

SIDIS in Hall C at Higher Energies

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Hall C Winter Meeting

January 12-13, 2023

1. Hall C 6 and 12 GeV SIDIS Results/Program
2. Measurements at Higher Energy

SIDIS with Modest Acceptance

Hall C uses magnetic focusing spectrometers with moderate acceptance

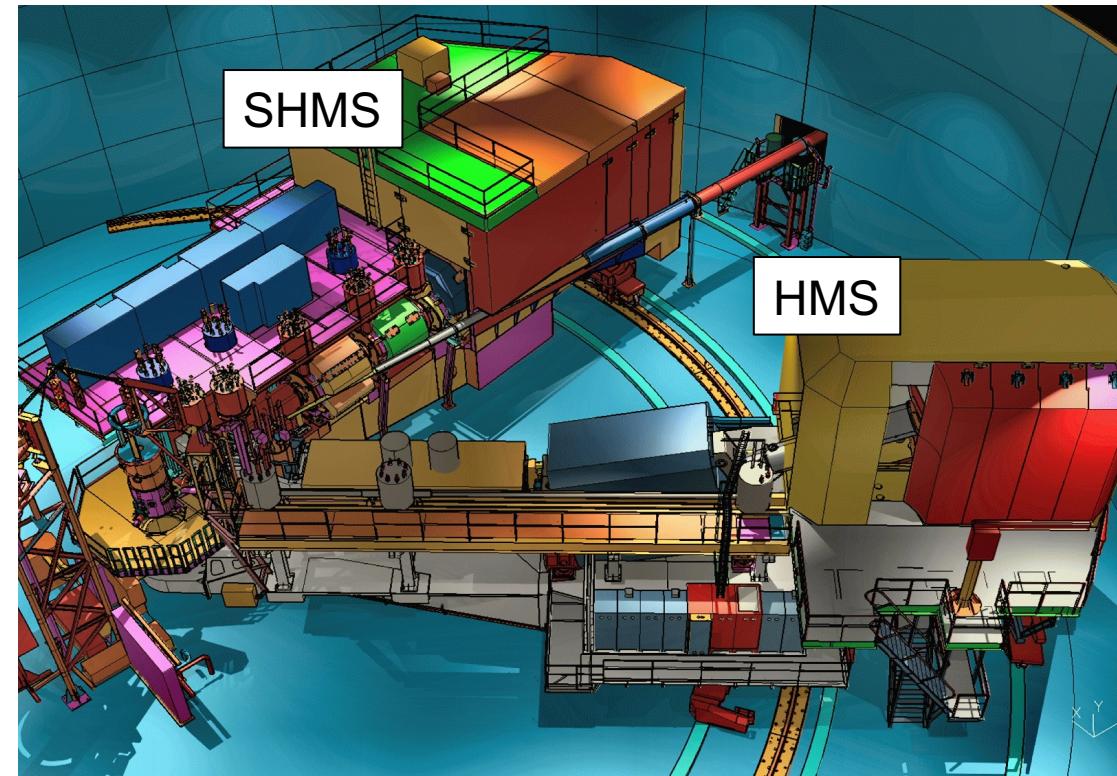
Optimal program:

- Targeted measurements in specific regions of phase space (i.e., low rate processes)
- Absolute cross sections, L-T separations, charge ratios

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

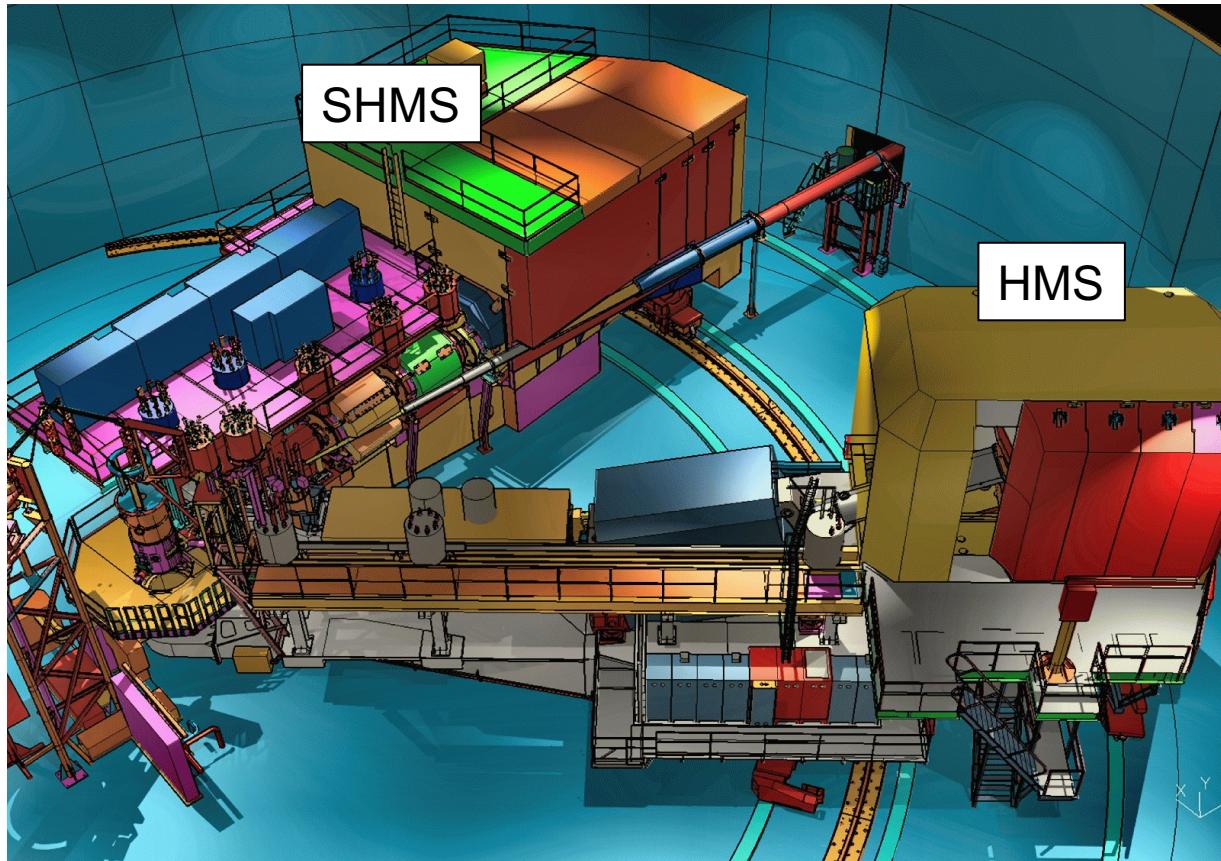
Excellent control of point-to-point systematic uncertainties required for precise L-T separations

- 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

SHMS and HMS in Experimental Hall C



Spectrometer properties

HMS: Electron arm

Nominal capabilities:

$d\Omega \sim 6 \text{ msr}$, $P_0 = 0.5 - 7 \text{ GeV}/c$

$\theta_0 = 10.5 \text{ to } 80 \text{ degrees}$

e ID via calorimeter and gas
Cherenkov

SHMS: Pion arm

Nominal capabilities:

$d\Omega \sim 4 \text{ msr}$, $P_0 = 1 - 11 \text{ GeV}/c$

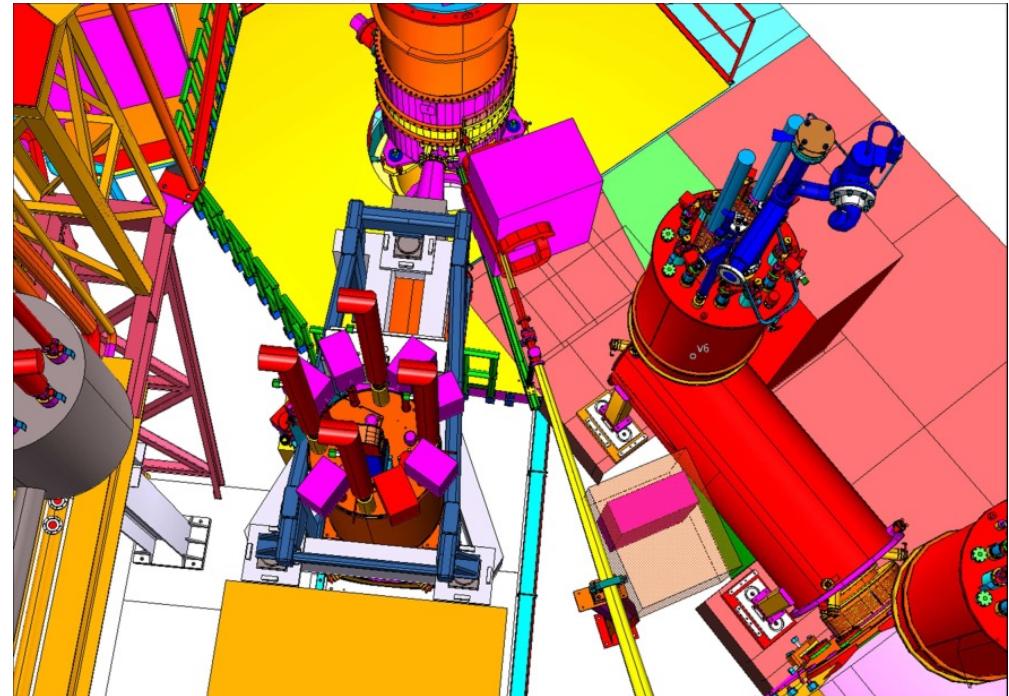
$\theta_0 = 5.5 \text{ to } 40 \text{ degrees}$

$\pi:K:p$ separation via heavy gas
Cherenkov and aerogel
detectors

Neutral Particle Spectrometer (NPS)

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

- NPS mounted on SHMS carriage – allows easy angle changes
- In addition to broadening SIDIS program, enables DVCS, DVMP (π^0), WACS measurements

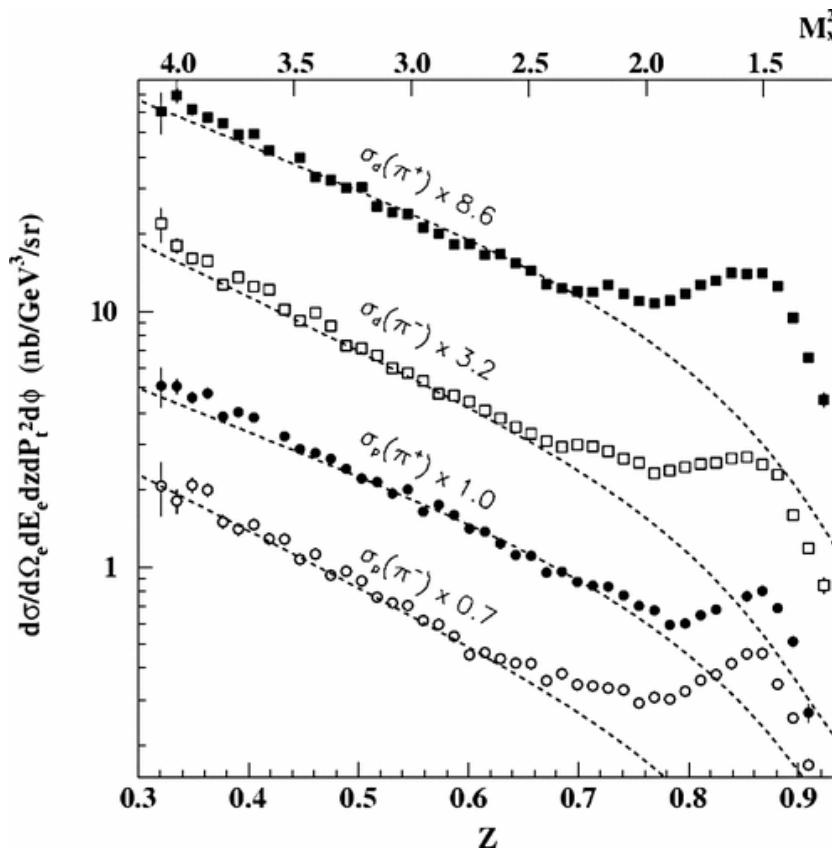


π^0 avoids complications from vector meson decay, smaller radiative tails from exclusive pion production

NPS installation will begin in spring 2023

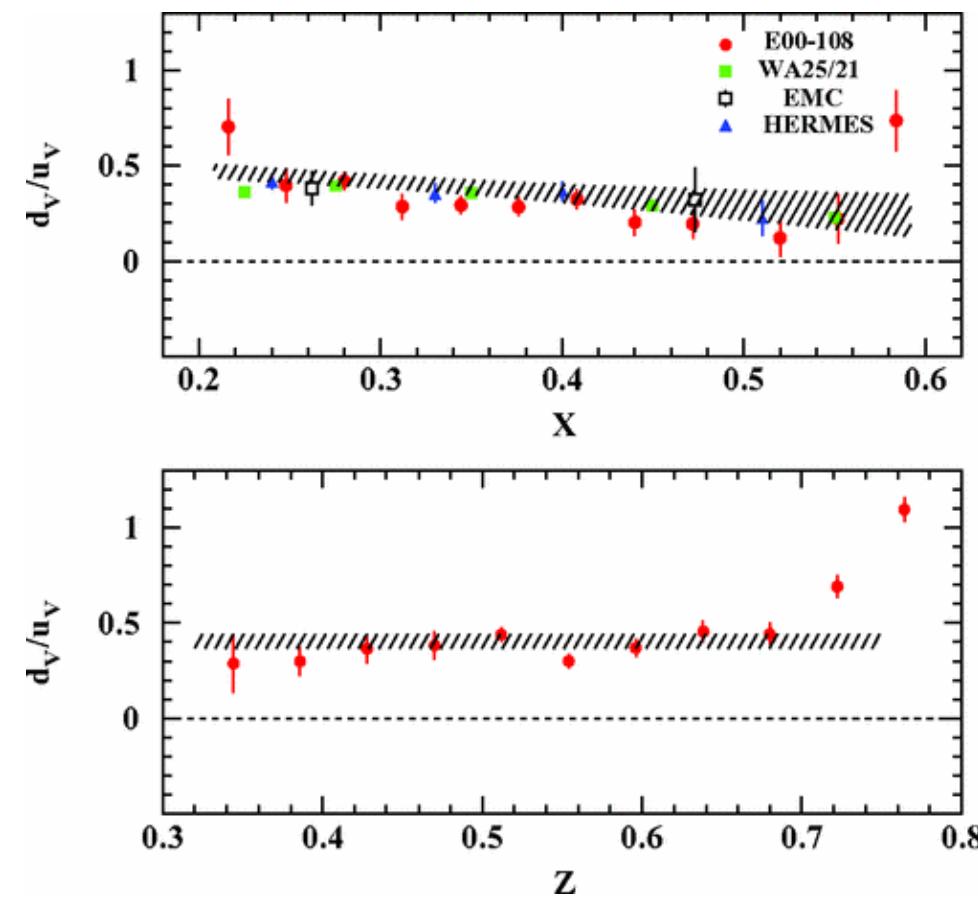
Hall C SIDIS Results from 6 GeV

E10-008: 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

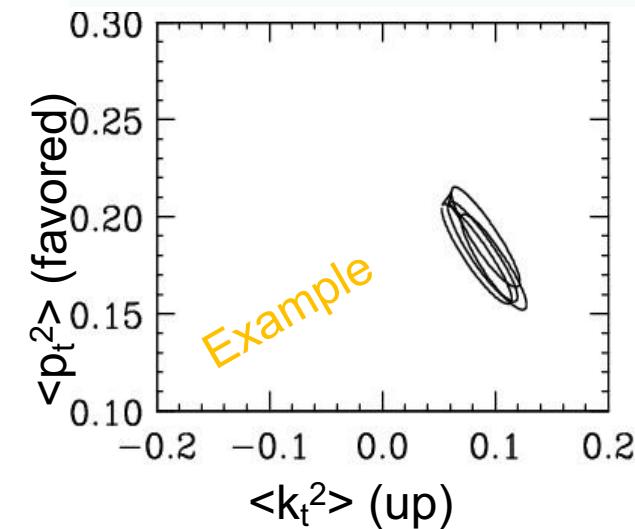
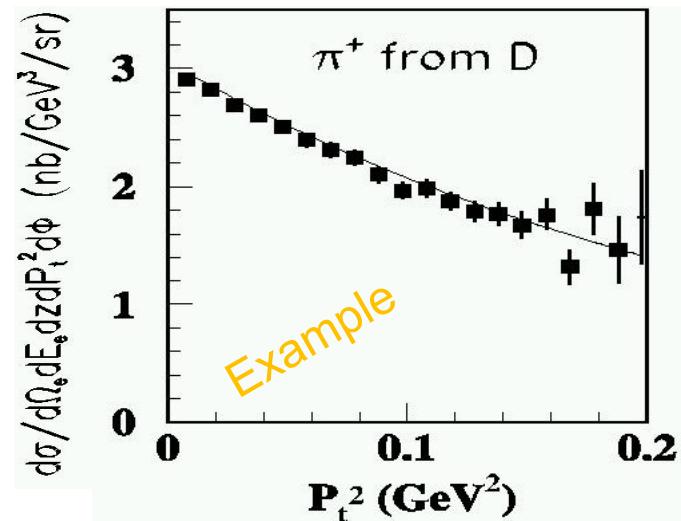
Hall C experiment E00-108 (6 GeV):

- 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



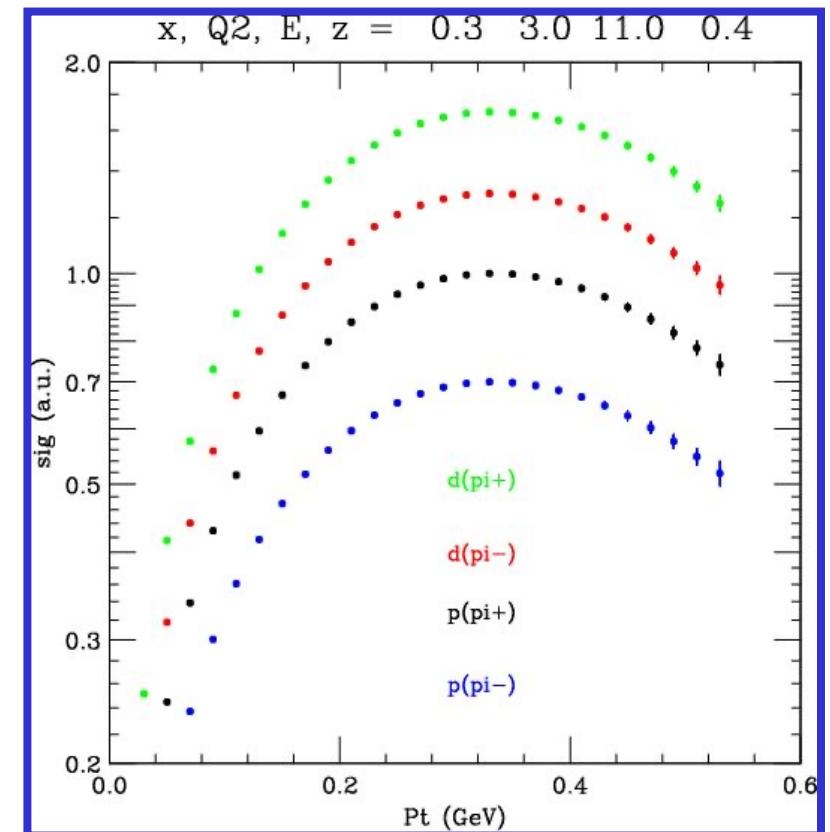
Hall C @ 12 GeV– P_T Dependent Cross Sections

E12-09-017: P_T Dependence of $\pi^{+/-}$ Production

Precise cross section measurements with HMS and SHMS

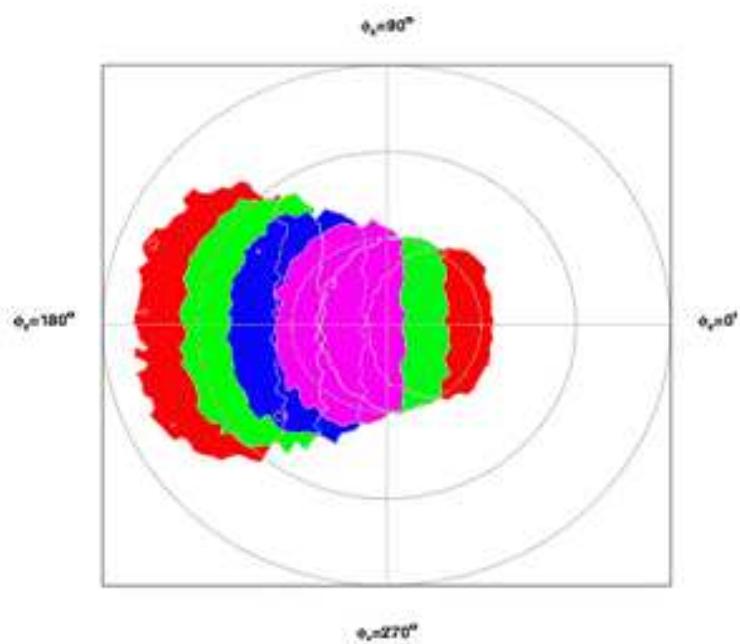
- Demonstrate understanding of reaction mechanism, test factorization
- Able to carry out precise comparisons of charge states, π^+/π^-
- Can do meaningful measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

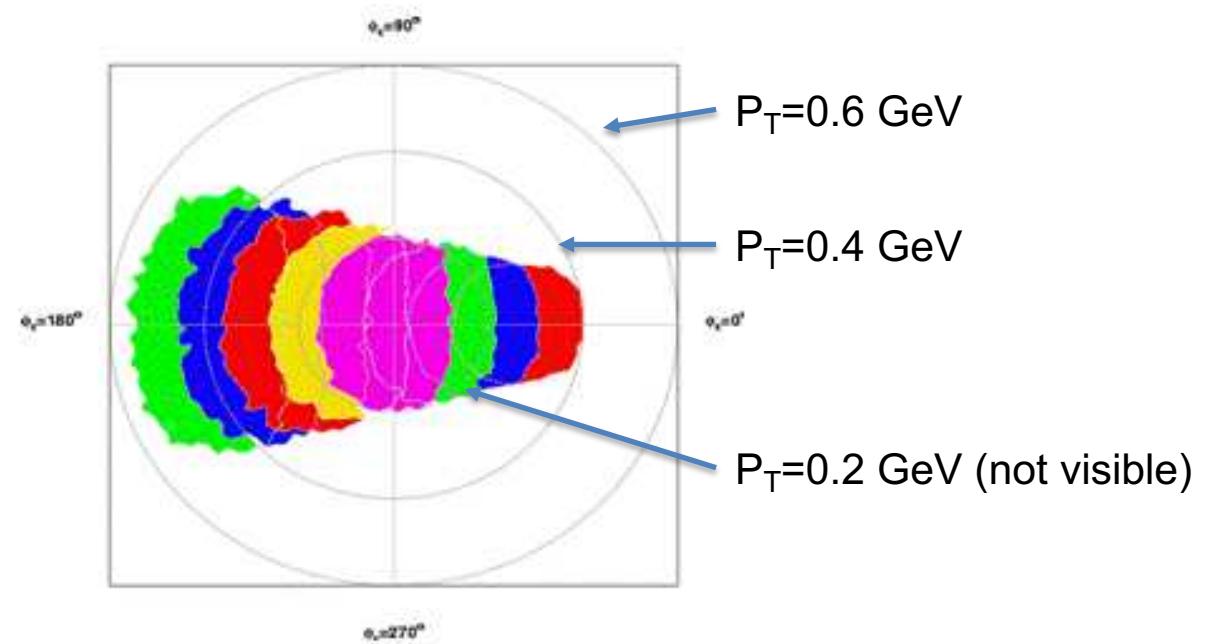


HMS-SHMS P_T/ϕ acceptance

Simulated, from P_T -SIDIS experiment (11 GeV)



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



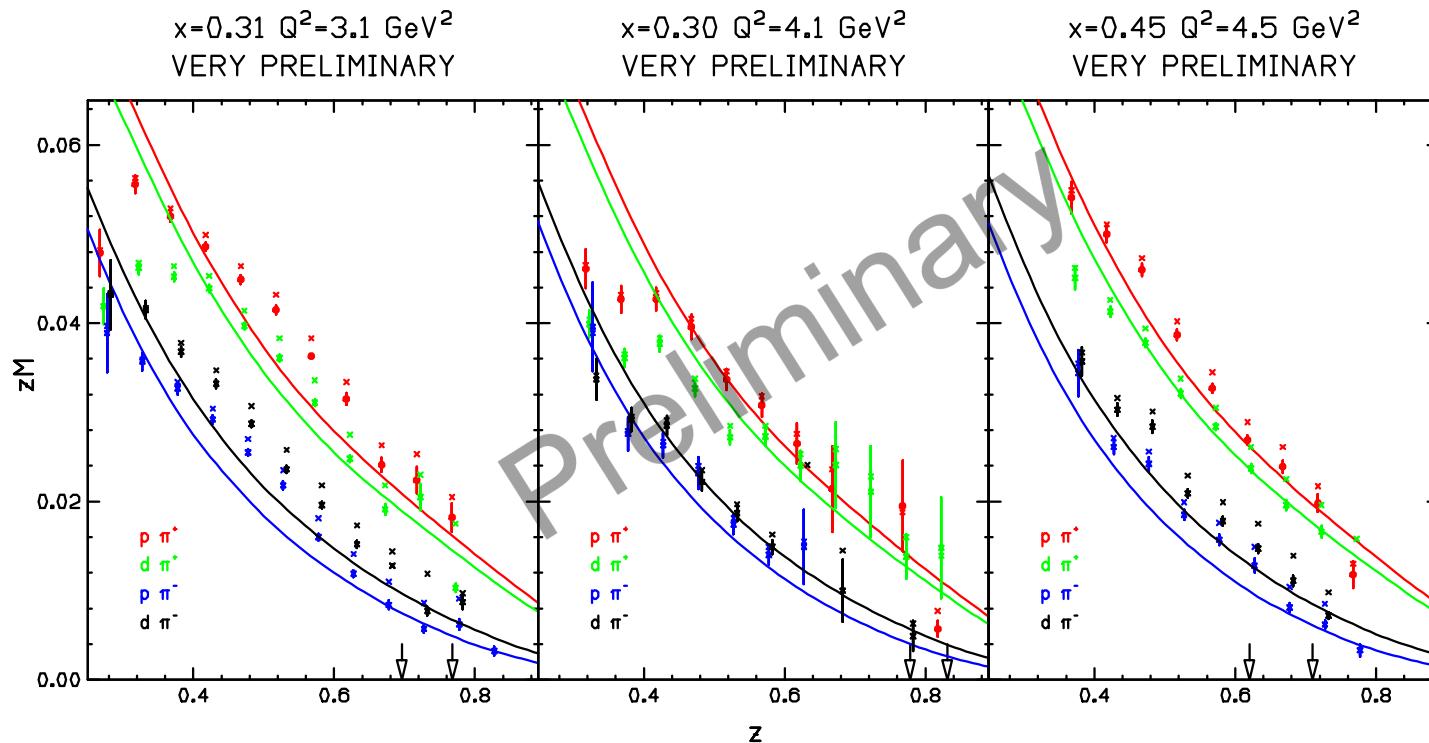
$x=0.3 \text{ } Q^2=3 \text{ GeV}^2$

Full ϕ coverage over limited P_T range \rightarrow larger P_T covers narrow range in ϕ

11 GeV SIDIS Preliminary Analysis

Multiplicities

- Data with and without diffractive ρ subtraction
- Curves: DSS FF w/cteq PDFs



$$y = M_0 b e^{-bp_T^2} (1 + Ap_T \cos \phi)$$

11 GeV SIDIS Preliminary Analysis

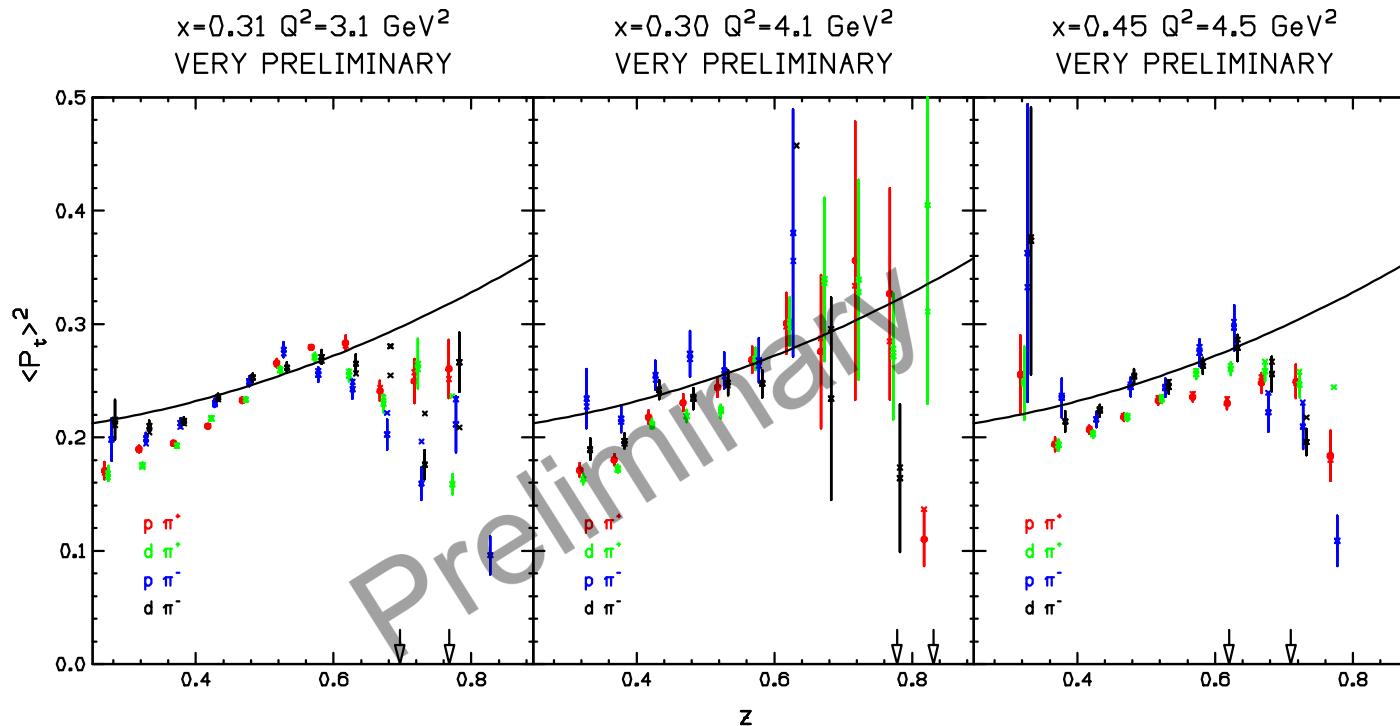
P_T widths

→ Data with and without
dissociative ρ subtraction

→ Curves:

$$\langle P_T^2 \rangle = \langle p_T^2 \rangle + z^2 \langle k_T^2 \rangle$$

$\langle P_T^2 \rangle$ and $\langle k_T^2 \rangle$ taken to
be 0.2 GeV^2



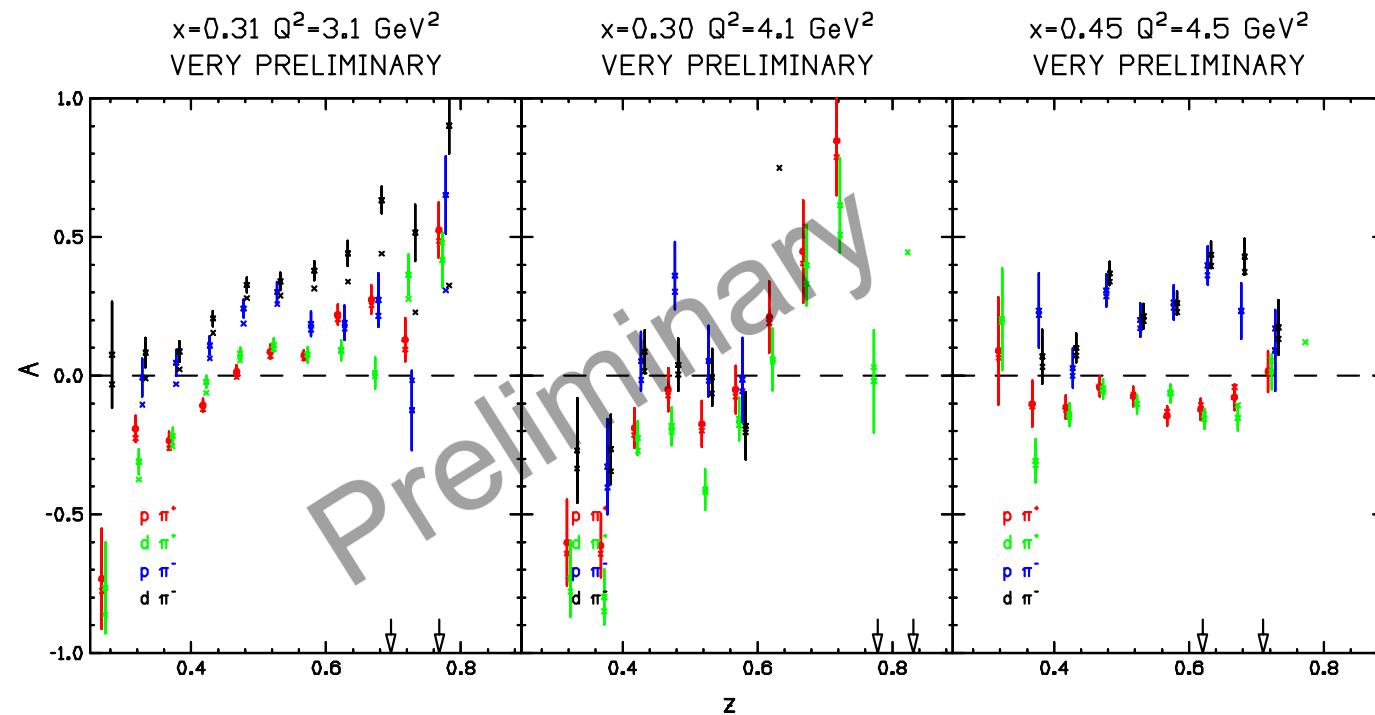
$$y = M_0 b e^{-bp_T^2} (1 + Ap_T \cos \phi)$$

Analysis from Peter Bosted

11 GeV SIDIS Preliminary Analysis

$\cos(\phi)$ term:

- Data with and without diffractive p subtraction
- "A" generally close to zero or positive
- Cahn effect would give $A < 0$



Analysis from Peter Bosted

$$y = M_0 b e^{-bp_T^2} (1 + A p_T \cos \phi)$$

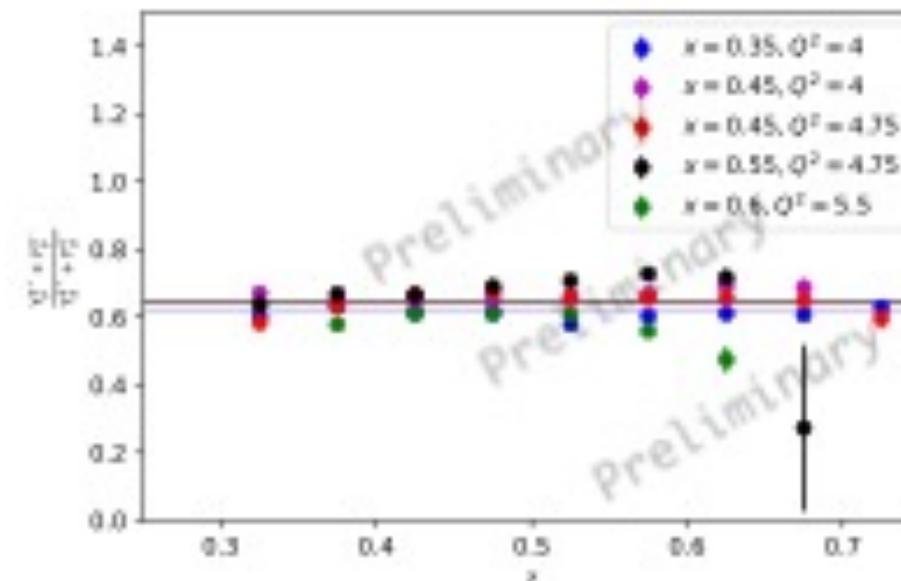
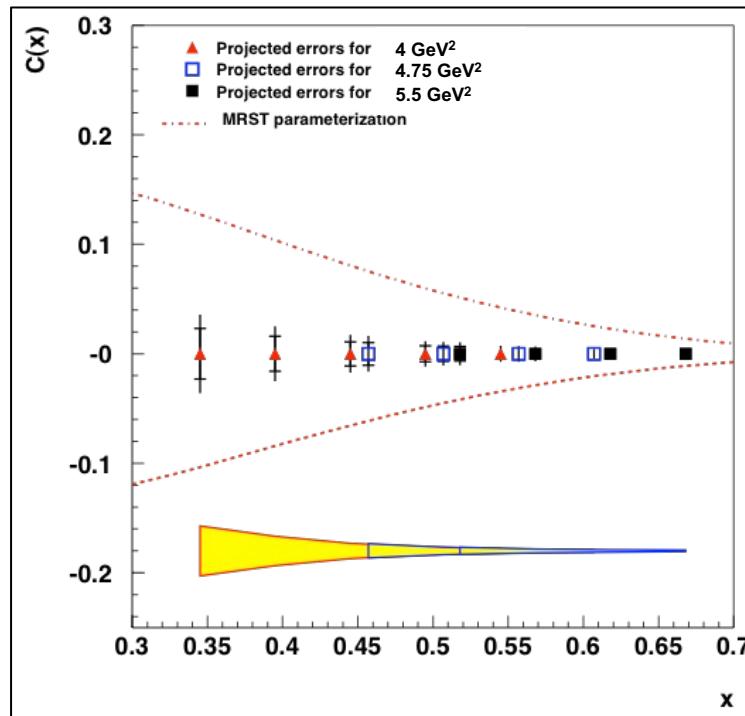
Hall C @ 12 GeV – Precise π^+/π^- Ratios (low P_T)

E12-09-002: Charge Symmetry Violating Quark Distributions via π^+/π^- in SIDIS

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

$$R_Y(x, z) = \frac{Y^{D\pi^-}(x, z)}{Y^{D\pi^+}(x, z)}$$

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



$$\frac{H(\pi^+ + \pi^-)}{D(\pi^+ + \pi^-)}$$

Hall C 12 GeV: $R = \sigma_L/\sigma_T$ in SIDIS

$$\frac{d\sigma}{dxdydzd\phi_h dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos(2\phi_h)} + \lambda_e \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\}$$

→ integrate over ϕ , unpolarized beam, only L and T terms remain
DIS → $F(x, Q^2)$ SIDIS → $F(x, Q^2, z, P_T)$

Knowledge of $R = \sigma_L/\sigma_T$ in SIDIS is essentially non-existing!

Integrated over z, p_T , hadron species $R_{SIDIS} \rightarrow R_{DIS}$

- R_{SIDIS} may vary with z, p_T
- Is R_{SIDIS} the same for π^+, π^- (K^+, K^-)? H and D?
- $R_{SIDIS} = R_{DIS}$ a test of quark fragmentation
- How does R transition from SIDIS to exclusive?

Hall C 12 GeV SIDIS Program – L-T Separations

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

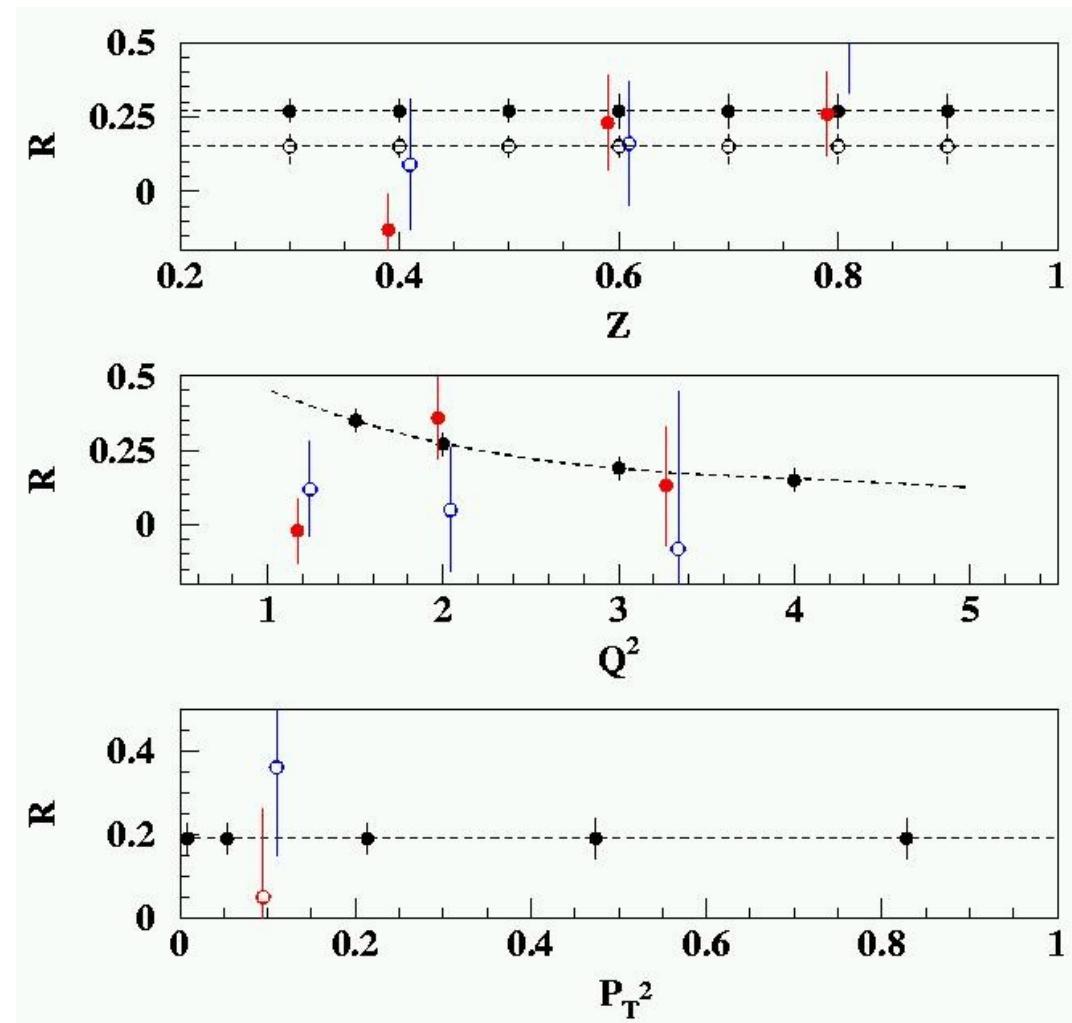
Precise measurements of R_{SIDIS} in
 $e+p \rightarrow e'+\pi^{+/-}+X$, $e+D \rightarrow e'+\pi^{+/-}+X$

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

→ ideally suited to Hall C equipment at 12 GeV

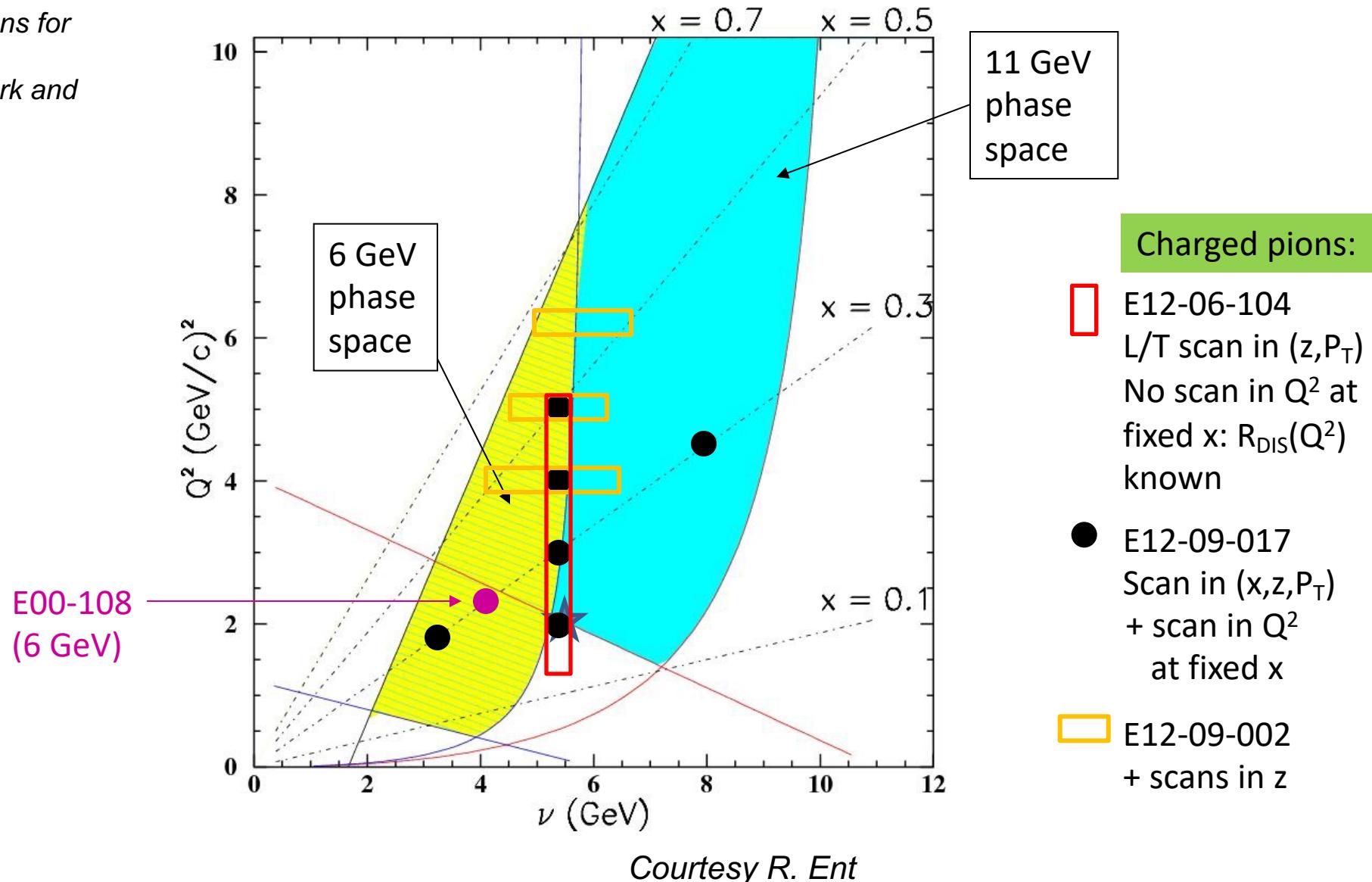
1. Scans in z at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV^2 ($x = 0.4$) → behavior of σ_L/σ_T for large z .
2. Cover $Q^2 = 1.5 - 5.0$ GeV^2 , → both H and D at $Q^2 = 2$ GeV^2
3. P_T up to ~ 1 GeV . Coverage in ϕ is excellent (o.k.) up to $P_T = 0.2$ (0.4) GeV .

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



12 GeV Hall C SIDIS Program – HMS+SHMS

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

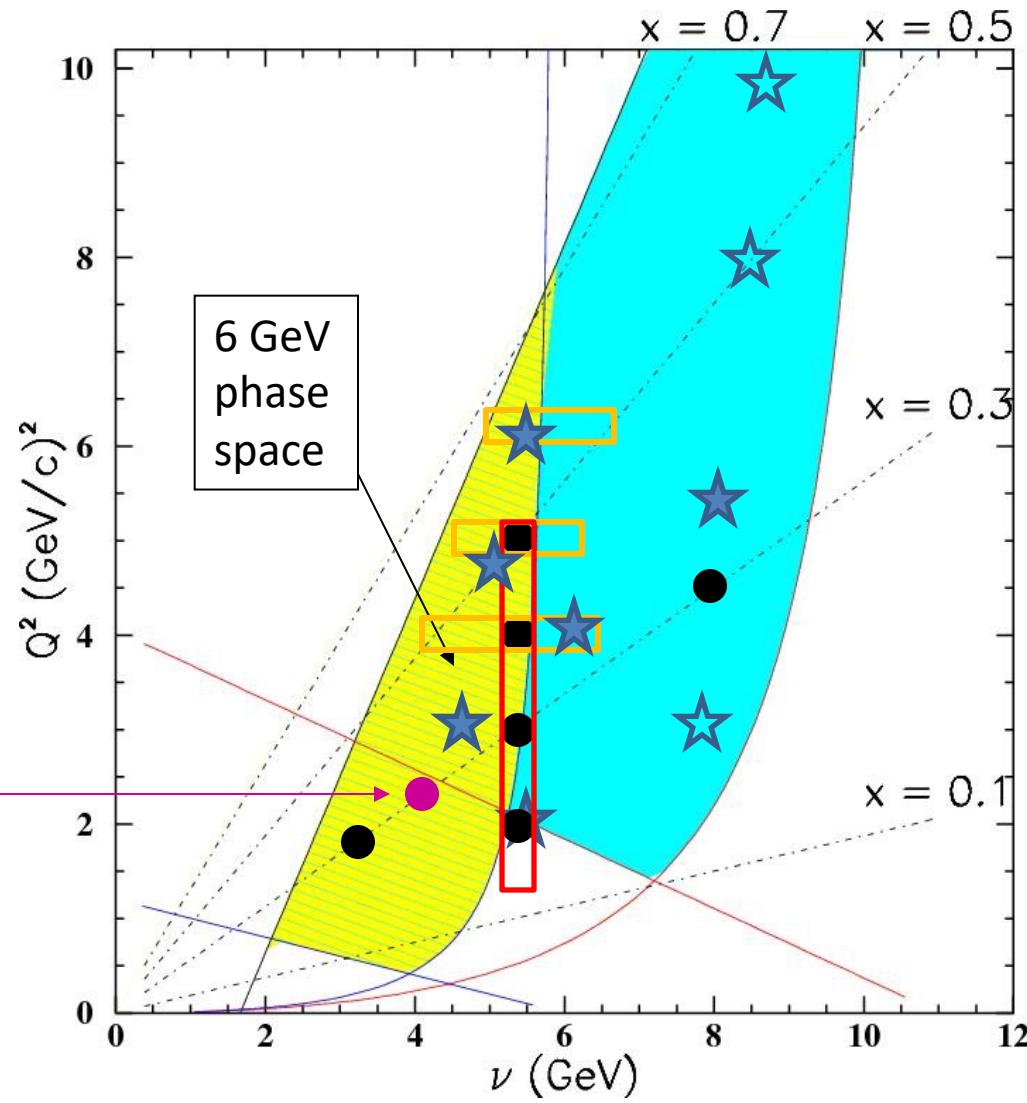


12 GeV Hall C SIDIS Program – HMS+SHMS+NPS

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

E00-108
(6 GeV)



- Charged pions:
- E12-06-104
L/T scan in (z, P_T)
No scan in Q^2 at fixed x : $R_{\text{DIS}}(Q^2)$ known
 - E12-09-017
Scan in (x, z, P_T)
+ scan in Q^2 at fixed x
 - E12-09-002
+ scans in z

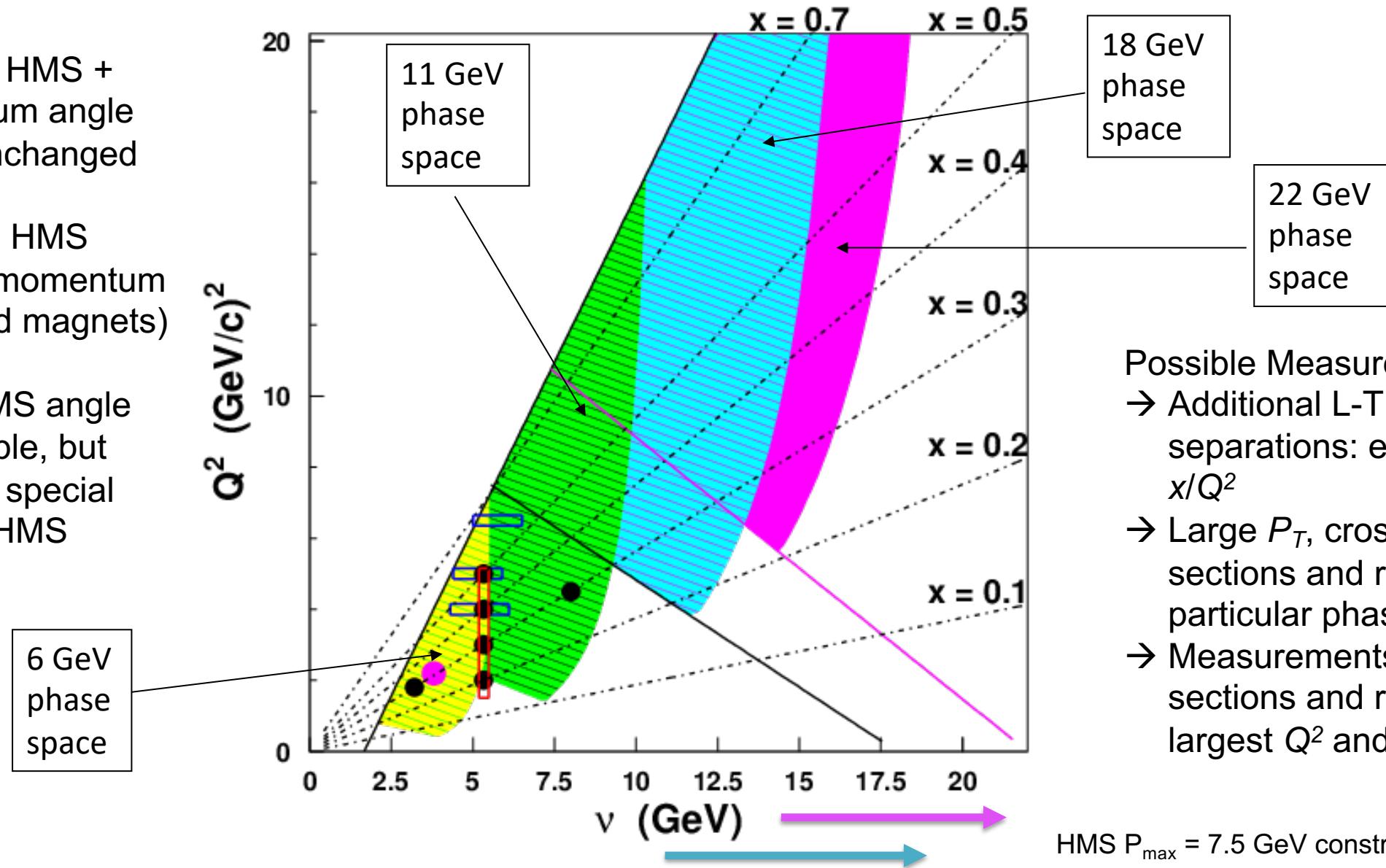
Courtesy R. Ent

22 GeV Hall C SIDIS Phase Space – HMS+SHMS

Assumptions: HMS + SHMS minimum angle constraints unchanged

→ Increase in HMS maximum momentum (higher field magnets)

→ Smaller HMS angle may be possible, but would require special bender like SHMS



HMS $P_{\max} = 7.5 \text{ GeV}$ constraint

Measurements at 22 GeV: Parallel Kinematics

HMS+SHMS has excellent momentum/angle resolution

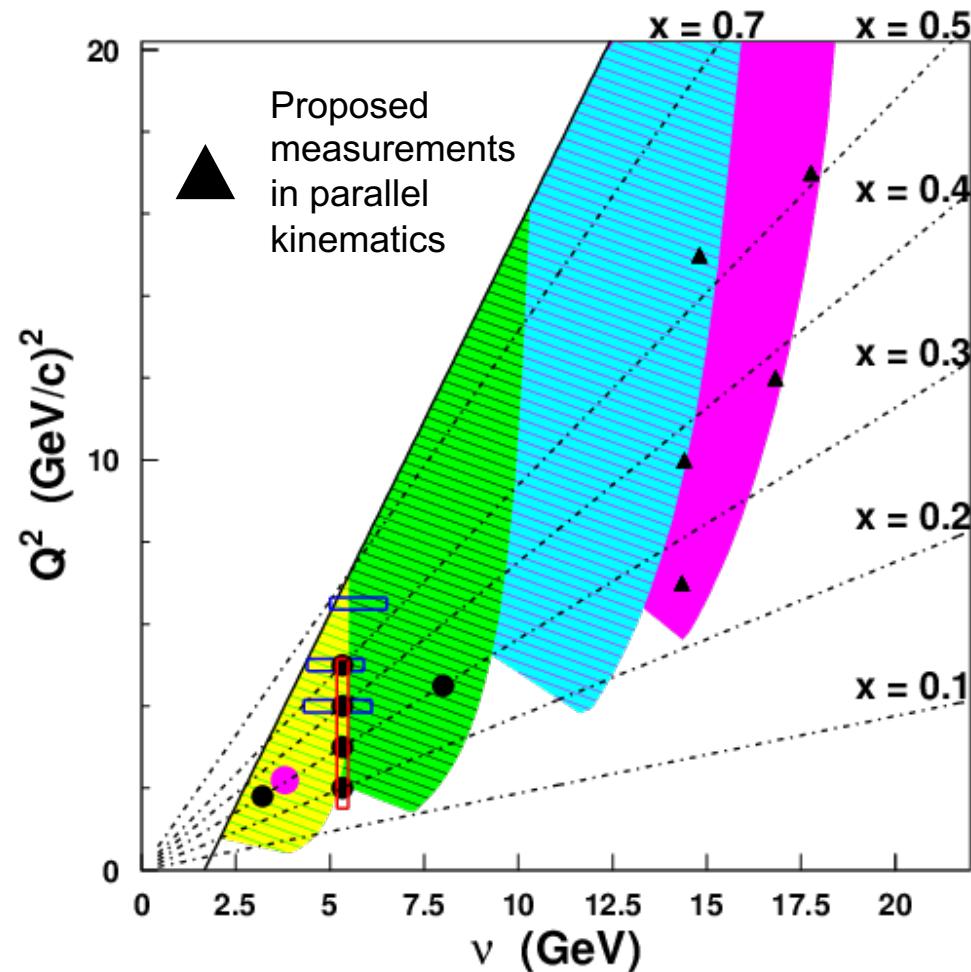
→ Complete ϕ coverage at low P_T

x	Q ₂	z
0.26	7	0.4-0.7
0.37	10	0.4-0.7
0.38	12	0.36-0.64
0.51	17	0.33-0.58
0.54	15	0.4-0.7

$P_T = 0-0.5$
 $W' > 2$ GeV for all settings

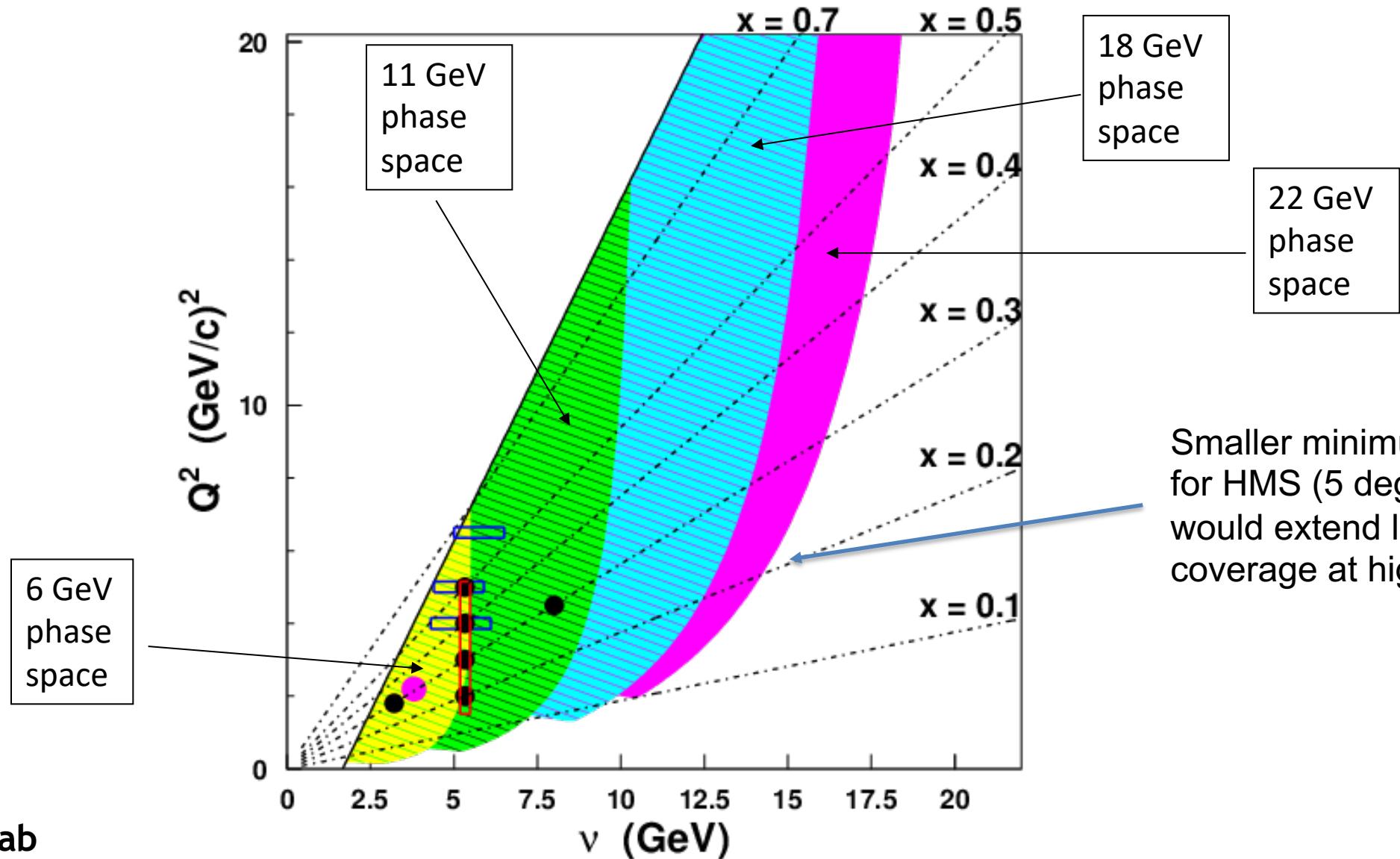
~45 days assuming 70 μA

No modifications to either HMS or SHMS needed for these measurements



Projections from Peter Bosted

Hall C SIDIS Phase Space – Smaller HMS angle

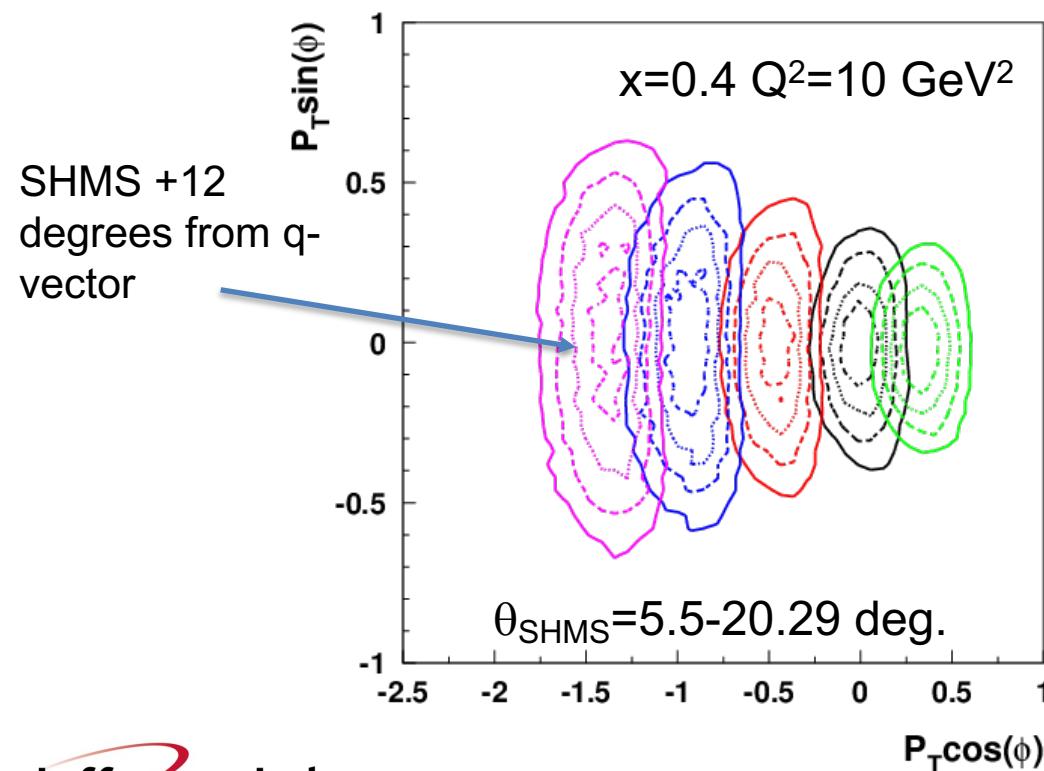


Measurements at 22 GeV: Large P_T

Access to large P_T by rotating SHMS away from q-vector
 → Interference term contribution difficult to constrain
 → Complicates possible L-T separations

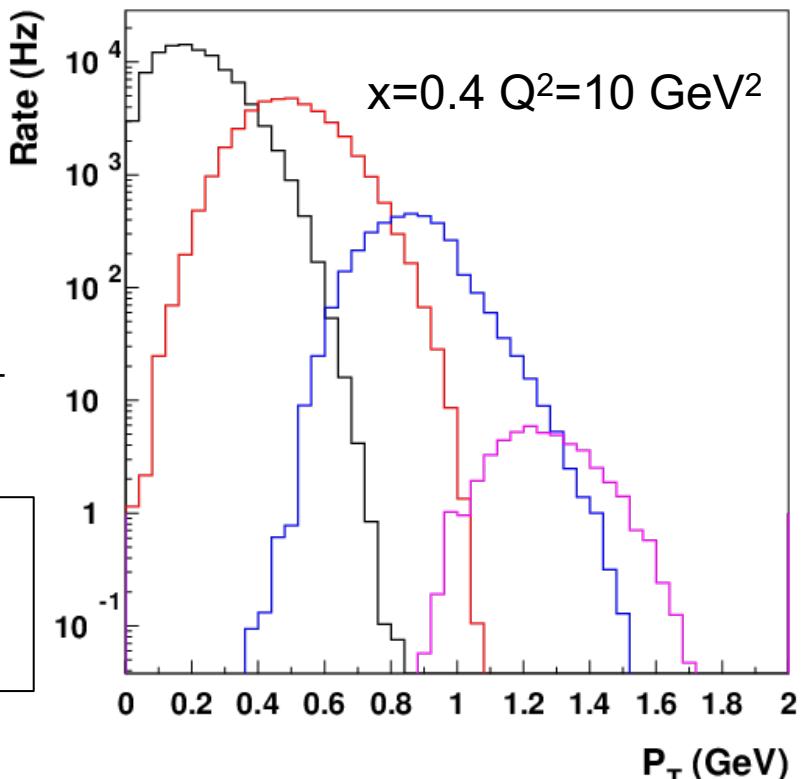
This x/Q^2 assumes upgraded HMS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\epsilon)} \left[F_T + \epsilon F_L + \sqrt{2\epsilon(1+\epsilon)} \cos\phi F_{LT} + \epsilon \cos 2\phi F_{TT} \right]$$



Projected rates
 → 10 cm LH2 target
 → 80 μA
 → 40 MeV bins in P_T

$\Delta\epsilon = 0.36$ possible if L-T separation desired



Hall C Program at Higher Energy

- Higher energy capabilities extends 12 GeV program to larger x , Q^2
 - Precision cross sections
 - L/T separations
 - Low rate processes \rightarrow large P_T
 - Precision ratios (π^+/π^- , and more)
 - Excellent $\pi/K/p$ separation
 - Neutral particle capabilities w/calorimeter (NPS)
- Upgraded equipment ?
 - Program could be carried out at 22 GeV w/existing HMS and SHMS (and NPS)
 - Higher momentum capability for electron arm (upgraded HMS?) would be beneficial
 - Smaller angle capability \rightarrow needed for access to lower x , anti-shadowing region

SHMS and SBS?

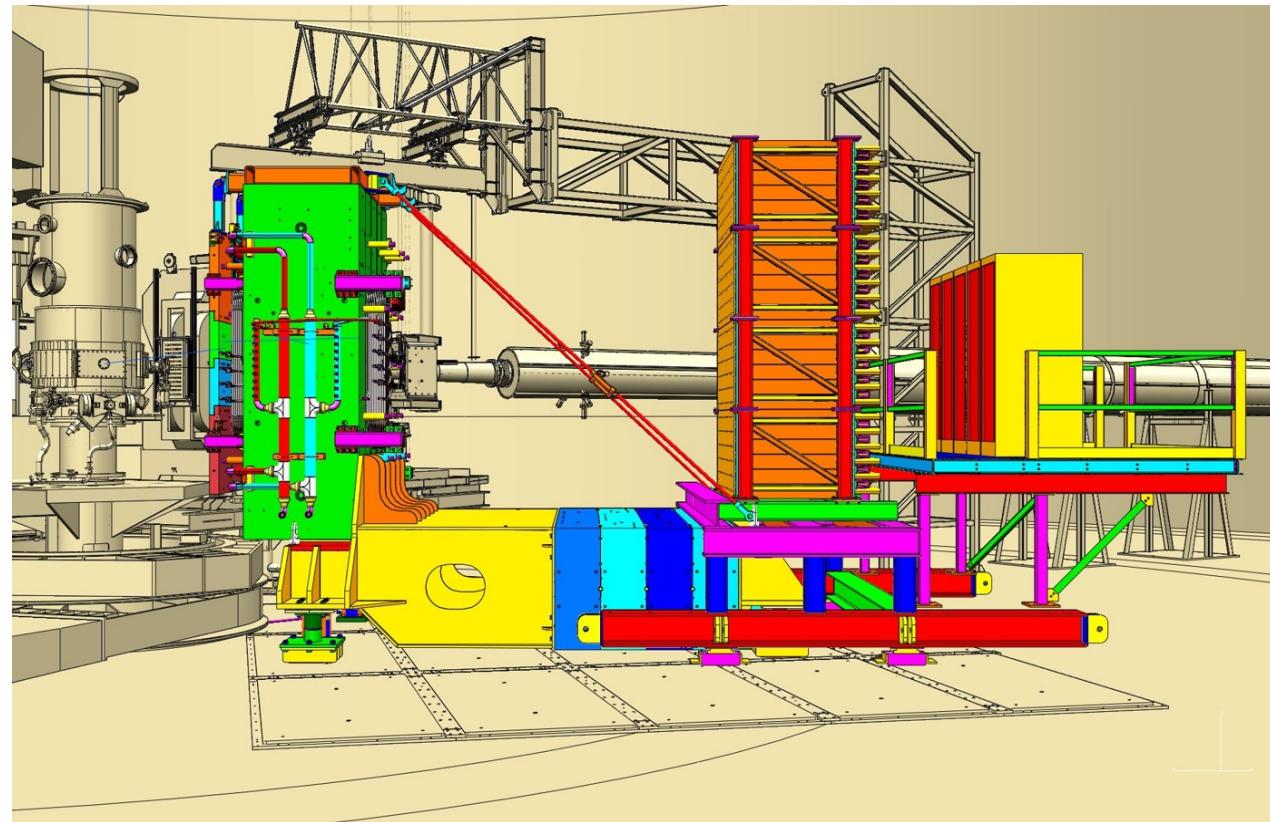
Super Big Bite Spectrometer built and being used in Hall A

- Dipole with large gap and large area detector stack
- Can be positioned at various positions/distances from the pivot
- Access very small angle by pushing the spectrometer far from pivot

$\Delta\Omega = 12 \text{ msr}$ at 5 degrees

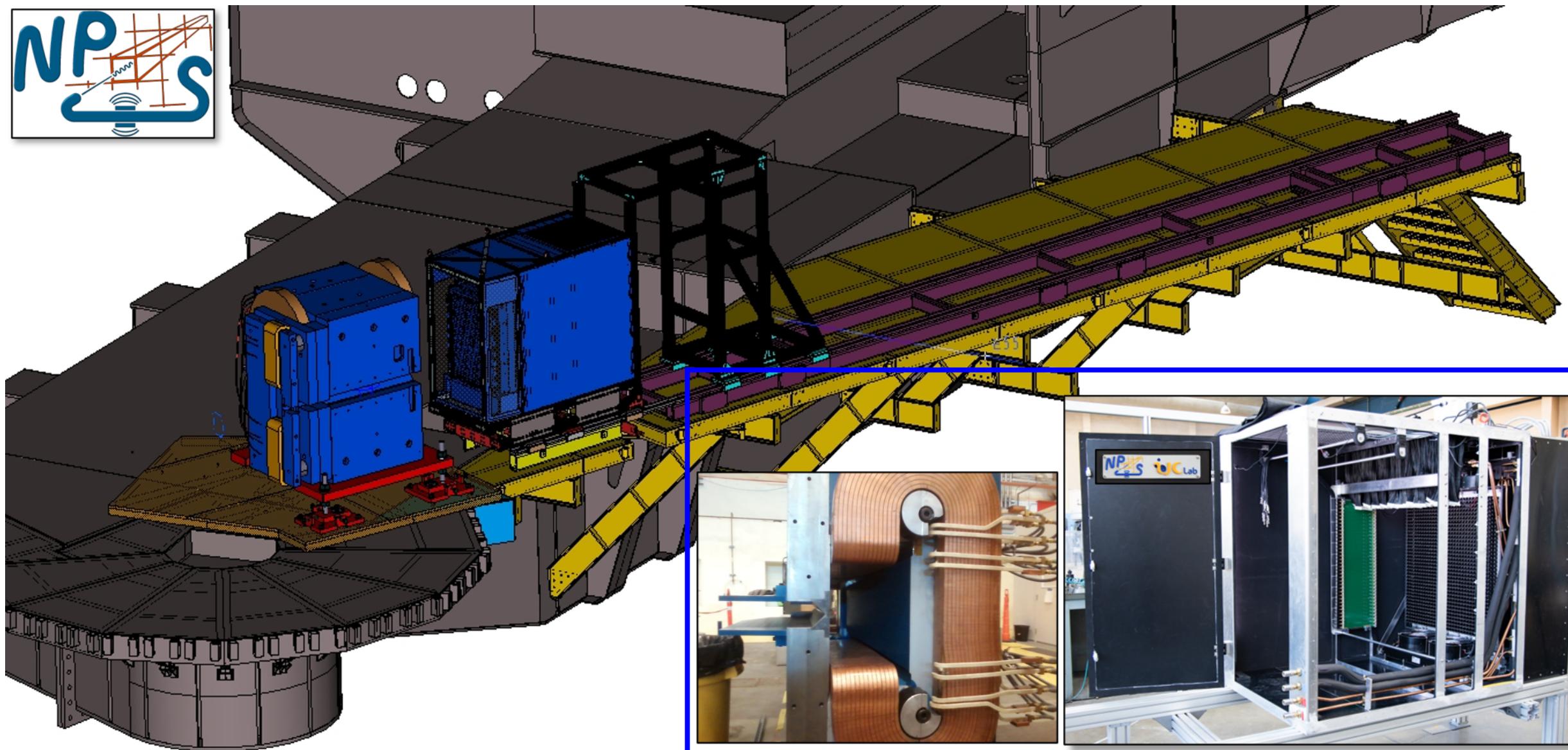
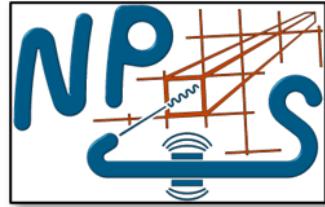
$\Delta\Omega = 72 \text{ msr}$ at 15 degrees

$P = 2\text{-}10 \text{ GeV}/c$

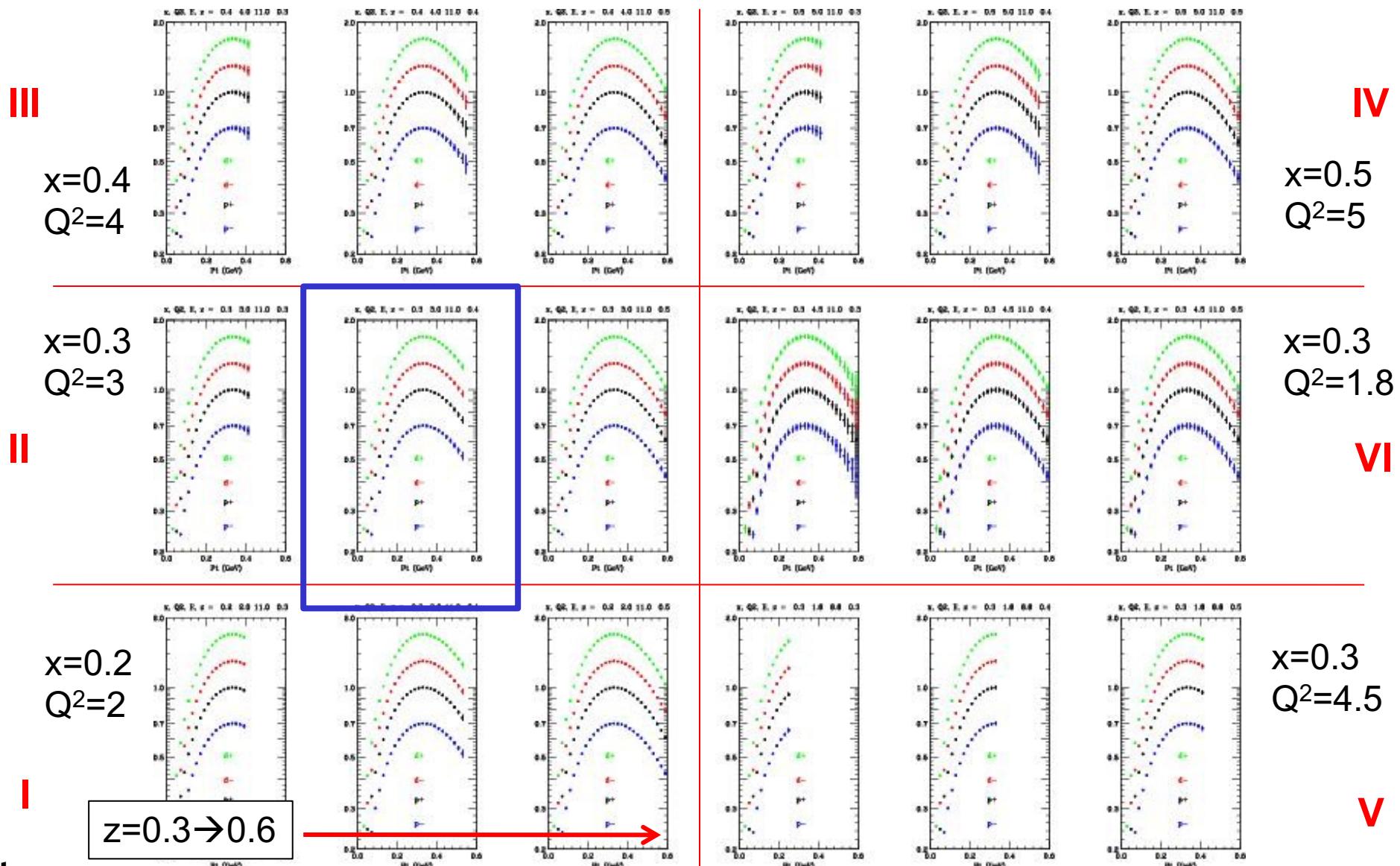


SBS could be paired with SHMS in Hall C → need new or raised stand
→ Not ideal for L/T separations, but cross sections, ratios still accessible

EXTRA

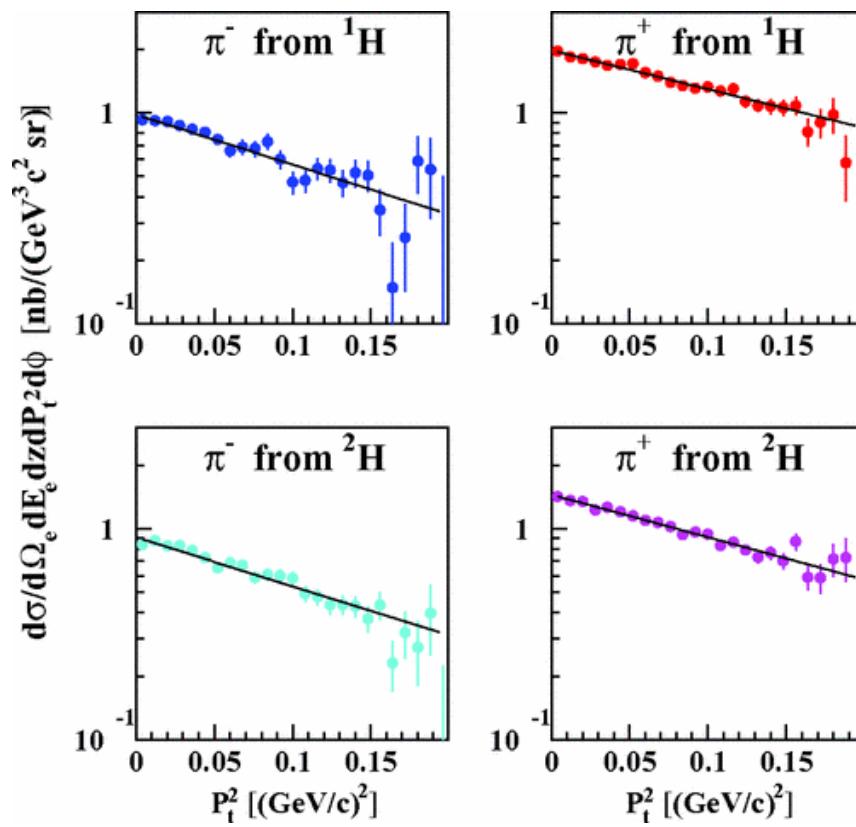


E12-09-017 Kinematics (proposal)

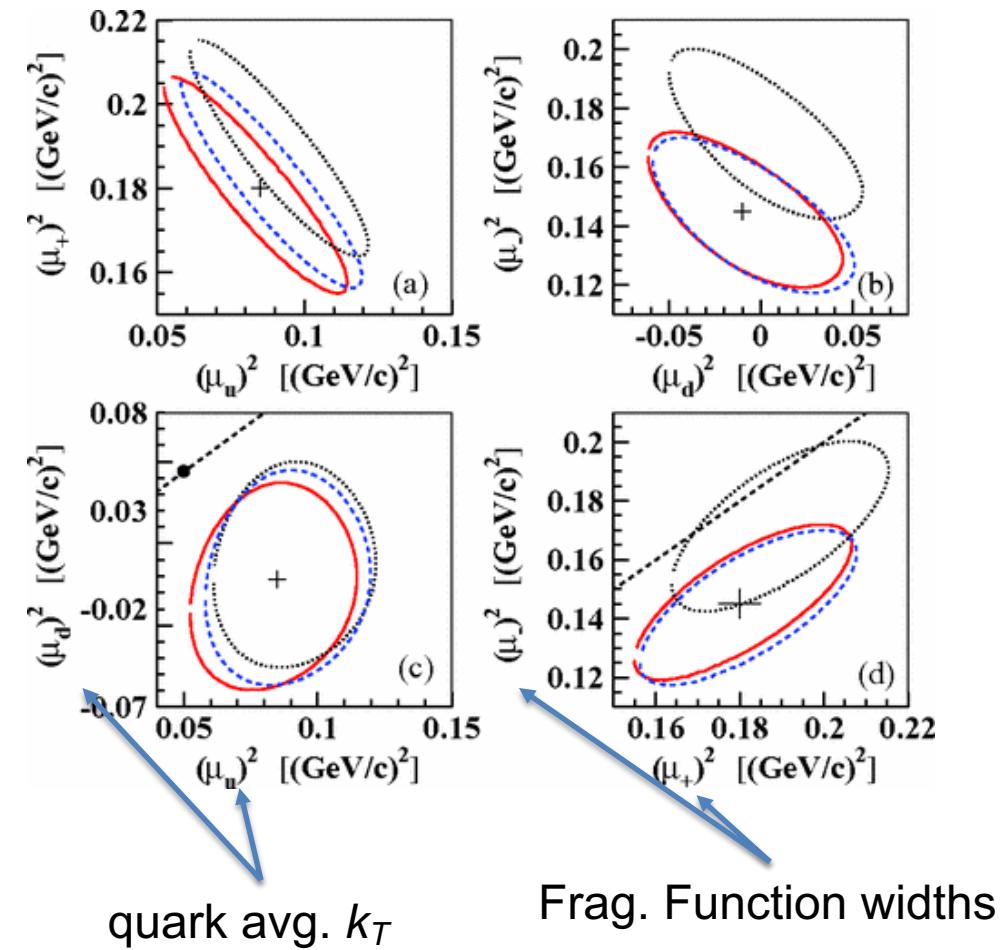


Hall C SIDIS Results from 6 GeV

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



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.

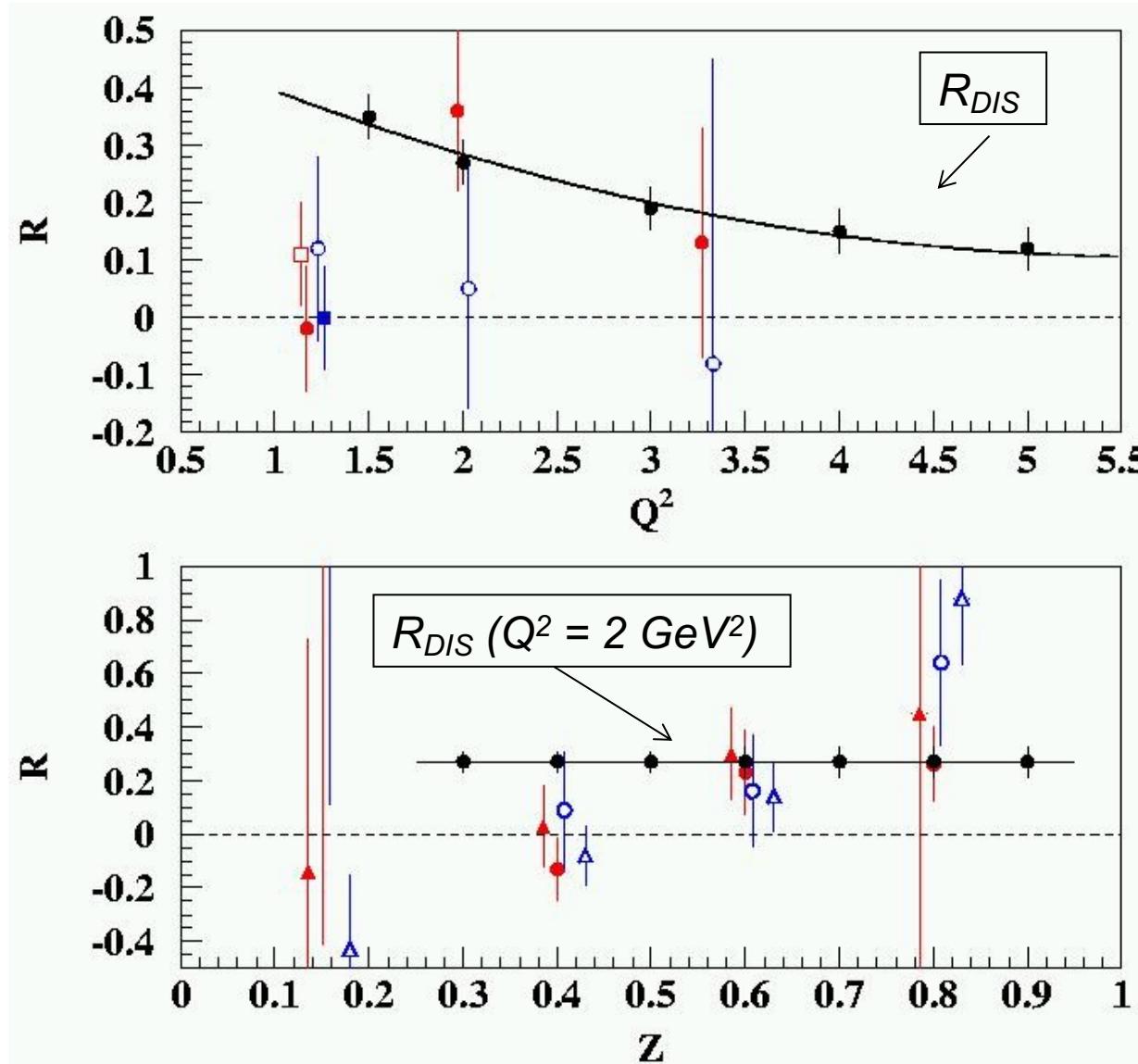
(assuming $\mu_{0,u} = \mu_{0,d}$)

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

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 ($e p \rightarrow e' \pi X$)

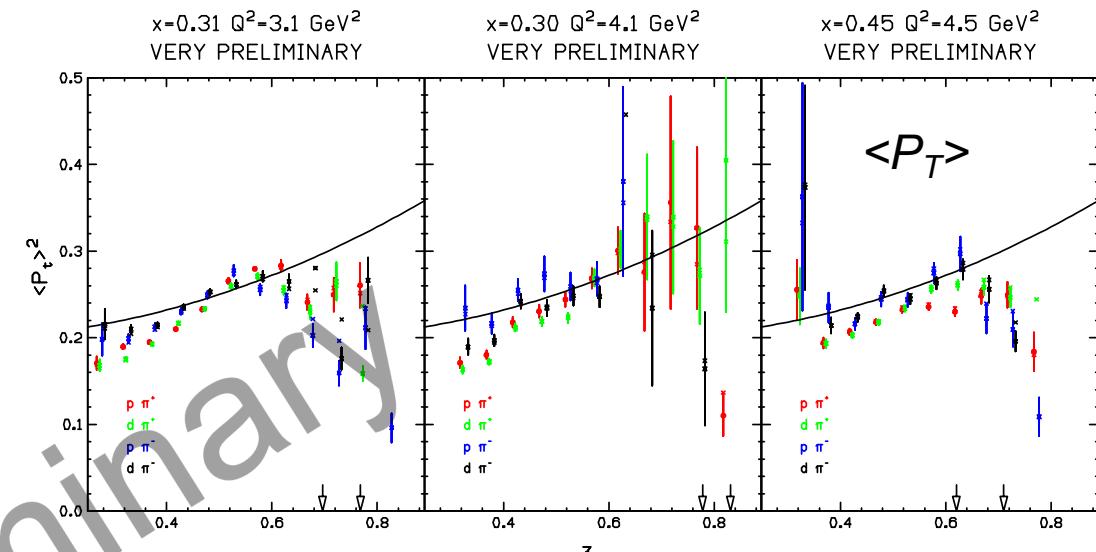
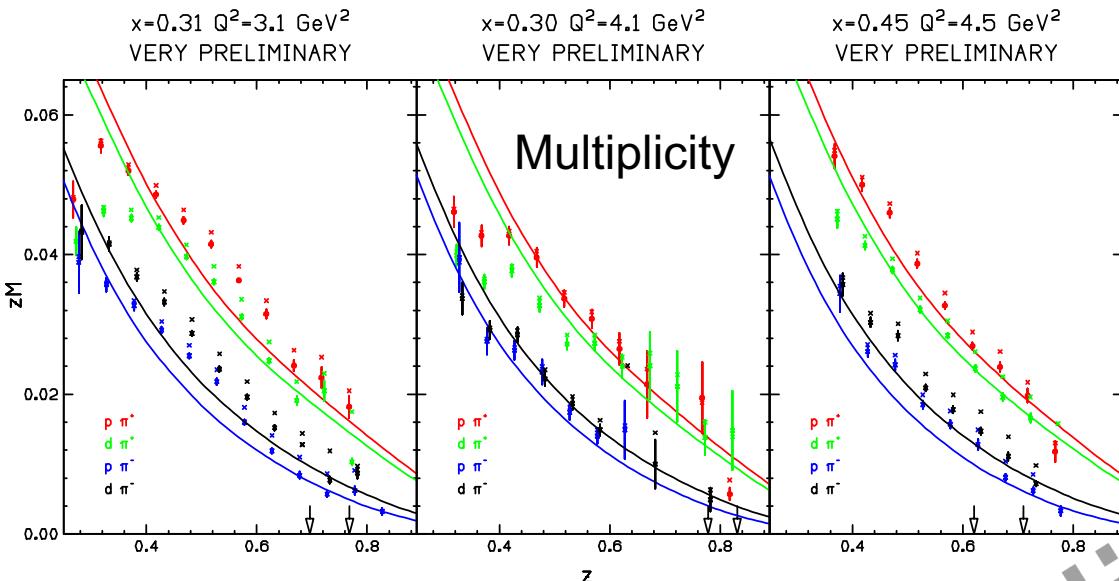
Cornell data
of 70's



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

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

11 GeV SIDIS Preliminary Analysis



Cross sections fit to the form:

$$y = M_0 b e^{-bp_T^2} (1 + A p_T \cos \phi)$$

