SIDIS in Hall C at Higher Energies

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Opportunities With JLab Energy and Luminosity Upgrade

September 26-30, 2022

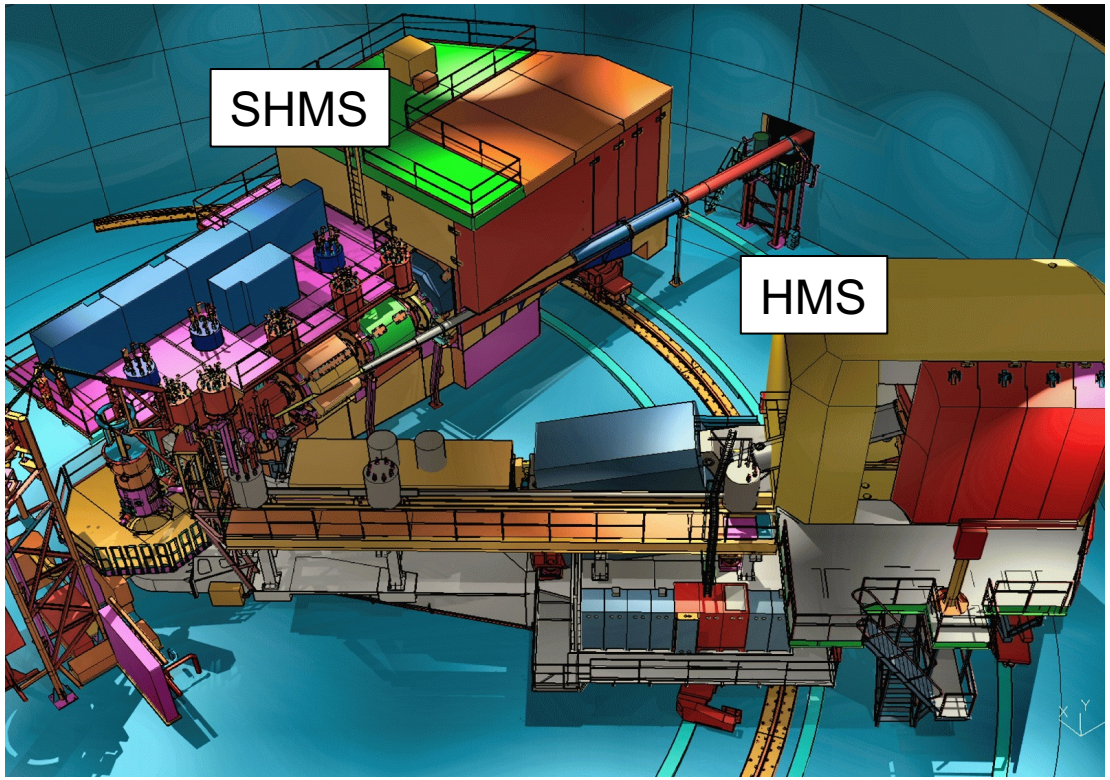
1. Hall C 6 and 12 GeV SIDIS Results/Program
2. Measurements at Higher Energy

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

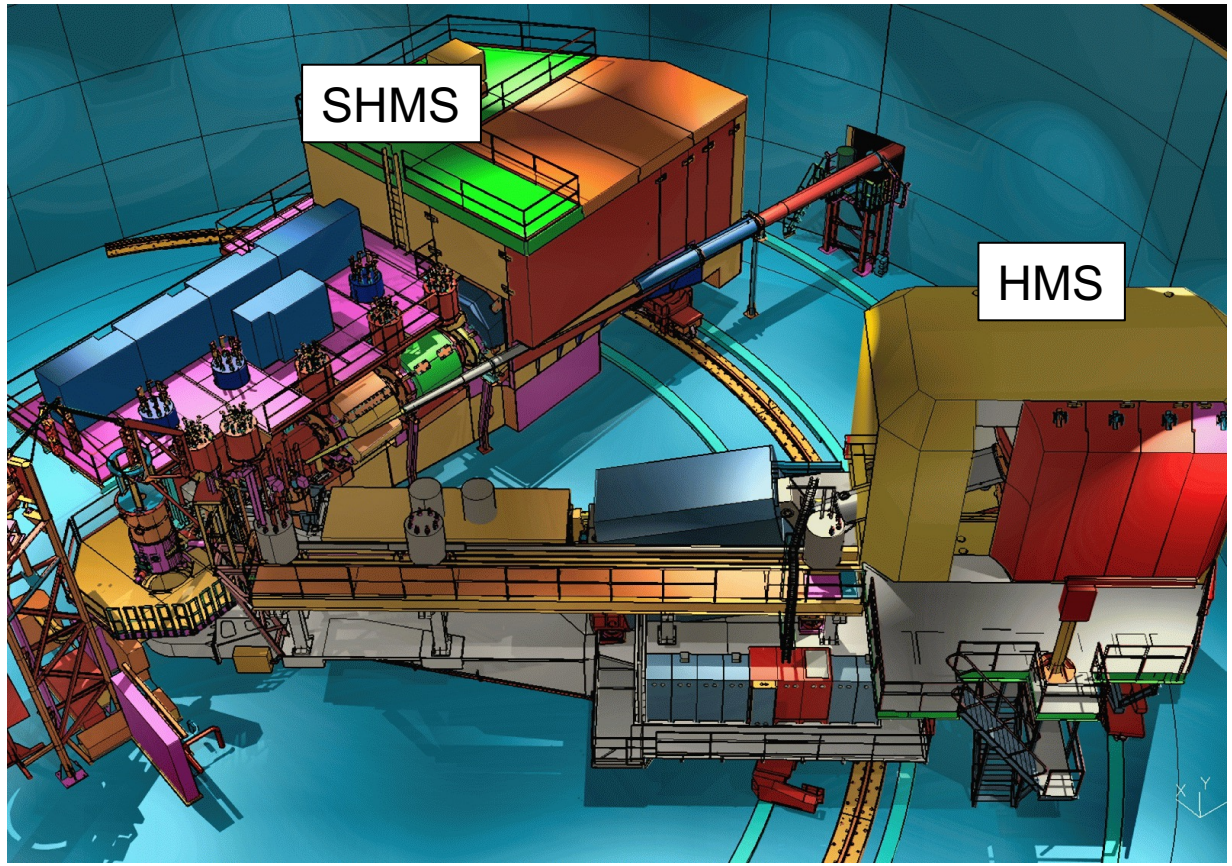
Complementary to large acceptance devices that can access large phase space all at once



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:
$d\Omega \sim 6$ msr, $P_0 = 0.5 - 7$ GeV/c
$\theta_0 = 10.5$ to 80 degrees
e ID via calorimeter and gas Cherenkov

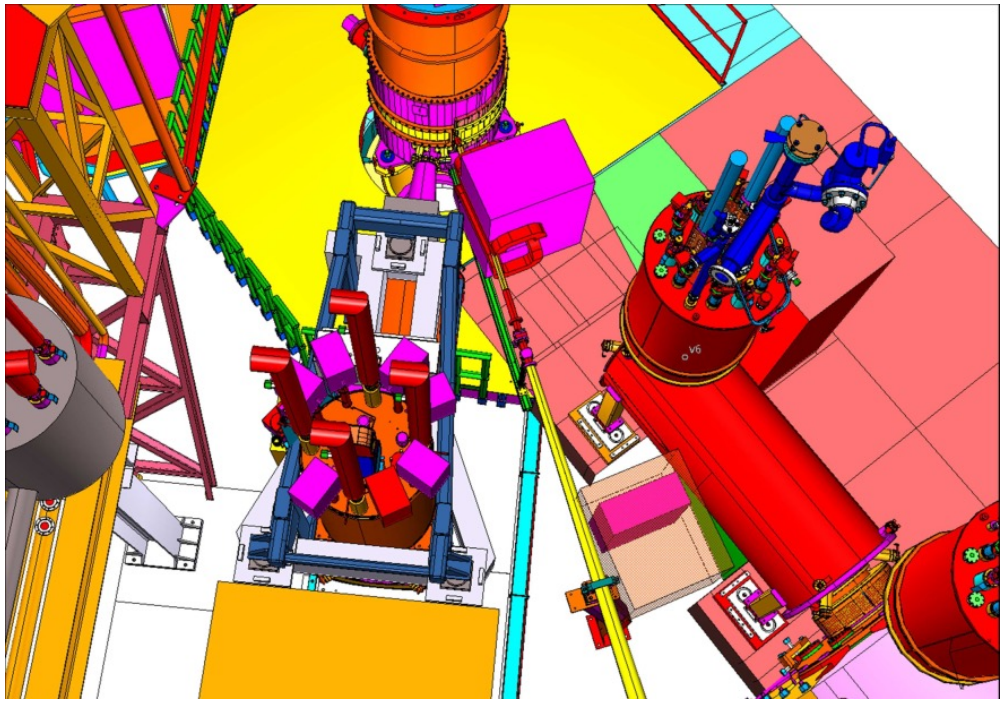
SHMS: Pion arm
Nominal capabilities:
$d\Omega \sim 4$ msr, $P_0 = 1 - 11$ GeV/c
$\theta_0 = 5.5$ to 40 degrees
***π:K:p* separation via heavy gas Cherenkov and aerogel detectors**

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

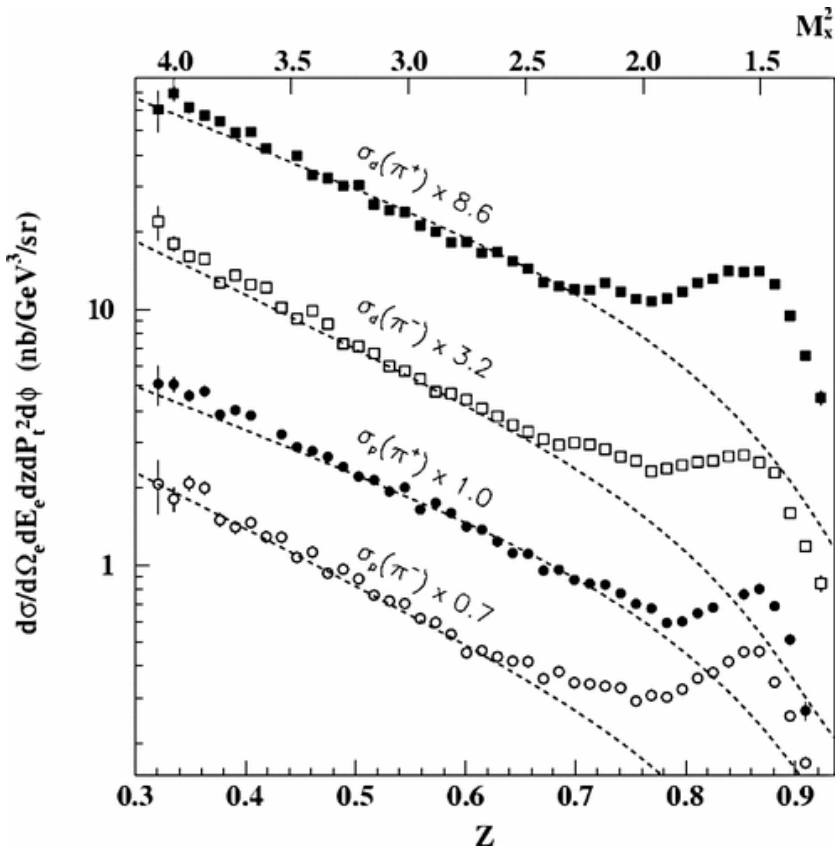


π^0 avoids complications from vector meson decay, smaller radiative tails from exclusive pion production

NPS installation will begin in spring 2023

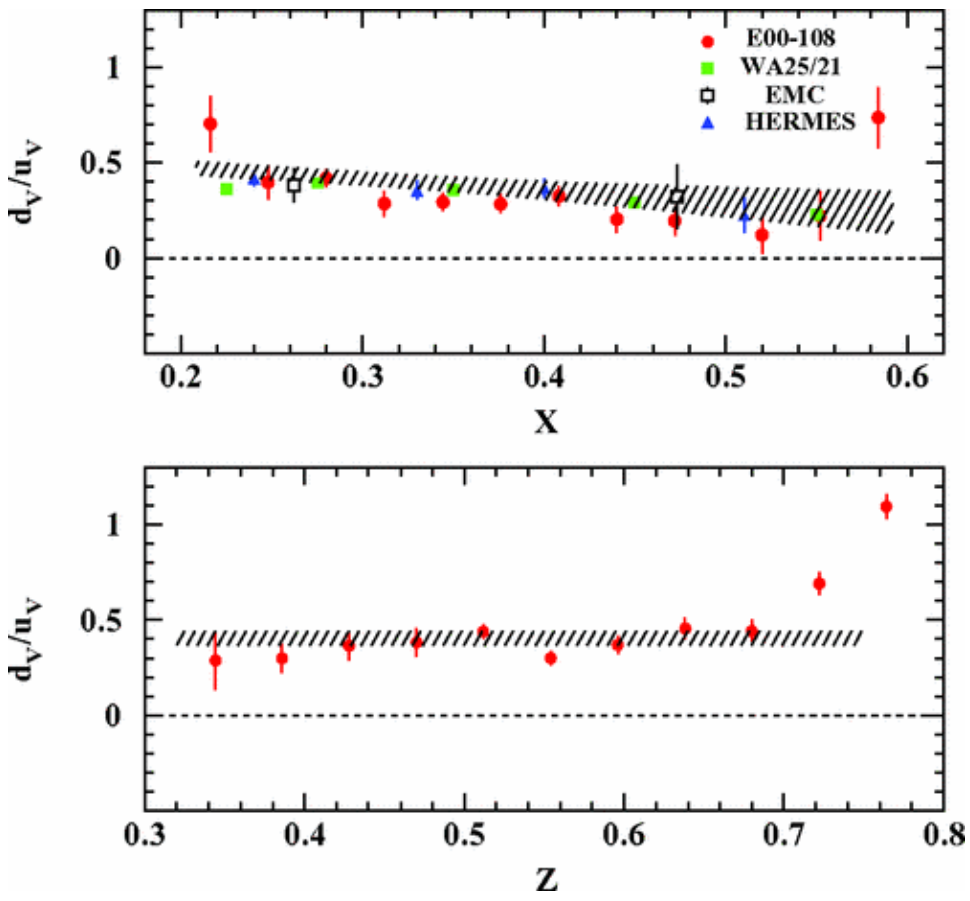
Hall C SIDIS Results from 6 GeV

E10-008: SIDIS π+/π- cross sections and ratios



T. Navasardyan et al. PRL 98, 022001

Surprisingly consistent with expectations from higher energy experiments

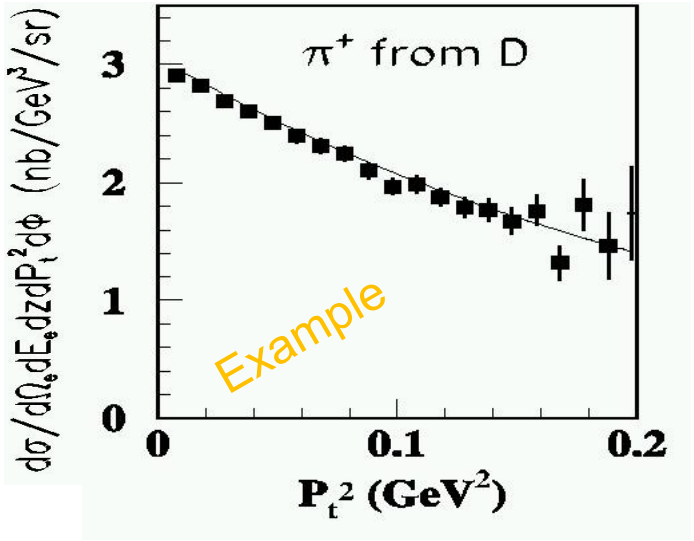


R. Asaturyan et al. Phys. Rev. C 85, 015202

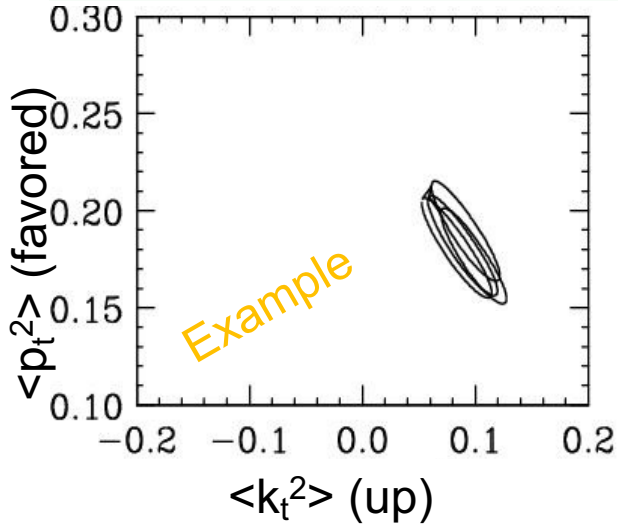
Hall C SIDIS Results from 6 GeV

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

PL B665 (2008) 20



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 …



Hall C @ 12 GeV– P_T Dependent Cross Sections

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

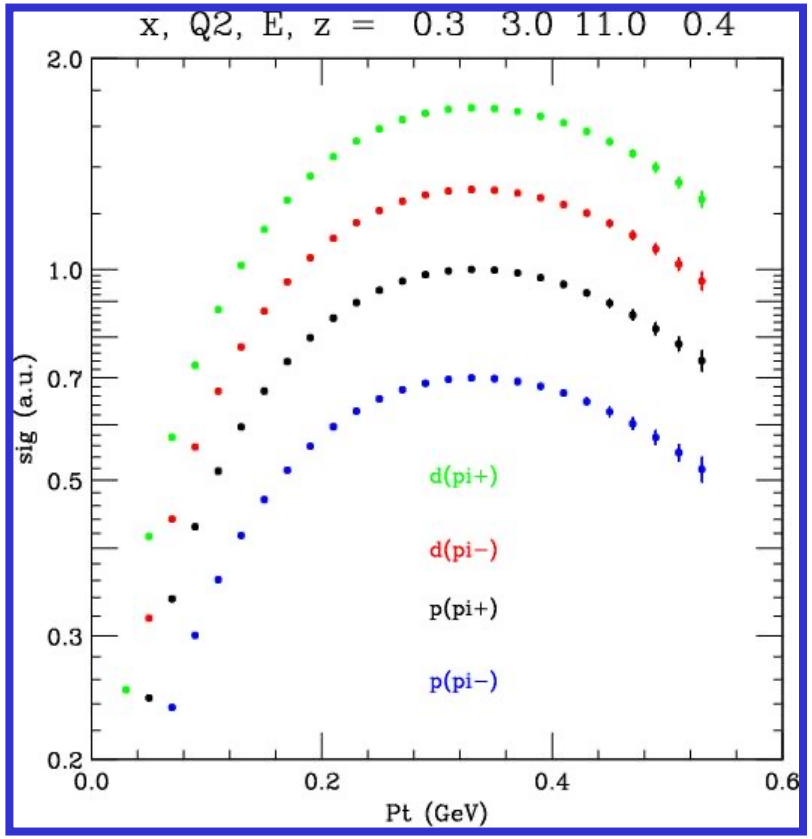
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

Precise cross section measurements with HMS and SHMS

→Demonstrate understanding of reaction mechanism, test factorization

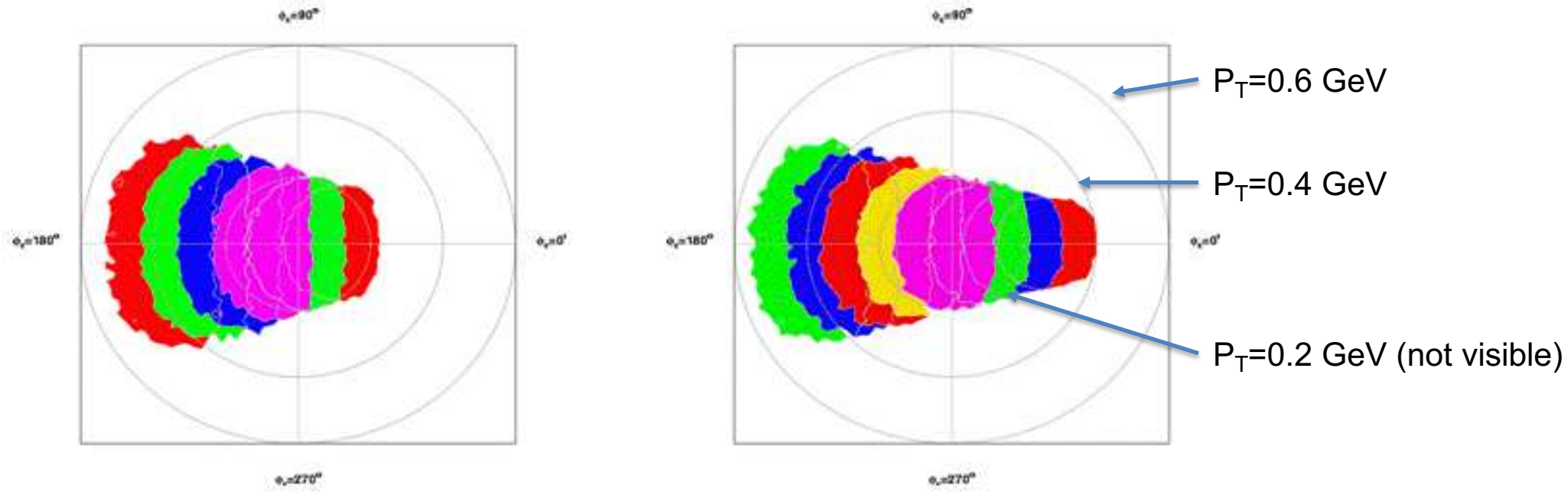
→Able to carry out precise comparisons of charge states, π+/π-

→ Can do meaningful measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!



HMS-SHMS P_T/ϕ acceptance

Simulated, from P_T-SIDIS experiment (11 GeV)



x=0.2 Q^2=2 GeV^2

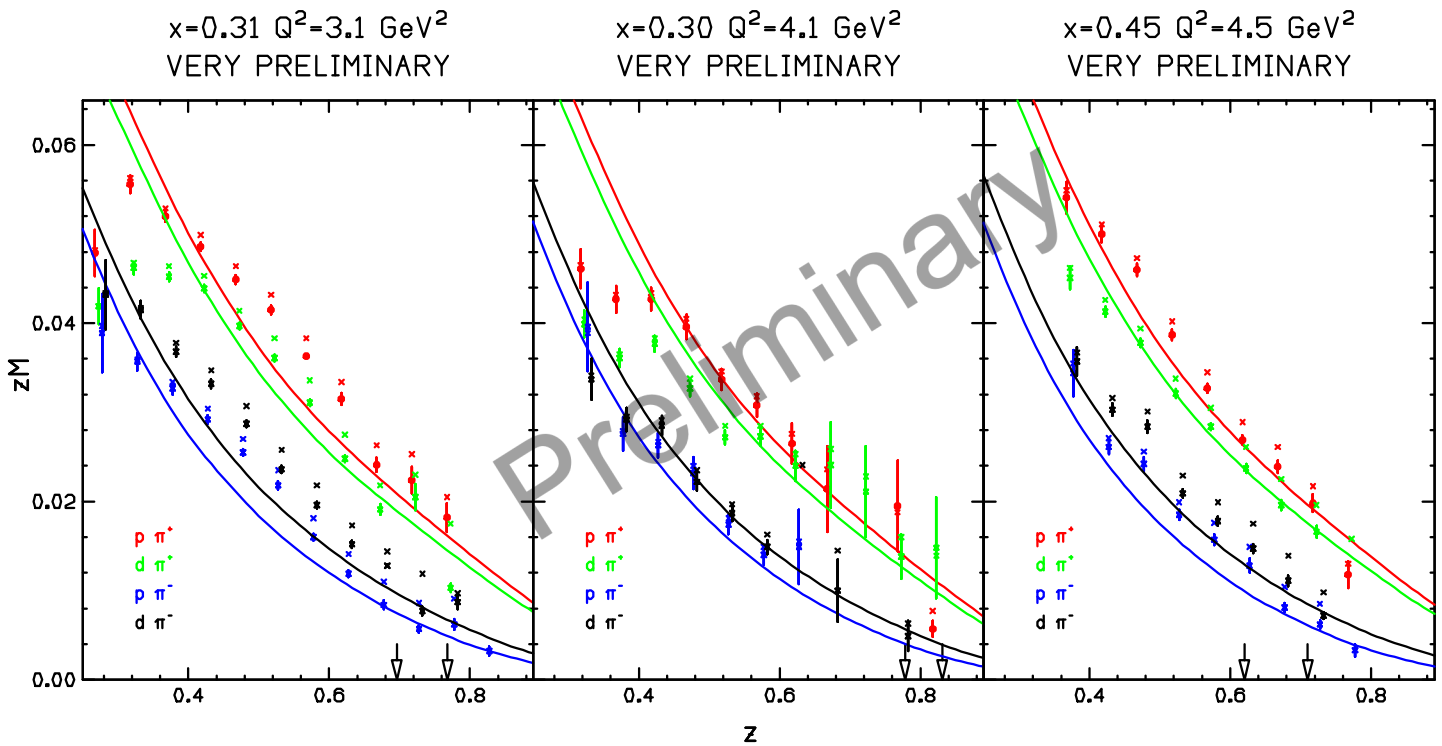
x=0.3 Q^2=3 GeV^2

Full ϕ coverage over limited P_T range → larger P_T covers narrow range in ϕ

11 GeV SIDIS Preliminary Analysis

Multpilicites

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



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

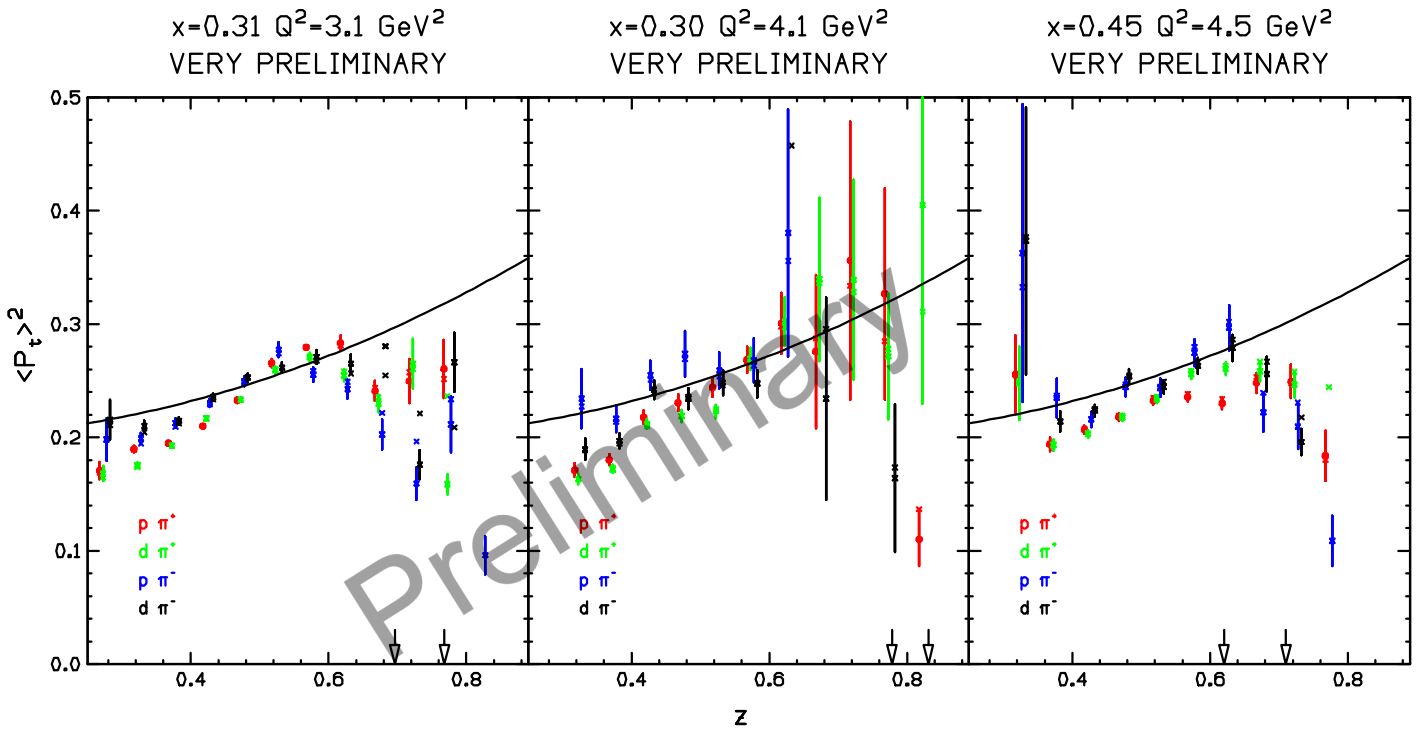
Analysis from Peter Bosted

11 GeV SIDIS Preliminary Analysis

P_T widths

→ Data with and without diffractive ρ subtraction
→ Curves:
$\langle P_T^2 \rangle = \langle pt^2 \rangle + z^2 \langle k_T^2 \rangle$

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



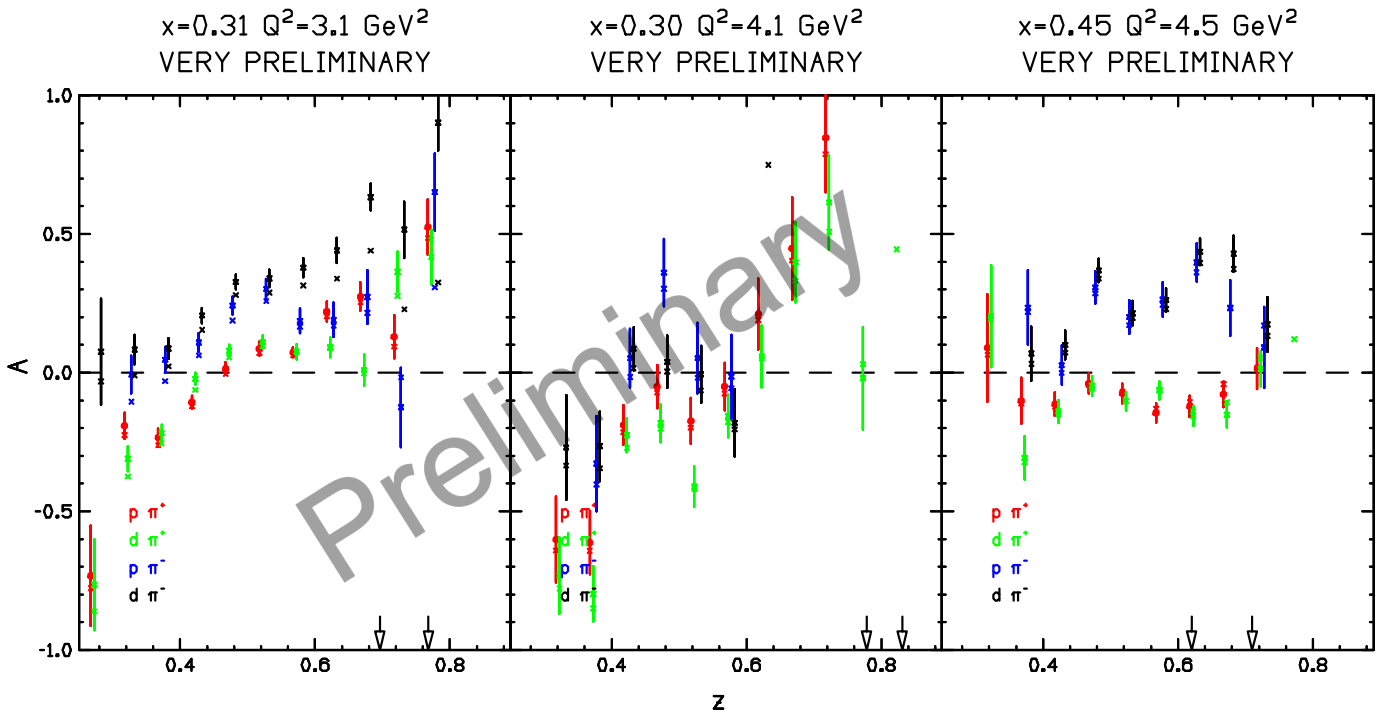
$$y = M_0 b e^{-bp_T^2}(1 + Ap_T \cos\phi)$$

Analysis from Peter Bosted

11 GeV SIDIS Preliminary Analysis

Cos(phi) term:

→ Data with and without diffractive ρ subtraction
→ ”A” generally close to zero or positive
→ Cahn effect would give A<0



Analysis from Peter Bosted

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

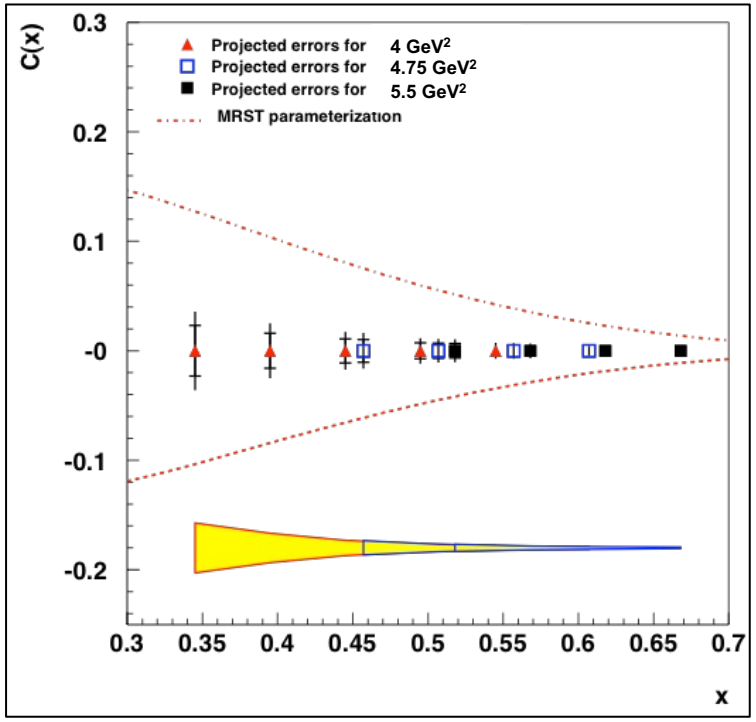
Hall C @ 12 GeV – Precise π^+/π^- Ratios (low P_T)

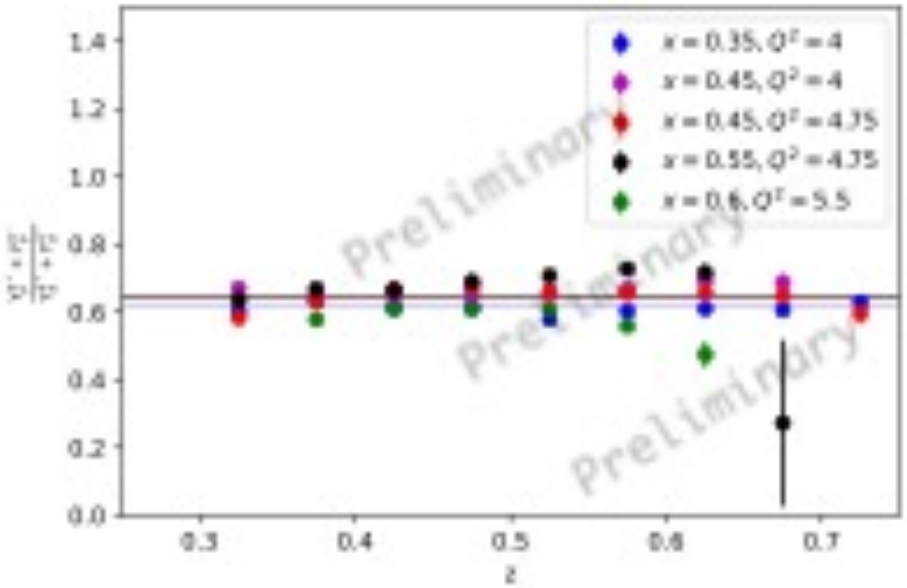
E12-09-002: Charge Symmetry Violating Quark Distributions via π^+/π^- in SIDIS

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

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

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





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

Shuo Jia: E12-09-002

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

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+$$

$$\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}+\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}+\lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

→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} → 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

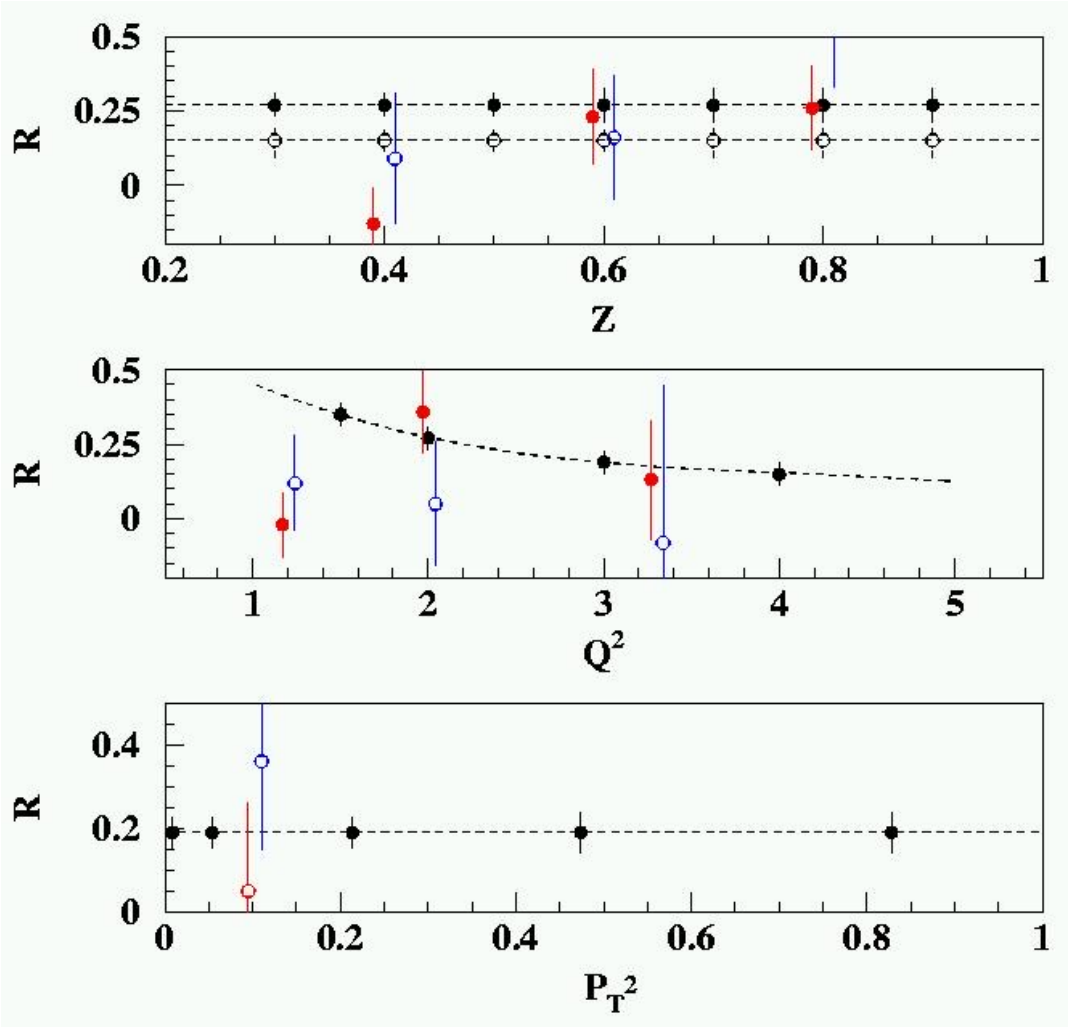
$e+p \rightarrow e'+\pi^{+/-}+X$, $e+D \rightarrow e'+\pi^{+/-}+X$

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

→ ideally suited to Hall C equipment at 12 GeV

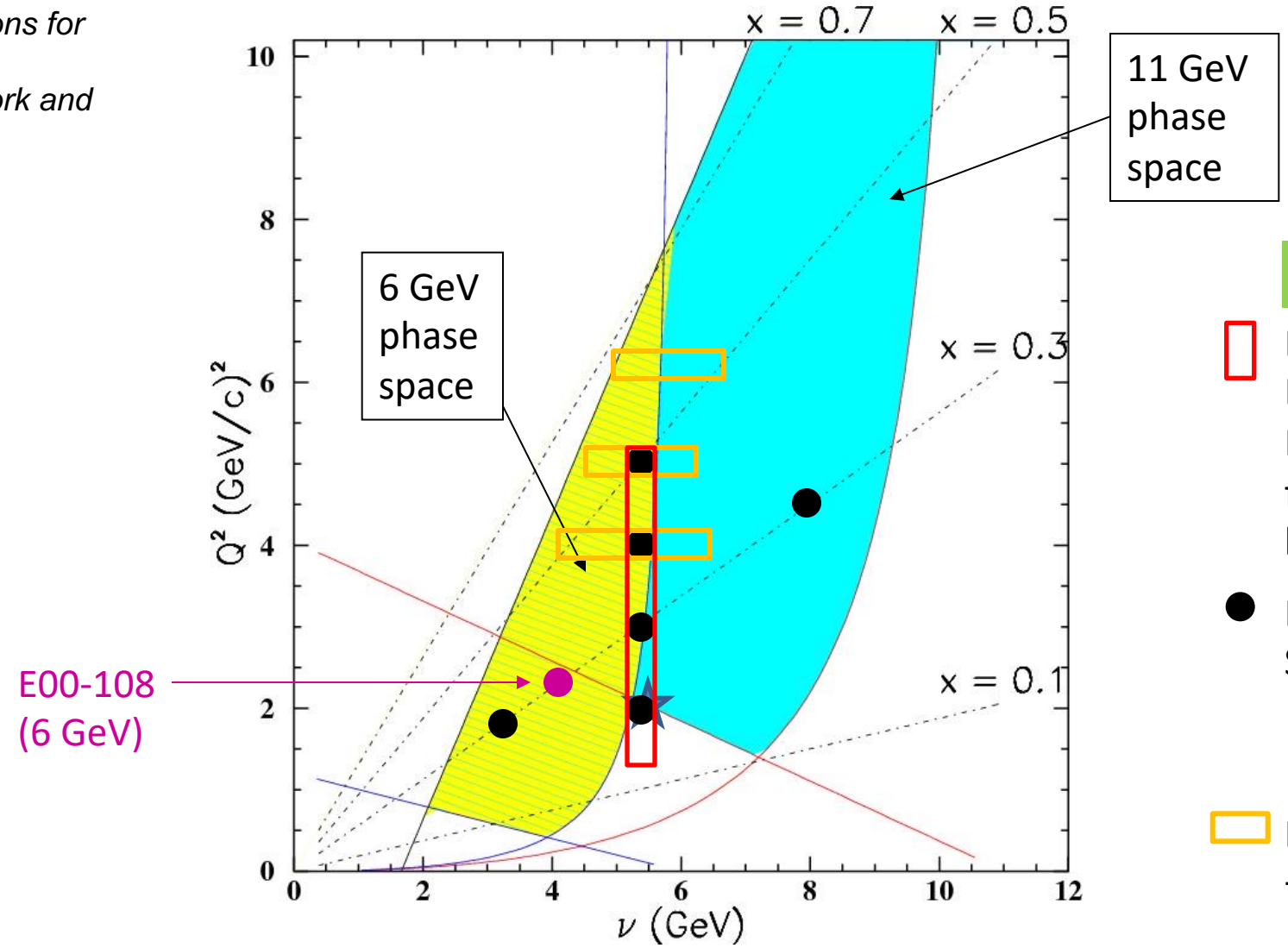
1. Scans in *z* at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV^2 ($x = 0.4$) → behavior of σ_L/σ_T for large z.
2. Cover $Q^2 = 1.5 – 5.0$ GeV^2, → both H and D at $Q^2 = 2$ GeV^2
3. P_T up to ~ *1* GeV. Coverage in ϕ is excellent (o.k.) up to $P_T = 0.2$ (0.4) GeV.

$R = \sigma_L/\sigma_T$ 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



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

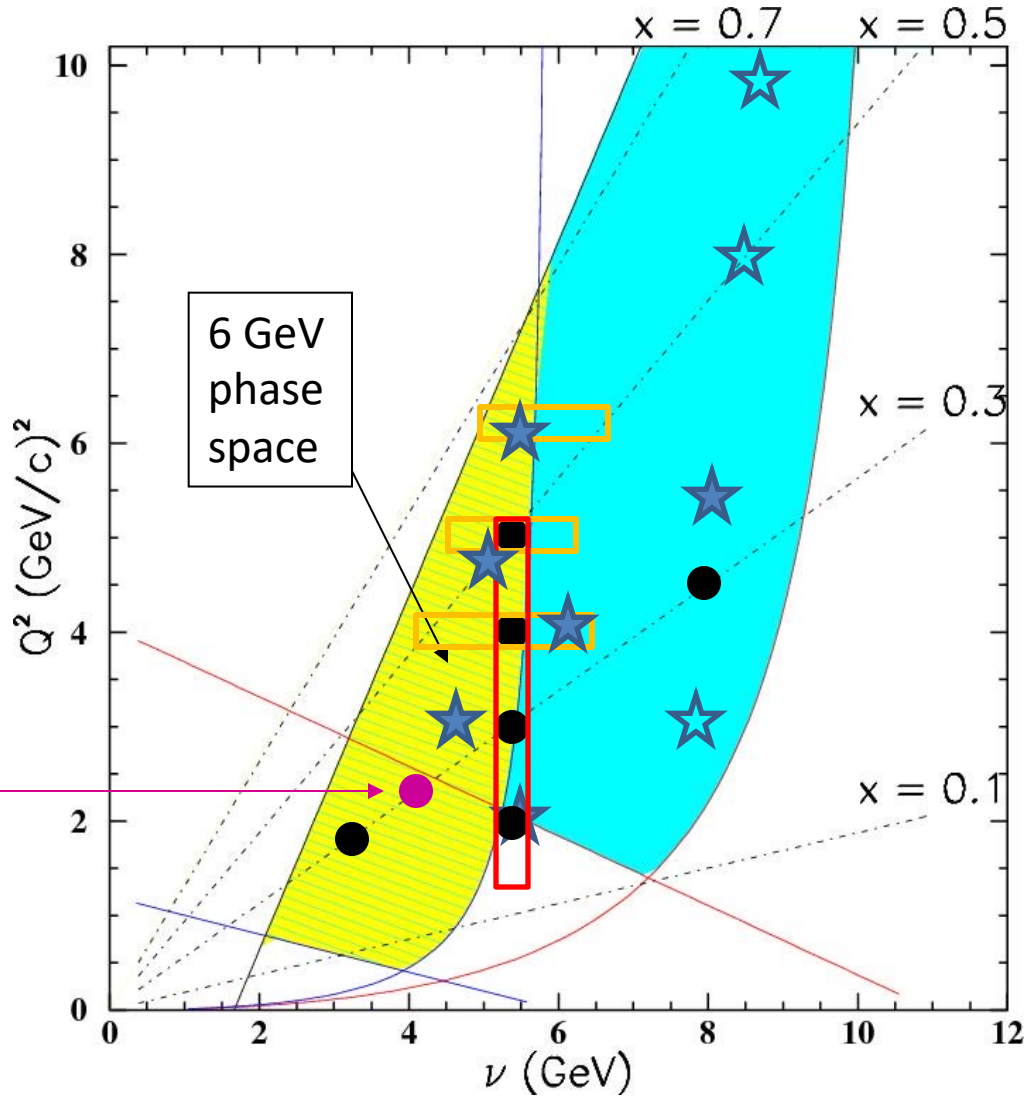
Courtesy R. Ent

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



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

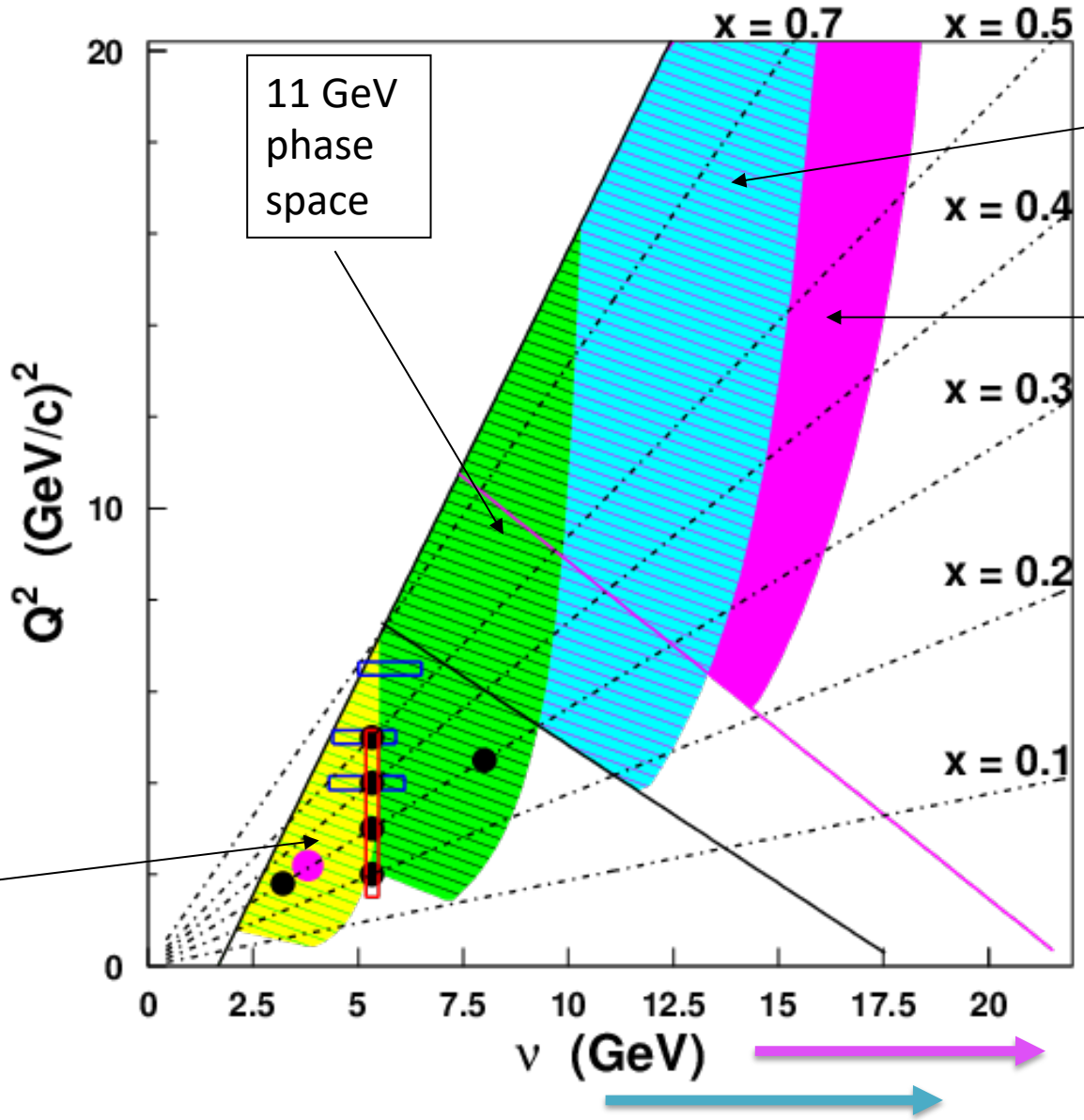
Courtesy R. Ent

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



Possible Measurements

→ Additional L-T separations: expanded x/Q^2

→ Large P_T, cross sections and ratios in particular phase space

→ Measurements of cross sections and ratios at largest Q^2 and x

HMS P_{max} = 7.5 GeV constraint

Measurements at 22 GeV: Parallel Kinematics

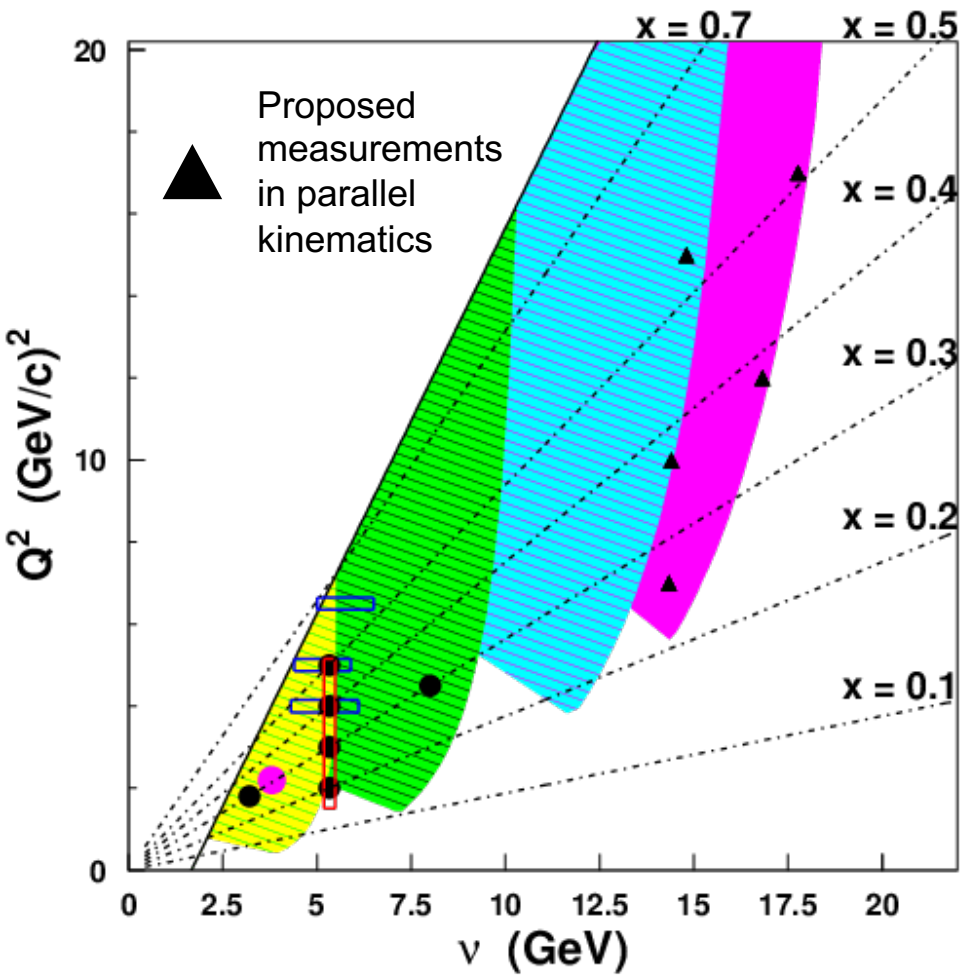
HMS+SHMS has excellent momentum/angle resolution
→ Complete ϕ coverage at low P_T

x	Q2	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

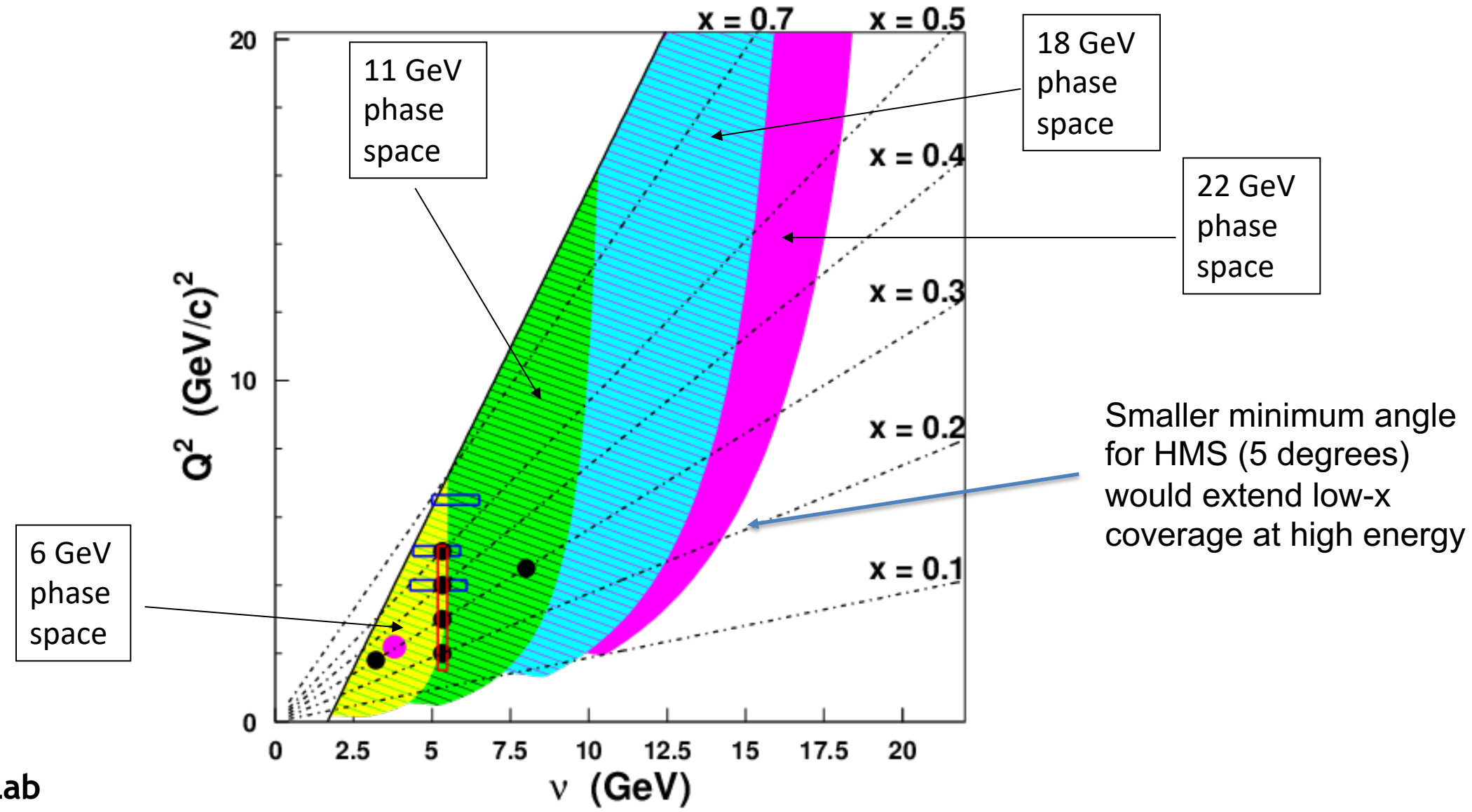
~45 days assuming 70 μA

No modifications to either HMS or SHMS needed for these measurements



Projections from Peter Bosted

Hall C SIDIS Phase Space – Smaller HMS angle



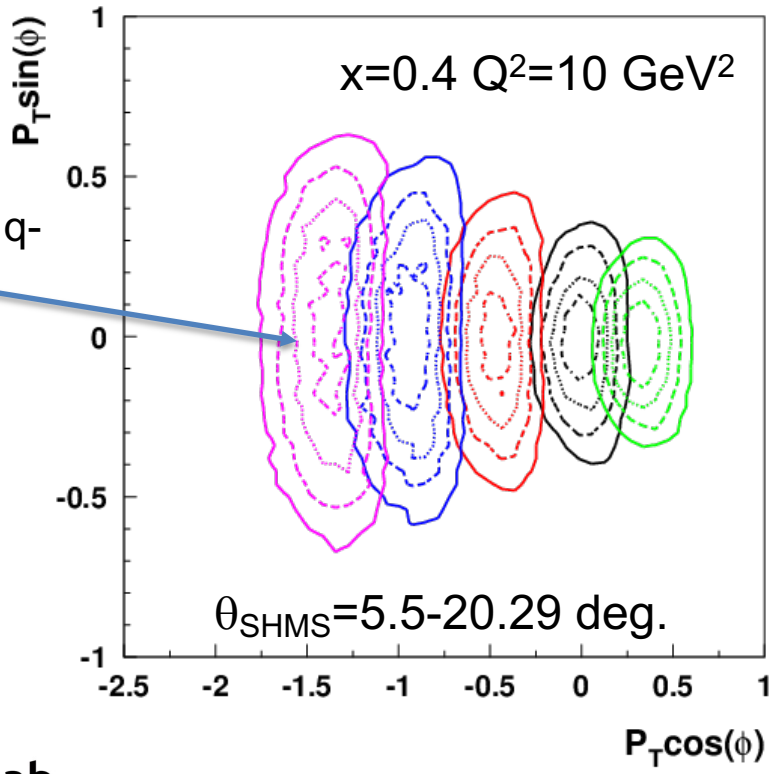
Measurements at 22 GeV: Large P_T

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/Q² assumes upgraded HMS

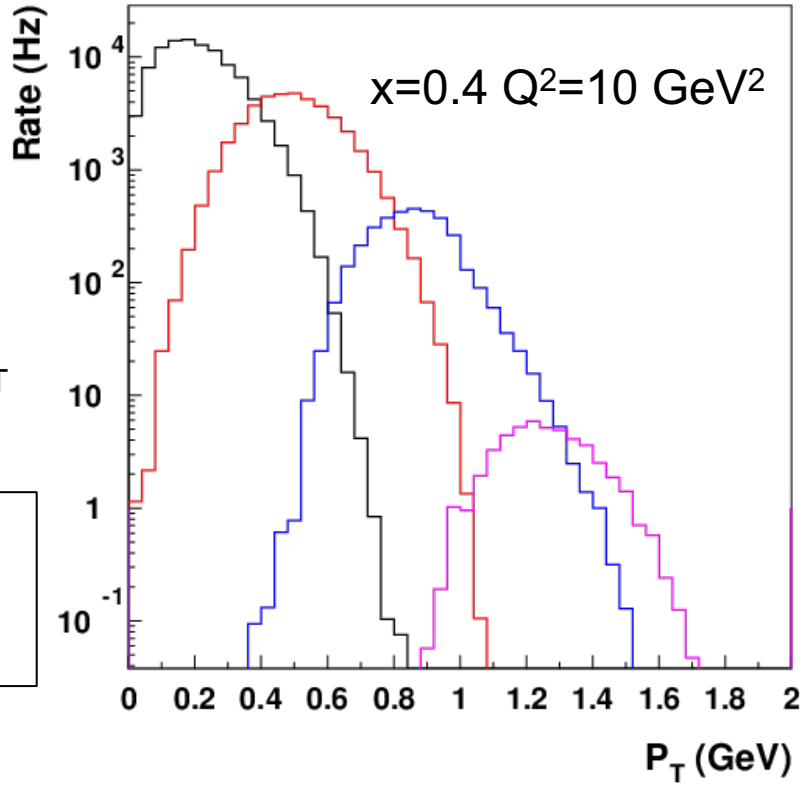
$$\frac{d\sigma}{dx dy dz dp_T^2 d\phi} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left[F_T + \epsilon F_L + \sqrt{2\epsilon(1+\epsilon)}\cos\phi F_{LT} + \epsilon\cos 2\phi F_{TT}\right]$$

SHMS +12 degrees from q-vector



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

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



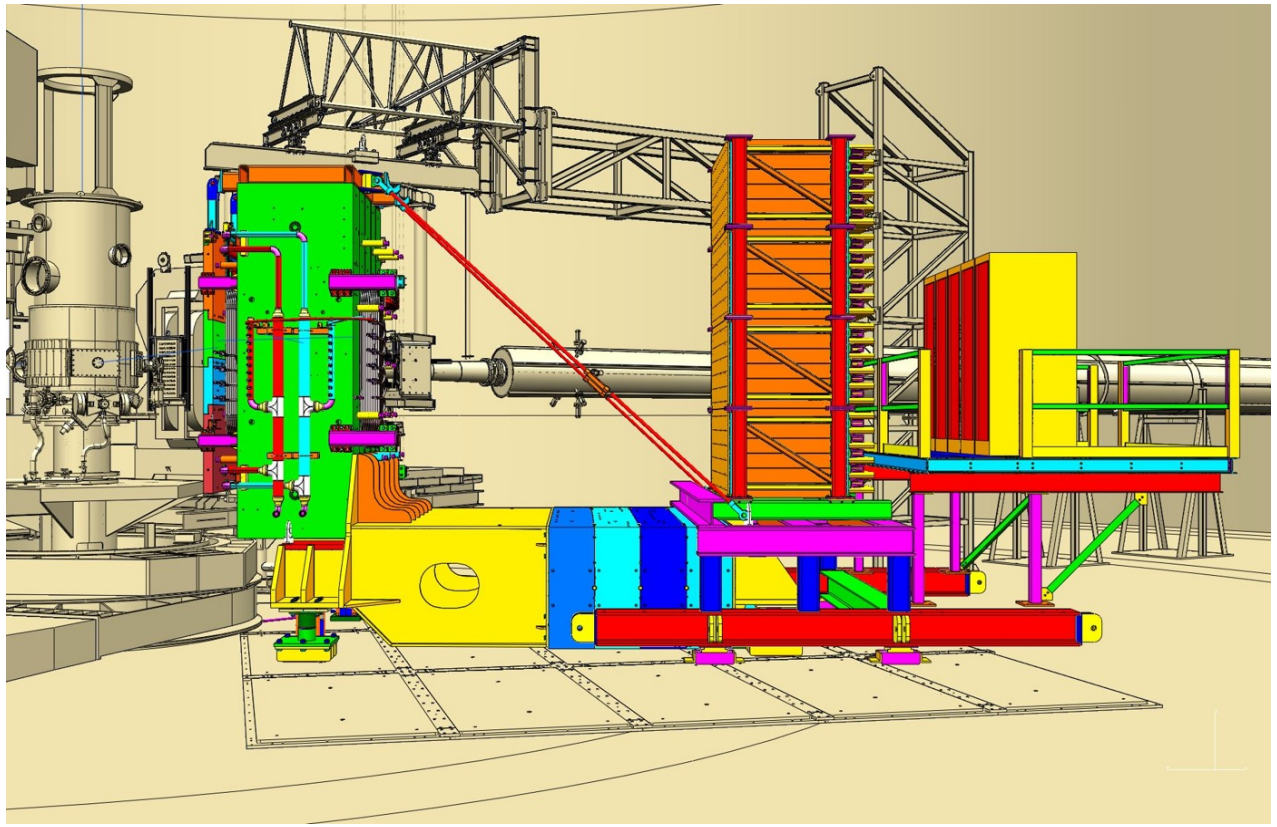
Hall C Program at Higher Energy

- Higher energy capabilities extends 12 GeV program to larger x, Q^2
  - Precision cross sections
  - L/T separations
  - Low rate processes → large P_T
  - Precision ratios (π+/π-, and more)
  - Excellent π/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 → needed for access to lower x, anti-shadowing region

SHMS and SBS?

Super Big Bite Spectrometer built and being used in Hall A

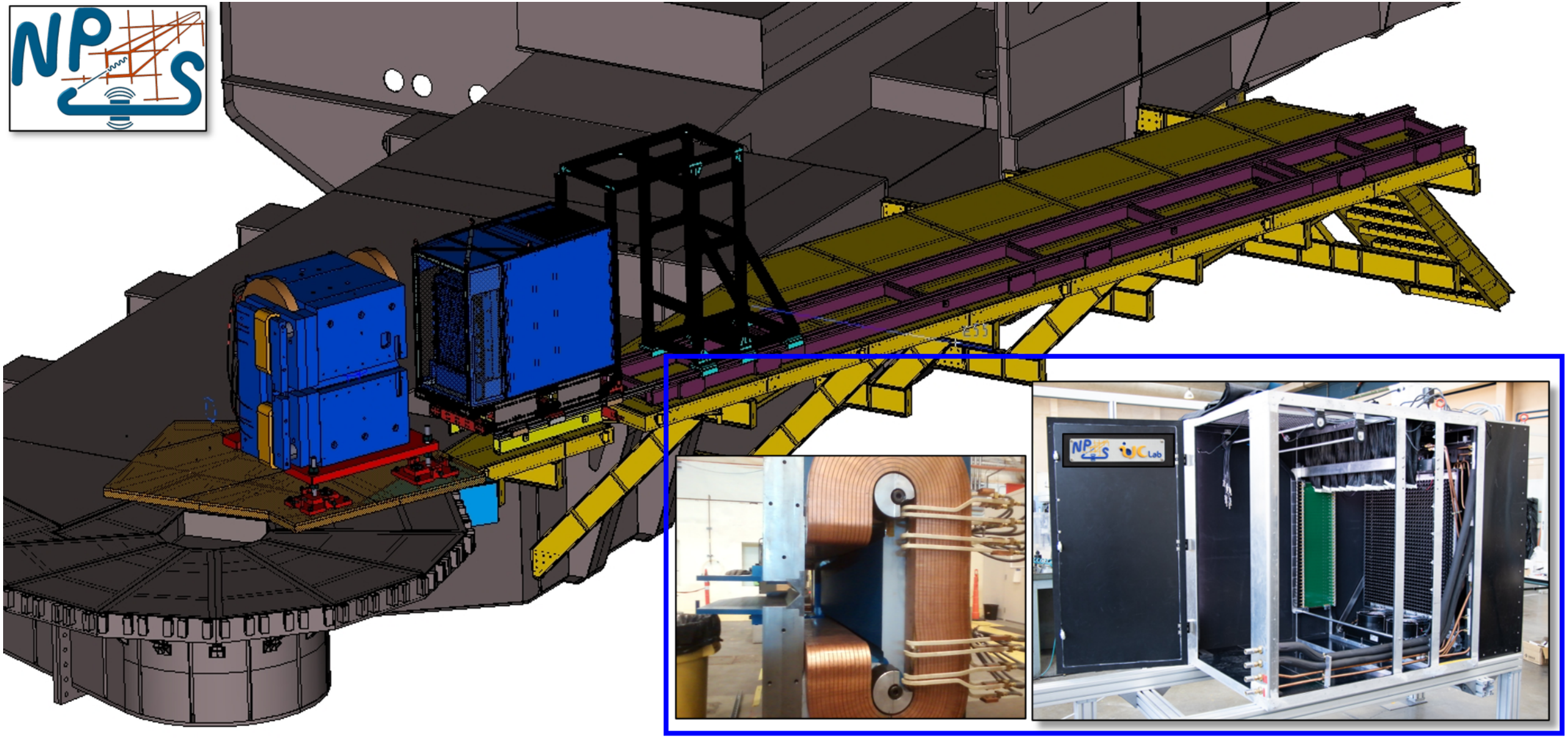
→ Dipole with large gap and large area detector stack
→ Can be positioned a various positions/distances from the pivot
→ Access very small angle by pushing the spectrometer far from pivot



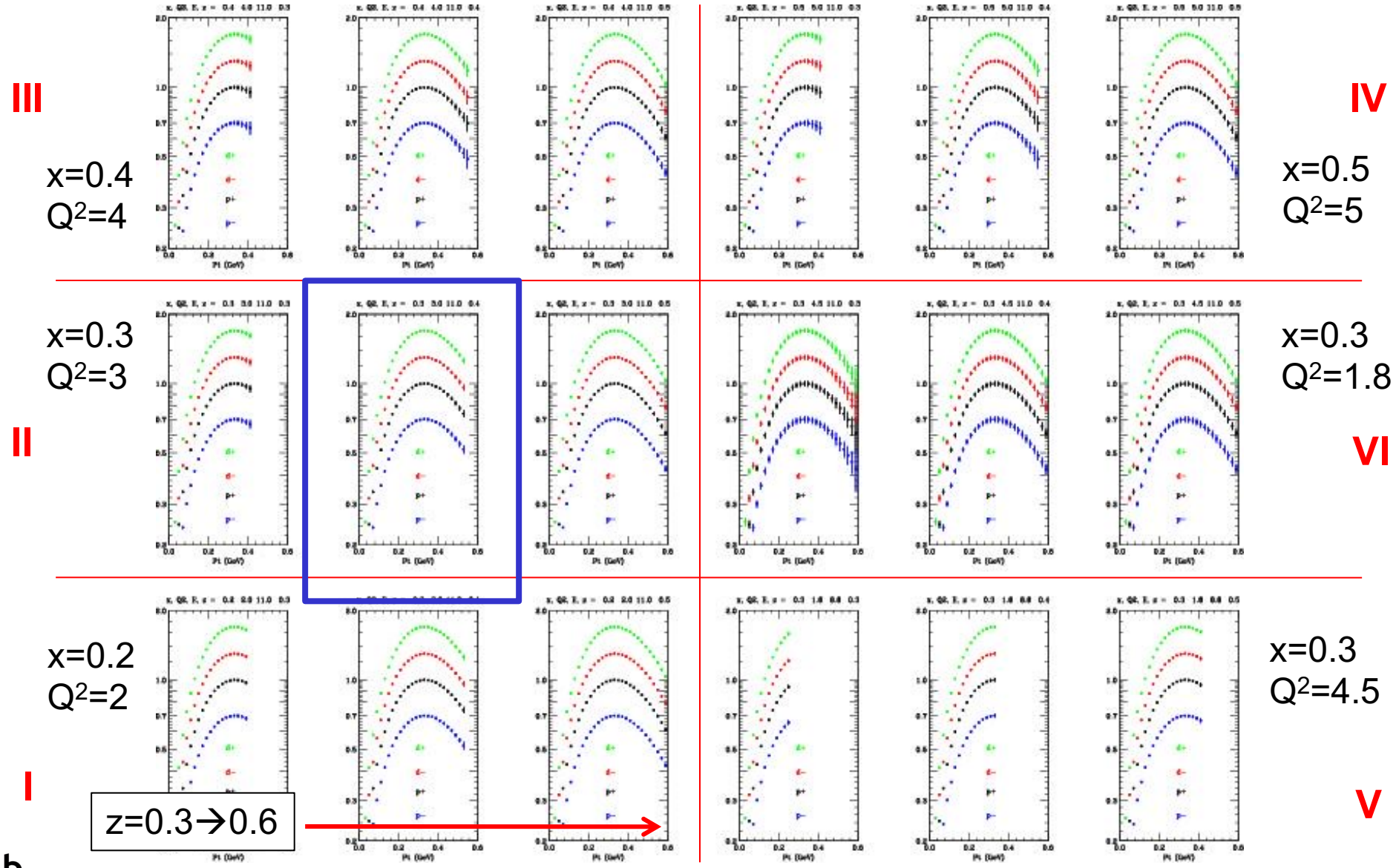
$\Delta\Omega$ = 12 msr at 5 degrees
$\Delta\Omega$ = 72 msr at 15 degrees
P = 2-10 GeV/c

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

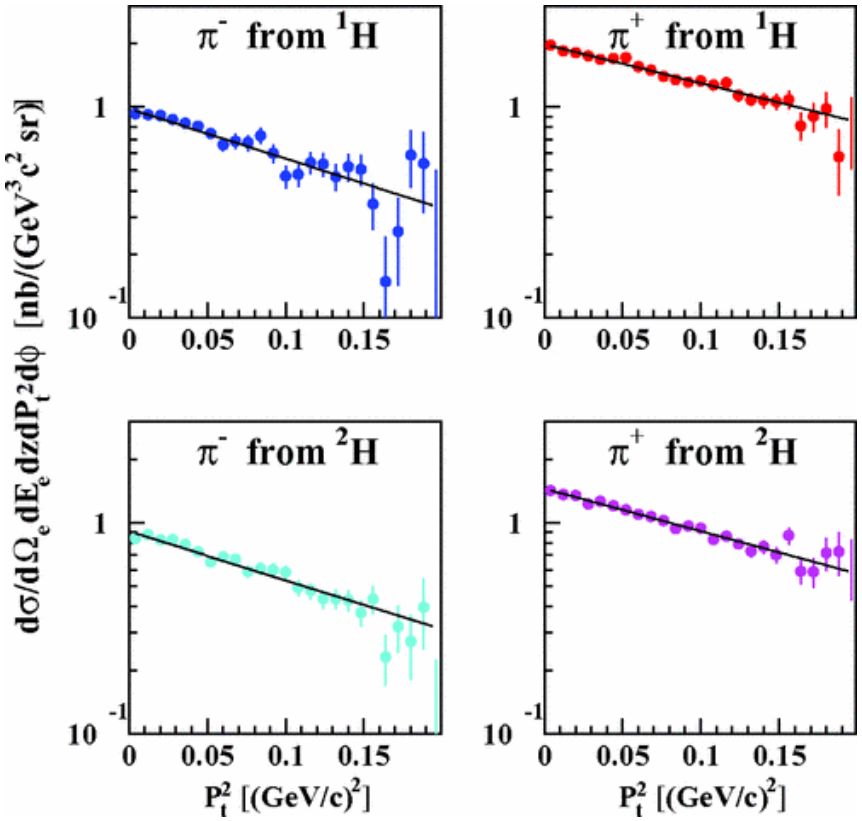


E12-09-017 Kinematics (proposal)

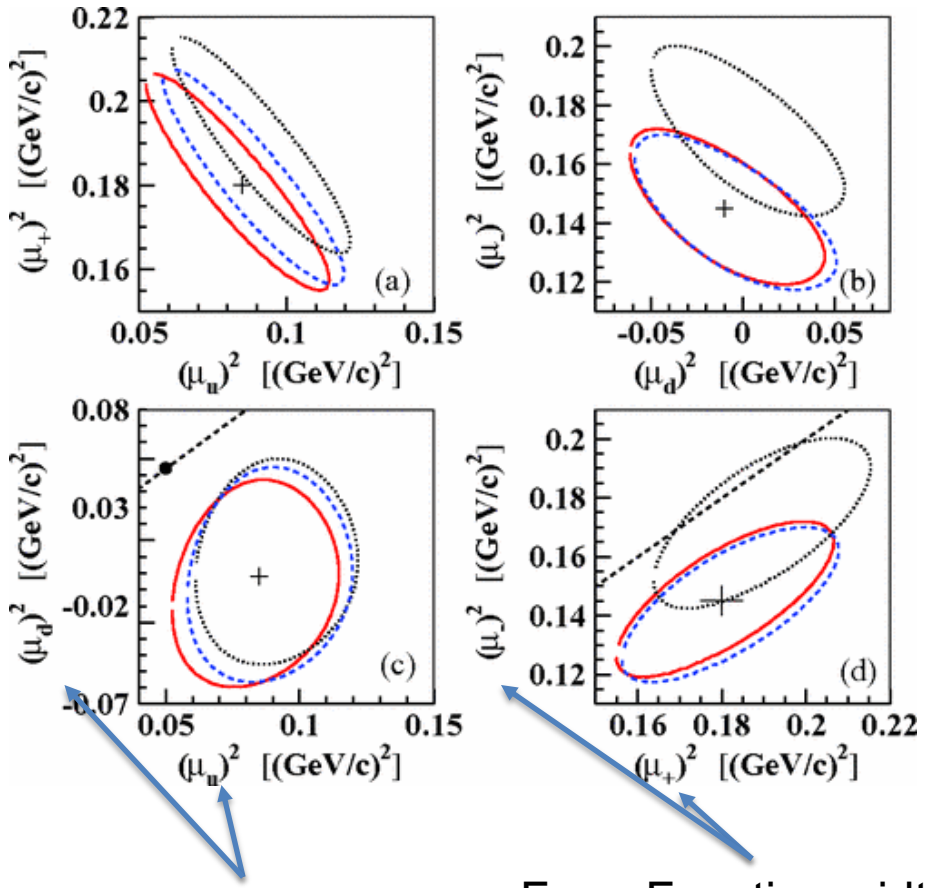


Hall C SIDIS Results from 6 GeV

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



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.

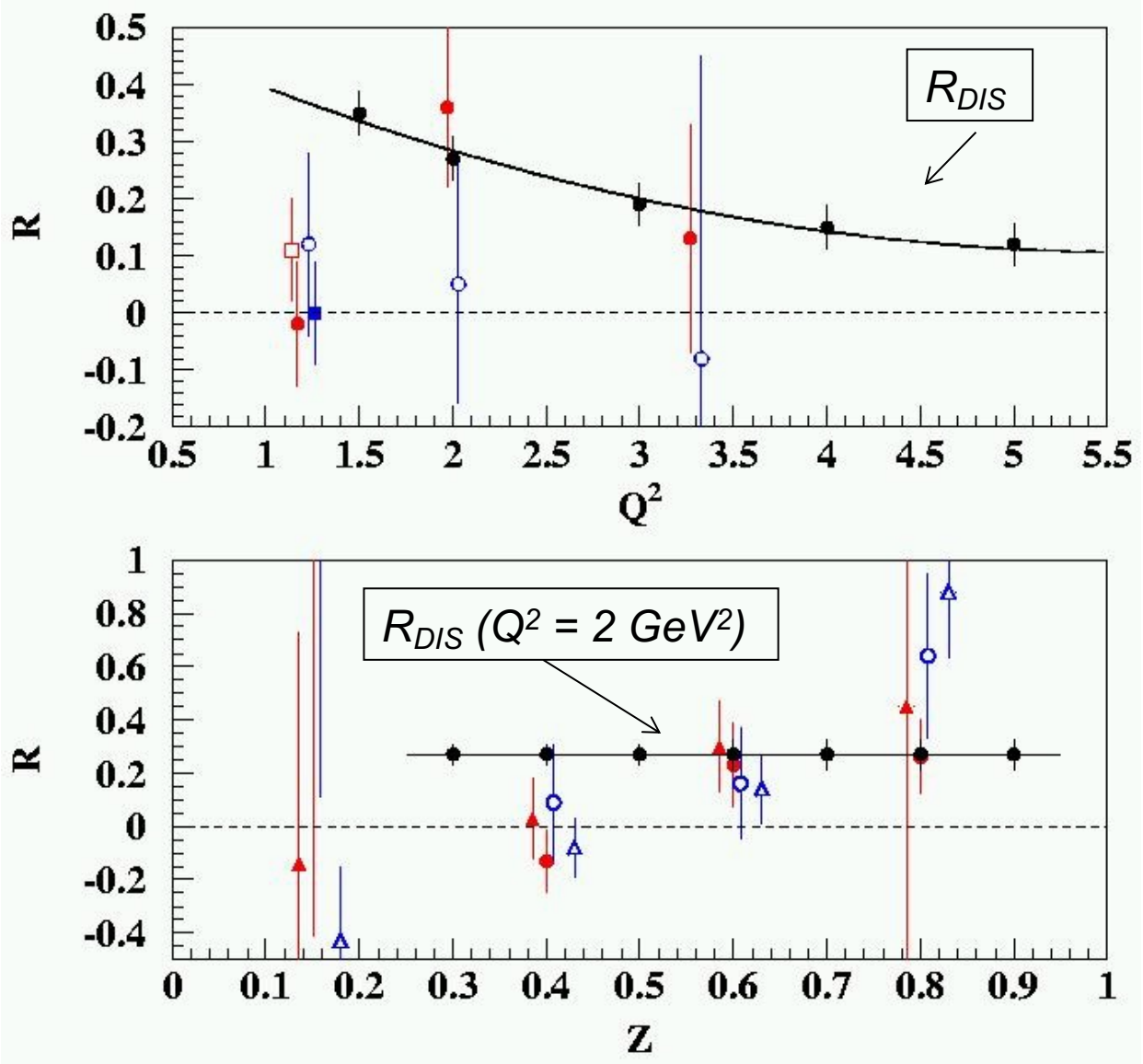
(assuming $\mu_{0,u} = \mu_{0,d}$)

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

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 → e'πX)

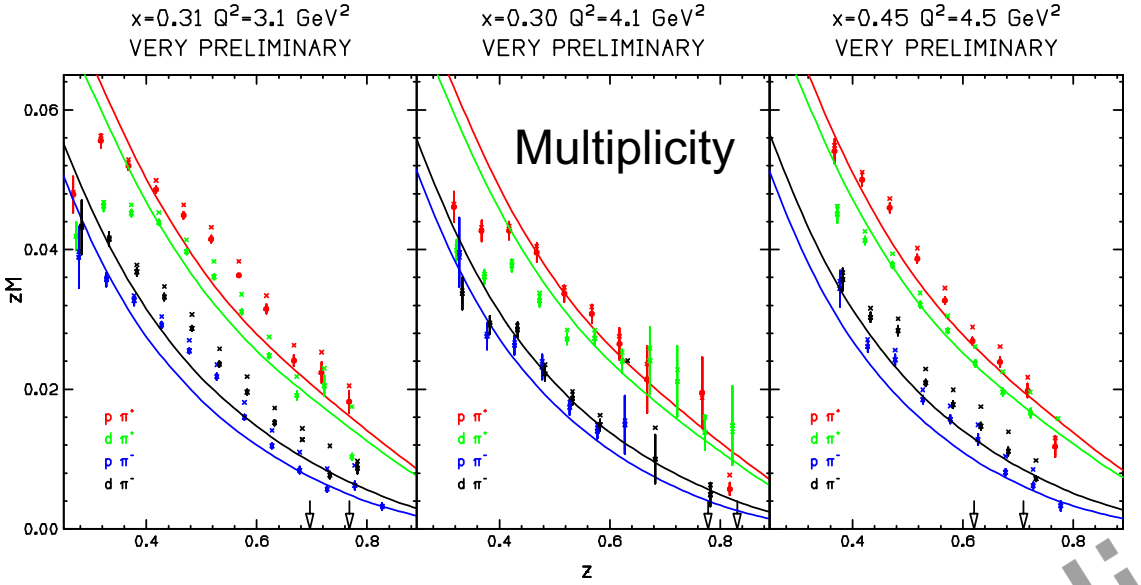
Cornell data of 70's

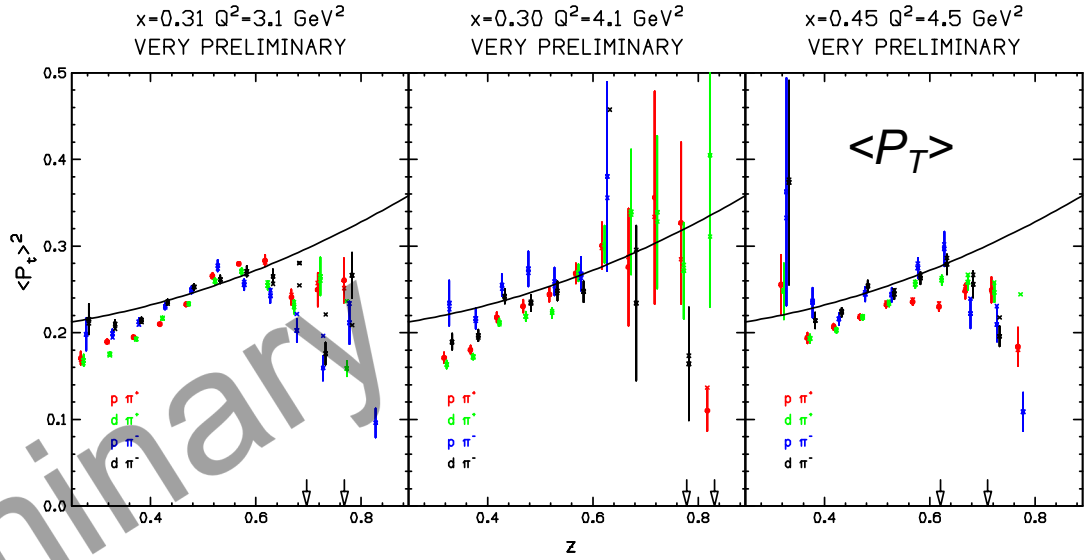


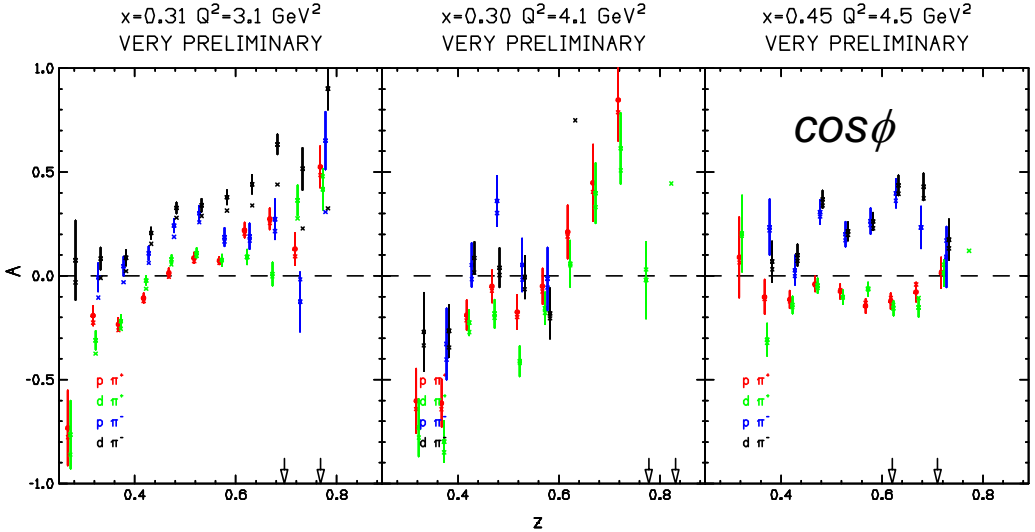
Conclusion: "data both consistent with $R = 0$ and $R =$" R_{DIS}"

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

11 GeV SIDIS Preliminary Analysis







Preliminary

Cross sections fit to the form:

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

Analysis by Peter Bosted