A New Angle Into the Proton

U-CHANNEL MESON ELECTROPRODUCTION

Alicia Postuma
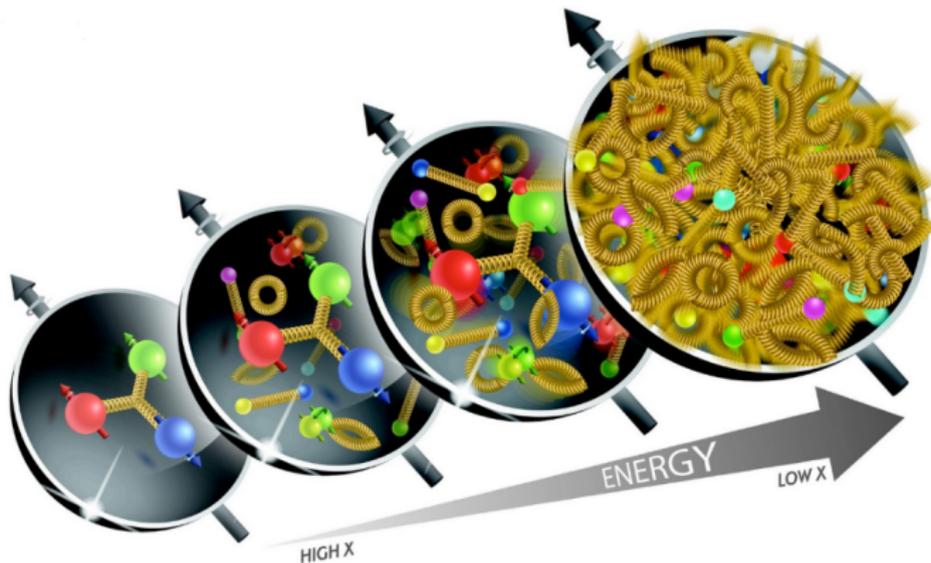
University of Regina

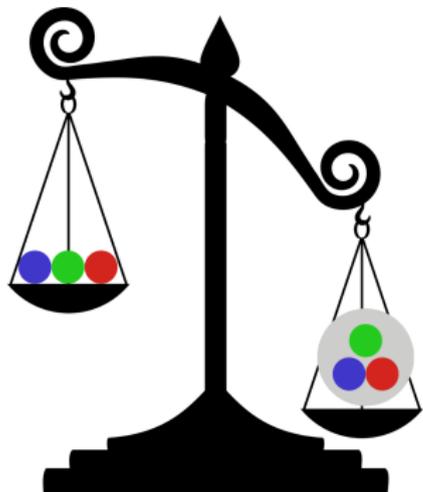**WNPPC 2026**

University of Regina

Due to the **running of α_S** and **gluon self-coupling**, proton structure is complicated and **varies drastically with measurement scale**

Image by Brookhaven National Lab: https://www.flickr.com/photos/brookhavenlab/albums/72157714316624996/

Motivation

Due to the **running of α_s** and **gluon self-coupling**, proton structure is complicated and **varies drastically with measurement scale**

⟶ Several puzzles exist:

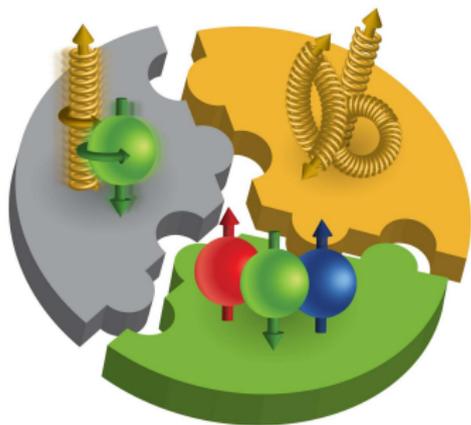- **Mass discrepancy:** Higgs mechanism contributes **<10%** of proton mass
- **Spin crisis:** valence quarks carry only around **20–30%** of proton spin
  quark spin + **gluon spin**
  + **orbital angular momentum**
- Need to reconsider other quantum numbers...

X. Ji, *Gauge-Invariant Decomposition of Nucleon Spin*, Phys. Rev. Lett **78** 610 (1997).

Due to the **running of α_S** and **gluon self-coupling**, proton structure is complicated and **varies drastically with measurement scale**
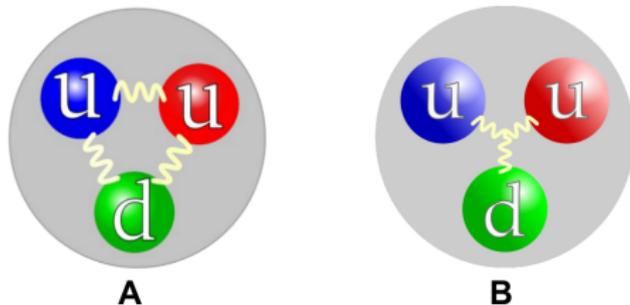
$\longrightarrow$ Several puzzles exist:

- **Mass discrepancy:** Higgs mechanism contributes **<10%** of proton mass
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Image by Brookhaven National Lab: https://www.flickr.com/photos/brookhavenlab/albums/72157714316624996/

Baryon Number Crisis?

Where is baryon number carried? In the **valence quarks (A)** or the **gluon junction (B)**?

A   B

- Conventional picture **A** is an assumption
- New picture **B** favoured by some lattice QCD calculations
- Neither picture is yet supported by experiment

G.C. Rossi & G. Veneziano, *A possible description of baryon dynamics in dual and gauge theories,* Nucl. Phys. B **123** 3 (1977).
Images from Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Quark_structure_proton.svg

Accelerated electron exchanges virtual photon γ^* with a proton, resulting in the production of a meson, e.g.:
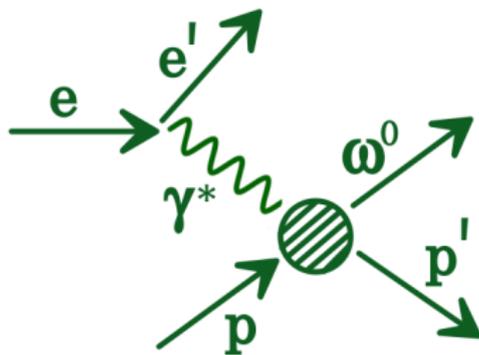
$$e + p \rightarrow e' + p' + \omega^0$$

Kinematic variables:
Q^2: 4-momentum of γ^*

$$Q^2 = -(\boldsymbol{p}_e - \boldsymbol{p}'_e)^2$$

W: centre of mass energy
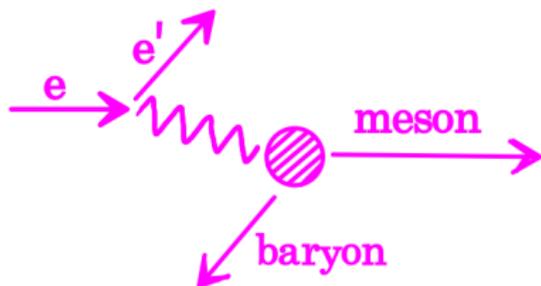$$W^2 = (\boldsymbol{p}_{\gamma^*} + \boldsymbol{p}_p)^2$$

This work: exclusive ω^0 production for Q^2 =2–5.5 GeV^2, W>2 GeV

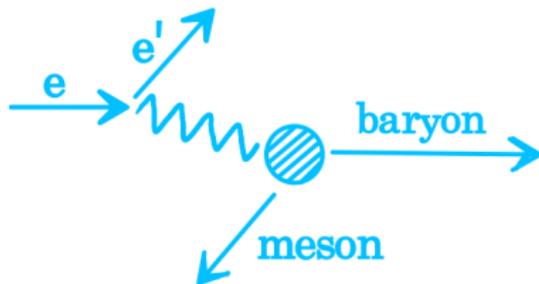Classify DEMP events based on Mandelstam variables t & u:

$$t = (\boldsymbol{p}_{\gamma^*} - \boldsymbol{p}_{meson})^2$$

$$u = (\boldsymbol{p}_{\gamma^*} - \boldsymbol{p}_{\mathrm{baryon}})^2$$

t-channel:

- $-t$ small, **meson** carries majority momentum
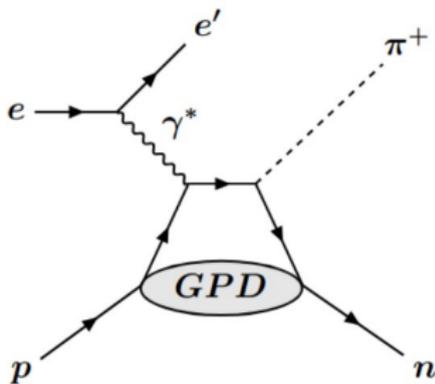- Meson moves **forward**
- Larger cross-section
- Well studied

u-channel:

- $-u$ small, **baryon** carries majority momentum
- Meson moves **backward**
- Smaller cross-section
- **Mostly unexplored...**

B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, *QCD description of backward vector meson hard electroproduction*, Phys. Rev. D **91** 094006 (2015).
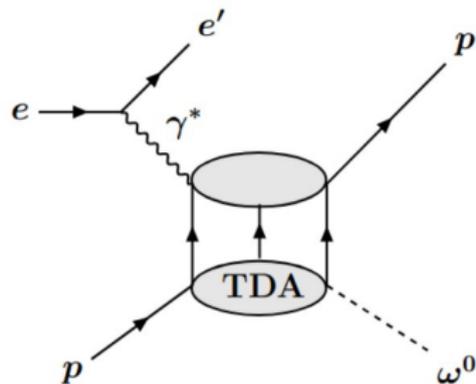
Backward-angle (*u*-channel) DEMP accesses **new kinematic territory** inside the proton.

_t_-channel:

- Access to **Generalized Parton Distribution** (GPD)
- GPDs encode position & momentum of **partons**

_u_-channel:

- Access to **Transition Distribution Amplitude** (TDA)
- TDAs encode momentum distribution of **baryon number**

B. Pire, K. Semenov-Tian-Shansky, and L. Szymanowski, *Transition distribution amplitudes and hard exclusive reactions with baryon number transfer,* Phys. Rep, **940** 1 (2021).

■ Hall C: electron beam → fixed target → spectrometers

■ Spectrometers are magnetic and moveable → choose charge, momentum, and angles to detect
■ Coincidence experiment: need simultaneous detection in **High Momentum Spectrometer** and **Super HMS**
■ **This work:** u-channel reactions from the **KaonLT** experiment
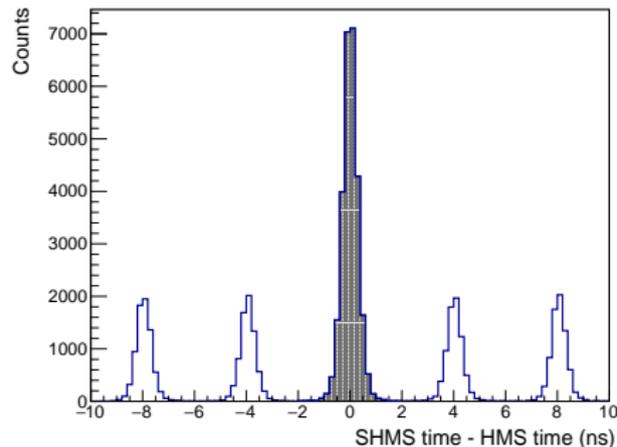
Jefferson Lab

Particle Identification (PID)

- Spectrometer detector stack contains **drift chambers** for **tracking**, **hodoscopes** for **triggering**, **threshold Cherenkovs** and **calorimeter** for **PID**

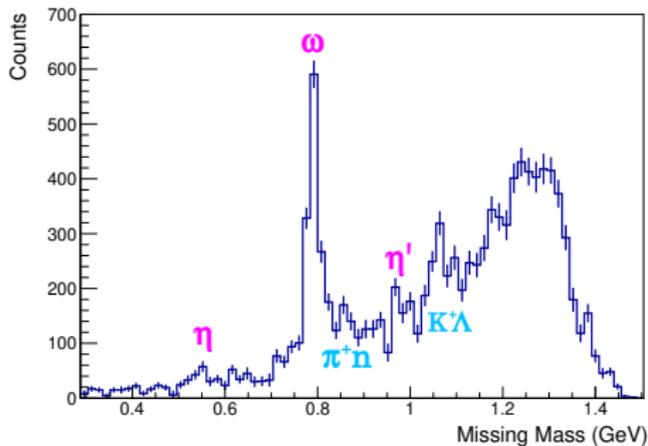- Fixed charge, momentum: PID via **mass separation**

$$e^- + p \rightarrow e^{-\prime} + p\prime + \omega^0$$
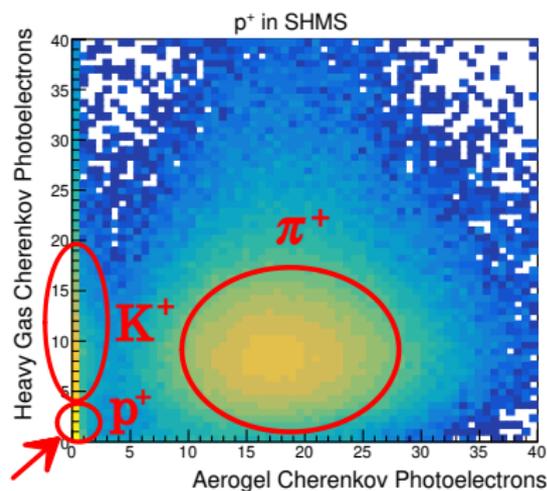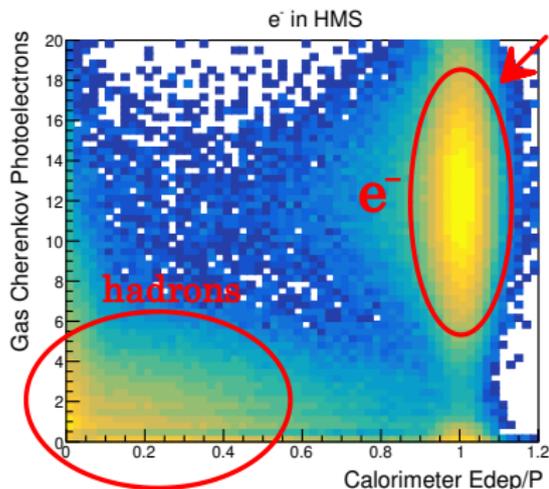
Select coincidences via
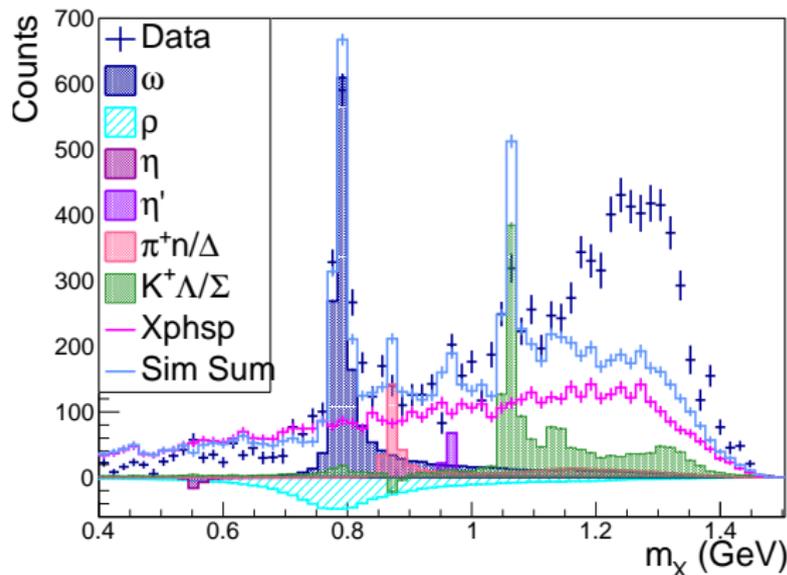$t_{COIN} = t_{SHMS} - t_{HMS} \approx 0$

Meson not detected $\rightarrow$ use missing mass $m_X \approx m_\omega = 0.782$ GeV
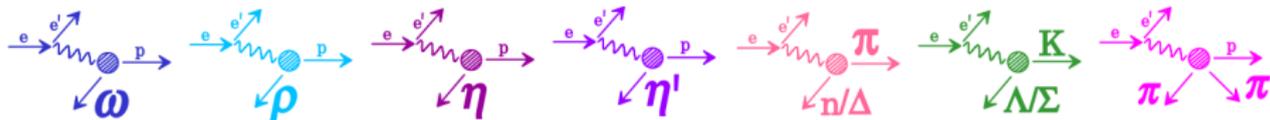

From 4-momentum conservation:

$$m_X^2 = \left(\boldsymbol{p}_e + m_p - \boldsymbol{p}_{e\prime} - \boldsymbol{p}_{p\prime} \right)^2$$

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Even after removal of experimental background, some **physics backgrounds** remain

$$e + p \rightarrow e' + p' + X$$

- Use simulations to disentangle different reactions

- **Goal:** cleanly separate ω production from other u-channel reactions

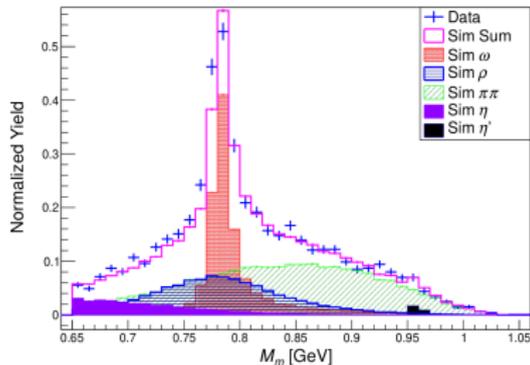- **Incomplete:** missing background processes above $m_X \approx 1.1$
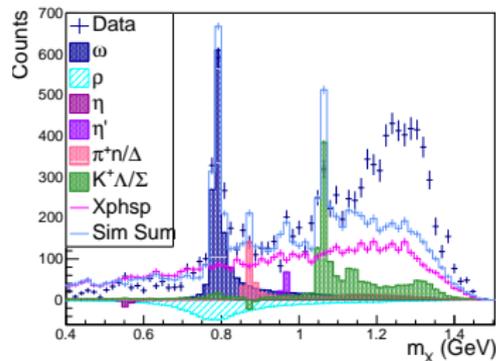
The Trouble with Phase Space

- Hall C Monte Carlo **SIMC** default phase space model **Xphsp** uses double pion production, $e + p \rightarrow e' + p' + \pi + \pi$
- This reproduced data when JLab $E_{beam} \leq 6$ GeV
- JLab upgraded to $E_{beam} \leq 12$ GeV $\longrightarrow$ more available phase space, e.g. production of $\geq 3\pi \longrightarrow$ Xphsp not sufficient
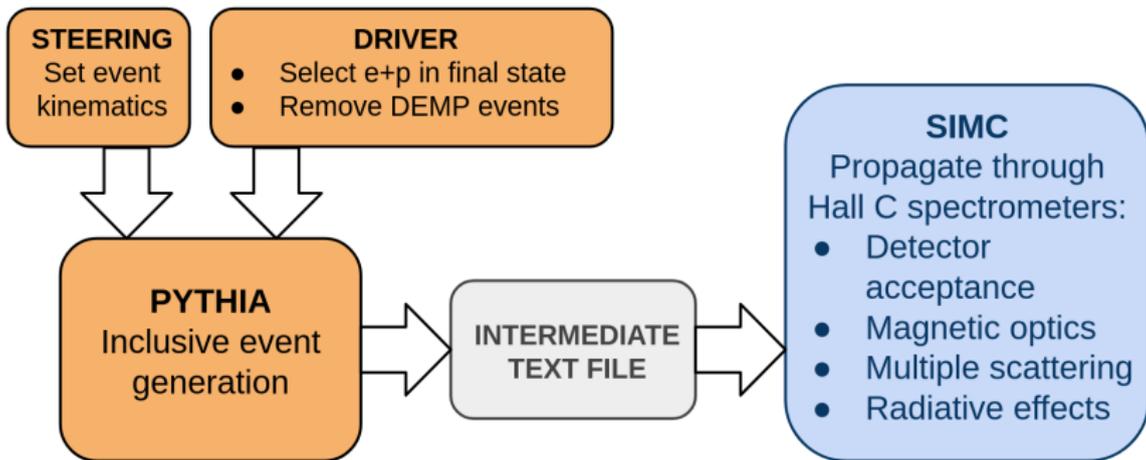
JLab 6 GeV

JLab 12 GeV

W.B. Li, 2017

A.C. Postuma, 2026

W.B. Li, *Exclusive Backward-Angle Omega Meson Electroproduction*, PhD Thesis, University of Regina (2017).

Solution: use existing program PYTHIA for event generation

C. Bierlich, S. Chakraborty, N. Desai, L. Gellersen, I. Helenius, P. Ilten, L. Lönnblad, S. Mrenna, S. Prestel, C. T. Preuss, T. Sjöstrand, P. Skands, M. Utheim, and R. Verheyen, *A comprehensive guide to the physics and usage of PYTHIA 8.3,* SciPost Phys. Codebases **8** (2022).

Even after removal of experimental background, some **physics backgrounds** remain

$$e + p \rightarrow e' + p' + X$$

- Use simulations to disentangle different reactions
- **Goal:** cleanly separate ω production from other u-channel reactions
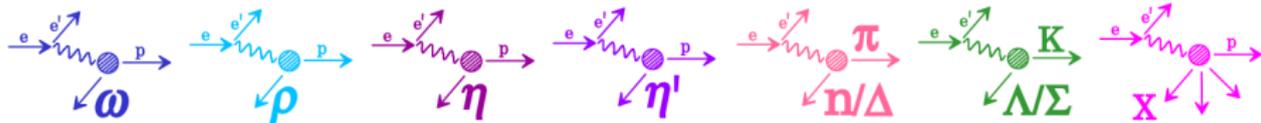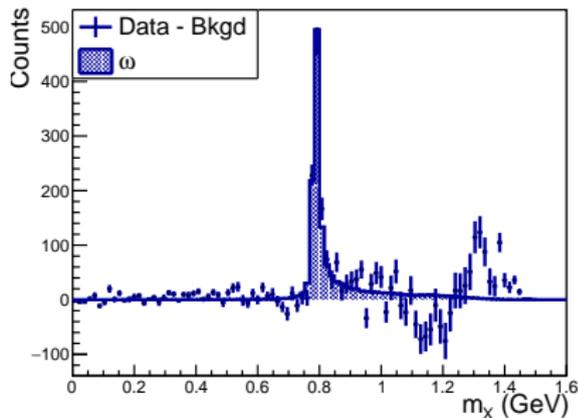- Significant progress over Xphsp!
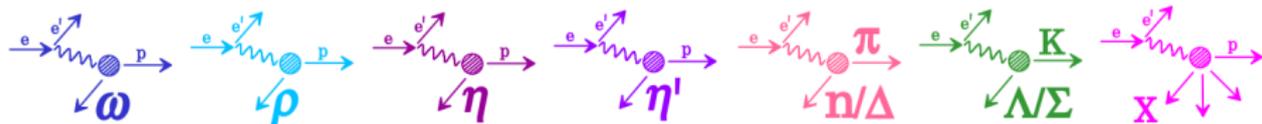
Subtract all background simulations from data, then integrate ω peak for yield of $e + p \rightarrow e' + p' + \omega$ events

Previous Results

$\gamma^* + p \rightarrow p + \omega$, $W = 2.47$ GeV, $Q^2 = 2.35$ GeV^2

- JML18
- JML04
- CLAS
- Fpi-2 (Scaled)

$\frac{d\sigma}{dt}$ [μb/GeV^2]

$-t$ [GeV^2]
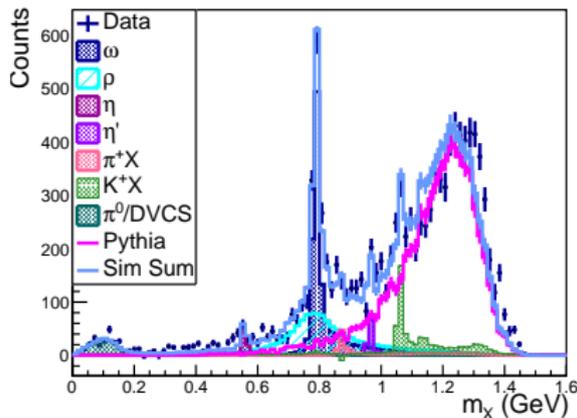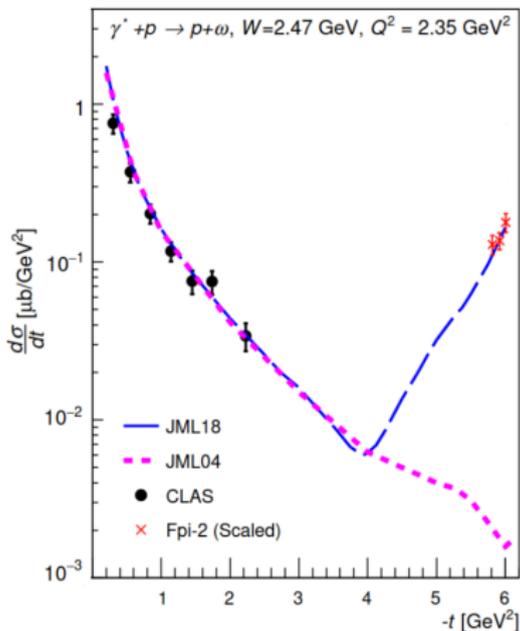
W.B. Li, 2019

- Normalize and apply corrections (e.g. detector efficiencies, luminosity) to yield
- Calculate cross-sections
- $\longrightarrow$ Search for **u-channel peak** at backward angles (high $-t$)
- $\longrightarrow$ **Extend previous results** to check if pattern persists over a range of kinematics
- **L/T separation** to check feasibility of TDA extraction *(see talks by N. Heinrich & M. Junaid)*

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Summary and Conclusions

- Jefferson Lab **Hall C** takes precision measurements of hadronic reactions to probe proton structure
- My research: study of **u-channel** meson electroproduction from the **KaonLT** experiment
- Backward angle observables needed to extract **TDAs**
- **Forward vs backward-angle** comparison gives insight on the evolution of proton structure
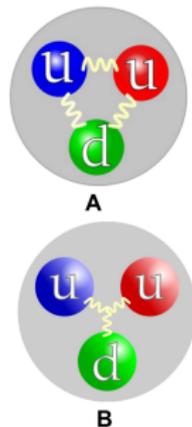
The u-channel has unique physics opportunities including **TDA extraction** and the study of **baryon number**.

Images from Wikimedia Commons, https://commons.wikimedia.org/wiki/File:Quark_structure_proton.svg

Acknowledgements

Supervisor: Dr. Garth Huber

KaonLT/PionLT Collaboration:

Dave Gaskell*, Nacer Hamdi, Nathan Heinrich, Garth Huber*, Tanja Horn*, Samir Jain, Muhammad Junaid, Stephen Kay, Vijay Kumar, B.C. Manoj, Pete Markowitz*, Gabriel Niculescu, Ioana Niculescu, Alicia Postuma, Kathleen Ramage, Julie Roche, Nermin Sadoun, Chi Kin Tam, Richard Trotta, Ali Usman

NSERC CRSNG

Bourses d'études supérieures du Canada
Vanier
Canada Graduate Scholarships

JL   Hall C

CINP ICPN   Canadian Institute of Nuclear Physics
Institut canadien de physique nucléaire

This research was carried out at the University of Regina, on Treaty 4 land, the territories of the nêhiyawak, Anihšināpēk, Dakota, Lakota, Nakoda, and the Métis/Michif Nation.

EXTRA SLIDES

- **Gluon junction** carrying baryon number, **ver**tex+par**ton**
- Suggested by gauge invariance of baryonic wave function
- Lower energy configuration due to shorter gluon strings
- **Lattice** simulations of proton wavefunction show gluon junction
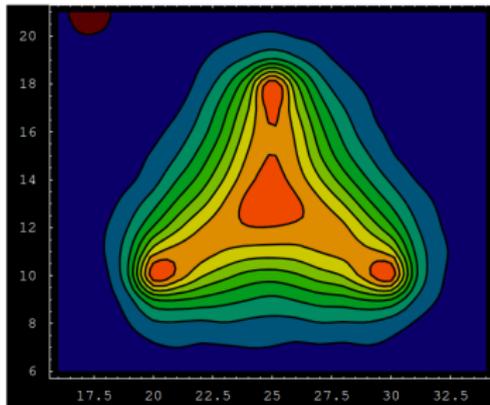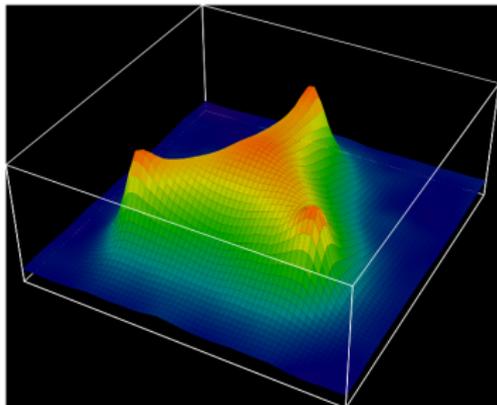
G.C. Rossi & G. Veneziano. Nucl. Phys. B 123 (1977).   X. Artu, Nucl. Phys. B 85 (1975).

H. Suganuma et al, Conference on Quark Confinement and the Hadron Spectrum 6 (2004), arXiv:hep-lat/0412026.

While u-channel DEMP accesses baryon number distribution via TDAs, other channels more directly test for the presence of a verton:

u-channel SIDIS

- Semi-Inclusive Deep Inelastic Scattering (SIDIS) in u-channel (baryon moving forwards)

$$e + p \rightarrow e' + p' + X$$

- Baryon asymmetry of pp collisions at the LHC

$\dfrac{d^3\sigma}{dp^3}$ $\sim e^{-y^*/2}$ $\sim e^{-y^*}$ y^*
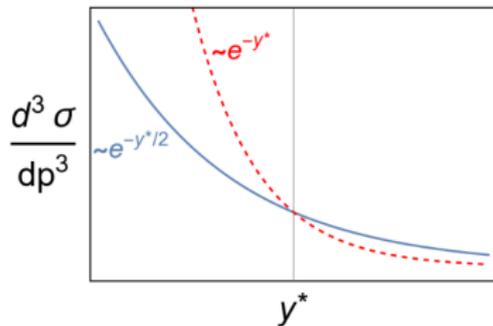
Rapidity of forward baryon
Red: conventional prediction
Blue: prediction with verton

D. Frenklakh, D.E. Kharzeev, & W.B. Li, arXiv:2312.15039 [hep-ph]

- "Hard" processes are perturbatively **calculable** (series expansion converges)

- "Soft" processes are non-perturbative (not directly calculable)

- Factorization splits a process into a convolution of a hard scattering and a soft function, e.g. TDA

- Can calculate **evolution** of TDA with Q^2

- QCD predicts factorization at **"sufficiently high"** Q^2
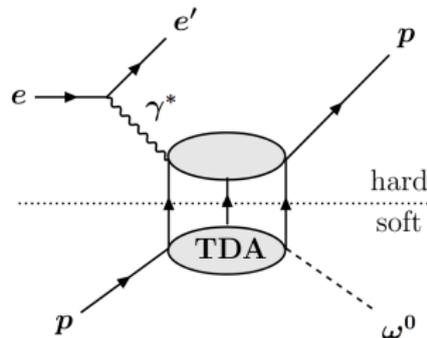
> Experiment needed to find onset of factorization $\rightarrow$ critical for proton structure & TDA extraction.

R. Devenish and A. Cooper-Sarkar, *Deep Inelastic Scattering* (Oxford University Press, 2004).

- Separate total cross-section σ into components based on virtual photon polarization σ_L, σ_T, σ_{LT}, σ_{TT}

$$2\pi\frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos2\phi$$
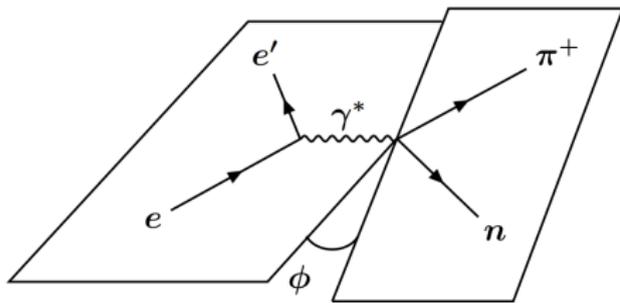
$$\epsilon = (1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2})^{-1}$$

σ_L: events involving **longitudinally** polarized γ^*

σ_T: events involving **transversely** polarized γ^*

σ_{LT}: longitudinal-transverse **interference**

σ_{TT}: transverse-transverse **interference**

u-Channel Rosenbluth Separation

$$2\pi \frac{d^2\sigma}{du\,d\phi} = \frac{d\sigma_T}{du} + \epsilon \frac{d\sigma_L}{du} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{du} \cos\phi + \epsilon \frac{d\sigma_{TT}}{du} \cos 2\phi$$
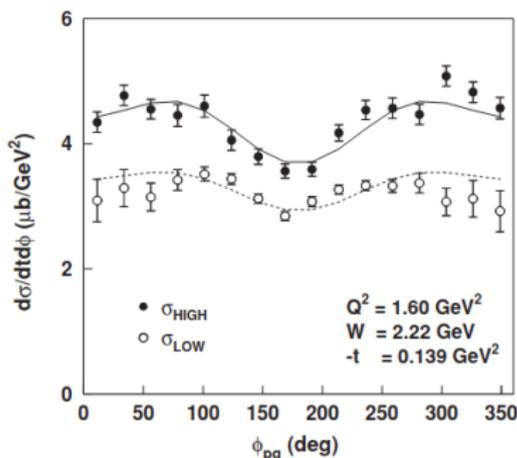
- The unseparated cross sections for two values of ϵ are plotted vs ϕ and fit with the Rosenbluth equation
- **Error magnification**: need high precision on unseparated cross-sections

$$\delta\sigma_L = \frac{1}{\Delta\epsilon} \sqrt{\delta\sigma_{HIGH}^2 + \delta\sigma_{LOW}^2}$$
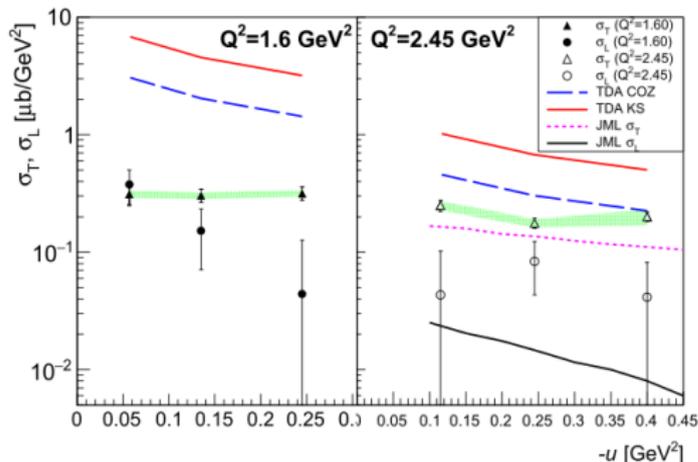
- Iterative procedure

Test **factorization**: TDA model predicts $\sigma_T \gg \sigma_L$ and $\sigma_T \propto 1/Q^8$ at sufficiently high Q^2

H. P. Blok et al. (Fπ Collaboration), Phys. Rev. C 78, 045202 (2008).

Previous Indications of Factorization

- Data approaching TDA prediction by $Q^2 \approx 2.5$ GeV^2 in both **Hall C** ω^0 production and **CLAS** π^+ production
- This work: $2.1 \leq Q^2 \leq 5.5$ GeV^2

Hall C ω^0

Agreement between σ_T and **TDA** is poor at Q^2=1.65 GeV^2, but decent at Q^2=2.45 GeV^2

CLAS π^+

TDA predictions approach σ_U at $Q^2 \approx 2.5$ GeV^2

K. Park et al (CLAS Collaboration), Phys. Lett. B **780** 340 (2018).
W.B. Li et al (Fπ Collaboration), Phys. Rev. Lett. **123** 182501 (2019).

KaonLT Experimental Settings

- Data taken at two values of ϵ for each (Q^2, x_B): facilitates Rosenbluth separation
- Multiple points at same x_B but different Q^2: test TDA predictions
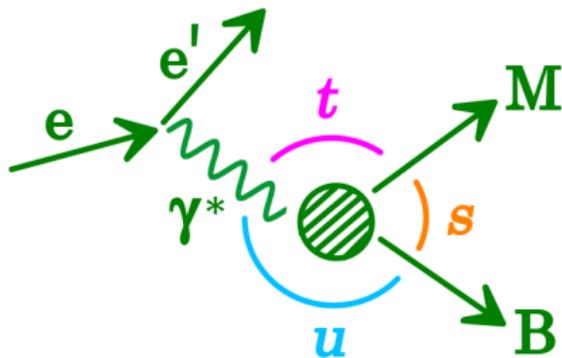- Lowest Q^2 point excluded from this analysis

E [GeV]	Q^2 [GeV^2]	W [GeV]	x_B	$\epsilon_{HIGH}/\epsilon_{LOW}$
10.6/8.2	5.5	3.02	0.40	0.53/0.18
10.6/8.2	4.4	2.74	0.40	0.71/0.48
10.6/8.2	3.0	3.14	0.25	0.67/0.39
10.6/6.2	3.0	2.32	0.40	0.88/0.57
10.6/6.2	2.1	2.95	0.21	0.79/0.25
4.9/3.8	0.5	2.40	0.09	0.70/0.45

G. Huber, T. Horn, and P. Markowitz, Update E12-09-011, Jefferson Lab PAC 38 (2011).

Consider generic DEMP event: $\gamma^* + p \rightarrow$ Meson + Baryon

Mandelstam variables:

$$t = (\boldsymbol{p}_{\gamma^*} - \boldsymbol{p}_M)^2$$

$$u = (\boldsymbol{p}_{\gamma^*} - \boldsymbol{p}_B)^2$$

$$s = (\boldsymbol{p}_M + \boldsymbol{p}_B)^2$$

$$s + t + u = \Sigma m^2$$

- 4-vector squared is Lorentz Invariant $\rightarrow$ useful kinematic quantities
- Due to 4-momentum conservation, the sum $s + t + u$ is equal to the sum of the masses of the 4 particles in the reaction
- At fixed s (CM energy W^2), small $-t \Leftrightarrow$ large $-u$, and vice versa
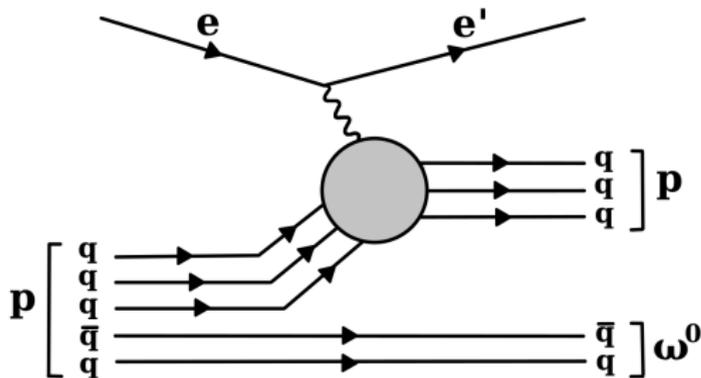- In DEMP, $t < 0$ and u is mostly negative

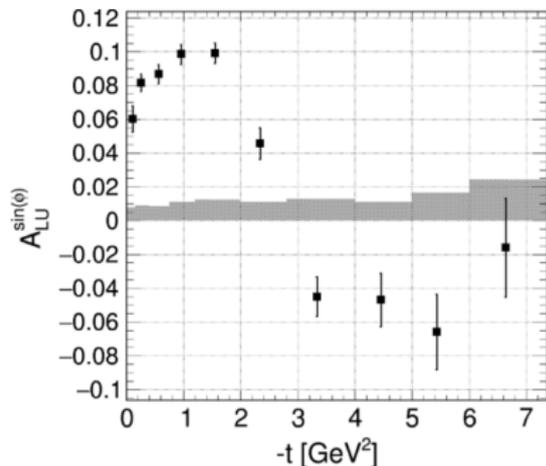- DEMP events where momentum is passed to the **proton** e.g.

$$e + p \rightarrow e' + \omega + p$$

- Complementary to t-channel (regular) DEMP events
- Unique access to $qqqq\bar{q}$ part of the proton wavefunction and the meson cloud of the proton

"Knocking the proton out of the proton"

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

u-Channel Beam-Spin Asymmetry

$$A_{LU} = \frac{1}{P}\left(\frac{N^+ - N^-}{N^+ + N^-}\right) \propto \frac{\sigma_{LT'}}{\sigma_0} sin\phi$$

CLAS measurements of A_{LU} for π^+ production show **sign change** → implies change in **reaction mechanism**

S. Diehl et al (CLAS Collaboration). Phys. Rev. Lett.**125**, 182001 (2020).

- Asymmetry caused by **helicity** ± of incident electron
- Looking for **evolution** from forward (*t*-channel) and backward (*u*-channel) region
- KaonLT data: insufficient statistics, **errors magnified** by background subtraction

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