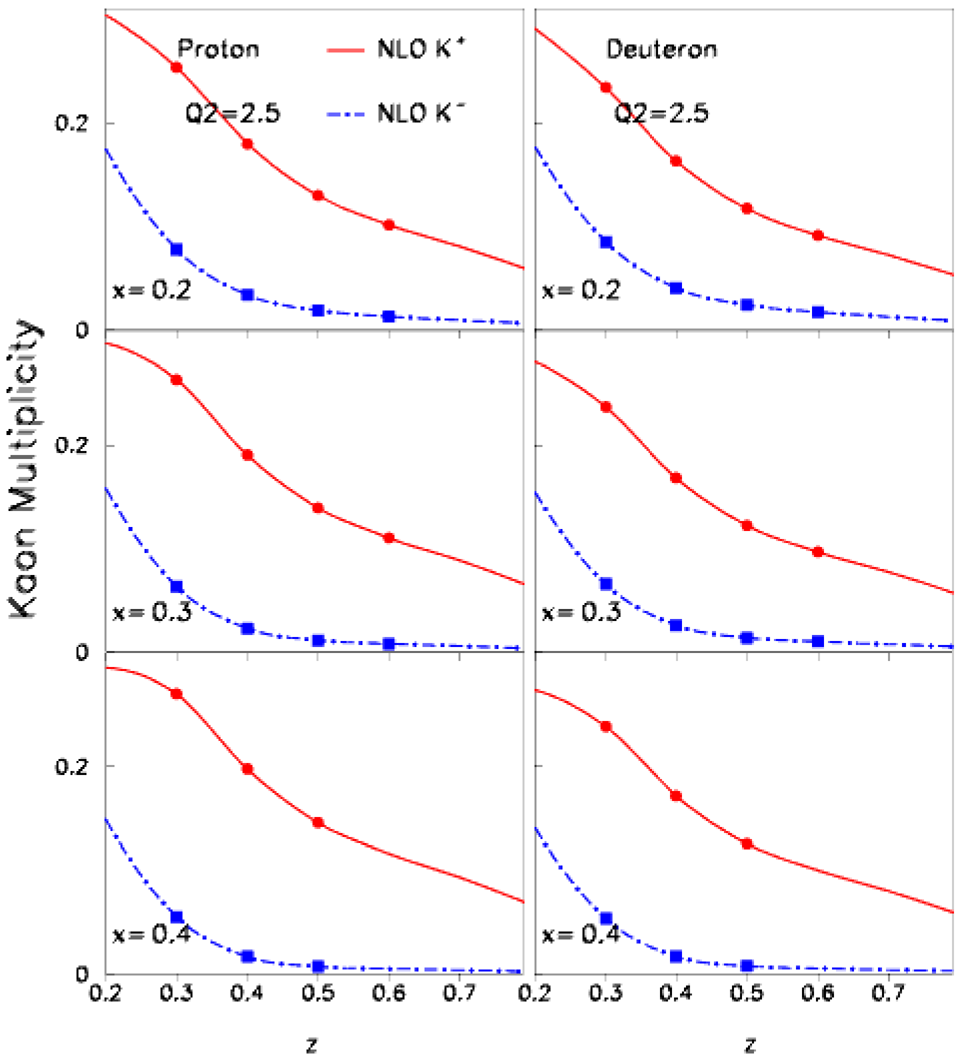
z-dependencies drop out.

Ratios are determined by PDFs only.



JLab 5.5 GeV data x=0.32, Q^2=2.3 GeV^2

Charged Kaon Multiplicities



PID limit to p_K<3.0 GeV.

SIDIS data interpretation at 11 GeV

- A complete understanding of SIDIS cross sections to NLO. How much unkowns still left ?
- Extract parton PDFs to compare with world data.
- Extract Frag. Func. to compare with NLO global fit (or e^+e^- data).
- Quantify interpretation uncertainties as systematics to TMD measurements.
- Build a precision data base for the next generation NLO-global fit which includes unpolarized and polarized SIDIS (and e^+e^-, pp) data.