PR12-24-001: Measurement of the Nuclear Dependence of R=σ_L/σ_T in Semi-Inclusive Deep Inelastic Scattering

Proposal to PAC 52

Spokespersons: P. Bosted (W&M),

W. Brooks (USM), R. Ent (JLab), D. Gaskell* (JLab),
E. Kinney (U. Colorado), H. Mkrtchyan (Yerevan)

PR12-24-001: Nuclear Dependence of R in SIDIS

Goal: Directly measure the nuclear dependence of $R=\sigma_L/\sigma_T$ in semi-inclusive DIS

→ No existing measurements of nuclear dependence of R in SIDIS

→ Potential impact on SIDIS results (dilution factor for polarized targets)

→ Potential impact on measurements of hadron-attenuation

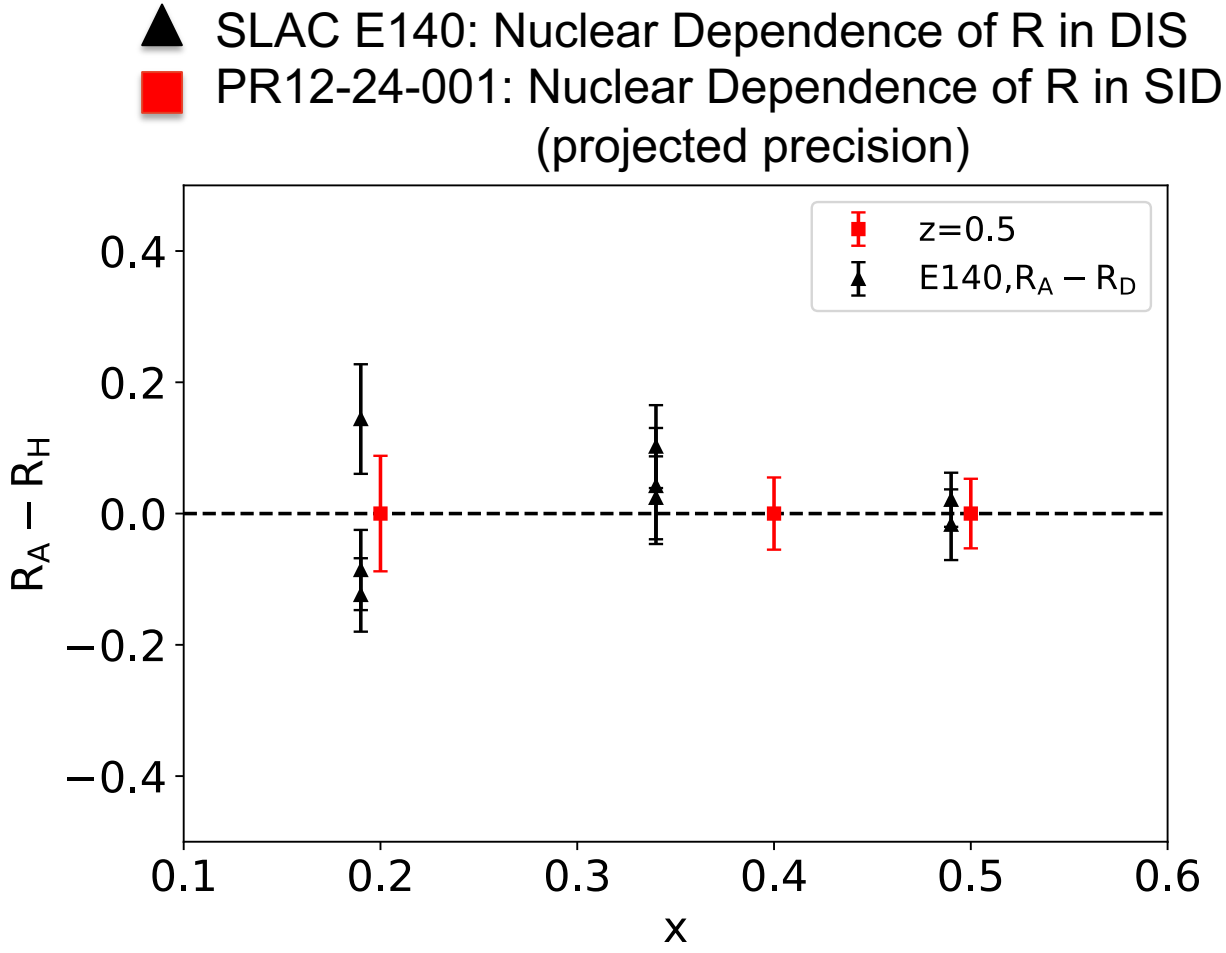
→ **Exploratory** measurement to determine if more comprehensive program merited

Experiment: Measure cross sections and ratios for H, D, C, Cu targets at 3 beam energies

→ Allows LT separation

→ **E12-06-104** (R in SIDIS on H and D) in Hall C experiment scheduled for CY2025.

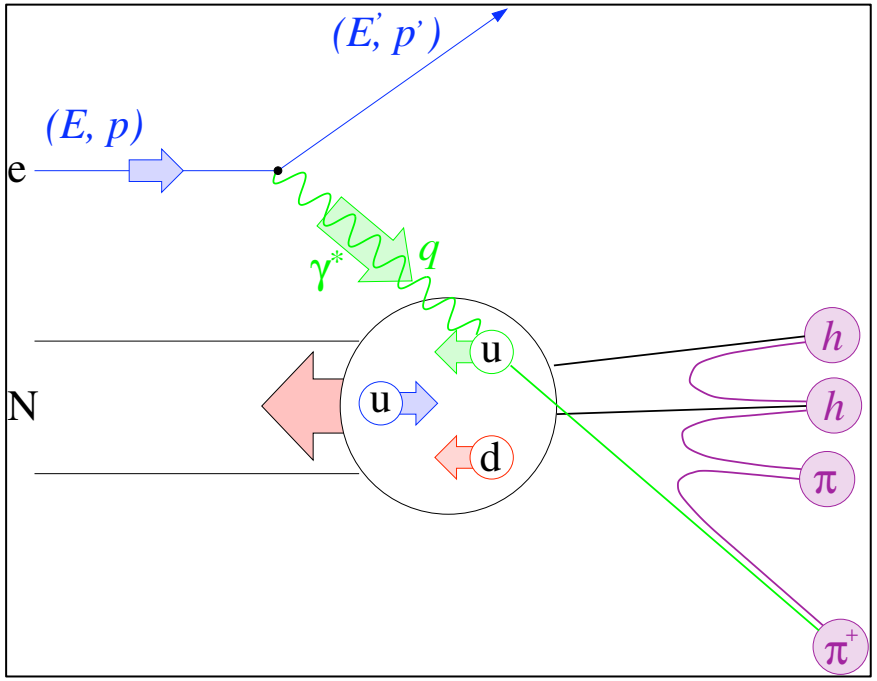
→ PR12-24-001 with E12-06-104 at select kinematics adding nuclear targets (^{12}C and ^{64}Cu).



Beam time request: 5 days

$R=\sigma_L/\sigma_T$ in SIDIS

Semi-inclusive DIS a key part of the JLab 12 GeV program
→ One-dimensional polarized and unpolarized PDFs
→ Three-dimensional hadron structure via TMDs



Naïve quark model:

$$\frac{d\sigma(x,Q^2,z)}{dz} = \sum_f e_f^2 q_f(x,Q^2) D_f^h(z)$$

Actual dynamics and cross section more complicated – contribution of longitudinal photons cannot be ignored

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

Longitudinal contribution from higher order interactions.
Simple estimate relates to quark transverse momentum

$$R = 4(M^2x^2 + k_T^2)/(Q^2 + 2k_T^2)$$

F.E. Close, An Introduction to Quarks and Partons, 1979

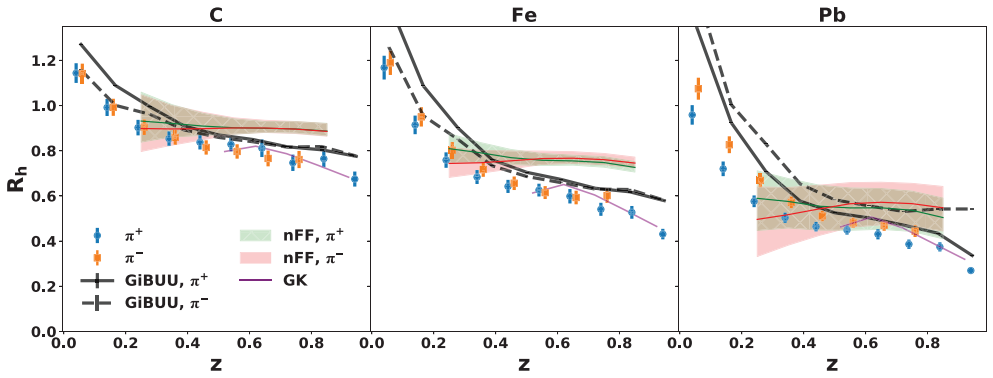
R_{SIDIS} in Nuclei

Measurement of R_{SIDIS} in nuclei perhaps most immediately relevant to measurements of hadron attenuation

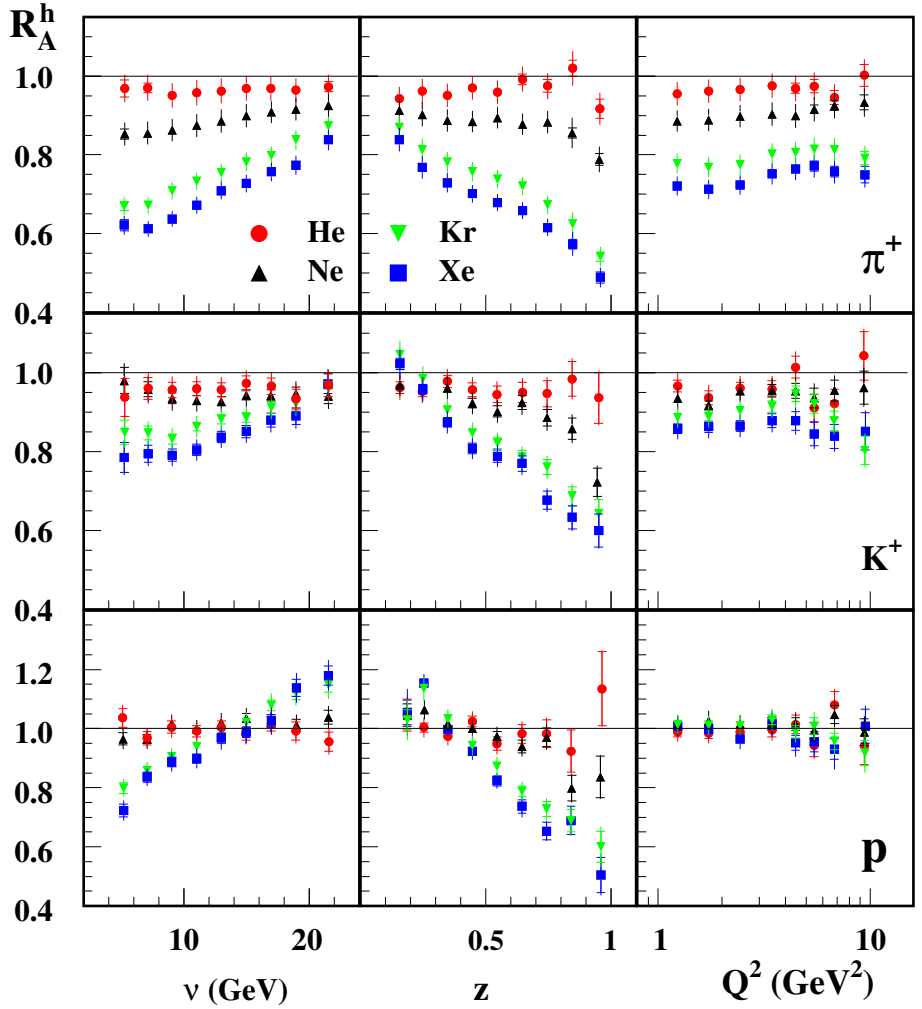
$$R_A^h = \frac{N_A^h/N_A^e}{N_D^h/N_D^e} = \frac{\left(\frac{d\sigma}{dz}\right)_A^h}{\left(\frac{d\sigma}{dz}\right)_D^h}$$

Can provide information about hadron formation time, quark energy loss, etc.

→ Knowledge of nuclear dependence of R_{SIDIS} needed for interpretation of these measurements

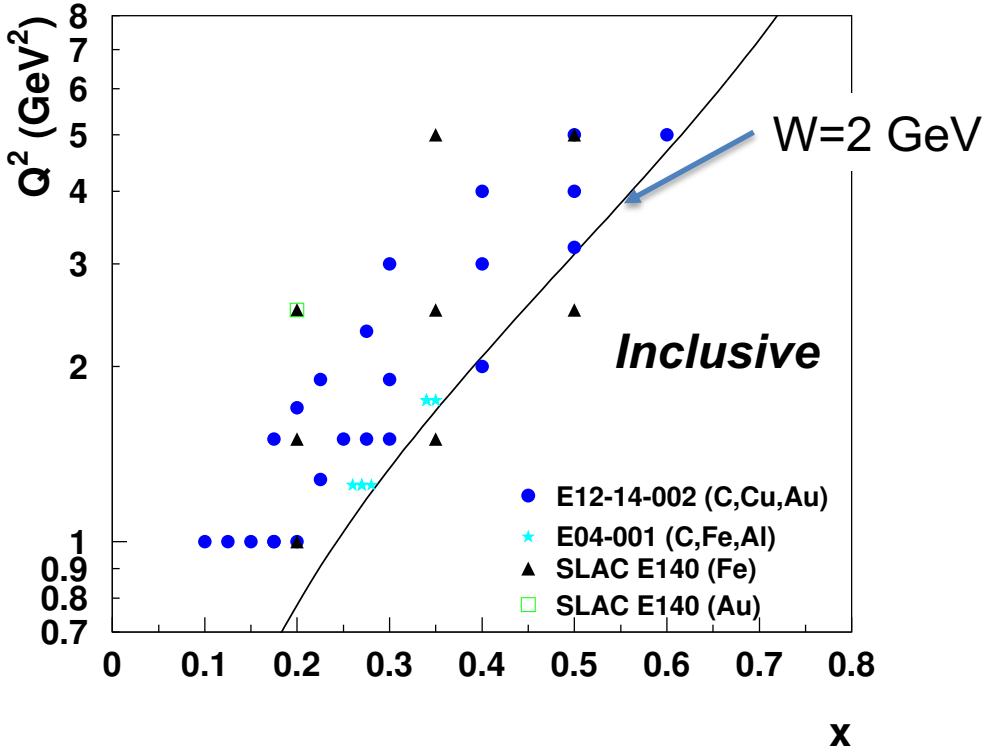


CLAS: Moran et al, PRC 105(1):015201 (2022)



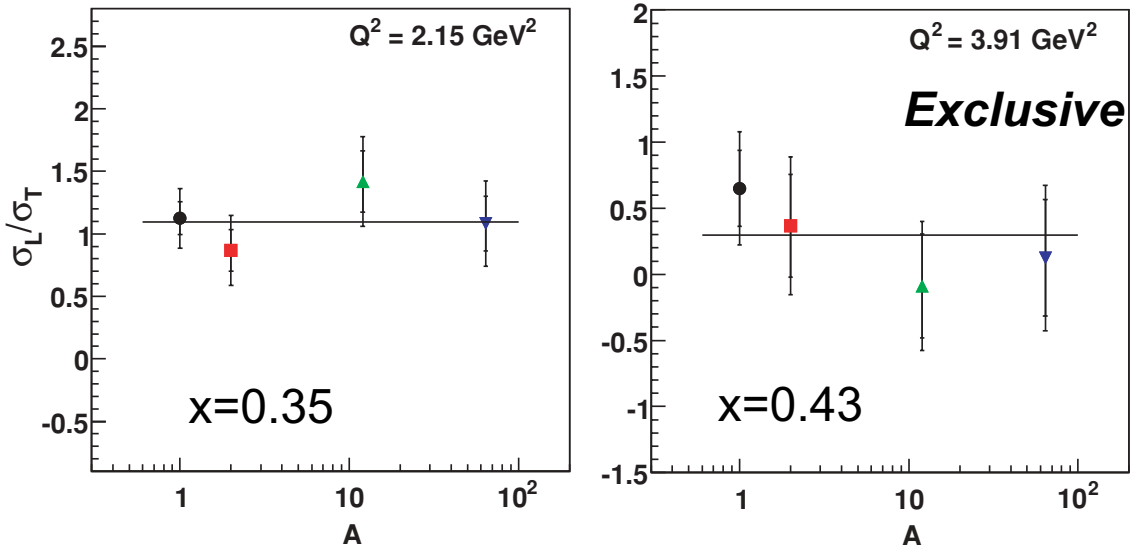
HERMES: Airapetian et al, Nuc. Phys. B, 780:1-27 (2007)

R in DIS and DVMP



Few *direct* measurements (via LT separation) of nuclear dependence of R in inclusive DIS

→ Hall C **E12-14-002** will provide additional measurements over large phase space for C, Cu, Au



Nuclear dependence of R in Deeply Virtual π+ Production measured as part of 6 GeV measurement of pion color transparency

[X. Qian et al. PRC 81:055209, 2010]

Measurement of nuclear dependence of R_{SIDIS} will provide important bridge between inclusive and exclusive regime

Experiment

Experiment will measure semi-inclusive π+ (and π-) production from **C** and **Cu**

→ Opportunity: Run with **E12-06-104** to allow easy comparison with SIDIS from H and D

→ Exploratory: Will only take data at subset of E12-06-104 kinematics

Beam energies = 6.6, 8.8, 11 GeV (3, 4, 5 pass)

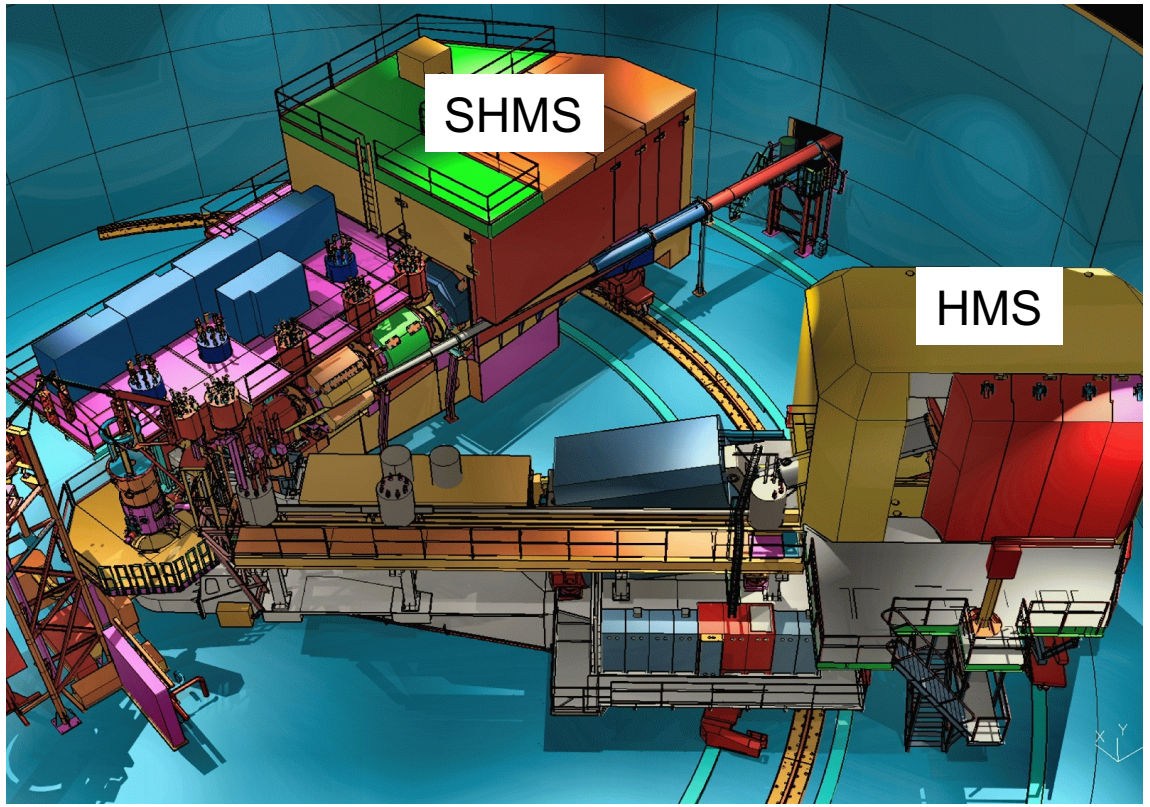
<u>Standard Hall C equipment:</u>

Electron arm: High Momentum Spectrometer (HMS)

→ This experiment: P=1.27-5.67 GeV, θ=10.5 to 45.41 deg.

Pion arm: Super High Momentum Spectrometer (SHMS)

→ This experiment: P=1.59-4.53 GeV, θ=6.3 to 15.96 deg.



HMS+SHMS provide excellent control of point-to-point systematics – crucial for LT separations

E12-06-104: Measurement of R_{SIDIS}

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

Almost no existing data on $R=\sigma_L/\sigma_T$ in SIDIS (p and n)
→ Limited data from Cornell
[Bebek et al, PRL 34, 759 (1975), PRL 37, 1525 (1976), PRD 15, 3085 (1977)]

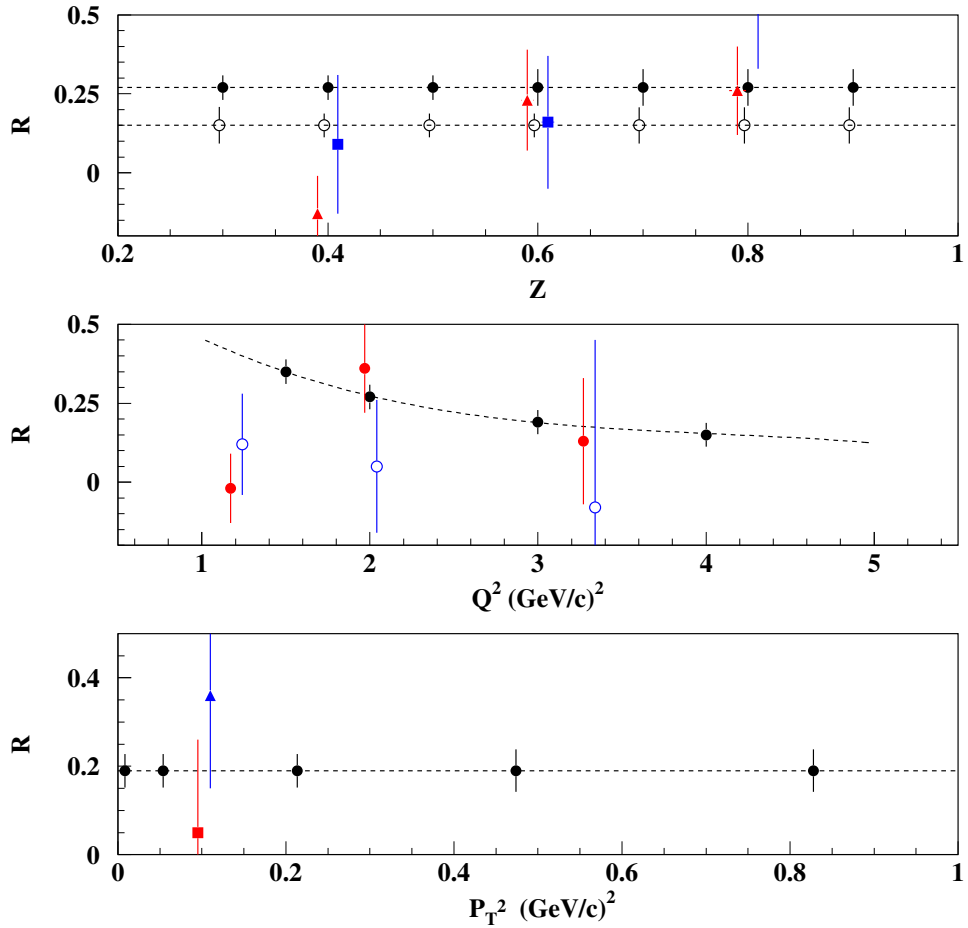
E12-06-104 is will make precise measurements of R_{SIDIS} in
$e+p \rightarrow e'+\pi^{+/-}+X$, $e+D \rightarrow e'+\pi^{+/-}+X$

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.

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



Expected to run in 2025

Detailed Kinematics

E12-06-104:

Data for π+ and π- from proton at all settings

Data from proton and deuteron at x=0.2

x	Q^2 (GeV^2)	z	θ_{pq} (degrees)	Targets	E_{beam} (GeV)	ϵ
0.2	**2.0**	**0.3,0.4,0.5,0.65,0.85**	**0.0**	LH2,LD2,**C,Cu**	**6.6**	**0.34**
		0.3,0.4,0.5,0.65,0.85	**0.0**	LH2,LD2,**C,Cu**	**8.8**	**0.66**
		0.3,0.4,0.5,0.65,0.85	**0.0**	LH2,LD2,**C,Cu**	**11.0**	**0.80**
0.4	**4.0**	0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C,Cu**	**6.6**	**0.31**
		0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C,Cu**	**8.8**	**0.65**
		0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C,Cu**	**11.0**	**0.79**
0.3	3.0	0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	6.6	0.33
		0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	8.8	0.66
		0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	11.0	0.88
0.15	1.5	0.5	0.0	LH2	6.6	0.35
		0.5	0.0	LH2	8.8	0.67
0.5	**5.0**	**0.5**	**0.0**	LH2, **C,Cu**	**6.6**	**0.30**
		0.5	**0.0**	LH2, **C,Cu**	**8.8**	**0.64**
		0.5	**0.0**	LH2, **C,Cu**	**11.0**	**0.79**

This experiment:
Bold = kinematic settings for measurements with C and Cu targets (π+ only)
Bold, red = kinematic settings for measurements with C and Cu targets (π+ **and** π-)

Detailed Kinematics

E12-06-104:

Data for π+ and π- from proton at all settings

Data from proton and deuteron at x=0.2

x	Q^2 (GeV^2)	z	θ_{pq} (degrees)	Targets	E_{beam} (GeV)	ϵ
0.2	**2.0**	**0.3,0.4,0.5,0.65,0.85**	**0.0**	LH2,LD2,**C,Cu**	**6.6**	**0.34**
		0.3,0.4,0.5,0.65,0.85	**0.0**	LH2,LD2,**C,Cu**	**8.8**	**0.66**
		0.3,0.4,0.5,0.65,0.85	**0.0**	LH2,LD2,**C,Cu**	**11.0**	**0.80**
0.4	**4.0**	0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C,Cu**	**6.6**	**0.31**
		0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C,Cu**	**8.8**	**0.65**
		0.3,0.4,**0.5**,0.65,0.85	**0.0**	LH2,**C,Cu**	**11.0**	**0.79**
0.3	3.0	0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	6.6	0.33
		0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	8.8	0.66
		0.5	-2.0,0.0,5.0,10.0,15.0,20.0	LH2	11.0	0.88
0.15	1.5	0.5	0.0	LH2	6.6	0.35
		0.5	0.0	LH2	8.8	0.67
0.5	**5.0**	**0.5**	**0.0**	LH2, **C,Cu**	**6.6**	**0.30**
		0.5	**0.0**	LH2, **C,Cu**	**8.8**	**0.64**
		0.5	**0.0**	LH2, **C,Cu**	**11.0**	**0.79**

Goals:

1. Measure nuclear dependence of R_{SIDIS} for range of x at fixed z
   → Low x: no or small nuclear effects (inclusive), Large x: EMC region
2. Measurement for range of z for at least one x
3. Both π+ and π- for (part of) z-scan
4. Multiple values of A to explore nuclear dependence

Rate Estimates

Rate estimates based on parametrization of Hall C π+ and π- SIDIS data taken at 10.2-10.6 GeV

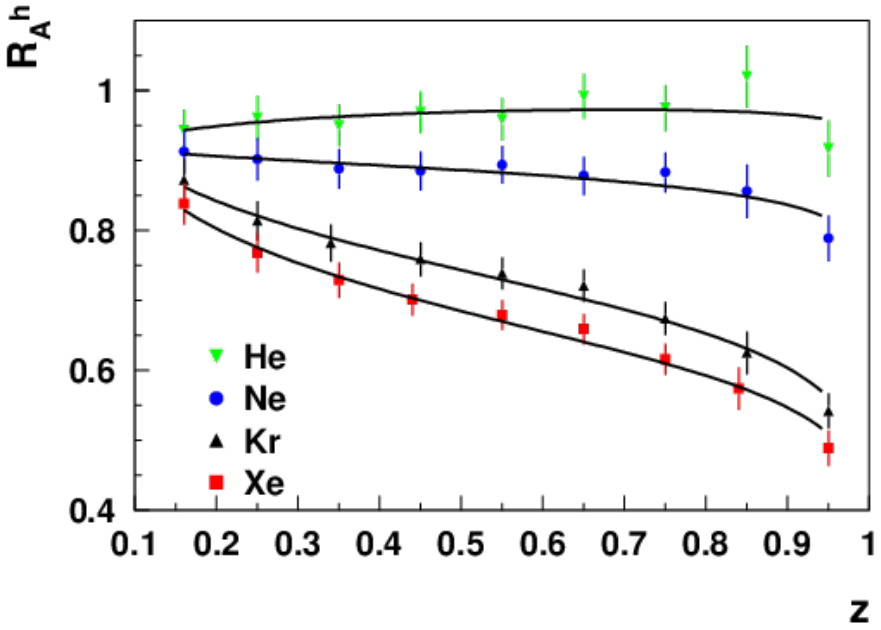
→ Developed by Peter Bosted for analysis of

- E12-09-017 ("Transverse Momentum Dependence of Semi-Inclusive Pion Production") and
- E12-09-002 ("Charge Symmetry Violating Quark Distributions via Precise Measurement of π+/π− Ratios in Semi–inclusive Deep Inelastic Scattering")

Hadron attenuation effects estimated using ad-hoc fit to HERMES results of the form

$$R_A^h = N_0 z^\alpha (1-z)^\beta$$

Fit A dependence of (N_0, α, β) to extrapolate to C and Cu



Beam Time Breakdown

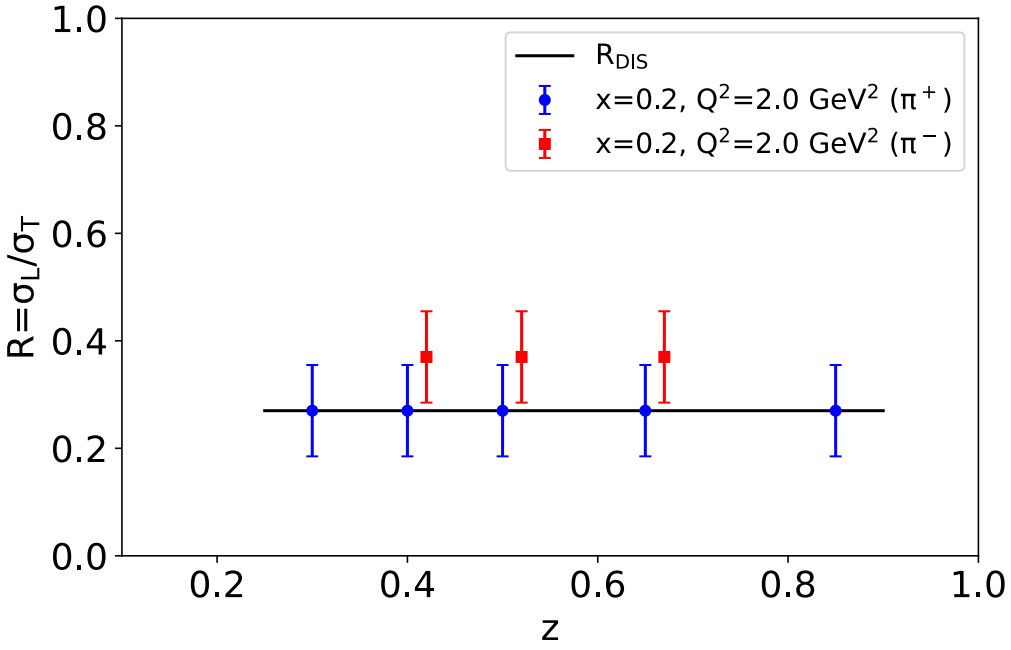
Targets:
C = 3% RL (1.28 g/cm^2)
Cu = 6% RL (0.77 g/cm^2)

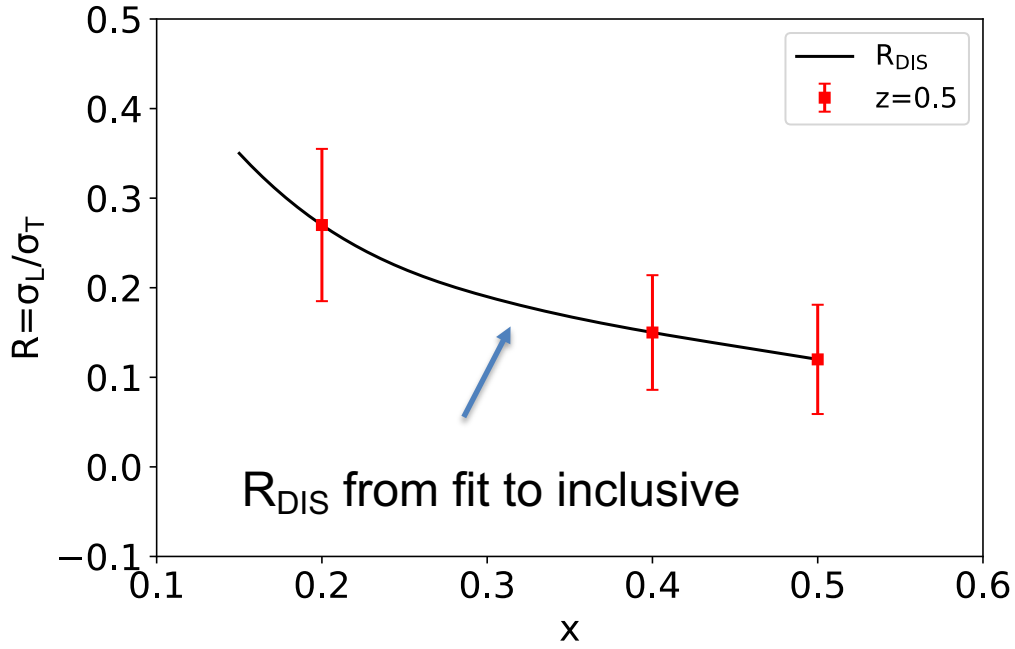
Beam currents:
I_{beam} = 25-50 μA

Statistics:
x=0.4, 0.5: 10k events
x=0.2: 5k events for low z
10k events z=0.85

x	Q^2 (GeV)^2	z	ε	Target	Time (π+) (hrs)	Time (π-) (hrs)
0.2	2.0	0.3-0.85 (0.4-0.65)	0.34, 0.66, 0.80	C	15.3	9.8
				Cu	19.1	13.5
				Subtotal (x=0.2)	**34.4**	**23.3**
0.4	4	0.5	0.31, 0.65, 0.79	C	7.3	-
				Cu	12.9	-
				Subtotal (x=0.4)	**20.2**	**-**
0.5	5	0.5	0.30, 0.64, 0.79	C	14.5	-
				Cu	16.4	-
				Subtotal (x=0.5)	**30.9**	**-**
				Total Production Time	**85.5**	**23.3**

Projections: R_A





Projected uncertainties for $R=\sigma_L/\sigma_T$ assuming point-to-point systematic uncertainties of 1.6%
→ 1.9% achieved in 6 GeV era, but expect improvement due to superior performance of SHMS
→ Scale/normalization uncertainties (overall target thickness, etc.) cancel in L/T ratio

Projections apply for both C and Cu targets

Extraction of R_A-R_H

Ultimate goal is to extract nuclear dependence of R in SIDIS

→ Rather than comparing R_A to R_H directly, precision can be improved by looking at ε dependence of target ratio

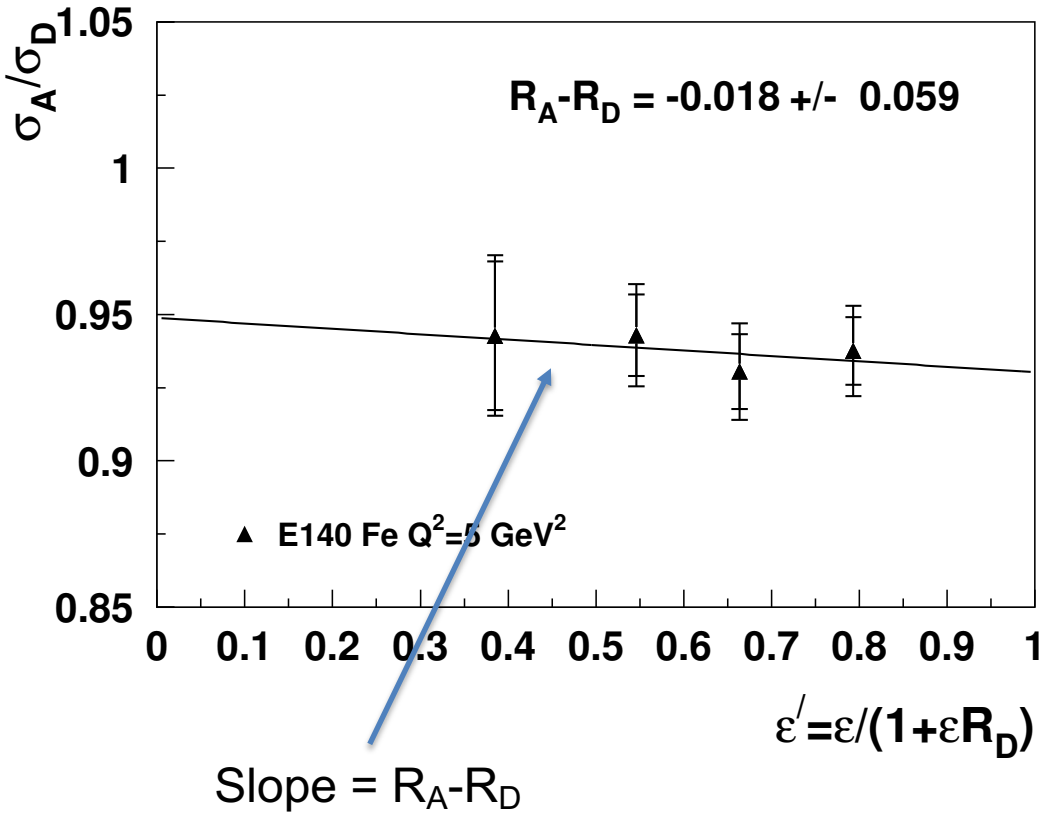
→ Point-to-point systematic uncertainty should be on the order of 1% for target ratio

$$\frac{\sigma_A}{\sigma_H} = \frac{\sigma_A^T}{\sigma_H^T}[1 + \epsilon'(R_A - R_H)]$$

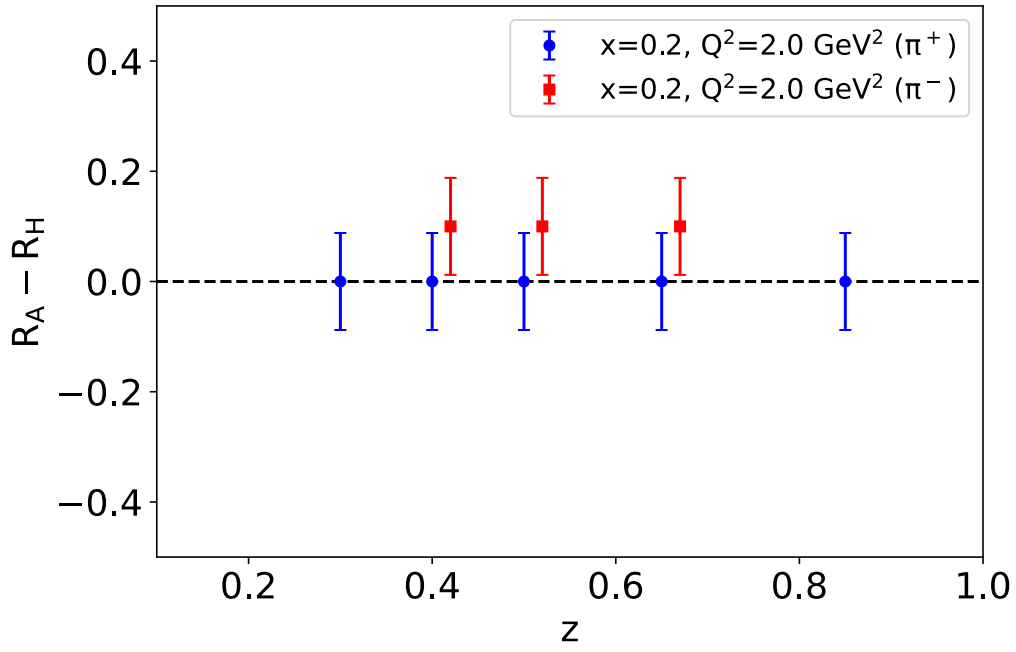
$$\epsilon' = \epsilon/(1 + \epsilon R_H)$$

Requires measurement/knowledge of R_H, but since absolute value is small, not a large contribution to overall uncertainty

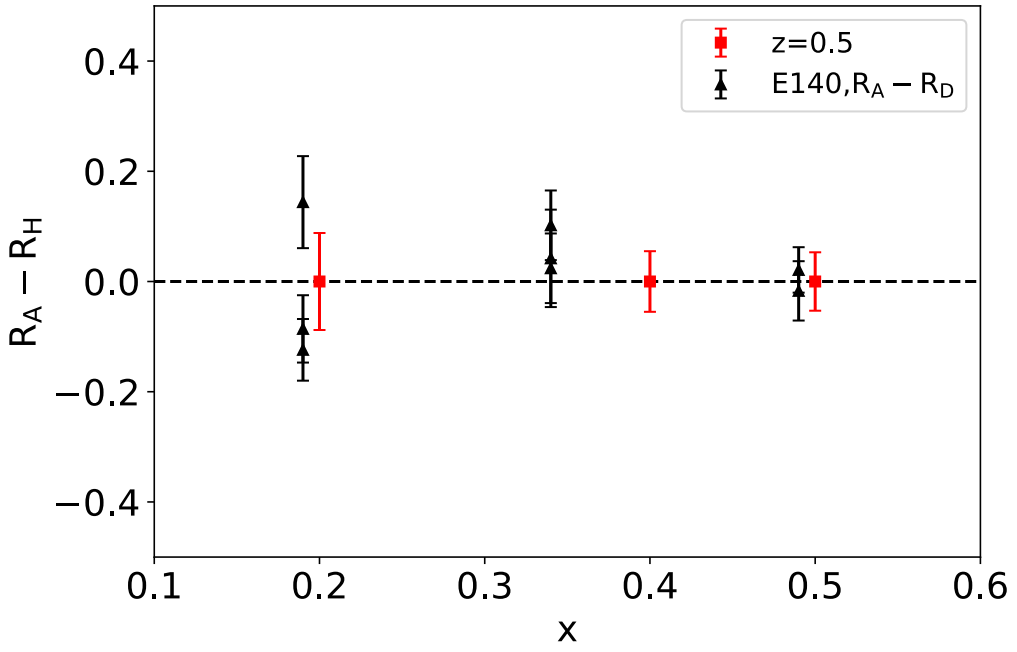
Example: R_A-R_D from SLAC E140 (inclusive DIS)



Projections: R_A-R_H



Projected uncertainties apply for both C and Cu



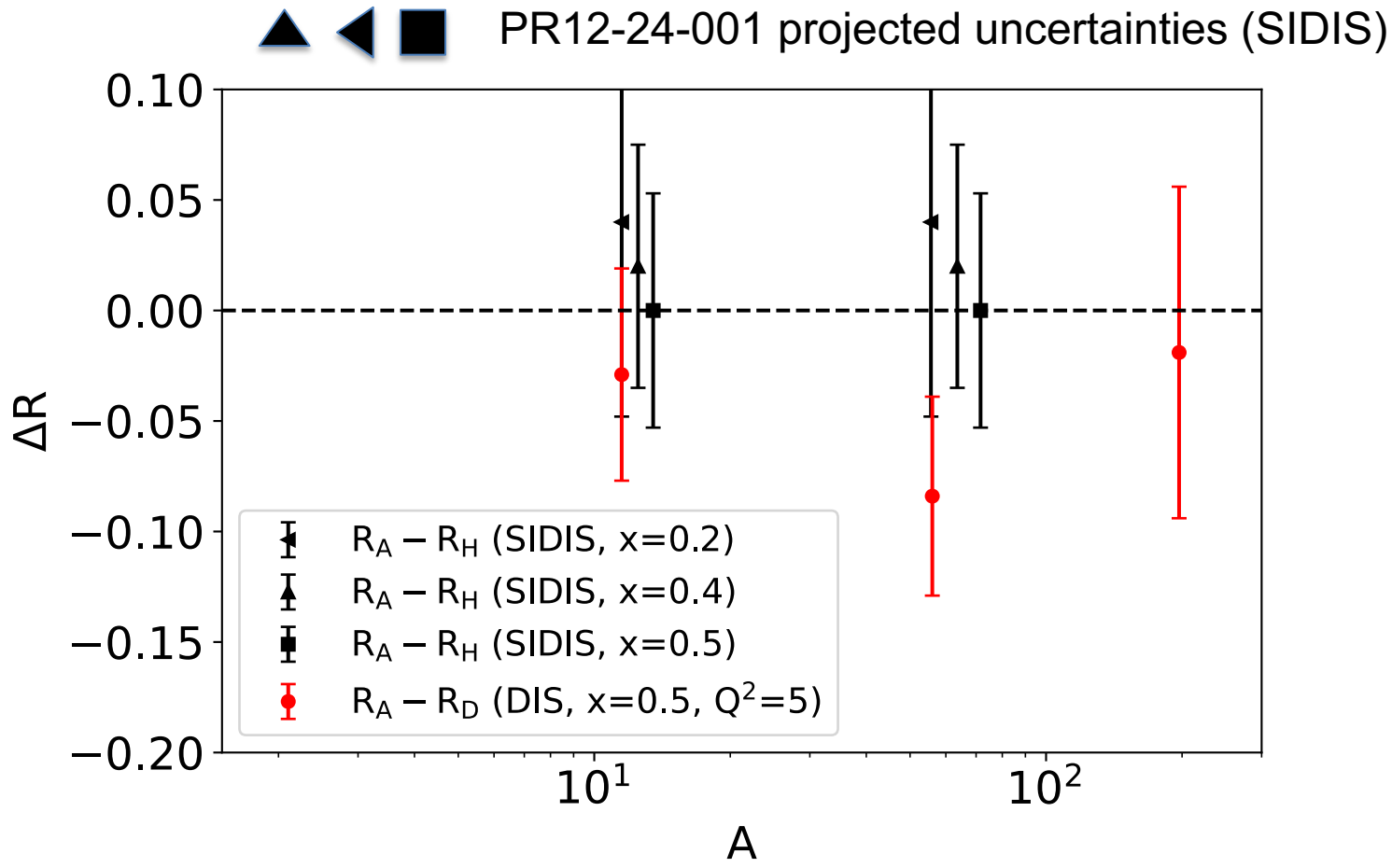
For reference: E140 measurements of R_A-R_D for Fe

→ Multiple Q^2 at each x

Beam time for these measurements = 5 days

A-Dependence of R_A-R_H

- → Can use C and Cu results to examine A dependence
- → Expected uncertainties comparable to multi-experiment extraction from C, Fe, Au targets
- → Common ~1% normalization uncertainty for all SIDIS points from LH2 target thickness



Extraction of R_A-R_D from multiple DIS experiments (JLab, SLAC E140 + E139)

Coulomb Corrections

Coulomb corrections will play a role in this experiment and must be included in the analysis

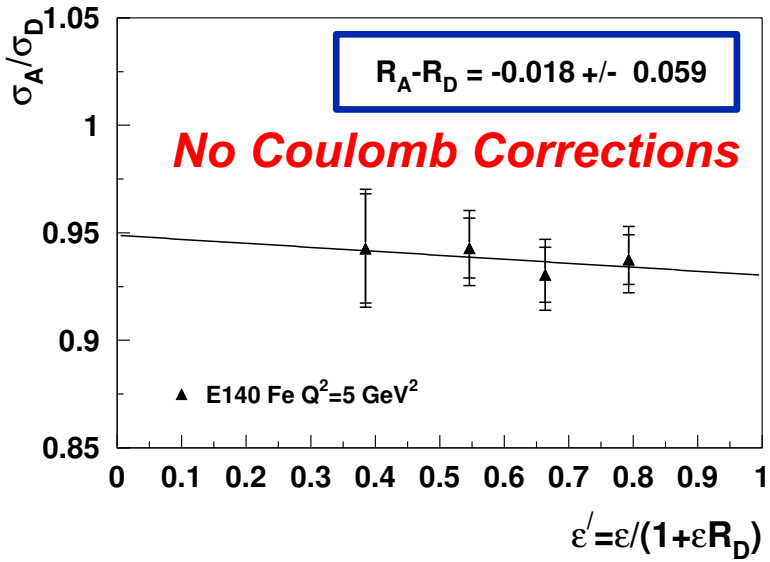
→ Electrons: will use same technique (improved EMA) as described in E12-14-002. Note that there are plans to test the improved EMA further using positrons (E12+23-003)

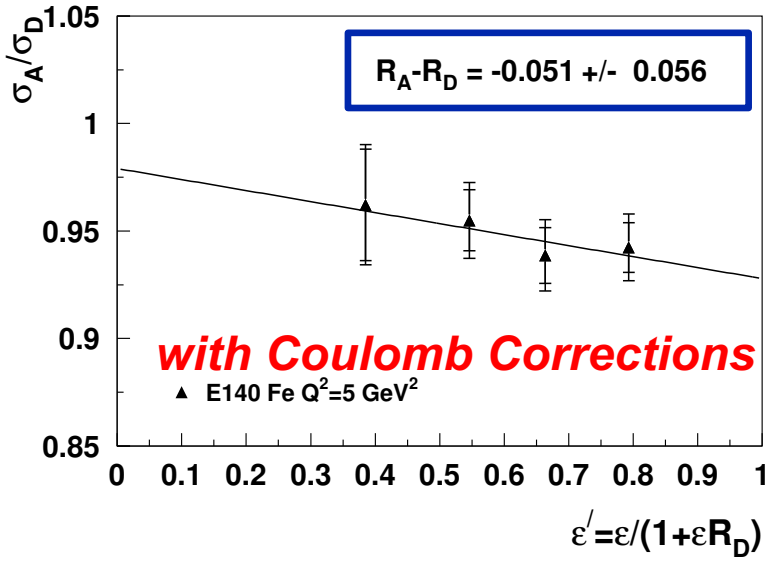
→ Effect is ***ε dependent*** since electron momentum is lower at low ε

Will also need to address acceleration/deceleration of pions due to Coulomb field. This is included in Hall C simulation package (SIMC)

→ This effect should be mostly ***ε independent*** since the pion momentum is the same

SLAC E140 (inclusive DIS)



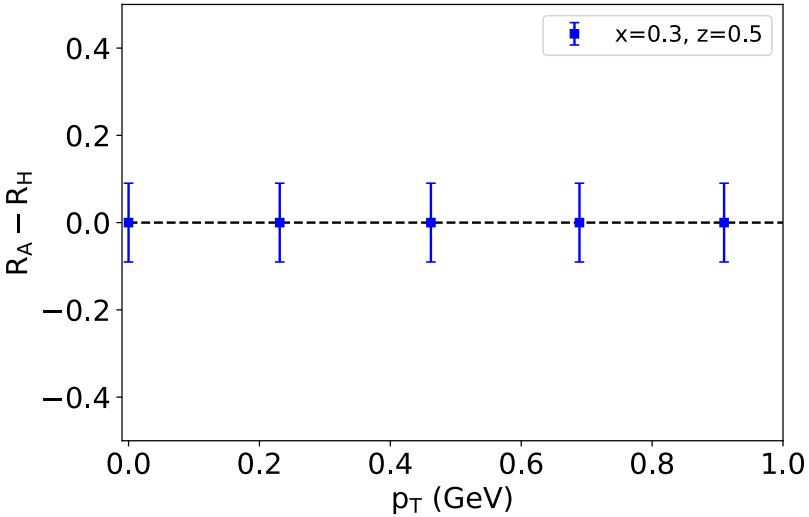


Alternate or Additional Measurements

Proposal readers inquired about possible measurements of the p_T dependence of R_A-R_H

→ E12-06-104 proposal includes a p_T scan at x=0.3, Q^2=3 GeV^2 up to p_T ~ 0.9 GeV (with limited ϕ-dependence)

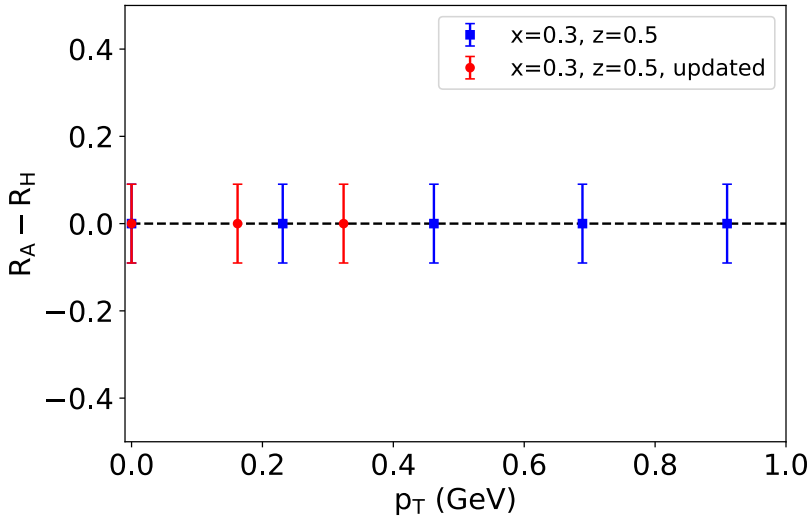
→ Adding these kinematics for the C and Cu targets is possible and would require an additional 2.5 days



Alternate or Additional Measurements

Proposal readers inquired about possible measurements of the p_T dependence of R_A-R_H

→ E12-06-104 proposal includes a p_T scan at x=0.3, Q^2=3 GeV^2 up to p_T ~ 0.9 GeV (with limited ϕ-dependence)
→ Adding these kinematics for the C and Cu targets is possible and would require an additional 2.5 days



BUT:

- E12-06-104 is scheduled to run in 2025, just after the LAD experiment E12-11-107 ("In Medium Nucleon Structure Functions, SRC, and the EMC effect")
- IFF PR12-24-001 is assumed to opportunistically run intermixed with E12-06-104
  - → The scheduled E12-06-104 kinematics are restricted to those compatible with LAD
  - → LAD requires a special scattering chamber configuration
  - → This implies the maximum accessible SHMS angle is ~ 20 degrees
  - → This limits the p_T acceptance for the R in SIDIS scan at x=0.3 to ~0.3 GeV
  - → This then translates into requiring an additional 1 day for the nuclear targets
  - → *Pending PAC feedback*, one could potentially swap this extra day with the x = 0.4 measurement.

Summary and Beam Time Request

In addition to production data-taking additional time requested for target changes/motion

→ 10 minutes per target change, 2 target changes for 30 settings (10 hours)

→ No time requested for kinematic changes – this is already included in E12-06-104 beam time

Activity	Time (hours)
π+ production data	85.5
π- production data	23.3
Target changes	10
Total	**118.5 (5 days)**

5 days of running in conjunction with E12-06-104 will allow an ***exploratory*** measurement of the nuclear dependence of $R=\sigma_L/\sigma_T$ in SIDIS

→ Important for interpretation of SIDIS and hadron attenuation measurements

→ Constrain possible initial state effects in nuclear SIDIS – complementary to planned measurements of R_A-R_D in inclusive scattering and existing measurements in exclusive reactions

→ Non-zero R_A-R_H can point to novel nuclear effects – motivating follow-up measurements

→ Would appreciate feedback from PAC on priority of p_T dependence vs. x = 0.4 measurements

EXTRA

Theory Advisory Report

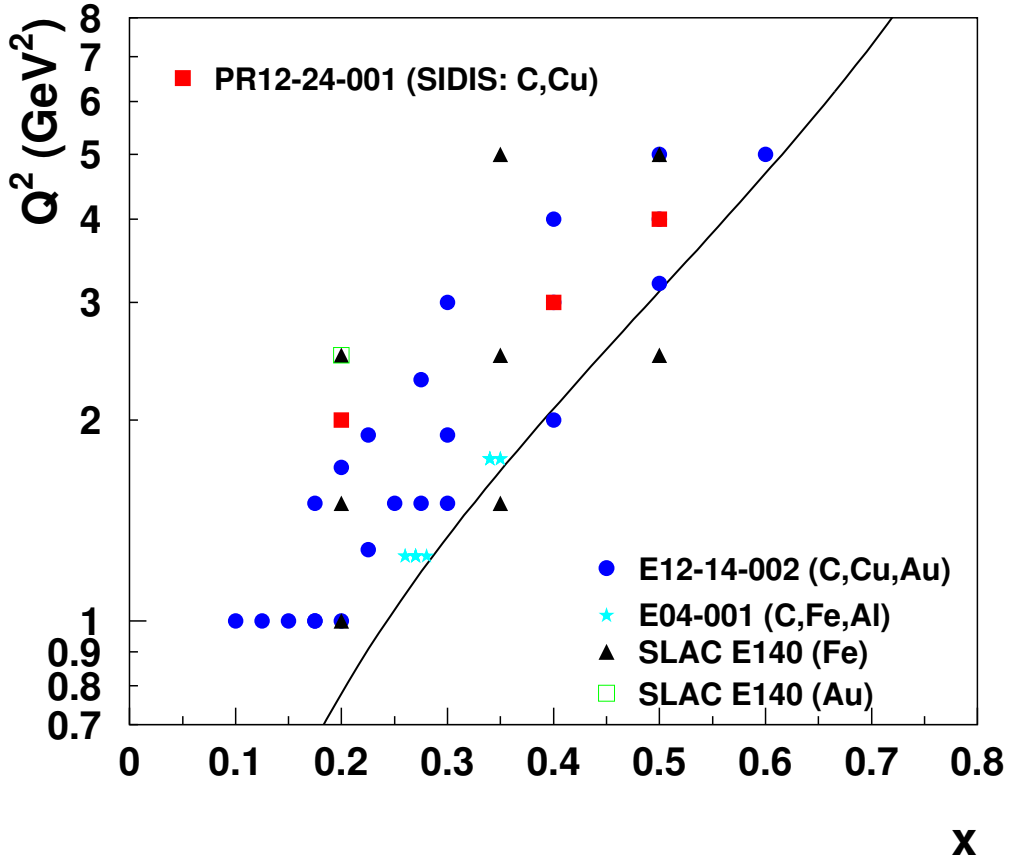
The proposal aims to explore the nuclear dependence of the ratio R = σL/σT in Semi- Inclusive Deep Inelastic Scattering (SIDIS). The plan is to conduct measurements using carbon and copper targets to determine if there is a significant nuclear dependence for R, which is crucial for interpreting SIDIS measurements and studying quark hadronization. The proposal points out that in most SIDIS measurements of the past R has been assumed to be the same as for inclusive DIS.

The proposal highlights a critical gap in experimental data concerning the relative contribution of longitudinal photons in SIDIS, one which impacts the accurate interpretation of SIDIS measurements. The proposal notes that while data for protons and deuterons will be gathered through experiment E12-06-104, there is a lack of data for heavier nuclei like carbon and copper. The new work aims to fill this gap by making limited exploratory measurements to detect any nuclear dependence for R in SIDIS. Quantifying a nuclear dependence of R in SIDIS could lead to new insights into the initial state effects or the presence of ε-dependent backgrounds with nuclear characteristics.

Direct Measurements of Nuclear Dependence of R

"Given the dearth of R measurements and the importance of studying its nuclear dependence, is there a way to also compare to the measurements from E12-14-002 and E04-001 in addition to the comparisons you show with the SLAC E140 data?"

Inclusive measurements:
SLAC E140: published 1994
JLab E04-001: preliminary results, mostly resonance region
JLab E12-14-002: Hall C, will possibly run in next few years



M. Diefenthaler, R. Ent (spokesperson), D. Gaskell (spokesperson), O. Hansen, M. McCaughan, A. Tadepalli
Thomas Jefferson National Accelerator Facility, Newport News, VA

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

W. Brooks (spokesperson)
Universidad Técnica Federico Santa María, Valparaíso, Chile

E. Kinney (spokesperson)
University of Colorado, Boulder, CO

H. Mkrtchyan (spokesperson), Vardan Tadevosyan
Yerevan Physics Institute, Yerevan, Armenia

T. Horn, C. Morean
Catholic University of America, Washington, D.C.

W. Li
Center for Frontiers in Nuclear Science and Stony Brook University, Stony Brook, NY

G. Niculescu
James Madison University, Harrisonburg, VA

P. Markowitz
Florida International University, Miama, FL

J. Arrington, T. J. Hague, S. Li
Lawrence Berkeley National Lab, Berkeley, CA

B. Devkota, D. Dutta, A. Nadeeshani, B. Tamang, E. Wrightson
Mississippi State University, Starkville, MS

P. King, A. Sen
Ohio University, Athens, OH

H. Atac
Temple University, Philadelphia, PA

G. Huber
University of Regina, Regina, SK, Canada

B. Duran, N .Fomin
University of Tennessee, Knoxville, TN

X. Zheng
University of Virgnia, Charlottesville, VA

N. Kalantarians
Virginia Union University, Richmond, VA

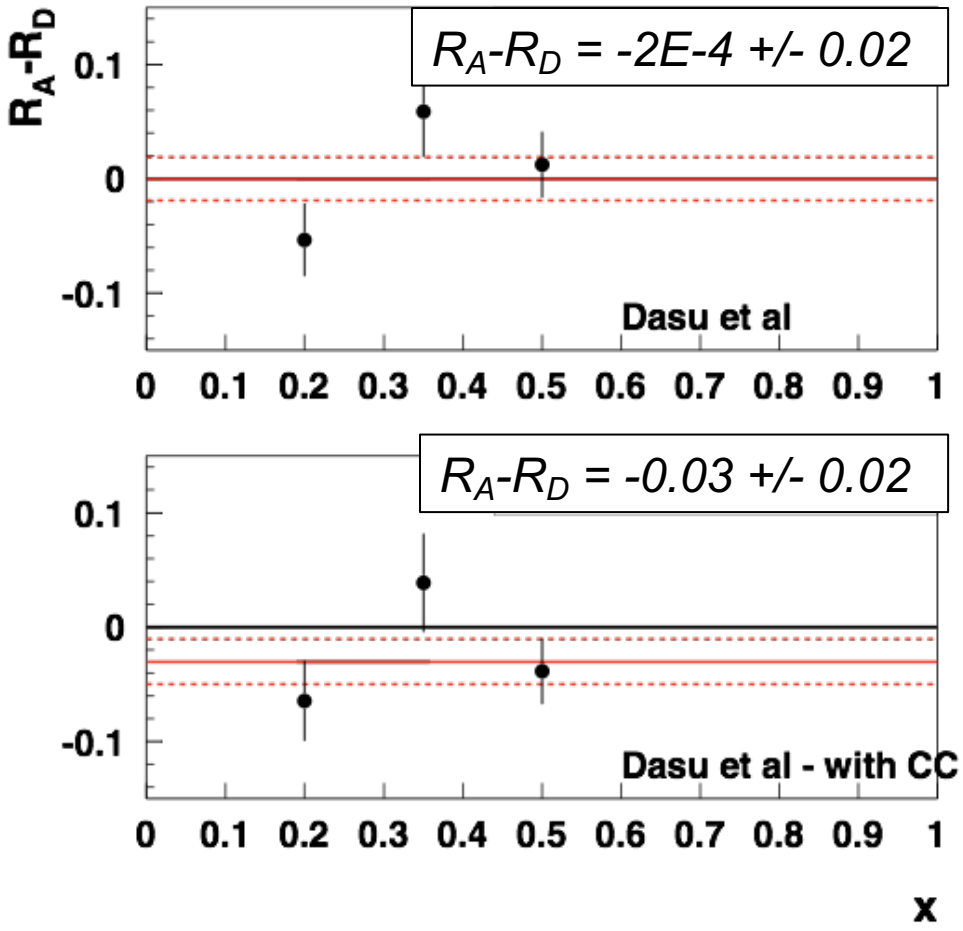
D. Adhikari

R_A-R_D: E140 Re-analysis

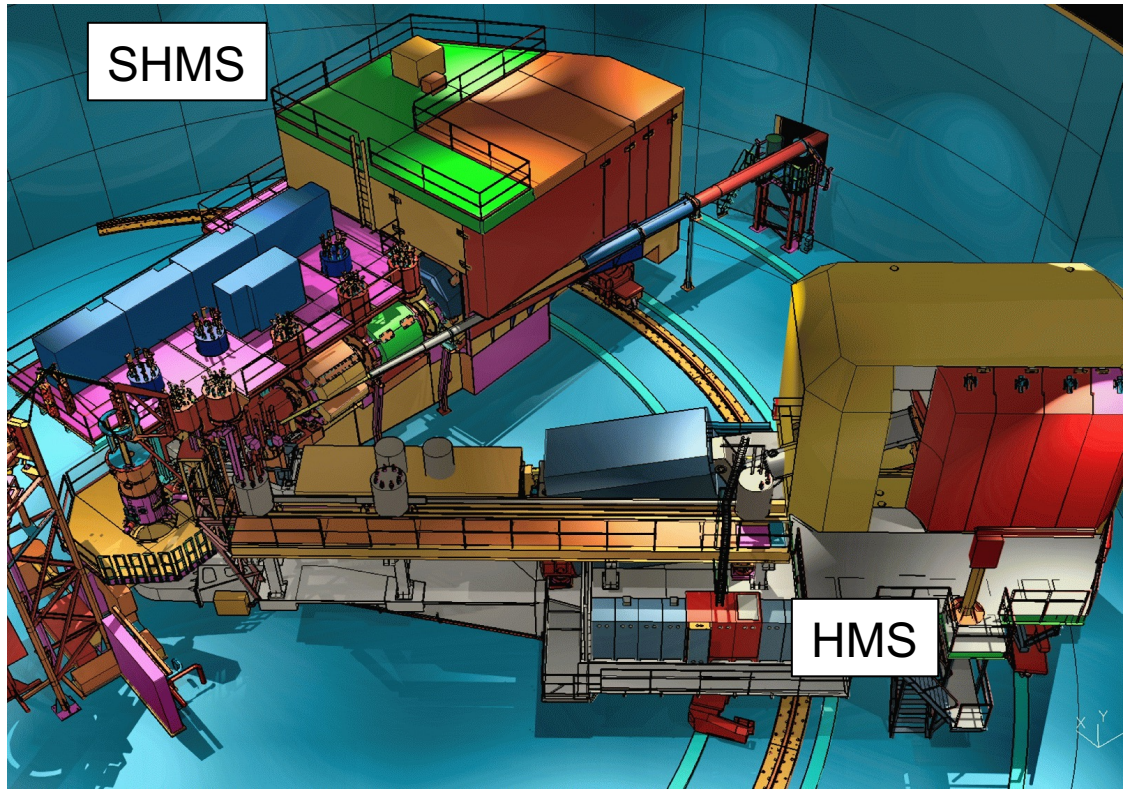
Re-analyzed E140 data using Effective Momentum Approximation for published “Born”-level cross sections

→ Total consistency requires application to radiative corrections model as well

Including Coulomb Corrections yields result 1.5 σ from zero when averaged over ***x***



Hall C: HMS and SHMS



Spectrometers

HMS:
dΩ ~ *6* msr, P_0= *0.5 – 7 GeV/c*
θ_0=*10.5 to 80 degrees*
e ID via calorimeter and gas Cerenkov

SHMS:
dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*
θ_0=*5.5 to 40 degrees*
e ID via heavy gas Cerenkov and calorimeter

Excellent control of point-to-point systematic uncertainties