A New Angle Into the Proton

u-Channel Meson Electroproduction

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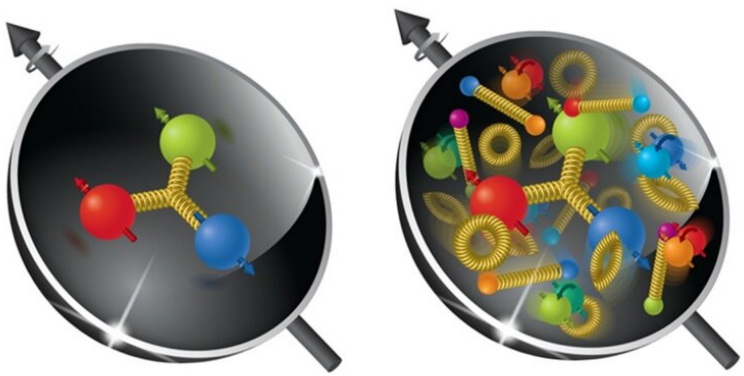
University of Regina

CAP Congress 2025



Motivation

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

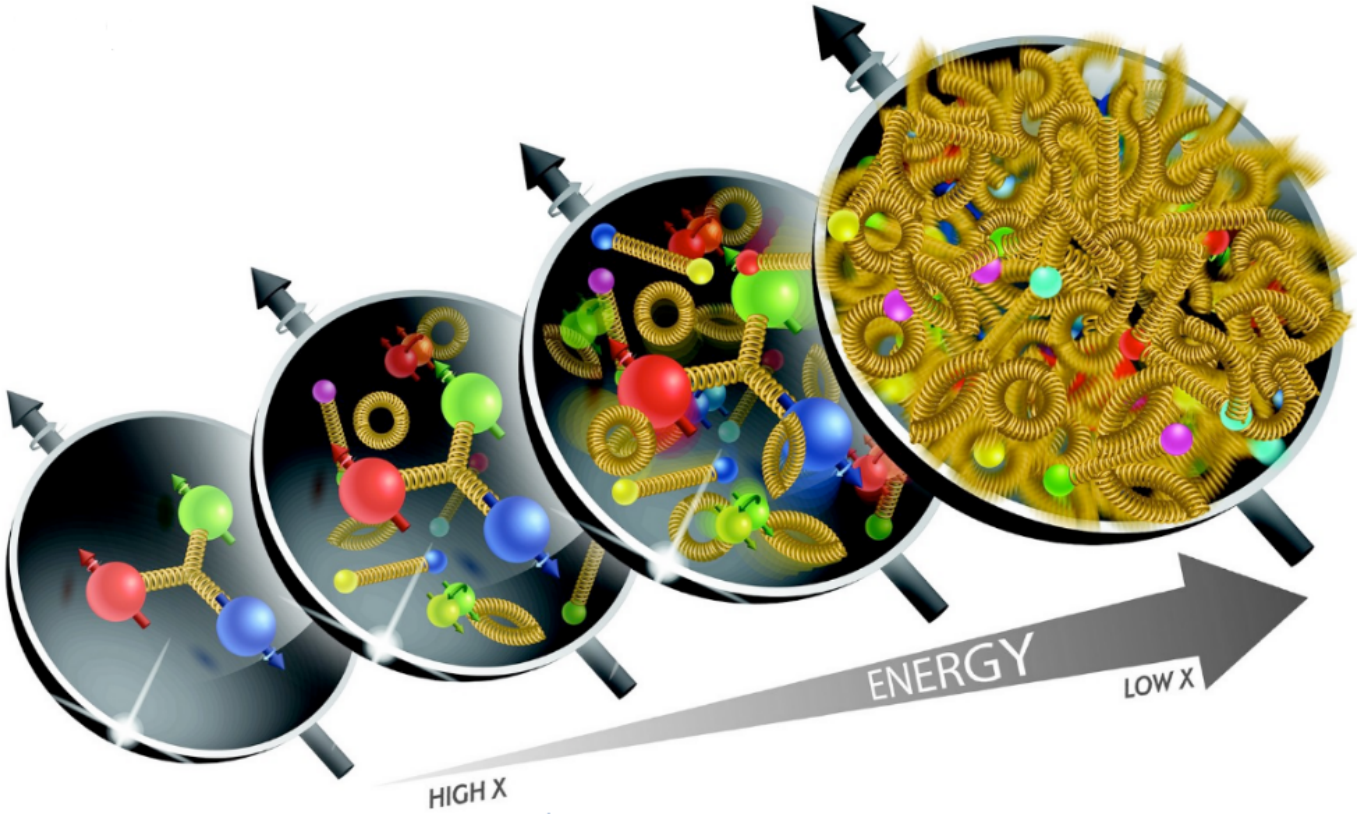


Image by Brookhaven National Lab: https://www.flickr.com/photos/brookhavenlab/albums/72157714316624996/

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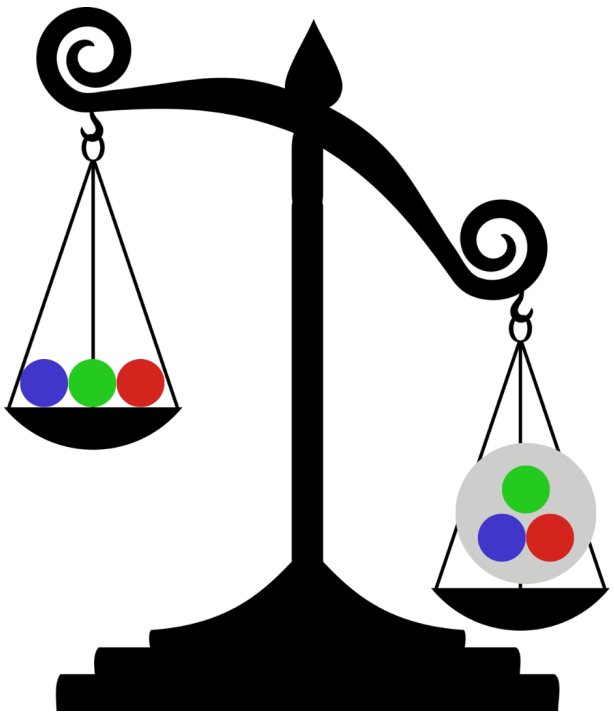
Due to the **running of α_S** and **gluon self-coupling**, proton structure is complicated and **varies drastically with measurement scale**

⟶ 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...

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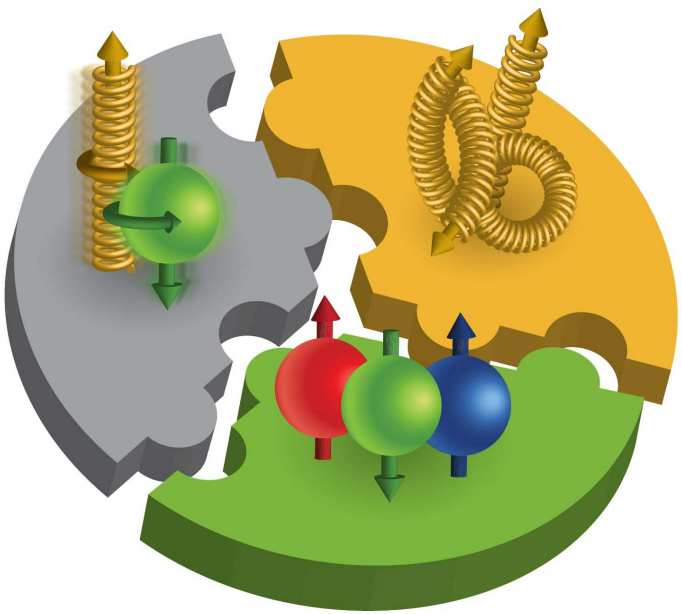

- **Mass discrepancy:** Higgs mechanism contributes **<10%** of proton mass
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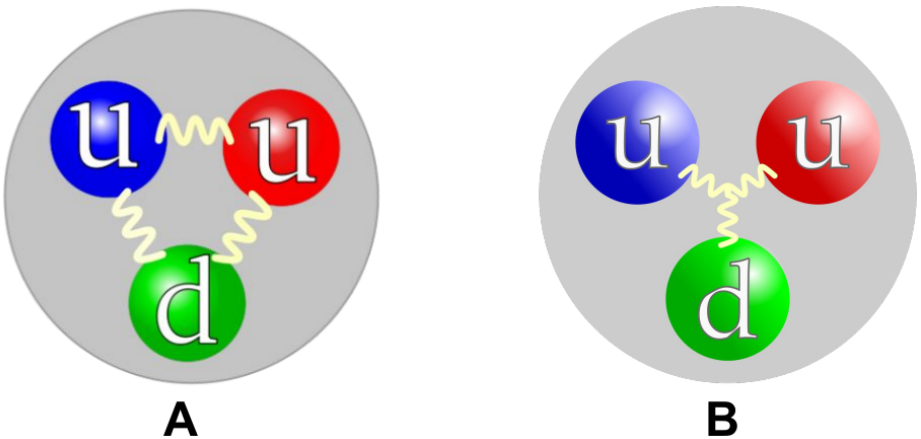
Proton Identity

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



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

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

Deep Exclusive Meson Production (DEMP)

Accelerated electron exchanges virtual photon γ^* with a proton, resulting in the production of a meson, e.g.:

$$e + p \rightarrow e' + \pi^+ + n$$

Kinematic variables:

Q^2: 4-momentum of γ^*

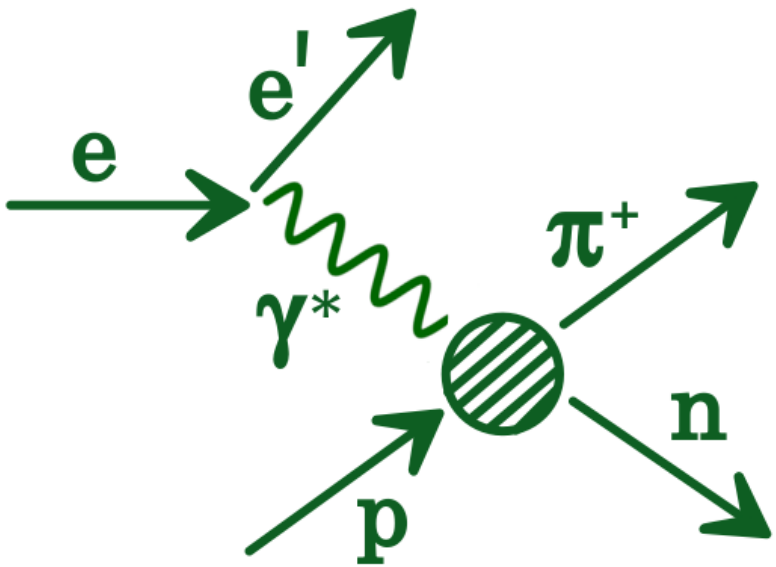
$$Q^2 = -(\boldsymbol{p}_e - \boldsymbol{p}'_e)^2$$

W: center of mass energy

$$W^2 = (\boldsymbol{p}_\pi + \boldsymbol{p}_n)^2$$

$\boldsymbol{x_B}$: Bjorken scaling variable

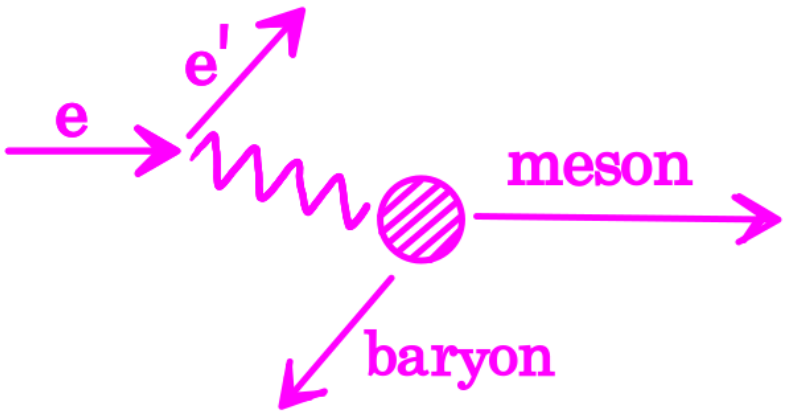
$$x_B = Q^2/2m_p(E_e - E_{e'})$$



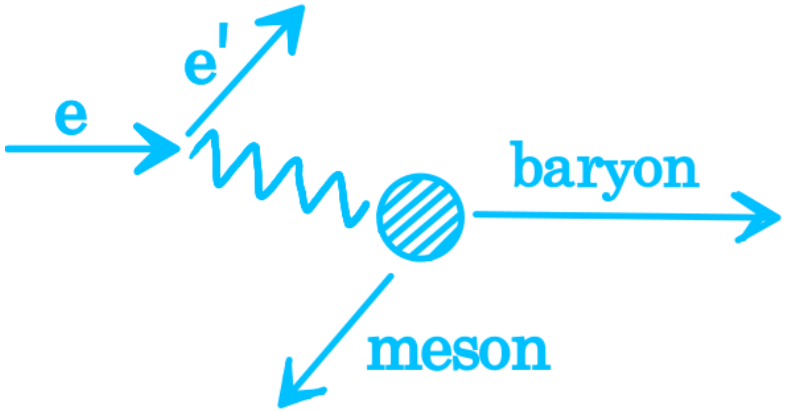
Forward and Backward-Angle DEMP

Classify DEMP events based on Mandelstam variables t & u:

$t = (p_{\gamma^*} - p_{meson})^2$



$u = (p_{\gamma^*} - p_{\text{baryon}})^2$



t-channel:

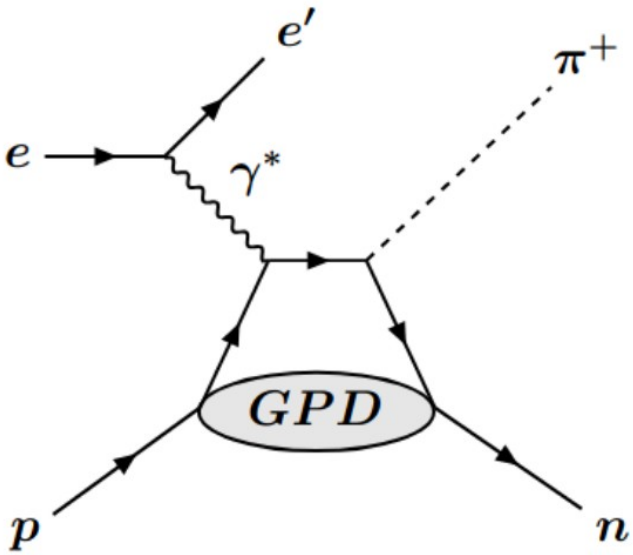
- $-t$ small, **meson** carries majority momentum
- Meson moves **forward**
- Well studied
- Larger cross-section

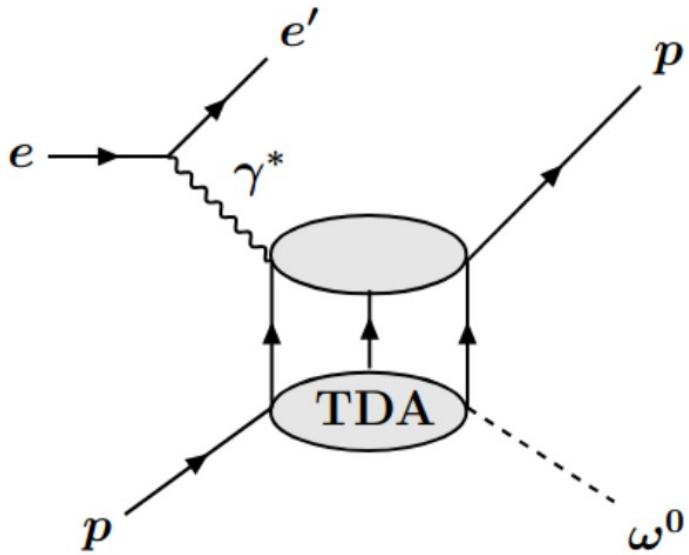
u-channel:

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

Forward and Backward-Angle Observables

Backward-angle (u-channel) DEMP accesses **new kinematic territory** inside the proton.





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

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

Hall C

- 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**

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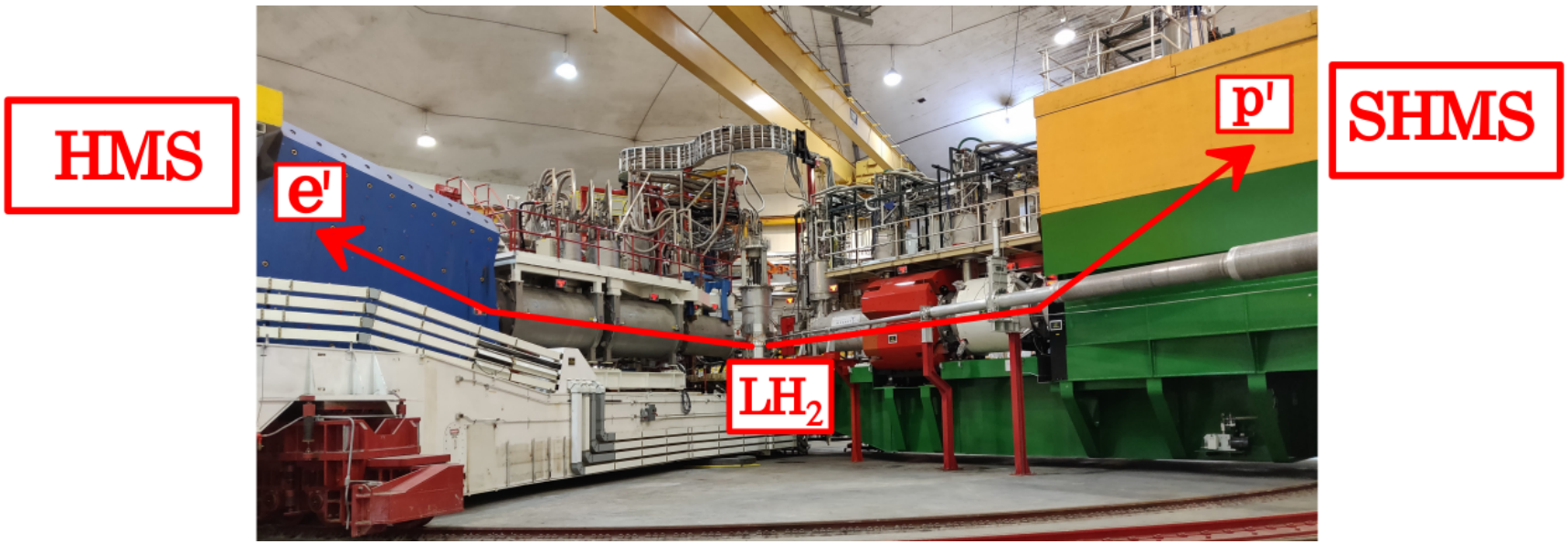
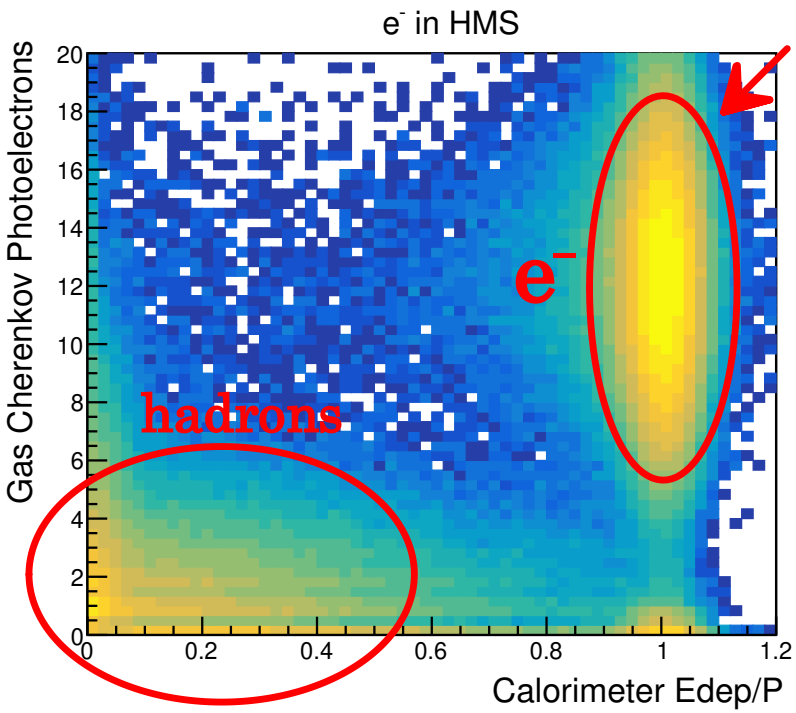
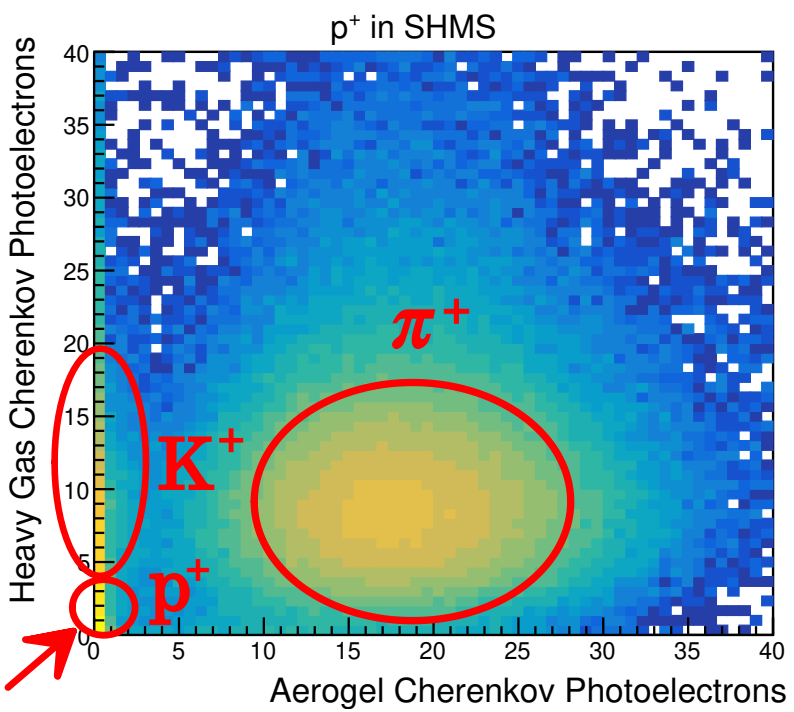


- Spectrometers are magnetic and moveable → choose charge, momentum, and angles to detect
- Coincidence experiment: need simultaneous detection in **High Momentum Spectrometer** and **Super HMS**
- **My data:** u-channel reactions from **KaonLT** experiment: Moderate Q^2 =2–5.5 GeV^2, above resonance region W>2

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**



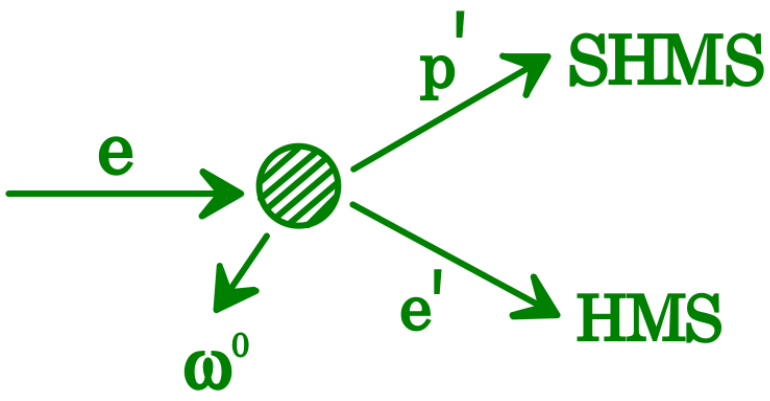


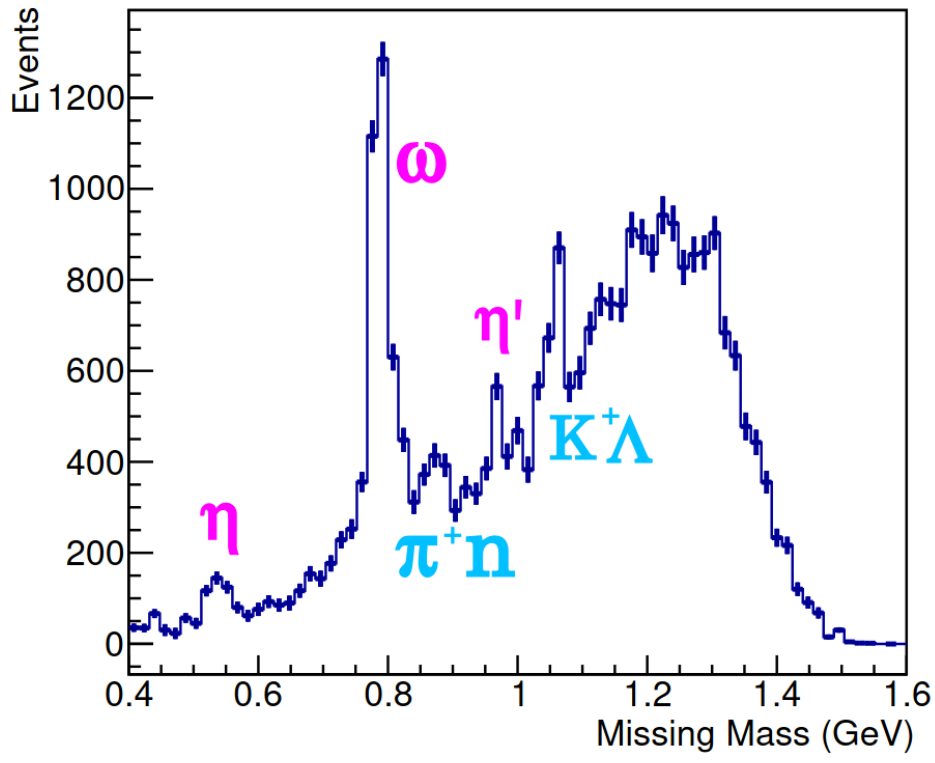
Event Selection

$$e^- + p \rightarrow e^{-\prime} + p' + \omega^0$$

- Select coincidences via $t_{COIN} = t_{HMS} - t_{SHMS} \approx 0$
- Meson not detected → use missing mass $m_X \approx m_\omega$

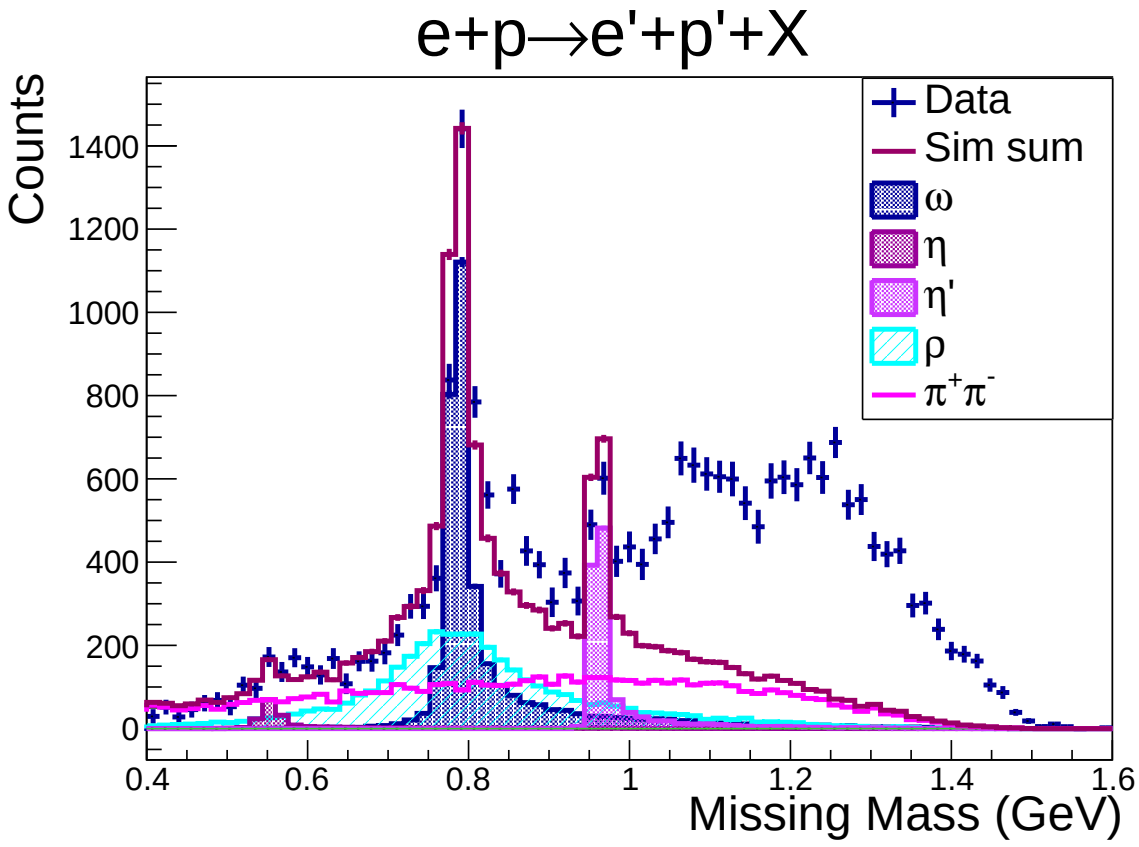
$$m_X^2 = (p_e + m_p - p_{e\prime} - p_{p\prime})^2$$



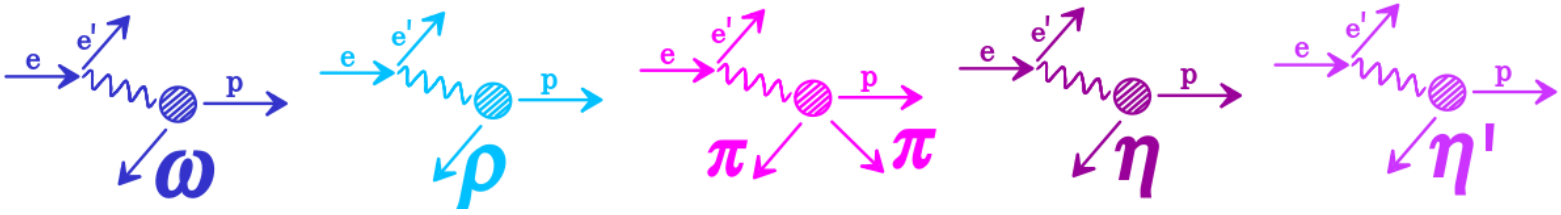


Background Study

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



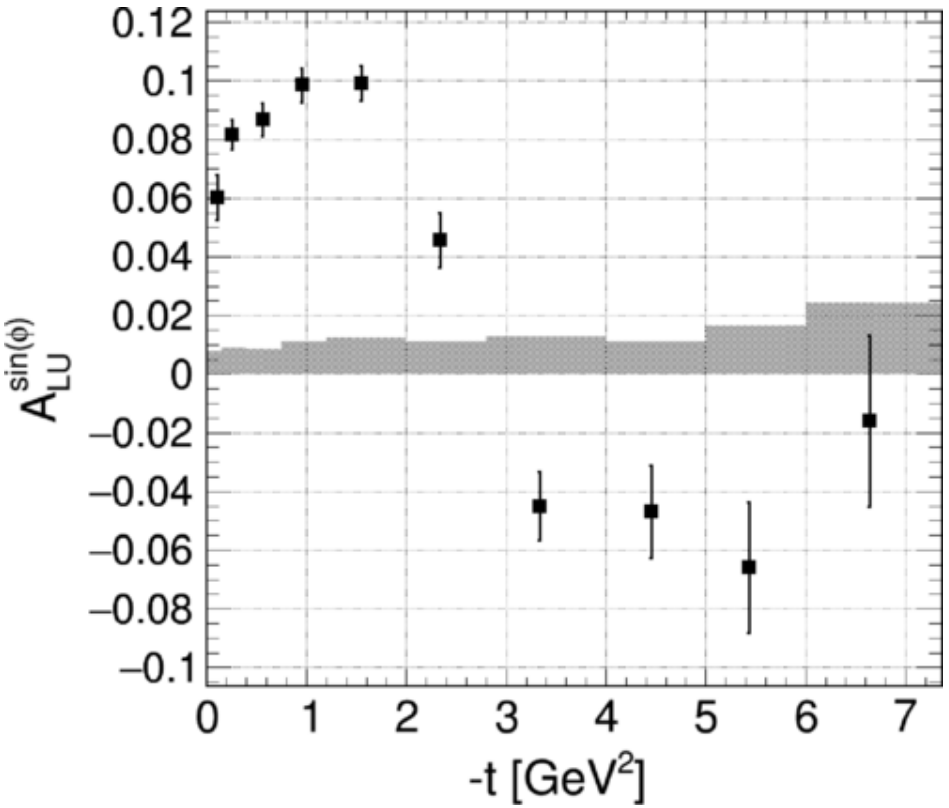
- Use simulations to disentangle different reactions
- **Goal:** cleanly separate ω production from other u-channel reactions
- **Incomplete:** missing background processes above $m_X \approx 1$



Future Work

- Determine and simulate additional backgrounds
- Calculate **beam-spin asymmetry** and **cross-section** of ω^0 production
- **Goal:** thorough comparison of **forward vs backward-angle** observables

Example: CLAS data of π^+ DEMP



Sudden **sign change** of asymmetry implies a change in **reaction mechanism**

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

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**.

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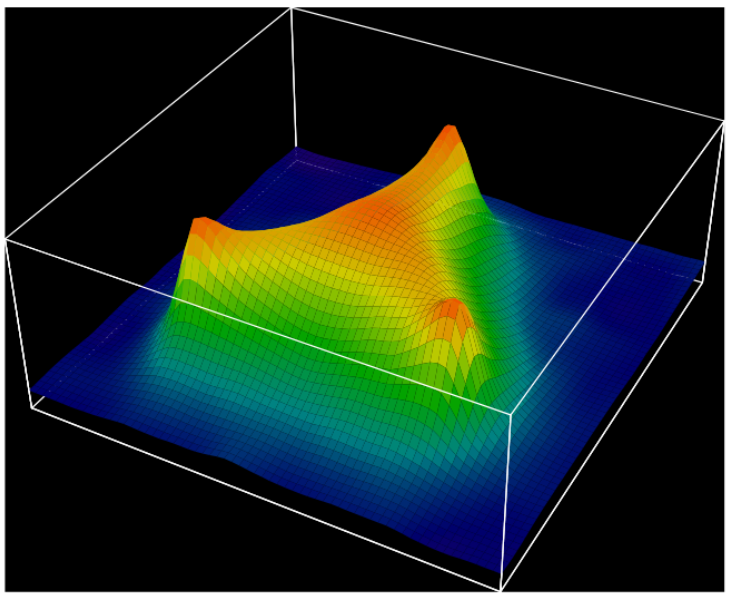
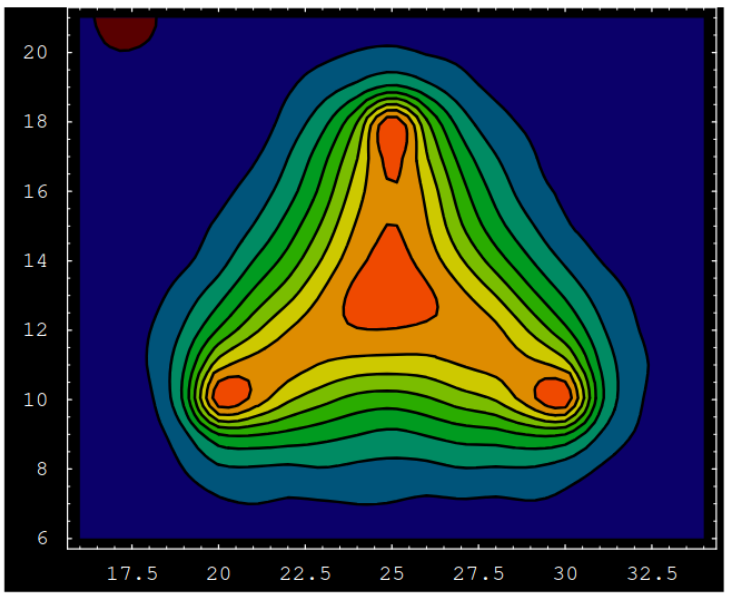
EXTRA SLIDES

The Verton

Suggested by gauge invariance of baryonic wave function
G.C. Rossi & G. Veneziano. Nucl. Phys. B 123 (1977).

Lattice simulations of proton wavefunction show gluonic junction, e.g.



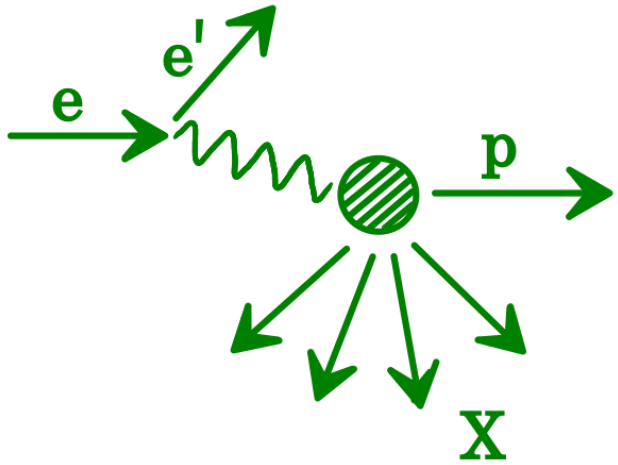


H. Suganuma et al, Conference on Quark Confinement and the Hadron Spectrum 6 (2004), arXiv:hep-lat/0412026.

Verton-Sensitive Observables

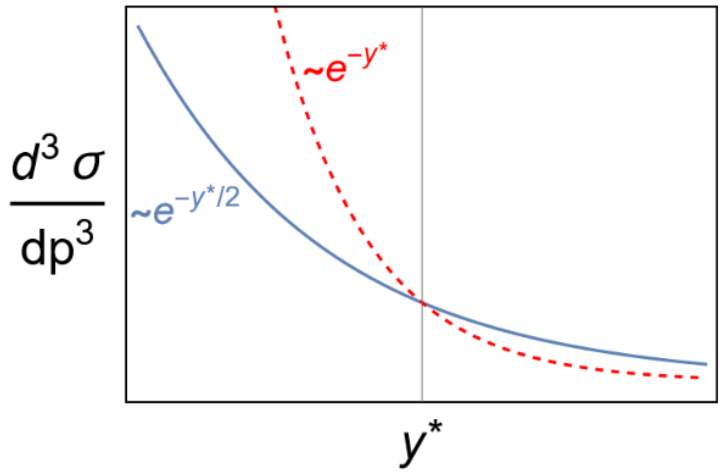
While u-channel DEMP accesses baryon number distribution via TDAs, other channels more directly test for the presence of a verton:

u-channel SIDIS



Semi-Inclusive Deep Inelastic Scattering (SIDIS), $e + p \to e' + p' + X$, with baryon moving forwards

Rapidity distribution of forward baryon:



Blue: prediction with verton
Red: conventional prediction

The baryon asymmetry of pp collisions at the LHC could also probe the verton

Hard/Soft Factorization

- "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 → critical for QCD.

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

The KaonLT Experiment

- DEMP reactions: detect scattered **electron** and positive **hadron** in **coincidence**
- t-channel: **meson** in SHMS, u-channel: **proton** in SHMS
- Data taken at two values of ϵ for each (Q^2,x_B): facilitates Rosenbluth separation
- High beam polarization during E=10.6 GeV run period: facilitates BSA calculation

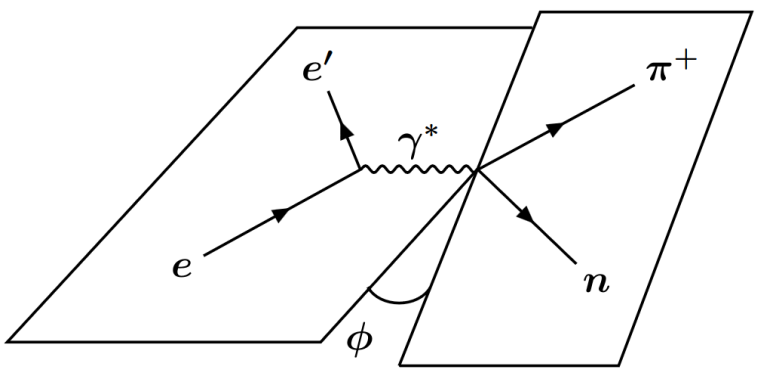
E [GeV]	Q^2 [GeV^2]	W [GeV]	x_B	$\epsilon_{HIGH}/\epsilon_{LOW}$
10.6/8.2	5.5	3.02	0.40	0.53/0.18
10.6/8.2	4.4	2.74	0.40	0.71/0.48
10.6/8.2	3.0	3.14	0.25	0.67/0.39
10.6/6.2	3.0	2.32	0.40	0.88/0.57
10.6/6.2	2.1	2.95	0.21	0.79/0.25
4.9/3.8	0.5	2.40	0.09	0.70/0.45

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

Rosenbluth Equation

- Separate total cross-section σ into components based on virtual photon polarization $\sigma_L, \sigma_T, \sigma_{LT}, \sigma_{TT}$
- Test of **factorization:** in the u-channel, $\sigma_L \gg \sigma_T$ and $\sigma_T \propto 1/Q^8$ are predicted

$$2\pi \frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$



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

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

σ_{LT}: longitudinal-transverse interference

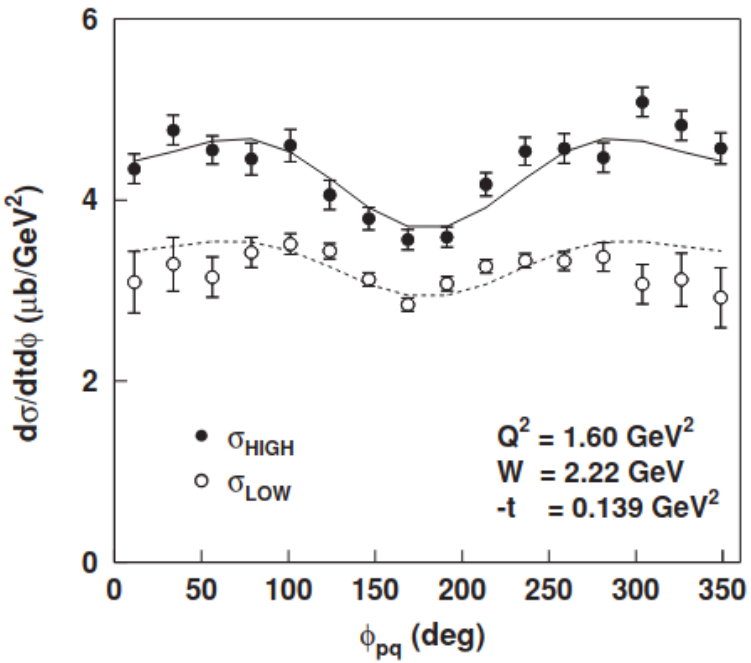
σ_{TT}: transverse-transverse interference

σ_{LT}: longitudinal-transverse polarized interference

$$\epsilon = (1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} \tan^2 \frac{\theta_{e'}}{2})^{-1}$$

u-Channel Rosenbluth Separation

$$2\pi \frac{d^2\sigma}{dud\phi} = \frac{d\sigma_T}{du} + \epsilon \frac{d\sigma_L}{du} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{LT}}{du} \cos\phi + \epsilon \frac{d\sigma_{TT}}{du} \cos 2\phi$$



- 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

$$\delta\sigma_L = \frac{1}{\Delta\epsilon} \sqrt{\delta\sigma^2_{HIGH} + \delta\sigma^2_{LOW}}$$

- Iterative procedure

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

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

Asymmetry Formalism

- Define the beam spin asymmetry A_{LU} as:

$$A_{LU} = \frac{1}{P}\left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right) = \frac{1}{P}\left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right)$$

- Polarized cross-section in Rosenbluth equation appears when separating events by helicity:

$$2\pi\frac{d^2\sigma}{dtd\phi} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$
$$+ h\sqrt{2\epsilon(1-\epsilon)}\frac{d\boldsymbol{\sigma_{LT'}}}{dt}\sin\phi$$

- Beam spin asymmetry provides much cleaner access to $\sigma_{LT'}$:

$$A_{LU} = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\boldsymbol{\sigma_{LT'}}}{\boldsymbol{\sigma_0}}\sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}cos\phi + \epsilon\frac{\sigma_{TT}}{\sigma_0}cos2\phi}$$

M. Diehl and S. Sapeta. Eur. Phys. J. C 41, 525-533 (2005).