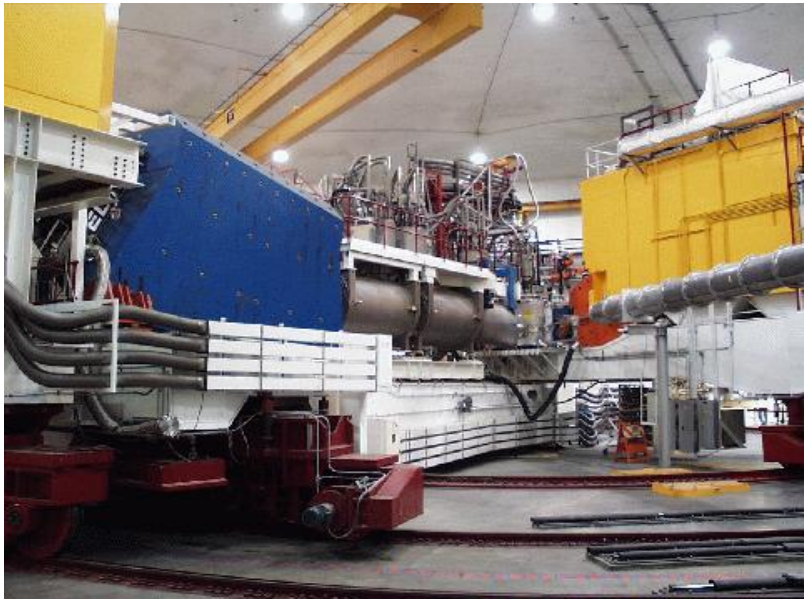
Probing nucleon structure with meson production in Hall C

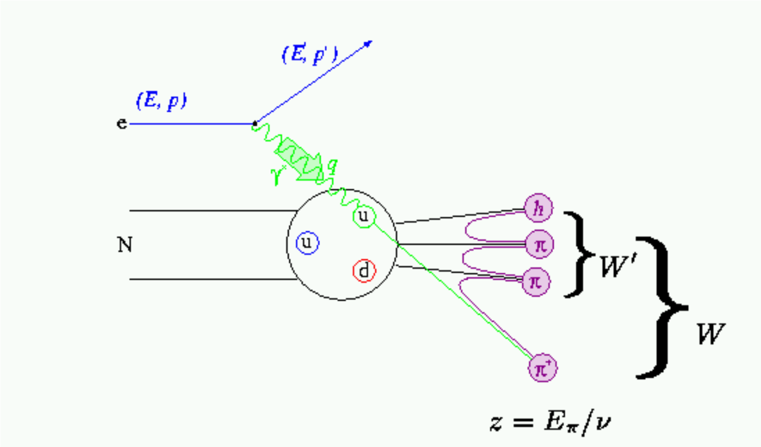
Stephen Wood and Hamlet Mkrtchyan

- **Semi-Inclusive Deep Inelastic Scattering**
- **Exclusive Meson Production**
- **Other applications of meson production**



Meson electroproduction in SIDIS

$$e + N \rightarrow e' + \pi + X$$



$$z = \frac{E_h}{\nu} \qquad x = \frac{Q^2}{2m\nu} \qquad \nu = E - E'$$

$$W^2 = m_p^2 + Q^2 \cdot \left(\frac{1}{x} - 1\right)$$

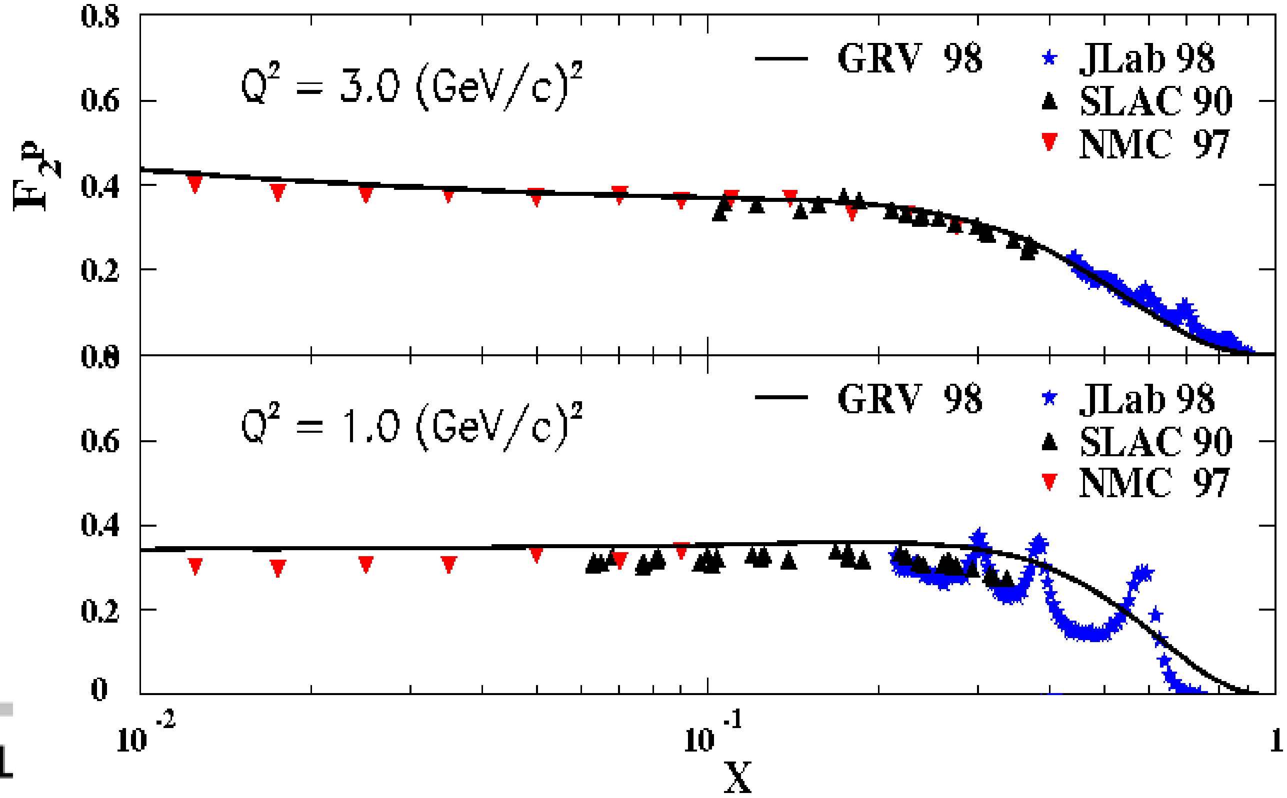
$\sigma \sim \Sigma f(x,Q^2) \cdot D(z)$

$$W'^2 = m_p^2 + Q^2 \cdot (1 - z) \cdot \left(\frac{1}{x} - 1\right)$$

- **At high energies the SIDIS process factorizes into a hard virtual photon-quark interaction and a subsequent quark hadronization.**
- **The cross section can be decomposed as a product of quark distribution functions and fragmentation function**
- **A consequence of this factorization is independence of the hardscattering process on z and hadronization on quark momentum x**

Quark-Hadron Duality

- The phenomena of quark-hadron duality in inclusive (e,e') scattering is well established (Bloom-Gilman, 1970's), and confirmed at JLab at low Q^2 and for the neutron.
- **JLab Meson Duality experiment: Verify, the existence of quark-hadron duality phenomenon in semi-inclusive pion electroproduction and low-energy factorization.**

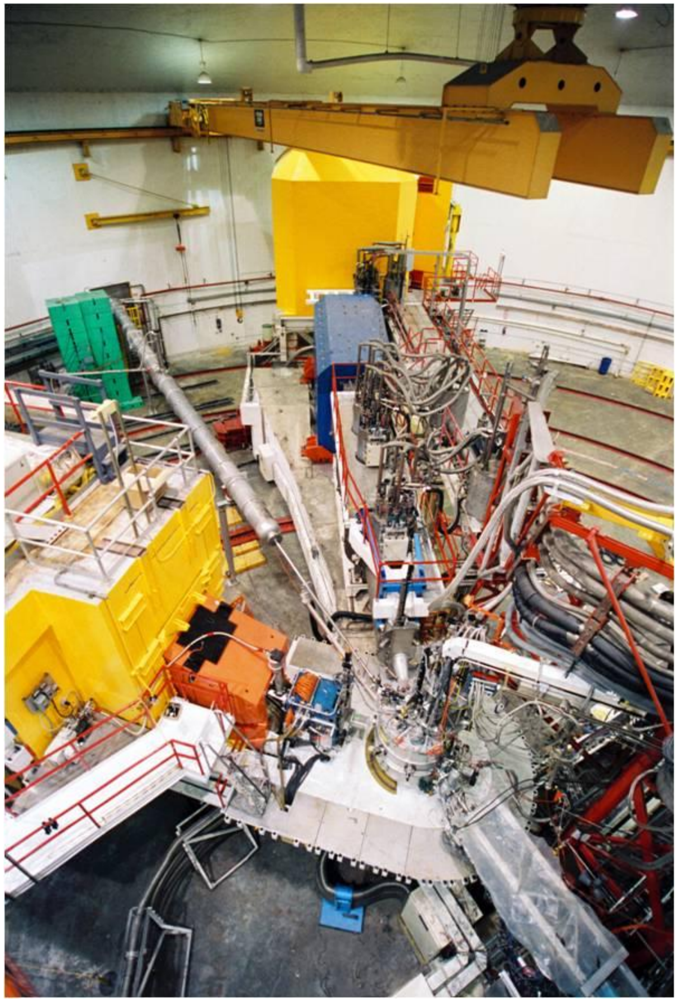


Hall C Basic Experimental Setup

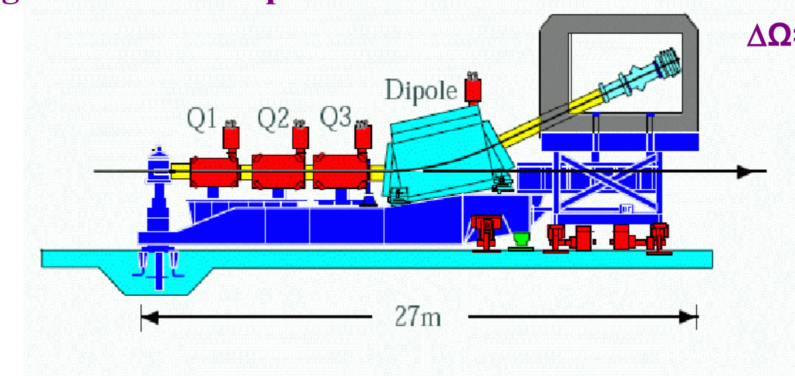
HMS π^+ π^-

SOS

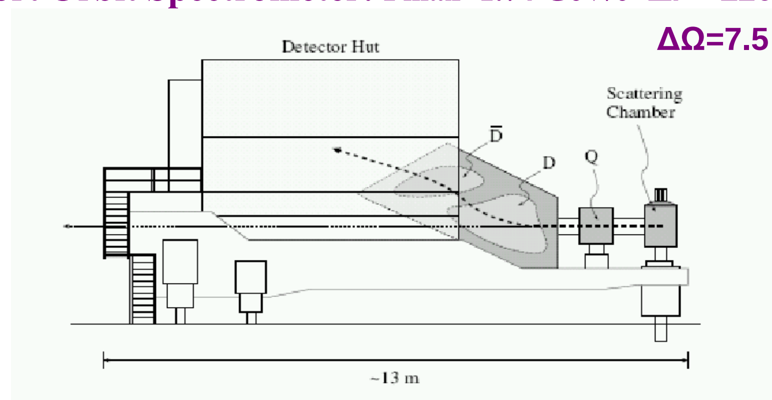
e^-



High Momentum Spectrometer: Pmax =7.4 GeV/c ΔP= ±10% ΔΩ=6.7msr



Short Orbit Spectrometer: Pmax=1.74 GeV/c ΔP= ±20% ΔΩ=7.5 msr



-- Momentum resolution: < 0.1%

-- Angular resolution: ~2.0 mrad

e, π, K, p particle ID

Overview of Meson Duality Experiment

- Coincidence measurement

HMS + SOS

- z-dependence (z=0.3-1.0) at x=0.3
- x-dependence (x=0.25-0.6) at z=0.55
- θ_π (0°-8°) at fixed z=0.55 and x=0.3 (P_t scan)

$$e + p \longrightarrow e' + \pi^{\pm} + X$$

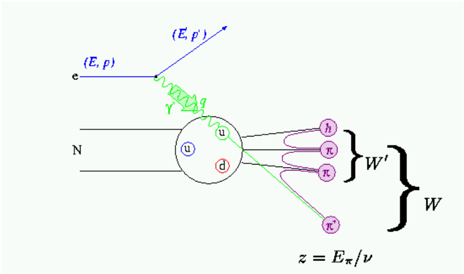
$$e + D \longrightarrow e' + \pi^{\pm} + X$$

- HMS to detect pions (π^- or π^+)
- SOS to detect electrons
- 4 cm LH2 and LD2 targets
- Al (dummy) to estimate cryo target wall contribution
- Beam energy 5.5 GeV
- Beam current 20-70 μA

Semi-inclusive $\pi^{\pm}$ electroproduction to the region M_x^2 > 1.5 GeV

Meson Duality: Experimental cross-section

$^{1,2}H(e,e'\pi^{\pm})X$



$\sigma \sim f(x,Q^2)\cdot D(z)$

- **At high energy the meson yield arises in term of a fit to the**
  $\sigma_{SIDIS} = \sigma_{DIS}\cdot\sum e_i^2[q_i(x,Q^2)D_i(z)]\cdot b e^{-bp_T^2}\{1+A\cos(\varphi)+B\cos(2\varphi)\}$

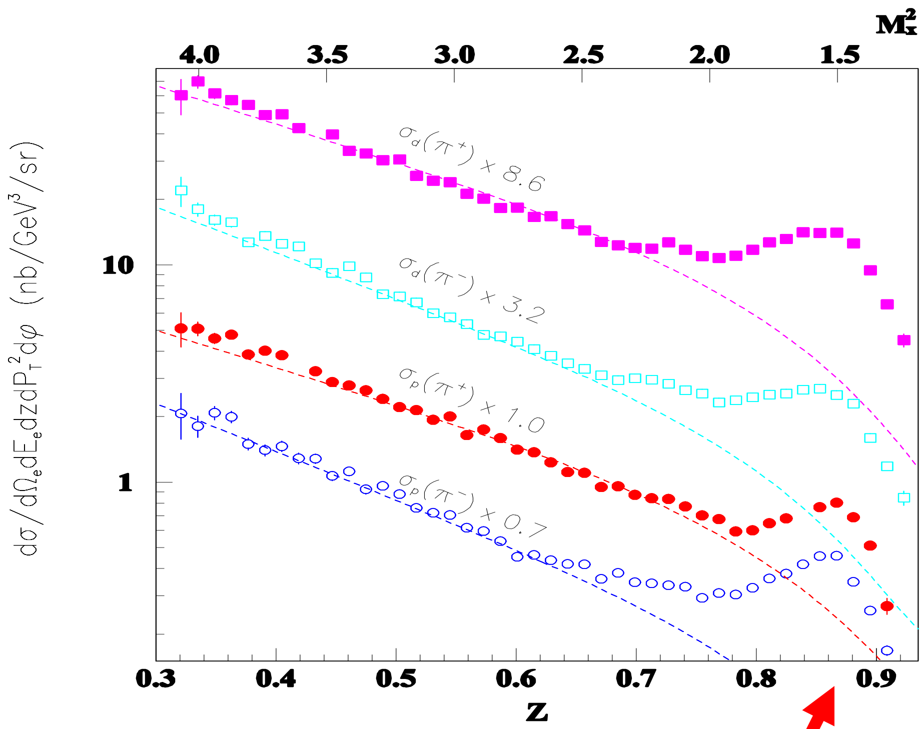
- **At $\theta_{\pi q}\sim 0$ (pion along the virtual photon direction) ~2π coverage in φ.**
  The φ-dependence effectively integrated out (for xscan and zscan)

- **Cross section modelled using high-energy factorization assuming no φ terms: $\sigma_{SIDIS} = \sigma_{DIS}\cdot\sum e_i^2[q_i(x,Q^2)D_i(z)]\cdot b e^{-bp_T^2}$**

- **Used for $q(x,Q^2)$ and $D^{\pm}(z)$ parameterization from high energies**

Will these high-energy assumptions describe data ?

z-dependence of cross section



$\sigma \sim f(x,Q^2)\cdot D(z)$

- **Good agreement between data and high energy prediction for Z<0.65**

  (using CTEQ5M for PDFs and Binnewies for Fragmentation)

- **Large excess at Z > 0.8 with respect to the prediction reflects the N–Δ transition**

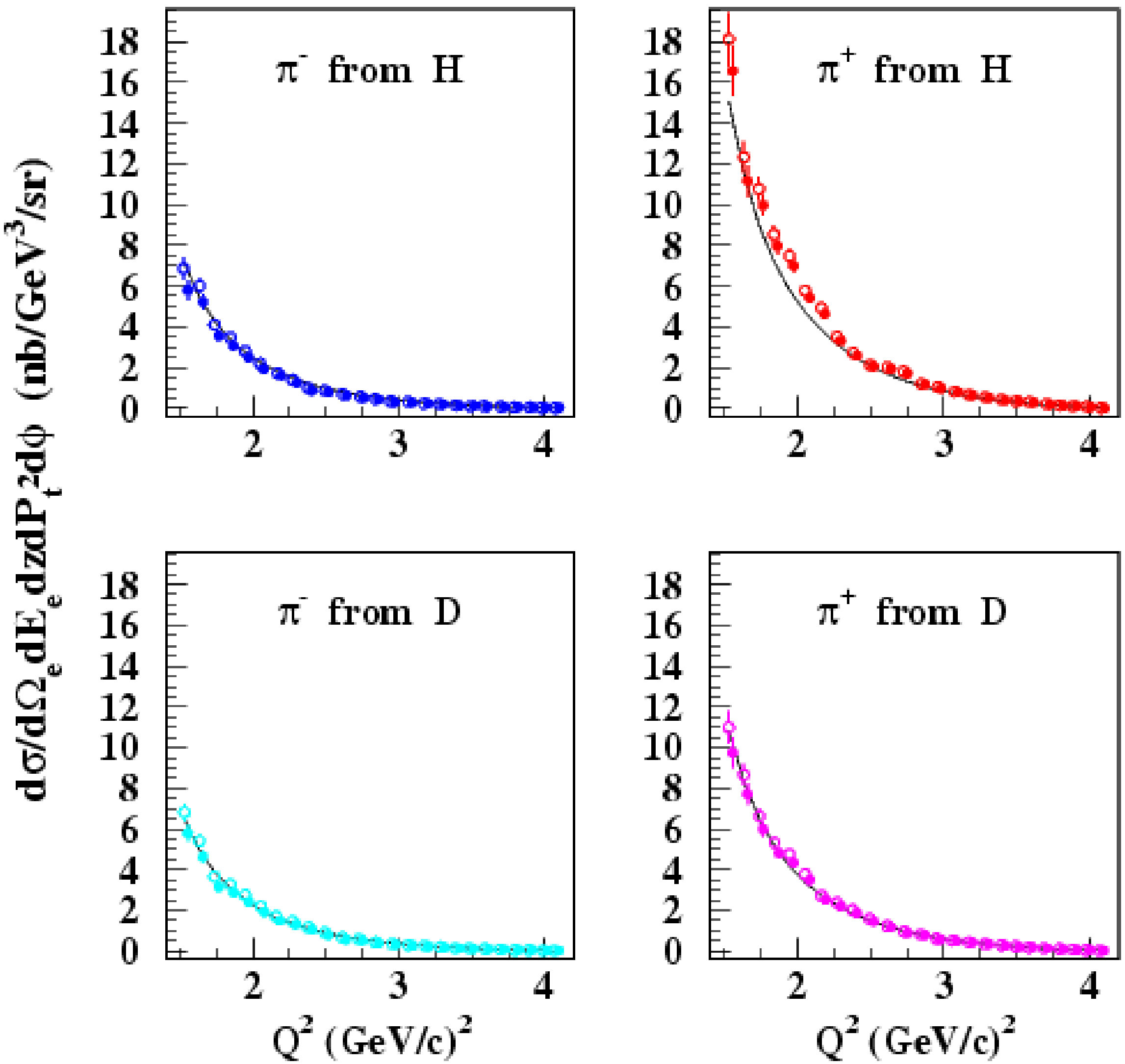
($m_\Delta^2 \approx 1.5$ GeV^2)

$$W'^2 = m_p^2 + Q^2 \cdot \left(\frac{1}{x} - 1\right) \cdot (1-z) \rightarrow W'^2 \equiv M_x^2 \sim (1-z)$$

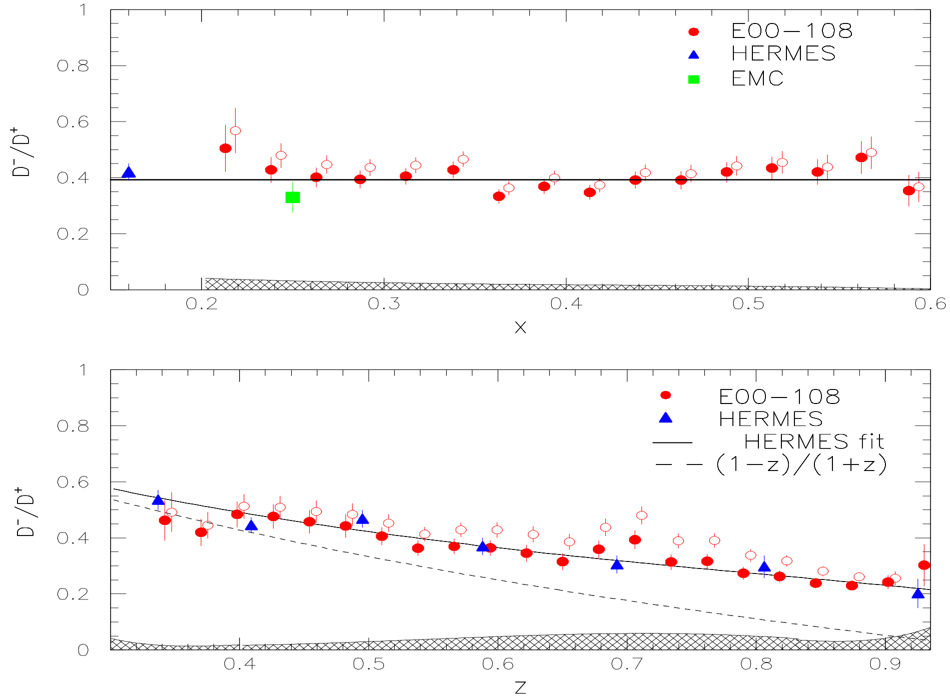
Within our kinematics (P_t ~0, x=0.3, Q^2=2.30 GeV^2), M_x^2 directly related to z:

Navasardyan et al., Phys. Rev. Lett. 98, (2007)

Q^2 -dependence of π^+ & π^- electroproduction cross section for H & D



D^-/D^+ from Deuteron π^+ to π^- ratio



$$\sigma_d^{\pi^+} \propto (4D^+ + D^-)(u+d)$$

$$\sigma_d^{\pi^-} \propto (4D^- + D^+)(u+d)$$

$$\frac{\sigma_d^{\pi^+}}{\sigma_d^{\pi^-}} = \frac{4D^+ + D^-}{4D^- + D^+}$$

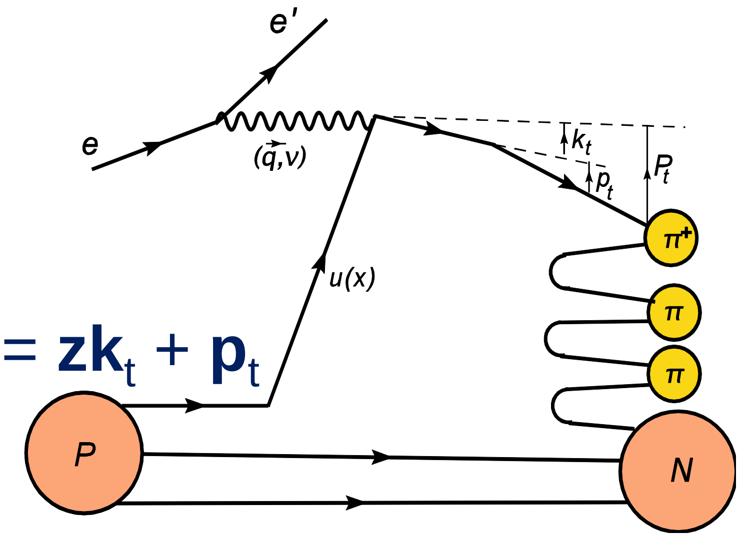
$D^-/D^+ = (4 - r) / (4r - 1)$

where $r = \sigma_d(\pi^+)/\sigma_d(\pi^-)$

$z = E_\pi/\nu$

- **Near-independence from x, as expected**
- **Results agree with HERMES & EMC**
- **The resonant contribution at z>0.8 cancel out ! (Close & Isgur)**

P_t in semi-inclusive pion electroproduction



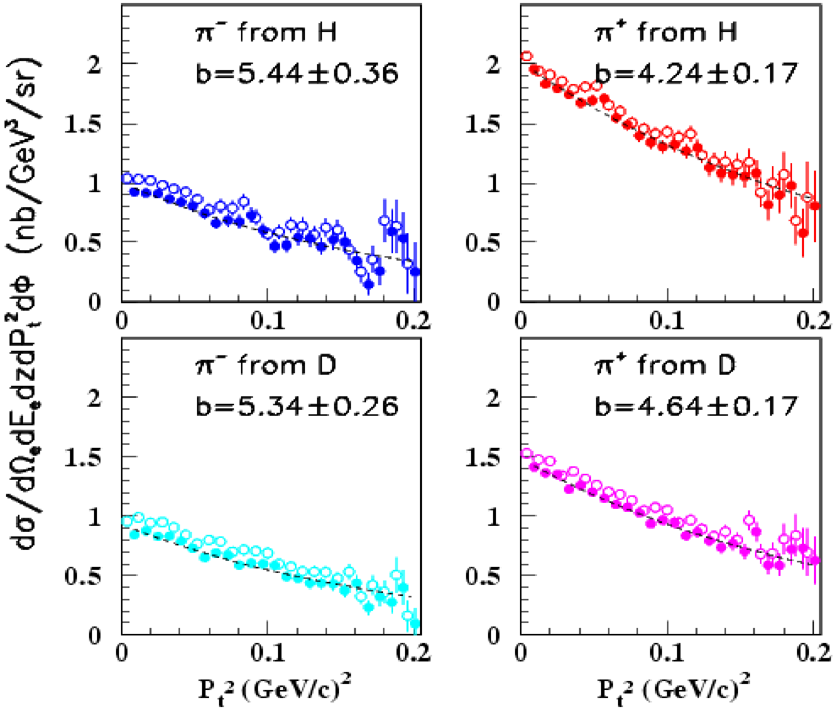
$$P_t = zk_t + p_t$$

- **Final transverse momentum of pion P_t arises from convolving the struck quark transverse momentum k_t with transverse momentum generated during fragmentation process p_t**

- **Assume the width quark and fragmentation functions are Gaussian in k_t and p_t ,and $\langle P_t^2 \rangle = \langle k_t^2 \rangle + \langle p_t^2 \rangle$**
- **Introduce separate width for u and d quarks, and separate width for D^+ and D^-**
- **$\sigma_{SIDIS} \sim \sigma_{DIS}$ (dN/dz) b exp($-bP_t^2$)**
- **Assume: $b^{\pm}_u = (z^2\mu_u^2 + \mu_{\pm}^2)^{-1}$ and $b^{\pm}_d = (z^2\mu_d^2 + \mu_{\pm}^2)^{-1}$**

The P_t^2-dependence of the cross-sections

$\sigma_{SIDIS} \sim \sigma_{DIS}$ (dN/dz) b exp(-bP_t^2) ➔ b ➔ $b^{\pm}_q$ ($b^{\pm}_u$ & $b^{\pm}_d$), and $b^{\pm}_q = (z^2\mu_q^2 + \mu_{\pm}^2)^{-1}$



$\sigma_p^{\pi+}$ =C[4c_1·exp(- $b^+_u P_t^2$)+(d/u)(D^-/D^+)c_2·exp(- $b^-_d P_t^2$)]

$\sigma_p^{\pi-}$ =C[4(D^-/D^+)c_3·exp(- $b^-_u P_t^2$)+(d/u)c_4·exp(- $b^+_d P_t^2$)]

$\sigma_n^{\pi+}$ =C[4(d/u)c_4·exp(- $b^+_d P_t^2$)+(D^-/D^+)c_3·exp(- $b^-_u P_t^2$)]

$\sigma_n^{\pi-}$ = C[4(d/u)(D^-/D^+)c_2·exp(- $b^-_d P_t^2$)+c_1·exp(- $b^+_u P_t^2$)]

Fit values:

- D^-/D^+ = 0.42± 0.01; d/u = 0.37± 0.02
- μ_u^2 = 0.09±0.03 GeV² μ_d^2 = 0.0±0.05 GeV²
- μ_+^2 = 0.18±0.03 GeV² μ_-^2 = 0.14±0.03 GeV²

- **Fit results for D^-/D^+ agree with HERMES data , and d/u ratio with LO GRV**
- **Fit tends to larger k_t width for d quarks than for u (as di-quark model)**
- **Fragmentation width μ_+ and μ_- are similar (as predicted by Anselmino)**

H. Mkrtchyan, P. Bosted et al., Phys. Lett. B665, 20 (2008)

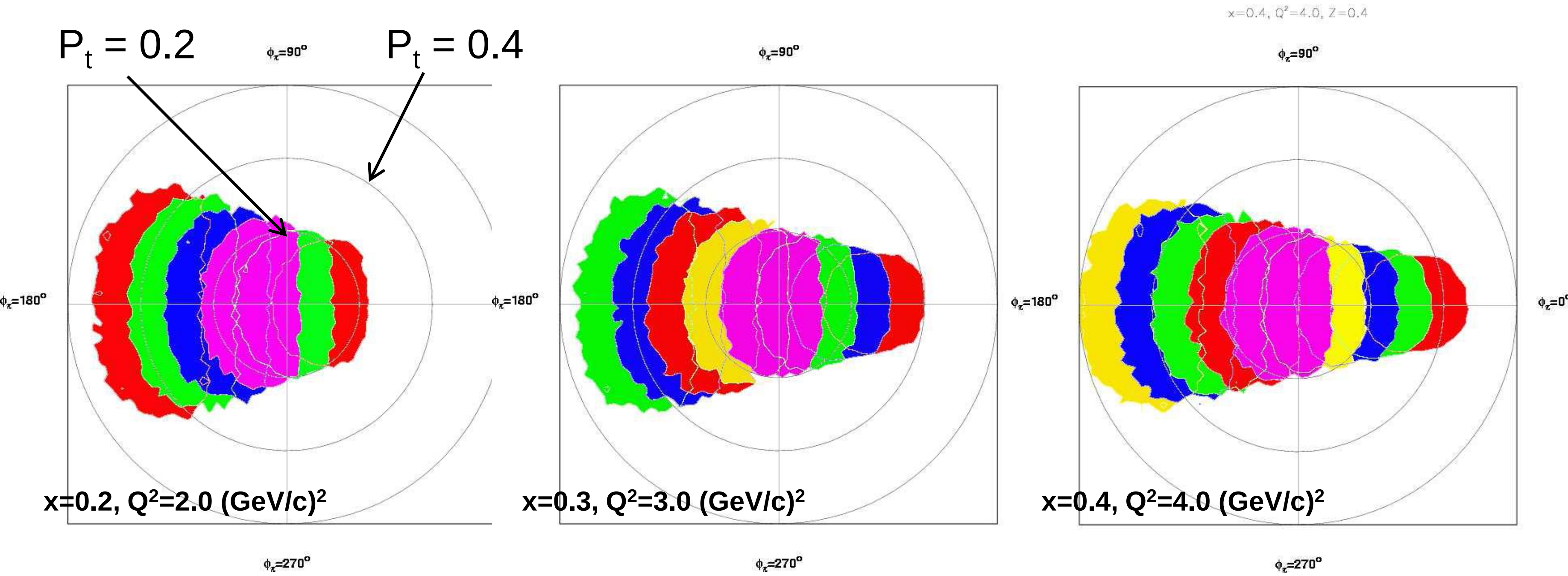
TMD of SIDIS at 12 GeV E12-09-017

Map transverse momentum dependence of (e,e′π) over range:

$0.2 < x < 0.5$, $2 < Q^2 < 5$ GeV^2, $0.3 < z < 0.5$ and $P_t < 0.5$ GeV

Combine with CLAS12 data to constrain transverse widths of u/d quarks and fragmentation functions

Obtain some statistics on transverse momentum dependence of (e,e′K)



Charge Symmetry Violation Test with SIDIS at 12 GeV

Charge Symmetry:

- $m_p \sim m_n$
- Energy levels mirror nuclei
- p vs n scattering lengths

Charge Symmetry is assumed in parton distribution functions:

- $u^p(x) = d^n(x)$

If Charge Symmetry, then $d(e,e'\pi^+)/d(e,e'\pi^-)$ depends on fragmentation functions not PDFs

Precision $N\pi^+/N\pi^-$ ratio gives $C(x) = \delta d(x) - \delta u(x)$ where:

$\delta u(x) = u^p(x) - d^n(x)$, $\delta d(x) = d^p(x) - u^n(x)$

Experiment E12-09-002:

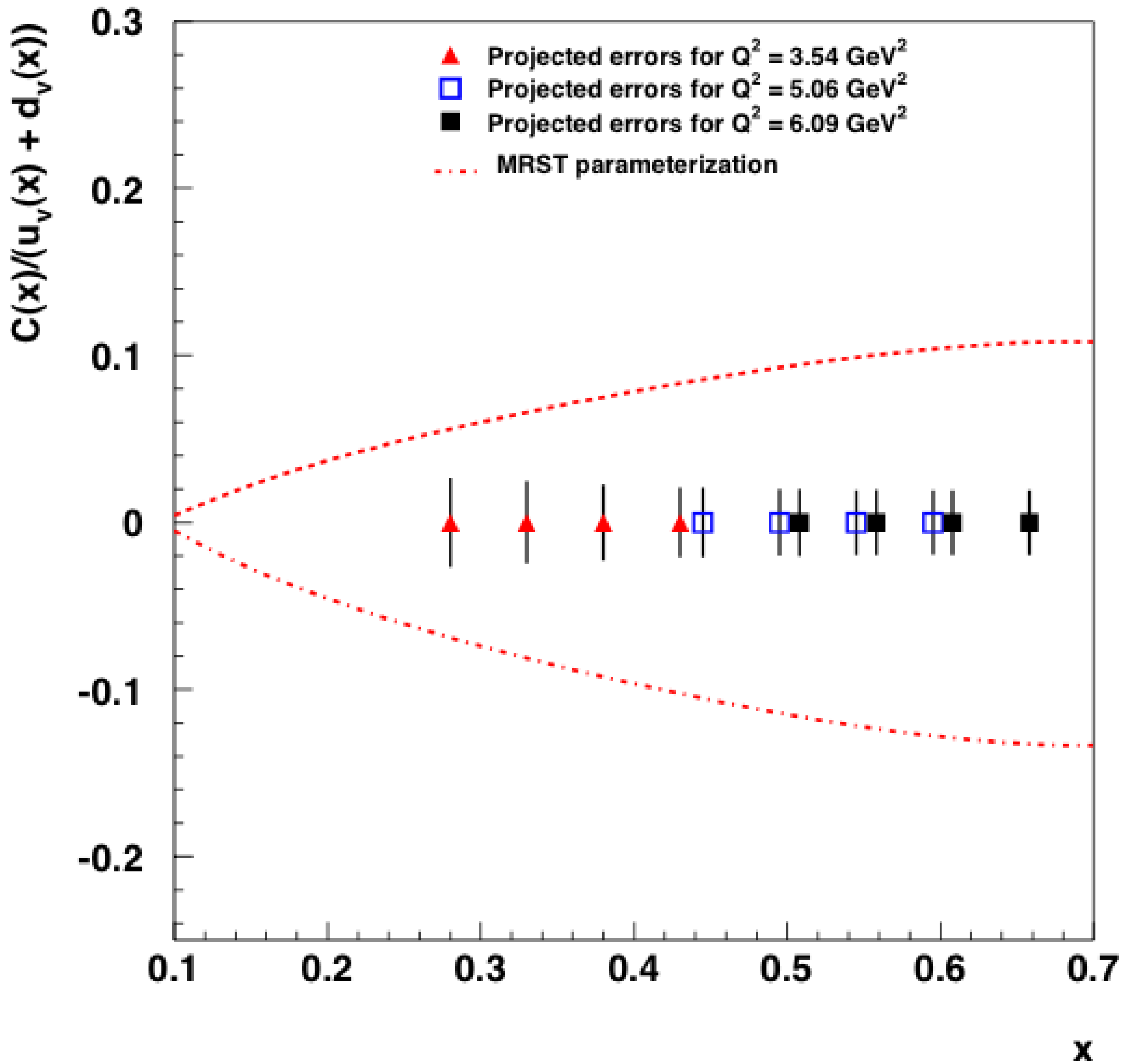
- Measure $d(e,e'\pi^+)/d(e,e'\pi^-)$ to 1% over range of kinematics
- $p(e,e'\pi^+)$, $p(e,e'\pi^-)$ for further factorization tests
- Requires careful control of π^+ π^- detection efficiency, radiative corrections

Charge Symmetry Violation Projections

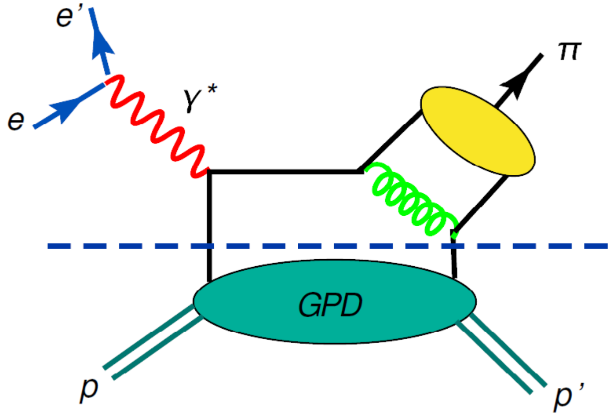
$$\delta d(x) = u_v^p(x) - d_v^n(x)$$

$$\delta u(x) = d_v^p(x) - u_v^n(x)$$

$$C(x) = \delta d(x) - \delta u(x)$$

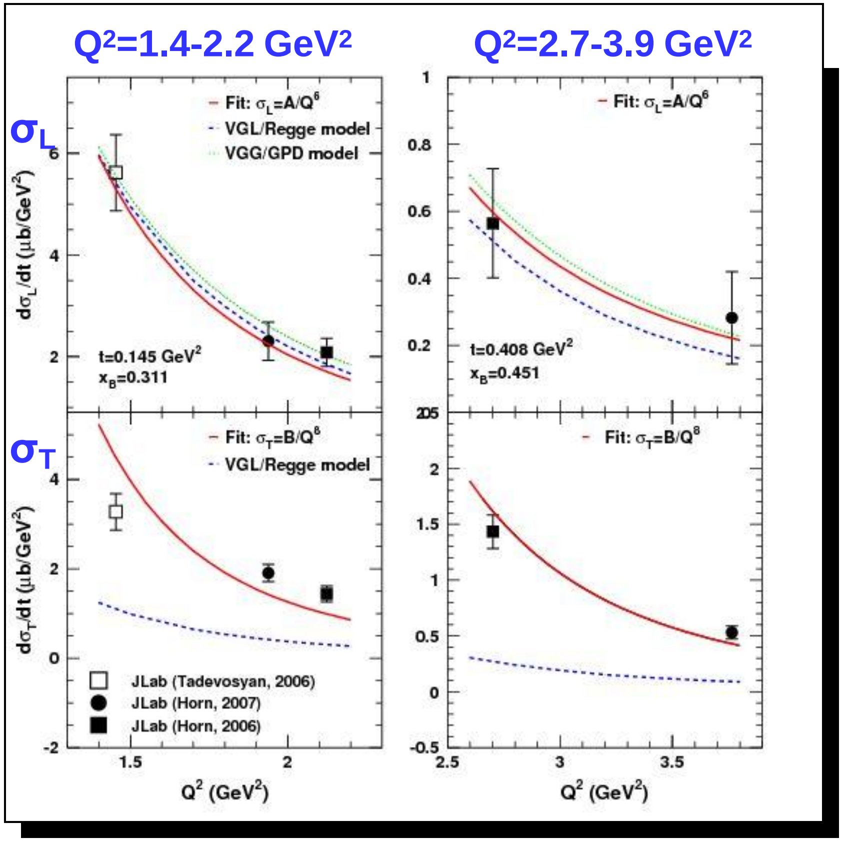


Scaling of exclusive pion electroproduction cross sections



- At sufficiently high Q^2 (> 10 GeV^2), meson electroproduction should factorize into hard (quark-knockout) and soft (nucleon GPD and meson formation).
- To leading order σ_L, should scale as $1/Q^6$ and σ_T as $1/Q^8$. (At fixed x and t).
- 12 GeV experiment (E12-07-105) will extend range of scaling tests and test dominance of σ_L. ($Q^2 \to 9$ GeV^2)

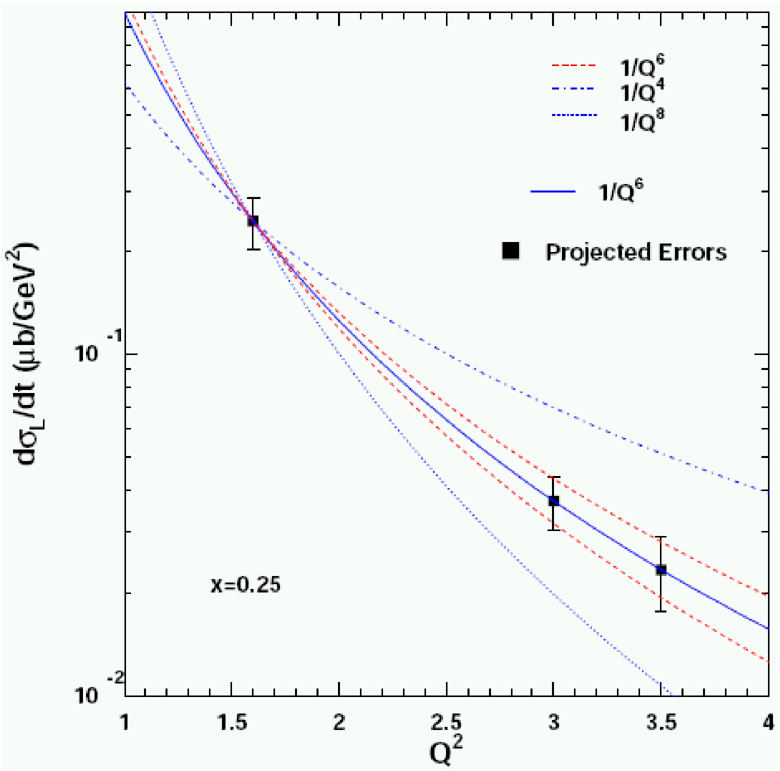
6 GeV Hall C Data

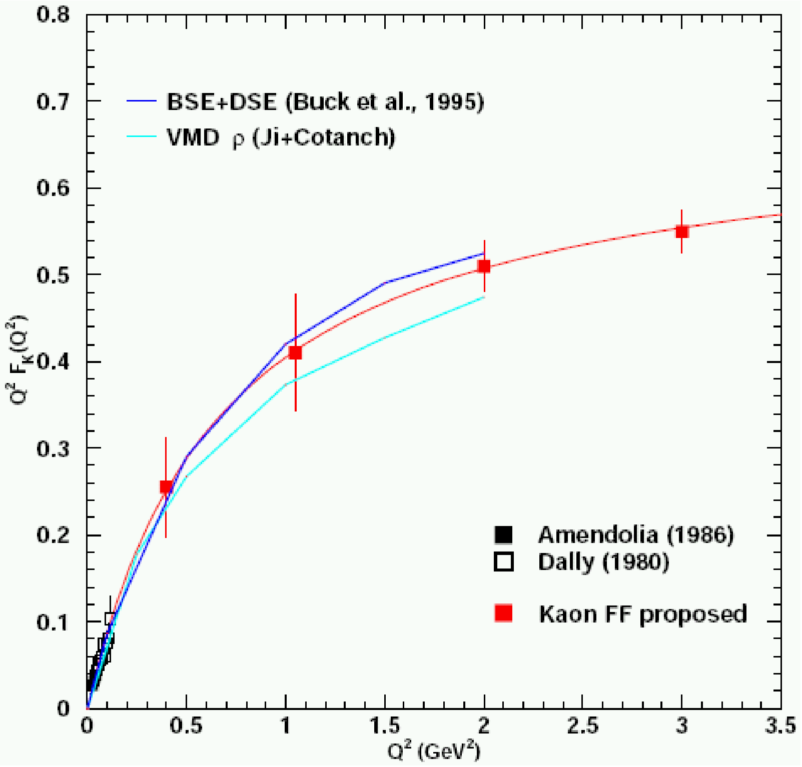


Horn et al., Phys. Rev. C. 78, 058201 (2008)

L-T separated Kaon Electroproduction at 5-11 GeV

E12-09-011: T. Horn (CUA), G. Huber (U of Regina), P. Markowitz (FIU)

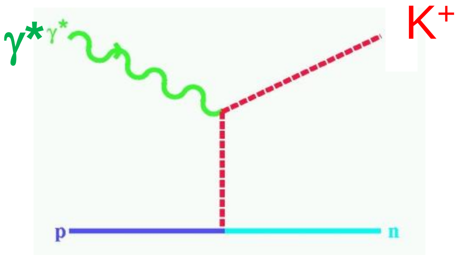




Projected errors on scaling and form factor.

Study kaon production mechanism and feasibility of

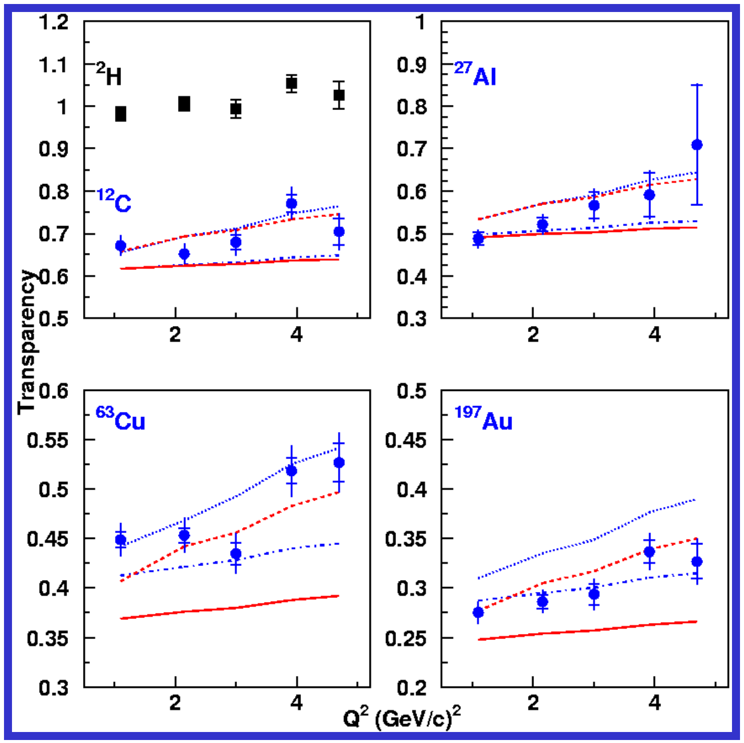
Kaon form factor extraction up to Q^2 = 3 GeV^2



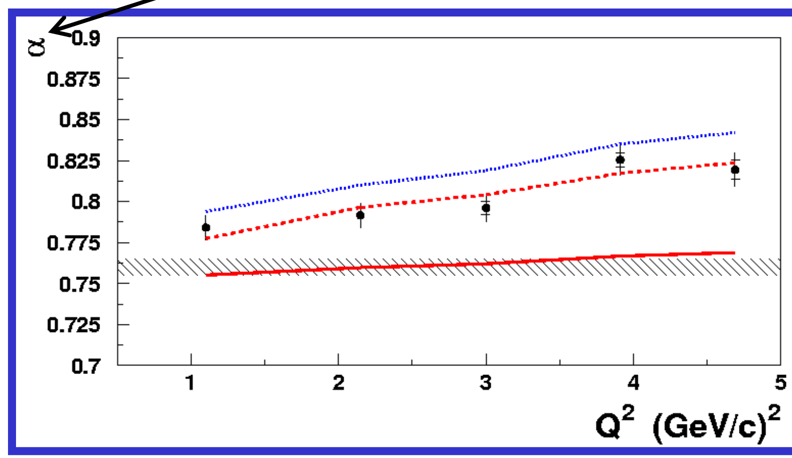
Pion Transparency in Nuclei: *D. Dutta, R. Ent , K. Garrow*

A(e,e′π⁺) $T = \frac{(\text{Data/Simulation})_A}{(\text{Data/Simulation})_p}$

- - - With CT
—— No CT
······ CT + SRC
– · – No CT + SRC



from fit of
$T(A) = A^{\alpha-1}$
at fixed Q^2

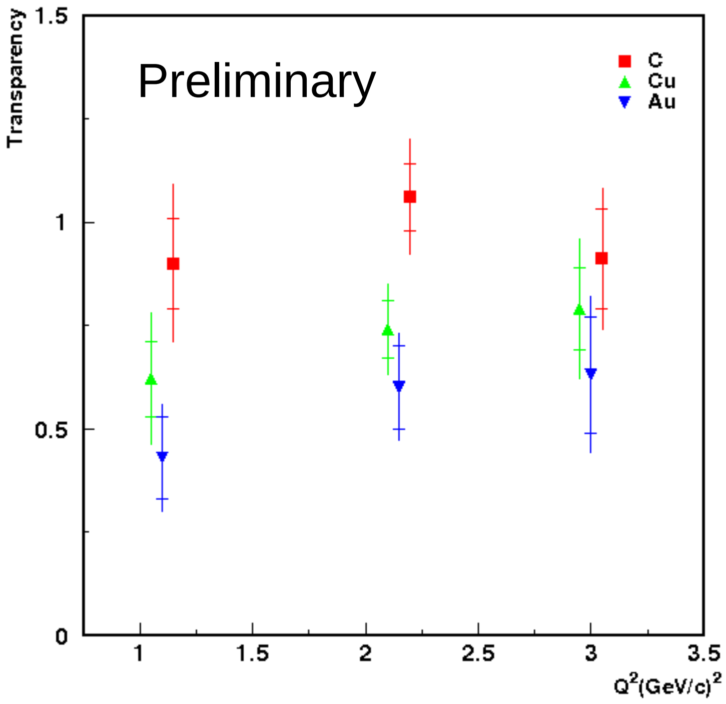


Clasie et al., Phys. Rev. Lett. 99, 242502 (2007)
Qian et al., Phys. Rev. C 81, 055209 (2010)

Larson, Miller and Strikman, PRC 74, 018201 (2006)
Cosyn, Martinez, Ryckebusch and Overmeire., PRC 74, 062201R (2006)

Onset of Color Transparency a precondition
For factorization.

Kaon Transparency in Nuclei



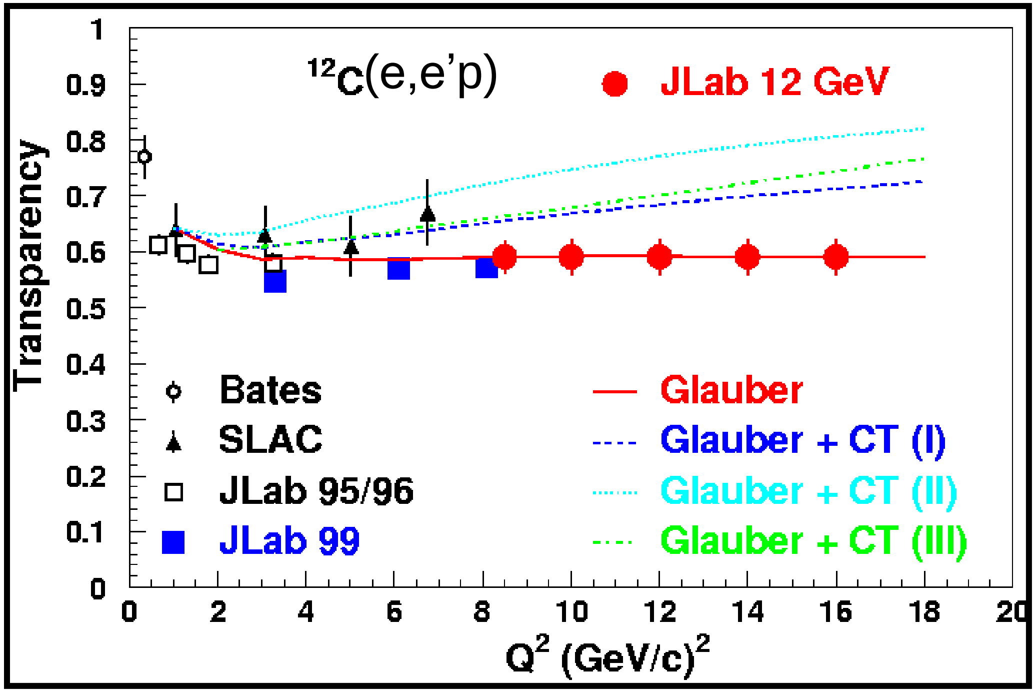
$$T = \frac{(\mathrm{Data/Simulation})_A}{(\mathrm{Data/Simulation})_d}$$

A(e,e'π^+) transparency experiment data contains some A(e,e'K^+) events

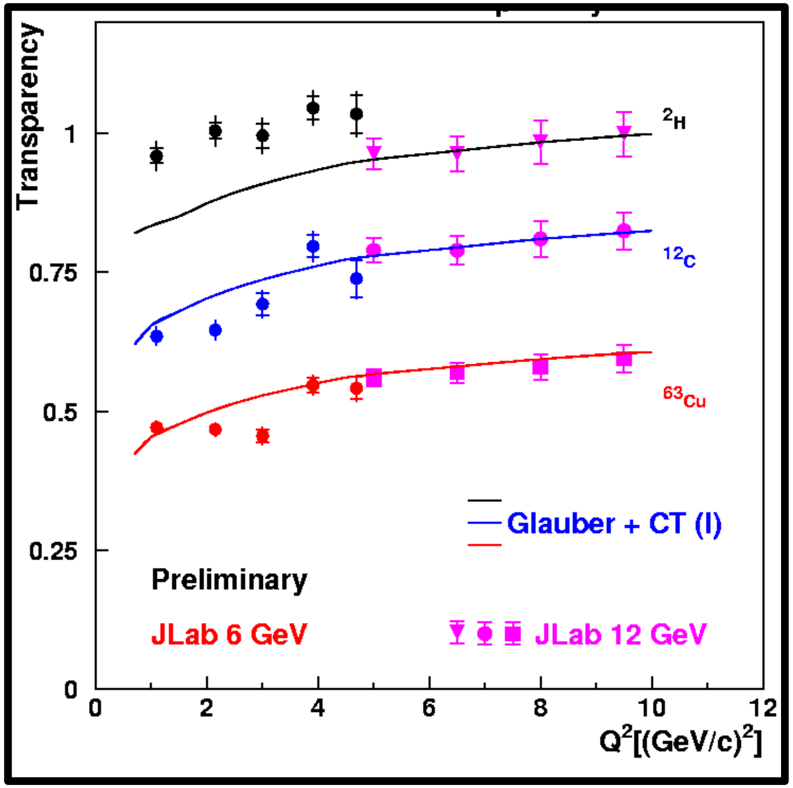
Analysis underway to extract Kaon transparencytra

Pion/Proton Transparency at 12 GeV

A(e,e′p) at 12 GeV (projected results)



A(e,e′π^+) at 12 GeV (projected results)

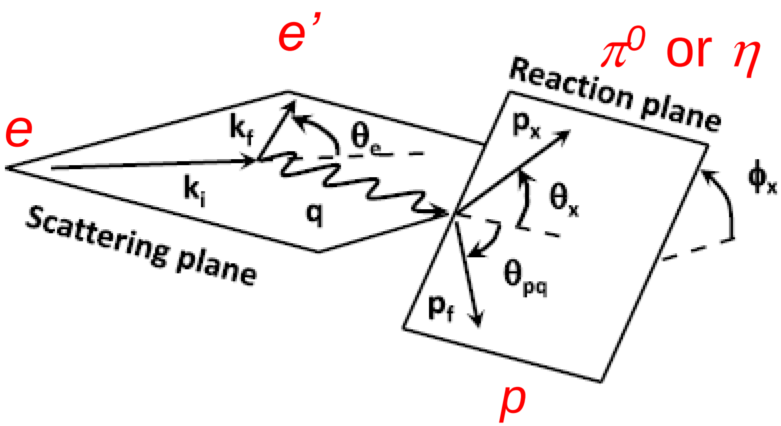


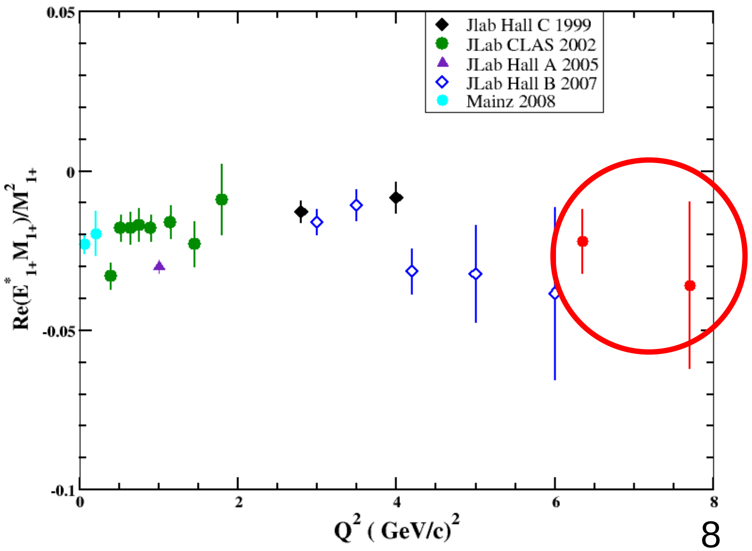
E12-06-107

Baryon Production at high Q^2

$\gamma^* + p \rightarrow \Delta \rightarrow p + \pi^0$

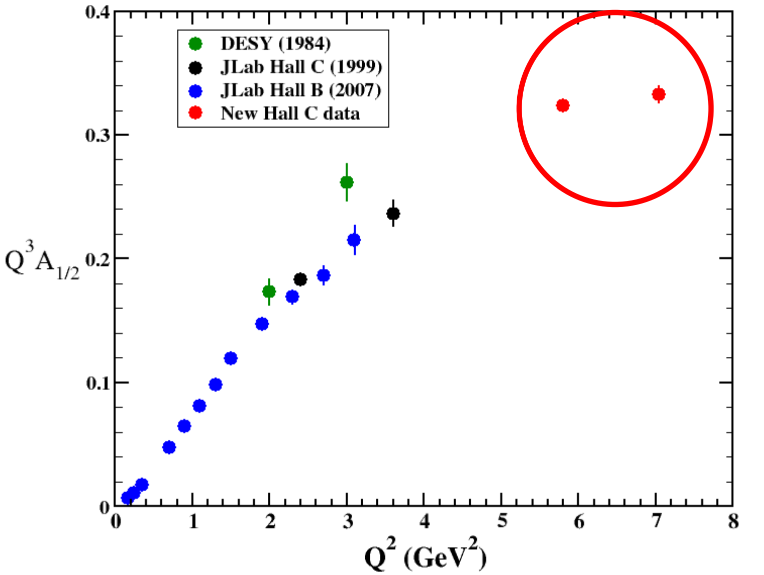
P_{33} E2/M1





$\gamma^* + p \rightarrow S_{11} \rightarrow p + \eta$

$A_{1/2}$ for S_{11}



Villano et al., Phys. Rev. C 80, 035203 (2009)
Dalton et al., Phys. Rev. C 80, 015205 (2009)

Hypernuclei

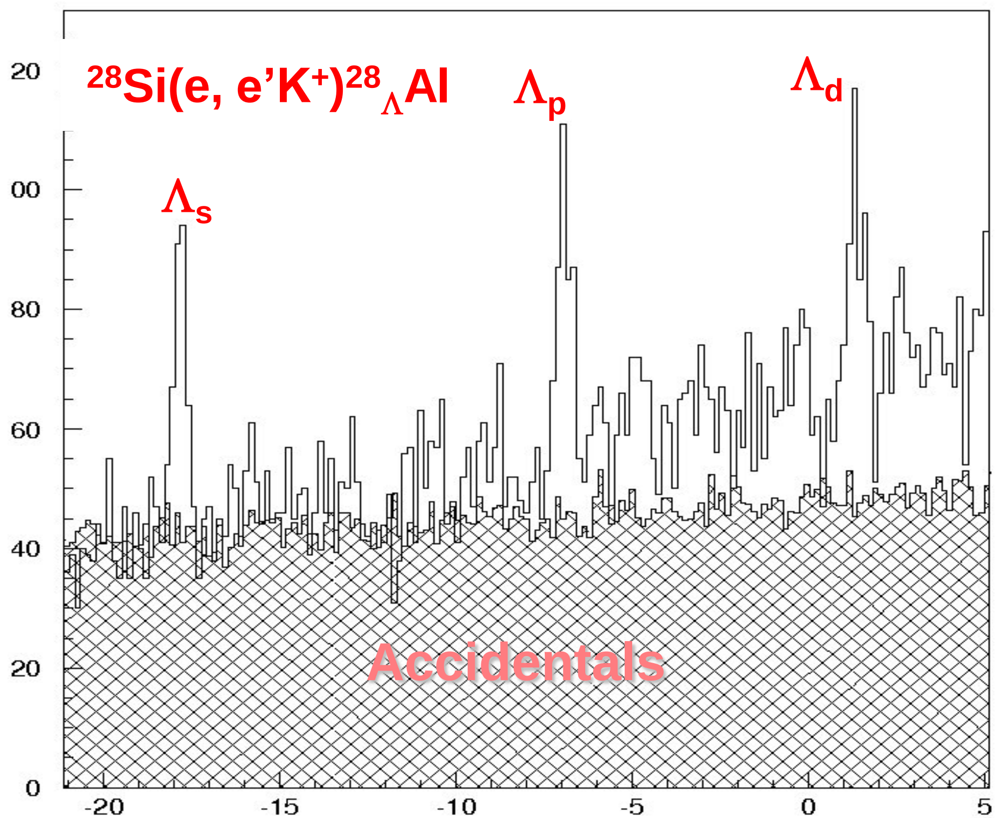
E01-011 (Tohoku U, Hampton U, FIU, JLab)

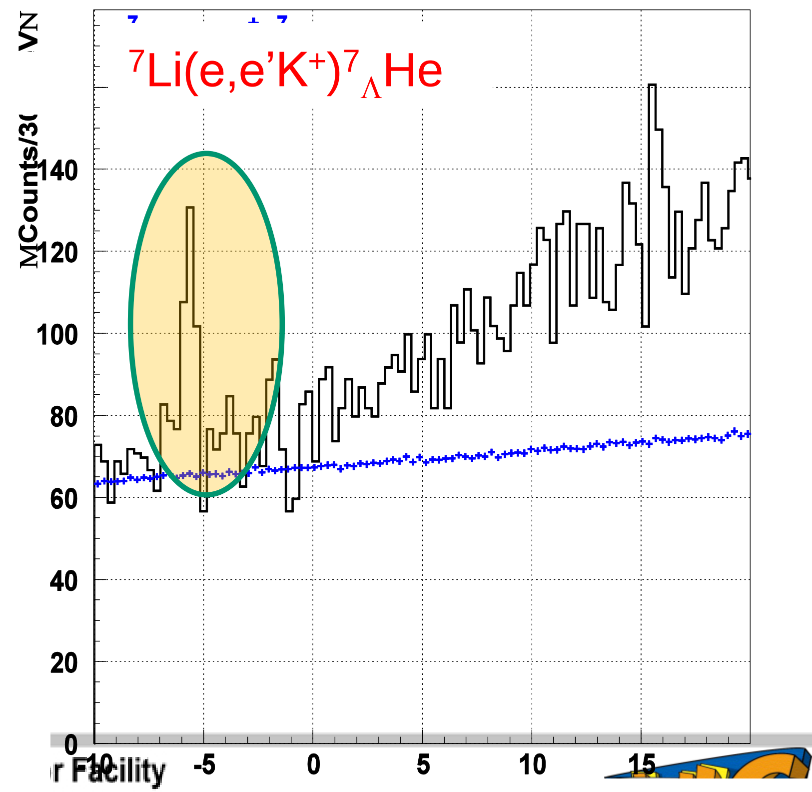
A(e,e'K+) $_{\Lambda}$A(Z-1)

Access unique hypernuclei

~400 keV FWHM resolution

1st observation of $^{28}_{\Lambda}$Al and $^{7}_{\Lambda}$He



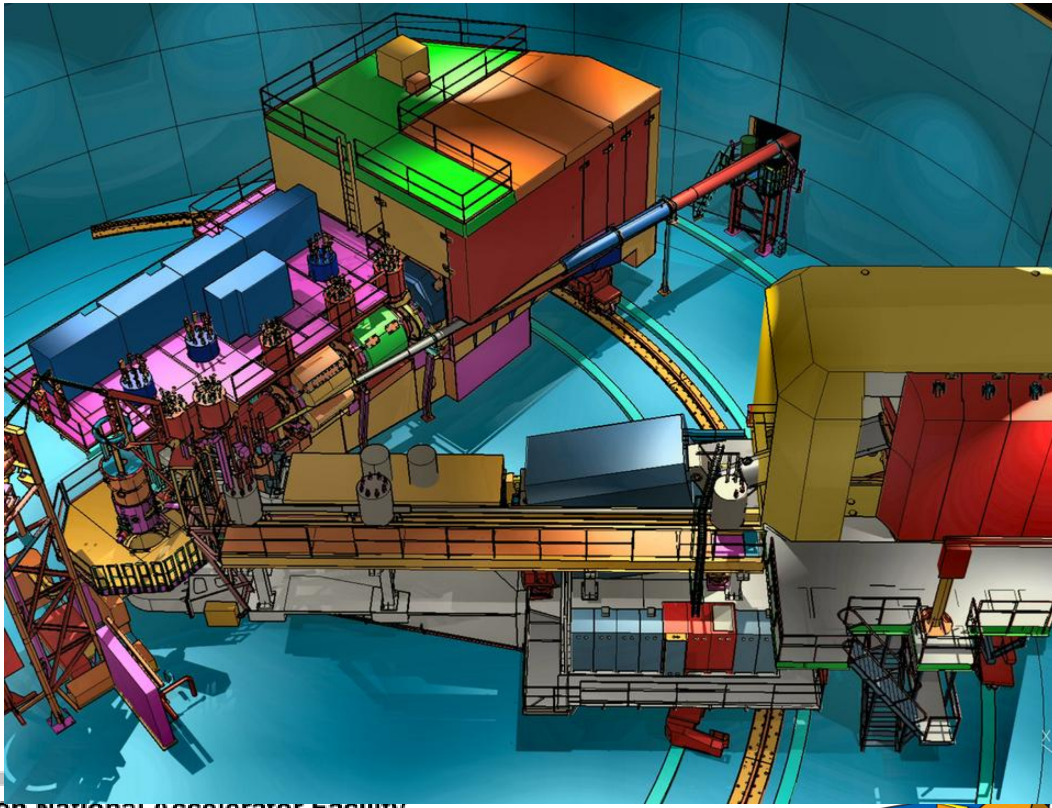


Hall C after 12 GeV Upgrade

- Beam Energy: 2 – 11 GeV/c
- Super High Momentum Spectrometer (SHMS)
  - Horizontal Bender, 3 Quads, Dipole
  - P $\rightarrow$ 11 GeV/c
  - dP/P 0.5 – 1.0x10^{-3}
  - Acceptance: 5msr, 30%
  - $5.5° < \theta < 40°$
- High Momentum Spectrometer (HMS)
  - P $\rightarrow$ 7.5 GeV/c
  - dP/P 0.5 - 1.0x10^{-3}
  - Acceptance: 6.5msr, 18%
  - $10.5° < \theta < 90°$

- Minimum opening angle: 17°
- Well shielded detector huts

- Ideal facility for:
  - Rosenbluth (L/T) separations
  - Exclusive reactions
  - Low cross sections (neutrino level)



Summary

- **Exploratory Meson Duality study will continue with 12 GeV SIDIS measurements:**
  - **Rosenbluth separation of SIDIS (σ_L/σ_T)**
  - **Transverse momentum**
  - **Charge Symmetry Violation of PDFs**
- **12 GeV exclusive meson production scaling tests and CT**
- **Other applications of meson production**
  - **Hypernuclei**
  - **Baryon production**
  - **Sub-threshold J/Ψ production in nuclei**
  - **Pion Form Factor**
  - **π^0 photo-production**