Probing *u*-channel Physics Observables from JLab Hall C to EIC

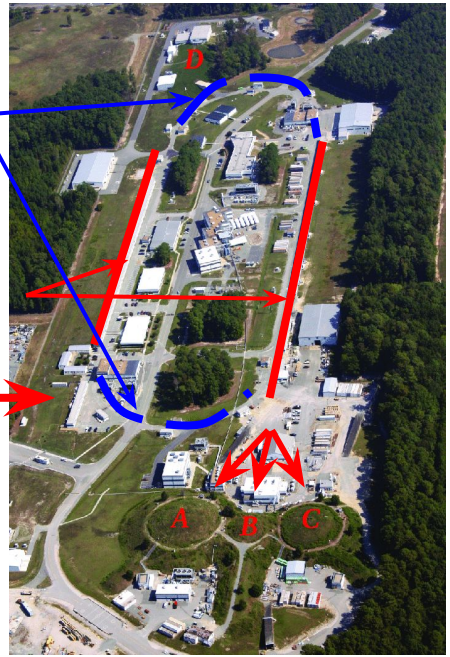
Wenliang (Bill) Li

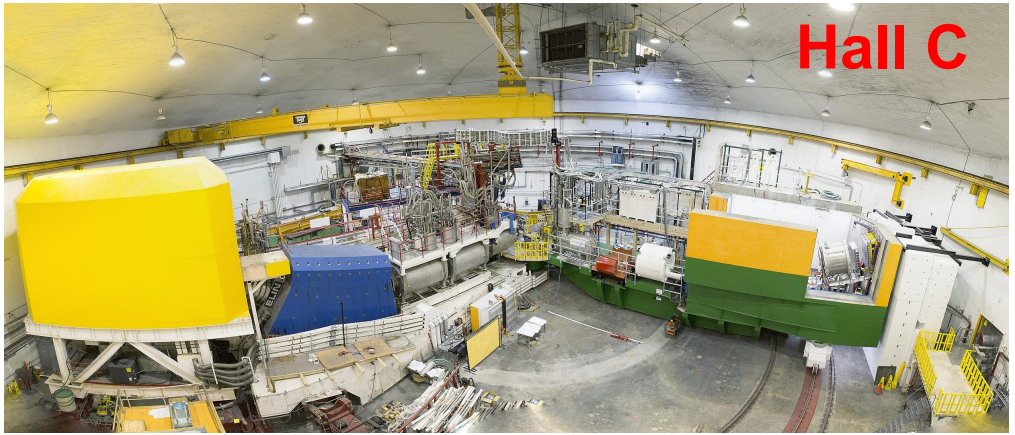
Joint postdoc at WM and JLab EIC Center

Virtual Seminar at DIS 2021, Stony Brook University

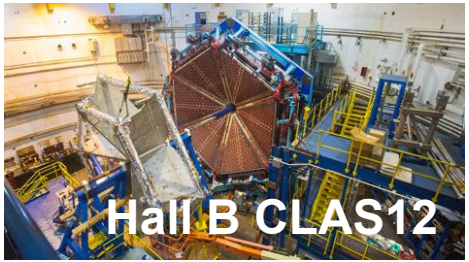
13/April/2020

Jefferson Lab Experimental Halls at 12 GeV

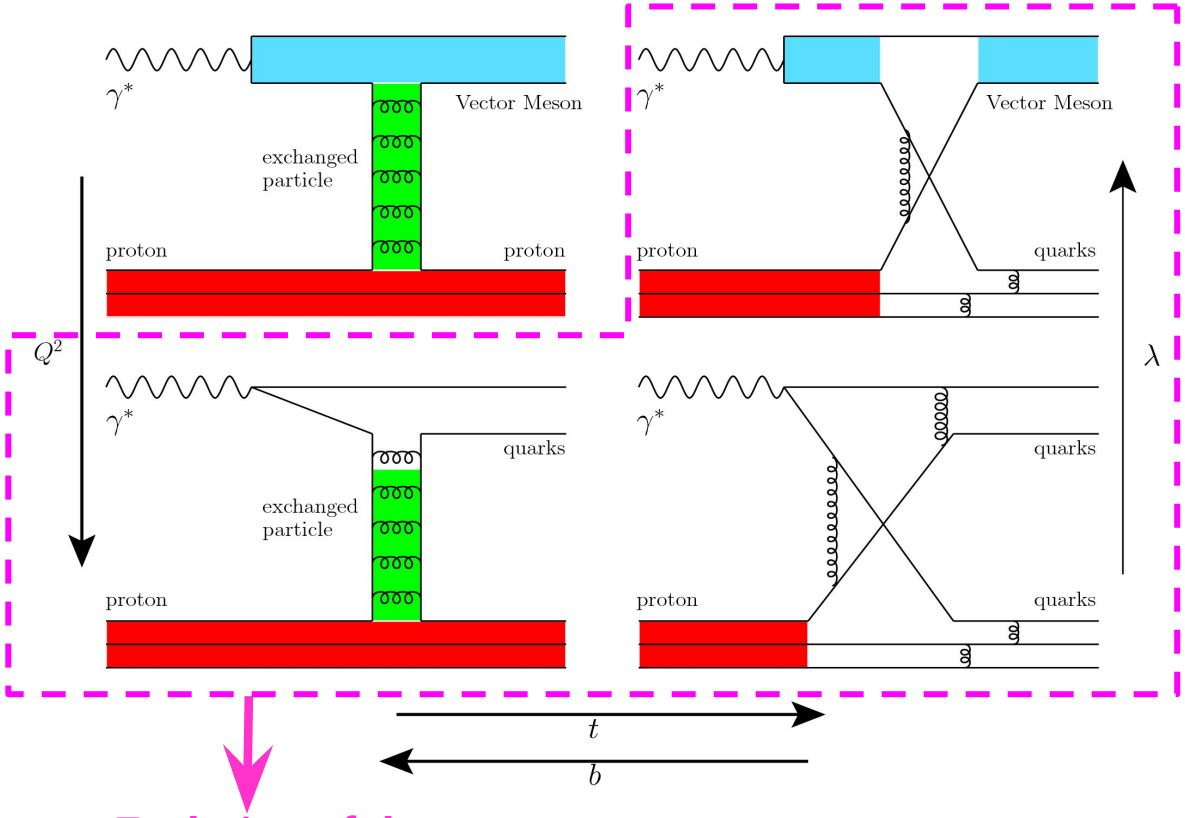




- **Facility:**
  - **Two Superconducting LINAC**
- **Electron beam energy up to 12 GeV**
- **Four Experimental and their objectives:**
  - **Hall A:** upgrading, not shown
  - **Hall B:** low lumi. beam, large acceptance. Study multiple interactions simultaneously.
  - **Hall C:** High Res. Spectrometers. High intensity beam. Study nucleon structure, LT separation.
  - **Hall D:** photon beam, large acceptance.



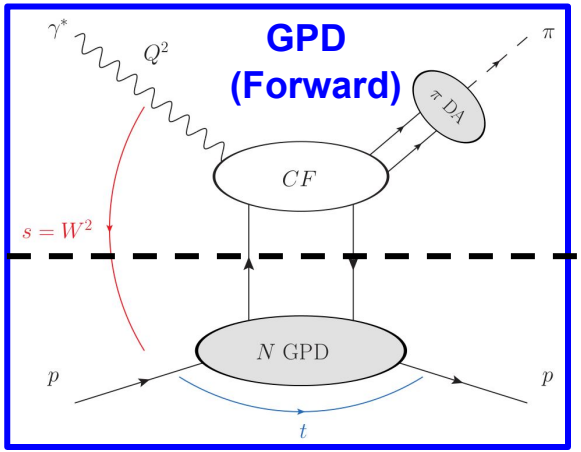
Hadronic Model: Transition (Evolution) of Proton Structure

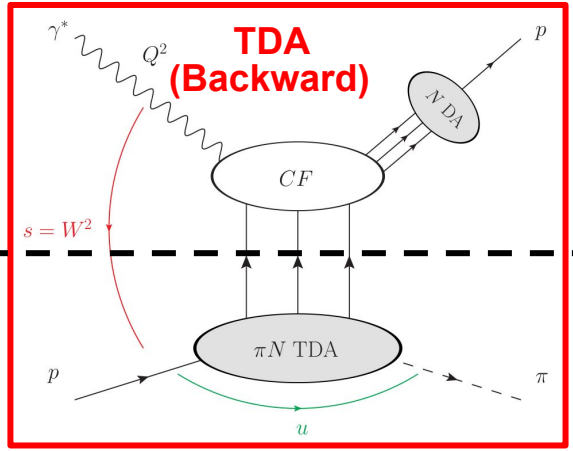


Evolution of the Proton Structure

- **Physical parameters:**
  - In *x*, *W* (or *s*), Q^2, *t*, *u*
- ***x* Evolution:**
  - Parton momentum fraction: 0.2-0.3 valence quark distribution is pronounced
- ***W* Evolution:**
  - Dictate if a process is in the resonance region
- **Q^2 Evolution**
  - Wavelength of the probe, or resolving power
- ***t* Evolution**
  - Inversely related to the Impact parameter b
- **What role does *u* play?**

GPD, SPD and TDA (Hard Structure)





Hard structure

Soft structure

Collinear factorization

By **X. Ji et al.** in 1997

Developed by **B. Pire**, **L. Szymanowski** and **K Semenov-Tian-Shansky** in 2000

Description to the unseen side of proton

Complete description of Nucleon

- **GPD**: It is extracted predominantly based in the forward angle observables.
- **TDA**: meson-nucleon Transition Distribution Amplitude (TDA) only accessible through backward (u-channel) meson production.

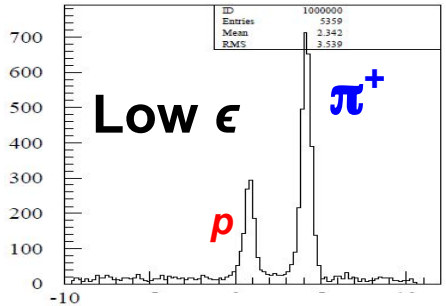
Gifted Backward-angle Observables

- **Fpi-2 (E01-004) 2003**
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged π** through exclusive π production
- **Primary reaction for Fpi-2**
  - **H(*e*, *e'* π^+)*n***
- **In addition, the experiment fortuitously received**
  - ***p*(*e*,*e'* *p*)ω**
- **Kinematics coverage**
  - ***W*= 2.21 GeV, Q^2=1.6 and 2.45 GeV^2**
  - Two ϵ settings for each Q^2

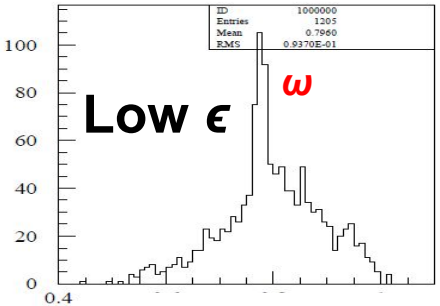
Q^2=2.45 GeV^2

2003

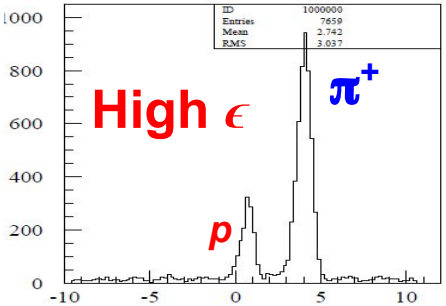
2003/07/25 08.56



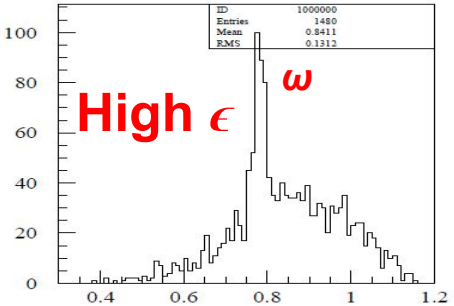
Coincidence time



***epX* missing mass**



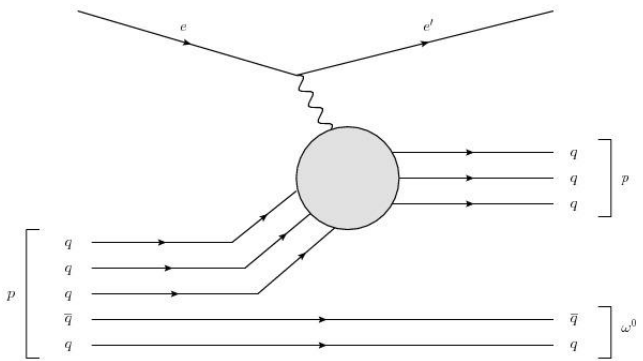
Coincidence time



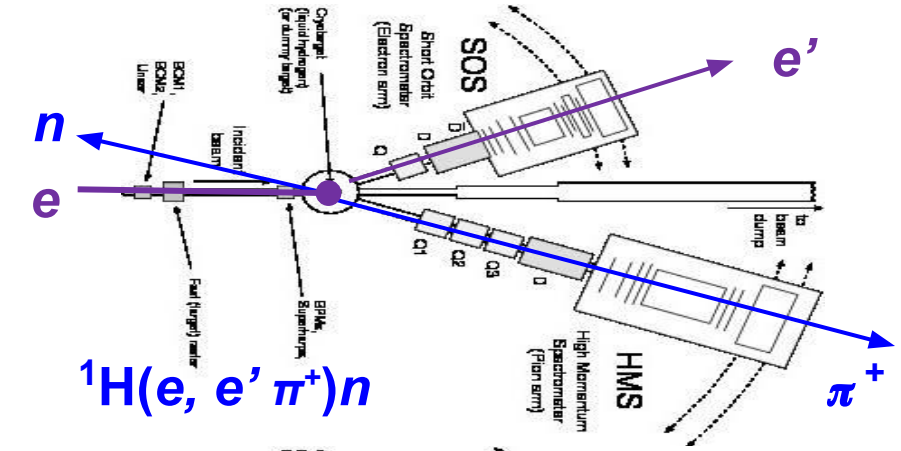
***epX* missing mass**

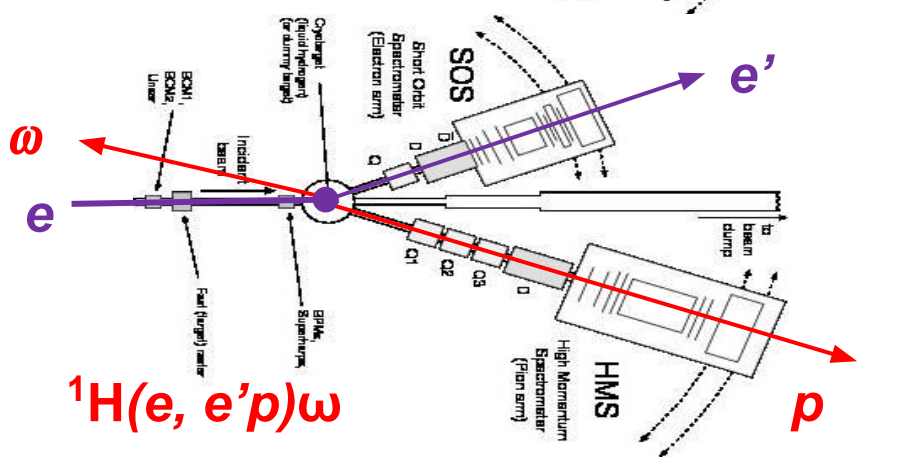
t-Channel π^+ vs *u*-Channel ω Production

- **Primary reaction for Fpi-2**
  - **H(*e*, *e'* π^+)*n***
  - ***n* (940 MeV)**
  - **π^+ (140 MeV)**
- **Unexpected reaction:**
  - **H(*e*,*e'* *p*)ω**
  - ***p* (940 MeV)**
  - **ω (783 MeV)**



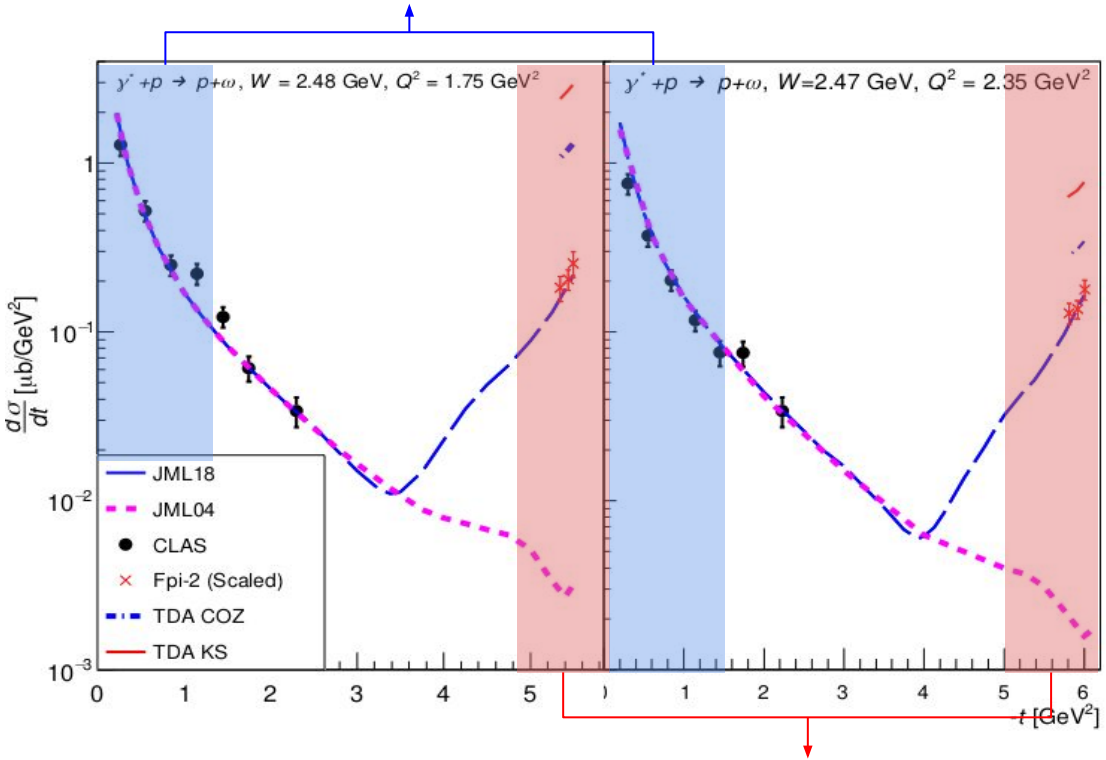
Mark Strikman & Christian Weiss: A proton being knocked out of a proton process





Results on Backward Angle Electroproduction

Forward ω electroproduction from CLAS 6 *(2004)*



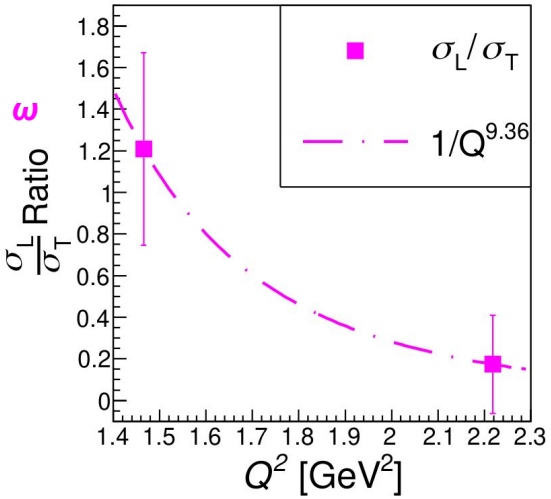
- **Topic of my Ph.D**
- **Analysis: *2013-2017***
- **Results published in *Phys. Rev. Let. (2019)***
- **The magnitude of u-channel peak is surprisingly large**

Backward angle ω electroproduction *(2017)*

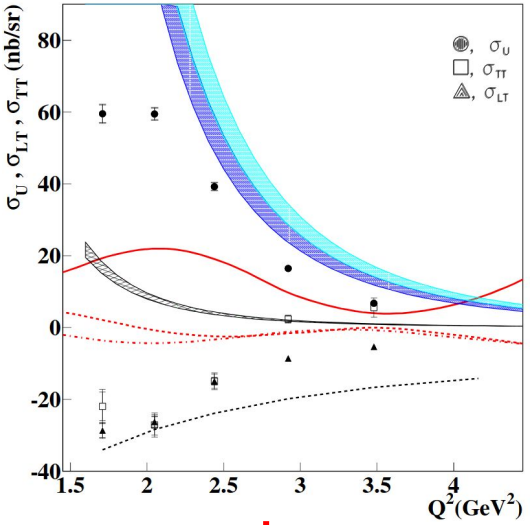
Validation of TDA Factorization Scheme

W.B. Li et al. (Jefferson Lab Fπ), Phys. Rev.Lett.123, 182501 (2019)

Hall C 6 GeV Backward ω (My analysis, 2017)



K. Park et al. (CLAS), Phys. Lett.B780, 340(2018)



Two qualitative predictions from TDA:

- $\sigma_T > \sigma_L$, $\sigma_L \sim 0$
- $\sigma_T \sim 1/Q^8$ scaling behavior

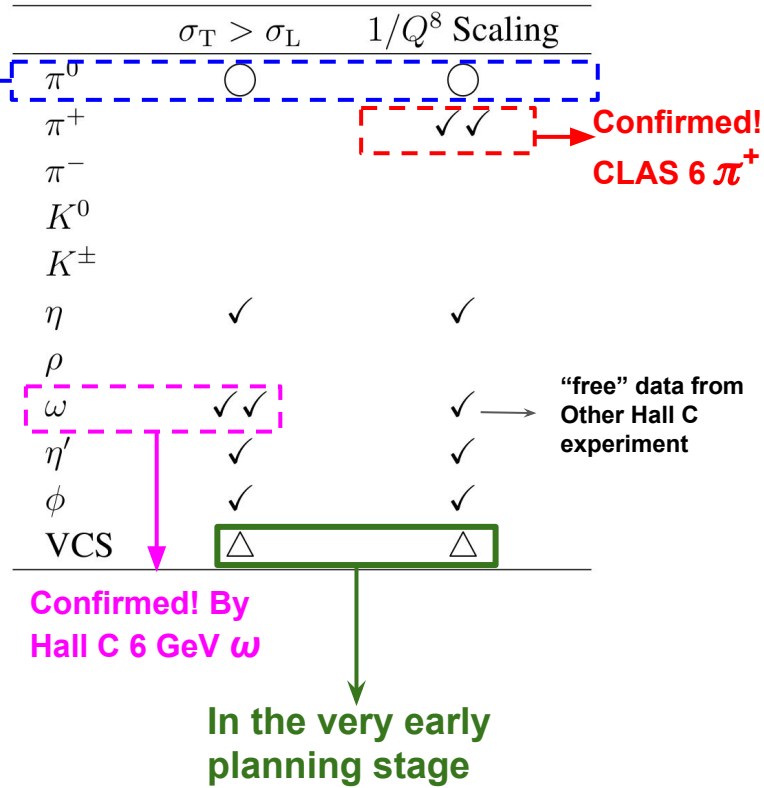
CLAS 6 backward π^+ production, (K. Park el. al, 2018)

This is the time for a dedicated backward angle study:

- Simultaneously testing both TDA predictions

First Dedicated Backward Angle Experiment

- **Probing backward-angle (*u*-channel) electroproduction of π^0 : E12-20-007**
  - First presented as Letter of Intent in 2018
  - Full proposal submitted in 2020
- **Received full approval by JLab Program Advisory Committee (PAC):**
  - Experiment fully approved for 29 PAC days
- **PAC recognized the pioneering nature of the measurement**
  - The exploration of backward pion electroproduction is feasible, and JLab is an ideal venue at which to perform it.
- **Significant symbolic meaning: First approved dedicated u-channel experiment**



E12-20-007 Collaborator List

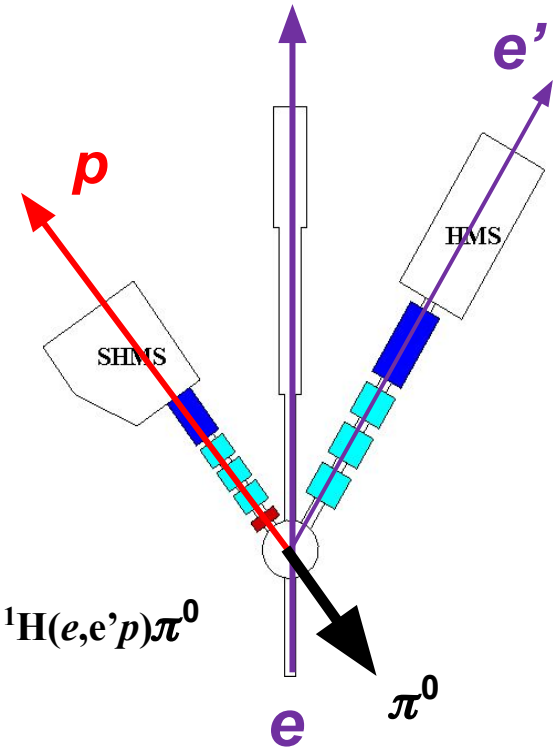
Wenliang (Bill) Li, Justin Stevens, David Armstrong, Todd Averett, Andrew Hurley, Lydia Lorenti, and Amy Schertz
College of William and Mary, Williamsburg, VA, USA
Garth Huber, Muhammad Junaid, Stephen Kay, Vijay Kumar, Zisis Papandreou, Dilli Paudyal, and Ali Usman
University of Regina, Regina, SK Canada
Kirill Semenov-Tian-Shansky
National Research Centre Kurchatov Institute: Petersburg Nuclear Physics Institute, RU-188300 Gatchina, Russia
Bernard Pire
CPHT, CNRS, Ecole Polytechnique, IP Paris, 91128-Palaiseau, France
Lech Szymanowski
National Centre for Nuclear Research (NCBJ), 02-093 Warsaw, Poland
Alexandre Camsonne, Jian-Ping Chen, Silviu Covrig Dusa, Filippo Delcarro, Markus Diefenthaler, Dave Gaskell, Ole Hansen, Doug Higinbotham, Astrid Hiller Blin, Mike McCaughan, Brad Sawatzky, and Greg Smith
Jefferson Lab, Newport News, Virginia, USA

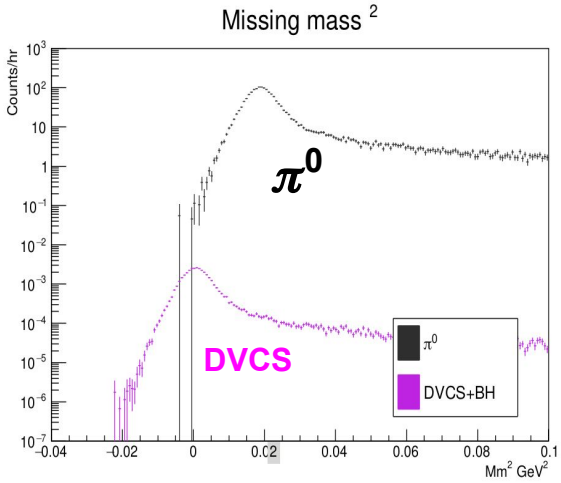
Arthur Mkrtchyan, Vardan Tadevosyan, Hakob Voskanyan, and Hamlet Mkrtchyan
A. Alikhanyan National Science Laboratory (Yerevan Physics Institute), Yereven, Armenia
Stefan Diehl, Eric Fuchey, and Kyungseon Joo
University of Connecticut, Mansfield, Connecticut, USA
Werner Boeglin, Mariana Khachatryan, Pete E. Markowitz, and Carlos Yero
Florida International University, Miami, Florida, USA
Moskov Amaryan, Florian Hauenstein, and Charles Hyde
Old Dominion University, Norfolk, VA, USA
Gabriel Niculescu and Ioana Niculescu
James Madison University, Harrisonburg, Virginia, USA
Paul King and Julie Roche
Ohio University, Athens, Ohio, USA

Darko Androic
University of Zagreb, Zagreb , Croatia
Konrad Aniol
California State University, Los Angeles, California, USA
Marie Boer
Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA
Wouter Deconinck
University of Manitoba, Winnipeg, Manitoba, Canada
Maxime Defurne
CEA, Universite Paris-Saclay, Gif-sur-Yvette, France
Mostafa Elaasar
Southern University at New Orleans, New Orleans, Louisiana, USA
Cristiano Fanelli
Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Stuart Fegan
University of York, Heslington, York, UK
Carlos Ayerbe Gayoso
Mississippi State University, Starkville, MS, USA
Narbe Kalantarians
Virginia Union University, Richmond, VA, USA
Daniel Lersch
Florida State University, Tallahassee, Florida, USA
Rafayel Paremuzyan
University of New Hampshire, Durham, New Hampshire, USA
Kijun Park
Hampton University Proton Therapy Institute, Hampton, Virginia, USA
Igor Strakovsky
The George Washington University, Washington, DC, USA

E12-20-007 Backward-angle $^1H(e,e'p)\pi^0$





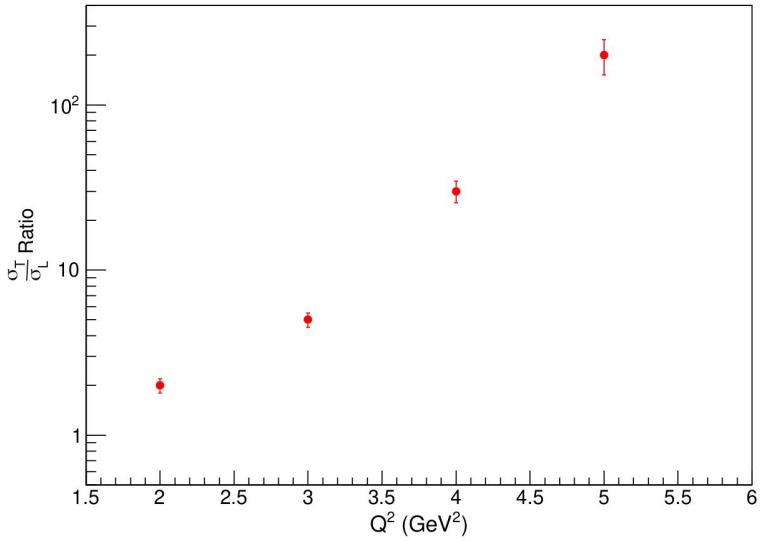
Q^2 GeV^2	W GeV	ϵ	x	θ_{pq} Degree
2.0	3.00	0.32	0.20	-3, 0
		0.79	0.20	-2.8, 0, +3
2.0	2.11	0.52	0.36	-3, 0, +3
		0.94	0.36	-3, 0, +3
3.0	2.49	0.54	0.36	-3, 0, +3
		0.86	0.36	-3, 0, +3
4.0	2.83	0.56	0.36	-3, 0, +3
		0.73	0.36	-3, 0, +3
5.0	3.13	0.26	0.36	-3, 0
		0.55	0.36	-3, 0, +3
6.25	3.46	0.27	0.36	0

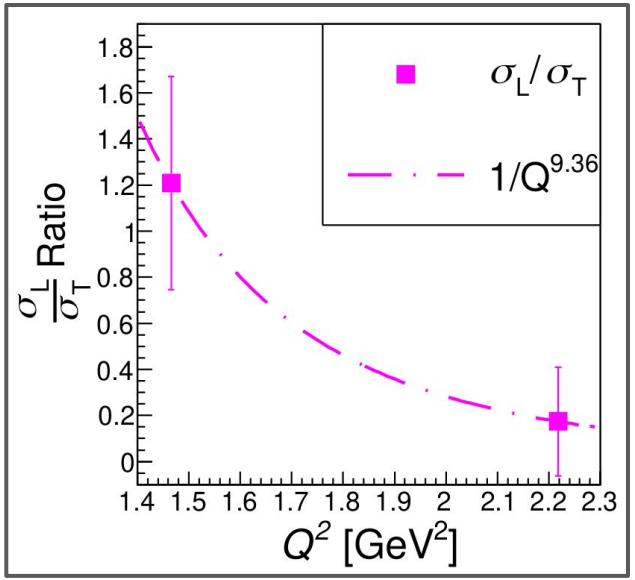
First dedicated *u*-channel electroproduction study above the resonance region:

- **Q^2 coverage: $2.0 < Q^2 < 6.25$ GeV^2, at x=0.36 and W > 2 GeV L/T separated cross section @ Q^2= 2, 3, 4 and 5 GeV^2.**
- u coverage: $0 < -u' + 0.5 < 0.5$ GeV^2
- **Additional W scaling check @ Q^2 = 2 GeV^2**
- **Additional Q^2 scaling check @ Q^2 = 6.25 GeV^2**

Objective 1: *TDA Prediction #1* $\sigma_T > \sigma_L$

Projected T/L ratio vs Q^2 (this proposal)



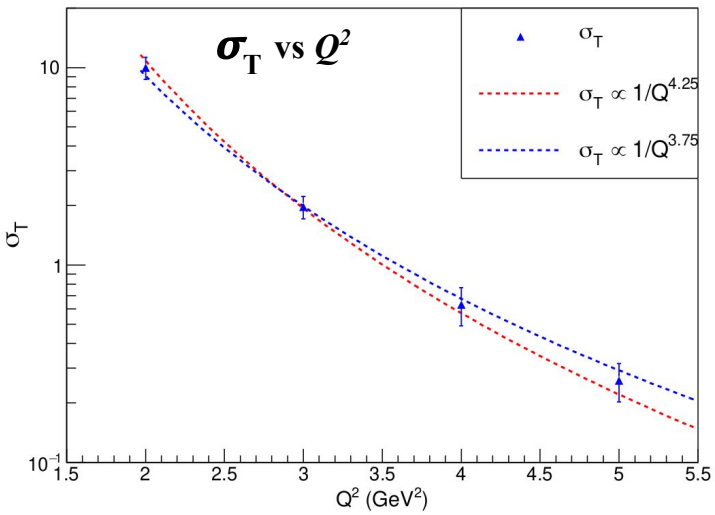


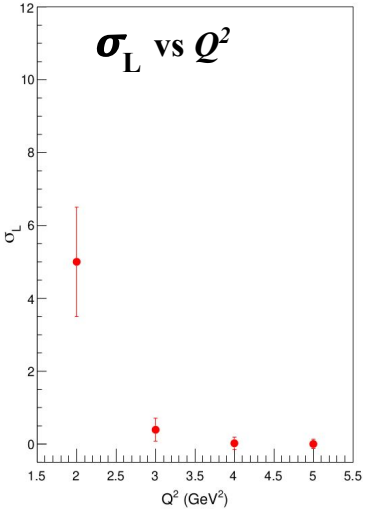
L/T ratio vs Q^2 (6 GeV F_π-2 experiment for ω)

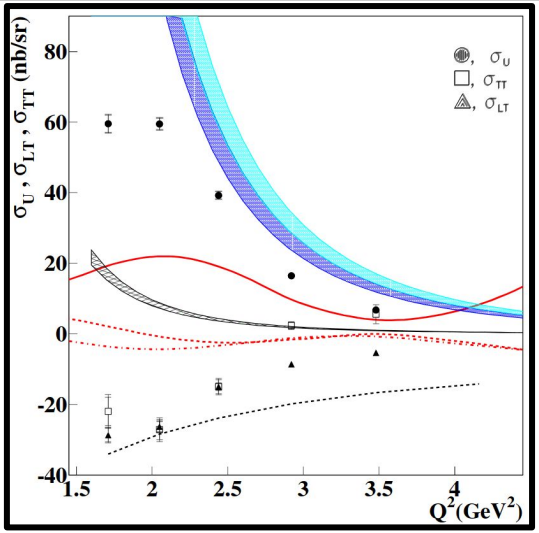
Objective 2: L/T Separated Cross section

- TDA predicts $\sigma_T > \sigma_L$
- Experimental criteria for concluding σ_T dominance: σ_T/σ_L increases as a function of Q^2 and reaches $\sigma_T/\sigma_L > 10$ at $Q^2 = 5$ GeV^2

Objective 2: *TDA Prediction #2, $\sigma_T \propto 1/Q^8$ Scaling*







σ vs Q^2 (CLAS 6 π^+ result)

Objective 3: L/T Separated Cross section

- TDA predicts $\sigma_T \propto 1/Q^8$.
- TDA predicts $\sigma_L \sim 0$, not a leading twist contribution effect.
- Experiment designed to $(Q^2)^n$, $3.75 < n < 4.25$

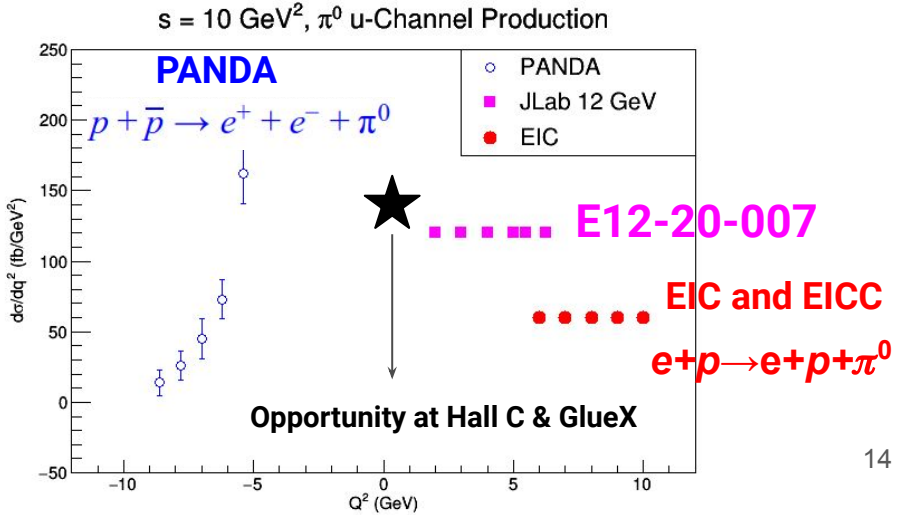
u-Channel studies at EIC

7.4 Understanding Hadronization

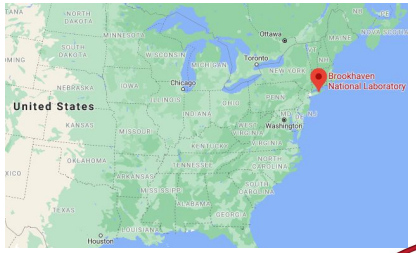
There is great potential also in studying **new particle production mechanisms** such as exclusive backward *u*-channel production. Given its high luminosity the EIC may be able to discover fundamental QCD particle production processes with low cross sections such as via hard (perturbative) C-odd three gluon exchange.

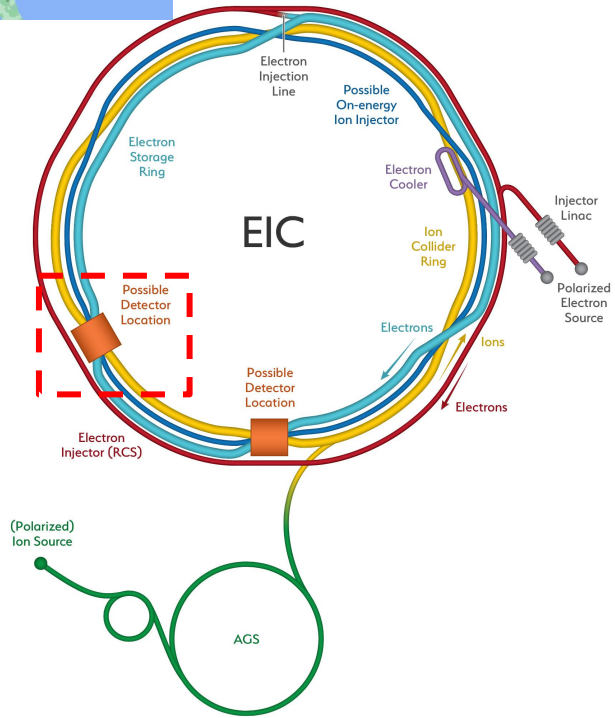
EIC YELLOW REPORT

- **As postdoctoral fellow at JLab EIC Center: developed Backward π^0 program for EIC**
  - Offers synergy to other planned data set
  - Feasibility studies included as part of the EIC Yellow report (published last week)

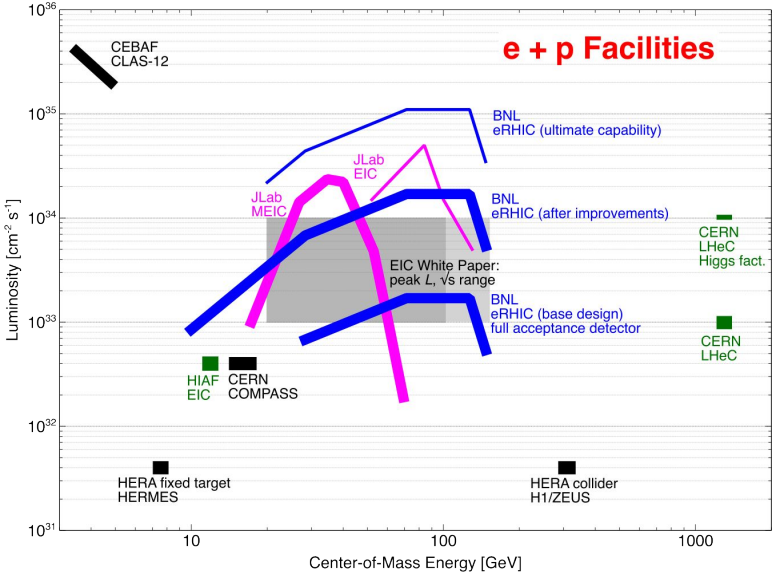


The BNL-EIC Project





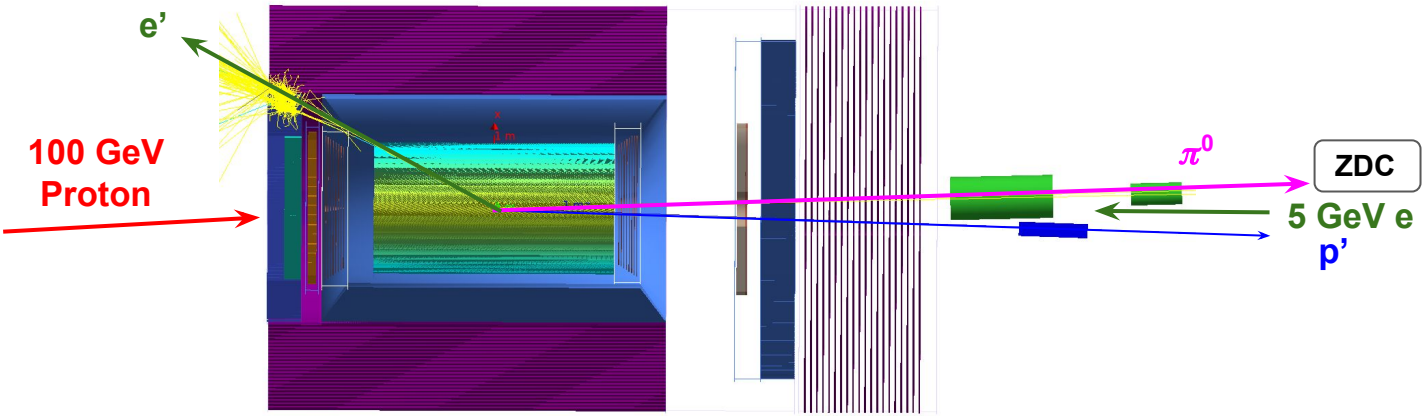
Interaction Region



The Electron-Ion Collider (EIC) is the next generation "Dream Machine" for Nuclear Physics Research.

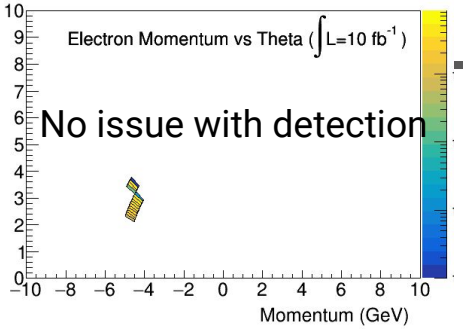
- Luminosity with 100 GeV p on 5 GeV e: 10 x10^{33} $cm^{-2}s^{-1}$ mi
- Project Location: Brookhaven National Laboratory, NY.
- Additional Information:
  - CD-0 approved ~ $2 B
  - Physics starts in 2031

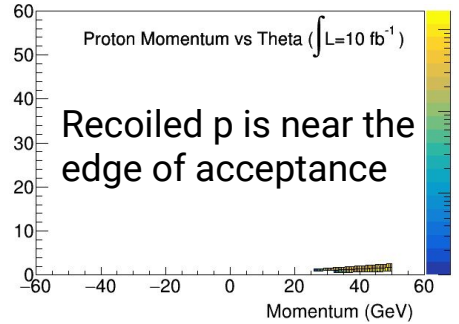
u-Channel Meson Production Setup

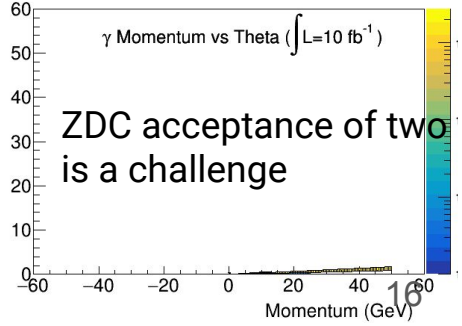


Q^2 (GeV^2)	W (GeV)	x_B	$\theta_{e'}$ (deg)	$\eta_{e'}$	$P_{e'}$ (GeV)	$\theta_{p'}$ (deg)	$\eta_{p'}$	$P_{p'}$ (GeV)	θ_{π^0} (deg)	η_{π^0}	P_{π^0} (GeV)	$-t$ (GeV^2)	$-u$ (GeV^2)
6.2	3.19		152	-1.39	5.31	-1.84	4.13	43.40	1.43	4.38	56.29	14.84	-0.37
7.0	3.19		150	-1.32	5.35	-1.92	4.09	45.50	1.43	4.38	54.12	16.19	-0.39
8.2	3.19		148	-1.24	5.40	-1.85	4.12	49.74	1.43	4.38	49.84	16.80	-0.42
9.3	3.19		146	-1.19	5.46	-1.92	4.09	51.90	1.43	4.38	47.60	18.19	-0.44
10.5	3.19		144	-1.12	5.52	-1.94	4.07	54.96	1.43	4.38	44.50	19.32	-0.47

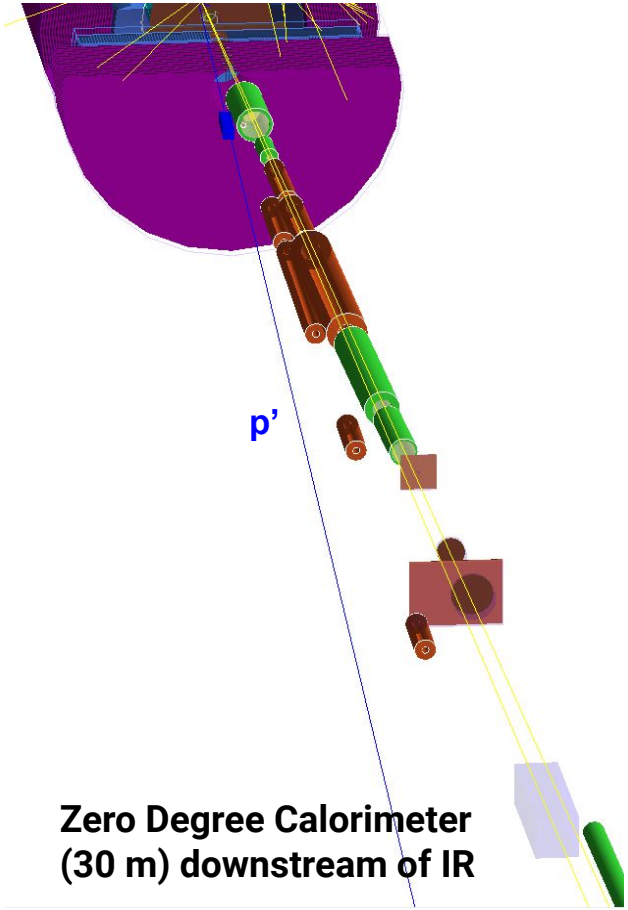
e' p' π^0



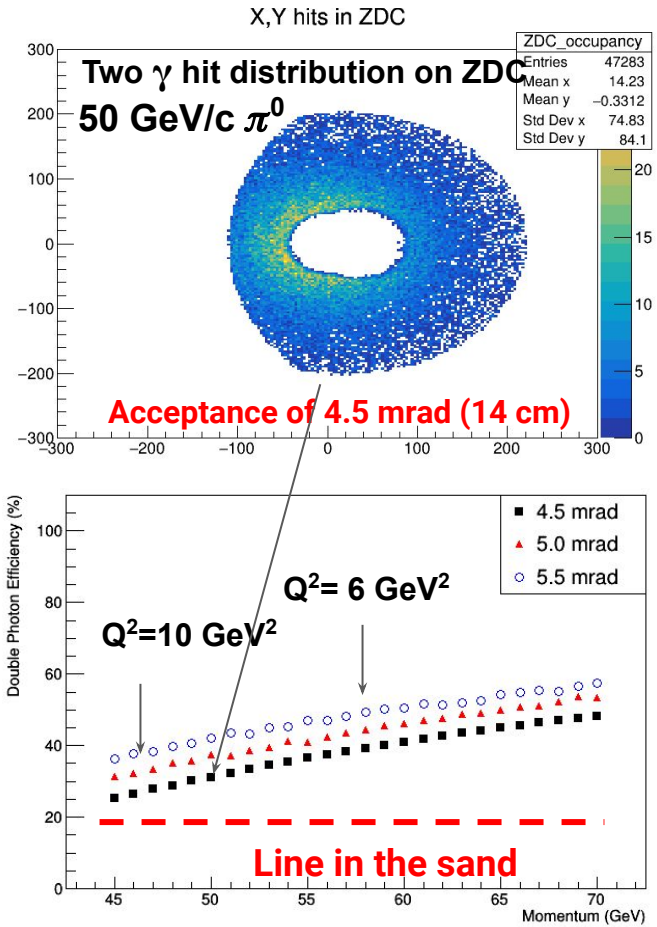




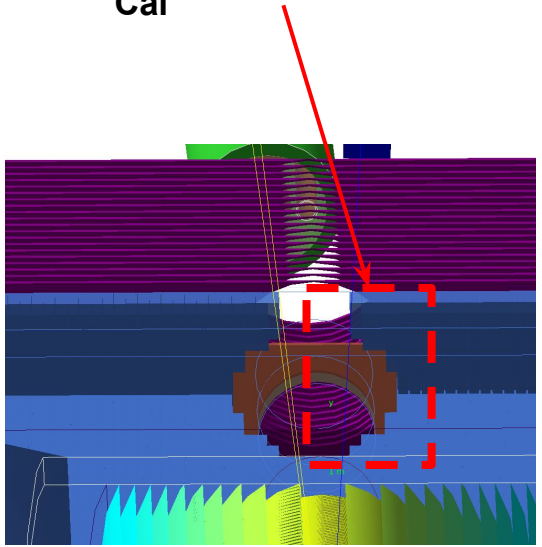
Realistic ZDC Acceptance for π^0 and p Detection



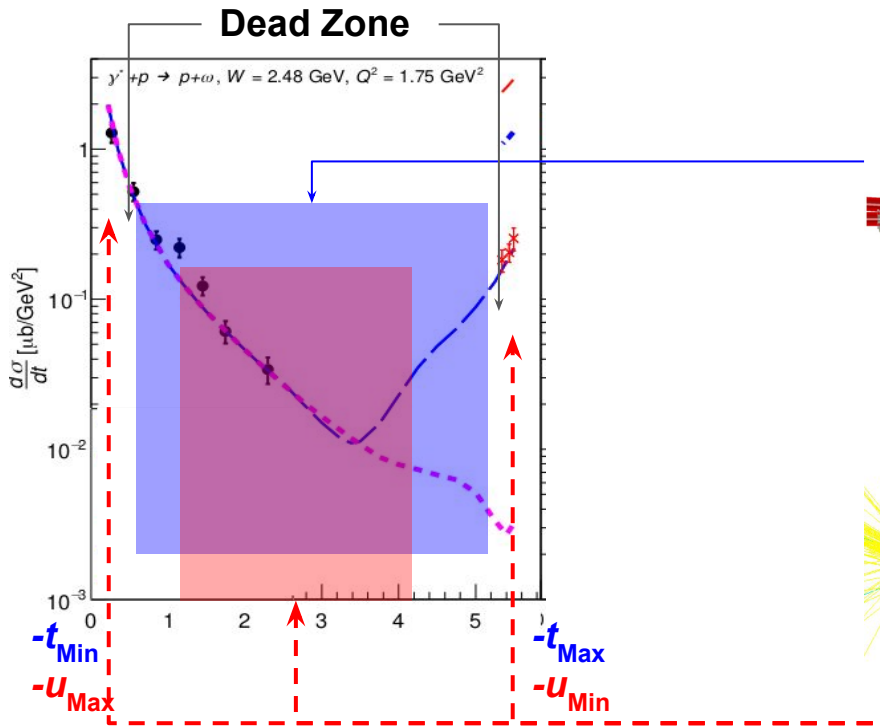
Zero Degree Calorimeter
(30 m) downstream of IR

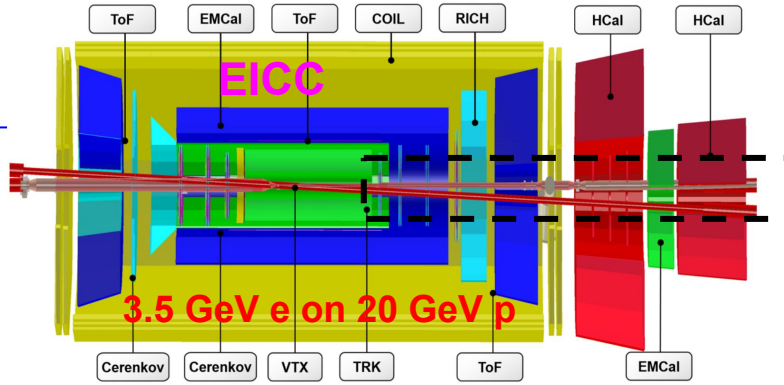


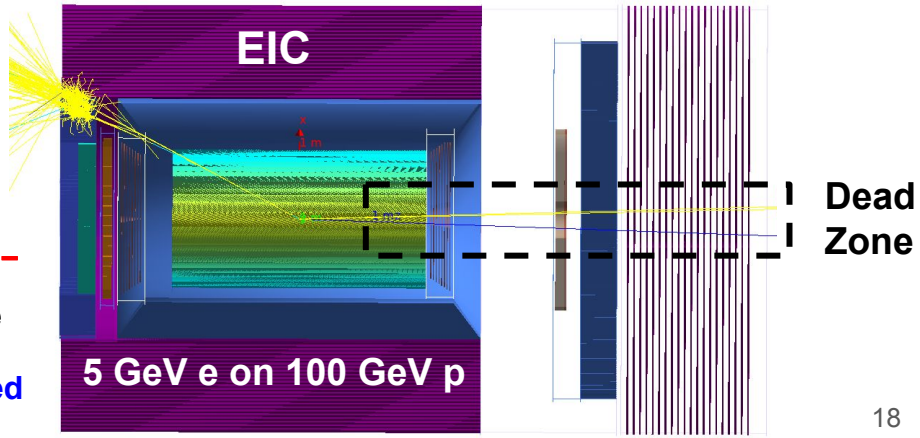
- Forward π^0 detection
  - 30-40% 2γ event eff.
- Forward p detection
  - Current not covered
  - Patching up forward EM Cal



EIC and EicC Complementarity

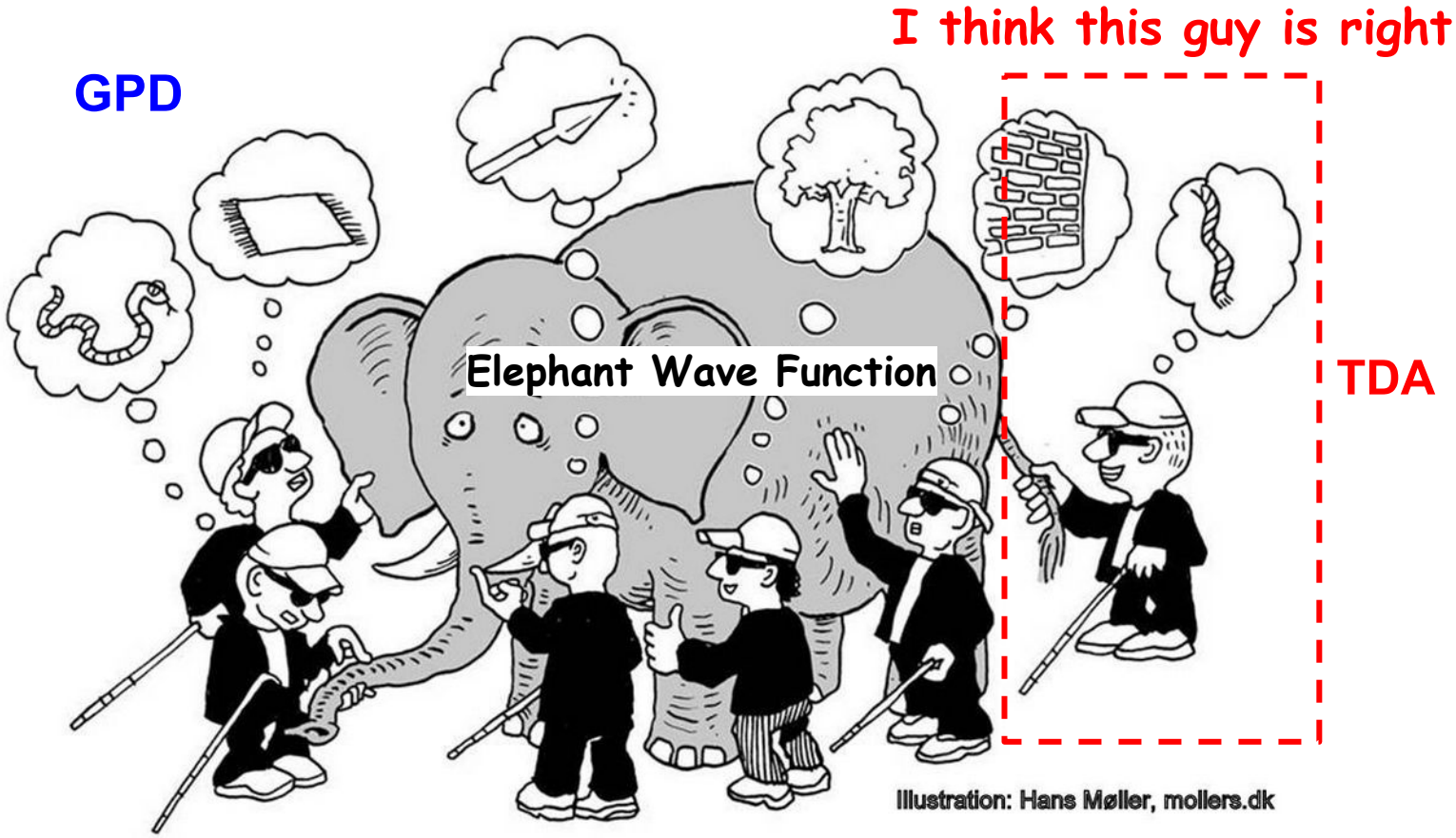




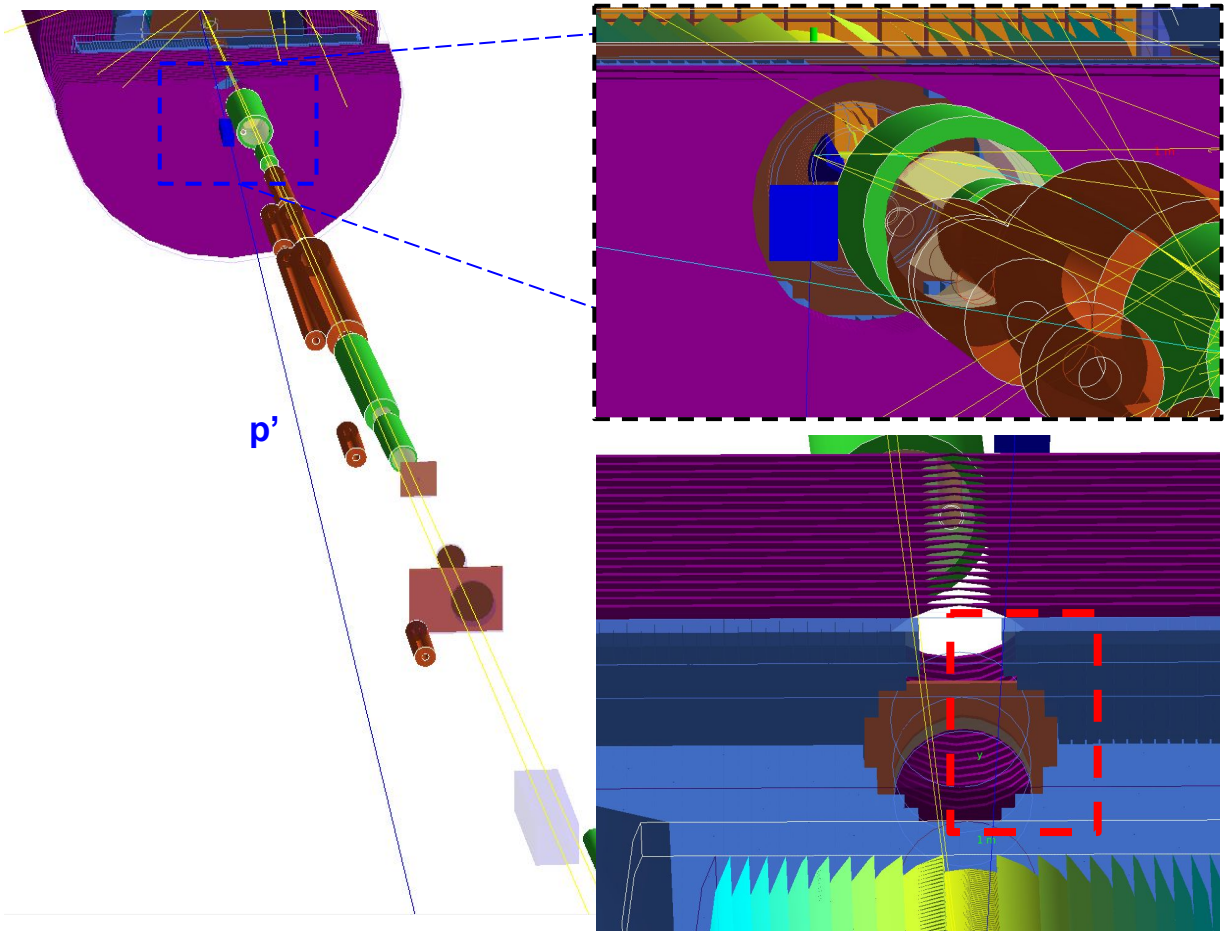


- EIC and EICC should be designed to avoid common dead zone overlap in phasespace. Studies needed
- Angular dependence asymmetry study is possible (needed to extract TDAs)

Thank You! And Let's Explore *u*-channel Physics Together!



A Proton Detection Problem



Proton detector issue!

- Proton will NOT be detector due to ventilation hole!
- Blue cube: new detector dropped in to help with acceptance study
- Completing feasibility study is critical now ! (designing stage)

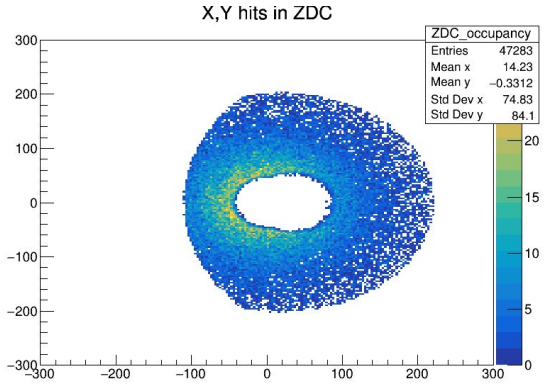
Physics Background (to my Best Knowledge)

- Double photon case:
  - Primary reaction: e+p → e'+p' + π^0
  - Ideal expected trigger: e'+p'+ 2 γ
  - Physics background: none
  - Less than ideal trigger: e'+2 γ
  - Background: $\Lambda \rightarrow n+\pi^0$

2 γ hit pattern

40 GeV/c π^0

4.5 mrad acceptance



- Single photon case:
  - Primary reaction: e+p → e'+p' + π^0
  - Ideal expected trigger: e'+p'+ γ
  - Physics background: DVCS, η, $\Lambda \rightarrow n+\pi^0$
  - Less than ideal trigger: e'+γ
  - Background: many many possibility

1 γ hit pattern

60 GeV/c π^0

4.5 mrad acceptance

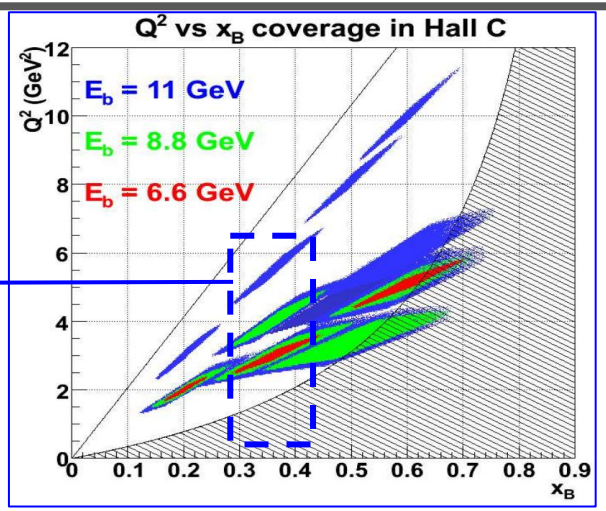
- We can use the double photon event to normalize the single photon events

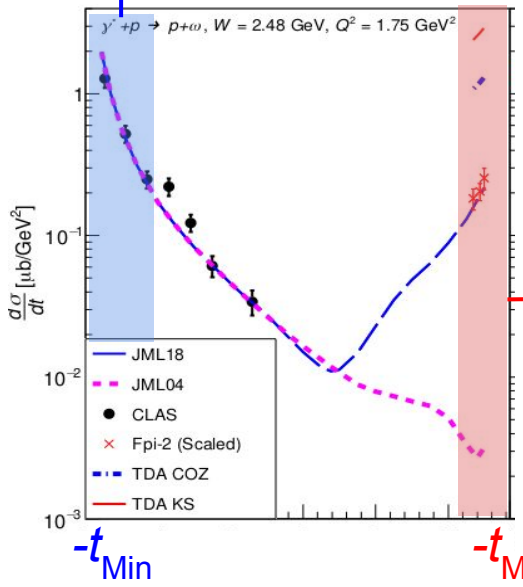
Objective 1: *Backward-angle Peaks*

Objective 1: Demonstrating the existence of the *u*-channel peaks for $H(e,e'p)\pi^0$

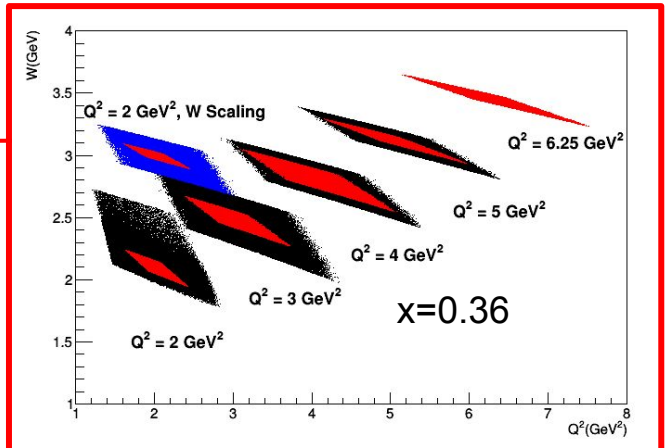
- E12-13-010 NPS experiment provides low -*t* L/T separated cross section

E12-13-010 NPS Experiment

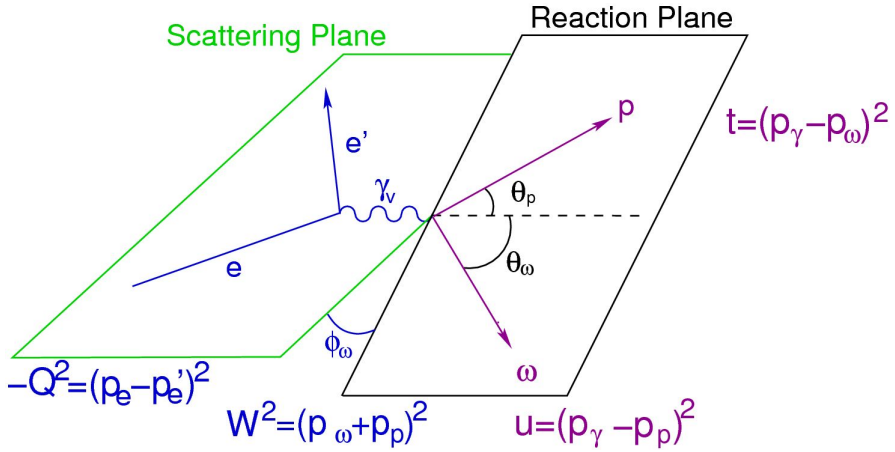




This proposal



The Rosenbluth Separation



Virtual-photon polarization:

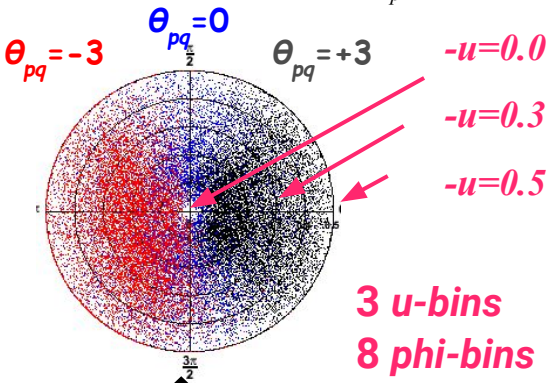
$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

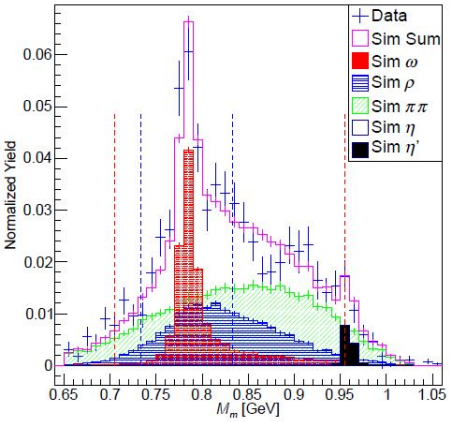
$$2\pi\frac{d\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

- **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

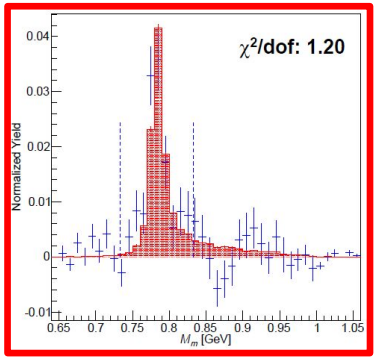
Iterative Procedure (Recipe) to a LT Separation

Improve ϕ coverage by taking data at multiple HMS angles, -3°< θ_p <+3°.



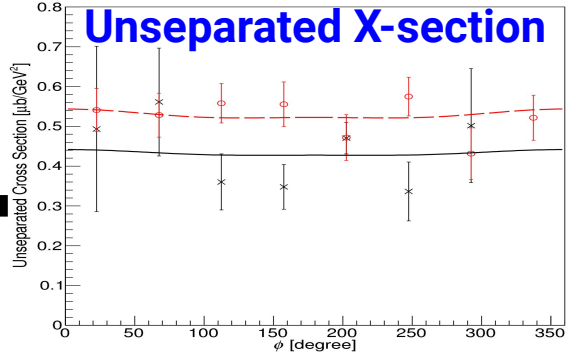


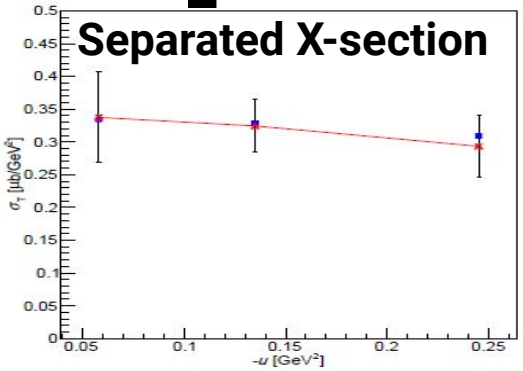
Background subtraction



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

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

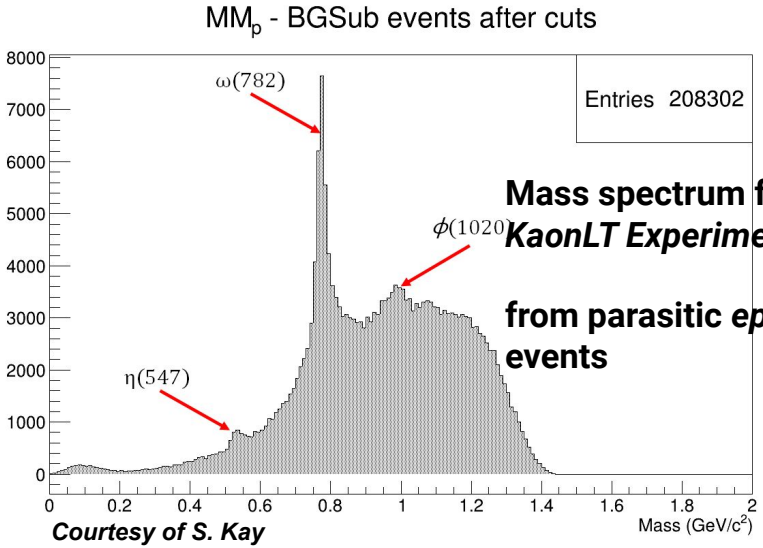
Extracting T, L, LT, TT via simultaneous fit

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

25

Question: *u*-channel peaks for other processes?

- **Is there a u-channel peak for other processes?**
  - **Answer: Yes**
- **Evidences:**
  - 6 GeV pioneering analysis efforts from Hall C and CLAS 6
  - Parasitic data from 12 GeV Hall C experiments



Courtesy of S. Kay

Mass spectrum from 12 GeV *KaonLT Experiment 2020*

from parasitic *ep* coincidence events

	$\sigma_T > \sigma_L$	$1/Q^8$ Scaling
π^0		
π^+		✓✓
π^-		
K^0		
$K^\pm$		
η	✓	✓
ρ		
ω	✓✓	✓
η'	✓	✓
ϕ	✓	✓
VCS		

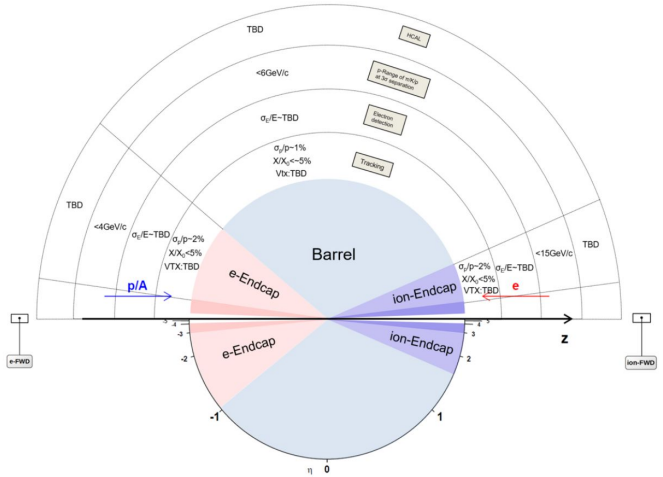
Confirmed!
By CLAS6 π^+

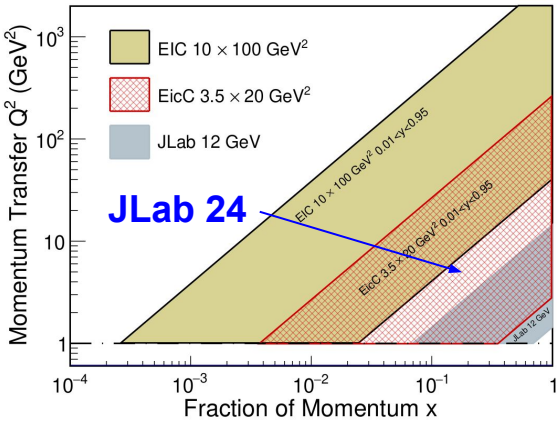
Parasitic Hall C Study

Confirmed! By Hall C 6 GeV ω

EicC Offers Unique Kinematics and other Benefits

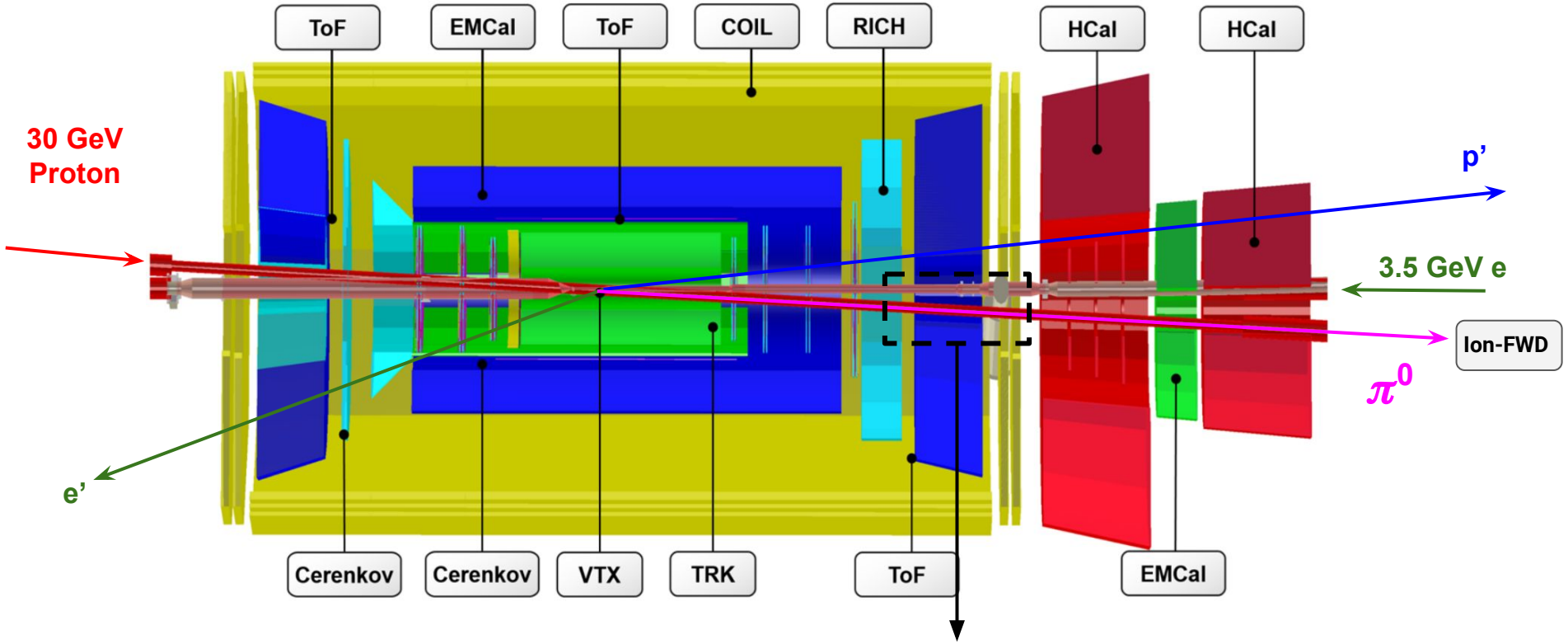
Particle	e	p
Circumference(m)	809.44	1341.58
Kinetic energy(GeV)	3.5	19.08
Momentum(GeV/c)	3.5	20
Total energy(GeV)	3.5	20.02
CM energy(GeV)	16.76	
$f_{collision}$ (MHz)	100	
Polarization	80%	70%
$B\rho$(T · m)	11.7	67.2
Particles per bunch($\times 10^9$)	170	125
$\varepsilon_x, \varepsilon_y$(nm · rad, rms)	60/60	300/180
β_x^*/β_y^*(m)	0.2/0.06	0.04/0.02
Bunch length(m, rms)	0.02	0.04
Beam-Beam Parameter ξ_y	0.09/0.05	0.004/0.004
Laslett tune shift	-	0.09
Energy loss per turn(MeV)	0.32	-
Total SR power(MW)	0.86	-
SR linear power density(kW/m)	3.3	-
Current(A)	2.7	2
Crossing angle(mrad)	50	
Hourglass	0.78	
Luminosity at nucleon level ($cm^{-2}s^{-1}$)	2.0×10^{33}	





Last time I had this was 11 years ago!

u-channel π^0 at EicC



Kinematics Table for $u = u_{min}$, $s = 10$ GeV^2

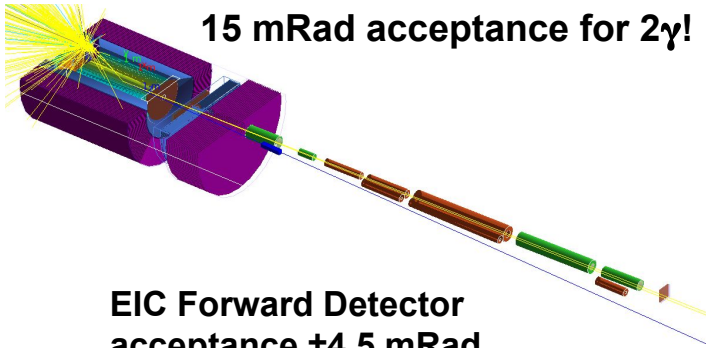
e' p' π^0

Q^2 (GeV^2)	$\theta_{e'}$ (deg)	$\eta_{e'}$	$P_{e'}$ (GeV)	$\theta_{p'}$ (deg)	$\eta_{p'}$	$P_{p'}$ (GeV)	θ_{π^0} (deg)	η_{π^0}	P_{π^0} (GeV)	P_γ (GeV)
3.4	150	1.31	3.62	15.00	2.03	5.83	2.86	3.69	13.99	7.00
4.7	145	1.15	3.71	14.26	2.07	7.13	2.86	3.69	12.61	6.31
6.2	140	1.10	3.81	14.13	2.09	8.26	2.86	3.69	11.39	5.70
8.0	135	0.88	3.93	13.91	2.10	9.97	2.86	3.69	10.05	7.02

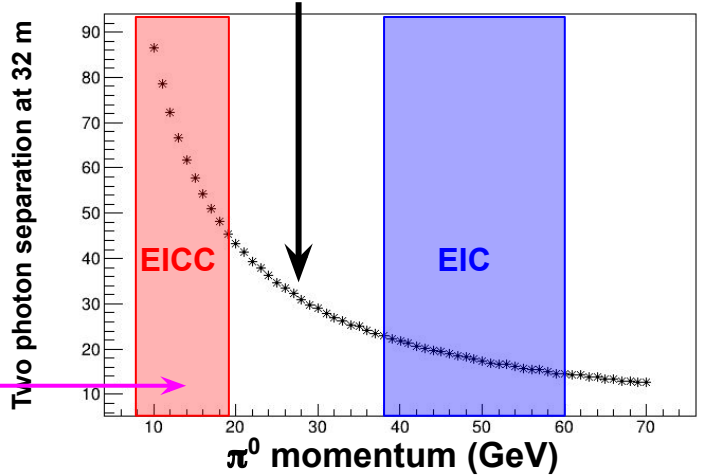
Gaining Momentum!

Much more comfortable ! No special attention needed

Momentum causing acceptance issue



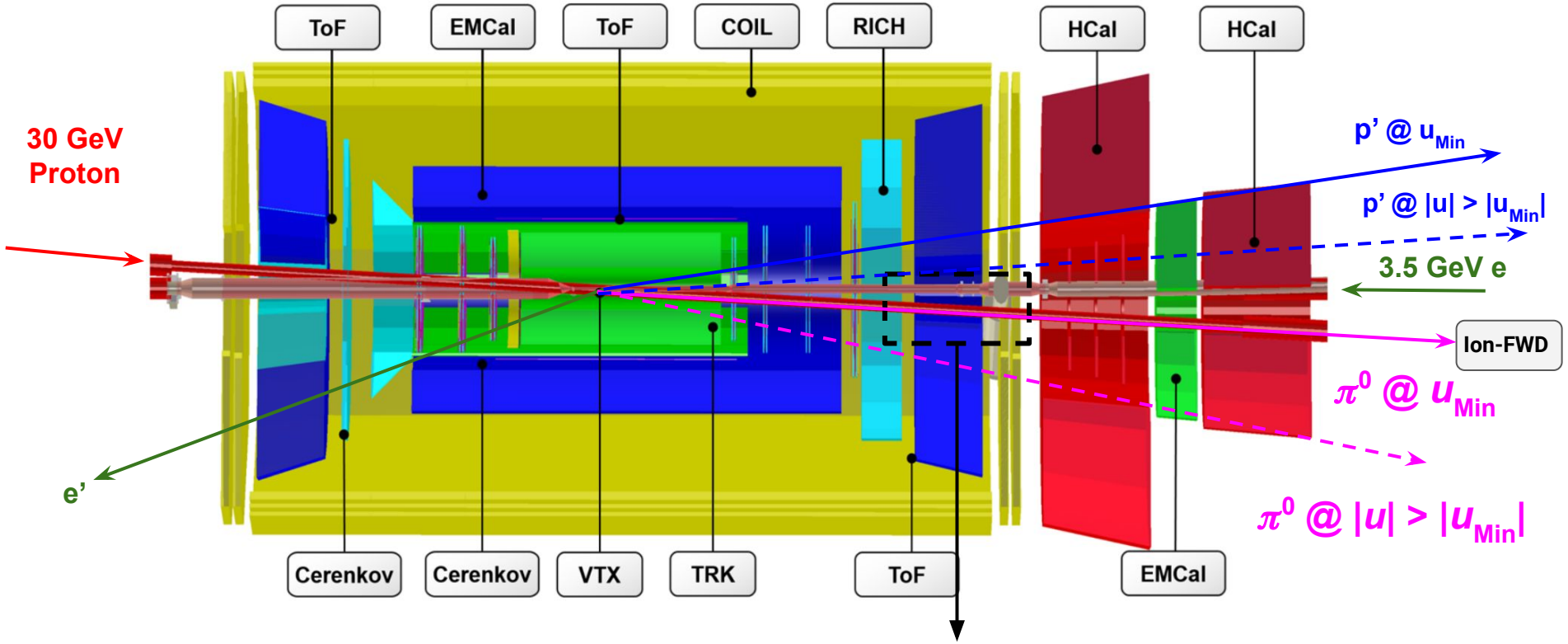
EIC Forward Detector acceptance ±4.5 mRad



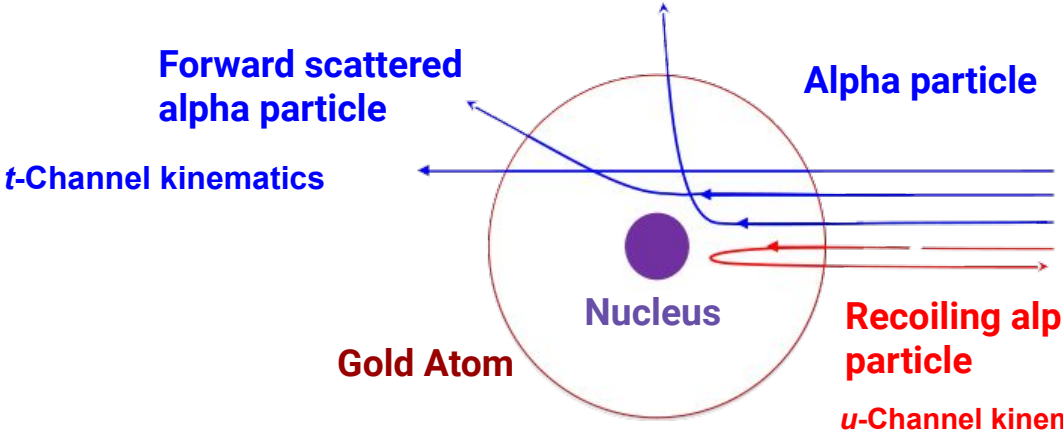
Viable observable

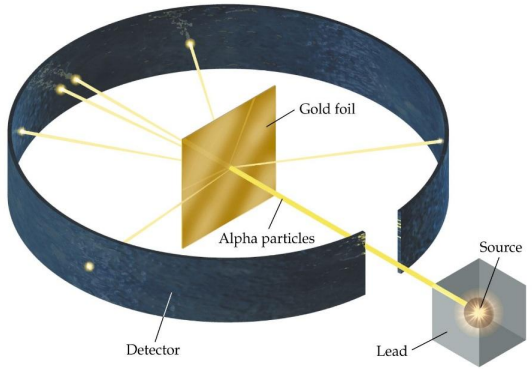
- Not completely exclusive **(ep, e'p'γ) γ**
- Huge backgrounds!

u-channel π^0 at EICC: much better $|u| > |u_{min}|$ setup!



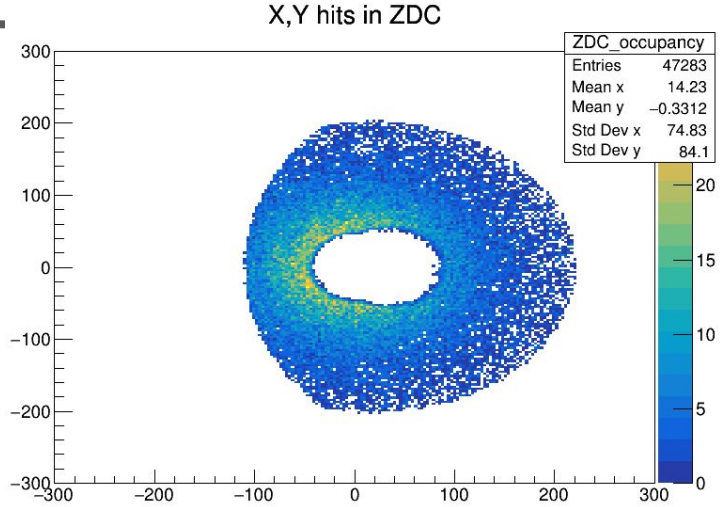
Backward-angle structure of Atom

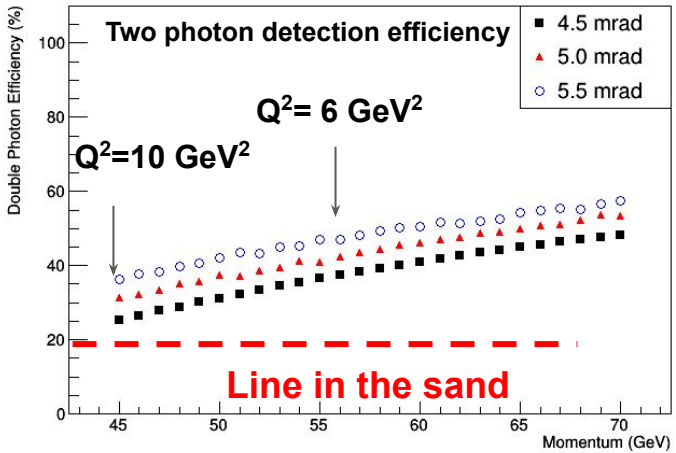


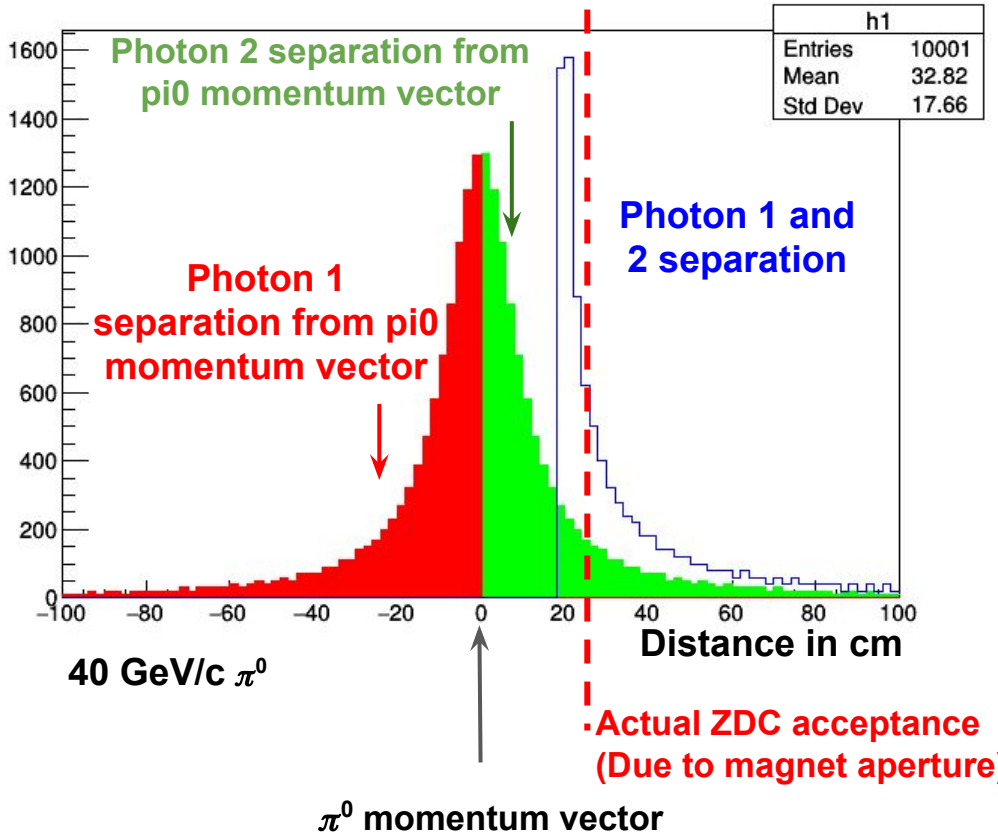


- Forward scattered alpha particle: extracting the interaction radius of the nucleus and mapping out the transverse structure of the atom (mostly empty)
- Recoiling alpha particle: stiffness of the "point-like" structure.
- Full structure = forward angle + backward angle observables.

Realistic ZDC Acceptance (through magnets Aperture)

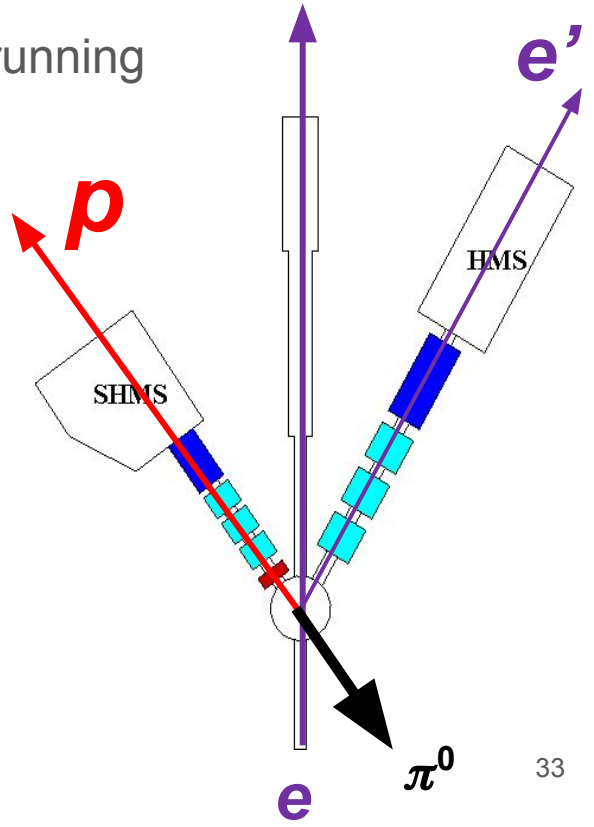






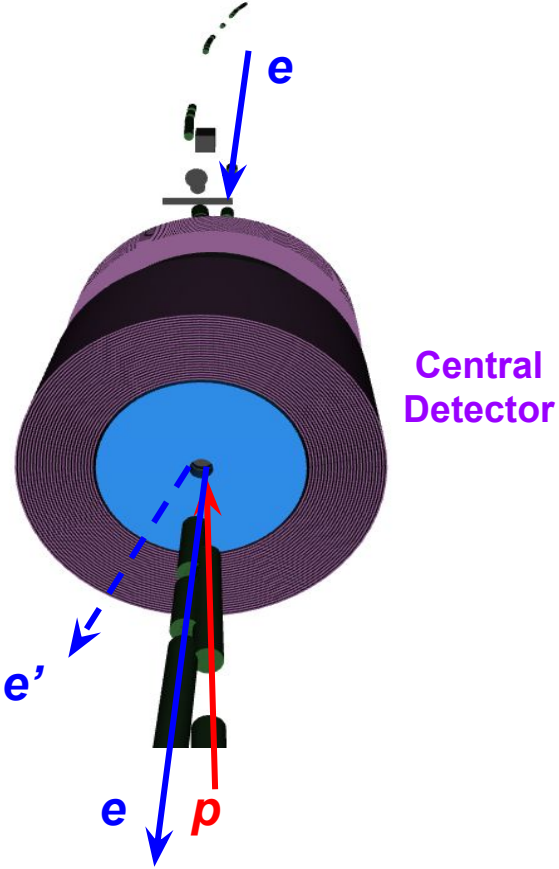
Requirements

- PAC has approved 29 days of beam (requested 29.4 days)
- Beam request: standard beam tune during the time of running with standard polarization
- **Equipment refurbishment:**
  - **HMS Aerogel PMT Replacement (new request)**
  - **SHMS Aerogel tray of n=1.0003 (already planned)**
- **Special detector configuration:**
  - **Installing NGC for SHMS**
  - **SHMS aerogel tray n=1.0003**
  - **HMS aerogel tray n=1.0011**
  - **Using Moller polarimeter**

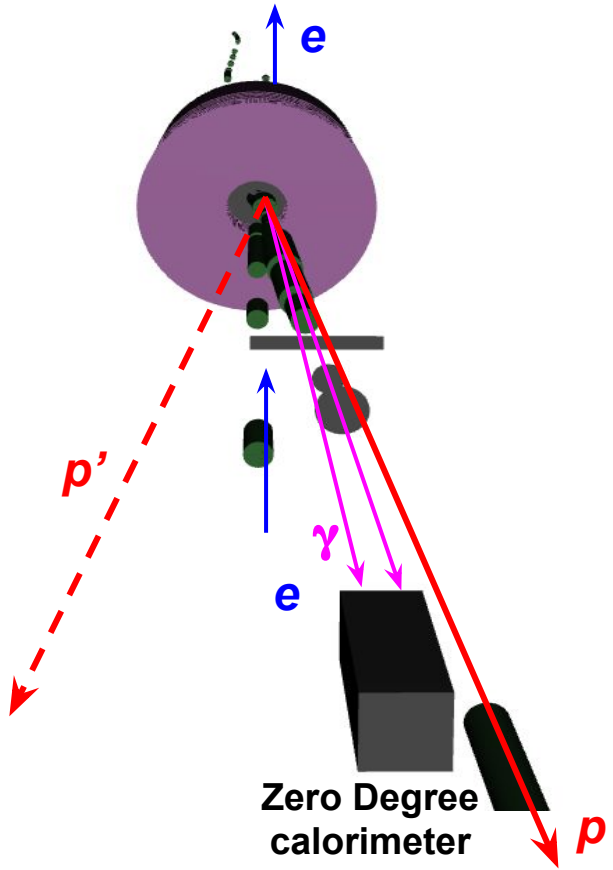


Visualizing u-channel π^0

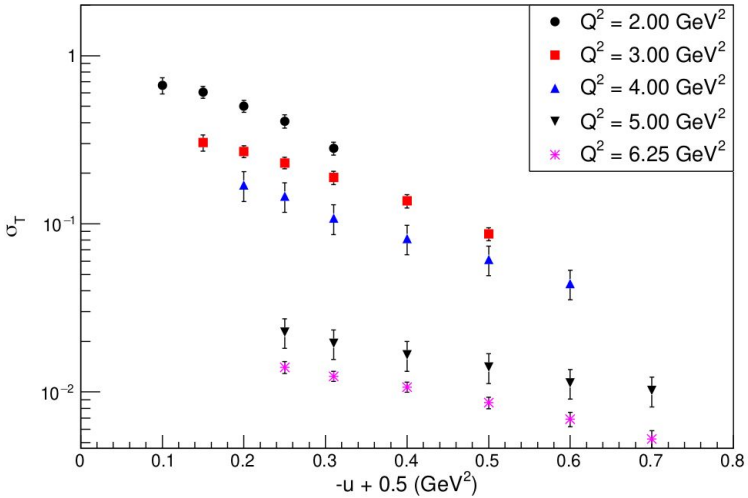
Incoming proton perspective



Incidence electron perspective



Objective 2: *u-dependence*



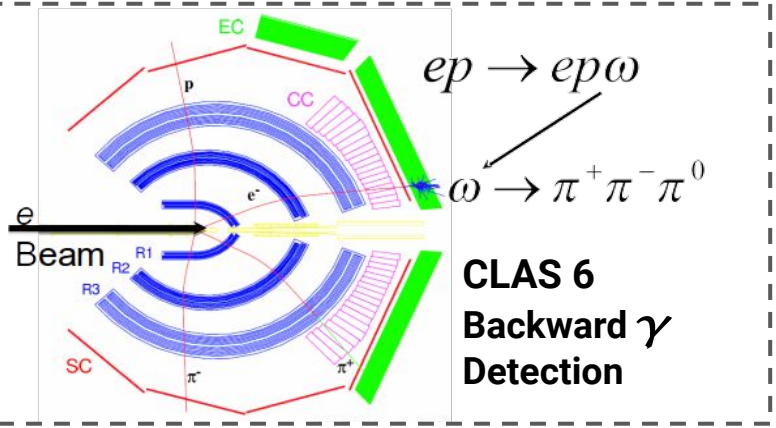
Objective 2: u-dependence of the separated cross section

- **Extracting -u dependence of the unseparated cross section and interaction radius:**

$$\sigma = Ae^{-b \cdot |u|}, \quad r_{int} = \sqrt{b}\,\hbar\, c$$

- **Study of parameter r_{int} as function of Q^2, probe the proton structure transition from hadronic to partonic degrees of freedom.** (Similar to the study by Halina Abramowicz, Leonid Frankfurt, Mark Strikman, arXiv:hep-ph/9503437, 1995.)

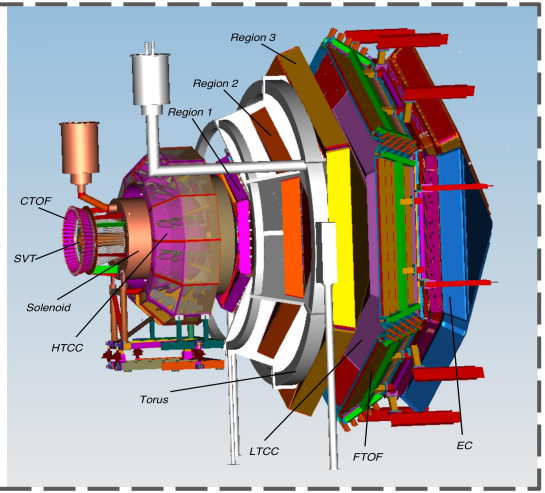
u-Channel Opportunities at CLAS 12



CLAS 6
Backward γ Detection

CLAS 12
No backward γ Detection capability

e beam →

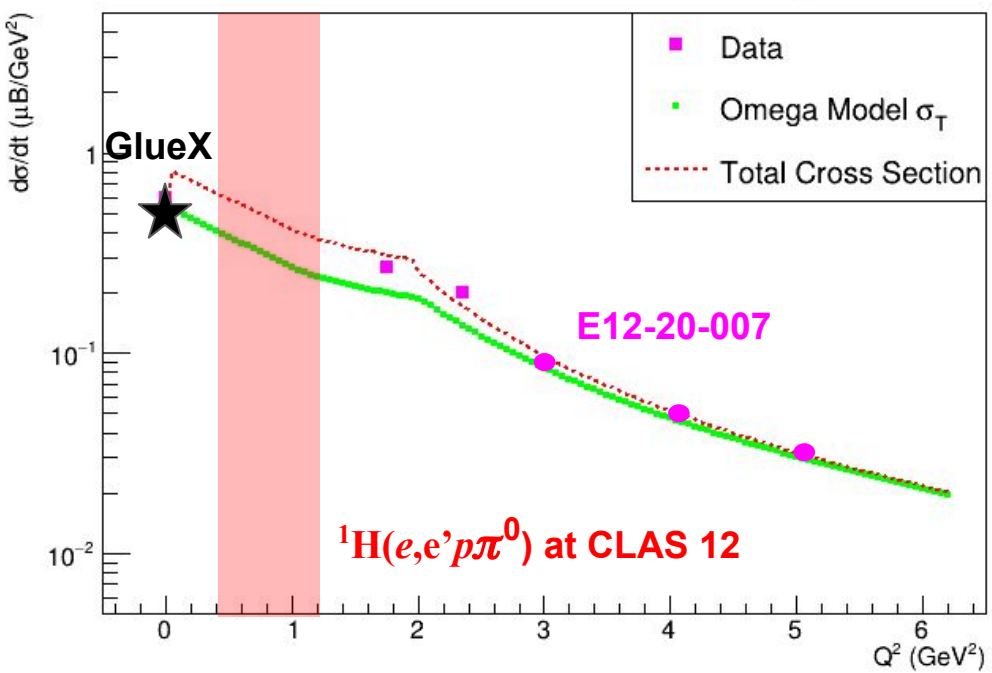


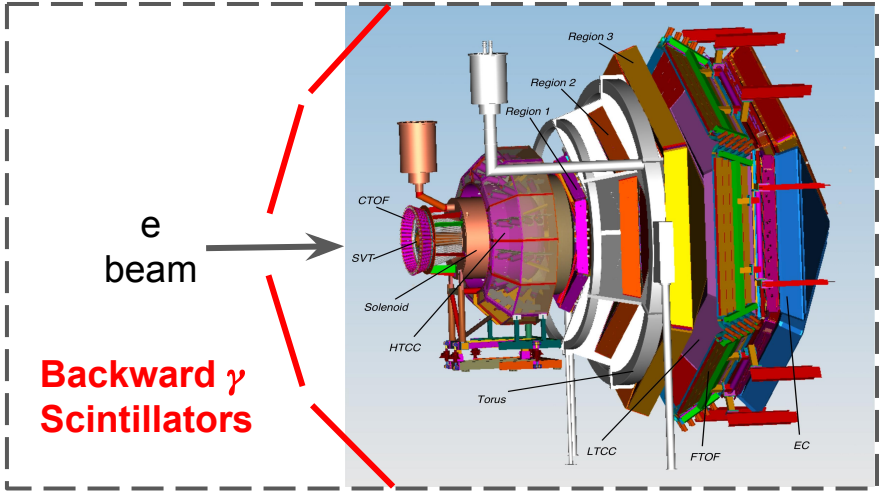
Harvesting u-channel meson production cross section at near u_{min} kinematics at Hall B CLAS 12 (consulted with S. Diehl)

- **π^0: good acceptance for -*t* of 5-6 GeV^2. u-channel measurements not possible.**
- **π^+:** full coverage of the *t* and *u* acceptance.
- **$\rho/\omega \rightarrow \pi^+\pi^-$:** decay well measured, full coverage of the *t* and *u* acceptance.
- **$\phi \rightarrow K^+K^-$:** full coverage of the t and u acceptance, very limited statistics at small *u*.

Possibility to address *u*-channel π^0 issue?

u-Channel Opportunities at CLAS 12





- **Adding Scintillators allows u-channel π^0**
- $0 < Q^2 < 1.2$ GeV kinematics only available with CLAS 12
- Offering unique opportunity

Timeline Recap of Events in Backward Proton Structure Study

- 2000: TDA framework first published
- 2003: JLab 6 GeV experiment collected parasitic ω and π
- 2017: u-Channel ω analysis completed (my graduation)
- 2018:
  - CLAS u-Channel π^+ published
  - u-Channel π^0 letter of intent submitted to JLab PAC
- 2019: u-Channel ω result published
- 2020:
  - CLAS 6 u-channel π^0 Beam Spin Asymmetry result published
  - u-Channel π^0 full proposal approved by PAC
  - JSA Post-doctoral Award given to *u*-channel programs
  - JLab EIC fellowship awarded to investigate *u*-channel π^0 at EIC
  - First u-channel physics workshop was hosted
- 2021 (present): EIC yellow report published with *u*-channel π^0 study
- 2025: Experiment E12-20-12 runs at Hall C
- 2030: Physics start at EIC, data available for u-channel π^0