Transverse Momentum Dependence of Semi-Inclusive Pion and Kaon Production

PAC-37 Proposal C12-09-017 (PAC-34 conditionally approved)
Spokespersons Peter Bosted, Rolf Ent, and Hamlet Mkrtchyan

- Not much is known about the orbital motion of partons
- Significant net orbital angular momentum of valence quarks implies significant transverse momentum of quarks

Goal: Map the p_T dependence ($p_T \sim \Lambda < 0.5$ GeV) of π^+ and π^- production off proton and deuteron targets to study the k_T dependence of (unpolarized) up and down quarks

Beam Time Request: 6.5 days at 8.8 GeV
25.5 days at 11.0 GeV
Total: 32 days
(not including ~5 days of overlap with E12-06-104)
(not including checkout, shared with E12-06-104 & C12-09-002)

Transverse Momentum Dependence of Semi-Inclusive Pion and Kaon Production

Conditionally Approved Proposal C12-09-017

Outline:

- SIDIS: general remarks and framework
- Transverse momentum dependence of charged pions
  - Results from E00-108 & simple model analysis
  - Analysis of CLAS, Hall C, HERMES (& other) data
- C12-09-017
  - Choice of kinematics
  - Experimental details
- C12-09-017 Kinematics and Projected Results
- Spin-off relevant for the general SIDIS program
  - Radiative correction modeling: linking to z = 1
  - Single-spin asymmetries
  - Low-energy (x,z) factorization for charged kaons
- C12-09-017 Beam Time Request

Semi-Inclusive Deep-Inelastic Scattering

Potentially rich physics arena for flavor decomposition, k_T-dependent parton distribution functions, fragmentation, etc., but also many potential issues…

Use advantages of multi-hall approach! (much approved already, in bold)

Hall B: Large acceptance (CLAS12), polarized H and D targets

→ **azimuthal distributions of final-state particles**

→ cross sections, **single & double-spin asymmetries**

→ start **kaon SIDIS** program with anticipated RICH

Hall A: Large acceptance in forward region with SOLID, Polarized 3He target

→ longitudinal & **transversely polarized 3He** PR12-11-007

→ pion & kaon run with BigBite and SBS C12-09-018

→ Access to $\vec{n}$ structure at high-x and high-Q^2

Hall C: Precision magnetic-spectrometer setup, π and K

→ **L/T separations** in SIDIS

→ precision cross sections and ratios of π^+ & π^- C12-09-017 C12-09-002

→ access to kinematic corners *as needed* (after CLAS12)

Transverse Momentum Dependence of Semi-Inclusive Pion and Kaon Production

Conditionally Approved Proposal C12-09-017

PAC34 Report

… concerns that the experimental coverage in the full multi-dimensional space may be too limited to obtain integrated or weighted observables that can be theoretically interpreted. For such observables this results in significantly larger systematic uncertainties than estimated.

Nonetheless, 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. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate p_T and phi-dependence for small p_T. The PAC strongly recommends that these measurements occur in the early years of 12 GeV operation.

The PAC **recommends approval** subject to the condition that the collaboration of this experiment and that of PR12-09-002 combine their measurement plans into a single coordinated experimental plan, so that running time to collect events at kinematics of use to both experiments is not duplicated needlessly. This combined proposal should be presented at the next PAC review.

Transverse Momentum Dependence of Semi-Inclusive Pion and Kaon Production

Conditionally Approved Proposal C12-09-017

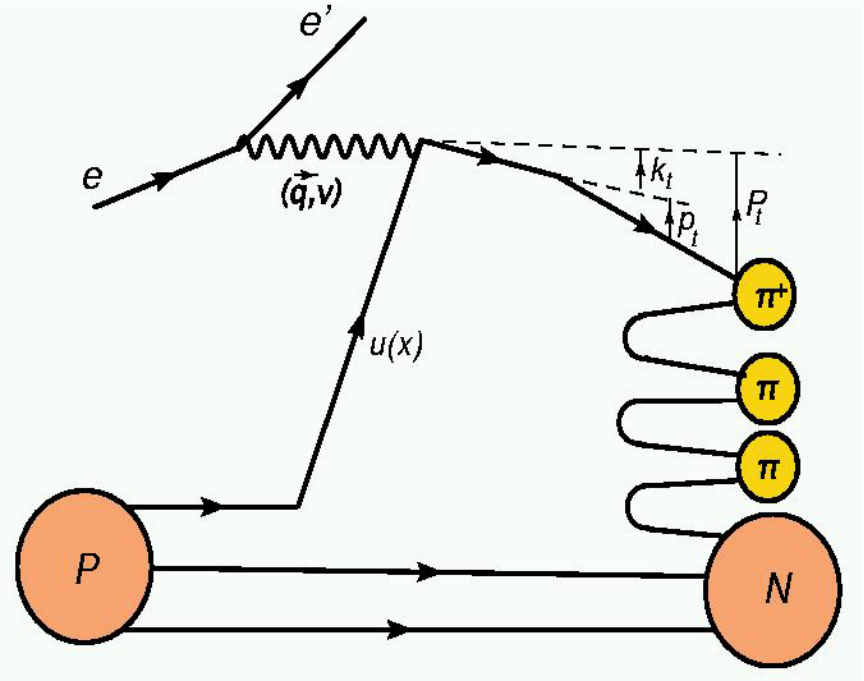
PAC34 Report (*continued*)

We agree that the use of polarized beams will provide useful azimuthal measurements at low p_T and also that the investigation of the kaon cross sections, while of much less statistical precision, will still be very interesting. Therefore **we support the construction of the aerogel Cerenkov detector and the data collection using polarized beams**. The latter is not expected to add any significant overhead or delay to the experiment.

Changes as compared to PR12-09-017:

1) An NSF-MRI award was granted to augment the SHMS detection package with an aerogel detector, allowing simultaneous measurement of kaon cross sections
2) Polarized electron beam has been included as the default, to obtain azimuthal beam asymmetry measurements at low p_T
3) The kinematics and checkout are coordinated with the approved E12-06-104 experiment and the companion proposal C12-09-002. The collaborations have large overlap.
4) Small changes to address the previous PAC-34 technical comments

SIDIS – k_T Dependence

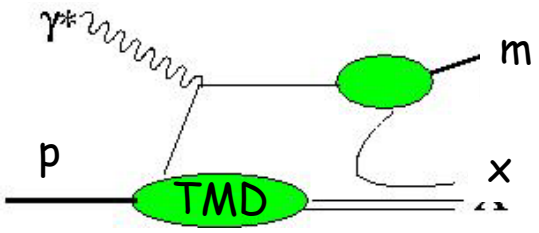


Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

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

Linked to framework of Transverse Momentum Dependent Parton Distributions

$$\sum e_q^2\, q(x)\, D_{q\to M}(z)$$



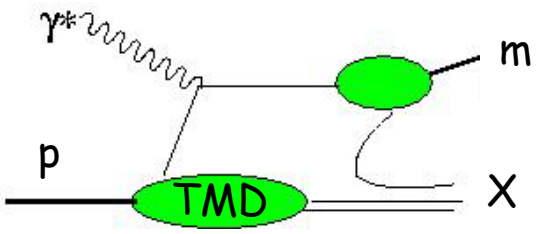
$$TMD^u(x,k_T)$$

$$f_1, g_1, f_{1T}^{\perp}, g_{1T}$$

$$h_1, h_{1T}^{\perp}, h_{1L}^{\perp}, h_1^{\perp}$$

Transverse momentum dependence of SIDIS

Linked to framework of Transverse Momentum Dependent Parton Distributions



$TMD^q(x,k_T)$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1\, h_{1T}^\perp$

Unpolarized target

Longitudinally pol. target

Transversely pol. target

Unpolarized k_T-dependent SIDIS: in framework of Anselmino et al. described in terms of convolution of quark distributions q and (one or more) fragmentation functions D, each with own characteristic (Gaussian) width → **Emerging new area of study**

I. Integrated over p_T and ϕ

Hall C: PRL 98:022001 (2007)
Hall B: PRD 80:032004 (2009)

II. P_T and ϕ dependence

Hall B: PRD 80:032004 (2009)
Hall C: PL B665 (2008) 20
Hall C: to be submitted to PRC

SIDIS Formalism

General formalism for (e,e'h) coincidence reaction w. polarized beam:

[A. Bacchetta et al., JHEP 0702 (2007) 093]

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

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

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

Use of polarized beams will provide useful azimuthal beam asymmetry measurements (F_{LU}) at low p_T complementing CLAS12 data

Main emphasis proposal: Transverse momentum dependence of SIDIS

$F_{UU}^{\cos(\phi)}$ and $F_{UU}^{\cos(2\phi)}$

(Approved experiment E12-06-104 addresses $F_{UU,T}$ and $F_{UU,L}$)

Transverse momentum dependence of SIDIS

General formalism for (e,e'h) coincidence reaction w. polarized beam:

[A. Bacchetta et al., JHEP 0702 (2007) 093]

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

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

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

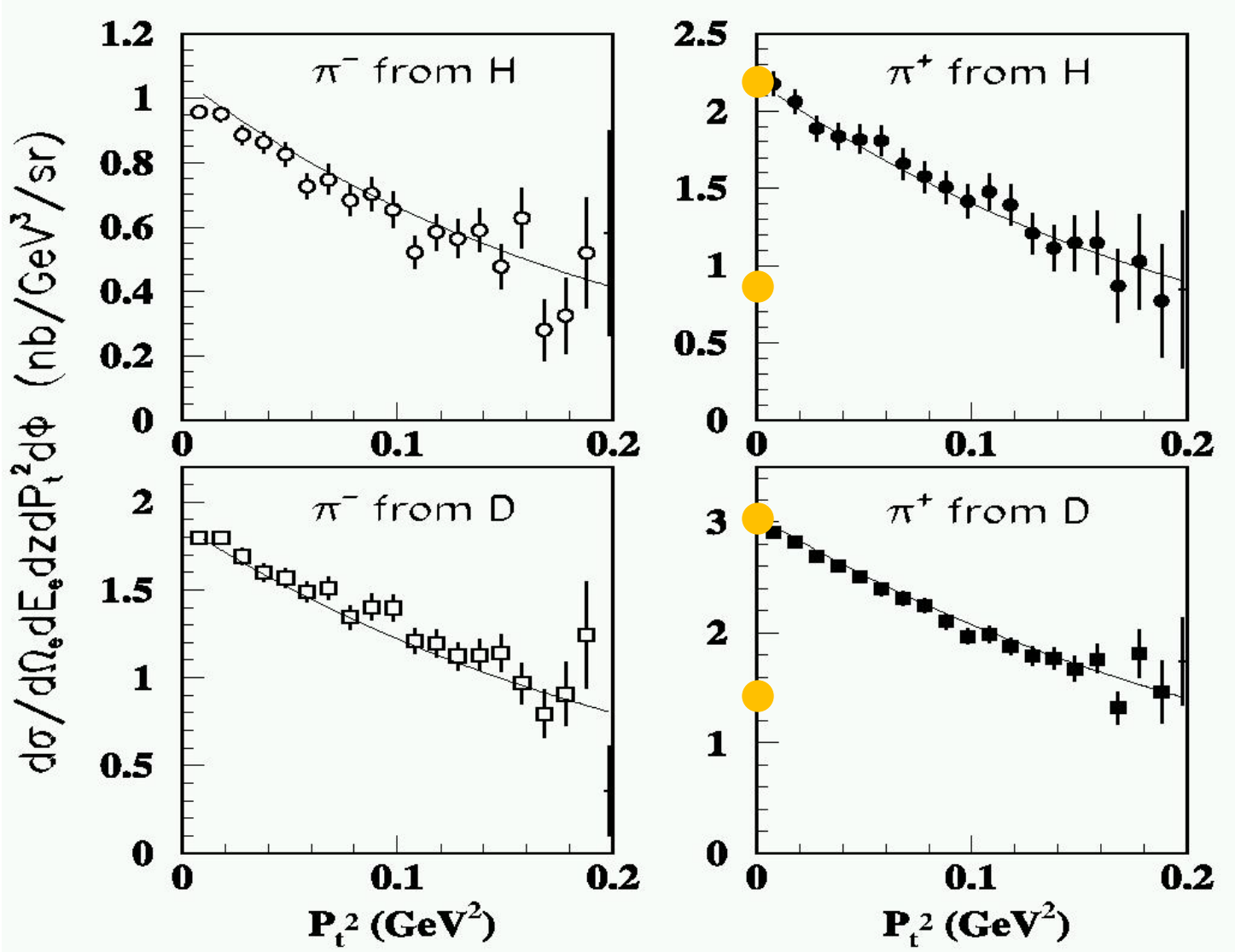
Azimuthal ϕ_h dependence crucial to separate out kinematic effects (Cahn effect) from twist-2 correlations and higher twist effects.

data fit on EMC (1987) and Fermilab (1993) data assuming Cahn effect → $\langle\mu_0^2\rangle$ = 0.25 GeV²

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

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

Transverse momentum dependence of SIDIS



P_t dependence very similar for proton and deuterium targets, but **deuterium slopes systematically smaller**?

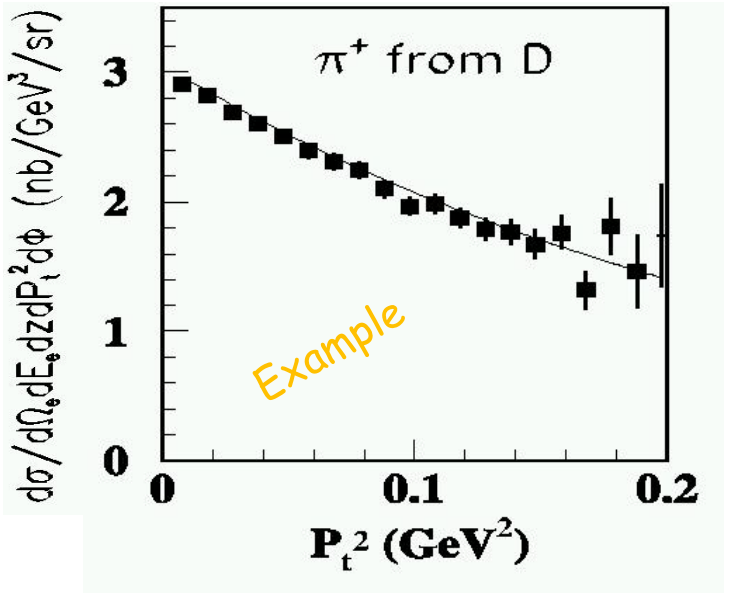
Unpolarized SIDIS – JLab E00-108 data

Constrain k_T dependence of up and down quarks *separately*

1) Probe π^+ and π^- final states

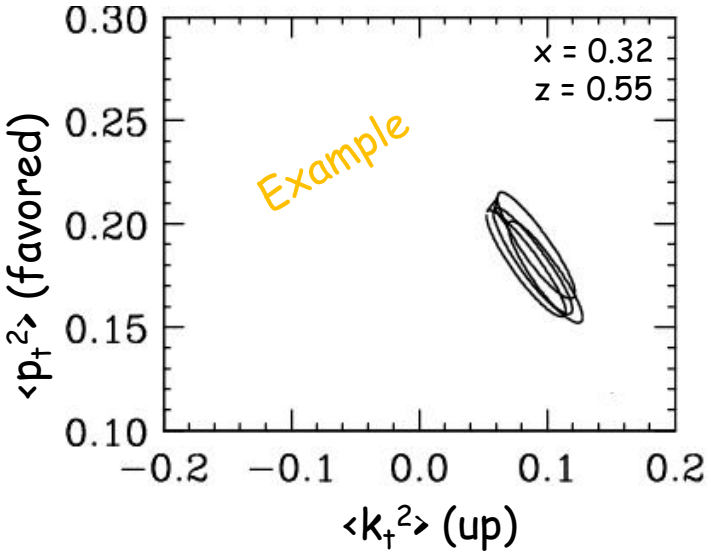
2) Use both **proton** and neutron (**d**) targets

3) Combination allows, in principle, separation of quark width from fragmentation widths *(if sea quark contributions small)*



1st example: Hall C, PL B665 (2008) 20

Numbers are close to expectations! But, simple model only with many 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, sea quarks are negligible, assume Cahn effect, etc.), **incomplete cos(ϕ) coverage, uncertainties in exclusive event & diffractive ρ contributions.**



Transverse momentum dependence of SIDIS

C12-09-017 Theory Report

1) Analyze in terms of model-independent P_T-dependent structure functions
2) Incorporate results from other experiments (HERMES, COMPASS, CLAS)
3) Model chosen for analysis is very simplistic, *e.g.*, kinematic Cahn dominance?

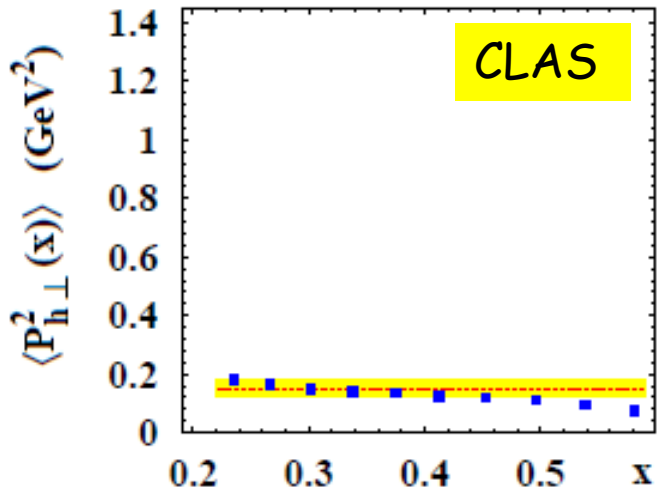
We agree! These comments mainly reflect that we used an overly simplistic model analysis in an early effort to both show the perspective of P_T-dependent SIDIS experiments, and to guide the projected physics outcome of C12-09-017.

An alternate analysis is performed in
Schweitzer, Teckentrup and Metz, PRD 81 (2010) 094019

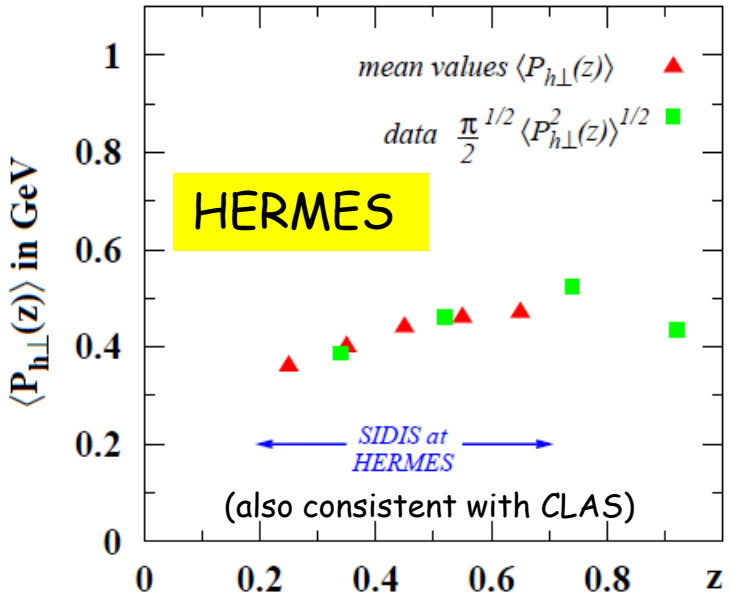
- Gauss model for P_T distributions
  - Do not assume kinematic dominance of Cahn effect
- Showing consistency of CLAS, Hall C, HERMES data
- Gaussian approach also describes Drell-Yan data, giving credence to the factorization approach used here

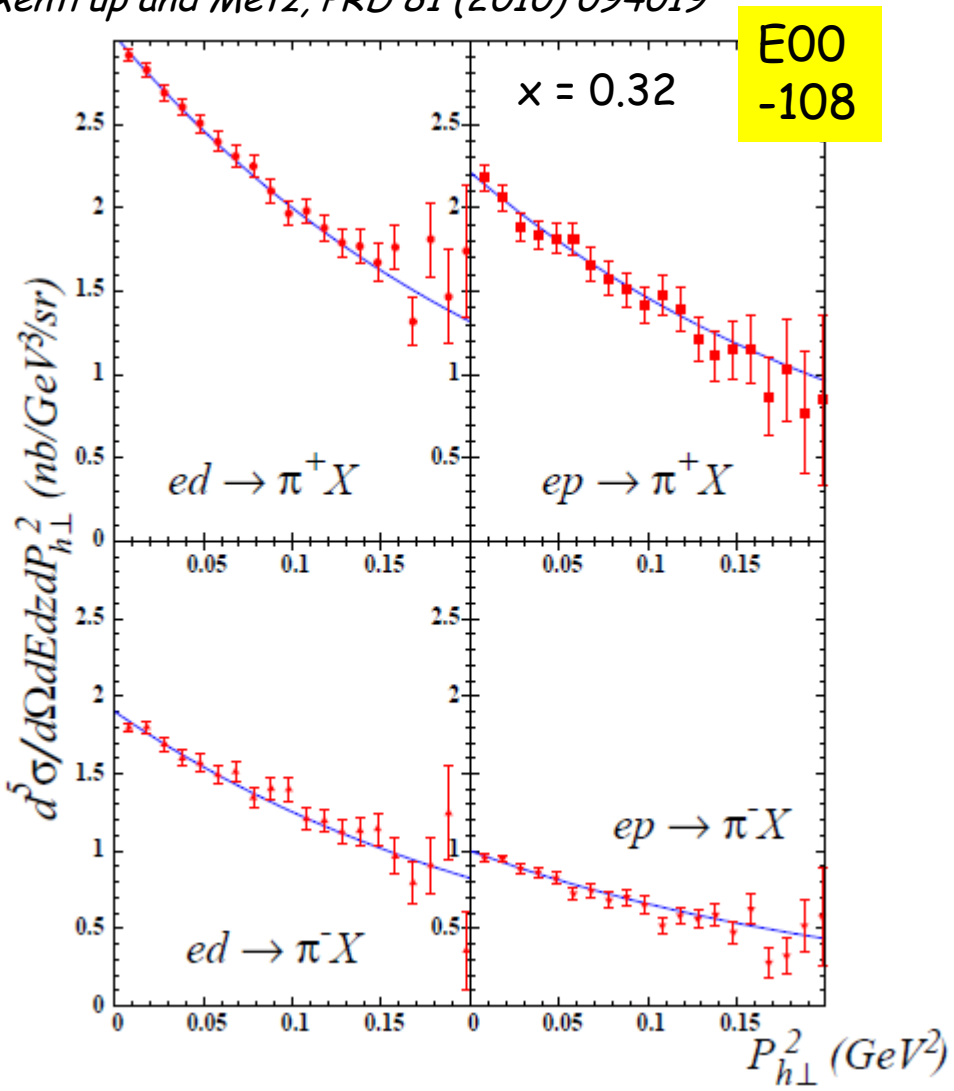
Transverse momentum dependence of SIDIS

Gaussian approach of Schweitzer, Teckentrup and Metz, PRD 81 (2010) 094019



Gauss: $\langle P_{h\perp}(z)\rangle^2 = \pi/4 \langle P_{h\perp}^2(z)\rangle$





Curves are from the Gauss model with the Gauss width fixed from CLAS data

Transverse Momentum Dependence: E00-108 Summary

E00-108 results were only suggestive at best:

- limited kinematic coverage
  - assumed (P_T,ϕ) dependency ~ Cahn effect
- very simple model assumptions

  but P_T dependence off D seems shallower than H

  and intriguing explanation in terms of flavor/k_T deconvolution

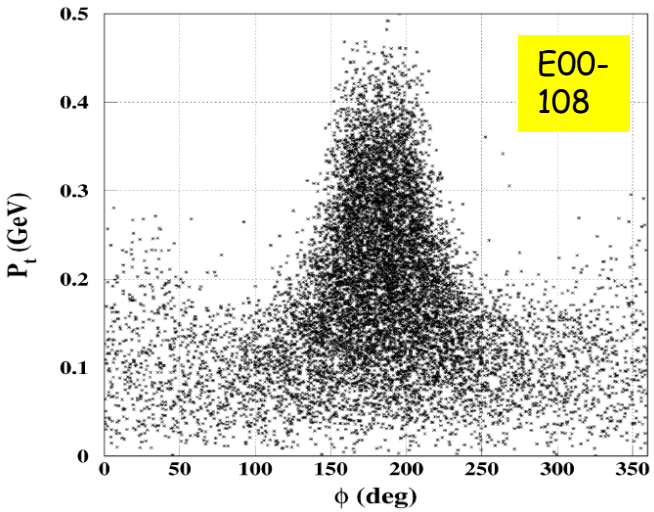
Many limitations could be removed with 12 GeV:

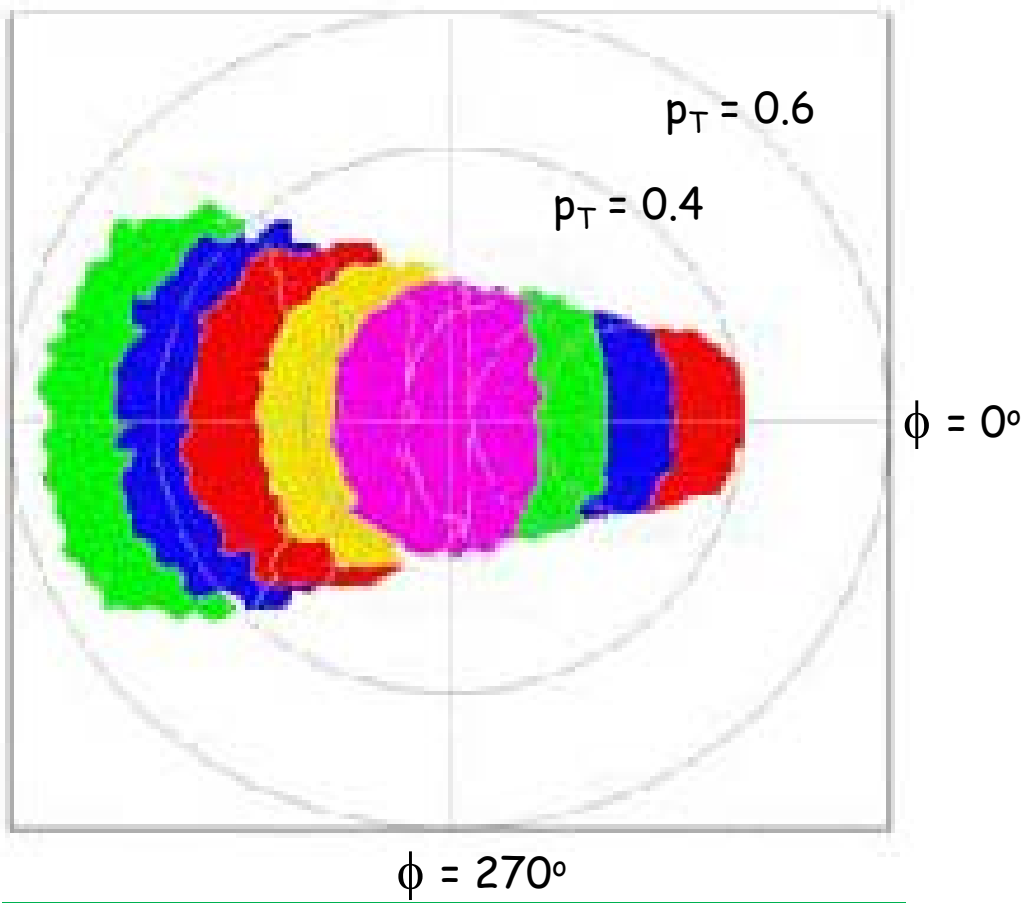
- wider range in Q^2
- improved/full coverage in ϕ (at low p_T)
- larger range in P_T
- wider range in x and z (to separate quark from fragmentation widths)
- possibility to check various model assumptions
  - Power of (1-z) for D^-/D^+
  - quantitative contribution of Cahn term
  - $D_u^{\pi^+} = D_d^{\pi^-}$
  - Higher-twist contributions
  - consistency of various kinematics (global fit vs. single-point fits)

C12-09-017: P_T coverage

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

- Excellent ϕ coverage
  up to p_T = 0.2 GeV
- Sufficient ϕ coverage
  up to p_T = 0.4 GeV
  (compared to the E00-108 case below, now also good coverage at $\phi \sim 0^o$)
- Limited ϕ coverage
  up to p_T = 0.5 GeV





$P_T \sim 0.5$ GeV: use ϕ dependencies measured in CLAS12 experiments (E12-06-112, E12-09-008, LOI12-09-005)

Choice of C12-09-017 Kinematics

- W^2 = 5.08 GeV^2 and larger (up to 11.38 GeV^2)

- Use SHMS angle down to 5.5 degrees (for π detection)
  HMS angle down to 10.5 degrees (e^- detection)
  separation HMS-SHMS > 17.5 degrees

- $M_X^2 = M_p^2 + Q^2(1/x - 1)(1 - z) > 2.9\ GeV^2$ *(up to 7.8 GeV^2)*

- Choice to keep Q^2/x fixed → q_γ ~ constant
  - *exception are data scanning Q^2 at fixed x*

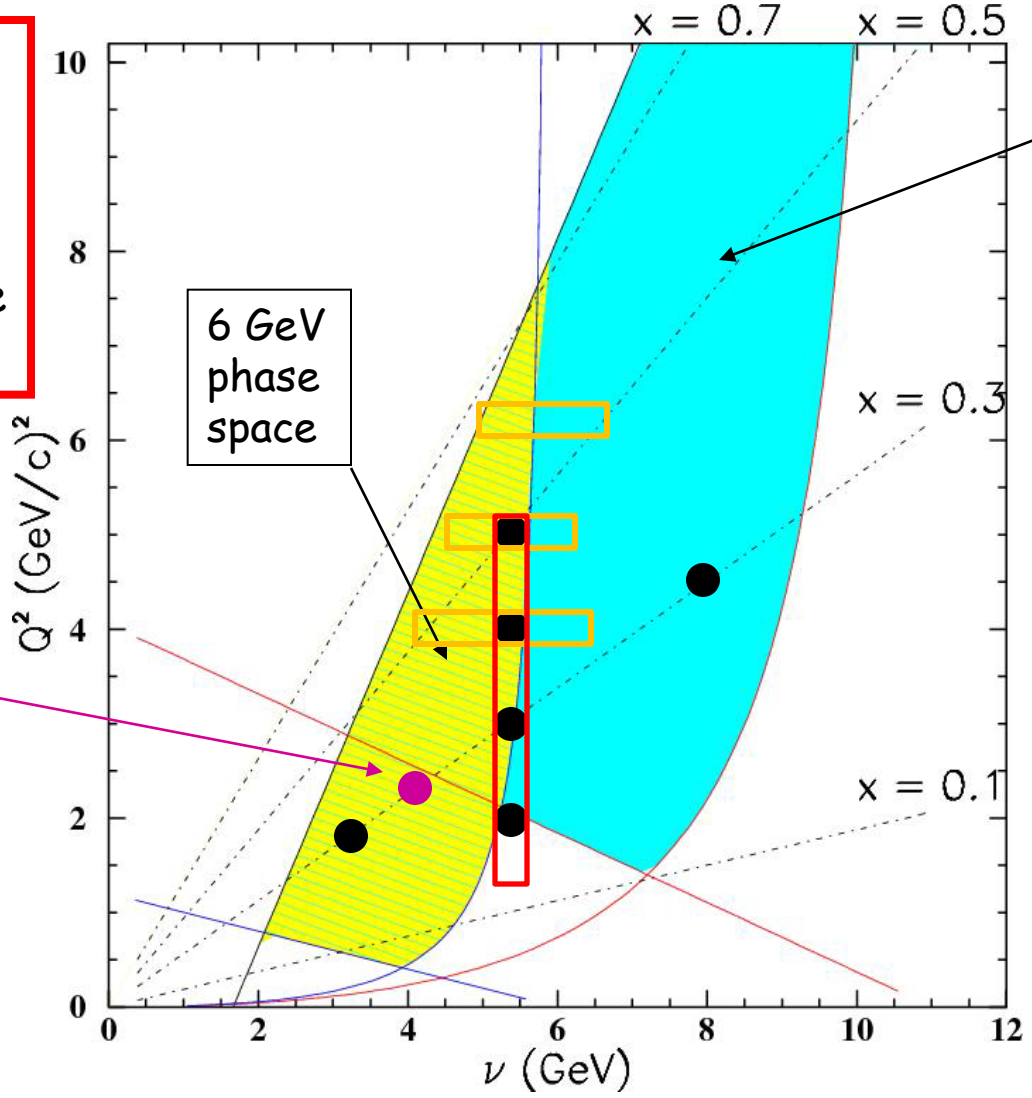
- All kinematics both for π^+ (and K^+) and π^- (and K^-),
  both for LH2 and LD2 (and Al dummy)

- Choose z > 0.3 (p_π > 1.7 GeV) to be able to neglect
  differences in $\sigma(\pi^+N)$ and $\sigma(\pi^-N)$
  - *not possible for x = 0.3, Q^2 = 1.80: p_π > 1.1 GeV*

Choice of Kinematics (typ. x/Q^2 ~ constant)

HMS + SHMS Accessible Phase Space for Deep Exclusive Scattering

<u>All together</u>: data base of precise SIDIS cross sections over nice range of *x* and Q^2!



E12-06-104
Scan in (z,p_T)
No scan in Q^2 at fixed x:
$R_{DIS}(Q^2)$ known

C12-09-017
Scan in (x,z,p_T)
+ scan in Q^2 at fixed x

C12-09-002
+ scans in z

For semi-inclusive, less Q^2 phase space at fixed x due to:
i) $M_X^2 > 2.5$ GeV^2; and ii) need to measure at both sides of Θ_γ

Choice of Kinematics – cont.

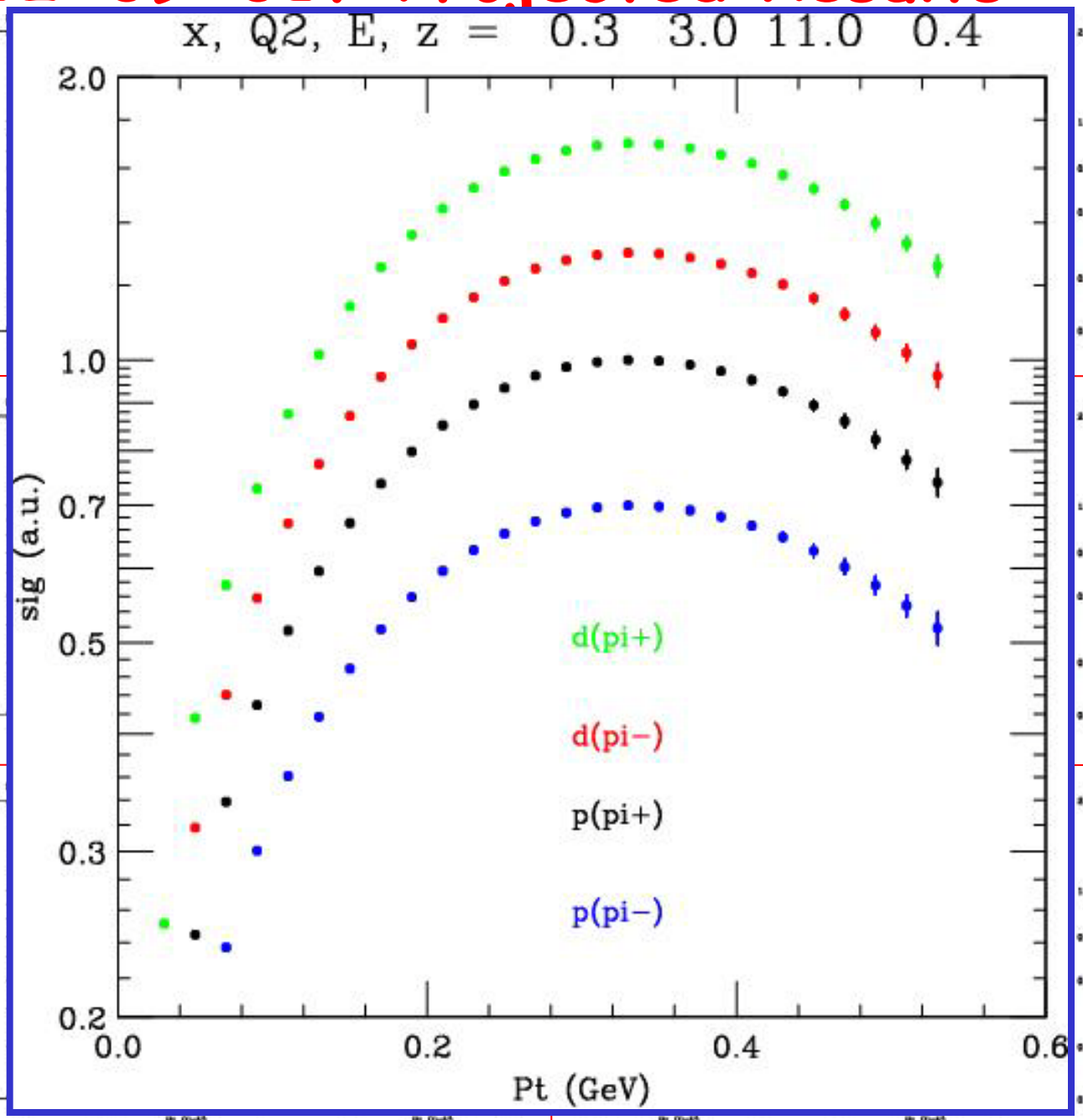
Kin	x	Q^2 (GeV^2)	z	P_π (GeV)	Θ_π (deg)
I	0.2	2.0	0.3 -0.6	1.7 – 3.3	8.0 – 23.0
II	0.3	3.0	0.3 -0.6	1.7 – 3.4	5.5 – 25.5
III	0.4	4.0	0.3 -0.6	1.7 – 3.4	5.5 – 25.5
IV	0.5	5.0	0.3 -0.6	1.7 – 3.5	8.0 – 28.0
V	0.3	1.8	0.3 -0.6	1.1 – 2.1	8.0 – 30.5
VI	0.3	4.5	0.3 -0.6	2.5 – 5.0	5.5 – 20.5

Map of p_T dependence in x and z,
in Q^2 to check (p_T/Q) and (p_T^2/Q^2) behavior

Kinematics I, II, III, and IV are identical to those where this collaboration also plans to map R (= σ_L/σ_T) in SIDIS in E12-06-104. This saves a total of five days, as follows:

1) three days of data taking
2) one day of dedicated checkout
3) one day for pass/kinematics changes and beam energy meas.

C12-09-017 Projected Results - I



III

II

I

IV

VI

V

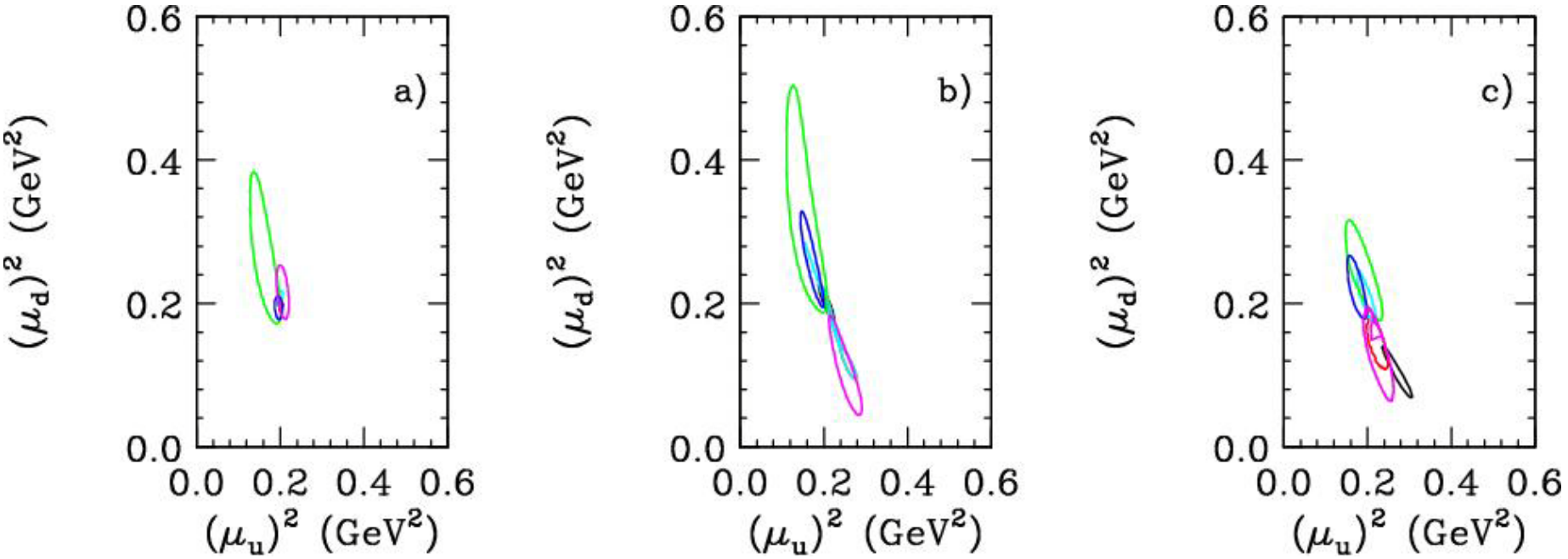
C12-09-017 Projected Results - II

Simulated data use $(\mu_u)^2 = (\mu_d)^2 = 0.2$, and then fit using statistical errors.

Step 1: Kinematics I-VI fitted separately, (p_T,ϕ) dependency ~ Cahn

Step 2: Add eight parameters to mimic possible HT, but assume Cahn
→ uncertainties grow with about factor of two

Step 3: Simulate with and without Cahn term
→ results remain similar as in step 2



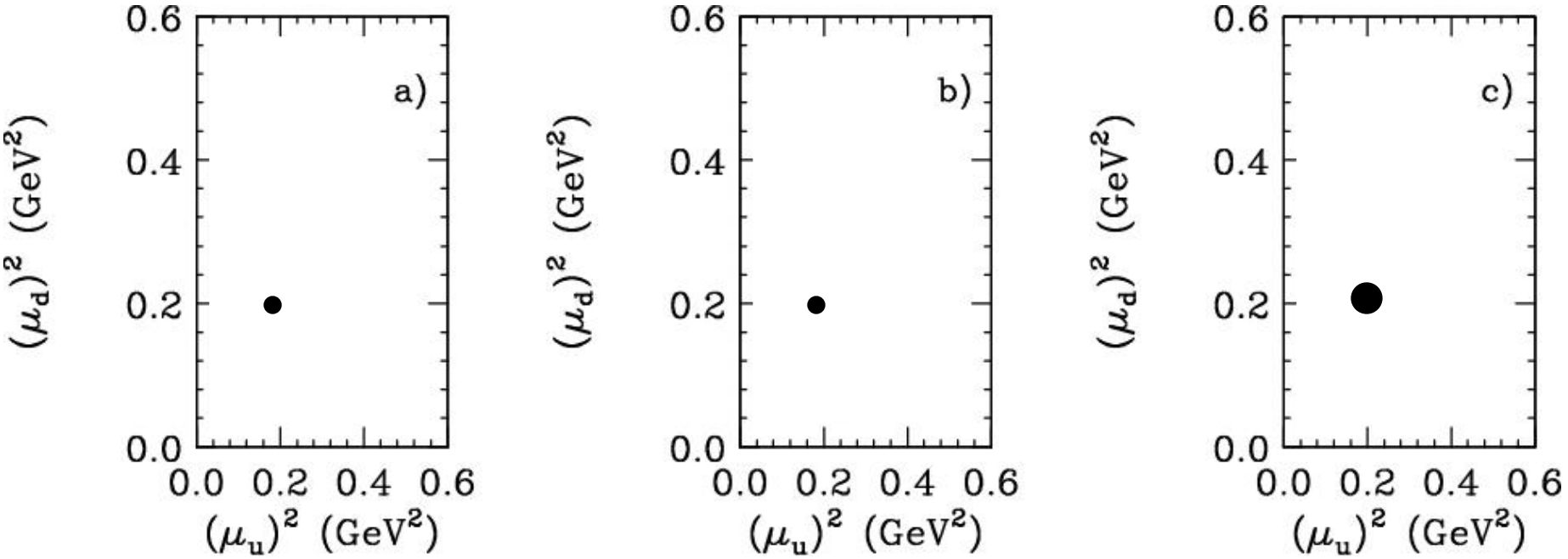
C12-09-017 Projected Results - II

Simulated data use $(\mu_u)^2 = (\mu_d)^2 = 0.2$, and then fit using statistical errors.

Step 1: Kinematics I-VI fitted separately, (p_T,ϕ) dependency ~ Cahn
(if all six fitted together, diameter < 0.01 GeV^2)

Step 2: Add eight parameters to mimic possible HT, but assume Cahn
→ uncertainties grow with about factor of two
(if all six fitted together, diameter remains < 0.01 GeV^2)

Step 3: Simulate with and without Cahn term
→ results remain similar as in step 2
(if all six fitted together, diameter grows to < 0.02 GeV^2)



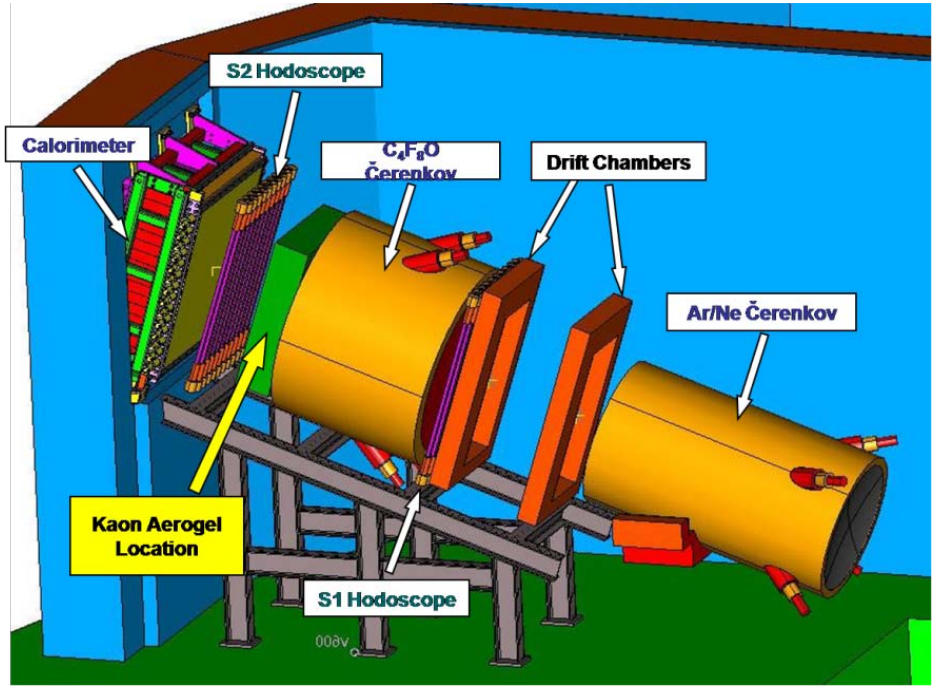
Experimental Details and Spin-Off

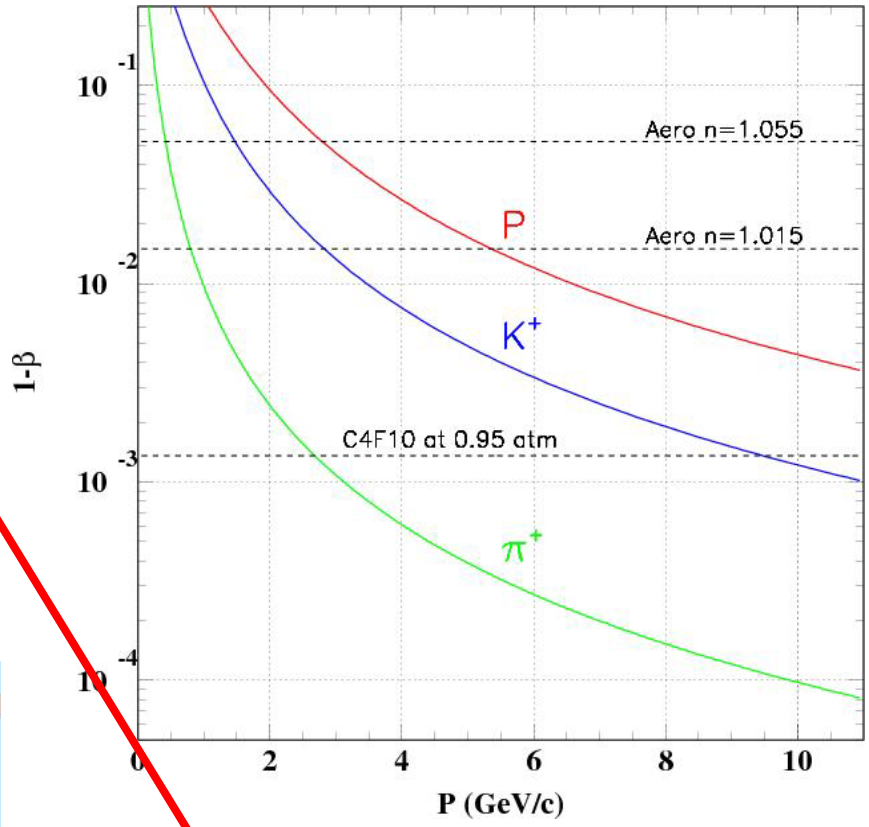
- Beam current is varied to keep the total SHMS rate below 700 kHz
  - *10-75 μA beam currents (with 10 cm LH2/LD2)*
  - *rate limitation to guarantee precision π^+/π^- ratios*
  - *Anticipated syst. uncertainty in ratio 0.9%*
  - *Real : Accidental ratio typically ~ 2 : 1*
- Syst. uncertainty has four roughly equal ingredients: spectrometer acceptance, tracking + detector efficiencies, radiative corrections
  - *to model latter, include dedicated runs at lower E and E'*
  - *Collaboration did similar (published) modeling efforts on JLab inclusive $^1H(e,e')$ and $^2H(e,e')$ scattering results*
- While this measurement is not ideally suited to measurement of Single-Spin Asymmetries (lack of full ϕ coverage), we expect to map such SSA's well up to p_T ~ 0.2 GeV (with errors of typ. 0.003-0.008), further facilitating k_T-dependence model checking
  - *Hence, we have requested 80% long. polarized beam*
- Kaon identification is allowed by the addition of an aerogel detector to the SHMS base detector package
  - study the low-energy (x,z) factorization for charged kaons
  - *Collaboration built HMS aerogel detector (NIM A548, 364)*

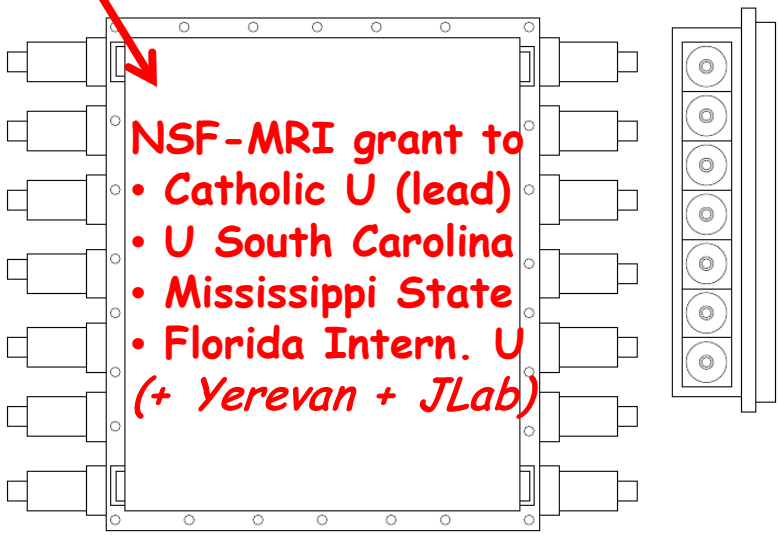
Kaon Identification

Particle identification in SHMS:

0) TOF at low momentum (~1.5 GeV)
1) Heavy (C_4F_8O) Gas Cherenkov to select π^+ (> 3 GeV)
2) 60 cm of empty space can be used for two aerogel detectors, *e.g.*:
   - n = 1.015 to select π^+ (> 1 GeV)
     select K^+ (> 3 GeV)
   - n = 1.055 to select K^+ (>1.5 GeV)





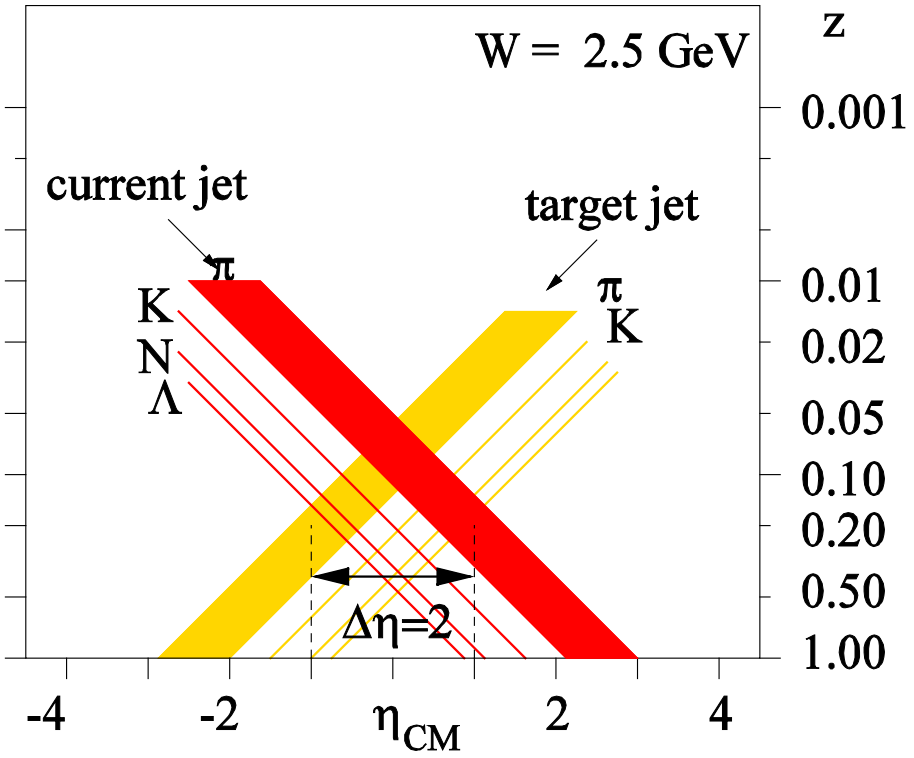


NSF-MRI grant to
- Catholic U (lead)
- U South Carolina
- Mississippi State
- Florida Intern. U

(+ Yerevan + JLab)

Spin-off: study x-z Factorization for kaons

P.J. Mulders, hep-ph/0010199 (EPIC Workshop, MIT, 2000)



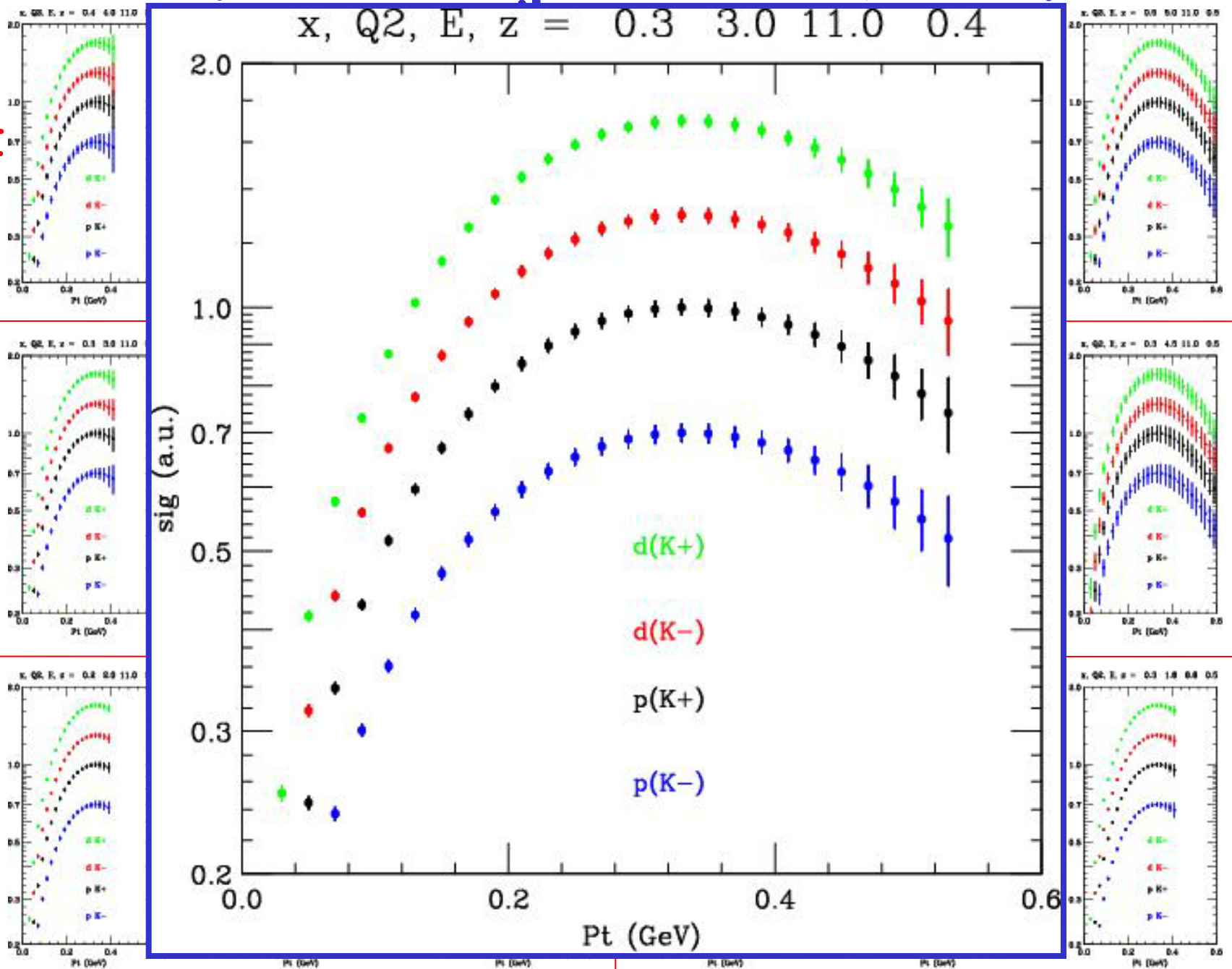
At large z-values easier to separate current and target fragmentation region
→ for fast hadrons factorization (Berger Criterion) "works" at lower energies

If same arguments as validated for π apply to K:

At W = 2.5 GeV: z > 0.6

(but, z < 0.65 limit may not apply for kaons!)

C12-09-017 Projected Results - Kaons



Transverse Momentum Dependence of Semi-Inclusive Pion and Kaon Production

- Not much is known about the orbital motion of partons
- Significant net orbital angular momentum of valence quarks implies significant transverse momentum of quarks

PR12-09-017: Map the p_T dependence ($p_T \sim \Lambda < 0.5$ GeV) of π^+ and π^- production off proton and deuteron targets to measure the k_T dependence of up and down quarks

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

Beam time request: 32 days of beam time in Hall C

Spin-off: Radiative correction modeling for $(e,e'\pi)$
Single-spin asymmetries at low p_T (< 0.2 GeV)
Low-energy (x,z) factorization for kaons

C12-09-017 Collaboration

A. Asaturyan, A. Mkrtchyan, H. Mkrtchyan (spokesperson),
V. Tadevosyan, S. Zhamkochyan
Yerevan Physics Institute, Yerevan, Armenia

P. Bosted (spokesperson)
College of William and Mary, Williamsburg, VA 23187

H. Avagyan, S. Covrig, R. Ent (spokesperson), H.C. Fenker,
D. Gaskell, M. Jones, D. Mack, J. Mei, Yi Qiang,
B. Sawatzky, G. Smith, P. Solvignon, S. Wood
Jefferson Lab, Newport News, VA 23606

A. Bacchetta
Universitá di Pavia and INFN, Sez. di Pavia, Pavia, Italy

I. Albayrak, O. Ates, M.E. Christy, C.E. Keppel, M. Kohl, Y. Li,
P. Monaghan, A. Pushpakumari, L. Tang, T. Walton, L. Yuan, L. Zhu
Hampton University, Hampton, VA 23668

G.M. Huber
University of Regina, Regina, Saskatchewan, Canada, S4S 0A2

D. Day, H. Baghdasaryan, N. Kalantarians
University of Virginia, Charlottesville, VA 22901

S. Danagoulian
North Carolina A & T State University, Greensboro, NC 27411

F.R. Wesselmann
Xavier University of Louisiana, New Orleans, LA

G. Niculescu, I. Niculescu
James Madison University, Harrisonburg, VA 22807

J. Dunne, D. Dutta
Mississippi State University, Mississippi, MS 39762

H. Gao, M. Huang, G. Laskaris, S. Malace, C. Peng, Q. J. Ye, Y. Zhang
Duke University/TUNL, Durham, NC 27708

T. Horn
Catholic University of America, Washington, DC 20064

Appendix

Choice of Kinematics – cont.

Kin	E (GeV)	E′ (GeV)	$\Theta_{e'}$ (deg)	W^2 (GeV^2)	Θ_γ (deg)	q_γ (GeV)
I	11.0	5.67	10.27	8.88	10.57	5.51
II	11.0	5.67	12.59	7.88	12.75	5.60
III	11.0	5.67	14.55	6.88	14.49	5.69
IV	11.0	5.67	16.28	5.88	15.96	5.78
V	8.8	5.60	10.96	5.08	17.90	3.47
VI	11.0	5.67	21.26	11.38	7.57	8.27

- Keep HMS momentum (~E′) constant for all kinematics
- Dedicated measurements (within requested beam time) will be added with E′ increased by 25% and possibly 50% for radiative correction modeling.

  (HMS goes to 7.3 GeV momentum → need to swap HMS-SHMS roles for 50%)
- E12-06-104 includes beam time at E = 6.6 GeV.
  We plan to dedicate part of that time also for radiative correction modeling.

C12-09-017: Beam Time Request

- Map yields as function of z and p_T at x = 0.2 and Q^2 = 2.0 GeV^2

  4.5 Days *(incl. overhead)*

- Map yields as function of z and p_T at x = 0.3 and Q^2 = 3.0 GeV^2

  5.8 Days

- Map yields as function of z and p_T at x = 0.4 and Q^2 = 4.0 GeV^2

  5.3 Days

- Map yields as function of z and p_T at x = 0.5 and Q^2 = 5.0 GeV^2

  5.3 Days

- Map yields as function of z and p_T at x = 0.3 and Q^2 = 1.8 GeV^2

  6.9 Days

- Map yields as function of z and p_T at x = 0.3 and Q^2 = 4.5 GeV^2

  4.0 Days

Total: **32 Days** *(incl. overhead)*

* Overhead consists of spectrometer polarity, momentum, and angle, and target changes

Systematic Uncertainties in π^+/π^- Ratios

Anticipated systematic uncertainties in ratios of transverse momentum dependences. The combined use of the CLAS12 experiments is assumed to fully constrain the (p_T,ϕ) dependency.

Project Source	HMS(*)	SHMS
Spectrometer Acceptance(**)	0.1%	0.4%
Tracking Efficiency(**)	0.1%	0.4%
Detection Efficiency(**)	0.1%	0.4%
Pion Absorption Correction		0.1%
Radiative Corrections(***)		0.5%
Added in Quadrature		**0.9%**

(*) HMS is kept at constant momentum of 5.67 GeV, at forward scattering angles (<22 degrees, hence viewing a 3.7 cm effective target length), at singles rates < 100 kHz, and at π/e ratios < 13.

(**) The main uncertainties are due to spectrometer polarity changes. The SHMS total rate is kept <700 kHz to constrain the tracking eff.

(***) Assuming dedicated measurements to constrain the required radiative correction model input.

Model P_T dependence of SIDIS

Gaussian distributions for P_T dependence, no sea quarks, and leading order in (k_T/q)

$$\sigma_p^{\pi+} = C\left[4c_1(P_t)e^{-b_u^+ P_t^2} + (d/u)\left(D^-/D^+\right)c_2(P_t)e^{-b_d^- P_t^2}\right],$$

$$\sigma_p^{\pi-} = C\left[4\left(D^-/D^+\right)c_3(P_t)e^{-b_u^- P_t^2} + (d/u)c_4(P_t)e^{-b_d^+ P_t^2}\right],$$

$$\sigma_n^{\pi+} = C\left[4(d/u)c_4(P_t)e^{-b_d^+ P_t^2} + \left(D^-/D^+\right)c_3(P_t)e^{-b_u^- P_t^2}\right],$$

$$\sigma_n^{\pi-} = C\left[4(d/u)\left(D^-/D^+\right)c_2(P_t)e^{-b_d^- P_t^2} + c_1(P_t)e^{-b_u^+ P_t^2}\right],$$

Inverse of total width for each combination of quark flavor and fragmentation function given by:

$$b_u^{\pm} = \left(z^2\mu_u^2 + \mu_{\pm}^2\right)^{-1}$$

And take Cahn effect into account, with e.g. (similar for c_2, c_3, and c_4):

$$c_1(P_t) = 1 + c_0\left(P_t, \langle\cos(\phi)\rangle\right)\mu_u^2 b_u^+$$

$$c_0\left(P_t, \langle\cos(\phi)\rangle\right) = \frac{4z(2-y)\sqrt{1-y}}{\sqrt{Q^2}[1+(1-y)^2]}\sqrt{P_t^2}\langle\cos(\phi)\rangle$$

Non-trivial contributions to (e,e'π) Cross Section

Radiative Corrections

- Typical corrections are <10% for z < 0.7.
- Checked with SIMC and POLRAD 2.0.
- Good agreement between both methods.

Exclusive Pions

- Interpolated low-W^2, low-Q^2 of MAID with high-W^2, high-Q^2 of Brauel/Bebek.
- Introduces large uncertainty at low z, but contributions there are small.
- Tail agreed to 10-15% with "HARPRAD".
- Further constraints with F^π-12 and πCT-12.

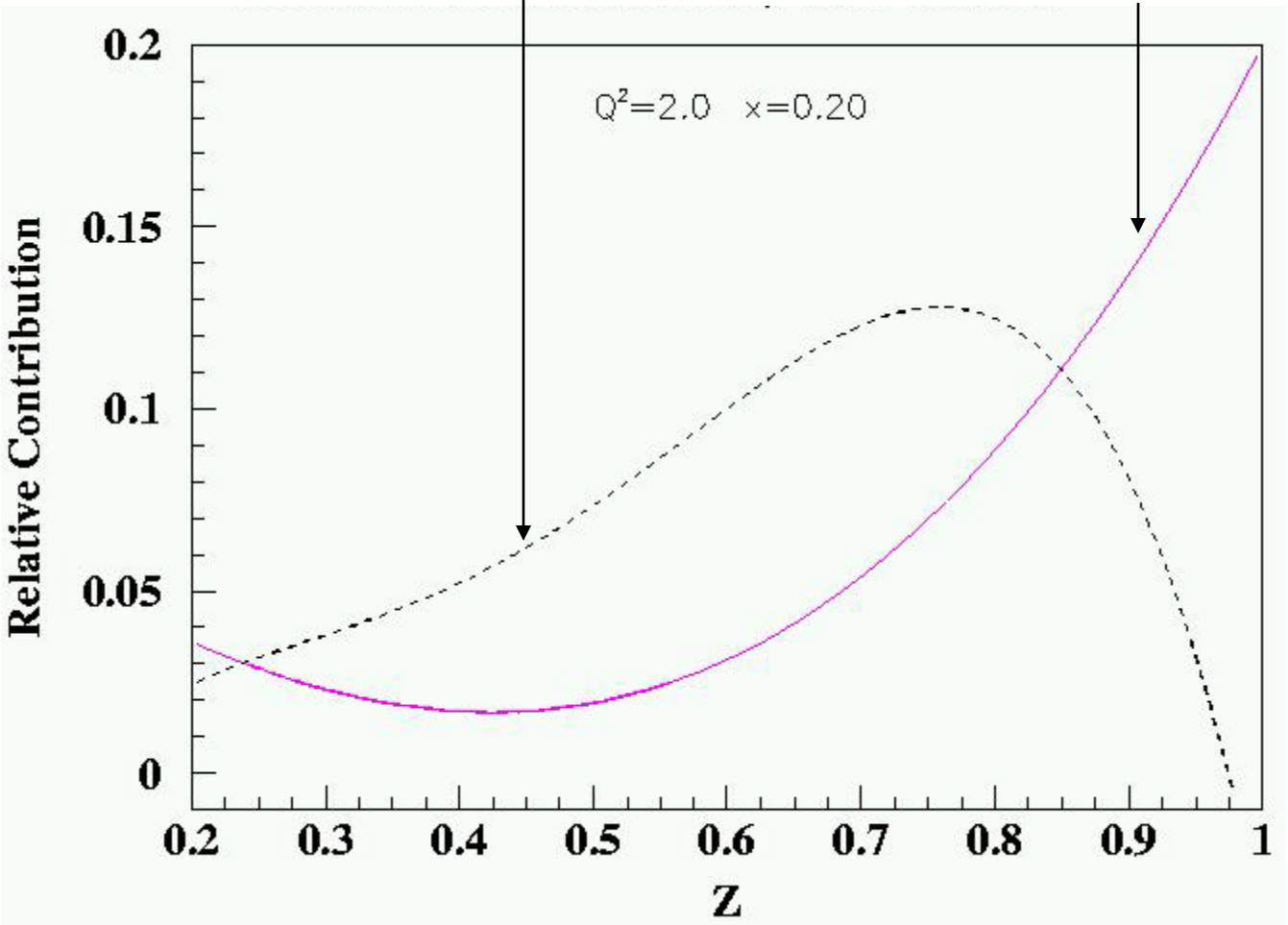
Pions from Diffractive ρ

- Used PYTHIA with modifications as implemented by HERMES (Liebing,Tytgat).
- Used this to guide ρ cross section in SIMC.
- simulated results agree to 10-15% with CLAS data (Harut Avagian).
- In all cases, quote results with/without diffractive ρ subtraction.

Non-trivial contributions to (e,e'π) Cross Section

Contributions from ρ

Radiation contributions, including from exclusive



Further data from CLAS12 (ρ) and Hall C (F^π-12, πCT-12) will constrain!