SIDIS with Charged Pions in Hall C

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Hall A/C Summer Meeting
July 15-16, 2022

1. Hall C 6 and 12 GeV SIDIS Experiments
2. Flavor dependence of charged pion fragmentation
3. ϕ and P_T dependence of multiplicities
4. CSV in nucleon PDFs

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

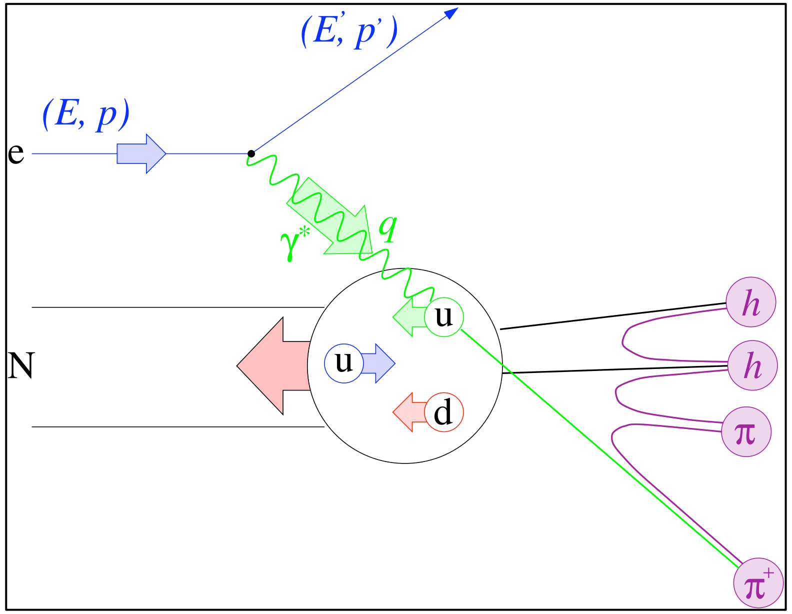
3D nucleon structure
Transverse degrees of freedom allow us to explore k_T dependence of quarks – access to orbital angular momentum
→ Transversity distribution
→ Transverse Momentum Distributions (TMDs)

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

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathrm{h}_1 h_{1T}^\perp$

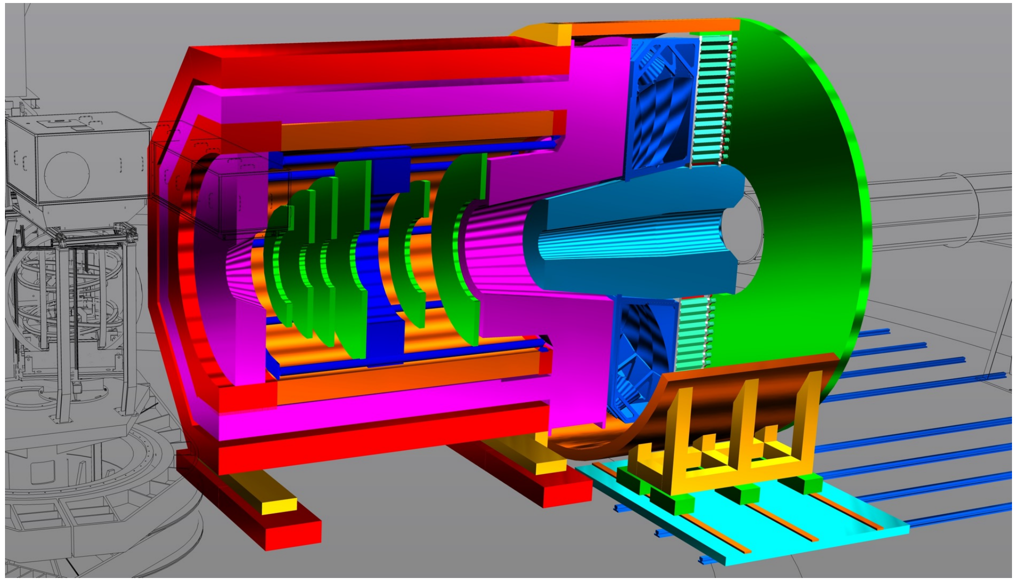
quarks

nucleon

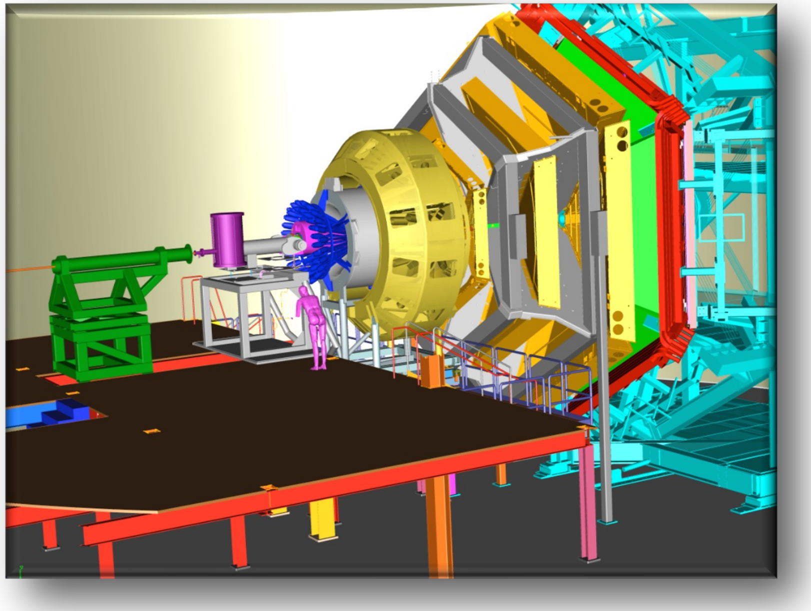


SIDIS with Large Acceptance

SoLID



CLAS12



$$\frac{d\sigma}{dxdyd\phi_S dzd\phi_h dp_{h\perp}^2} = \sigma_{unpol} + \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}|\mathbf{S}_\perp|[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)}\sqrt{2\epsilon(1+\epsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} +$$

$$\sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)}]$$

SIDIS has several observables that depend on measuring the azimuthal dependance

→ Also need large P_T acceptance, multidimensional binning crucial

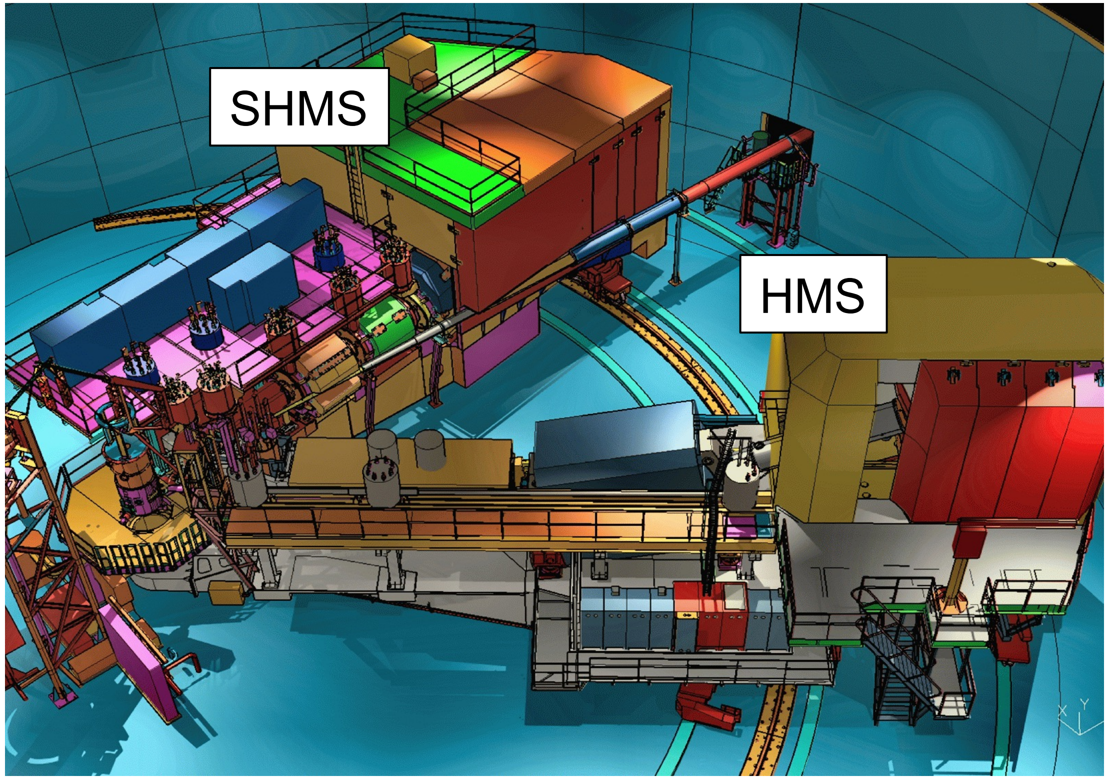
→ Well suited to large acceptance devices like CLAS12 and SoLID

Role of Hall C in JLab SIDIS Program

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**

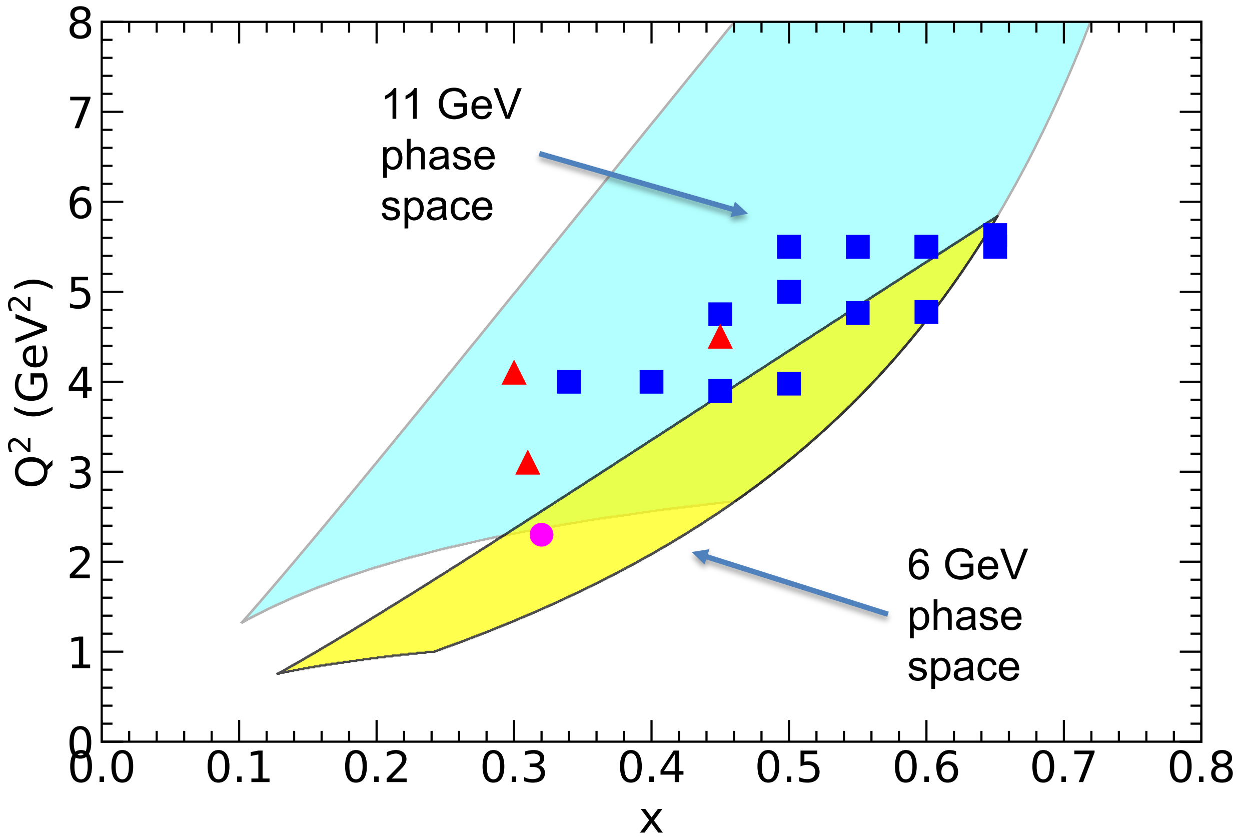
Complementary to large acceptance devices that can access large phase space all at once



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

Hall C SIDIS Experiments



E00-108: "Duality in Meson Electroproduction"
→ 6 GeV, first Hall C SIDIS measurement

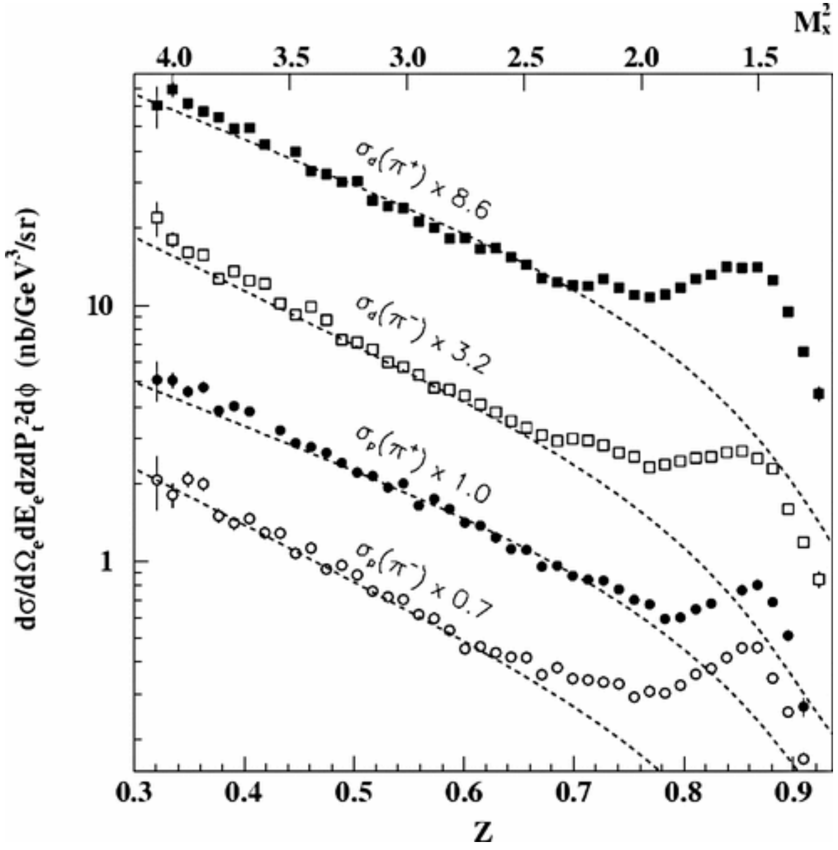
E12-09-017: "Transverse Momentum Dependence of Semi-Inclusive Pion Production"
→ Scans in *z* and P_T, *x*-dependence at fixed Q^2

E12-09-002: "Charge Symmetry Violating Quark Distributions via Precise Measurement of π+/π− Ratios in SIDIS"
→ Scans in *z* at each x/Q^2 (parallel kinematics)
→ Deuterium at every setting, hydrogen at select settings

Hall C SIDIS experiments will provide information on the fundamental reaction mechanism/cross section
→ Consistency with simple factorization assumptions?
→ Charge symmetry of FF?

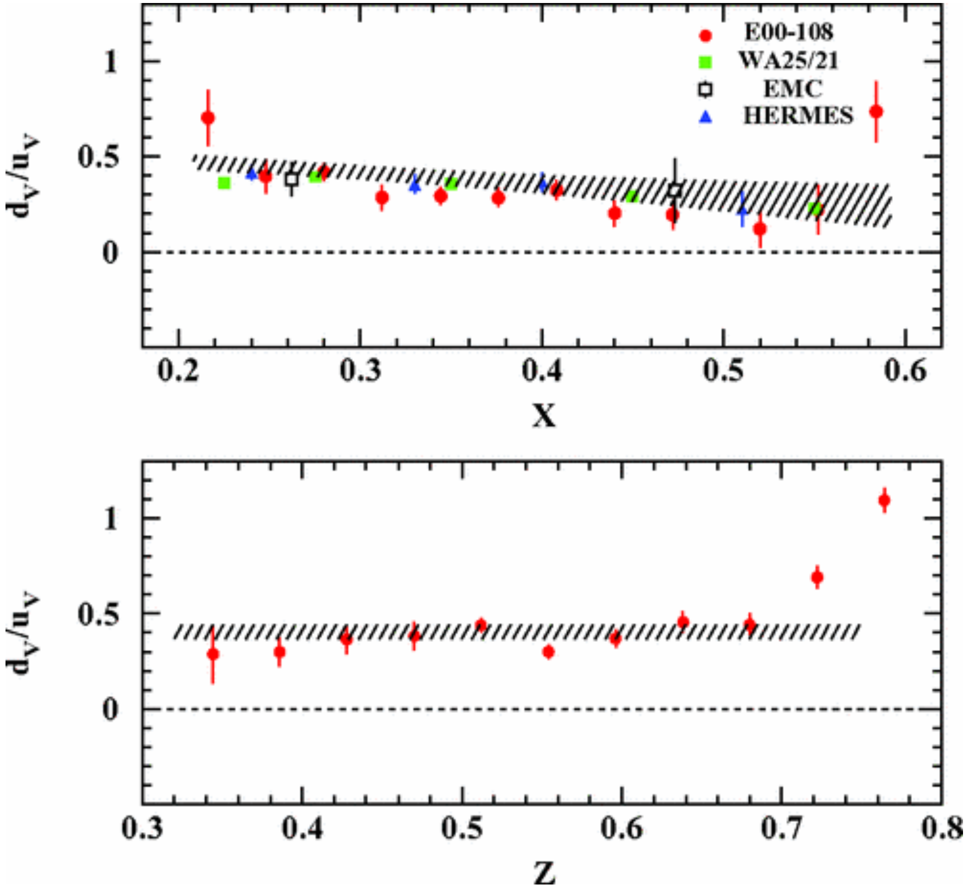
Hall C SIDIS Results from 6 GeV

E00-008: SIDIS π+/π- cross sections and ratios



T. Navasardyan et al. PRL 98, 022001

Surprisingly consistent with expectations from higher energy experiments



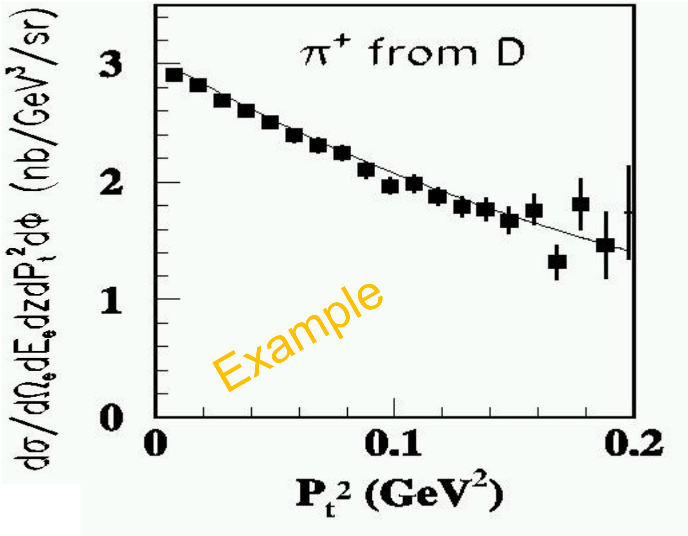
R. Asaturyan et al. Phys. Rev. C 85, 015202

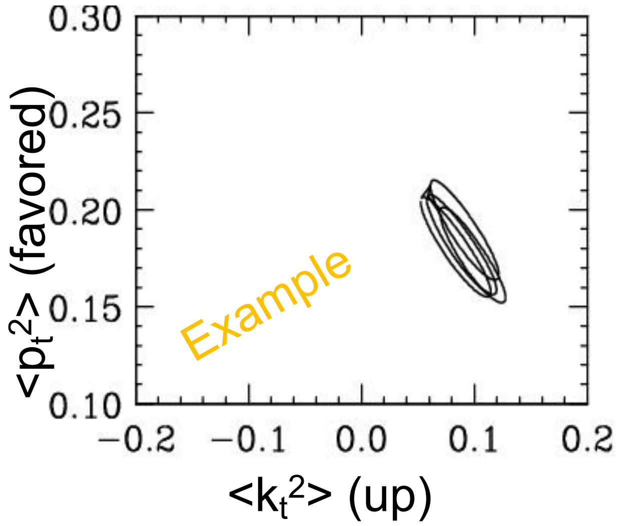
Hall C SIDIS Results from 6 GeV

Hall C experiment E00-108 (6 GeV):
→ Measured P_T dependent cross sections in semi-inclusive pion production
→Measured both π+ and π-
→Proton and deuteron (neutron) targets
→Combination allows (in principle) disentanglement of quark and fragmentation widths

Simple model, with several assumptions:
→ *factorization valid*
→ *fragmentation functions do not depend on quark flavor*
→ *transverse momentum widths of quark and fragmentation functions are Gaussian and can be added in quadrature*
→ *more …*

PL B665 (2008) 20





SIDIS Cross sections and Fragmentation Functions

Naïve quark model:

P_T-integrated fragmentation function

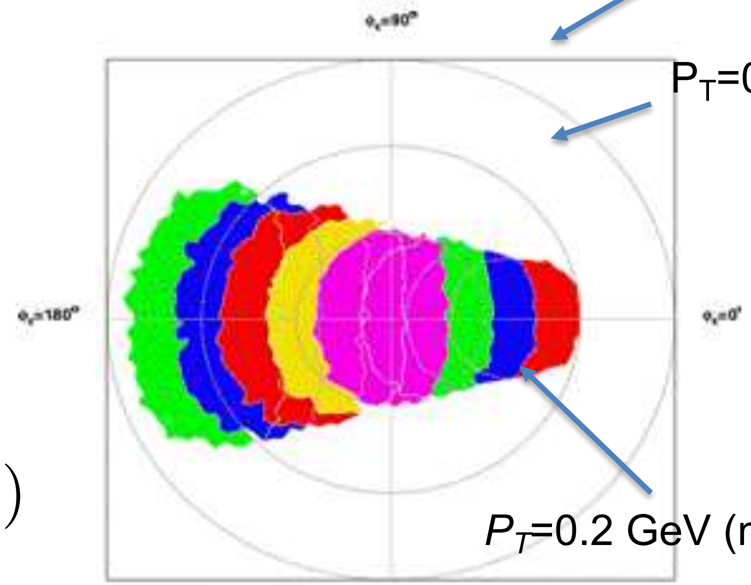
$$\frac{d\sigma(x,Q^2,z)}{dz} = \frac{\sigma_{ee'\pi X}}{\sigma_{ee}} = \sum_f e_f^2 q_f(x,Q^2) D_f^h(z)$$

Assuming charge and isospin symmetry:

$$\boxed{\begin{aligned} D^+ &= D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+} \\ D^- &= D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^-} \end{aligned}}$$

For finite P_T acceptance, cannot ignore P_T dependence of fragmentation functions

$$D_f^h(z) \rightarrow D_f^h(z, P_T)$$



P_T=0.6 GeV

P_T=0.4 GeV

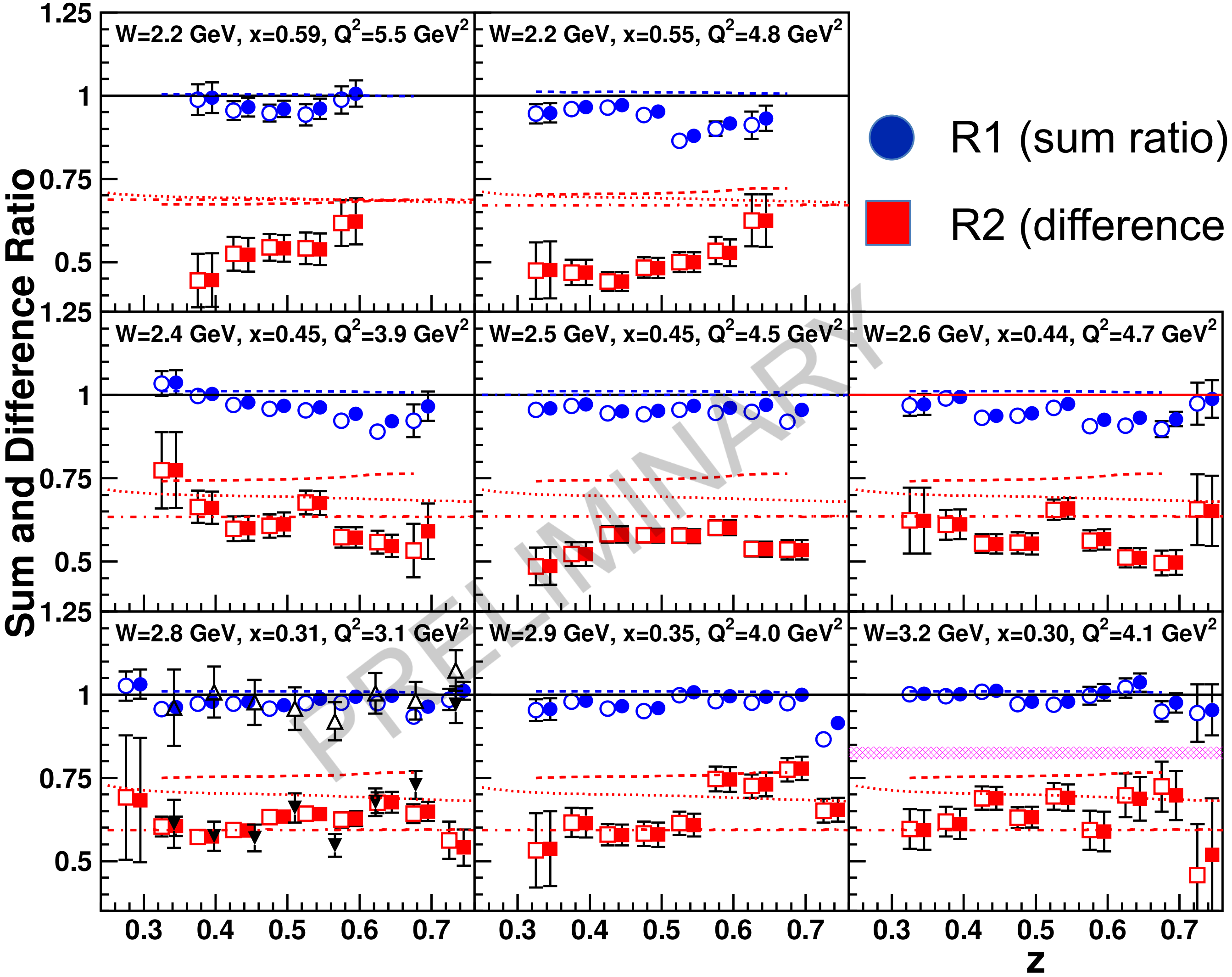
P_T=0.2 GeV (not visible)

x=0.3 Q^2=3 GeV^2

Cross section also includes contributions from longitudinal photons, ϕ dependent terms

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

Tests of Naïve Factorization



● R1 (sum ratio)

🟥 R2 (difference ratio)

$$M^{\pi^\pm}_{p/d}(x, Q^2, z) = \sigma^{\pi^\pm}_{p/d}(x, Q^2, z)/\sigma^{ee}_{p/d}$$

Note: integration over (finite) P_T acceptance

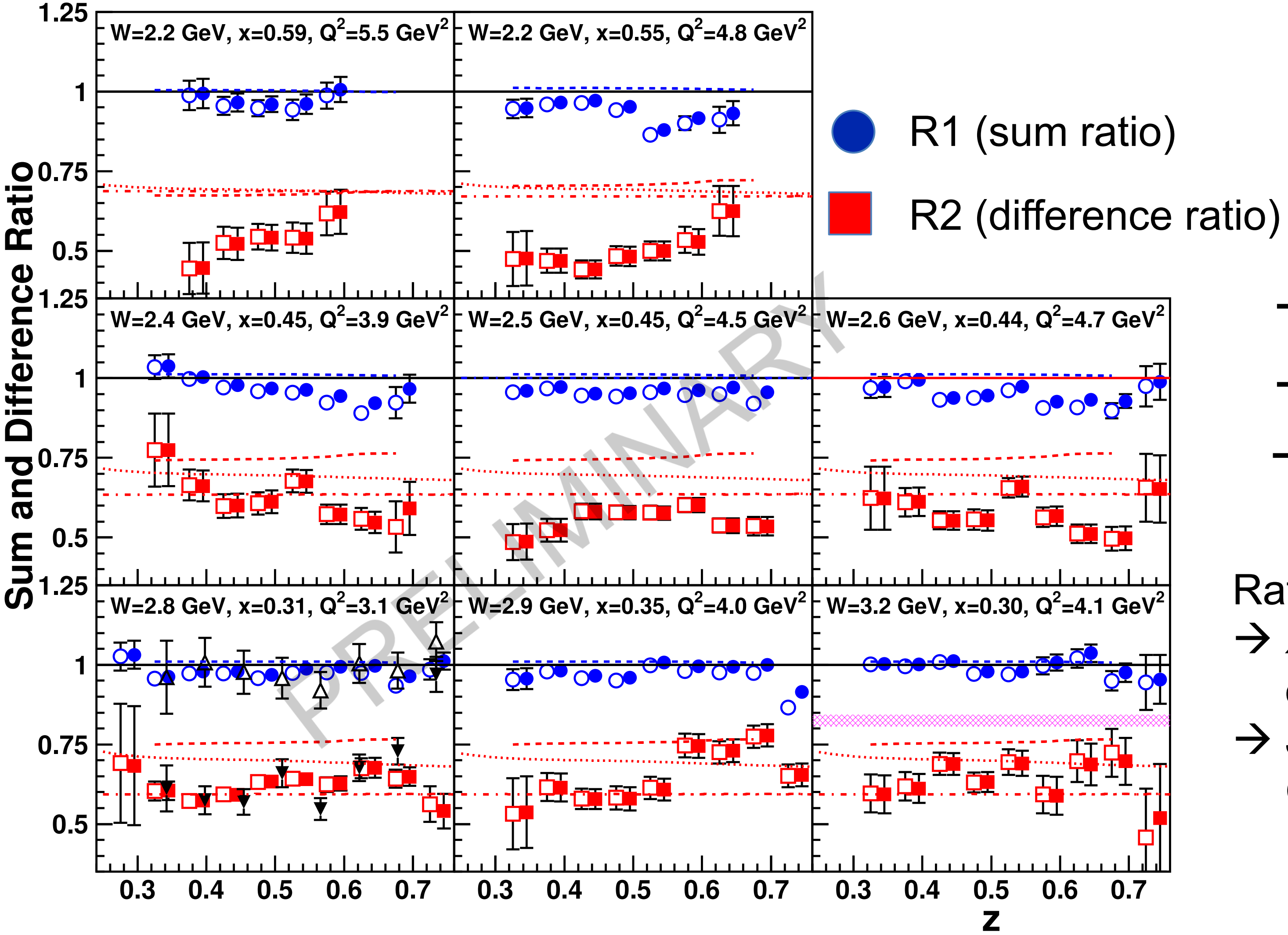
$$R_1(z) = \frac{M_d^{\pi^+}(z) + M_d^{\pi^-}(z)}{M_p^{\pi^+}(z) + M_p^{\pi^-}(z)} = 1$$

$$R_2(z) = \frac{M_d^{\pi^+}(z) - M_d^{\pi^-}(z)}{M_p^{\pi^+}(z) - M_p^{\pi^-}(z)} = \frac{3\,(4u(x) + d(x))}{5\,(4u(x) - d(x))}$$

Assumes no difference in P_T distribution for π^+ or π^-, and same for p and d targets

E12-09-017 and E12-09-002 combined analysis

Tests of Naïve Factorization



Closed symbols: no ρ subtraction
Open symbols: with ρ subtraction

——— ········· Models with isospin symmetry

- - - - - - - FF from MAPS

-·-·-·-·-· FF from DSS

Ratios agree with naïve expectation at larger *W*

→ *x* and *W* anti-correlated, which is right degree of freedom?

→ JLab 6 GeV results at *x*=0.31 at lower *W*=2.4 GeV agree well with larger W results

MAPS = A. Bacchetta et al, J.400 of High Eng. Phys. 10, 127 (2022), DSS= D. deFlorian, et al, PRD75, 114010 (2007), PRD 91, 014035395 (2015)

CSV/ISV in Fragmentation Functions

Relax assumption of charge/isospin symmetry:

$$D_u^{\pi^+} \neq D_d^{\pi^-}$$

Favored

$$D_u^{\pi^-} \neq D_d^{\pi^+}$$

Un-favored

Can use π^+/π^- multiplicities from p/d to determine 4 remaining fragmentation functions

$$M_p^{\pi^+}(x,Q^2,z) = \frac{D_{u\pi^+}(z)\left[4u(x)+\bar{d}(x)\right] + D_{d\pi^+}(z)\left[d(x)+4\bar{u}(x)\right]}{4u(x)+4\bar{u}(x)+d(x)+\bar{d}(x)}$$

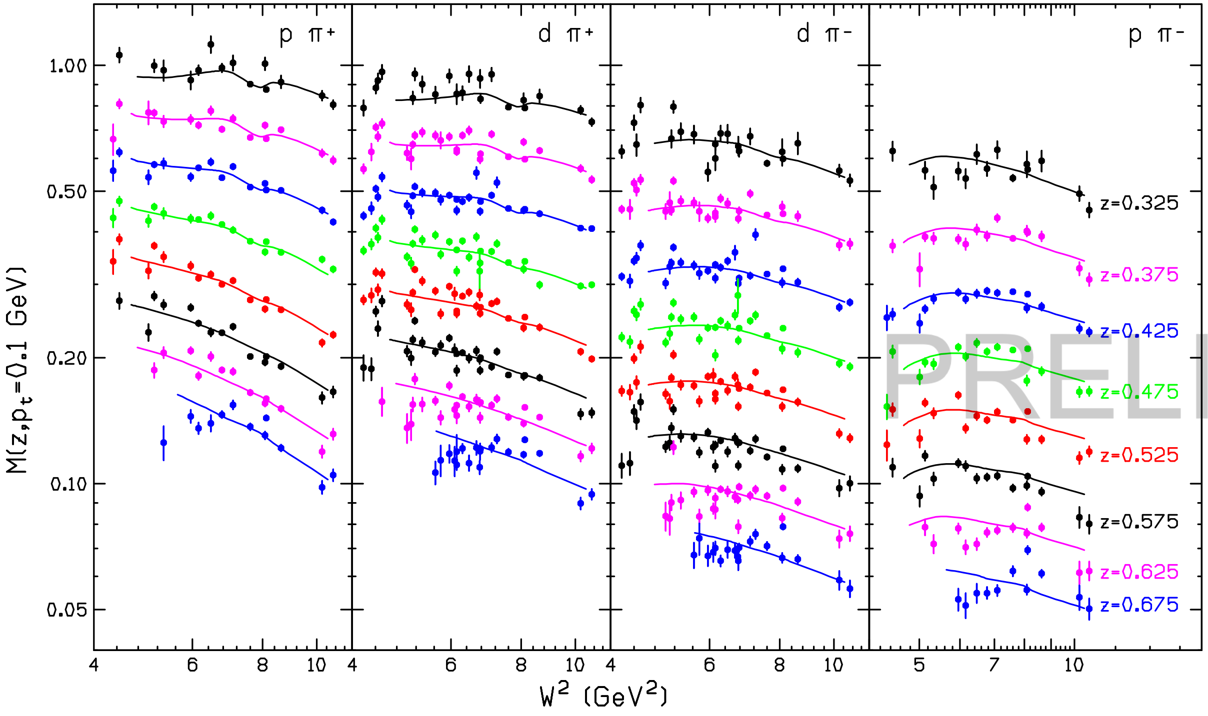
$$M_p^{\pi^-}(x,Q^2,z) = \frac{D_{d\pi^-}(z)\left[4\bar{u}(x)+d(x)\right] + D_{u\pi^-}(z)\left[\bar{d}(x)+4u(x)\right]}{4u(x)+4\bar{u}(x)+d(x)+\bar{d}(x)}$$

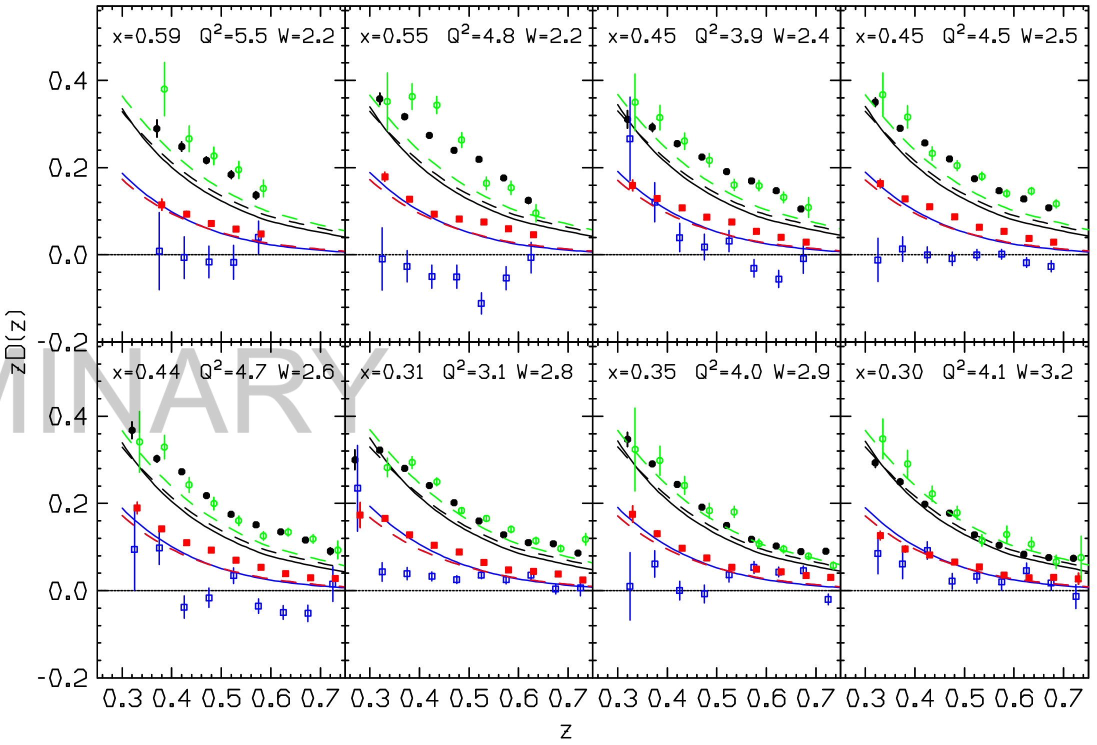
$$M_d^{\pi^+}(x,Q^2,z) = \frac{D_{u\pi^+}(z)[4u(x)+4d(x)+\bar{u}(x)+\bar{d}(x)]}{5[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)]} + \frac{D_{d\pi^+}(z)[u(x)+d(x)+4\bar{u}(x)+4\bar{d}(x)]}{5[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)]}$$

$$M_d^{\pi^-}(x,Q^2,z) = \frac{D_{d\pi^-}(z)[4\bar{u}(x)+4\bar{d}(x)+u(x)+d(x)]}{5[u(x)+d(x)+\bar{u}(x)+\bar{d}(x)]} + \frac{D_{u\pi^-}(z)[\bar{u}(x)+\bar{d}(x)+4u(x)+4d(x)]}{5[u(x)+d(x)+\bar{u}(x)+\bar{d}(x)]}$$

Multiplicities and FF

Multiplicities → Extracted (effective) fragmentation functions





● $D_u^{\pi^+}$ ○ $D_d^{\pi^-}$

■ $D_u^{\pi^-}$ □ $D_d^{\pi^+}$

—— JAM - - - DSS

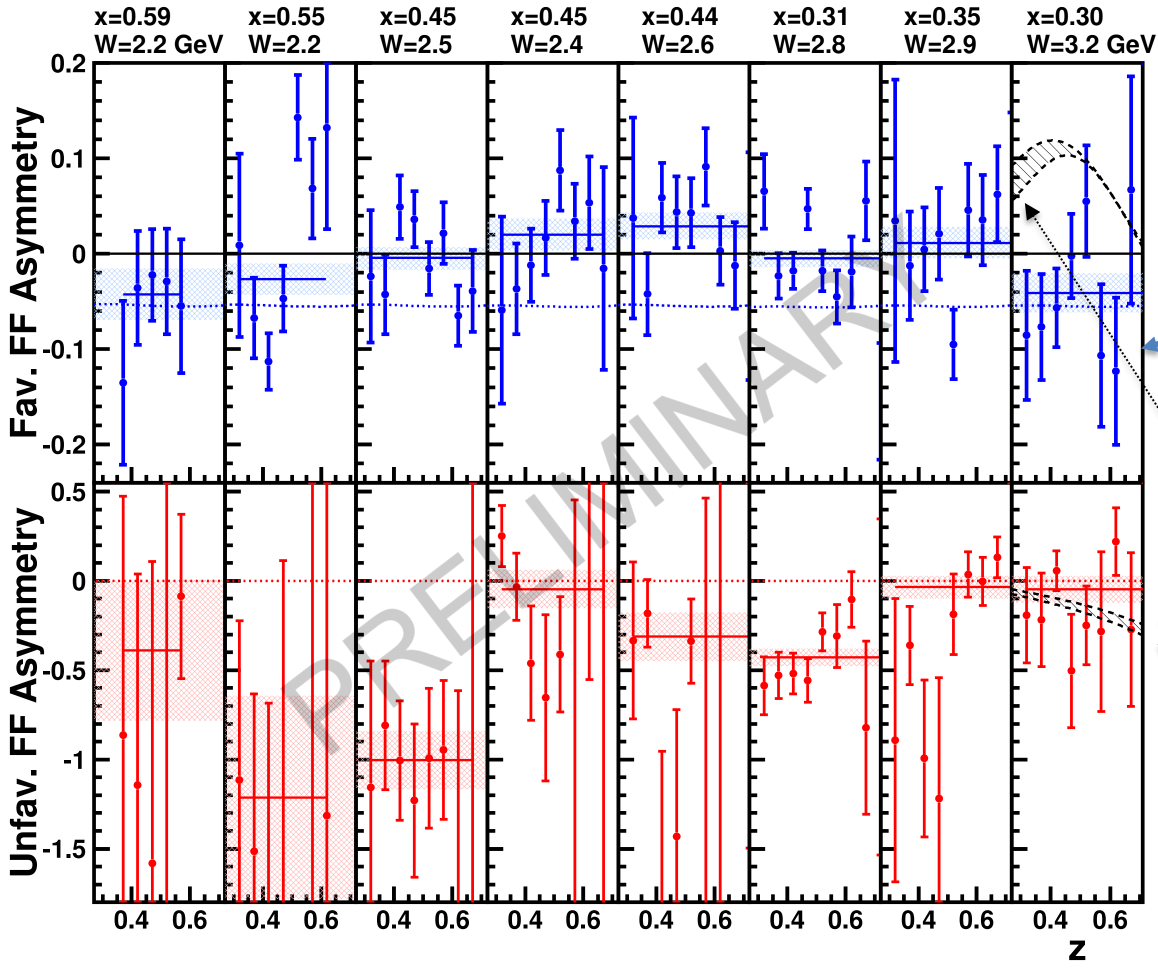
ϕ-averaged multiplicities evaluated at P_T=0.1 GeV

Empirical fit

JAM = Moffat et al PRD 104, 016015 (2021)

Favored and Unfavored FF Asymmetries

W=2.2→3.2 x=0.59←0.3



Explore CSV in FF via favored and unfavored FF asymmetries:

$$A_f(z) = \frac{D_u^{\pi^+} - D_d^{\pi^-}}{D_u^{\pi^+} + D_d^{\pi^-}}$$

$$A_{uf}(z) = \frac{D_d^{\pi^+} - D_u^{\pi^-}}{D_d^{\pi^+} + D_u^{\pi^-}}$$

…………………… DSS fits

Global fit from Peng and Ma

Results most consistent with CS/IS expectation at highest W (lowest x)

Hem Bhatt thesis, draft paper in circulation

ϕ and P_T dependence of Multiplicities

Previous analysis averaged over ϕ, bin-centered to single value of P_T

ϕ and P_T dependence of FF functions also of interest

→ *cos(ϕ)* dependence related to Cahn effect → twist-3

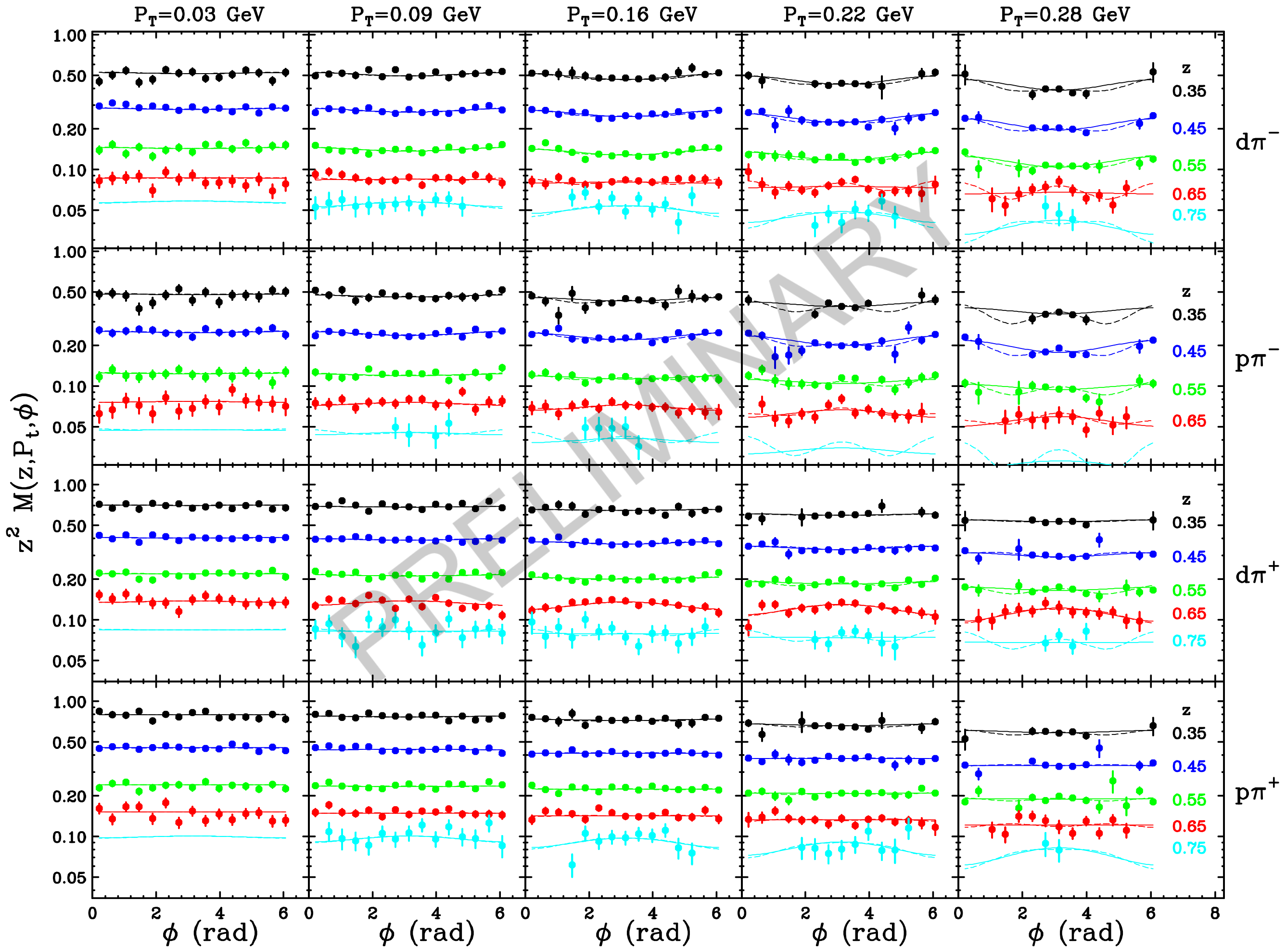
→ P_T dependence can be related to intrinsic quark k_T

$$\langle \vec{P}_{hT}^2 \rangle \simeq \langle \vec{p}_\perp^2 \rangle + z^2 \langle \vec{k}_T^2 \rangle$$

ϕ and P_T dependence can be extracted by fit to multiplicities of the form:

$$M(x, Q^2, z, P_{hT}, \phi) = \frac{dN}{dz} b e^{-bP_{hT}^2} \left(\frac{1 + A\cos\phi + B\cos 2\phi}{2\pi} \right)$$

Assumes Gaussian P_T dependence



x=0.3, Q^2=3 GeV^2

Figure courtesy Peter Bosted

ϕ and P_T dependence of Multiplicities

$$M(x, Q^2, z, P_{hT}, \phi) = \frac{dN}{dz} b e^{-bP_{hT}^2} \left(\frac{1 + A\cos\phi + B\cos 2\phi}{2\pi} \right)$$

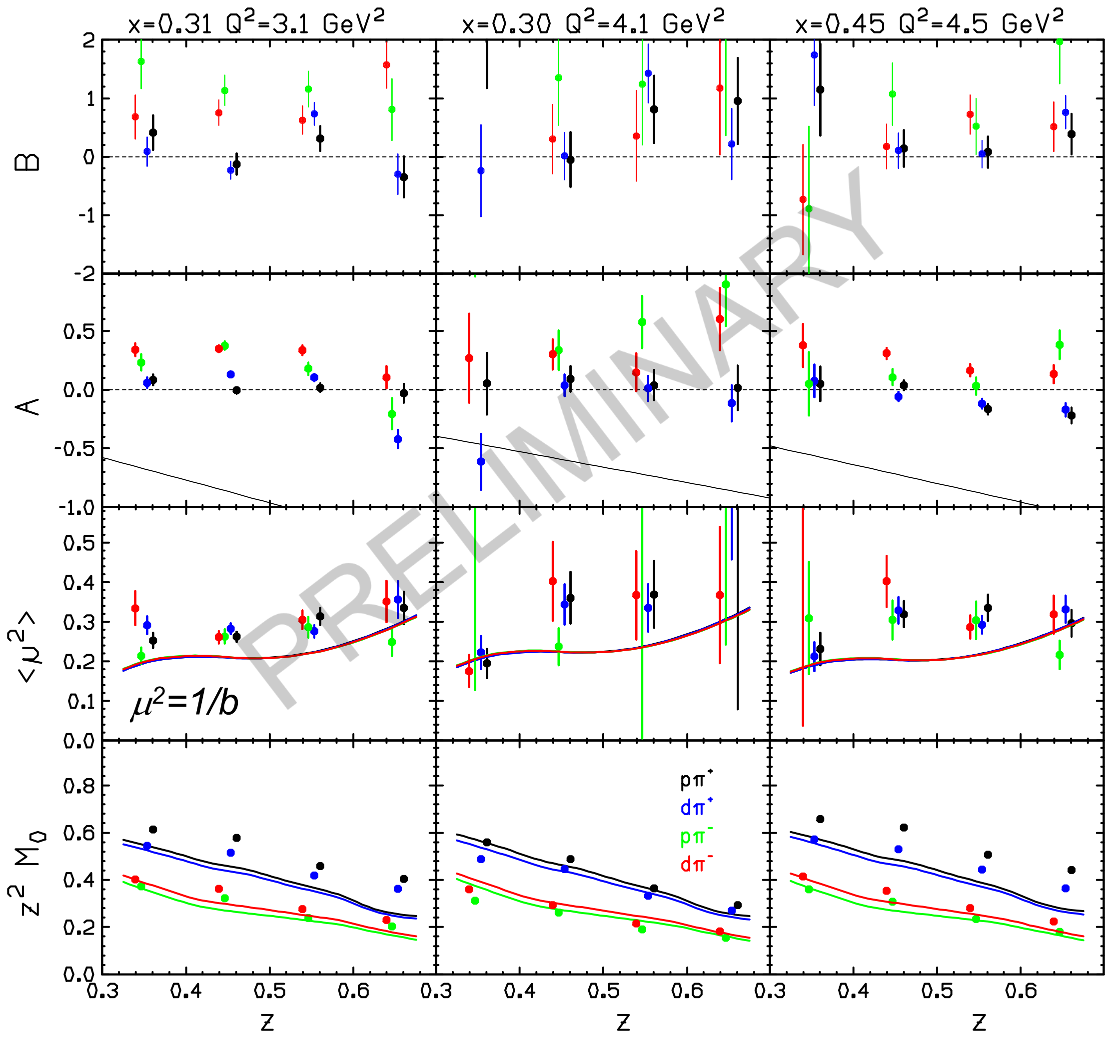
Results of 4-parameter for P_T<0.25 GeV

Solid curves for z^2M_0 and μ^2 from MAPS global fit
→ Curve for *A* parameter from Cahn prediction, assuming $<k_T>$=0.3 GeV

P_T dependence very similar for all 4 cases
→ Relevant for CSV/ISV tests in previous results

cos(ϕ) dependence very different from Cahn effect expectation
→ This term involves L-T interference – perhaps suggest larger than expected longitudinal contribution?

cos(2ϕ) term appears non-zero and positive for p/d π^-



Larger *x* and Q^2 provides improved constraints for global fits

Figure courtesy Peter Bosted

Extended P_T Dependence

HMS+SHMS does not have complete ϕ coverage at large P_T

→ Can look at P_T dependence for a “slice” in ϕ

— Z=0.35
— Z=0.45
— Z=0.55
— Z=0.65

4 parameter fit for P_T<0.25 GeV

– –
– –
– –
– –

3 parameter fit for all P_T

– · –
– · –
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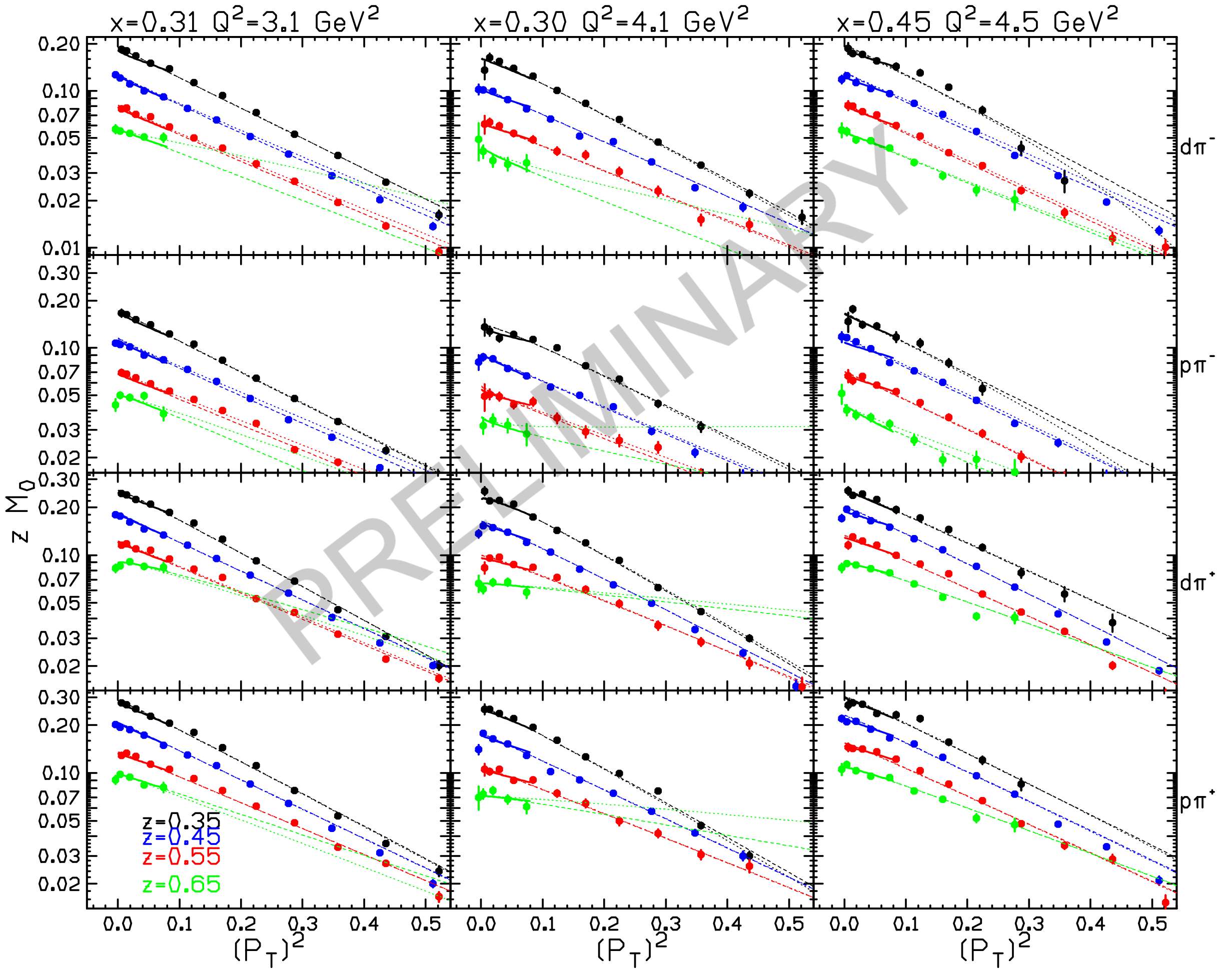
4 parameter fit for all P_T

155 < ϕ <205 degrees



Paper draft in progress

Figure courtesy Peter Bosted

Charge Symmetry Violation in Quark PDFs

Ratio of π^+/π^- cross sections from isoscalar target sensitive to CSV quark distributions

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

$B(x,z)$ from PDFs

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

$\Delta(z)=D^-(z)/D^+(z)$

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

$\delta d=d^p-u^n$ and $\delta u=u^p-d^n$

$$R(x,z) = \frac{4R_Y(x,z)-1}{1-R_Y(x,z)}$$

where

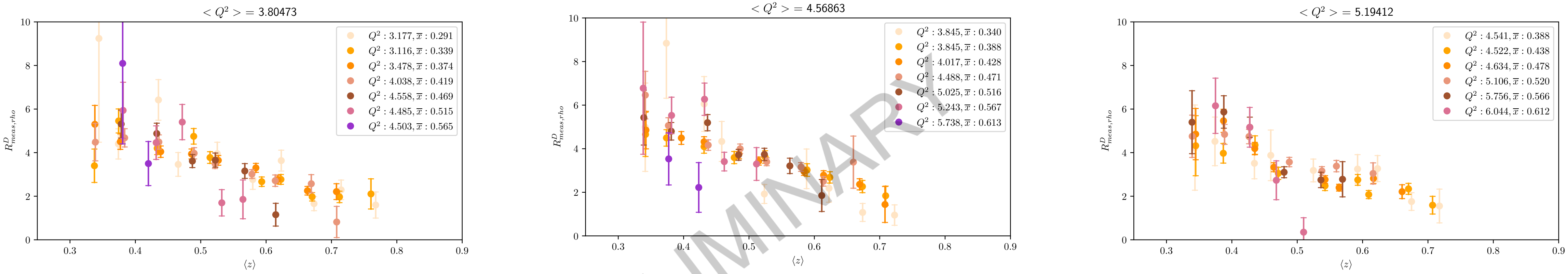
$$R_Y = \frac{Y_D^{\pi^-}}{Y_D^{\pi^+}}$$

Assumes factorization in SIDIS process, no (or small) ISV/CSV in fragmentation

E12-09-002 measured SIDIS charged pion ratios from deuterium for Q^2=4, 4.5, 5 GeV^2
→ Range of x at each Q^2, range of z for each (x, Q^2)

Charge Symmetry Violation in Quark PDFs

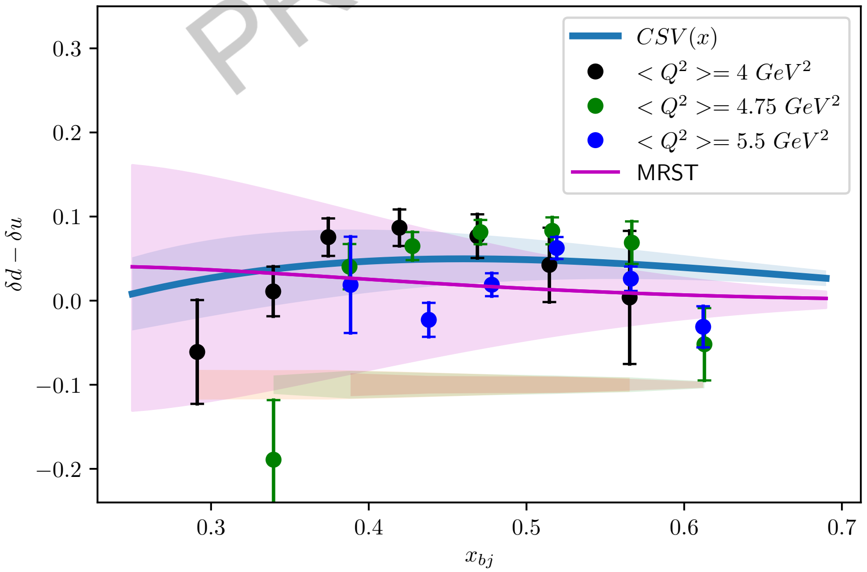
R^d_{meas} vs. *z*



Q^2=4 GeV^2 Q^2=4.5 GeV^2 Q^2=5 GeV^2

Δ(*z*) from fit to Hall C data

→ Impact from global FF fits was also explored



Quark CSV results from E12-09-002

CSV term extracted from fit of the form:

$$\delta d - \delta u = x^a(1-x)^b(x-c)$$

Shuo Jia thesis, paper draft in progress

Hall C (near) Future: Measurement of R_{SIDIS}

E12-06-104: Measurement of the Ratio $R=\sigma_L/\sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering

Almost no existing data on $R=\sigma_L/\sigma_T$ in SIDIS (p and n)
→ Limited data from Cornell
[Bebek et al, PRL 34, 759 (1975), PRL 37, 1525 (1976), PRD 15, 3085 (1977)]

E12-06-104 is will make precise measurements of R_{SIDIS} in

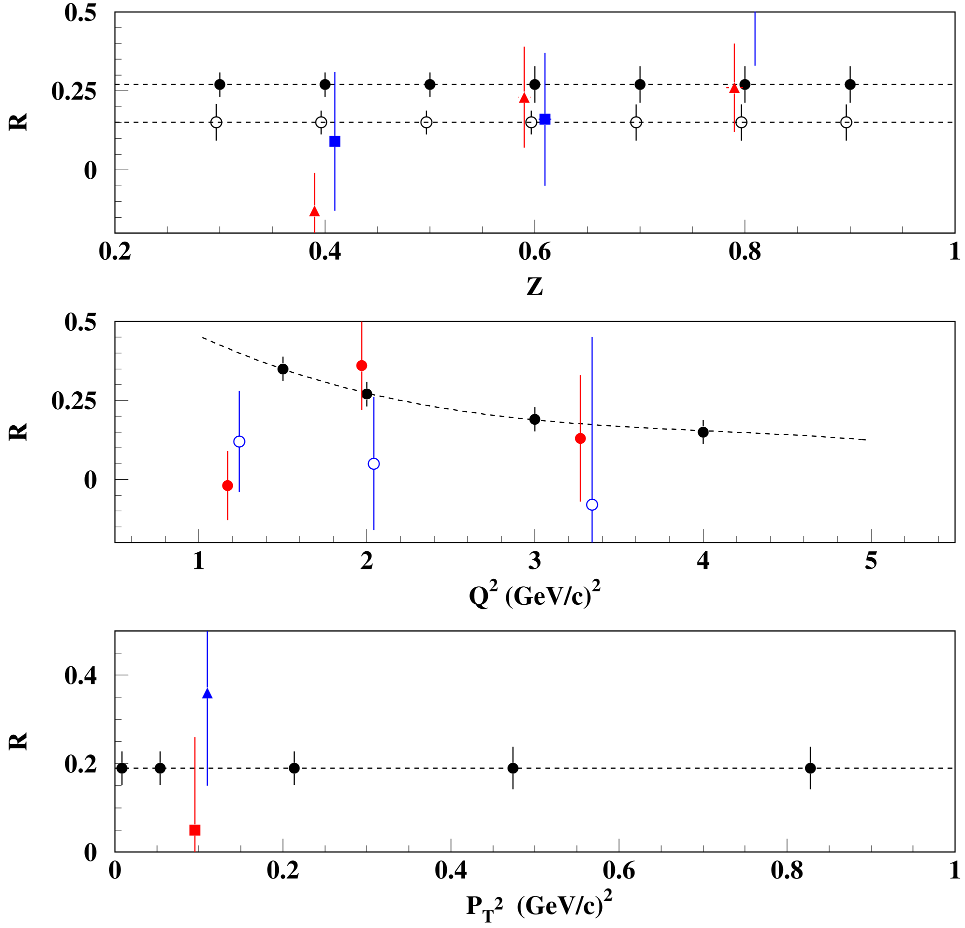
$e+p \rightarrow e'+\pi^{+/-}+X$, $e+D \rightarrow e'+\pi^{+/-}+X$

L-T separation requires excellent understanding of acceptance, control of point-to-point systematic errors

→ Ideally suited to Hall C equipment at 12 GeV

1. Scans in z at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV^2 ($x = 0.4$) → behavior of σ_L/σ_T for large z.
2. Cover $Q^2 = 1.5 – 5.0$ GeV^2, → both H and D at $Q^2 = 2$ GeV^2
3. p_T up to ~ 1 GeV.

R = σ_L/σ_T in SIDIS (ep → e'$\pi^{+/-}$X)



Expected to run in 2025

Nuclear Dependence of R in SIDIS

Goal: Directly measure the nuclear dependence of $R = \sigma_L / \sigma_T$ in semi-inclusive DIS

→ No existing measurements of nuclear dependence of R in SIDIS

→ Potential impact on SIDIS results (dilution factor for polarized targets)

→ Potential impact on measurements of hadron-attenuation

→ **Exploratory** measurement to determine if more comprehensive program merited

Experiment: Measure cross sections and ratios for H, D, C, Cu targets at 3 beam energies

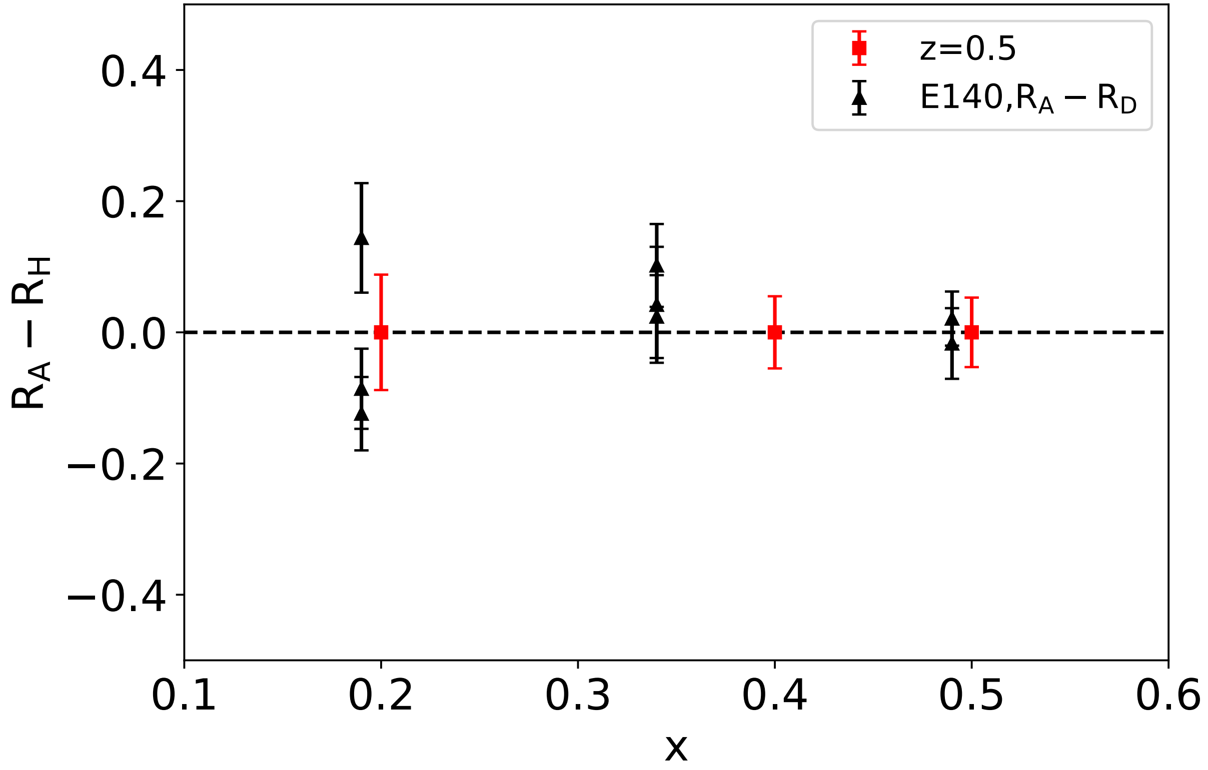
→ Allows LT separation

→ **E12-06-104** (R in SIDIS on H and D) in Hall C experiment scheduled for CY2025.

→ E12-24-001 with E12-06-104 at select kinematics adding nuclear targets (^{12}C and ^{64}Cu).

▲ SLAC E140: Nuclear Dependence of R in DIS

🟥 PR12-24-001: Nuclear Dependence of R in SIDIS (projected precision)



Will measure R_A-R_H for

→ 2-3 values of *x* (*x*=0.2 to 0.5)

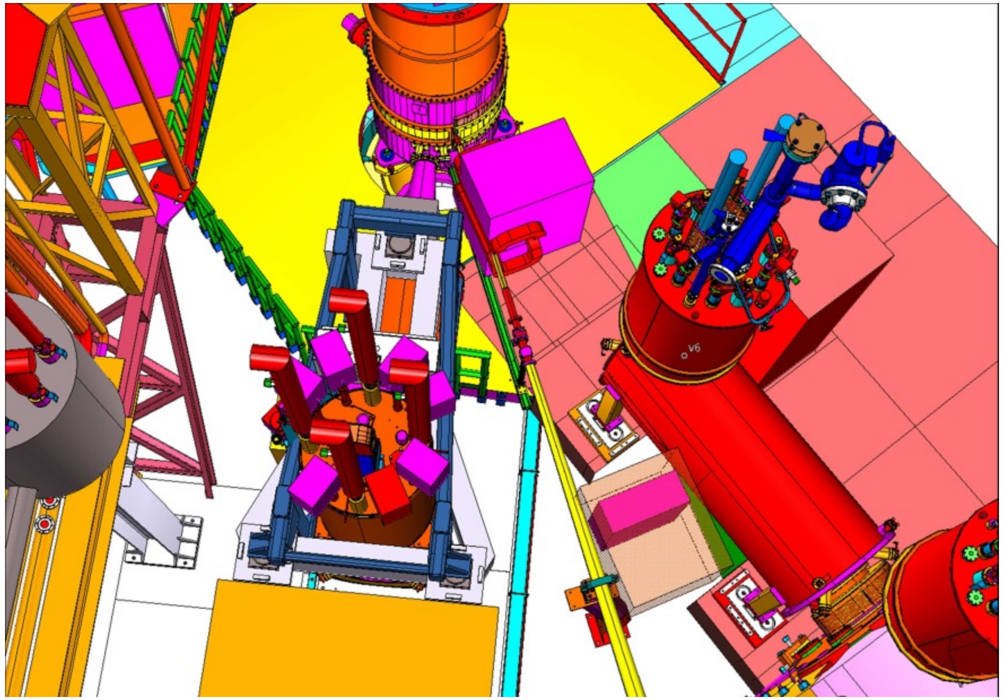
→ Range of *z* for *x*=0.2

→ Range of P_T at one value of *x*

π^0 SIDIS with Neutral Particle Spectrometer (NPS)

π^0 avoids complications from vector meson decay, smaller radiative tails from exclusive pion production

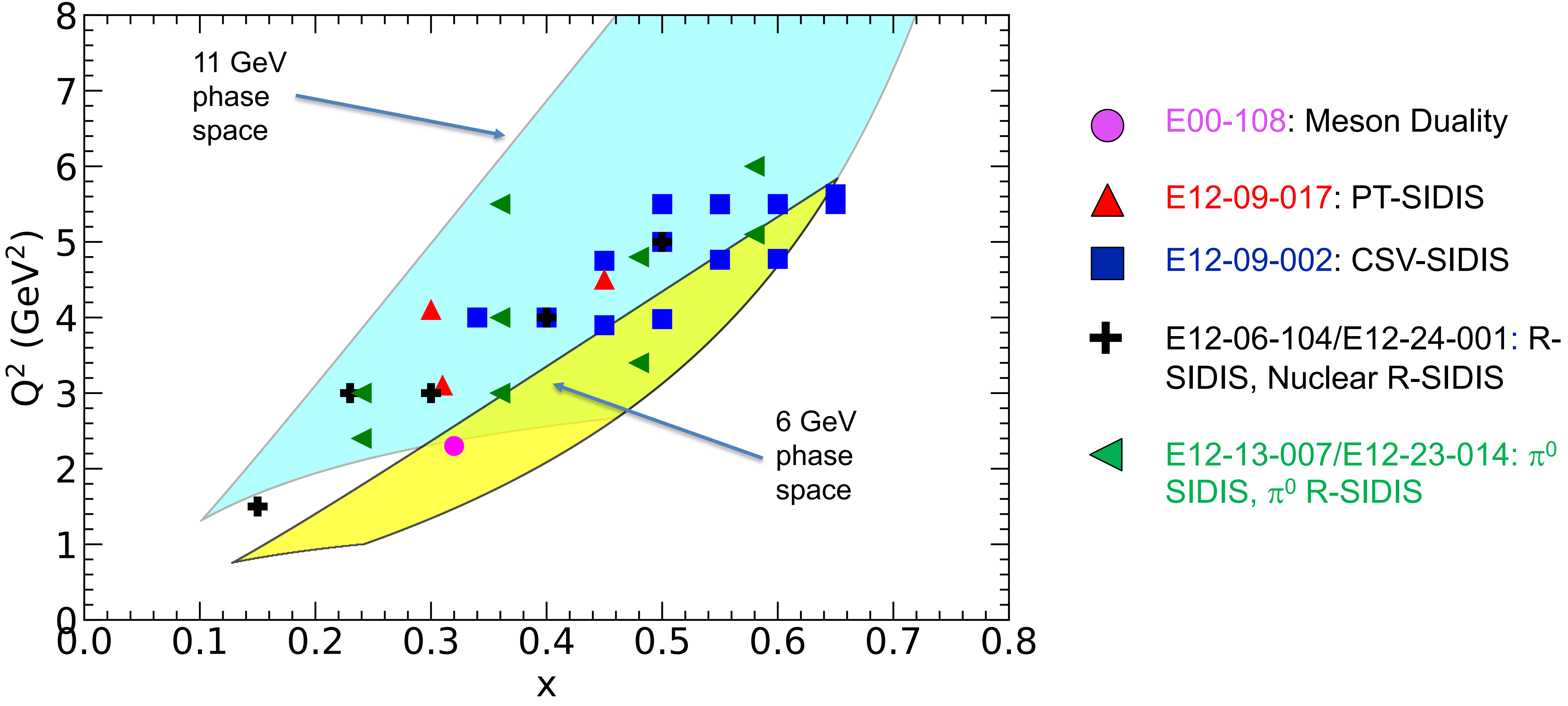
Calorimeter + sweeper magnet adds capability to detect neutral particles: γ and π^0



→ NPS provides complete ϕ coverage for larger region of P_T

First NPS run just completed → large amount of SIDIS π^0 (and exclusive π^0 and DVCS) data to analyze

Hall C SIDIS Experiments - Updated



● E00-108: Meson Duality

▲ E12-09-017: PT-SIDIS

■ E12-09-002: CSV-SIDIS

✚ E12-06-104/E12-24-001: R-SIDIS, Nuclear R-SIDIS

◀ E12-13-007/E12-23-014: π^0 SIDIS, π^0 R-SIDIS

Summary

- Hall C plays an important (complementary) role in JLab SIDIS program
  - Strengths include precision cross sections, ratios (target and charge), LT separations
- Analysis from E12-09-017 (PT-SIDIS) and E12-09-002 (CSV-SIDIS) nearing completion
  - First draft paper from combination of both experiments circulating
  - 2 more drafts in progress
- R-SIDIS experiment planned to run in calendar 2025
  - Measurements with nuclear targets will be included
- NPS has added capability for π^0 SIDIS measurements

EXTRA

12 GeV Hall C SIDIS Program – HMS+SHMS+NPS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

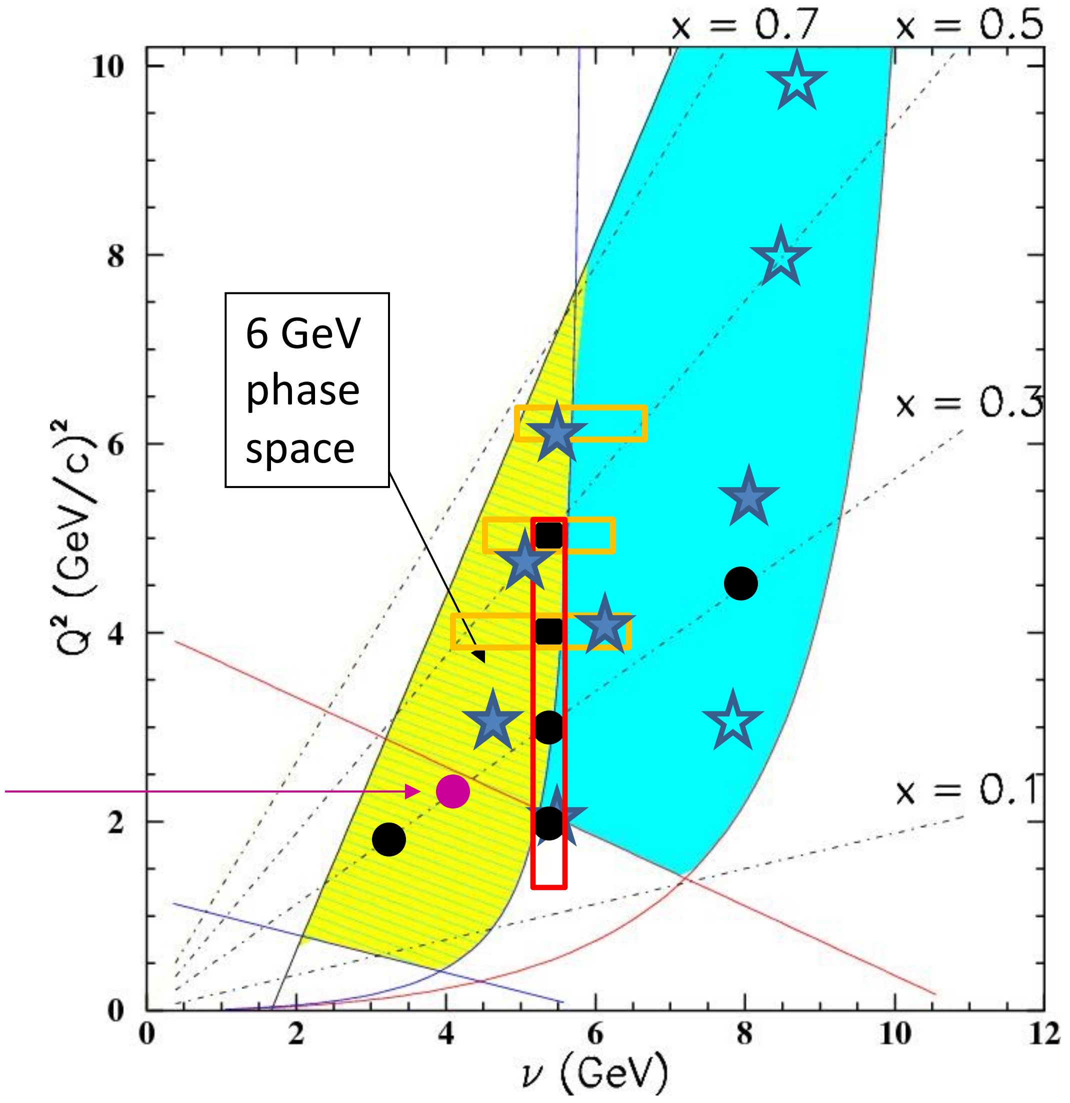
★ E12-13-007

Neutral pions:

Scan in (x,z,P_T)

Overlap with E12-09-017 & E12-09-002

☆ Parasitic with E12-13-010



6 GeV phase space

E00-108 (6 GeV)

Charged pions:

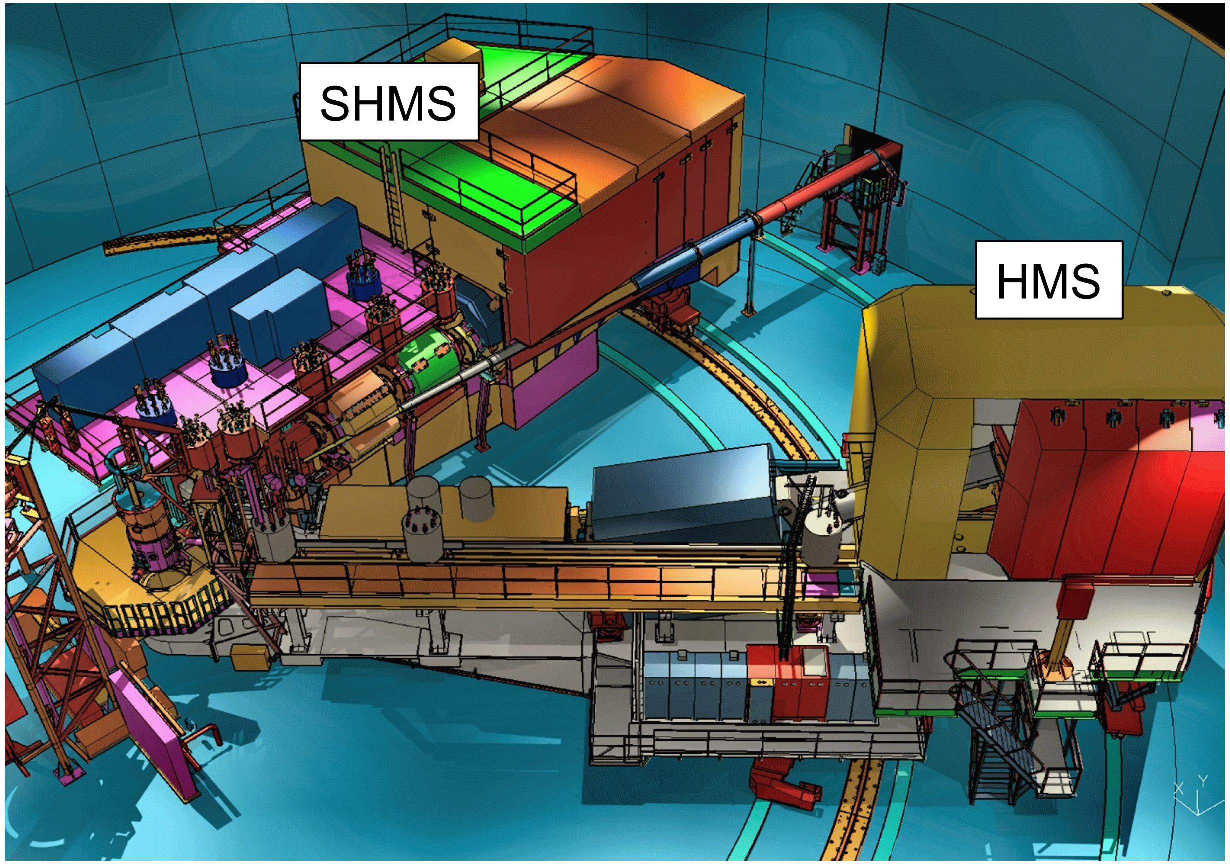
🟥 E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

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

🟨 E12-09-002
+ scans in z

Courtesy R. Ent

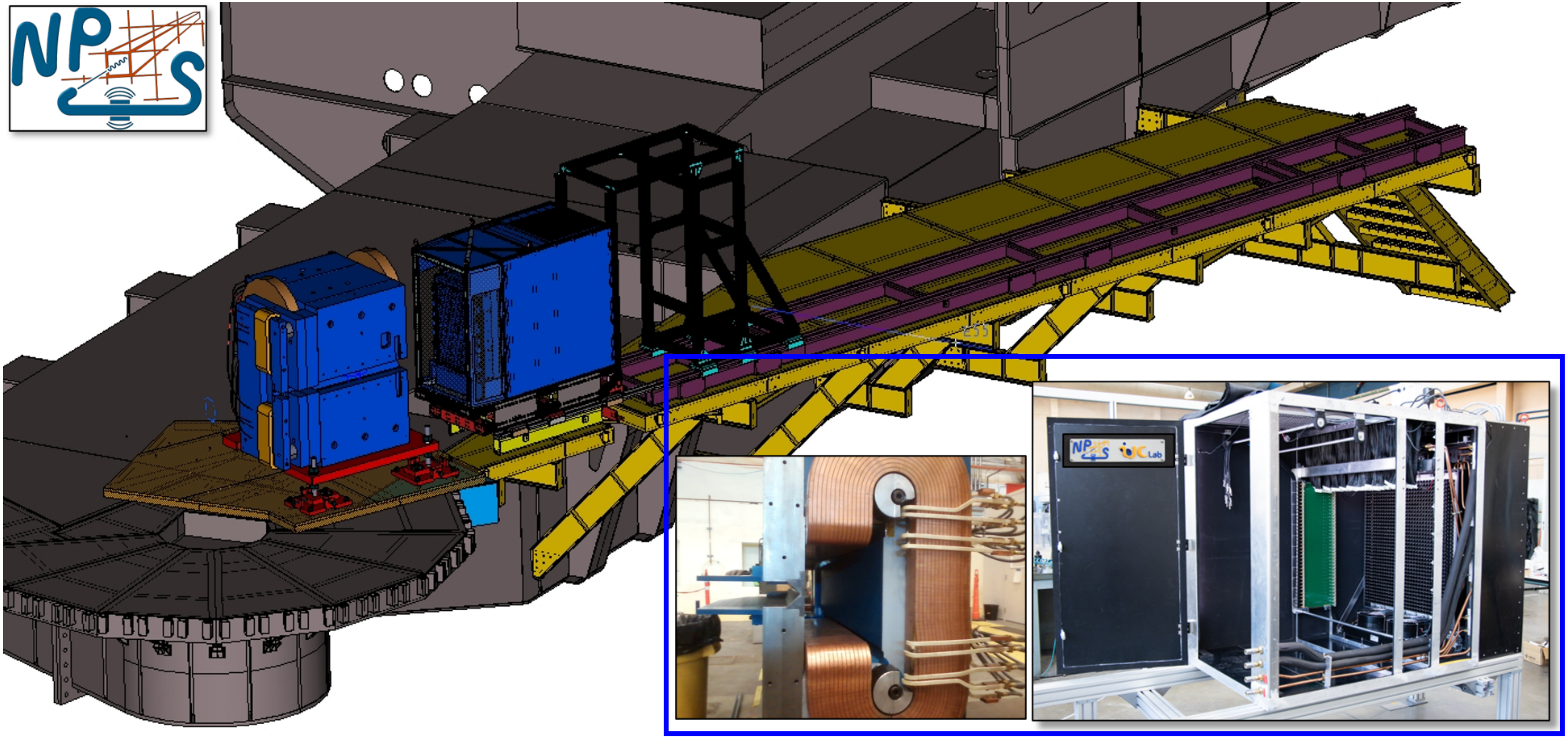
SHMS and HMS in Experimental Hall C



Spectrometer properties

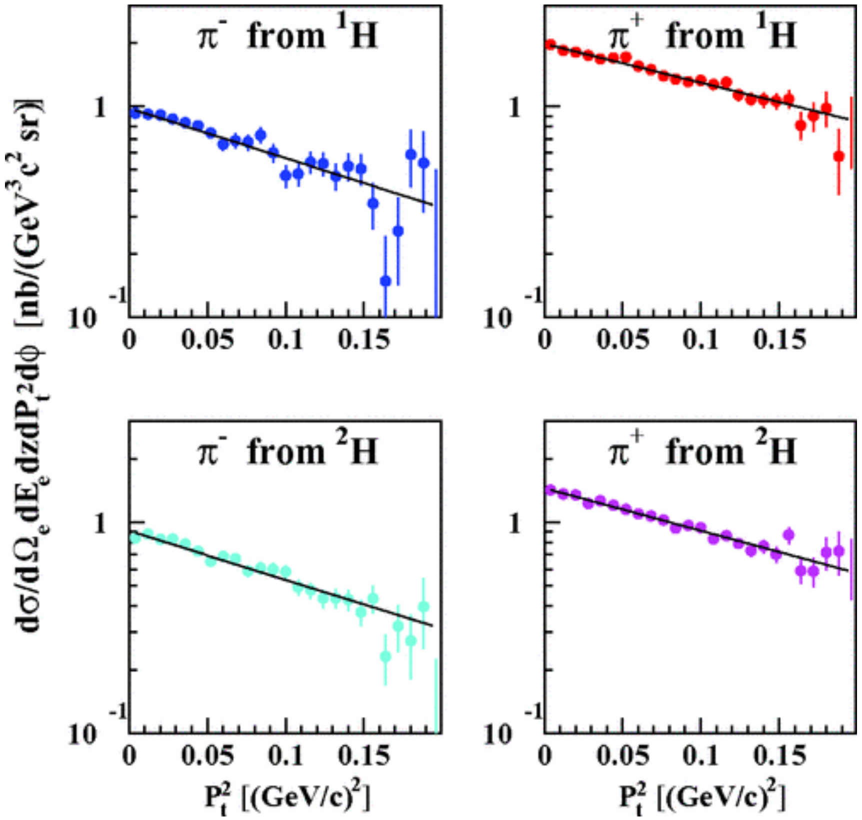
HMS: Electron arm
Nominal capabilities:
dΩ ~ *6* msr, P_0= *0.5 – 7 GeV/c*
θ_0=*10.5 to 80 degrees*
e ID via calorimeter and gas Cherenkov

SHMS: Pion arm
Nominal capabilities:
dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*
θ_0=*5.5 to 40 degrees*
***π:K:p* separation via heavy gas Cherenkov and aerogel detectors**

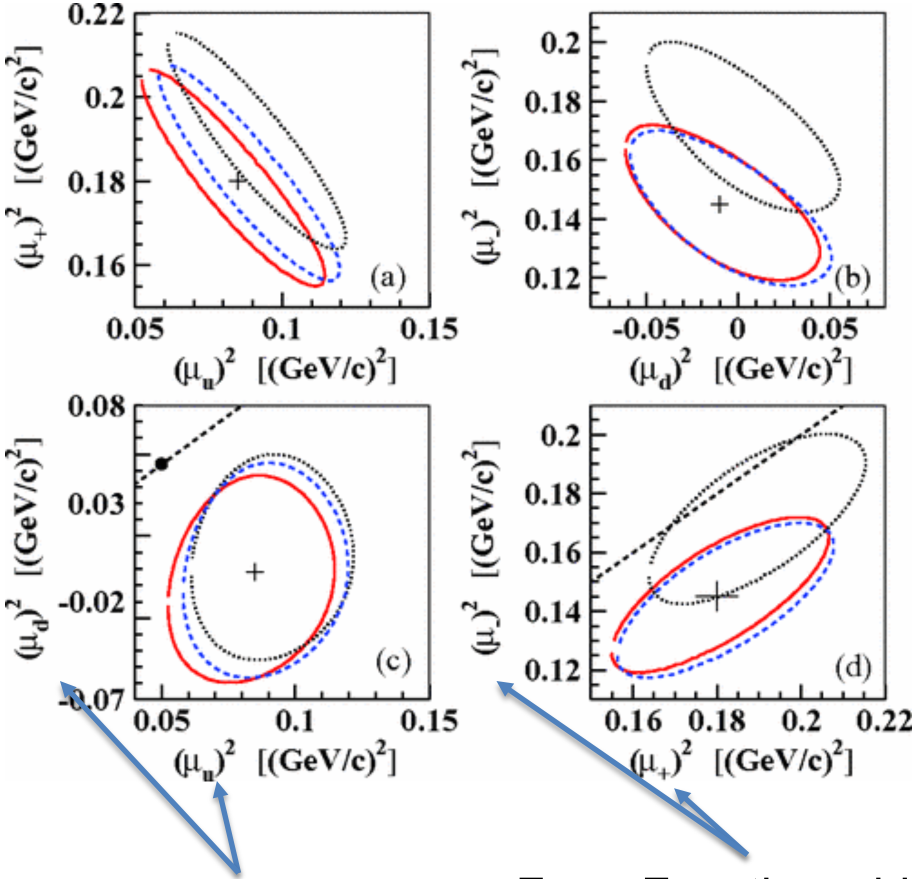


Hall C SIDIS Results from 6 GeV

Used P_T dependence of unpolarized cross sections to place constraints on up/down quark, favored/unfavored FF widths



R. Asaturyan et al. Phys. Rev. C 85, 015202



quark avg. k_T

Frag. Function widths

Transverse Momentum Dependence of SIDIS

Unpolarized k_T-dependent SIDIS: in framework of Anselmino et al *[hep-ph/0608048]*, described in terms of convolution of quark distributions *f* and (one or more) fragmentation functions *D*, each with own characteristic (Gaussian) width

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

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0 describes transverse momentum of quarks

μ_D describes p_T dependence of Frag. Func.

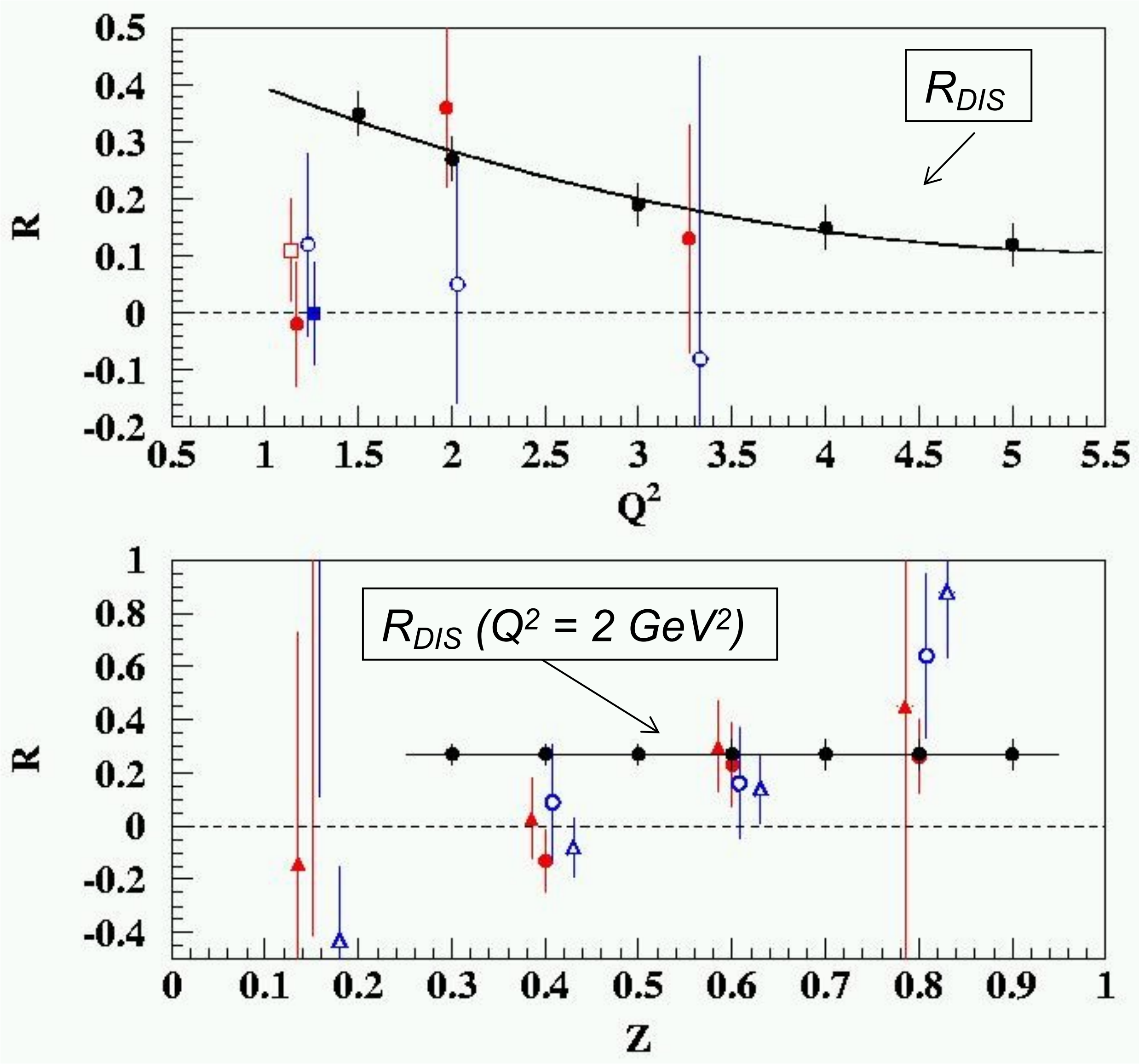
(assuming $\mu_{0,u} = \mu_{0,d}$)

$$\left[1+(1-y)^2-4(2-y)\sqrt{1-y}\,\frac{z\mu_0^2|\mathbf{P}_{hT}|}{Q(\mu_D^2+\mu_0^2z^2)}\cos\varphi_h\right]\frac{\exp\left(-\frac{\mathbf{P}_{hT}^2}{\mu_D^2+\mu_0^2z^2}\right)}{\mu_D^2+\mu_0^2z^2}\sum_q e_q^2\, f_1^q(x)\, D_q^h(z)$$

Possibility to constrain k_T dependence of up and down quarks *separately* by combination of π^+ and π^- final states, proton and deuteron targets

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

Cornell data of 70's



Conclusion: "data both consistent with $R = 0$ and $R =$" R_{DIS}"

Some hint of large R at **large z** in Cornell data?