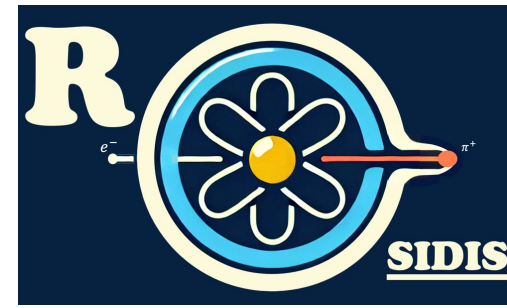
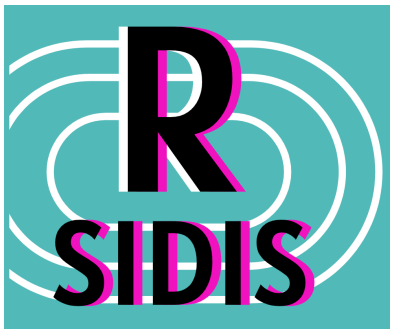




# Measurement of $R=\sigma_L/\sigma_T$ in SIDIS

Dave Gaskell

Workshop on the Physics Program with High Luminosity Facilities

October 5-9, 2026

1. SIDIS Measurements in Hall C
2.  $R$  in DIS and SIDIS
3. Extensions at High Luminosity with Large Acceptance Devices

# JLab SIDIS Program

JLab has an extensive program of measurements in semi-inclusive DIS (SIDIS)

1D nucleon structure

→ deconvolution of polarized PDFs

→ constraints on unpolarized sea

3D nucleon structure

Transverse degrees of freedom allow us to explore  $k_T$  dependence of quarks – access to orbital angular momentum

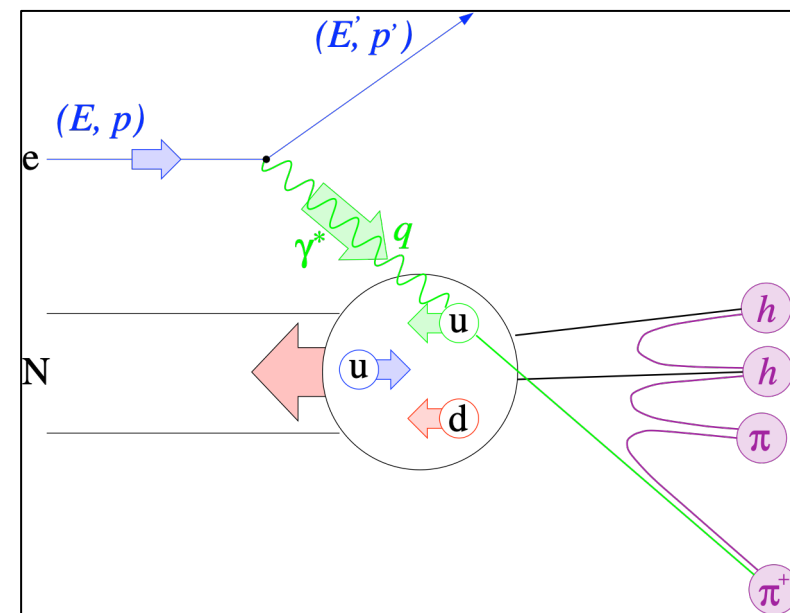
→ Transversity distribution

→ Transverse Momentum Distributions (TMDs)

Experiments include measurements using longitudinal and transversely polarized targets, single (electron) spin asymmetries, hadron

| N/q | U              | L        | T                  | ← quarks |
|-----|----------------|----------|--------------------|----------|
| U   | $f_1$          |          | $h_1^\perp$        |          |
| L   |                | $g_1$    | $h_{1L}^\perp$     |          |
| T   | $f_{1T}^\perp$ | $g_{1T}$ | $h_1 h_{1T}^\perp$ |          |

↑  
nucleon



# JLab SIDIS Program

JLab has an extensive program of measurements in semi-inclusive DIS (SIDIS)

1D nucleon structure

→ deconvolution of polarized PDFs

→ constraints on unpolarized sea

3D nu

Transv

explore  $k_T$  dependence of quarks – access to

orbital angular momentum

→ Transversity distribution

→ Transverse Momentum Distributions

(TMDs)

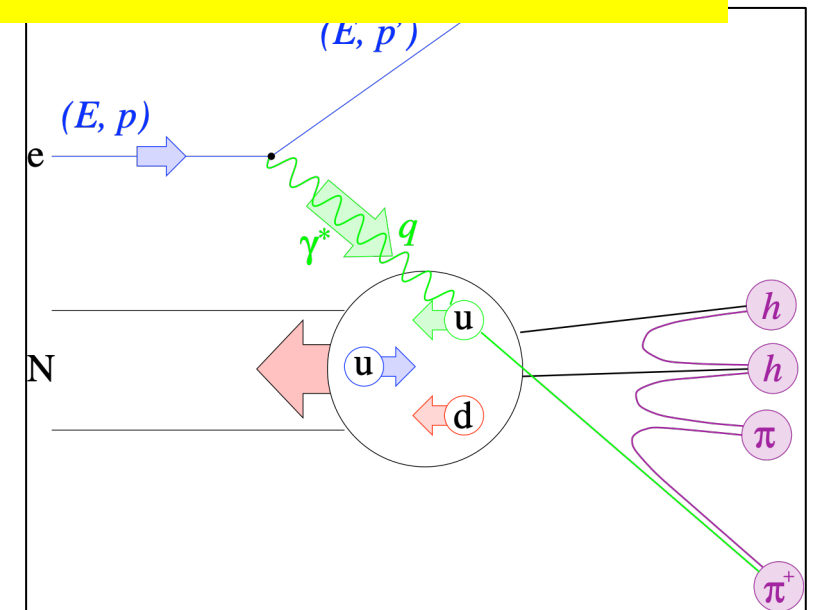
Experiments include measurements using longitudinal and transversely polarized targets, single (electron) spin asymmetries, hadron

| N/q | U     | L     | T              |
|-----|-------|-------|----------------|
| U   | $f_1$ |       | $h_1^\perp$    |
| L   |       | $g_1$ | $h_{1L}^\perp$ |

← quarks

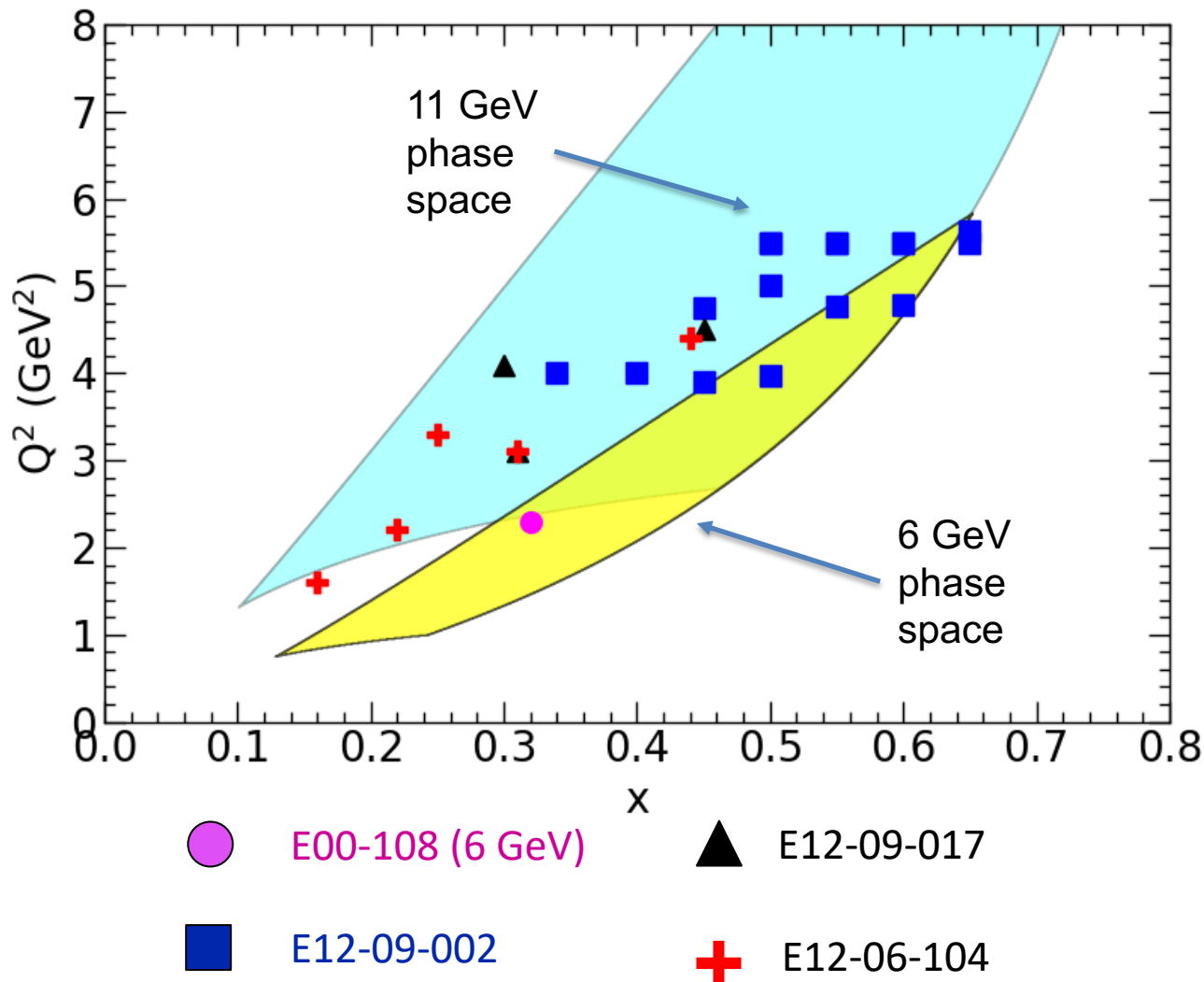
Program assumes applicability of factorization assumptions and understanding of SIDIS reaction

nucleon



# Hall C SIDIS\* Program

\*Charged pions  $\rightarrow \pi^0$  included in NPS program



E00-108: “Duality in Meson Electroproduction”  
 $\rightarrow$  6 GeV, first Hall C SIDIS measurement

E12-09-017: “Transverse Momentum  
Dependence of Semi-Inclusive Pion Production”  
 $\rightarrow$  Scans in  $z$  and  $P_t$ ,  $x$ -dependence at fixed  $Q^2$

E12-09-002: “Charge Symmetry Violating Quark  
Distributions via Precise Measurement of  $\pi^+/\pi^-$   
Ratios in SIDIS”  
 $\rightarrow$  Scans in  $z$  at each  $x/Q^2$  (parallel kinematics)  
 $\rightarrow$  Deuterium at every setting, hydrogen at select  
settings

E12-06-104/E12-24-001: “Measurement of the  
Ratio  $R$  in Semi-Inclusive Deep-Inelastic  
Scattering”  
 $\rightarrow$  L-T separations for  $\pi^+/\pi^-$  from H, D, A  
 $\rightarrow$  Scans in  $z$ ,  $x$ ,  $P_t$

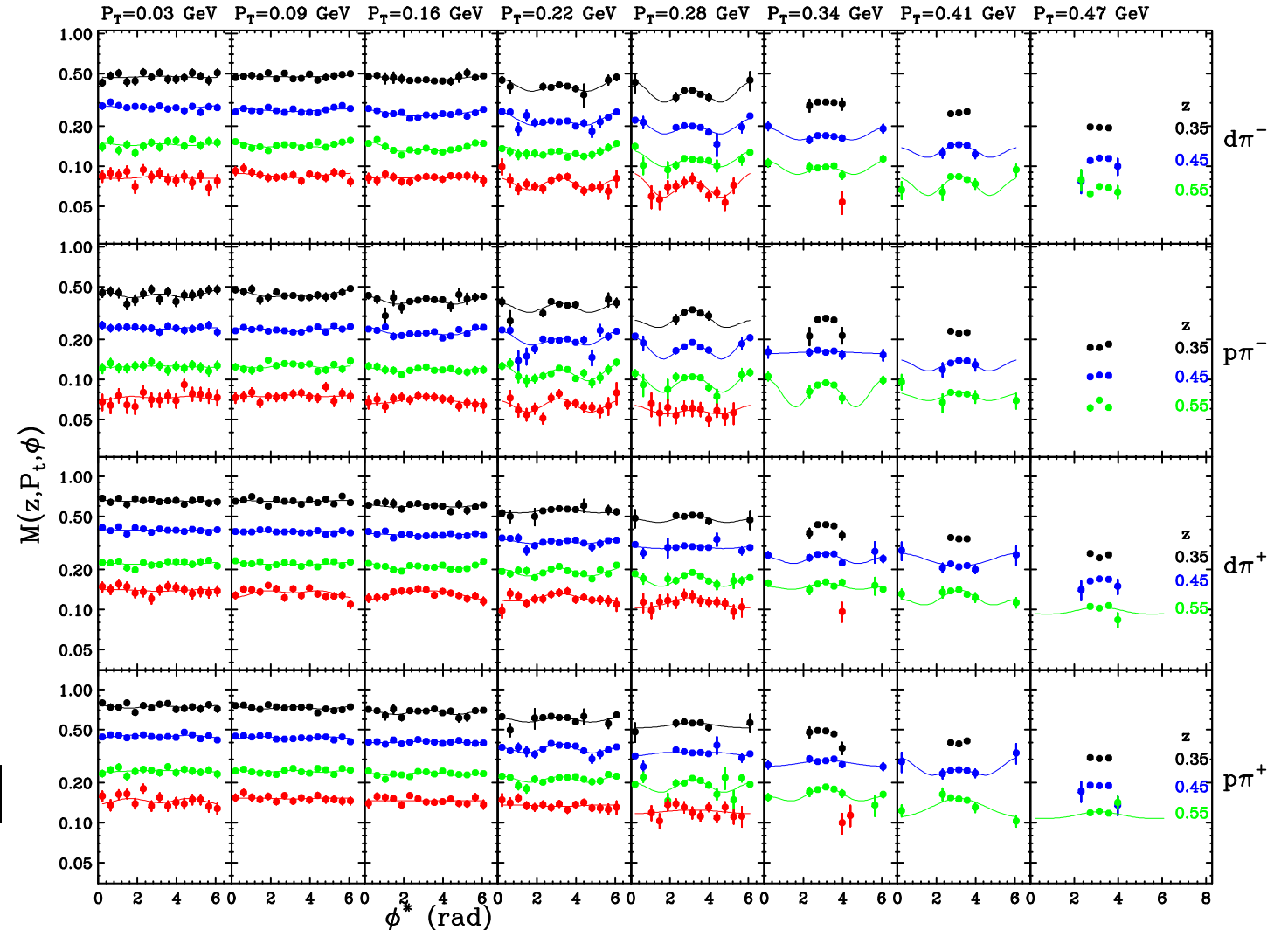
# Hall C Results: $P_T$ and $\phi$ Dependent Multiplicities

$P_T$  and  $\phi$  dependence  
extracted for several  
kinematics

- I)  $x=0.31$ ,  $Q^2=3 \text{ GeV}^2$
- II)  $x=0.30$ ,  $Q^2=4.1 \text{ GeV}^2$
- III)  $x=0.45$ ,  $Q^2=4.5 \text{ GeV}^2$

Multiplicity can be extracted by fit to the  
following form:

$$M(z, P_t, \phi) = M_0 [1 + A \cos \phi + B \cos 2\phi]$$



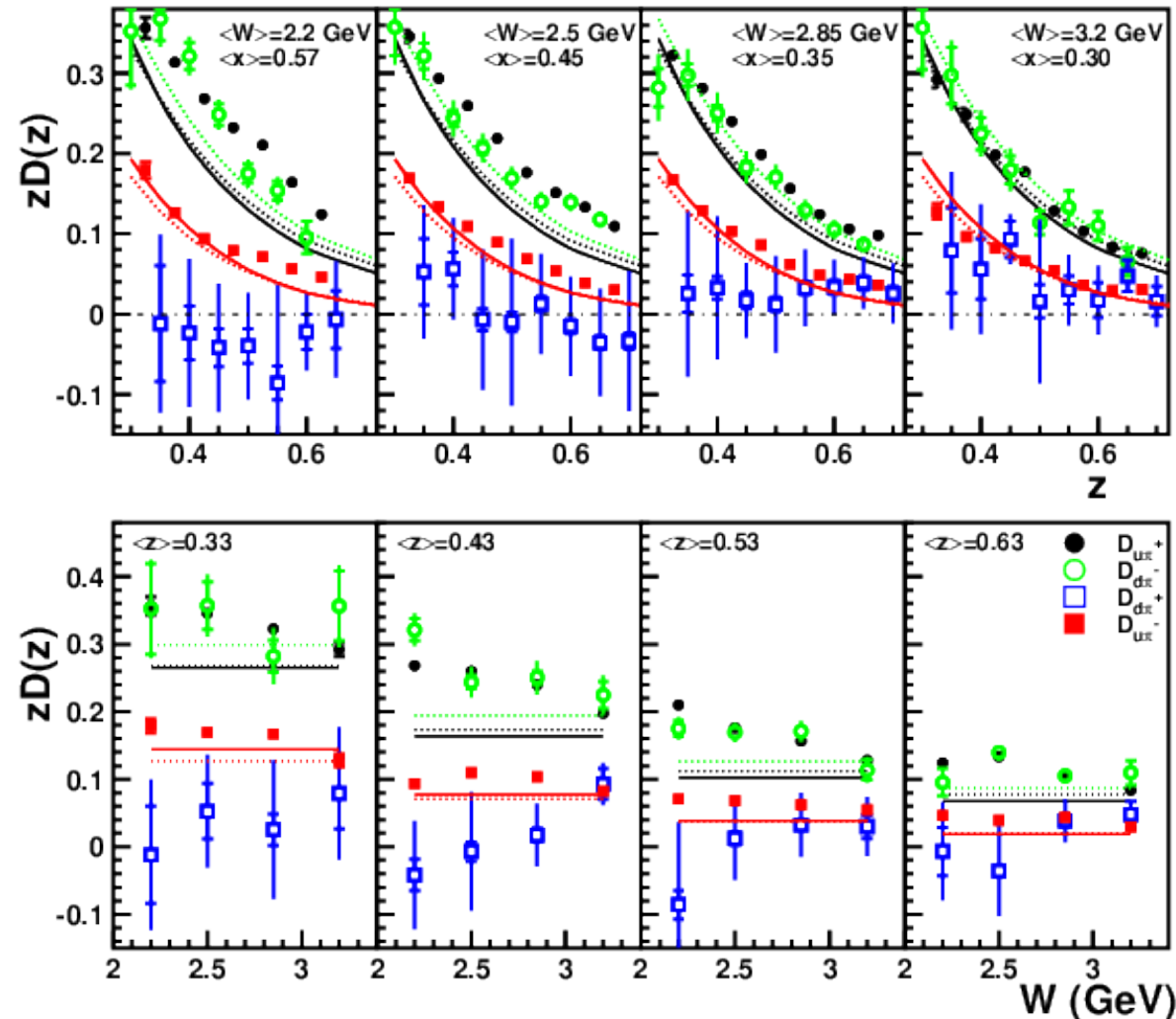
$x=0.31$ ,  $Q^2=3 \text{ GeV}^2$

# Hall C Results: Flavor Dependent Fragmentation Functions

Multiplicities for  $\pi^+$  and  $\pi^-$  from proton and neutron (deuteron) used to extract 4 FFs

- Integrated over  $P_T$  range in acceptance (up to about 0.2 GeV), nominal  $P_T=0.1$  GeV
- Assumed same  $P_T$  dependence for both charges/targets (true within uncertainties)

Clear difference between unfavored fragmentation functions at lower  $W$  (larger  $x$ )



$D_d^{\pi^+}$

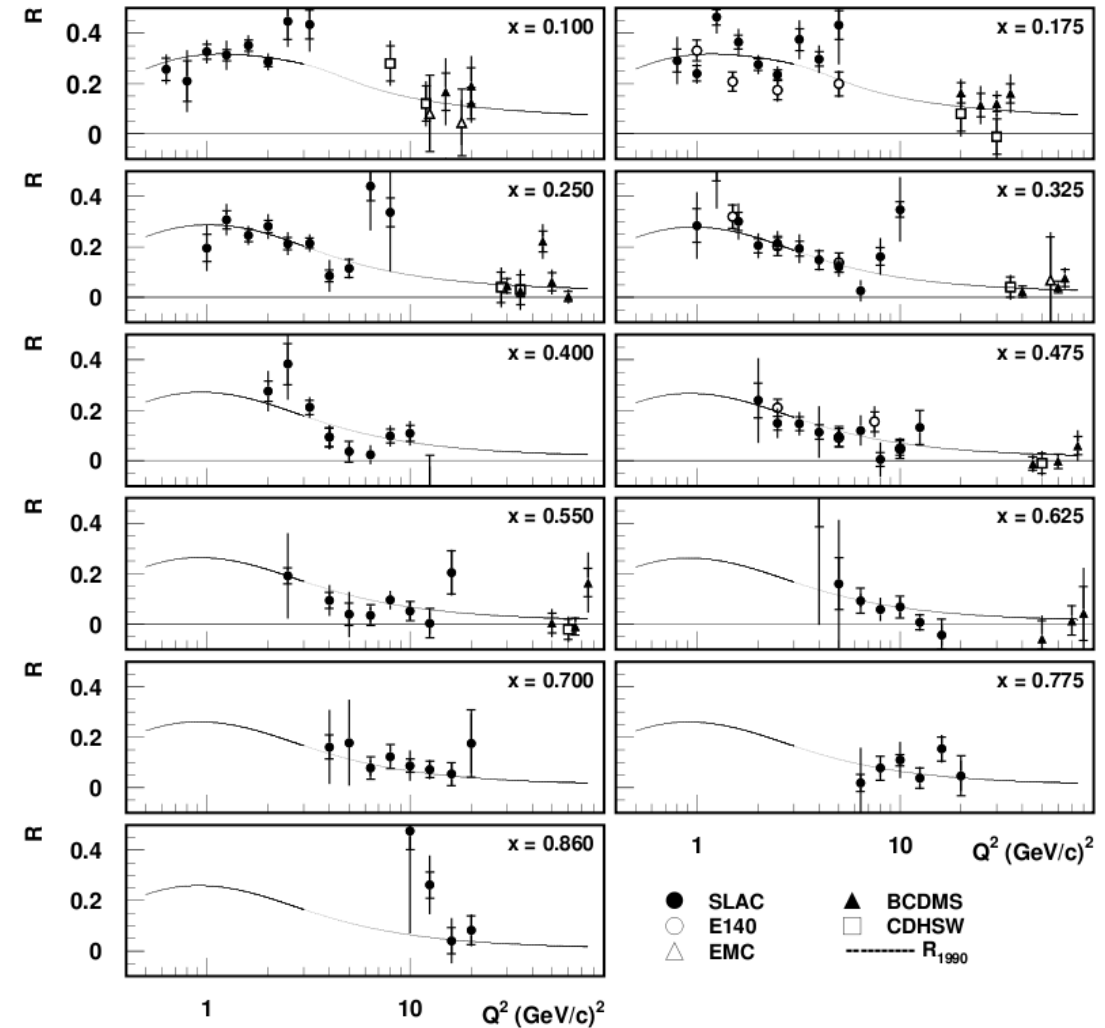
→ Uncertainties larger due to small differences in flavor dependent multiplicities

# $R = \sigma_L / \sigma_T$ in DIS and SIDIS

**What is the role of  $R = \sigma_L / \sigma_T$  in DIS and SIDIS?**

**DIS:** In the naïve parton model,  $R=0$   
→ non-zero  $R$  from intrinsic  $k_T$  of quarks, contributions from gluons  
→ Well-studied in lepton scattering via Rosenbluth separation – demonstrated to show expected  $Q^2$  dependence, magnitude

**SIDIS:**  $R_{SIDIS}$  often assumed to be the same as  $R_{DIS}$  in experiment analyses  
→ Little experimental verification that they are the same (essentially unmeasured)  
→ Different dynamics may lead to differences in  $R$



*L.W. Whitlow et al., Phys. Lett. B 250, 193 (1990)*

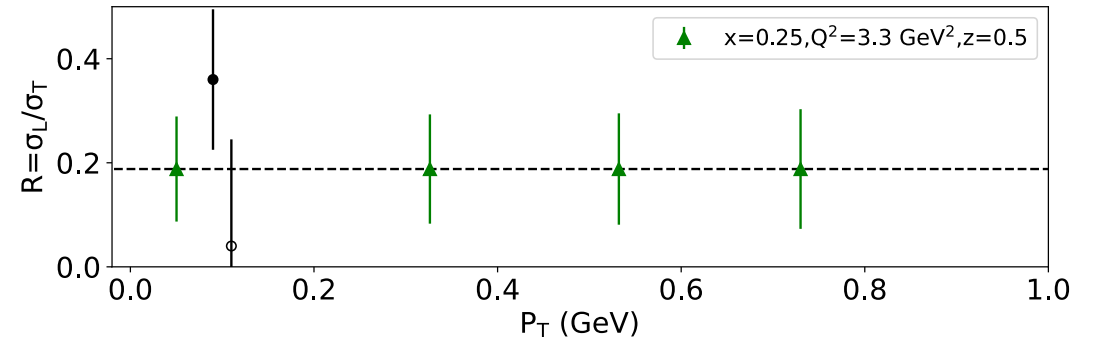
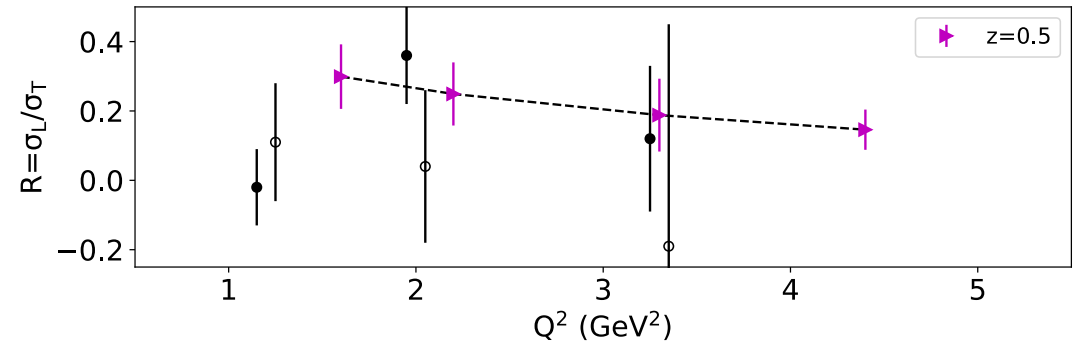
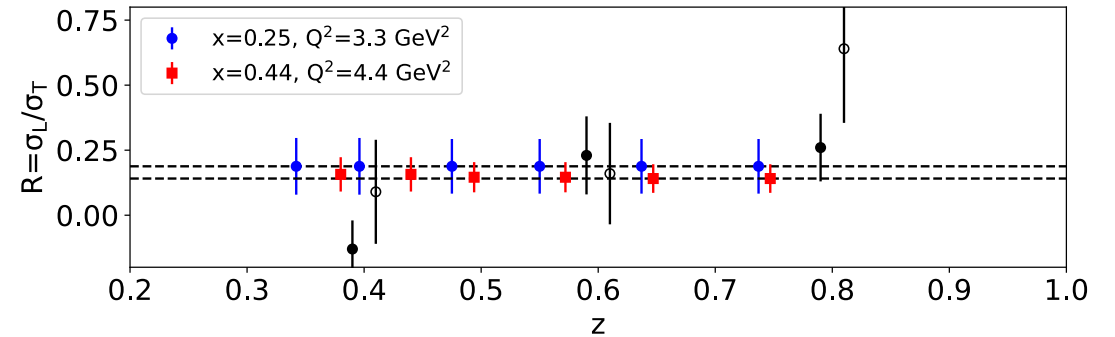
# R-SIDIS Experiments in Hall C

**E12-06-104:** Measurement of the Ratio  $R = \sigma_L / \sigma_T$  in Semi-Inclusive Deep-Inelastic Scattering  
 → Ran in summer of 2025 and 2026

- $R_{SIDIS} = R_{DIS}$  ?
- Measure  $R_{SIDIS}$  dependence  $z$ ,  $P_T$
- Is  $R_{SIDIS}$  the same for  $\pi^+$ ,  $\pi^-$  ( $K^+$ ,  $K^-$ )? H and D?
- How does  $R$  transition from SIDIS to exclusive?

1. Scans in  $z$  at  $Q^2 = 3.3$  ( $x = 0.25$ ) and  $4.4$   $\text{GeV}^2$  ( $x = 0.44$ ) → behavior of  $\sigma_L / \sigma_T$  for large  $z$ .
2. Cover  $Q^2 = 1.6 - 4.4$   $\text{GeV}^2$ , → both H and D at  $Q^2 = 3.1, 3.3, 4.4$   $\text{GeV}^2$
3.  $P_T$  up to  $\sim 0.8$   $\text{GeV}$ . Coverage in  $\phi$  is excellent (o.k.) up to  $P_T = 0.2$  ( $0.4$ )  $\text{GeV}$ .

**$R = \sigma_L / \sigma_T$  in SIDIS ( $ep \rightarrow e' \pi^+ / - X$ )**



# R-SIDIS Experiments in Hall C

**E12-24-001** ran with E12-06-104 to measure the nuclear dependence of  $R$  in SIDIS

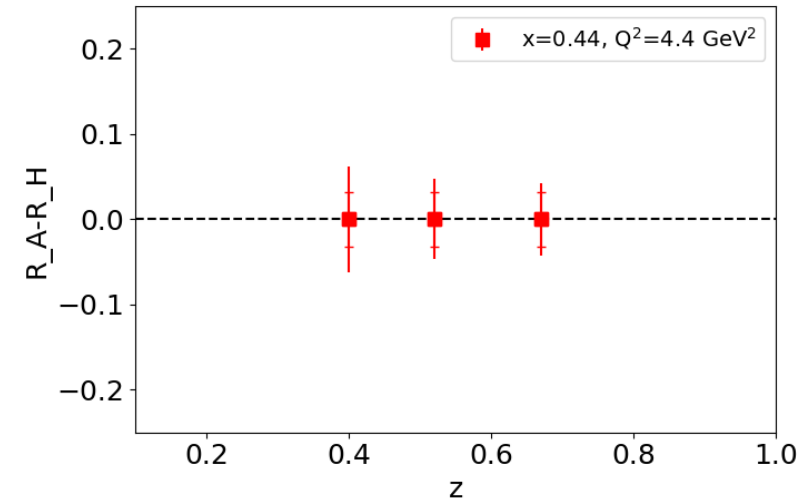
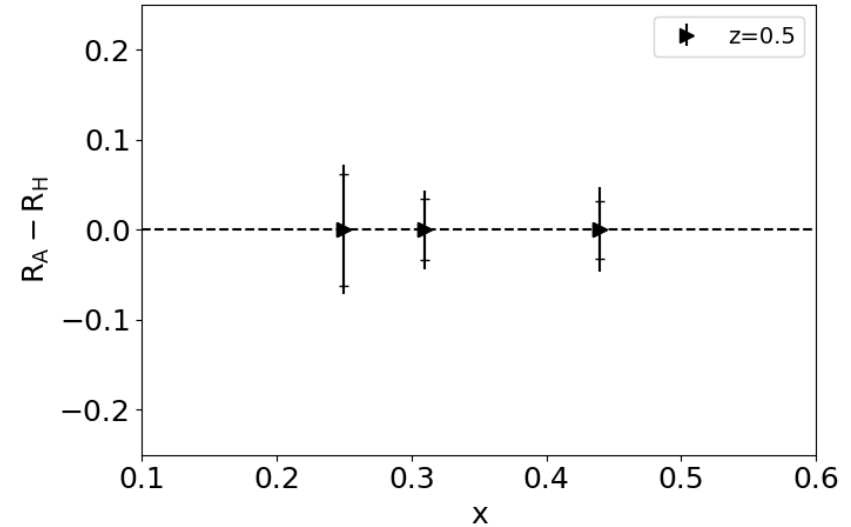
- Use H, D measurements from R-SIDIS, add data from C and Cu targets
- Measure epsilon dependence of target ratio to extract  $R_A - R_D$

$$\frac{\sigma_A}{\sigma_H} = \frac{\sigma_A^T}{\sigma_H^T} [1 + \epsilon' (R_A - R_H)]$$

$\epsilon' = \epsilon / (1 + \epsilon R_H)$

**Exploratory** measurement to look for novel nuclear effects

- $\Delta R$  same for inclusive and SIDIS?
- If non-zero, impacts hadron attenuation measurements
- Possible sensitivity to nuclear pions?



# SIDIS with Hall C Standard Equipment

Hall C uses magnetic focusing spectrometers with moderate acceptance

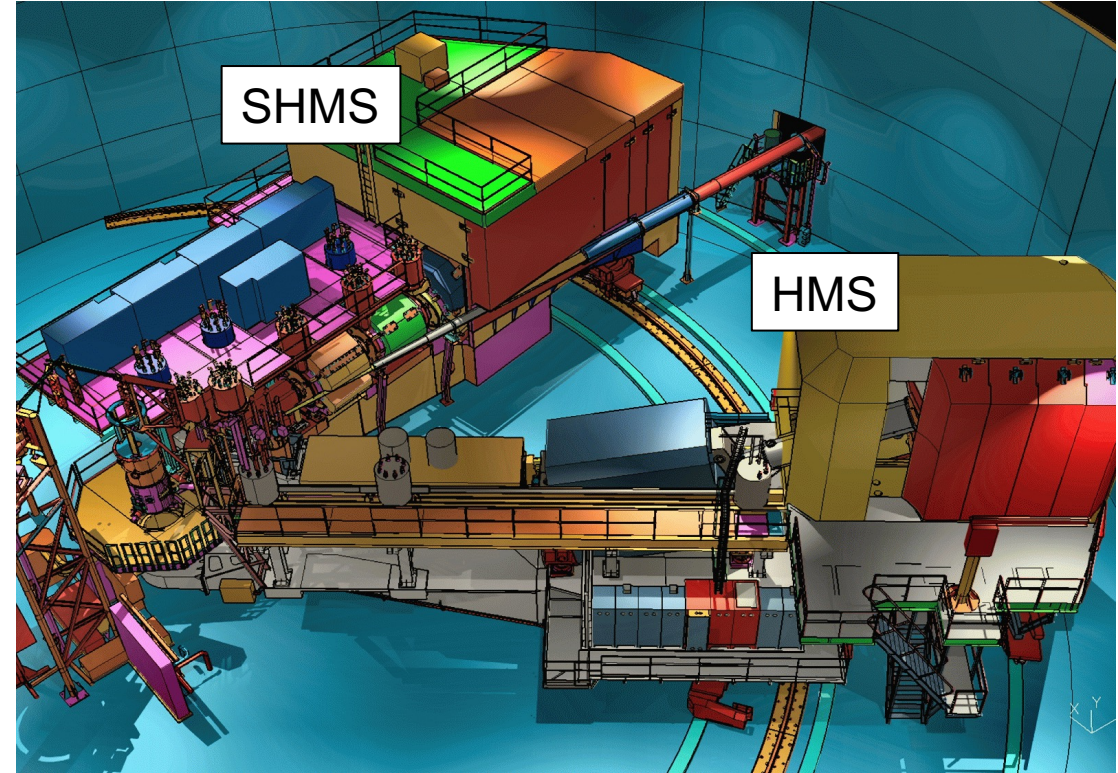
Optimal Hall C SIDIS program:

→ Targeted measurements in specific regions of phase space (i.e., low-rate processes)

→ **Absolute cross sections, L-T separations, ratios (target or charge)**

Complementary to large acceptance devices that can access large phase space all at once

Excellent control of point-to-point systematic uncertainties required for precise L-T separations  
→ Ideally suited for focusing spectrometers  
→ One of the drivers for SHMS design

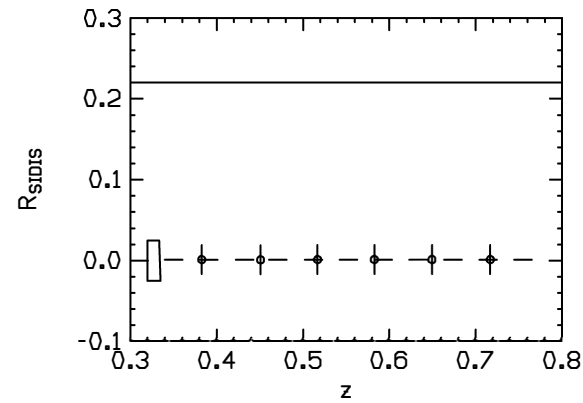
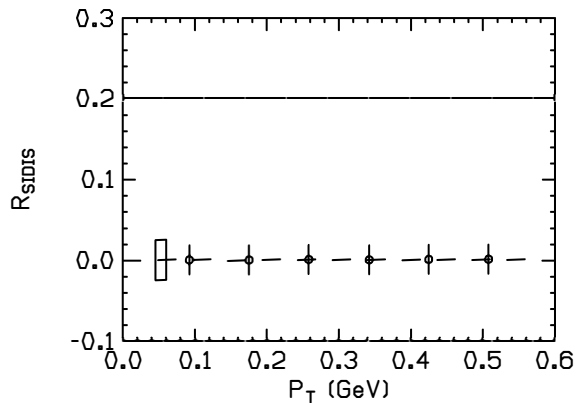


Identical acceptance for positive and negative polarity  
→ Precision measurement of charged meson ratios

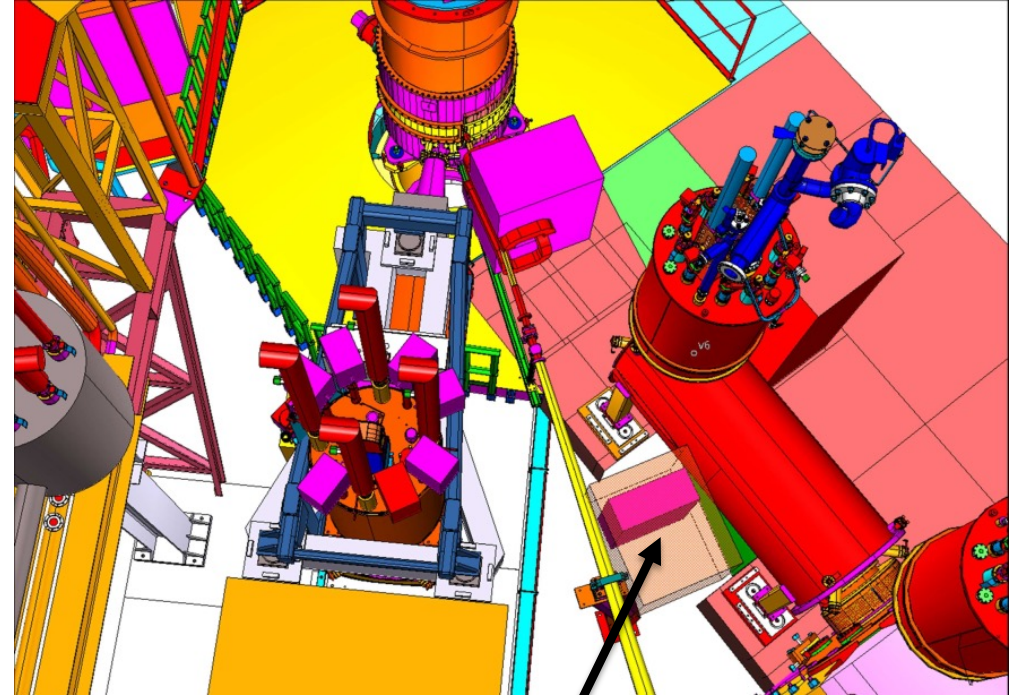
# R-SIDIS Experiments in Hall C - $\pi^0$ with NPS

$\pi^0$  avoids complications from vector meson decay, smaller radiative tails from exclusive pion production

Calorimeter + sweeper magnet adds capability to detect neutral particles:  $\gamma$  and  $\pi^0$



First NPS run completed in 2023 → large amount of SIDIS  $\pi^0$  (and exclusive  $\pi^0$  and DVCS) data under analysis



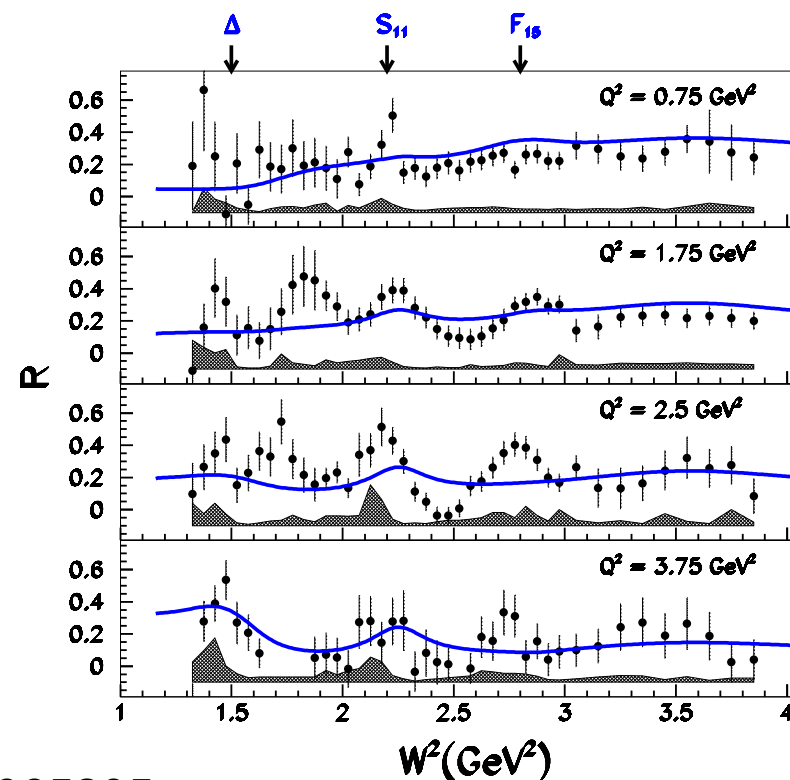
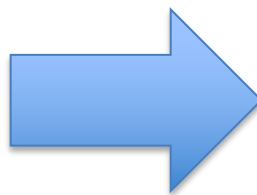
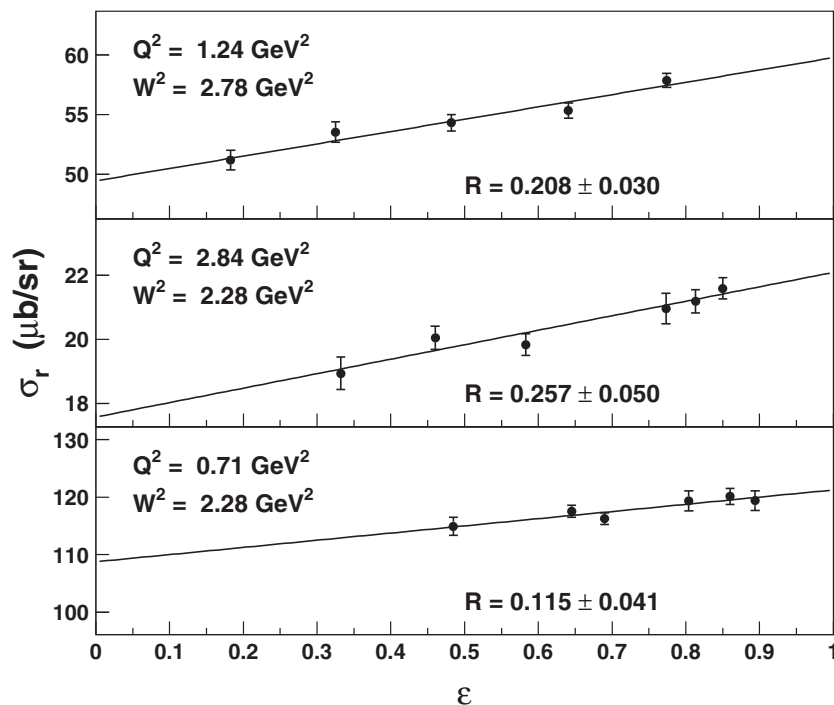
# (Inclusive) Rosenbluth (L-T) Separations

Inclusive measurements:

$$\frac{d\sigma}{d\Omega dE} = \Gamma [\sigma_T(\nu, Q^2) + \epsilon \sigma_L(\nu, Q^2)]$$

Vary  $\epsilon$  by making measurements at different beam energies while keeping  $x$  and  $Q^2$  fixed)

$$\epsilon = \left[ 1 + 2 \left( 1 + \frac{Q^2}{4M^2 x^2} \right) \tan^2 \frac{\theta}{2} \right]^{-1}$$



# (Inclusive) Rosenbluth (L-T) Separations

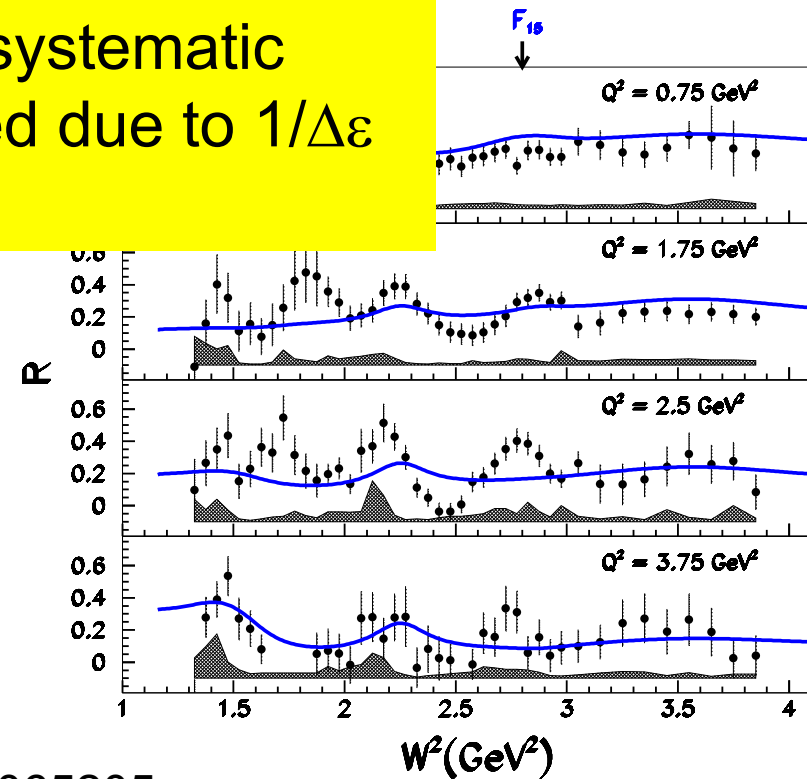
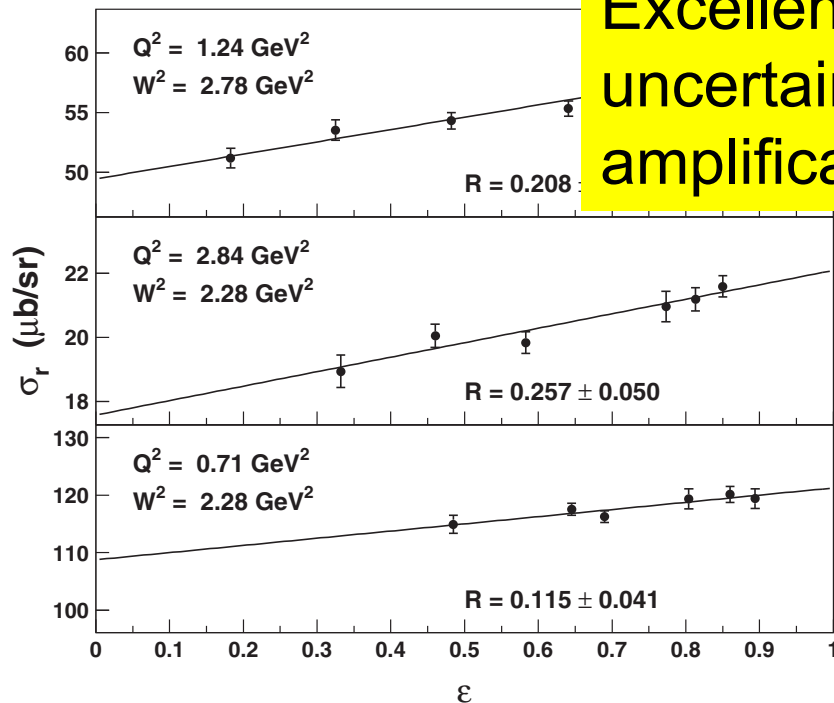
Inclusive measurements:

$$\frac{d\sigma}{d\Omega dE} = \Gamma \left[ \sigma_T(\nu, Q^2) + \epsilon \sigma_L(\nu, Q^2) \right]$$

Vary  $\epsilon$  by making measurements at different beam energies while keeping  $x$  and  $Q^2$  fixed)

$$\epsilon = \left[ 1 + 2 \left( 1 + \frac{Q^2}{4M^2 x^2} \right) \tan^2 \frac{\theta}{2} \right]^{-1}$$

Excellent control of systematic uncertainties required due to  $1/\Delta\epsilon$  amplification



# SIDIS Cross Section

Unpolarized cross section → requires 3 more degrees of freedom

$$\frac{d\sigma}{dE_e d\Omega_e dP_\pi d\Omega_\pi} = \Gamma \left[ \frac{d\sigma_T}{dP_\pi d\Omega_\pi} + \epsilon \frac{d\sigma_L}{dP_\pi} d\Omega_\pi + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dP_\pi d\Omega_\pi} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dP_\pi d\Omega_\pi} \cos 2\phi \right]$$

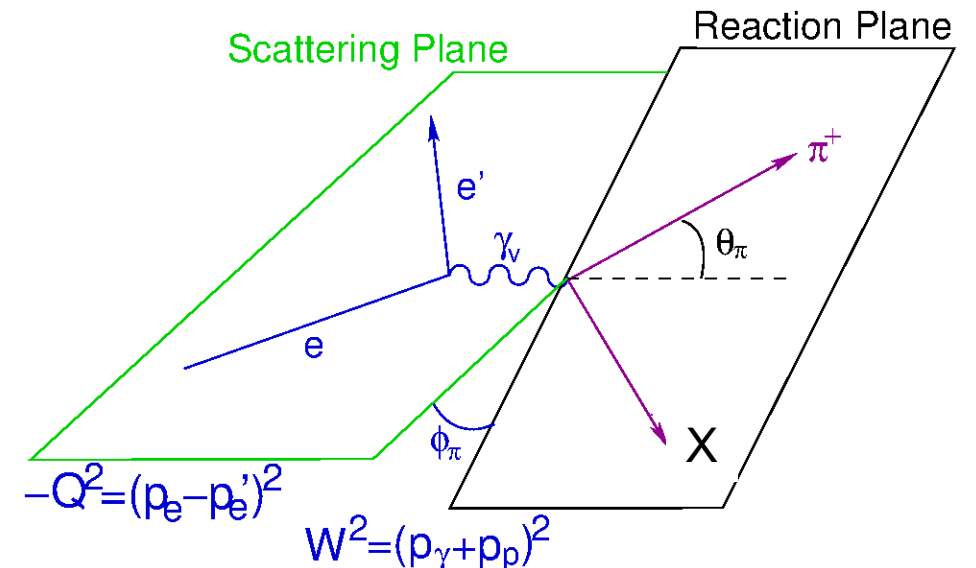
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi} = \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\epsilon)} \left[ F_T + \epsilon F_L + \sqrt{2\epsilon(1+\epsilon)} \cos \phi F_{LT} + \epsilon \cos 2\phi F_{TT} \right]$$

Inclusive: structure functions depend just on  $x$  and  $Q^2$

SIDIS: structure functions depend on  $x, Q^2, z$ , and  $P_T$

$$z = \frac{q \cdot p}{q \cdot P} = \frac{E_h}{\nu} \quad p_{\parallel} = \frac{p \cdot q}{|q|} \quad p_T = (p^2 - p_{\parallel}^2)^{\frac{1}{2}}$$

$$\cos \phi = \frac{(-\vec{q} \times \vec{k}) \cdot (-\vec{q} \times \vec{p}_h)}{|\vec{q} \times \vec{k}| |\vec{q} \times \vec{p}_h|}$$



# Rosenbluth separations for SIDIS/Exclusive

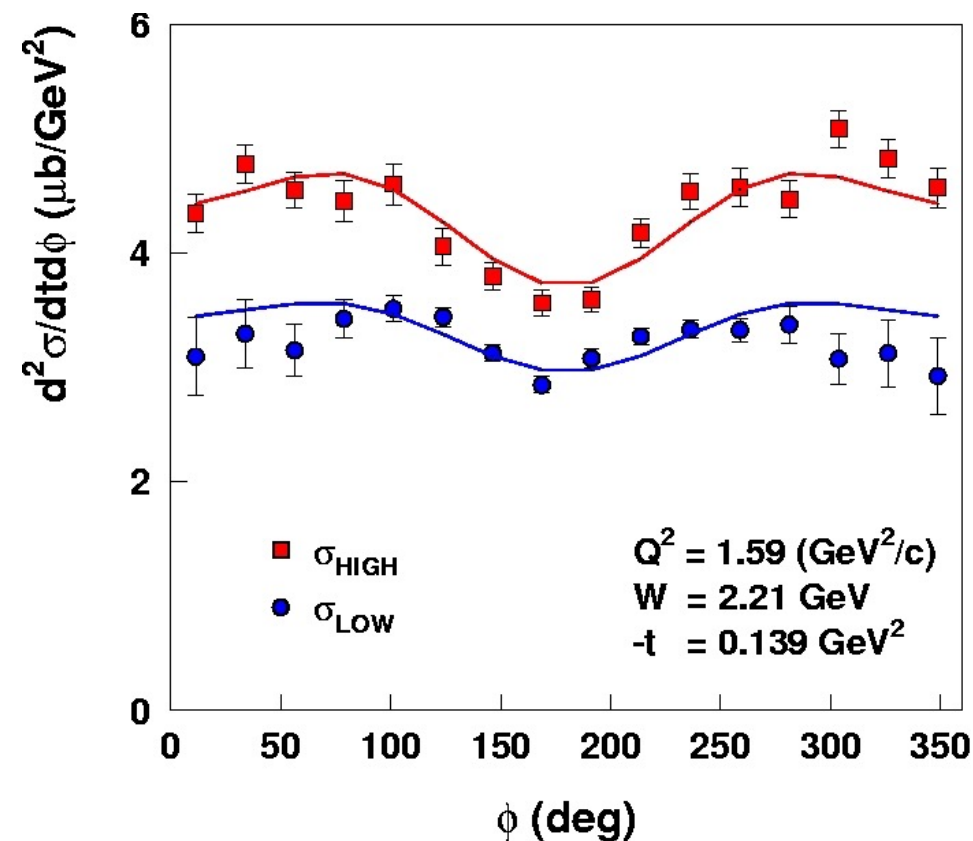
$$\frac{d\sigma}{dE_e d\Omega_e dP_\pi d\Omega_\pi} = \Gamma \left[ \frac{d\sigma_T}{dP_\pi d\Omega_\pi} + \epsilon \frac{d\sigma_L}{dP_\pi} d\Omega_\pi + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dP_\pi d\Omega_\pi} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dP_\pi d\Omega_\pi} \cos 2\phi \right]$$

L-T separation for meson production more complicated due to  $\phi$  dependent terms

We're most interested in  $\sigma_L$  and  $\sigma_T$

Need to extract cross section at fixed  $x$ ,  $Q^2$ ,  $z$ , and  $P_T$  vs.  $\phi$  at each beam energy ( $\epsilon$ )

Need to perform multiparameter fit over all  $\epsilon$  settings  $\rightarrow$  extract L, T, LT, TT terms simultaneously



Example from exclusive pion production (Fpi-2)

# Example: $F_\pi$ Experiments

$F_\pi$ -1 ( $F_\pi$ -2) ran in Hall C in 1997 (2003)

- Used SOS/HMS (well understood magnetic focusing spectrometers)
- Good control of kinematic offsets

Total  $\epsilon$  uncorrelated (point-to-point) uncertainty  
~ 2%

## Largest contributions

1. Model dependence (bin centering, radiative corrections)
2. Electron scattering angle  
→ 0.5 mrad
3. Acceptance

Even if systematic uncertainties small, final unc. on  $R$  can still be large

| Correction          | Uncorr.<br>(pt-to-pt)<br>(%) | $\epsilon$ uncorr.<br>$t$ corr.<br>(%) | Corr.<br>(scale)<br>(%) |
|---------------------|------------------------------|----------------------------------------|-------------------------|
| Acceptance          | 1.0 (0.6)                    | 0.6                                    | 1.0                     |
| Model Dep           | 0.2                          | 1.1-1.3                                | 0.5                     |
| $d\theta_e$         | 0.1                          | 0.7-1.1                                |                         |
| $dE_{beam}$         | 0.1                          | 0.2-0.3                                |                         |
| $dP_e$              | 0.1                          | 0.1-0.3                                |                         |
| $d\theta_\pi$       | 0.1                          | 0.2-0.3                                |                         |
| Radiative corr      |                              | 0.4                                    | 2.0                     |
| Pion absorption     |                              | 0.1                                    | 2.0                     |
| Pion decay          | 0.03                         |                                        | 1.0                     |
| HMS Tracking        |                              | 0.4                                    | 1.0                     |
| SOS Tracking        |                              | 0.1                                    | 0.5                     |
| Charge              |                              | 0.3                                    | 0.4                     |
| Target Thickness    |                              | 0.2                                    | 0.9                     |
| CPU dead time       |                              | 0.2                                    |                         |
| HMS Trigger         |                              | 0.1                                    |                         |
| SOS Trigger         |                              | 0.1                                    |                         |
| Ele DT              |                              | 0.3                                    |                         |
| Coincidence block.  |                              | 0.1                                    |                         |
| Particle ID         |                              | 0.2                                    |                         |
| Total ( $F_\pi$ -2) | 1.2 (0.9)                    | 1.8-1.9                                | 3.5                     |
| Total ( $F_\pi$ -1) | 0.7                          | 1.7-2.0                                | 2.8                     |

# Projected Uncertainties for Hall C 12 GeV Experiments

Most experiments use projected point-to-point uncertainties assumed in the proposal for the pion-LT experiments

Precision should be improved by new SHMS

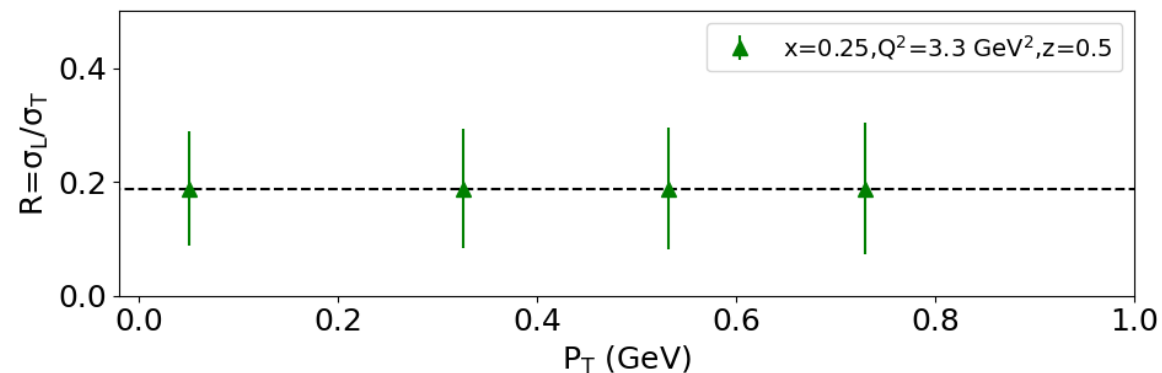
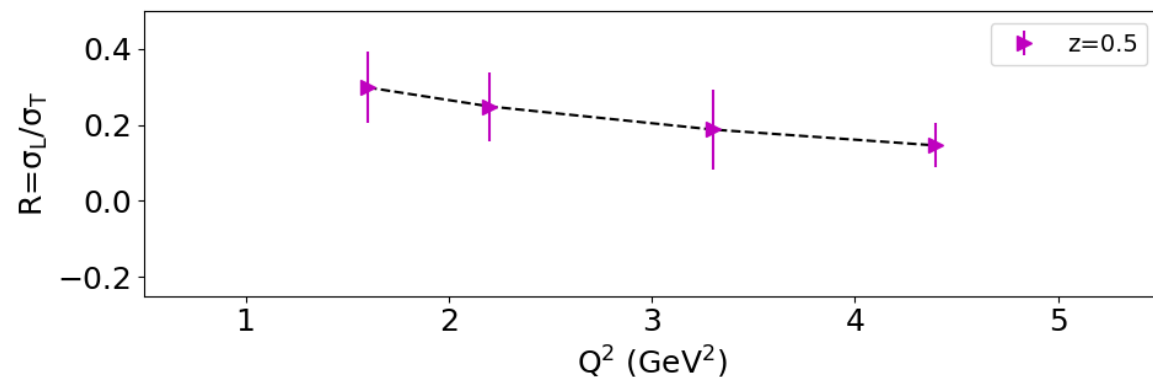
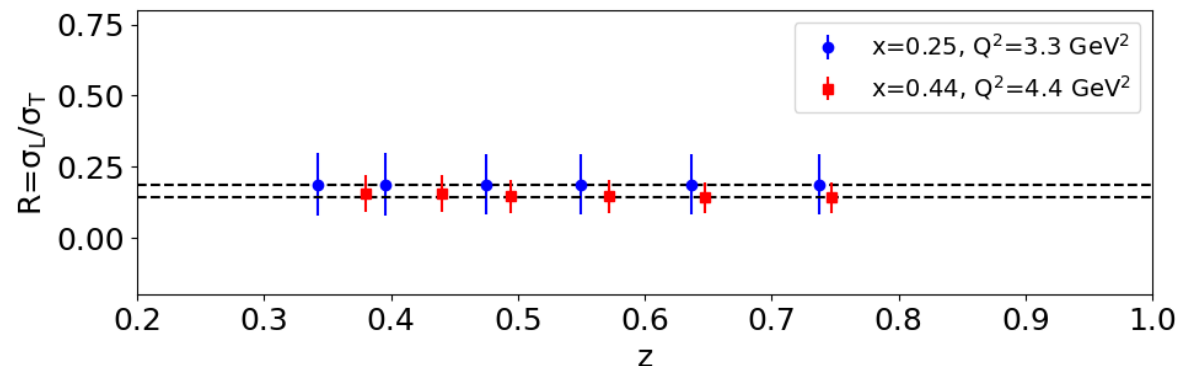
→ Acceptance and optics easier to understand than SOS

→ Total  $\varepsilon$ -uncorrelated uncertainty = **1.7%**

| Source                | Type of systematic uncertainty |                     |           |
|-----------------------|--------------------------------|---------------------|-----------|
|                       | pt-to-pt (%)                   | $t$ -correlated (%) | scale (%) |
| Acceptance            | 0.4                            | 0.4                 | 1.0       |
| Target Thickness      |                                | 0.2                 | 0.8       |
| Beam Charge           |                                | 0.2                 | 0.5       |
| HMS+SHMS Tracking     | 0.1                            | 0.1                 | 1.5       |
| Coincidence Blocking  |                                | 0.2                 |           |
| PID                   |                                | 0.4                 |           |
| $\pi$ Decay           | 0.03                           |                     | 0.5       |
| $\pi$ Absorption      |                                | 0.1                 | 1.5       |
| Monte Carlo Generator | 0.2                            | 1.0                 | 0.5       |
| Radiative Corrections | 0.1                            | 0.4                 | 2.0       |
| Offsets               | 0.4                            | 1.0                 |           |
| Quadrature Sum        | 0.6                            | 1.6                 | 3.3       |
| Fpi-2 Values          | 0.9                            | 1.9                 | 3.5       |

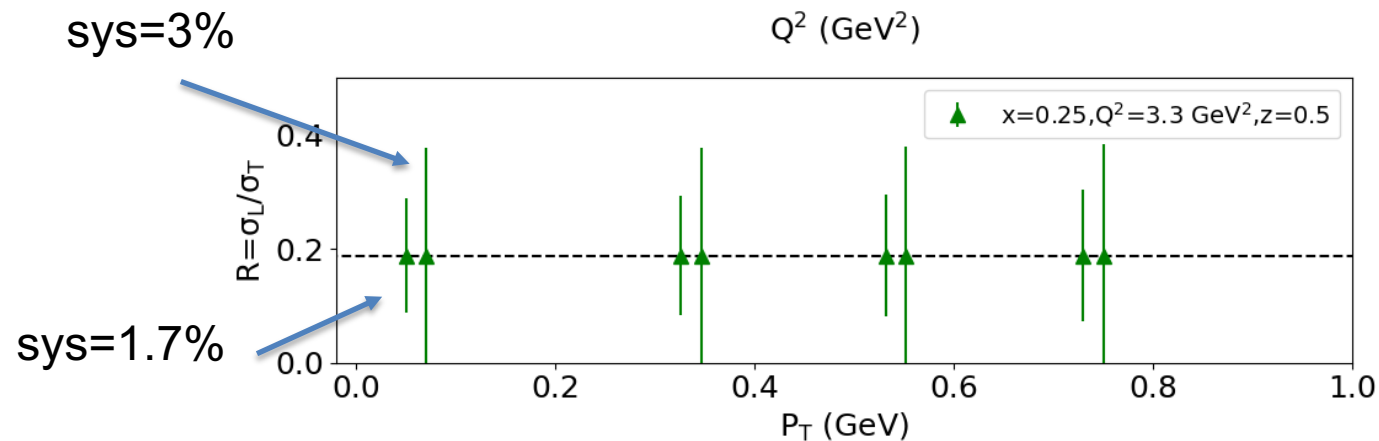
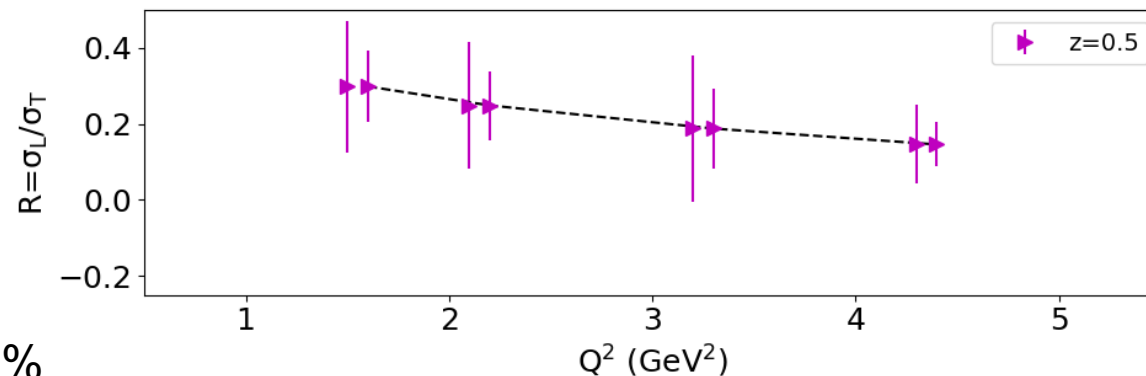
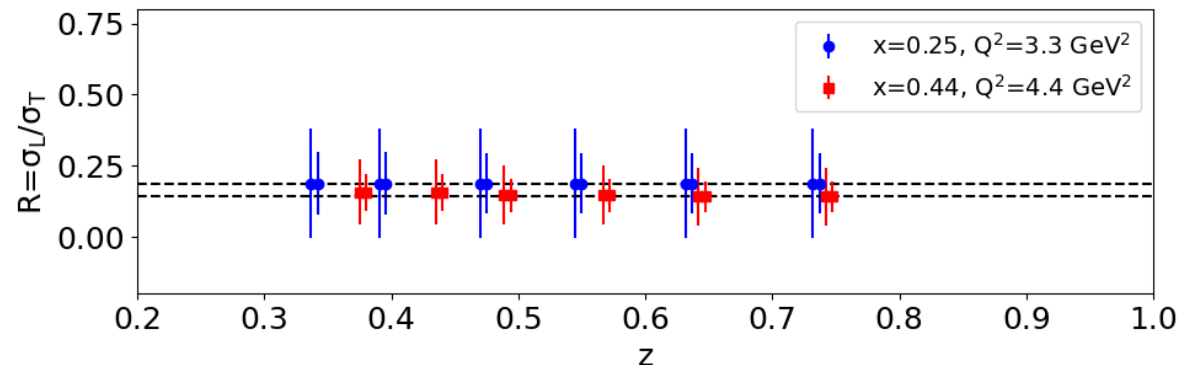
# R-SIDIS: Projected Uncertainties

- Projected uncertainties for R-SIDIS kinematics
  - statistics typically 1% or better
- Point-to-point systematics as noted
- $\Delta\varepsilon$  always at least 0.3
- What would be the impact if point-to-point systematics were twice as large?



# R-SIDIS: Projected Uncertainties

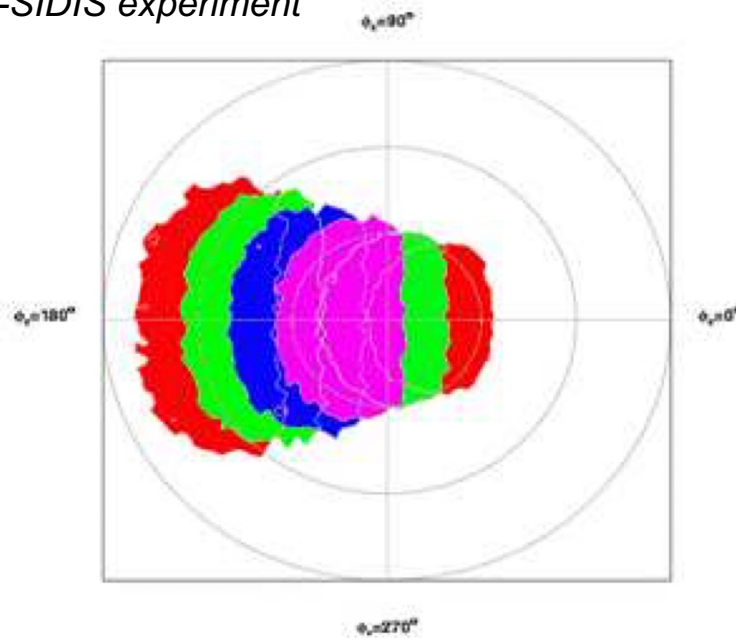
- Projected uncertainties for R-SIDIS kinematics
  - statistics typically 1% or better
- Point-to-point systematics as noted
- $\Delta\varepsilon$  always at least 0.3
- What would be the impact if point-to-point systematics were twice as large?
- Impact on measurements of  $R$  significant



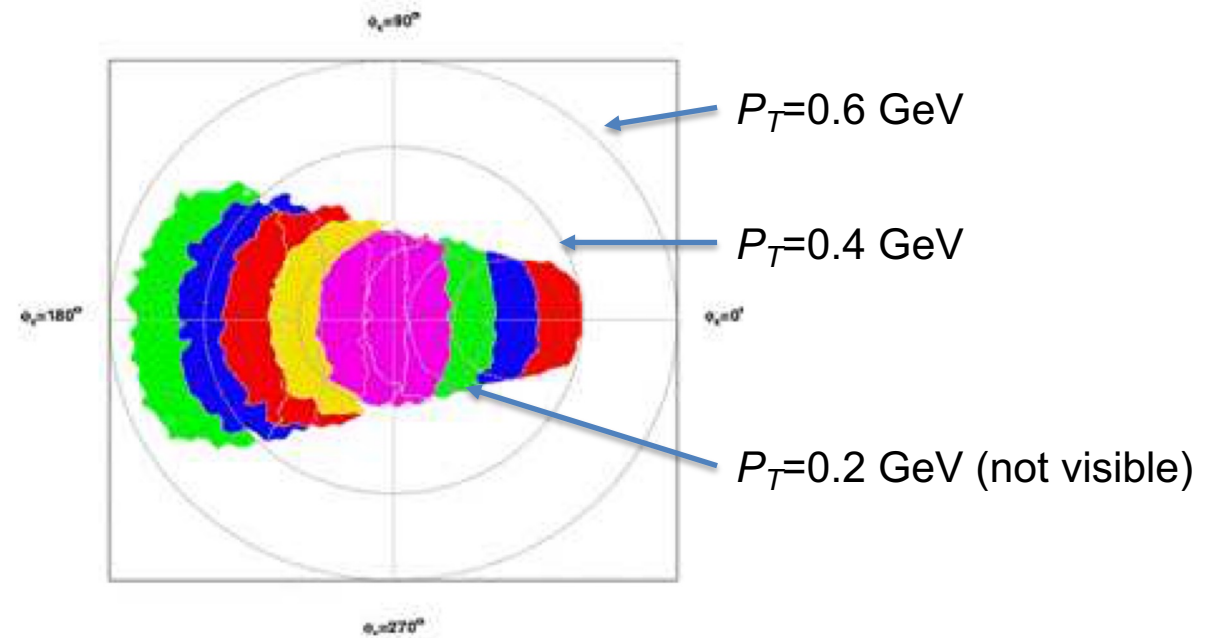
# Limitations of Magnetic Focusing Spectrometers

$$\sigma \sim F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$

Simulated, from PT-SIDIS experiment



$x=0.2 \quad Q^2=2 \text{ GeV}^2$



$x=0.3 \quad Q^2=3 \text{ GeV}^2$

Hall C Spectrometers can measure full  $\phi$  coverage over limited  $P_T$  range  
→ Measure large  $P_T$  range over narrow range in  $\phi$

# Limitations of Magnetic Focusing Spectrometers

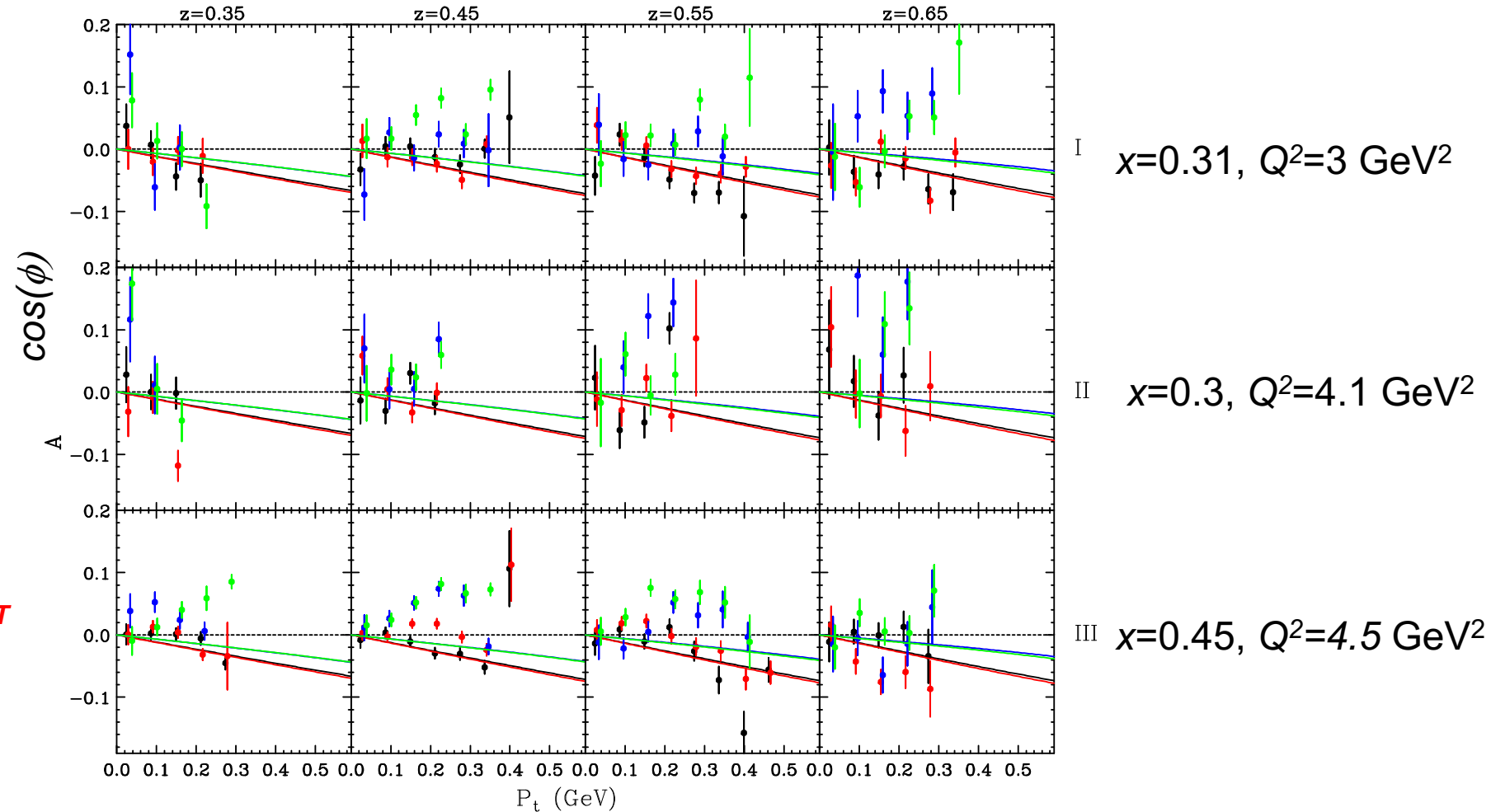
$$\sigma \sim F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$

- $\pi^+$  from p
- $\pi^+$  from d
- $\pi^-$  from d
- $\pi^-$  from p

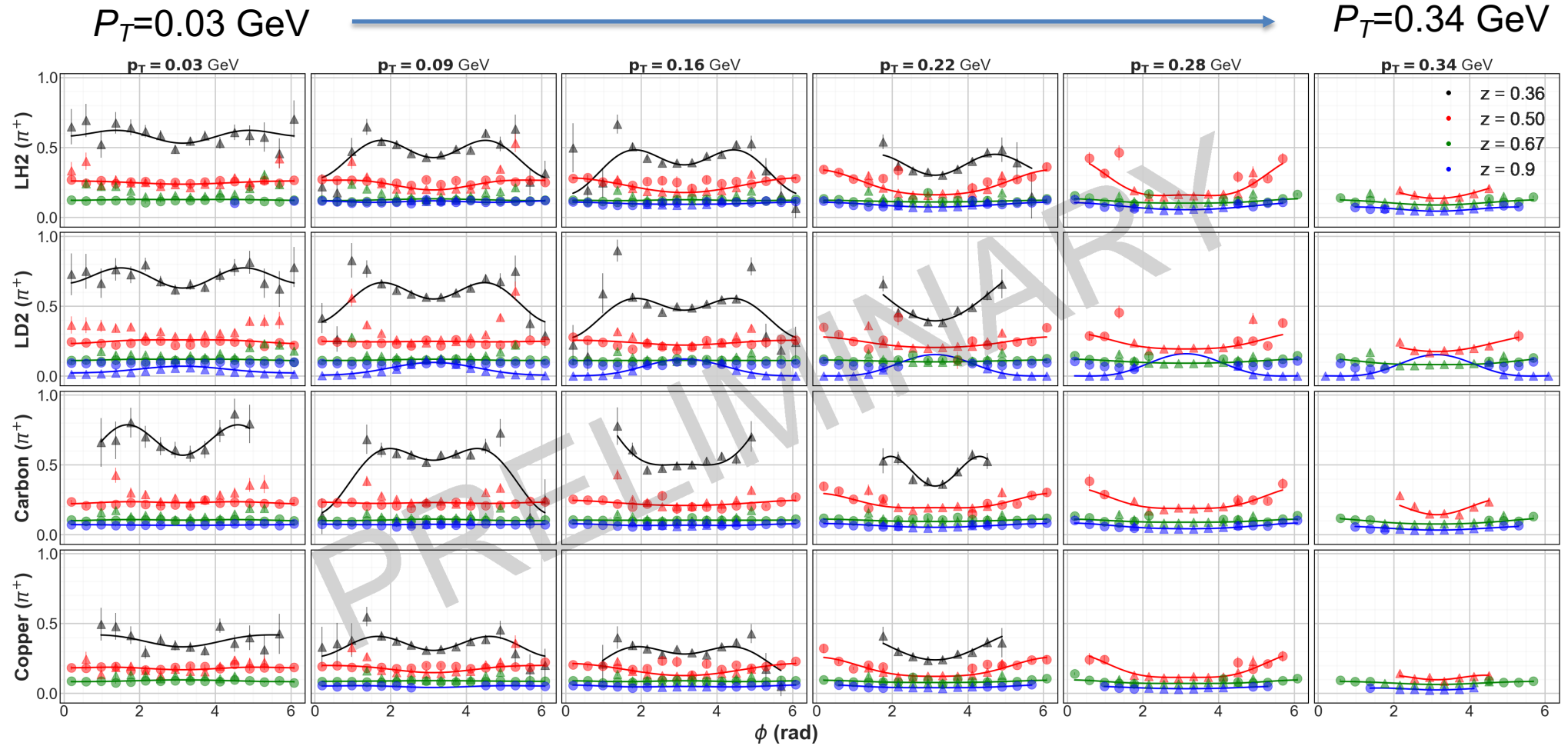
Focusing spectrometers provide excellent control of systematic uncertainties

→ Limited range of  $P_T$  accessible with full  $\phi$  coverage

→ **L-T separation at large  $P_T$  requires more input**



# Preliminary R-SIDIS Multiplicities

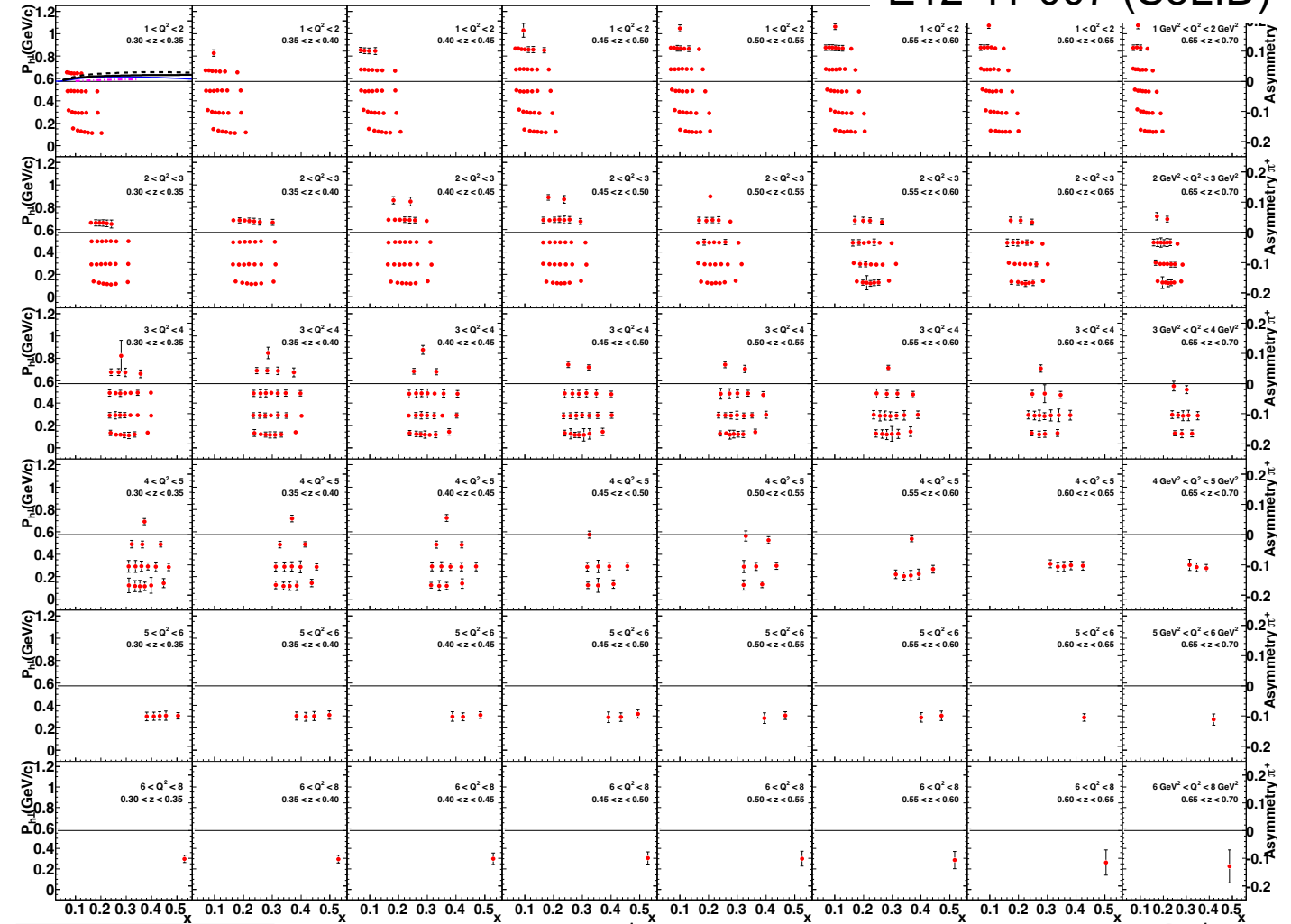


Julio Gil Gutierrez, UTK

# Large Acceptance, High Luminosity Device

E12-11-007 (SoLID)

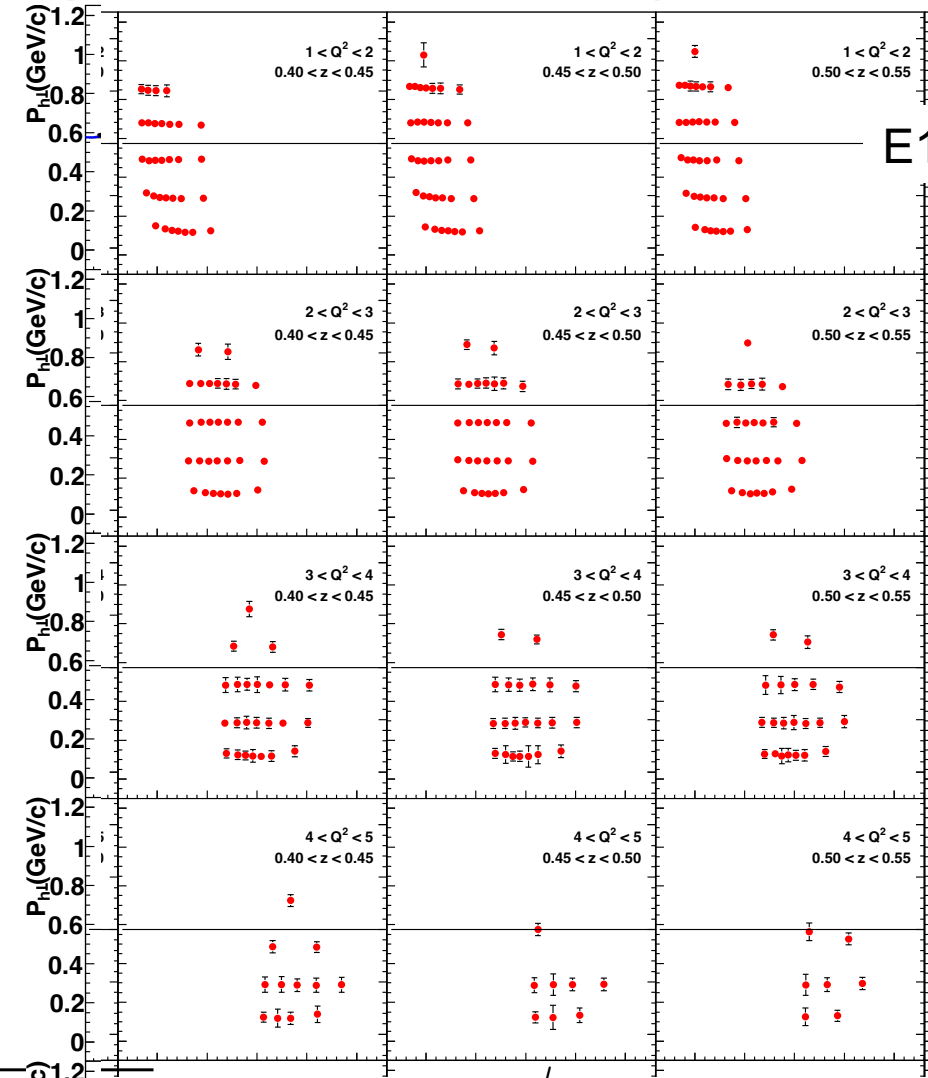
- Large acceptance device likely will have larger point-to-point systematics
- Precision measurements of interference terms  $[\cos(\phi), \cos(2\phi)]$  at large  $P_T$  + large  $P_T$  measurements with spectrometers allows access to  $R$
- Good/uniform acceptance at large  $P_T$  needed
- Systematic uncertainty for acceptance still important for interference terms → what can be achieved for these devices?



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# Large Acceptance, High Luminosity Device

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E12-11-007 (SoLID)

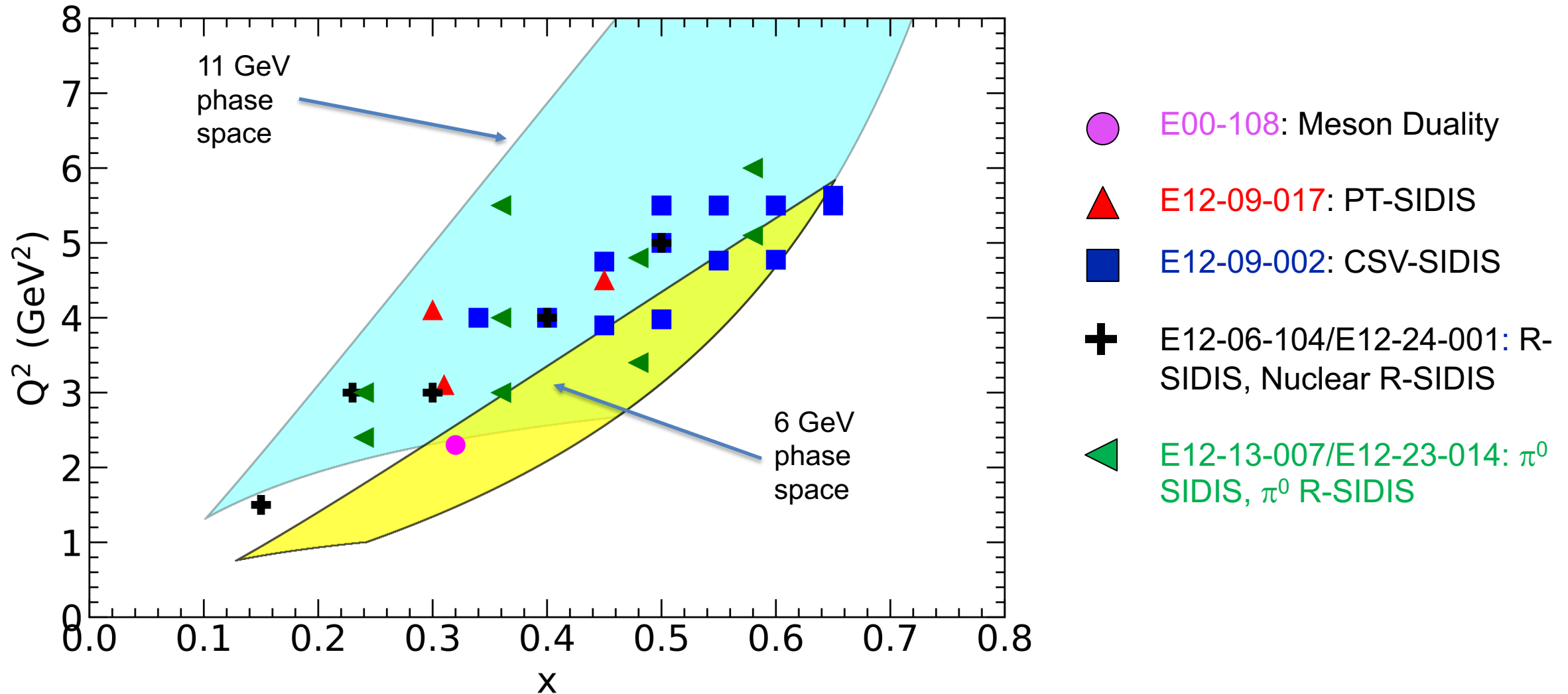
$$\sigma \sim F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \epsilon \cos 2\phi_h F_{UU}^{\cos 2\phi_h}$$

# Summary

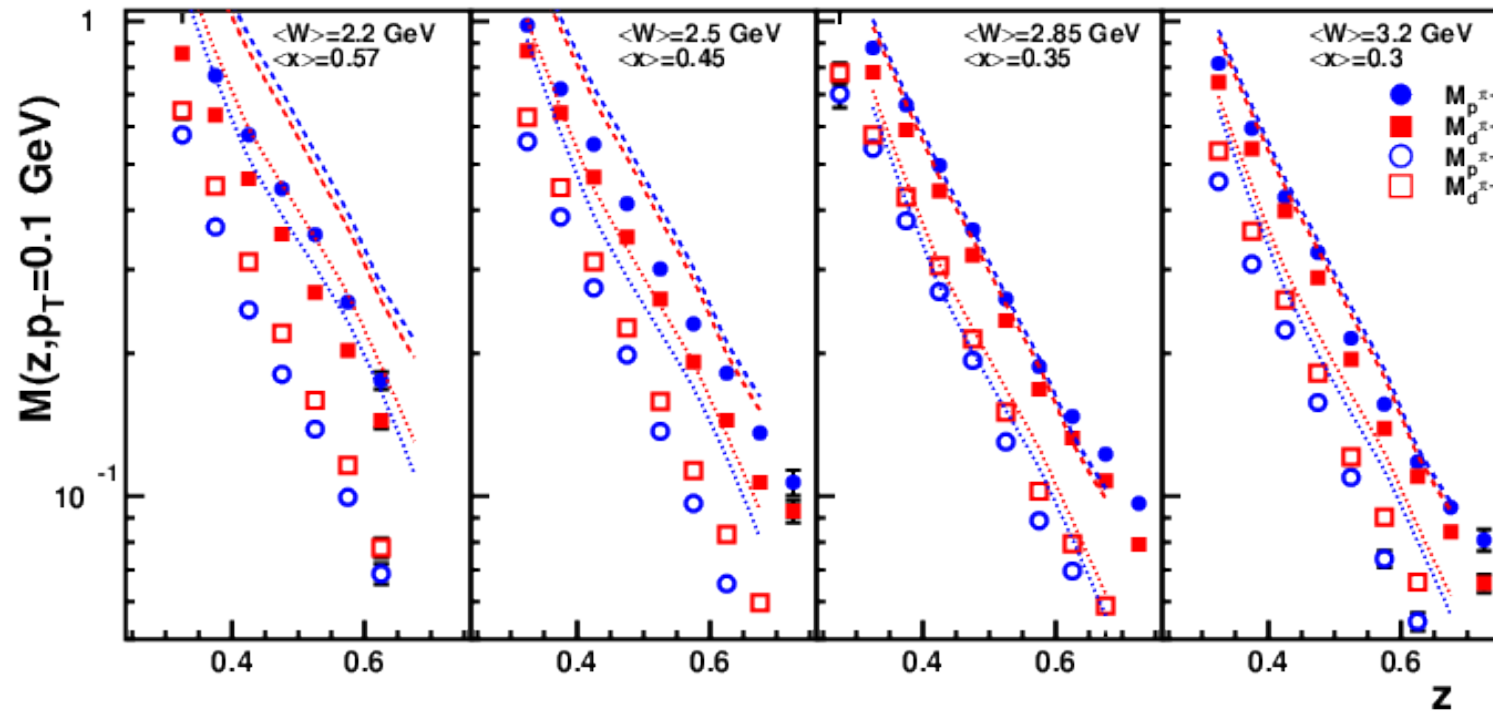
- Measurement of  $R$  in SIDIS (or any reaction) requires excellent control of point-to-point systematic uncertainties
  - Ideal for magnetic focusing spectrometers  $\rightarrow$  same acceptance for all settings
- Acceptance is limited to relatively small  $P_T \rightarrow$  perhaps up to 0.3 or 0.4 GeV
  - Incomplete  $\phi$  coverage, can't determine interference terms
  - Limits  $P_T$  range of L-T separations
- Large acceptance detector operating at high luminosity can allow access to  $\cos\phi$  and  $\cos 2\phi$  interference terms  $\rightarrow$  extend measurements of  $R_{SIDIS}$  to large  $P_T$

# EXTRA

# Hall C SIDIS Experiments (charged and neutral pions)



# Multiplicities vs. $z$



# $P_t$ dependence for $\langle\phi\rangle=180^\circ$

$150^\circ < \phi < 210^\circ$

