2020 Backward-angle Physics Workshop: u-channel π^0 Production from JLab 12 GeV to EIC

Wenliang (Bill) Li

William and Mary Postdoctoral Researcher

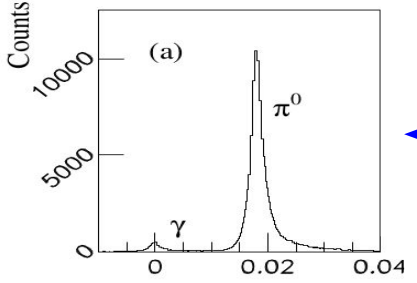
Wenliang Li, Dept. of Physics, William and Mary, Williamsburg, VA 23185, USA.

Outline

- Introduction to the backward π^0 physics
  - Few 6 GeV measurements
- Backward π^0 production at JLab 12 GeV
  - Newly approved E12-20-007
- Backward π^0 production at EIC
  - Preliminary studies (part of Yellow Report)

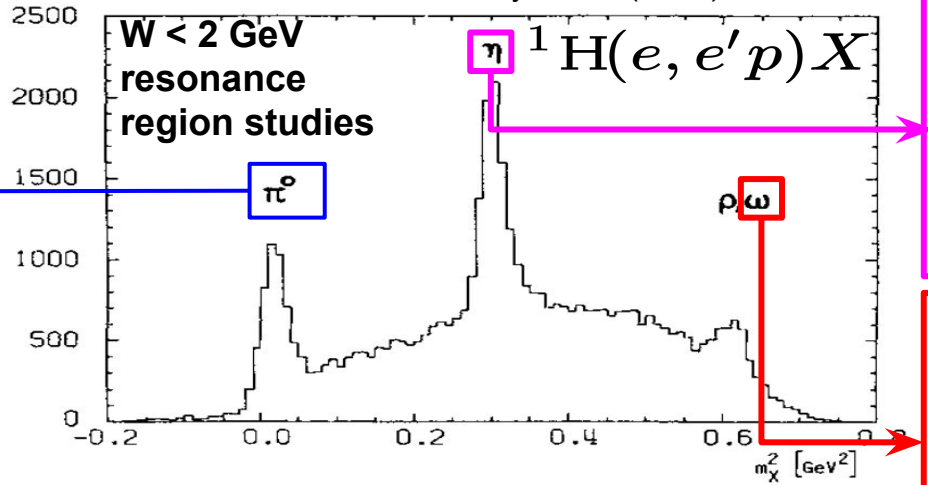
6 GeV Backward Angle Physics at W < 2 GeV

G. Laveissière et al. Phys. Rev. C 79, 015201 (2004)



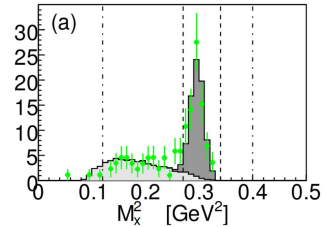
Hall A VCS experiments:
E93-050
E00-110
Hall C: E01-002

F. W. Brasse et. al. Z. Phys. C22 (1984) 33



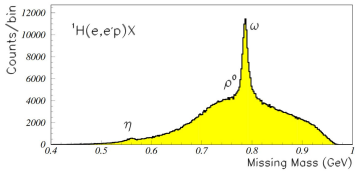
DESY spectrometer experiment

M. Dalton et al. Phys. Rev. C 80, 015205 (2008)



Hall C E01-002

P. AmbrozwiczPhys. Rev. C 70, 035203 (2004)



Hall C E91-016

- **Accessing Backward Angle (CM) meson is not a new concept via missing mass distribution**
- **Common features: Resonance region studies.**

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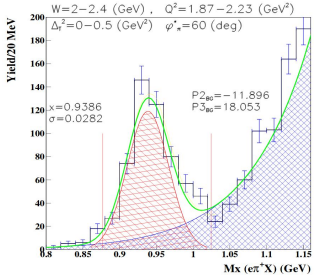
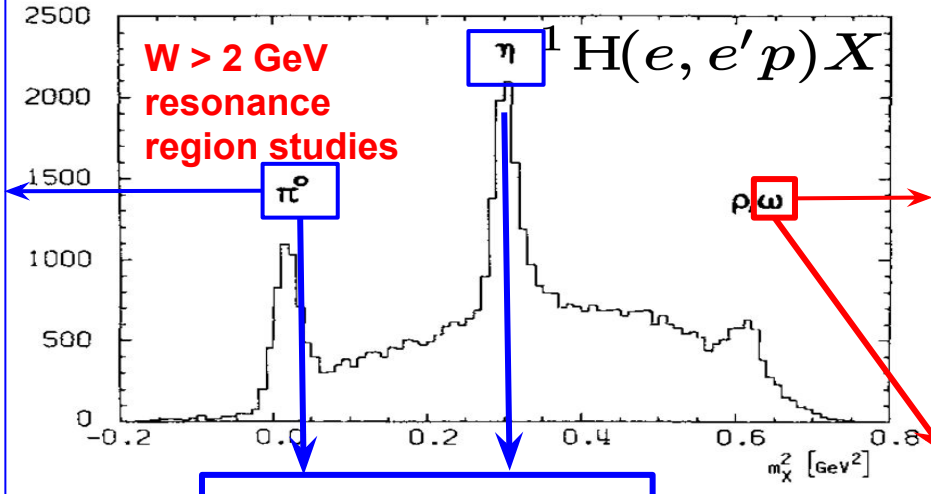
6 &12 GeV Backward Angle Physics at W > 2 GeV

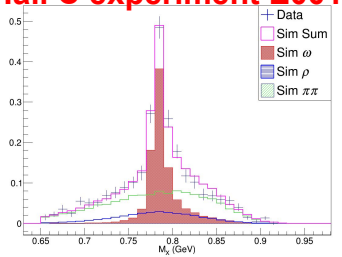
Charged Pion Production from CLAS 6



- $^1H(e, e'\pi^+)X$
  - Talk by K. Park
- $^1H(e, e'\pi^0)X$
  - Talk by S. Diehl



Hall C experiment E001-004



- $^1H(e, e'p)X$
  - Talk by G. Huber

12 GeV $^1H(e, e'p)\pi^0$
- E12-20-007
- This talk

12 GeV $^1H(e, e'p)X$
- E12-09-011
- S. Kay's Talk

- Backward angle in this talk: backward angle physics above the resonance region ($W>2$ GeV^2)
  - $u' \rightarrow u_{min}$, $t > Q^2$
- This talk is about an example of e+p→ e' + p'+ π^0
  - JLab 12 → EIC (Q^2 scaling route)

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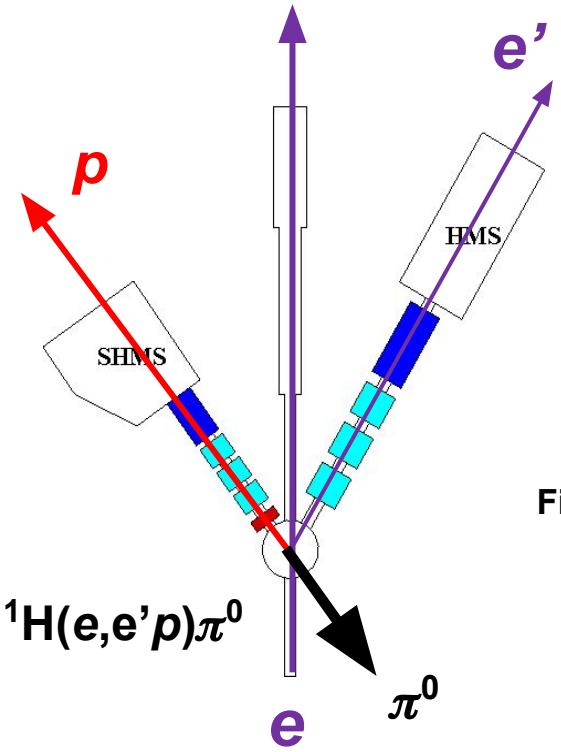
E12-20-007 Backward-angle $^1H(e,e'p)\pi^0$ at Hall C



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**
- **E12-20-007 is approved by PAC 48 with 29 PAC days of running! (First dedicated u-channel study at JLab)**

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Particle Identification

HMS as *e* arm (most settings)

- Standard *e* PID, HGC < 1 atm various pressure
- Aerogel: n=1.0011 tray for proton ID (for e- detection setting)

SHMS as proton arm (most settings)

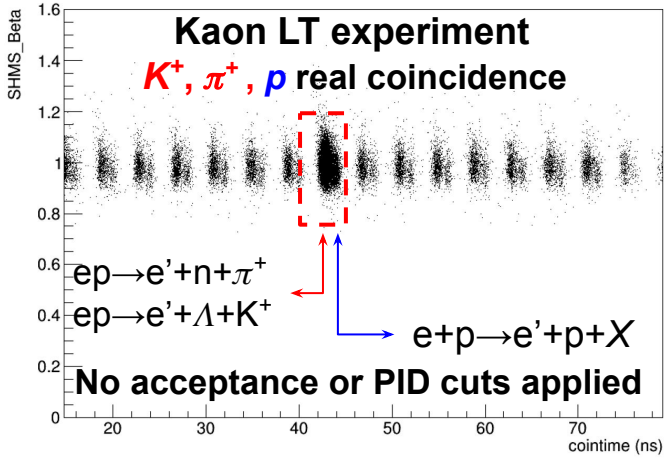
- NGC installation (for e- detection setting)
- HGC: 1 atm vetoing π and K
- Aerogel: n=1.0003 tray for proton ID (threshold cut at 3 p.e.)

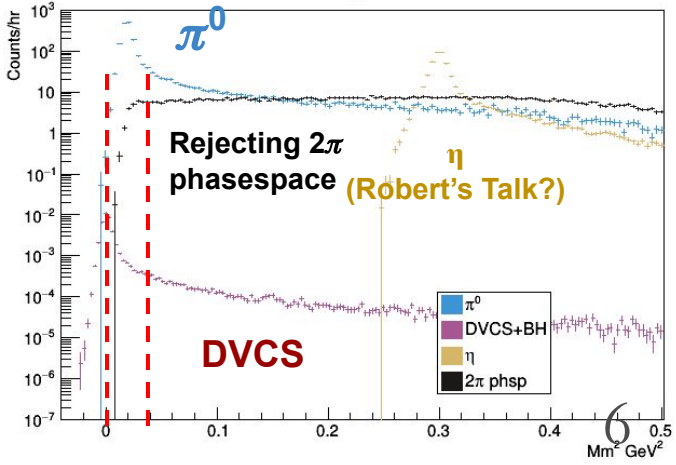
SHMS β vs Coincidence timing structure:

- Coincidence timing is the primary method for the proton

Primary Physics Background

- Two pion exchange phase-space
- DVCS





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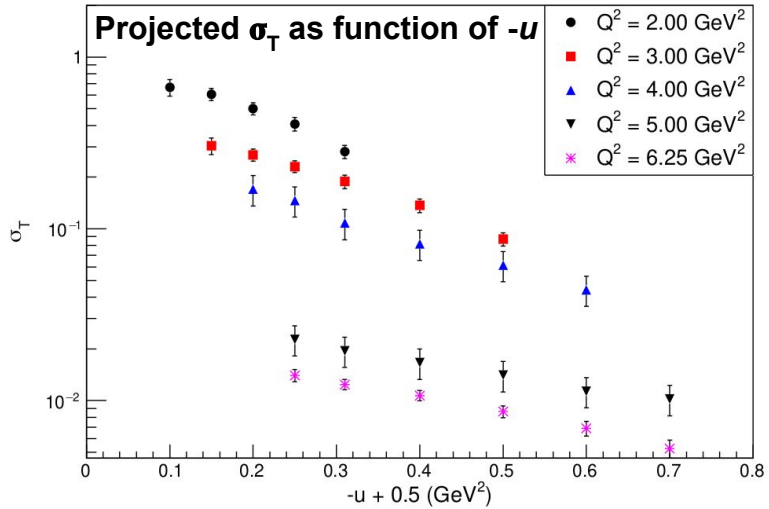
Main objective #1: Soft-hard Transition Predictions



Objective #1: u-dependence of the separated cross section

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

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

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

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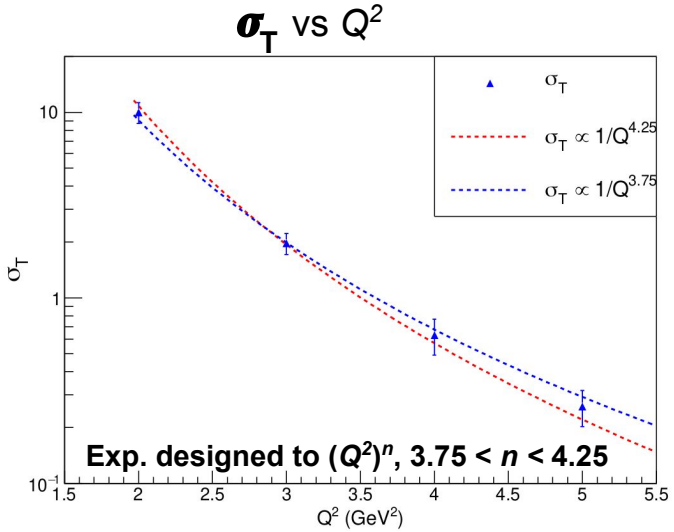
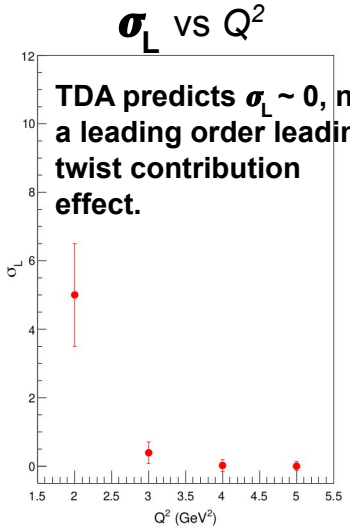
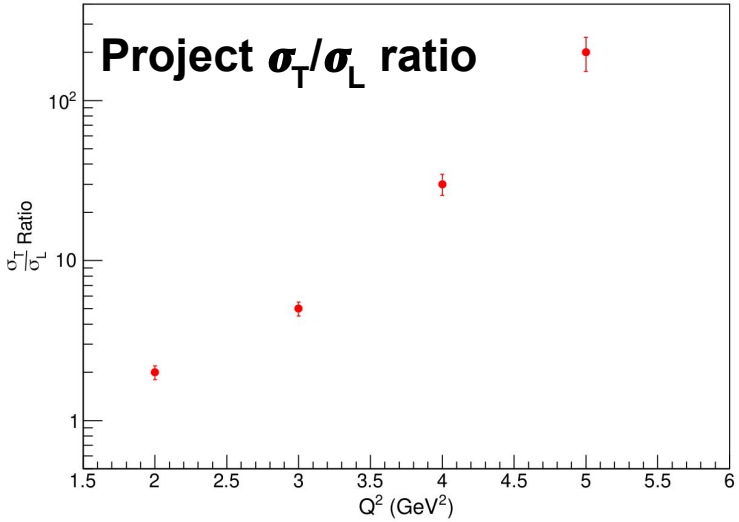
Main objective #2: TDA Predictions







- **The end results from the measurement will**
  - **Confirm if $\sigma_T >> \sigma_L$, as it was predicted by TDA (see Kirill's presentation)**
  - **Confirm $\sigma_T \propto 1/Q^8$ as it was predicted by TDA**
- **Gain insights regarding soft-hard transition.**
  - **No definitive conclusion based on single channel (must combine with ω result)**

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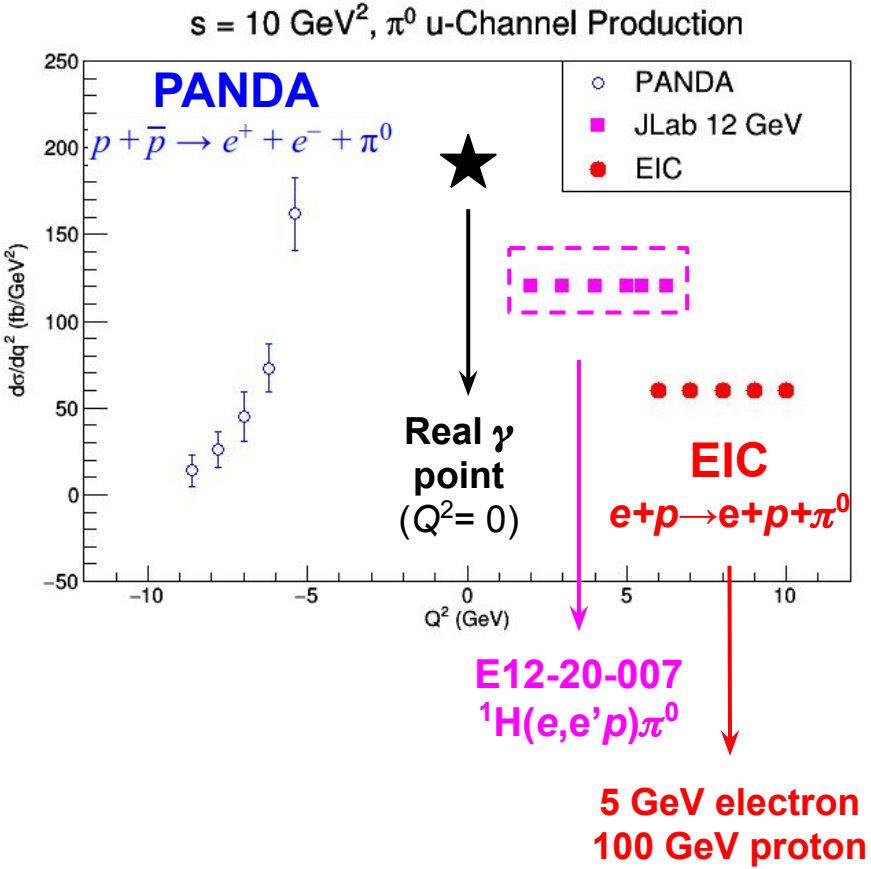
Prospect of *u*-channel π^0 Study at s=10 GeV^2



- **PANDA**
  - **proton anti-proton annihilation**
  - **S. Diehl's talk**
- **JLab 12 GeV: E12-20-007**
  - **^{1}H(e,e'p)π^0, a simple measurement**
- **Future Electron-ion Collider (EIC)**
  - e-p collision: **e+p→e+p+π^0**
  - L/T separation not required if **$\sigma_T >> \sigma_L$, is demonstrated by E12-20-007**
- **Real photon**
  - no *u*-channel data available
  - See next slide

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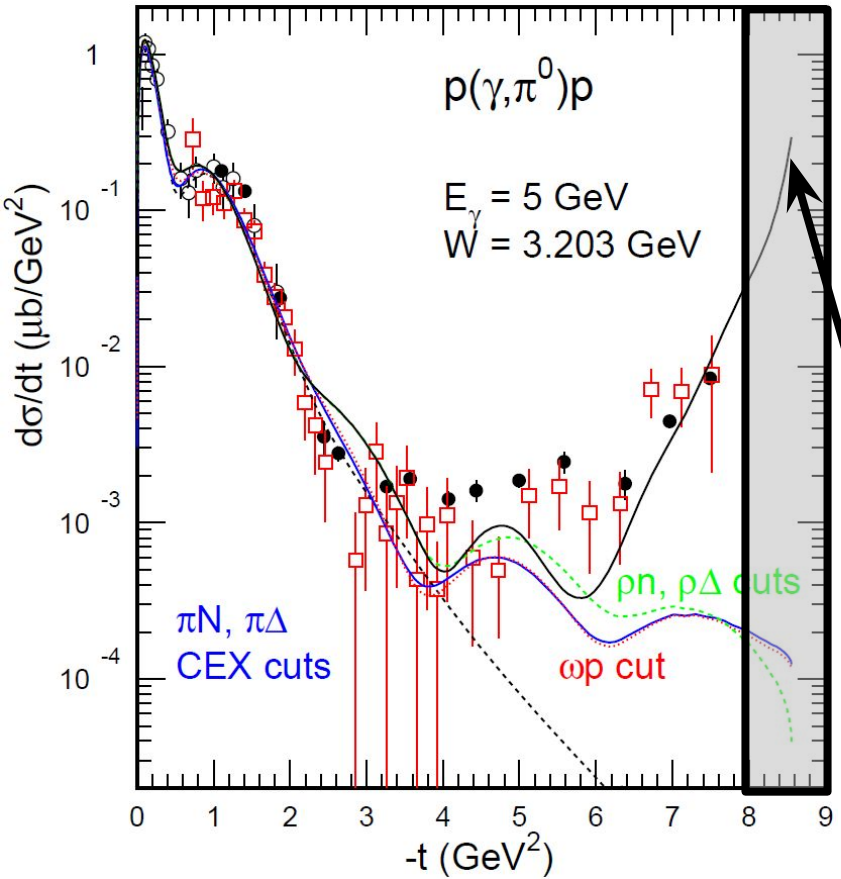
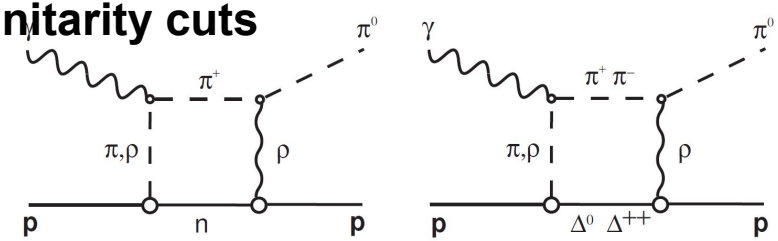
π^0 Production Measurement via Real Photon

L.M. Laget, Progress in Particle and Nuclear Physics 111 (2020) 103737



- **$p(\gamma, \pi^0)p$ study as function of $-t$, s~10 GeV^2**
  - Open circles: DESY data
  - Open squares: 6 GeV CLAS data
  - Full circles: SLAC data
- **Slide line = baryon pole + rescattering unitarity cuts**



- **a *u*-channel peak is anticipated real photon**
  - No measurement available yet
  - Open question: would the γ^* extrapolate to the real photon point?

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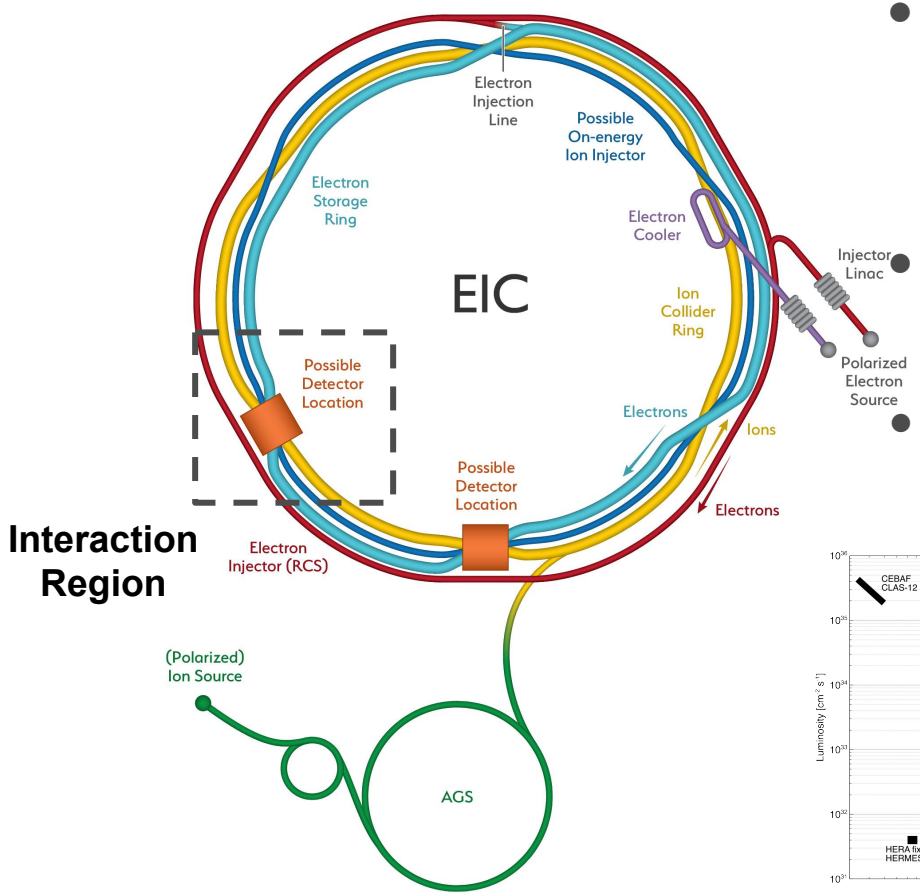
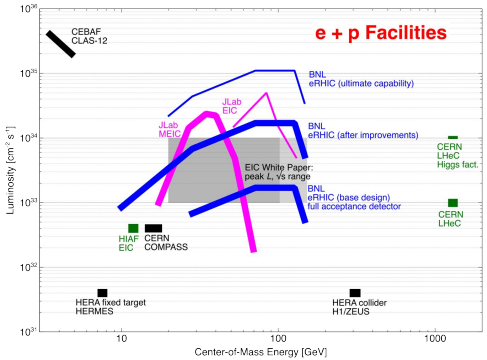
BNL-EIC Project

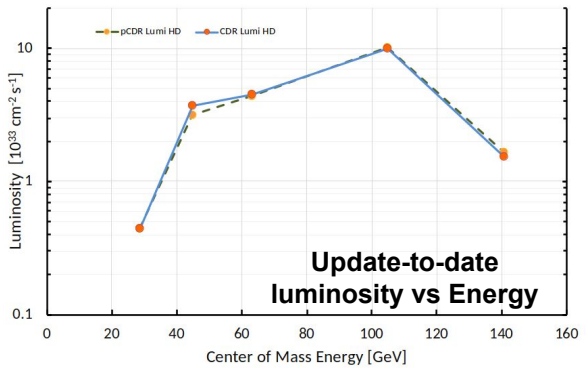


- **Next generation Electron-Ion Collider (EIC)**
  - Current consists of 1 interaction region (IR)
  - Luminosity with 100 GeV p on 5 GeV e: 10 x10^{33} $cm^{-2}s^{-1}$

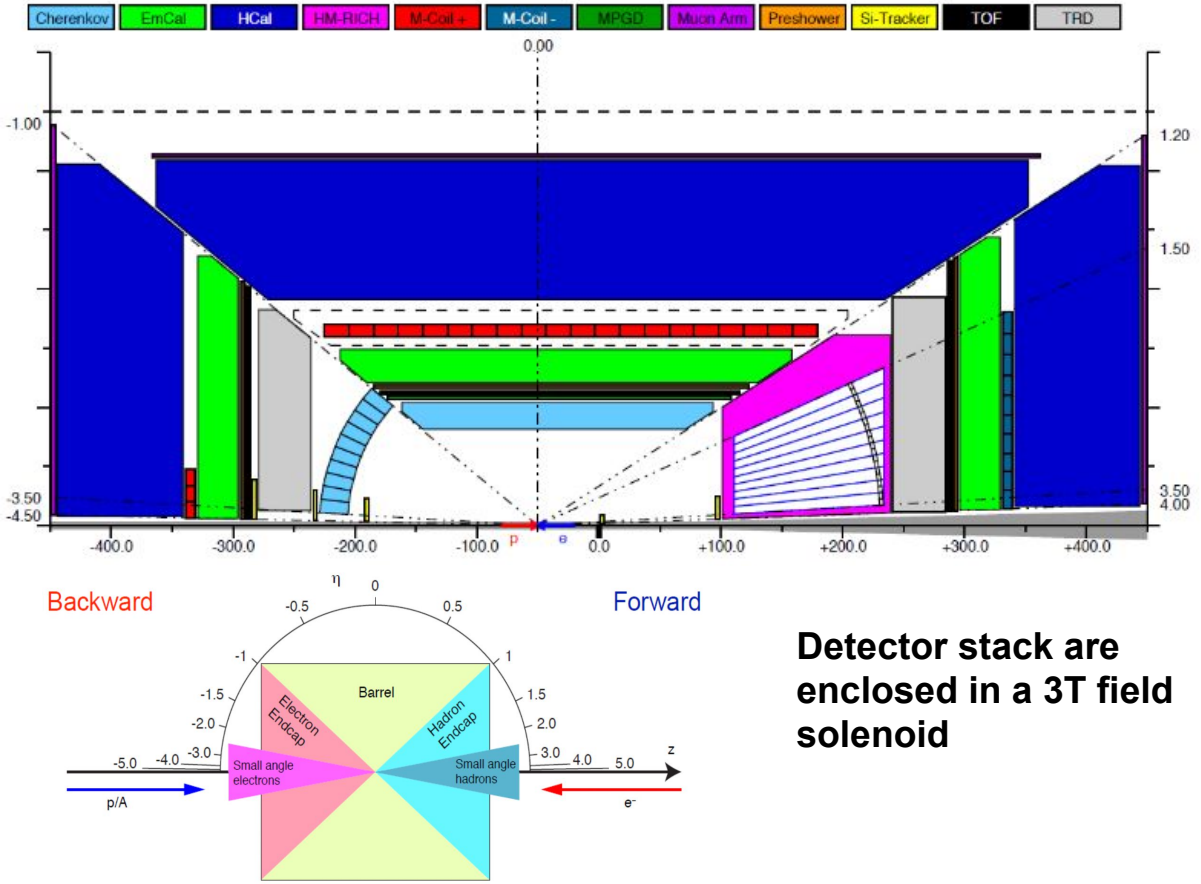
- **Project location:**
  - Brookhaven National Lab (BNL), NY

- **Project information:**
  - CD-0 approved ~ $2 B
  - Completion in ~10-15 years





EIC Central Detector Update-to-date Concept



Detector stack are enclosed in a 3T field solenoid

Hadron End Cap

- $\eta > 1$ (~45 Degrees)
- HCal + EmCal
- RICH
- Tracking

Electron End Cap

- $\eta < -1$
- HCal+EmCal
- Tracking
- Cherenkov PID

Barrel Calorimeter

- $-1 < \eta < 1$
- Not needed for the *u*-channel
- Used as veto

Zero-degree Calorimeter (not shown)

- Expecting neutral particles

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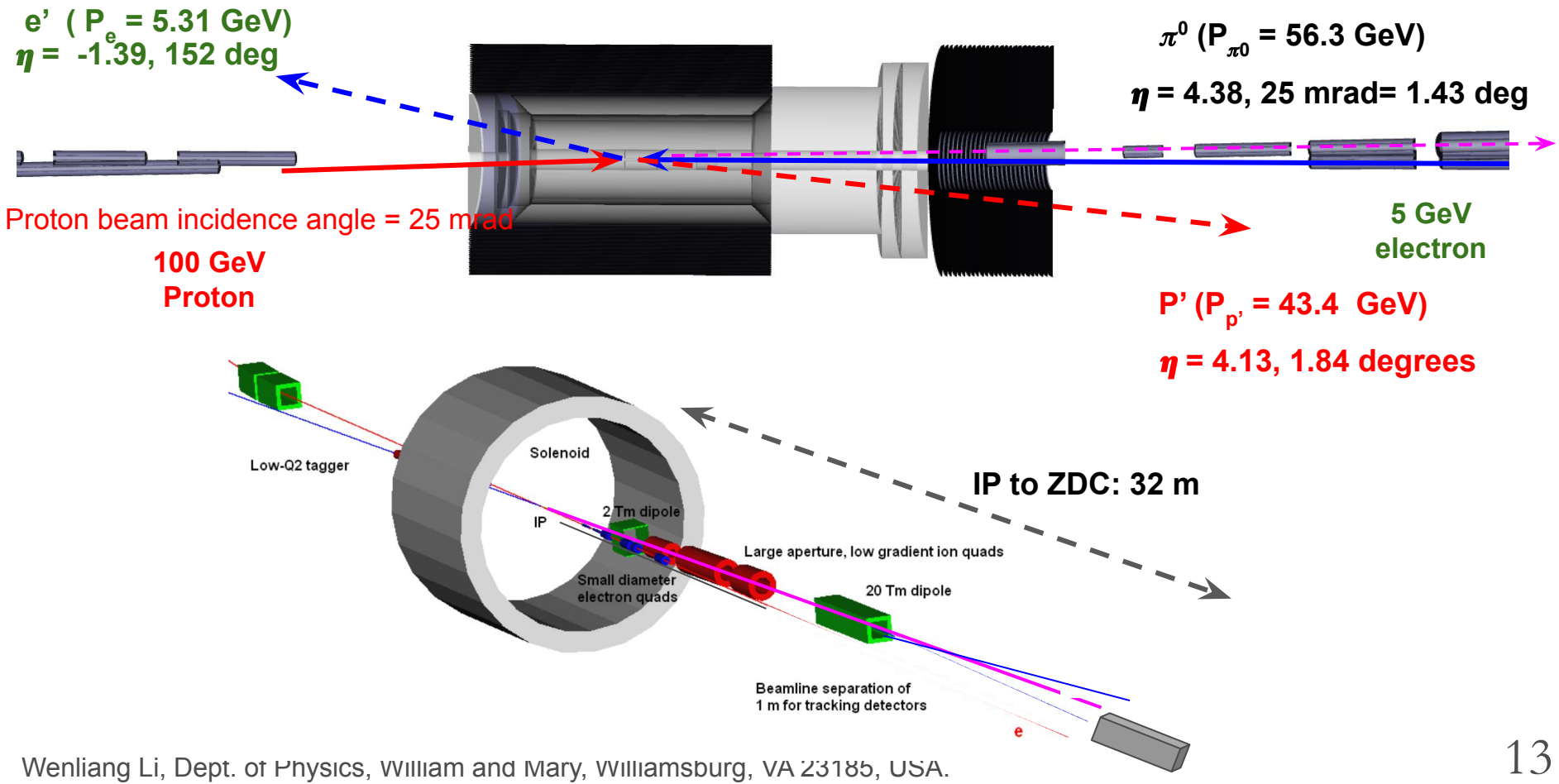
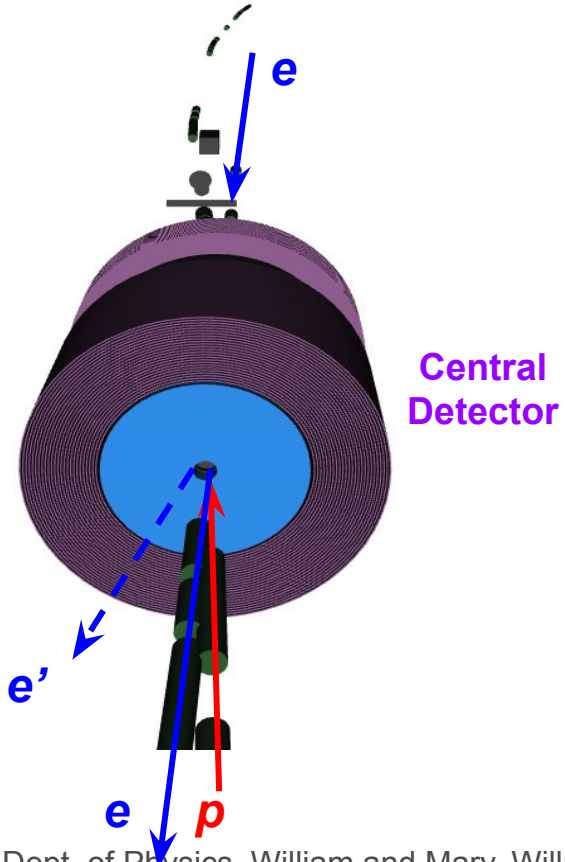
Interaction picture

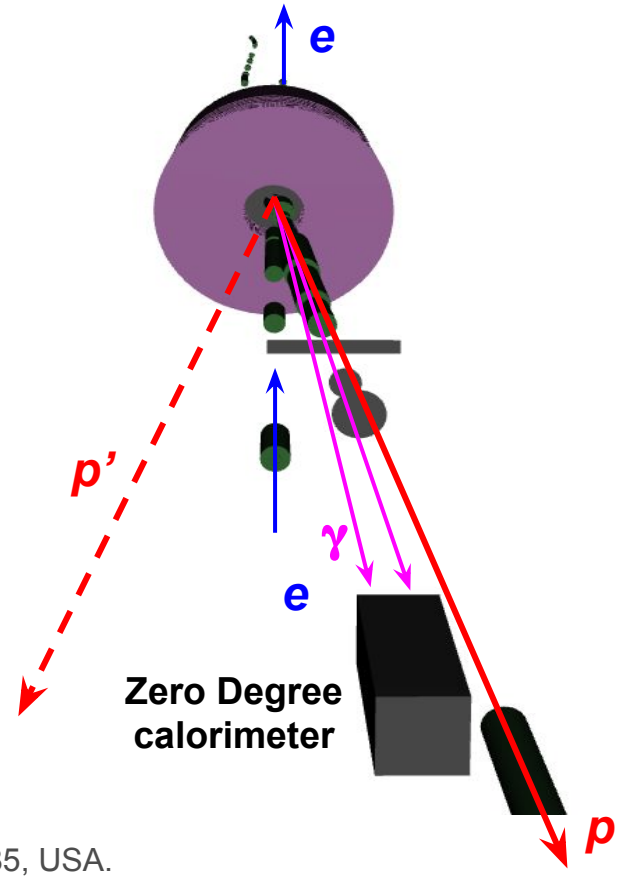


Visualizing u-channel π^0

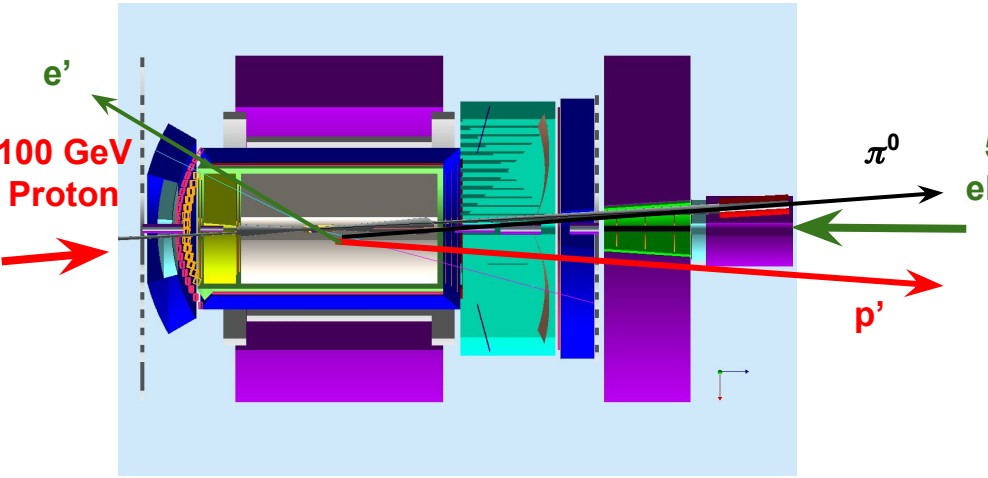
Incoming proton perspective



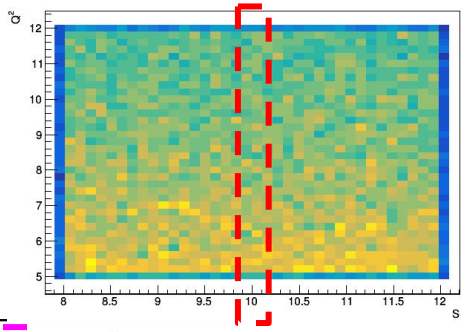
Incidence electron perspective

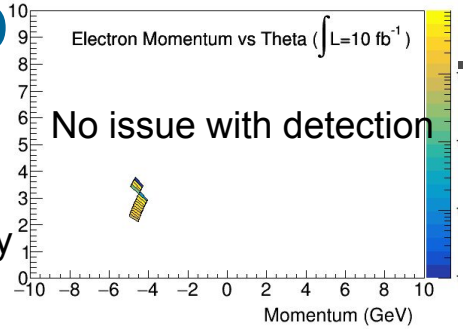


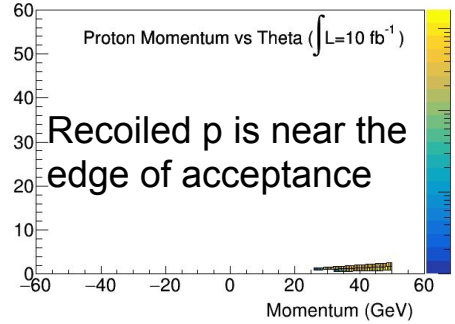
U-channel Meson Production Setup

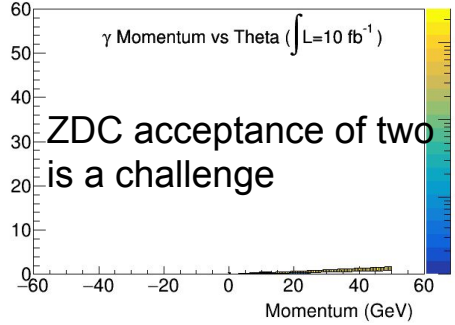


Q^2 vs S intentionally constrained









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

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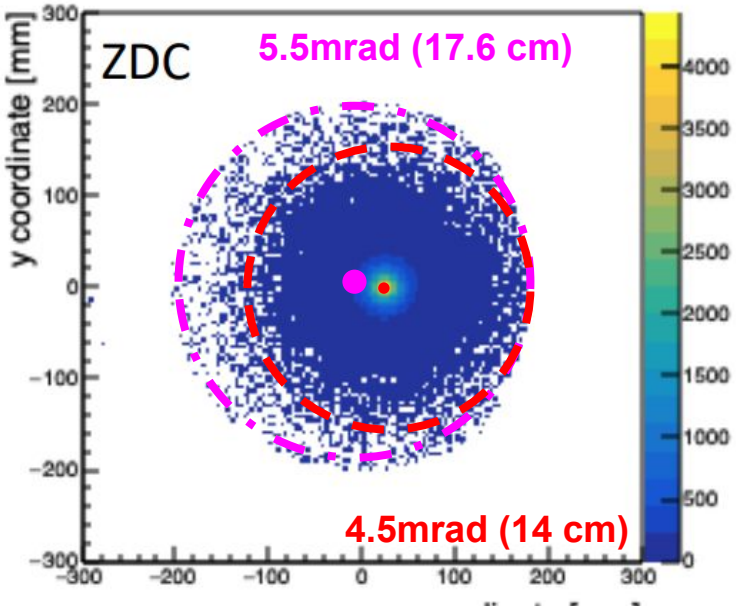
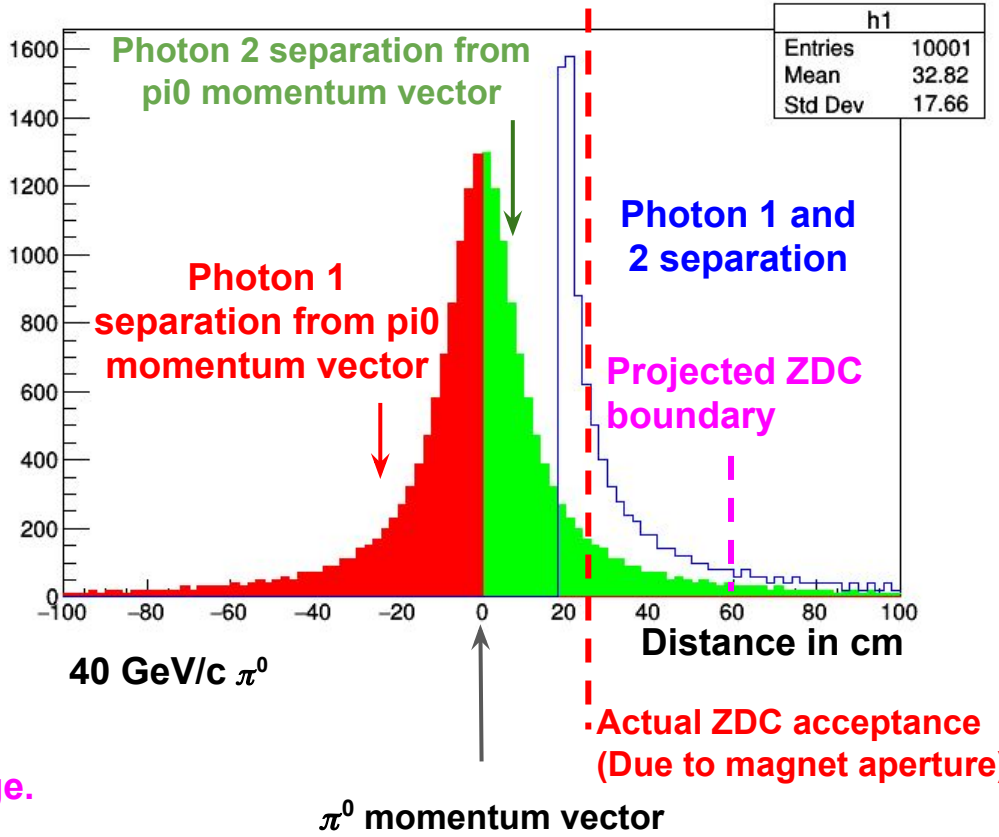
Realistic ZDC Acceptance (through magnets Aperture)

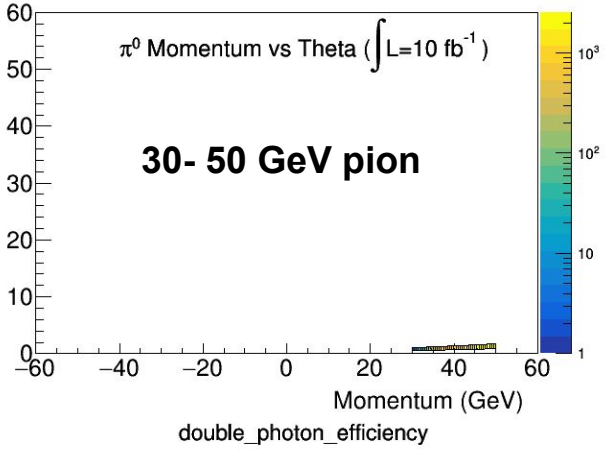


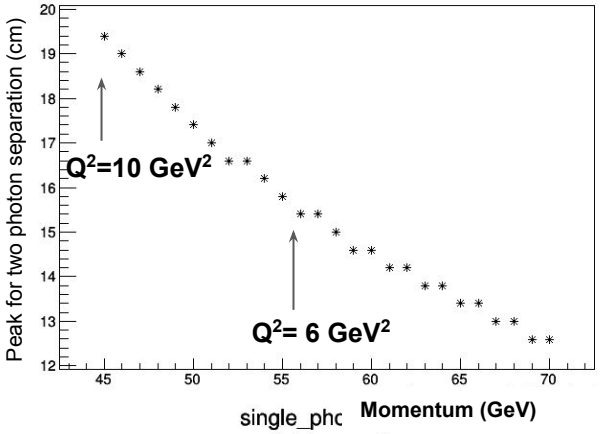
DVCS simulation with deuterium, spectating neutron distribution on ZDC, from Alex

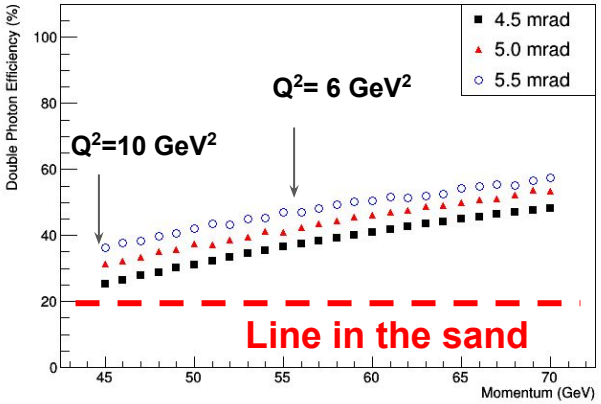
A slight shift in -u' will give us larger coverage.

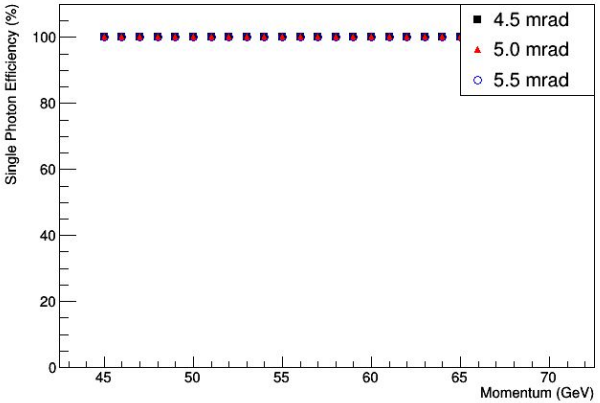


$\pi^0 \rightarrow 2\gamma$ Detection at ZDC







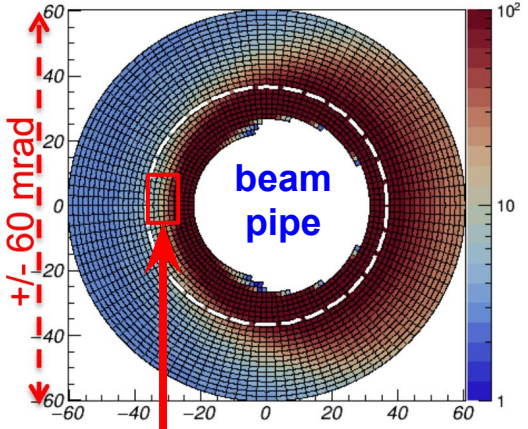


- Double photon efficiency for the nominal π^0 event is larger than 20%
- Detector (magnetic aperture) constrains:
  - Fixing center of the neutral particle at ZDC
  - Ensuring largest possible symmetrical acceptance

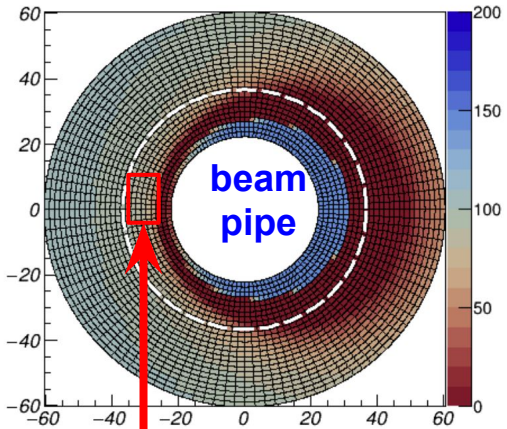
Recoil Proton Detection

Figures created by Alexander Kiselev

Material in acceptance, [%]



Max space available for Si tracker, [cm]



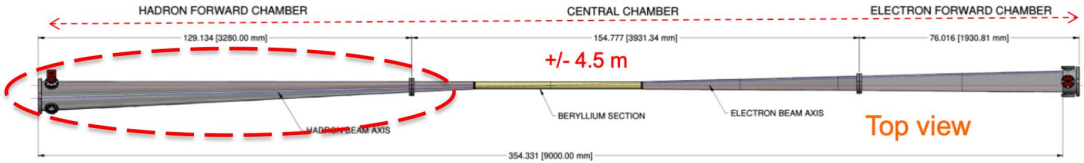
Recoiled *p* detection region $|\eta| < 4.15$

White Circle: $|\eta| = 4.0$

$\|\eta\| = 3.00$	$\|\eta\| = 3.50$	$\|\eta\| = 4.00$	$\|\eta\| \sim 4.38$	$\|\eta\| = 4.50$
~99.5 mrad	~60.4 mrad	~36.6 mrad	25.0 mrad	~22.2 mrad

Proton End Cap constrain

- Recoiled proton $|\eta| < 4.13$
- Limited detector acceptance near the incidence electron and outgoing proton beam pipe
- Preliminary assessment: Acceptance is feasible with reduced efficiency, further simulation work is required.



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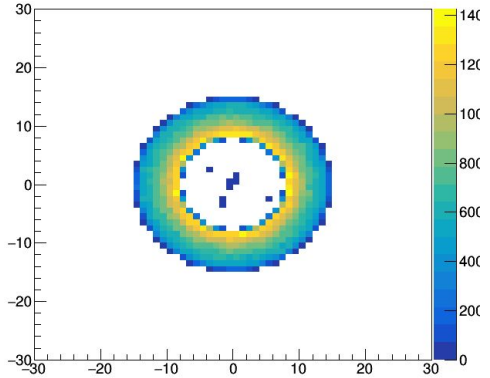
Physics background (to our current best knowledge)

- 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: Δ->n+π^0

2 γ hit pattern

40 GeV/c π^0

4.5 mrad acceptance

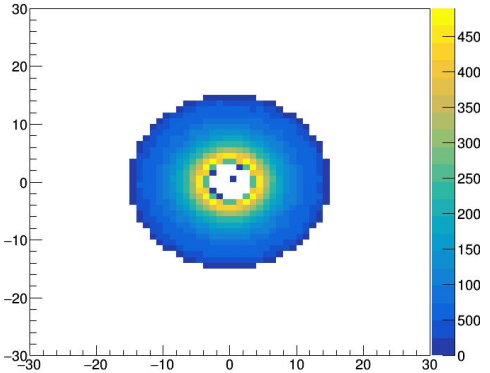


- Single photon case:
  - Primary reaction: e+p-> e'+p' + π^0
  - Ideal expected trigger: e'+p'+ γ
  - Physics background: DVCS, eta,Δ->n+π^0
  - Less than ideal trigger: e'+γ
  - Background: many possibilities

2 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

Conclusion and Thank you !

- **Exclusive *u*-channel π^0 at proposed *s* =10 GeV^2 is a feasible measurement**
  - Prefered (golden) observable e'+p' + 2γ is achievable !
  - To be included in the EIC Yellow Report as an example

- **Large kinematics available at EIC can support *u*-channel *W* scaling study (while fixing Q^2) with u-channel π^0 with current IR and detector design.**

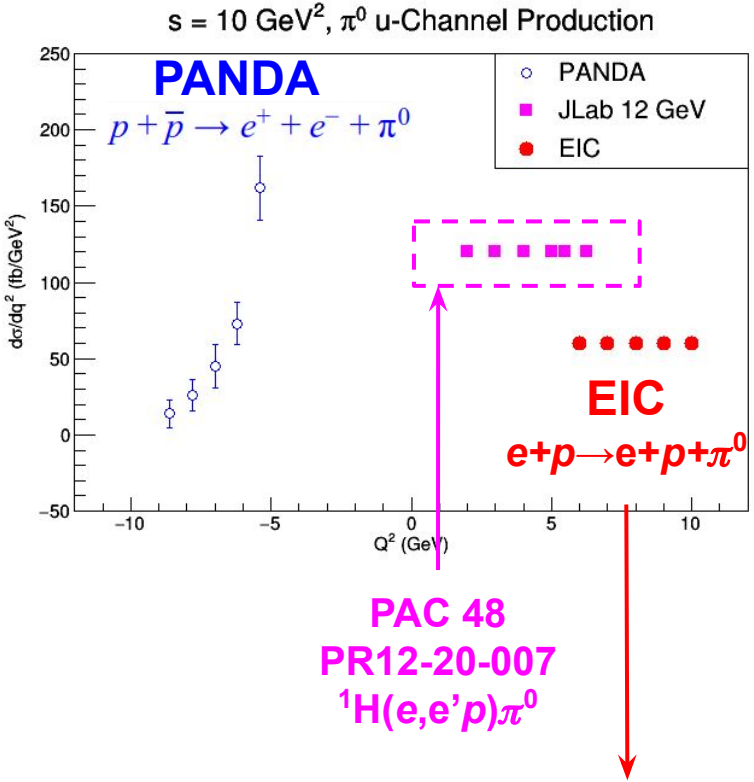
- **L/T separation capability is to be determined (likely to be very challenging)**

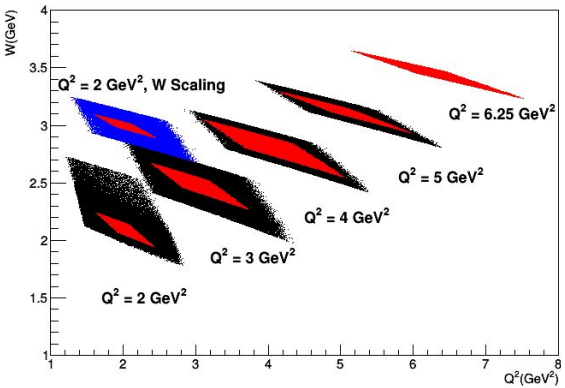
- **Feasibility of other mesons such as η and ω is to come**

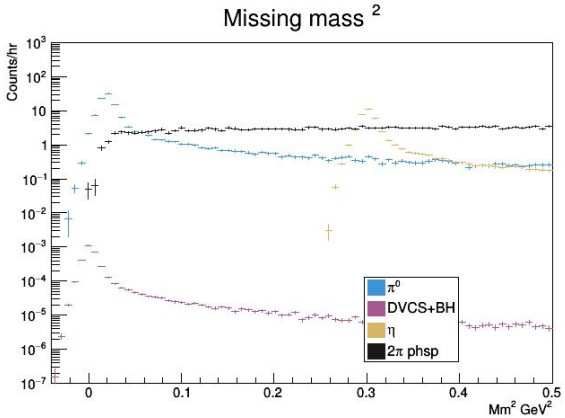
Wenliang Li, Dept. of Physics, William and Mary, Williamsburg, VA 23185, USA.

Wenliang Li, Dept. of Physics, William and Mary, Williamsburg, VA 23185, USA.

PR12-20-007 Submitted PAC 48







Proposal PR12-20-007 submitted to PAC 48

- A standard JLab Hall C L/T separation measurement: $^1H(e,e'p)\pi^0$

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

- Q^2 coverage: $2.0 < Q^2 < 6.25$ GeV², at x=0.36 and W > 2 GeV L/T separated cross section @ Q^2= 2, 3, 4 and 5 GeV².
- u coverage: $0 < -u' + 0.5 < 0.5$ GeV²
- Additional W scaling check @ $Q^2 = 2$ GeV²
- Additional Q^2 scaling check @ $Q^2 = 6.25$ GeV²

EIC $e+p \rightarrow e+p+\pi^0$ for 5 GeV e on 41 GeV p

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

5 GeV e on 100 GeV p

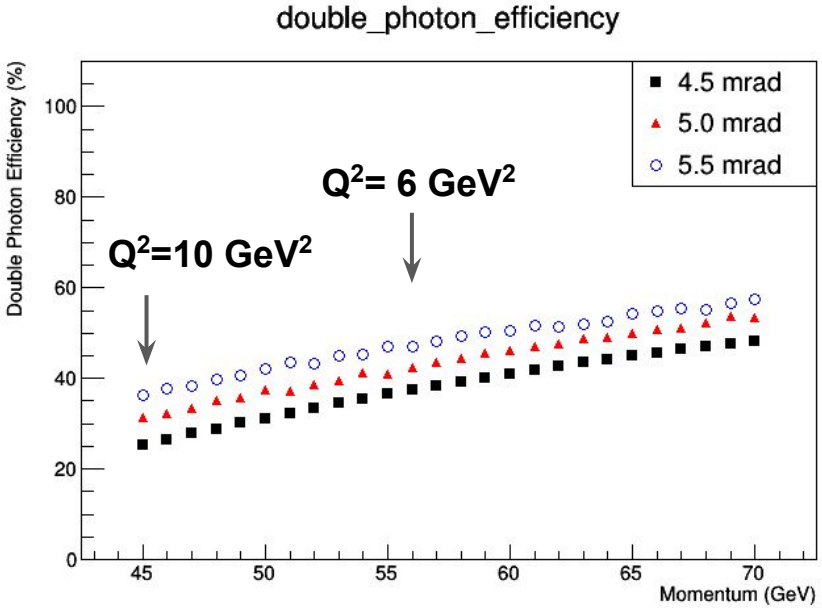
Q^2 (GeV^2)	W (GeV)	x_B	$\theta_{e'}$ (deg)	$\eta_{e'}$	$P_{e'}$ (GeV)	$\theta_{p'}$ (deg)	$\eta_{p'}$	$P_{p'}$ (GeV)	θ_{π^0} (deg)	η_{π^0}	P_{π^0} (GeV)	$-t$ (GeV^2)	$-u$ (GeV^2)
6.1	3.15		152	-1.39	5.25	-6.54	2.86	17.69	1.43	4.38	23.05	14.67	-0.37
7.1	3.14		150	-1.32	5.29	-6.55	2.86	18.97	1.43	4.38	21.73	15.61	-0.40
8.1	3.14		148	-1.24	5.34	-6.67	2.84	19.96	1.43	4.38	20.69	16.83	-0.42
9.1	3.14		146	-1.19	5.39	-6.71	2.84	21.16	1.43	4.38	19.44	17.90	-0.44
10.4	3.19		144	-1.12	5.43	-7.72	2.70	19.95	1.43	4.38	20.61	21.29	-0.42

5 GeV e on 41 GeV p

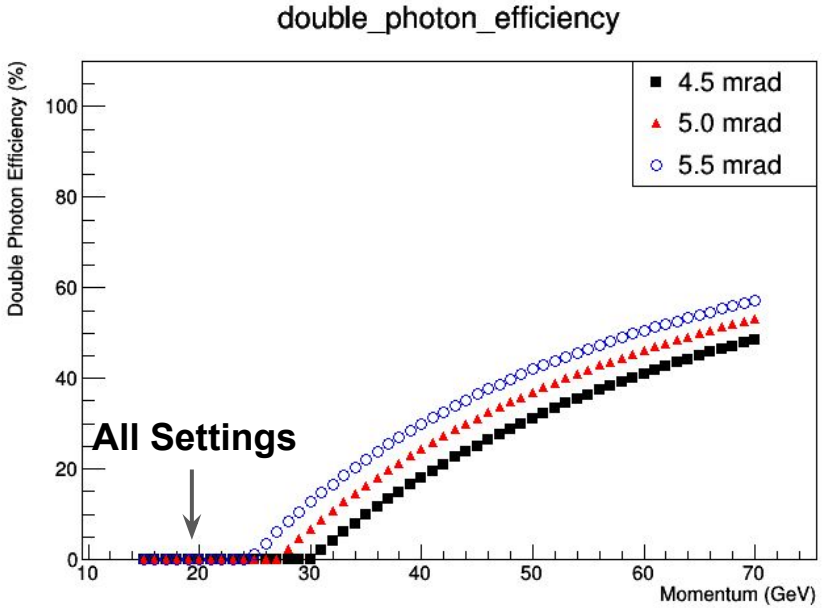
Much improved

Momentum too low!

EIC $e+p \rightarrow e+p+\pi^0$ for 5 GeV e on 41 GeV p



5 GeV e on 100 GeV p



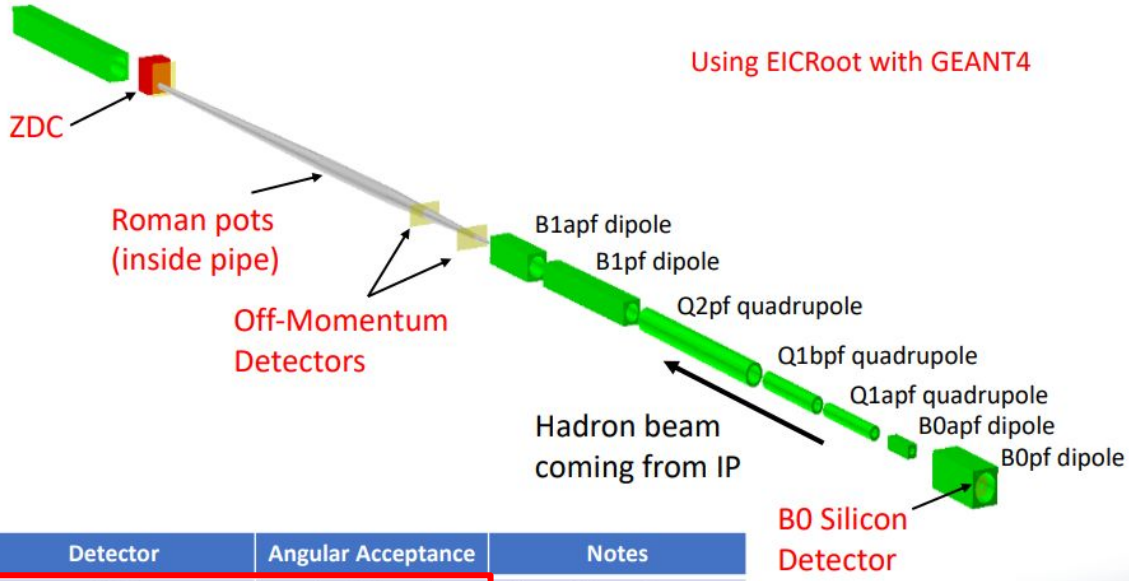
5 GeV e on 41 GeV p

Conclusion:

- No double photon detection on the ZDC!
- Proton will be at a more optimal angle
- 5 GeV e on 100 GeV p is more optimal.
- The setting configuration of 10 GeV e on 100 GeV p is similar

From Pavia Meeting

Central Integration – Beam Pipe



Detector	Angular Acceptance	Notes
ZDC	θ < 5.5 mrad	About 4.0 mrad at $\varphi \sim \pi$
Roman Pots	0.0 < θ < 5.0 mrad	Need 10σ cut.
Off-Momentum Detectors	0.0 < θ < 5.0 mrad	Roughly .4 < x_L < .6
B0 Sensors	5.5 < θ < 20.0 mrad	Still need to optimize.

$$x_L = \frac{p_{z,nucleon}}{p_{z,beam}}$$

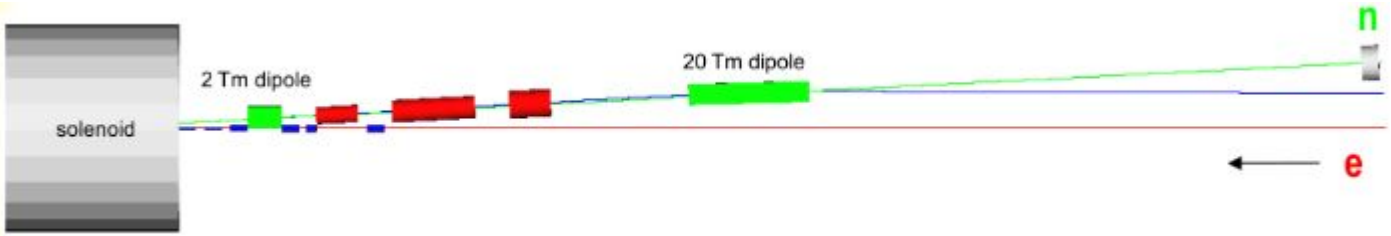
Slide from Alex Jentsch

4

This corresponds to 17.6 cm radius circle at 32 meters from IR! much smaller than expected 60x60 cm^2 square!

What does this mean for the two photons?

Detecting a 20-50 GeV pi0



- At 20-50 GeV, π^0-> 2 gamma decay angle (between two photon) is 0.8-0.4 degree.

- Best way to detect π^0 at neutro $\sin\theta_{\max} = \frac{m_\pi}{2E_\gamma}$ we need to insert lead to slow down π^0? Resolution needed to distinguish pi0 from single photon DVCS events?

- Simulation is needed to answer these questions

- Some feedbacks and suggestions from experts:
  - Abhay: PHENIX central arm, 5 meters from IR. pi0->2photon separation at about 20 GeV. Our calorimeter granularity 2.7 cm square facing the IR.
  - Elke: In Star, ECal at 7m and separate pi0 up to 60 gev
  - Preshower to the calorimeter?

Question and Discussion

- How ready is fast-smear and full simulation for the tagging detector to perform photon/neutron PID study?
- Small angle proton detection, complications?
- Backward π^0 is just the beginning
  - Study on u-channel η, ω, π^+ is in the plan (not inclued in YR)
  - Our currently knowledge of *u*-channel physics in the DIS region almost none
    - Unknown *W* dependence (EIC possible)
    - Unknown x_B dependence (EIC + 12 GeV possible)
    - Unclear -*t* dependence (EIC possible, but required significant modification to ZDC, bigger ZDC)
    - L/T Separation possibility? (Need more study)
- More and more *u*-channel data will come out of 12 GeV, on all meson production channels
- Would be there a universality (*t*-channel and *u*-channel) effort in the EIC era?