L/T Separations in Hall C Status and **Opportunities**

Wenliang (Bill) Li

Hall C Collaboration Meeting
18/Feb/2022

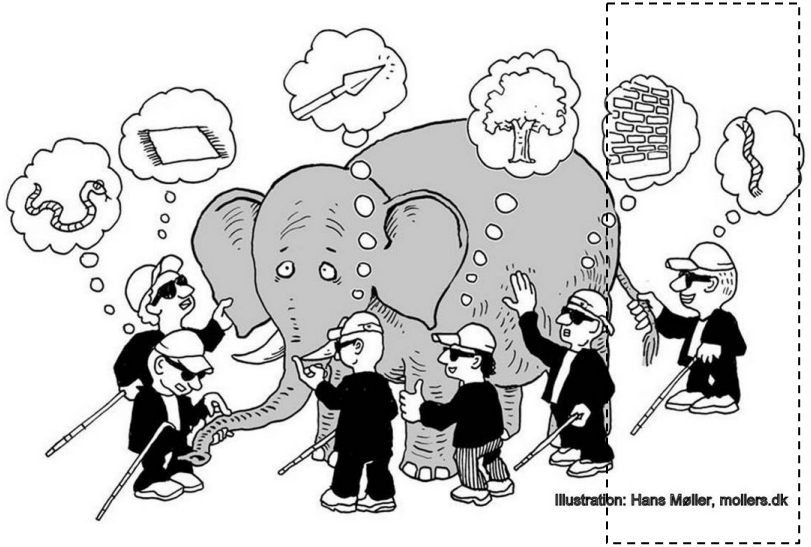
Outline

- L/T Separation Methodology Overview
  - Unveiling the secrets of R/T separation experts

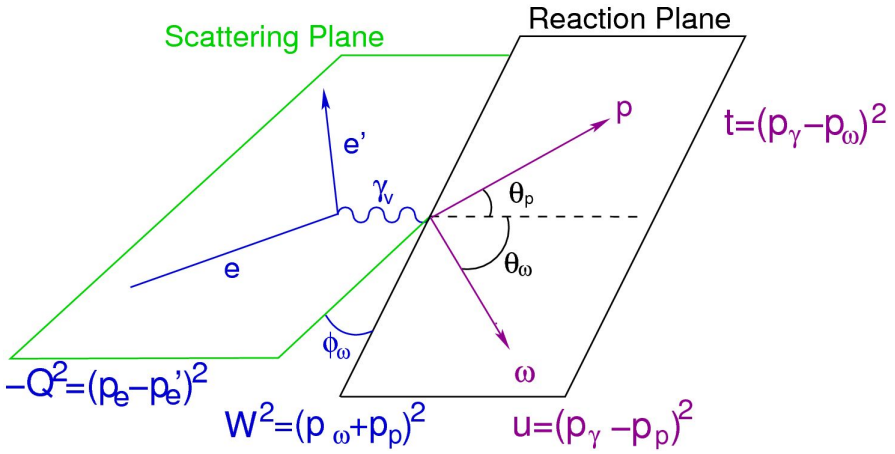
- Hall C L/T Program Status
  - Pion Form Factor
  - Neutral Pion Spectrometer
  - u-Channel π^0

- Opportunities ? !

This is not a *u*-Channel talk !



The Rosenbluth Separation



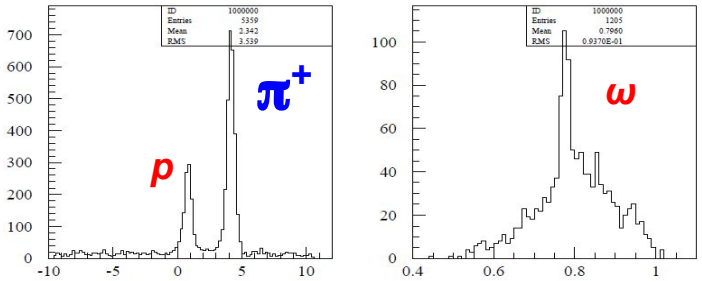
Virtual-photon polarization:

$$\varepsilon=\left(1+2\frac{(E_e-E_{e'})^2+Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

$$2\pi\frac{d\sigma}{dtd\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

- **Rosenbluth Separation requirements:**
  - Separate measurements at different ε (virtual photon polarization)
  - All Lorentz invariant physics quantities: Q^2, W, t, u, remain constant
  - Beam energy, scattered e angle and virtual photon angle will change as the result, thus event rates are dramatically different

Two Measurement at the Same Kinematics Variable

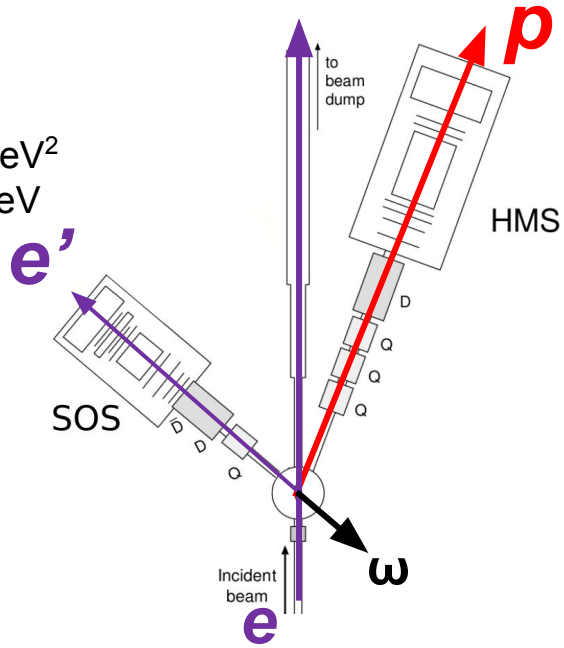


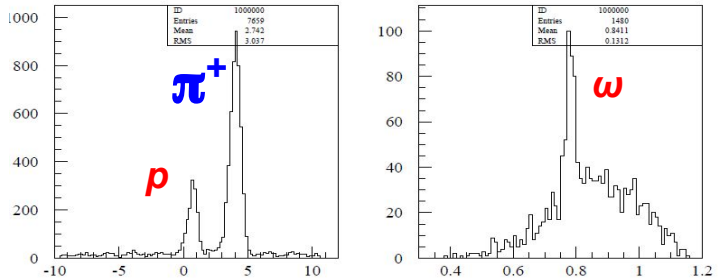
Low ϵ

ϵ = 0.27

Q^2 = 2.45 GeV^2

W = 2.21 GeV



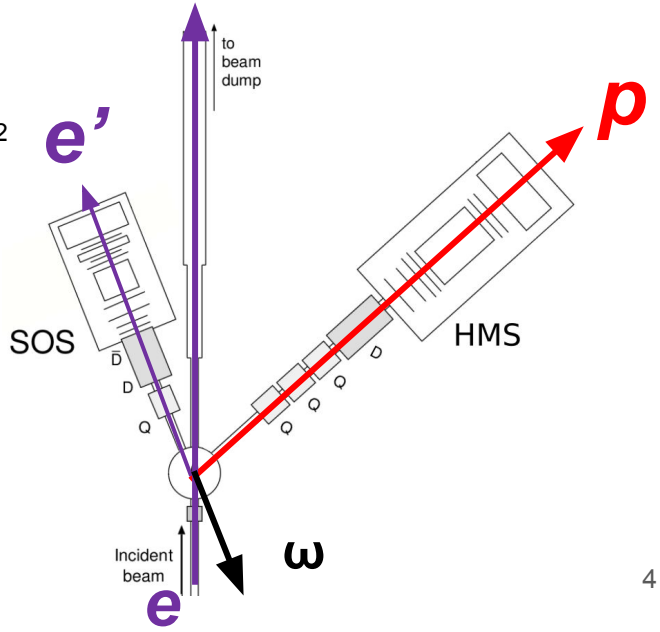


Low ϵ

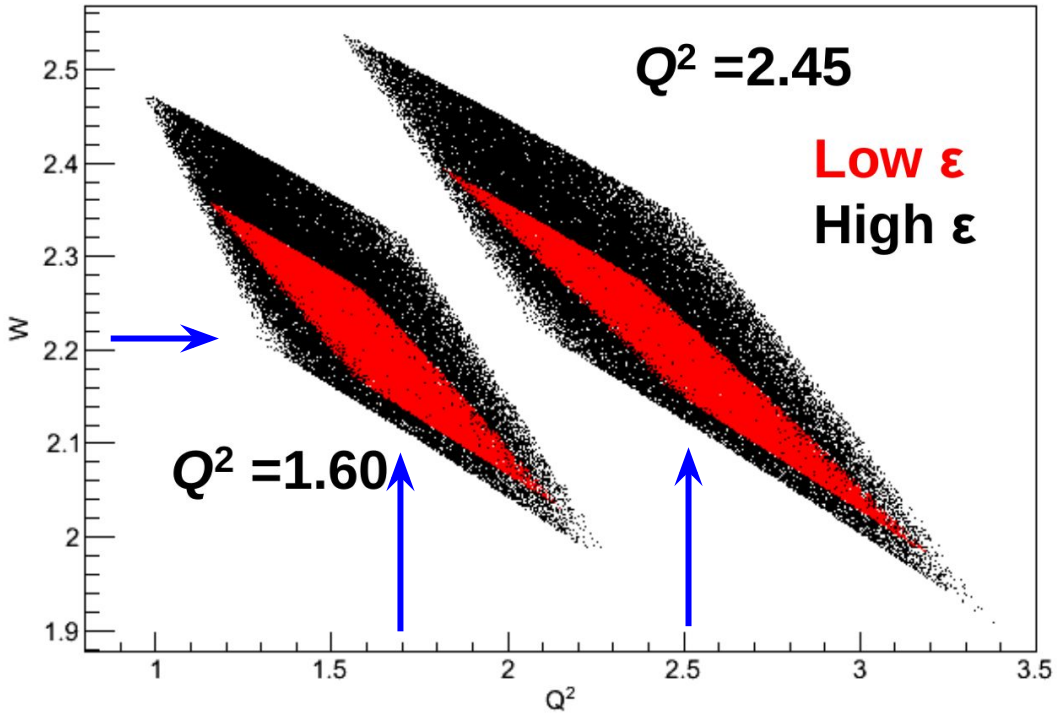
ϵ = 0.554

Q^2 = 2.45 GeV^2

W = 2.21 GeV



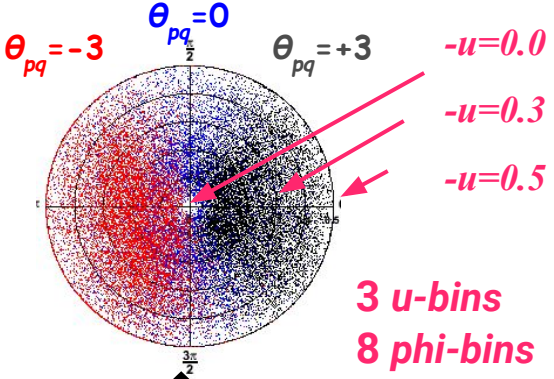
Diamond plot

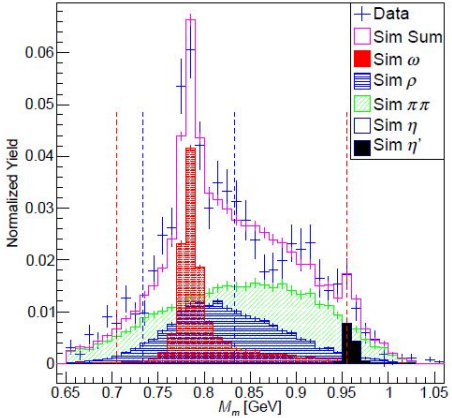


- L/T expert's secrete #1 diamond plot
- Kinematics information
- Overlap between the two diamonds

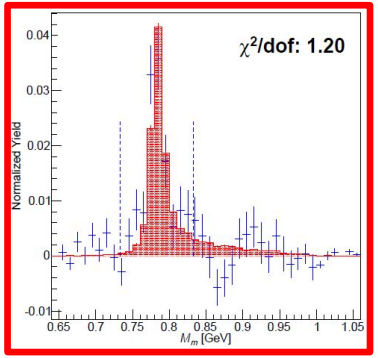
Iterative Procedure (Recipe) to a LT Separation

Improve ϕ coverage by taking data at multiple HMS angles, $-3^{o} < \theta_p < +3^{o}$.





Background subtraction

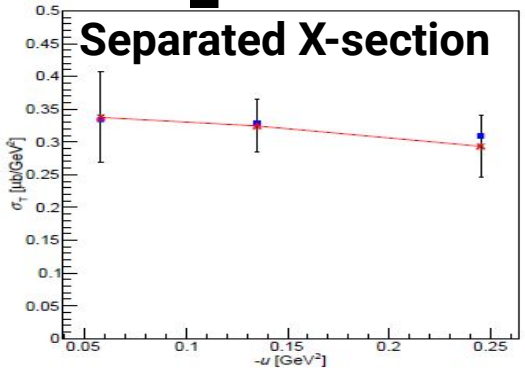


$$R = \frac{Y_{Exp} - Y_{\rho\ \mathrm{sim}} - Y_{Xspace\ \mathrm{sim}} - Y_{\eta\ \mathrm{sim}}}{Y_{\omega\ \mathrm{sim}}}$$

Combine ratios for settings together, propagating errors accordingly.

$$\frac{d^2\sigma}{dtd\varphi}_{EXP} = R \frac{d^2\sigma}{dtd\varphi}_{SIMC}$$

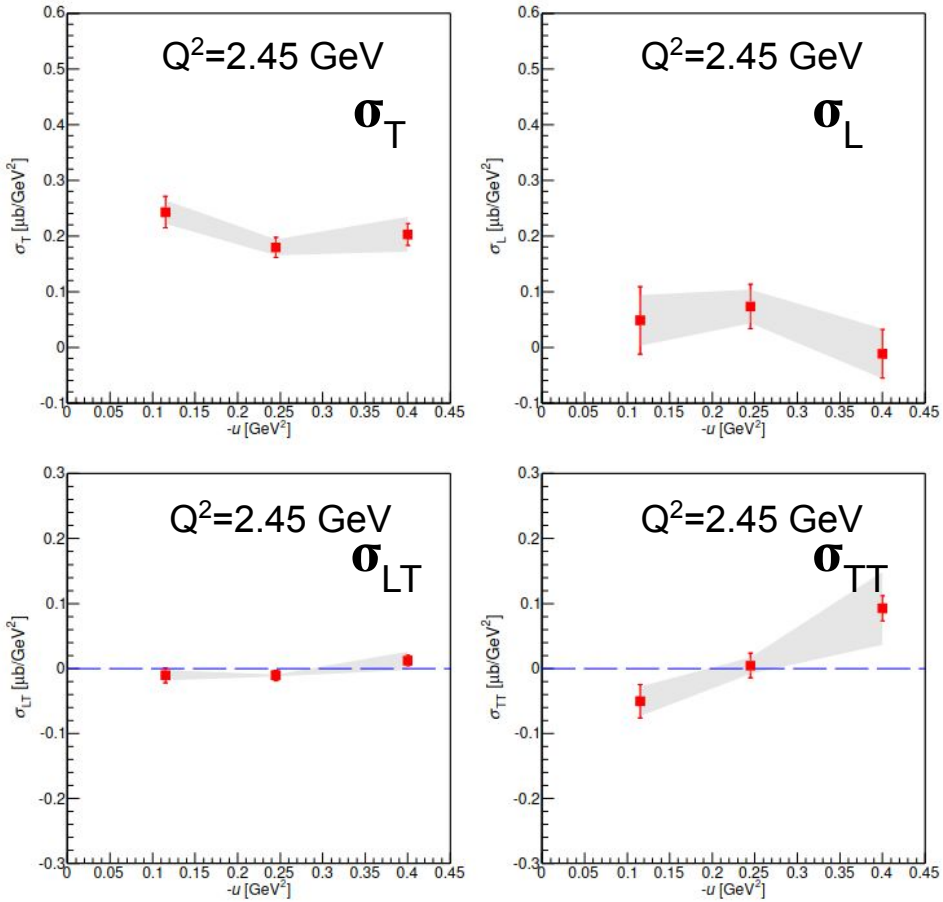
Empirical Model

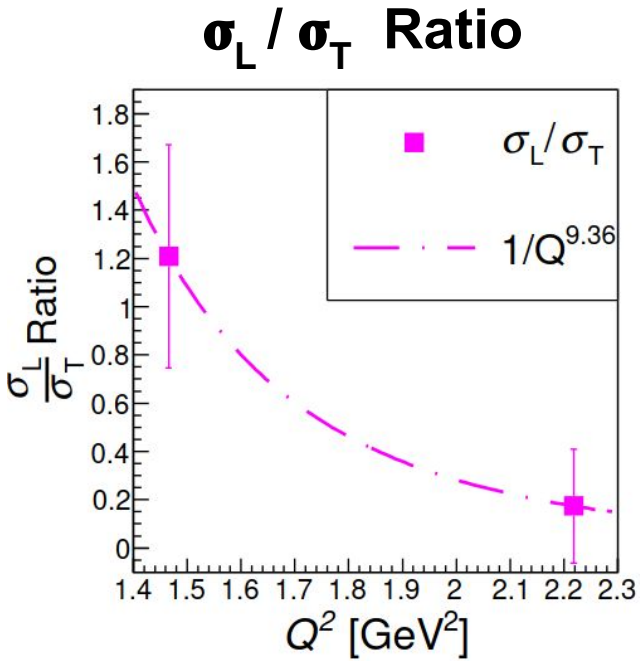


Extracting T, L, LT, TT via simultaneous fit

$$2\pi \frac{d\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \sqrt{2\varepsilon(\varepsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

LT Results from 6 GeV ω Electroproduction





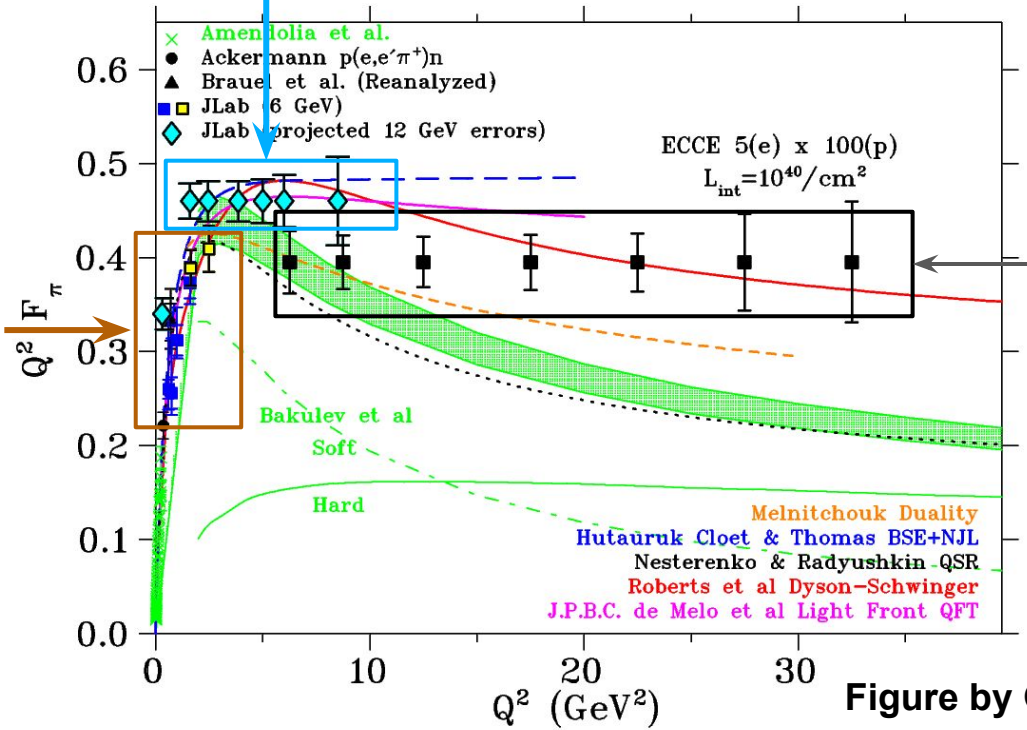
L/T Separation Study and Hall C

Fpi-12 E12-19-006 (2020)
88 days
(T. Horn*, G. Huber*, D. Gaskell)
(running at Hall C right now!)

Shift sign-up Page:
https://misportal.jlab.org/mis/apps/physics/shiftSchedule/index.cfm?experimentRunId=HALLC-PIONLT

Fpi-2 E-01-004 (2001)
14 days
(H. Blok*, G. Huber, D. Mack)

Fpi-1 E-93-021 (1993)
9 days
(D. Mack*, R. Whitney)



Fpi @ EIC (data by 2032)
10fb^{-1} a year of running
(G. Huber and others)

Figure by G. Huber and S. Kay

Hall C 12 GeV LT Separation Experiment Summary

SHMS + HMS, (ongoing), partially completed, see status in following slides.

	Experiments	PAC	Rating
E12-19-006	Study of the L–T Separated Pion Electroproduction to High Q2	88	A
E12-09-011	Studies of the L-T Separated Kaon Electroproduction Cross Section from 5-11 GeV	40	B+
E12-13-010	Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C	53	A
E12-20-007	Backward-angle Exclusive pi0 Production above the Resonance Region	29	B

NPS + HMS, received ERR, being scheduled, running in 2024-2025?

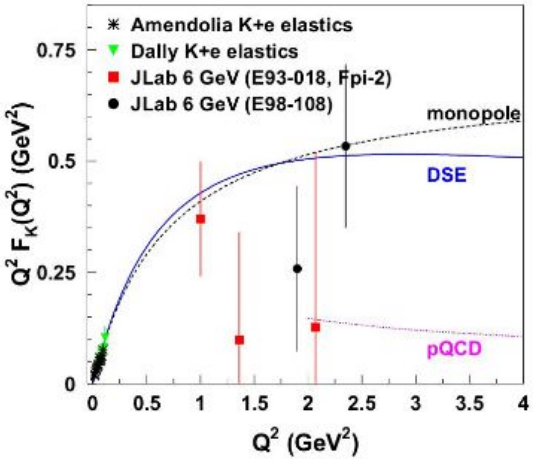
Simple experiment, ERR not required, beam time request is being submitted

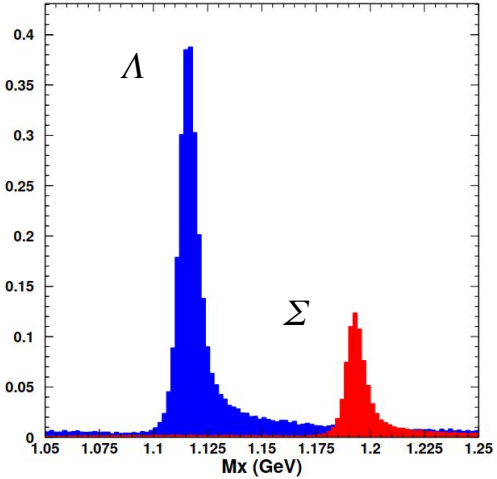
We completed ~15% of the Hall C L/T program so far.

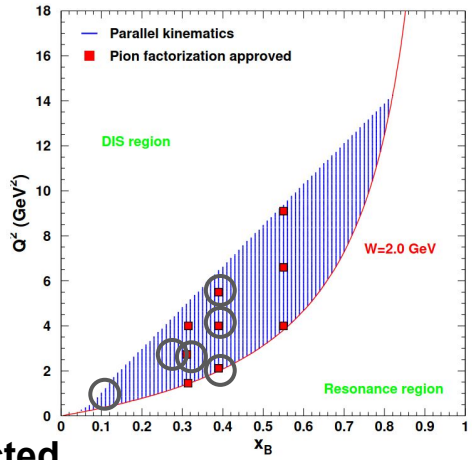
E12-09-011: L-T Separated Kaon Electroproduction

- **The p(e, e′K)Λ,Σ experiment ran in Hall C at Jefferson Lab over the fall 2018 and spring 2019. Spokesperson: T. Horn*, G. Huber**

- **30-40% completed?**







Data Collected

E (GeV)	Q^2 (GeV^2)	W (GeV)	x	$\varepsilon_{high}/\varepsilon_{low}$	$\Delta\varepsilon$
10.6/8.2	5.5	3.02	0.40	0.53/0.18	0.35
10.6/8.2	4.4	2.74	0.40	0.72/0.48	0.24
10.6/6.2	3.0	2.32	0.40	0.88/0.57	0.31
10.6/8.2	3.0	3.14	0.25	0.67/0.39	0.28
10.6/6.2	2.115	2.95	0.21	0.79/0.25	0.54
4.9/3.8	0.5	2.40	0.09	0.70/0.45	0.25

Information taken from Richard's talk:
https://indico.jlab.org/event/517/contributions/9318/attachments/7543/10495/KaonLT_HallC_WinterTalk2022.pdf

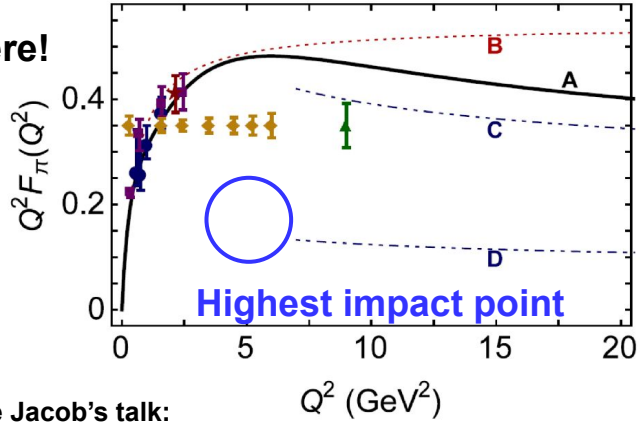
E12-19-006: Charged Pion Form Factor

Q^2	W	x	$-t_{min}$	Type	E_e	ϵ	θ_q	$\theta_{\pi q}$	Hrs
0.38	2.20	0.087	0.008	LH+	2.8	0.286	5.70	0, +2, +4°	11.1
					3.7	0.629	8.87	-2, 0, +2, +4°	14.8
					4.6	0.781	10.33	-4, -2, 0, +2, +4°	18.5
1.60	3.00	0.165	0.029	LH+	6.7	0.408	6.36	0, +2°	9.9
					8.8	0.689	8.70	-2, 0, +2°	12.8
					~~11.0~~	~~0.817~~	~~9.91~~	~~-2, 0, +2°~~	~~12.8~~
1.60	3.00	0.165	0.029	LD+	6.7	0.408	6.36	0, +2°	9.9
					11.0	0.817	9.91	-2, 0, +2°	12.8
1.60	3.00	0.165	0.029	LD-	6.7	0.408	6.36	0, +2°	18.7
					~~11.0~~	~~0.817~~	~~9.91~~	~~-2, 0, +2°~~	~~12.8~~
2.45	3.20	0.208	0.048	LH+	8.0	0.383	6.26	0, +2°	9.9
					8.8	0.505	7.30	-1.8, 0, +2°	12.8
					~~11.0~~	~~0.709~~	~~9.03~~	~~-2, 0, +2°~~	~~12.8~~
3.85	*3.07*	*0.311*	*0.120*	*LH+*	*8.0*	*0.301*	*6.53*	*-1.03, 0, +2°*	*33.5*
					8.8	*0.436*	*7.97*	*-2, 0, +2°*	*18.2*
					9.9	*0.572*	*9.31*	*-2, 0, +2°*	*13.3*
					11.0	*0.666*	*10.27*	*-2, 0, +2°*	*12.8*
3.85	3.07	0.311	0.120	LD+	8.0	0.301	6.53	-1.03, 0, +2°	33.5
					11.0	0.666	10.27	-2, 0, +2°	12.8
3.85	3.07	0.311	0.120	LD-	8.0	0.301	6.53	0, +2°	118.8
					11.0	0.666	10.27	-2, 0, +2°	12.8
5.00	*2.95*	*0.390*	*0.209*	*LH+*	*8.0*	*0.238*	*6.35*	*0, +2°*	*74.5*
					9.9	*0.530*	*9.76*	*-2, 0, +2°*	*41.1*
					11.0	*0.633*	*10.88*	*-2, 0, +2°*	*27.0*
6.00	*3.19*	*0.392*	~~*0.214*~~	~~*LH+*~~	~~*9.2*~~	~~*0.184*~~	~~*5.13*~~	~~*0.37, +2°*~~	~~*182.2*~~
					~~*9.9*~~	~~*0.304*~~	~~*6.64*~~	~~*0, +2°*~~	~~*80.6*~~
					11.0	*0.452*	*8.22*	*-2, 0, +2°*	*71.9*

Highest Q^2=8.5 GeV^2 also completed

- **T. Horn*, G. Huber*, D. Gaskell**
- **Very important and long experiment**
  - Took data in 2019, 2021 and 2022
- **Shift sign-up Page:** https://misportal.jlab.org/mis/apps/physics/shiftSchedule/index.cfm?experimentRunId=HALLC-PIONLT
- **<30% completed?**

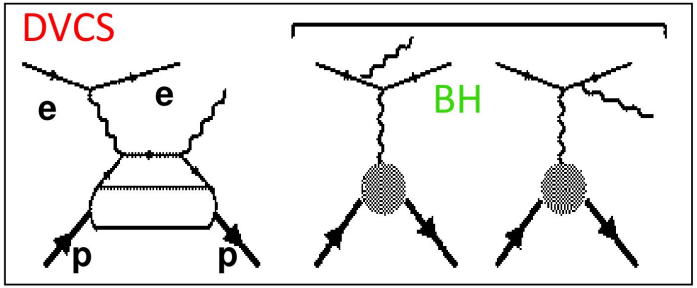
We are here!

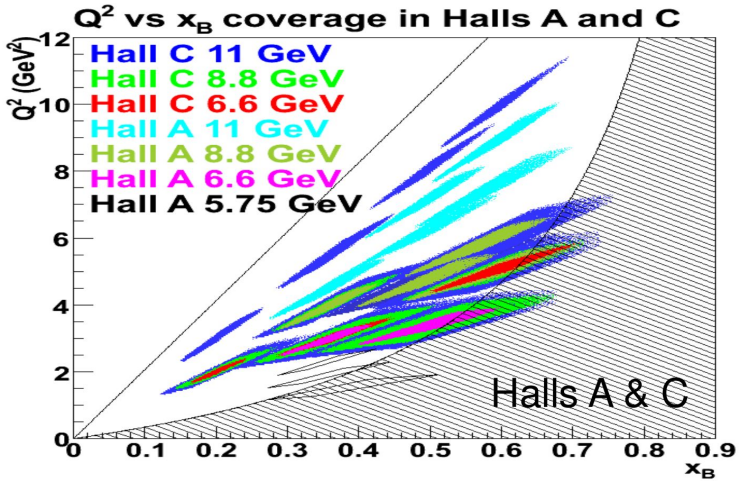


Full detail see Jacob's talk: https://indico.jlab.org/event/517/contributions/9319/attachments/7544/10497/HallC_winter_meeting_PionIT2022.pdf

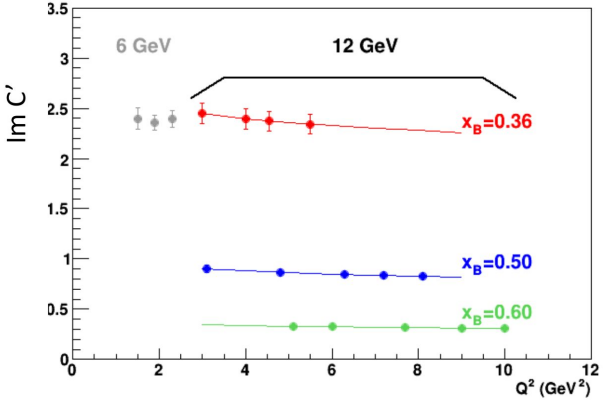
E12-13-010 DVCS and π^0 at Hall C (PAC 40)

- E12-13-010 performs measurement of DVCS at Hall C
- Spokesperson: C. Munoz Camacho*, T. Horn, C. Hyde, R. Paremuzyan, J. Roche (NPS collaboration)
- Scaling of the Compton Form Factor
- L/T Separation of the π^0





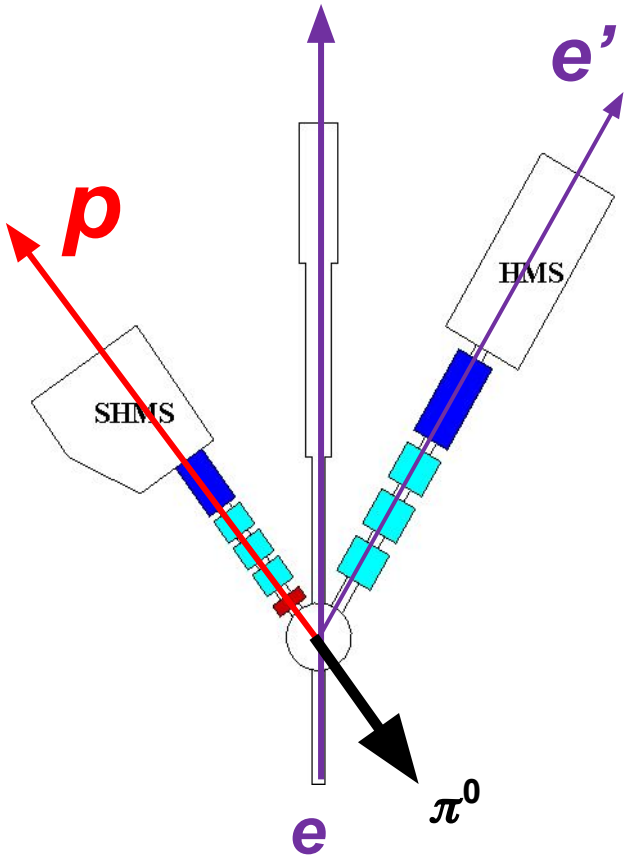
12 GeV projections: confirm formalism

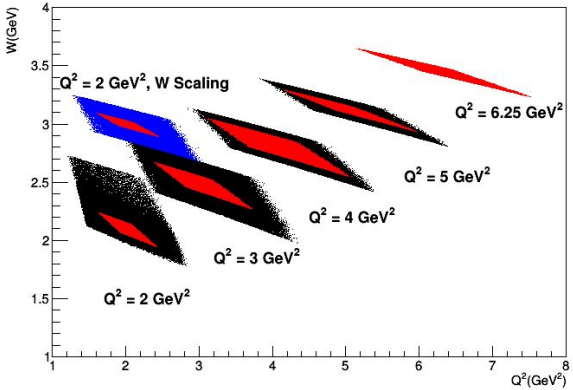


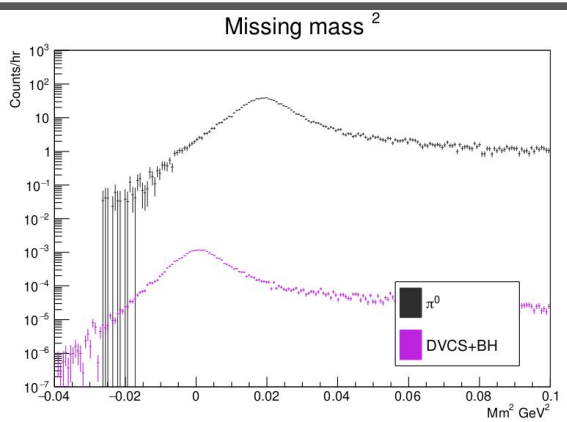
Full detail see Carlos' recent talk:
https://indico.jlab.org/event/503/contributions/9160/attachments/7497/10428/HallA2022.pdf
David's talk
https://indico.jlab.org/event/517/contributions/9328/attachments/7552/10508/NPSPhys_HallC_DJH_Feb22.pdf

Figures from T. Horn and the NPS Collaboration

E12-20-007: Backward-angle π^0 (PAC 48)







First dedicated *u*-channel electroproduction study above the resonance region: ^{1}H(e,$e'p$)π^0

- Q^2 coverage: $2.0 < Q^2 < 6.25$ GeV^2.
- x=0.36
- u coverage: $0 < -u' < 0.5$ GeV^2

Objective:

- **Study soft-hard transition**
- **Validating TDA**

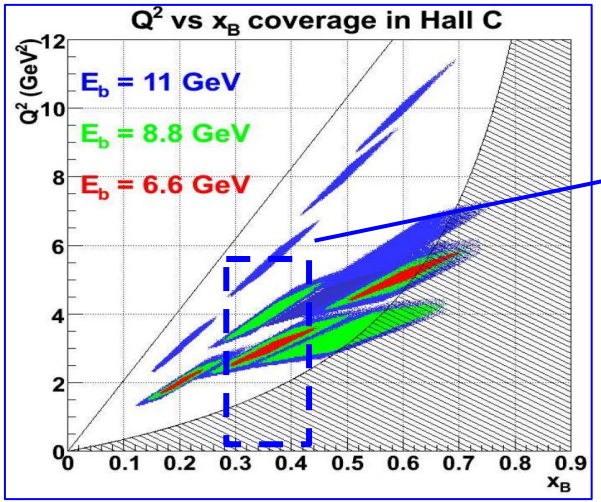
My Previous talk:
https://indico.jlab.org/event/422/contributions/7649/attachments/6435/8535/2021_Jan_JLab_Hall_C_Collaboration_Meeting.pdf

Synergy between E12-13-010 and E12-20-007

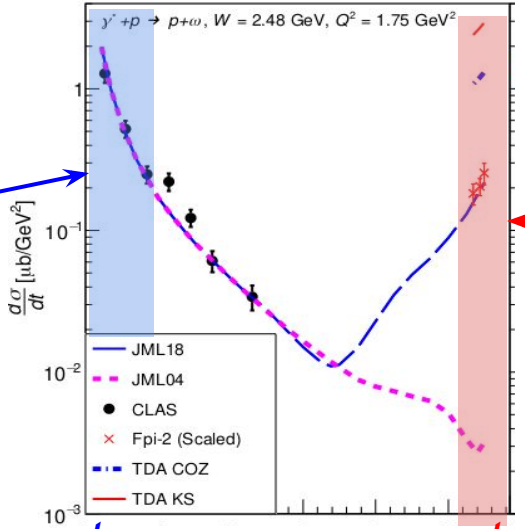
E12-13-010 NPS experiment provide low -*t* L/T separated cross section

Demonstrating the existence of the *u*-channel peaks for H(e,e'p)π^0 and provide L/T separated cross section

E12-13-010 NPS Experiment

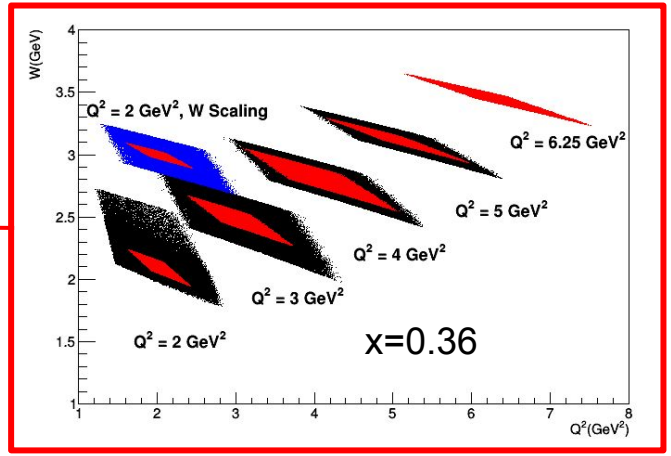


Demo plot for ω electroproduction



$-t_{Min}$ $-t_{Max}$

E12-20-007



t-Channel and *u*-Channel Opportunities

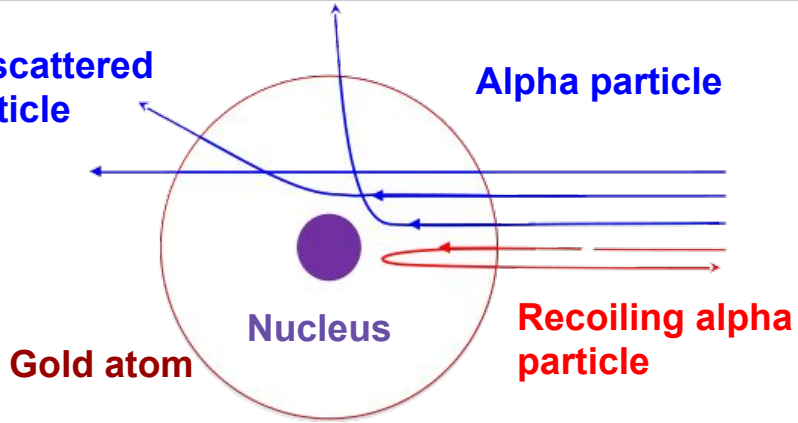
	t-Channel L/T Separation	u-Channel L/T Separation
π^0	○	○
π^+	✓	
π^-		
K^0		
K^+	✓	
K^-		
η		
ρ		
ω		✓
η'		
ϕ		
DVCS	○	

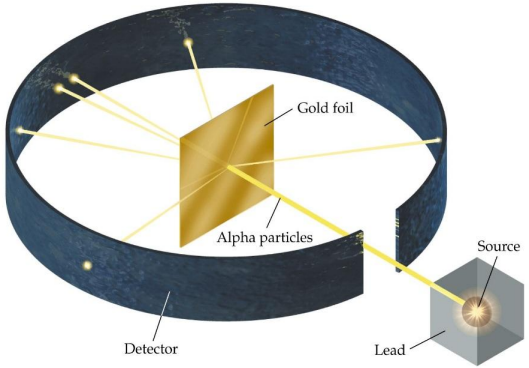
Ticks: data taken
circle: upcoming experiment

Clean channels are measured and pushed to the 12 GeV limit

Wide open for new proposal!

Backward-angle structure of Atom





- **Forward scattered alpha particle: extracting the interaction radius of the nucleus and mapping out the transverse structure of the atom (mostly empty)**
- **Recoiling alpha particle: stiffness of the "point-like" structure.**
- Full structure must incorporate both forward angle and backward angle observables.

Backward Nuclear Femtography?

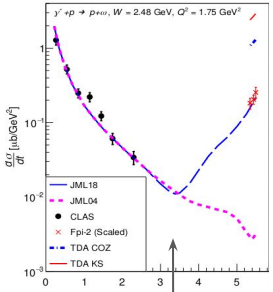
Article Talk Read Edit View history

Rutherford backscattering spectrometry

From Wikipedia, the free encyclopedia

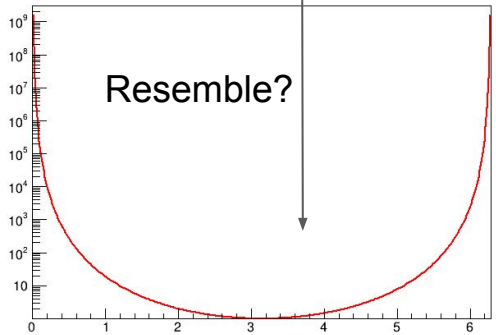
Rutherford backscattering spectrometry (RBS) is an analytical technique used in materials science. Sometimes referred to as high-energy ion scattering (HEIS) spectrometry, RBS is used to determine the structure and composition of materials by measuring the backscattering of a beam of high energy ions (typically protons or alpha particles) impinging on a sample.

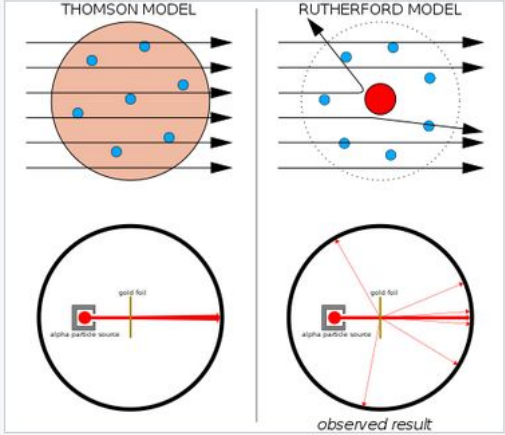
Contents [hide]



1/(sin(x/2)**4)

$$\frac{d\omega}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4E_0}\right)^2 \frac{1}{(\sin\theta/2)^4}$$ [2]

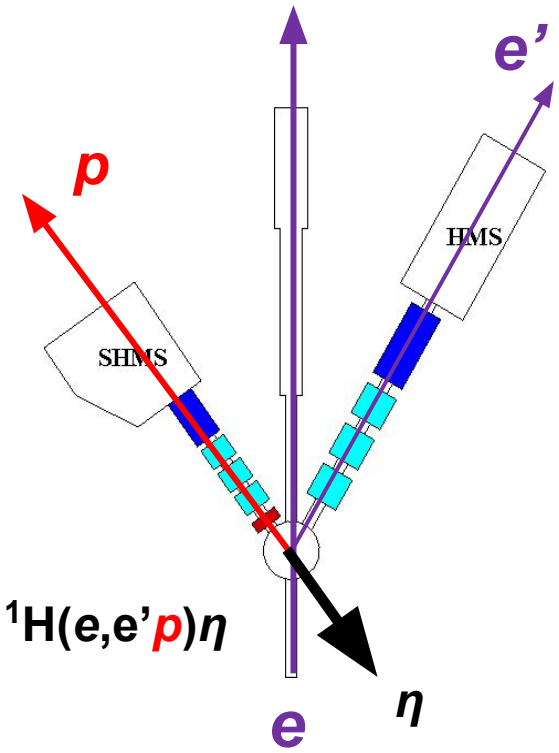




Left: Expected results: alpha particles passing through the plum pudding model of the atom undisturbed.
Right: Observed results: a small portion of the particles were deflected, indicating a small, concentrated positive charge.

Figure from Wikipedia

u-Channel *η* Electroproduction L/T Study

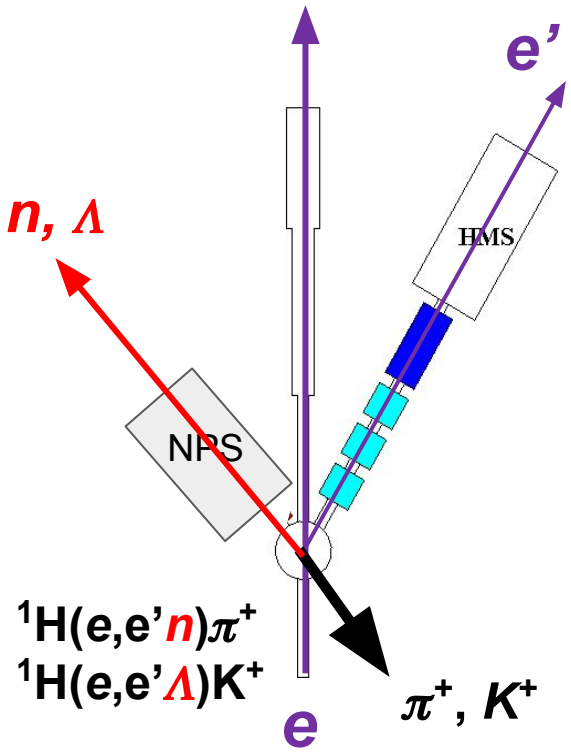


	Backward-angle Peak Seen?	L/T Separation
π^0	○	
π^+	✓✓	
π^-		
K^0		
K^+		
K^-		
η	✓	
ρ		
ω	✓✓	✓✓
η'	✓	
ϕ	✓	
DVCS	□	

Very low hanging fruit. Data mining is enough for the L/T separation study

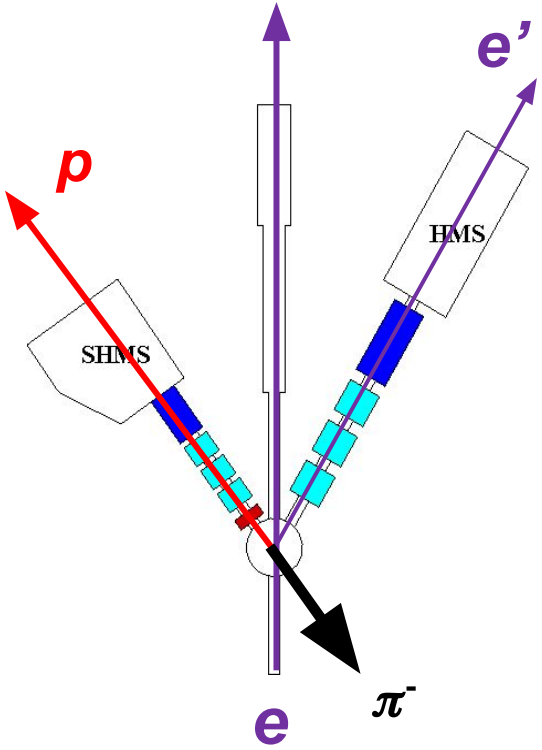
Data mining is enough to extract cross section, not enough for L/T seperation

u-Channel π^+, K^+ Electroproduction L/T Study



	Backward-angle Peak Seen?	L/T Separation
π^0	○	
π^+	✓✓	
π^-		
K^0		
K^+		
K^-		
η	✓	
ρ		
ω	✓✓	✓✓
η'	✓	
ϕ	✓	
DVCS	□	

u-Channel π^- Electroproduction L/T Study



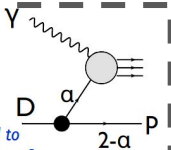
	Backward-angle Peak Seen?	L/T Separation
π^0	○	
π^+	✓✓	
π^-		
K^0		
K^+		
K^-		
η	✓	
ρ		
ω	✓✓	✓✓
η'	✓	
ϕ	✓	
DVCS	□	

Ideally: n(e,e'*p*)π^-

Realistically: D(e,e'*p*)X

Looked similar to Mark's e+D Tagg Study?

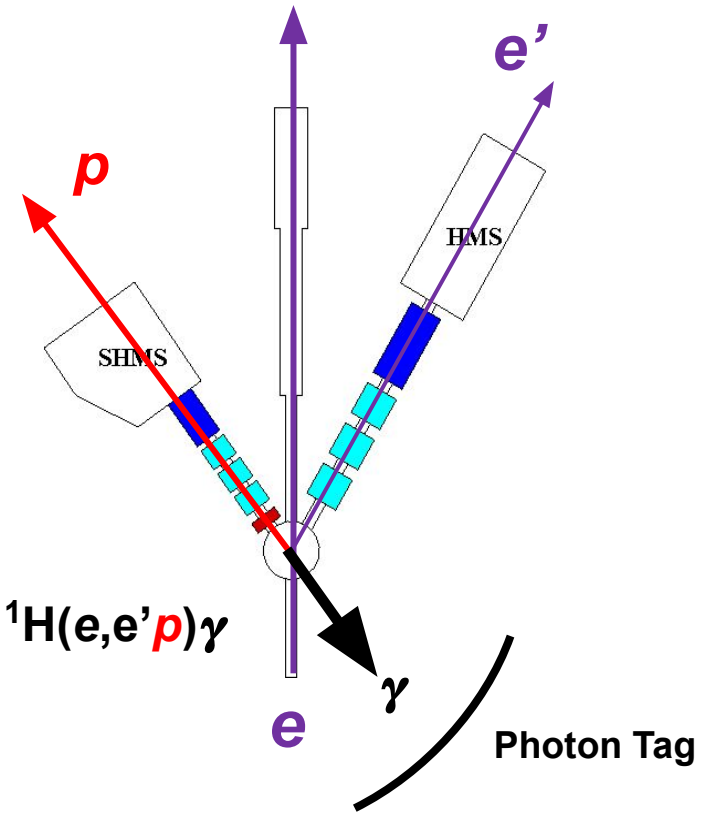
Tagging of proton and neutron in e+D→e+ backward N +X as a probe of the origin of the EMC effect (FS 85)



interesting to measure tagged structure functions where modification is expected to increase quadratically with tagged nucleon momentum. It is applicable for searches of the form factor modification in (e,e'N).

https://indico.jlab.org/event/517/contributions/9323/attachments/7539/10491/hallc22.pdf

u-Channel DVCS L/T Study



	Backward-angle Peak Seen?	L/T Separation
π^0	○	
π^+	✓✓	
π^-		
K^0		
K^+		
K^-		
η	✓	
ρ		
ω	✓✓	✓✓
η'	✓	
ϕ	✓	
DVCS	□	

In 10 Years (my wishful thinking)

	Backward-angle Peak Seen?	L/T Separation
π^0	○	
π^+	✓✓	
π^-		
K^0		
K^+		
K^-		
η	✓	
ρ		
ω	✓✓	✓✓
η'	✓	
ϕ	✓	
DVCS	□	

Dedicated L/T studies will be completed!

Data mining L/T studies will be completed!

In the process of being completed?

Q: when do we start with the *u*-Channel polarized target program? :D

Summary and Thank You!

- **Hall C LT summary**
- **Vast opportunities in *u*-Channel L/T studies.**