Dependence of Charged Pion Production on Transverse Momentum from Semi-Inclusive Deep Inelastic Electron Scattering from ^1H and ^2H

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On behalf of P. Bosted[2], R. Ent[3], H. Mkrtchyan[4] and the E12-09-17 Collaboration

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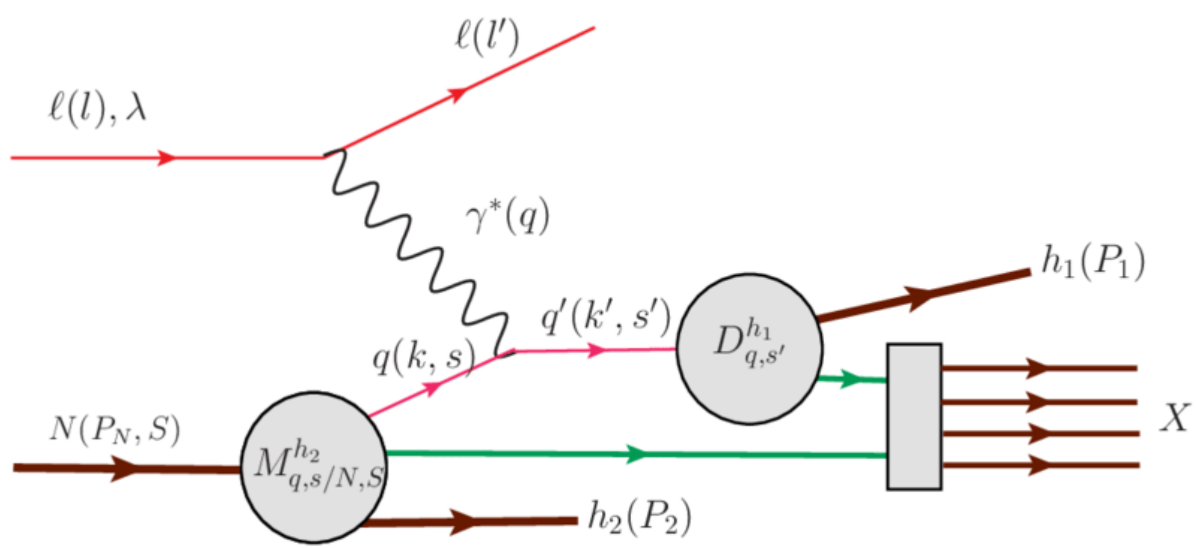


Preliminaries and Outline

- 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 theirs!

- Semi-Inclusive Deep Inelastic Scattering (SIDIS)
- Earlier Hall C Measurements
- Experimental Description
- Results
- Summary and Outlook

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!

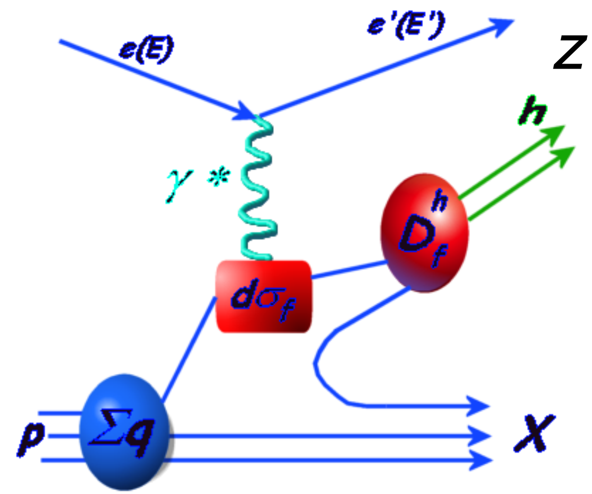
Do parton distributions and fragmentation functions factorize at Jefferson Lab energies?

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

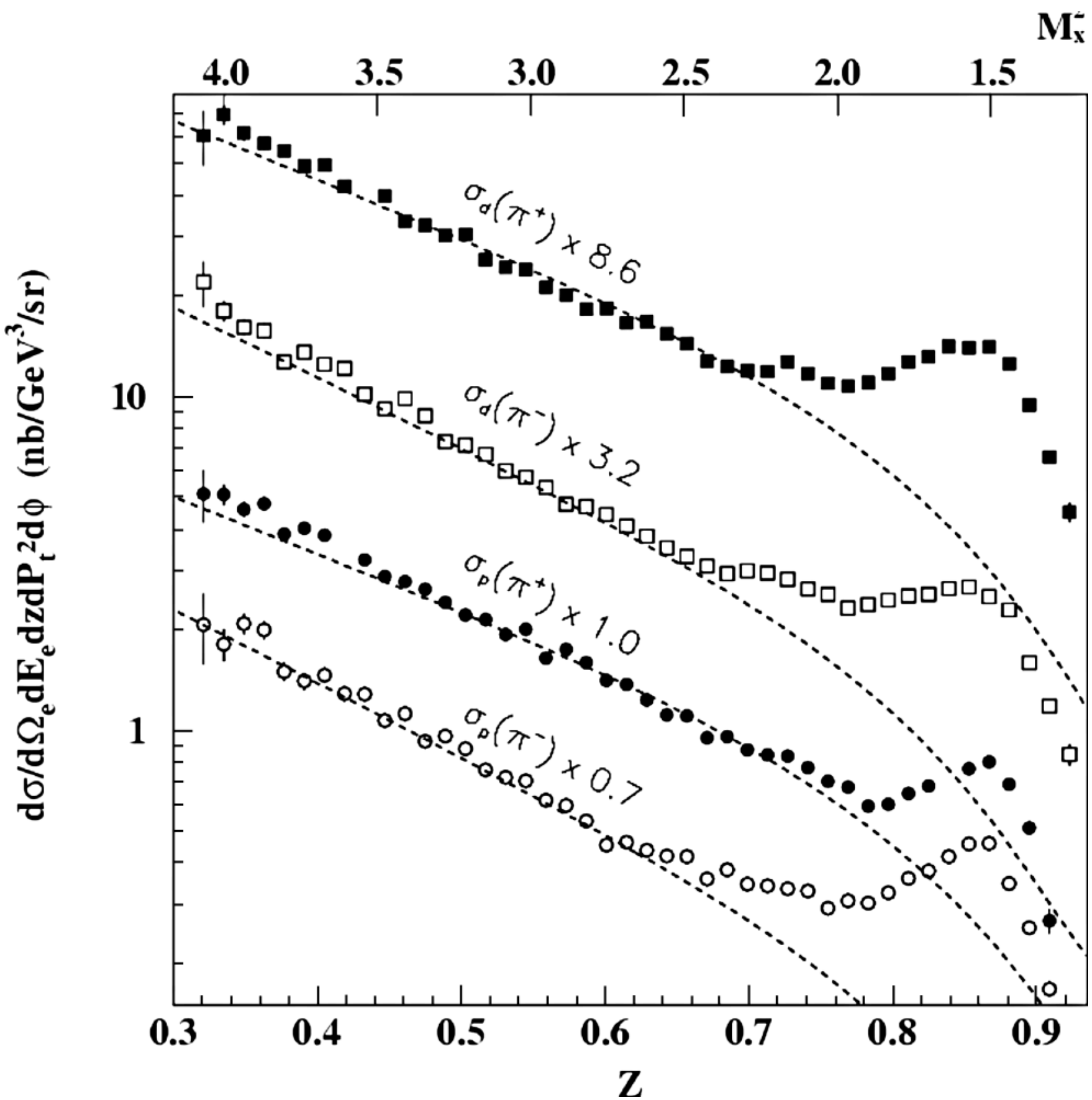
With p_T and k_T dependences, some kind of convolution is necessary to obtain final $P_{h\perp}$

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

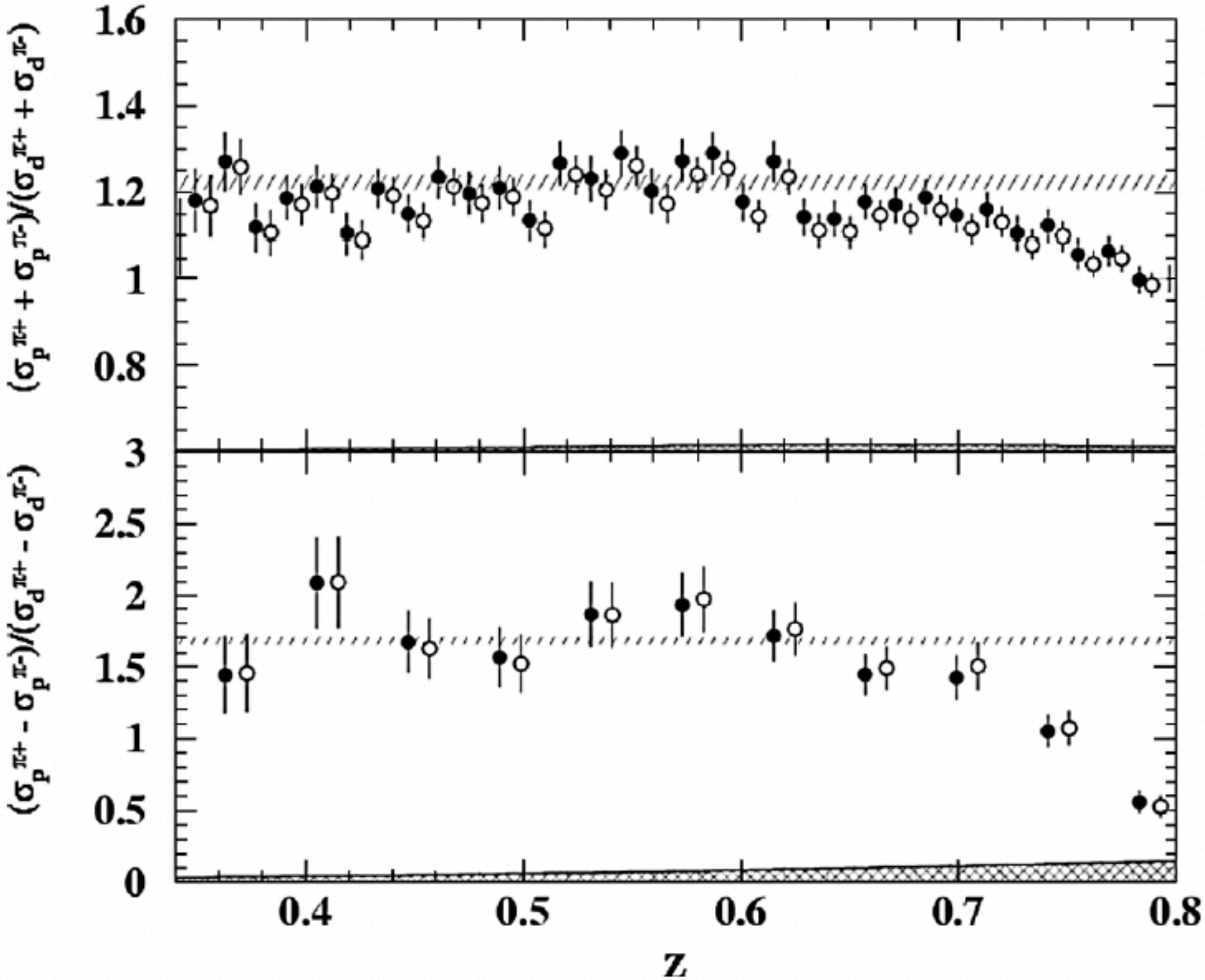
T. Navasardyan et al., PRL 98 022001 (2007)



Factorization Test: E00-108

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

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



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).)

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}(1+\frac{\gamma^2}{2x}) \Big\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} \Big\}$$

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⊥/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:

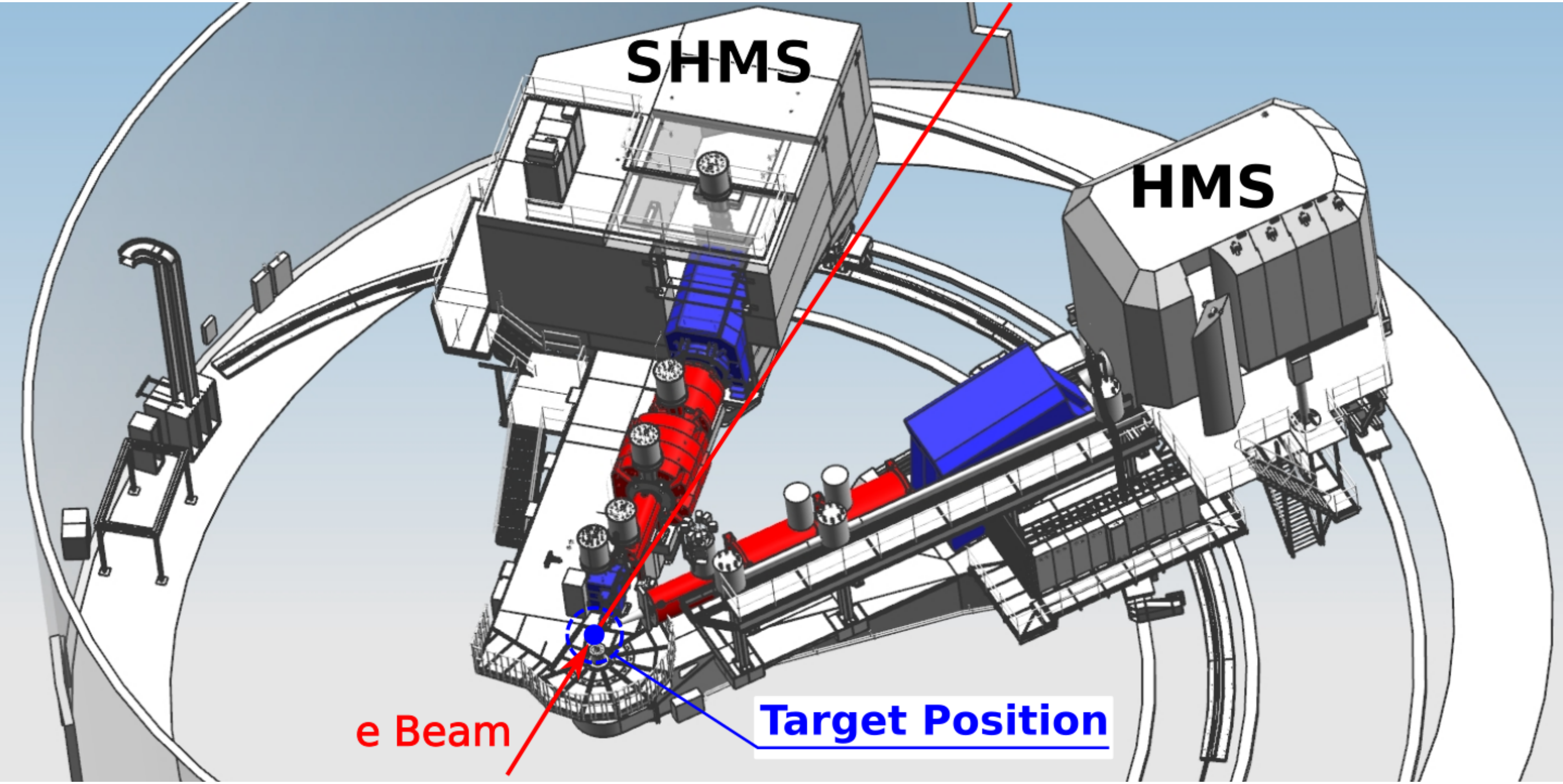
$$M(x,Q^2,z,P_{hT},\phi) = \frac{d\sigma_{ee'\pi X}}{d\sigma_{ee'X}} = \frac{M_0}{2\pi < \mu^2 >} e^{-P_{hT}^2/<\mu^2>} (1 + A\cos\phi + B\cos 2\phi)$$

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

Experimental Setup: Hall C Spectrometers at Jefferson Lab

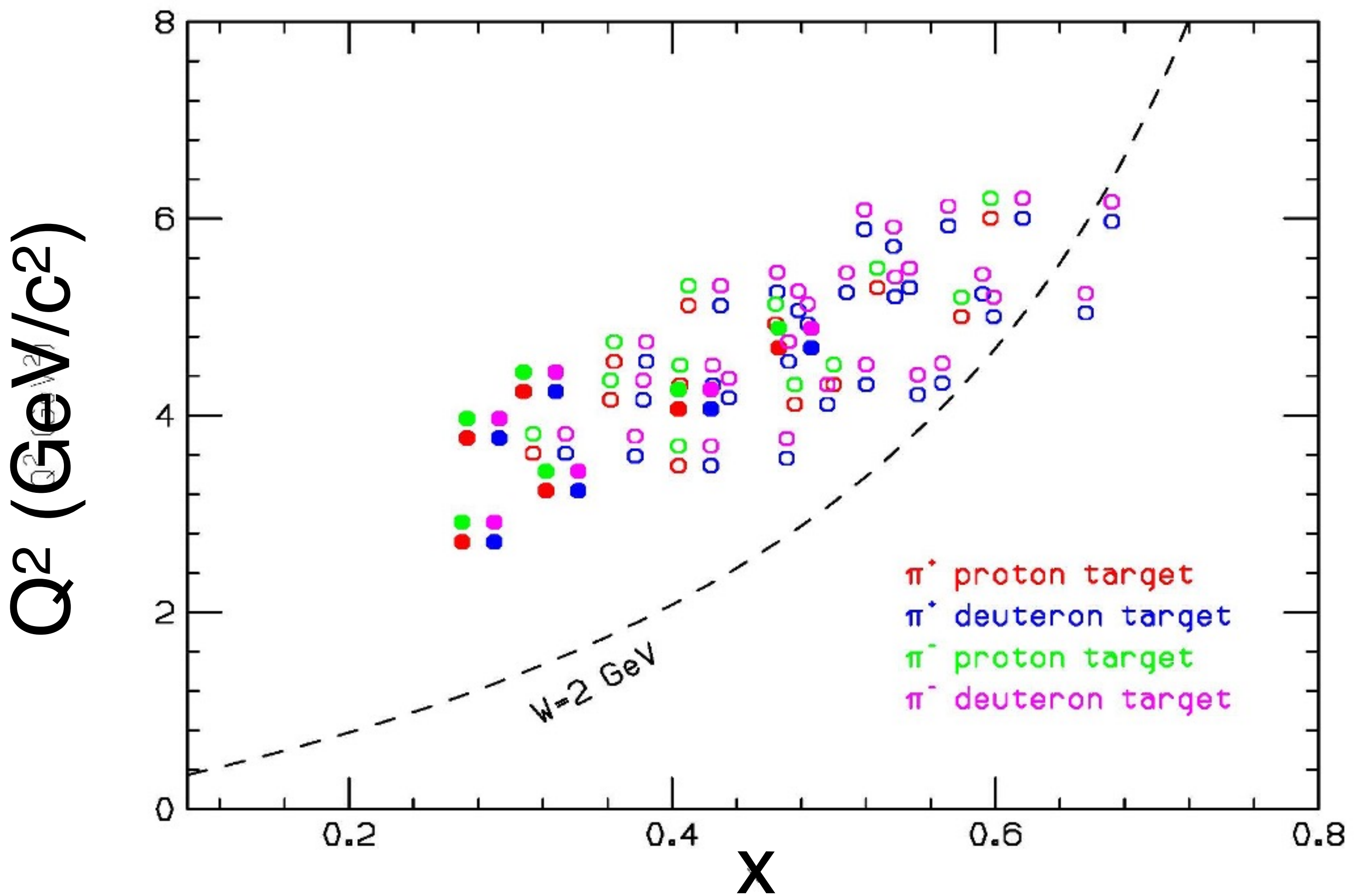
- CW Electron Beam, energies up to 11 GeV
- Two magnetic focusing spectrometers on common pivot: HMS and SHMS
- High cooling power 10 cm liquid Hydrogen and Deuterium targets plus Al window dummy for background subtraction
- $W^2 = 5.08$ GeV^2 and larger (up to 11.38 GeV^2)
- SHMS angle down to 6.6° (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)
- Improved coverage in all kinematic variables, especially ϕ and p_T
- Chose to keep Q^2/x fixed $q_Y \sim$ constant (exception are data scanning Q^2 at fixed x)
- All kinematics both for π^+ (and K^+) and π^- (and K^-), both for LH2 and LD2 (and Aluminum dummy)

Hall C Spectrometers

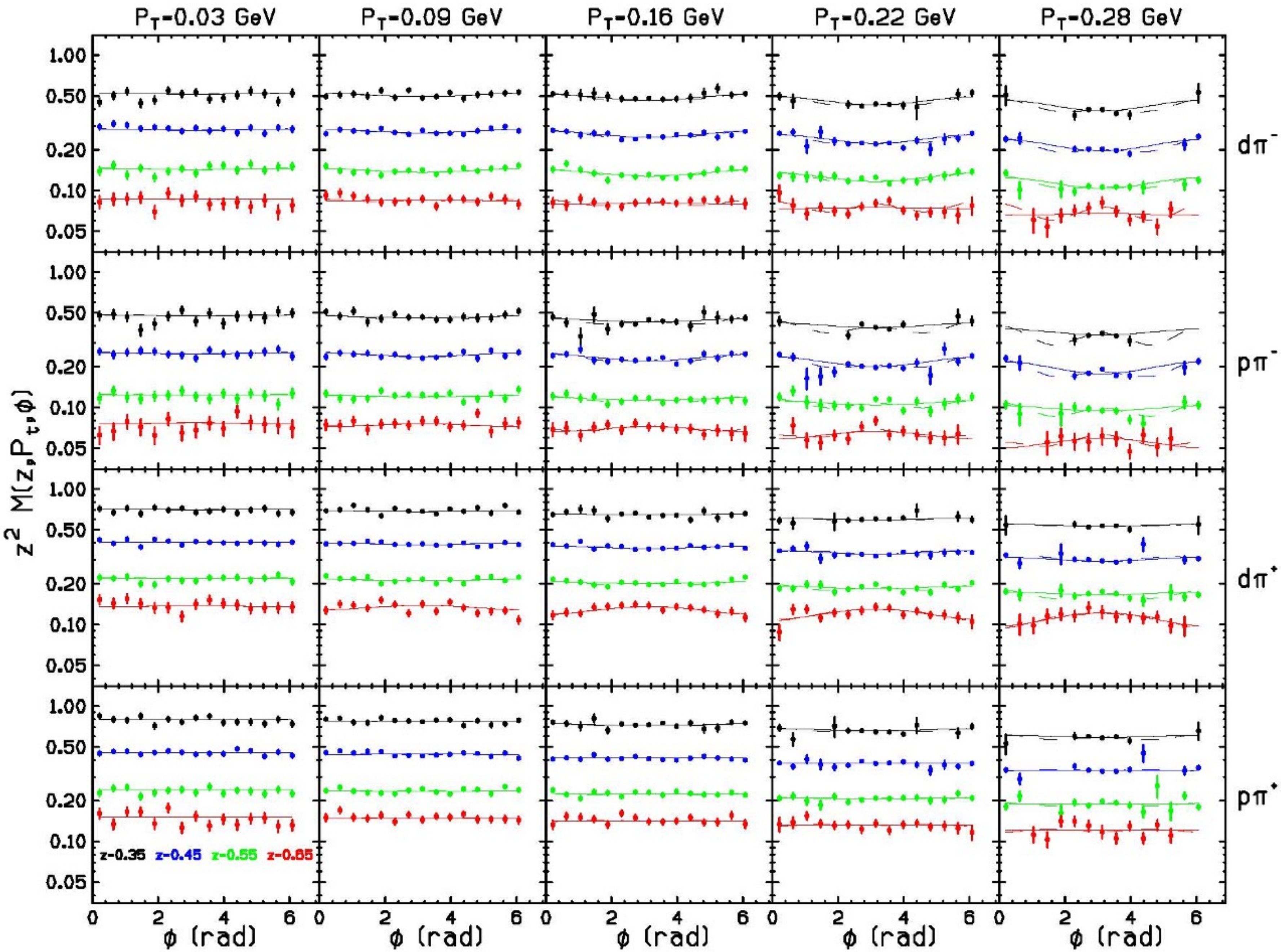


Kinematic Coverage in (x, Q2)

- 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



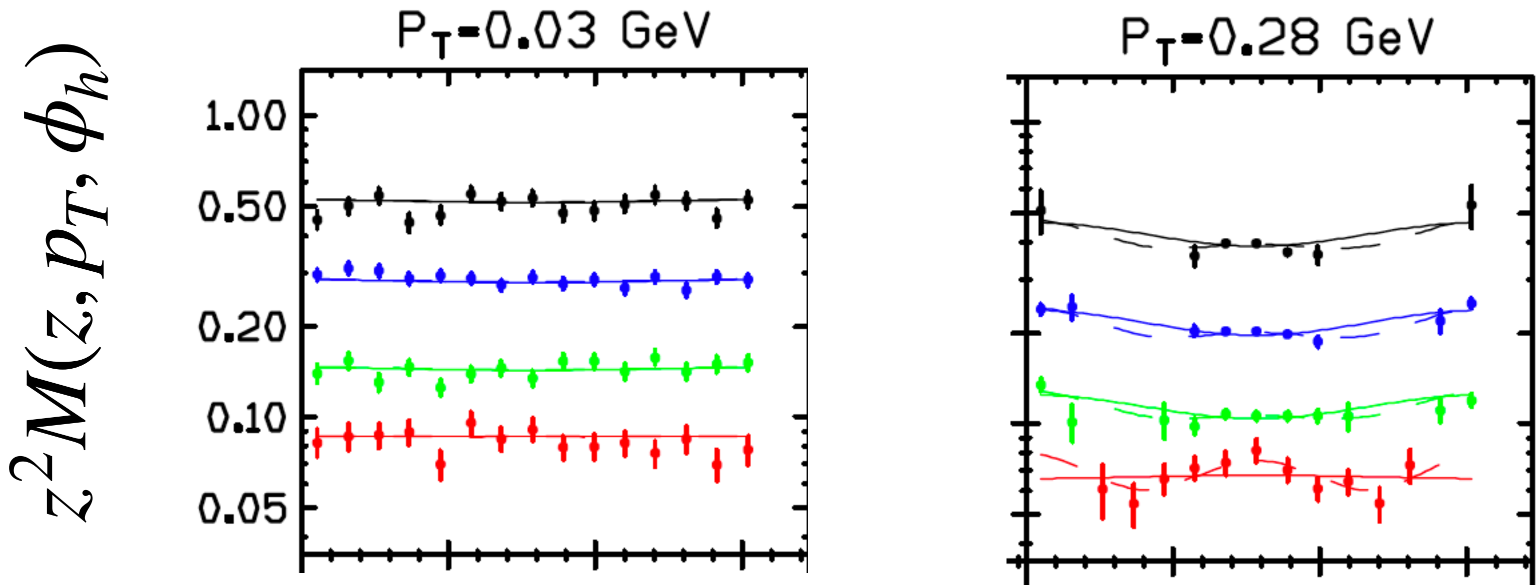
Azimuthal Dependence at x=0.3, Q^2 = 3.0 GeV/c^2



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

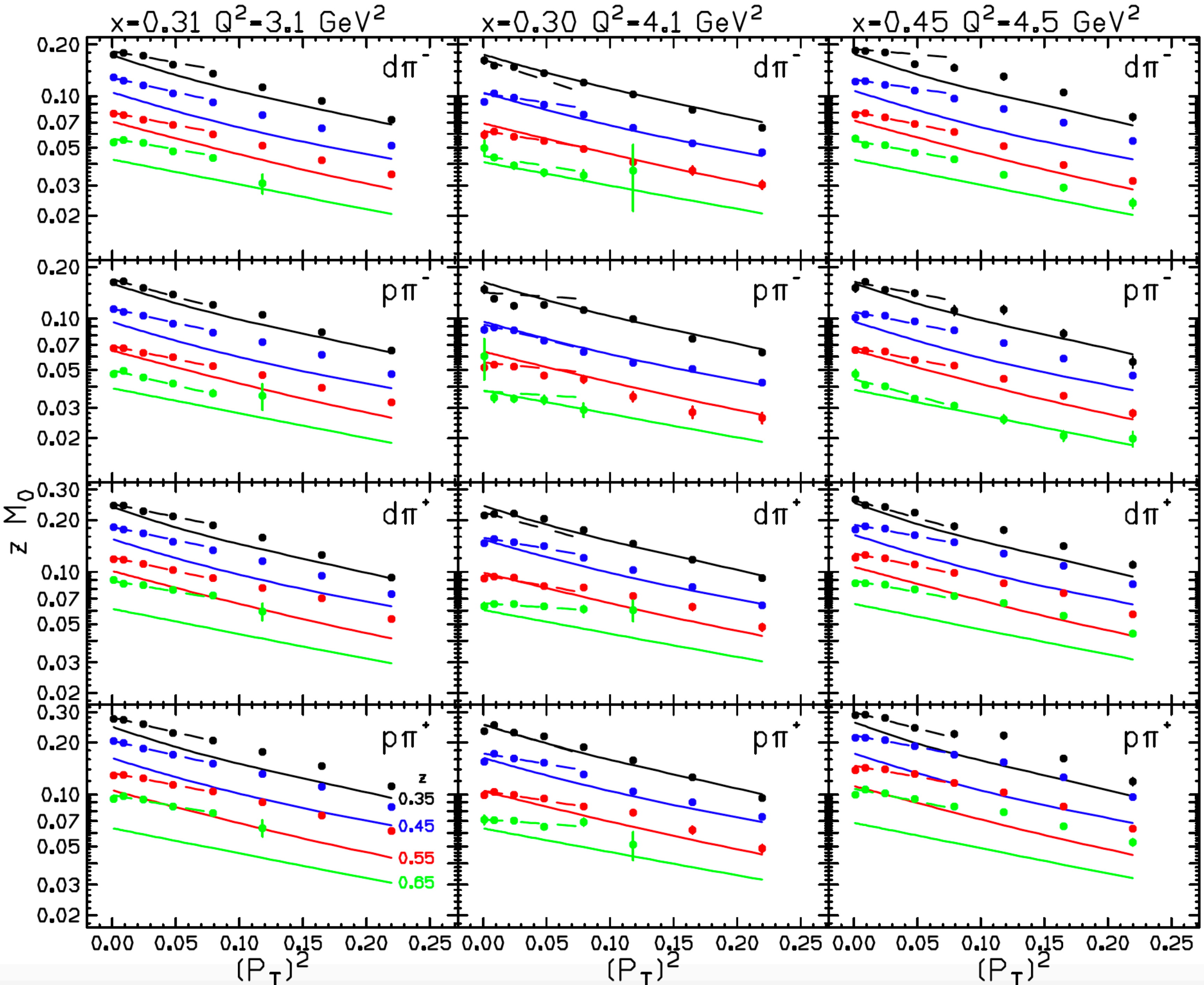
Insets of Azimuthal Dependence at x=0.3, Q^2 = 3.0



dπ^-

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

Transverse Momentum Dependence

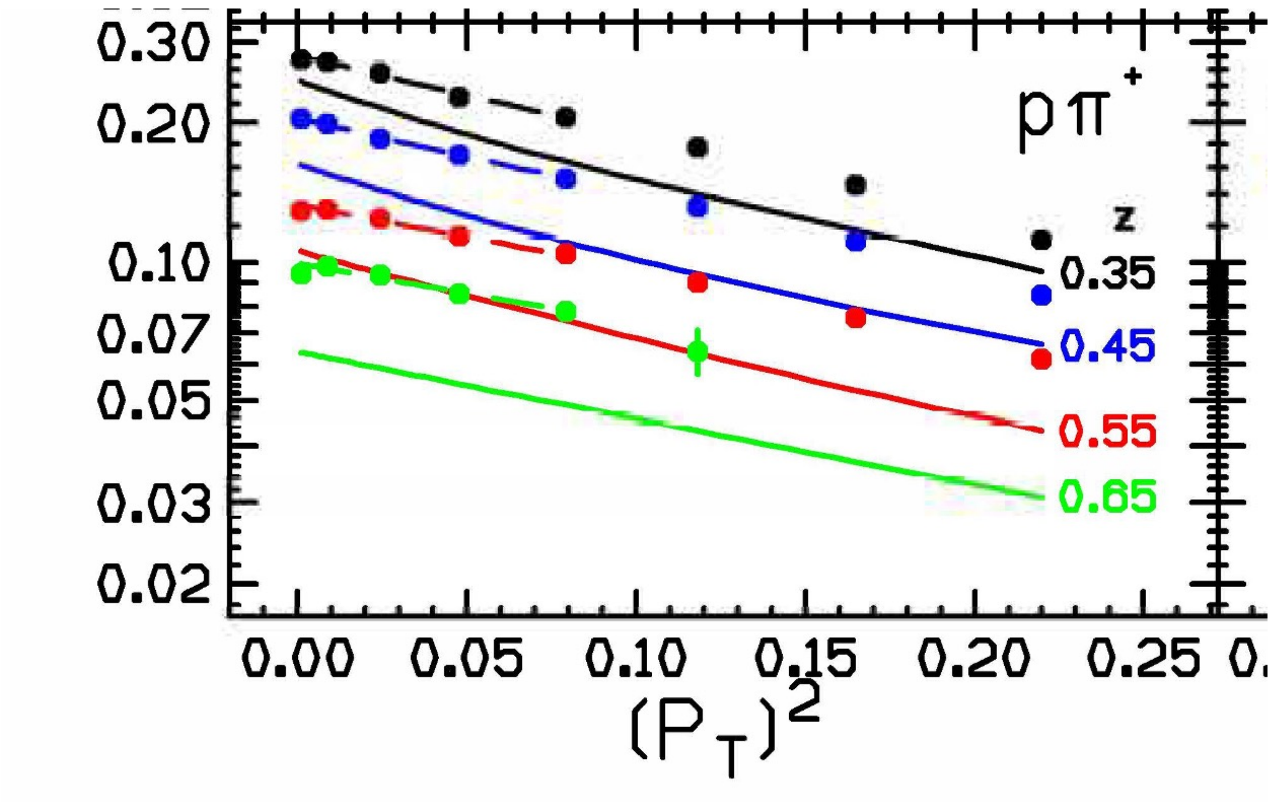


z=0.35
z=0.45
z=0.55
z=0.65

Dashed: Fit to 1st 5 bins

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

Inset of Transverse Momentum Dependence

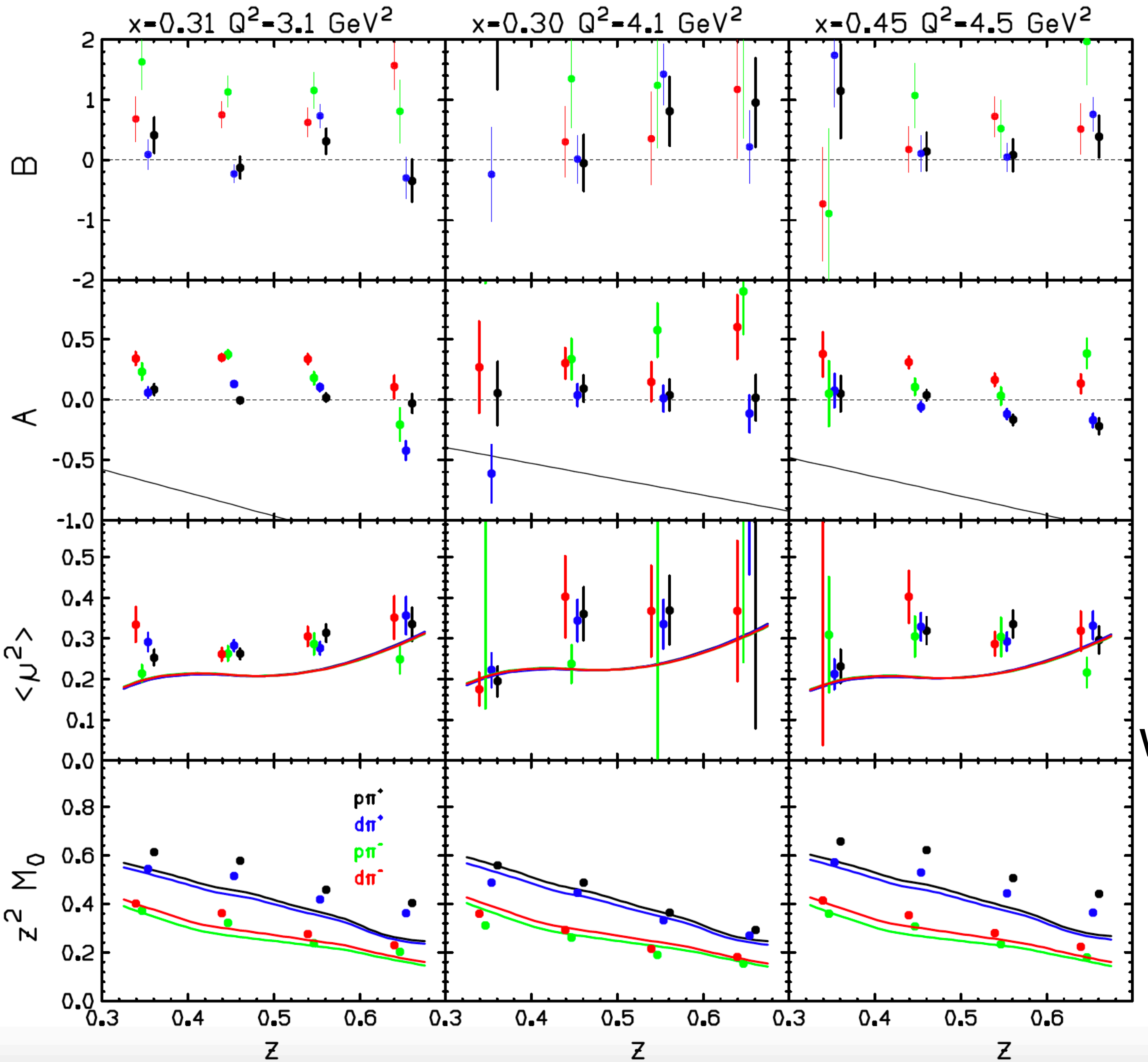


- Slopes are smaller at low transverse momentum than at higher values.

➡ Single width gaussian gives poor fit

- Better agreement with MAP slopes at higher transverse momentum.

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



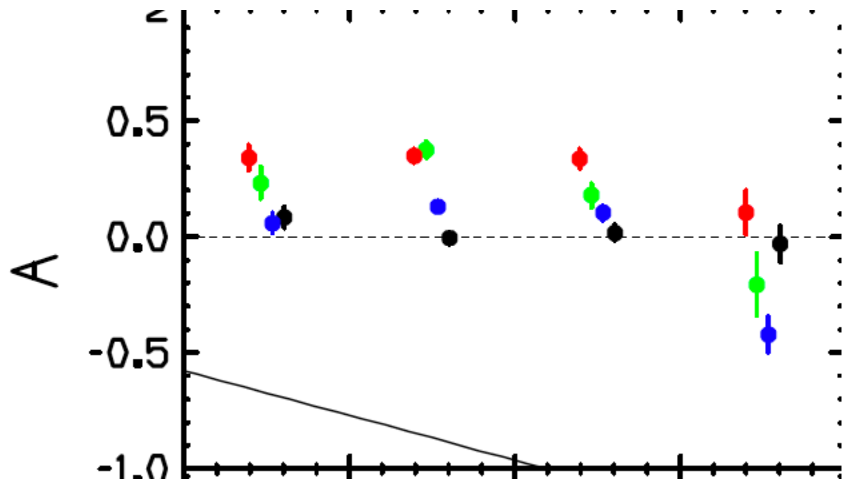
$p\pi^+$ $d\pi^+$ $p\pi^-$ $d\pi^-$

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)

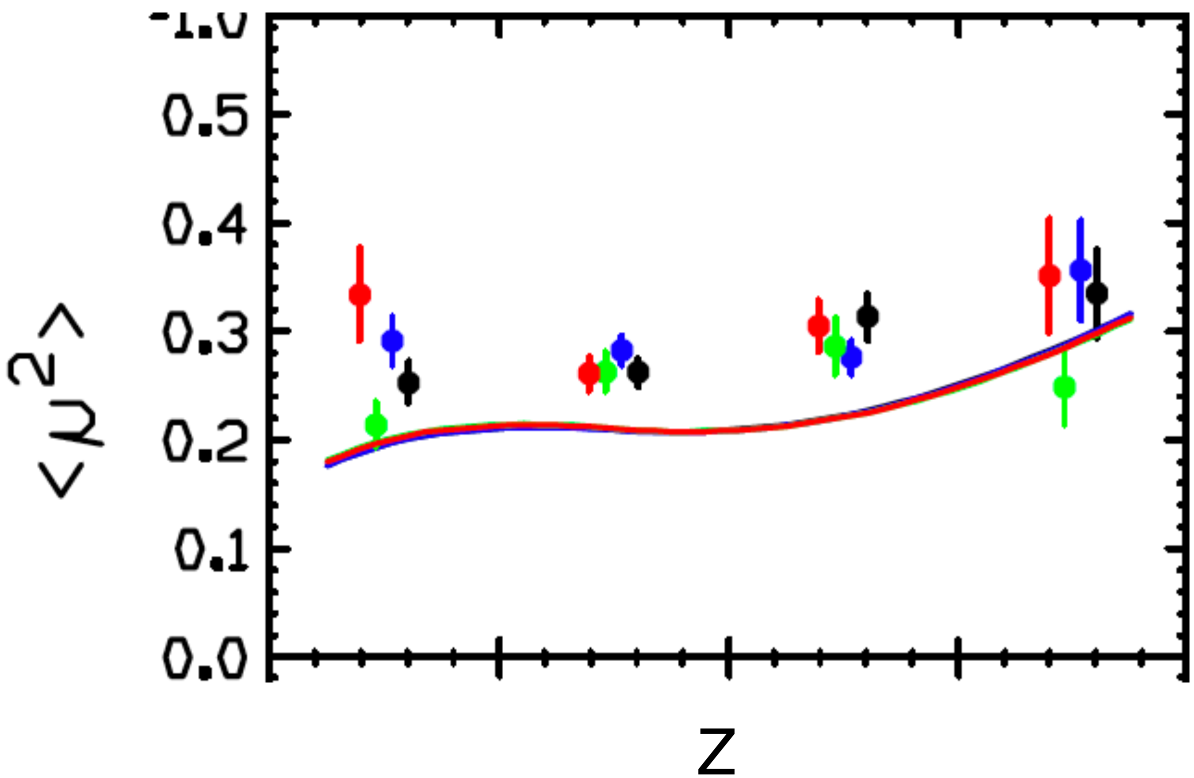


pπ^+ dπ^+ pπ^- dπ^-

“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, Q^2=3.0 GeV/c^2)



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

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

Summary and Outlook

- 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!
- Currently running in Hall C: Measurement of π^0 SIDIS (at same time as DVCS) using new Neutral Particle Detector. Longitudinal/transverse separated cross sections of high stat precision expected
- Measurement of Longitudinal/transverse ratio R in charged π SIDIS presently scheduled to take place in 2025 (first precise measurement!)