A JSA Postdoc Award Synopsis: Studying Backward-angle Physics from JLab 12 GeV to EIC

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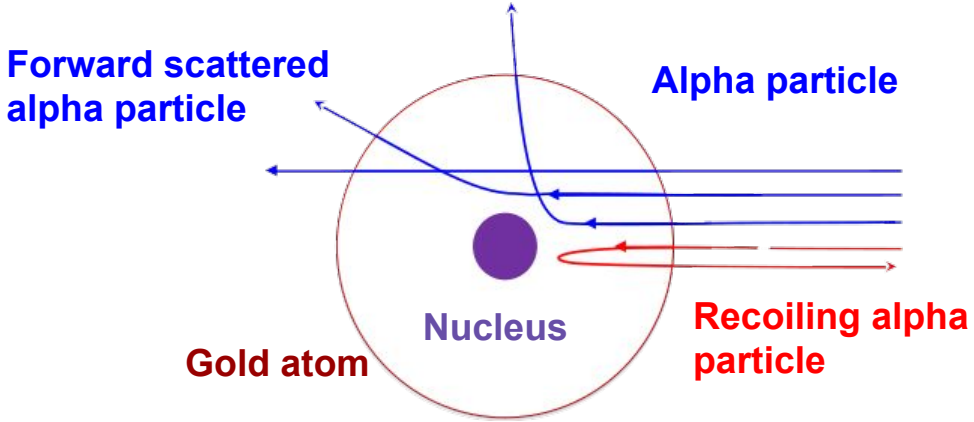
A postdoc at William and Mary

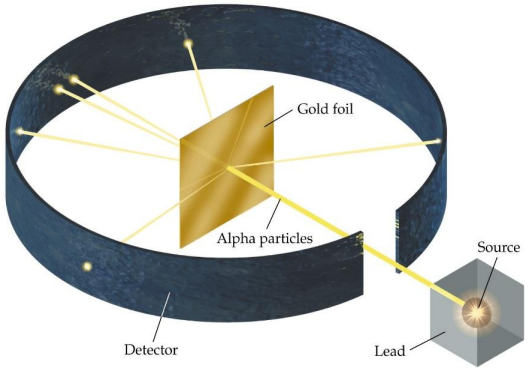
22/June/2020

Outline

- Introducing the backward angle physics:
  - What is backward angle physics?
  - How do we access it?
  - Why do we want to study it?
- Theory interpretation to the u-channel physics observables
- List of plan tasks during for the post-doc award
- Measure of success
- Progress so far

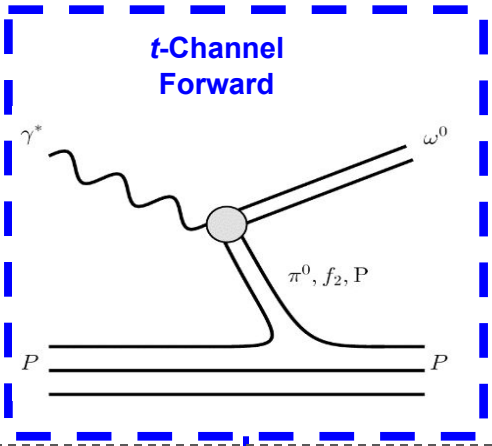
Backward-angle structure of Atom

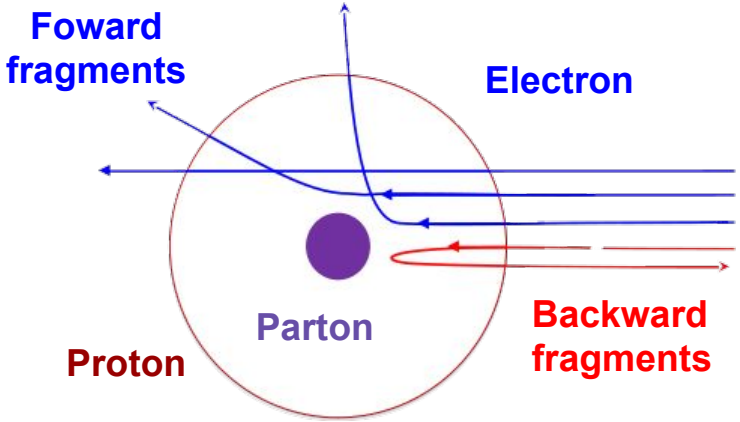


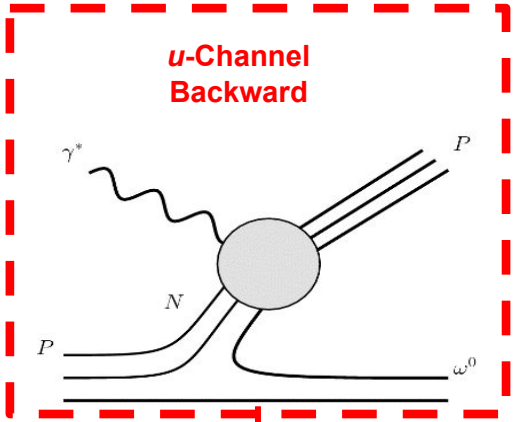


- **Forward scattered alpha particle: extracting the interaction radius of the nucleus and mapping out the transverse structure of the atom (mostly empty)**
- **Recoiling alpha particle: stiffness of the "point-like" structure.**
- Full structure must incorporate both forward angle and backward angle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

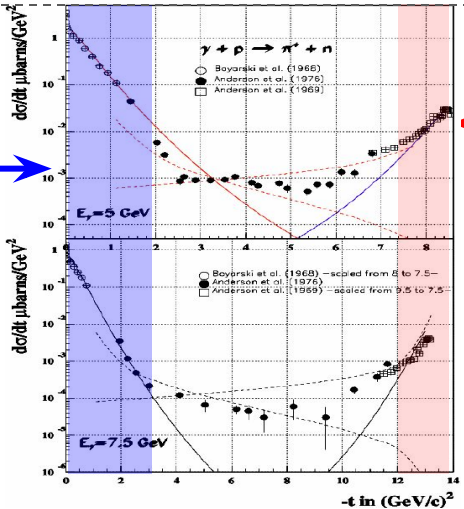
Structure of Proton







Meson pole contribution

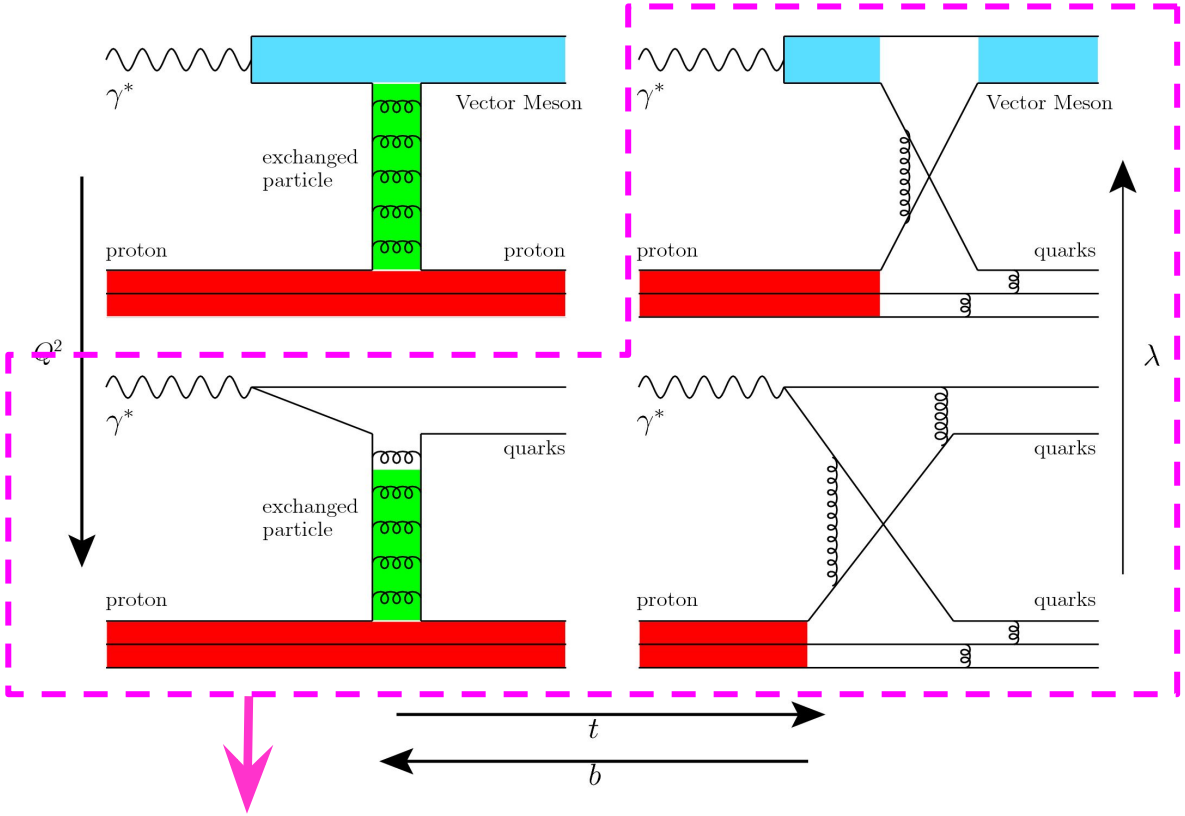


Baryon pole contribution

Transition:
Soft structure→Hard structure→Soft structure

M. Guidal, J.-M. Laget, and M. Vanderhaeghen.
*Physics Letters B*400(1): 6 – 11, 1997.

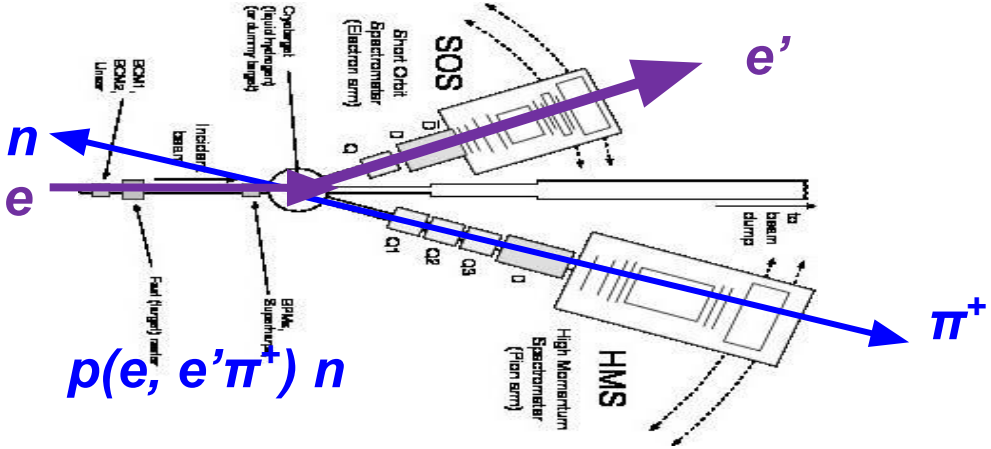
Hadronic Model: Transition (Evolution) of Proton Structure

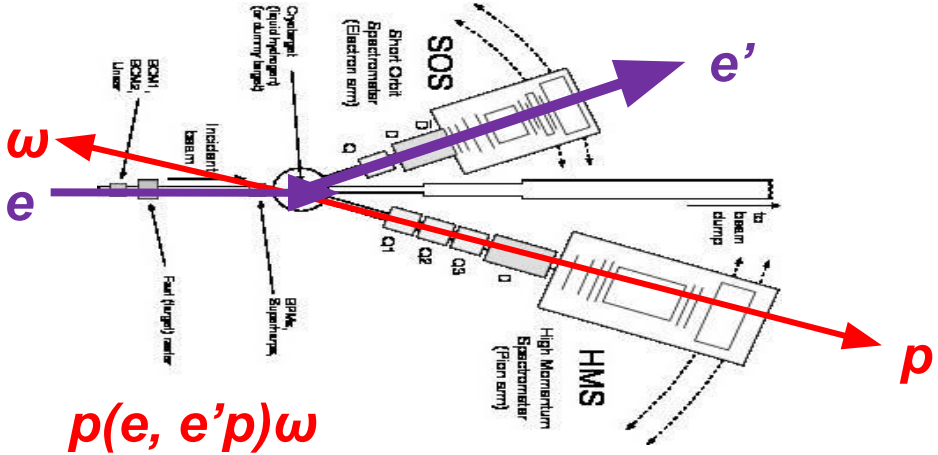


Evolution of the Proton Structure

- 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 about ***u***? Any role?

t-Channel π vs *u*-Channel ω^0 Production



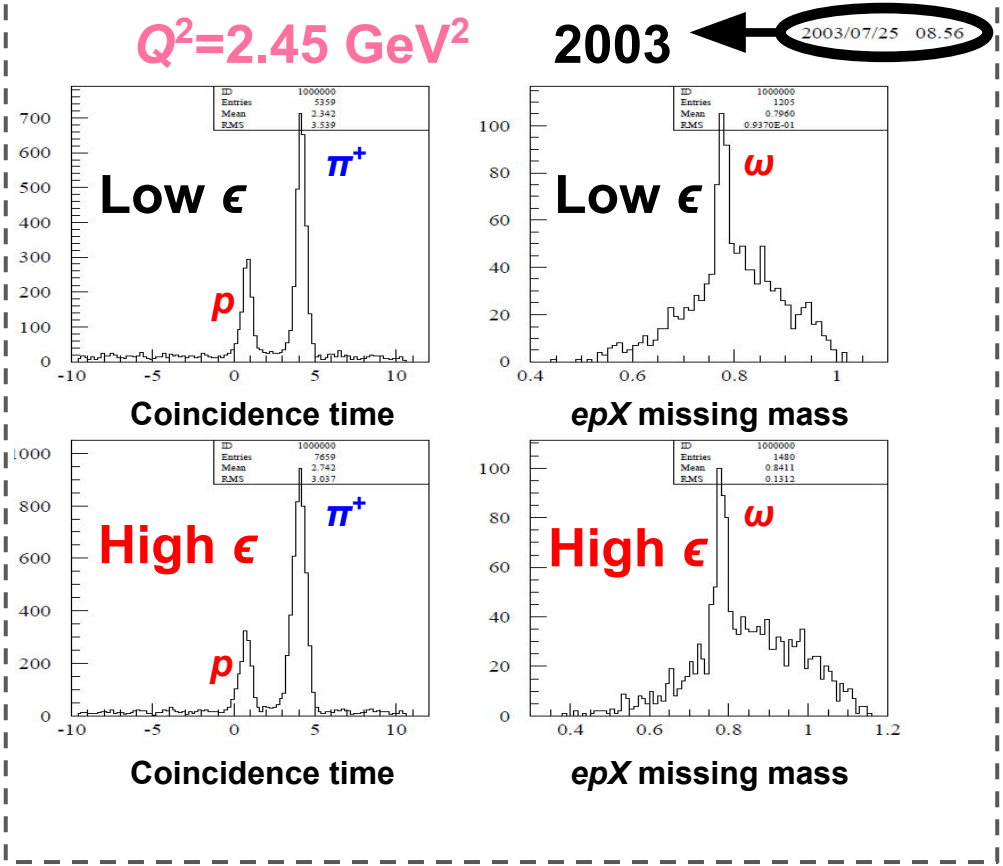


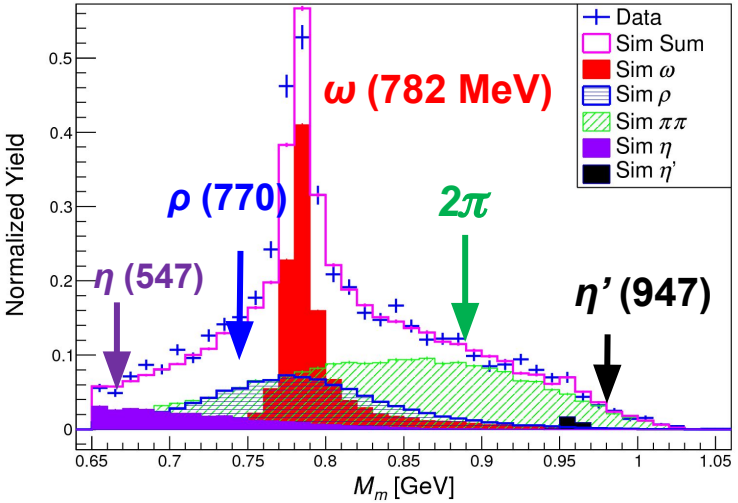
- **Fpi-2 (E01-004) 2003**
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged π** through exclusive π production
- **Primary reaction for Fpi-2**
  - $p(e, e' \pi^+)n$
- **In addition, we have for free**
  - $p(e,e' p)\omega$
- **Kinematics coverage**
  - W= 2.21 GeV, Q^2=1.6 and 2.45 GeV^2
  - Two ϵ settings for each Q^2
- **LT Separation!**

Backward Angle ω Electroproduction from 6 GeV Era

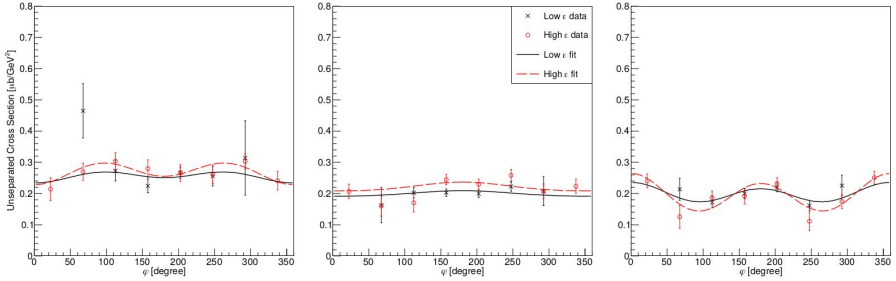
Q^2=2.45 GeV^2

2003



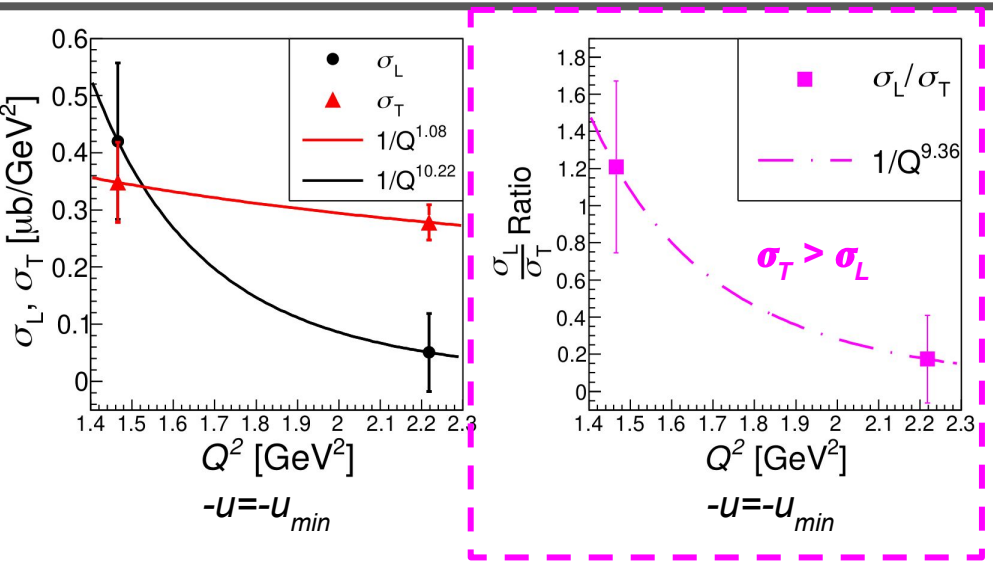


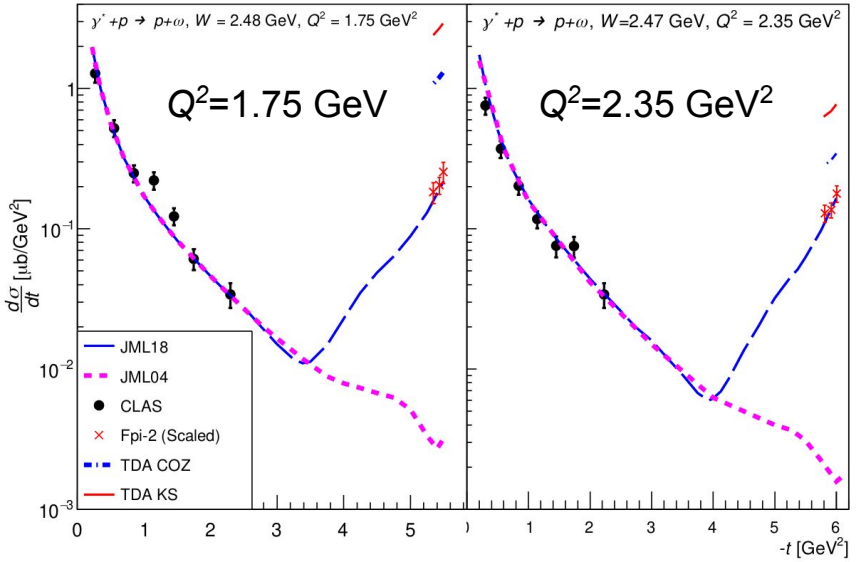
Q^2=2.45 GeV^2



(a) $-u \leq 0.19$ GeV^2 (b) $0.19 < -u \leq 0.30$ GeV^2 (c) $0.30 < -u \leq 0.50$ GeV^2

Backward Angle ω Electroproduction from 6 GeV Era

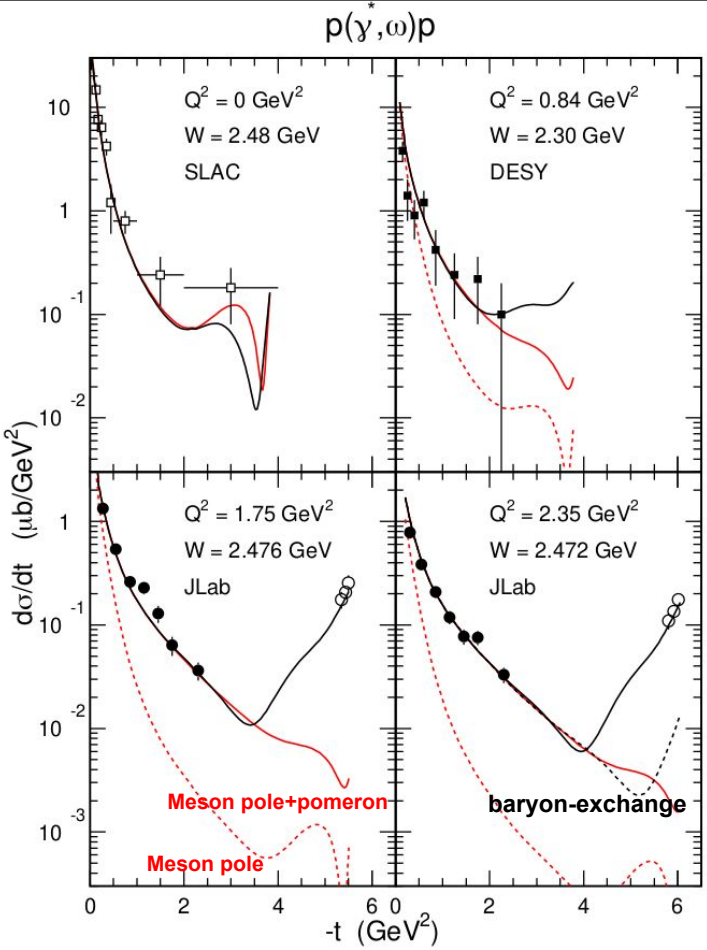




Phys. Rev. Lett. 123 (2019) 182501

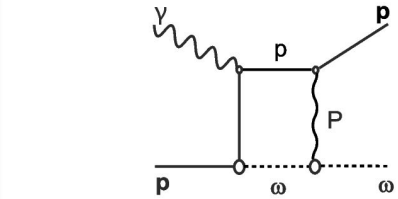
- Key observation:
  - $\boldsymbol{\sigma_L}$ dropped significantly as question of Q^2, as a result: $\boldsymbol{\sigma_T > \sigma_L}$ observed at Q^2 ~2.35 GeV^2
  - Sharp u-channel ω Electroproduction peaks are observed at both 1.75 and 2.35 GeV^2
  - Forward-backward ratio is 10:1!

The Regge Approach (Soft structure)

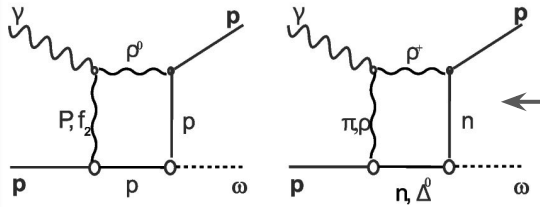


Unitarity cut in *u*-channel

Images credit to J-M. Laget



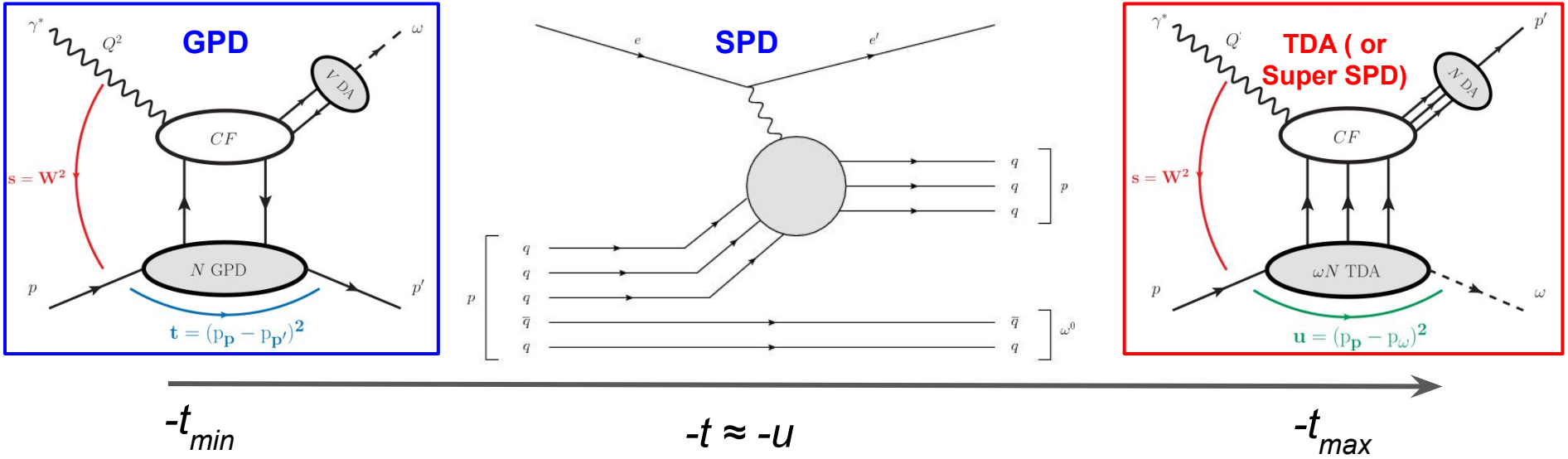
Nucleon pole Exchange diagram



Additional ρ re-scattering within nucleon diagrams

- **Regge Study by J-M. Laget in 2018**
- **Key findings:**
  - Nucleon pole contribution along could not explain the sharply rising slop at $-t = -t_{max}$.
  - ρ re-scattering within nucleon diagrams is required
  - Work is in progress**. L/T separation study was not attempted.**
- **Another Regge effort from Be-Geel Yu is also work in progress. Attempting the L/T separation prediction.**

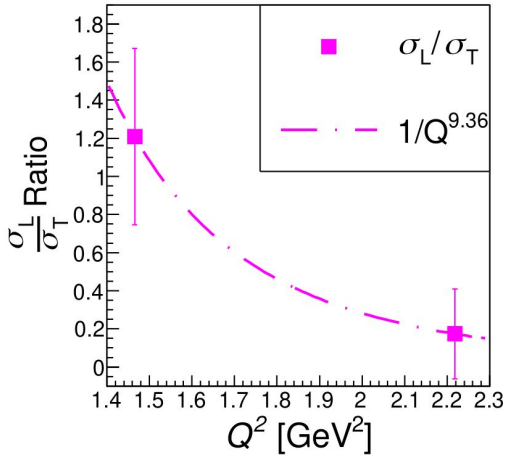
GPD, SPD and TDA (Hard structure)

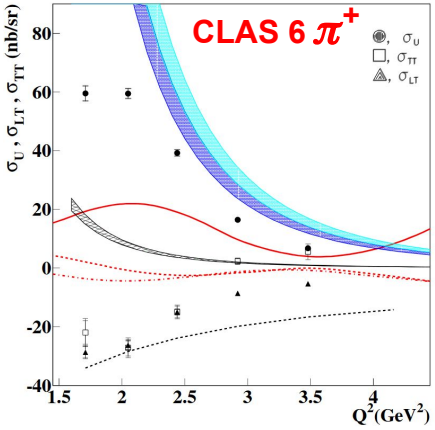


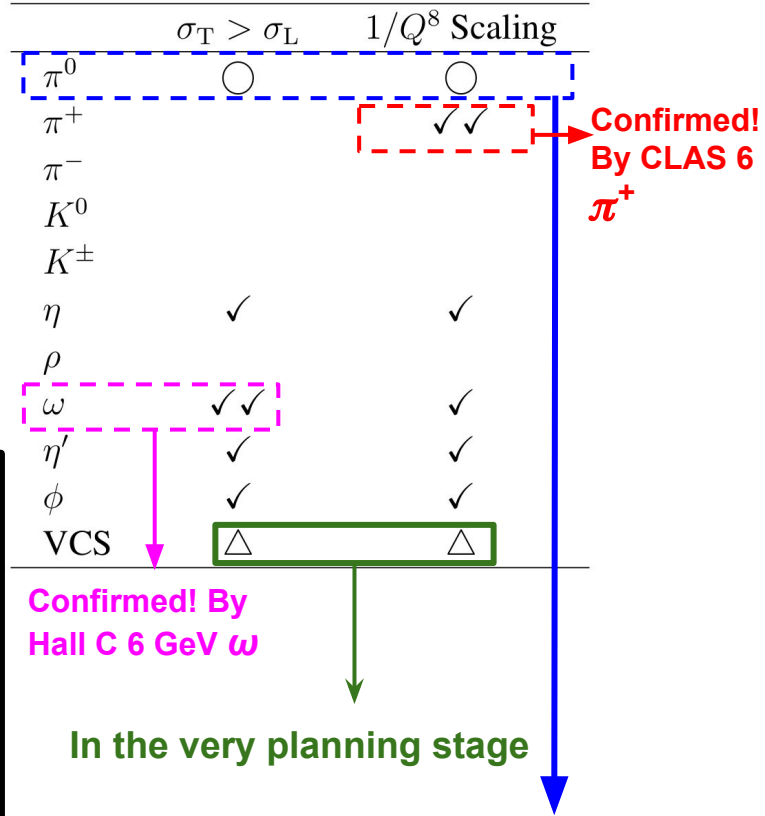
Complete description of Nucleon

- **GPD**: is like a hadron tomography of the proton. It is extracted predominately based the forward angle observables.
- **SPD**: Skewed Parton Distribution. Discovered Frankfurt and Strikman in 2003. Hadron tomography of the proton at large skewness. At extreme skewness, known as the **Super SPD**.
- **TDA**: meson-nucleon Transition Distribution Amplitude (TDA), similar to super SPD. Rediscovered by B. Pire, and L Szymanowski and K Semenov-Tian-Shansky.. Tomography of partonic distributions in the nucleon --> meson and vice versa transitions probed in the backward angle kinematics

Validation of TDA or *u*-Channel Factorization Scheme







Two qualitative predictions from TDA:

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

Three phases of validating TDA with JLab 12 GeV meson electroproduction :

- **Stage 0: find *u*-channel peaks for all mesons (12 GeV)**
- **Stage 1: test TDA predictions (12 GeV)**
- **Stage 2: extractions of TDAs**

Others: parasitic data may be available

JSA Award List of Tasks

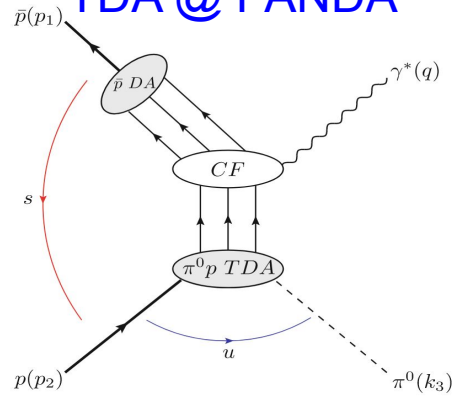
- Invite Dr. K. Semenov-Tian-Shansky (as a TDA expert) for a research visit to deepen discussion in u-channel physics
- Developing coherent and comprehensive 12 GeV strategy
  - Priorities list of prime observables: takes into account realistic constrains and avalaible resources
  - *u*-channel DVCS: kinematics survey
  - Supporting more single pion beam spin assymmetries development from CLAS
- TDA cross section predictions 12 GeV and EIC kinematics
- Hosting first *u*-channel physics workshop

Measure of Success:

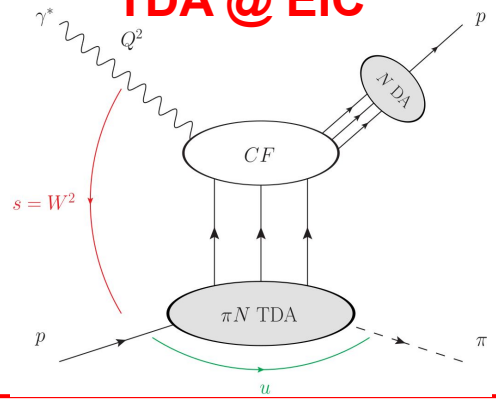
- Completing and publishing the workshop white paper on the backward angle physics strategy for JLab 12 GeV.
- Completing and publishing the EIC backward-angle π^0 feasibility study (work in progress).
- Completing the relevent section in Yellow report (work in progress).
- Presenting PAC48 proposal (submitted to PAC).

JLab 12 GeV to EIC Transition: *u*-channel π^0 production

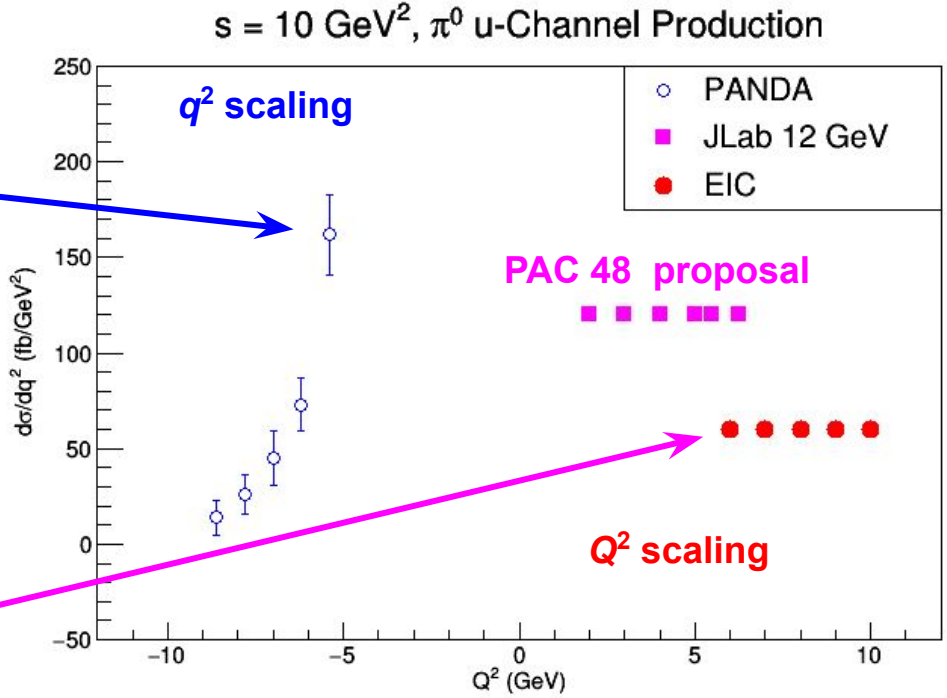
TDA @ PANDA



TDA @ EIC

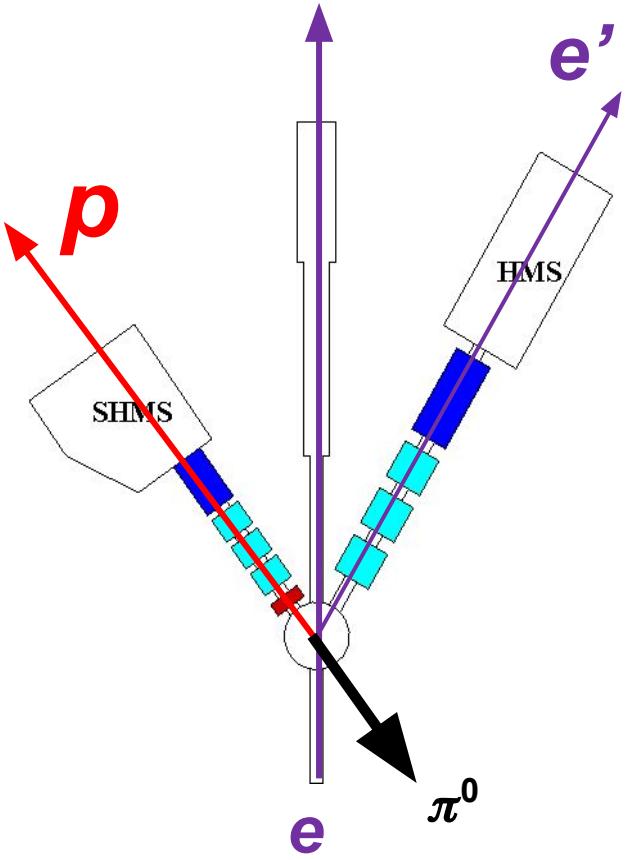


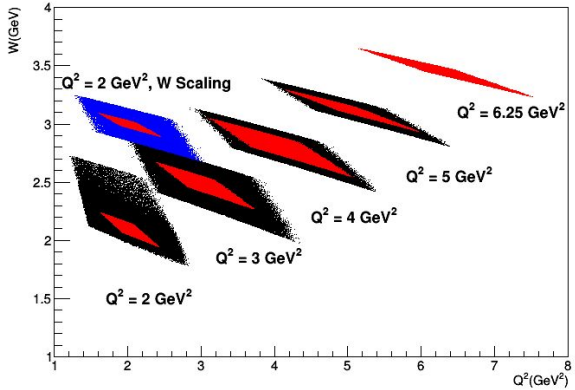
The PANDA Collaboration, Eur. Phys. J. A (2015) 51: 107

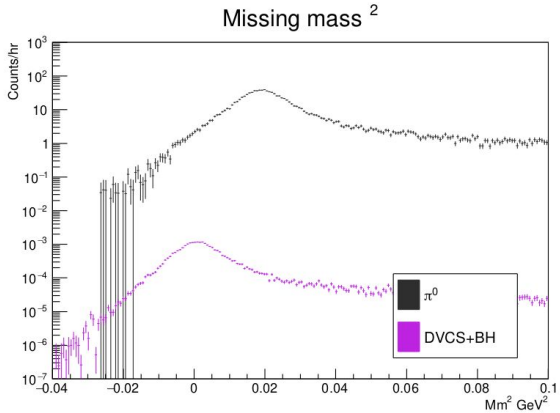


Same TDAs for PANDA and EIC, the ultimate universality check

Progress Report on PAC 48 Proposal: Backward-angle π^0







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

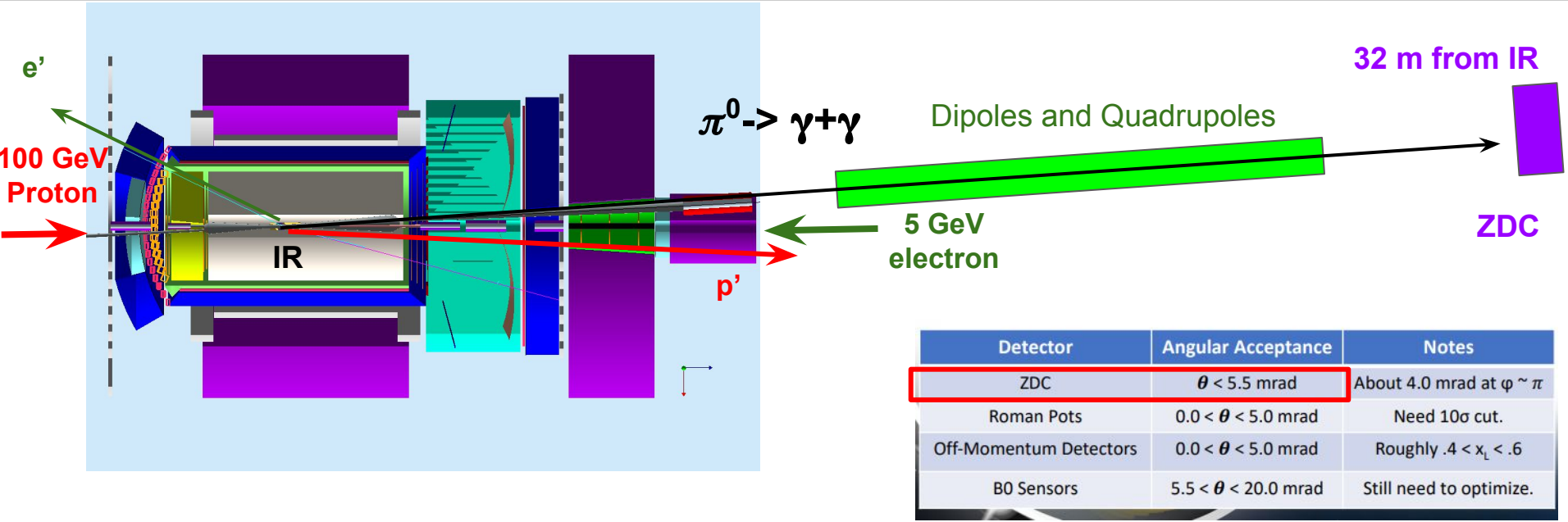
- Q^2 coverage: 2.0 < Q^2 < 6.25 GeV^2.
- *x*=0.36
- *u* coverage: 0 < -*u*' < 0.5 GeV^2

Submitted to PAC 48!

Objective:

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

Progress Report on *u*-channel π^0 @ EIC

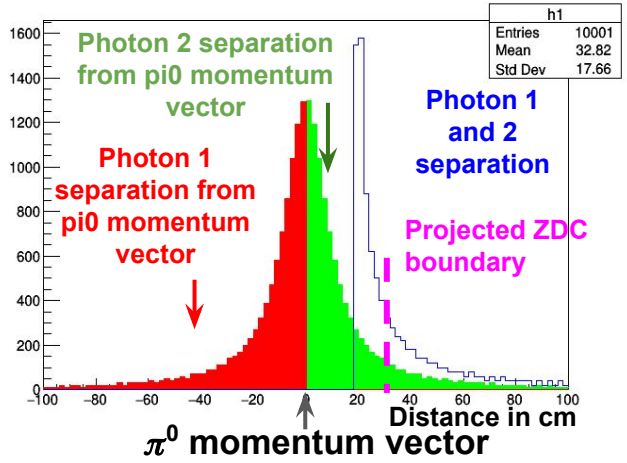


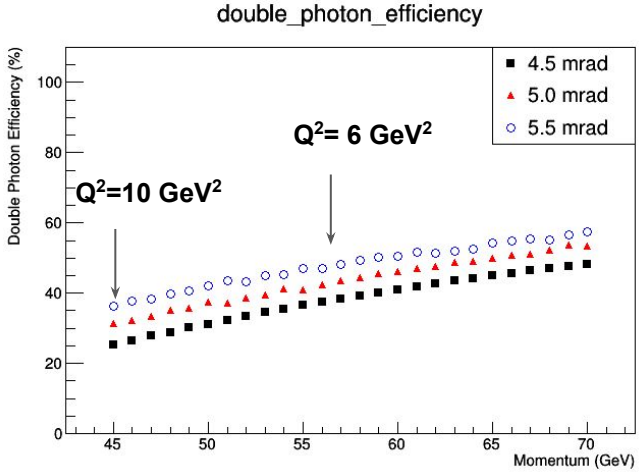
Detector	Angular Acceptance	Notes
ZDC	θ < 5.5 mrad	About 4.0 mrad at φ ~ π
Roman Pots	0.0 < θ < 5.0 mrad	Need 10σ cut.
Off-Momentum Detectors	0.0 < θ < 5.0 mrad	Roughly .4 < x_L < .6
B0 Sensors	5.5 < θ < 20.0 mrad	Still need to optimize.

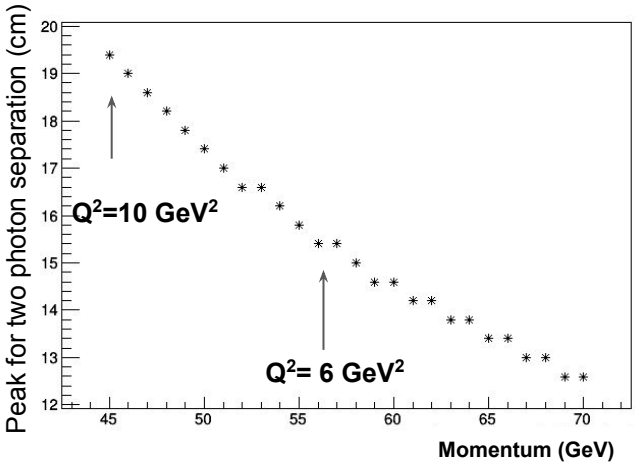
Q^2 (GeV^2)	W (GeV)	x_B	$\theta_{e'}$ (deg)	$\eta_{e'}$	$P_{e'}$ (GeV)	$\theta_{p'}$ (deg)	$\eta_{p'}$	$P_{p'}$ (GeV)	θ_{π^0} (deg)	η_{π^0}	P_{π^0} (GeV)	$-t$ (GeV^2)	$-u$ (GeV^2)
6.2	3.19		152	-1.39	5.31	-1.84	4.13	43.40	1.43	4.38	56.29	14.84	-0.37
7.0	3.19		150	-1.32	5.35	-1.92	4.09	45.50	1.43	4.38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

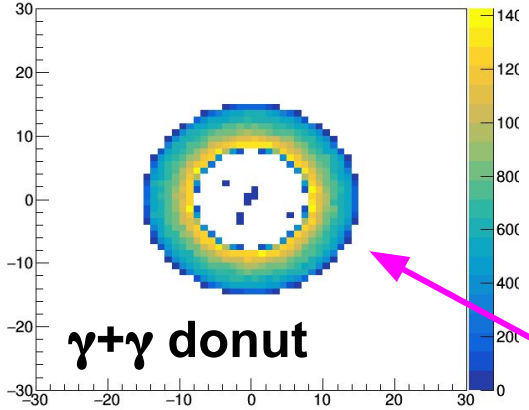
u'=0 GeV

Progress Report on *u*-channel π^0 @ EIC









Preliminary conclusion:

- *u*-channel π^0 at EIC with current design is a feasible measurement
- Ideal expected trigger: e'+p'+ 2 γ, is very clean with very little background, with reduced efficiency
- **Next step: process to full geant4 simulation**

The EIC fellowship award will help completing the YR and feasibility studies

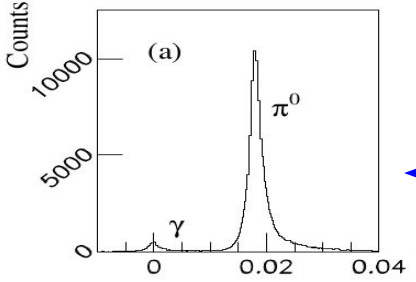
ZDC 2 γ hit pattern @ 40 GeV/c π^0 4.5 mrad acceptance

Progress Report: First *u*-channel Physics Workshop

- **Thanks to the suppot from JLab, JSA and William & Mary, workshop is on track for Seprember 21st-23rd, 2020.**
  - **Indico page of the workshop: https://www.jlab.org/indico/event/375**
  -
- **The workshop have representatives from all four halls, from JLab 6, 12 GeV, PANDA and EIC**
  - **u-channel electroproduction examples at 12 GeV**
    - Backward DVCS (Hall **B**, **C**)
    - CLAS 12 single pion spin assymmetry (Hall **B**)
    - U-channel meson production (omega, rho, phi) production from Kaon LT experiment (Hall **C**)
  - **u-channel photoproduction examples at 12 GeV**
    - Timelike Compton scattering (Hall **B**, **C** and **D**)
    - Wide angle compton scattering (Hall **C**)
    - ω Photoproduction off Proton Target at Backward Angles (Hall **D**)
    - Σ-K+ Photoproduction at Backward Angle at GlueX Experiment (Hall **D**)
    - ω Photoproduction off Proton Target at Backward Angles (Hall **D**)
  - **Theory prospective:**
    - Meson-Nucleon Transition Distribution Amplitude
    - Photon-nucleon together with meson-nucleon TDAs
    - Skewed Parton Distribution
    - *u*-channel Regge Approach
  - **Future prospective of u-channel physics**
    - *u*-channel π^0 production at EIC
    - Studying TDA with pp → e+e−+π^0 at the PANDA Experiment
- **A summary whitepaper is planned: outlining the JLab 12 GeV to EIC u-channel physics strategy**

A Lesson from the Past

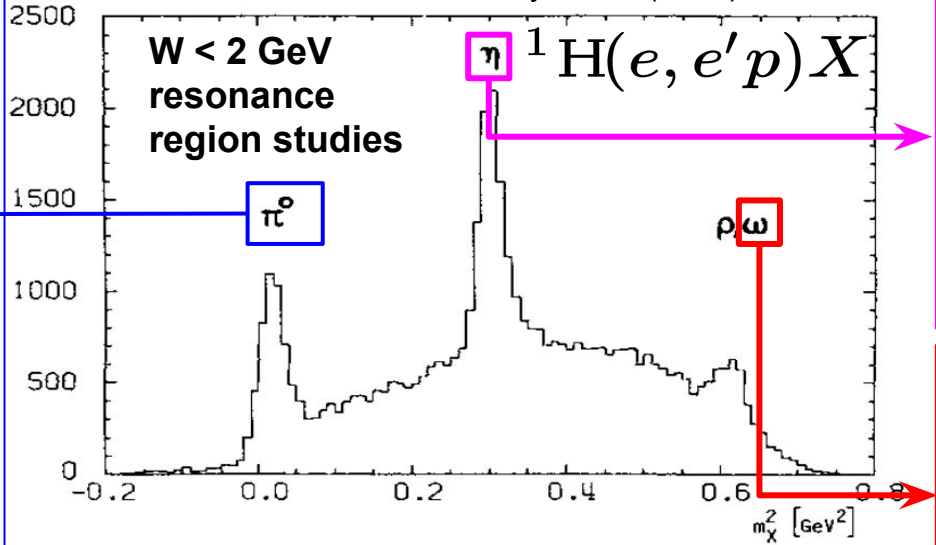
G. Laveissière et al. Phys. Rev. C 79, 015201 (2004)



Hall A VCS: E93-050

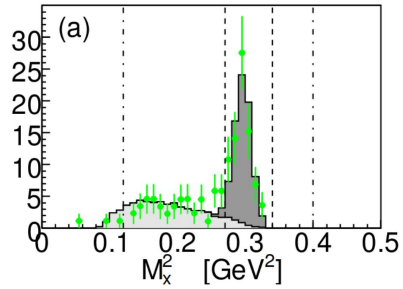
Hall C VCS: E12-15-001

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



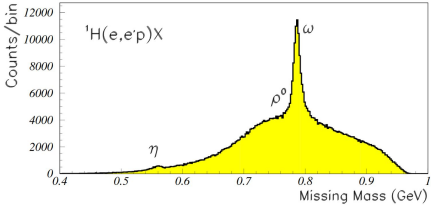
***u*-channel meson spectral at DESY spectrometer experiment from 1984**

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



Hall C E01-002

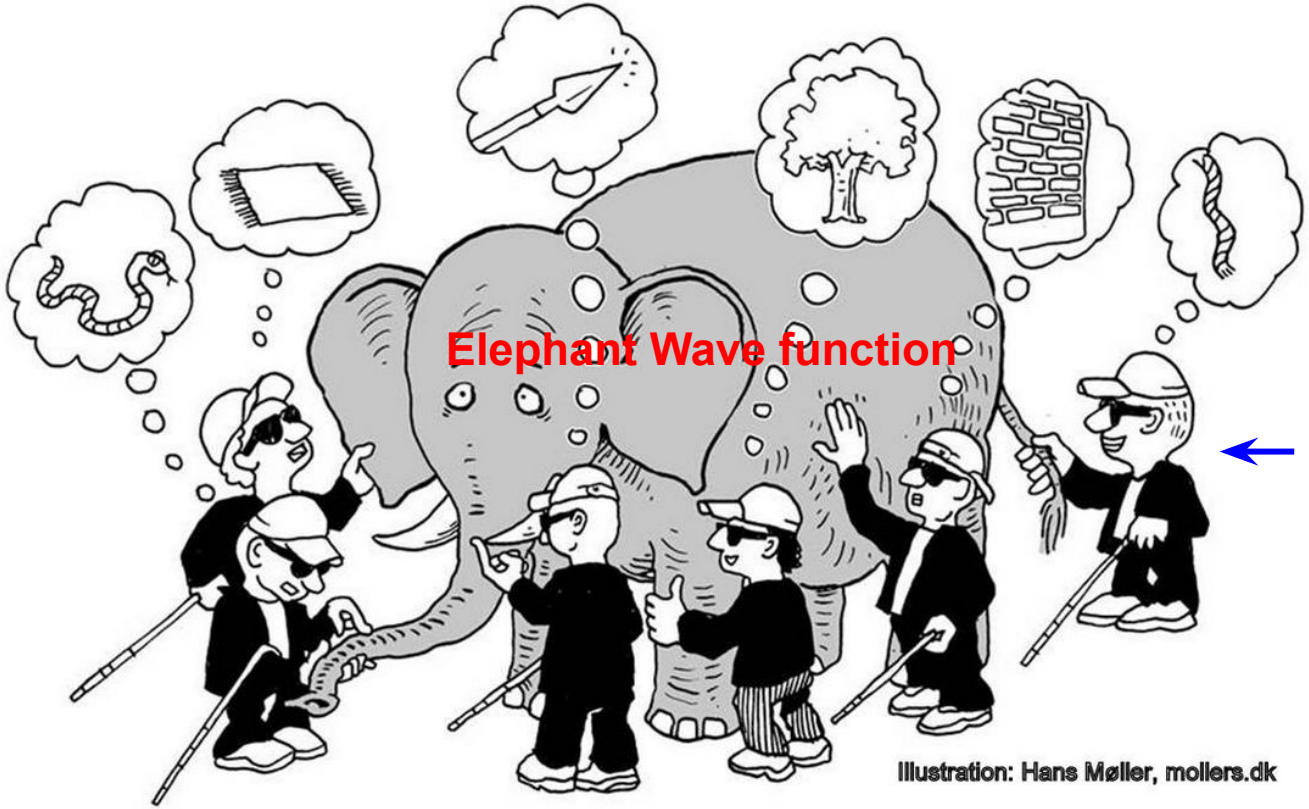
P. AmbrozwiczPhys. Rev. C 70, 035203 (2004)



Hall C E91-016

- Now is the time to resurrect u-channel meson productions at 12 GeV kinematics and future EIC.
- **Goal of our activity: to inspire a wave of backward-angle physics measurements**

Thank you for your attention!



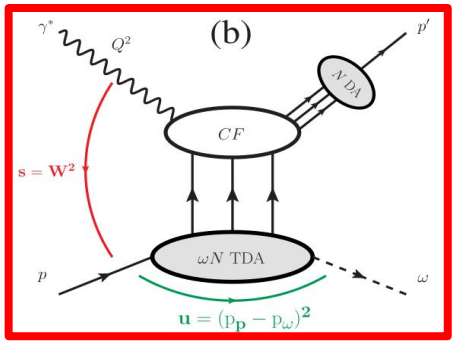
Thank you for the supports

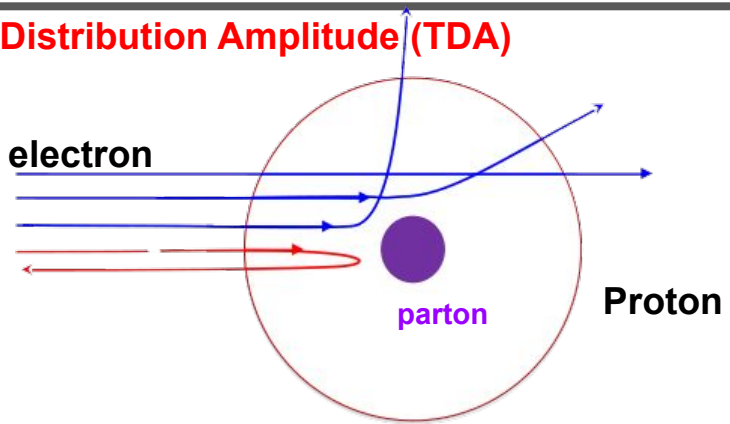
- **Gratitude to the JSA, JLUO award selection committee,**
- **Gratitude to Garth and Justin guidance, advance and support**
- **Gratitude to the TDA theorist: Bernard, Lech and Kirill, and assistance from JLab theory center: Christian**
- **Thanks to my Hall A/C, CLAS TDA working group and Hall D colleagues**
- **My people from the postdocs and graduate students community**
- **Great support from William and Mary Physics department**

Backup

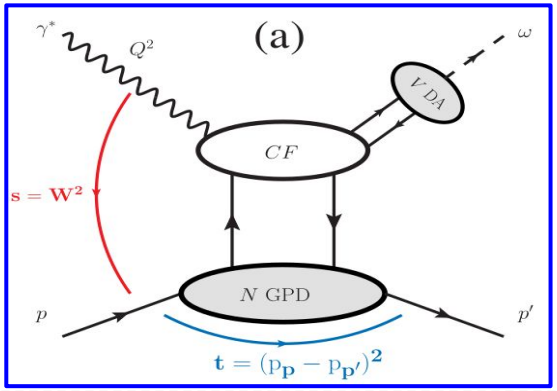
Backward-angle structure of Proton

Meson-nucleon Transition Distribution Amplitude (TDA)



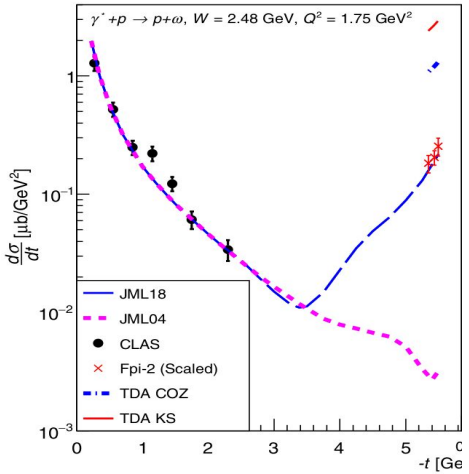


GPD



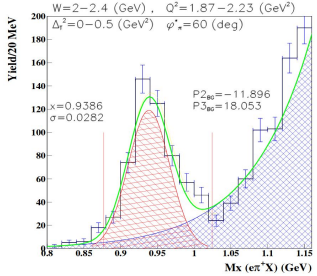
- Complete description of Nucleon
  - GPD = Hadron tomography of the proton
  - TDA = tomography of partonic distributions in the nucleon --> meson and vice versa transitions probed in the backward angle kinematics

- Backward-angle cross section is not 0!
  - backward angle cross section is 1/10 of the forward angle cross section at observed Q^2



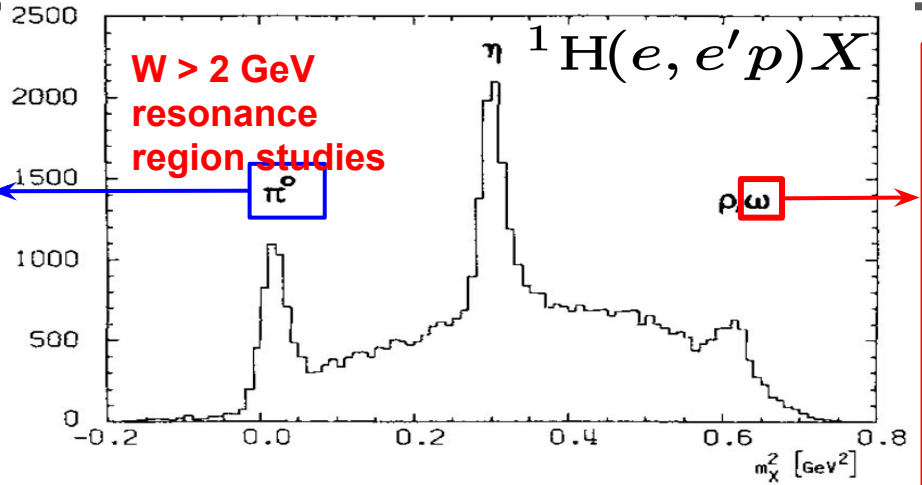
6 GeV Backward Angle Physics at W > 2 GeV

Charged Pion Production from CLAS 6

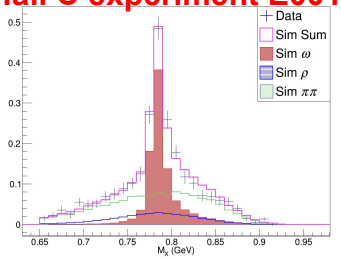


^{1}H(e, e'π$^+$)X

- **Q^2 Scaling**



Hall C experiment E001-004

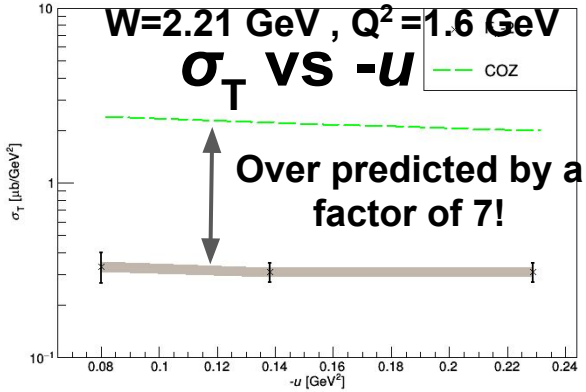


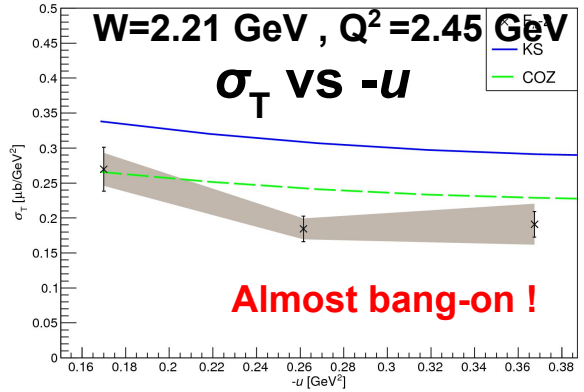
^{1}H(e, e'p)X

- **Parasitic data**
- **Full L/T separation**

- **Backward angle physics in this talk: backward angle physics above the resonance region (W>2 GeV^2)**
- ***u'* -> u_{min}, *t* > Q^2**
- **A systematic backward angle physics program:**
  - **JLab 6 -> JLab 12 -> EIC**

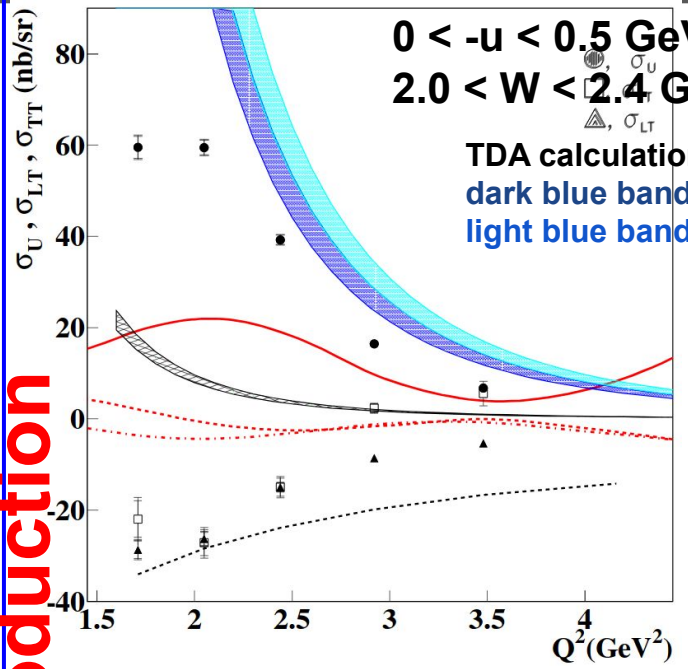
Comprison to TDA calculation





TDA Calculation by B. Pire, K. Semenov, L. Szymanowski, Private Communication. (2015)

Hall C Omega Production

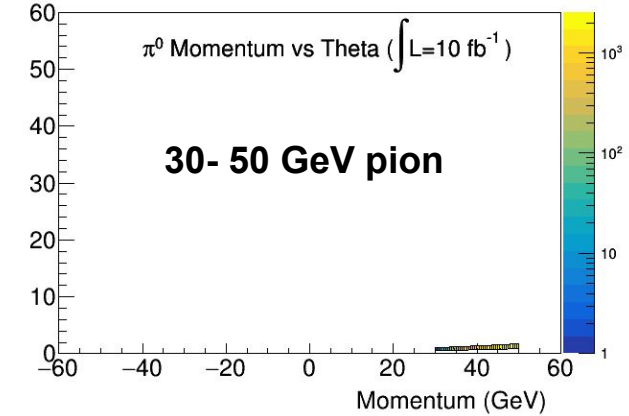


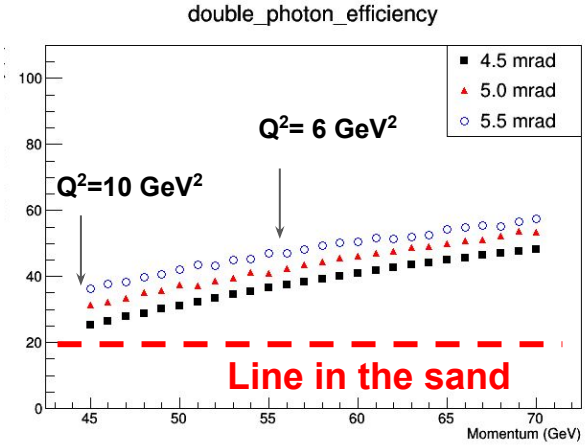
Hall B charged π production

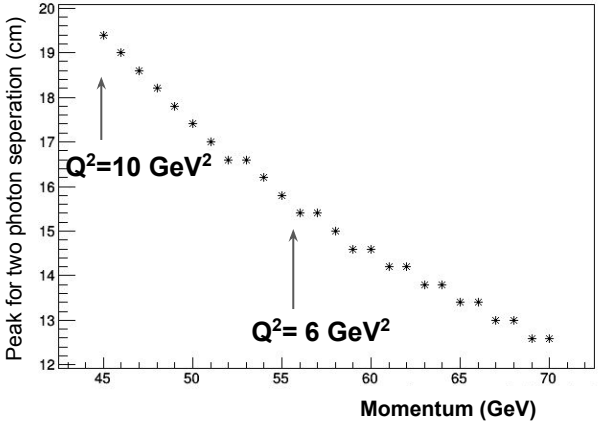
K. Park et. al,Physics Letters B
Volume 780, 10 May 2018, Pages 340-345, (2017)

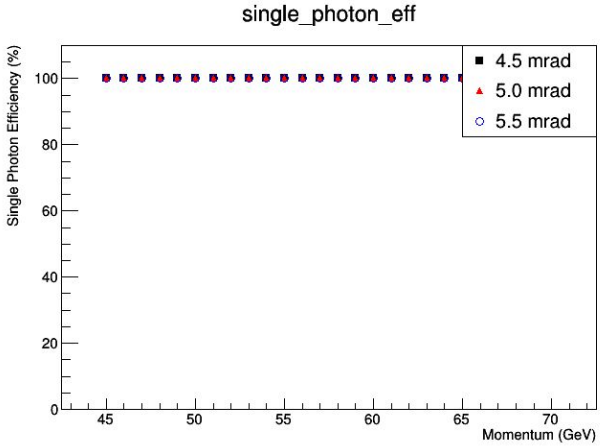
Indication of early TDA scaling !?

Impact to the efficiency









- 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

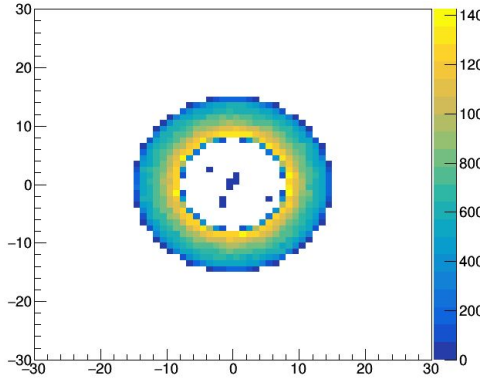
Physics background (to our current best knowledge)

- 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: Λ->n+π^0

2 γ hit parttern

40 GeV/c π^0

4.5 mrad acceptance

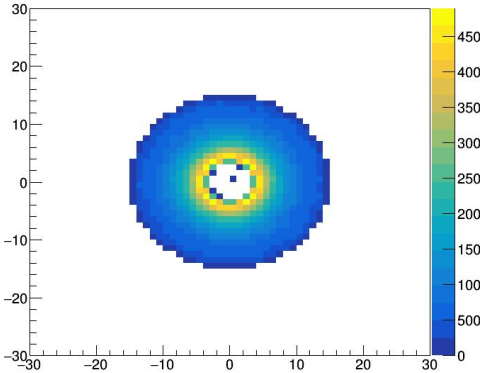


- Single photon case:
  - Primary reaction: e+p-> e'+p' + π^0
  - Ideal expected trigger: e'+p'+ γ
  - Physis background: DVCS, eta, Λ->n+π^0
  - Less than ideal trigger: e'+γ
  - Background: many many possibility

2 γ hit parttern

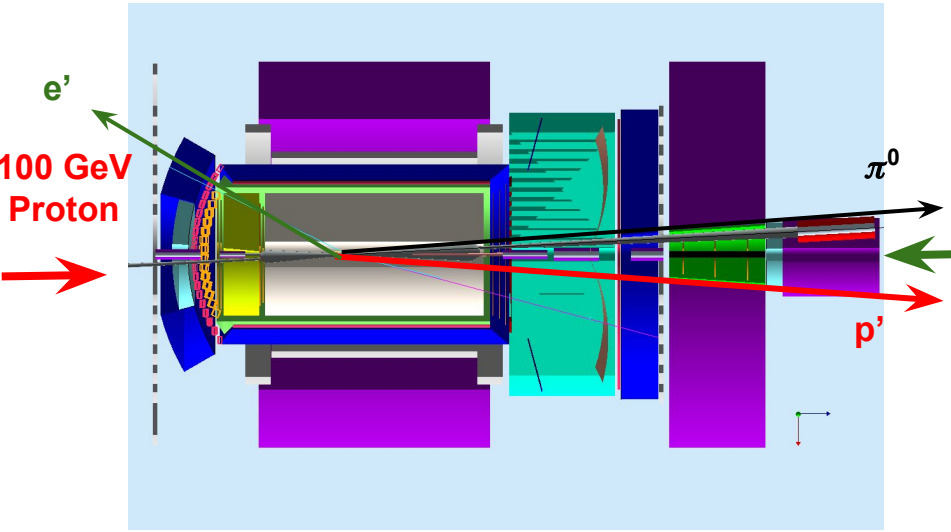
60 GeV/c π^0

4.5 mrad acceptance

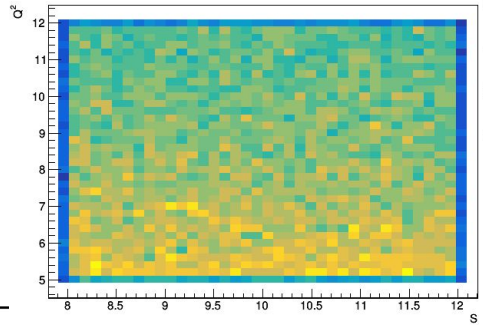


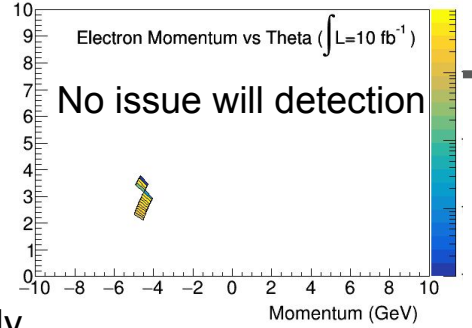
- We can use the double photon event to normalize the single photon events

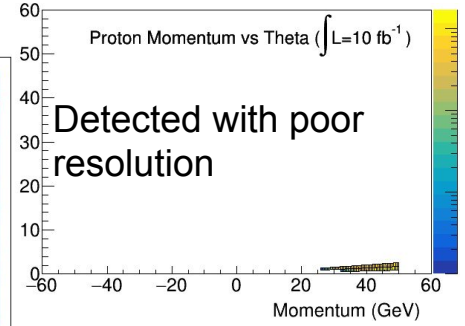
U-channel Meson Production Setup

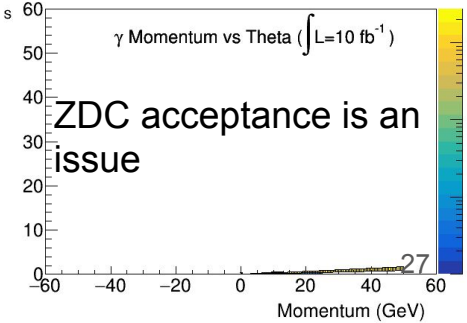


Q^2 vs S intentionally constraint







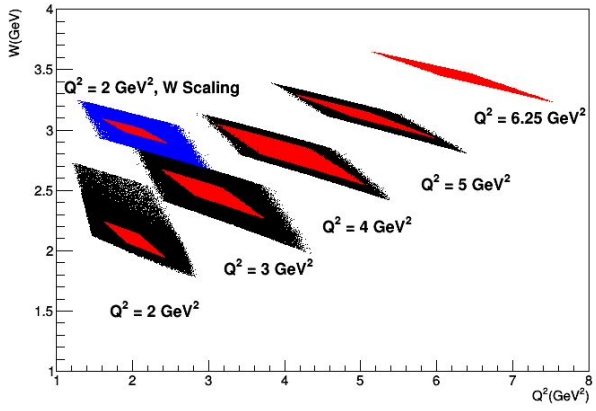


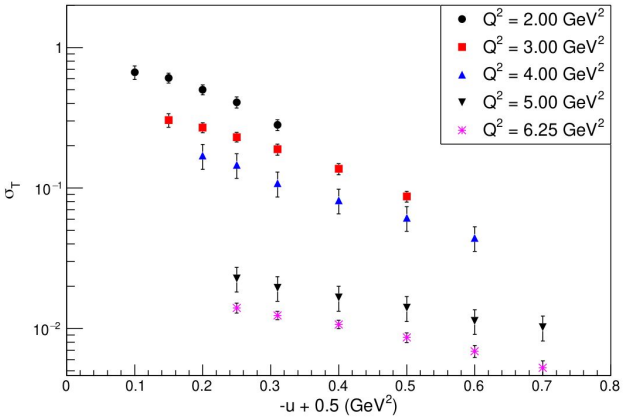
Q^2 (GeV^2)	W (GeV)	x_B	$\theta_{e'}$ (deg)	$\eta_{e'}$	$P_{e'}$ (GeV)	$\theta_{p'}$ (deg)	$\eta_{p'}$	$P_{p'}$ (GeV)	θ_{π^0} (deg)	η_{π^0}	P_{π^0} (GeV)	$-t$ (GeV^2)	$-u$ (GeV^2)
6.2	3.19		152	-1.39	5.31	-1.84	4.13	43.40	1.43	4.38	56.29	14.84	-0.37
7.0	3.19		150	-1.32	5.35	-1.92	4.09	45.50	1.43	4.38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

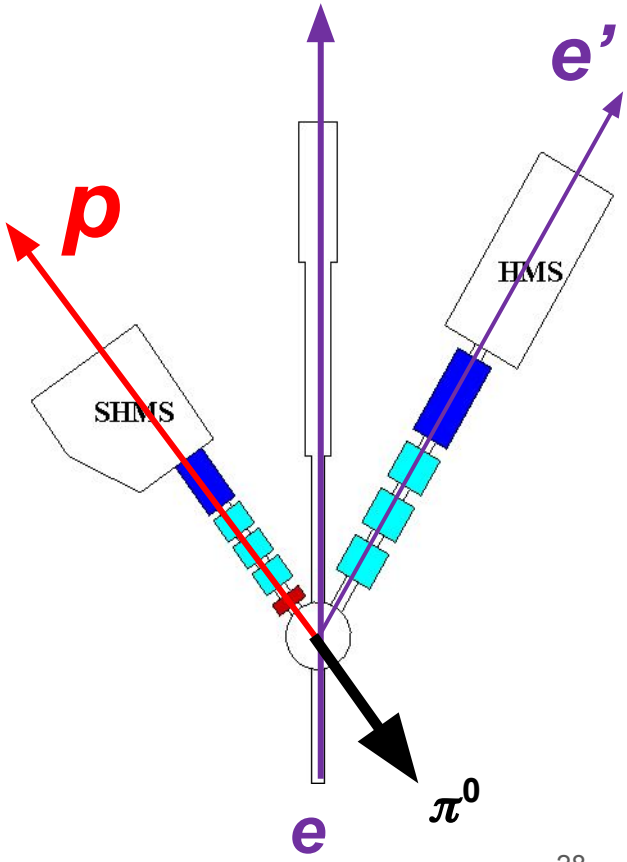
New Proposal to PAC 48 on Backward-angle π^0 Production

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

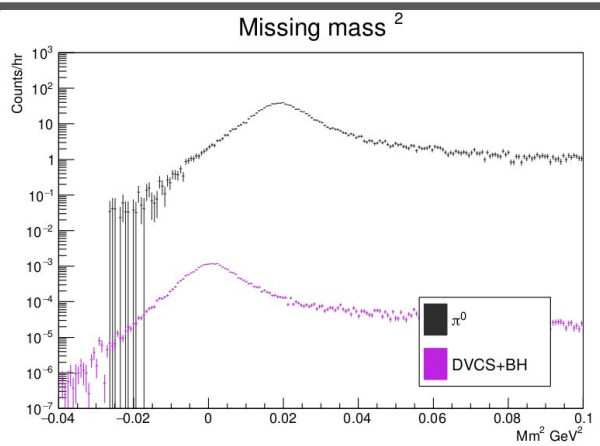
- ^{1}H(*e*,*e'p*)π^0
- Q^2 coverage: 2.0 < Q^2 < 6.25 GeV^2.
- L/T separation at Q^2 = 2.0, 3.0, 4.0 and 5.0 GeV^2
- Fixed *x*=0.36 for all settings
- *u* coverage: 0 < -*u*' < 0.5 GeV^2



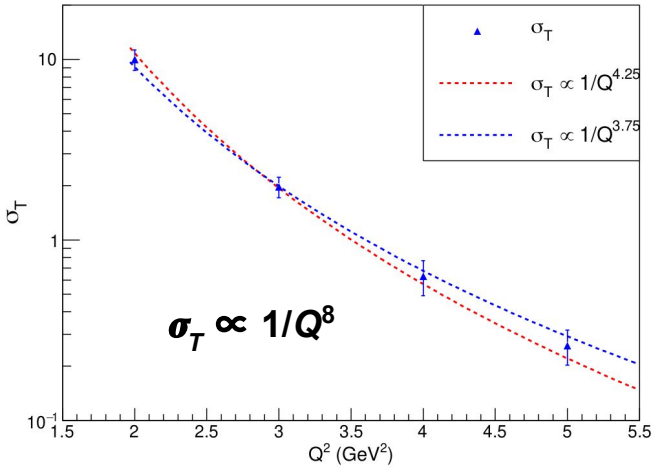


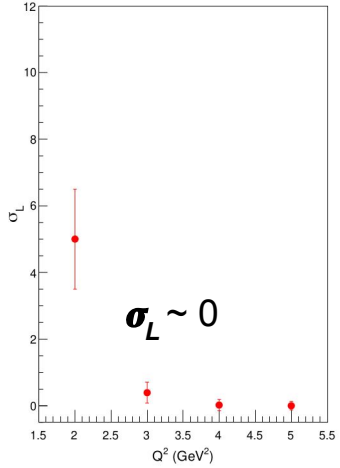


New Proposal to PAC 48 on Backward-angle π^0 Producrtion



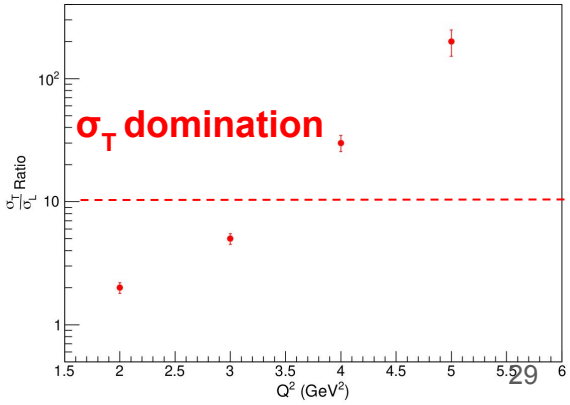
Q^2= 4 GeV^2, W=2.8 GeV, x=0.36





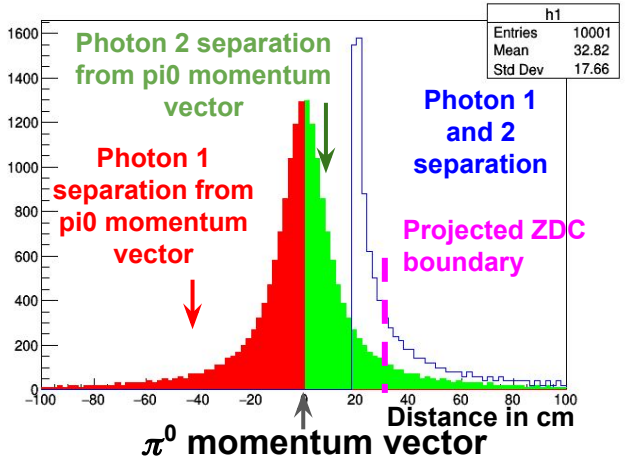
Experiment objective

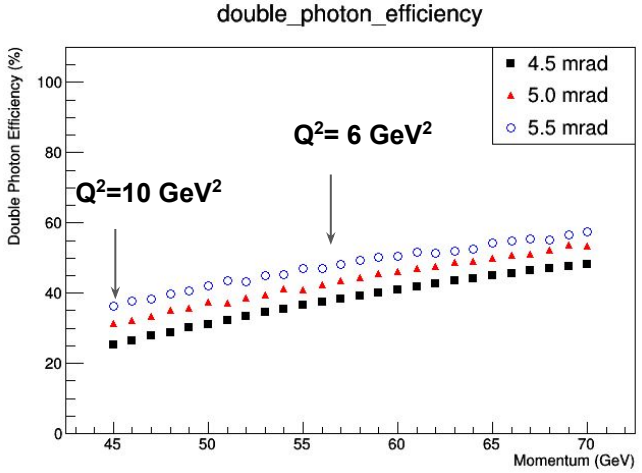
1. Demonstrate existence of u-channel peaks
2. *u*-dependence of L/T seperated cross sectio
3. If peaks exist, test TDA prediction: $\sigma_T > \sigma_L$
4. If $\sigma_T > \sigma_L$, test $\sigma_T \propto 1/Q^8$

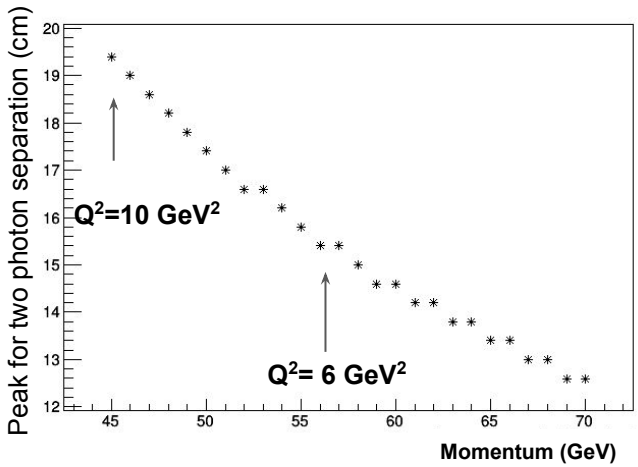


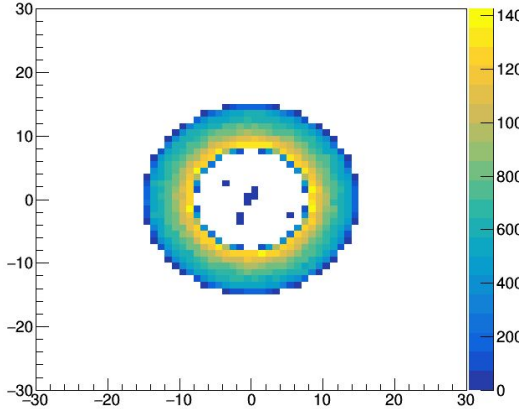
We are pleased to report the proposal was submitted to PAC 48

π^0 Events on ZDC









Preliminary conclusion:

- *u*-channel π^0 at EIC with current design is a feasible measurement
- Ideal expected trigger: e'+p'+ 2 γ, is very clean with very little background, with reduced efficiency
- **Next step: process to full geant4 simulation**

2 γ hit pattern

40 GeV/c π^0

4.5 mrad acceptance

Budget & Measure of Success

Planned Budget (in the proposal):

- Dr. Kirill Semonov-Tian-Shansky's research trip to WM
  - Accommodation: $ 3000
  - Airfare: $1600
  - Visa application: $ 800
  - Transportation: $ 600

Require re-evaluation

- Participating conferences (Bill and Kirill): 3000
- Computational equipment (storage hard drives): $ 900
- Office space is provided by WM in kind

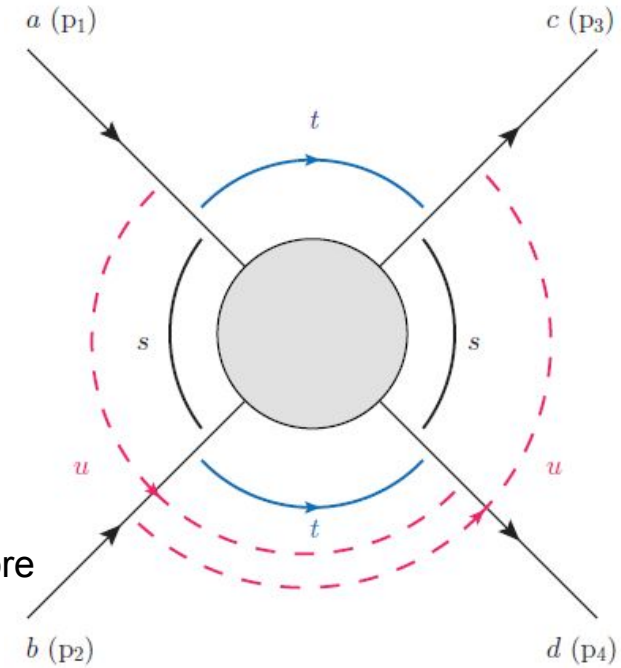
Measure of Success:

- PAC48 proposal on backward-angle pi0 production avoce the resonance region (submitted to PAC).
- Hosting u-channel physics workshop and completing a white paper on the backward angle physics strategy for JLab 12 GeV.
- Completing and publishing the EIC backward-angle pi0 feasibility study (work in progress).
- Completing the pi0 u-channel pi0 production section in Yellow report (work in progress).

Mandelstam variables (*s*,*t*,*u*-Channels)

Projectile Before

Target Before



$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$

$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$

- ***t***: Four-momentum-transfer squared between **target before and after interaction.**

$$\xi = 0, t \approx t_{min}, u \approx u_{max}, t < Q^2$$

- ***u***: Four-momentum-transfer squared between **virtual photon before interaction and target after interaction**

$$\xi = 1, t \approx t_{max}, u \approx u_{min}, t > Q^2$$

- ***t*-channel*: -t ~ 0*, after interaction**
  - Target: stationary,
  - Meson: forward

- ***u*-channel: *-u~0,* after interaction**
  - Target: forward
  - Meson: stationary
  - **Disclaimer: "Backward physics" is a marketing term, and it is equilent to u-channel physics**
  - Equivelent to "extremely large momentum transfer"

List of Tasks for the JSA Award

- Knowledge exchange within in theory community (K)
  - Inspire more collabration between local and european experts on u-channel physics
- Developing coherent and comprehensive 12 GeV stratagy (K+B)
  - Priorities list of prime observables: takes into account realistic constains and avalaible resources (K+B)
  - *u*-channel DVCS: kinematics survey (B)
  - Supporting more single pion beam spin assymmetries development from CLAS (K)
- TDA cross section predictions 12 GeV and EIC kinmatics (K)
- Hosting first *u*-channel physics workshop (B)

What channel is more important?

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

Strategy Based on TDA, SPD and Regge approach