# Probing the Baryon Junction via *u*-Channel SIDIS at SoLID

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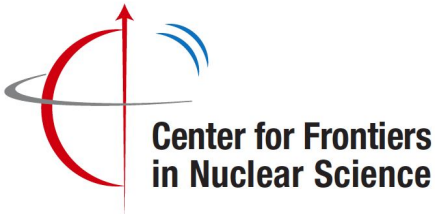
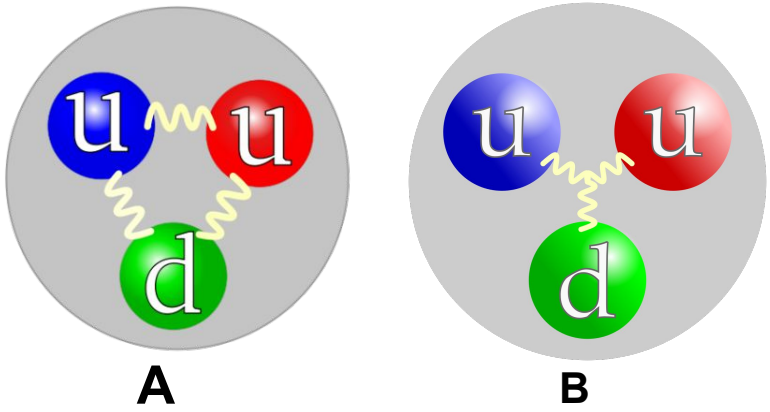
**@ 2023 SoLID Winter Collaboration Meeting**

**Sep/26/2023**




# Who carries the baryon number?

- **Nucleon internal structure:**



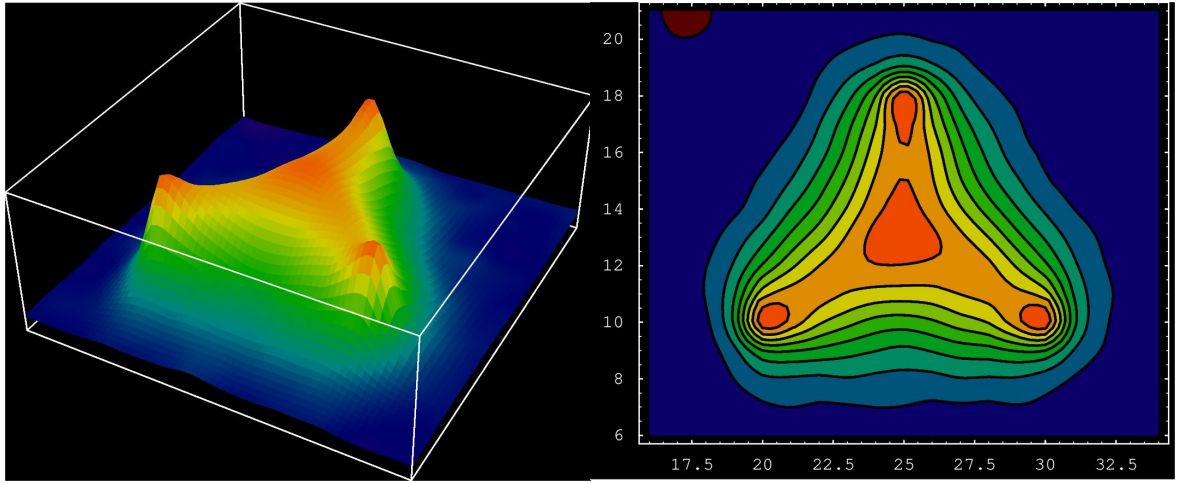

**A** **B**

**Question: which one is correct?**

**A**: implies quark carries fractional baryon number

**B**: existence of a **"Junction" like structure** that potentially carries the baryon number.

# Theory insights on baryon junction

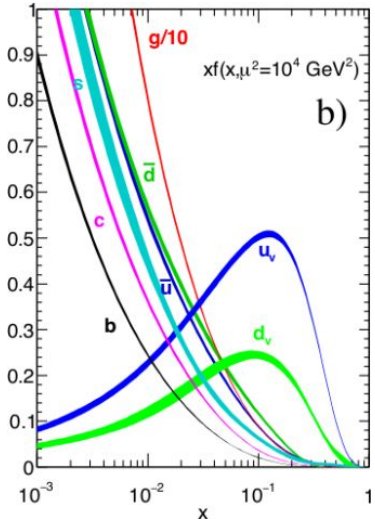


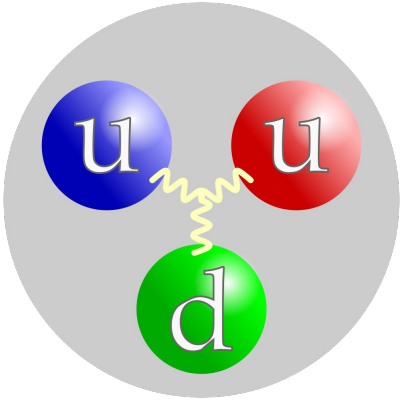

Hideo Suganuma, Toru T. Takahashi, Fumiko Okiharu, Hiroko Ichie, arXiv:hep-lat/0412026 , 2004

- **The lattice results show the presence of a "baryon junction" inside proton – a purely gluonic field configuration that represents entanglement among the quarks and carries baryon number!**
- **It has been predicted to exist on the basis of local gauge invariance of the baryon wave function (G.C. Rossi, G. Veneziano, Nuclear Physics B, Volume 123, Issue 3, 1977)**
- **It was also argued to dramatically affect the transport of baryon number in high energy processes (DK, 1996).** arXiv:nucl-th/9602027

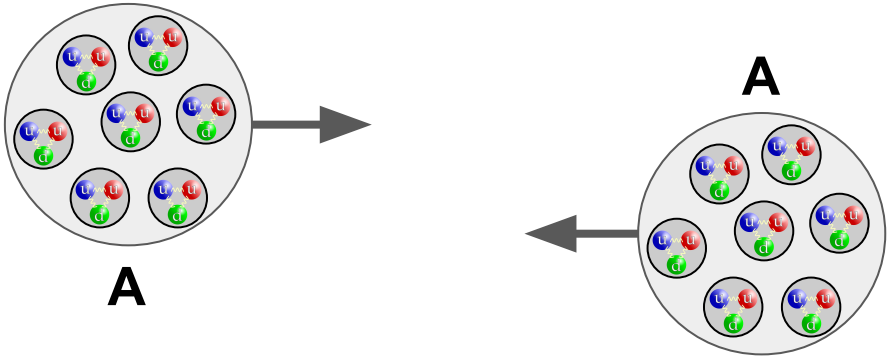
# What do we measure it?

- **What and where do we measure nucleon structure functions?**
  - Gluon distributions: **heavy-ion collisions** and **future EIC**
  - Valence quark contribution: JLab
- **Baryon junction-like-structure →gluon distribution**
  - Heavy-ion collisions!

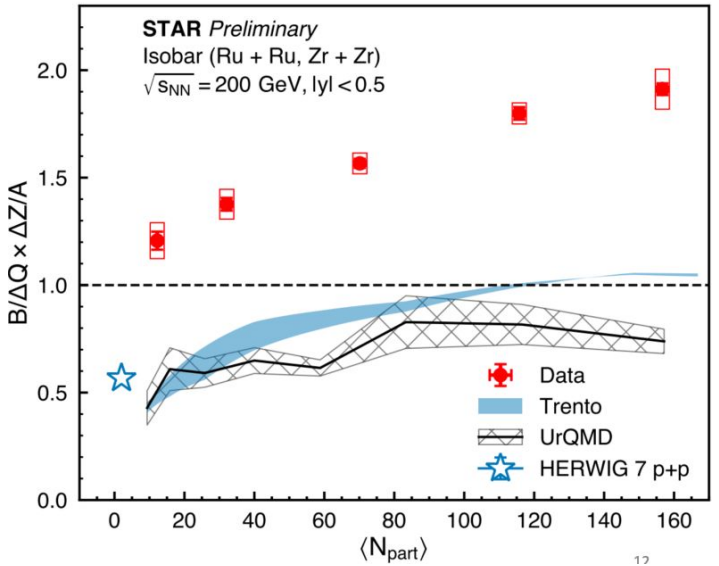


# Probing Baryon Junction with A-A at RHIC




Tommy Tsang (KSU) for STAR, APS GHP 2023



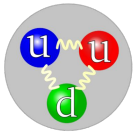

**Charge vs. baryon transport in A+A collisions:**

- If Valence quarks carry electric charge & baryon number:

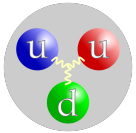
$$\frac{Z}{\text{Charge Stoppoing}} \times \frac{\text{Baryon Stopping}}{A} \cong 1$$

- If valence quarks carry electric charge & junctions cary baryon number

$$\frac{Z}{\text{Charge Stoppoing}} \times \frac{\text{Baryon Stopping}}{A} > 1$$



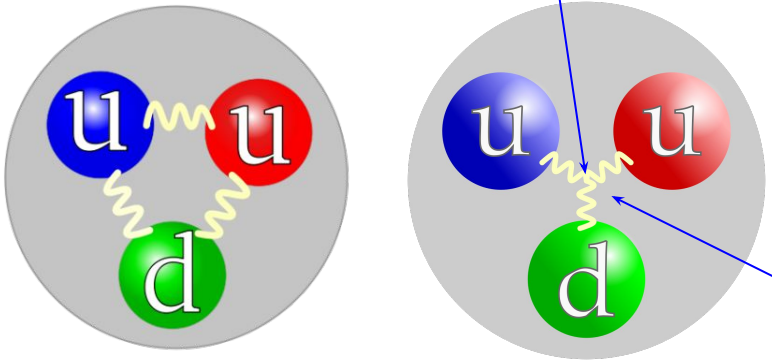
**Theory: Quark Models: equal or less baryon compared to electric charge**



**Data: More baryon transported to central rapidity than electric charge**

# Probing Baryon Junction direction via Exclusive u-Channel Processes?

- **Which proton it more correct?**

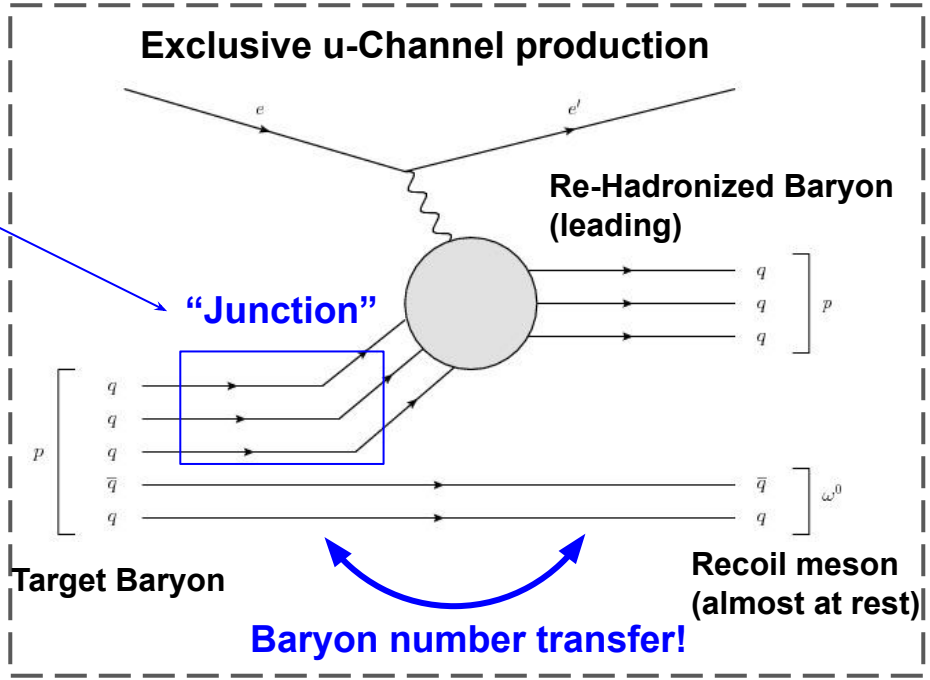



**A** **B**

**A**: implies quark carries fractional baryon number

**B**: **a "Junction" like structure**

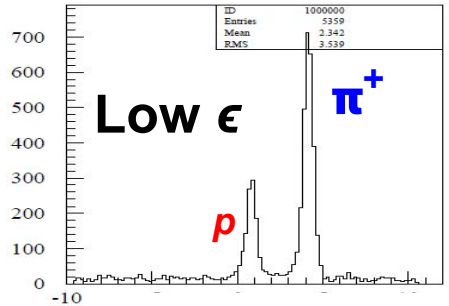
- **How do we probe this in JLab 12 GeV?**
  - May be. If manage to force the transfer of baryon number in the target and recoil particles, then Yes.

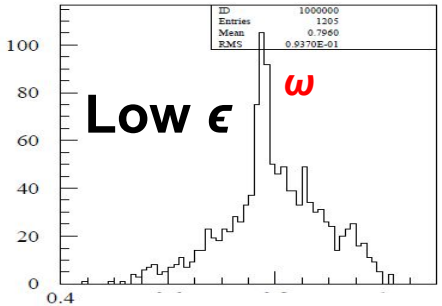


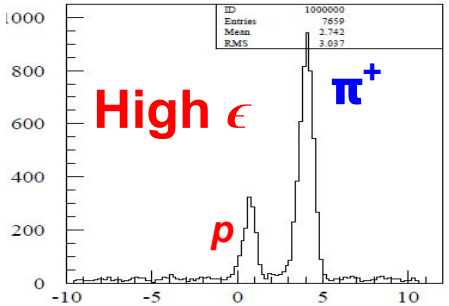
# Gifted Backward-angle Observables

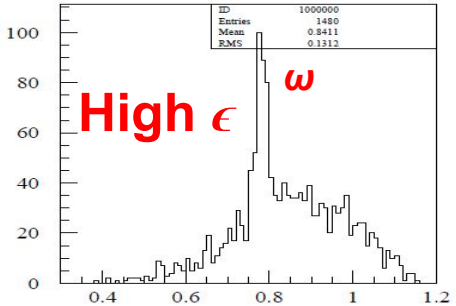
- **Fpi-2 (E01-004) 2003**
  - Spokesperson: **Garth Huber, Henk Blok**
  - Standard HMS and SOS (e) configuration
  - **Electric form factor of charged $\pi$** through exclusive $\pi$ production
- **Primary reaction for Fpi-2**
  - **H(*e*, *e'* $\pi^+$)*n***
- **In addition, the experiment fortuitously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

$Q^2$=2.45 GeV$^2$ **2003** 2003/07/25 08.56



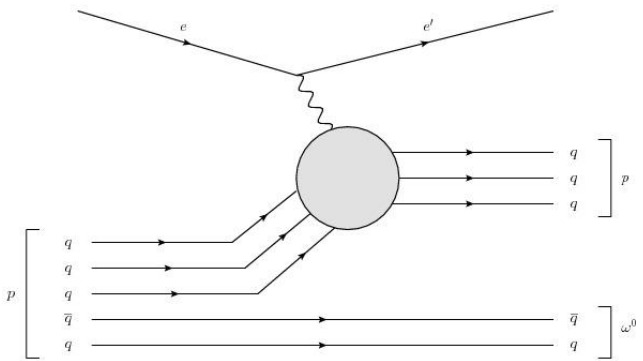



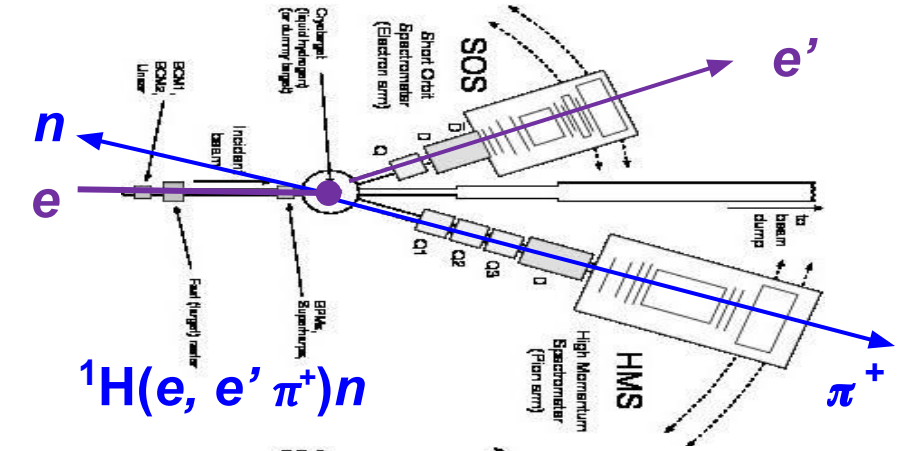



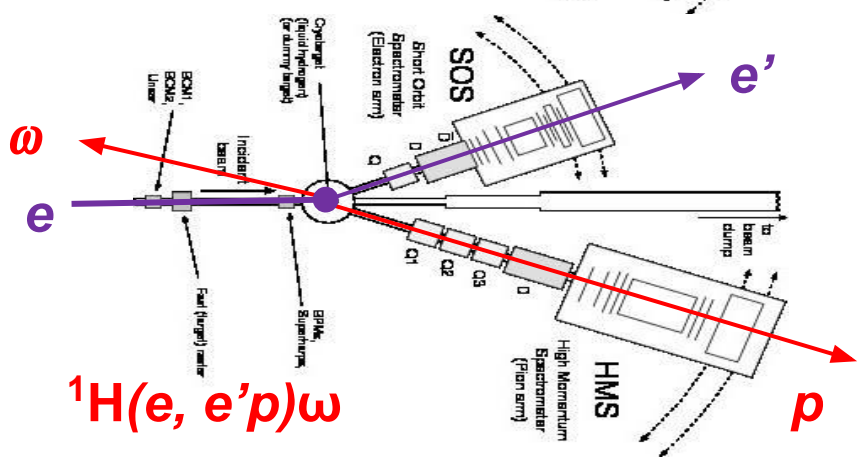
# *t*-Channel $\pi^+$ vs *u*-Channel $\omega$ Electroproduction

- **Primary reaction for Fpi-2**
  - H(*e*, *e'* $\pi^+$)*n*
  - *n* (940 MeV)
  - $\pi^+$ (140 MeV)
- **Unexpected reaction:**
  - H(*e*,*e'* *p*)$\omega$
  - *p* (940 MeV)
  - $\omega$ (783 MeV)




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

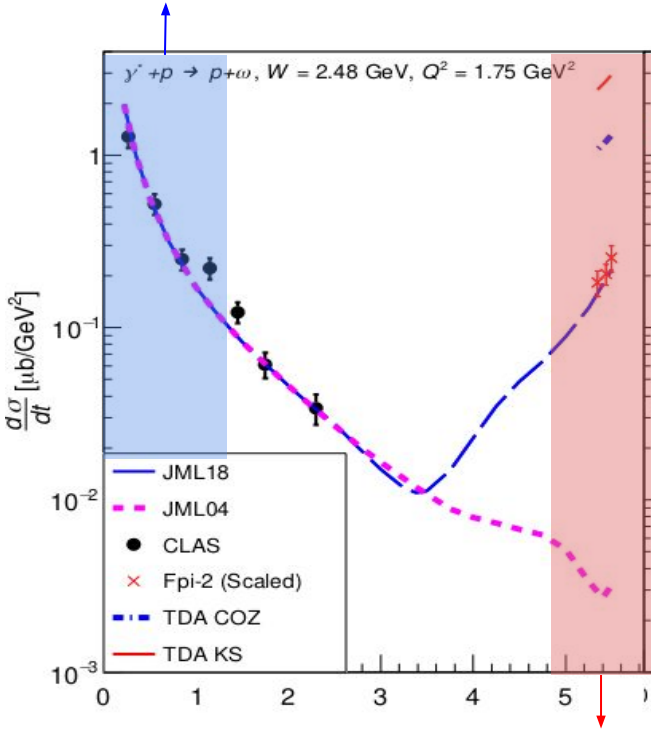


# Two Key Discoveries from Fpi-2 ω Analysis

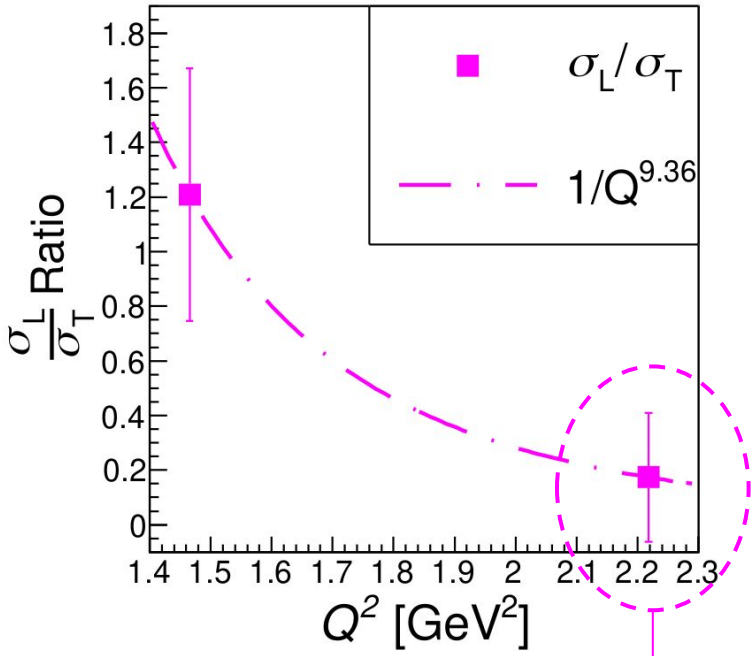
## Discovery 1: Unexpected large *u*-Channel peak

**Forward ω electroproduction from CLAS 6 *(2004)***




**Backward angle ω electroproduction *(2017)***

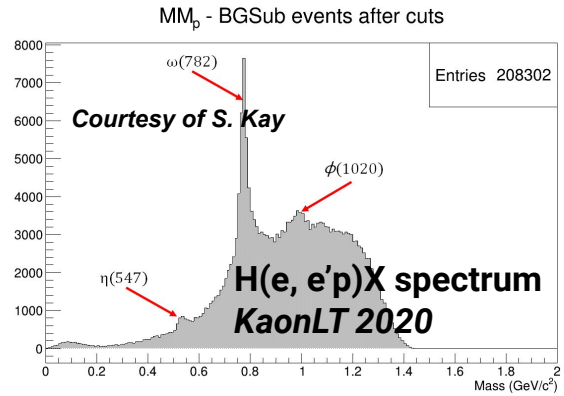
## Discovery 2: $\sigma_T > \sigma_L$, $\sigma_L \sim 0$

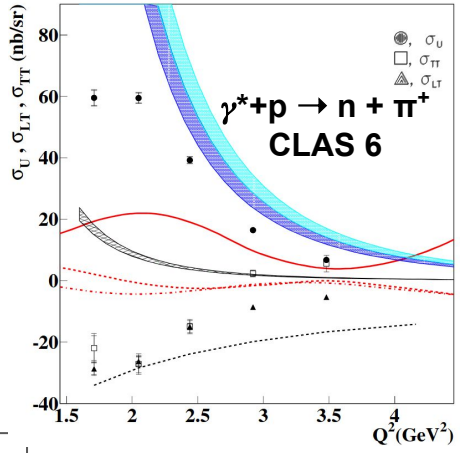


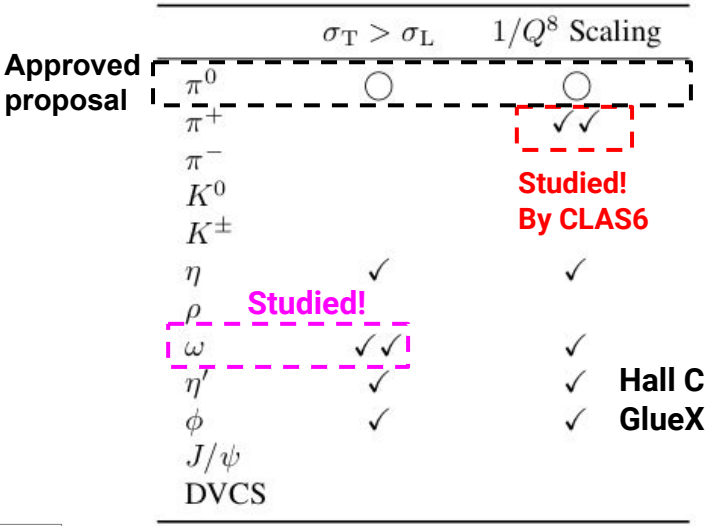

$$\frac{\sigma_T}{\sigma_L} \sim 0 \text{ at } Q^2 = 2.2\,\text{GeV}^2$$

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

# Question: Are there *u*-channel peaks for other processes? Yes!

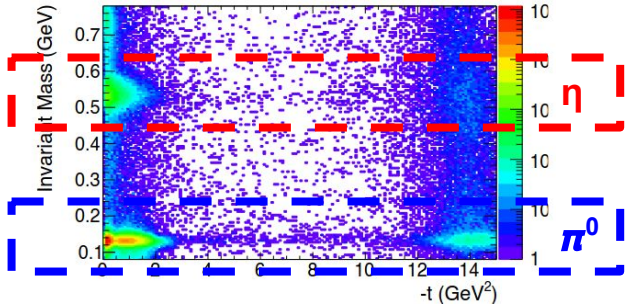


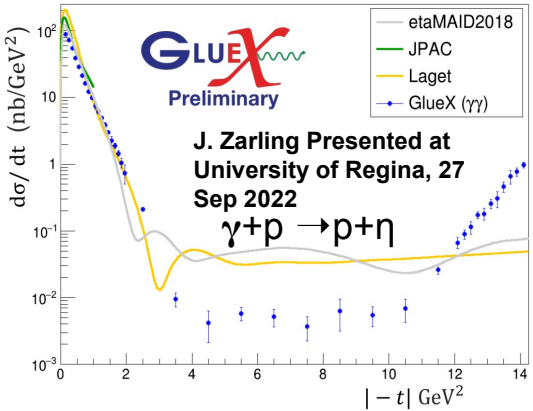

## GlueX mass vs -t Phasespace

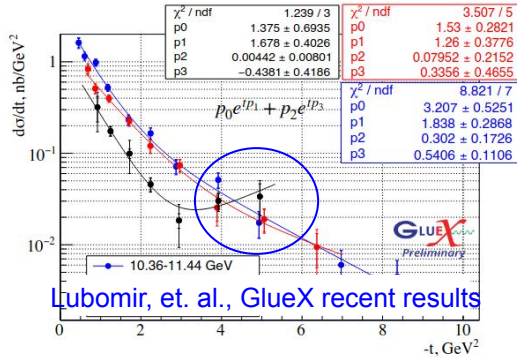
t-channel u-channel




By J.R. Stevens, at u-channel Physics workshop, 2020

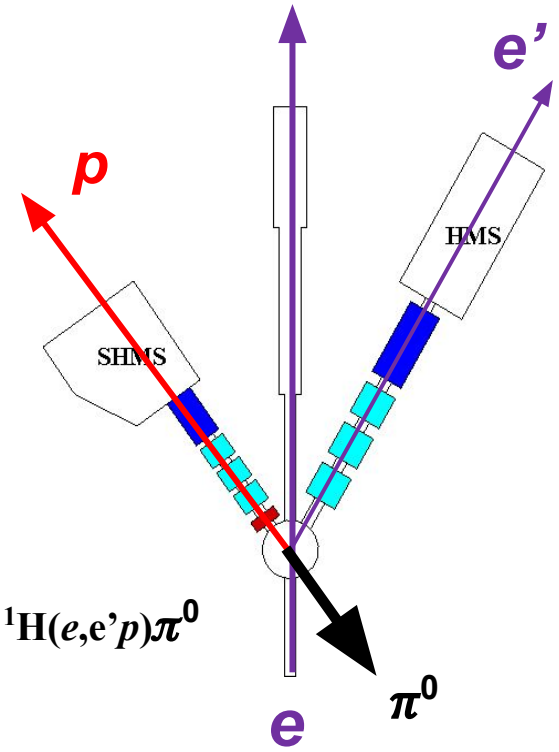
$E_\gamma = 8.25 \pm 0.25$ GeV

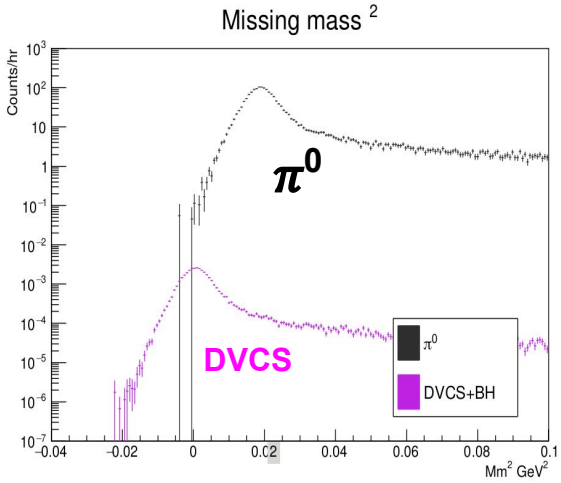



Lubomir, et. al., GlueX recent results

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




| $Q^2$ GeV$^2$ | W GeV | $\epsilon$ | x | $\theta_{pq}$ 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:**

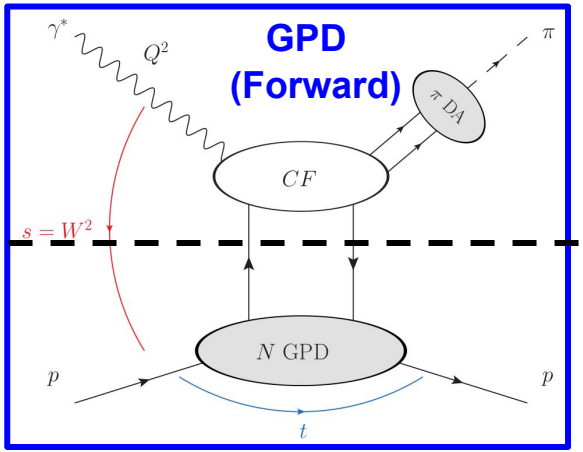
- **$Q^2$ coverage: $2.0 < Q^2 < 6.25$ GeV$^2$, at $x$=0.36 and W > 2 GeV L/T separated cross section @ $Q^2$= 2, 3, 4 and 5 GeV$^2$.**
- ***u* coverage: 0 < -*u*' +0.5 < 0.5 GeV$^2$**
- **Additional *W* scaling check @ $Q^2$ = 2 GeV$^2$**
- **Additional $Q^2$ scaling check @ $Q^2$ = 6.25 GeV$^2$**

# GPD and TDA (Hard Structure Approach)

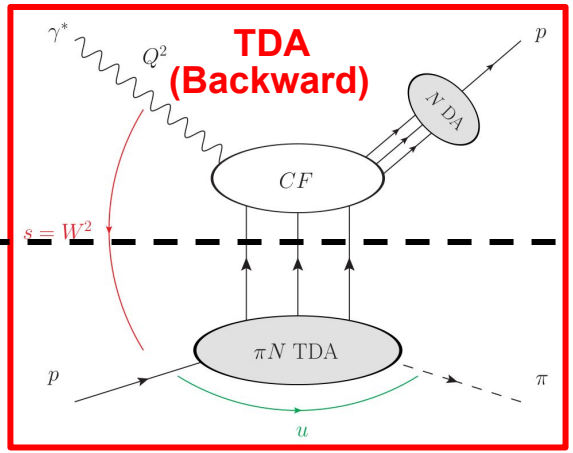
Hard structure

Soft structure

Collinear factorization




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



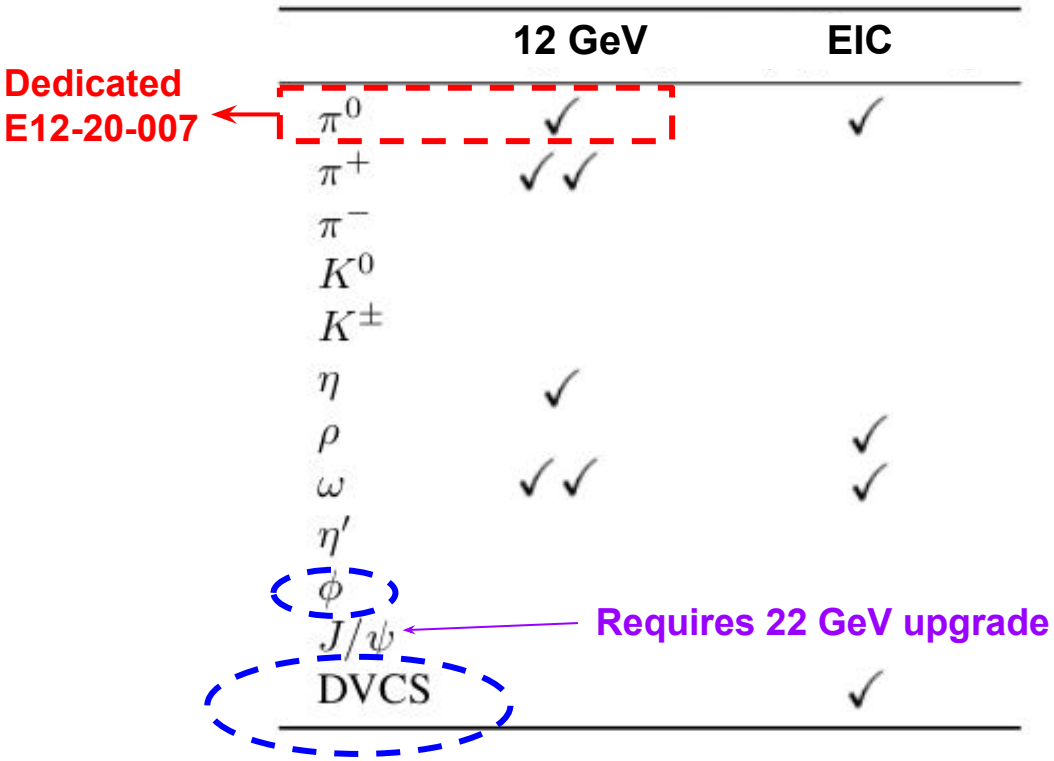

Developed by **B. Pire**, **L. Szymanowski** and **K Semenov-Tian-Shansky** in 2005

**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.

# *u*-Channel Exclusive Electroproduction



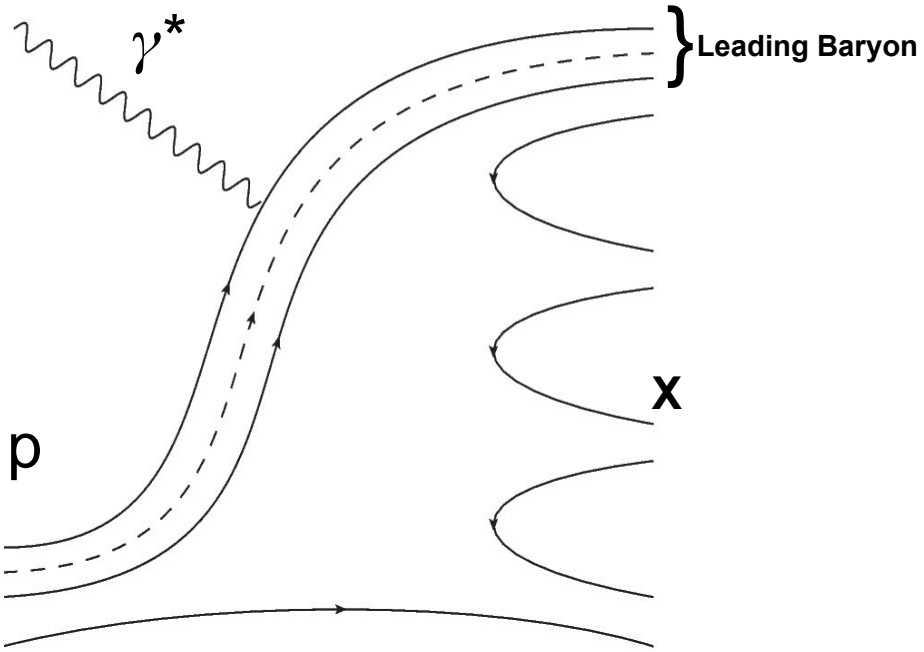

- We are good shape with the exclusive productions! :D

✓✓ Data already available

✓ Studies planned

**Large community interests, will be developed into proposal in the upcoming years**

# Inclusive or Semi-inclusive u-Channel processes?

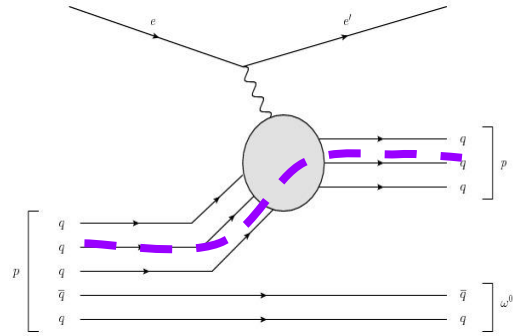



- **Interaction: e + H→e' + B + X**
  - **e(H, e'B)X**
- **B: Leading baryon**
  - Candidates: p, n, $\Lambda$, $\Sigma$
  - Small Mandelstam variable -*u*
  - Fix target: Maximum momentum gain
  - Collider: Maximum momentum loss

# Semi-Inclusive u-Channel study Cases?

D. Frenklakh, Dmitri Kharzeev,
https://indico.cern.ch/event/1139644/contributions/5490519/

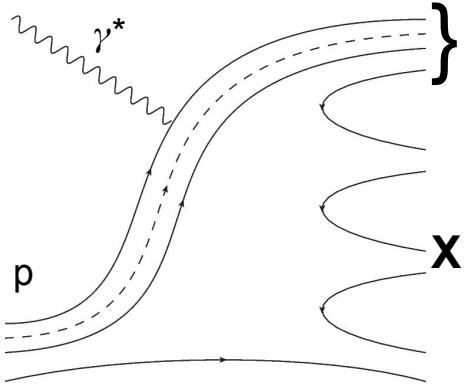
## Case 0: J/3q exchange



Complicated form factor leads inconclusive exchange mechanism

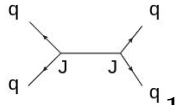
Indistinguishable exchange mechanism: 3q vs Junction (after hadronazation)

## Case 1: J+2q exchange




Leading Baryon

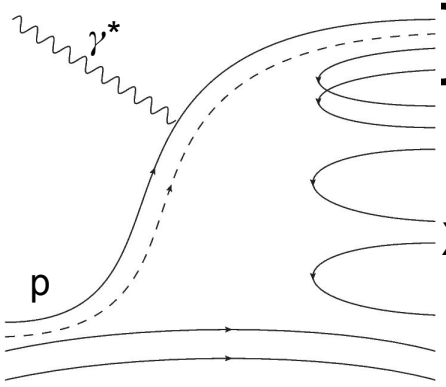
Coupling:




Regge interception: $\alpha(0) = -\frac{1}{2}$

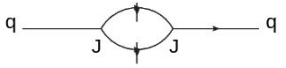
Baryon Multiplicity: $n_x = 1n^{(1)}$

## Case 2: J+q exchange




Leading Baryon

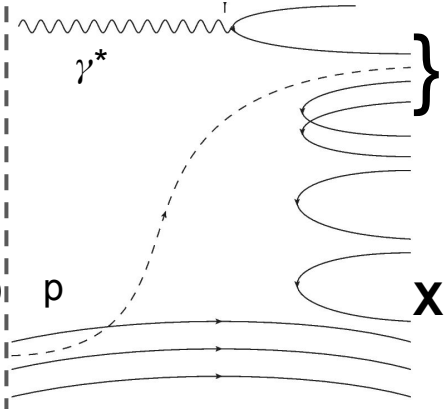
Coupling:




Regge interception: $\alpha(0) = 0$

Baryon Multiplicity: $n_x = 2n^{(1)}$

## Case 3: J exchange



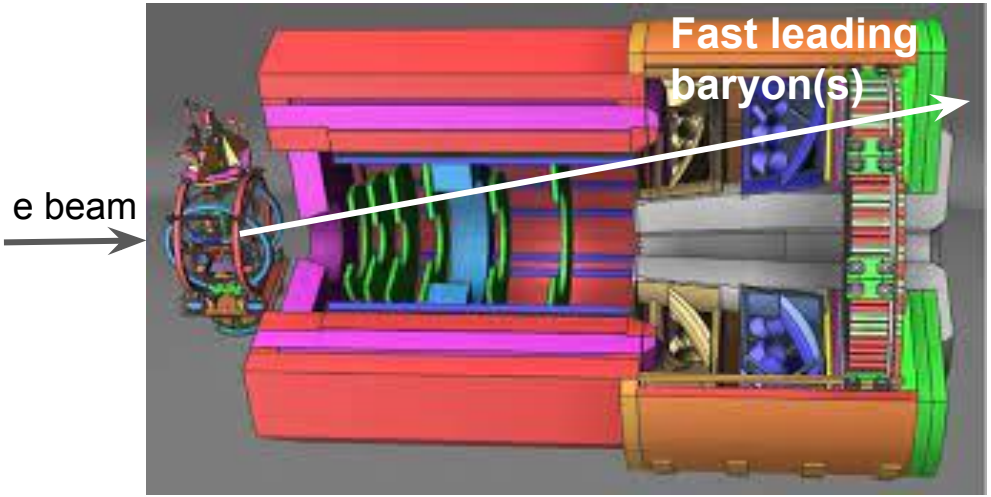

Leading Baryon

Coupling:

Regge interception: $\alpha(0) = +\frac{1}{2}$

Baryon Multiplicity: $n_x = 3n^{(1)}$

# Probing u-Channel Inclusive processes during JLab 12 GeV



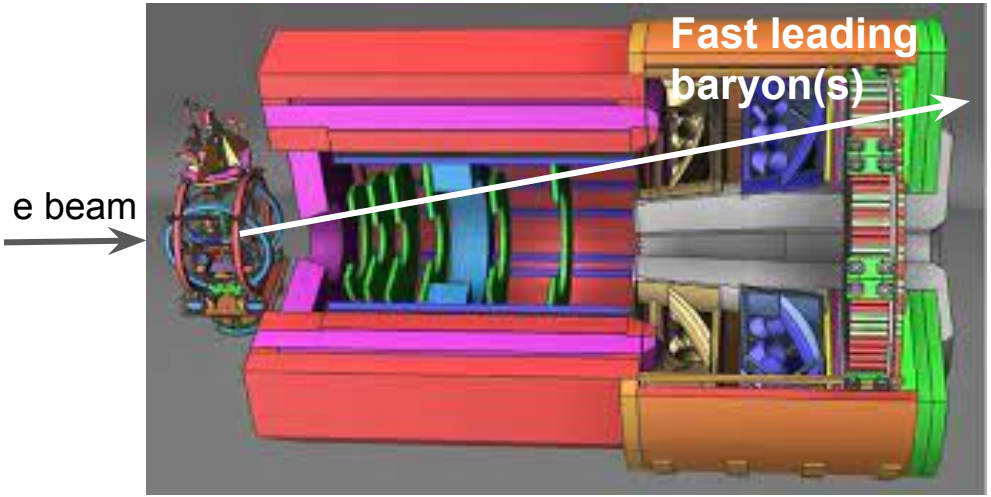

**SoLID experiment is ideal venue to study the u-Channel inclusive processes !**

**Experimental condition:**

- $Q^2 \sim 1\ \mathrm{GeV}^2$
- High luminosity
- LH2 target
- Detecting baryon with large forward momentum: p, n, $\Lambda$, $\Sigma$
- Semi-inclusive DIS

**Conclusion:** SoLID is an ideal venue for such measurement!

# Probing u-Channel Inclusive processes during JLab 12 GeV

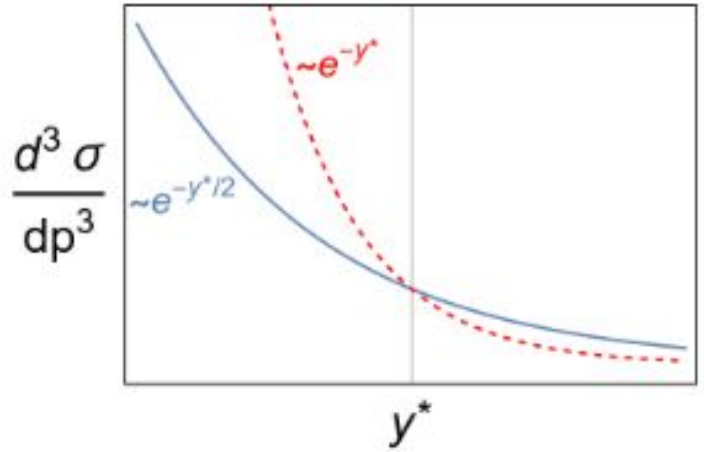



**SoLID experiment is ideal venue to study the u-Channel inclusive processes !**

- Publication and SoLID run group proposal will soon follow

**Experimental observable:**

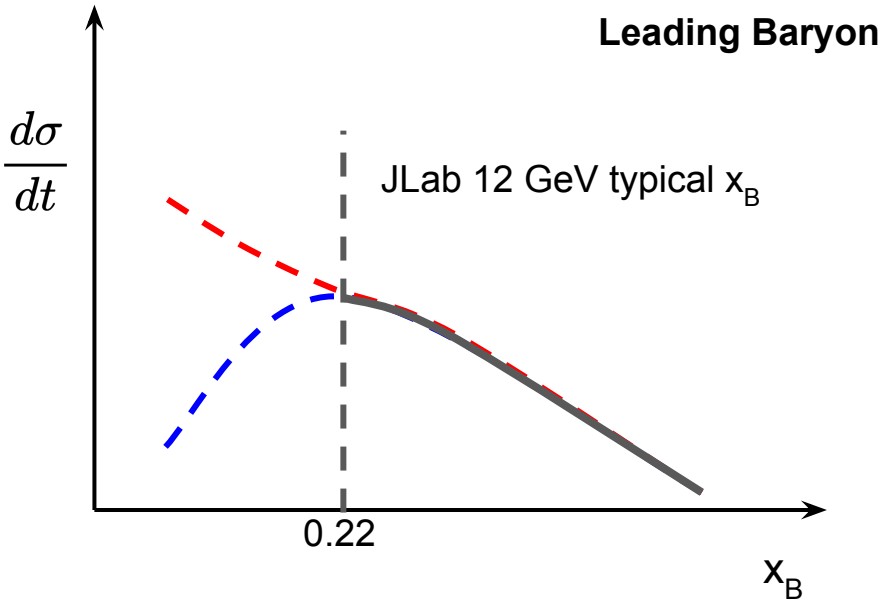
- Detecting baryon with large forward momentum: p, n, $\Lambda$, $\Sigma$
  - Differential cross section as function of rapidity (or -t)
  - Multiplicity
  - Fit data to the specific various Regge trajectories



# Conclusively Demonstrate the Baryon Junction Structure

- **How do we conclude the "junction"**
  - **Junctions**: are construct of gluons: **Junction -> u-Channel cross section enhancement at low $x_b$**
  - **No junction: u-Channel cross section suppressed -> valence quark contribution**

- **The JLab and EIC data are equally critical to test the hyposased $x_B$**

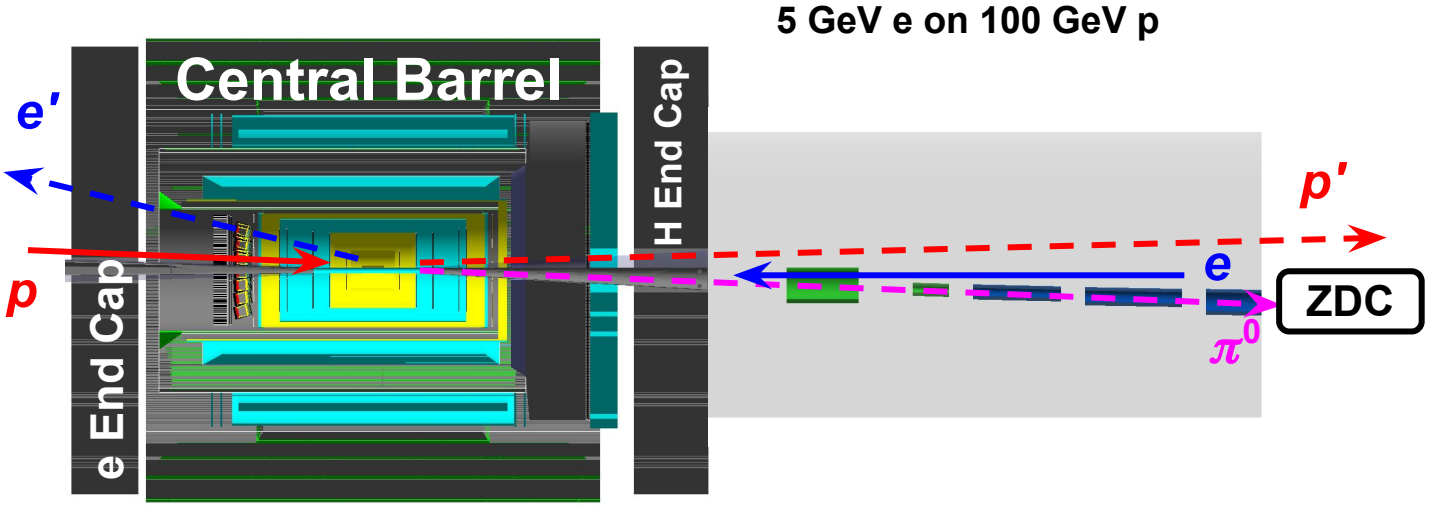


# Plan and Summary

- ***u*-Channel inclusive DIS processes can be linked to uncover the <u>baryon number mystery</u>**

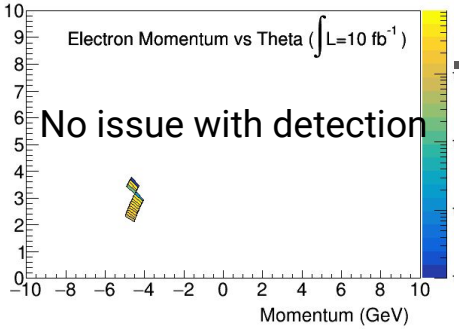
- **Developing u-Channel SIDIS into a SoLID run-group proposal**
  - Looking into how to proton/baryon PID
    - Time of light
    - Tracking/flight path
    - Calorimeter
  - Simulation needed?

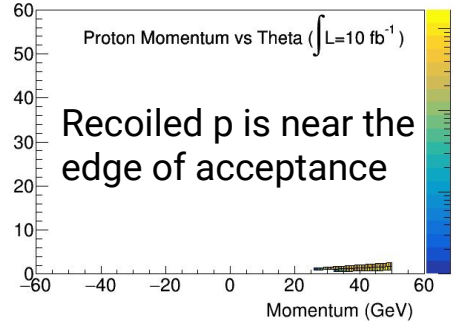
# u-Channel Meson Production Setup at EIC

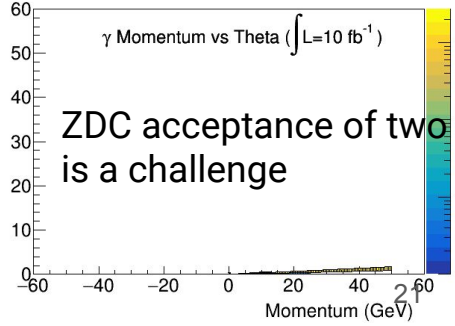



| $Q^2$ (GeV$^2$) | $W$ (GeV) | $x_B$ | $\theta_{e'}$ (deg) | $\eta_{e'}$ | $P_{e'}$ (GeV) | $\theta_{p'}$ (deg) | $\eta_{p'}$ | $P_{p'}$ (GeV) | $\theta_{\pi^0}$ (deg) | $\eta_{\pi^0}$ | $P_{\pi^0}$ (GeV) | $-t$ (GeV$^2$) | $-u$ (GeV$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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' $\pi^0$



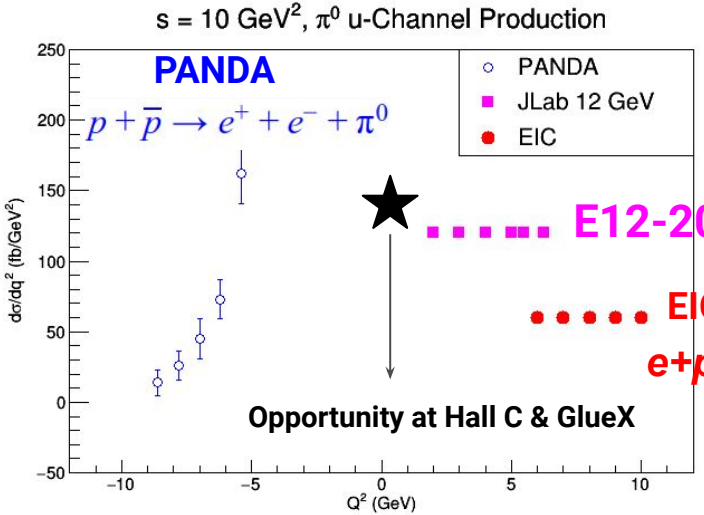
# *u*-Channel studies at EIC

### 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**

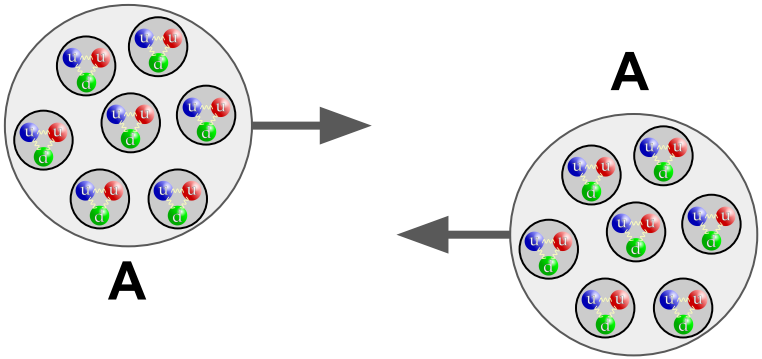
- **Backward π $^{0}$ program for EIC**






- **Recent u-Channel EIC publication:**
  - ***Backward-angle (u-Channel) production at an electron-ion collider,*** **D. Cebra, Z. Sweger, S. Klein, et. al., PhysRevC.106.015204**
  - **Modeling Backward-Angle (u-channel) Virtual Compton Scattering at an Electron-Ion Collider, Z. Sweger, S. Klein, et. al., https://arxiv.org/abs/2308.10478**

# Probing Baryon Junction with A-A at RHIC




- **If baryon number carried by:**
  - Valence quarks - B/Q = A/Z
  - Baryon junctions - B/Q > A/Z

- Use Isobar collision data:
  - Ru+Ru: A = 96, Z = 44
  - Zr+Zr: A = 96, Z = 40
- Definition of baryon stopping and charge difference in midrapidity
  - $B = \left(N_p - N_{\bar{p}}\right) + \left(N_n - N_{\bar{n}}\right)$
  - $Q = \left(N_{\pi^+} + N_{K^+} + N_p\right) - \left(N_{\pi^-} + N_{K^-} + N_{\bar{p}}\right)$
  - $\Delta Q = Q_{\mathrm{Ru}} - Q_{\mathrm{Zr}}$ and $\Delta Z = Z_{\mathrm{Ru}} - Z_{\mathrm{Zr}}$
- Measure $B/\Delta Q$
- Calculate $\Delta Z/A$

# u-Channel Beam Spin Asymmetry (CLAS 6 measurement)

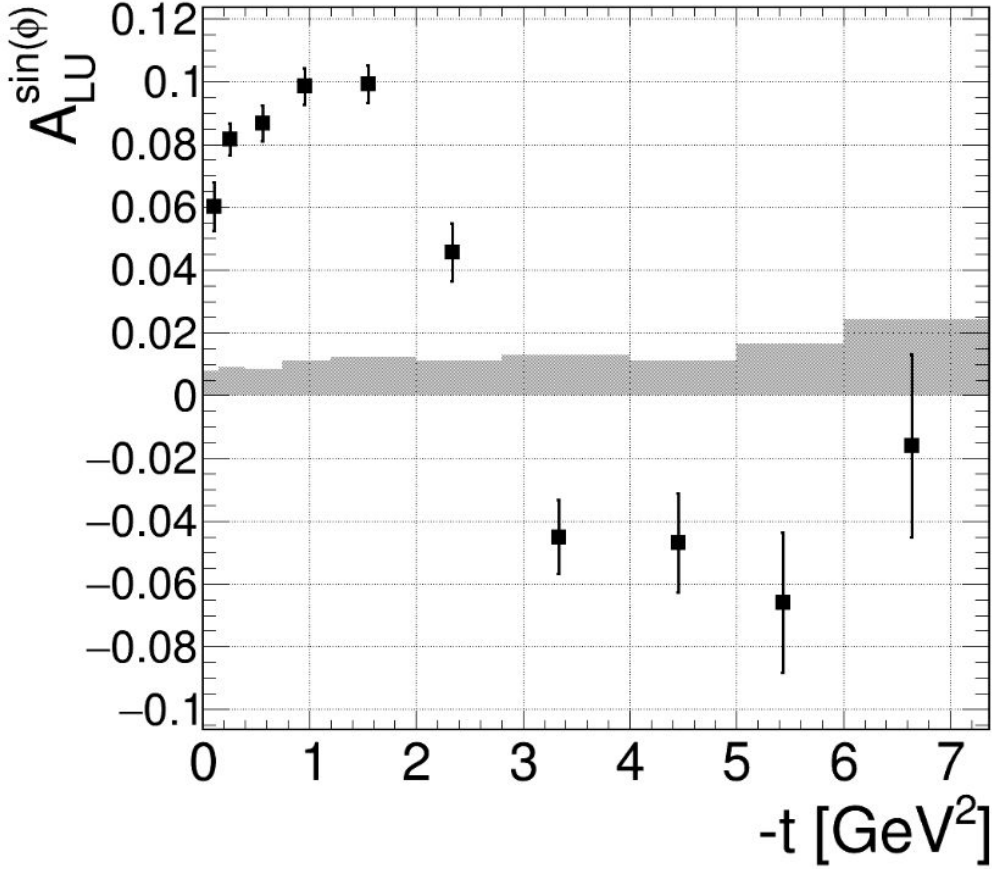
$$BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

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

***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 sig for $\sigma_{LT}$ indication sudden change of production mechanism**
- **Similar study at 12 GeV will be done for ρ/ω, $\phi$**

**Potential observable to map out the transition in production mechanism**




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

Asymmetry Result