u-Channel Processes at EIC

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@ APCTP EIC Workshop

03/Nov/2022

Stony Brook University

Center for Frontiers in Nuclear Science

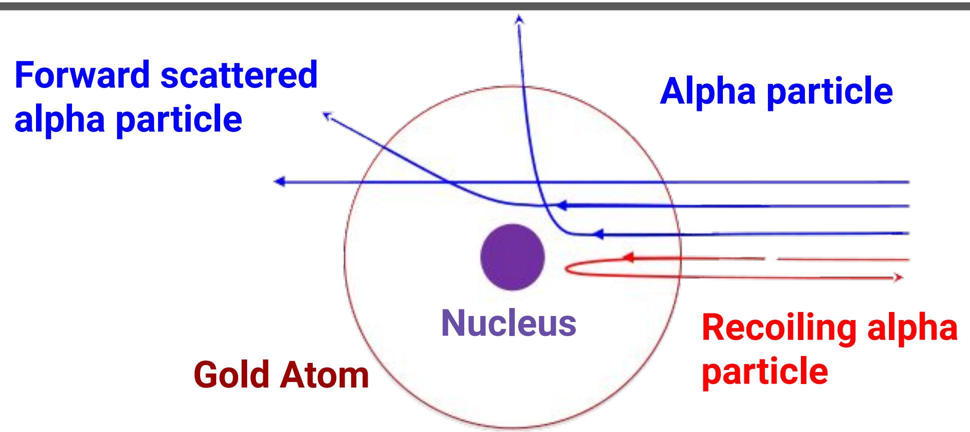
Talk Objective

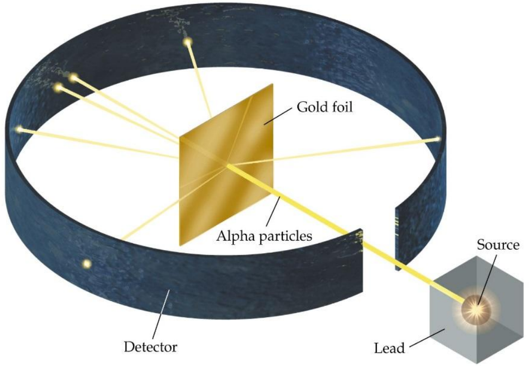
- GPD vs TDA, and what we could obtain from the study
  - Where is the factorization theme limit?
  - Could we have universality issue?

Significant Korean involvement and leadership

- JLab setup vs EIC
  - Why EIC could perform this measurement “naturally”
- What is actually possible for u-channel observable
  - DVMP
  - DVCS
  - Asymmetry measurements
  - Nuclear Transparency

Backward-angle structure of Atom

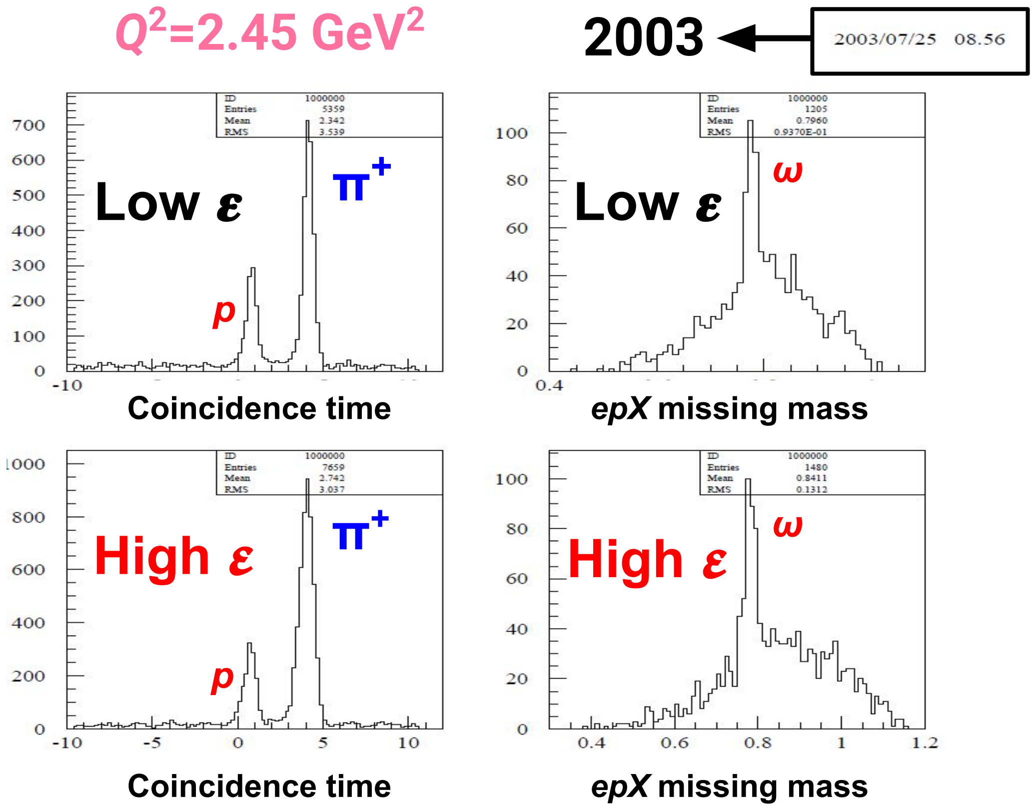




- Forward scattered alpha particle: extracting the interaction radius of the nucleus and mapping out the transverse structure of the atom (mostly empty)
- Recoiling alpha particle: stiffness of the “point-like” structure.
- Full structure = forward angle + backward angle observables.

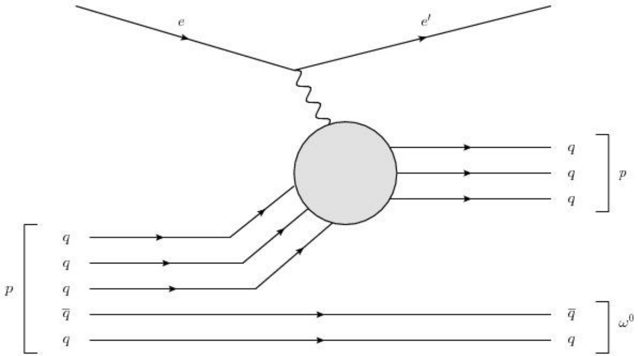
Gifted Backward-angle Observables

- **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

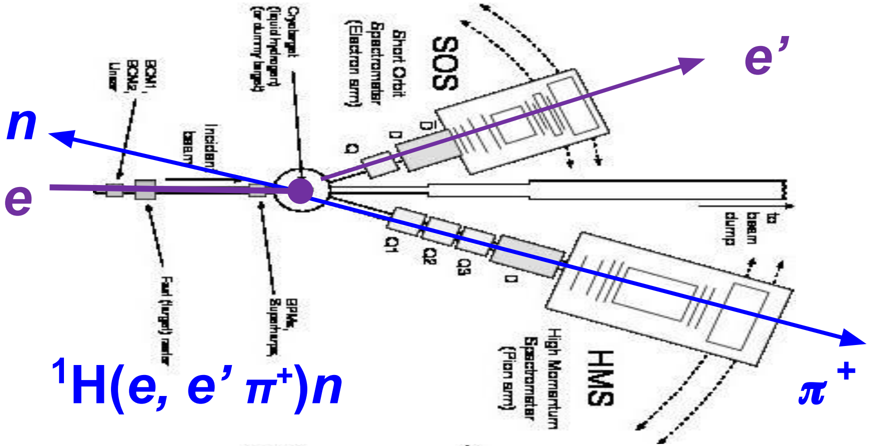


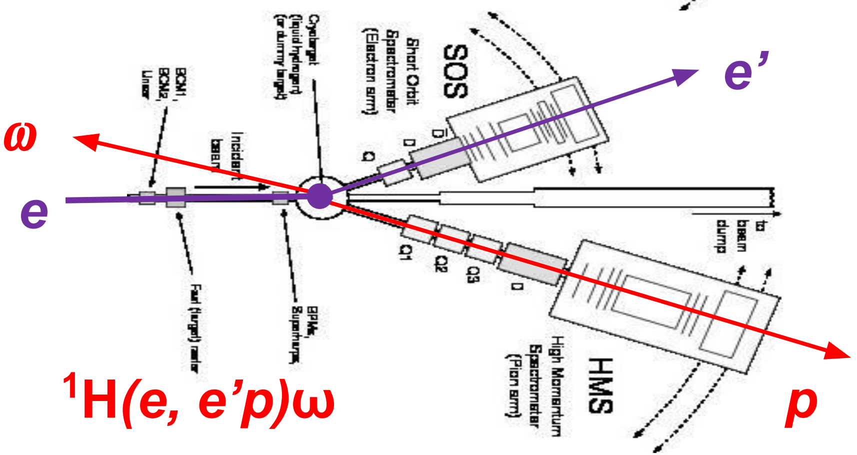
t-Channel π^+ vs *u*-Channel ω Production

- **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

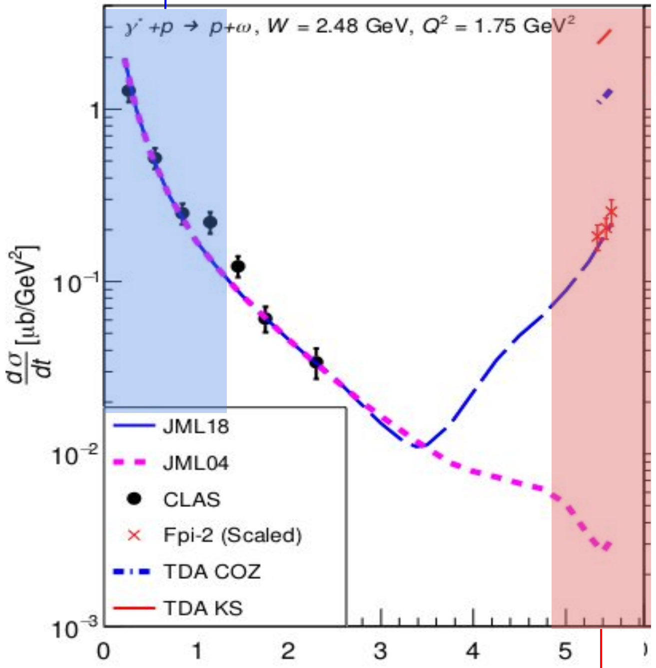




Two Key Discoveries from Fpi-2 ω Analysis

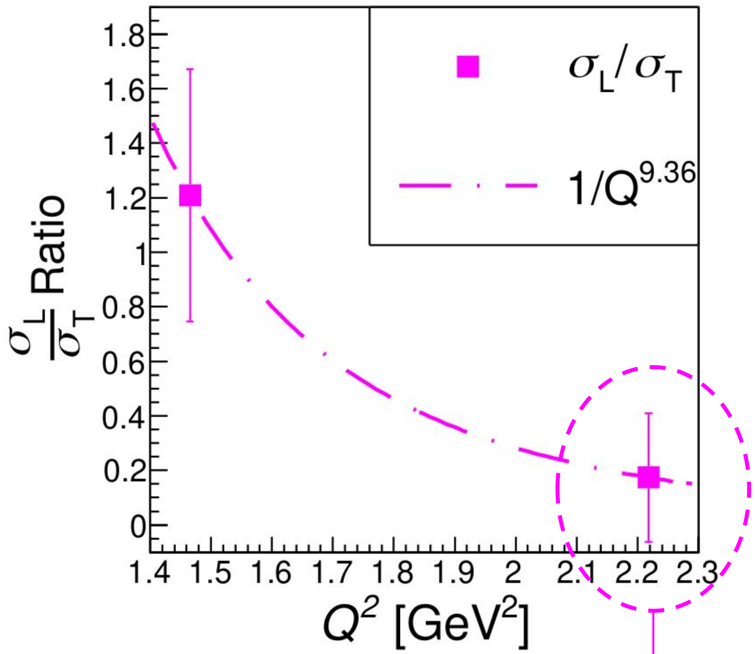
Discovery 1: Unexpected large *u*-Channel peak

Forward ω electroproduction from CLAS 6 *(2004)*



Backward angle ω electroproduction *(2017)*

Discovery 2: $\sigma_T > \sigma_L$, $\sigma_L \sim 0$

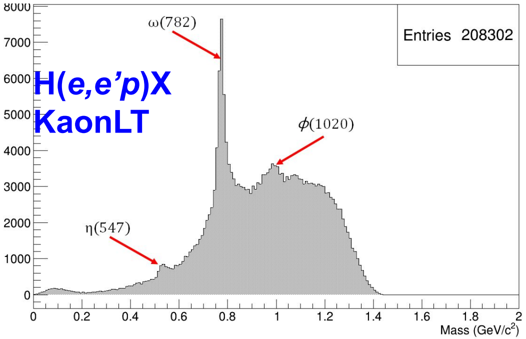


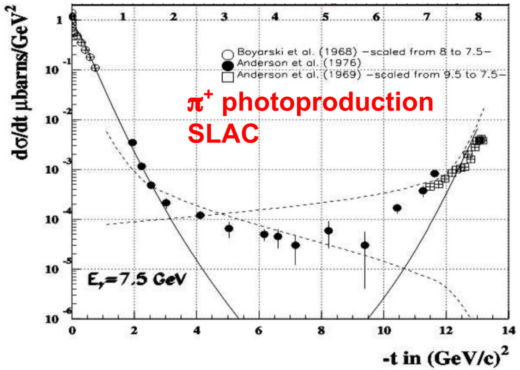
$$\frac{\sigma_T}{\sigma_L} \sim 0 \text{ at } Q^2 = 2.2\,\mathrm{GeV}^2$$

Therefore, $\boldsymbol{\sigma_T > \sigma_L}$

Probing the u-channel observables

- **Is there a u-channel peak for other processes?**
  - **Answer: Yes**



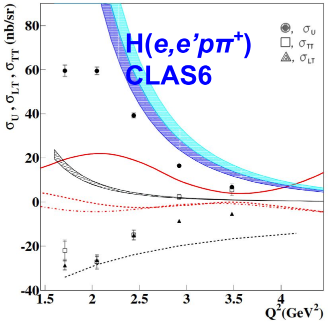


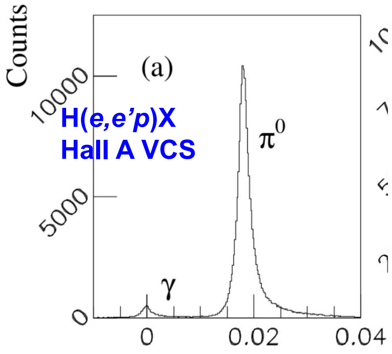
Approved proposal

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

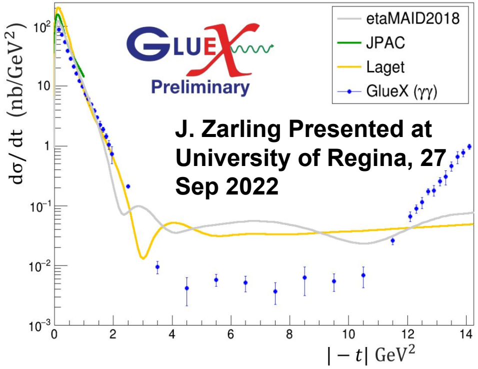
Confirmed! By CLAS6

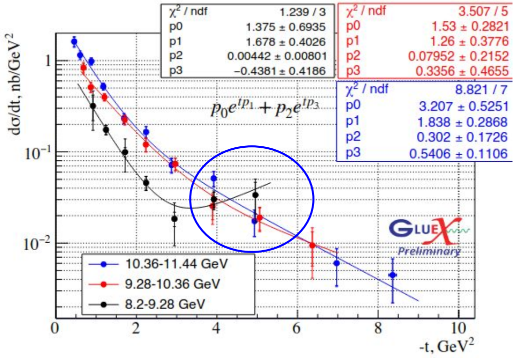
Confirmed!





$E_\gamma = 8.25 \pm 0.25$ GeV



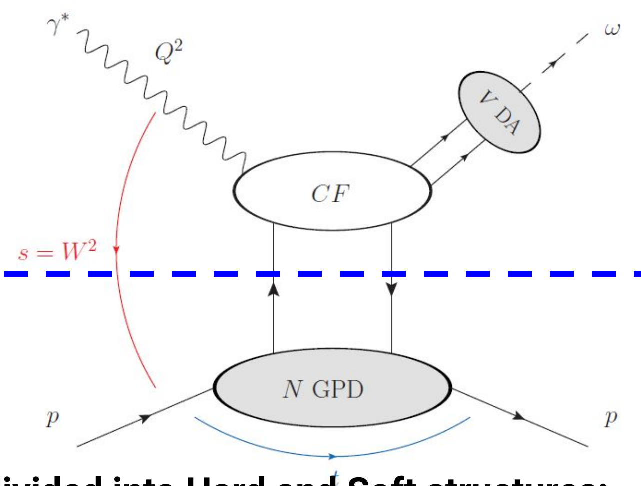


Generalized Parton Distribution

Interaction with hard structure calculable

Hard structure

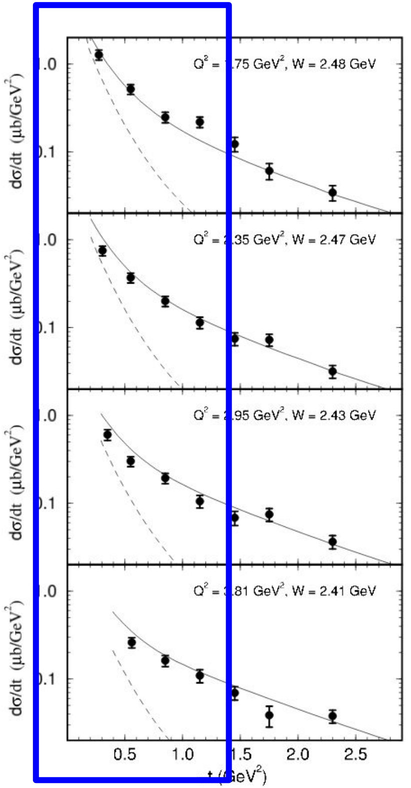
Soft structure



Deep exclusive ω electroproduction

Collinear factorization

forward = small -t

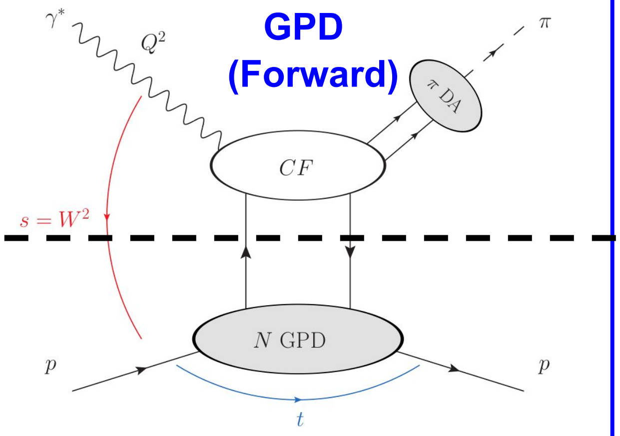


- **Proton structure is divided into Hard and Soft structures:**
  - Hard structure is calculable by perturbative methods
  - Framework uses Hard structure information to **extrapolate to the Soft structure**
- **Condition for Factorization Scheme:**
  - **At sufficiently large momentum transfer**
  - **Produced meson fragments scatter to extreme forward.**
    - Framework ignores the structure information from backward-angle interactions
- **Question: missing the description for backward structure of proton?**

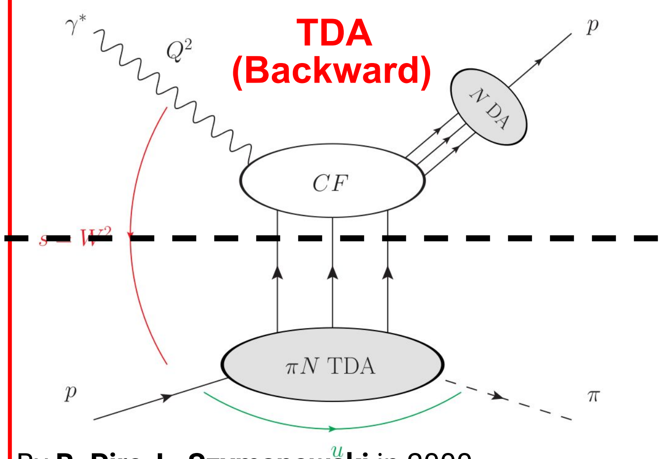
GPD, SPD and TDA (Hard Structure)

Hard structure

Soft structure



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



By **B. Pire, L. Szymanowski** in 2000

Perfected by K. Semenov-Tian-Shansky (2022), Kyungpook National University

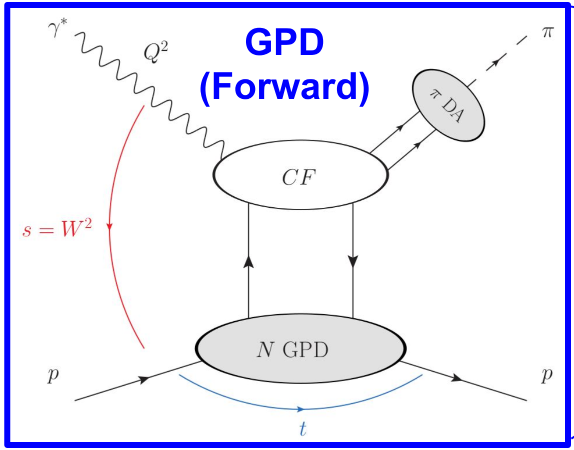
Description to the unseen side of proton

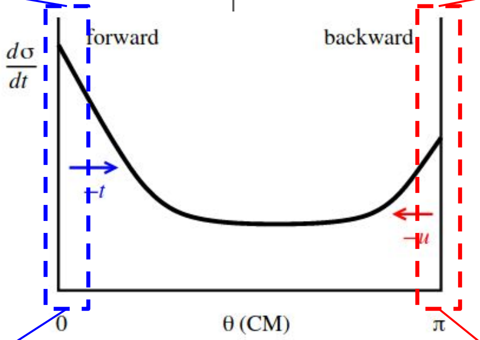
Collinear factorization

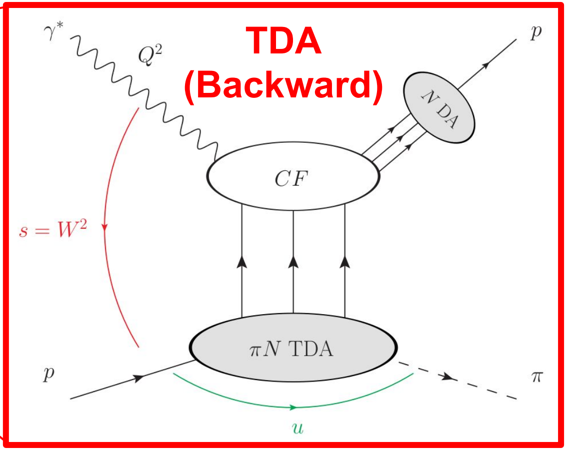
Complete description of Nucleon

- **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.

GPD vs TDA Fact sheet 1







- Factorization: Q^2→large, $-t$ →small
- Systematically study forward DVCS & DVMP
- Formalism: four compact structures

$$\int_{-1}^{1} dx H_q(x,\xi,t) = F_1^q(t), \quad \int_{-1}^{1} dx E_q(x,\xi,t) = F_2^q(t),$$

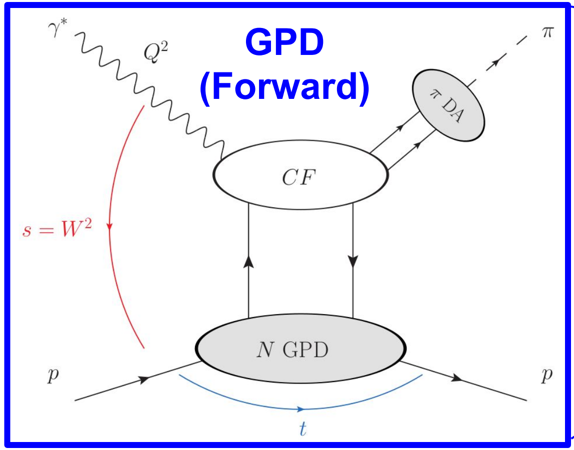
$$\int_{-1}^{1} dx \tilde{H}_q(x,\xi,t) = G_A^q(t), \quad \int_{-1}^{1} dx \tilde{E}_q(x,\xi,t) = G_P^q(t),$$

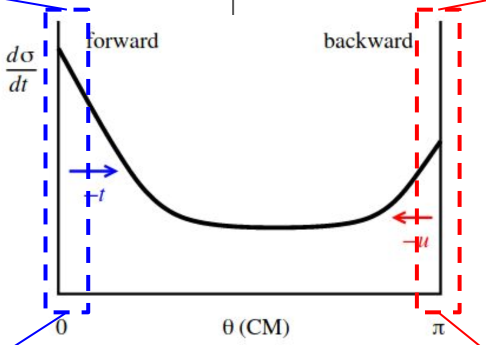
- Factorization: Q^2→large, $-u$→small ($-t$→large)
- Systematically study backward DVCS & DVMP?
- Formalism: experimentalist friendly, directly linked to cross section (example later)

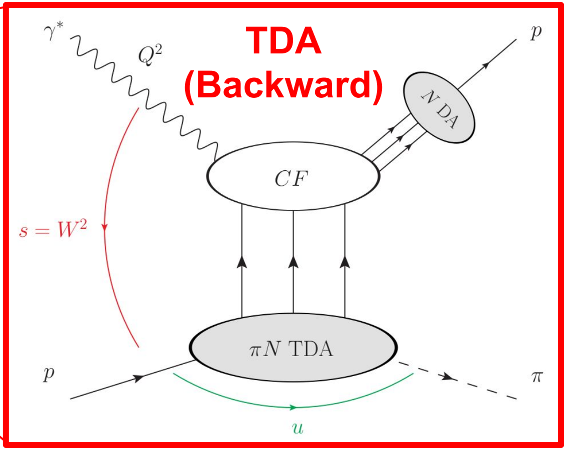
$$H^{\pi N}_{s.f.} = \{V^{\pi N}_{1,2}, A^{\pi N}_{1,2}, T^{\pi N}_{1,2,3,4}\}$$ π↔p TDAs

$$H^{\gamma N}_{s.f.} = \left\{V^{\gamma N}_{1\varepsilon}, A^{\gamma N}_{1\varepsilon}, T^{\gamma N}_{1\varepsilon,\,2\varepsilon}\right\}$$ γ↔p TDAs

GPD vs TDA Fact sheet 2







Cons:

- **Ignores *u*-Channel σ peak**
- **No direct access, intermediate theory framework is needed, Compton Form Factor is required.**

$$\mathcal{F} = \int_{-1}^{+1} dx\, F(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)$$

$$\tilde{\mathcal{F}} = \int_{-1}^{+1} dx\, \tilde{F}(x,\xi,t)\left(\frac{1}{\xi - x - i\epsilon} + \frac{1}{\xi + x - i\epsilon}\right)$$

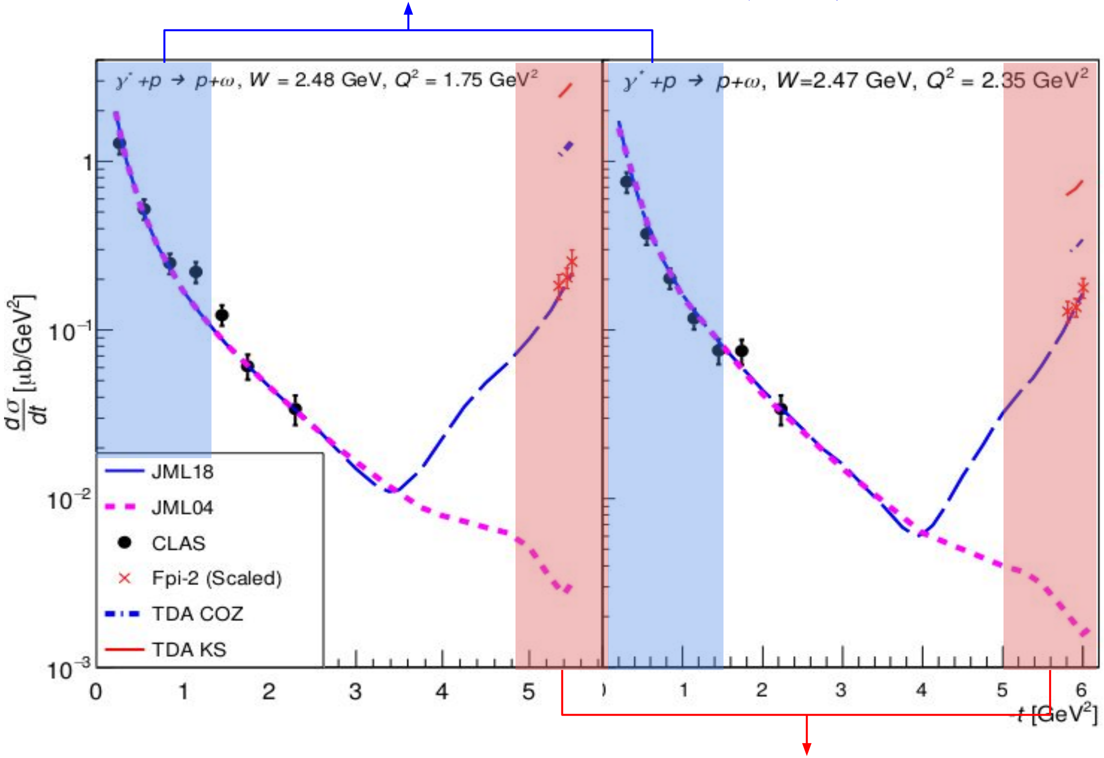
$$F = H, E\ ,\ \tilde{\mathcal{F}} = \tilde{\mathcal{H}}, \tilde{\mathcal{E}},\ F = H, E,\ \tilde{F} = \tilde{H}, \tilde{E}.$$

Cons:

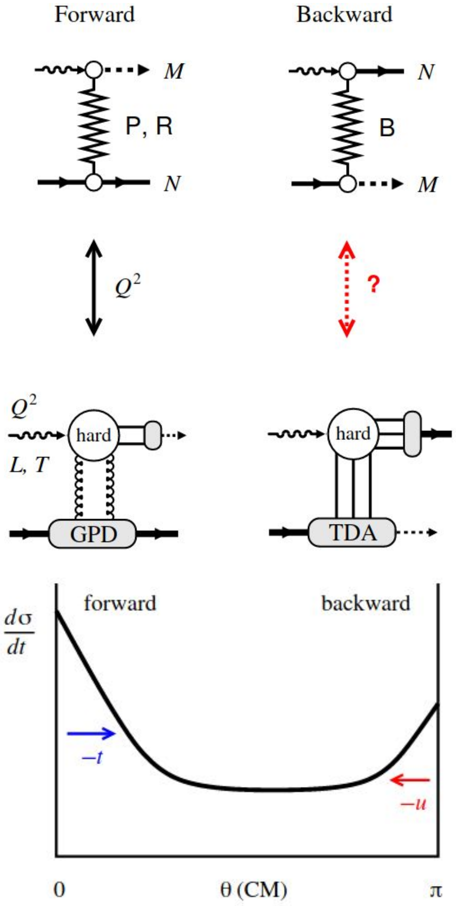
- **Ignores *t*-Channel σ peak**
- **Require Empirical Nucleon Distribution Amplitude as input, example**
  - **KS:** King and Sachrajda nucleon wave functions parameterization
  - **COZ:** Chernyak, Ogloblin and I. R. Zhitnitsky nucleon wave functions parameterization

u-Channel production is in its <u>infant form</u>

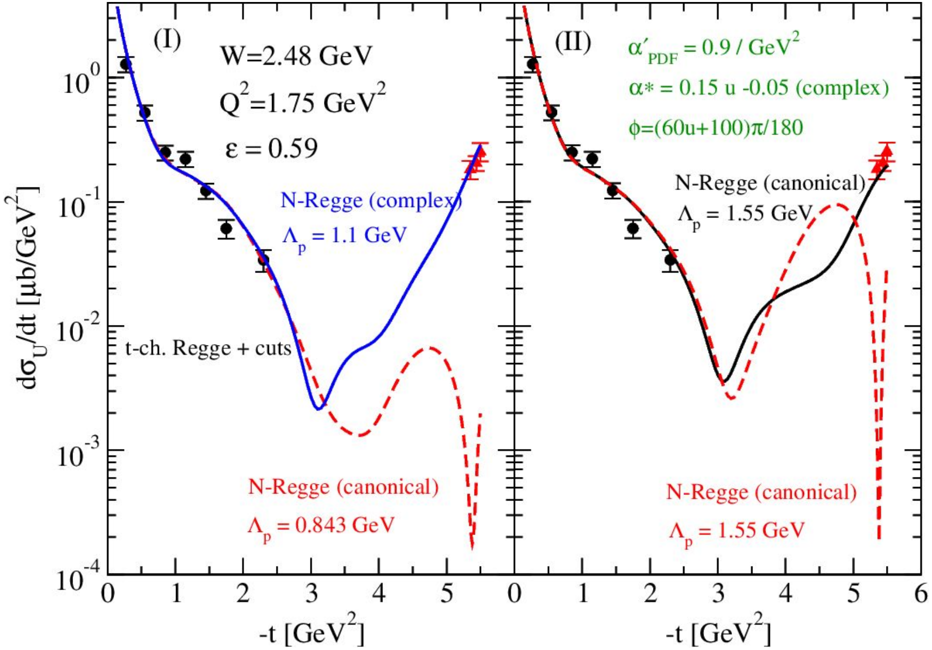
Forward ω electroproduction from CLAS 6 *(2004)*

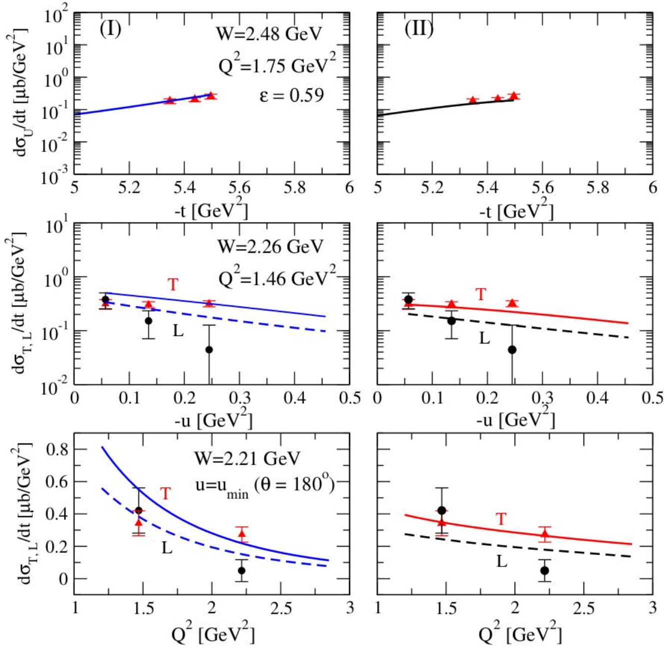


Backward angle ω electroproduction *(2017)*

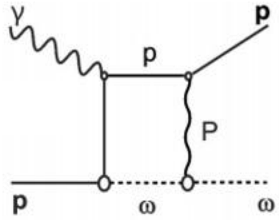


Alternative Interpretation of u-Channel Interaction



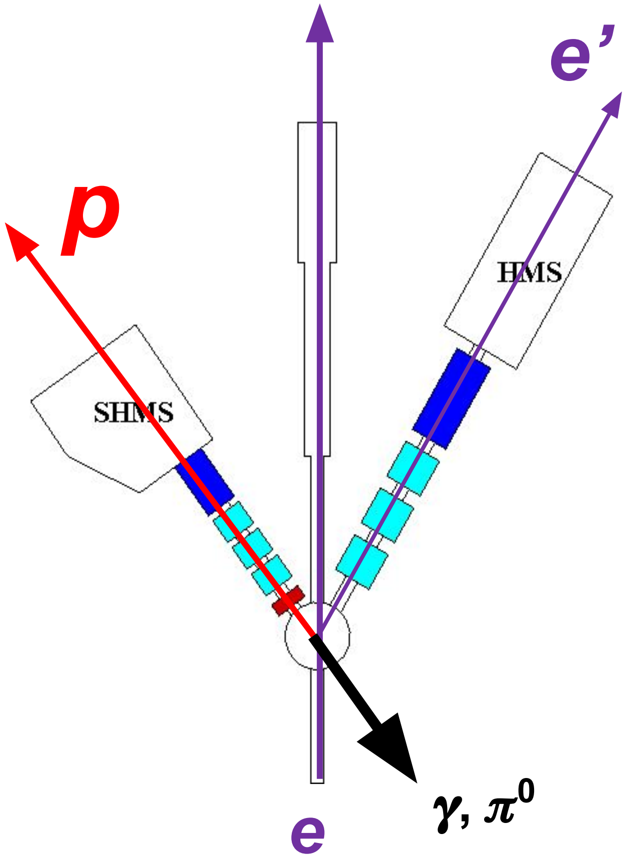


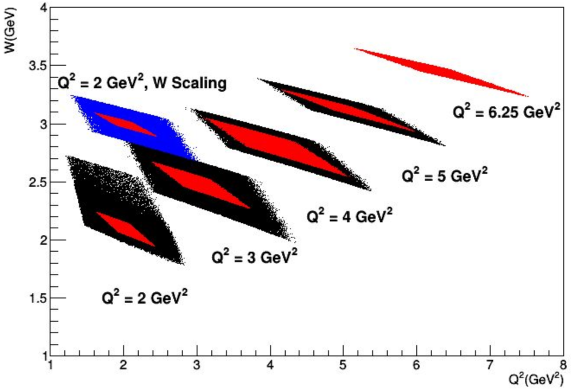
- **Great work reproduced unseparated σ_u, and separated σ_L ,σ_T are produced with softer Reggeon exchange**
- **Higher kinematics data is required to further distinguish the partonic model from Regge model**

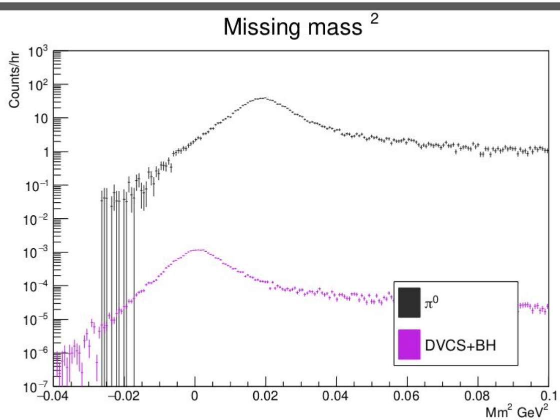


by Byung Geel Yu, Korea Aerospace University

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

- Fully approved by PAC: 29 PAC days
- Q^2 coverage: $2.0 < Q^2 < 6.25$ GeV^2.
- x=0.36
- u coverage: $0 < -u' < 0.5$ GeV^2

Objectives:

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

A dedicated large acceptance is needed at JLab

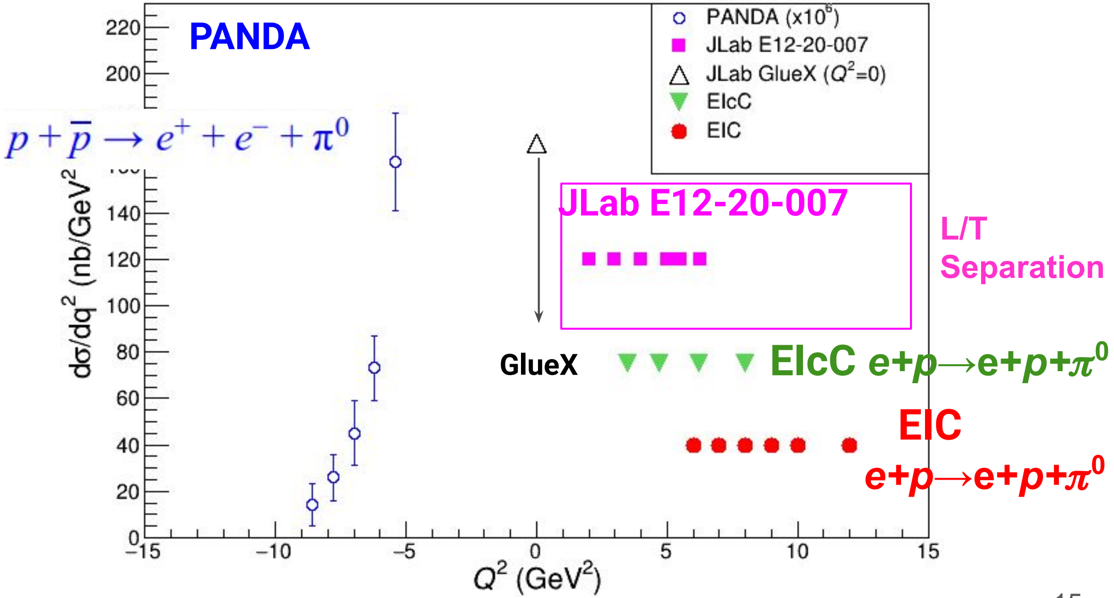
u-Channel studies at EIC

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.

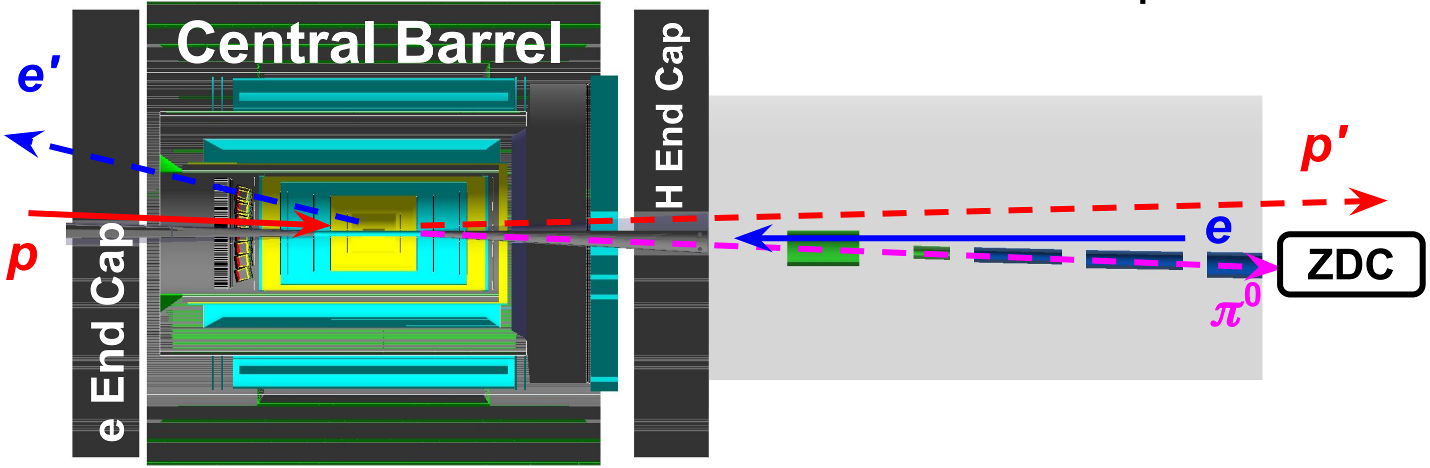
- **Backward π^0 program for EIC**
  - Synergies to other planned data set

s =10 GeV^2, π^0 u-Channel Production



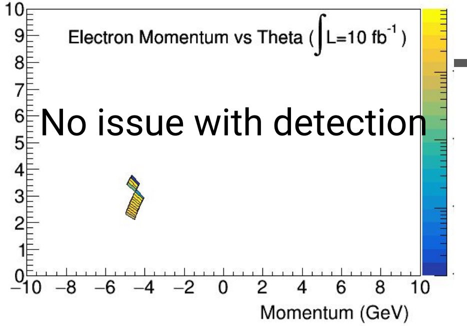
u-Channel Meson Production Setup

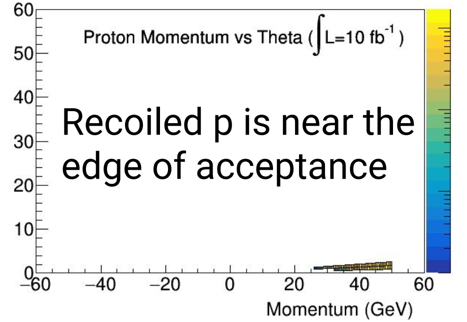
5 GeV e on 100 GeV p

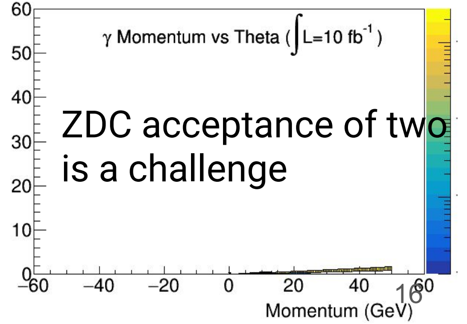


Q^2 (GeV^2)	W (GeV)	x_B	$\theta_{e'}$ (deg)	$\eta_{e'}$	$P_{e'}$ (GeV)	$\theta_{p'}$ (deg)	$\eta_{p'}$	$P_{p'}$ (GeV)	θ_{π^0} (deg)	η_{π^0}	P_{π^0} (GeV)	$-t$ (GeV^2)	$-u$ (GeV^2)
6.2	3.19		152	-1.39	5.31	-1.84	4.13	43.40	1.43	4.38	56.29	14.84	-0.37
7.0	3.19		150	-1.32	5.35	-1.92	4.09	45.50	1.43	4.38	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

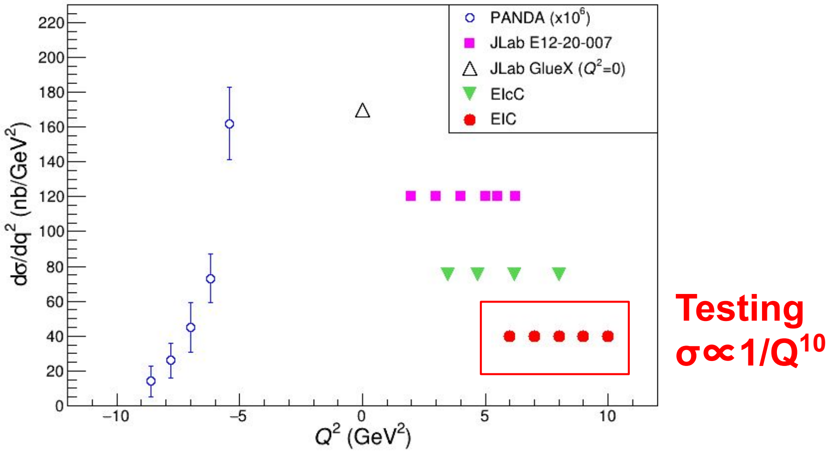
e' p' π^0

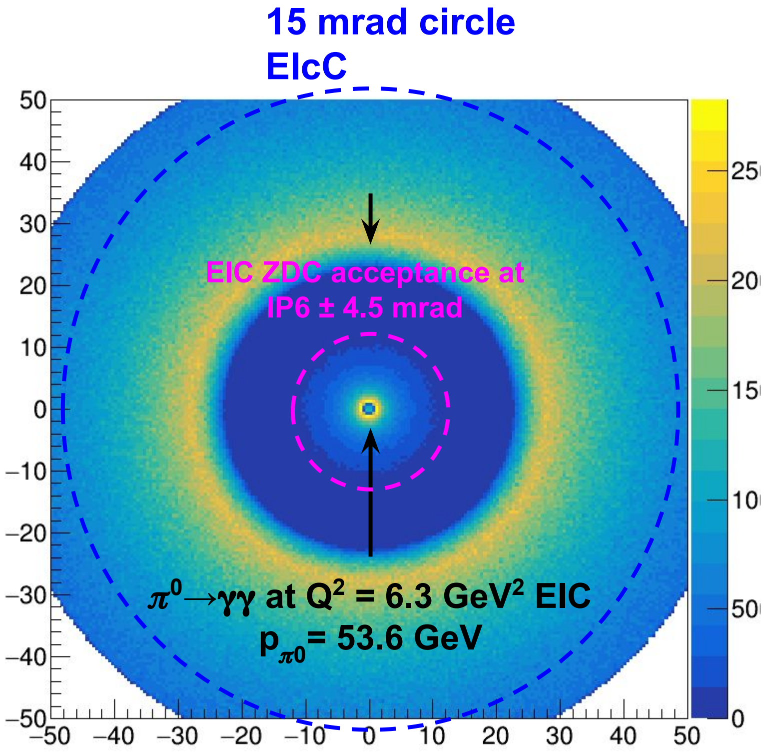


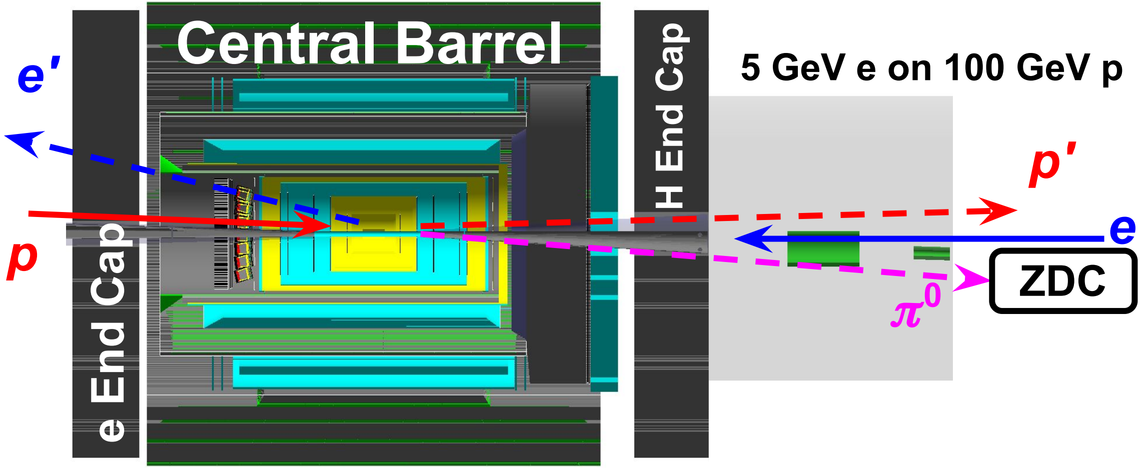




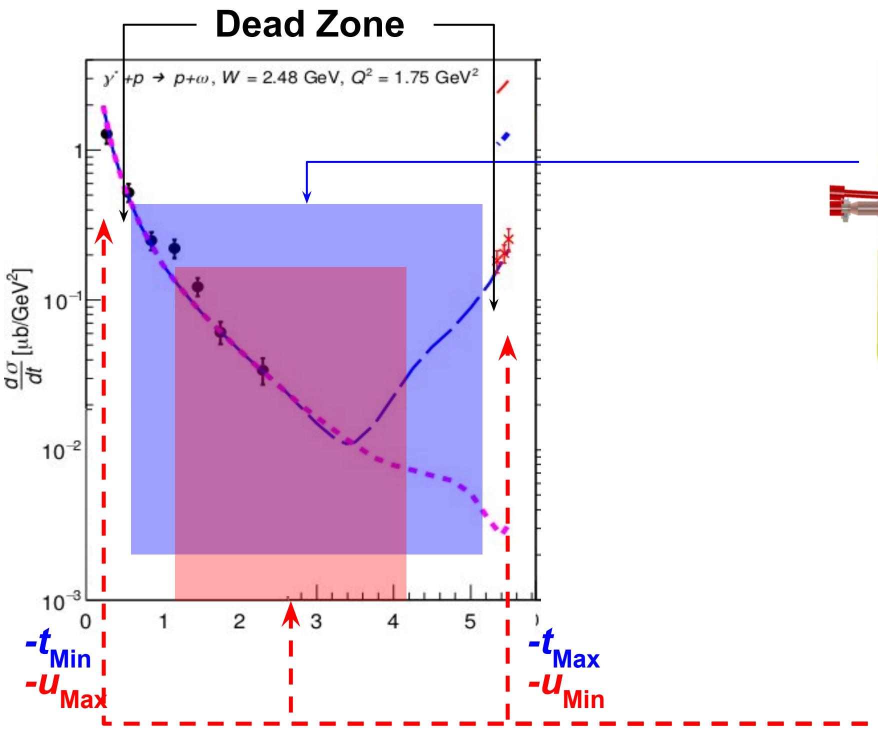
u-Channel Meson Production Setup

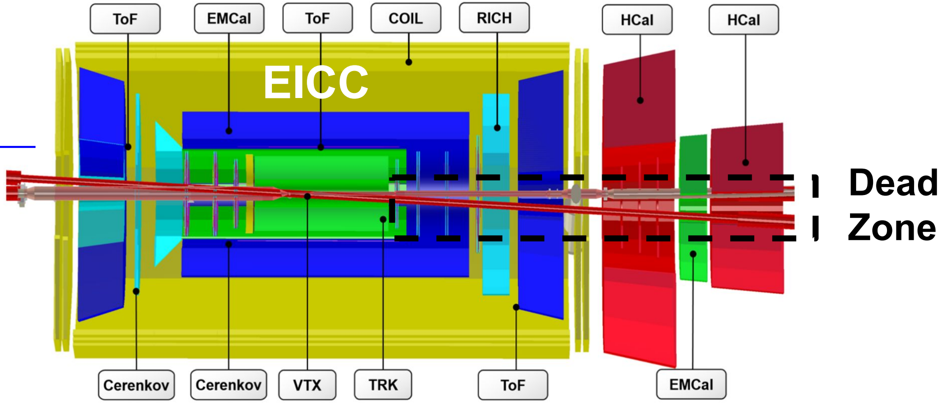


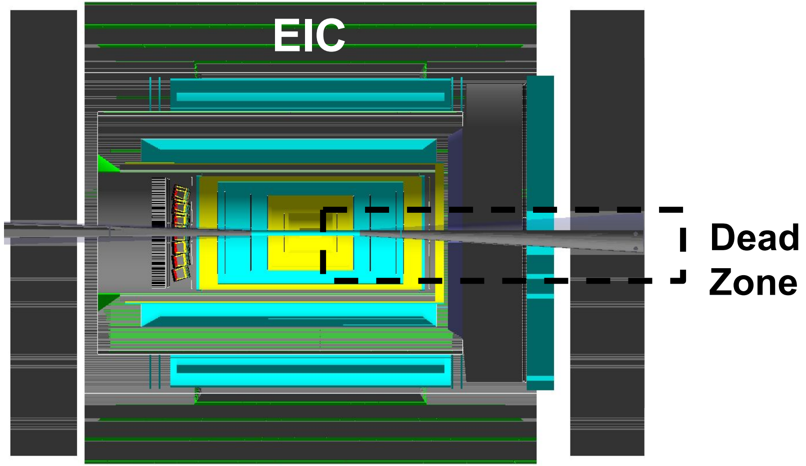




EIC and EicC Complementarity

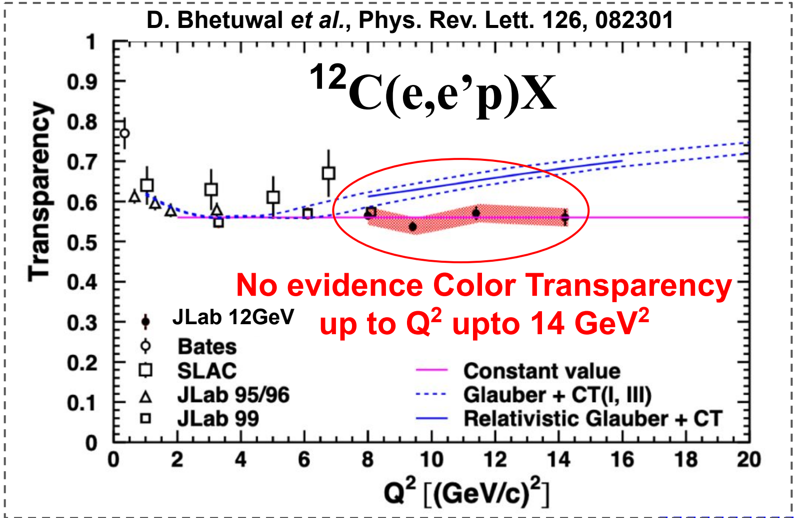


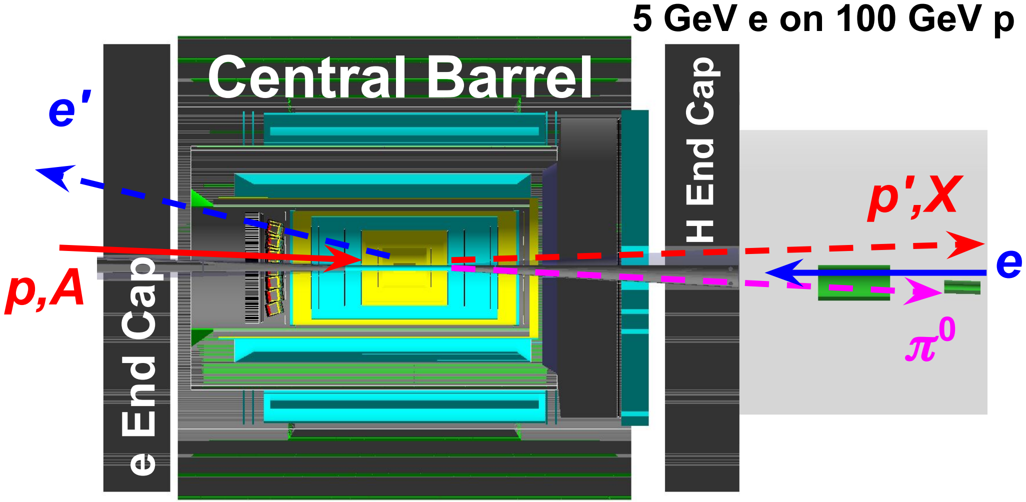


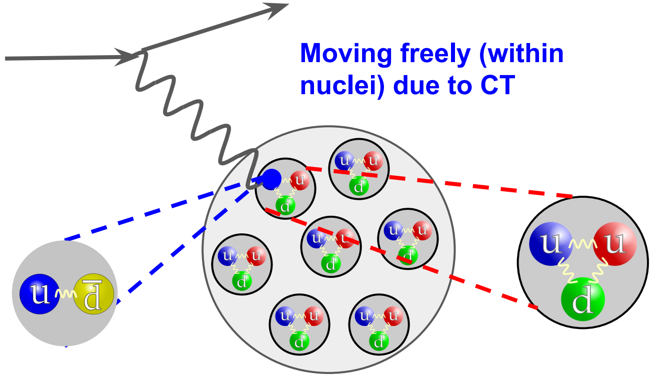


- EIC and EICC should be designed to avoid common dead zone overlap in phasespace. Studies needed
- Angular dependence asymmetry study is possible (needed to extract TDAs)

Testing Nuclear Color Transparency via *u*-Channel Kinematics

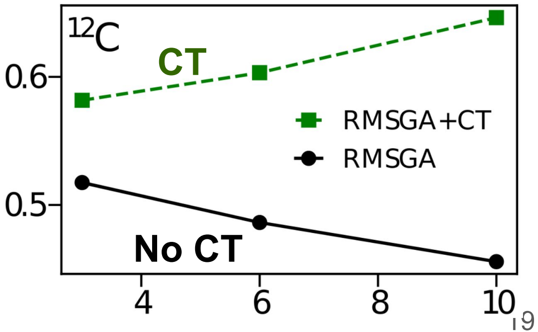






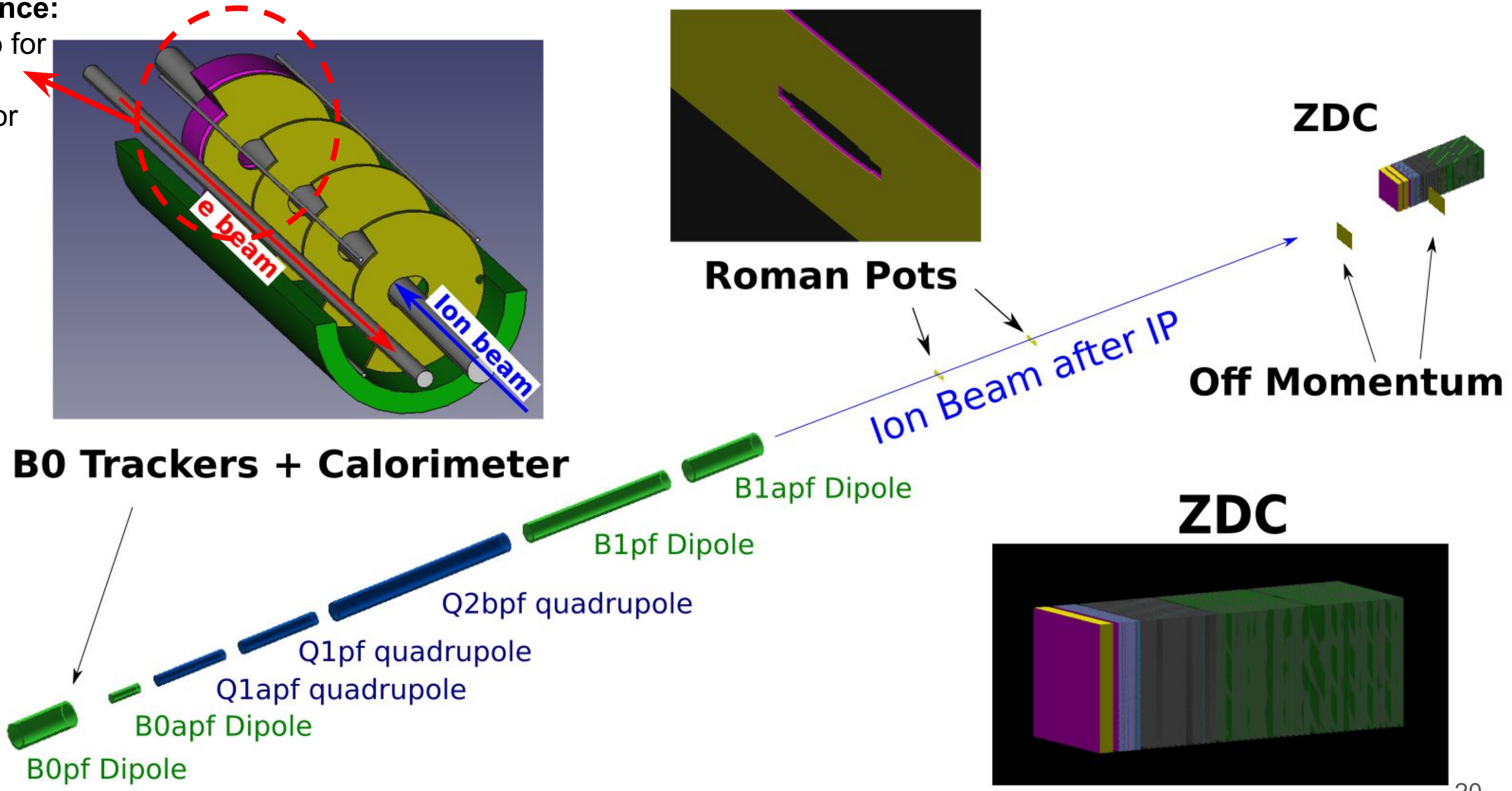
CT onset predicted
$^{12}C(e,e'p)X\pi^0$ by W. Cosyn

A new CT observable through u-Channel meson electroproduction by
G. Huber, W.B. Li, W. Cosyn, B. Pire
https://arxiv.org/abs/2202.04470

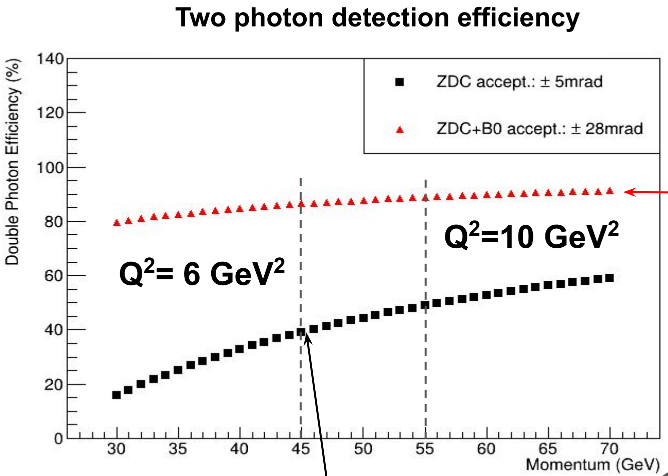


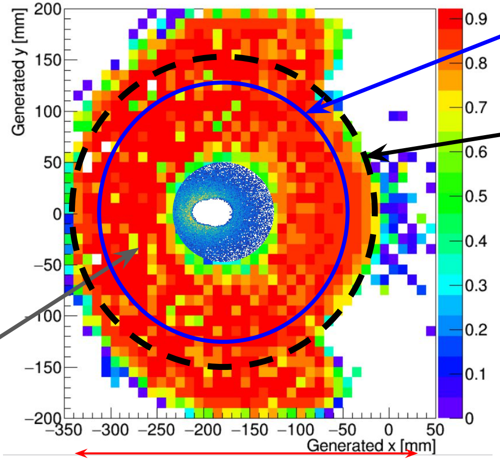
ECCE vs ATHENA Beamline Components

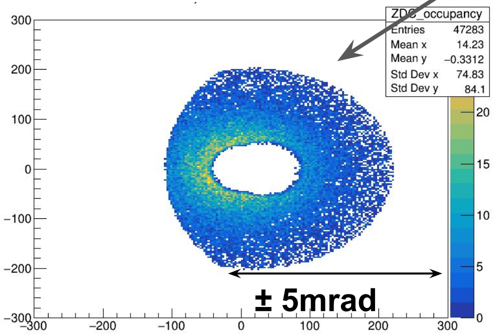
Only major difference:
- Full EM Calo for ECCE
- Preshower for ATHENA



Enhanced acceptance and resolution with B0 calorimeter



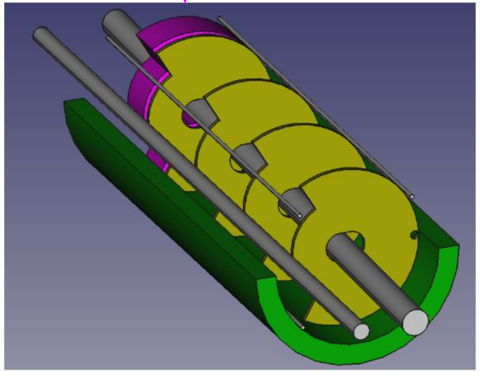




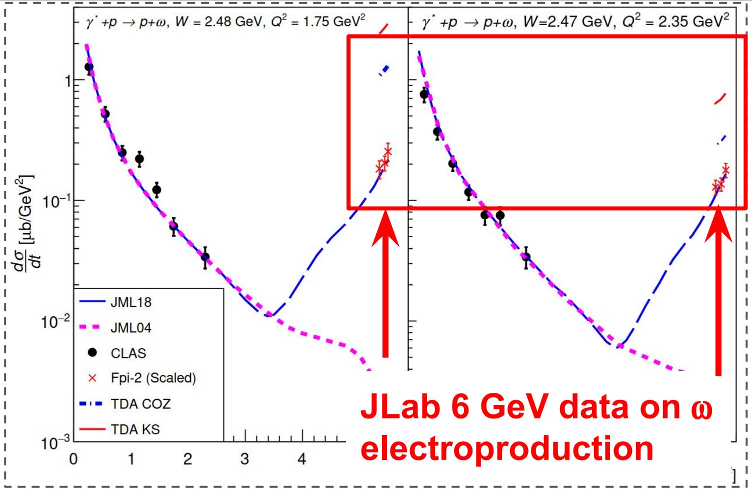
Remark 1: Higher acceptance: η study is possible

Remark 2: Higher π^0 efficiency makes u-channel DVCS possible

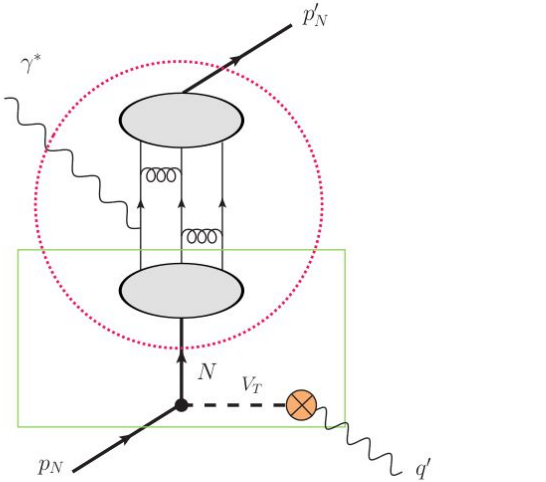
B0 Calorimeter



DPAP Question: How long would it take to measure u-Channel DVCS?

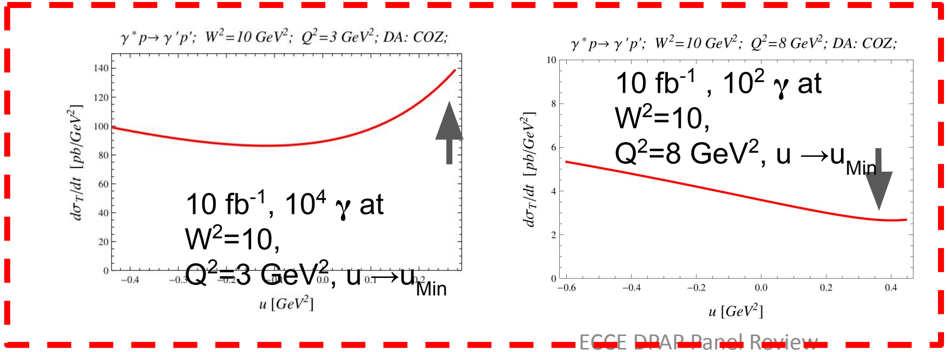


ω data encourages searching for DVCS through u-channel VMD



(ω, ρ, ϕ) → γ

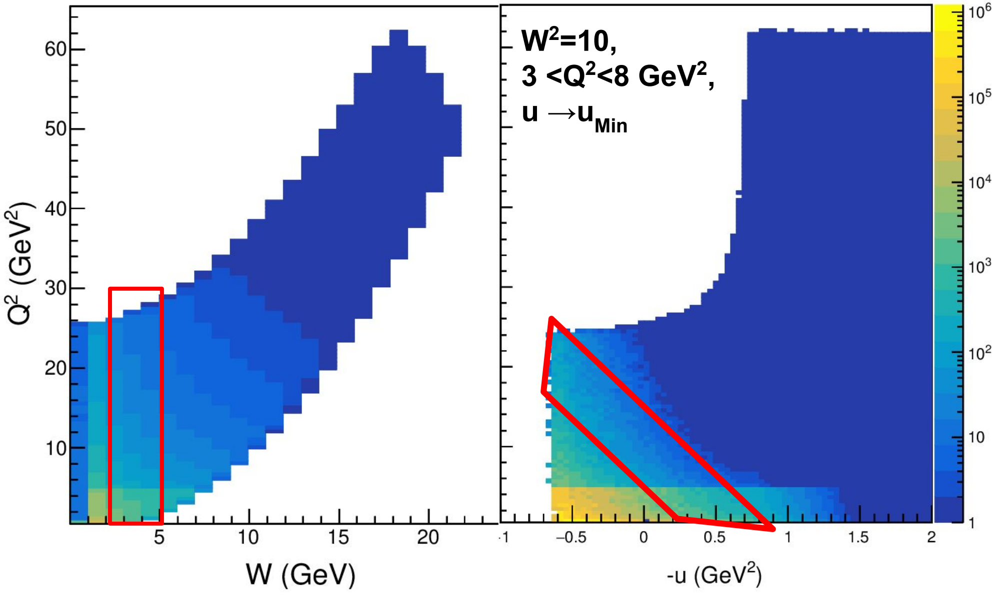
Recent TDA-VMD prediction



Theory predicts a consercative cross section estimate at JLab kinematics and beyond at x range of 0.1< x 0.3

Prediction by K. Semenov-Tan-Shansky, B. Pire, Lech Szymanowski

Question: How long would it take to measure u-channel DVCS?



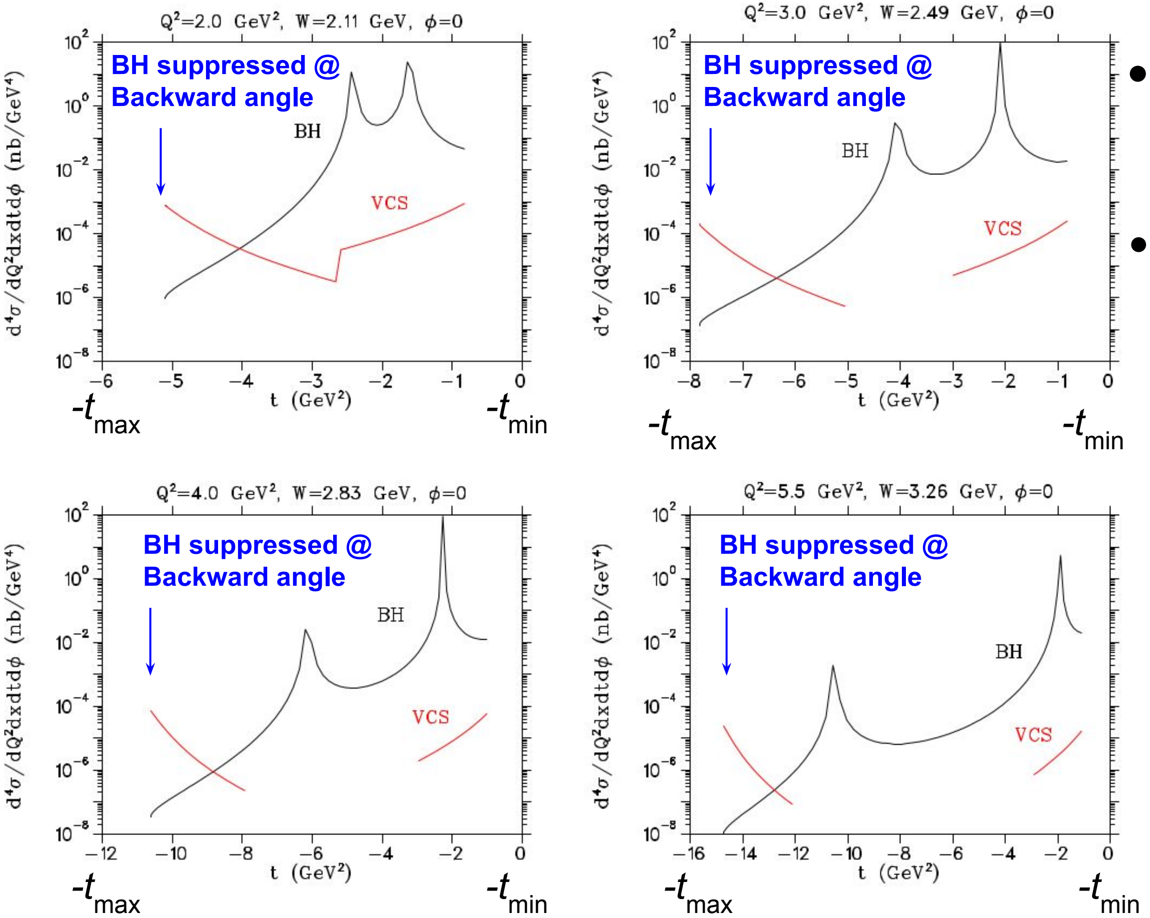
Kinematics coverage for u-Channel π^0 electroproduction. Coverage for the DVCS is similar. z-axis represents the expected number of events with 10 fb^{-1} integrated luminosity for π^0, where DVCS cross section is expected to be 10^2 less.

JLab kinematics and extension (x ~ 0.1 - 0.3): data driven model conservatively predicts sub 5% (statistical uncertainty) measurement (1% Q^2 = 3 GeV^2) with 10 fb^{-1}. (see previous page for estimation)

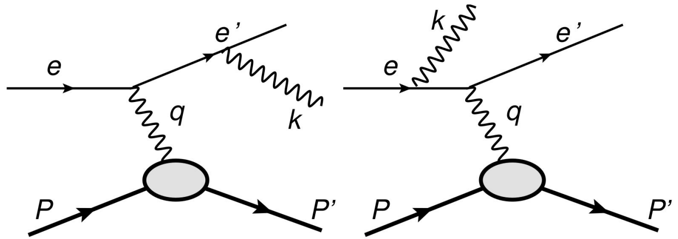
EIC kinematics at x < 0.1: no data driven model prediction, exploring into unknown territory, 1/10 of the t-Channel cross section is a reasonable starting point. Alternatively, one could assume DVCS cross section is 10^2 smaller than the π^0.

This work needs to be finished by K. Semenov-Tan-Shansky (KNU), B. Pasquini (Pavia, Italy)

BH is highly suppressed (as a reward!)



- **Bethe-Heitler suppressed in $-t \sim -t_{Max}$ or $-u \sim -u_{Min}$**
  - **Used the classic BH description**
- **BH don't associate with the nucleon structure**
  - **Highly suppressed in the u-channel kinematics due to forward going electron momentum**



Insight into EIC u-Channel Beam Spin Asymmetry

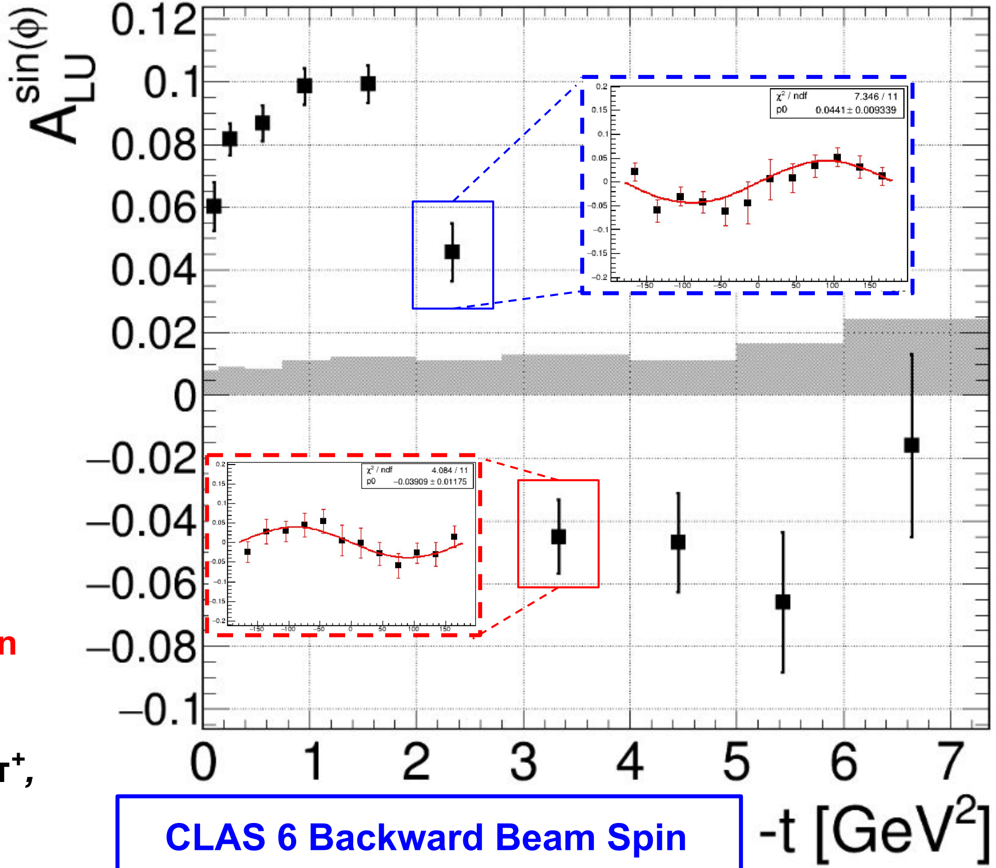
$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

$$A_{LU}^{\sin\phi} = \frac{\sqrt{2\epsilon(1-\epsilon)}\ \sigma_{LT'}}{\sigma_T + \epsilon\sigma_L}$$

***u*-Channel Beam Spin Asymmetry (S. Diehl, Kyungseon Joo, et. al):**

- Longitudinally polarized e beam on a unpolarized target
- Average e polarization was 75%
- **Result indicating a sudden change of sign for σ_{LT} indication sudden change of production mechanism**
- **Similar study at 12 GeV will be done for π^+, ρ/ω, ϕ**

Could this be done during EIC ?

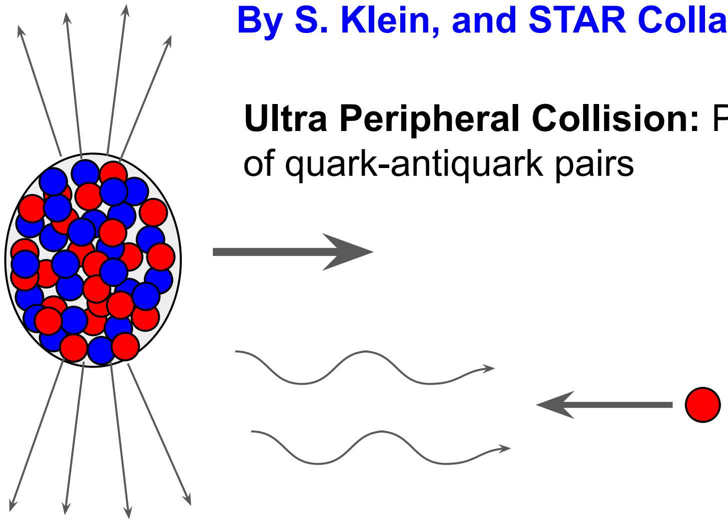


CLAS 6 Backward Beam Spin Asymmetry Result

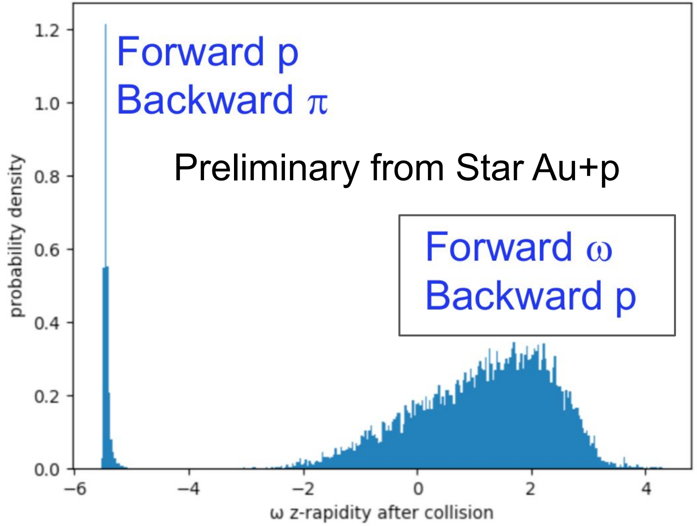
S. Diehl *et al.* (CLAS Collaboration) Phys. Rev. Lett. 128, 062005

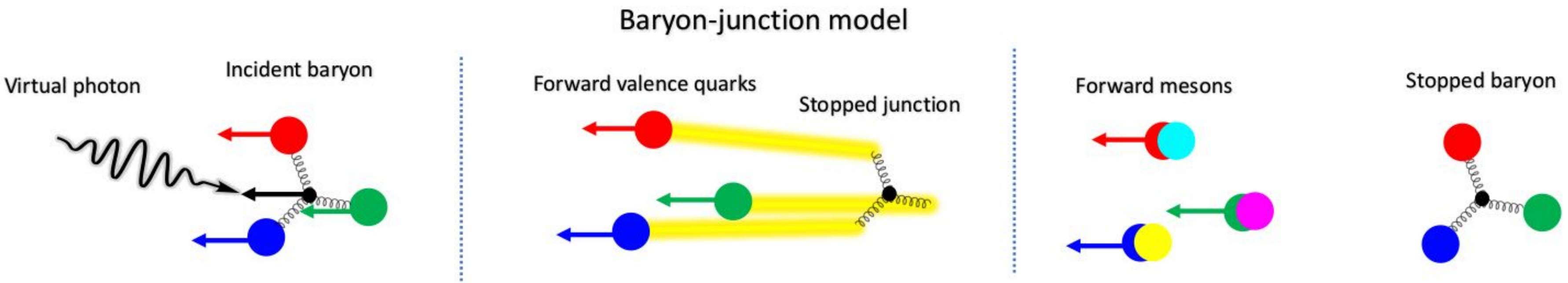
Ultra Peripheral Collision (UPC) at Hadron-Hadron Colliders

By S. Klein, and STAR Collaboration



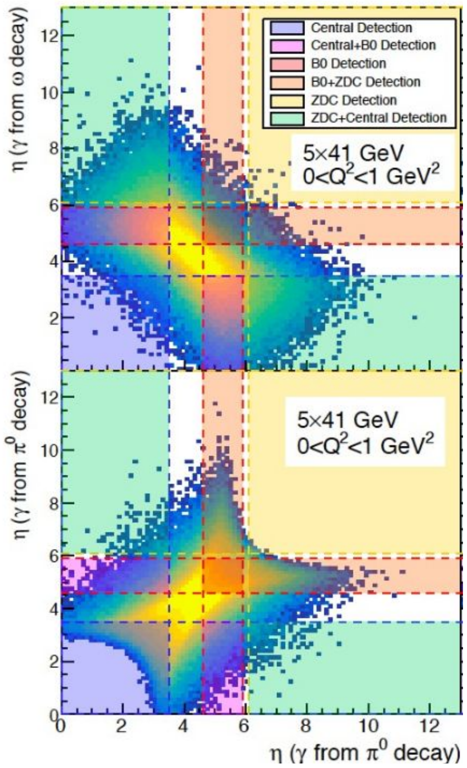
Ultra Peripheral Collision: Photoproduction of quark-antiquark pairs

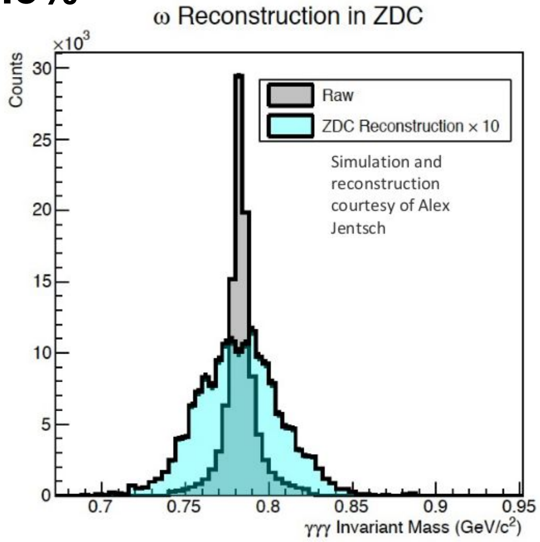




ω Photoproduction based on UPC

$\omega \rightarrow \pi^0\gamma \rightarrow \gamma\gamma\gamma$ **B.R ≈ 8.5%**





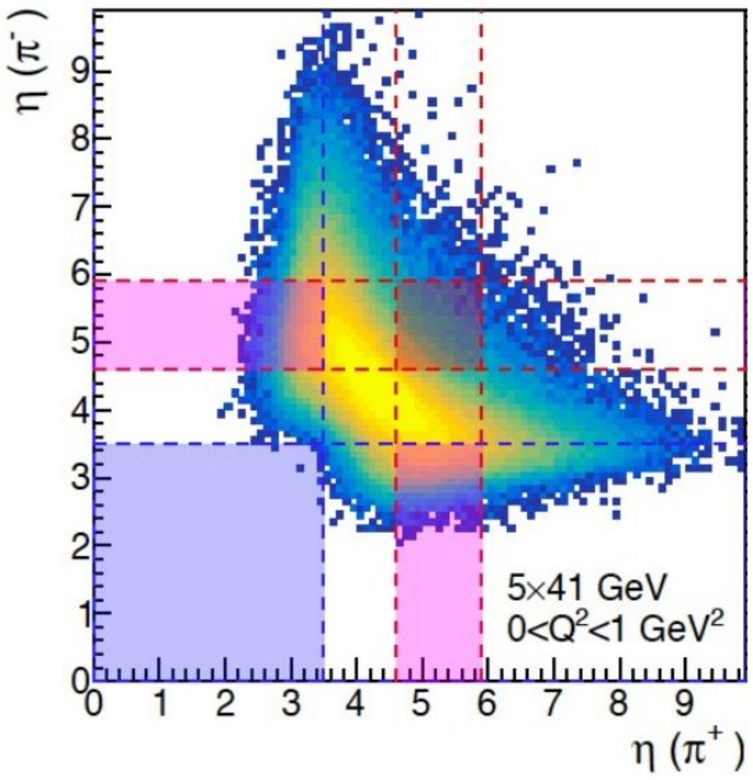
By Z. Sweger, S. Klein, et. al.
arXiv:2204.07915

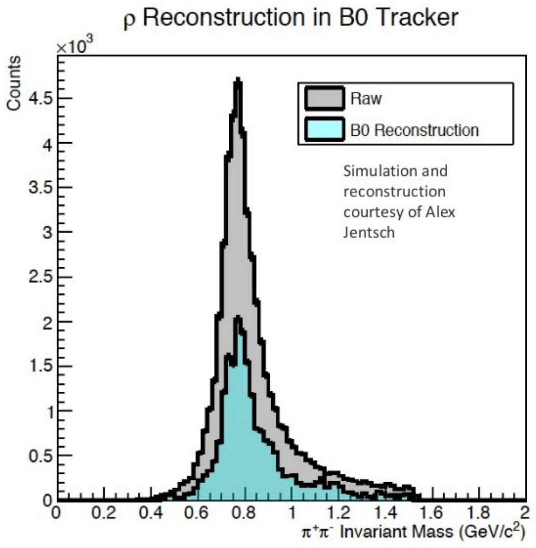
Proton beam energy	ω eff. cent.+ZDC	ω eff. cent.+B0+ZDC
41 GeV	1.4%	18%
100 GeV	1.3%	41%
275 GeV	6%	63%

Challenging measurement!

ρ Photoproduction based on UPC

$\rho \to \pi^+\pi^-$ **B.R ≈ 100%**





Proton beam energy	ρ eff. cent.+B0
41 GeV	13%
100 GeV	49%
275 GeV	0.7%

Much more feasible

Z. Sweger, S. Klein, et. al.
arXiv:2204.07915

Summary

- EIC is a “natural” venue to study u-Channel interactions
  - DVMP
  - DVCS
  - Asymmetry measurements
  - Nuclear Transparency

- u-Channel interactions carry unique information about nucleon wave function
  - This will be unveiled with data from EIC

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

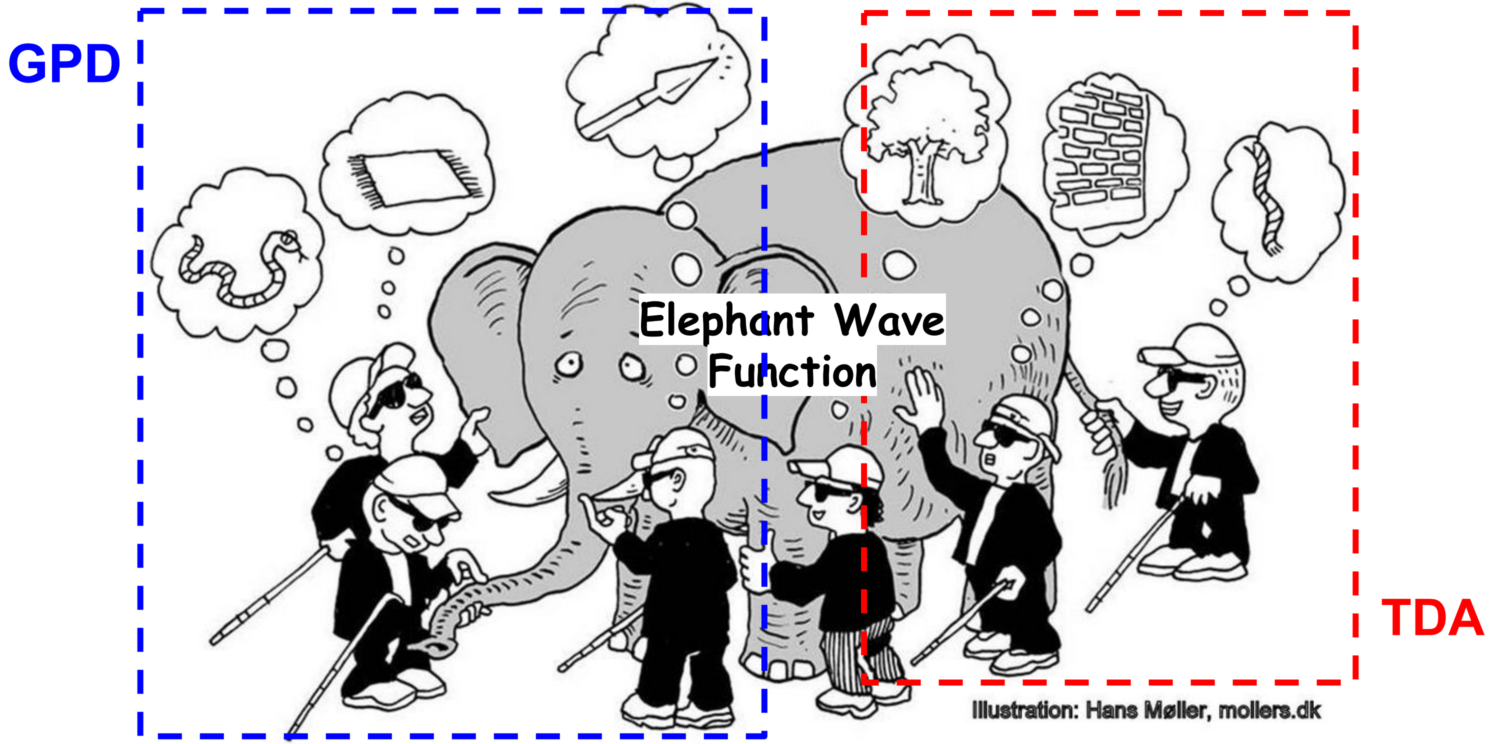
Full study under way

ATHETA Exclusive WG Study

$\omega \to \pi^+\pi^-\pi^0$, where π^0 is tagged by ZDC (very challenging), study by S. Klein, and others
arXiv:2204.07915

Only Possibly with full B0 calorimeter

Thank you!



- **A personal thank you to APCTP to supporting young scientists especially towards theory!**

Backups

TDA Meson Production Cross Section

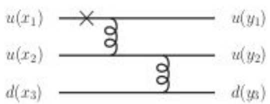
- Unpolarized exclusive meson production cross section for $\boldsymbol{\pi^0}$:

$$\frac{d^2\sigma_T}{d\Omega_\pi} = |\mathcal{C}^2| \frac{1}{Q^6} \frac{\Lambda(s, m^2, M^2)}{128\,\pi^2 s(s-M^2)} \frac{1+\xi}{\xi} \left(|\mathcal{I}|^2 - \frac{\Delta_T^2}{M^2}|\mathcal{I}'|^2\right)$$

$$\mathcal{I} = \int \left(2\sum_{\alpha=1}^{7} T_\alpha + \sum_{\alpha=8}^{14} T_\alpha \right)$$

$$\mathcal{I}' = \int \left(2\sum_{\alpha=1}^{7} T'_\alpha + \sum_{\alpha=8}^{14} T'_\alpha \right)$$

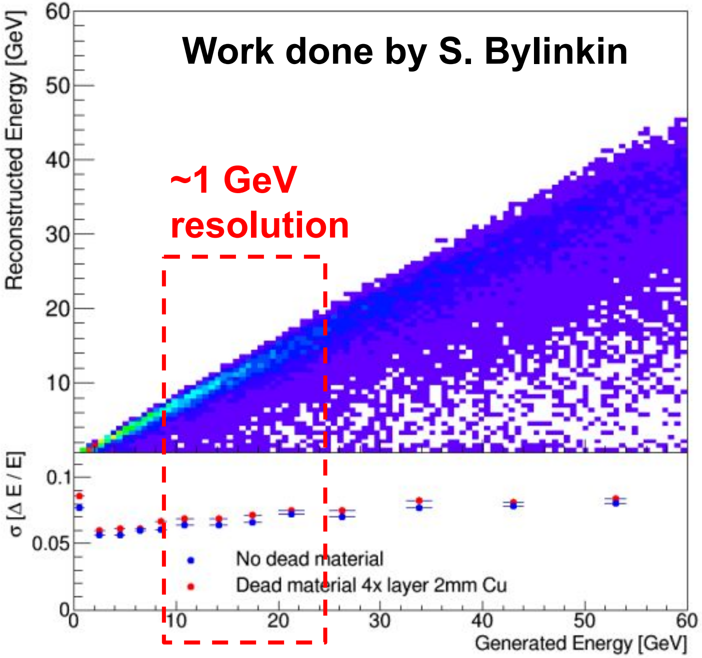
First expansion is shown as an example

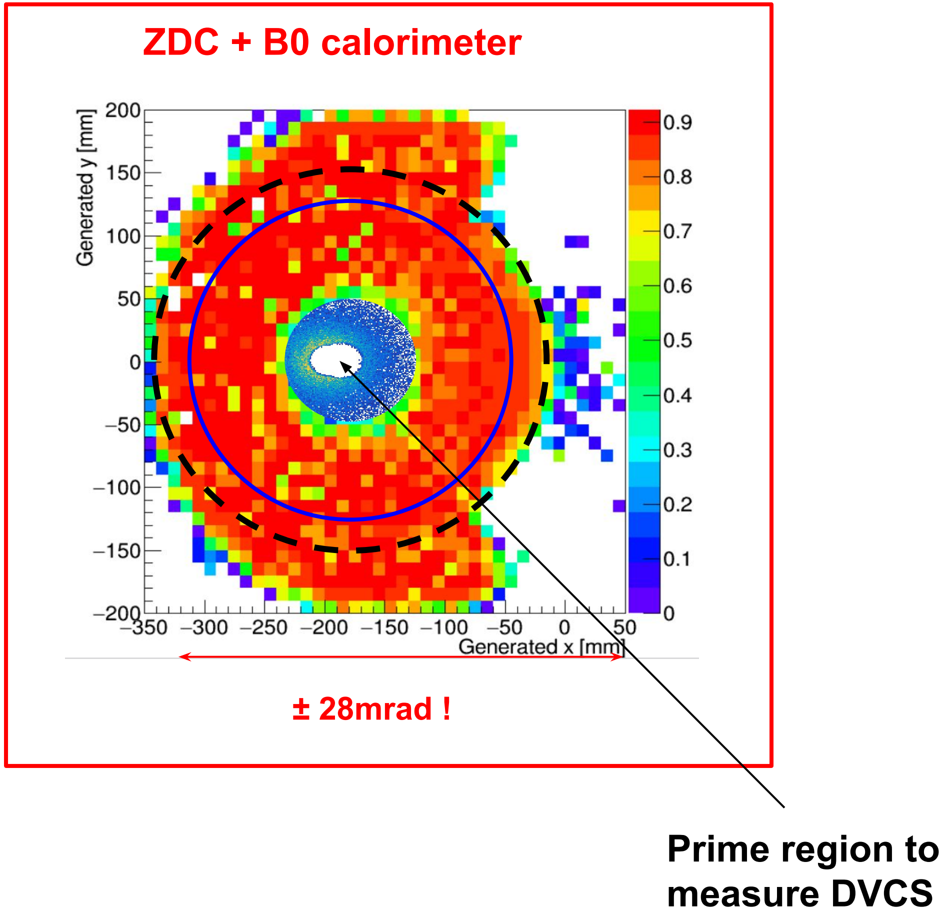
α		T_α	T'_α
1		$\frac{-Q_u(2\xi)^2[(V_1^{p\pi^0}-A_1^{p\pi^0})(V^p-A^p)+4T_1^{p\pi^0}T^p+2\frac{\Delta_T^2}{M^2}T_4^{p\pi^0}T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$	$\frac{-Q_u(2\xi)^2[(V_2^{p\pi^0}-A_2^{p\pi^0})(V^p-A^p)+2(T_2^{p\pi^0}+T_3^{p\pi^0})T^p]}{(2\xi-x_1-i\epsilon)^2(x_3-i\epsilon)(1-y_1)^2y_3}$

Red dashed boxes: TDAs
Blue dashed boxes: Nucleon DAs
Green box: Transition Form Factor (extracted from the *u*-slope)

J. P. Lansberg, B. Pire, K. Semenov-Tian-Shansky, L. Szymananovski, Phys. Rev. D 85, 054021, 2011

Resolution



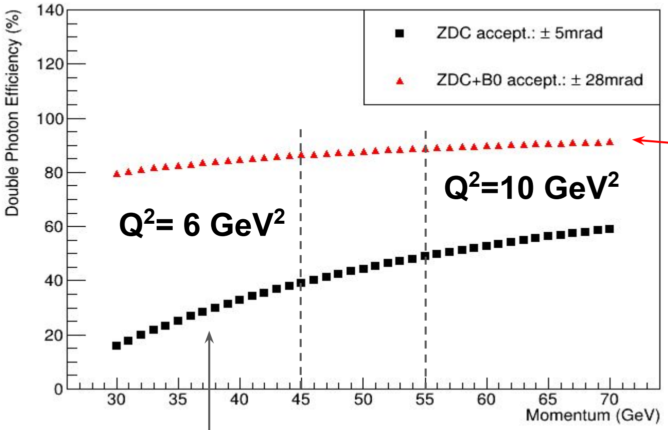


DVCS measurement requires (rejecting π^0):

- Energy cuts: $\pi^0 \rightarrow \gamma(\gamma)$, the detected γ will give
- position cuts: complinarity of the $\pi^0 \rightarrow \gamma\gamma$

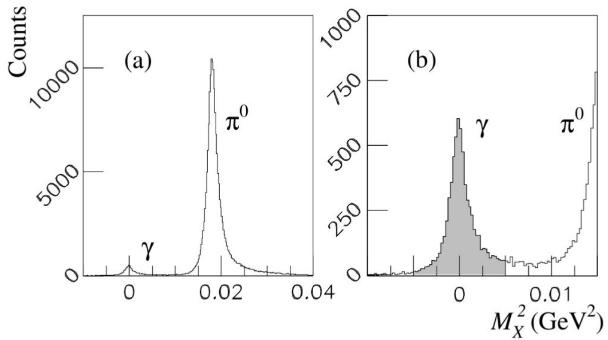
Enhanced acceptance and resolution with B0 calorimeter

Two photon detection efficiency



Only u-Channel π^0 is possible

u-Channel DVCS is a possible!



Hall A VCS experiment.
Phys. Rev. C 79 (2009) 015201

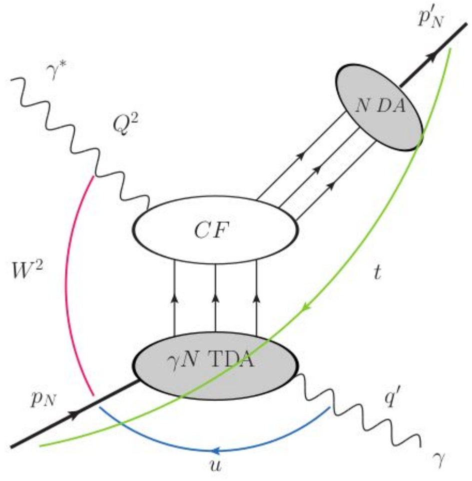
40-50 MeV resolution

u-Channel DVCS is included in the ECCE proposal!

- B0 calorimeter rejects pion background
- exclusivity

Calorimeter performance see presentation from Sasha Bylinkin:
https://jleic-docdb.jlab.org/cgi-bin/private/ShowDocument?docid=616

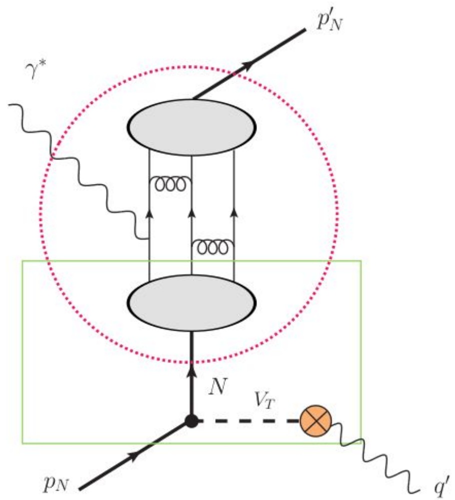
Question: How long would it take to measure u-channel DVCS?



Transition distribution Amplitude (TDA) Representation of DVCS (B. Pire, L. Szymanowski, K. Semenov-Tian-Shansky in 2002)

A subset u-Channel DVCS mechanism based on JLab data

u-Channel Vector Meson Dominance (VMD) Model



A illustration of a real photon emitted in the u-Channel Kinematics through Vector Meson Dominance Model (VDM) (K. Semenov-Tian-Shansky, B. Pire, B. Pasquini, L. Szymanowski in 2021)