Overview of SIDIS Experiments in Halls C

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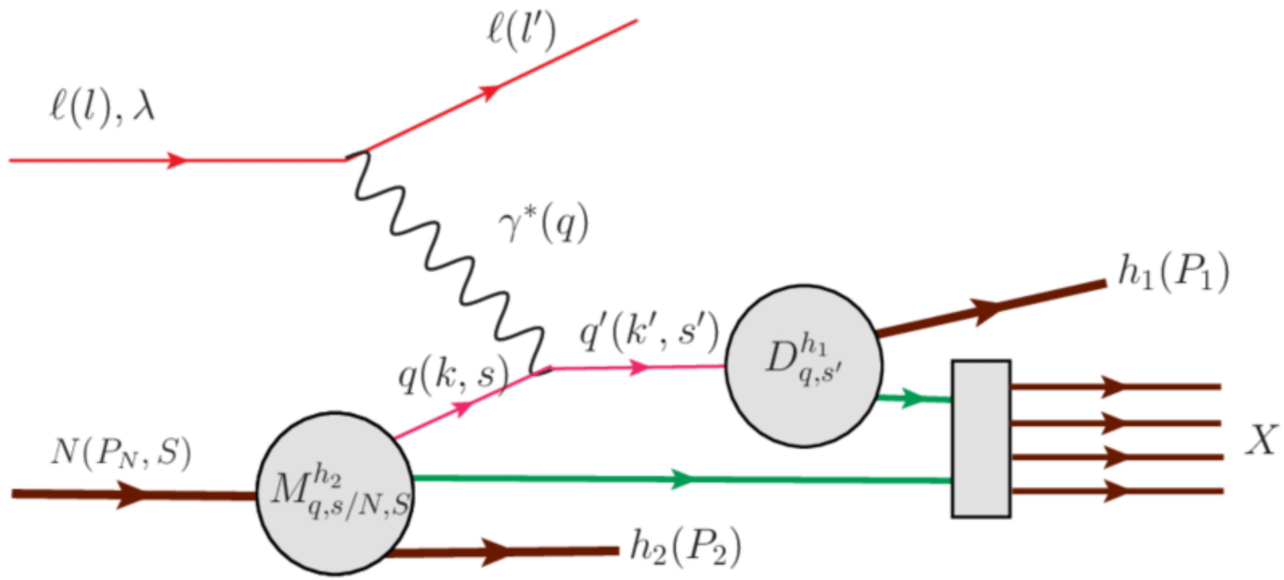


- Semi-Inclusive Deep Inelastic Scattering (SIDIS)
- Past, Present and Future of Hall C SIDIS
- Opinions

Preliminaries

Thanks to the many people for sharing their slides from previous talks.

My apologies in advance for any mis-statements or misrepresentations I may make; they are my mistakes, not yours!

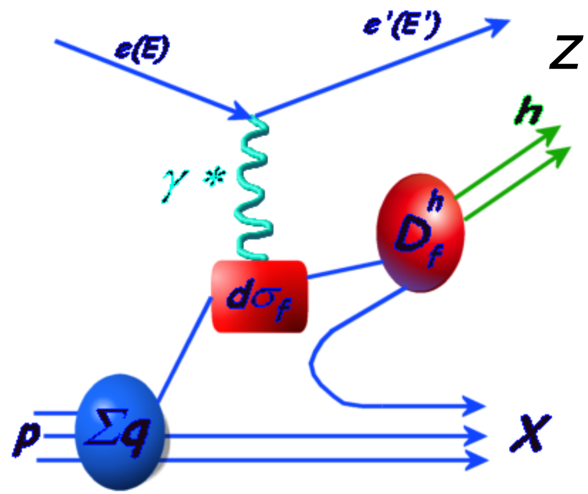
Do parton distributions and fragmentation functions factorize at Jefferson Lab energies?

Flavor Decomposition of SIDIS

$$\frac{1}{\sigma_{(e,e')}}\frac{d\sigma}{dz}(ep \rightarrow hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$

$f_q(x)$: parton distribution function

$D_q^h(z)$: fragmentation function



$z = E_h/\nu$

$M_x^2 = W'^2 \sim M^2 + Q^2 (1/x - 1)(1 - z)$

- Leading-Order (LO) QCD
- after integration over $p_{h\perp}$ and Φ_h
- NLO: gluon radiation mixes x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

With p_T and k_T dependences, some kind of convolution is necessary to obtain final $P_{h\perp}$

SIDIS in Hall C

Past

E00-108: 6 GeV beam with HMS and SOS spectrometers $\pi^{+/-}$ (H,D)

Present

E12-09-002 (CSV): 12 GeV with HMS and SHMS $\pi^{+/-}$ (D)

E12-09-017 (pT-SIDIS) $\pi^{+/-}$, $K^{+/-}$ (H,D)

E12-13-007 (π^0-SIDIS) HMS and NPS + PR12-23-014 (R) (H,D)

Future!

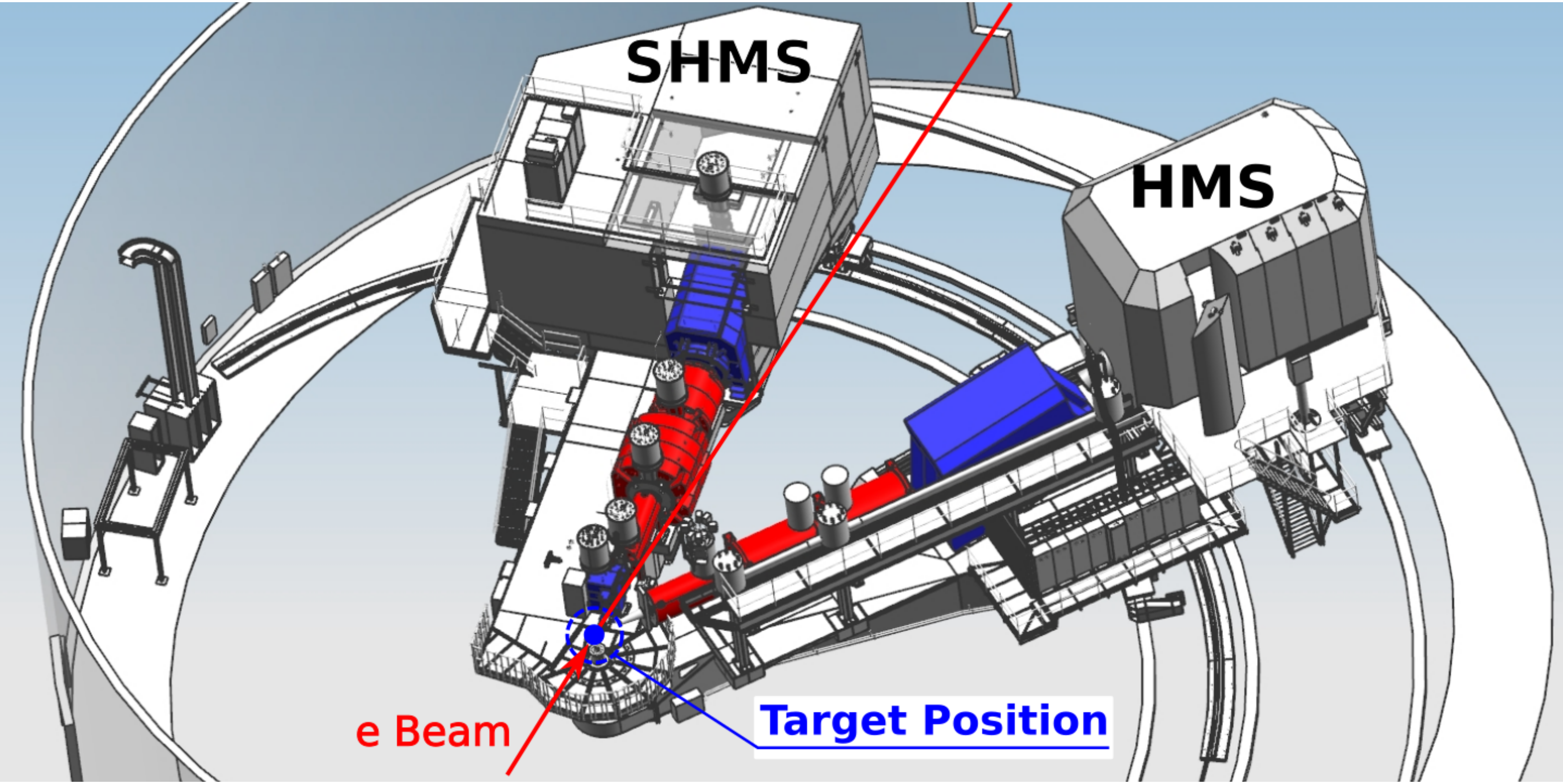
E12-06-104 (R-SIDIS) $\pi^{+/-}$ (H,D)

C12-15-006 Tagged DIS!

Experimental Setup: Hall C Spectrometers at Jefferson Lab

- CW Electron Beam, energies up to 11 GeV
- Two magnetic focusing spectrometers on common pivot: HMS and SHMS
- High cooling power 10 cm liquid Hydrogen and Deuterium targets plus Al window dummy for background subtraction
- W^2 = 5.08 GeV^2 and larger (up to 11.38 GeV^2)
- SHMS angle down to 6.6° (for π detection)
- HMS angle down to 13.5° (e^-detection) (separation HMS-SHMS > 17.5°)
- $M_X^2 = M_p^2 + Q^2(1/x - 1)(1 - z) > 2.9$ GeV^2 (up to 7.8 GeV^2)

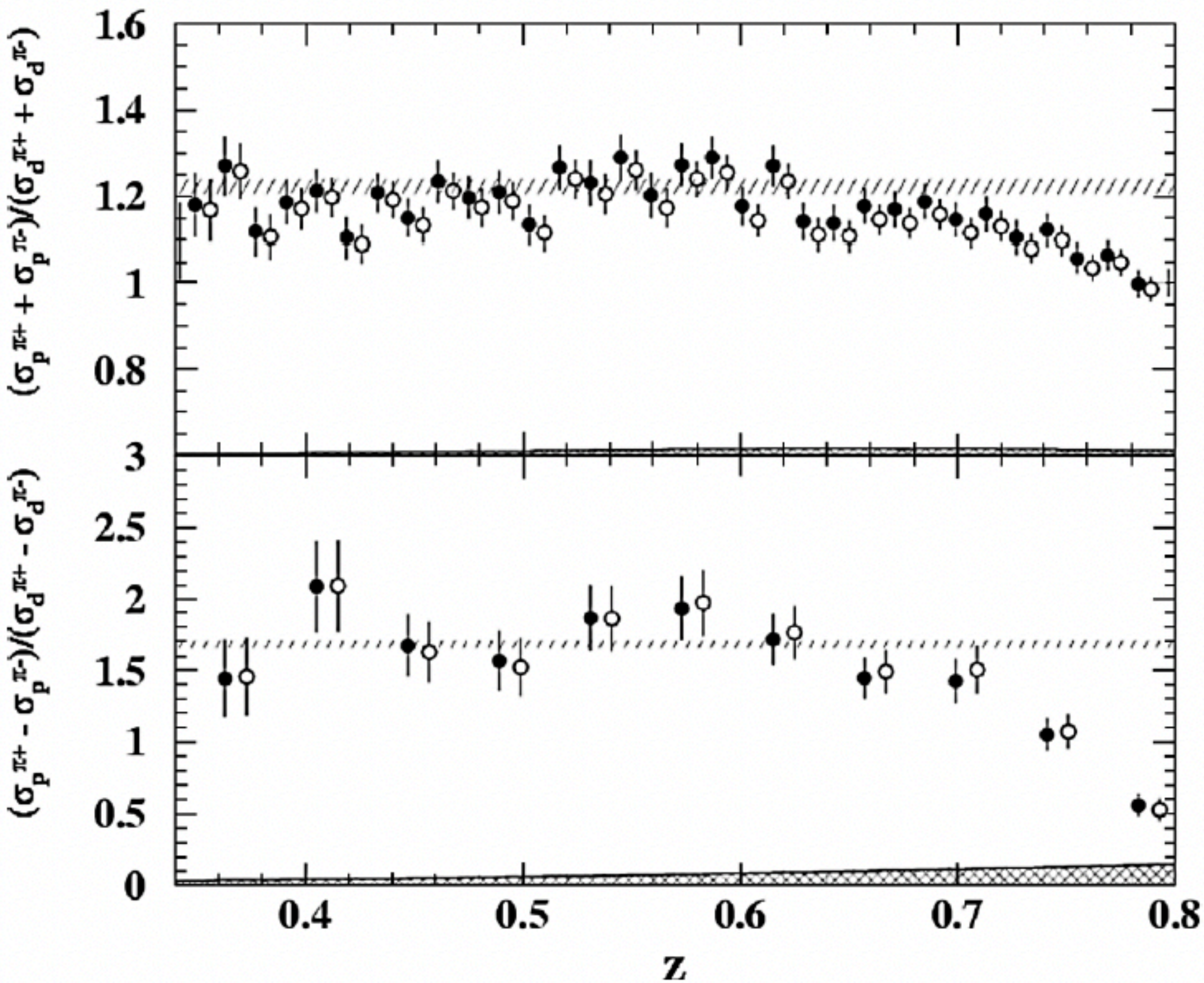
Hall C Spectrometers



Past

Factorization Test: E00-108

$$\frac{\sigma_p(\pi^+)+\sigma_p(\pi^-)}{\sigma_d(\pi^+)+\sigma_d(\pi^-)}=\frac{4u(x)+4\bar{u}(x)+d(x)+\bar{d}(x)}{5[u(x)+d(x)+\bar{u}(x)+\bar{d}(x)]},\qquad \frac{\sigma_p(\pi^+)-\sigma_p(\pi^-)}{\sigma_d(\pi^+)-\sigma_d(\pi^-)}=\frac{4u_v(x)-d_v(x)}{3(u_v(x)+d_v(x))},$$



x = 0.32

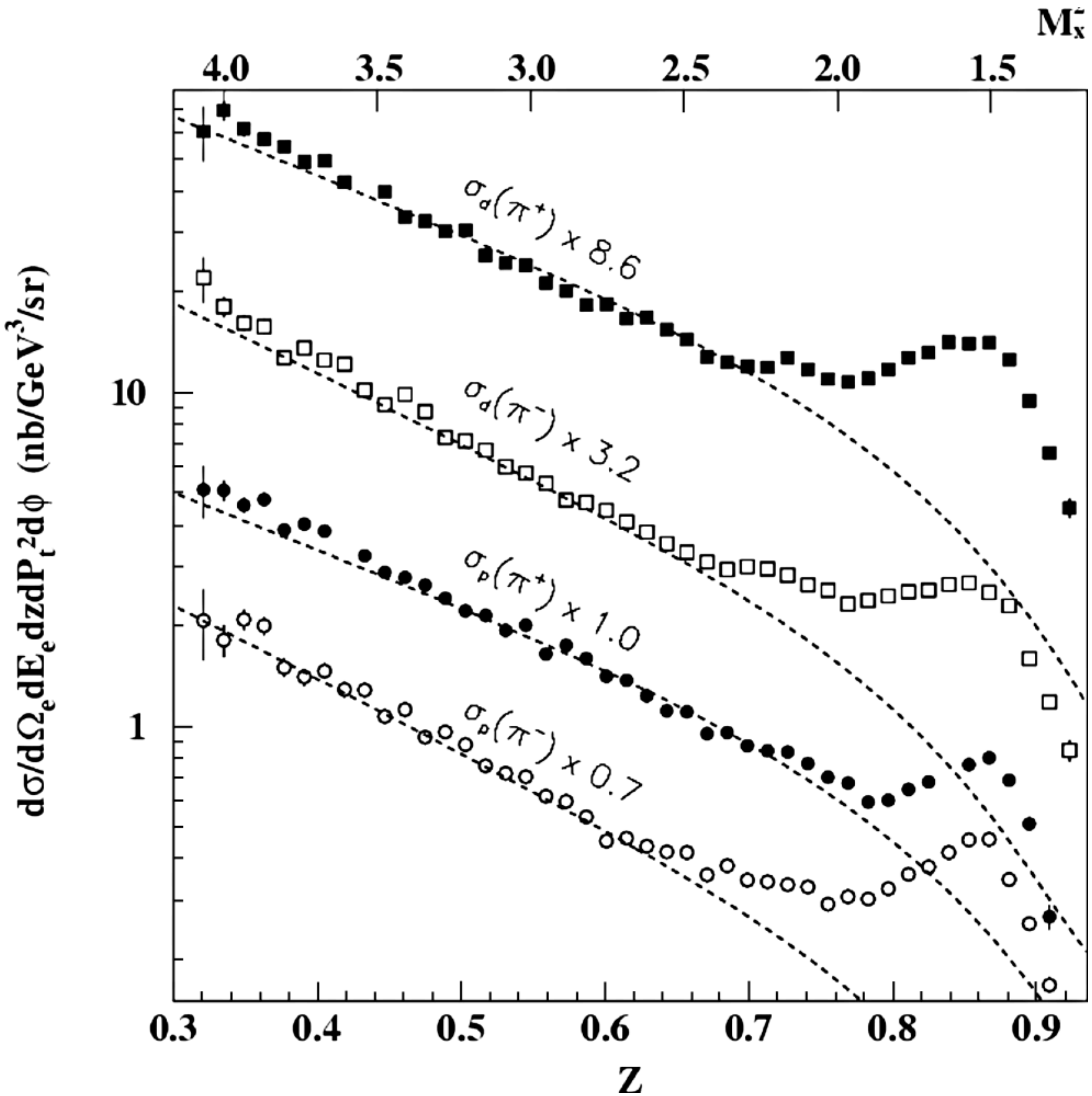
JLab E00-108 Results

T. Navasardyan et al., PRL 98 022001 (2007)

Cross section/simulation based on factorization prediction

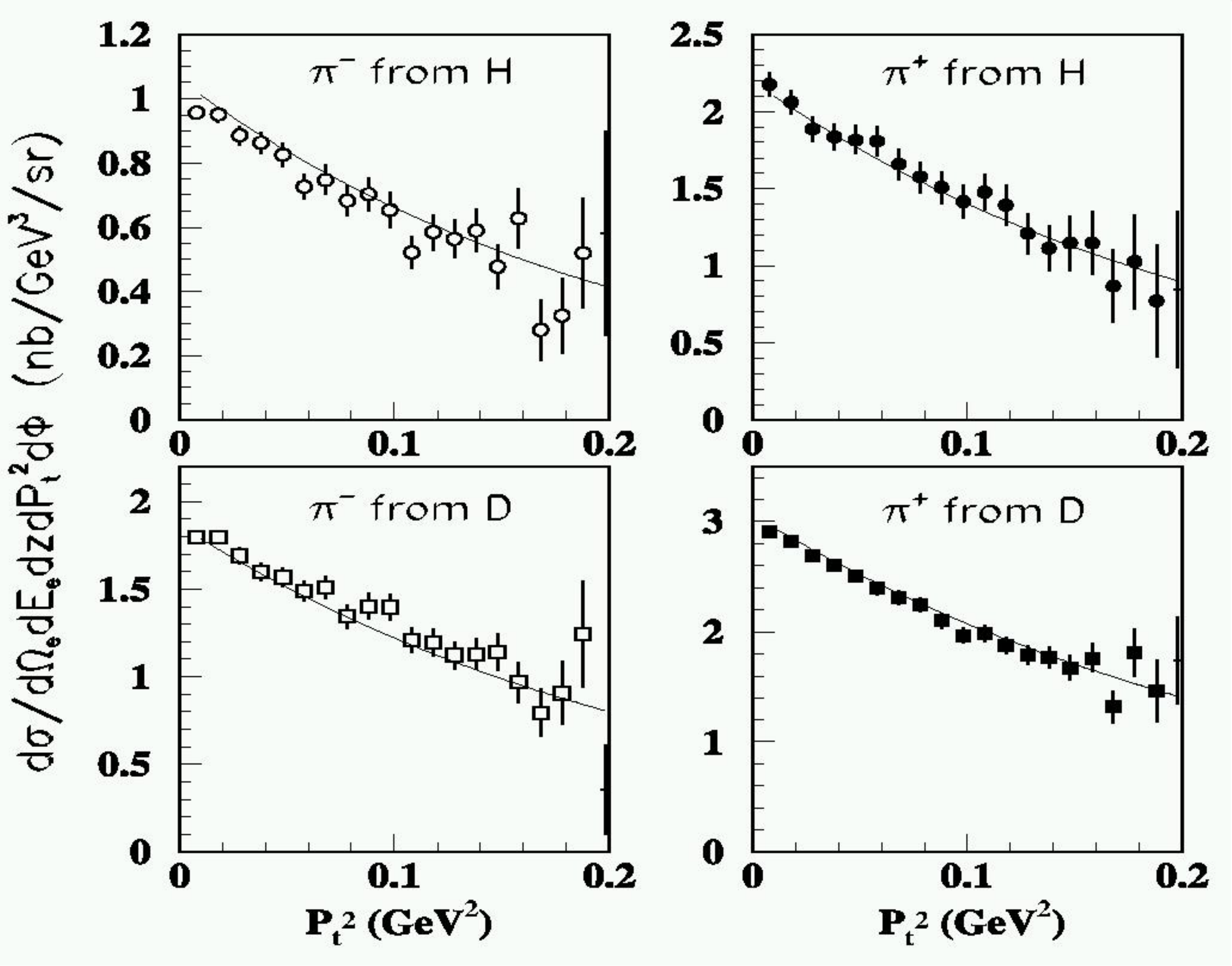
Good Agreement at low z

Delta Resonance at high z



x = 0.32

JLab Measurement: E00-108



- E= 5.5, x=0.3, Q^2=2.3
- Similar, but different slopes for H, D
- Using simple gaussian+Cahn model, combined data yields momentum widths of pdf and fragmentation functions

from Phys. Lett. B665 (2008) 20

Present

Charge Symmetry Violation (CSV) Experiment E12-09-002

Introduction

What is Charge symmetry?

Charge symmetry (CS) is a specific rotation in isospin space. It is the invariance with respect to rotation of π about the T2 axis.

$$[H, P_{CS}] = 0$$
$$P_{CS} = \exp(i\pi T2)$$

$$P_{CS}\,|d\rangle = |u\rangle$$
$$P_{CS}\,|u\rangle = -\,|d\rangle$$

Low Energy: CS in nuclei

CS operator interchanges neutrons and protons

- pp and nn scattering lengths are nearly the same
- $M_n \simeq M_p$
- $B(n, {}^3He) \simeq B(p, {}^3H)$ and energy levels in other mirror nuclei are equal (to 1%)
- $m({}^3He) \simeq m({}^3H)$

After electromagnetic corrections CS respected down to $\sim$ 1%

QCD: Quark level

- $u^p(x, Q^2) = d^n(x, Q^2)$
  $d^p(x, Q^2) = u^n(x, Q^2)$
- Origin of CS violations:
  $\rightarrow$ Electromagnetic interaction
  $\rightarrow$ $\delta m = m_d - m_u$

Naively, one would expect CSV would be on the order of $(m_d - m_u)/\langle M\rangle$, where $\langle M\rangle$ is roughly $0.5 - 1.0$ GeV
$\rightarrow$ CSV effect about 1%

CSV

Motivation

- **Charge symmetry violation** is an important ingredient for pushing the **precision frontier in the partonic structure of the nucleon**
- Charge symmetry is often assumed in extracting PDFs from data – where the data is limited in sensitivity to CS violation
- The validity of charge symmetry is a necessary condition for many relations between structure functions and sum rules
- Flavor symmetry violation extraction $\bar{u}(x) \neq \bar{d}(x)$ relies on the implicit assumption of charge symmetry (in the sea quarks)
- Charge symmetry violation viable part of explanation for the anomalous value of the Weinberg angle extracted by NuTeV experiment
- CSV is related to our understanding of the flavor dependence of the quark masses (one of the key unsolved problems in Physics –
  why is $m_d \sim m_u \neq m_s \neq m_c \neq m_b \neq m_t$)

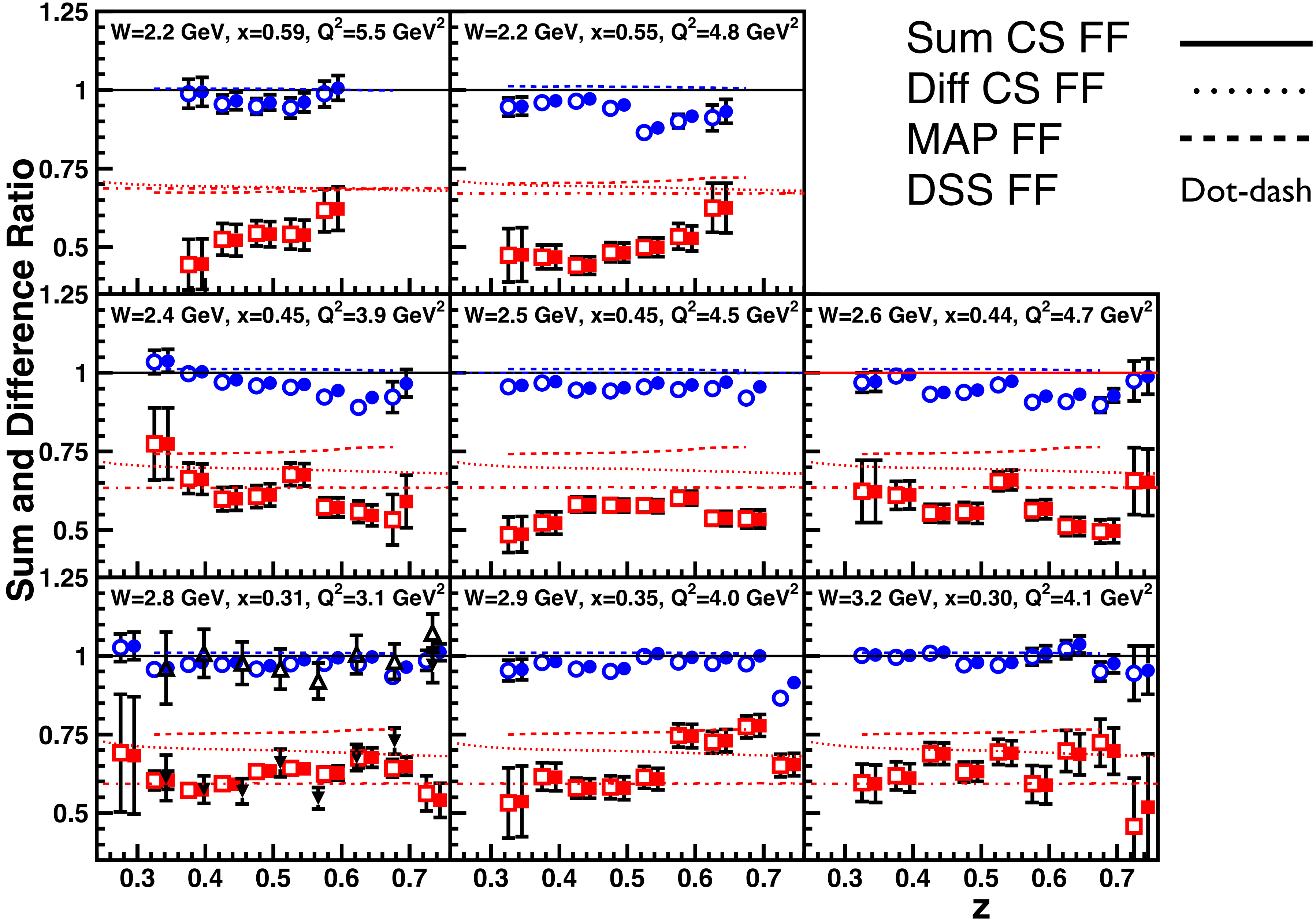
CSV: Sum/Difference Test - 1

Using Charged Pion SIDIS from h and d targets and assuming CSV…

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

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

CSV: Sum/Difference Test - 2

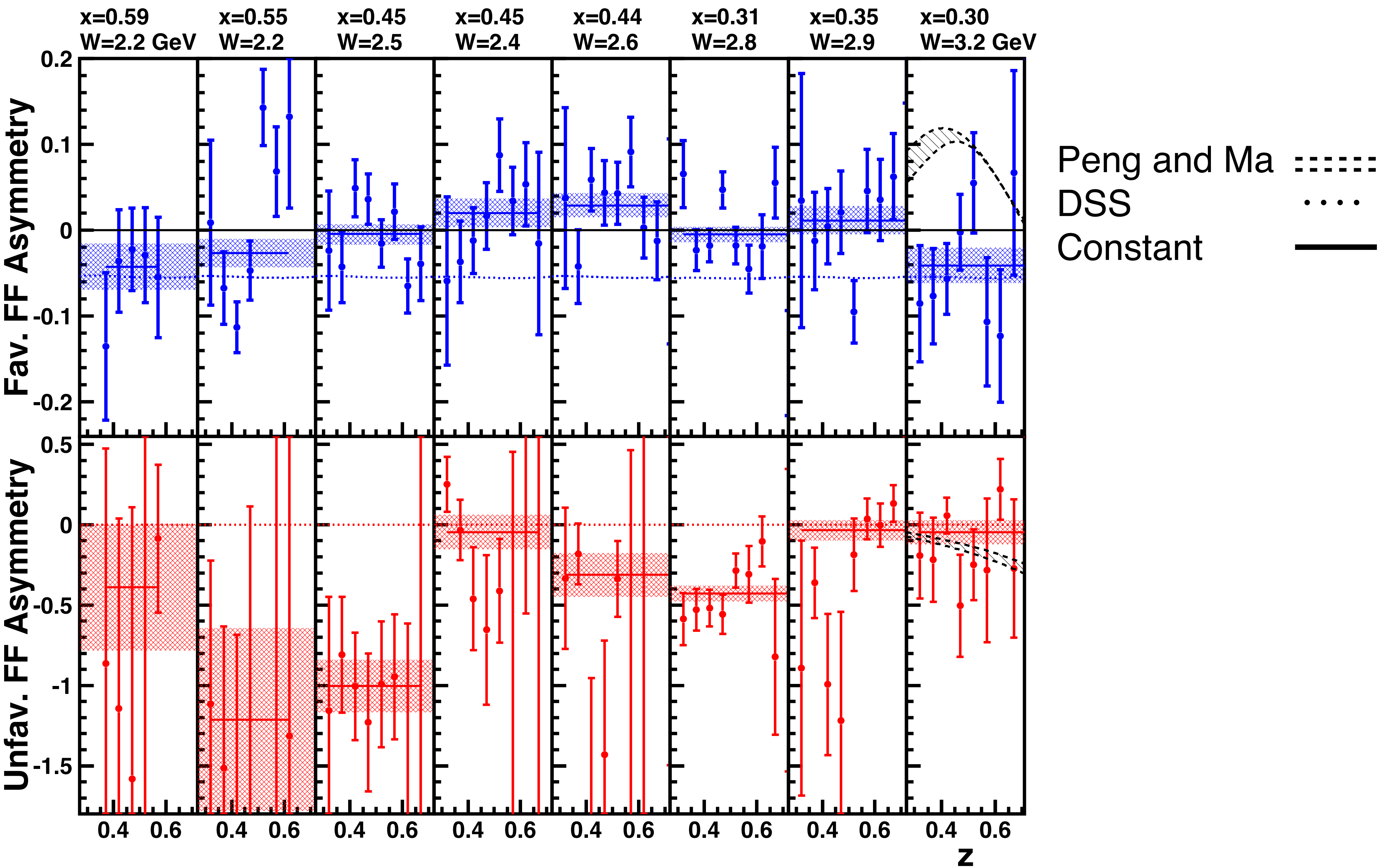


Fragmentation Function Asymmetry - 1

Assuming no CSV in PDFs…

$$A_{\mathsf{f}}(z) = \frac{D_{u\pi^+} - D_{d\pi^-}}{D_{u\pi^+} + D_{d\pi^-}}, \quad A_{\mathsf{uf}}(z) = \frac{D_{d\pi^+} - D_{u\pi^-}}{D_{d\pi^+} + D_{u\pi^-}}$$

Fragmentation Function Asymmetry - 2



Jefferson Lab Exp. E12-09-017: Precise measurements of (e,e'$\pi^{\pm}$) and (e,e'$K^{\pm}$) cross sections at Semi-Inclusive Deep Inelastic Scattering (SIDIS) Kinematics

- Precise measurements to test the assumptions of factorization of SIDIS process at photon invariant momentum transfer $Q^2=q^2-\nu^2$, at moderate Bjorken $x = Q^2/2M\nu$ (M is proton mass)
- Allow exploration of assumptions of favored/disfavored fragmentation of different flavor quarks using ^1H and ^2H targets
- Investigate possible target mass effects
- Investigate possible higher twist effects
- Complement SIDIS measurements in large open acceptance detector CLAS at Jefferson Lab Hall B

SIDIS Differential Cross Section

Measurement of 6-fold differential cross section with unpolarized target has five structure functions (formalism from Bacchetta *et al.*, JHEP 0702, 93 (2007).)

$$\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} \right.$$

$$\left. + \lambda_e \sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} \right\}$$

Virtual Photon Polarization: ϵ
Electron helicity: λ_e
Hadron azimuthal angle: ϕ_h

Structure functions depend on x, Q^2, p_T!

SIDIS cross section model with Transverse Momentum-dependent Parton and Fragmentation Distributions (TMDs)

$f_q(x, \mathbf{k}_\perp)$ *: parton distribution function as function of intrinsic parton k_T*

$D_q^h(z, \mathbf{p}_\perp)$ *: fragmentation function as a function of fragmentation p_T*

Cross section for SIDIS hadron of fractional energy z_h and transverse momentum P_T

$$\frac{d^5\sigma^{\ell p \to \ell h X}}{dx_B \, dQ^2 \, dz_h \, d^2\boldsymbol{P}_T} = \sum_q e_q^2 \int d^2\boldsymbol{k}_\perp \; f_q(x, \boldsymbol{k}_\perp) \, \frac{2\pi\alpha^2}{x_B^2 s^2} \, \frac{\hat{s}^2 + \hat{u}^2}{Q^4}$$

$$\times D_q^h(z, \boldsymbol{p}_\perp) \, \frac{z}{z_h} \, \frac{x_B}{x} \left(1 + \frac{x_B^2}{x^2} \frac{k_\perp^2}{Q^2}\right)^{-1}$$

from Anselmino et al. (hep-ph/0412316v1)

Multiplicity Parameterization

Now perform $k_\perp$ integration and keep terms order $O(k_\perp/Q)$ on previous cross section expression to get

$$\frac{d^5\sigma^{\ell p\to\ell h X}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4} f_q(x_B)\, D_q^h(z_h) \Big[(1+(1-y)^2) - 4\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\, z_h\, P_T}{\langle P_T^2\rangle\, Q}\cos\phi_h\Big] \frac{1}{\pi\langle P_T^2\rangle} e^{-P_T^2/\langle P_T^2\rangle},$$

where $< P_T^2 > = < p_\perp^2 > + z^2 < k_\perp^2 >$

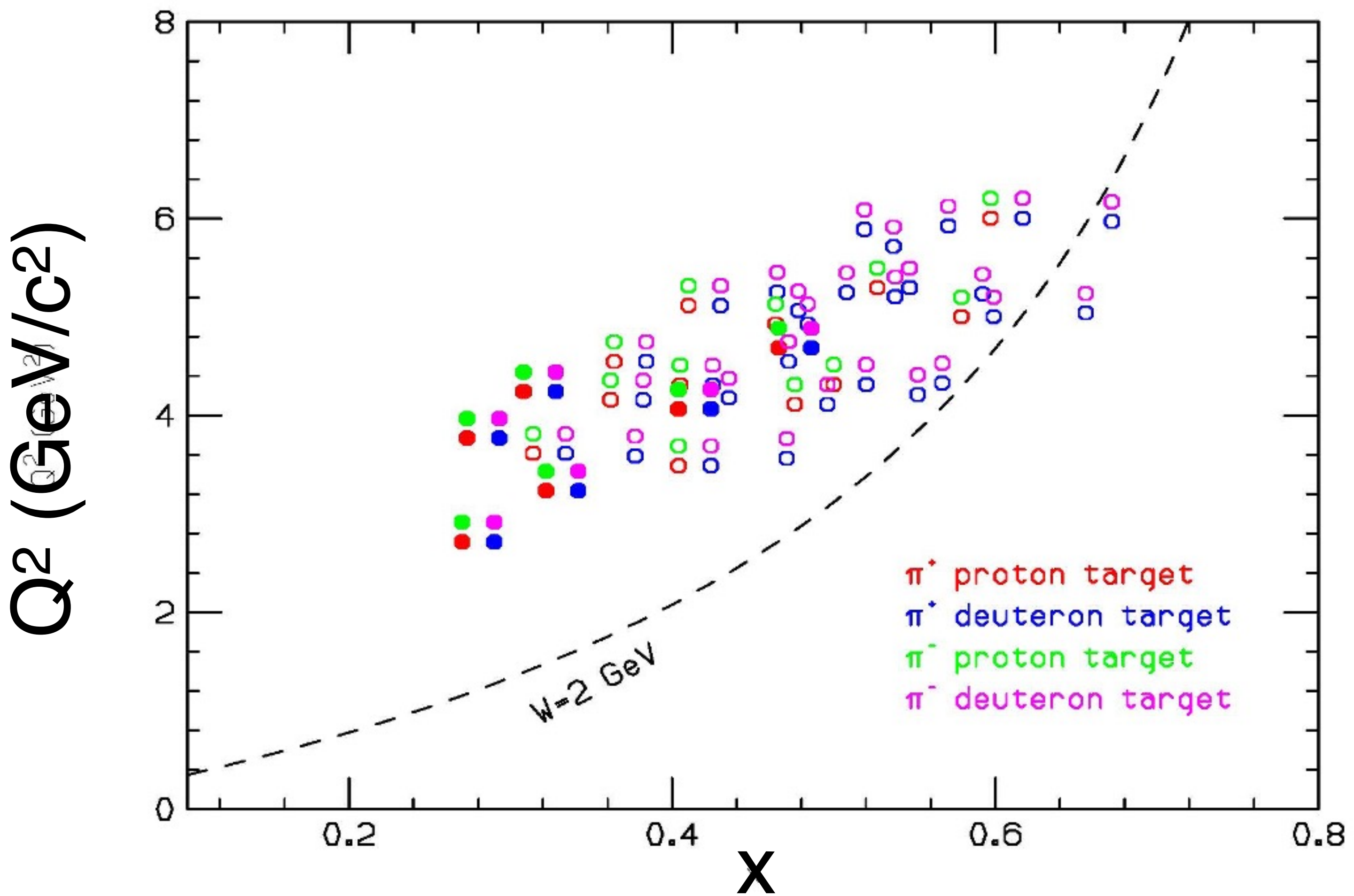
We divide by DIS cross section and fit the multiplicities with:

$$M(x,Q^2,z,P_{hT},\phi) = \frac{d\sigma_{ee'\pi X}}{d\sigma_{ee'X}} = \frac{M_0}{2\pi < \mu^2 >} e^{-P_{hT}^2/<\mu^2>}(1 + A\cos\phi + B\cos 2\phi)$$

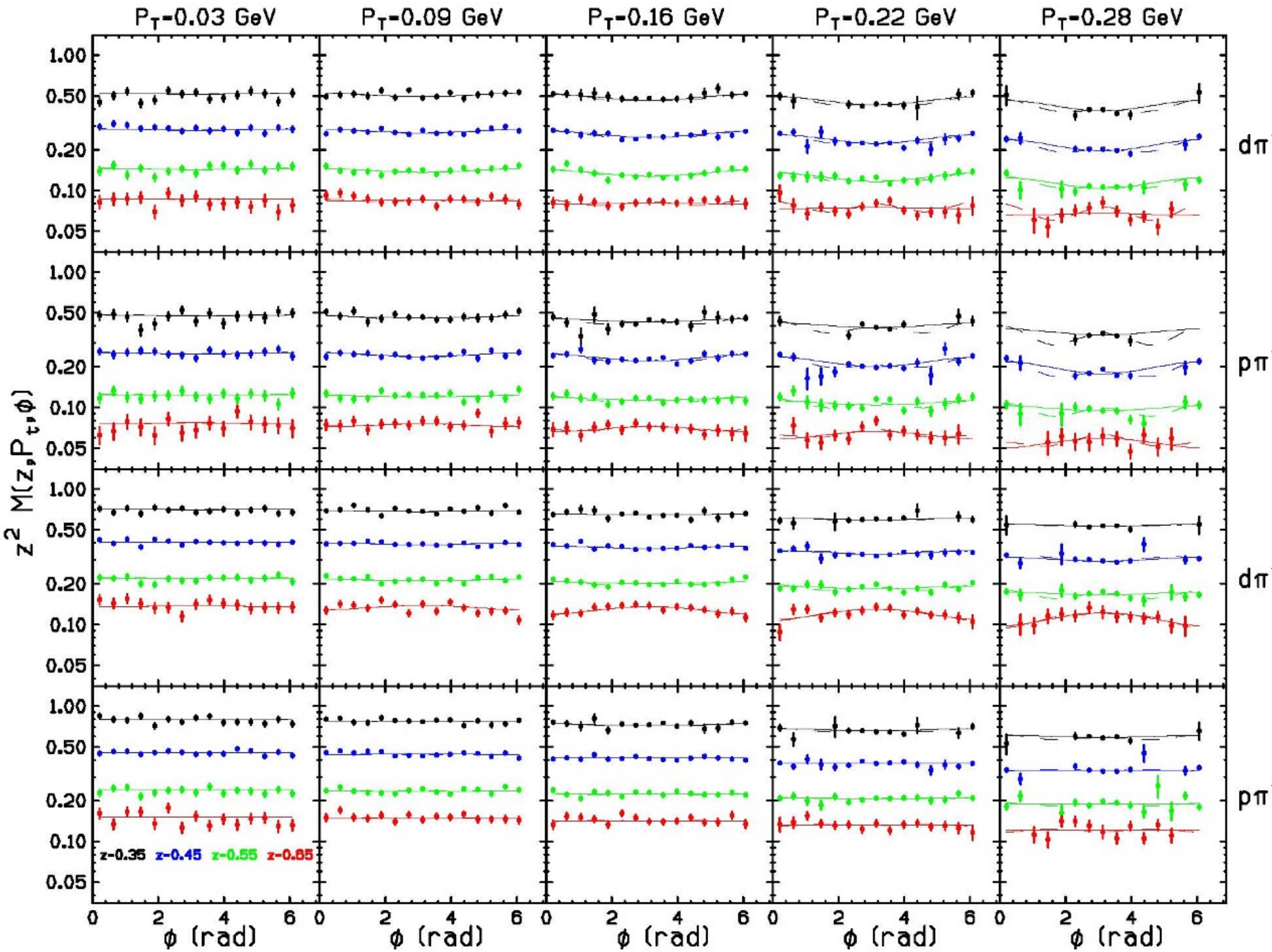
$M_0, < \mu^2 >, A, B$ are fit parameters

Kinematic Coverage in (x, Q2)

- Solid circles are from pt-SIDIS, open circles CSV SIDIS
- Each circle represents 10,000 to 1,000,000 events
- Dominated by valance quark distributions



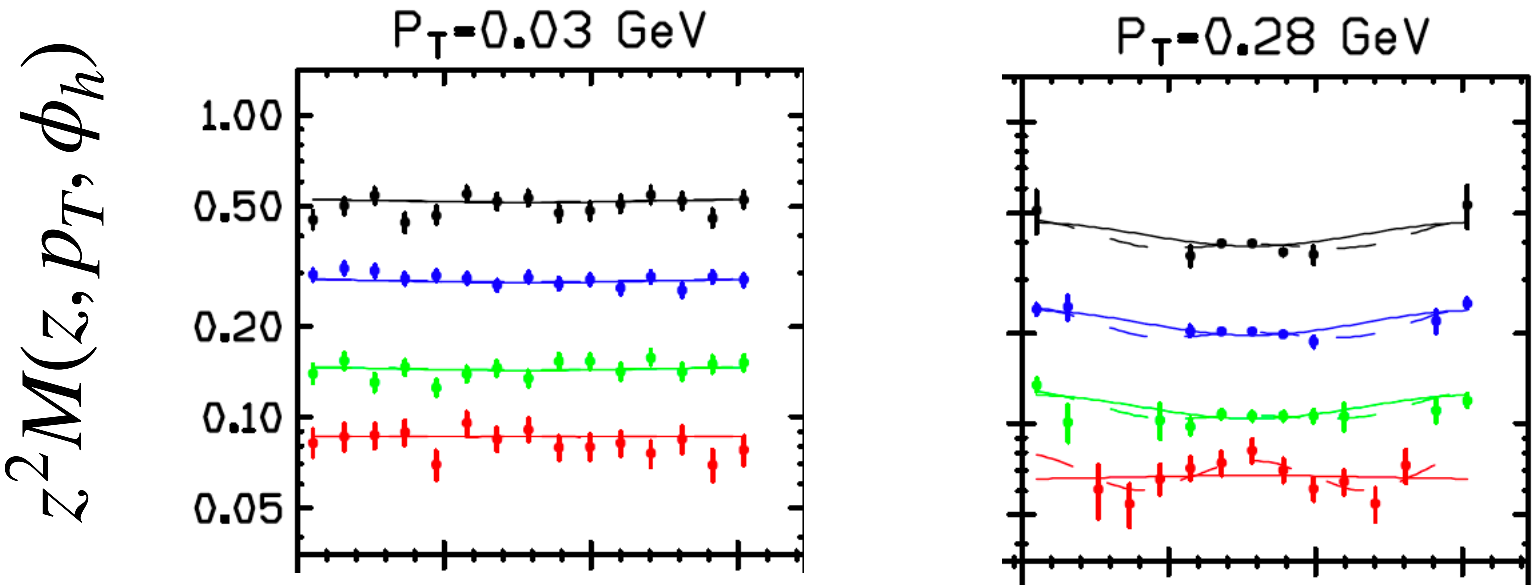
Azimuthal Dependence at x=0.3, Q^2 = 3.0



z=0.35
z=0.45
z=0.55
z=0.65

Also,
x =0.3, Q^2=4.0
x =0.45, Q^2=4.5

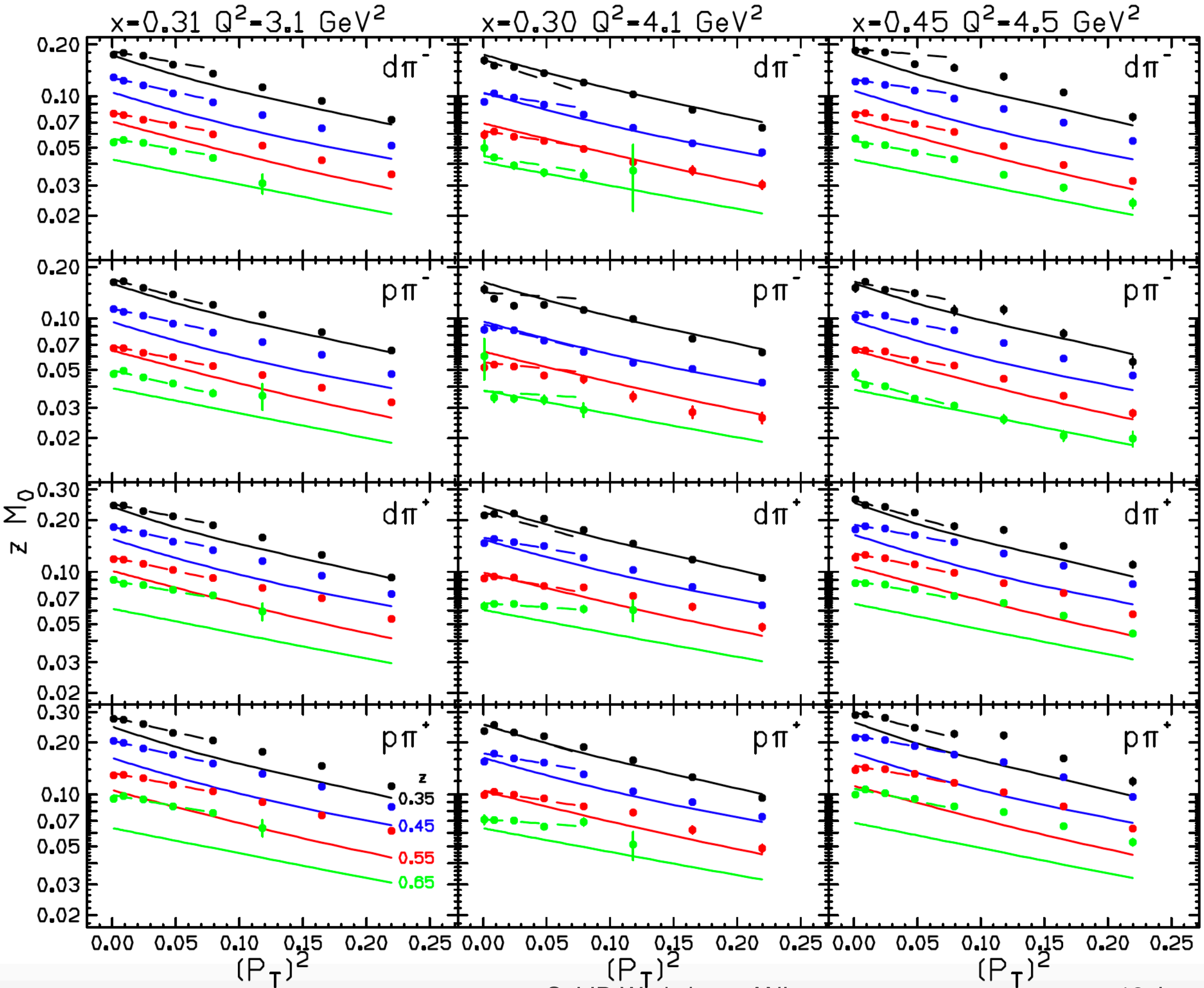
Insets of Azimuthal Dependence at x=0.3, Q^2 = 3.0 GeV/c^2



$d\pi^-$

- Dashed curves are 4 parameter fit (solid B=0)
- ϕ_h modulation appears to increase at higher p_T

Transverse Momentum Dependence

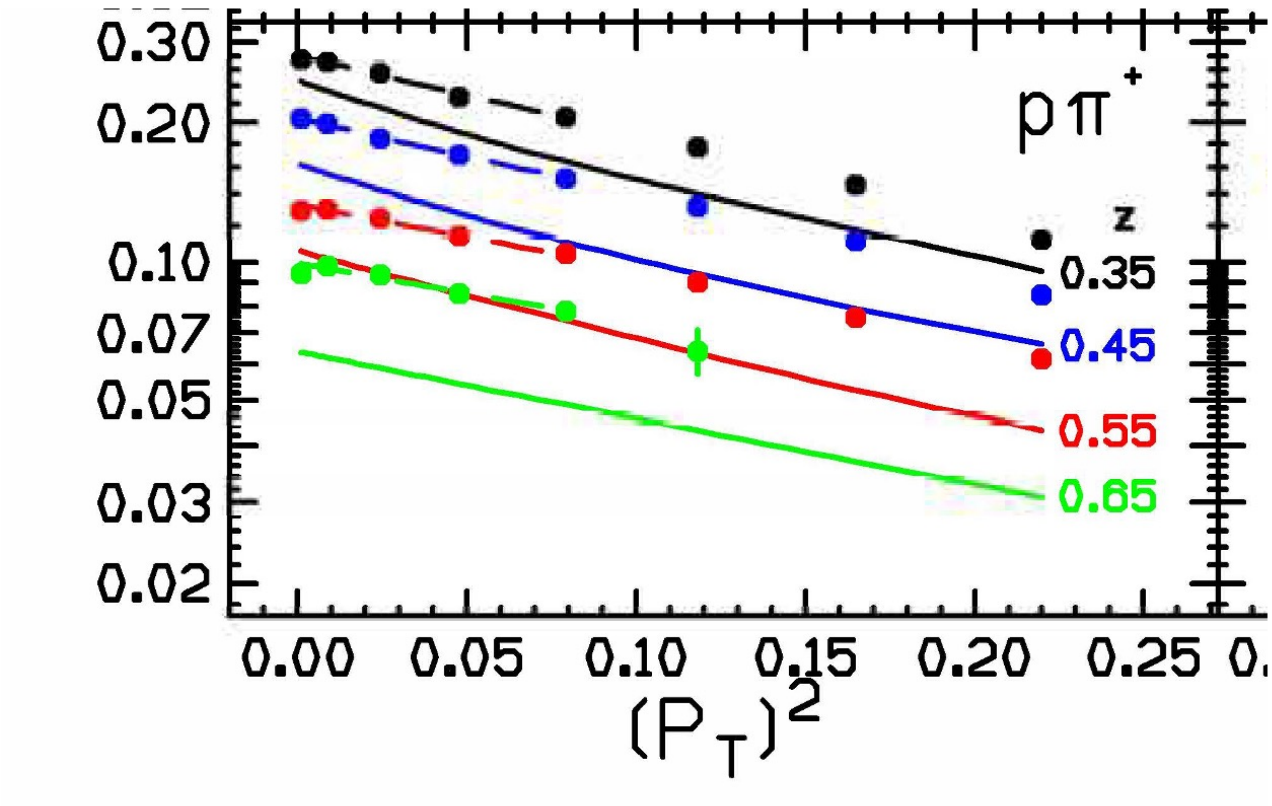


z=0.35
z=0.45
z=0.55
z=0.65

Dashed: Fit to 1st 5 bins

Solid: Curves from MAP: Bacchetta et al, JHEP 10 (2022)

Inset of Transverse Momentum Dependence

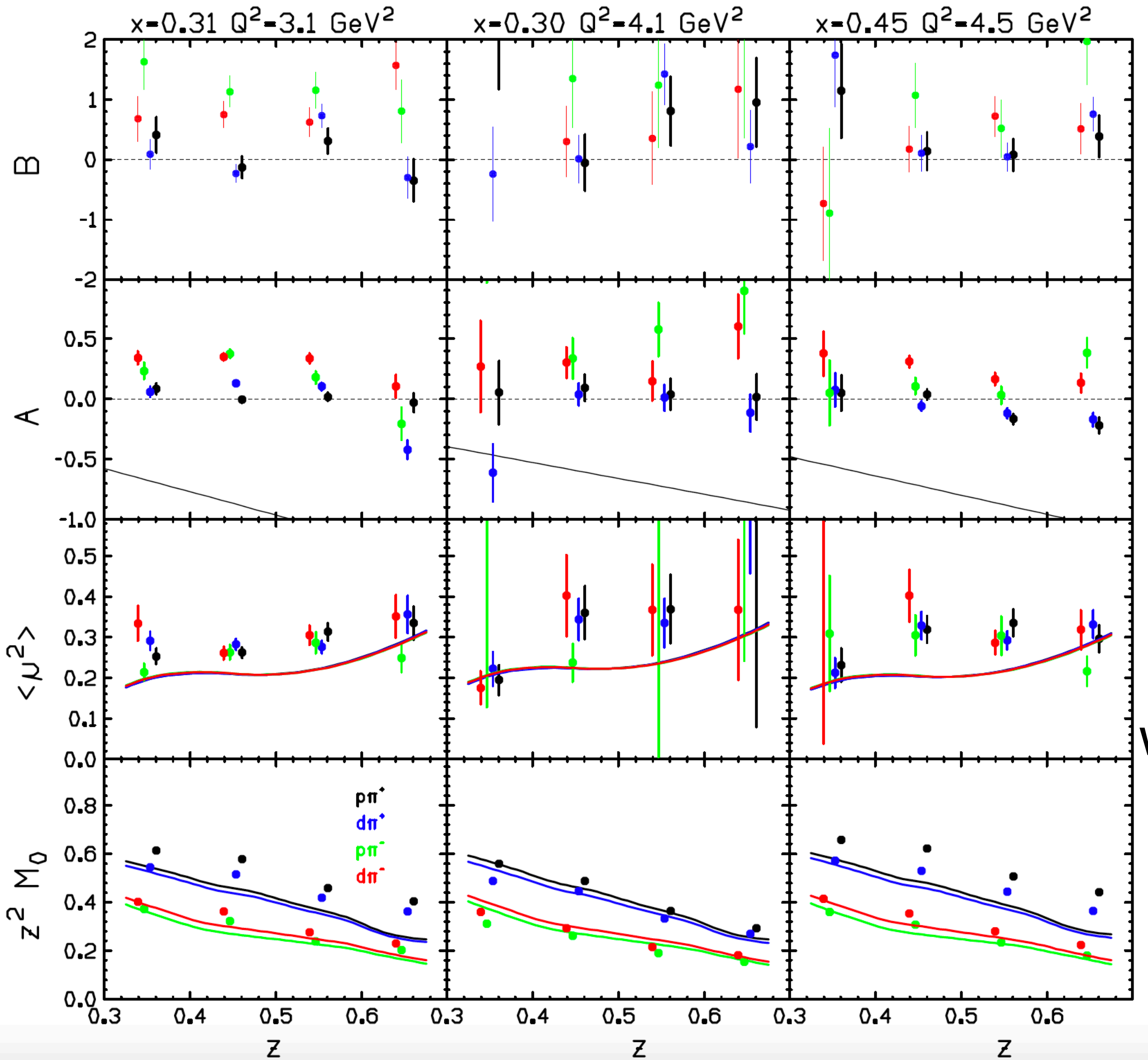


- Slopes are smaller at low transverse momentum than at higher values.

  ➡ Single width gaussian gives poor fit

- Better agreement with MAP slopes at higher transverse momentum.

Four-parameter Fit Results (1st 5 p_T bins)



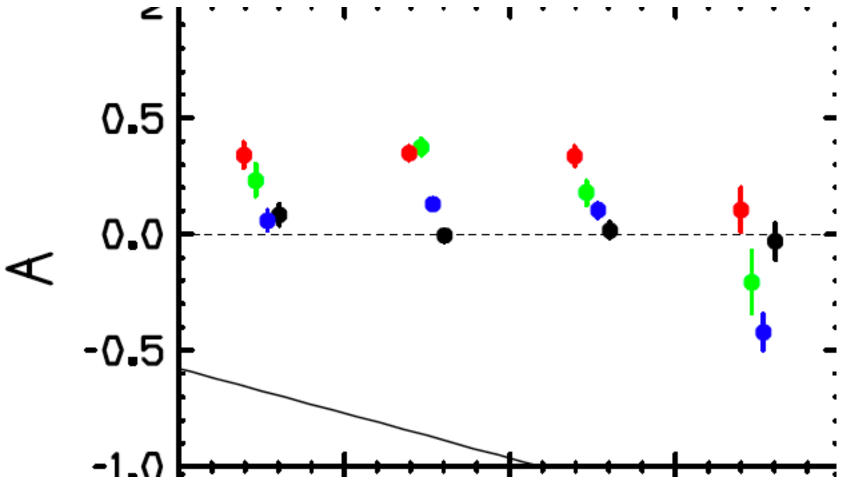
$p\pi^+$ $d\pi^+$ $p\pi^-$ $d\pi^-$

A,B $\approx$ 0 for π^+

A,B > 0 for π^-

Qualitative agreement with MAP (colored solid curves)

Inset of “A” Fit Results (x=0.3, Q^2=3.0 GeV/c^2)

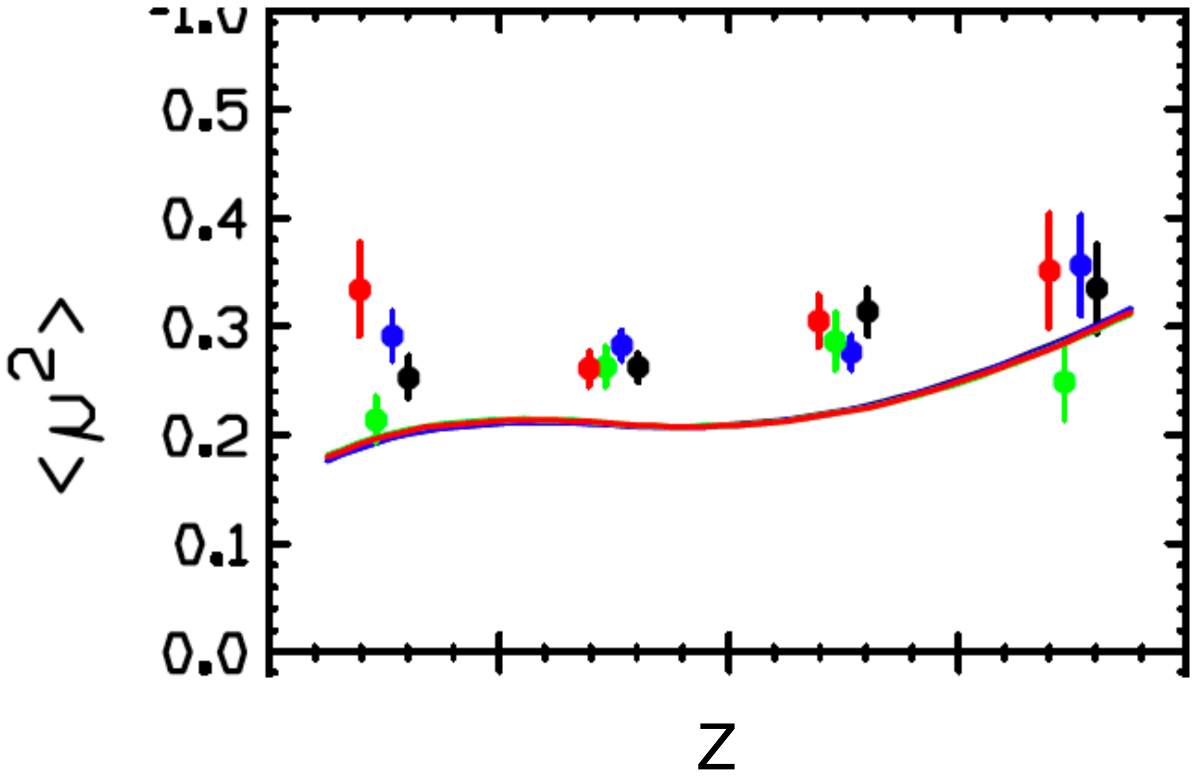


$p\pi^+$ $d\pi^+$ $p\pi^-$ $d\pi^-$

“A” parameter does not agree with Cahn kinematic term evaluated with average quark transverse momentum of 300 MeV (solid curve).

$$\frac{d^5\sigma^{\ell p\to\ell hX}}{dx_B\, dQ^2\, dz_h\, d^2\boldsymbol{P}_T} \simeq \sum_q \frac{2\pi\alpha^2 e_q^2}{Q^4} f_q(x_B)\, D_q^h(z_h) \Big[(1+(1-y)^2) - 4\,\frac{(2-y)\sqrt{1-y}\,\langle k_\perp^2\rangle\, z_h\, P_T}{\langle P_T^2\rangle\, Q} \cos\phi_h \Big] \frac{1}{\pi\langle P_T^2\rangle} e^{-P_T^2/\langle P_T^2\rangle} ,$$

Inset of " $<\mu^2>$ " Fit Results (x=0.3, Q²=3.0 GeV/c²)



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

- Little target dependence seen
- Low pT slopes ($\sim 1/<\mu^2>$) smaller than MAP expectations

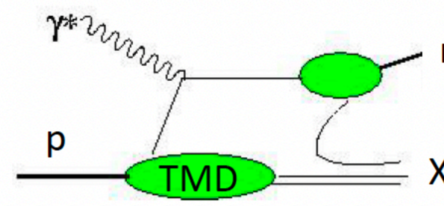
Summary for E12-09-017

- Analysis of large body of precise cross sections finished by Peter Bosted (approximately 21000 cross sections!)
- Phenomenological evaluation in terms of multiplicities, p_T gaussian width, and cosine dependences in azimuthal angle
- Non-constant p_T slope and positive/non-zero azimuthal dependences suggest higher-twist effects are important
- Charged kaon SIDIS to come soon!

E12-13-007 – SIDIS basic $(e,e'\pi^0)$ cross sections

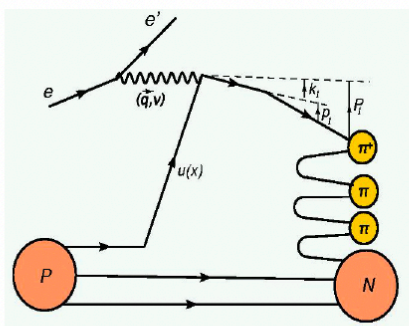
Linked to framework of *Transverse Momentum Dependent Parton Distributions*

- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation
- Need to constrain TMD evolution w. precision data
- Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data



$TMD^q(x,k_T)$

Transverse momentum widths of quarks with **different flavor (and polarization)** can be different



$P_T = p_t + z\,k_t + O(k_t^2/Q^2)$

E12-13-007 goal: Measure the basic SIDIS cross sections of π^o production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

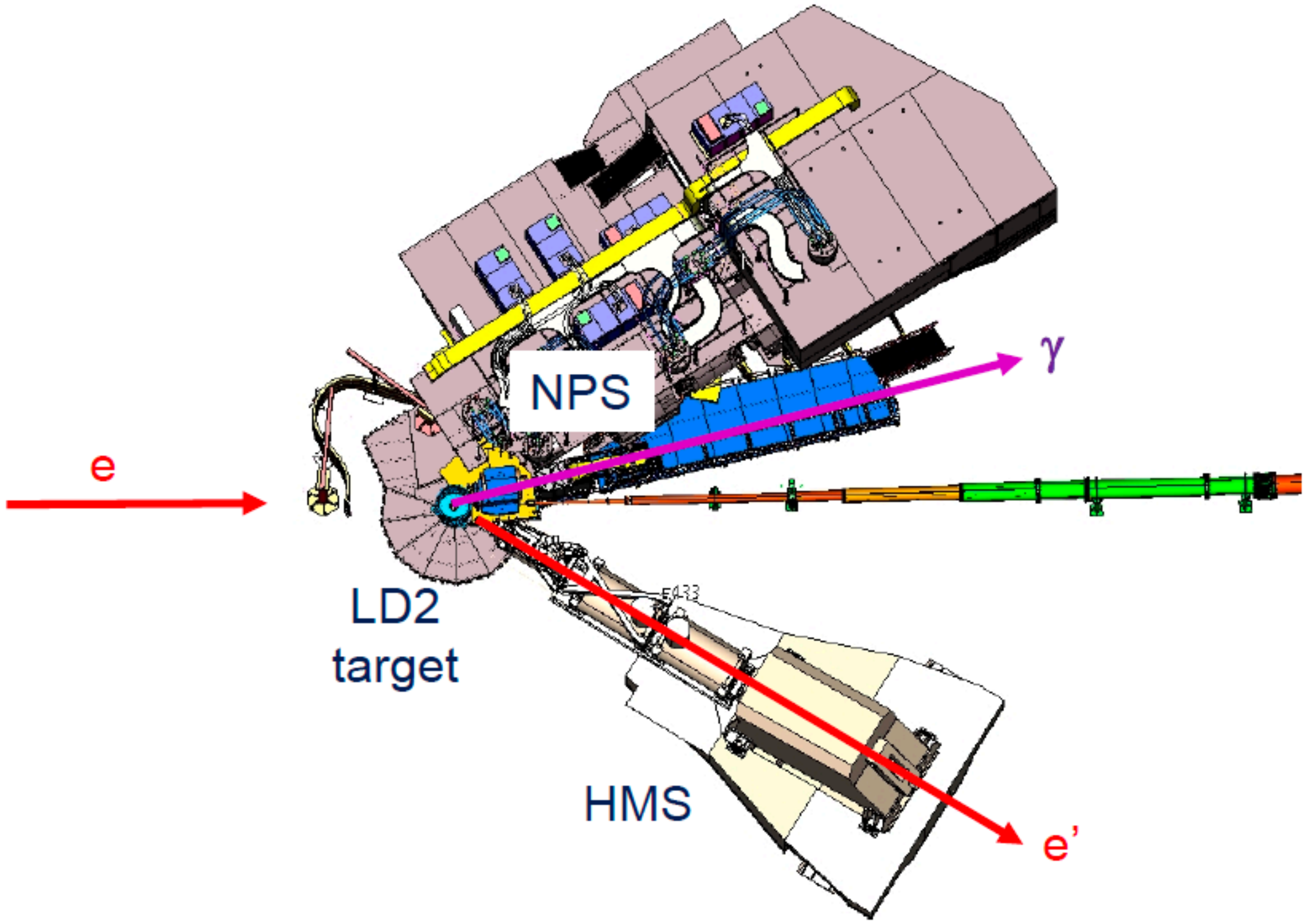
Requires new ~25 msr Neutral-Particle Spectrometer

Advantages of $(e,e'\pi^o)$ beyond $(e,e'\pi^{+/-})$

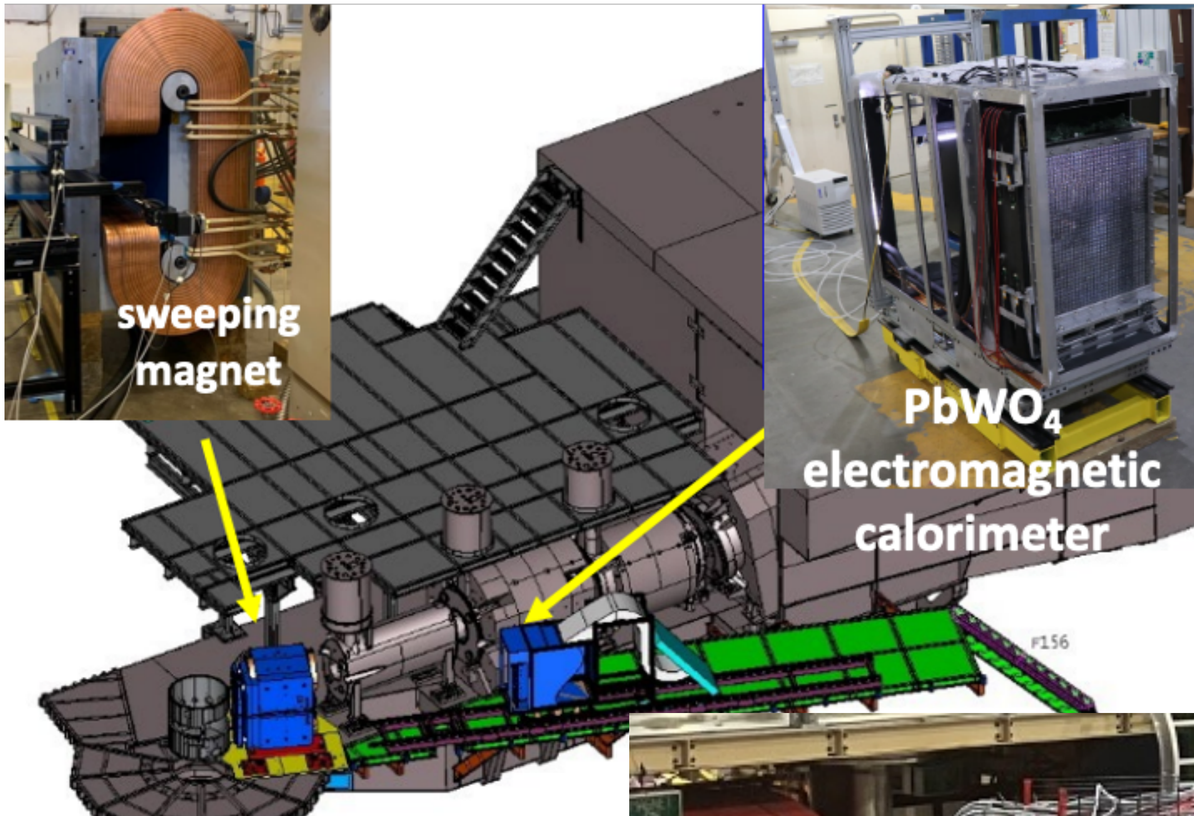
- ❑ Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions
- ❑ Can verify: $\sigma^{\pi^o}(x,z) = ½ (\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- ❑ Confirms understanding of flavor decomposition/k_T dependence

PAC: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon."

Experiment E12-13-007: π^0 SIDIS

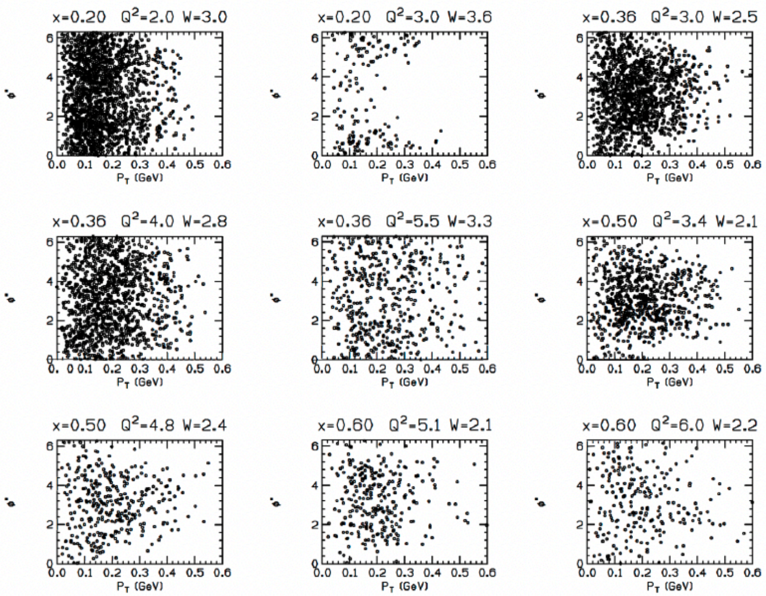


Neutral Particle Spectrometer (NPS – Hall C JLab)



PR12-23-014: SIDIS basic $(e,e'\pi^0)$ cross sections

Angles for which NPS has good acceptance in (z,p_T)

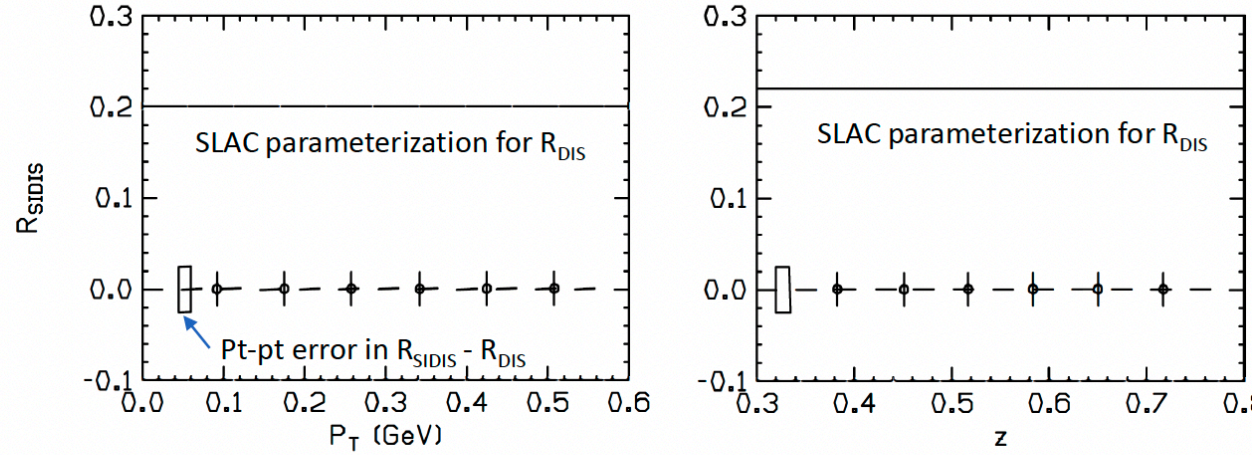


Set	x	Q^2	W	E	ϵ	E'	θ_e	θ_π	d	I	D_p	D_d
		GeV^2	GeV	GeV		GeV	deg	deg	m	μA	day	day
Ib	0.20	2.0	3.0	8.5	0.64	3.17	15.7	8.9	4	50	0.1	0.1
IIIa	0.36	3.0	2.5	6.4	0.51	1.96	28.3	11.2	3	28	0.1	0.1
IVb	0.36	4.0	2.8	8.5	0.52	2.58	24.7	9.9	4	40	0.1	0.1
V	0.36	5.5	3.3	10.6	0.41	2.46	26.6	7.5	4	40	0.3	0.3
VIIIa	0.60	5.1	2.1	6.4	0.46	1.87	38.1	13.2	3	28	0.3	0.3
VIa	0.50	3.4	2.1	6.4	0.67	2.78	25.3	16.9	6	28	0.1	0.1

New Run Group addition proposal to PAC51 (P. Bosted, E. Kinney, H. Mkrtchyan, V. Tadevosyan, R. Ent, T. Horn, et al.)

Measure $R_{LT}= \sigma_L/\sigma_T$, the ratios of d/u cross sections, the transverse momentum dependence of the cross section, and the spin-independent and beam-spin-dependant modulations of the cross section

Projections for R_{LT} SIDIS as function of p_T and z



Physics goals are driven by the need to more fully understand the production processes that enter SIDIS for better understanding of the 3D nucleon structure

- Dynamic and target higher twist, deep-exclusive processes, VM, CSV

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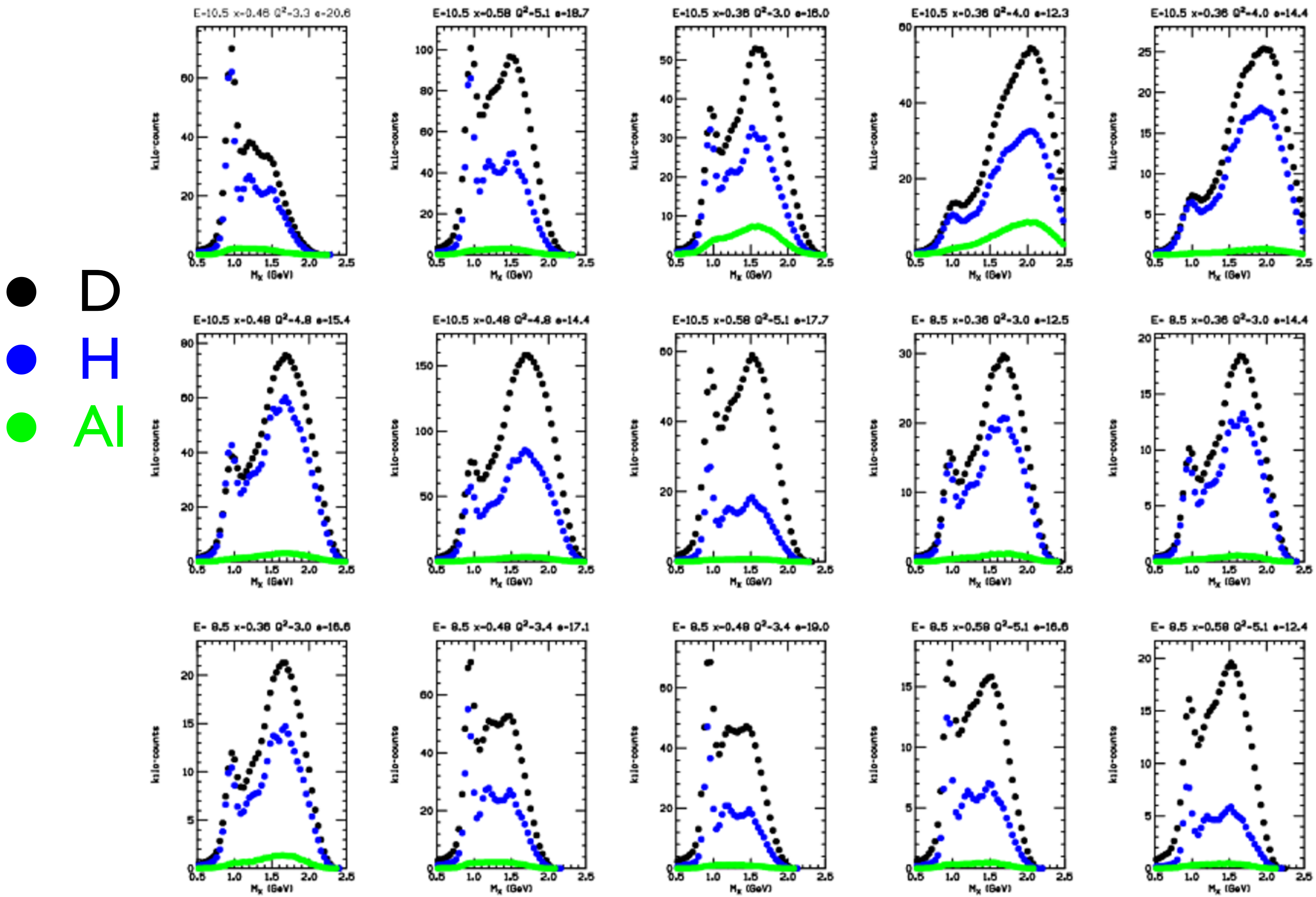
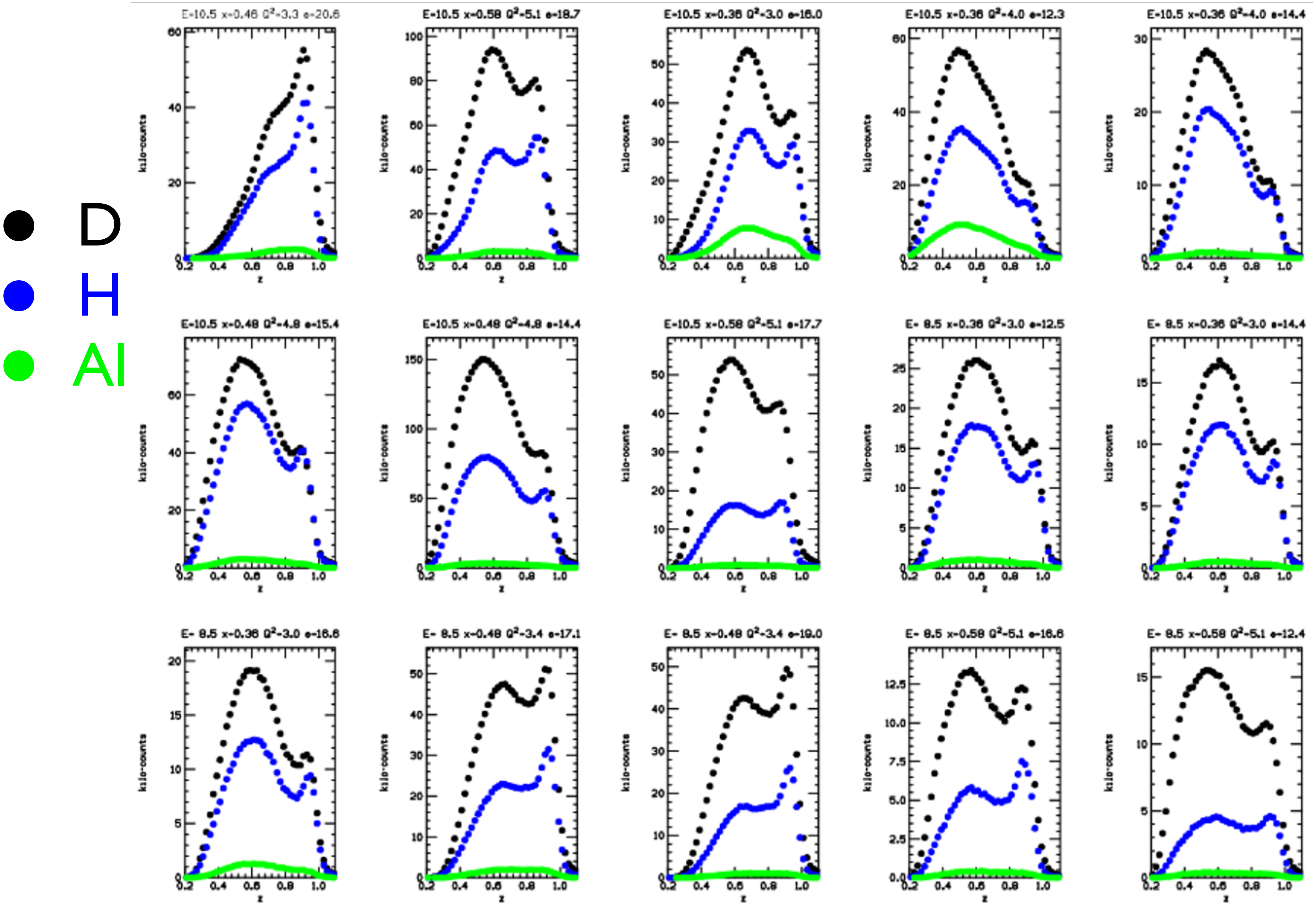
Online Results from NPS Run: M_x

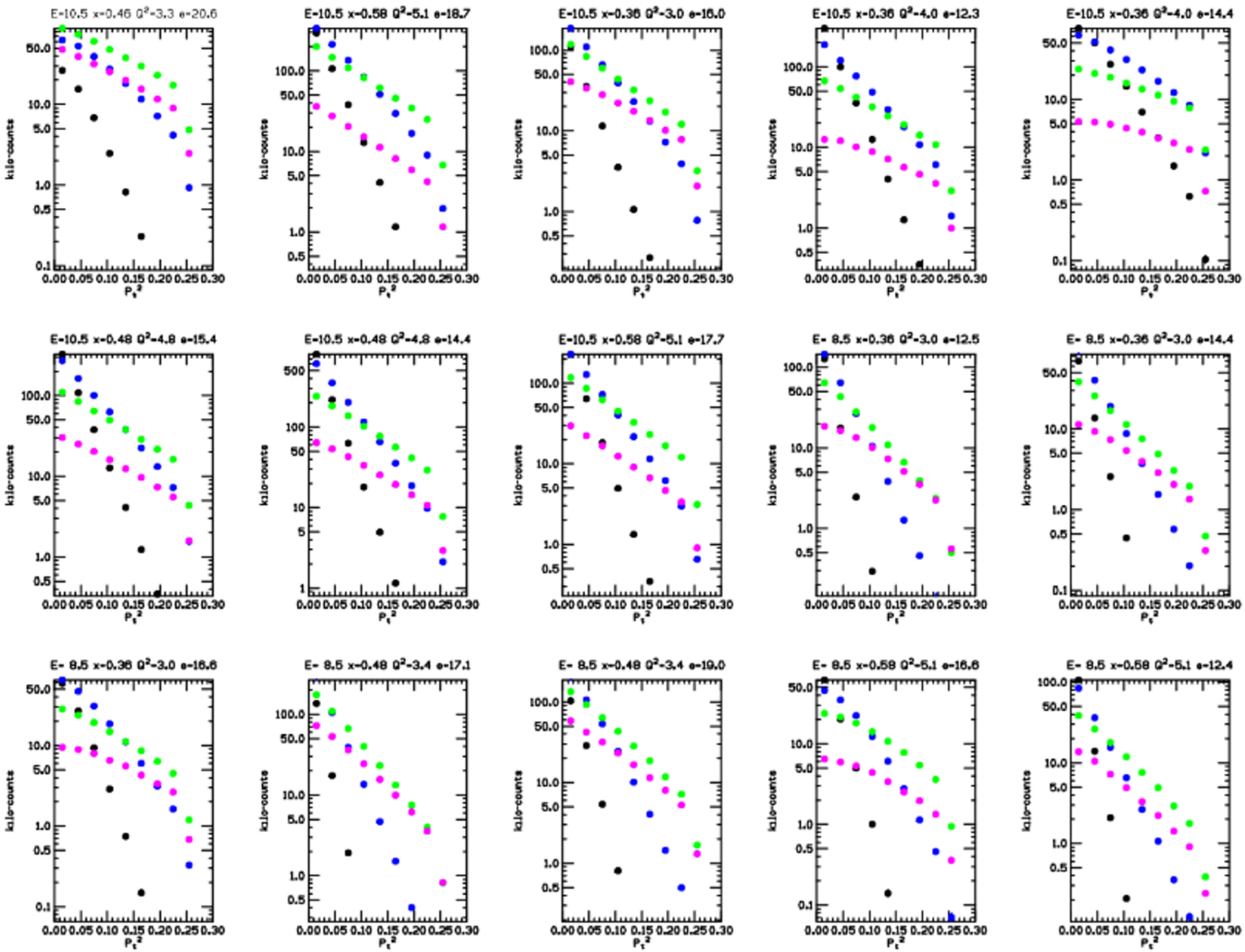


Online Results from NPS Run: z



Online Results from NPS Run: P_T

- 0.3<Z<0.5
- 0.5<Z<0.7
- 0.7<Z<0.9
- 0.9<Z<1.1



Summary for E12-13-007

- Commissioning and Data production with NPS completed after long 9 month run!
- Offline Analysis underway!
- Longitudinal/Transverse Separated cross sections will be obtained (with comparable/better precision than charged pion)

Future

Experiment E12-06-104: R SIDIS

Measurement of the ratio $R = \sigma_L/\sigma_T$ in Semi-Inclusive Deep Inelastic Scattering

E12-06-104, *Spokespersons:* P. Bosted, R. Ent, E. Kinney, and H. Mkrtchyan

- This experiment will make precise measurements of R in charged π and K SIDIS on H and D targets as a function of Q^2, fractional hadron momentum z, and hadron transverse momentum p_T
- Standard technique to measure R: Vary the virtual photon polarization ε by using different incident beam energies and electron scattering angles, while keeping the Q^2, x, z, and p_T constant. Will use the two magnetic spectrometers in Hall C.

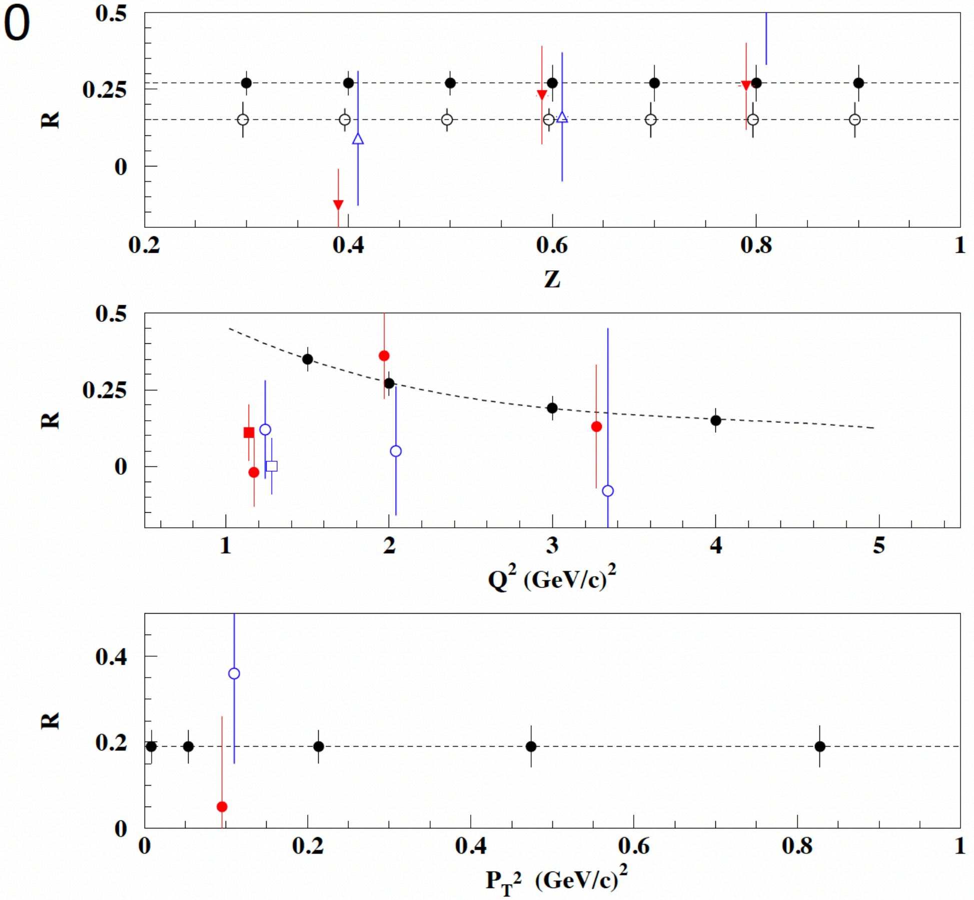
$$\varepsilon = \left[1 + 2\left(\frac{Q^2}{4M^2x^2}\right)\tan\frac{\theta^2}{2}\right]^{-1}$$

$$\sigma = \Gamma(\sigma_T + \varepsilon\sigma_L + \varepsilon\cos(2\phi)\sigma_{TT} + [\varepsilon(\varepsilon+1)/2]^{1/2}\cos(\phi)\sigma_{LT})$$

Experiment E12-06-104: R SIDIS

$R = \sigma_L/\sigma_T$ is a basic aspect of the photon-parton interaction

- First DIS evidence that quarks had spin ½ (R→0 as $Q^2 \rightarrow \infty$)
- Almost no experimental knowledge of R in SIDIS

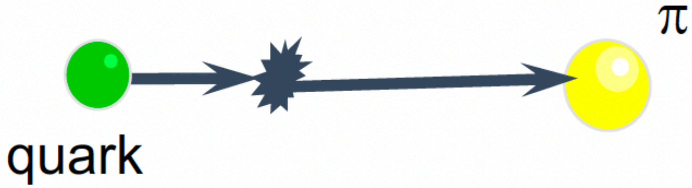


Projections for E12-06-104 vs existing Cornell Data
(projections assume $R_{SIDIS} = R_{DIS}$)
Comparable 1.6% systematic uncertainties not indicated

Projections: Solid Black H, Open Black D π
Cornell:
Top panel: solid red (open blue) π^+ (π^-) on LH_2
Middle : solid red (open blue) dots are π^+ (π^-) on LH_2
solid red (open blue) squares are π^+ (π^-) on LD_2
Bottom : solid red (open blue) dots are for π^+ (π^-) on LH_2

Experiment E12-06-104: R SIDIS

- An essential measurement in understanding SIDIS in LO factorized form at these energies



$\sim \sum e_q^2 q(x)\, D_q^{\pi}(z)$

  - Previous JLab cross section experiments experiments suggest this factorized picture is valid at JLab energies at appropriate final hadronic state energies

- We will be able to test many common assumptions used in SIDIS analyses:

$$R_{SIDIS} = R_{DIS}?$$

$$R^{\pi^+}_{SIDIS} = R^{\pi^-}_{SIDIS}? \qquad R^{H}_{SIDIS} = R^{D}_{SIDIS}? \qquad R^{\pi^+}_{SIDIS} = R^{K^+}_{SIDIS}? \qquad R^{K^+}_{SIDIS} = R^{K^-}_{SIDIS}?$$

- Important for determining spin structure function g_1^h (need term $(1 + \varepsilon R)$ to get g_1^h/F_1^h from $A_{\parallel}^h$)
- At low z, expect DIS Q^2 behavior ($\sim 1/Q^2$), but as z→ 1, expect Deep-Exclusive Q^2 behavior ($\sim Q^2$)
- Completely unknown p_T behavior, which might impact on TMD analyses

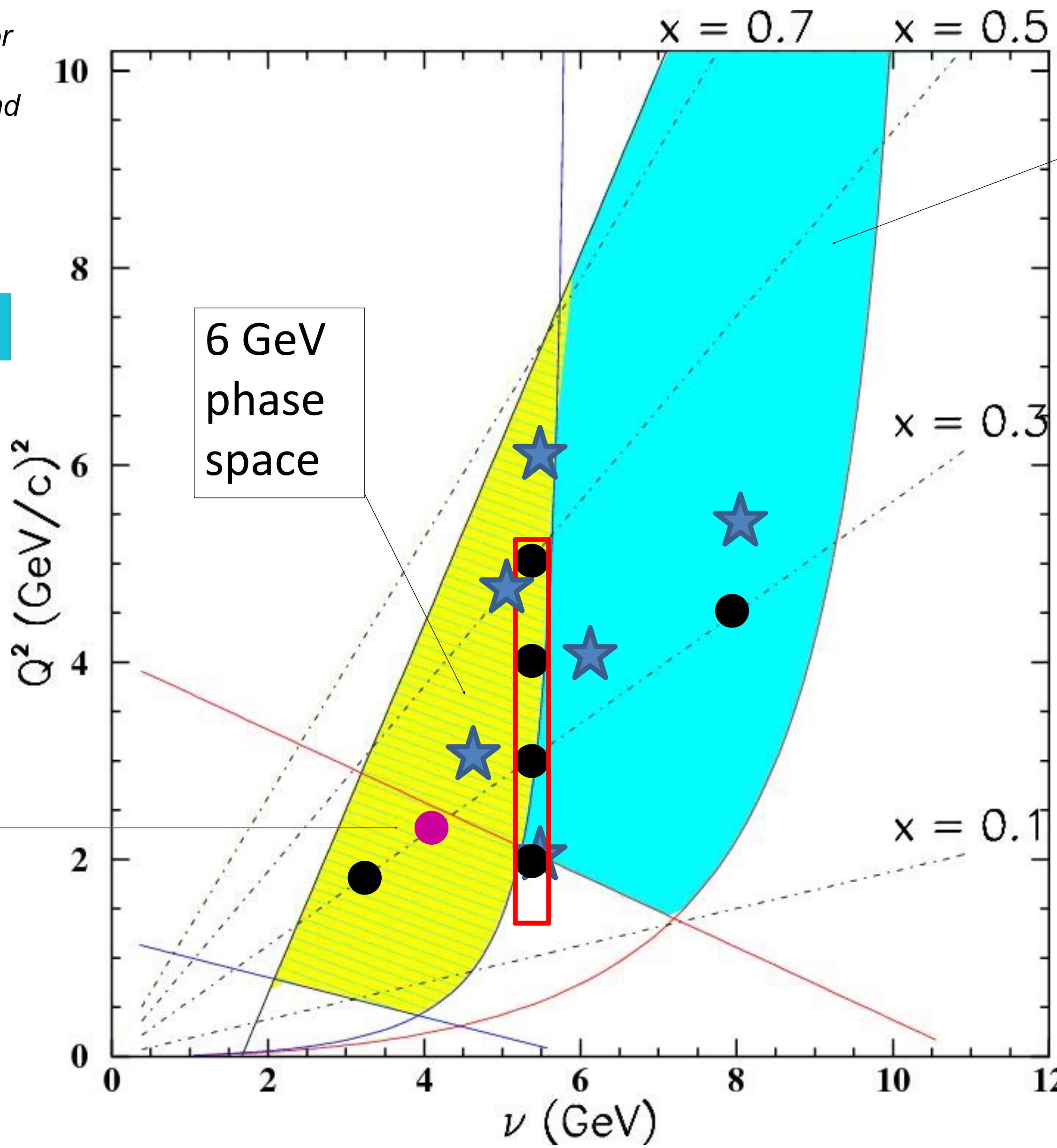
Hall C Kinematic Reach

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

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

E00-108 (6 GeV)



11 GeV phase space

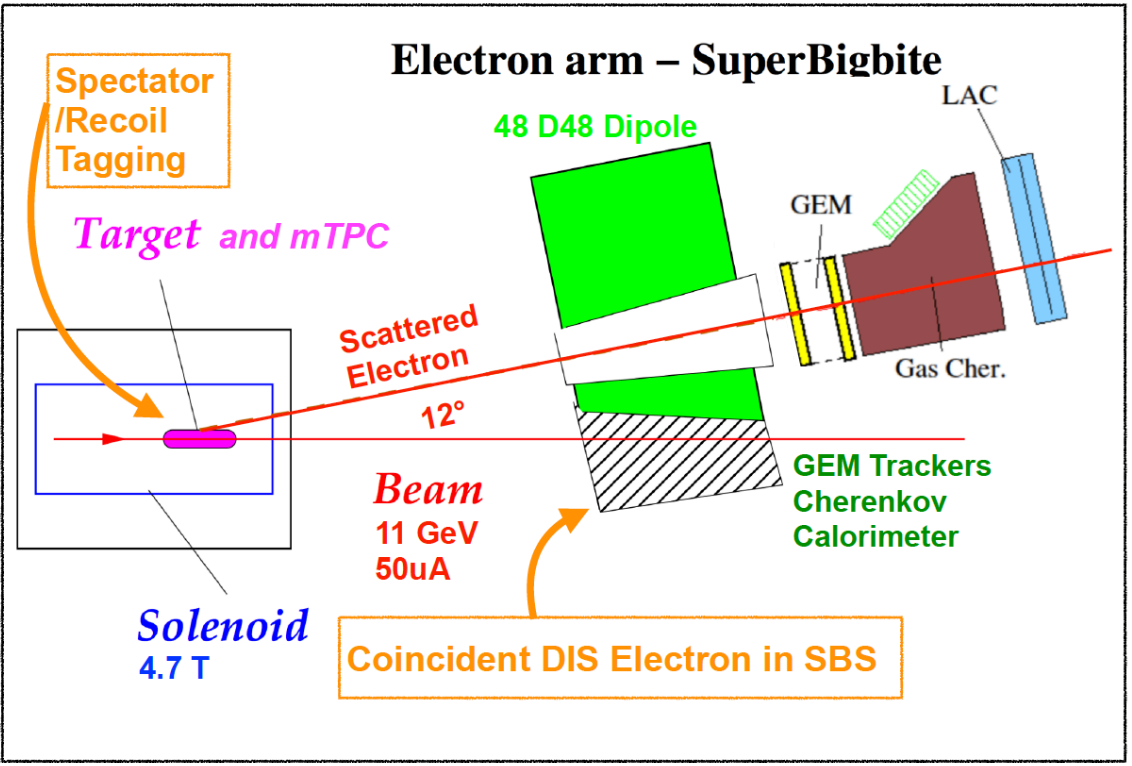
Charged pions:

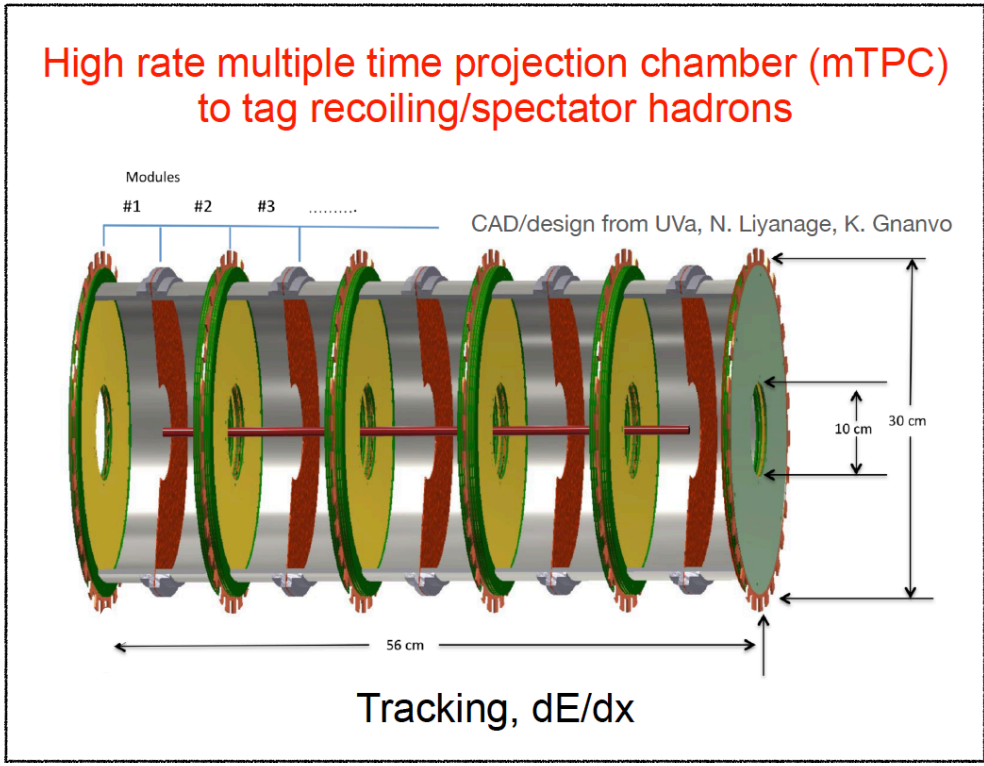
- ▭ E12-06-104
  L/T scan in (z,P_T)
  No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known
- ● E12-09-017
  Scan in (x,z,P_T)
  + scan in Q^2
  at fixed x

The Tagged Deep Inelastic Scattering (TDIS) Experiment

Knowledge of meson structure is critical to a complete understanding of the emergence hadron mass.

Lack of meson targets ⇒ No direct measurement





TDIS is a direct measurement of the mesonic content of nucleons and extraction of the pion's F_2 structure functions, by deep inelastic scattering off the virtual-meson cloud.

The well established spectator tagging used to access the "meson cloud" target.

C1 conditionally approved with A- rating for 27 PAC days (up for jeopardy review @ PAC 51)

Two Additional Run-group Experiments Approved

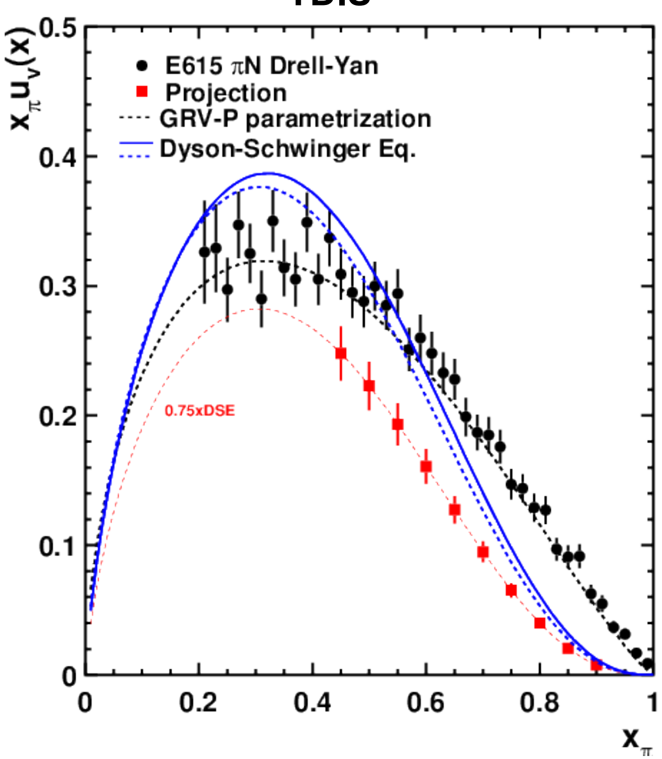
Run-group: TDIS, kaon-TDIS and neutron-TDIS

Many-fold increased interest in the technique and the science goal - over 50 publications with more than 1200 citations (e.g. LRP white paper & EIC yellow report).

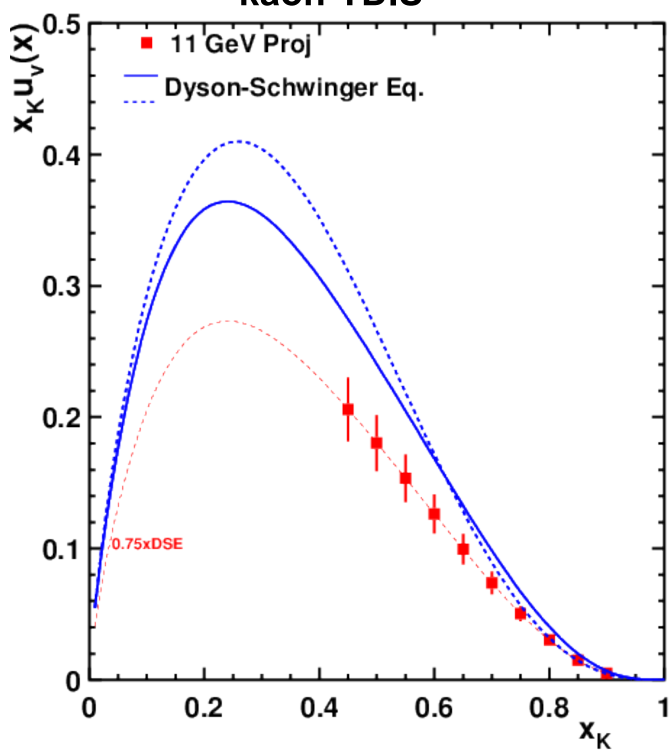
Significant theory progress - global QCD analysis including leading neutron HERA data

Substantial experimental progress - mTPC based recoil detector, streaming readout, simulations validated with BoNUS12 data, high rate & high occupancy tracking algorithm

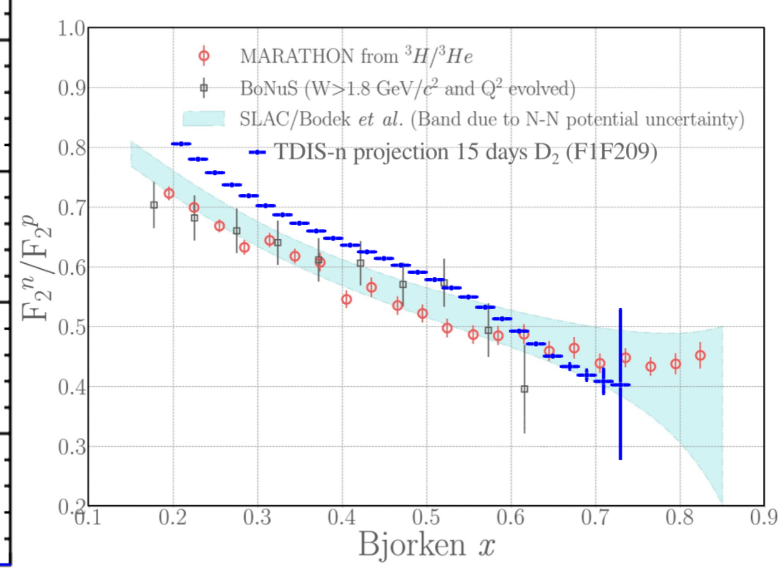
TDIS



kaon-TDIS



neutron-TDIS



TDIS will be a pioneering experiment and a necessary first step for future experiments at the EIC and 22 GeV JLab.

Strong Hall C Capabilities

Hall C is at the high luminosity frontier, precisely measuring small cross sections and performing longitudinal/transverse separations are our bread and butter

The ability to rapidly switch between different targets can greatly reduce systematic uncertainties, and a wide choice of nuclei is possible

Do not fail to appreciate the ability to set a spectrometer at a precise angle; alignment of large collider detectors takes years

High luminosity measurements with polarized beams and targets are well established capabilities at Jefferson Lab

Flexibility to change experimental layout (spectrometers, calorimeters, compact photon source) allows for optimized measurements with precision

Concluding Opinions

The general capabilities of the Hall allow a broad SIDIS program already at 12 GeV; the focus is on precise measurements of small cross sections and the ability to perform longitudinal/transverse separations.

The first 12 GeV experiments have produced new results!

The high precision Hall C experiments will complement those of Hall B.

As we explore SIDIS at 12 GeV, we will move beyond the nucleon as a collection of free point objects! These are the signatures of the emergent physical structure we wish to understand!!!