# Exclusive Backward–Angle Meson Electroproduction – Unique access to *u*–channel physics

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University of Regina

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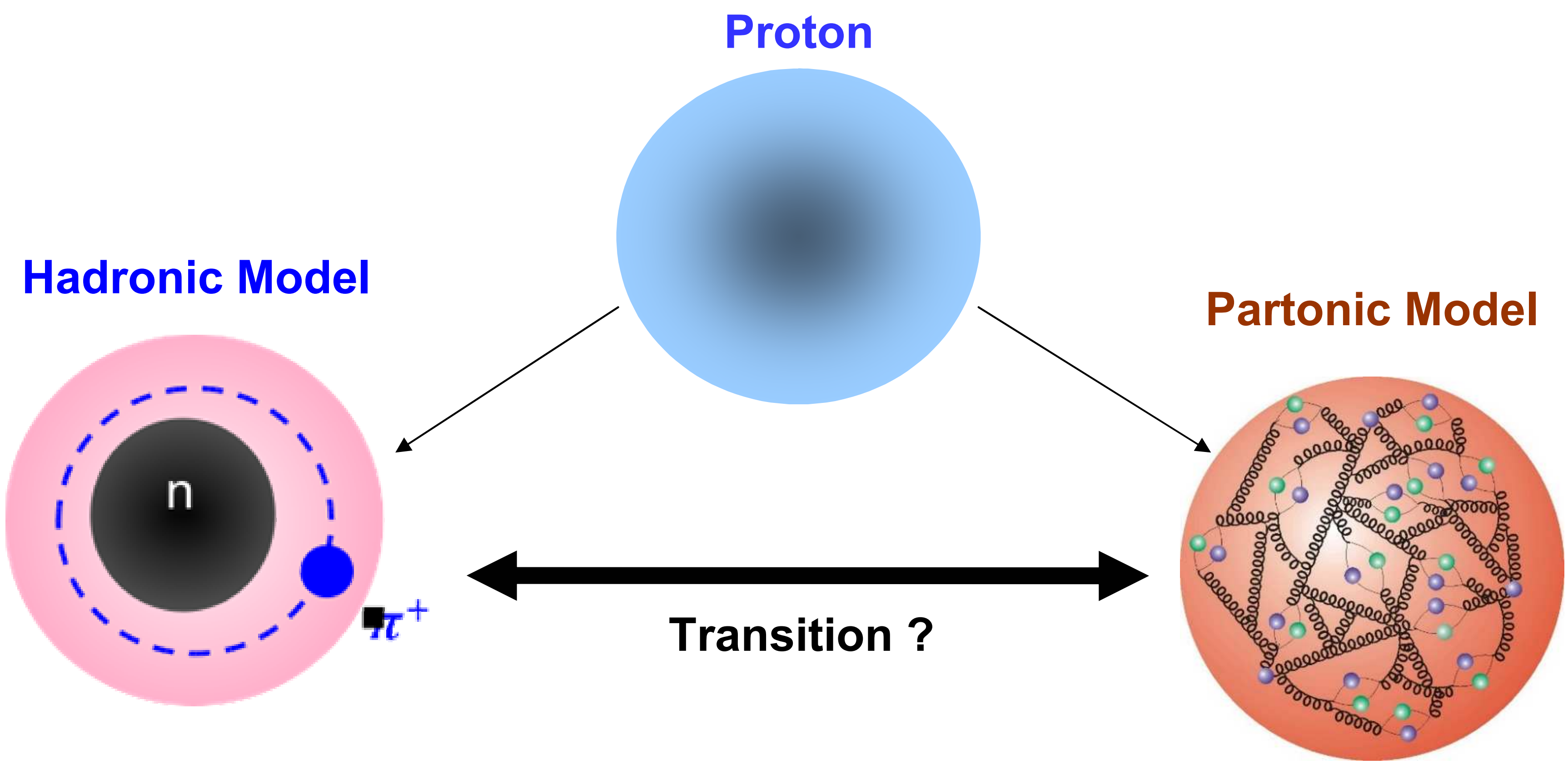
# Scientific Motivation

**The Key Science Problem:**

- How does Quantum Chromodynamics (QCD) work in the confinement regime?
- Proton structure is dependent on the properties of the probe.
- Studying the transition of QCD

- **Objective:**
  - Establish a new experimental approach
    - Backward–angle (*u*–channel) observables
    - L/T separation

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# Jefferson Lab Hall C Experimental Setup

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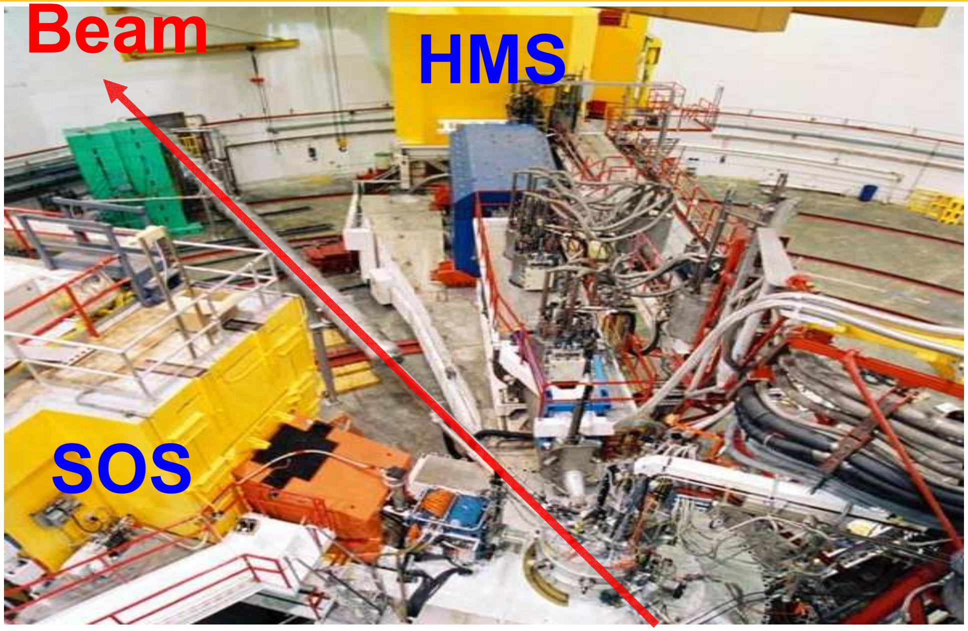
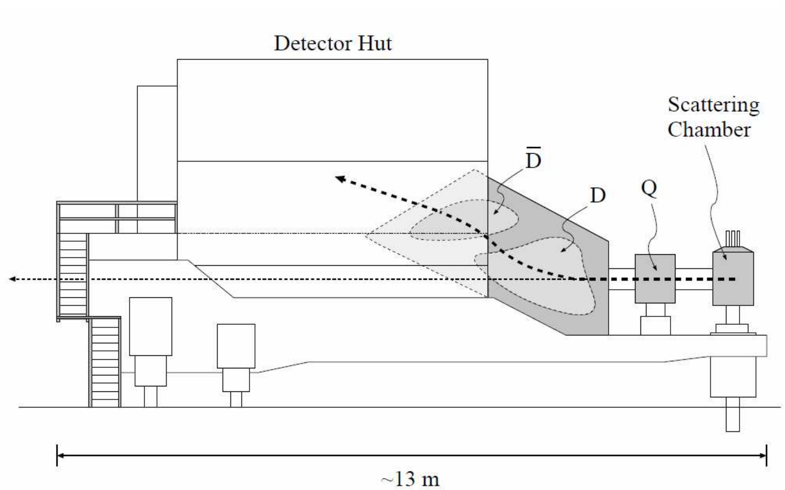
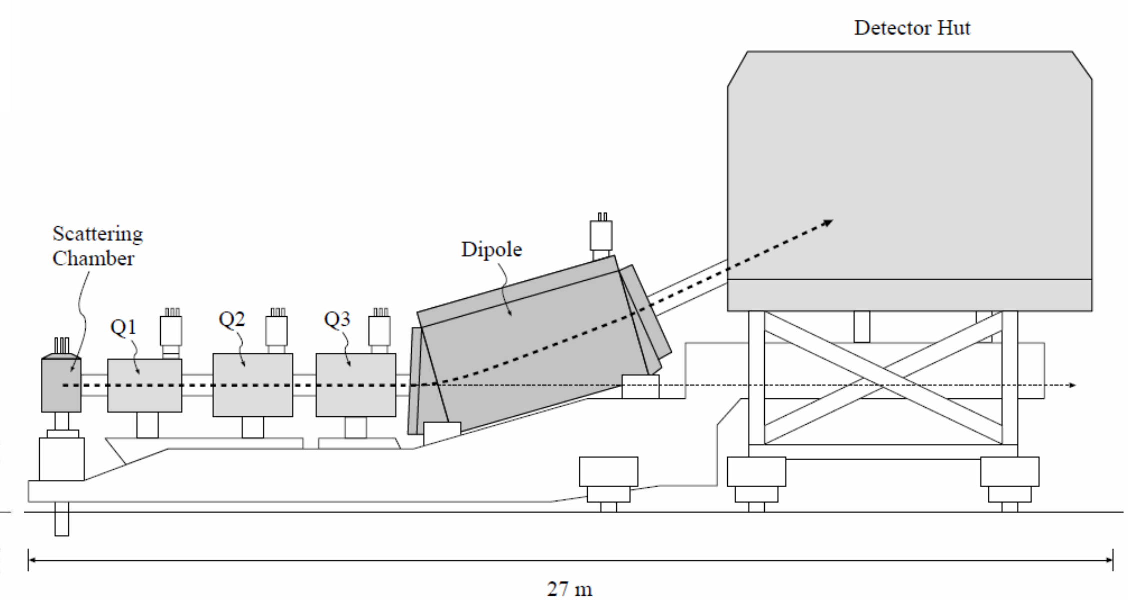



- **HMS (QQQD)**
  - **Angle Acceptance:** 6 msr
  - **Momentum:** 0.5–7.5 GeV/c
  - **Momentum Acceptance:** $\pm$9%
  - **Angular, Position Resolution:** 1mr and 1mm
- **SOS (QDDbar)**
  - **Angle Acceptance:** 9 msr
  - **Momentum:** 0.1–1.8 GeV/c
  - **Momentum Acceptance:** $\pm$20%
- **One of last analyses from 6 GeV era.**




Short Orbit Spectrometer (SOS)




High Momentum Spectrometer (HMS)

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# $t$–Channel $\pi^+$ vs $u$–Channel $\omega$ Production

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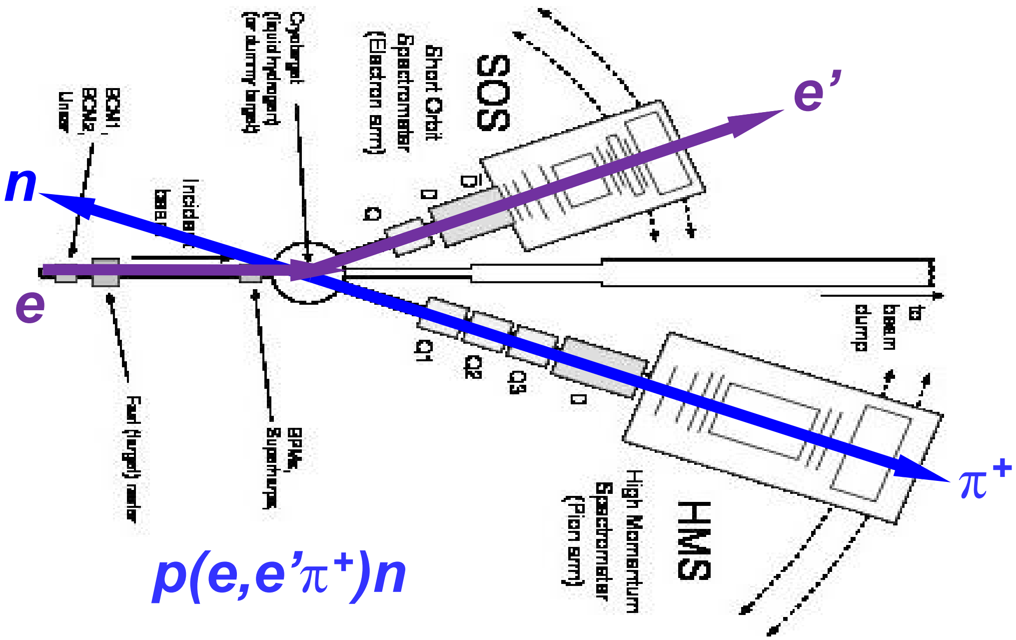
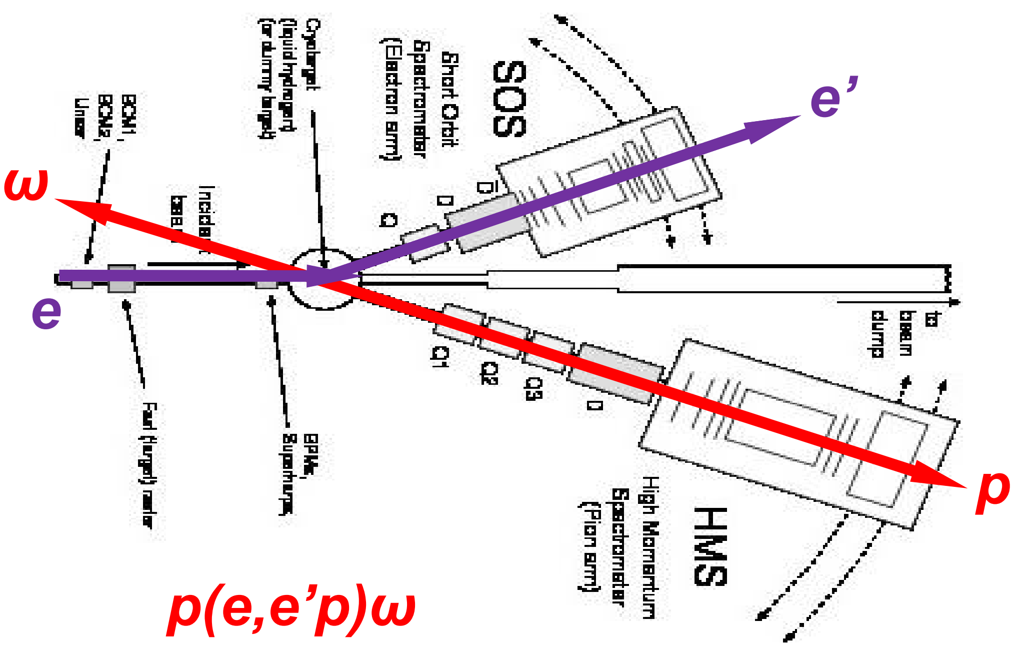
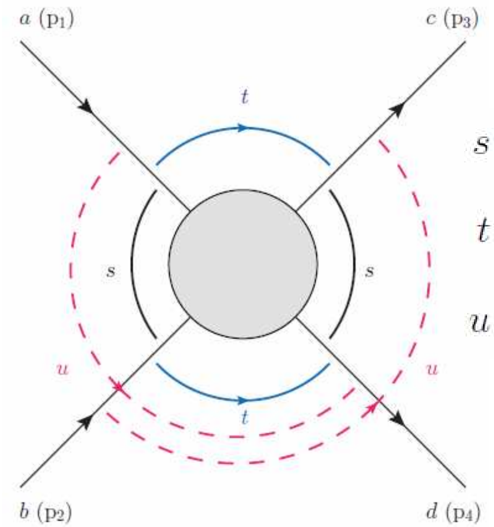



$p(e,e'\pi^+)n$



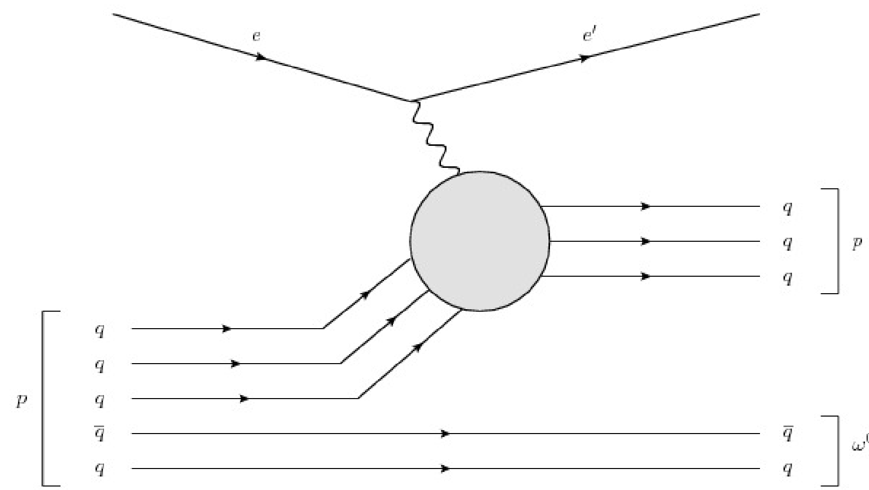

$p(e,e'p)\omega$




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

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

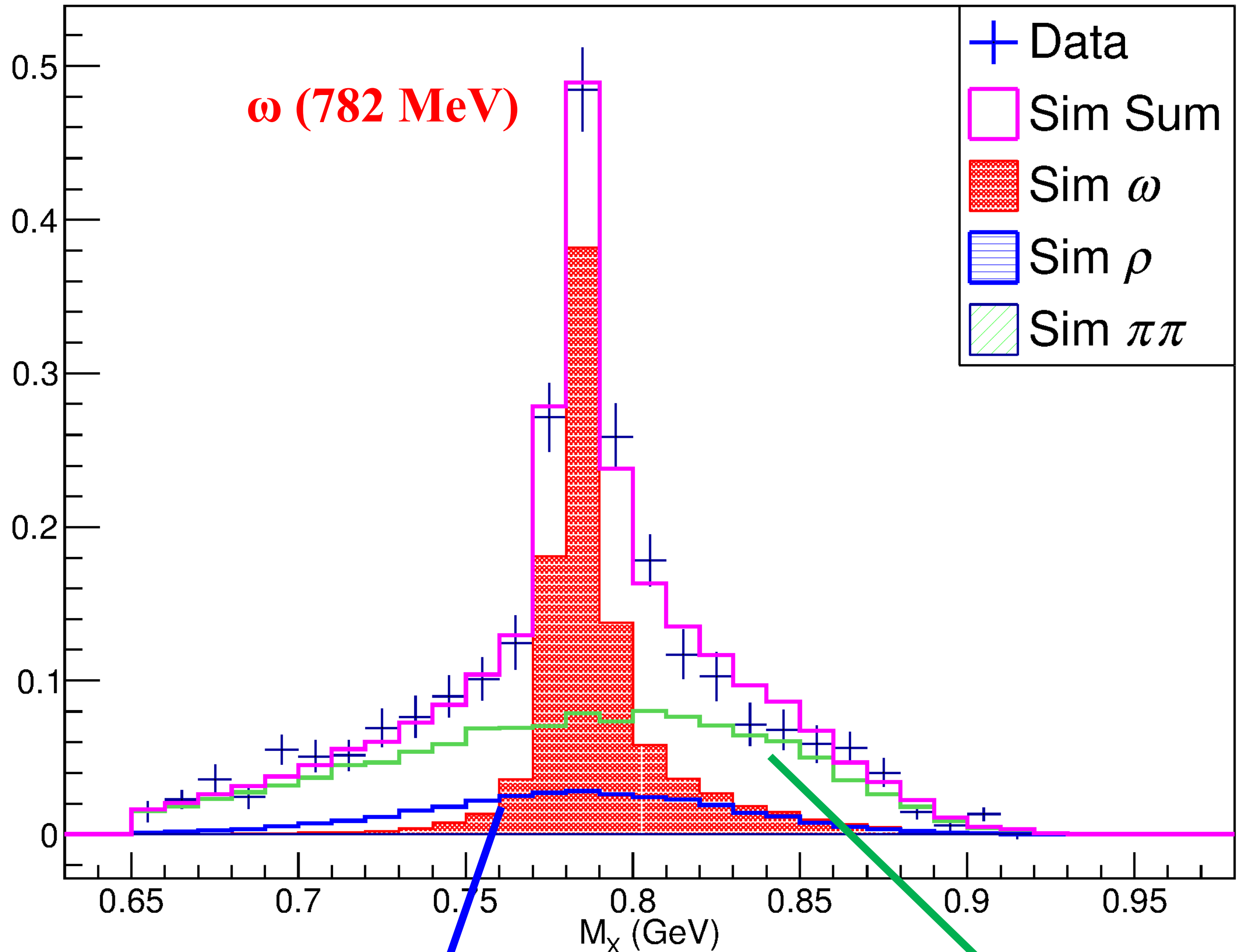
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$




Mark Strikman: Knocking the proton out of the proton process.

# Physics Background Subtraction

$$M_x = \sqrt{(E_e + m_p - m_{e'} - E_p)^2 - (\vec{p}_e - \vec{p}_{e'} - \vec{p}_p)^2}$$




**ρ (770 MeV)**
HERMES Empirical parameterization
with Soding skewness factor

**2π production phase-space**

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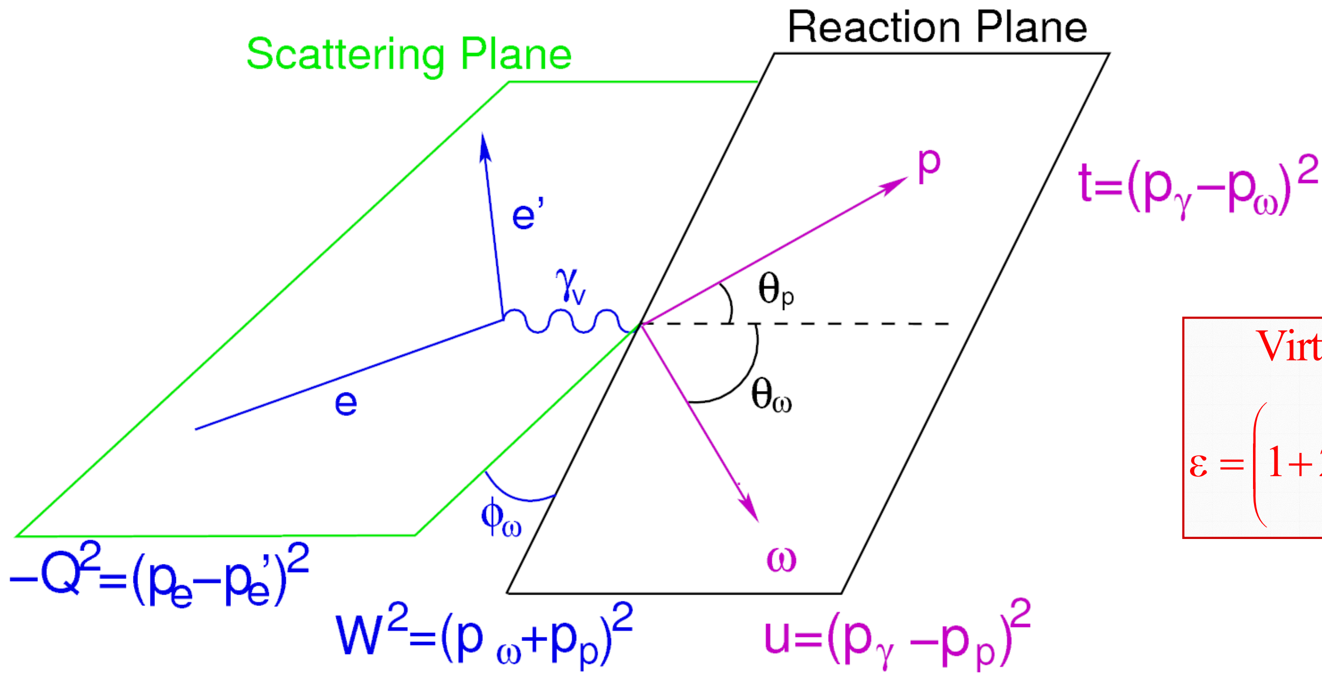
# Rosenbluth (L/T/LT/TT) Separation




Virtual-photon polarization:

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

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

Rosenbluth Separation requires:

- Separate measurements at different ε (virtual photon polarization)
- All Lorentz invariant physics quantities: $Q^2$, $W$, $t$, $u$, remain constant
- Beam energy, scattered e' angle and virtual photon angle will change as a result, event rates are dramatically different at high, low ε

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# Iterative Procedure for L/T Separation

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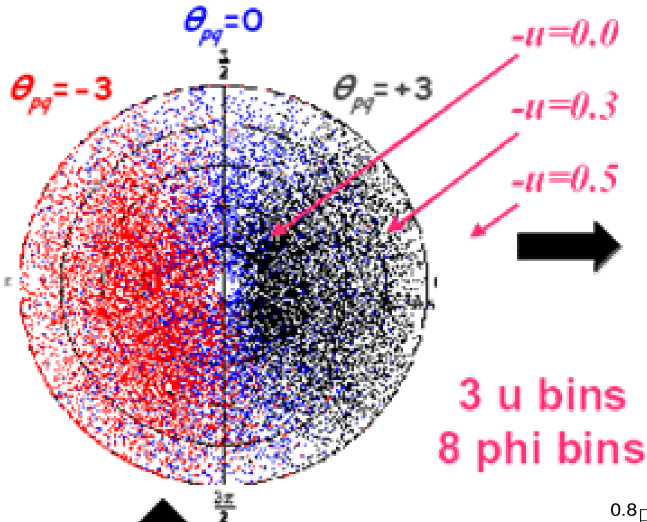
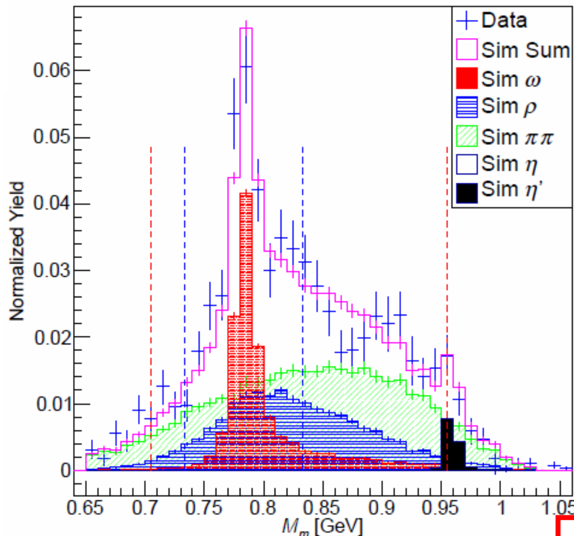
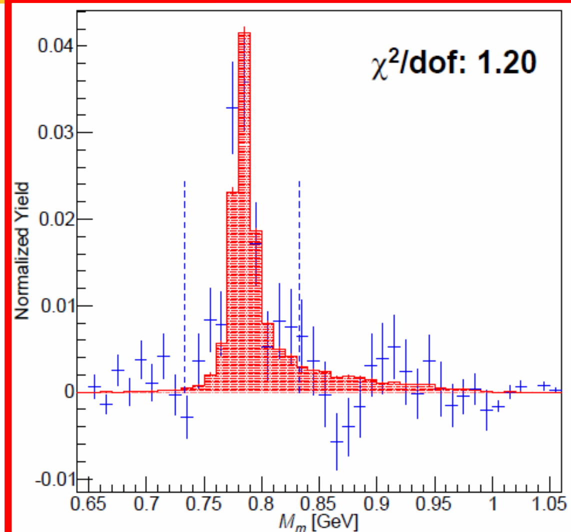
Improve φ coverage by taking data at multiple HMS angles, $-3^{\circ}<\theta_{pq}<+3^{\circ}$.




3 u bins
8 phi bins



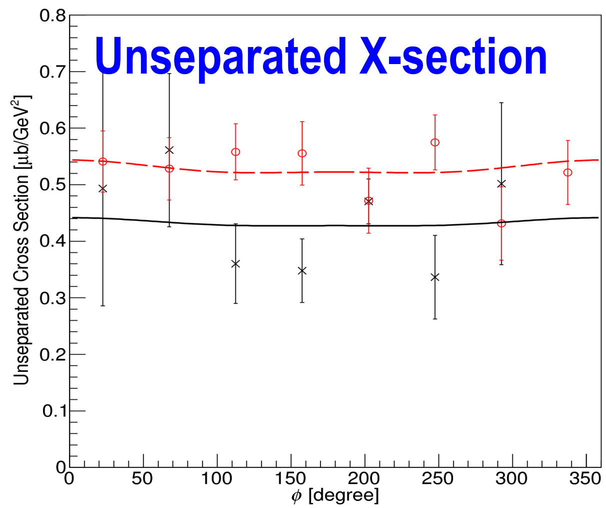



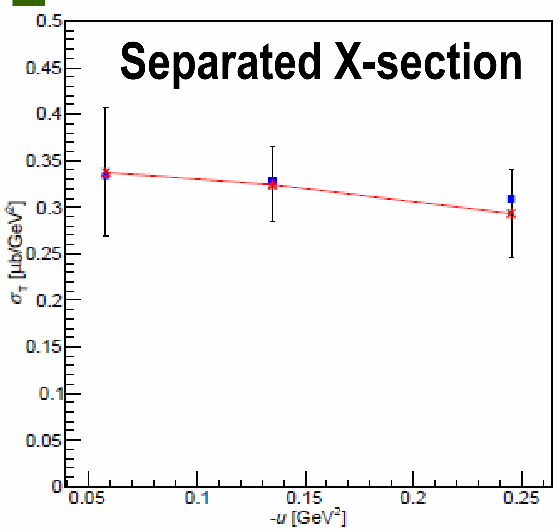

$$R = \frac{Y_{Exp} - Y_{\rho\ sim} - Y_{Xspace\ sim} - Y_{\eta\ sim}}{Y_{\omega\ sim}}$$

Combine ratios for settings together, propagating errors accordingly.

$$\left.\frac{d^2\sigma}{dt\,d\varphi}\right|_{EXP} = R \left.\frac{d^2\sigma}{dt\,d\varphi}\right|_{SIMC}$$

Empirical Model




Extract L,T,LT,TT via simultaneous fit

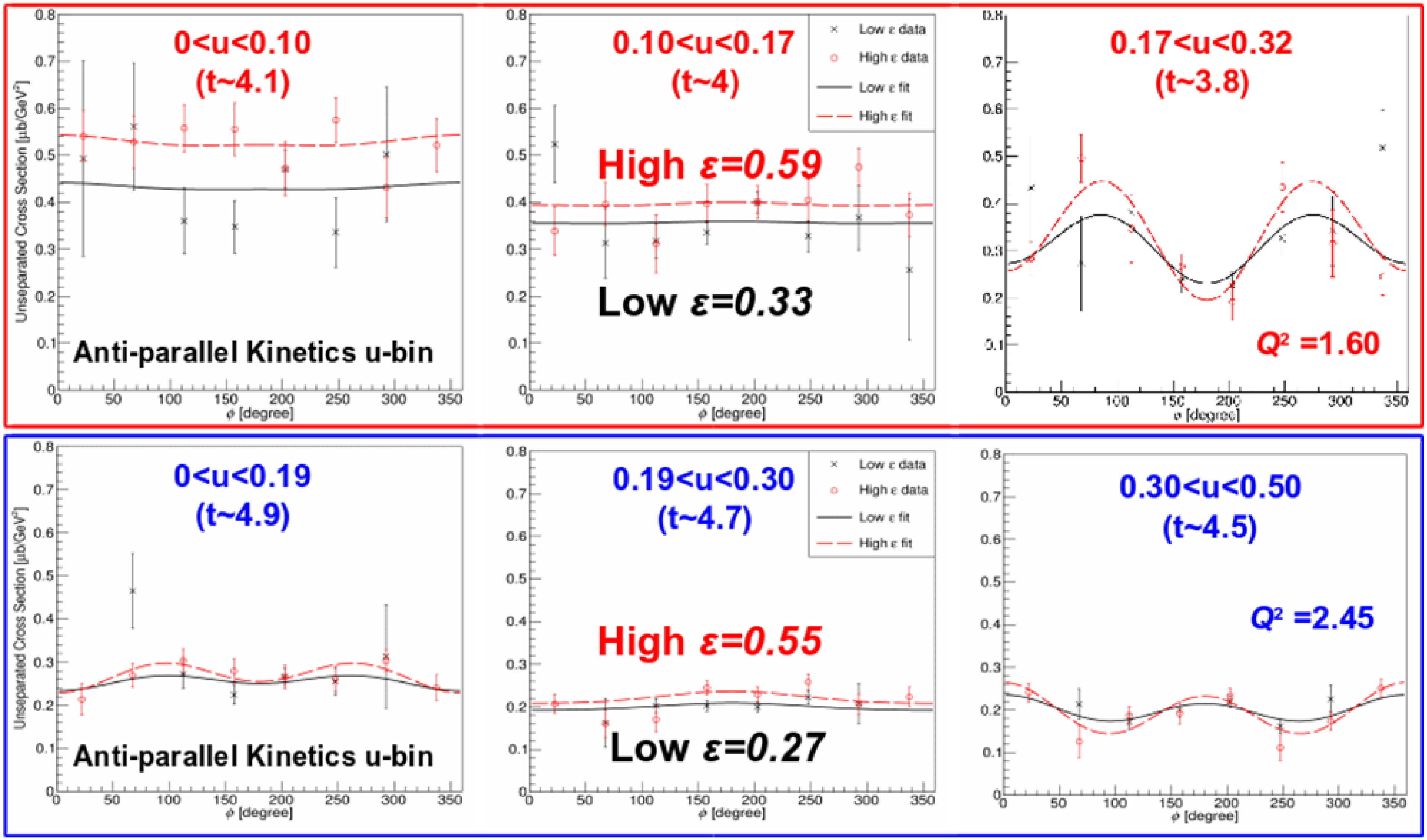
$$2\pi\frac{d^2\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

# Unseparated Cross Sections (Money Plot)

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

$Q^2$=1.60 GeV$^2$

$Q^2$=2.45 GeV$^2$

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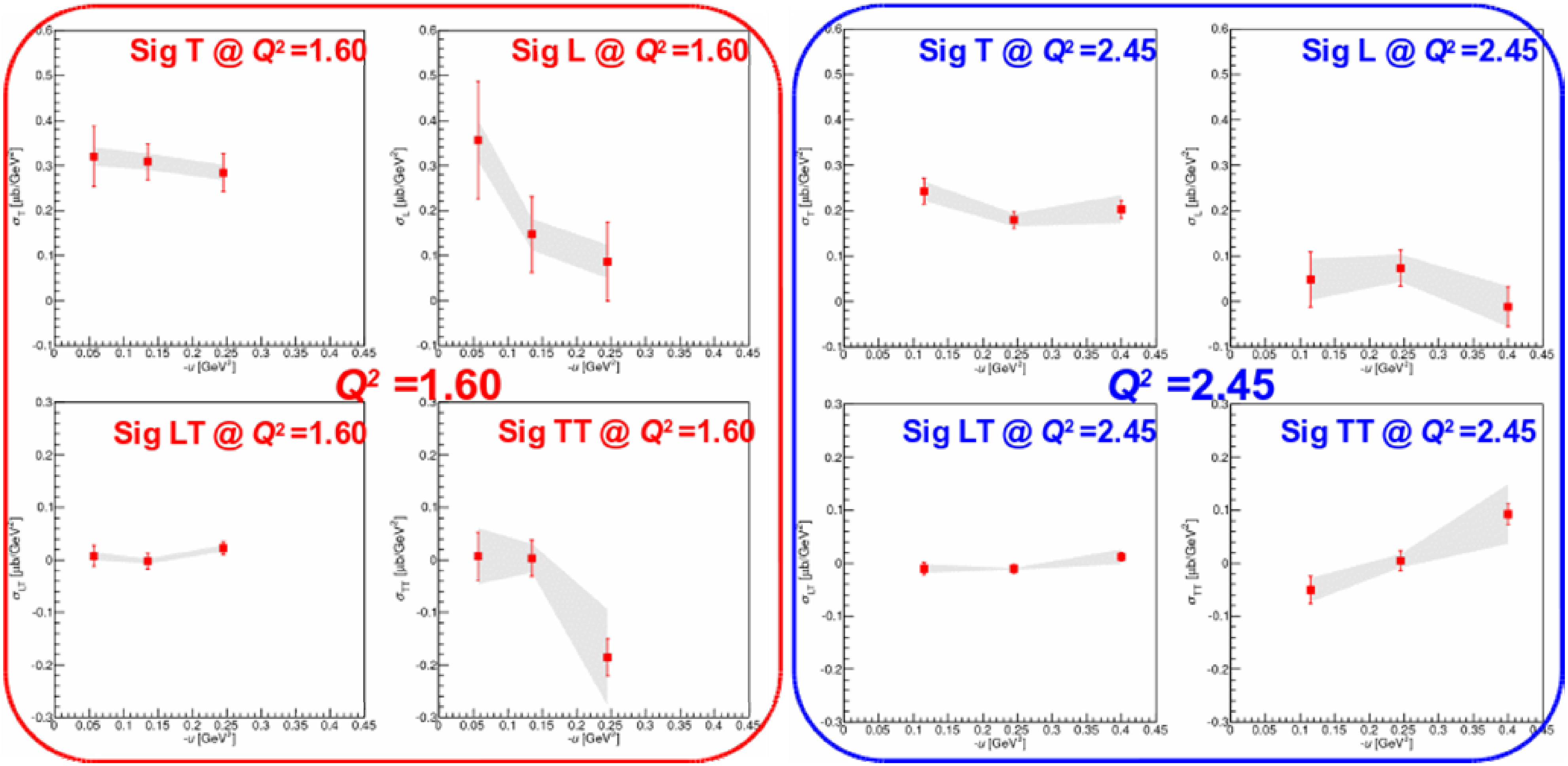
# Separated Cross Sections $\frac{d\sigma}{dt}$ vs $-u$




**Observations:**

- $\sigma_T$ falls slowly with $-u$; $\sigma_L$ falls faster.
- $\sigma_{LT}$ is small; $\sigma_{TT}$ has sign flip for different $Q^2$ values.

Error bars = statistical and uncorrelated syst. unc; Error bands = correlated syst. unc.

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# Hadronic Model: Evolution of Proton Structure

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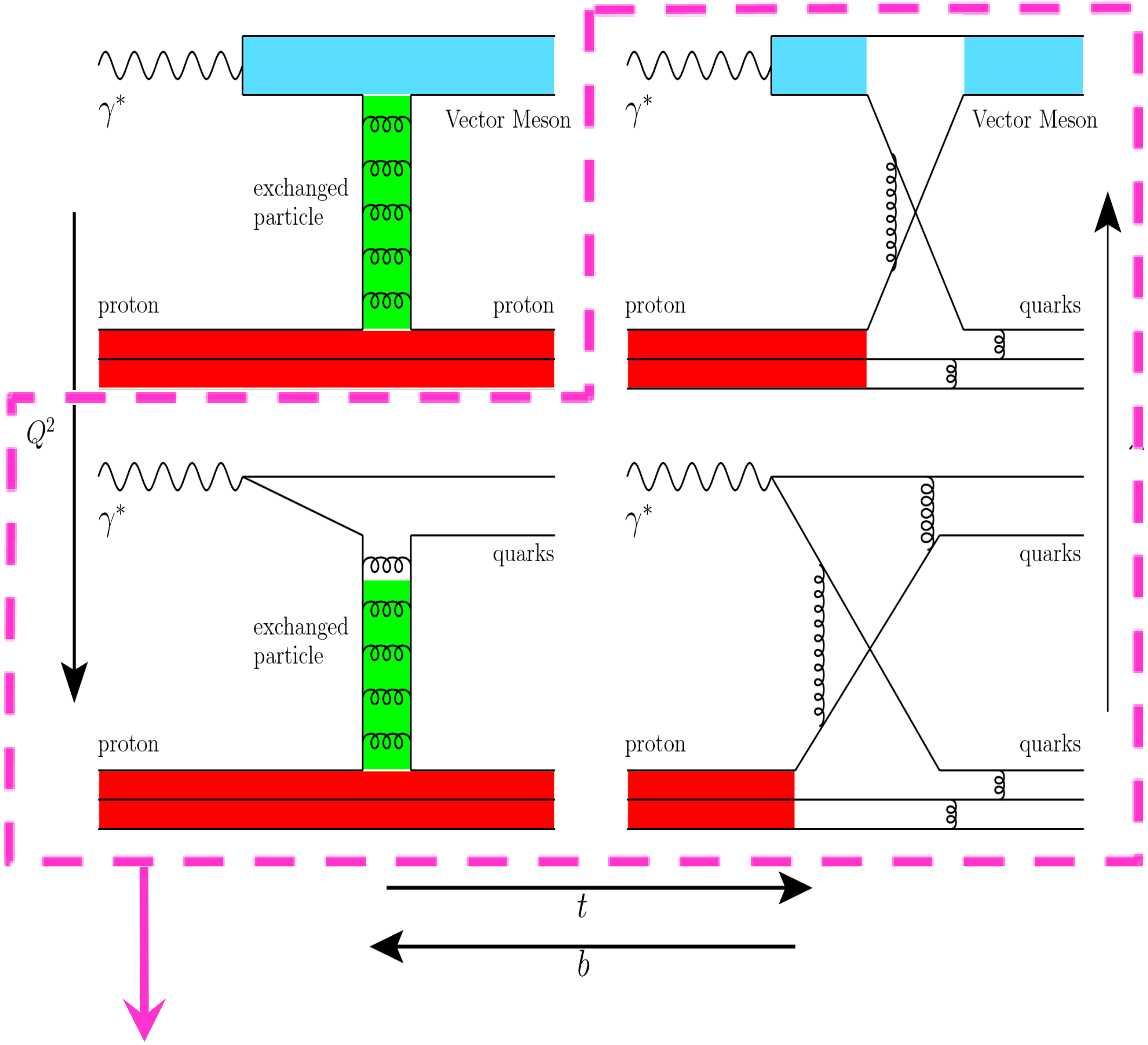


**Evolution of the Proton Structure**

- Physics observables
  - ***t*, *W* (*s*), $Q^2$, *x***
- *x* Evolution:
  - 0.2-0.3 valence quark distribution is pronounced
- *W* Evolution:
  - Above the resonance region
- **$Q^2$ Evolution**
  - **Wavelength of the probe**
- ***t* Evolution**
  - **Impact parameter**
- What about ***u***?
  - **Physical interpretation unclear**

# Hadronic Model: Regge Model by JM Laget

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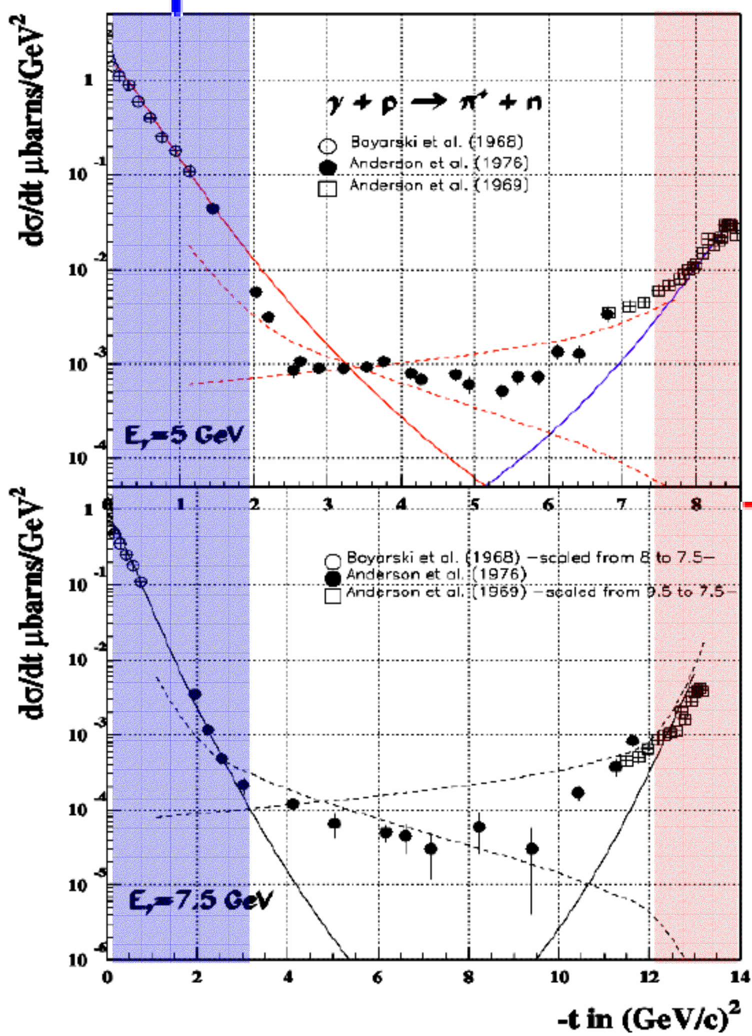
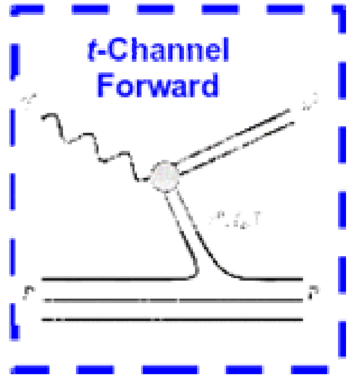
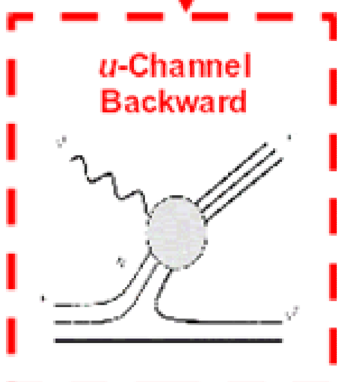
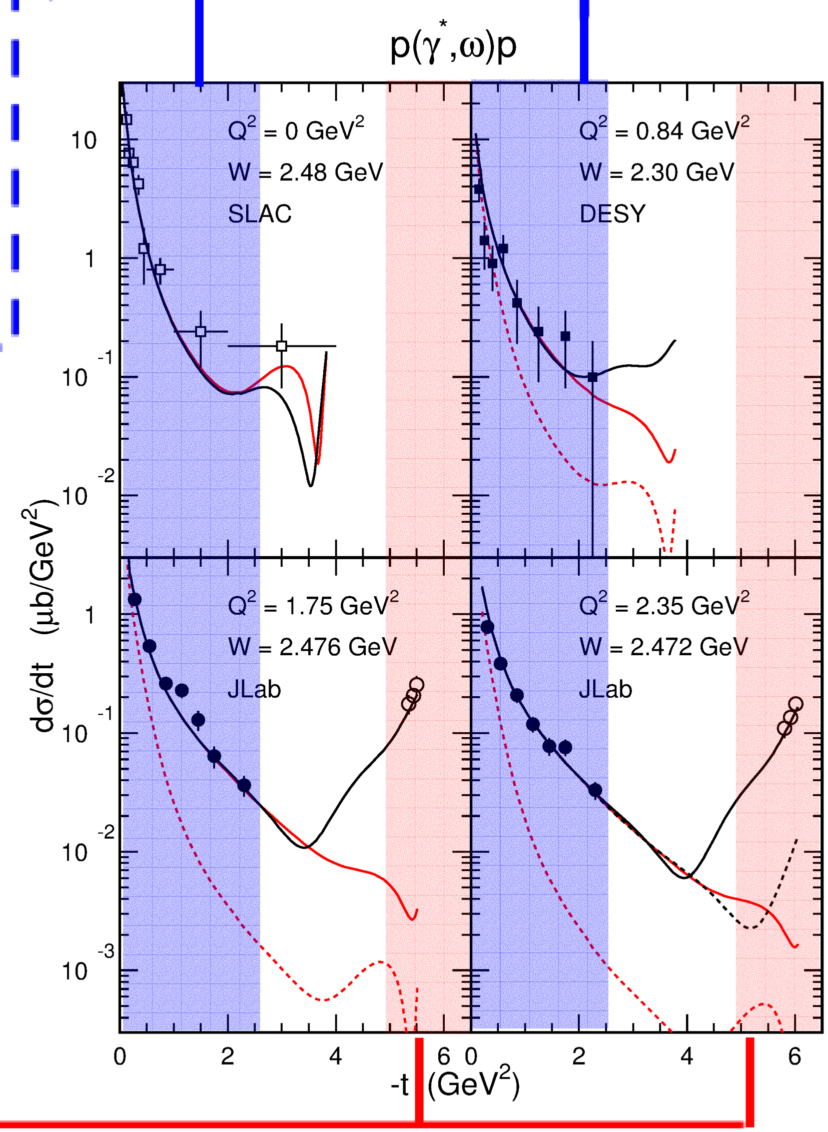
M. Guidal, J.-M. Laget, and M. Vanderhaeghen. *Physics Letters* B400(1):6 – 11, 1997.



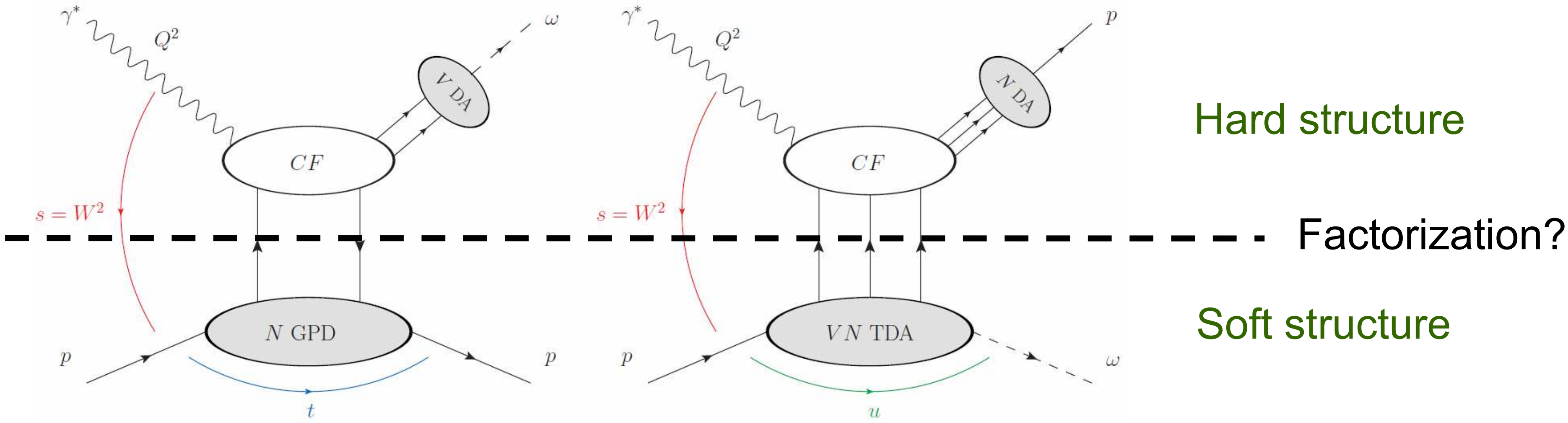




J.M. Laget, Private Communication (2018)




**Soft structure → Hard → Soft transition!**

# Partonic Model: TDA and Factorization




*t*-channel (Forward) *u*-channel (Backward)

- **Nucleon to Meson Transition Distribution Amplitude (TDA)**
  - **Backward angle analog of GPD**
  - **Translate from *t*–space to *u*. Translate *V*–DA to *N*–DA**
  - **No consensus on applicability of TDA factorization regime.**
- **Interactions of Interest:**

  ***u*–channel pseudocalar meson and vector meson production**
- **Two Predictions of TDA:** [B. Pire, K. Semenov, L. Szymanowski, PRD **91**(2015)094006]
  - **Dominance of the transverse polarization** of the virtual photon resulting in the suppression of the longitudinal cross section by at least $1/Q^2$: $\sigma_T > \sigma_L$.
  - Characteristic $1/Q^8$–scaling behavior of $\sigma_T$ for fixed Bjorken x.

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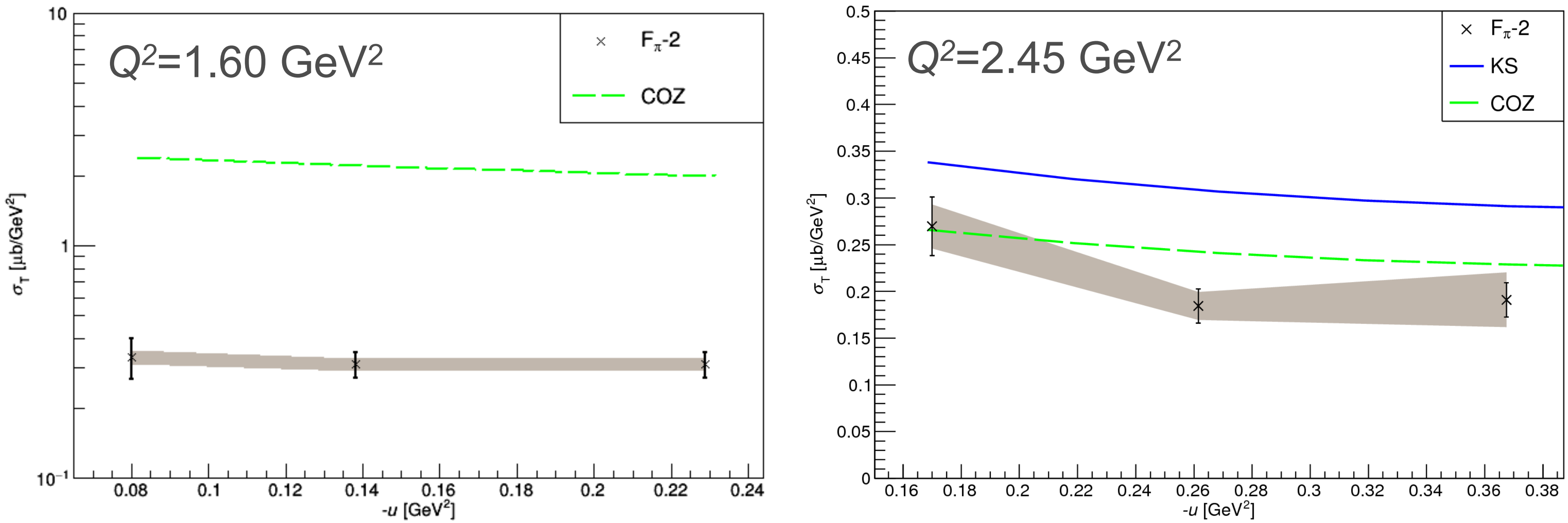
# Partonic Model: TDA Prediction

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




- **TDA prediction undershoots data by a factor of 7 at $Q^2$=1.60, but has impressive agreement with data at $Q^2$ =2.45 GeV$^2$**
  - *A true prediction, calculation made 2 years before data analysis was completed.*
  - TDA model also has good agreement with new CLAS $\pi^+$ backward angle data for $Q^2$>2.50 GeV$^2$ [K. Park, et al., PLB **780**(2018)340].
  - TDA expected to dominate for $Q^2$: >10 GeV$^2$, but some indications that TDA factorization scheme may begin to apply as soon as $Q^2$=2 GeV$^2$.

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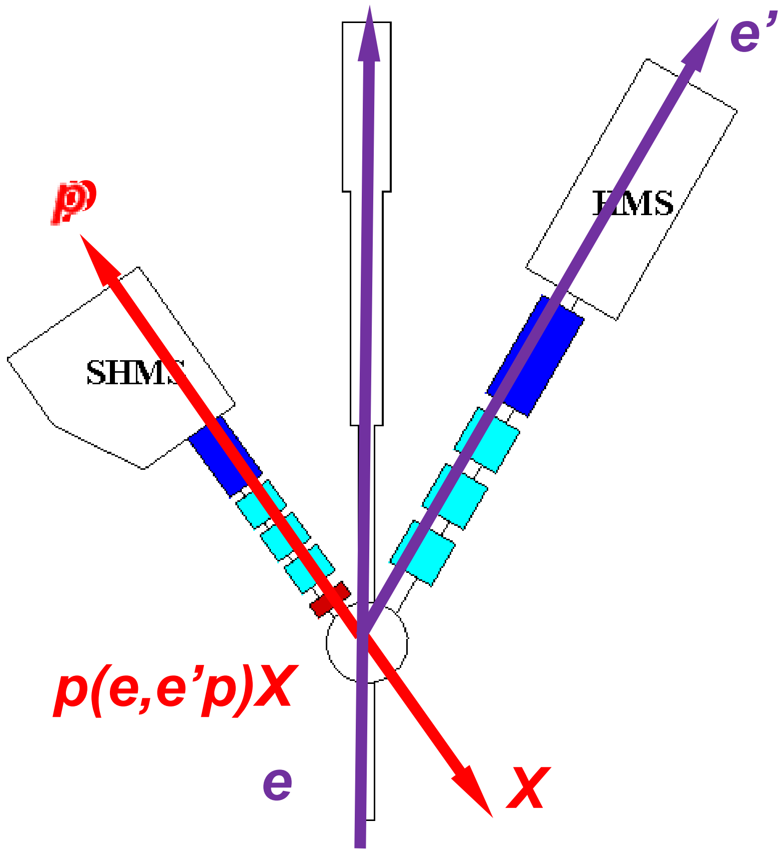
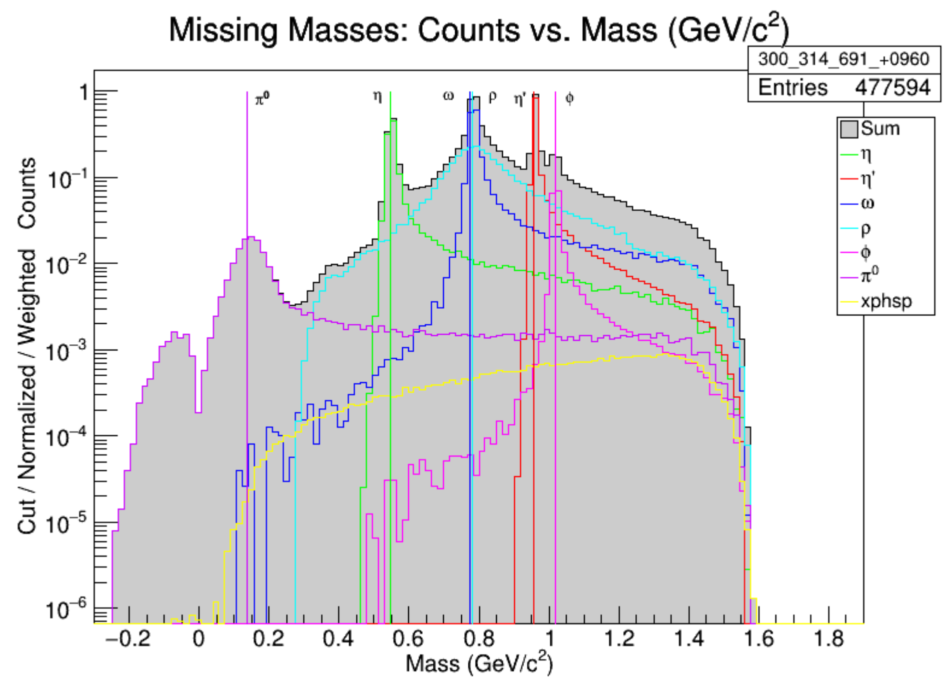
# Future Backward Meson Production Opportunities




Simulation at $Q^2$=3.00 $W$=3.14 $x$=0.25 $\varepsilon$=0.69




Plot by: M. Hladun, URegina BSc Hons (2018)

- **Upcoming Jefferson Lab 12 GeV experiments**
  - $K^+$ L/T–experiment (E12–09–011):
    - Backward angle $\eta$, $\omega$, $\rho$, $\eta'$, ϕ will be obtained parasitically
    - Scheduled for Aug 22–Dec 19, 2018
  - Large ϕ Emission Angle Experiment at CLAS: E12–12–007
  - LOI (2018): **Backward $\pi^0$** production at Hall C
- Backward–angle program with PANDA @ FAIR–GSI

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# Mandelstam variables (*s*,*t*,*u*-channels)

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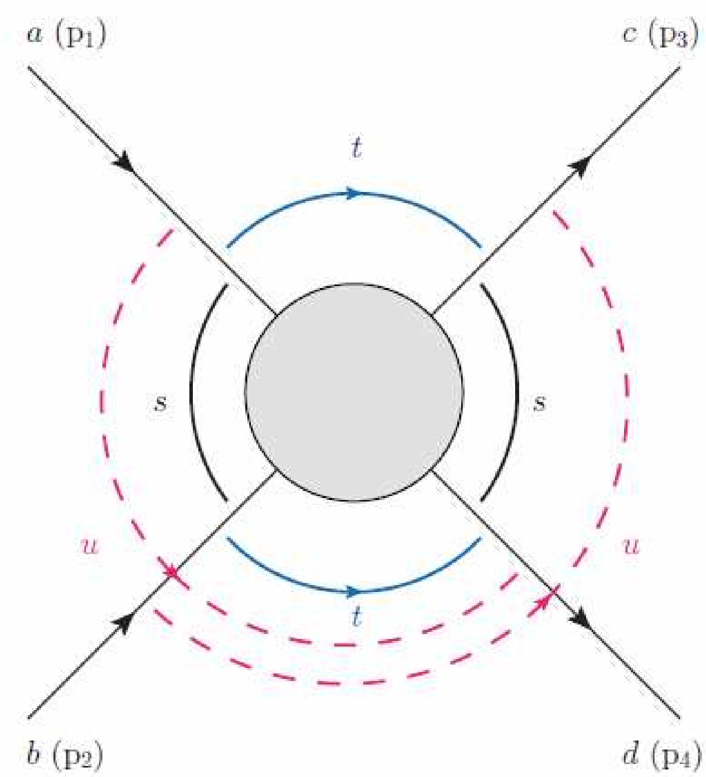


$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$

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

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

***s***: invariant mass of the system

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

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

***t*-channel*: -t ~ 0*, after interaction**
- **Target: stationary,**
- **Meson: forward**
- **Measure of how forward could the meson go.**

***u*-channel: *-u~0,* after interaction**
- **Target: forward**
- **Meson: stationary**
- **Measure of how backward could the meson go**

# Systematic Uncertainties

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| Correction | Uncorrelated (Pt-to-Pt) (%) | $\epsilon$ uncorr. $u$ corr. (%) | Correlated (scale) (%) | Section |
|---|---|---|---|---|
| HMS Cherenkov | | | 0.02 | Sec. 3.6.3 |
| HMS Aerogel | | | 0.04 | Sec. 5.3.7 |
| SOS Calorimeter | | | 0.17 | Sec. 3.6.4 |
| SOS Cherenkov | | | 0.02 | Sec. 3.6.3 |
| HMS beta | 0.4 | | | Sec. 5.1.2 |
| HMS Tracking | | 0.4 | 1.0 | Sec. 5.3.3 |
| SOS Tracking | | 0.2 | 0.5 | Sec. 5.3.3 |
| HMS Trigger | | 0.1 | | Sec. 3.7 |
| SOS Trigger | | 0.1 | | Sec. 3.7 |
| Target Thickness | | 0.3 | 1.0 | Secs. 3.5.2, 5.3.5 |
| CPU LT | | 0.2 | | Sec. 5.3.2.2 |
| Electronic LT | | 0.1 | | Sec. 5.3.2.1 |
| Coincidence Blocking | | | 0.1 | Sec. 5.3.6 |
| $d\theta$ | 0.1 | 0.7-1.1 | | Ref. [3] |
| $dE_{\rm Beam}$ | 0.1 | 0.2-0.3 | | Ref. [3] |
| $dp_e$ | 0.1 | 0.1-0.3 | | Ref. [3] |
| $d\theta_p$ | 0.1 | 0.2-0.3 | | Ref. [3] |
| PID | | 0.2 | | Sec. 5.1.1 |
| Beam Charge | | 0.3 | 0.5 | Sec. 3.4 |
| Radiative Correction | | 0.3 | 1.5 | Sec. 4.1.4 |
| Acceptance | 1.0 | 0.6 | 1.0 | Sec. 3.8 |
| Proton Interaction | | | 0.7 | Sec. 5.3.9 |
| Background Fitting Limit | 2.0 | 0.8 | 0.8 | Secs. 6.5.3, 6.10.2 |
| $\omega$ Integration Limit | 1.7 | 1.0 | 0.3 | Secs. 6.6, 6.10.2 |
| Model Dependence | 0.7 | | | Secs. 6.2.1, 6.10.2 |
| Total | 2.9 | 1.7-2.0 | 2.6 | |

- **Unseparated $\sigma$**
  - **Statistical**
  - **Systematic Error**
    - **Uncorrelated Error**
    - **$\epsilon$ uncorrelated $u$ correlated**
    - **Scale error**
- **Model dependent Error to the separated (Scale error)**
  - **Parameterization**
  - **$\phi$ limits**
  - **$u$ limits (small contribution)**