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

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Scientific Motivation

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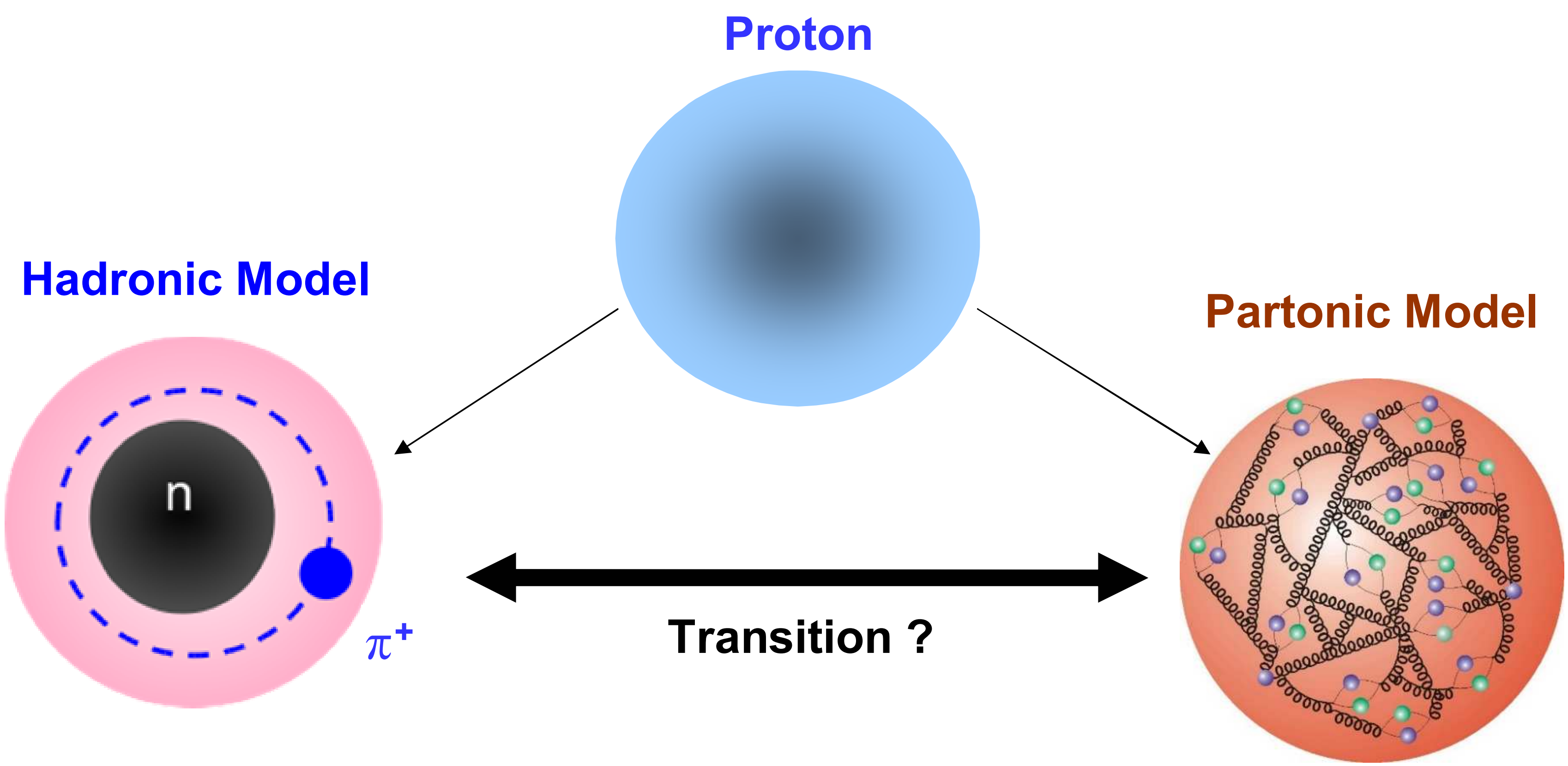
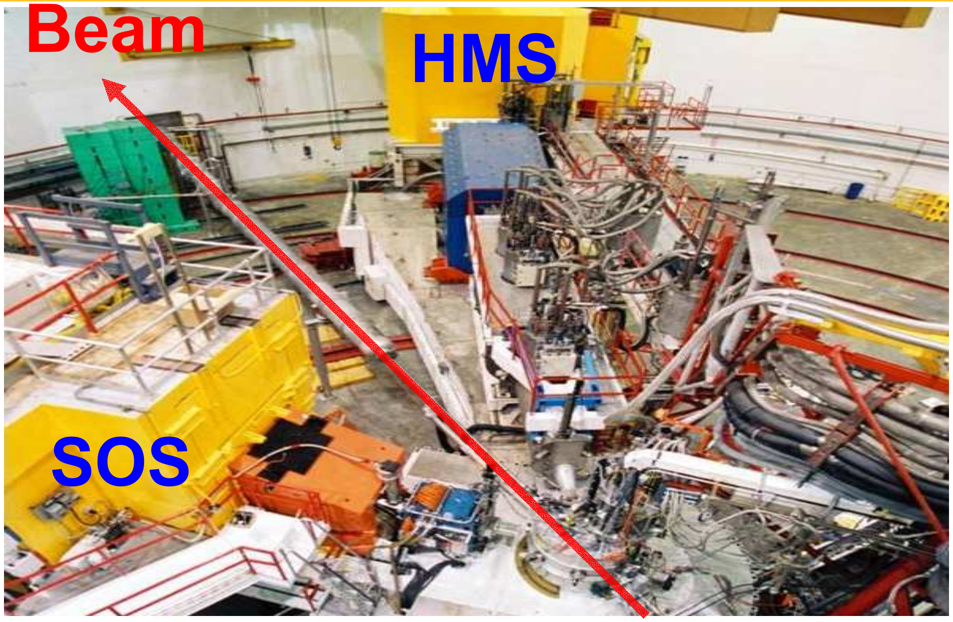
The Key Science Problem:

- 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

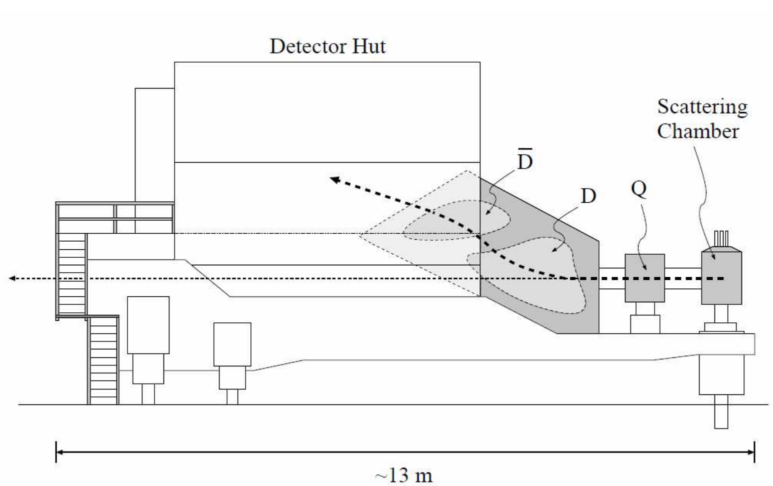
- **Objective:**
  - Establish a new experimental approach
    - Backward–angle (*u*–channel) observables
    - L/T separation



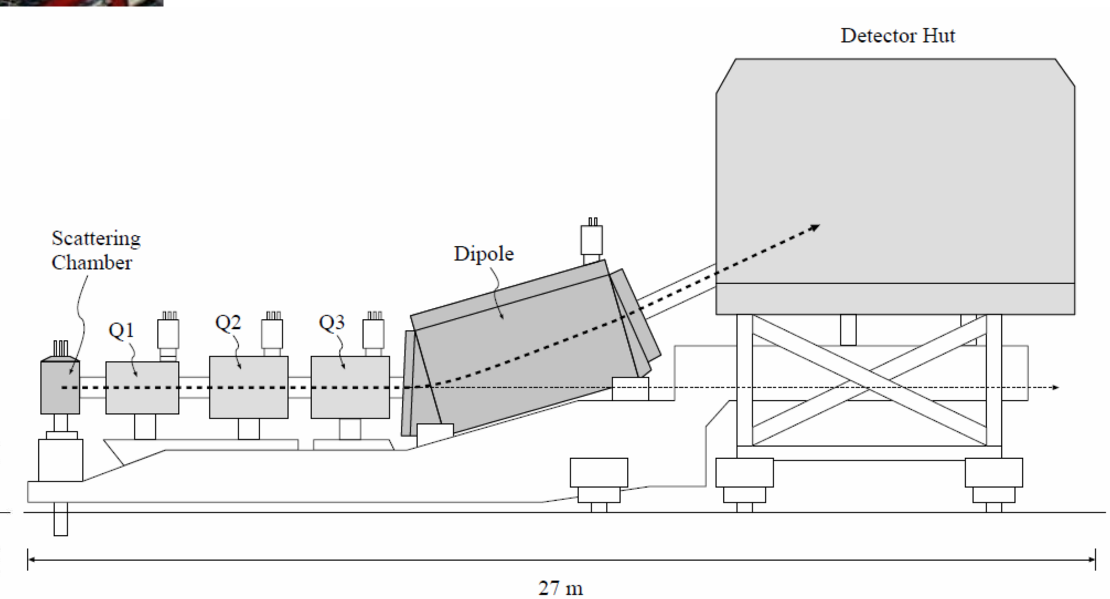
Jefferson Lab Hall C Experimental Setup



- **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 π^+ vs *u*–Channel ω Production

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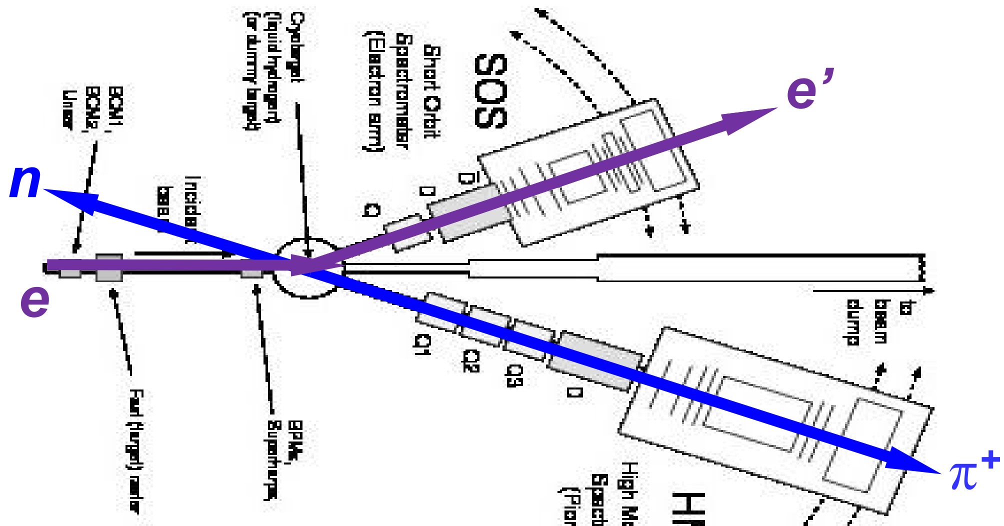
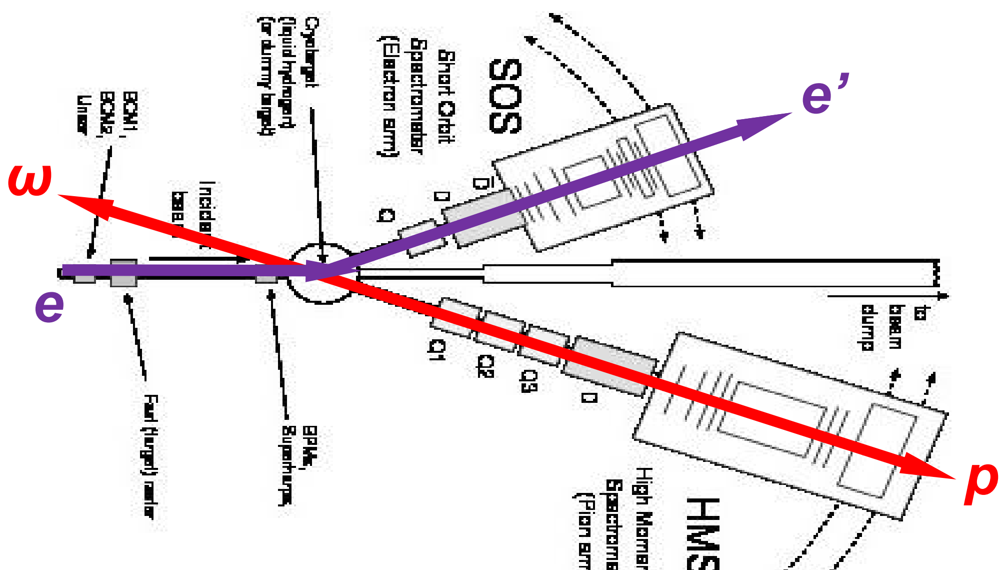
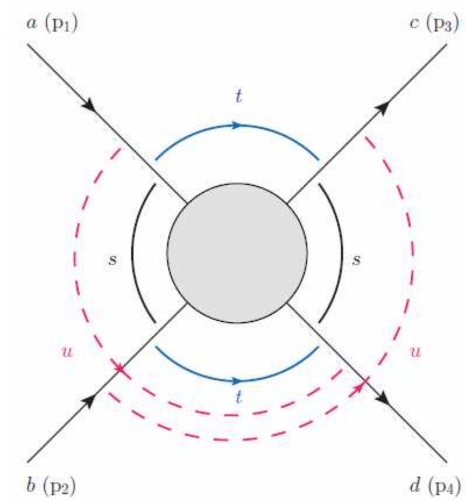


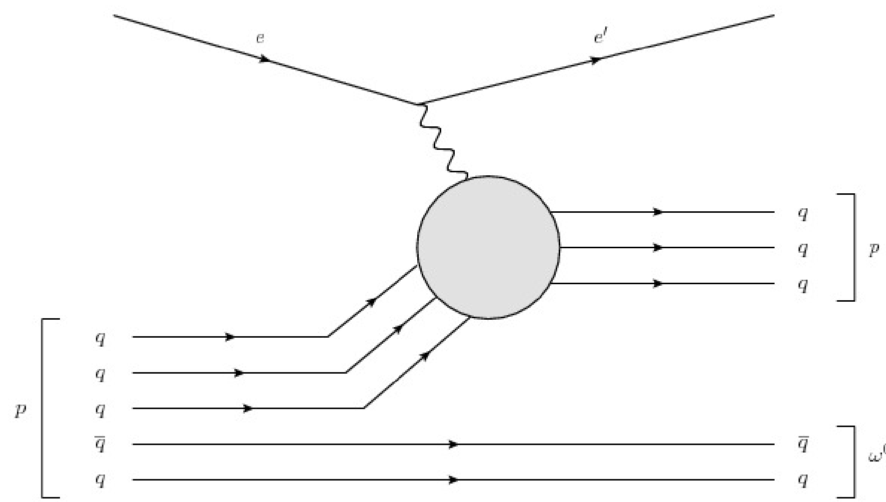
$p(e,e'\pi^+)n$



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



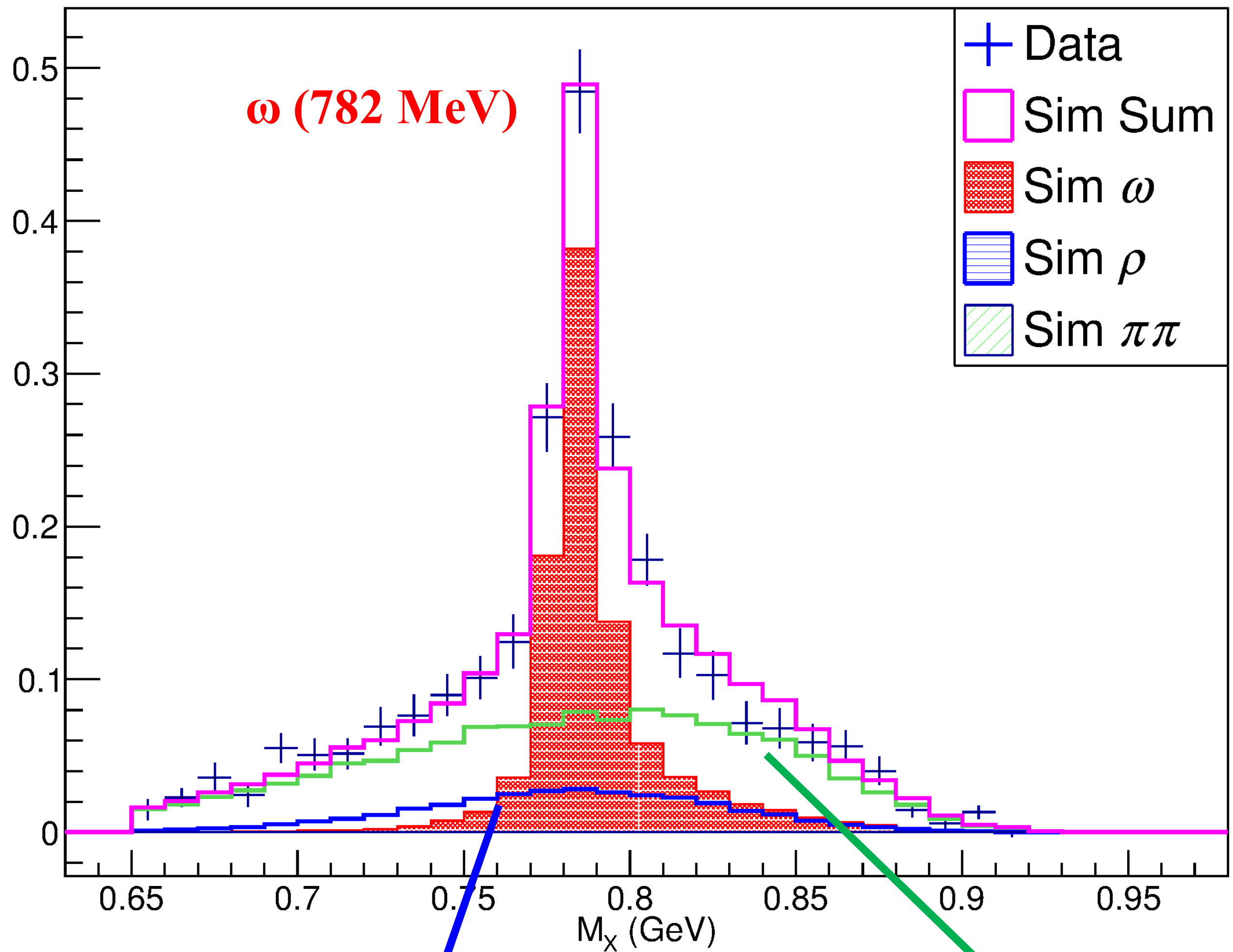
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$u = (p_1 - p_4)^2 = (p_2 - p_3)^2$$



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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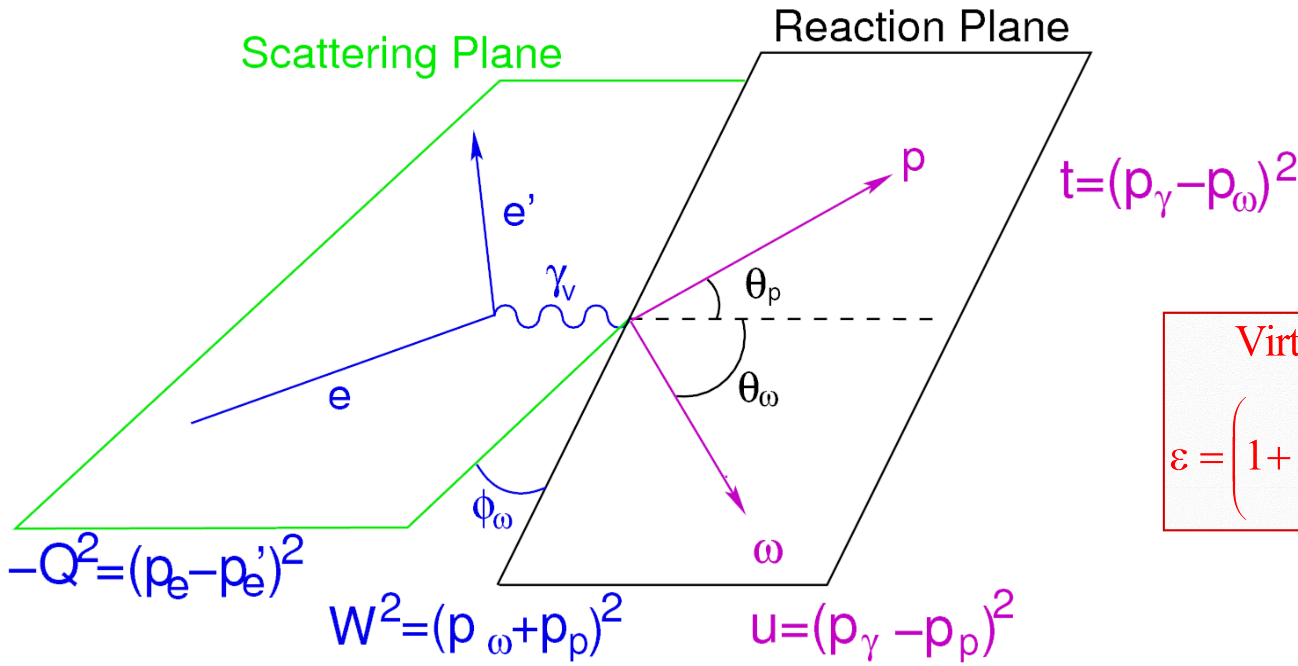
Rosenbluth (L/T/LT/TT) Separation



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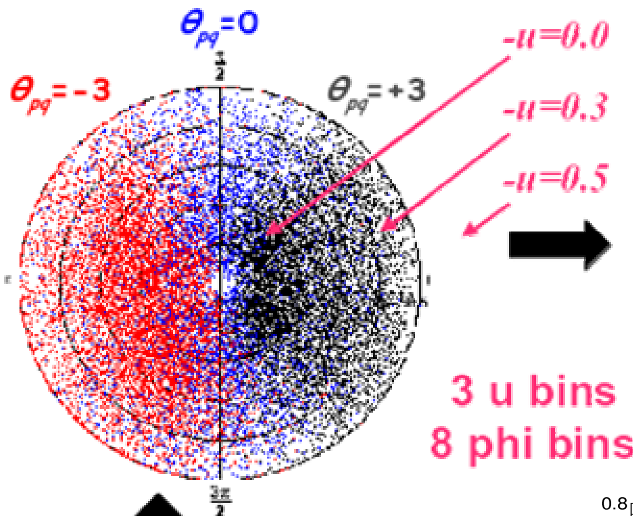
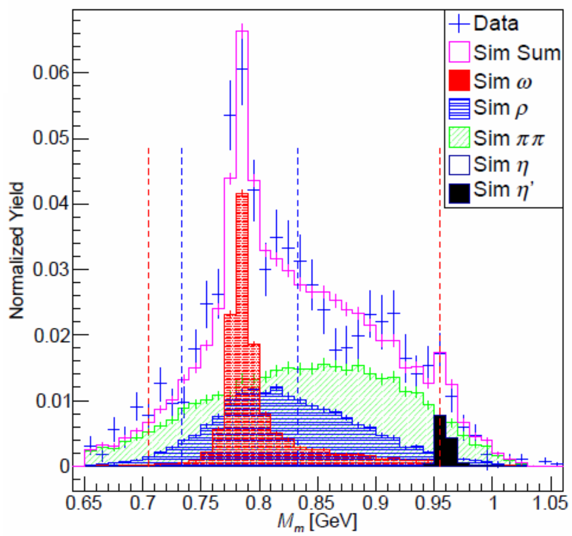
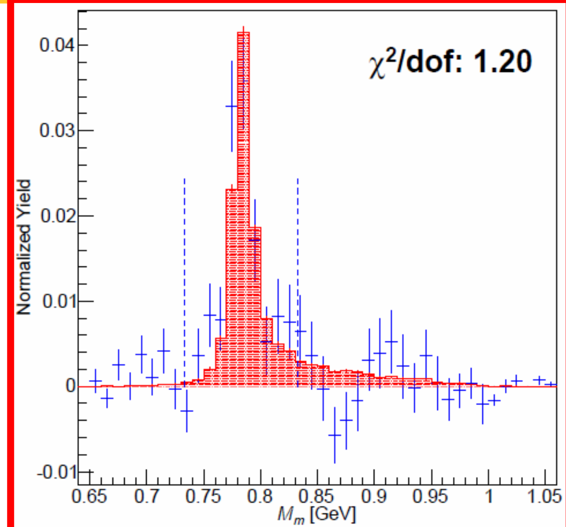
Improve φ coverage by taking data at multiple HMS angles, $-3^{o}<\theta_{pq}<+3^{o}$.



3 u bins
8 phi bins



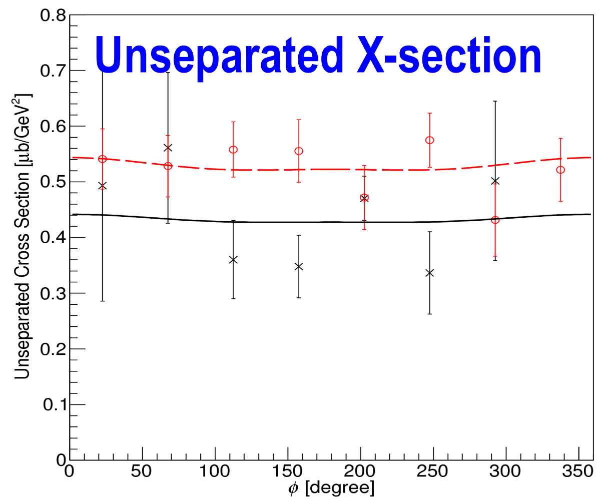


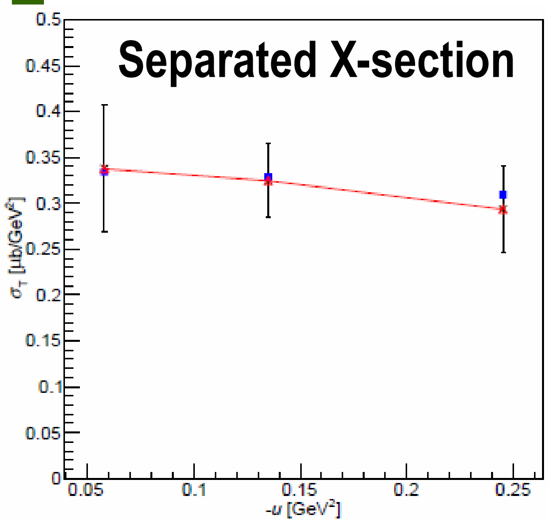
$$R=\frac{Y_{Exp}-Y_{\rho\ sim}-Y_{Xspace\ sim}}{Y_{\omega\ sim}}$$

Combine ratios for settings together, propagating errors accordingly.

$$\frac{d^2\sigma}{dtd\varphi}_{EXP}=\boxed{R}\,\frac{d^2\sigma}{dtd\varphi}_{SIMC}$$

Empirical Model





Extract L,T,LT,TT via simultaneous fit

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

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

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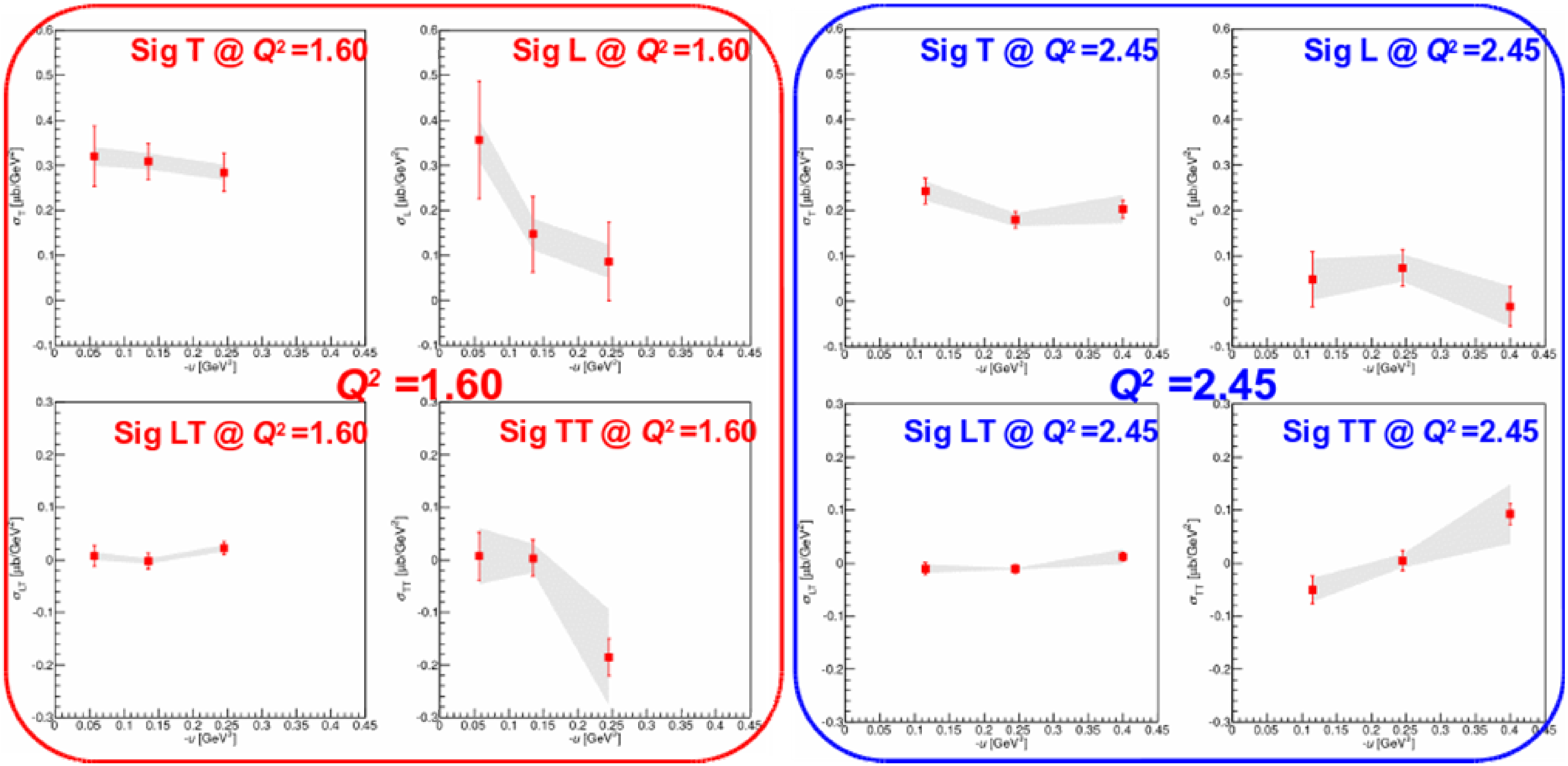
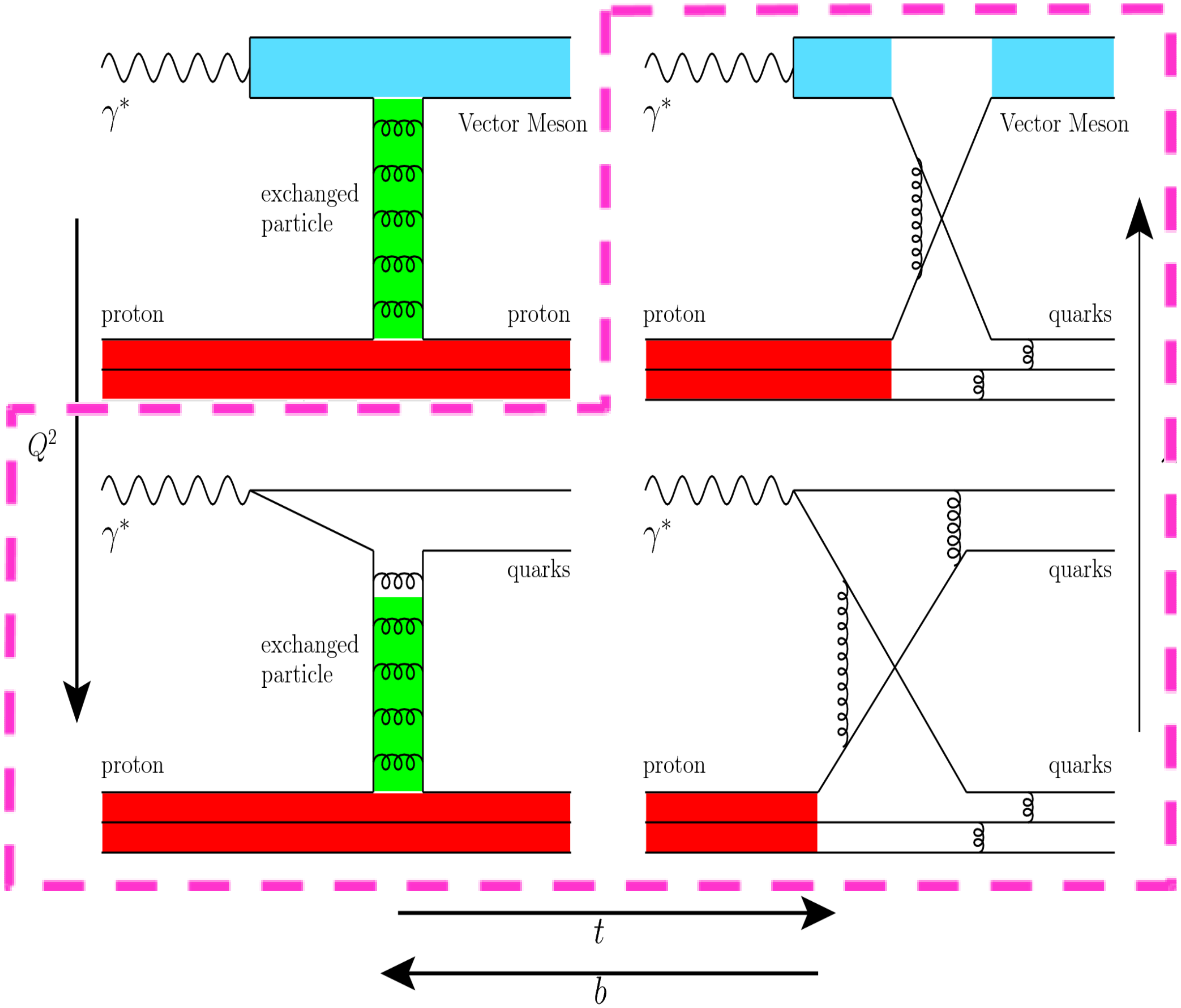


Observations:

- σ_T falls slowly with $-u$; σ_L falls faster.
- σ_{LT} is small; σ_{TT} has sign flip for different Q^2 values.

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

Hadronic Model: Evolution of 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**

Evolution of the Proton Structure

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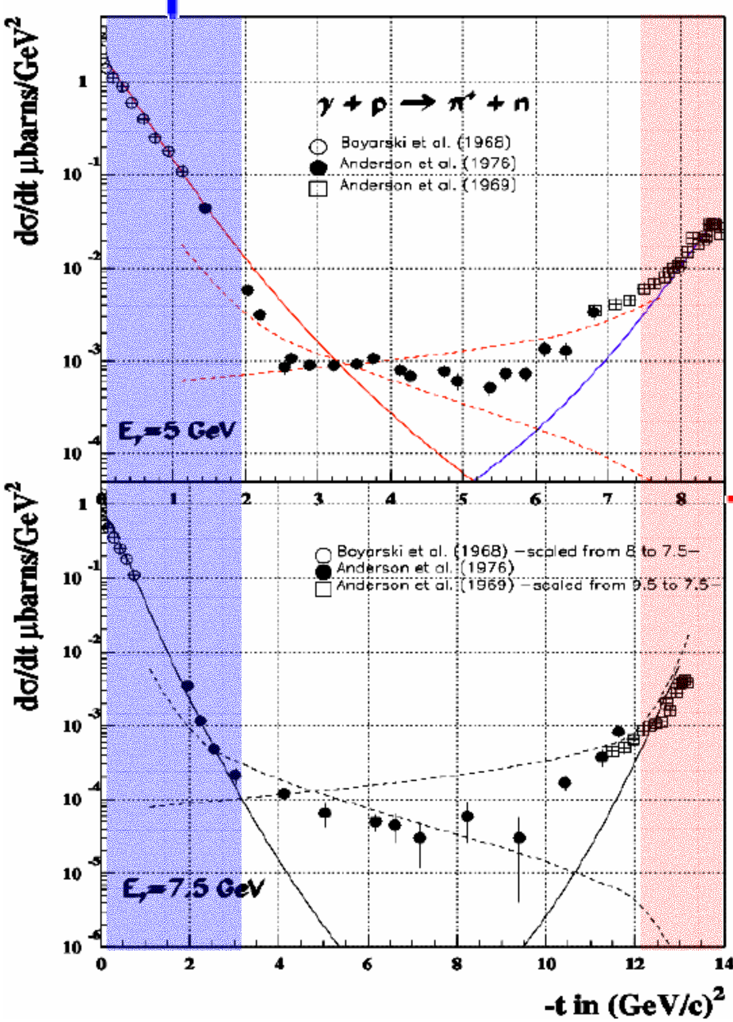
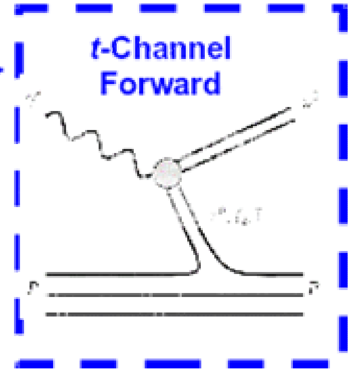
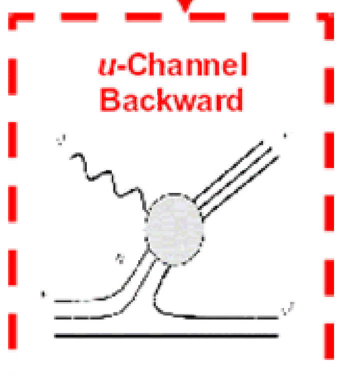
Hadronic Model: Regge Model by JM Laget

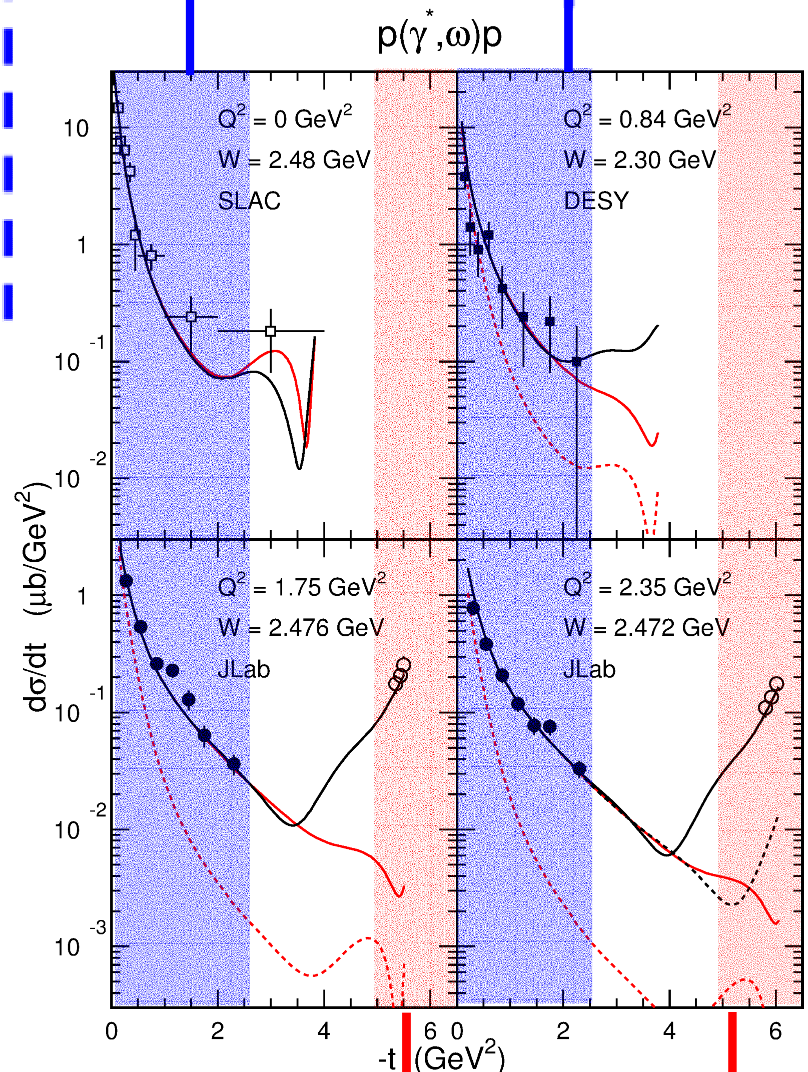
M. Guidal, J.-M. Laget, M. Vanderhaeghen, PLB **400**(1997)6

J.-M. Laget, Private Communication (2018)









Soft structure → Hard → Soft transition!

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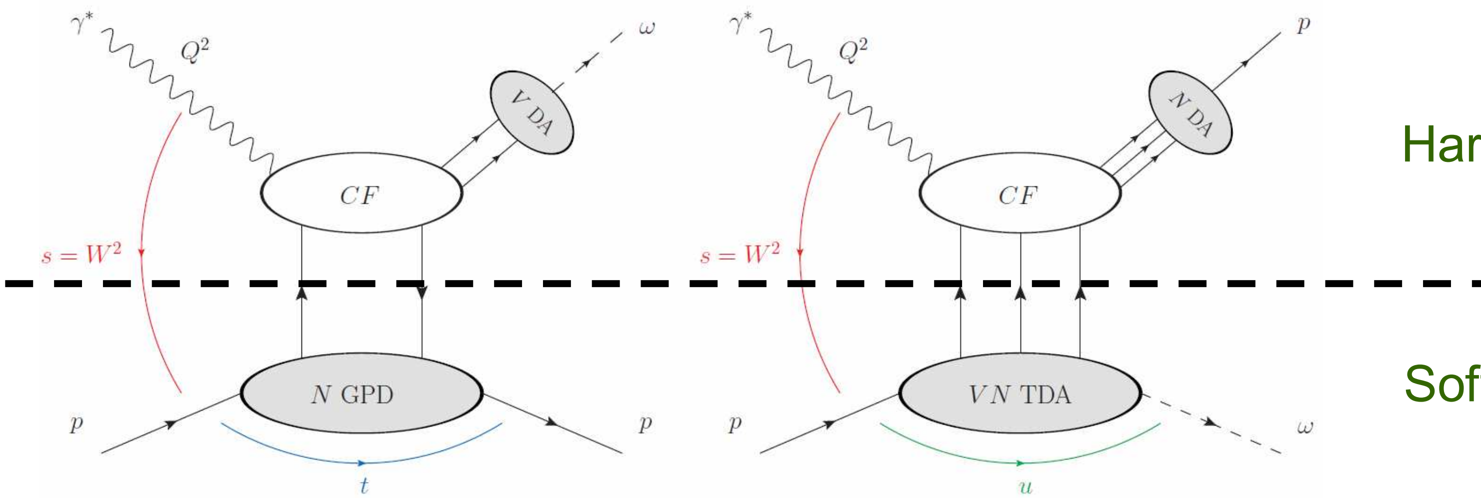
Partonic Model: TDA and Factorization



- **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 σ_T for fixed Bjorken x.

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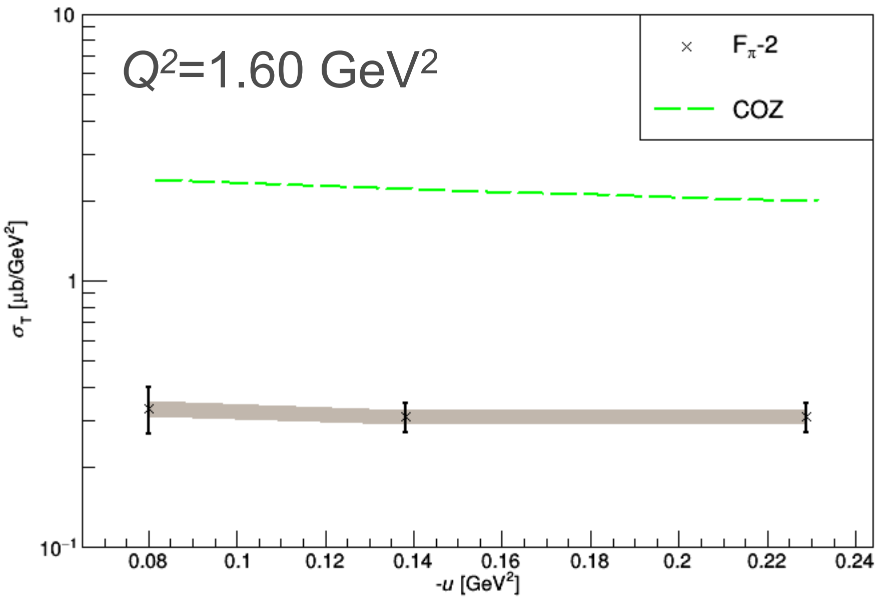
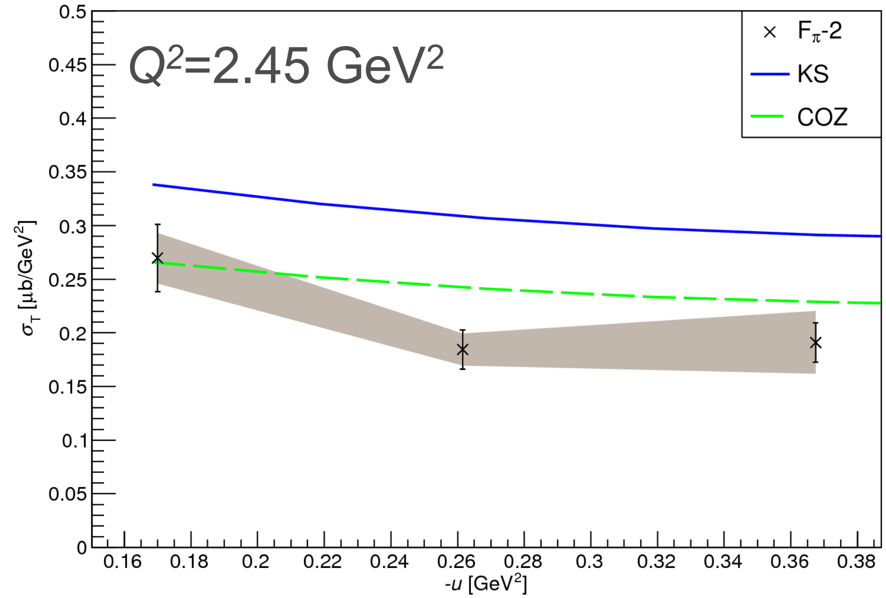
Partonic Model: TDA Prediction

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 π^+ 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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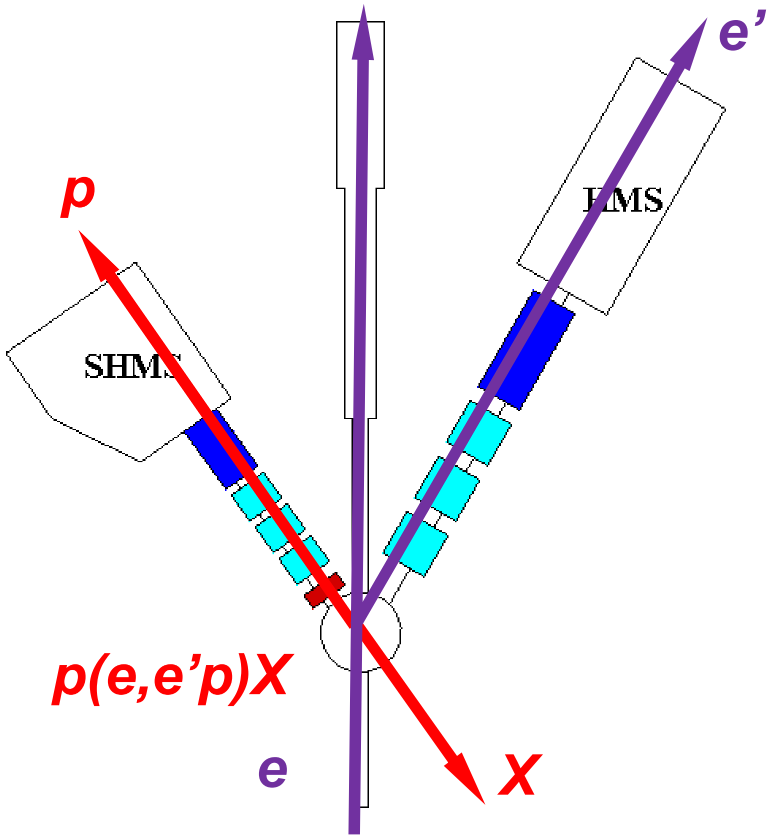
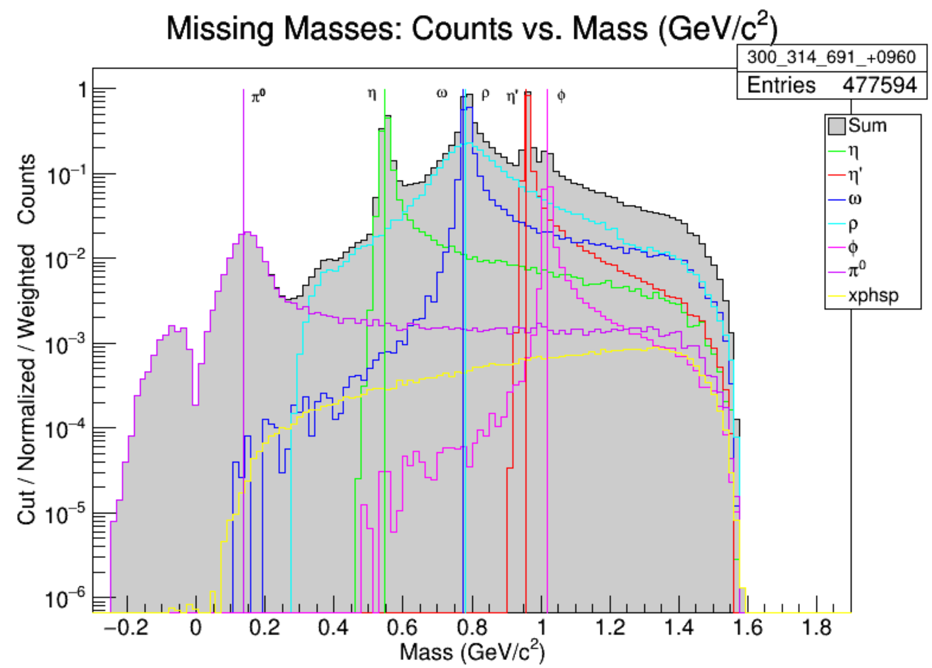
Future Backward Meson Production Opportunities



Simulation at Q^2=3.00 W=3.14 x=0.25 ε=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 η, ω, ρ, η', 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 π^0** production at Hall C
- Backward–angle program with PANDA @ FAIR–GSI

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Unseparated Cross Sections (Money Plot)

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

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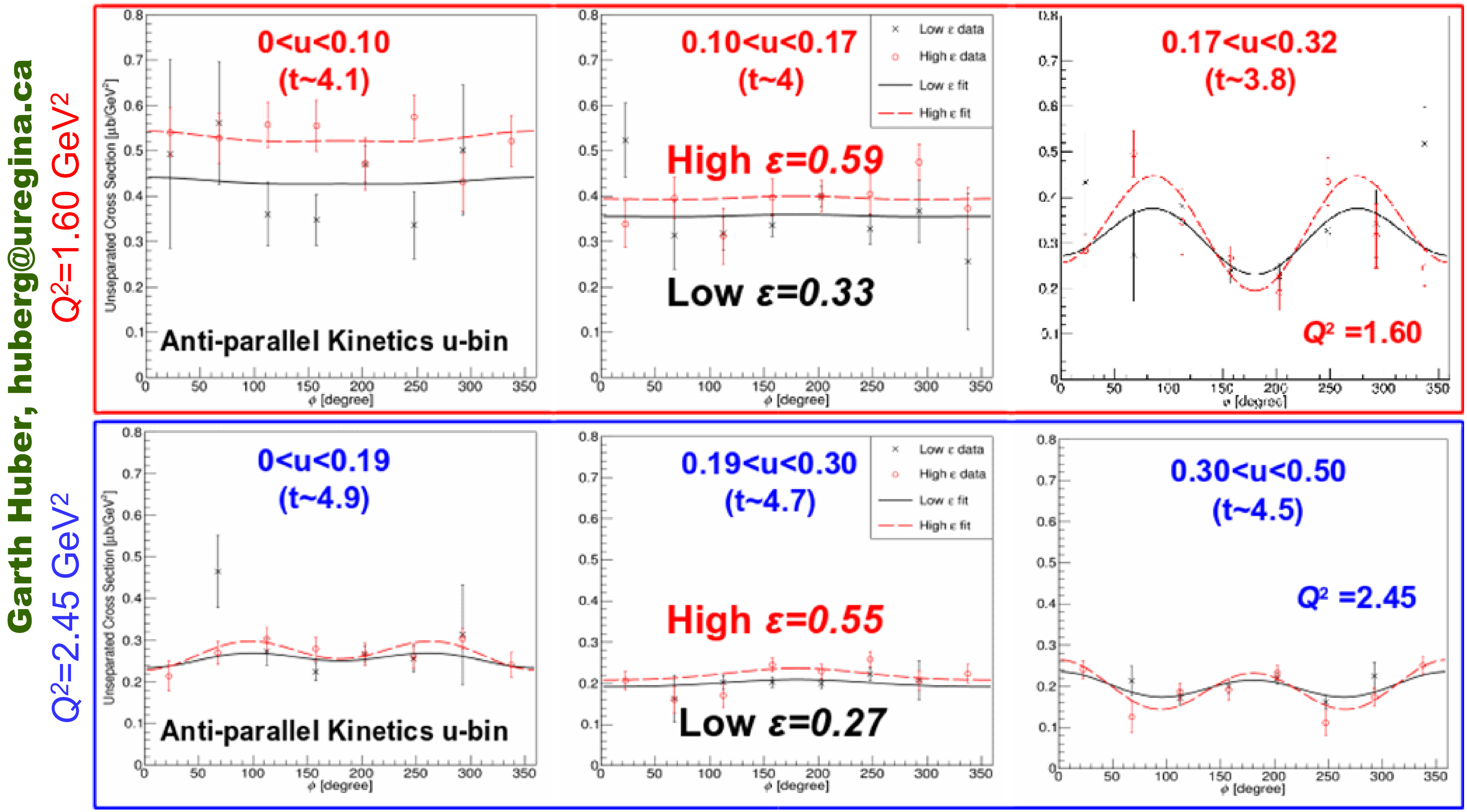
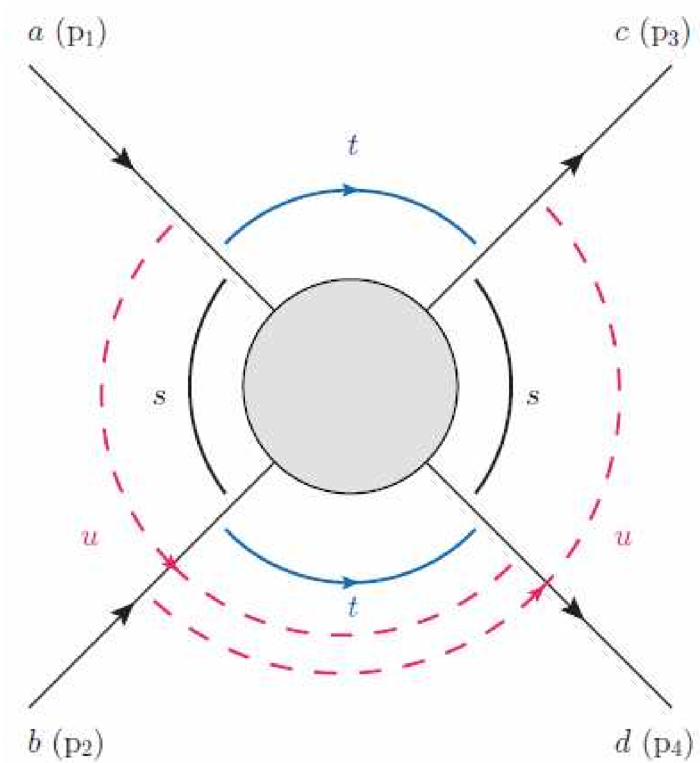


Mandelstam variables (*s*,*t*,*u*-channels)



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

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

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

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**

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Systematic Uncertainties

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Correction	Uncorrelated (Pt-to-Pt) (%)	ϵ 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_{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
ω 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 σ**
  - **Statistical**
  - **Systematic Error**
    - **Uncorrelated Error**
    - **ϵ uncorrelated u correlated**
    - **Scale error**
- **Model dependent Error to the separated (Scale error)**
  - **Parameterization**
  - **ϕ limits**
  - **u limits (small contribution)**