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.

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

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

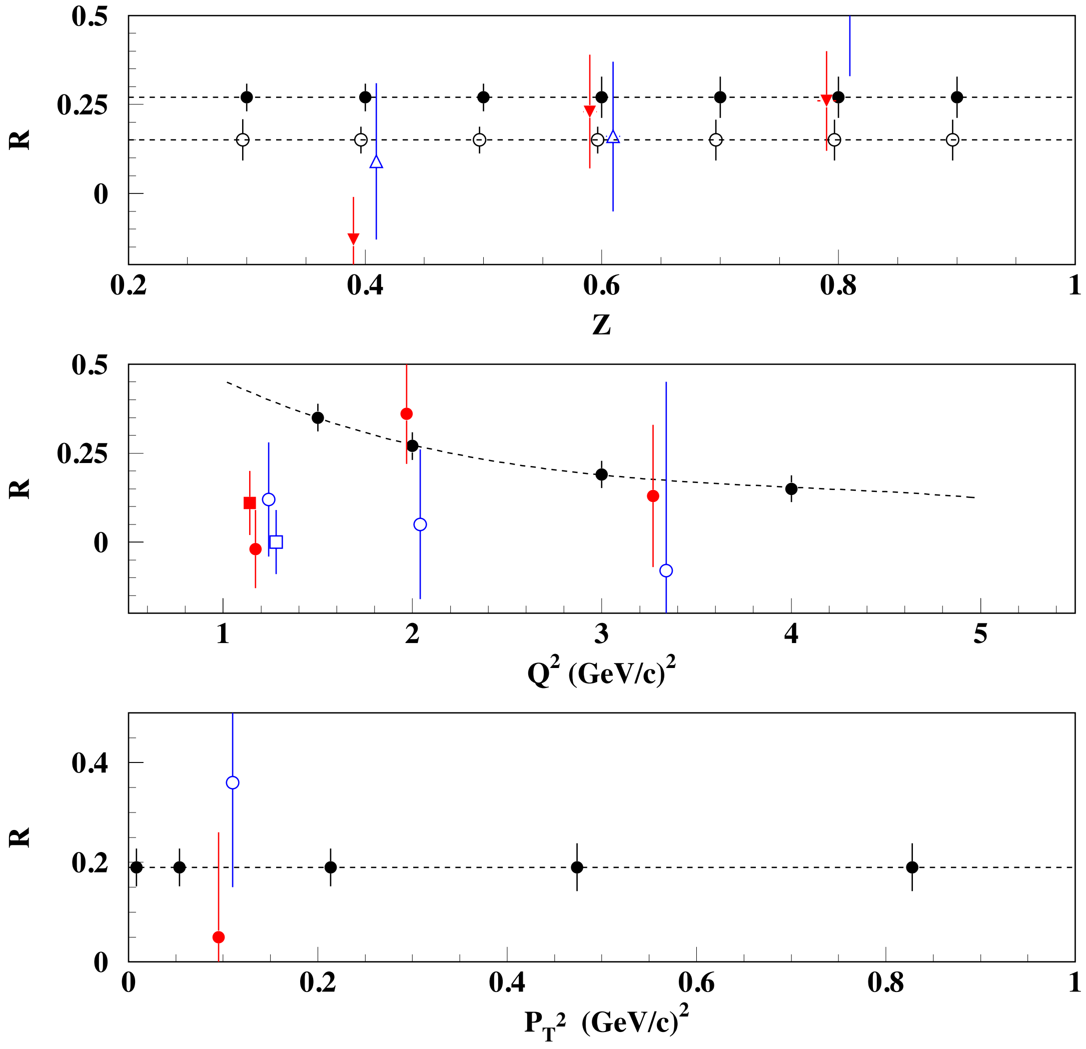
$R = \sigma_L/\sigma_T$ is a basic aspect of the photon-parton interaction

- First DIS evidence that quarks had spin ½ (R→0 as $Q^2 \to \infty$)
- At moderate fixed x, falls as $1/Q^2$
- At moderate Q^2 finite, non-zero, sensitive to indirect gluon effects and higher twist
- In naïve quark model, sensitive to intrinsic transverse momentum k_T:

$$R = 4(M^2x^2 - \langle k_t^2 \rangle)/(Q^2 + 2\langle k_t^2 \rangle)$$

Connected to TMDs!

Previous compared to proposed



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

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

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

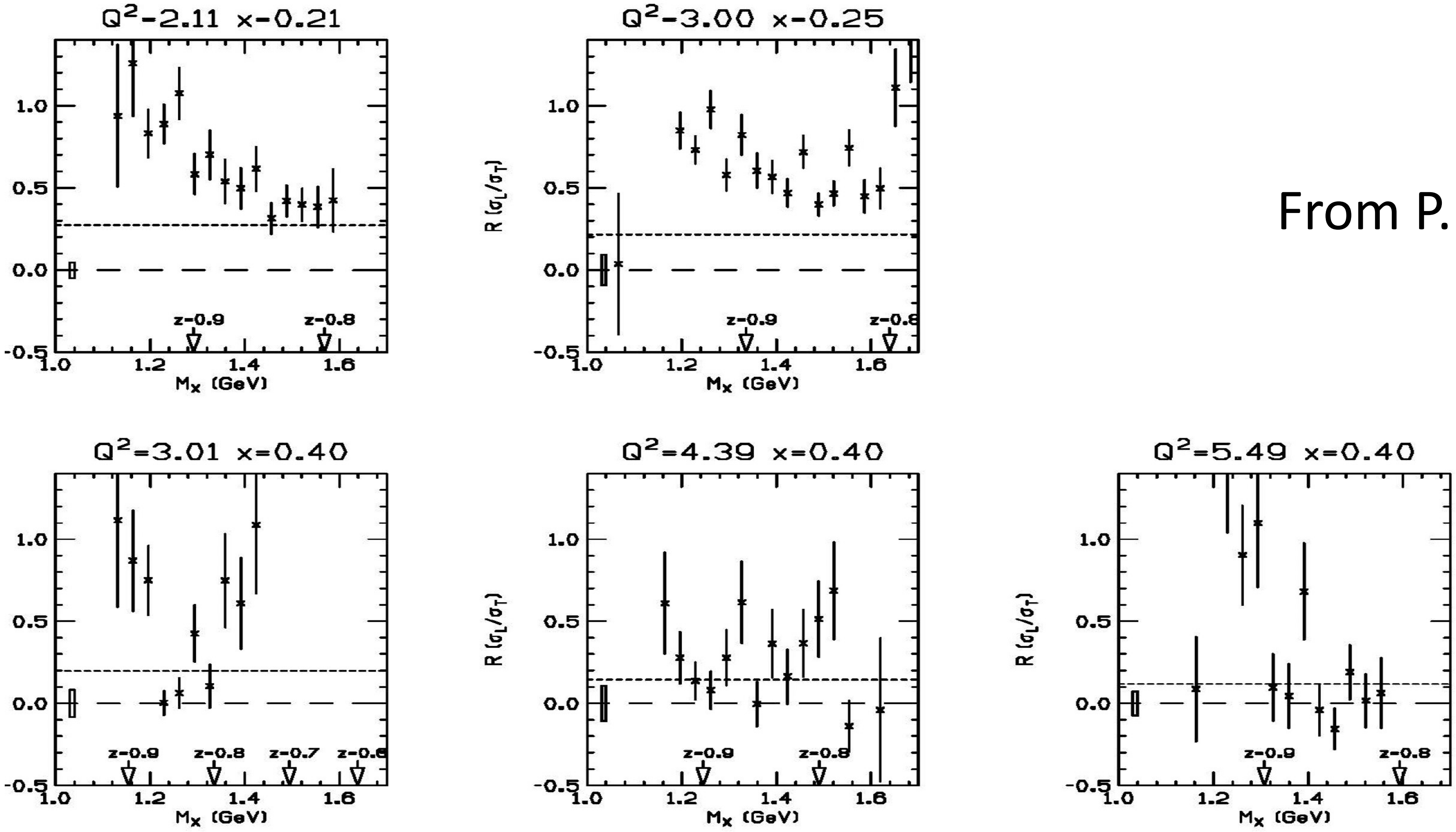
$$R^{\pi^+}_{SIDIS} = R^{\pi^-}_{SIDIS}? \qquad R^{H}_{SIDIS} = R^{D}_{SIDIS}? \qquad R^{\pi^+}_{SIDIS} = R^{K^+}_{SIDIS}? \qquad R^{K^+}_{SIDIS} = R^{K^-}_{SIDIS}?$$

- Important for determining spin structure function g_1^h (need term $(1 + \varepsilon R)$ to get g_1^h/F_1^h from $A_{\|}^h$)

- 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

Preliminary SIDIS Results from Hall C!!!



From P. Bosted

E12-06-104: Original Choice of Kinematics & Beam Time

- Map R^H_{SIDIS} and R^D_{SIDIS} as a function of z at x = 0.2 and Q^2 = 2.0 GeV^2

  168 Hours

  - **Need to experimentally see if $R^H_{SIDIS} = R^D_{SIDIS}$, just as $R^H_{DIS} = R^D_{DIS}$!**

- Map R^H_{SIDIS} as a function of z at x = 0.4 and Q^2 = 4.0 GeV^2

  319 Hours

  - **Test dominance of quark fragmentation**
  - **Study the inclusive-exclusive connection (soft vs. hard gluon exchange?)**

- Map R^H_{SIDIS} as a function of p_T^2 at x = 0.3 and Q^2 = 3.0 GeV^2

  311 Hours

  - **Extend understanding of fragmentation process to high p_T**
  - **No guidance from factorization theorems here yet**

- Add kinematics to map R^H_{SIDIS} for Q^2 = 1.5 - 5.0 GeV^2

  88 Hours

  - **Does R_{SIDIS} behave like R_{DIS} as function of Q^2?**

+75 Hours
(overhead)

= 40 days

These data required for our understanding of SIDIS, and will further our understanding of fragmentation.
These data enter into completely unknown territory!

Original Kinematic Plan: z dependence at x=0.2, Q^2=2.0

TABLE I. L/T Separations as a function of z at (x, Q^2) = (0.20,2.00)

x	Q^2 (GeV^2)	W^2 (GeV^2)	z	W'^2 (GeV^2)	E' (GeV)	θ_e (deg)	q_γ (GeV)	θ_γ (deg)	ϵ	Eo (GeV)	R_{DIS}
0.20	2.00	8.88	0.30	6.48	1.271	28.26	5.513	6.27	0.34	6.6	0.27
			0.30	6.48	3.471	14.70	5.513	9.19	0.66	8.8	0.27
			0.30	6.48	5.671	10.27	5.513	10.57	0.80	11.0	0.27
0.20	2.00	8.88	0.40	5.68	1.271	28.26	5.513	6.27	0.34	6.6	0.27
			0.40	5.68	3.471	14.70	5.513	9.19	0.66	8.8	0.27
			0.40	5.68	5.671	10.27	5.513	10.57	0.80	11.0	0.27
0.20	2.00	8.88	0.50	4.88	1.271	28.26	5.513	6.27	0.34	6.6	0.27
			0.50	4.88	3.471	14.70	5.513	9.19	0.66	8.8	0.27
			0.50	4.88	5.671	10.27	5.513	10.57	0.80	11.0	0.27
0.20	2.00	8.88	0.65	3.68	1.271	28.26	5.513	6.27	0.34	6.6	0.27
			0.65	3.68	3.471	14.70	5.513	9.19	0.66	8.8	0.27
			0.65	3.68	5.671	10.27	5.513	10.57	0.80	11.0	0.27
0.20	2.00	8.88	0.85	2.08	1.271	28.26	5.513	6.27	0.34	6.6	0.27
			0.85	2.08	3.471	14.70	5.513	9.19	0.66	8.8	0.27
			0.85	2.08	5.671	10.27	5.513	10.57	0.80	11.0	0.27

Original Kinematic Plan: z dependence at x=0.4, Q^2=4.0

TABLE II. L/T Separations as a function of z at (x, Q^2) = (0.40,4.00)

x	Q^2 (GeV^2)	W^2 (GeV^2)	z	W'^2 (GeV^2)	E' (GeV)	θ_e (deg)	q_γ (GeV)	θ_γ (deg)	ϵ	Eo (GeV)	R_{DIS}
0.40	4.00	6.88	0.30	5.08	1.271	40.40	5.692	8.32	0.31	6.6	0.19
			0.30	5.08	3.471	20.85	5.692	12.54	0.65	8.8	0.19
			0.30	5.08	5.671	14.55	5.692	14.49	0.79	11.0	0.19
0.40	4.00	6.88	0.40	4.48	1.271	40.40	5.692	8.32	0.31	6.6	0.19
			0.40	4.48	3.471	20.85	5.692	12.54	0.65	8.8	0.19
			0.40	4.48	5.671	14.55	5.692	14.49	0.79	11.0	0.19
0.40	4.00	6.88	0.50	3.88	1.271	40.40	5.692	8.32	0.31	6.6	0.19
			0.50	3.88	3.471	20.85	5.692	12.54	0.65	8.8	0.19
			0.50	3.88	5.671	14.55	5.692	14.49	0.79	11.0	0.19
0.40	4.00	6.88	0.65	2.98	1.271	40.40	5.692	8.32	0.31	6.6	0.19
			0.65	2.98	3.471	20.85	5.692	12.54	0.65	8.8	0.19
			0.65	2.98	5.671	14.55	5.692	14.49	0.79	11.0	0.19
0.40	4.00	6.88	0.85	1.78	1.271	40.40	5.692	8.32	0.31	6.6	0.19
			0.85	1.78	3.471	20.85	5.692	12.54	0.65	8.8	0.19
			0.85	1.78	5.671	14.55	5.692	14.49	0.79	11.0	0.19

Original Kinematic Plan: p_T^2 dependence at x=0.3, Q^2=3.0

TABLE III. L/T Separations as a function of p_T^2 at $(x, Q^2) = (0.30, 3.00)$

x	Q^2 (GeV^2)	W^2 (GeV^2)	z	W'^2 (GeV^2)	E' (GeV)	θ_e (deg)	q_γ (GeV)	θ_γ (deg)	ϵ	Eo (GeV)	R_{DIS}	θ_{pq} (deg)
0.30	3.00	7.88	0.50	4.380	1.271	34.80	5.603	7.44	0.33	6.6	0.19	-2.0
			0.50	4.380	3.471	18.03	5.603	11.05	0.66	8.8		
			0.50	4.380	5.671	12.59	5.603	12.75	0.80	11.0		
0.30	3.00	7.88	0.50	4.380	1.271	34.80	5.603	7.44	0.33	6.6	0.19	0.0
			0.50	4.380	3.471	18.03	5.603	11.05	0.66	8.8		
			0.50	4.380	5.671	12.59	5.603	12.75	0.80	11.0		
0.30	3.00	7.88	0.50	4.380	1.271	34.80	5.603	7.44	0.33	6.6	0.19	5.0
			0.50	4.380	3.471	18.03	5.603	11.05	0.66	8.8		
			0.50	4.380	5.671	12.59	5.603	12.75	0.80	11.0		
0.30	3.00	7.88	0.50	4.380	1.271	34.80	5.603	7.44	0.33	6.6	0.19	10.0
			0.50	4.380	3.471	18.03	5.603	11.05	0.66	8.8		
			0.50	4.380	5.671	12.59	5.603	12.75	0.80	11.0		
0.30	3.00	7.88	0.50	4.380	1.271	34.80	5.603	7.44	0.33	6.6	0.19	15.0
			0.50	4.380	3.471	18.03	5.603	11.05	0.66	8.8		
			0.50	4.380	5.671	12.59	5.603	12.75	0.80	11.0		
0.30	3.00	7.88	0.50	4.380	1.271	34.80	5.603	7.44	0.33	6.6	0.19	20.0
			0.50	4.380	3.471	18.03	5.603	11.05	0.66	8.8		
			0.50	4.380	5.671	12.59	5.603	12.75	0.80	11.0		

Original Kinematic Plan: Q^2 dependence at z=0.5

TABLE IV. Additional L/T Separations as a function of Q^2 at variable (x, Q^2).

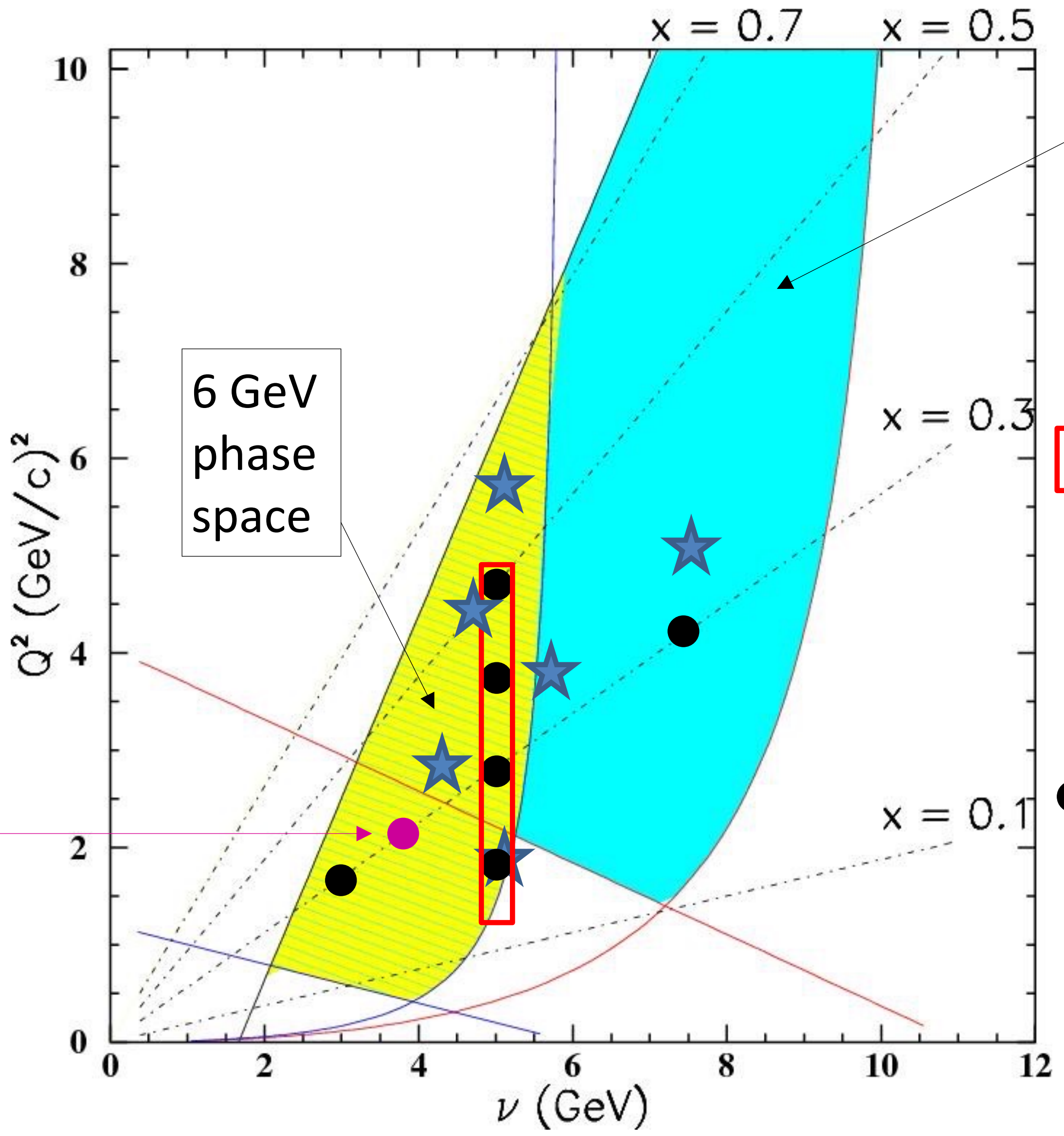
x	Q^2 (GeV^2)	W^2 (GeV^2)	z	W'^2 (GeV^2)	E' (GeV)	θ_e (deg)	q_γ (GeV)	θ_γ (deg)	ϵ	Eo (GeV)	R_{DIS}
0.15	1.50	9.38	0.50	5.130	1.271	24.41	5.468	5.51	0.35	6.6	0.35
			0.50	5.130	3.471	12.72	5.468	8.04	0.67	8.8	0.35
0.50	5.00	5.88	0.50	3.380	1.271	45.41	5.779	9.01	0.30	6.6	0.12
			0.50	3.380	3.471	23.34	5.779	13.77	0.64	8.8	0.12
			0.50	3.380	5.671	16.28	5.779	15.96	0.79	11.0	0.12

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)



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

E12-06-104 Running with Real, Existing Accelerator and Spectrometers

- Beam at 250 MHz instead 500 MHz @11 GeV with 4-Hall ops (accidentals worse)
- Singles rates need to be kept below 500 kHz (for detector and tracking efficiency understanding), original proposal underestimated SHMS momentum acceptance
- Accuracy of beam current measurement suffers at low currents (less than 15 μA)

  - ➢ These effects increase running time significantly

- Large SHMS acceptance allows us to get optimized z coverage with fewer central momentum settings; we can also reduce high z statistical goals (10k to 5k events)
- Use of existing Kaon LT data (for H/π^+ only)
- Further optimization of run plan in terms of number of beam energies and p_T range/settings; specifics depend on scheduling (beam energies + currents available)

  - ➢ With these realities and with our experience from the past years of Hall C running, we are confident we can still achieve our measurement goals within the previously approved 40 days.

Present Beam Schedule

- LAD - Sept 19 2024 to Dec 17 2024
- R-SIDIS – Start January 10 2025
  - R-SIDIS at 6.6 GeV at 60uA for 18 calendar days
  - R-SIDIS at 8.8 GeV at 60uA for 20 calendar days
  - R-SIDIS at "11.0" GeV at 50uA for 23 calendar days
  - R-SIDIS at 6.6 GeV at 60uA for 23 calendar days
- then the pion CT experiment.

- Power constraints from concurrent Hall A running will limit current at 5-pass to 32 μA
- Optimization/planning ongoing! Attempt to match π^0-SIDIS kinematics

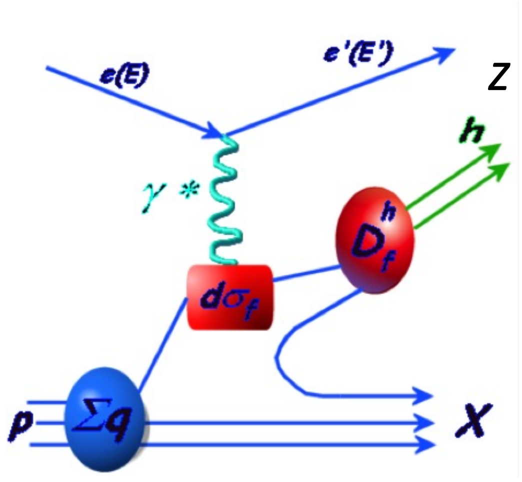
E12-09-017: Precision $(e,e'\pi^{\pm})$,$(e,e'K^{\pm})$ cross sections at low $P_{h\perp}$

Flavor Decomposition of SIDIS

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

$f_q(x)$ *: parton distribution function*

$D_q^h(z)$: fragmentation function



$z = E_h/\nu$

- 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

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

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

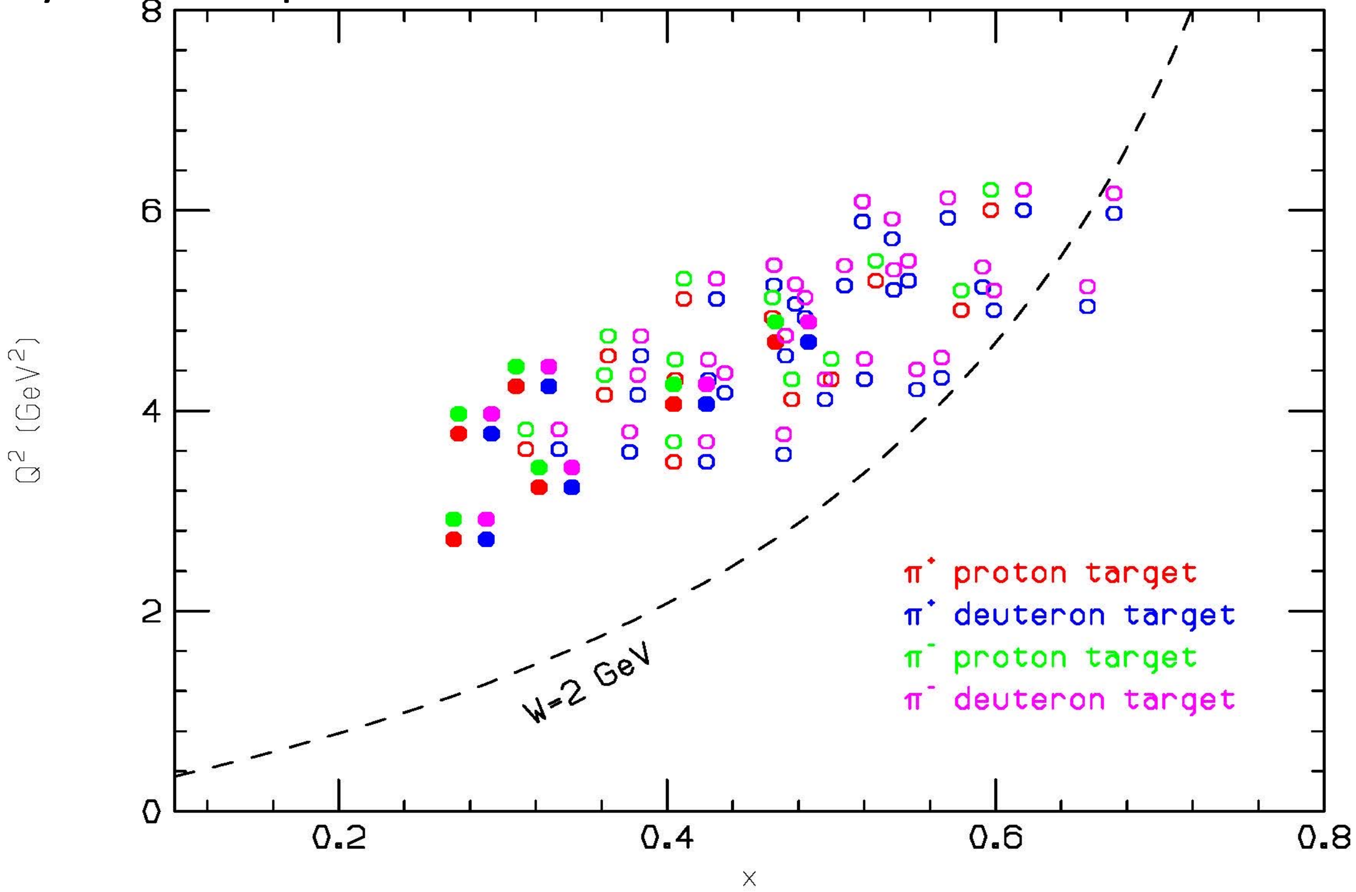
Kinematic coverage in (x,Q^2)

Solid circles are from pt-SIDIS, open circles CSV SIDIS

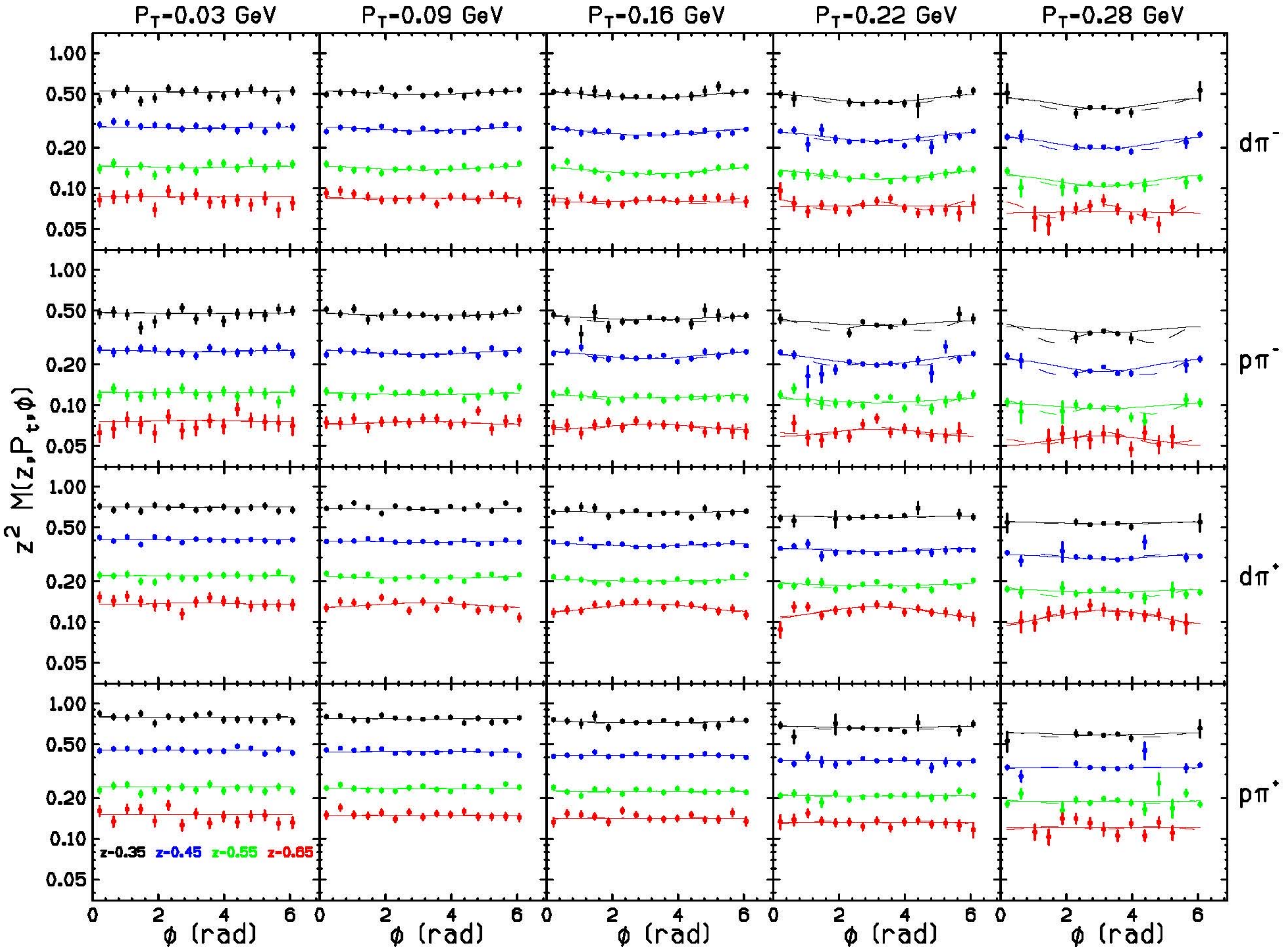
CLAS coverage extends to lower x and lower Q^2

each circle has 10,000 to 1000,000 events

Dominated by valance quark distributions



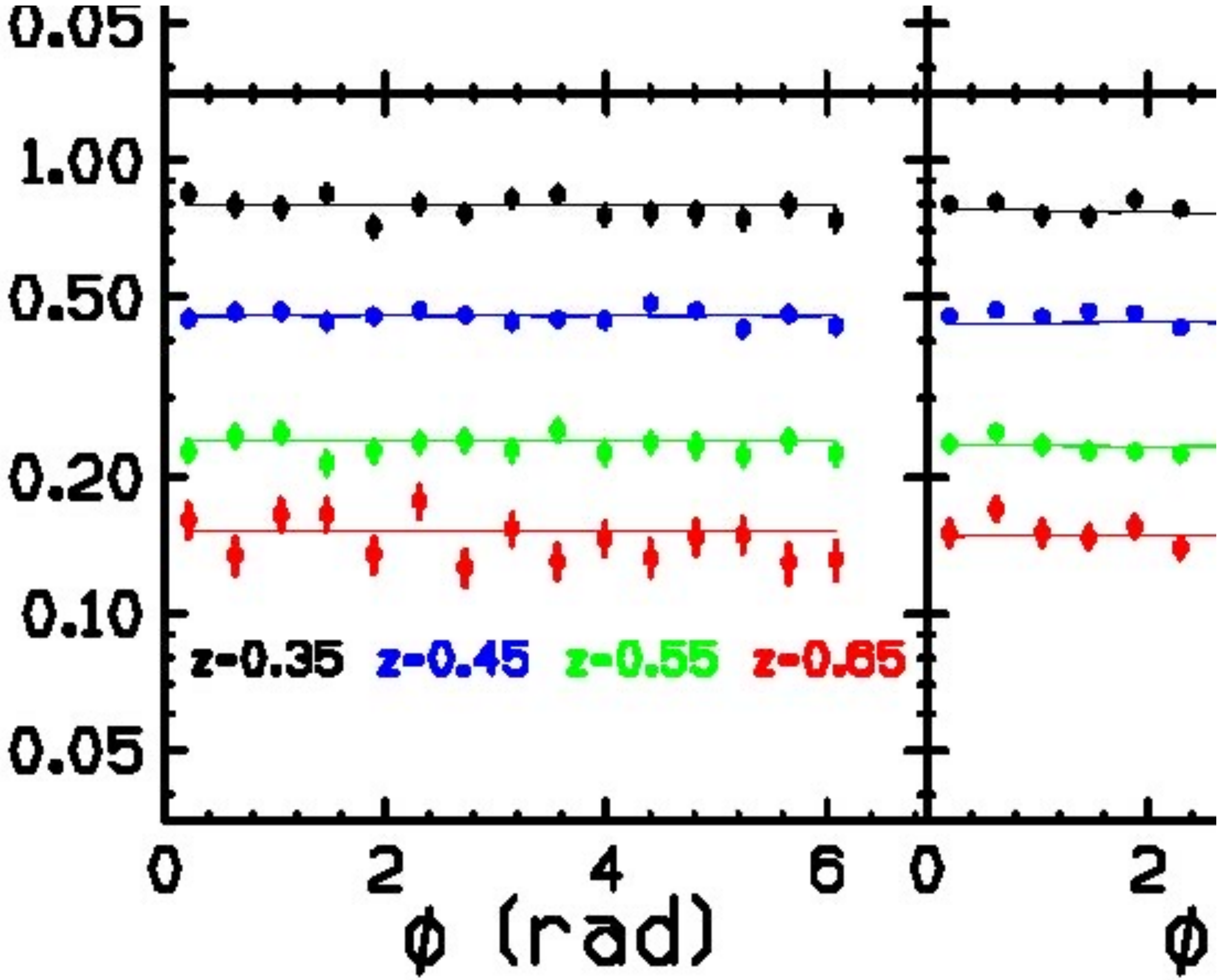
Latest Results - X = 0.3 Q^2=3 GeV^2



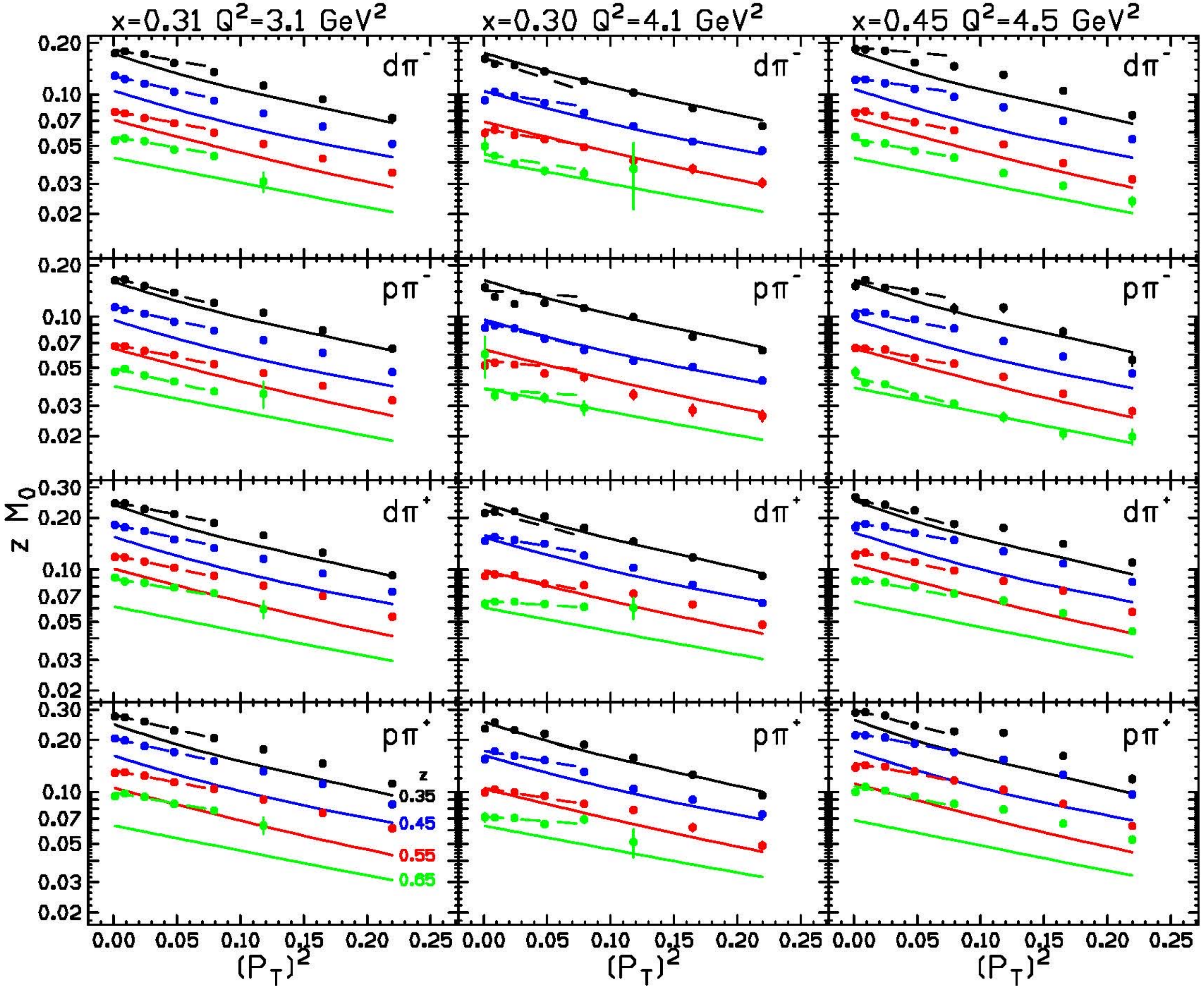
Multiplicity versus azimuthal angle for five bins in Pt, four bins in z (colors), and four cases

Curves are fits assuming a Gaussian dependance of width

Solid curves have B=0


0.05
1.00
0.50
0.20
0.10
0.05
z-0.35
z-0.45
z-0.55
z-0.65
0
2
4
6
0
2
ϕ (rad)
ϕ

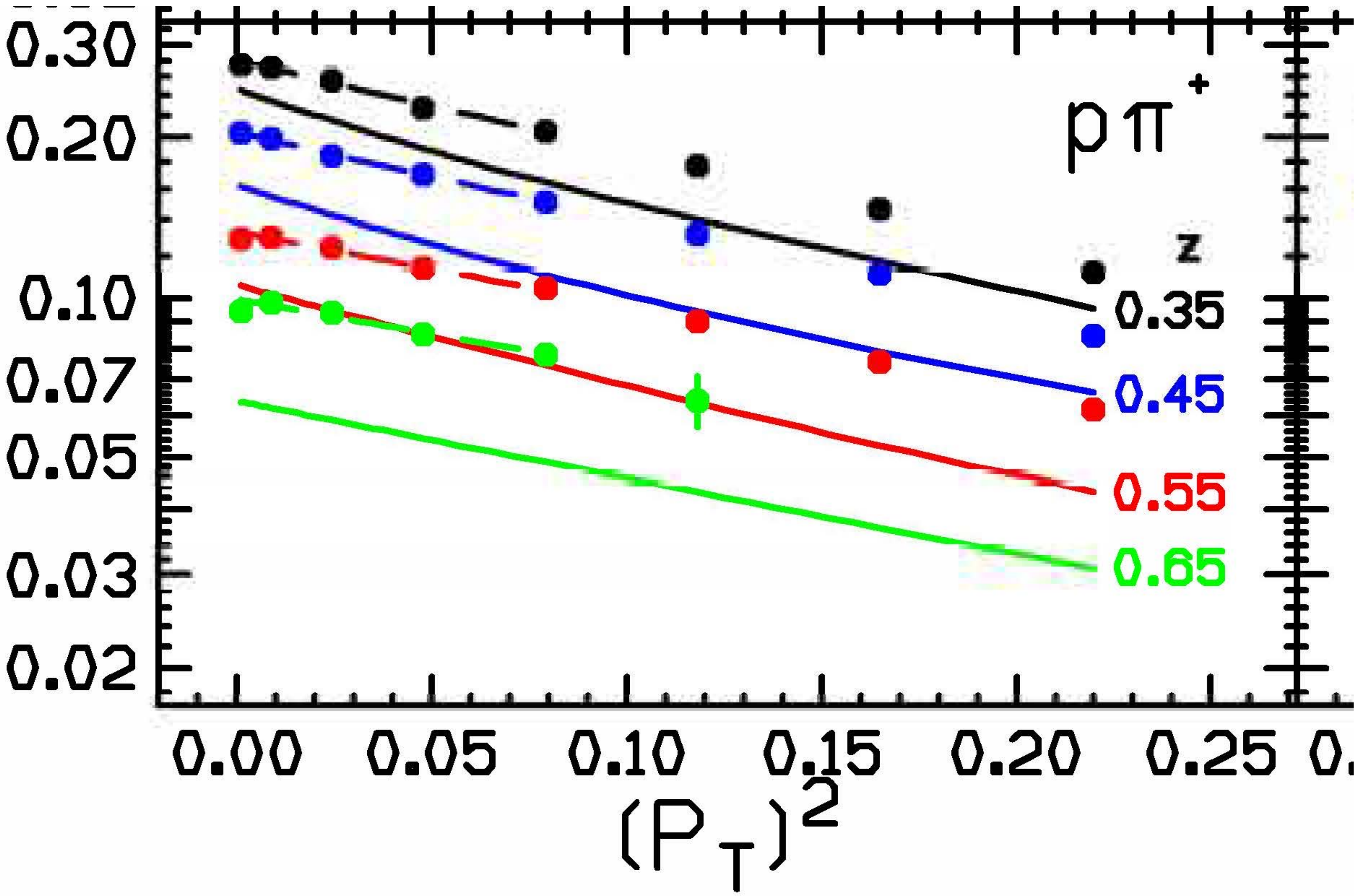
Latest Results – PT dependence



Multiplicity versus transverse momentum squared for three (x,Q2) settings, four cases, and four z bins, averaged over azimuthal angle.

Dashed curves are gaussian fit to first five bins

Solid curves from MAPS



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

Better agreement with MAPS slopes at higher transverse momentum

We measured 6-fold differential cross sections with polarized beam. There are contributions from five structure functions.

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

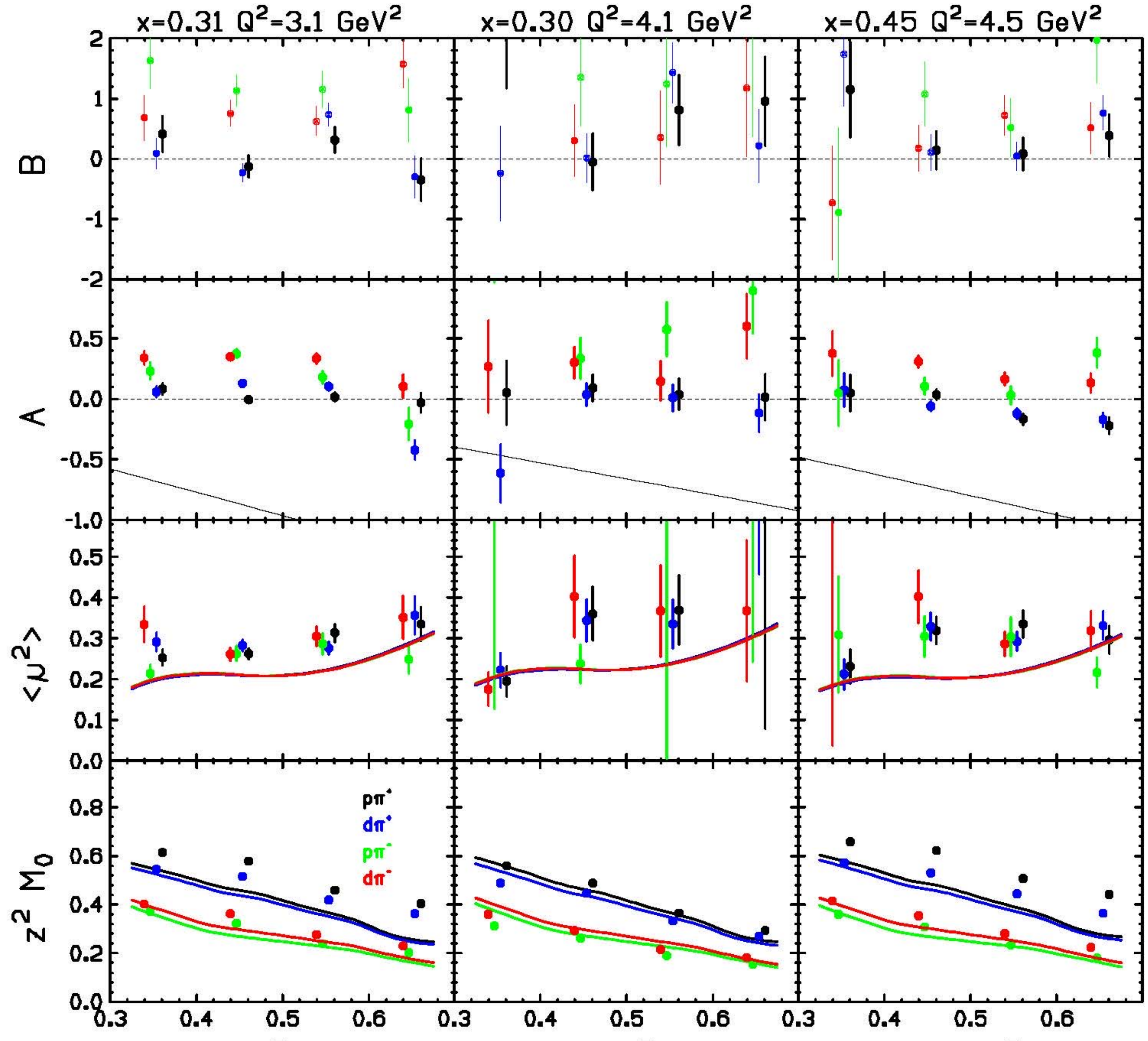
$$\Big\{F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h}$$

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

Define Multiplicity M as ratio of SIDIS cross section to DIS cross section.

$M(Pt) = M0(pt) * (1 + A*pt*\cos(\phi) + B*pt^2 \cos(2\phi))$

Latest Results – Fit analysis

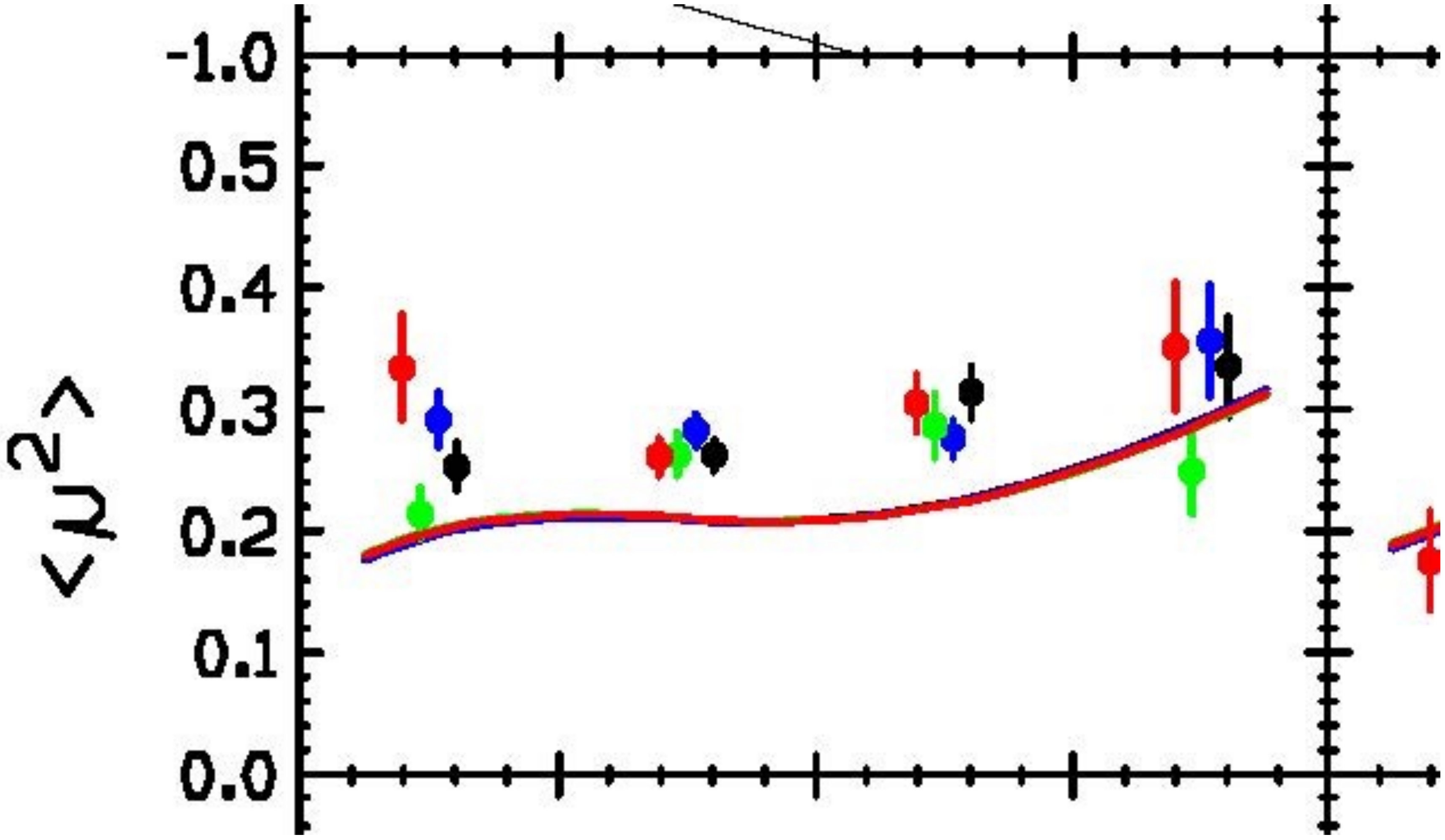


Four-parameter fit results for first five transverse momentum bins as a function of z for four cases and three (x,Q2) settings.

Both A and B are consistent with zero for positive pions, but greater than zero for negative pions

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

Other higher twist contributions seem to be important to evaluate.



Gaussian widths are constent between the four cases. This may place constraints on the difference in average transverse momentum of up and down quarks

Slopes are low Pt are shallower than MAPS calculations.

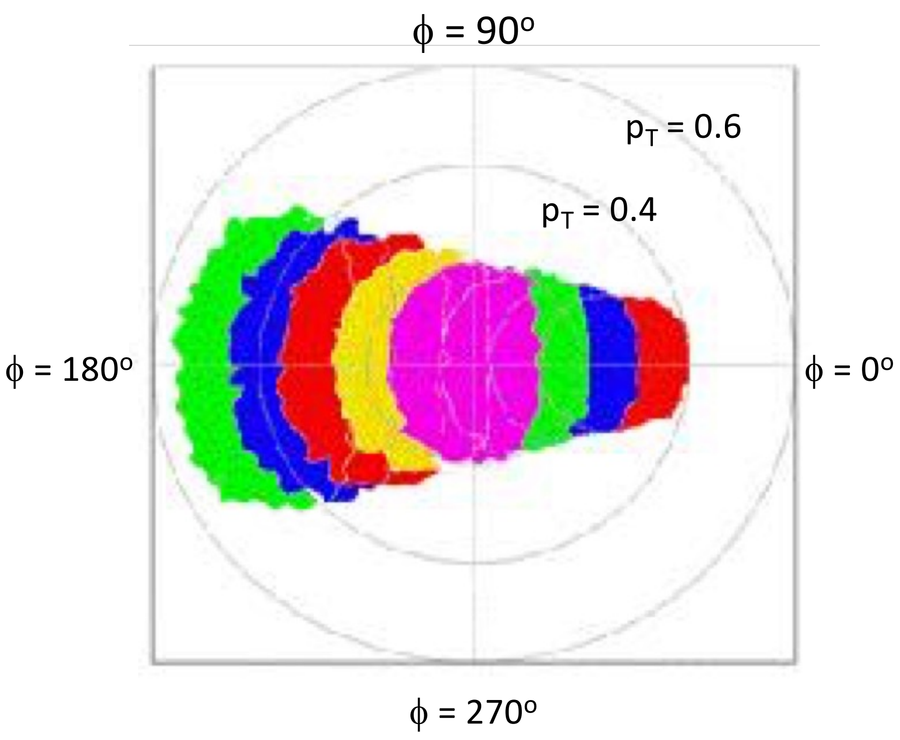
p_T - SIDIS (E12-09-017) Status

- Data analysis essentially completed by Peter Bosted (21000 cross sections!)
- Phenomenological evaluation in terms of multiplicities, p_T gaussian width, and sinusoidal dependence in azimuthal angle
- Draft manuscript exists, but progress slowed by ongoing π^0-SIDIS experiment
- Goal to finish and submit manuscript in Spring 2024

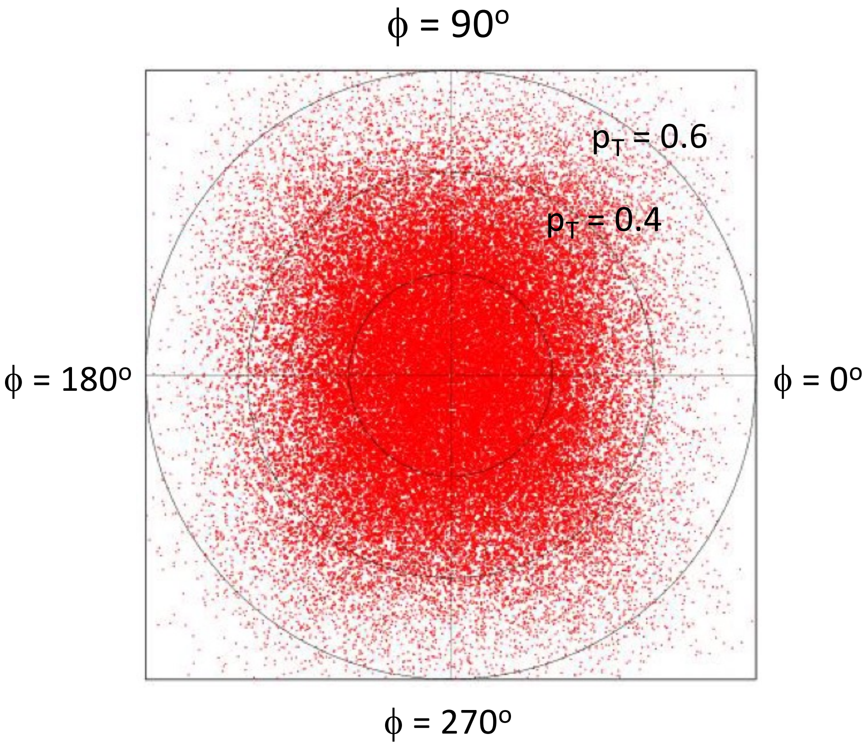
Backup

$P_{h\perp}$ Coverage of SIDIS experiments

$(e,e'\pi^{\pm})$ with SHMS
E12-09-017



$(e,e'\pi^{0})$ with NPS
E12-13-007



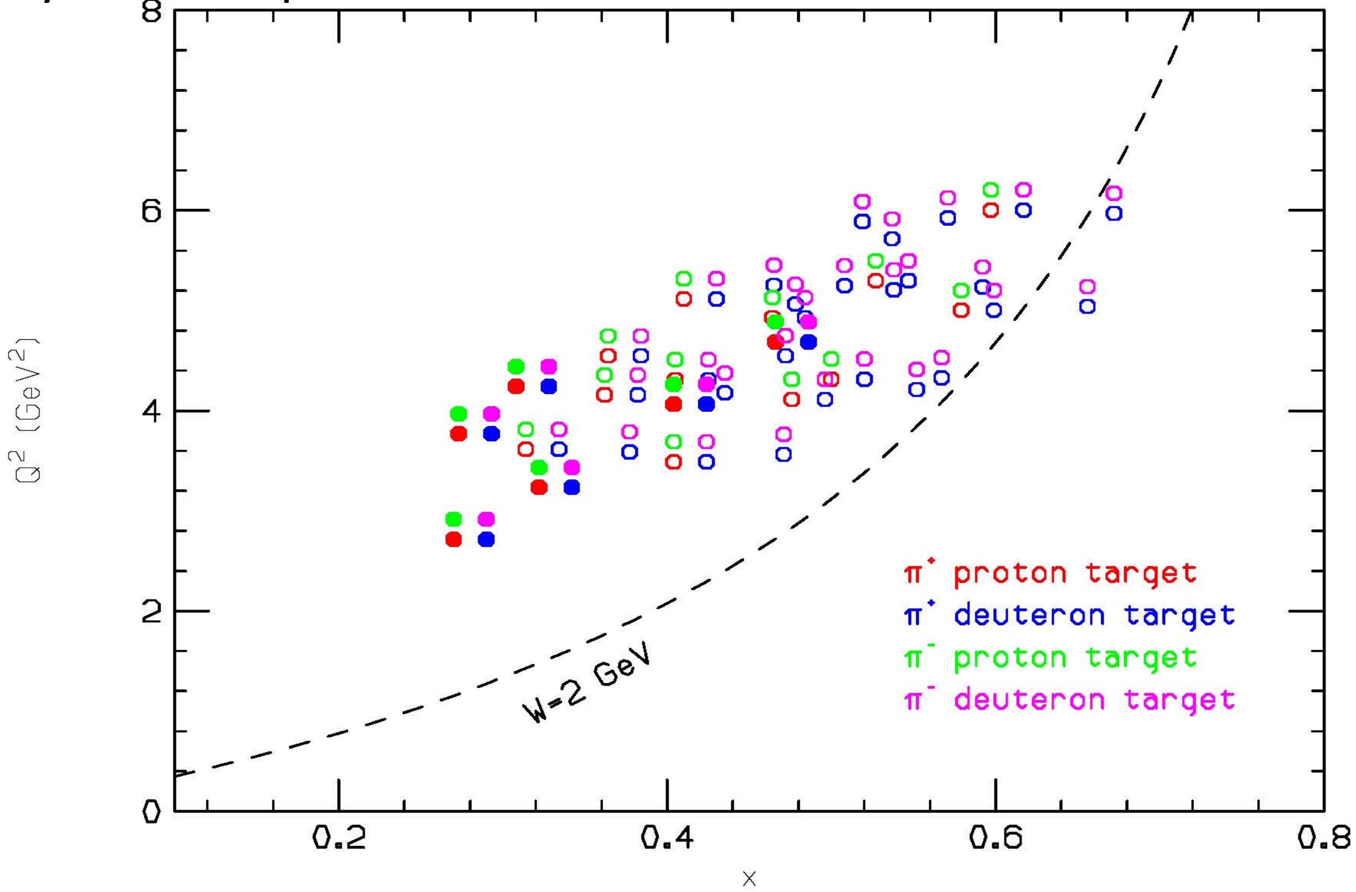
Kinematic coverage in (x,Q^2)

Solid circles are from pt-SIDIS, open circles CSV SIDIS

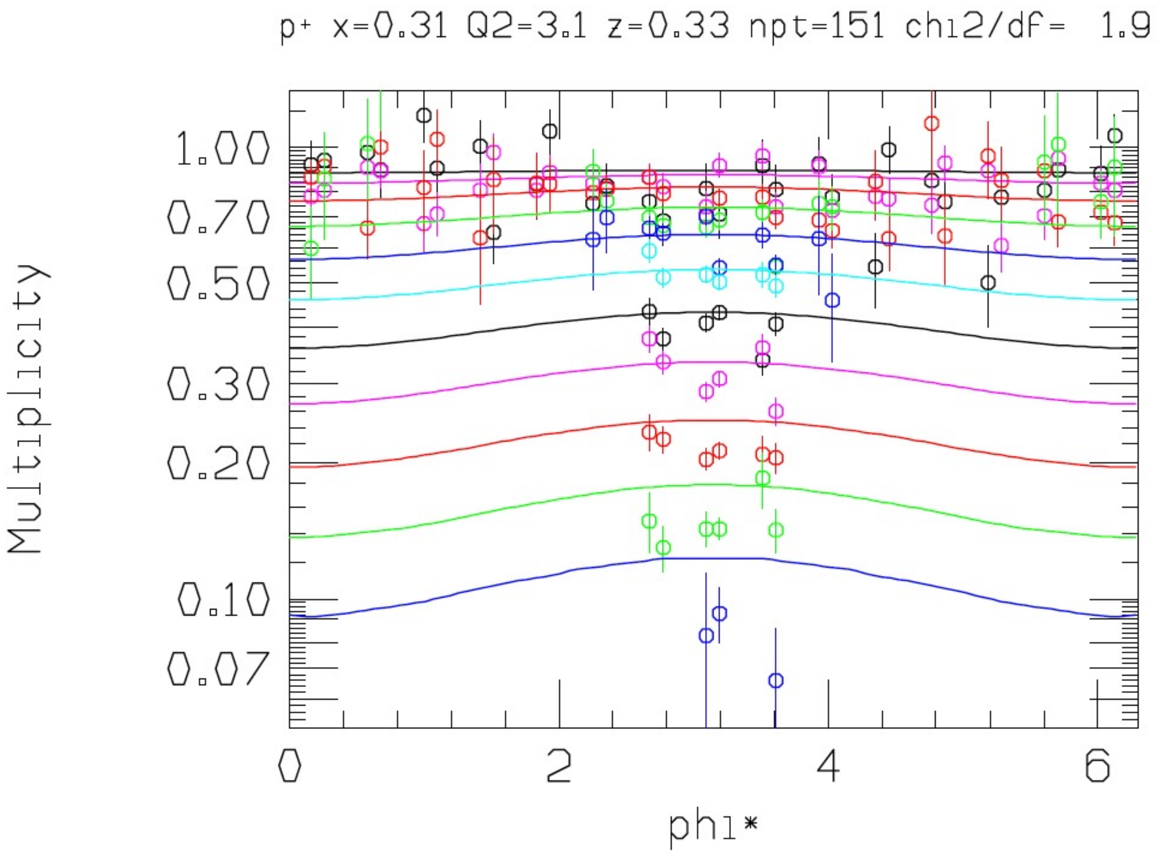
CLAS coverage extends to lower x and lower Q^2

each circle has 10,000 to 1000,000 events

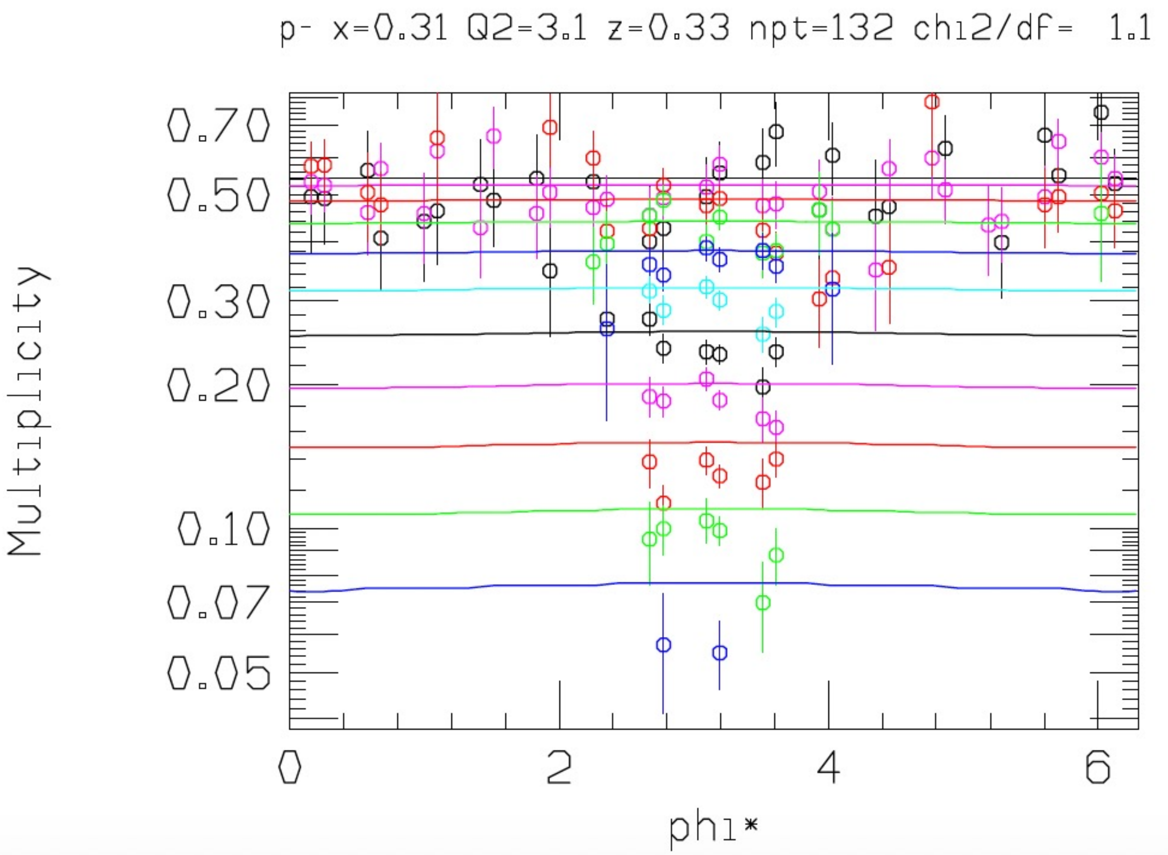
Dominated by valance quark distributions



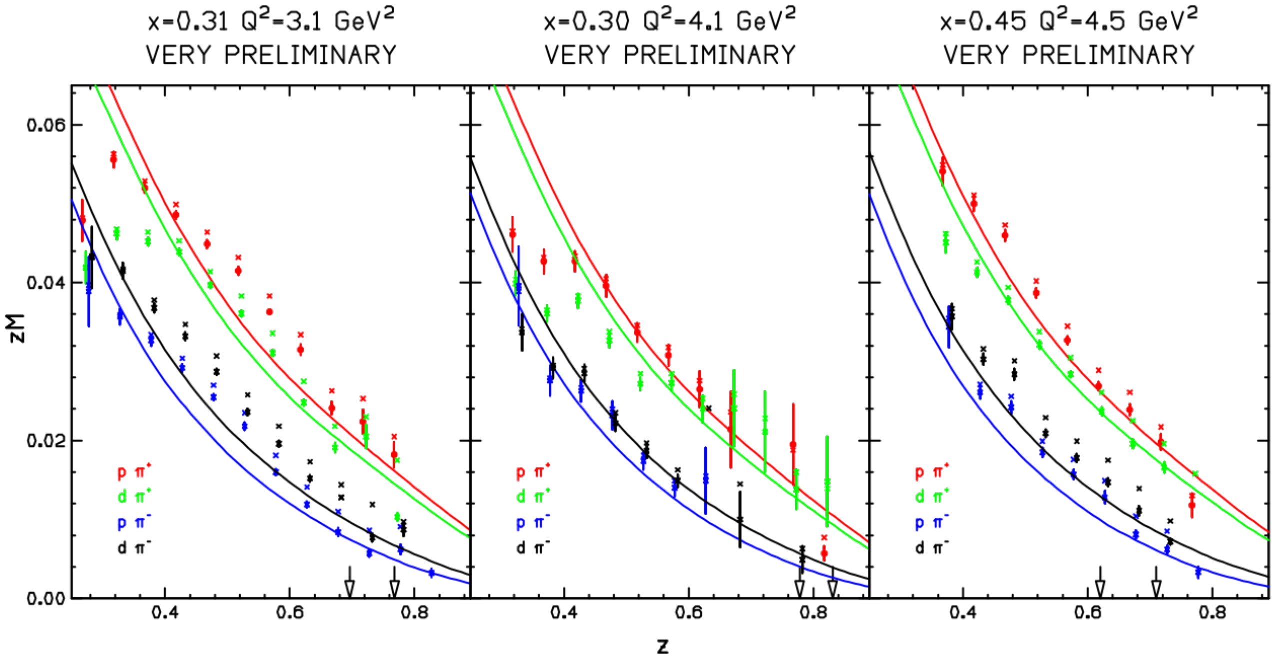
Fit Examples -1-



Fit Examples -2-

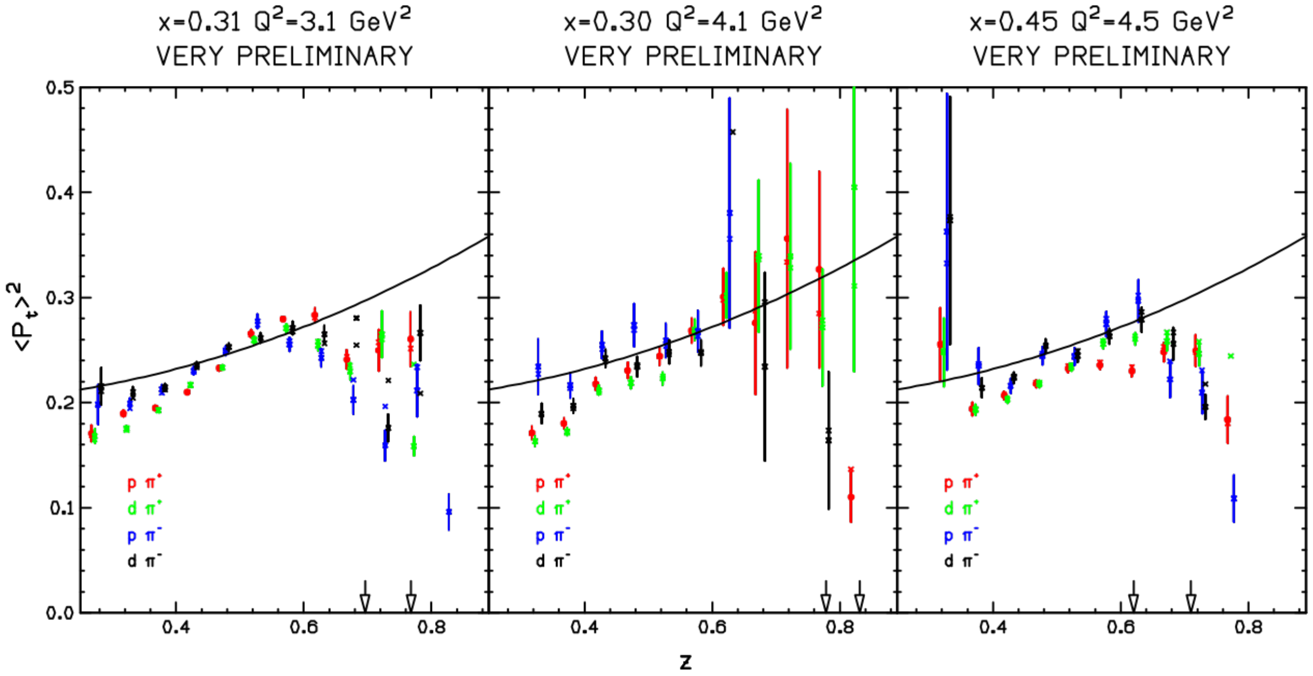


Fit to zM_0



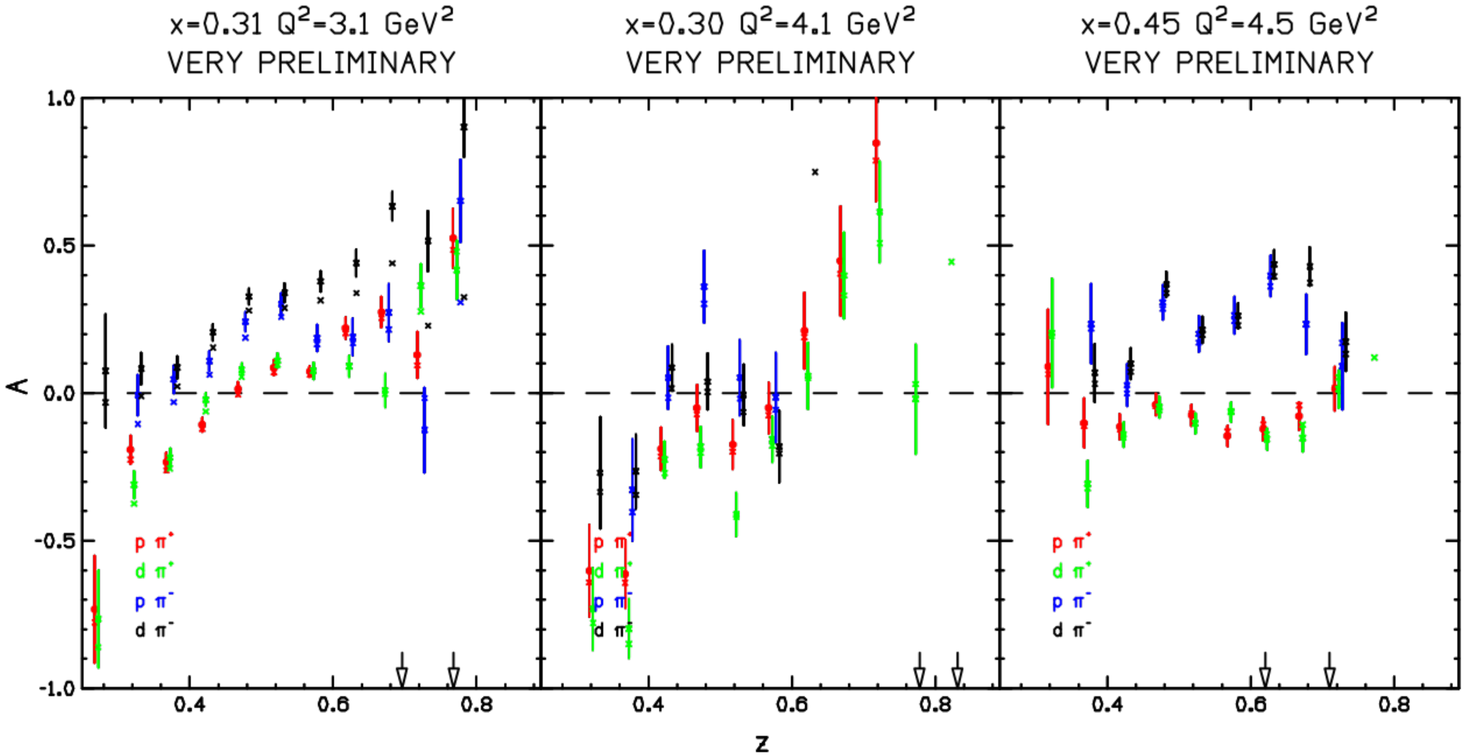
The results compared to the predictions using DSS fragmentation functions with CTEQ5 pdfs. The solid circles are with DVM rho subtraction using the standard SIMC parametrization, while the crosses (with no error bars) show how the results would look with no rho subtraction. The left-hand arrow at the bottom shows the z value for which (W')**2=3 GeV, while the right-hand arrow is for (W')**2 = 2.5 GeV**2. The DVM correction improves the agreement. If the correction were scaled up by a factor of two, the agreement would be better.

Fit to b (1/b shown)



The curve is of the form $\langle P_T^2 \rangle = \langle p_t^2 \rangle + z^2 \langle k_\perp^2 \rangle$ where $\langle p_t^2 \rangle$ is the width from fragmentation (PB used 0.2 GeV^2 for both favored and unfavored FF), and $\langle k_\perp^2 \rangle$ is the intrinsic quark transverse momentum width, which PB took to be 0.2 GeV^2 for both up and down quarks. Note fall off approaching (W')**2 > 3 GeV^2. The values for pi+ are all a bit smaller (for both p and d targets) than for pi-, possibly indicated a narrow width for favored fragmentation than for unfavored fragmentation.

Fit to A



Generally they increase with increasing z, are are significantly greater than 0 for pi-, but closer to zero for pi+. The Cahn effect would predict negative values of A, in contradiction with the data.