Semi-Inclusive DIS in JLab Hall C in the 12 GeV Era

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with thanks to my collaborators
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- Brief review of high energy model of SIDIS
- SIDIS Results from E00-108
- Precision (e,e'$\pi^{\pm}$),(e,e'$K^{\pm}$) cross sections at low $P_{h\perp}$
- Precision (e,e'π^0) cross sections at low $P_{h\perp}$
- L/T Separation of SIDIS (e,e'$\pi^{\pm}$) cross section

Exploring the 3D Momentum Structure of the Nucleon

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - ✳ High luminosity, large acceptance experiments with polarized beams and targets
  - ✳ Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions
- SIDIS cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of parton and transverse momentum (p_T) created during the fragmentation process.
  - ✳ Important to gain sufficient $P_{h\perp}$ data with different hadronic final states to allow momentum dependent fragmentation to be studied.

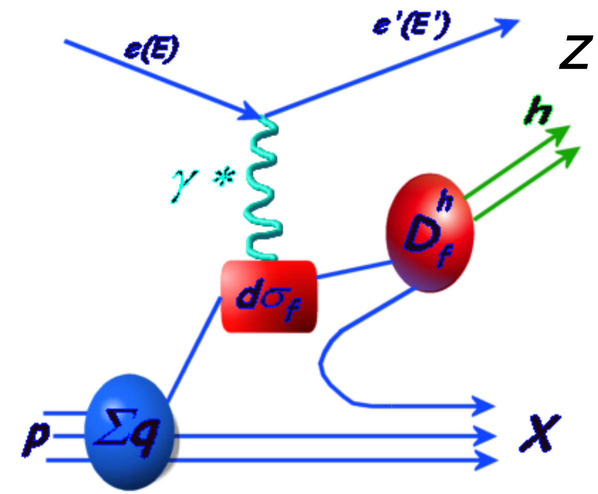
Do parton distributions and fragmentation functions factorize at Jefferson Lab energies?

Flavor Decomposition of SIDIS

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

$f_q(x)$: parton distribution function

$D_q^h(z)$: fragmentation function



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

- 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

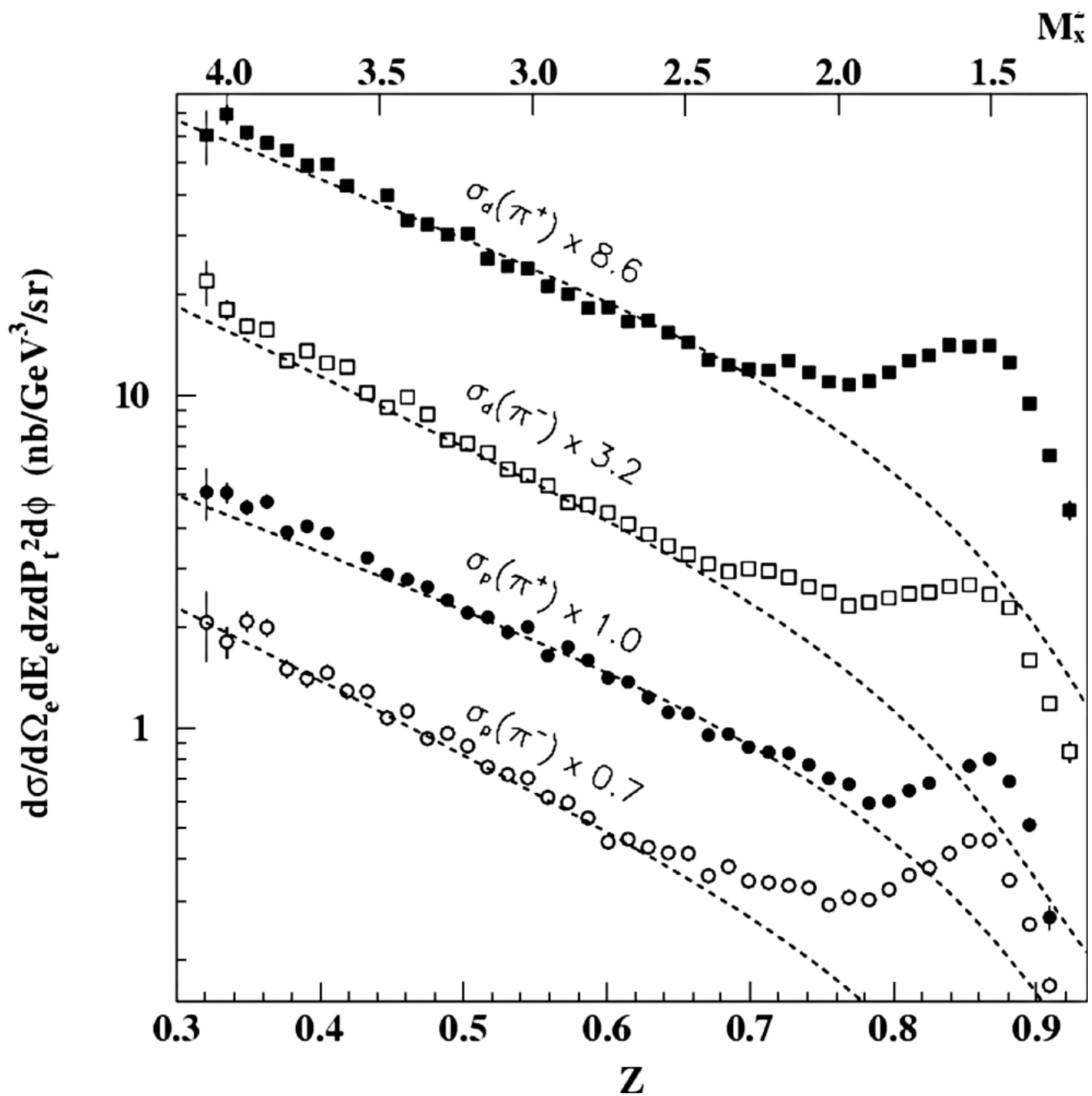
With p_T and k_T dependences, some kind of convolution is necessary to obtain final $P_{h\perp}$

Jlab E00-108 Results

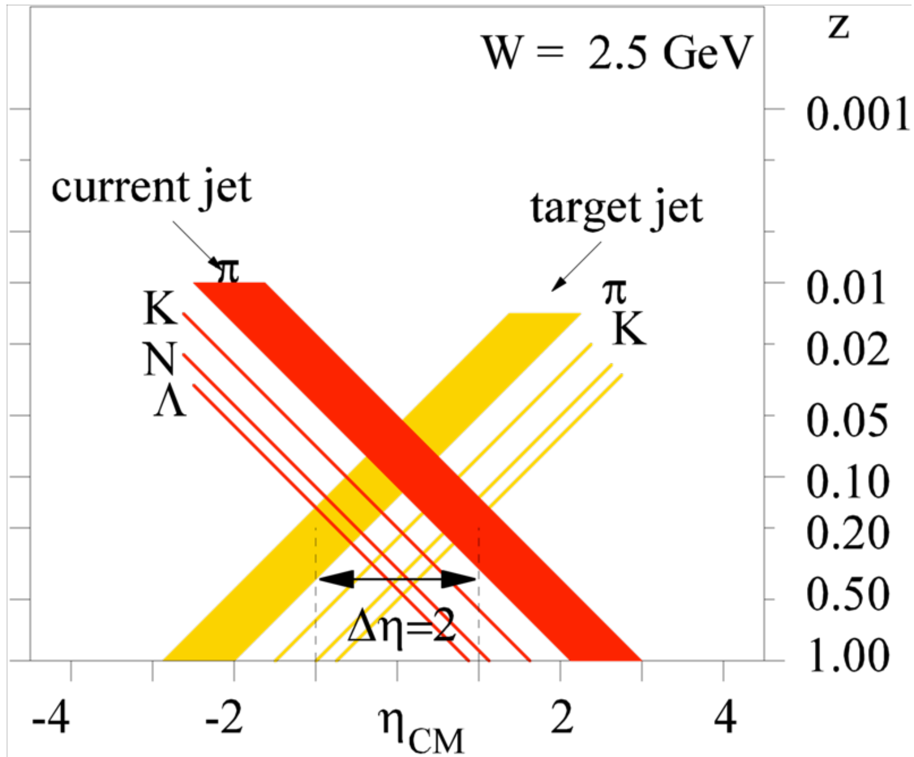
- Cross section/simulation based on factorization prediction

- Good Agreement at low z
- Delta Resonance at high z

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



Current vs Target?

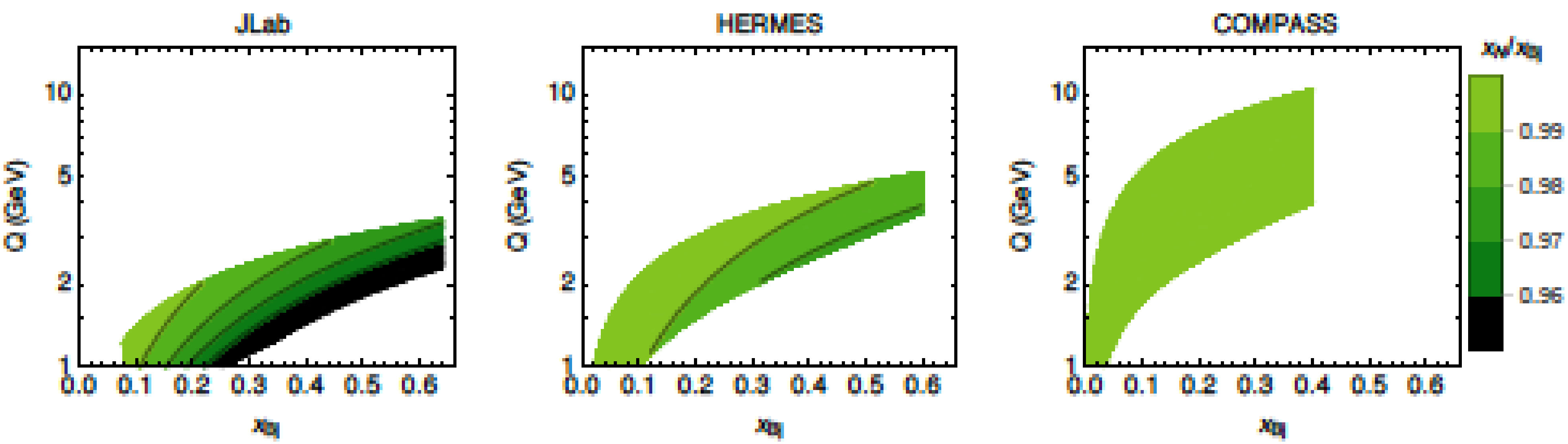


P.J. Mulders, hep-ph/0010199 (EPIC Workshop, MIT, 2000)

- Strict application of Berger “criterion” will limit useful range of kinematics; can we push our understanding to develop a more sophisticated measure?
- How do we expand this picture to handle large p_T?

New Theoretical Guidance

Mapping the Kinematical Regimes of Semi-Inclusive Deep Inelastic Scattering,
M. Boglione, A. Dotson, L. Gamberg, S. Gordon, J.O. Gonzalez-Hernandez, A. Prokudin, T.C. Rogers, and N. Sato, (2019), ArXiv:1904.12882



Example: Study of kinematic deviation between Nachtmann and Bjorken x

Brief Overview of SIDIS Program at Jefferson Lab

- Hall B
  - ➡ CLAS12 with good acceptance for precise determination of azimuthal distributions
  - ➡ Broad program of measurements including polarization, and investigation of target fragmentation region
- Hall A
  - ➡ Pol. ^{3}He targets for neutron TMDs (SOLID & BB+SBS)
- Hall C
  - ➡ High luminosity for precise measurement of kinematic dependences: testing the validity of flavor decomposition framework at 11 GeV kinematics with R and cross sections

Precision SIDIS in Hall C

- Using magnetic spectrometers one can explore the highest luminosities! Hall C has SHMS and HMS.
- Common pivot allows most precise L/T separations
- New Neutral Particle Spectrometer (NPS) adds π^0 capability with good acceptance.

➡ Precise cross sections/ratios for (e,e' $\pi^{\pm}$) and (e,e' $\pi^{0)}$ measurements at DIS kinematics

➡ New cross sections/ratios for (e,e' $K^{\pm}$)

➡ First direct determination of L/T ratio for SIDIS cross sections!

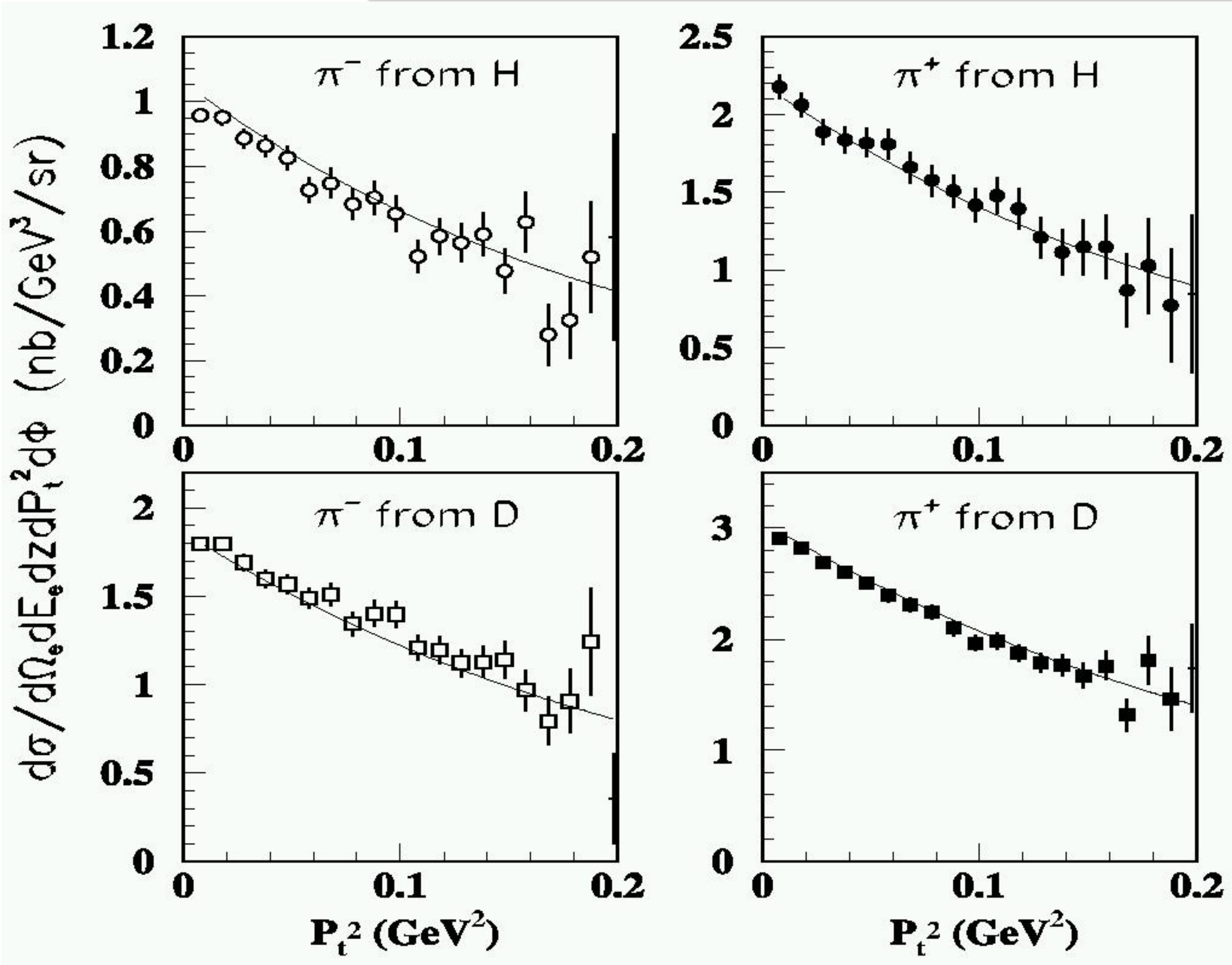
➡ Charged Symmetry Violation in SIDIS

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

- Precision measurements to test the assumptions in factorization of SIDIS
- Explore assumptions of favored/disfavored fragmentation of different flavor quarks
- Look for target mass effects
- Higher twist effects
- Complementary to Hall B SIDIS measurements

Experiment E12-09-017

Earlier JLab Measurements: E00-108



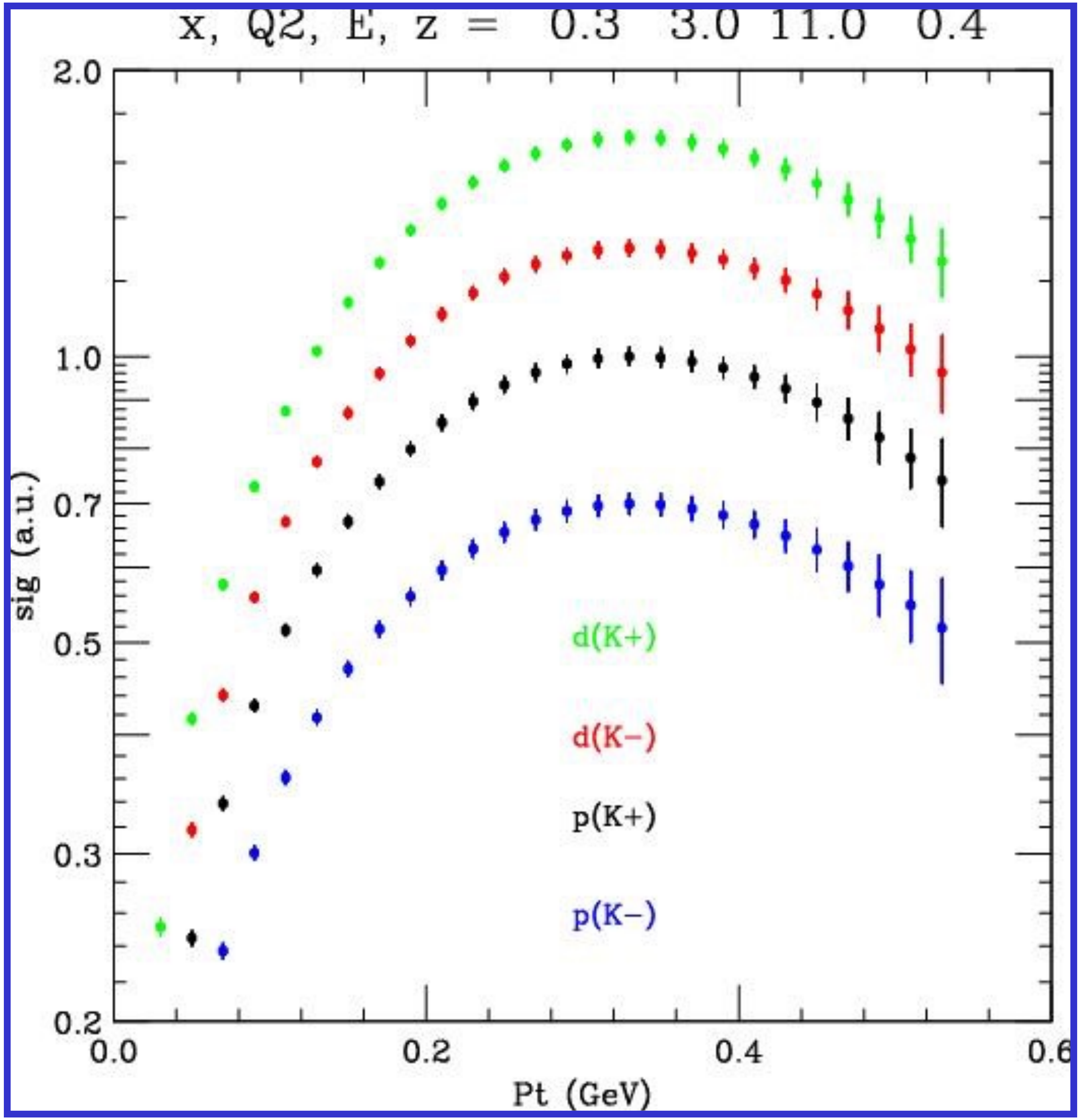
- E= 5.5, x=0.3, Q^2=2.3
- Similar, but different slopes for H, D
- Using simple gaussian+Cahn model, combined data yields momentum widths of pdf and fragmentation functions

from Phys. Lett. B665 (2008) 20

New experiment at 11 GeV: E12-09-17

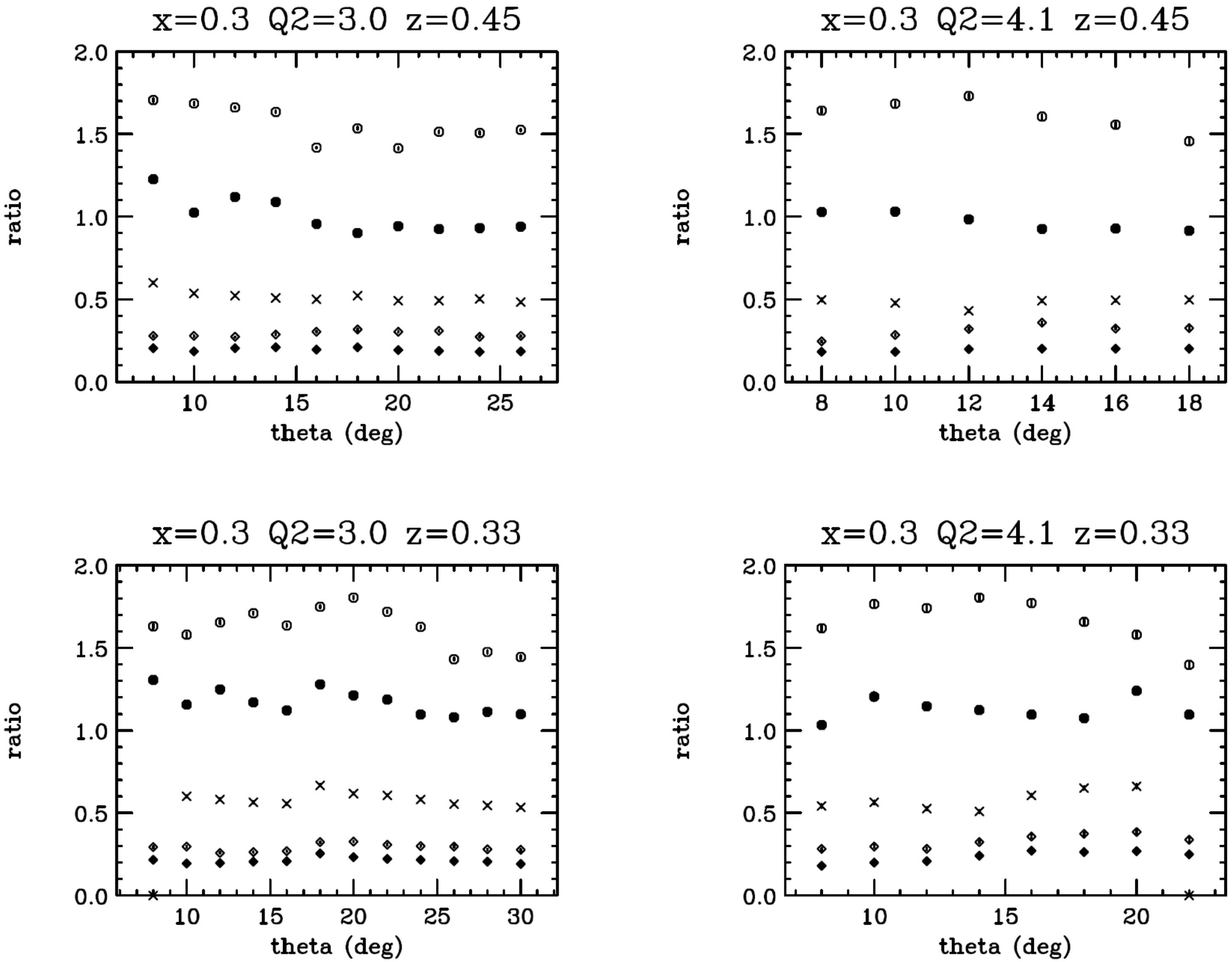
- $W^2 = 5.08\ GeV^2$ and larger (up to $11.38\ GeV^2$)
- Used SHMS angle down to 6.6 degrees (for π detection)
  HMS angle down to 13.5 degrees (e^- detection)
  separation HMS-SHMS > 17.5 degrees
- $M_X^2 = M_p^2 + Q^2(1/x - 1)(1 - z) > 2.9\ GeV^2$ (up to $7.8\ GeV^2$)
- Improved coverage in all kinematic variables, especially ϕ and p_T
- 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 Aluminum dummy)

Example of Expected Charged Kaon Precision



E12-09-017 Quasi-Online Results – Pions

not normalized by target density: just ratios of counts/mC corrected for computer dead time.



Ratio to pi+ from LH2 of
pi+ from LD2 (open circles)
pi+ from Al (open diamonds)
pi- from LH2 (crosses)
pi- from LD2 (filled circles)
pi- from Al (filled diamonds)

Anashe Bandari & Peter Bosted

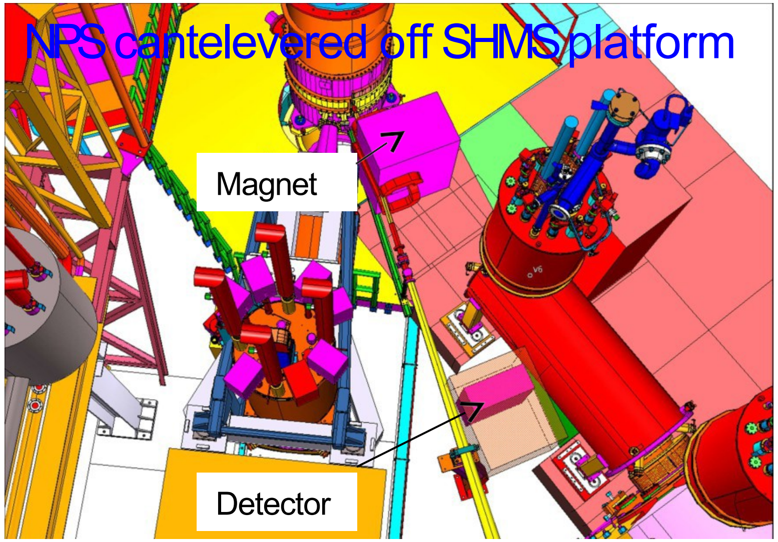
Precision (e,e'π^0) cross sections at low $P_{h\perp}$

- Neutral pions are a good test and consistency check of flavor assumptions in extraction of TMDs with TM fragmentation
- Experimental measurement cleaner in terms of ρ (vector meson) contamination, exclusive pole contributions and hadron EM radiation effects
- Combined with charged pion/kaon data provides important constraint for analyzing future SIDIS experiments and TMD extraction

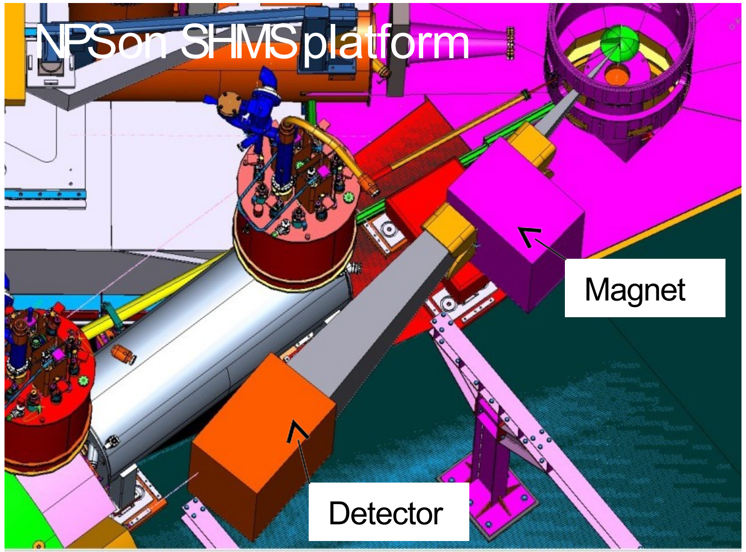
Experiment E12-13-007

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0). The NPS will be remotely rotatable off the SHMS platform.



NPS angle range: 5.5 – 30 degrees



NPS angle range: 25 – 60 degrees

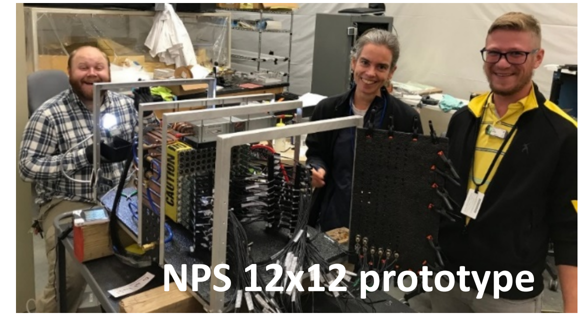
The large interest for such a device can be exemplified by the PAC-approved program:

E12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization
E12-13-010 – Exclusive Deeply Virtual Compton and Neutral Pion Cross Section Measurements in Hall C

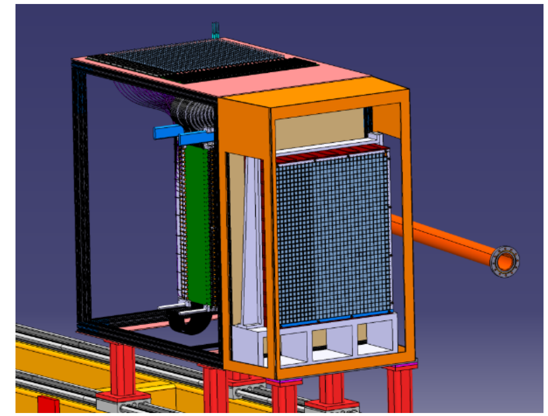
(E12-13-007 & E12-13-010 can run as one run group – first run group in Hall C)

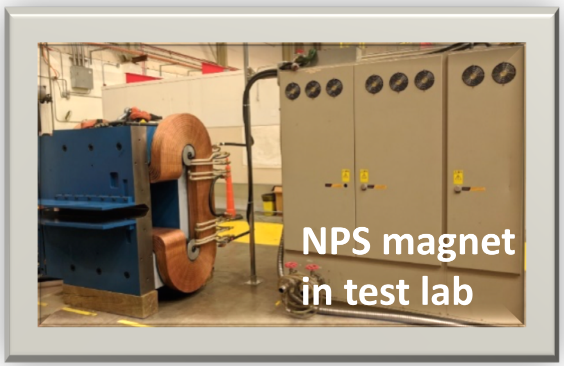
E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons **(runs as run group with E12-14-003)**
E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering

Neutral Particle Spectrometer (NPS)

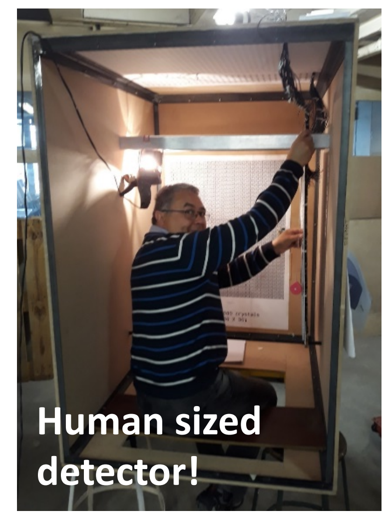


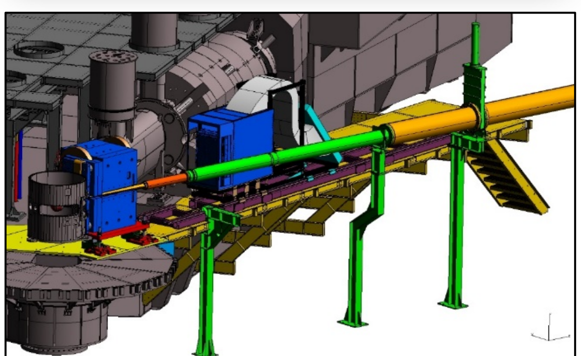
- ❑ NPS passed ERR with recommendations
  - ➢ Experiments: E12-13-010/007, E12-14-003/005
- ❑ NPS 12x12 prototype test successfully completed
- ❑ NPS subsystem status
  - ➢ Magnet provided by CUA and ODU (NSF MRI) - ready for mapping





- ➢ Detector frame designed (IPN-Orsay)
- ➢ Crystal testing ongoing (CUA), final procurement underway
- ➢ PMTs on-site, HV base fabrication near completion (OU)
- ➢ Software development ongoing (IPN-Orsay, JMU, U. Glasgow, JLab)
- ➢ Trigger/Electronics/DAQ - (JLab)

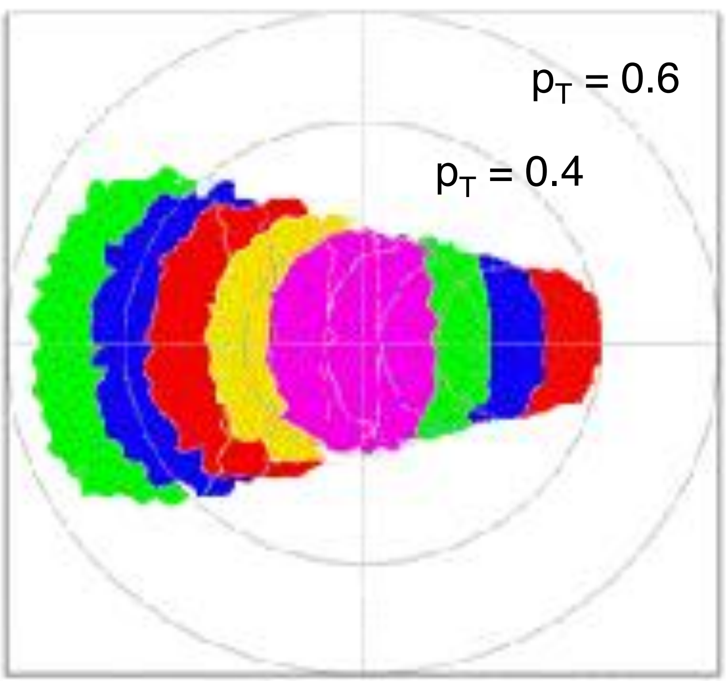




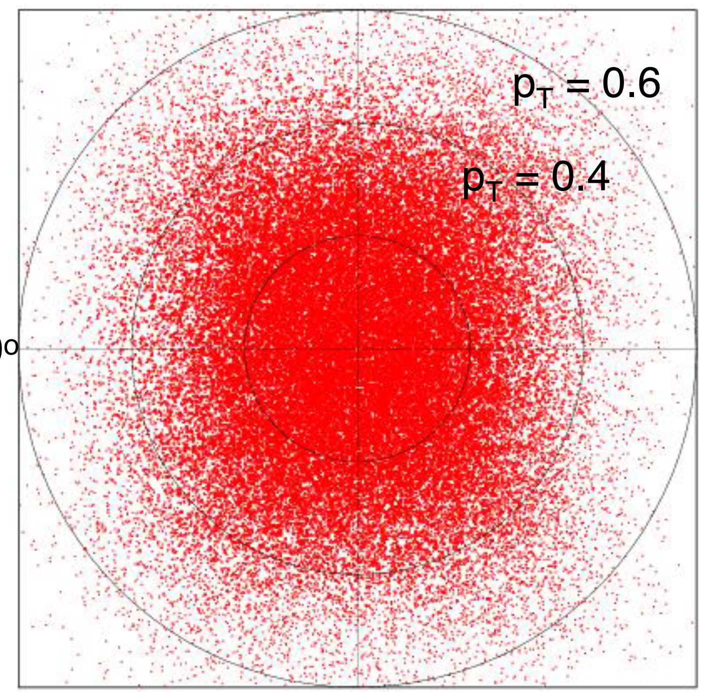
- ➢ Mechanical – systems identified, e.g. SHMS platform extension designed, installation plan being developed and tuned (Jlab)

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

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



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

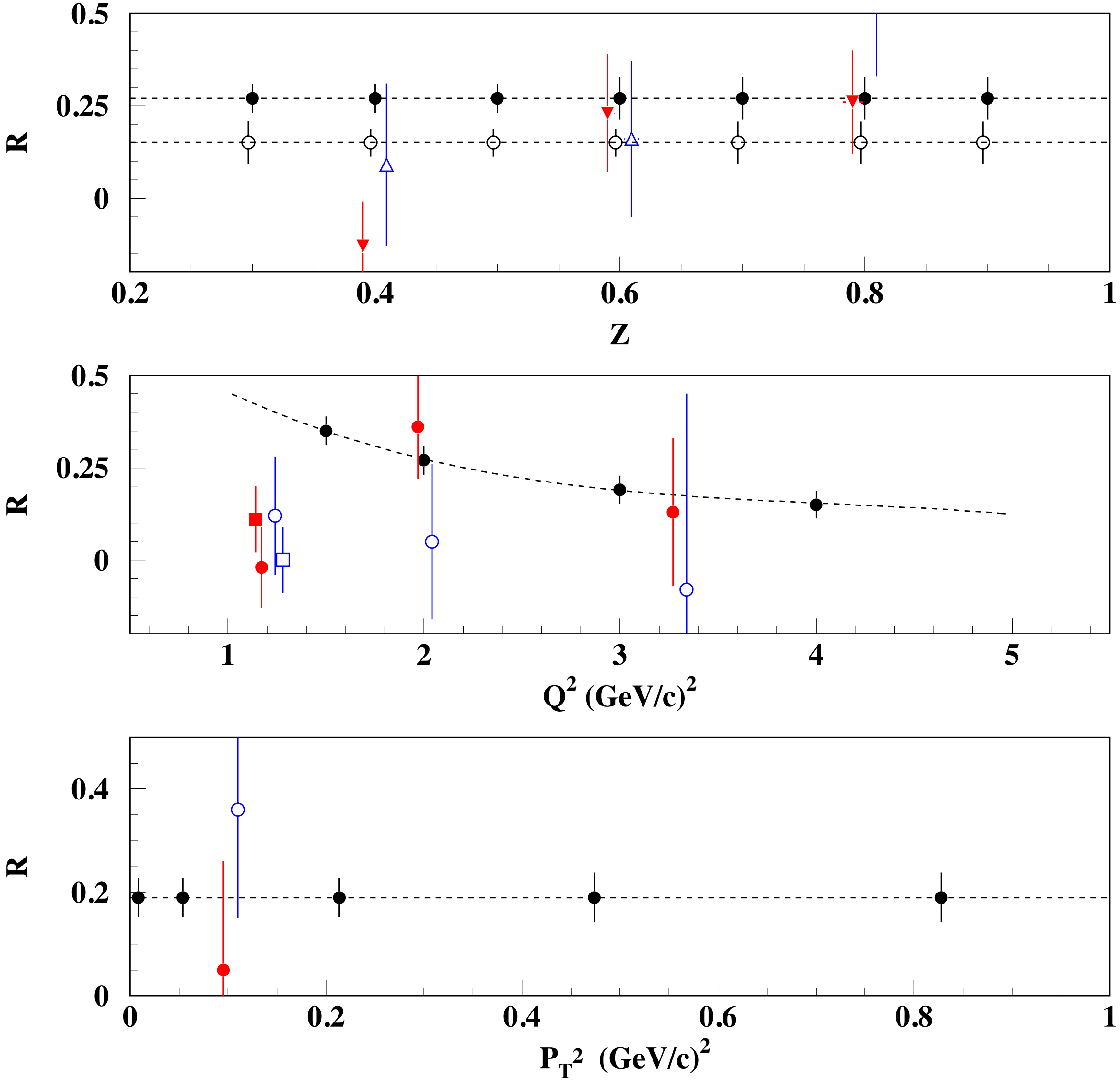


L/T Separation of SIDIS (e,e'π±) cross section

- All SIDIS flavor analyses assume a value of $R_{SIDIS} = \sigma_L/\sigma_T$ as it has never been measured!
- Common assumption is $R_{SIDIS} = R_{DIS}$
- How does R_{SIDIS} depend on *z*?
- How does R_{SIDIS} depend on hadron type?
- How does R_{SIDIS} depend on $P_{h\perp}$?
- Do we understand Q^2 dependence in SIDIS and in Exclusive ($z \rightarrow 1$) regimes?
- Hall C spectrometers ideal for precise R measurement

Experiment E12-06-104

Existing and Expected R = σ_L/σ_T Results



Projections for E12-06-104 vs existing Cornell Data (projections assume $R_{SIDIS} = R_{DIS}$)
Comparable 1.6% systematic uncertainties not indicated

Planned scans in z at Q^2 = 2.0 (x = 0.2) and 4.0 GeV^2 (x = 0.4)
→ should settle the behavior of σ_L/σ_T for large z.

Planned data cover range Q^2 = 1.5 – 5.0 GeV^2, with data for both H and D at Q^2 = 2 GeV^2

Planned data cover range in P_T up to ~ 1 GeV.
The coverage in ϕ is excellent (o.k.) up to P_T = 0.2 (0.4) GeV.

Projections: Solid Black H, Open Black D π
Cornell:
Top: 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

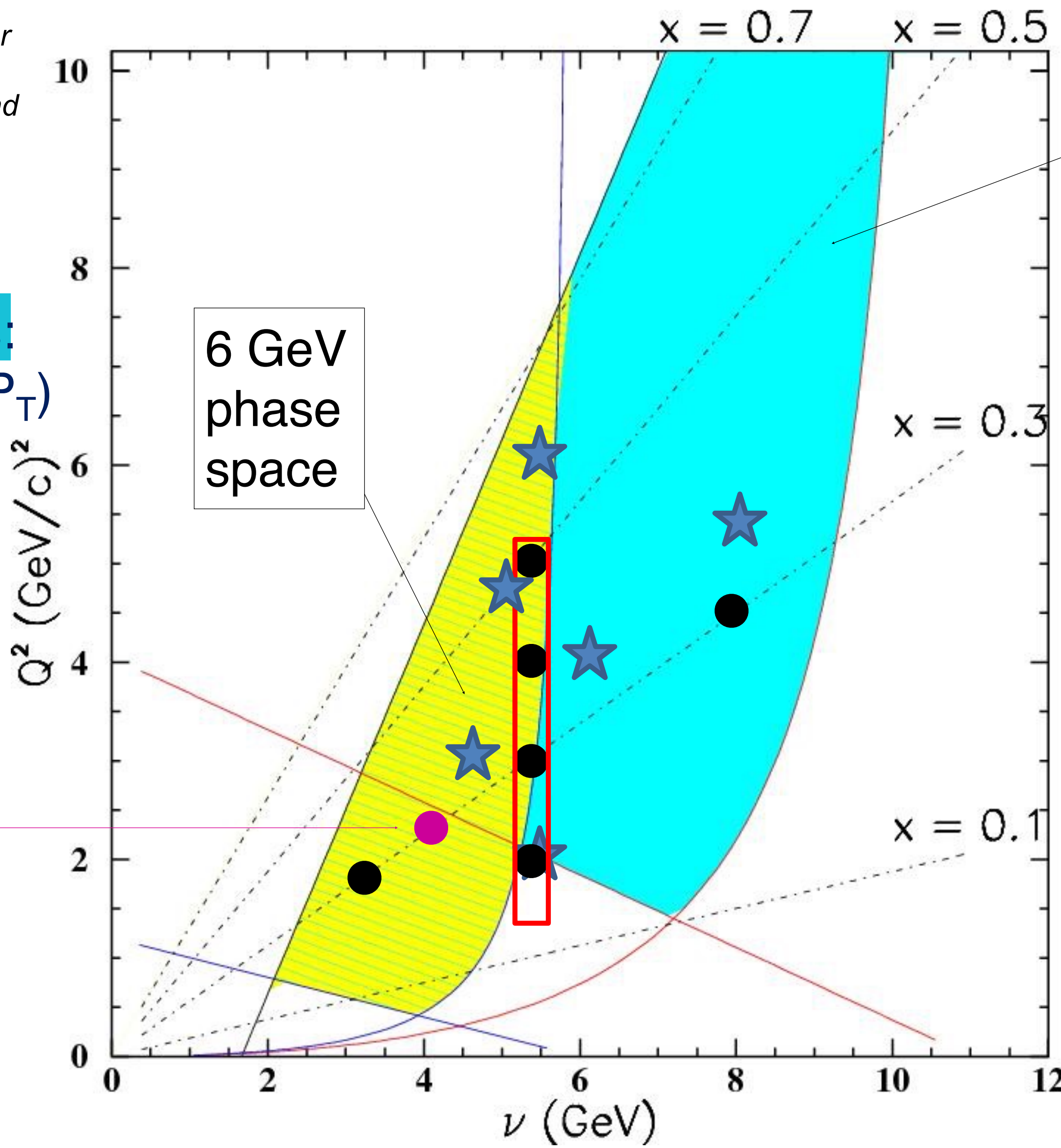
Hall C Kinematic Reach

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)



11 GeV phase space

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

Timescales

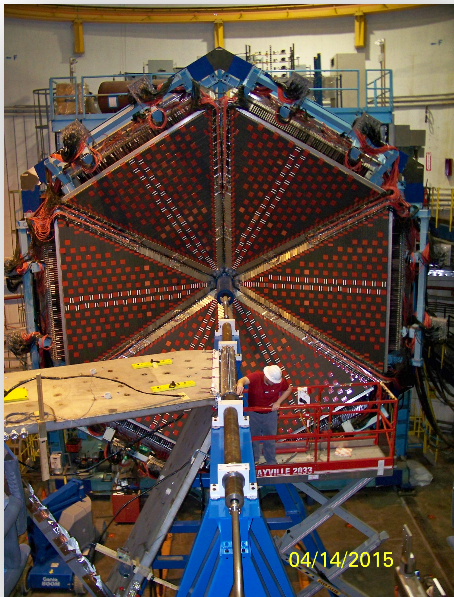
- Charge pion, kaon measurements made in late 2017/early 2018; preliminary results expected fall 2019.
- Neutral pion measurements beam requested in 2020/2021
- R measurements: PAC47 increased priority from A- to A, beam requested in 2020/2021

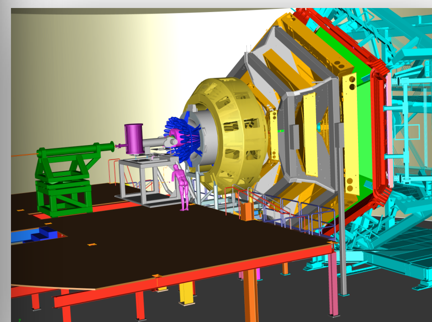
Summary

- Broad program at Jefferson Lab to determine the flavored partonic 3D momentum and spatial structure of the nucleon
- Important to verify the theoretical framework in this kinematic region with precise experimental determination of dependences on hadron momentum in SIDIS
- E12-09-017, E12-13-007, and E12-06-104 will provide SIDIS charged pion+kaon data to make these tests and will also explore new territory with $(e,e'\pi^0)$ and R_{SIDIS} measurements

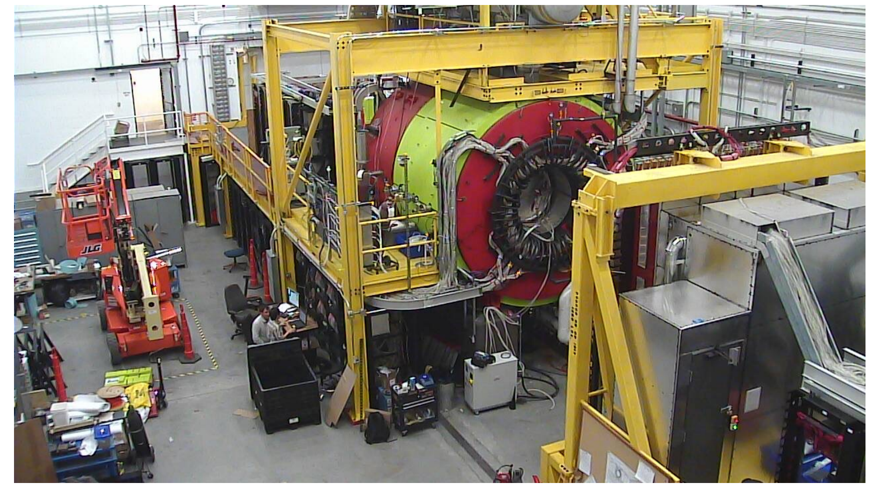
12 GeV Scientific Capabilities

Hall B **– understanding nucleon structure via generalized parton distributions**

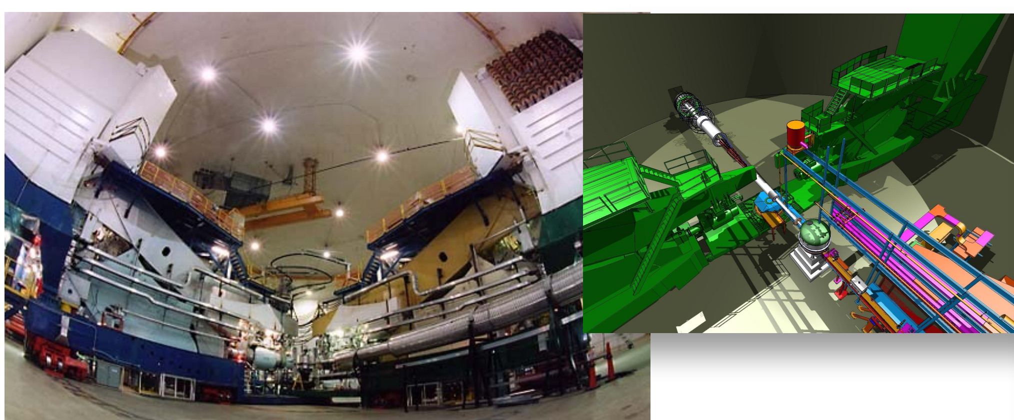




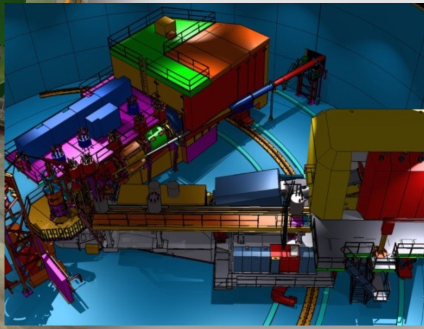
Hall D **– exploring origin of confinement by studying exotic mesons**



Hall A **– form factors, future new experiments (e.g., SoLID and MOLLER)**



Hall C **– precision determination of valence quark properties in nucleons/nuclei**



SIDIS Cross Section

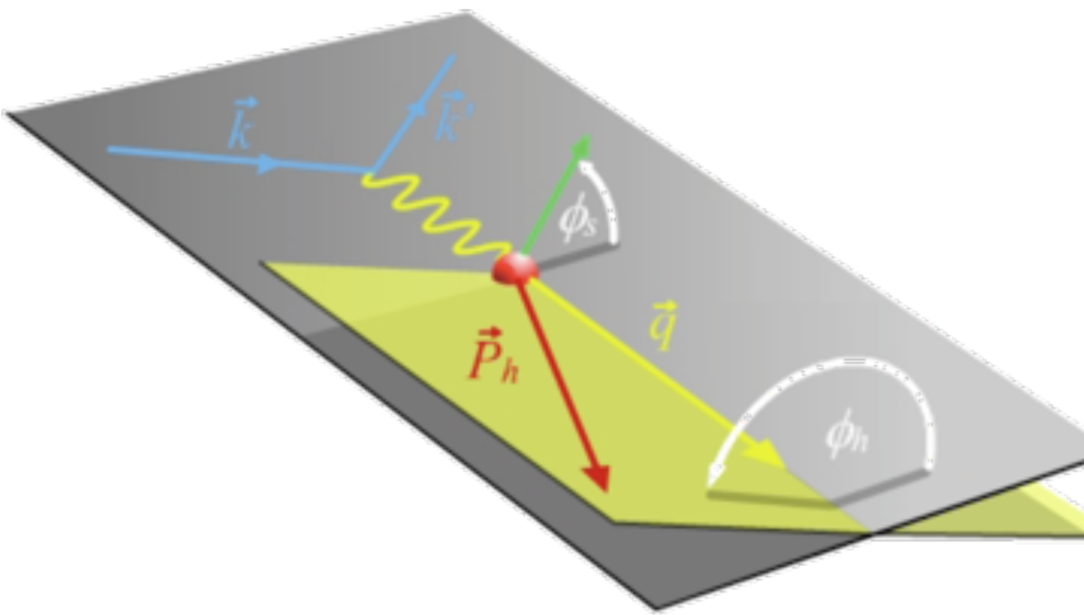
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} +$$

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

Q^2 = Virtual Photon Mass

ε = Virtual Photon Polarization

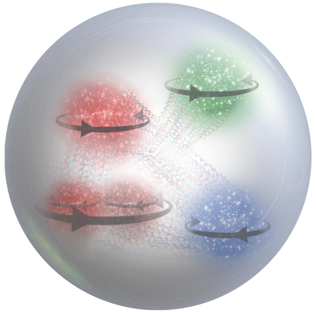
λ = Long. Beam Polarization



General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

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

Features of partonic 3D non-perturbative distributions



$$f^a(x, k_T^2; Q^2)$$

Ex. TMD PDF for a given combination of parton and nucleon spins

nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 (transversity) $h_{1T}^\perp$ (pretzelosity)

transversity pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

How Can We Verify Factorization?

R. Ent Slide

Neglect sea quarks and assume no p_t dependence to parton distribution functions

→ Fragmentation function dependence drops out in Leading Order

$$[\sigma_p(\pi^+) + \sigma_p(\pi^-)]/[\sigma_d(\pi^+) + \sigma_d(\pi^-)]$$

$$= [4u(x) + d(x)]/[5(u(x) + d(x))]$$

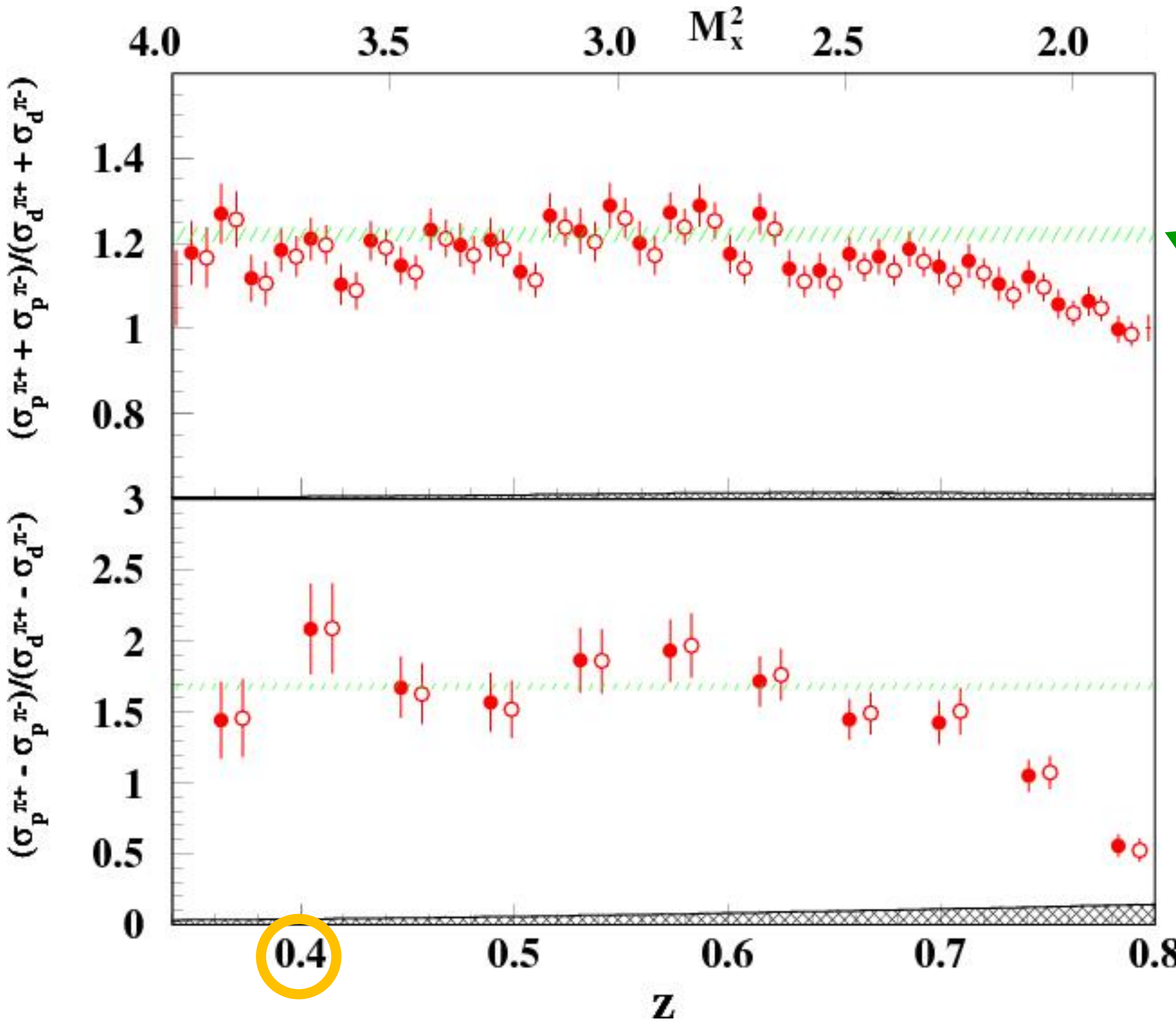
$$\sim \sigma_p/\sigma_d$$ *independent of z and p_t*

$$[\sigma_p(\pi^+) - \sigma_p(\pi^-)]/[\sigma_d(\pi^+) - \sigma_d(\pi^-)]$$

$$= [4u(x) - d(x)]/[3(u(x) + d(x))]$$

independent of z and p_t, but more sensitive to assumptions

E00-108: Onset of the Parton Model



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GRV & CTEQ, @ LO or NLO

Good description for p and d targets for $0.4 < z < 0.65$

(Note: $z = 0.65 \sim M_x^2 = 2.5\ GeV^2$)

Closed (open) symbols reflect data after (before) events from coherent ρ production are subtracted

E00-108: Onset of the Parton Model

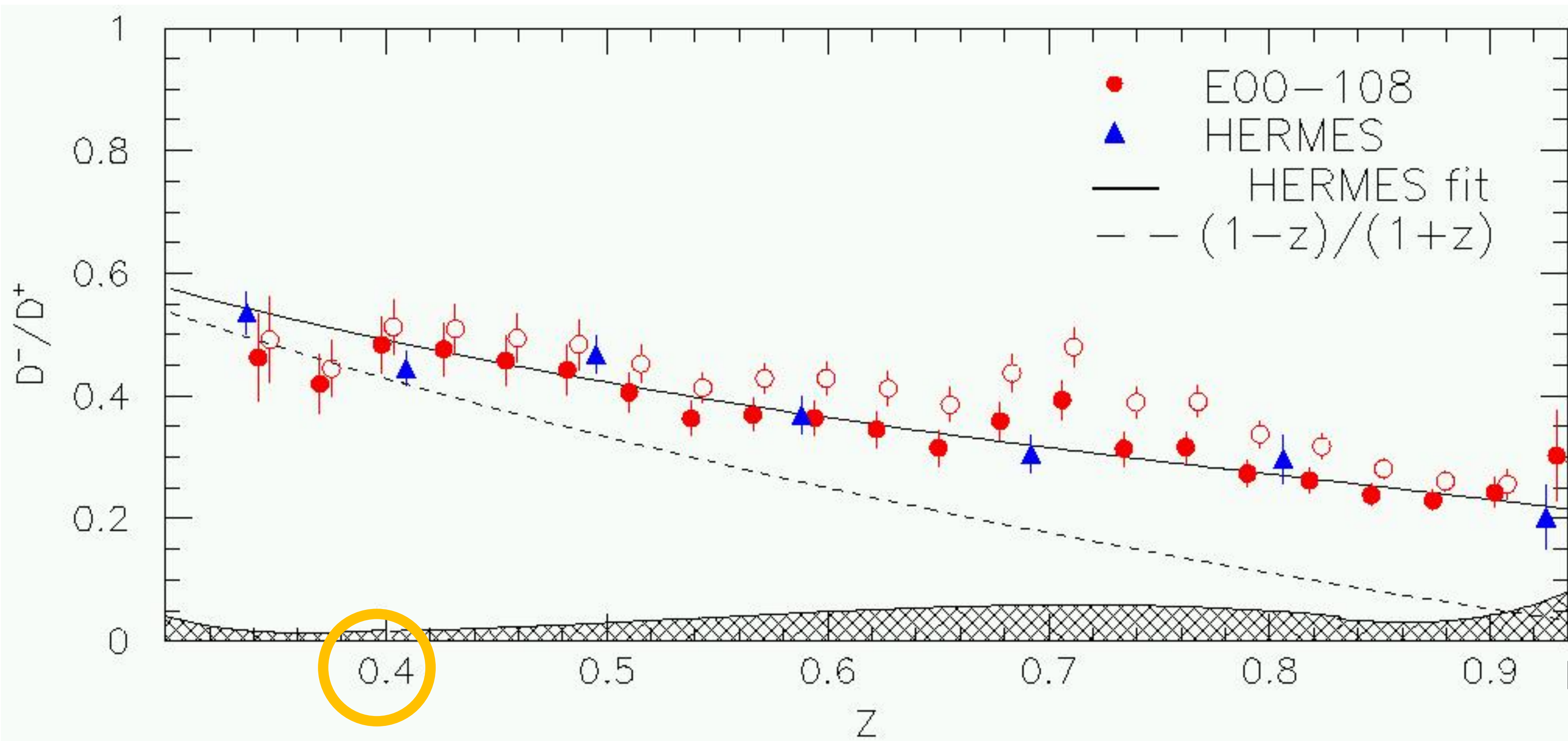
$$\Sigma e_q^2 q(x)\, D_q^{\pi}(z)$$

factorization

Collinear Fragmentation

$$\frac{D^-}{D^+} = \frac{4-R}{4*R-1} \qquad R = \frac{N_{\pi^+}}{N_{\pi^-}}$$

(Deuterium data)



R. Ent Slide

W' = 2 GeV ~ z = 0.35 → data predominantly in "resonance region"

What happened to the resonances?