# Factorization and Transverse Momentum in SIDIS at JLab

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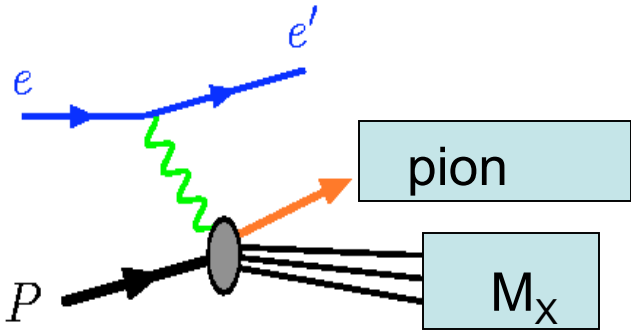
*Trieste, Italy, May 2006*

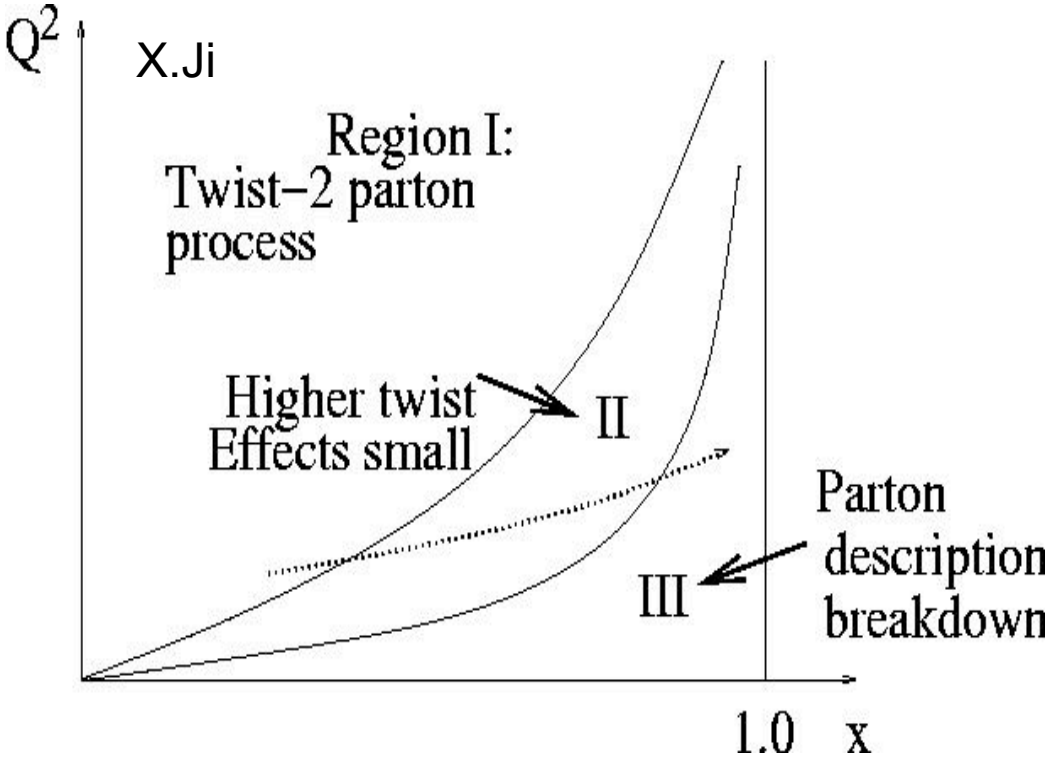
- **Semi-inclusive processes**
- **Factorization as a test of quark-hadron duality**
- **Factorization tests in unpolarized SIDIS**
- **Facorization tests in polarized SIDIS**
- **Tranverse momentum in fragmentation**

# Semi-inclusive DIS



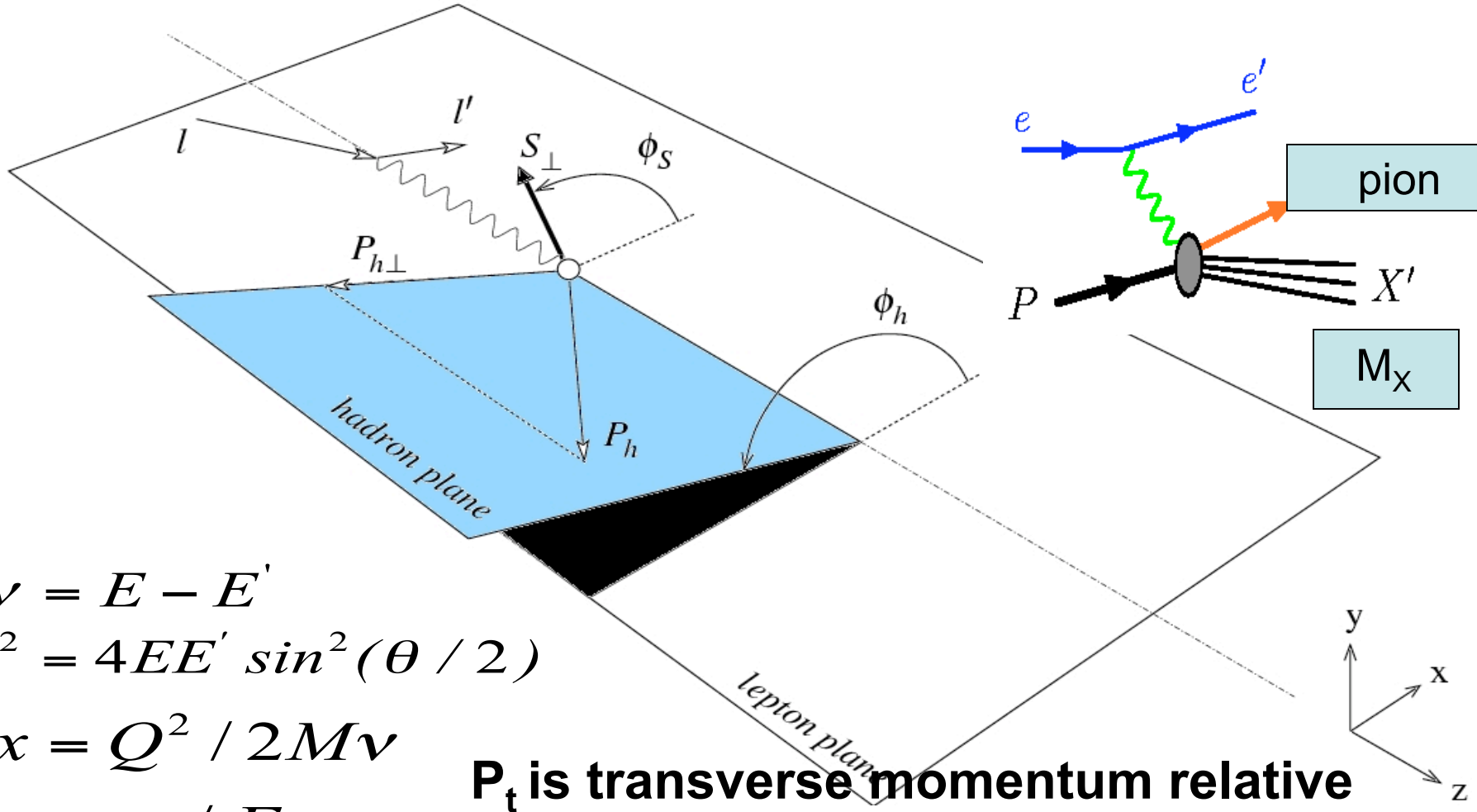

**Main focus of SIDIS studies:**

- **orbital motion of quarks ($p_t$, $\phi$ dependence)**
- **parton distributions (separate valence, sea)**




- **Where region I/II boundary?**
- **Can useful information come from Region II?**

# SIDIS kinematic plane and relevant variables




$$\nu = E - E'$$

$$Q^2 = 4EE' \sin^2(\theta/2)$$

$$x = Q^2 / 2M\nu$$

$$y = \nu / E$$

$$z = E_h / \nu$$

**$P_t$ is transverse momentum relative to virtual photon**

**$W^2=M^2+Q^2(1/x-1)$ is invariant mass of total hadronic final state**

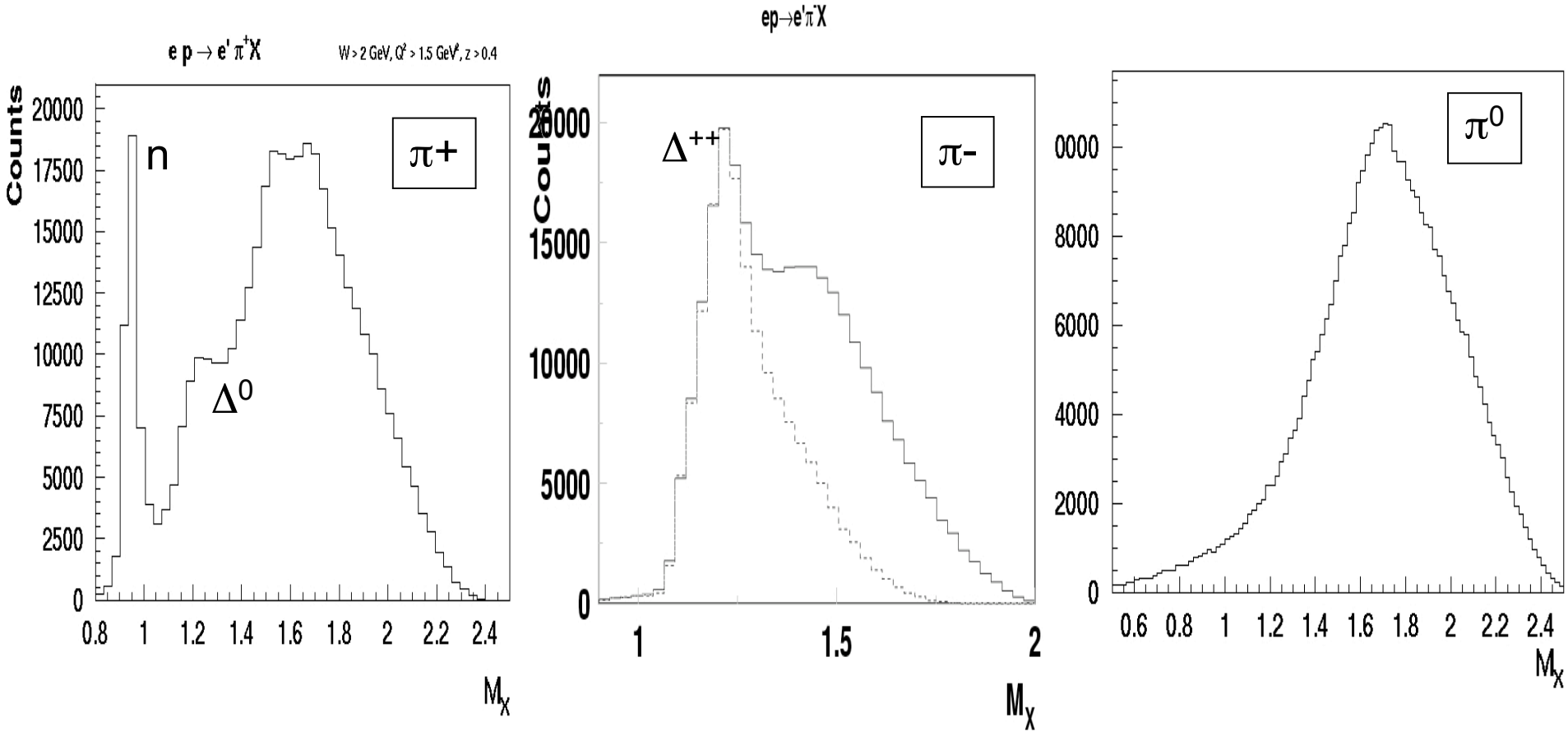
# Factorzation

**Basic idea: hit a single quark in nucleon which then hadronizes into a jet with negligible interaction with remenant quarks.**

# Factorzation

**Cross sections factorize into product of parton distribution functions (depend on x and $p_t$) (i.e. $u(x,p_t)$, $d(x,p_t)$ and current fragmentation functions (depend on z and $p_t$) (i.e. $D^+(z,p_t)$, $D^-(z,p_t)$). High z used to distinguish current fragmentation from target fragmentation.**

# Missing mass of pions in ep->e'πX



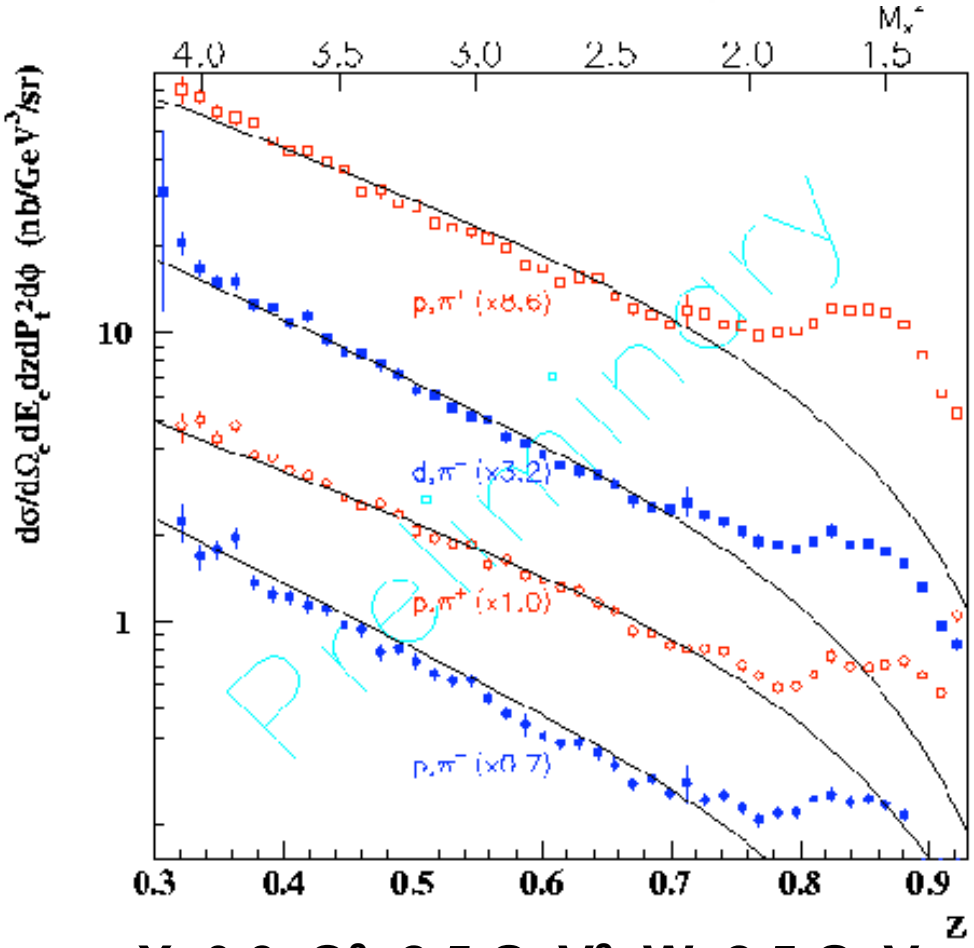

**Duality question: will factorization work if $M_x$<2 GeV, even though Delta(1232) reonance Visible? For pi-, guess need $M_x$>1.4 GeV.**

# EXPERIMENT E00-108 at JLAB

- Unpolarized electrons E=6 GeV
- Scattered electrons E'=1.6 GeV, 25 to 40 deg. Average $Q^2$ 2.5 $GeV^2$.
- W about 2.5 GeV, but $M_x$<2 GeV.
- Detected positive and negative pions near 12 degrees
- Proton and deuteron targets
- Made scans in x, z. $p_t$<0.2 GeV

# Z-Dependence of cross sections

$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$




X=0.3, $Q^2$=2.5 $GeV^2$, W=2.5 GeV

**Good agreement with prediction using CTEQ5M PDFs and Binnewies fragmentation functions, except for z>0.7, or Mx>1.4 GeV.**

# In more detail, form super-ratios

$$\sigma^{eH\to ehX} = \sum_q f^{H\to q} \otimes \sigma^{eq\to eq} \otimes D^{q\to h}$$

**Simple LO picture in valence region:**

$\sigma_p(\pi^+) = 4u(x,p_t)D^+(z,p_t) + d(x,p_t)D^-(z,p_t)$
$\sigma_p(\pi^-) = 4u(x,p_t)D^-(z,p_t) + d(x,p_t)D^+(z,p_t)$
$\sigma_d(\pi^+) = [u(x,p_t)+d(x,p_t)]\,[4D^+(z,p_t) + D^-(z,p_t)]$
$\sigma_d(\pi^-) = [u(x,p_t)+d(x,p_t)]\,[4D^-(z,p_t) + D^+(z,p_t)]$

$R_{pd+} = [\sigma_p(\pi^+) + \sigma_p(\pi^-)] / [\sigma_d(\pi^+) + \sigma_d(\pi^-)]$
$= [4u(x,p_t) + d(x,p_t)] / 5[u(x,p_t)+d(x,p_t)]$
$= \sigma_p(x)/\sigma_d(x)$ **for any z, x, $p_t$ (if d and u have same $p_t$ depdendence)!**

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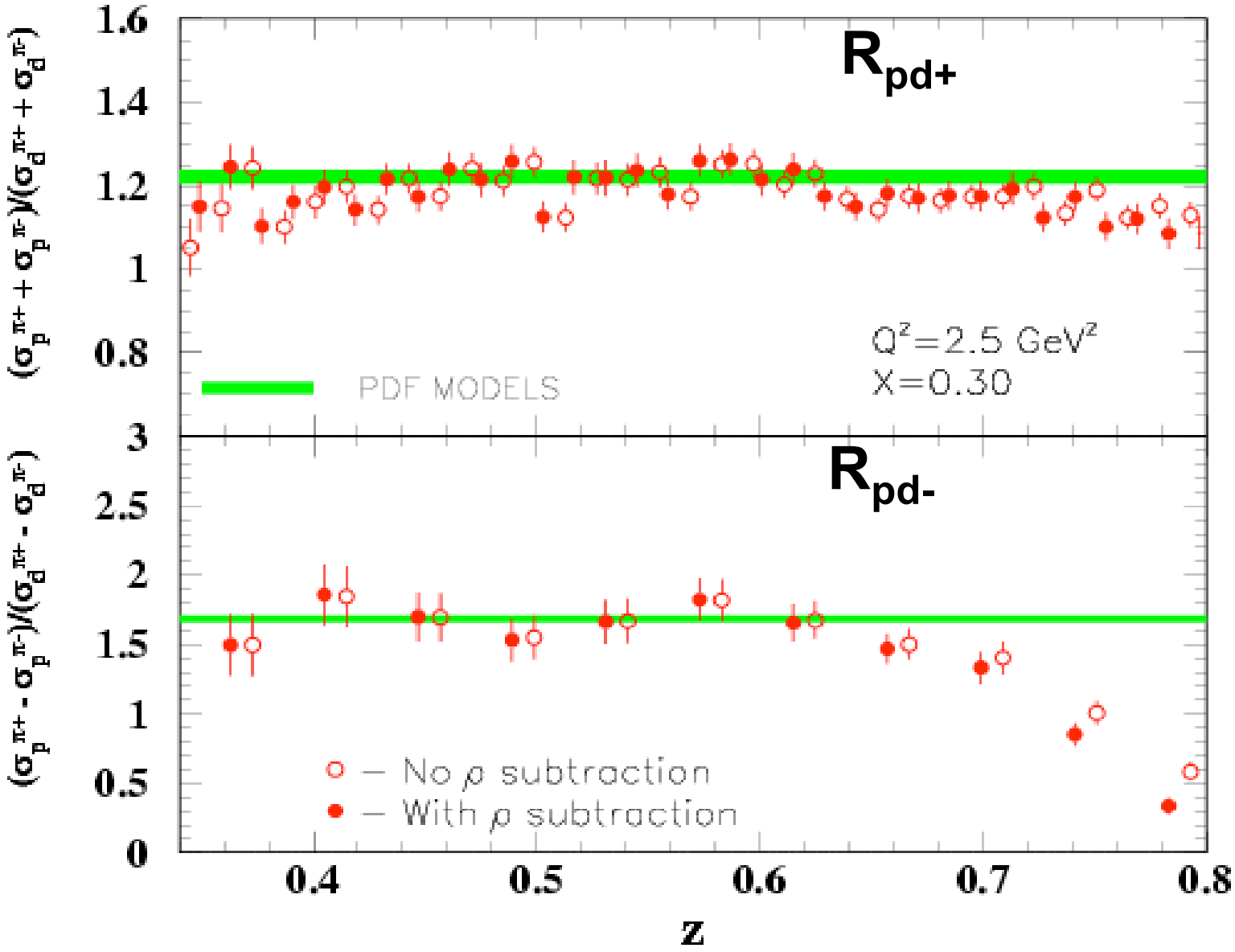
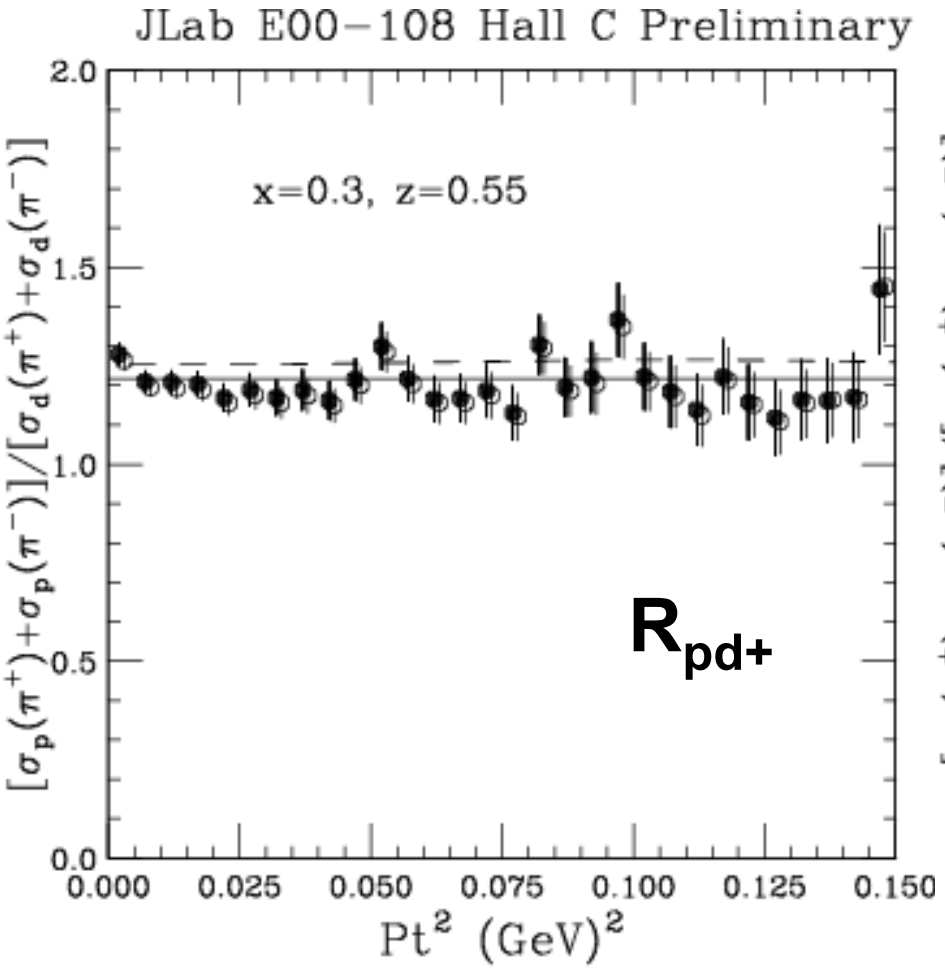
$\sigma_d(\pi^+) = [u(x,p_t)+d(x,p_t)]\,[4D^+(z,p_t) + D^-(z,p_t)]$
$\sigma_d(\pi^-) = [u(x,p_t)+d(x,p_t)]\,[4D^-(z,p_t) + D^+(z,p_t)]$

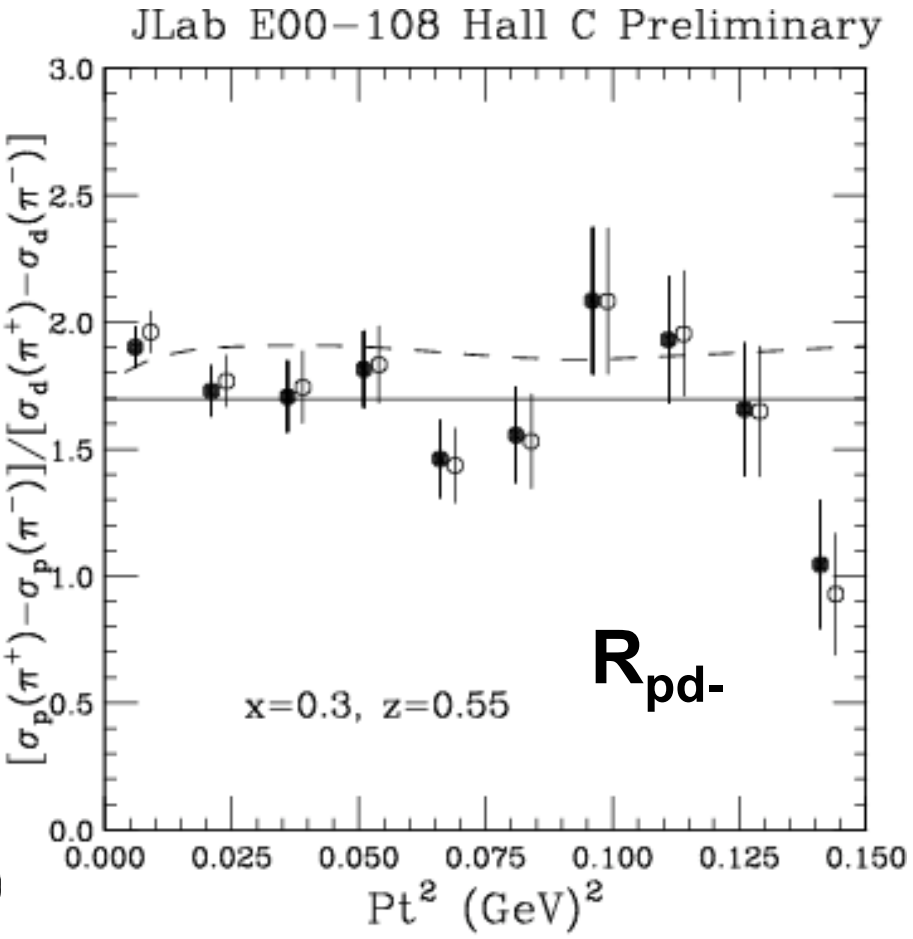
$R_{pd^-} = [\sigma_p(\pi^+) - \sigma_p(\pi^-)] / [\sigma_d(\pi^+) - \sigma_d(\pi^-)]$
$= [4u_v(x,p_t) - d_v(x,p_t)] / 3[u_v(x,p_t)+d_v(x,p_t)]$

**for any z, x!**

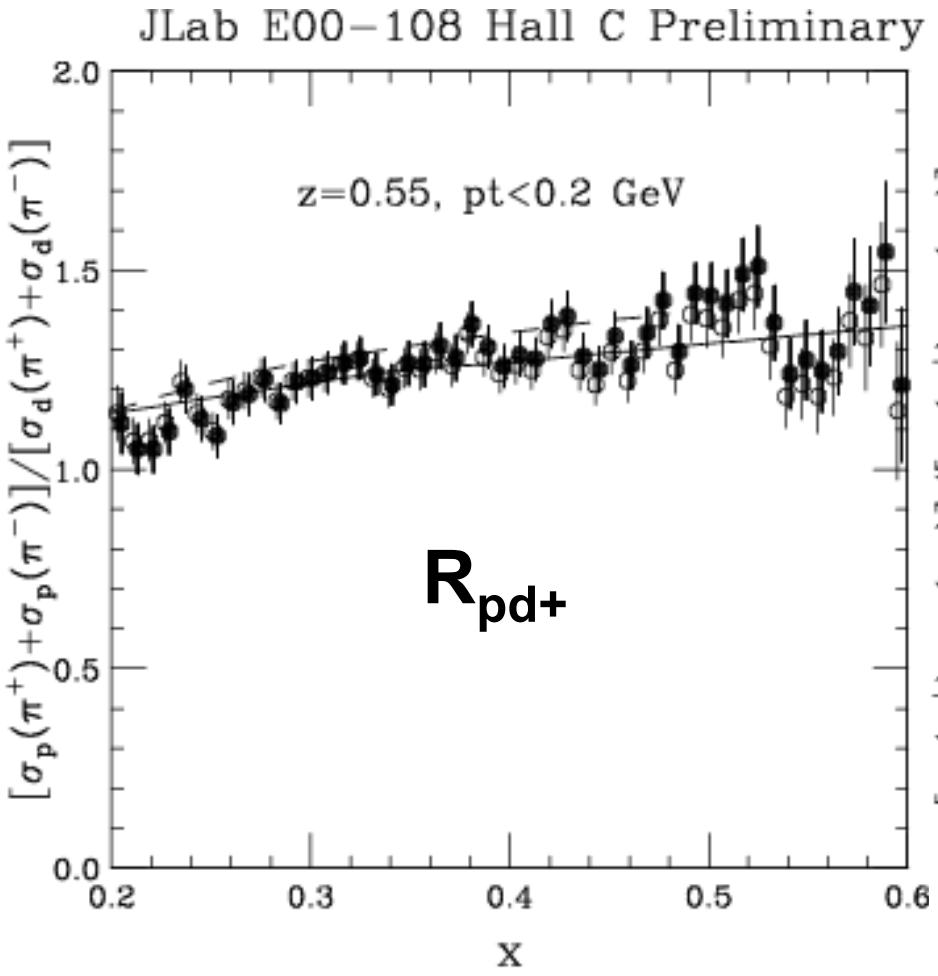


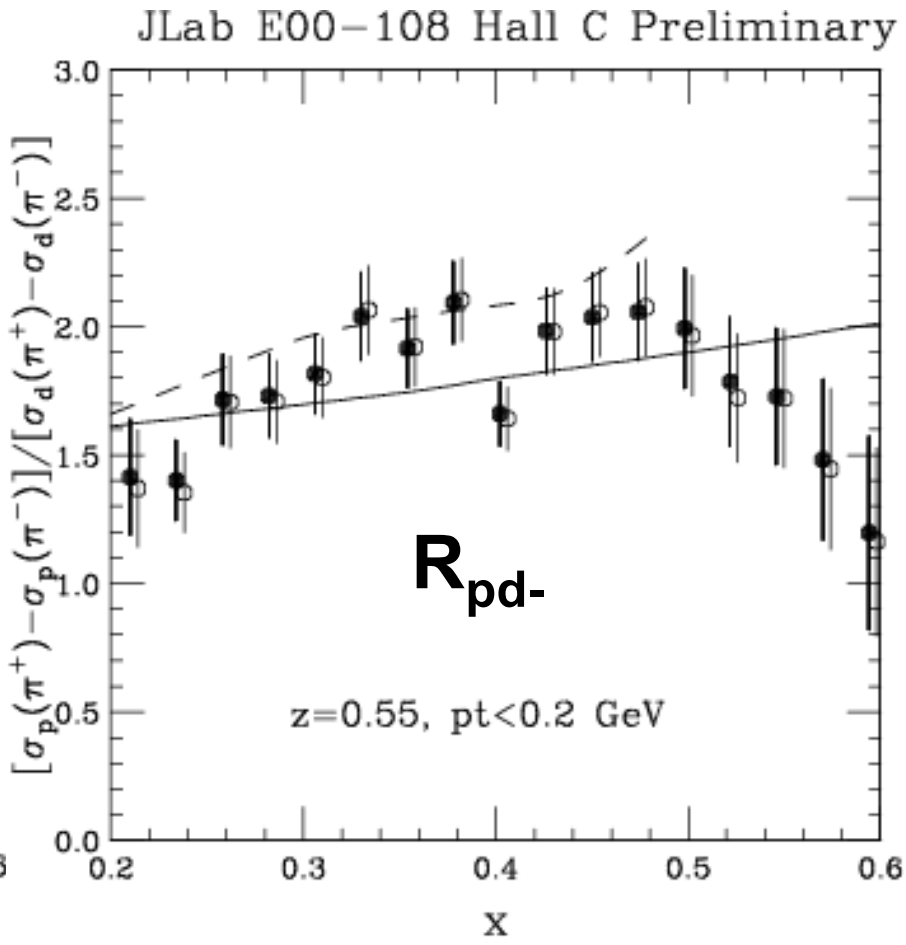

**Both ratios agree PDF models for z<0.7 (Nx>1.4 GeV)**



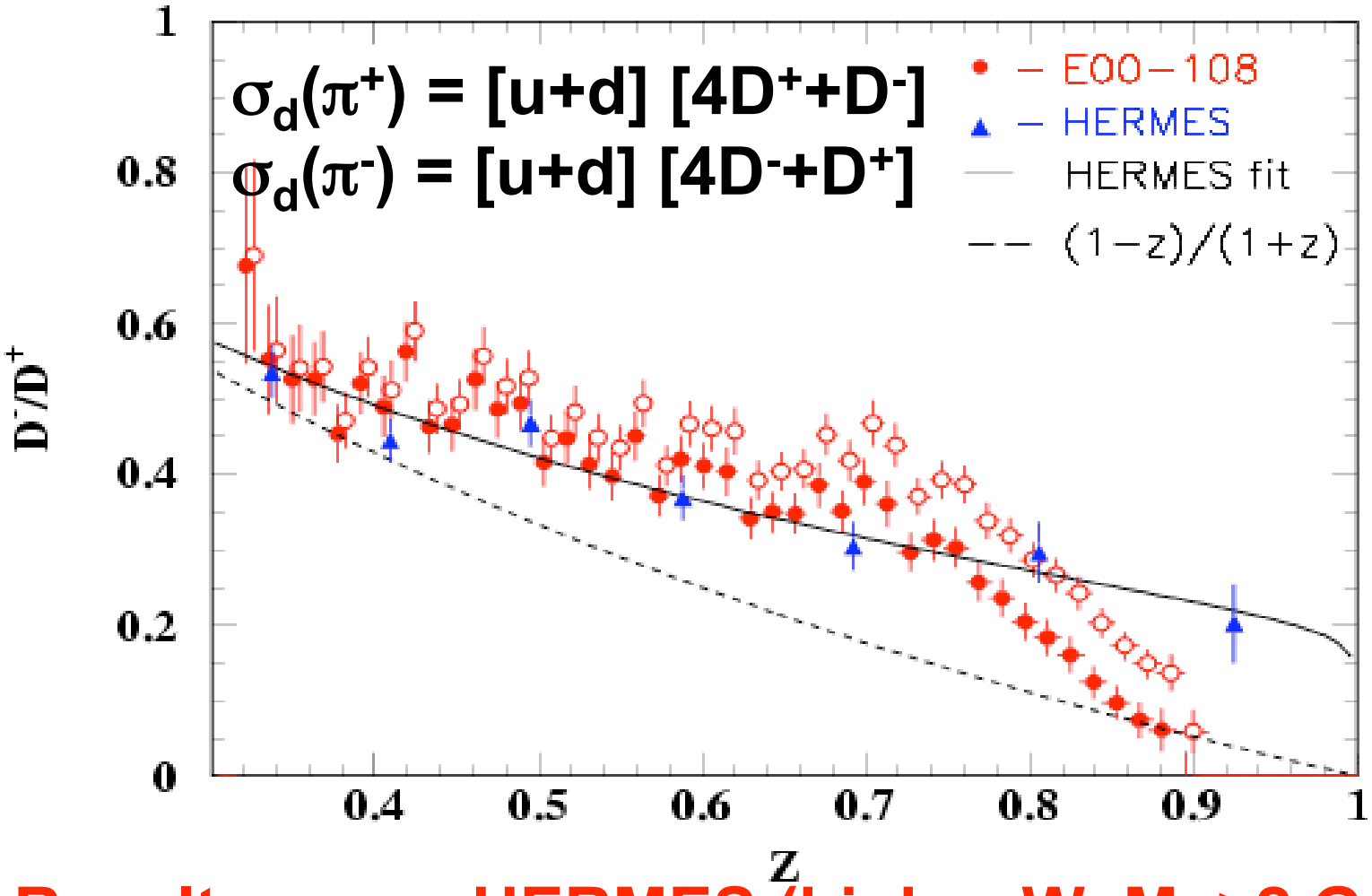

**Both ratios independent of $p_t$ (to 0.3 GeV) for z=0.55**



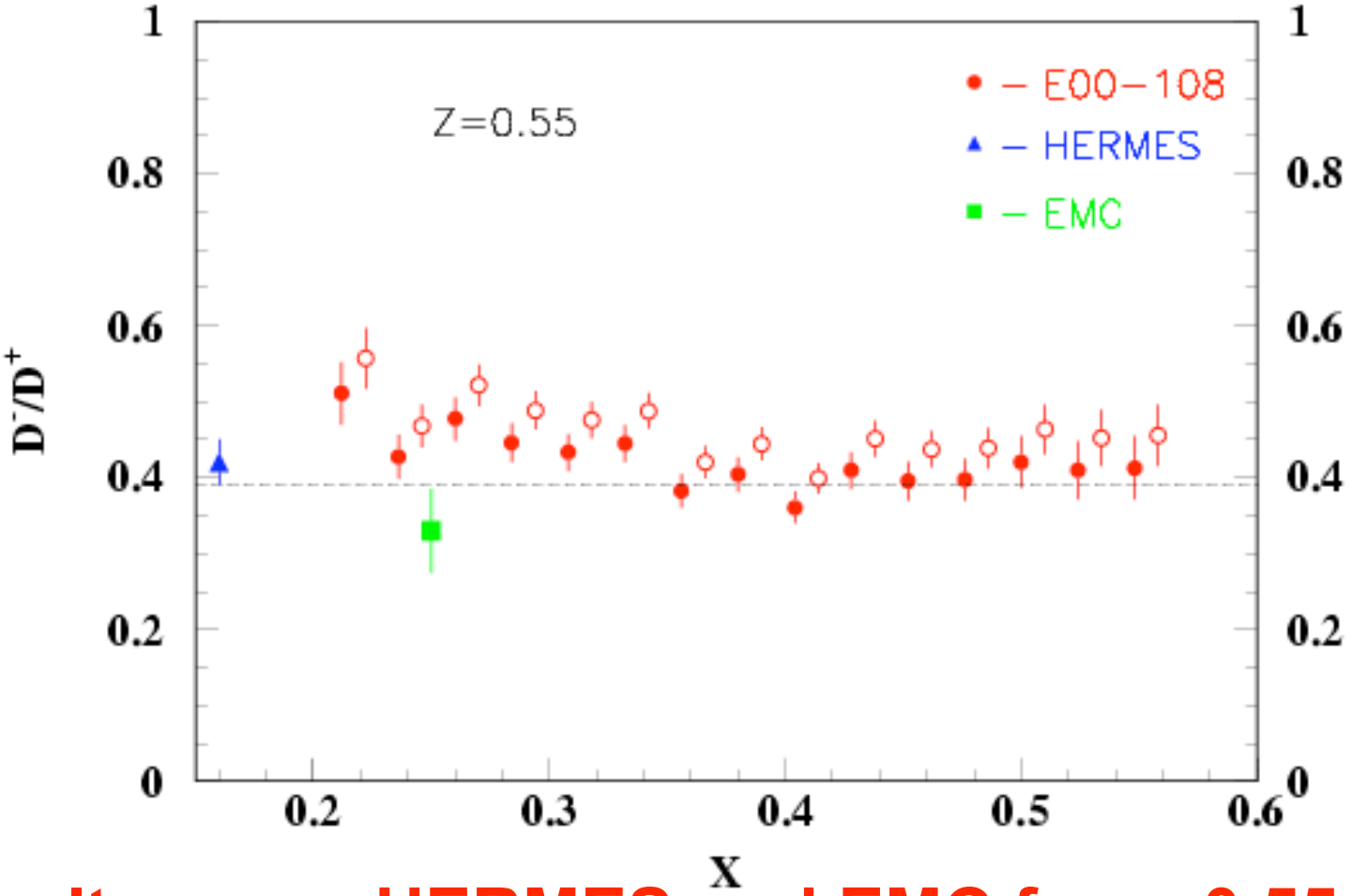

**Both ratios agree PDF models 0.2<x<0.5 for z=0.55**

# Another test: $D^-/D^+$ from Deuteron $\pi^+$ to $\pi^-$ ratio




**Results agree HERMES (higher W, Mx>2 GeV) up to z=0.7 (Mx>1.4 at pt=0), after rho correction**

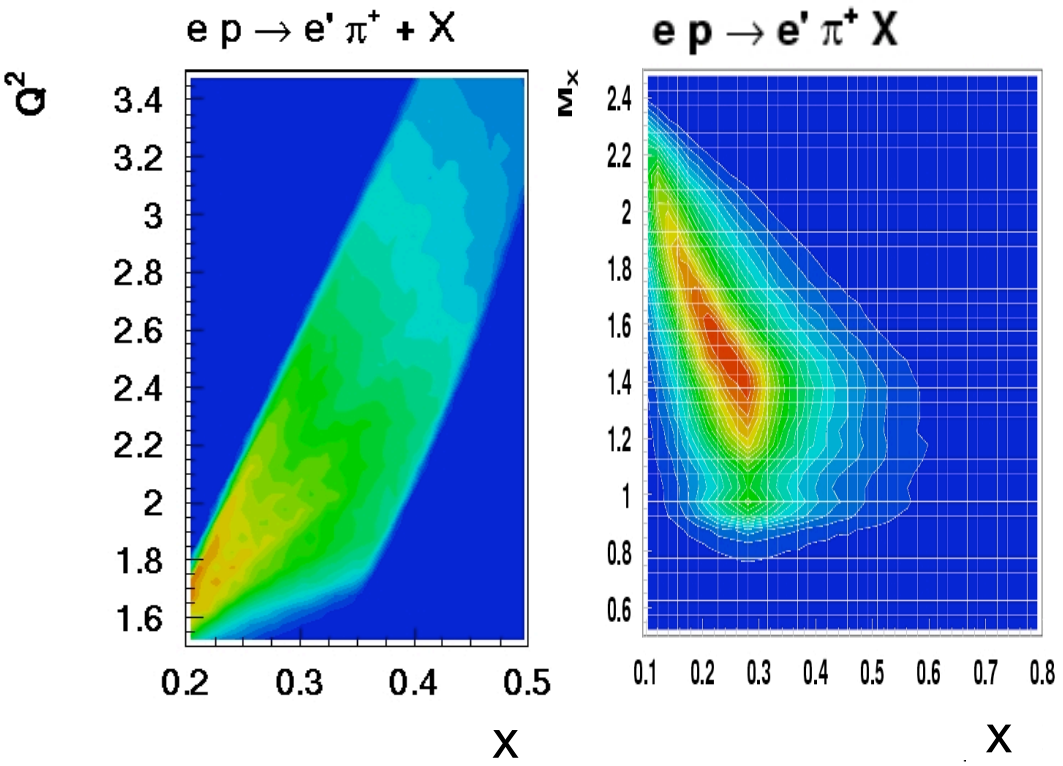
# Another test: $D^-/D^+$ from Deuteron $\pi^+$ to $\pi^-$ ratio

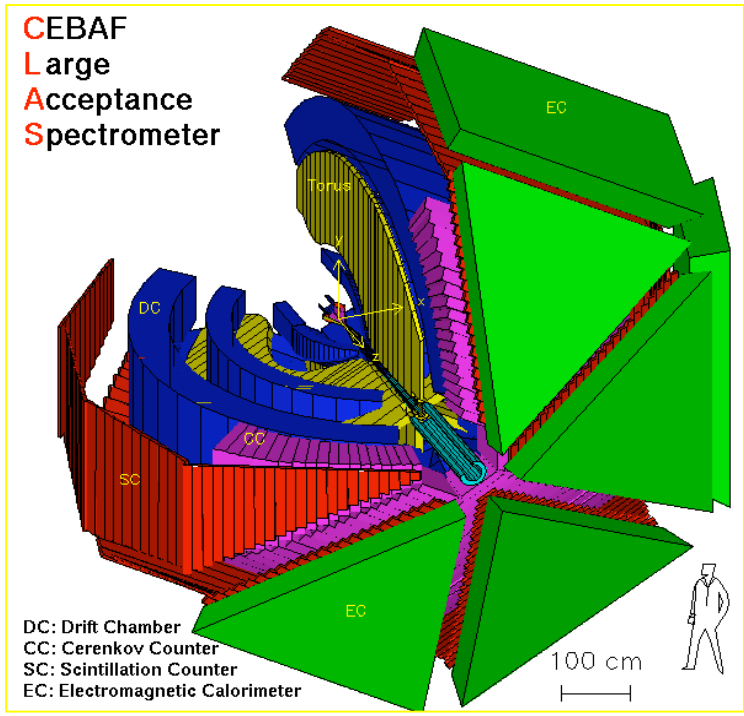



**Results agree HERMES and EMC for z=0.55 and x>0.35. Maybe some x depdendence x<0.35 (sea quark correction?)**

# Now to polarized SIDIS at JLAB using CLAS

**Scattering of 5.7 GeV polarized electrons off polarized $NH_3$, $ND_3$**



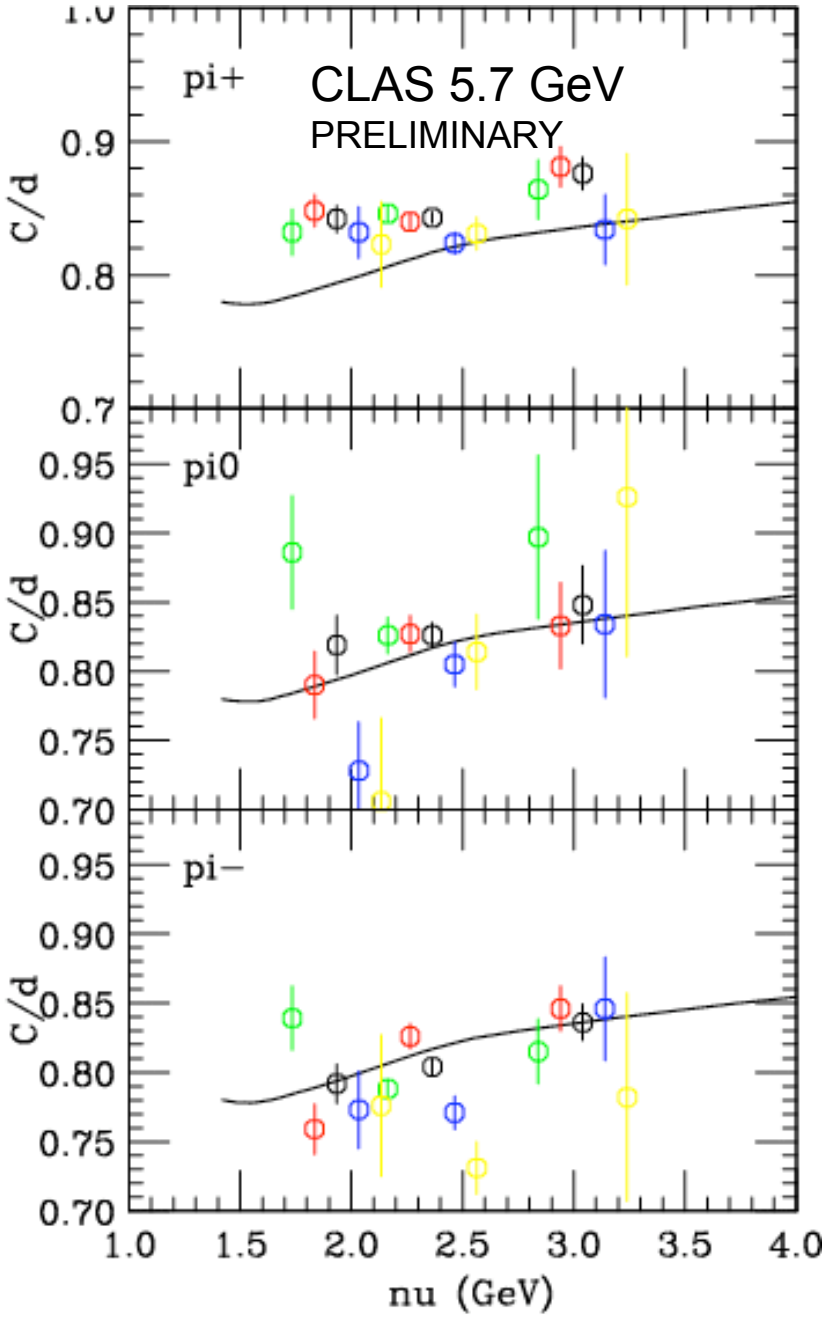




➢~8M $\pi^+$ in SIDIS kinematics

# Determination of $g_1/F_1$ (approximately $A_1$)

$$A_1^p \approx \frac{1}{P_B P_T f D_{LL}(y)} \frac{N^{+-} - N^{++}}{N^{+-} + N^{++}}$$

- Target polarization about 0.7 (0.3) for $NH_3$ ($ND_3$)
- Longitudinal beam polarization $P_B$ about 0.7
- Dilution factor f varies from 0.1 to 0.3: used Lund model for n/p ratio (agrees with Hall C data) and preliminary Hall B data for A-dependence
- Depolarization factor $D_{LL}(y)$ evaluated assuming $R=\sigma_L/\sigma_T$ same as for inclusive.
- Assumed $A_{perp}=0$ (not measured)
- "$\pi^+$" and "$\pi^-$" include some $K^+$, $K^-$ for P>1.5 GeV
- $\pi^0$ events cleanly identified with two photons




**To obtain fraction of events from polarized protons (deuterons) in NH3 (ND3), used recent data for deuteron to carbon ratio in SIDIS from E02-104 (Will Brooks). Few representative points shown. MUCH MORE DATA coming soon over wide kinematic range. Studies quark propogation in cold QCD matter.**

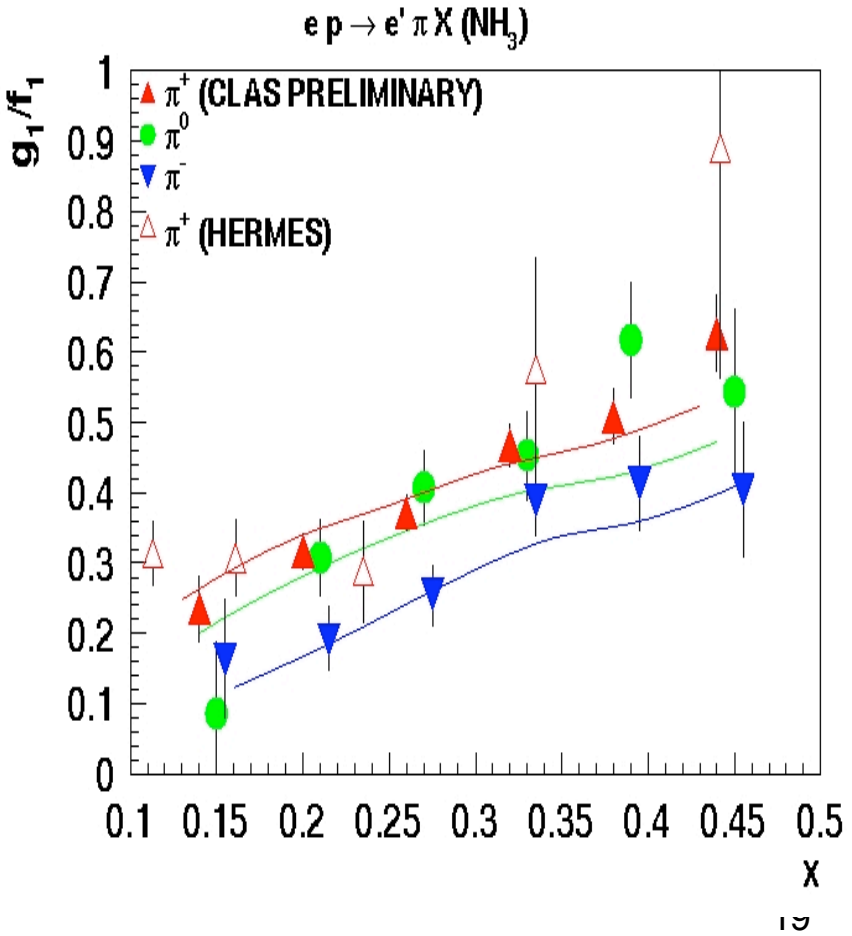
# x-depenence of SIDIS proton $g_1/F_1$

W>2 GeV, $Q^2$>1.1 $GeV^2$, 0.4<z<0.7

- Good agreement with HERMES $\pi$+ data at higher W.

- x-dependence follows PEPSI (Lund) Monte Carlo using GRSV polarized PDFs (LO)

- Magnitude also in good agreement with simulation



# Polarized SIDIS: factorization tests

**Simple picture in valence region:**

$\sigma_p(\pi^+) = 4u(x)D^+(z) + d(x)D^-(z)$
$\sigma_p(\pi^-) = 4u(x)D^-(z) + d(x)D^+(z)$
$\delta\sigma_p(\pi^+) = 4\delta u(x)D^+(z) + \delta d(x)D^-(z)$
$\delta\sigma_p(\pi^-) = 4\delta u(x)D^-(z) + \delta d(x)D^+(z)$

$(g_1/F_1)_{+-} = [\delta\sigma_p(\pi^+) + \delta\sigma_p(\pi^-)] / [\sigma_p(\pi^+) + \sigma_p(\pi^-)]$

$= [4\delta u(x) + \delta d(x)] / [4u(x) + d(x)]$

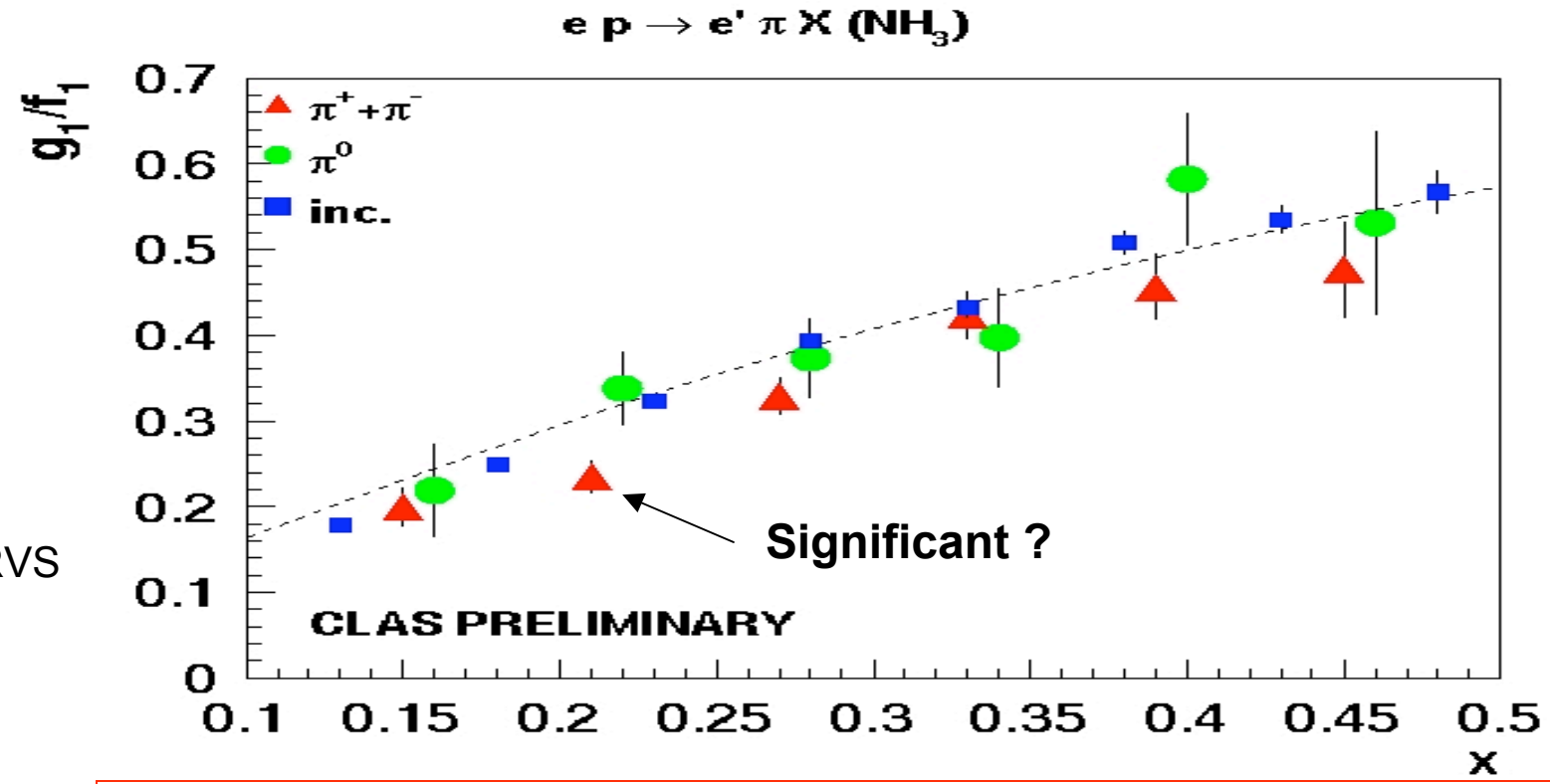
$= (g_1/F_1)_{inclusive}$

Similarly for $\pi^0$ $(g_1/F_1)_0 = (g_1/F_1)_{inclusive}$

**$(g_1/F_1)_{+-}$ and $(g_1/F_1)_0$ should be independent of z and $p_t$, and equal to inclusive $(g_1/F_1)$**

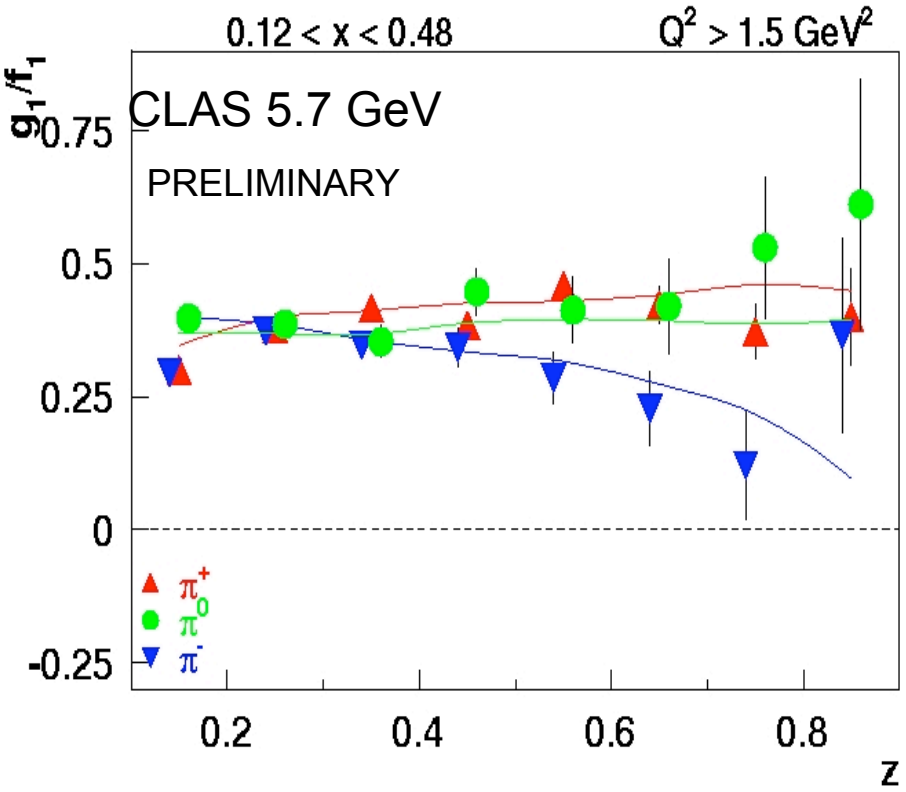
# Polarized SIDIS factorization test

GRVS




**$g_1/F_1$ for inclusive, for the sum of $\pi^+$,$\pi^-$, and for $\pi^0$ are fairly consistent with each other in the range 0.4<z<0.7, as expected in LO if factorization works. Cuts used: Mx>1.4 GeV, $Q^2$>1.1 $GeV^2$, W>2 GeV**

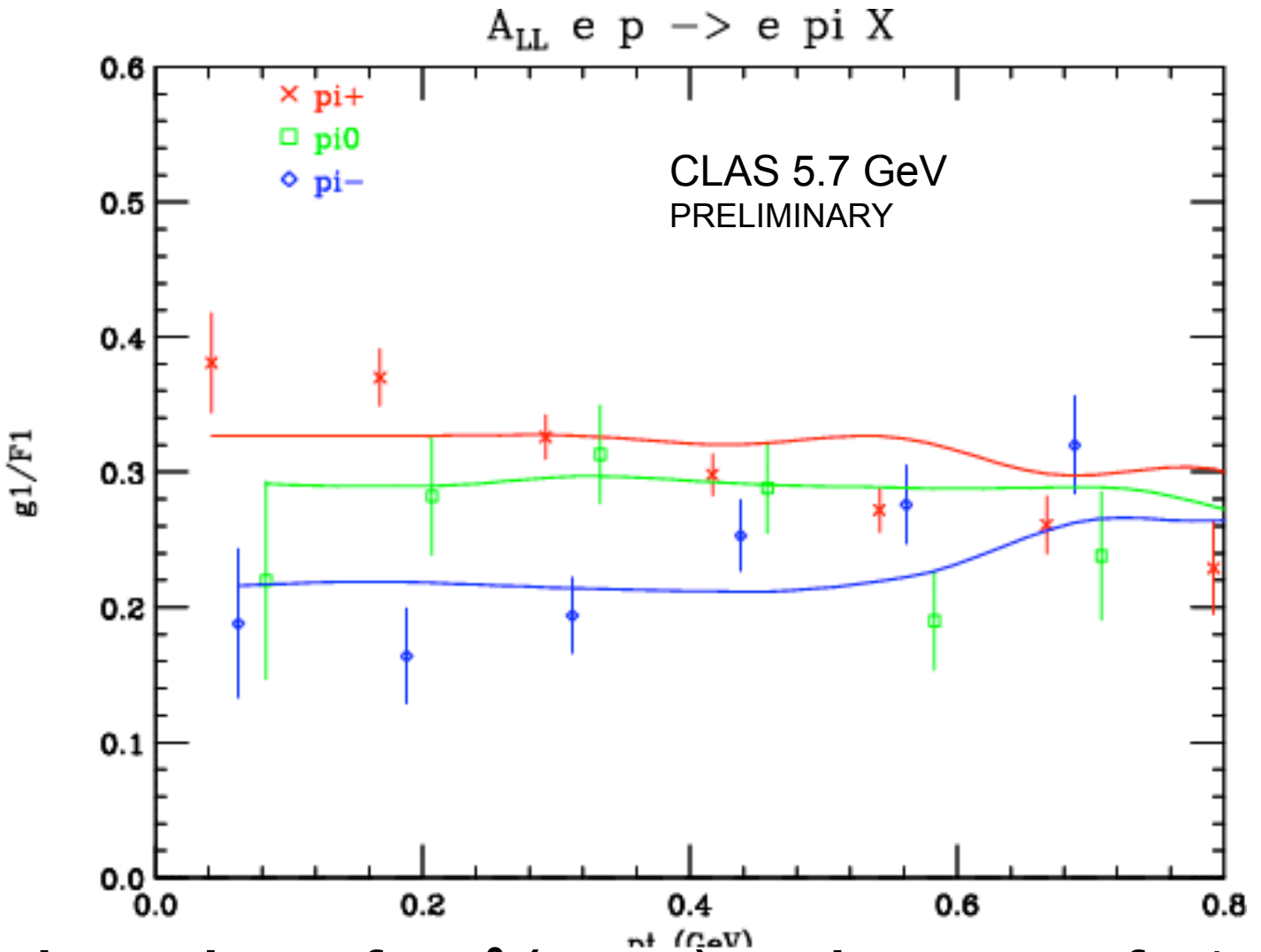
# z-depenence of SIDIS proton $g_1/F_1$




**No significant z-dependence seen for $\pi^0$ and $\pi^+ + \pi^-$ for 0.3<z<0.7, as expected if factorization holds**

**Good agreement with PEPSI predictions including dropoff at high z for $\pi^-$, due to increasing importance of $\delta d(x)$, in turr due to increase of $D^+/D^-$ with increasing z**

# $p_t$-depenence of SIDIS proton $g_1/F_1$




$p_t$

**No $p_t$ dependence for $\pi^0$ (green), and average of $\pi^+$ (red) and $\pi^-$ (blue) as expected if factorization works**

# $p_t$-depenence of SIDIS proton $g_1/F_1$

**BUT, $A_1$ $\pi^+$ decreases with $p_t$ at fixed $x,Q^2,z$ while $A_1$ $\pi^-$ increases.**

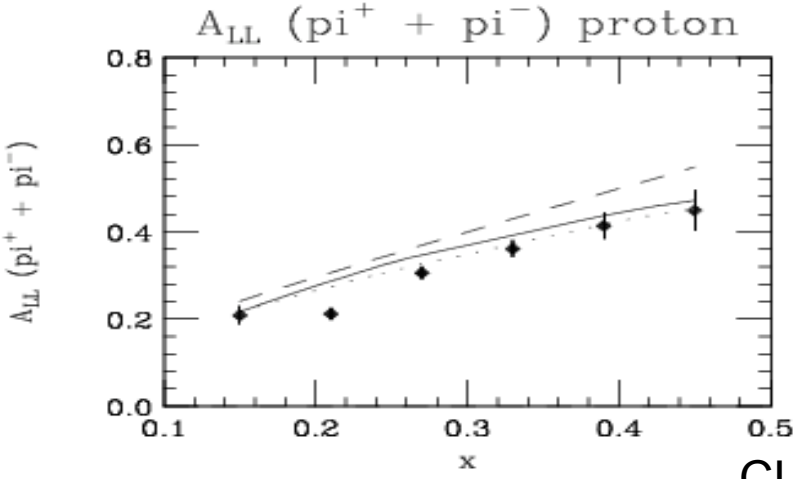
$$\delta\sigma_p(\pi^+) = 4\delta u(x,p_t)D^+(z,p_t) + \delta d(x,p_t)D^-(z,p_t)$$
$$\delta\sigma_p(\pi^-) = 4\delta u(x,p_t)D^-(z,p_t) + \delta d(x,p_t)D^+(z,p_t)$$

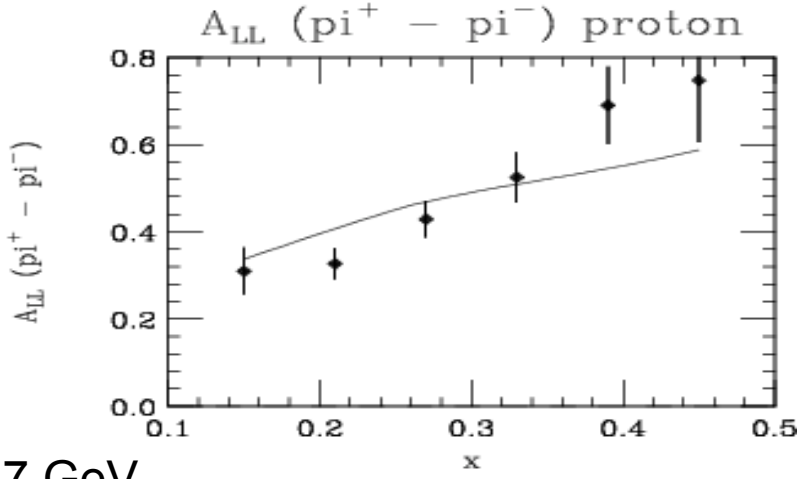
**Hard to explain in terms of different $p_t$ distributions for quarks, or influence of exclusive processes like diffractive rho production.**

**Simplest explanation is that $D^-/D^+$ increases with $p_t$ (I.e. unfavored fragmentation has a wider transverse momentum dependence) First hint?**

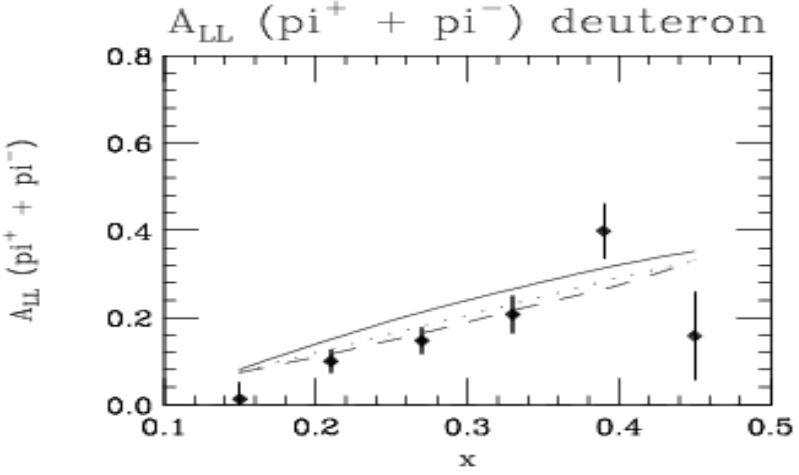
**This effect magnified in $g_1$ compared to $F_2$ due to $\delta d$ negative while $\delta u$ positive**

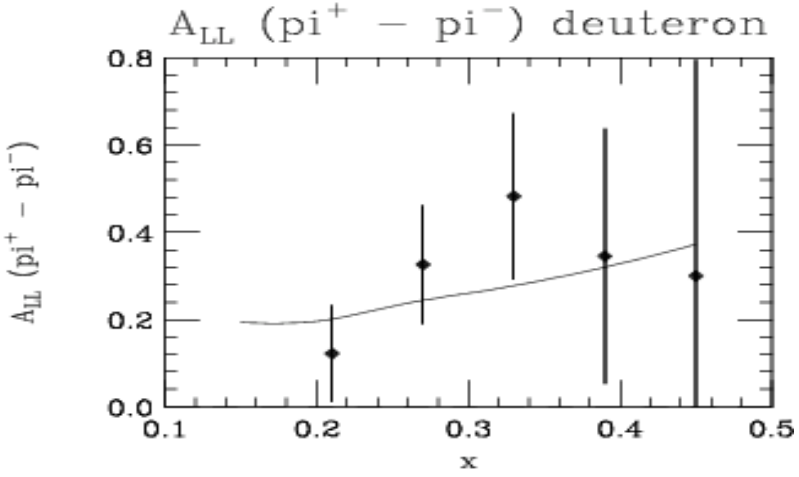
**In region where factorization tests hold, can use data to constrain polarized PDFs in NLO analysis(separate out polarized up, down valence and sea quark parton distributions).**



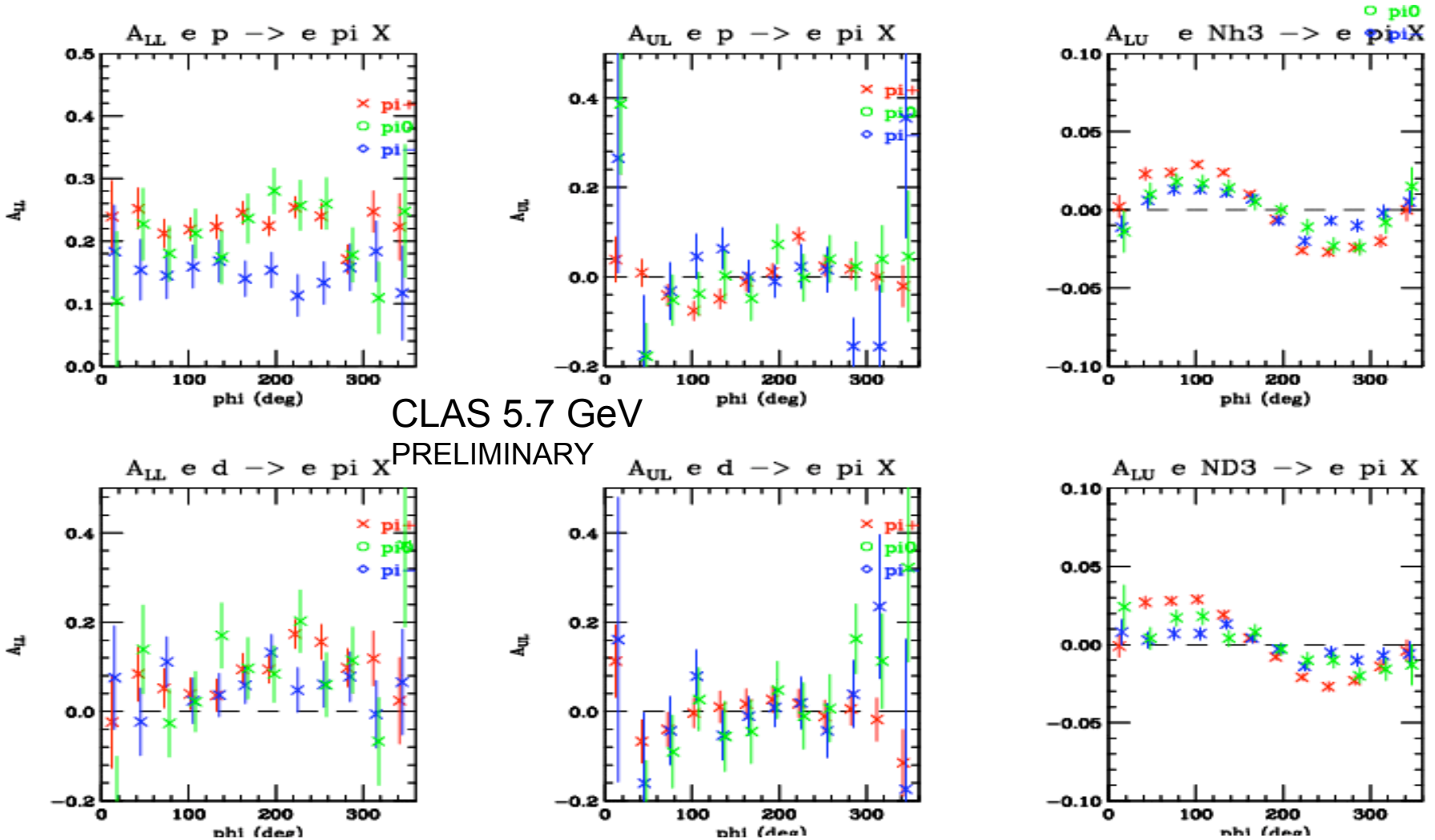




CLAS 5.7 GeV
PRELIMINARY



**In region where factorization tests hold, analyze phi depdendence of $A_{LL}$, $A_{LU}$, and $A_{UL}$ to learn about orbital motion of quarks, polarized fragmentation, and higher twist contributions.**



# Future

- **20x more $\pi^+$, $\pi$ -, 40x more $\pi^0$ for $g_1/F_1$ at 6 GeV on proton (using CLAS)**
- **3x more $\pi^+$ and $\pi^-$ $g_1/F_1$ data on deuteron (Hall C)**
- **Jlab upgrade to 11 GeV electrons combined with major upgrade to CLAS will allow huge increase in kinematic coverage and statstical accuracy in SIDIS!**

# Summary

- **Factorization in SIDIS pion production seems to work for $0.3<z<0.7$, $W>2$ GeV, $Mx>1.4$ GeV, $0.2<x<0.5$, $Q^2>1$ GeV$^2$.**
- **Opens opportunity for studies of PDF's, and orbital motion of quarks**
- **Jlab upgrade will allow definitive measruements for $x>0.1$**
- **Laat but not least, is $p_t$ dependence of fragmentation function different for favored and unfavored?**