# Hall C 12 GeV Semi Inclusive Experiments

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**Joint Hall A & C Summer Meeting, June 5-6, 2014**

# Outline

Introduction

- The E00-108 experiment findings
- SIDIS kinematics & formalism

Hall C 12 GeV SIDIS experiments:

- E12-06-104 ($R = \sigma_L/\sigma_T$)
- E12-09-002 ($\pi^+/\pi^-$)
- E12-09-017 ($P_T$)
- E12-13-007 ($\pi^0$)

Summary

# E00-108 Experiment

E00-108 "Duality in meson production", the first SIDIS experiment in Jlab.

- Charged pion production off Hydrogen and Deuterium targets in semi-inclusive DIS kinematics: 1.5 $GeV^2 < Q^2 < 4.2$ $GeV^2$, $0.22 < x < 0.58$, $0.3 < z < 1.$, $W^2 \sim 5.7$ $GeV^2$ typically (always > 4.2 $GeV^2$).
- Looked for signature of quark – hadron duality via search for quark scattering and subsequent fragmentation (a.k.a ($x$, $z$) factorization) at low loss energies.
- Ran in 2003 in Hall C. Utilized 5.5 GeV, 20 -60 µA beam on 4 cm LH2 and LD2 targets. Detected 1.7 GeV e' in SOS, 1.3 – 4.1 GeV $\pi^{\pm}$ in HMS.
- Main results have been published in
  T. Navasardyan et al. Phys. Rev. Lett. 98, 022001 (2007)
  H. Mkrtchyan et al., Phys. Lett., B665, 20-25 (2008)
  R. Asaturyan,1 R. Ent,2,3 H. Mkrtchyan et al.,Phys. Rev. C 85, 015202 (2012)

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Within the framework of quark scattering → fragmentation factorization ansatz

$$N^{\pi^{\pm}}(x,z) \propto \sum_i e_i{}^2[q_i(x)D_{q_i}{}^{\pi^{\pm}}(z) + \bar{q}_i(x)D_{\bar{q}_i}{}^{\pi^{\pm}}(z)]$$

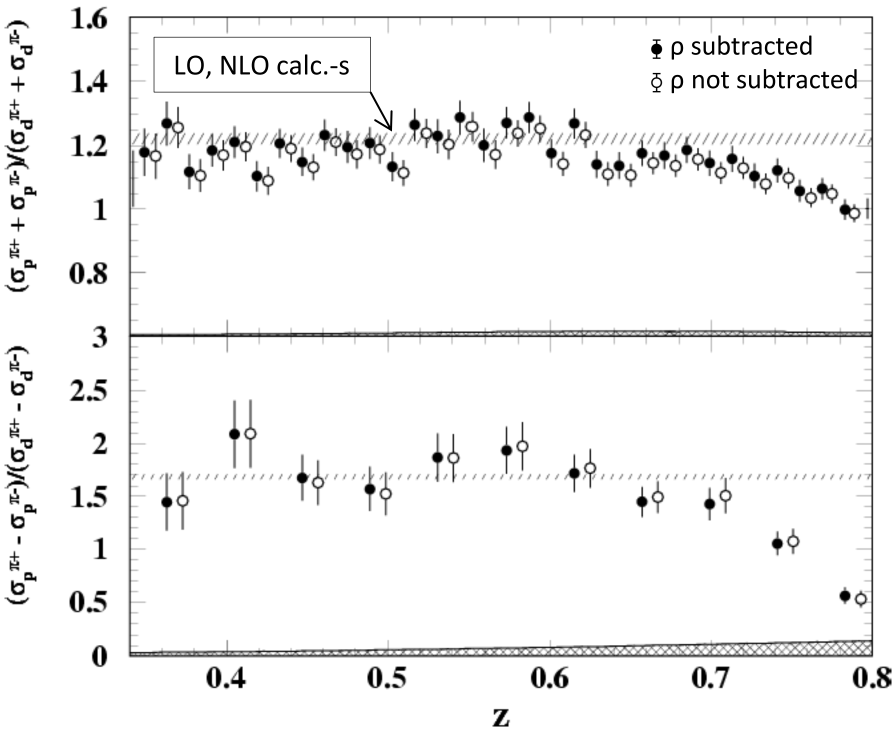
$x = \frac{Q^2}{2M\nu}$, , z= $\frac{E_\pi}{\nu}$ –– elasticity

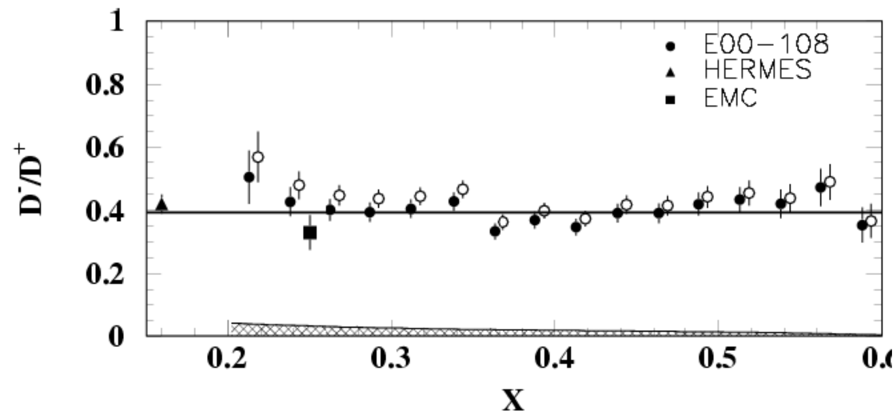
# E00-108 Ratios

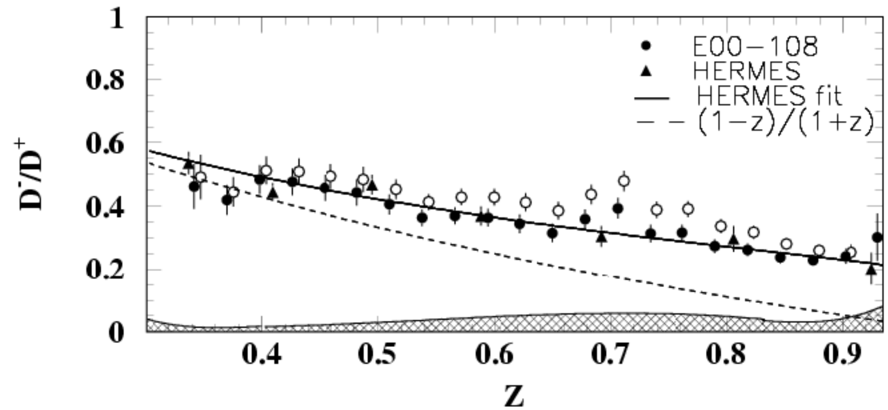
$$\frac{\sigma_p(\pi^+)+\sigma_p(\pi^-)}{\sigma_d(\pi^+)+\sigma_d(\pi^-)}=\frac{4u(x)+4\bar{u}(x)+d(x)+\bar{d}(x)}{5[u(x)+d(x)+\bar{u}(x)+\bar{d}(x)]}$$

$$\frac{\sigma_p(\pi^+)-\sigma_p(\pi^-)}{\sigma_d(\pi^+)-\sigma_d(\pi^-)}=\frac{4u_v(x)-d_v(x)}{3[u_v(x)+d_v(x)]}$$

$$\frac{D^-(z)}{D^+(z)}=\frac{4-\frac{\sigma_d(\pi^+)}{\sigma_d(\pi^-)}}{4\frac{\sigma_d(\pi^+)}{\sigma_d(\pi^-)}-1}$$



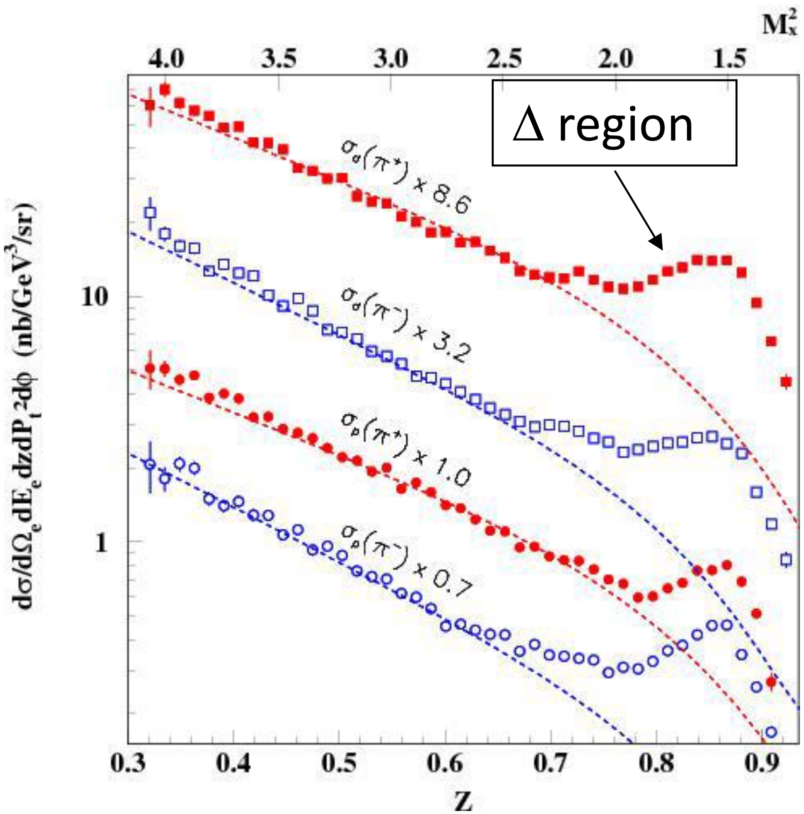

The H/D ratios are independent of *z* for *z*<0.7.

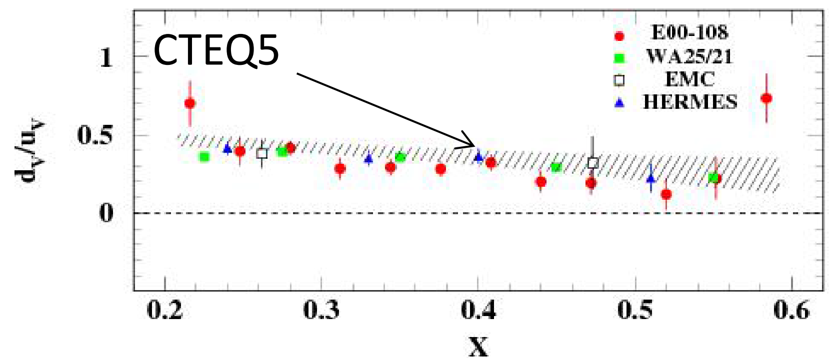
The $D^-/D^+$ ratios are independent of *x*.

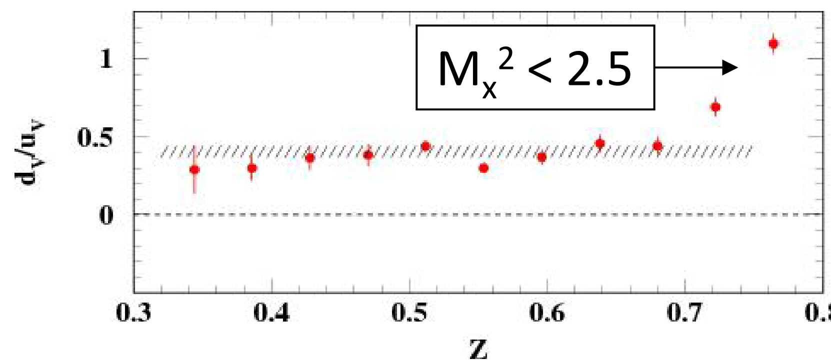
# E00-108 Cross sections

$$R^{-}_{pd}(x) = \frac{\sigma_p^{\pi^+}(x,z) - \sigma_p^{\pi^-}(x,z)}{\sigma_d^{\pi^+}(x,z) - \sigma_d^{\pi^-}(x,z)} = \frac{4u_v(x) - d_v(x)}{3[u_v(x) + d_v(x)]}$$

$$\frac{d_v}{u_v} = \frac{4 - 3R^{-}_{pd}}{3R^{-}_{pd} + 1}$$



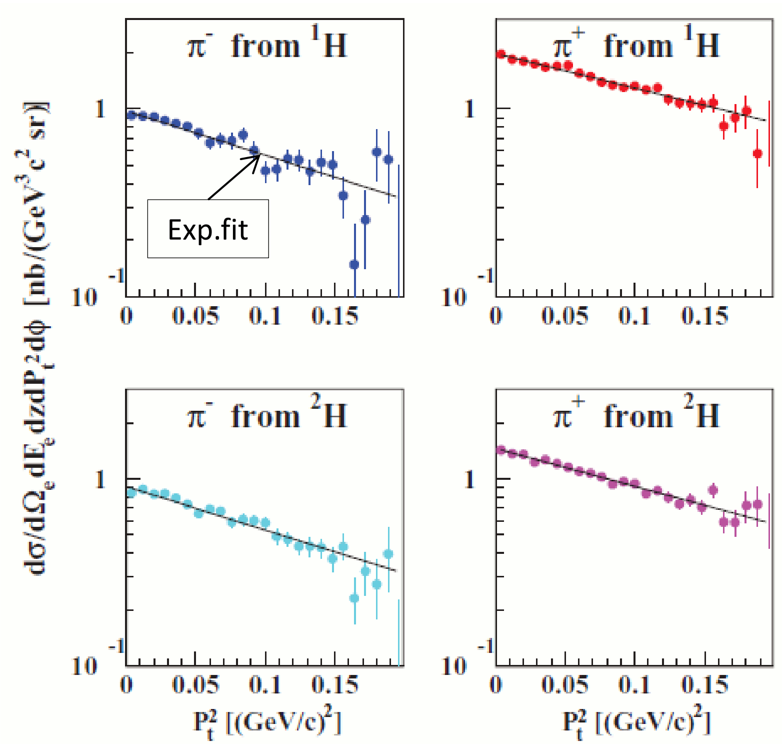

The cross sections agree with high energy expectations up to z < 0.7.

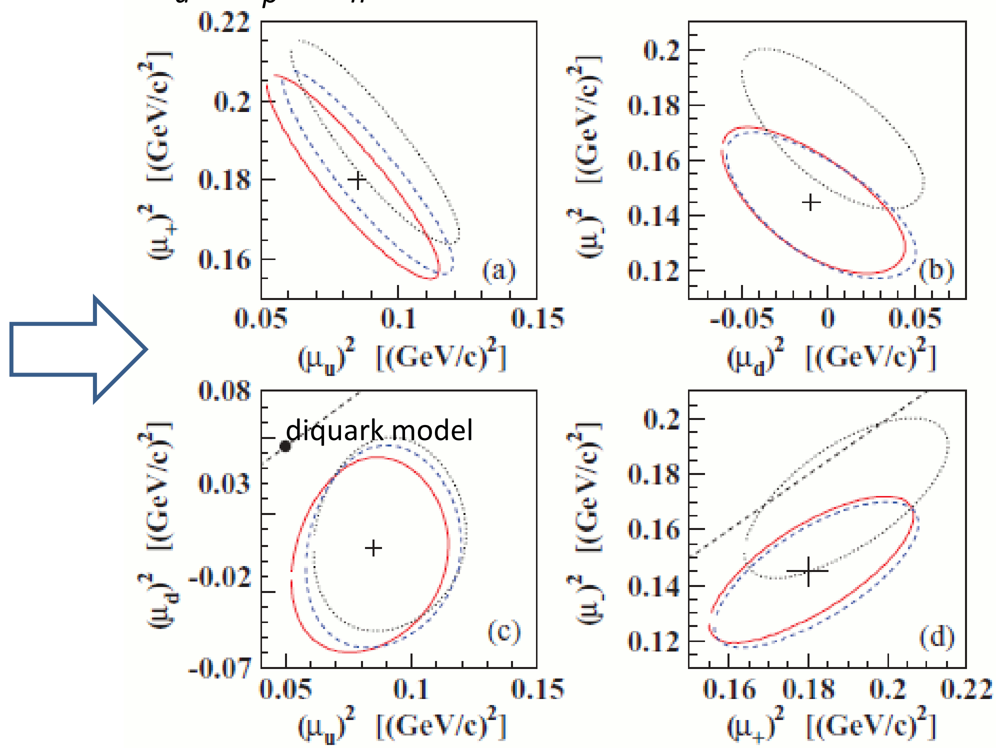
The $d_v/u_v$ ratios are independent of $z$ for $z < 0.7$.

# E00-108 $P_T$ dependence

Assumptions:

- $P_t = zk_t + p_t$ ($k_t$ for quark, $p_t$ - for pion relative to the quark);
- Separate widths for *u* and *d* quarks, and for $D^+$ and $D^-$ ($\mu_u$, $\mu_d$, $\mu_+$, $\mu_-$);
- The quark and FF widths are Gaussian and combine quadratically;
- Neglect sea quarks;
- $\sigma_d = \sigma_p + \sigma_n$.




From fit to data for $\mu_u$, $\mu_d$, $\mu_+$, $\mu_-$, $D^-/D^+$, $d/u$ and a constant ($\chi^2$ = 68 /73 ):

$d/u$ = 0.39 ± 0.03 @ x=0.3 (0.40 from LO GRV98);
$D^-/D^+$ = 0.43 ± 0.01 @ z=0.55 (0.42 from HERMES);

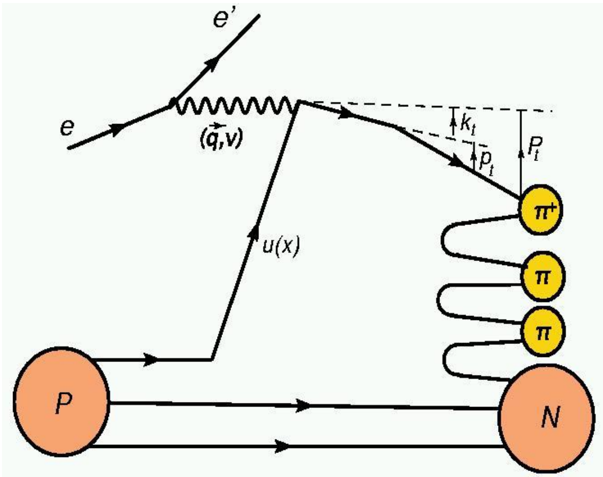
$\mu_u < \mu_+$ , $\mu_d < \mu_-$ ;
$\mu_u^2 = 0.07 \pm 0.03$ (GeV/$c$)$^2$, $\mu_d^2 \approx 0$.

# E00-108 Key Findings

E00-108 Conclusions:

- Observed, *for the first time*, the quark-hadron duality phenomenon in pion electroproduction reactions.
- Various ratios from data point to factorization of the reaction in a sequential electron-quark scattering and a quark-pion fragmentation process, provided that $W^2 > 4.0$ GeV$^2$ and $z < 0.7$ (beyond the resonance region in $M_X$).
- The azimuthal dependence is small, as compared to the exclusive pion electro-production (consistent with data from other groups and theoretical expectations based on a SIDIS approach).
- $P_T$ dependence of the cross section shows a possible flavor dependence of the quark distribution and/or FFs.
- In the context of a simple model with only valence quarks and only two FFs, the transverse momentum $k_t$ width of $u$ quarks is larger than that for $d$ quarks, for which the width is consistent with zero within the statistical uncertainties.
- The transverse momentum $p_t$ widths of the favored and unfavored FFs are similar to each other and both larger than the two quark widths (consistent with theoretical expectations based on fits to the world data).
- However, some of the findings are suggestive, due to limited kinematics coverage and complications in the analysis. Small but not negligible systematic differences in the data to theory comparisons are found.

# SIDIS kinematics and formalism




$$x = \frac{Q^2}{2M\nu}$$

$z = \frac{E_\pi}{\nu}$ –– elasticity

$$P_t = p_t + z k_t + O\left(k_t^2/Q^2\right)$$

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

$M_X^2 = W'^2 \sim M^2 + Q^2\left(\frac{1}{x} - 1\right)(1 - z)$, in parallel kinematics and $\frac{Q^2}{\nu^2} \ll 1$

Semi –inclusive DIS kinematics : $Q^2 > 1$ GeV$^2$, $W^2 > 4$ GeV$^2$, $W'^2 > 2.5$ GeV$^2$

At high $Q^2$ and $\nu$

$$\frac{\frac{d\sigma}{d\Omega_{e'} dE_{e'} dz dP_t^2}}{\frac{d\sigma}{d\Omega_{e'} dE_{e'}}} = \frac{dN}{dz} b e^{-bP_t^2} \frac{1 + A\cos\varphi + B\cos 2\varphi}{2\pi}, \qquad \frac{dN}{dz} \sim \sum_i e_i^2 q_i(x, Q^2) D_{q_i \to \pi}(z, Q^2)$$

Possible measurement and analysis scenarios:

- Determine cross sections versus $x$, $z$, $Q^2$, $P_t$
- Determine yield ratios versus $x$, $z$, $Q^2$, $P_t$ (validity of $x$-$z$ factorization, etc)
- Disentangle $k_t$ and $p_t$ (quark scattering and fragmentation) widths from $P_t$-scans
- Disentangle $A(x, z, Q^2, P_t)$ and $B(x, z, Q^2, P_t)$ ($\sigma_{LT}$, $\sigma_{TT}$)

# Hall C 12 GeV SIDIS experiments

New opportunities with 12 GeV CEBAF beam and SHMS in Hall C:

- Wider phase space, extension to high (ν, $Q^2$ ) region.
- Better accuracies (*when SHMS acceptance understood*)
- New NPS spectrometer ($\pi^0$ detection)

Current 12 GeV SIDIS program in Hall C:

- **E12-06-104**, Measurement of the Ratio $R=\sigma_L/\sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering, P. Bosted, R. Ent, H. Mkrtchyan spockespersons, A- rating, 40 days.
- **E12-09-002**, Precise Measurement of **$\pi^+/\pi^-$ Ratios** in Semi-inclusive Deep Inelastic Scattering PartI: **Charge Symmetry violating Quark Distributions**, D. Dutta, D. Gaskell, K. Hafidi spokespersons, A- rating, 22 days.
- **E12-09-017**, **Transverse Momentum Dependence** of Semi-Inclusive Pion Production, P. Bosted, R. Ent, H. Mkrtchan spokespersons, A- rating, 32 days.
- **E12-13-007**, Measurement of Semi-Inclusive **$\pi^0$ Production** as **Validation of Factorization**, R. Ent, T. Horn, H. Mkrtchyan, V.Tadevosyan spokespersons, A-, 25 days.

# E12-06-104 ($R = \sigma_L/\sigma_T$) Motivation

- $R_{SIDIS}$ is expected to be similar to $R_{DIS}$ but never has been checked. This expectation is backed by quark—hadron duality found at low energies.
- $R_{DIS}$~$1/Q^2$, while $R$ in deep exclusive production scales with $Q^2$. Hence, $R_{SIDIS}$ is expected to fail at $z$->1 (exclusive limit).
- At low energies $R_{SIDIS}$ may depend also on $P_T$. Expect $R_{SIDIS}$ mimic angular distributions of decay of nucleon resonances at low $P_T$, and anneal to $R_{DIS}$ at high $P_T$.

* Complication: diffractive $\rho$ contribution to $R_{SIDIS}$ has rising with $Q^2$ behavior.

- Verify $R_{SIDIS} = R_{DIS}$
- Check semi-inclusive to exclusive transition in $z$-dependence of $R$
- Verify that $R_{SIDIS}$ anneals to $R_{DIS}$ at large $P_T$
- Verify that $R_{SIDIS}$ follows the $Q^2$ dependence of $R_{DIS}$

<u>Advantages for the general 12 GeV SIDIS program</u>: implications for measurements of light quark sea flavor asymmetry, flavor decomposition of the nucleon spin at $x$>0.1, azimuthal asymmetries.

# E12-06-104 ($R = \sigma_L/\sigma_T$) Measurements

Measurement program:

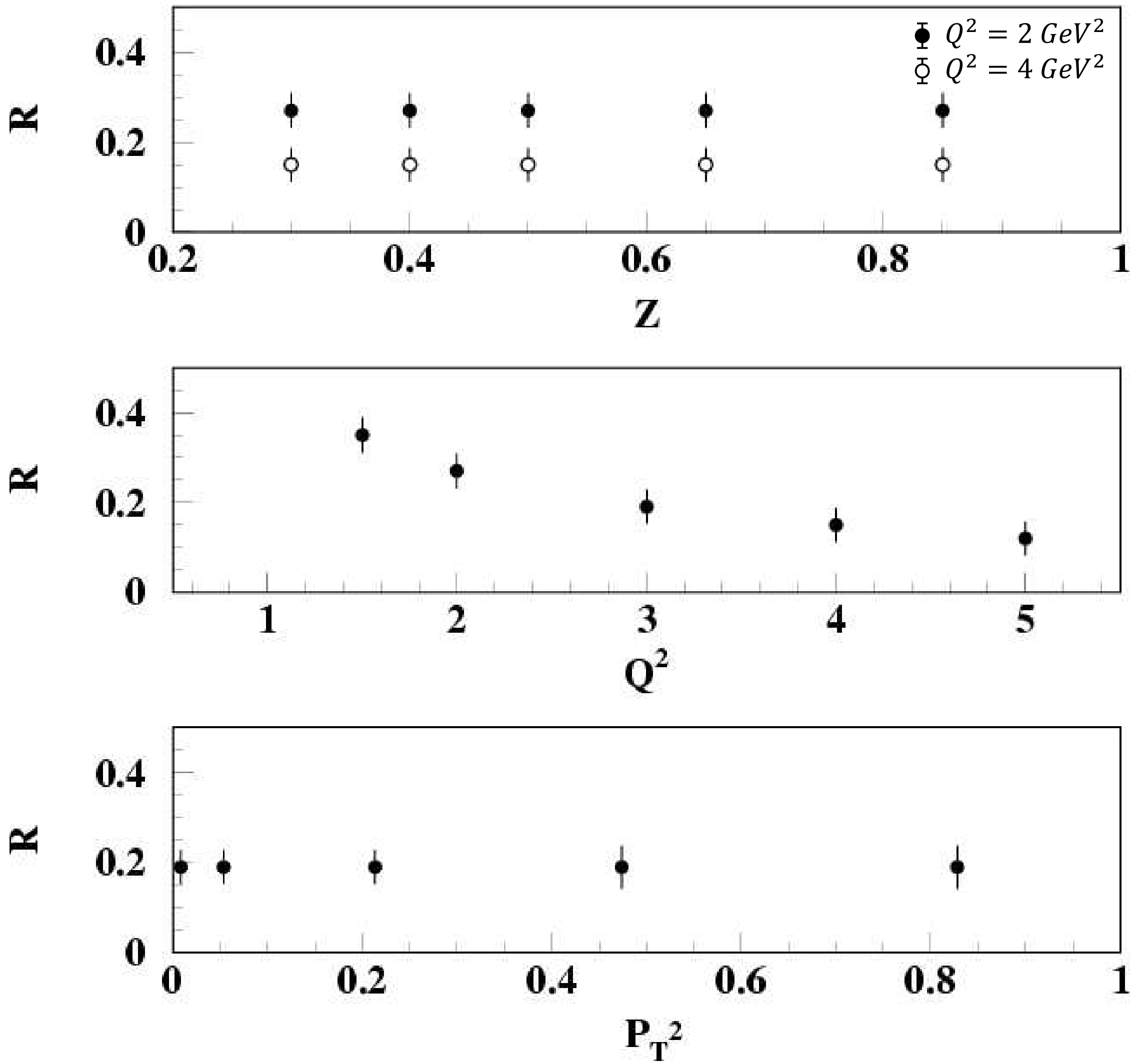
- Map $R$ in $z$ at $x$ = 0.2 and $Q^2$ = 2 GeV$^2$, for both $H$ and $D$ targets. Kinematics chosen compatible with the flavor decomposition program at Jlab. Specifically, verify $R^H_{SIDIS} = R^D_{SIDIS}$.
- Map $R^H$ in $z$ at $x$ = 0.4 and $Q^2$ = 4 GeV$^2$.
- Map $R^H$ in $p_T^2$ at $x$ = 0.3 and $Q^2$ = 3 GeV$^2$.
- Map $R^H$ in $Q^2$ from 1.5 to 5 GeV$^2$.

Experimental conditions:

- Assumed 10 cm LH2/LD2 targets (~ point-like).
- Beam current 50 μA, raster size 2x2 cm$^2$ (target density fluctuations <1%).
- Beam energies of 6.6, 8.8 and 11 GeV for Rosenbluth separations at fixed $x$, $Q^2$, $z$ and $p_T^2$. $\Delta\varepsilon \approx 0.5$, typically.
- Coincident detection of $e'$ in HMS and $\pi^{\pm}$ in SHMS (at small pion angles).
- Measure inclusive cross section simultaneously to determine $R_{DIS}$.

*Expect systematic uncertainties of 1.1 – 1.6%!*

# E12-06-104 ($R = \sigma_L/\sigma_T$) Projected Results




E12-06-104 projected results assuming $R_{\mathrm{SIDIS}} \sim R_{\mathrm{DIS}}$.

# E12-09-002 ($\pi^+/\pi^-$) Motivation

- ❖ Charge symmetry (CS) is an approximate symmetry in the nuclear world, respected to better than 1%: $M_p \approx M_n$, energy levels in mirror nuclei (after Coulomb corrections), …
- ❖ At the quark level CS implies $u^p(x,Q^2) = d^n(x,Q^2)$, $d^p(x,Q^2) = u^n(x,Q^2)$. *Is widely assumed but never thoroughly checked!*
- ❖ In QCD charge symmetry violation (CSV) originates from EM interactions (small at high energies) and $\delta m = m_d - m_u$.
- ❖ Naively, CSV ~ $(m_d - m_u)/\langle M\rangle$, where $\langle M\rangle$ ~ 0.5 – 1 GeV from the strong Hamiltonian → ~1%!

Hints on CSV:

- ✓ Large flavor symmetry violations in proton sea, $\bar{u}_p(x) \neq \bar{d}_p(x)$ (NMC, NA51 at CERN, E866 at FNAL).
- ✓ "NuTeV anomaly" might be removed by the assumed valence quark CSV.
- ✓ A quark model ((Sather) and MIT bag model (Rodionov at al.) theory calculations both predict CS in $u^p(x)$ and $d^n(x)$ to within 1%, while $d^p(x)$ and $u^n(x)$ violate by >5% at large $x$.
- ✓ The MRST phenomenological data analysis showed CSV effects, larger than from the theory by 3 – 4 times.

# E12-09-002 ($\pi^+/\pi^-$) Formalism 1

Obtain CSV from the charged pion yield ratio on *D* target:

$$R^D_{meas} = \frac{4Y^{D\pi-}(x,z) - Y^{D\pi+}(x,z)}{Y^{D\pi+}(x,z) - Y^{D\pi-}(x,z)}$$

Assuming (*x*,*z*) factorization, charge conjugation invariance ($D_u{}^{\pm} \approx D_{\bar{u}}{}^{\mp}, D_d{}^{\pm} \approx D_{\bar{d}}{}^{\mp}$), charge symmetry ($D_d{}^{\pi-}(z) \approx D_u{}^{\pi+}(z), D_d{}^{\pi+}(z) \approx D_u{}^{\pi-}(z), u^p(x) \approx d^n(x), d^p(x) \approx u^n(x)$), impulse approximation ($Y^{D\pi\pm}(x,z)$=$Y^{p\pi\pm}(x,z) + Y^{n\pi\pm}(x,z)$), and expanding to 1-st order the small quantities $\delta d(x), \delta u(x), \delta \mathrm{D}(\mathrm{x})$ and sea quark contribution

small!

$$R^D_{meas}(x,z) = A[\Delta(z)] - B[\Delta(z)]\delta D(z) + C[\Delta(z)]\frac{4[\delta d(x) - \delta u(x)] + 15[\bar{u}^p(x) + \bar{d}^p(x)]}{3[u^p{}_v(x) + d^p{}_v(x)]} +$$

$$D[\Delta_s(z), \Delta(z)]\frac{s(x) + \bar{s}(x)}{u^p{}_v(x) + d^p{}_v(x)}$$

where

$$\Delta(z) = \frac{D_u{}^{\pi-}(z)}{D_u{}^{\pi+}(z)}, \Delta_s(z) = \frac{D_s{}^{\pi+}(z) - D_s{}^{\pi-}(z)}{D_u{}^{\pi+}(z)},$$

$$\delta D(z) = \frac{D_u{}^{\pi+}(z) - D_d{}^{\pi-}(z)}{D_u{}^{\pi+}(z)}.$$

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

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

# E12-09-002 ($\pi^+/\pi^-$) Formalism 2

With neglect of CSV contribution from the fragmentation function (estimated to be ~1%)

$$D(z)R(x,z) + CSV(x) = B(x,z)$$

where

$$D(z) = \frac{1-\Delta(z)}{1+\Delta(z)},$$

$$R(x,z) = \frac{5}{2} + R^D{}_{meas},$$

$$CSV(x) = \frac{-4(\delta d - \delta u)}{3(u_v + d_v)},$$

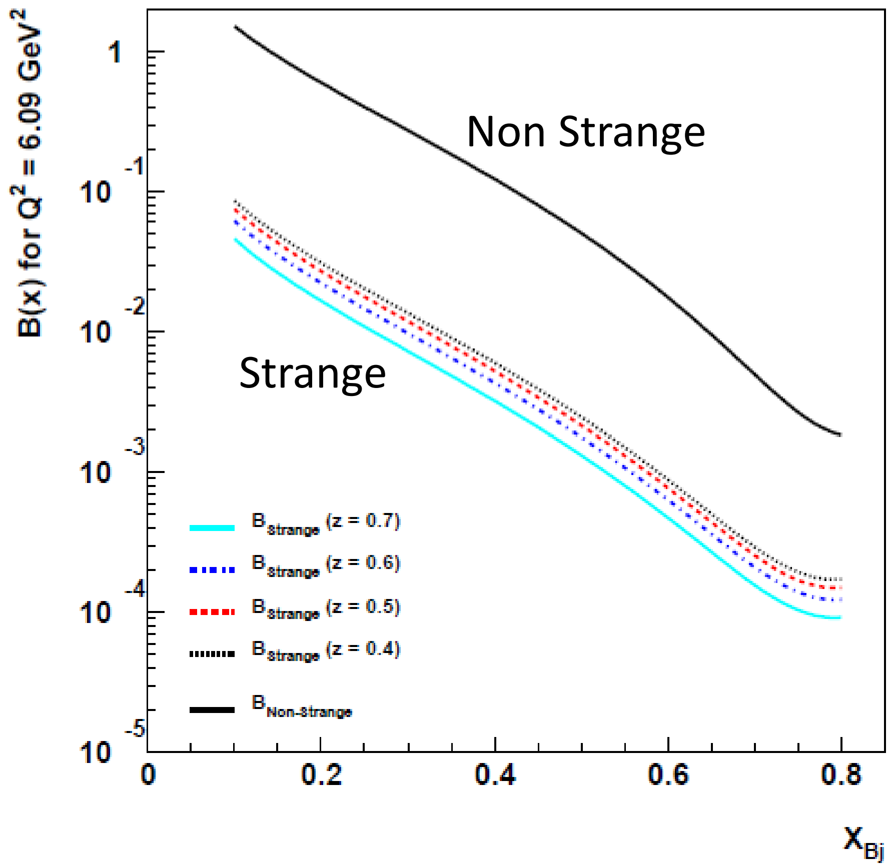
$$B(x,z) = \frac{5}{2} + R^D{}_{sea\_s}(x,z) + R^D{}_{sea\_NS}(x),$$

$$R^D{}_{sea\_s}(x,z) = \frac{\Delta_s(z)[s(x)+\overline{s(x)}]}{[1+\Delta(z)][u^p{}_v(x)+d^p{}_v(x)]},$$

$$R^D{}_{sea\_NS}(x) = \frac{5[\bar{u}^p(x)+\bar{d}^p(x)]}{u^p{}_v(x)+d^p{}_v(x)}.$$

At x>0.35 $R^D{}_{sea\_s}$ dies away, and $B \equiv B(x)$.

$R^D{}_{sea\_NS}$ remains the main source of theory systematical uncertainties.



# E12-09-002 ($\pi^+/\pi^-$) Measurements

HMS-SHMS pair is well suited for coincident measurements at small angles and large momenta needed for E12-09-002.
Same acceptance for $\pi^+$ and $\pi^+$, clear advantage over large acceptance devices.

Measure in "DIS" kinematics: $Q^2 > 1$ GeV$^2$, $W^2 > 4$ GeV$^2$. In addition, keep $M_X$ out of the resonance region, $W'^2 > 2.5$ GeV$^2$ (according to E00-108 findings).

Take $\pi^+$, $\pi^-$ data on 4x4 (x,z) grids, for 3 $Q^2$ settings:

1) $Q^2$ = 3.5 GeV$^2$; x = 0.30, 0.35, 0,40, 0.45; z = 0.4, 0.5, 0.6, 0.7;
2) $Q^2$ = 5.1 GeV$^2$; x = 0.45, 0.50, 0,55, 0.60; z = 0.4, 0.5, 0.6, 0.7;
3) $Q^2$ = 6.1 GeV$^2$; x = 0.50, 0.55, 0,60, 0.65; z = 0.4, 0.5, 0.6, 0.7.

16 data points per $Q^2$ and charge, to solve for 8 variables $D(z_i)$, $CSV(x_i)$, i=1,4.

Detect e' in SHMS, $\pi^\pm$ in HMS (*parallel kinematics*). e' momenta from 4.5 to 6.8 GeV and angles from 12.5° to 20.21°. Pion momenta from 1.67 GeV to 4.55 GeV and angles from 10.7° to 19.93.°

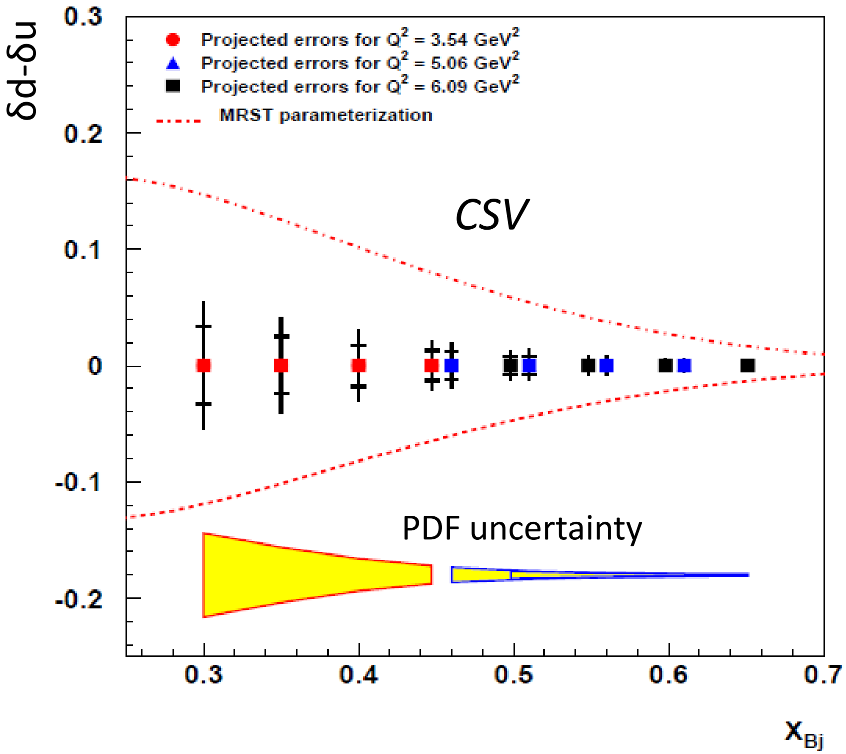
Assume 50 μA max. beam current for neg. polarity, and 25 μA for pos. polarity on a 10 cm LD2 target (to constrain singles rates < 1 MHz).

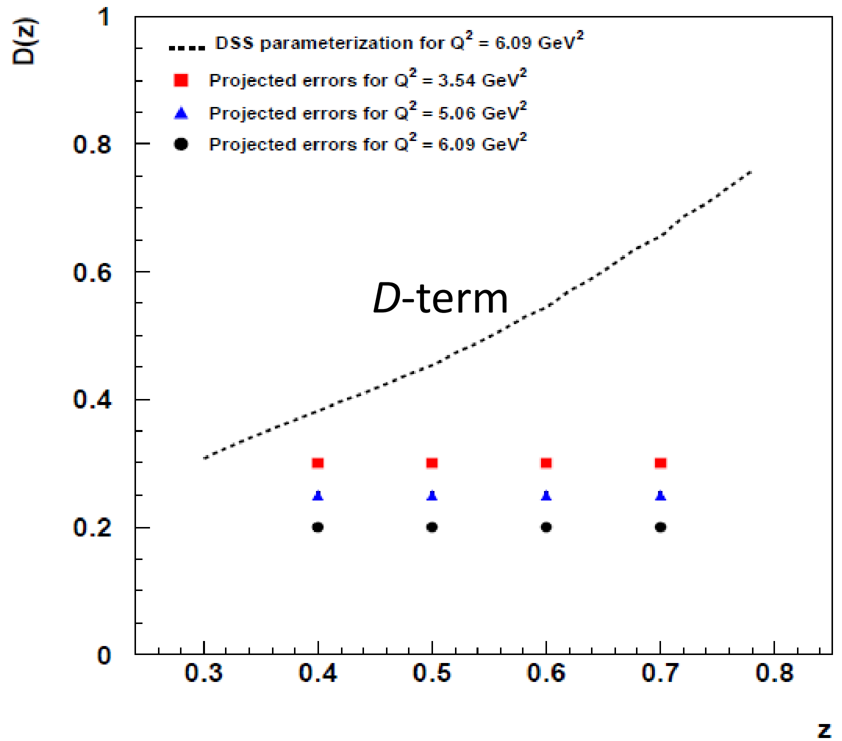
Pion PID in HMS:

- $P_{HMS}$ = 1.67 – 2.62 GeV: Aerogel (n=1.015) for kaon rejection.
- $P_{HMS}$ = 2.86 – 4.54 GeV: $C_4F_{10}$ gas Čerenkov at 0.96 atm for kaon rejection.
- Reject electrons at neg. polarity in the calorimeter, and in $C_4F_{10}$ gas Č below 2.62 GeV.

# E12-09-002 ($\pi^+/\pi^-$) Expected Results

Diffractive ρ and excl. radiative tail dominate in systematic uncertainties *at high z*.
The ρ contribution, up to 20% in yields, largely cancels in $\pi^+/\pi^-$ ratios (0.2-0.7%).
Rad. tail, uncorrelated, up to 7% in the yields, contributes 0.1-0.6% in the ratios.
Total systematic uncertainty 0.49-1.02%. Total uncertainty on $Y(\pi^+)/Y(\pi^-)$ 0.5-1.8%.



# E12-09-017 ($P_T$) Motivation

In contrast to $Q^2$ and $x$ dependencies, very little is known about the $k_T$ dependence of the quark PDFs.

From the size of nucleon, $k_T$ is expected to be ~ few hundred MeVs, with larger values for sea quarks (small $x$), and smaller values at $x \rightarrow 1$ (quark momentum longitudinal).

Parton spin contributions to the nucleon spin are small, which implies significant angular momentum of quarks, hence significant $k_T$.

In SIDIS, when ($x$, $z$) factorization is valid, $P^{\pi}_T = zk_T + p_T$. "Soft" non-perturbative processes are expected to generate small fragmentation $p_T$–s of Gaussian distribution.

$k_T$ –s of $u$ and $d$ quarks can be distinguished *if* flavor independent fragmentation functions ($D^+$ and $D^-$) are assumed (as demonstrated in E00-108).

The cross sections have been decomposed in terms of TMD PDFs and FFs for low $P_T$ in a theory study (see A.Bachetta et al, JHEP 0702, 093 (2007)).

E12-09-017 aims at precise determination of $P_T$ dependence of ratio of $\pi^+$ and $\pi^-$ cross sections, which will be combined with azimuthal asymmetries in the reaction on unpolarized $H$ (E12-06-112 experiment) and $D$ targets from CLAS12.

From the combined data transverse momentum widths of $u$ and $d$ quarks, and favored and unfavored fragmentation functions will be obtained.

# E12-09-017 ($P_T$) Measurements

Results from E00-108 on the transverse momenta are suggestive at best, due to limited kinematic coverage. A wider range of $Q^2$ ( to resolve additional higher twist effects), full $\phi$ coverage, larger $P_T$ range, wide range in $z$ to distinguish quark width terms (weighted by powers of $z$) from fragmentation widths (likely vary slowly with $z$) are needed. **These should be attainable by this experiment in combination with CLAS12.**

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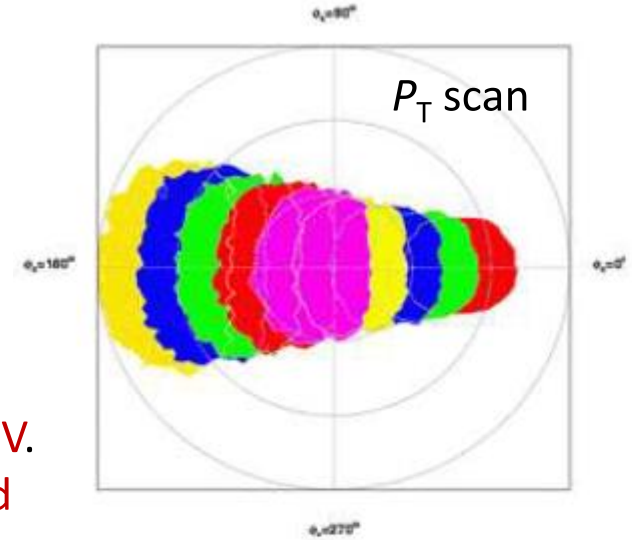
Map $P_T$ of SIDIS production of $\pi^{\pm}$ from $H$ and $D$ targets over the ranges $0.2<x<0.5$, $2<Q^2<5$ GeV$^2$, $0.3<z<0.5$, $P_T<0.5$ GeV.
Keep $z < 0.7$ ($Mx > 1.5$ GeV) to be in the factorization regime.

Take data at 6 main kinematic settings:

1. $(x, Q^2) = (0.2, 2.0$ GeV$^2)$;
2. $(x, Q^2) = (0.3, 3.0$ GeV$^2)$;
3. $(x, Q^2) = (0.4, 4.0$ GeV$^2)$;
4. $(x, Q^2) = (0.5, 5.0$ GeV$^2)$;
5. $(x, Q^2) = (0.3, 1.8$ GeV$^2)$; <- $Q^2$ scan
6. $(x, Q^2) = (0.3, 4.5$ GeV$^2)$. <- $Q^2$ scan

The 5-th setting requires 8.8 GeV beam energy, others 11 GeV.
At each setting measurements will be done for z=0.3, 0.4 and 0.5, and scans in $P_T$ up to 0.5 GeV by HMS rotation away from the virtual photon direction.




***Partial overlap with E12-06-104 ($R_{LT}$), 20% reduction in beam time!***

# E12-09-017 ($P_T$) Projected Results

Experimental conditions: 10 cm LH2 and LD2 targets. 8.8 and (predominantly) 11 GeV beam energies, up to 80 μA beam current. Detect e’ in HMS, pions in SHMS.

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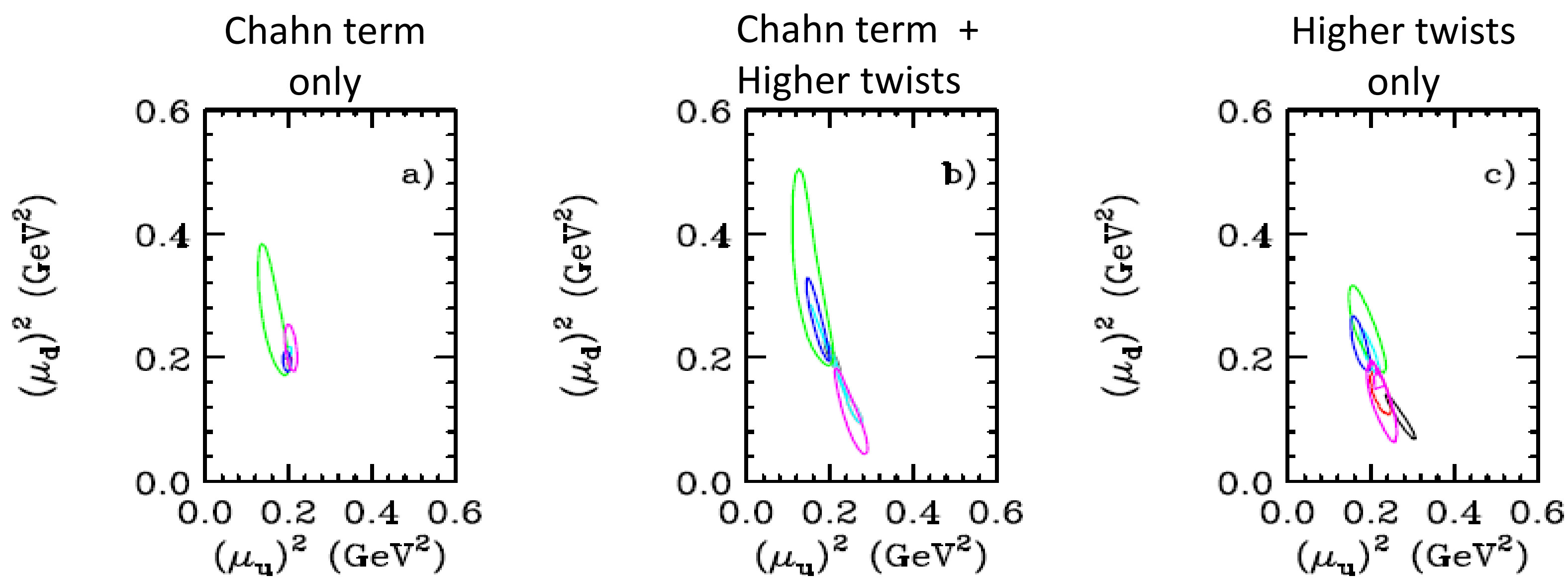
Projected systematic uncertainties on ratios come mostly from SHMS acceptance, tracking and hadron detection efficiencies (0.4% each). The total uncertainty is 0.9%.
Systematic Error on cross sections from the ρ diffractive production is 0.5 – 2%.
From radiative corrections -- 0.5%.




Analysis of simulated data. The colors indicate the 6 main kinematic settings. Note: the **simultaneous analysis** of all the 6 settings together renders error **ellipses of ~0.01 – 0.02 sizes**.

# E12-09-017 ($P_T$) Related measurements

With a dedicated kaon aerogel detector:

Test onset of low energy factorization for SIDIS charged kaon production (similar to E00-108), and map transverse momentum dependence.

With longitudinally polarized beam:

Measure beam SSA at $P_T$ = 0.05, 0.10, 0.15 and 0.20 with stat. errors from 0.003 to 0.008 (except ($x$, $Q^2$) = (0.3, 0.5)). Expect less or compatible systematic errors.

- Will significantly constrain models.
- First accurate determination of neutron SSA at low $P_T$.
- $A_{LU}$ is sensitive to correlations, such as between quark and gluon momenta, and between spin and orbital motion.
- Sin(φ*) dependent, may vary from 0.2 to 0.6 at Jlab kinematics for $\pi^+$. Much less for $\pi^-$. Significant $x$, $Q^2$, $z$ and $P_T$ dependences.
- Can be measured for $P_T < 0.3$ GeV (full φ coverage).

# E12-13-007 ($\pi^0$) Motivation

Probe factorization of semi-inclusive $\pi^0$ production onto hard electron-quark scattering and subsequent quark $\rightarrow$ pion fragmentation (($x$,$z$) factorization).

Study $P_T$ dependence in near parallel kinematics.

*Check* $\sigma(\pi^0) = \left(\sigma(\pi^+) + \sigma(\pi^-)\right)/2$ *basic assumption*.

Often neglected but important tool in study of hadron structure by SIDIS.

Will augment measurements of $P_T$ dependence in $\pi^\pm$ production (E12-09-017).

Will take data simultaneously with E12-13-010 "DVCS & DVNP" experiment.

Measurements of cross sections from $\pi^0$ production versus $x$ and $z$ are needed to avoid potential experimental and theoretical pitfalls in the analysis of pion SIDIS production in general. Several issues can be addressed, as such:

- $\pi^0$ production may be different from $(\pi^+ + \pi^-)/2$ at $z \rightarrow 1$, for *no* pole contributions in exclusive limit;
- Target mass $M^2/Q^2$ and produced hadron mass $m_\pi^2/Q^2$ corrections (at $z \rightarrow 1$, for *finite* $Q^2 \sim 4$ GeV$^2$);
- Validity of description of quark fragmentation into a charged pion with only 2 fragmentation functions $D^+$ and $D^-$, while fragmentation into $\pi^0$ may be described by an average FF;
- Difficulties in obtaining the $d_v/u_v$ ratio (sensitivity to the quality of exp. data and to the applicability of the (x,z) fragmentation).

# E12-13-007 ($\pi^0$) Measurements and Analysis

- Measure cross-sections for semi-inclusive $\pi^0$ electro-production from proton target with 3% precision, for $0.2<x<0.6$, $2<Q^2<6$ GeV$^2$, $0.4<z<0.8$ and $P_T<0.4$ GeV/c.
- (e,e'$\pi^0$) coincidence measurements, with e' in HMS and $\pi^0$ in the Neutral Particle Spectrometer.
- Accumulate (e,e') inclusive yields simultaneously in HMS to reduce systematics in the SIDIS analysis.

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Analysis will closely relate to the Hall C charged meson SIDIS production experiments:

- E00-108 "Duality in meson electroproduction";
- E12-09-017 "Transverse Momentum Dependence of Semi-Inclusive Pion Production"

Advantages over the charged pion production:

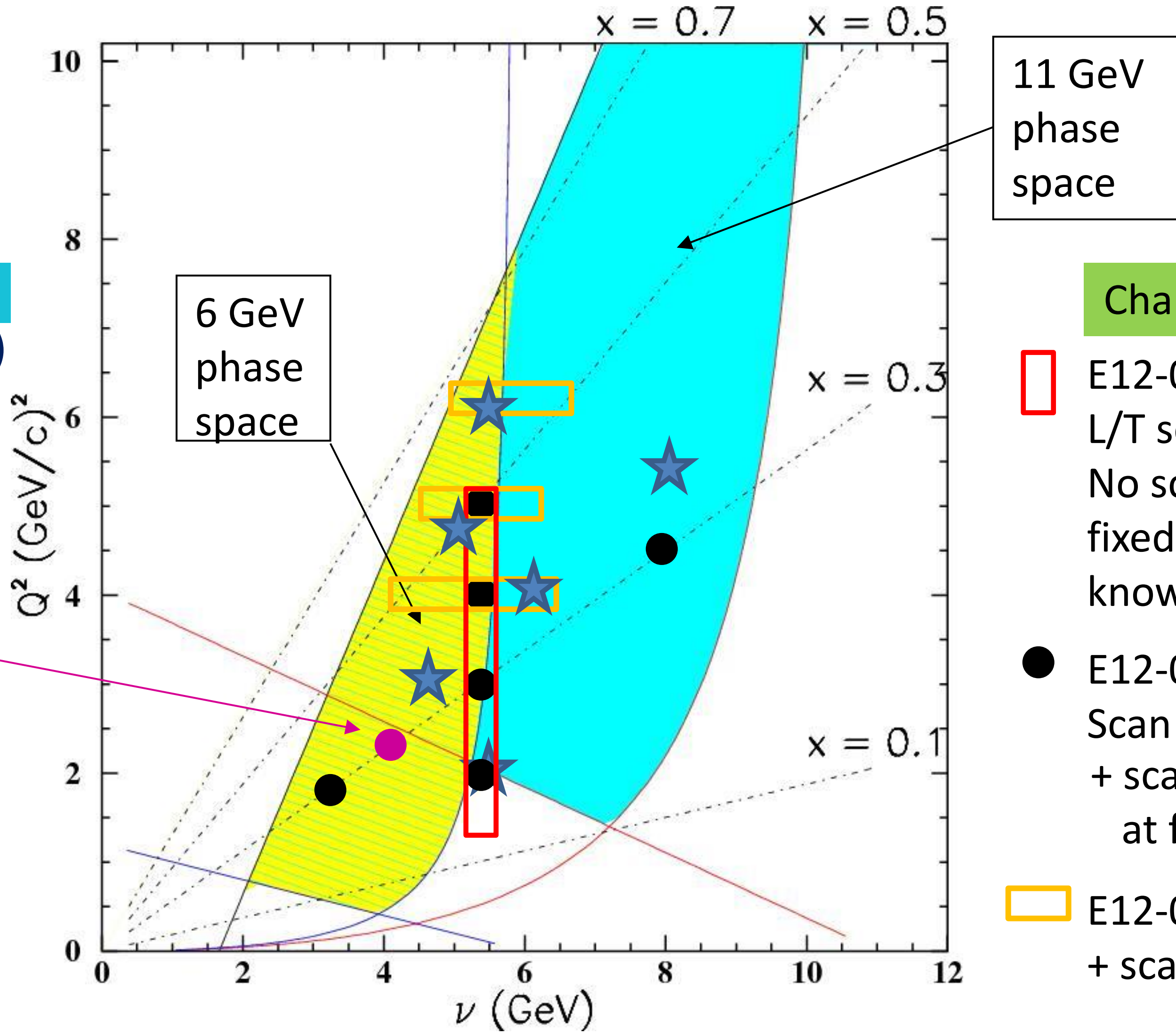
- ✓ No $\rho_0$ contribution
- ✓ No pole contributions, hence no radiative tail at large *z*
- ✓ Reduced resonance contribution (e.g. ep → e'$\pi^0\Delta^+$ is much reduced compared to ep → e'$\pi^-\Delta^{++}$ )
- ✓ Cross section proportional to average fragmentation function $D=(D^+ + D^-)/2$, hence easier to disentangle quark and fragmentation functions

# E12-13-007 ($\pi^0$) Kinematics

Phase space compatible with E12-09-017, E12-09-002 (Hall C) & E12-06-112 (Hall B).

E12-13-007
Neutral pions:
Scan in ($x,z,P_T$)
Overlap with
E12-09-017 &
E12-09-002

E00-108




Charged pions:

E12-06-104
L/T scan in ($z,P_T$)
No scan in $Q^2$ at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in ($x,z,P_T$)
+ scan in $Q^2$ at fixed x

E12-09-002
+ scans in z

# E12-13-007 ($\pi^0$) Settings, $P_T$ studies

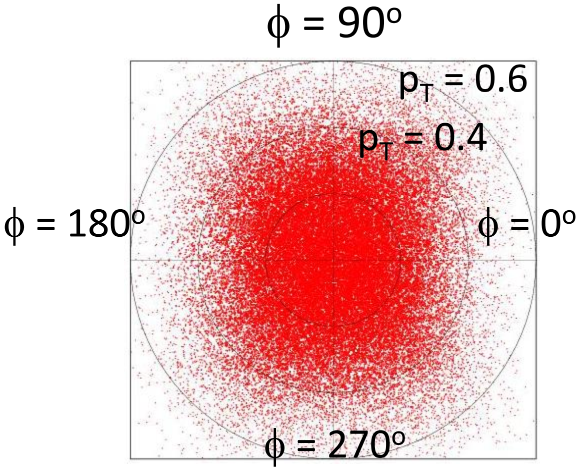
At each $(x,Q^2)$ of 6 main settings, scan in $z$ from 0.4 to 0.8, and in $P_T$ up to 0.3 – 0.4 GeV.

| Kinematics | E (GeV) | E' (GeV) | $\theta_e$ (deg) | $W^2$ (GeV$^2$) | $\theta_\gamma$ (deg) | $q_\gamma$ (GeV) | $x$ | $Q^2$ (GeV$^2$) | $z$ |
|---|---|---|---|---|---|---|---|---|---|
| A | 11.0 | 5.67 | 10.27 | 8.88 | 10.57 | 5.513 | 0.20 | 2.0 | 0.4–0.8 |
| B | 11.0 | 6.56 | 11.70 | 6.21 | 16.20 | 4.767 | 0.36 | 3.0 | 0.5–0.8 |
| C | 11.0 | 5.08 | 15.38 | 7.99 | 12.44 | 6.250 | 0.36 | 4.0 | 0.4–0.8 |
| D | 11.0 | 2.86 | 24.15 | 10.66 | 7.93 | 8.472 | 0.36 | 5.5 | 0.3–0.8 |
| E | 11.0 | 5.88 | 15.65 | 5.68 | 16.57 | 5.565 | 0.50 | 4.8 | 0.4–0.8 |
| F | 11.0 | 5.67 | 17.84 | 4.88 | 17.23 | 5.865 | 0.60 | 6.0 | 0.4–0.8 |

*The factorization limit $M_x$>2.5 GeV$^2$ (z<0.8) is likely to be relaxed due to less resonances!*

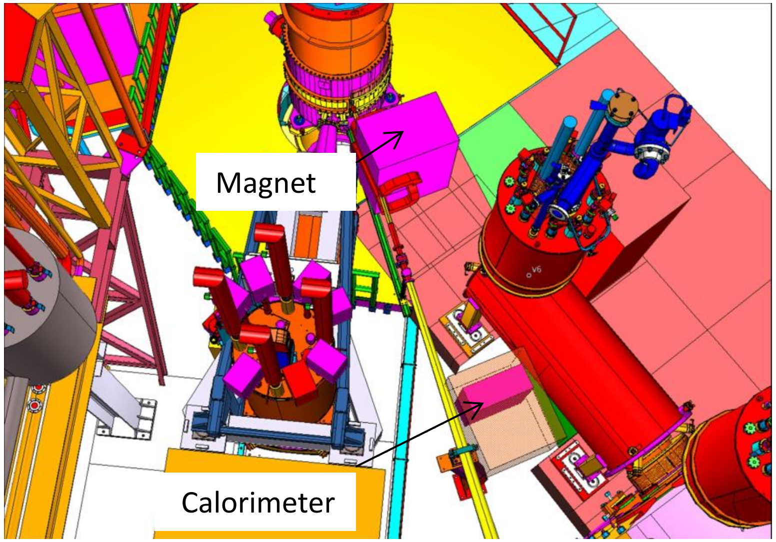
## $\phi$ coverage and $P_T$ studies

- Good $\phi$ coverage up to $P_T$ = 0.4 GeV, cos($\phi$) and cos(2$\phi$) moments can be disentangled (relevant to E12-06-112 in Hall B).
- Limited $\phi$ coverage at $P_T$ = 0.5 GeV. Use f($\phi$) from CLAS12?
- Study $P_T$ dependence in $x$, $z$ ($P_T = p_t + z\, k_t + O(k_t^2/Q^2)$), and in $Q^2$ to check ($p_T/Q$) and ($p_T^2/Q^2$) behavior.

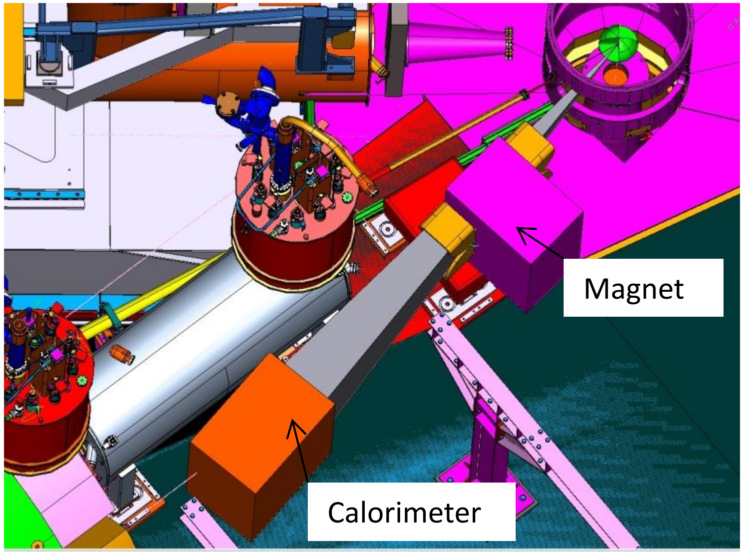


# E12-13-007 ($\pi^0$) NPS

The Neutral Particle Spectrometer (*NPS*) is designed for detection of (decay) $\gamma$–s .
The angular acceptance by design is well matched to the HMS acceptance. Hence will be used in pair with HMS for precision (coincidence) cross section measurements of neutral particles ($\gamma$,$\pi^0$).
Key components: 0.3 Tm warm magnet, to sweep off low energy charged background; 25 msr (at 4m from target) segmented EM calorimeter (PbWO and/or $PbF_2$ crystals).
Allows small and large angle configurations, by mounting on different sides of the SHMS platform.




*Cantilevered of SHMS carriage (5.5° – 30°)*




*Mounted on SHMS platform (25° – 60°)*

Approved experiments utilizing NPS: E12-13-010 "DVCS and DVNP", E12-13-007 "SIDIS $\pi^0$". NPS based proposals: WACS, "$\pi^0$ photoproduction", "ALLRCS".

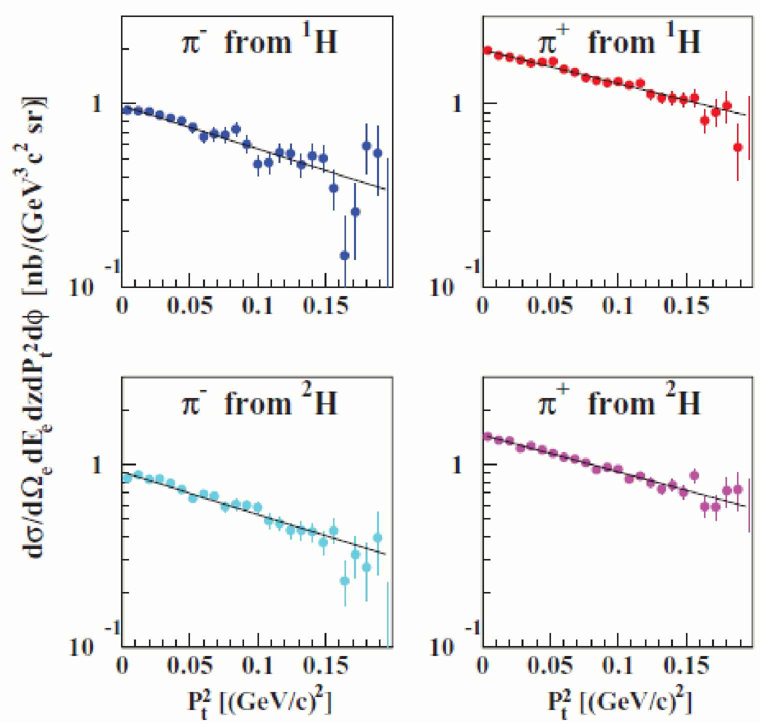
# Summary

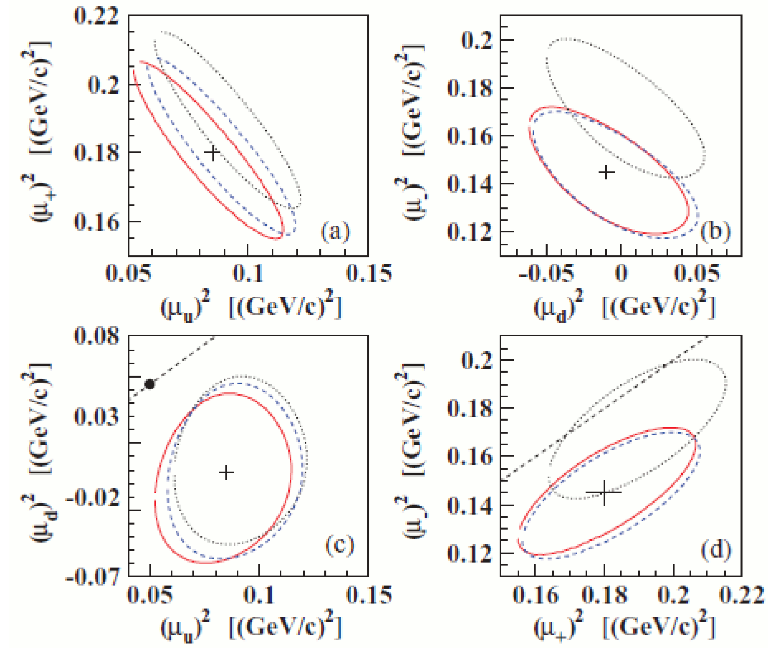
- E00-108, the first SIDIS measurement in Hall C has found compelling evidences of quark hadron duality in charged meson production down to $Q^2 \sim 1.5$ GeV$^2$.
- A series of findings from E00-108 render a deeper insight into the SIDIS process and structure of nucleon, but remain suggestive because of the limited kinematic coverage.
- E00-108 inspired a number of 12 GeV projects in Hall C focused on different aspects of the SIDIS process:
  - E12-06-104 will determine $R = \sigma_L/\sigma_T$ via cross section Rosenbluth separation;
  - E12-09-002 will search for charge symmetry violations in quark distributions via precision measurement of *x* and *z* dependences of $\pi^+/\pi^-$ ratio;
  - E12-09-017 will render cross sections and precise $\pi^+/\pi^-$ ratios versus $P_T$;
  - E12-13-007 will augment the SIDIS pion production program with inclusion of $\pi^0$ final state.
- By taking advantage of the HMS-SHMS pair of focusing magnetic spectrometers in Hall C, these measurements are indispensable when it comes to high precision, small systematic uncertainties.
- Combined with data from large acceptance devices (CLAS12), results from these measurements will provide important information on the SIDIS processes and nucleon structure.

Than you for your attention!

# Back up slides

# E00-108 key findings




$$\sigma_p^{\pi^+}(P_t) = C\left[4c_1(P_t)e^{-b_u^+ P_t^2} + \left(\frac{d}{u}\right)\left(\frac{D^-}{D^+}\right)c_2(P_t)e^{-b_d^- P_t^2}\right]$$

$$\sigma_p^{\pi^-}(P_t) = C\left[4\left(\frac{D^-}{D^+}\right)c_3(P_t)e^{-b_u^- P_t^2} + \left(\frac{d}{u}\right)c_4(P_t)e^{-b_d^+ P_t^2}\right]$$

$$\sigma_n^{\pi^+}(P_t) = C\left[4\left(\frac{d}{u}\right)c_4(P_t)e^{-b_d^+ P_t^2} + \left(\frac{D^-}{D^+}\right)c_3(P_t)e^{-b_u^- P_t^2}\right]$$

$$\sigma_n^{\pi^-}(P_t) = C\left[4\left(\frac{d}{u}\right)\left(\frac{D^-}{D^+}\right)c_2(P_t)e^{-b_d^- P_t^2} + c_1(P_t)e^{-b_u^+ P_t^2}\right]$$

$$b_u^{\pm} = \left(z^2\mu_u^2 + \mu_{\pm}^2\right)^{-1}, \quad b_d^{\pm} = \left(z^2\mu_d^2 + \mu_{\pm}^2\right)^{-1}$$

$$c_1(P_t) = 1 + c_0[P_t, \langle\cos(\phi)\rangle]\mu_u^2 b_u^+,$$

$$c_2(P_t) = 1 + c_0[P_t, \langle\cos(\phi)\rangle]\mu_d^2 b_d^-,$$

$$c_3(P_t) = 1 + c_0[P_t, \langle\cos(\phi)\rangle]\mu_u^2 b_u^-,$$

$$c_4(P_t) = 1 + c_0[P_t, \langle\cos(\phi)\rangle]\mu_d^2 b_d^+,$$

$$c_0[P_t, \langle\cos(\phi)\rangle] = \frac{4z(2-y)\sqrt{1-y}}{\sqrt{Q^2}[1+(1-y)^2]}\sqrt{P_t^2}\langle\cos(\phi)\rangle$$

# E12-06-104 ($R = \sigma_L/\sigma_T$) Motivation

$$\frac{d\sigma}{d\Omega_e dE_e d\Omega_\pi dM_x} = \Gamma \frac{d\sigma}{d\Omega_\pi dM_x}$$

$$\Gamma = \frac{\alpha}{2\pi^2}\frac{E'_e}{E_e}\frac{1}{Q^2}\frac{1}{1-\epsilon}\frac{W^2-M^2}{2M}$$

$$\frac{d\sigma}{d\Omega_\pi dM_x} = \frac{d\sigma_T}{d\Omega_\pi dM_x} + \epsilon\frac{d\sigma_L}{d\Omega_\pi dM_x} + \epsilon\frac{d\sigma_{TT}}{d\Omega_\pi dM_x}\cos 2\phi_{pq} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{d\Omega_\pi dM_x}\cos\phi_{pq} \, ,$$

- Verify $R_{\mathrm{SIDIS}} = R_{\mathrm{DIS}}$
- Check semi-inclusive to exclusive transition in *z*-dependence of *R*
- Verify that $R_{\mathrm{SIDIS}}$ anneals to $R_{\mathrm{DIS}}$ at large $P_{\mathrm{T}}$
- Verify that $R_{\mathrm{SIDIS}}$ follows the $Q^2$ dependence of $R_{\mathrm{DIS}}$

Advantages for the general 12 GeV SIDIS program: implications for measurements of light quark sea flavor asymmetry, flavor decomposition of the nucleon spin at *x*>0.1, azimuthal asymmetries.