Probing Hadron Structure with Exclusive Pion Production Reaction at Jefferson Lab

Muhammad Junaid
Department of Physics
University of Regina, Canada

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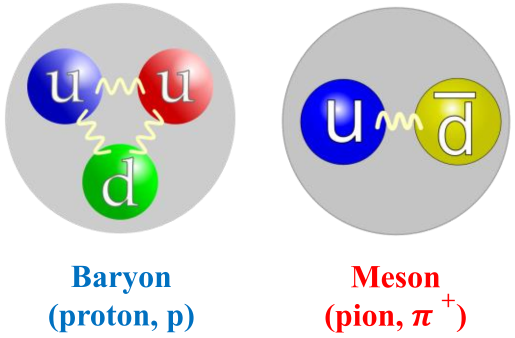
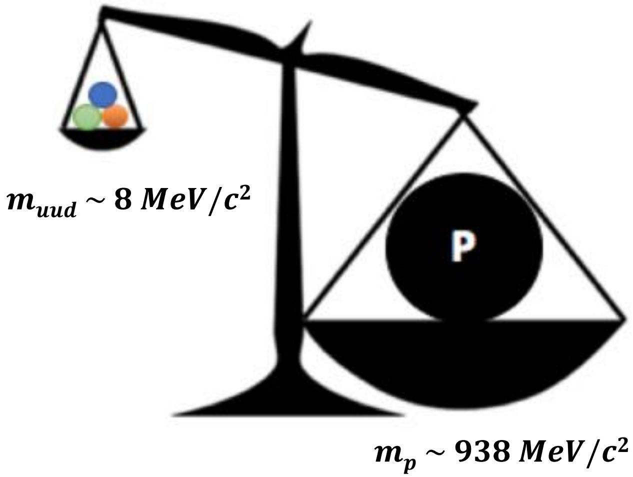
Scientific Motivation

- Hadrons are classified into two groups:
  - **Baryons** combination of quark-quark-quark states (qqq or $\overline{q}\overline{q}\overline{q}$).
  - **Mesons** combination of quark-antiquark states ($q\overline{q}$).

- Interaction of quarks and gluons is successfully described by **Quantum Chromodynamics (QCD).**
- **But unable to construct the quantitative description of hadrons in terms of the underlying constituents, quarks and gluons.**





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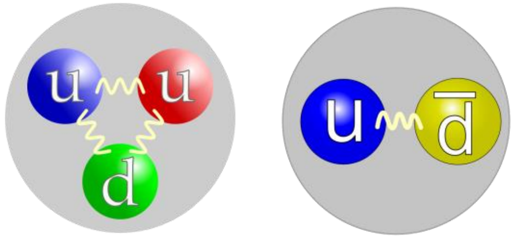
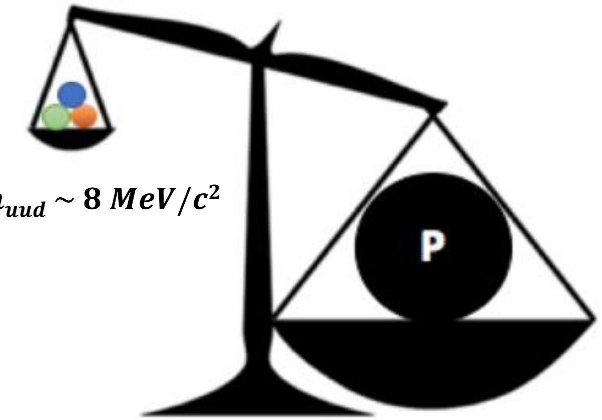
- **Pion** is the lightest meson and gives an ideal testing ground for our understanding of the bound $q\bar{q}$ hadronic system.
- **Form factor** ($F(Q^2)$) is an important observable that can be studied to understand the internal structure of hadrons by describing the transverse spatial position of partons within hadrons.

- **Measuring the pion form factor at various Q^2 (up to $8.5 GeV^2$) checks the validity of QCD-based theories, including the transition region between perturbative and non-perturbative approaches.**





Pion Form Factor Measurement

- Above $Q^2 > 0.3\text{GeV}^2$, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e, e'\pi^+)n$

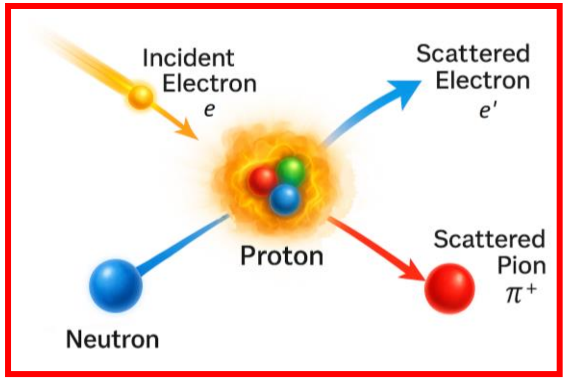
- Indirect measurement – Form factor extraction requires a model.

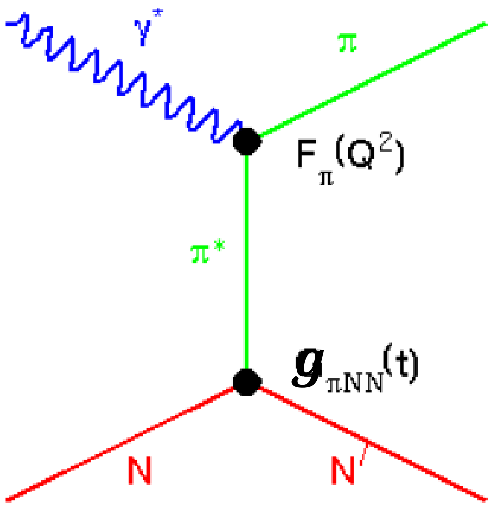
- Need to extract σ_L from the total cross-section.

- As an illustration of how σ_L connects to $F_\pi^2(Q^2, t)$, we consider a simple Born Term Model;

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_\pi^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

- In reality, we use Regge base model such as VGL, YCK and PKT Models for $F_\pi^2(Q^2, t)$ extraction.





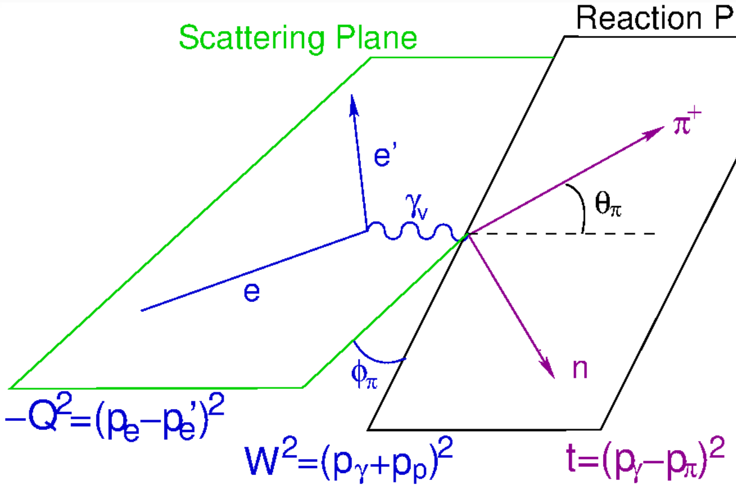
Rosenbluth Separation

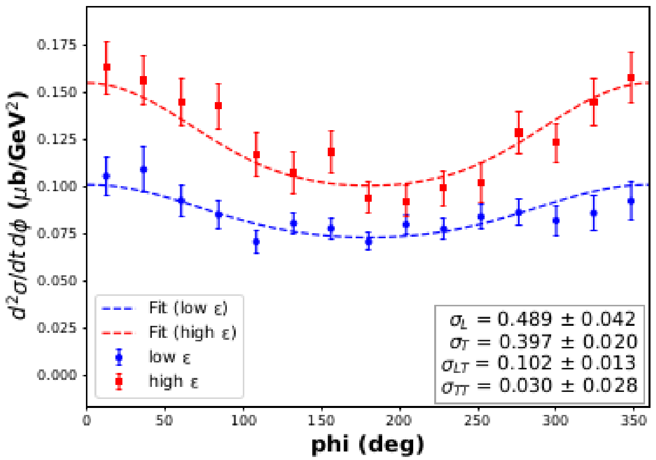
- **Rosenbluth separation required to isolate σ_L for L/T separation.**
- **The Physical cross-section for the electroproduction process is given by;**

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

- Here “ϵ” is polarization of virtual photon.

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





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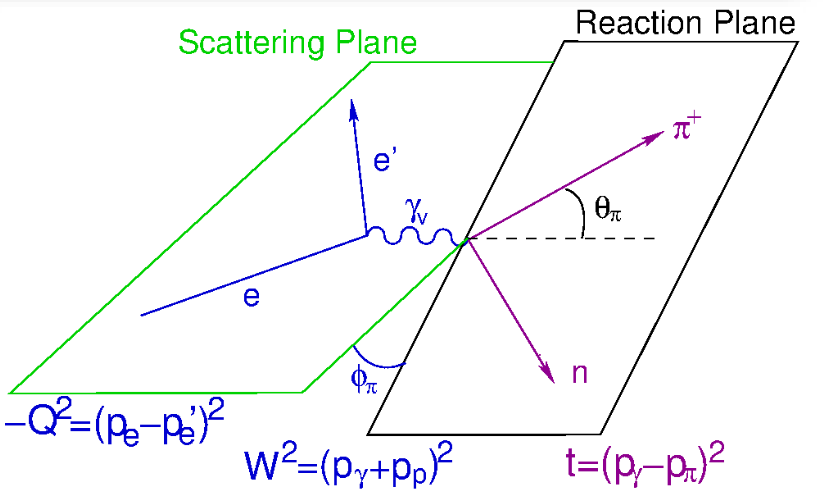

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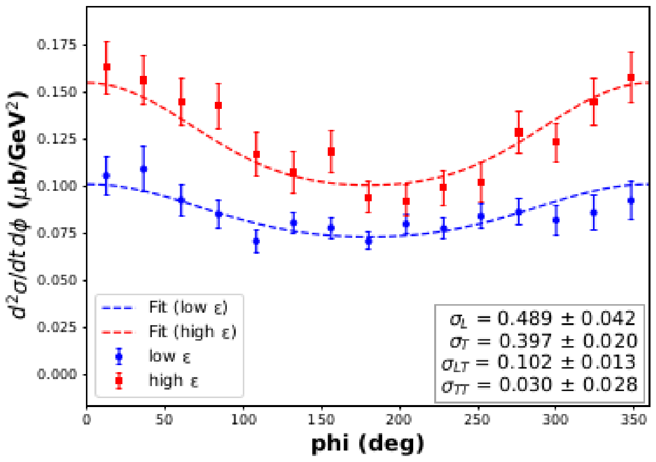
$$\epsilon = \left[1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} . \tan^2\frac{\theta_{e'}}{2}\right]^{-1}$$

- Perform two scattering measurements with different beam energies "E_e" to vary "ϵ" and separate different cross-section terms.

- Careful control of point-to-point systematics crucial, $^1/_{\Delta\epsilon}$ error amplification in σ_L.

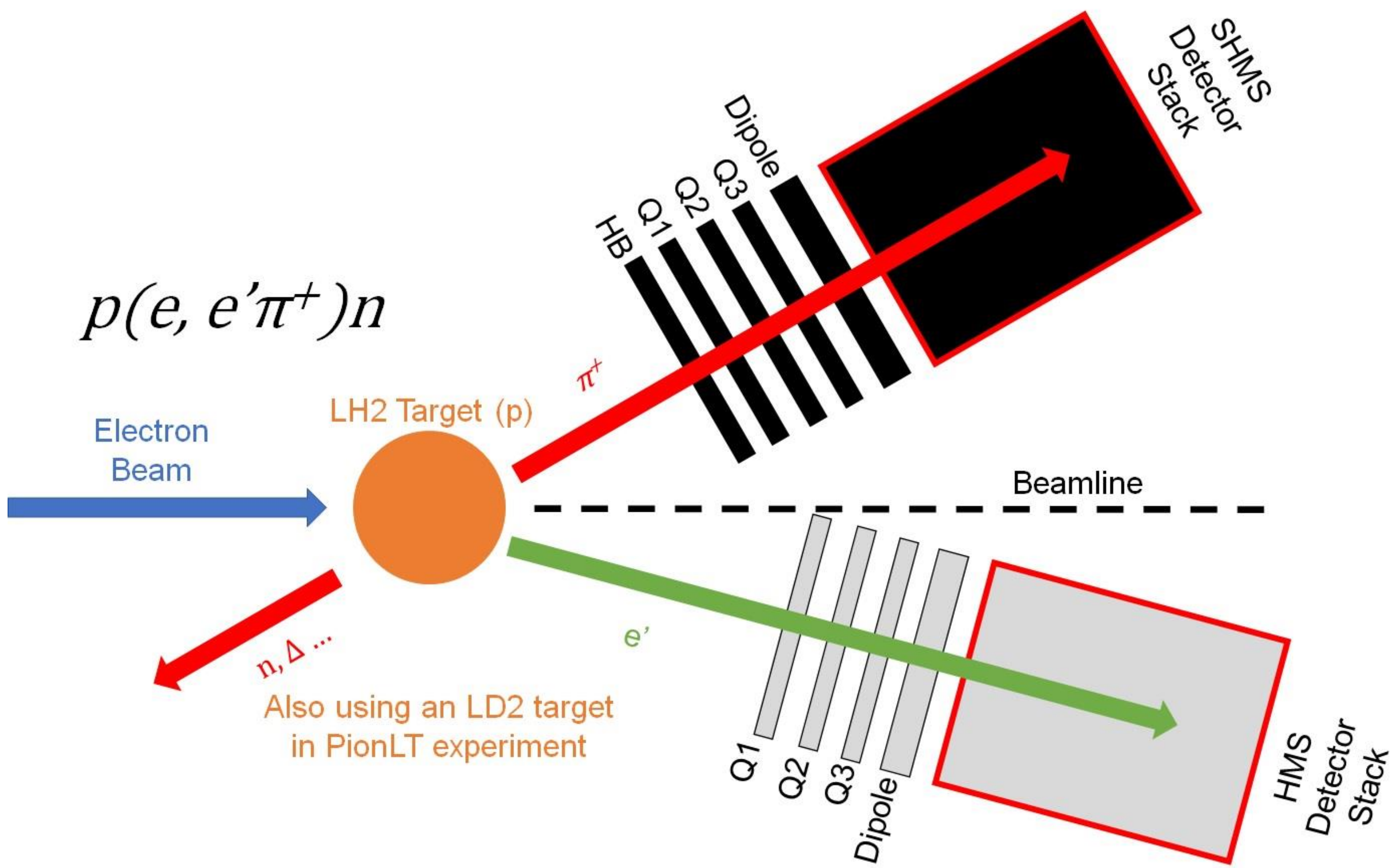
$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2}\frac{1}{\sigma_L}\sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}$$

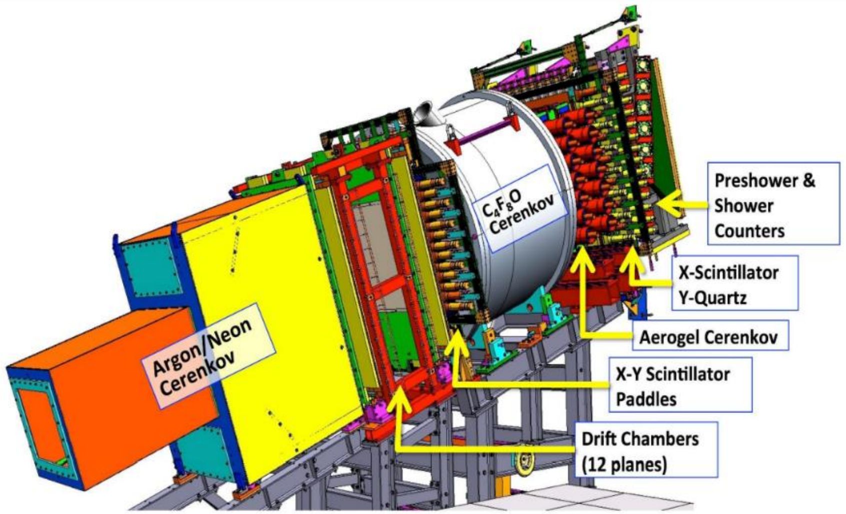
Where "$\sigma_1 = \sigma_T + \epsilon_1\,\sigma_L$" and "$\sigma_2 = \sigma_T + \epsilon_2\,\sigma_L$".

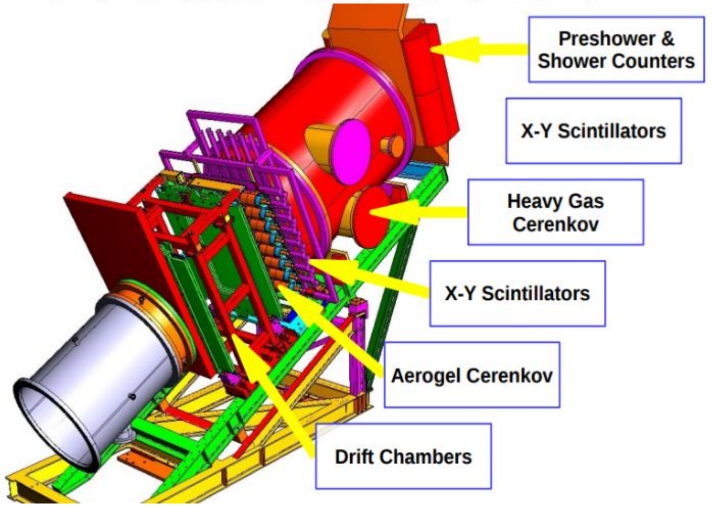


- Careful attention must be paid to systematic studies such as spectrometer acceptance, kinematics, efficiencies, etc.

Schematic view of Hall C Spectrometers





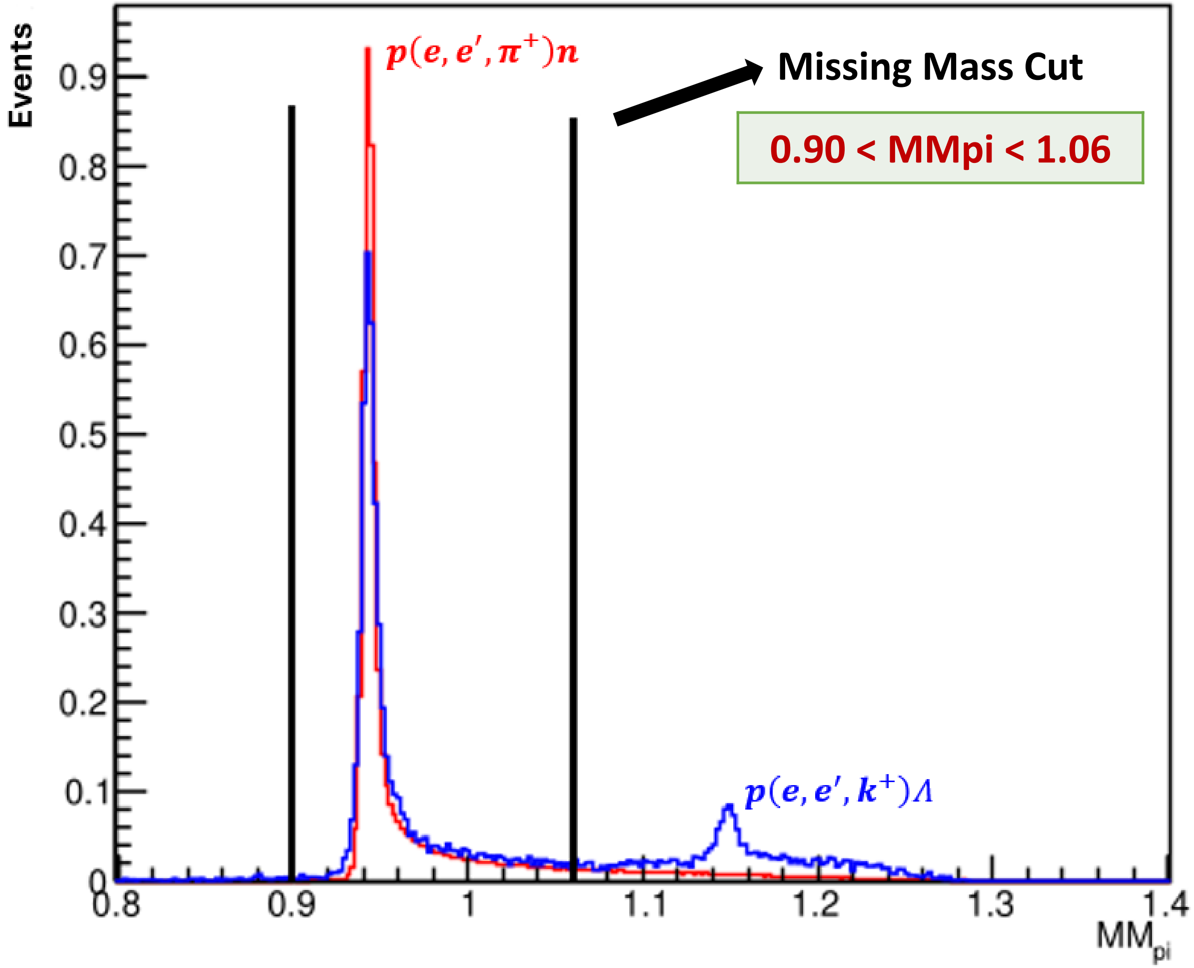


Reconstruction of Missing Particle

- Selected electrons in HMS and pions in the SHMS.
- Missing Mass reconstruction

$$M_m = \sqrt{(E_e + m_P - E_{e'} - E_{\pi^+})^2 - (p_e - p_{e'} - p_{\pi^+})^2}$$

- Blue represents the experimental data missing mass plot.
- Red represents the Monte Carlo missing mass plot.
- To eliminate the remaining background, a missing-mass cut was applied to both the Monte Carlo and experimental data.



Q^2 = 3.85 GeV^2, W = 2.62 GeV (2 epsilons)

Cross-section Measurements

- The ratio method is used to calculate the experimental cross-sections.

$$\frac{d^2\sigma}{dtd\phi}_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dtd\phi}_{SIMC}$$

- The same cuts and kinematic selection criteria were applied to both the data and the Monte Carlo.
- This technique is model-dependent.
- Requires the Monte Carlo empirical model to reproduce data.
- Only reliable if Monte Carlo reproduces the data well in both shape and normalization.

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- This technique is model-dependent.
- Requires the Monte Carlo empirical model to reproduce data.
- Only reliable if Monte Carlo reproduces the data well in both shape and normalization.

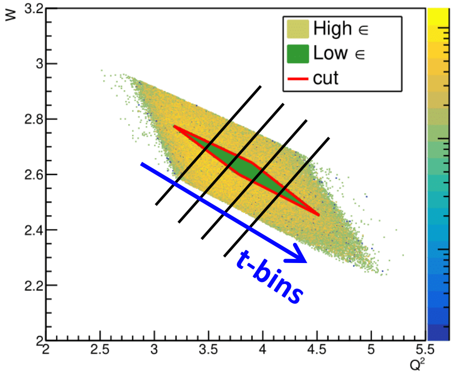
- Fit the Rosenbluth equation to extract the cross-section components.

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

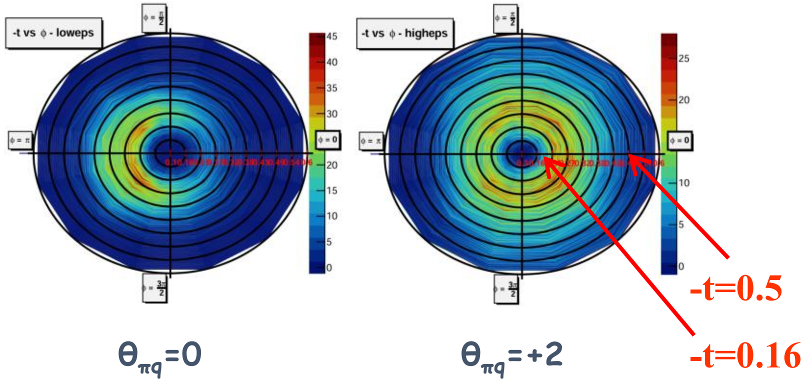
- Need to iteratively tune L/T/LT/TT empirical model until Monte Carlo reproduces experimental data.

L/T Separation Iteration Procedure

Diamond cut



Improve φ coverage by taking data at multiple π (HMS) angles, $-2^o < \theta_{\pi q} < 2^o$.



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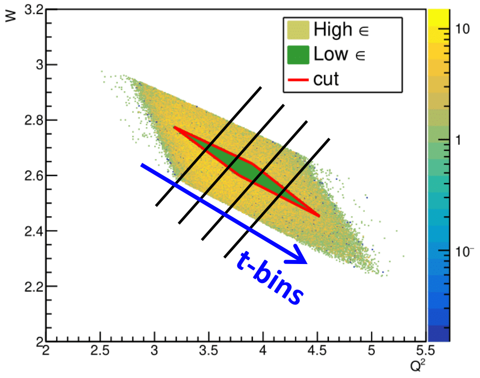

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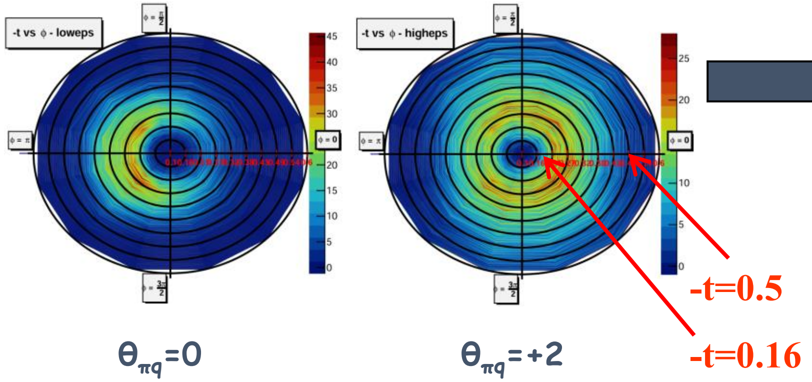


$\theta_{\pi q}=0$ $\theta_{\pi q}=+2$

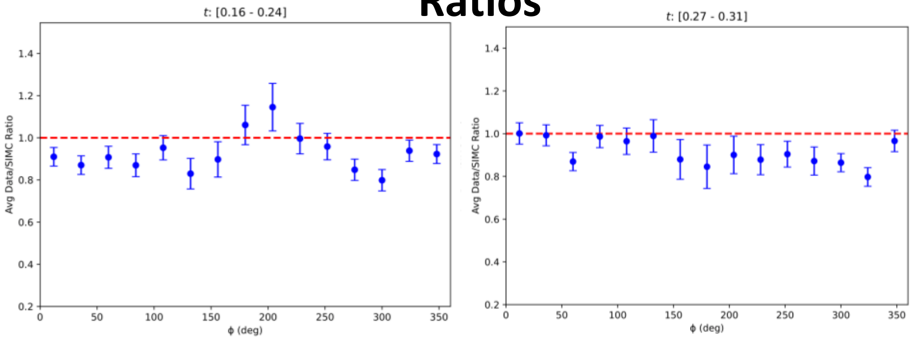
Q^2 = 3.85 GeV^2, W = 2.62 GeV (2 epsilons)

For each π HMS setting, form ratio:

$$R = \frac{Y_{EXP}}{Y_{SIMC}}$$

Combine ratios for π settings together, propagating errors accordingly.

Ratios



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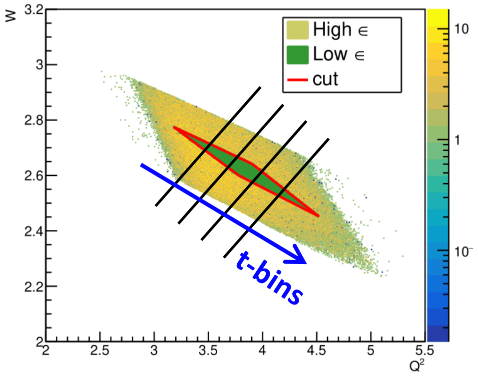

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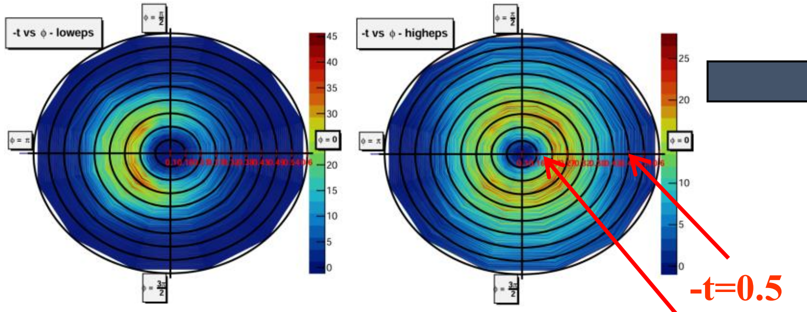

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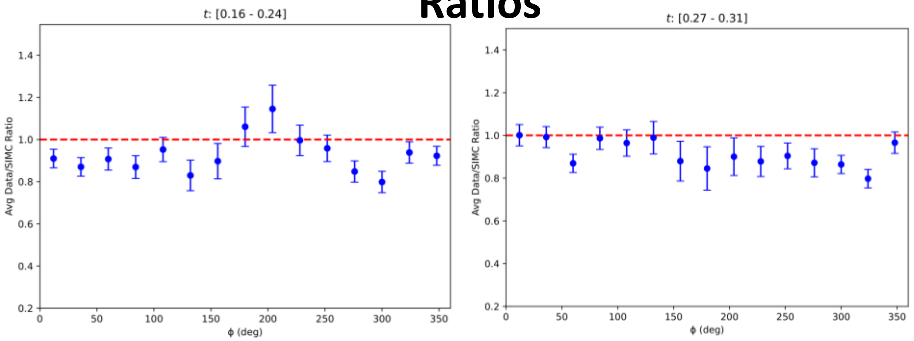
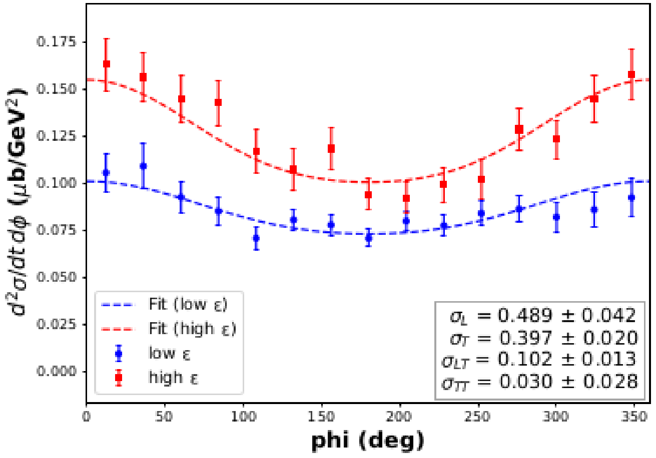


$$\left.\frac{d^2\sigma}{dtd\varphi}\right|_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\left.\frac{d^2\sigma}{dtd\varphi}\right|_{SIMC}$$

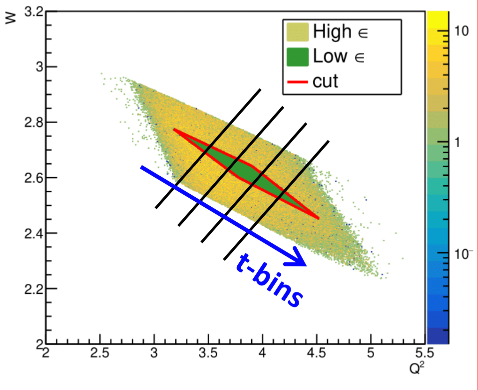
$$2\pi\frac{d\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Extract via simultaneous fit of L,T,LT,TT



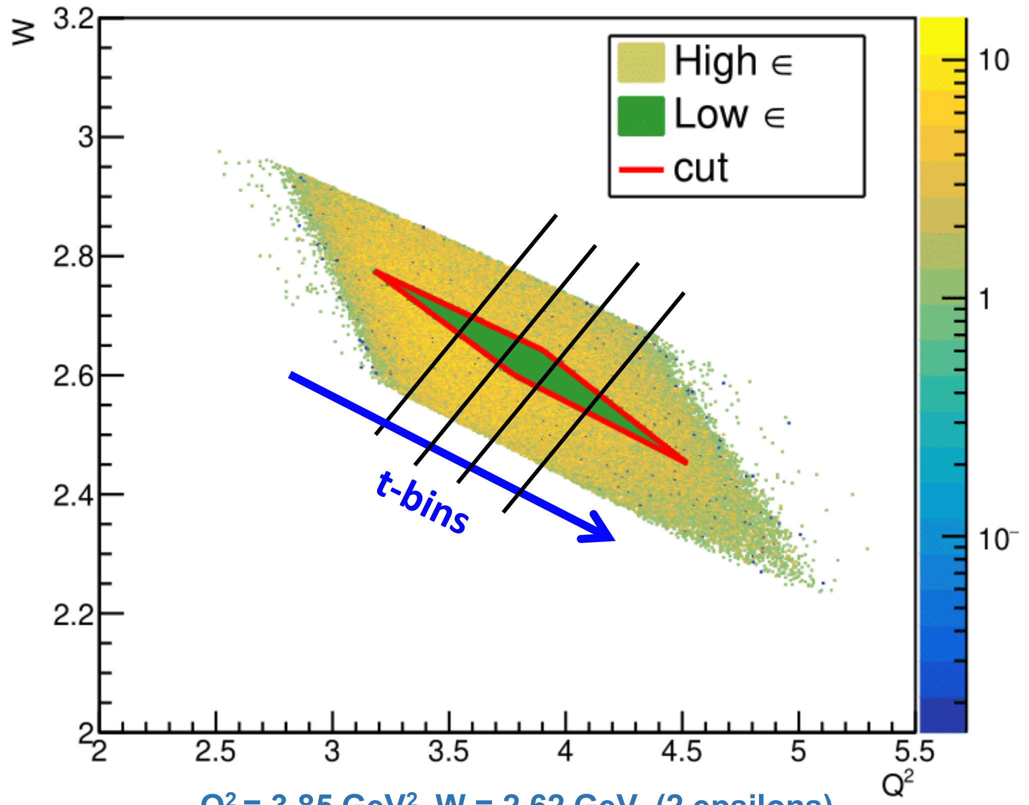
Diamond Region Selection

Diamond cut



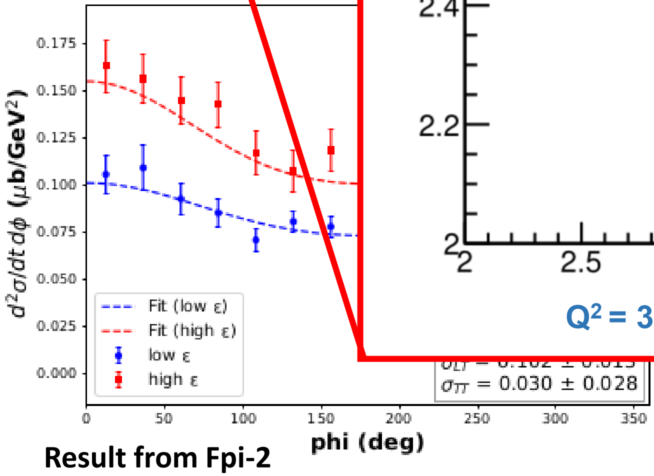
Improve φ coverage by taking data at

For each π HMS setting, form ratio:



Q² = 3.85 GeV², W = 2.62 GeV (2 epsilons)

- **Electron spectrometer acceptance is larger for high ϵ.**
- **Selected an overlapped phase-space region.**
- **Divided data into 5 t-bins based on data statistics.**
- **Purpose is to ensure consistency across different kinematic settings and measure the t-dependence**



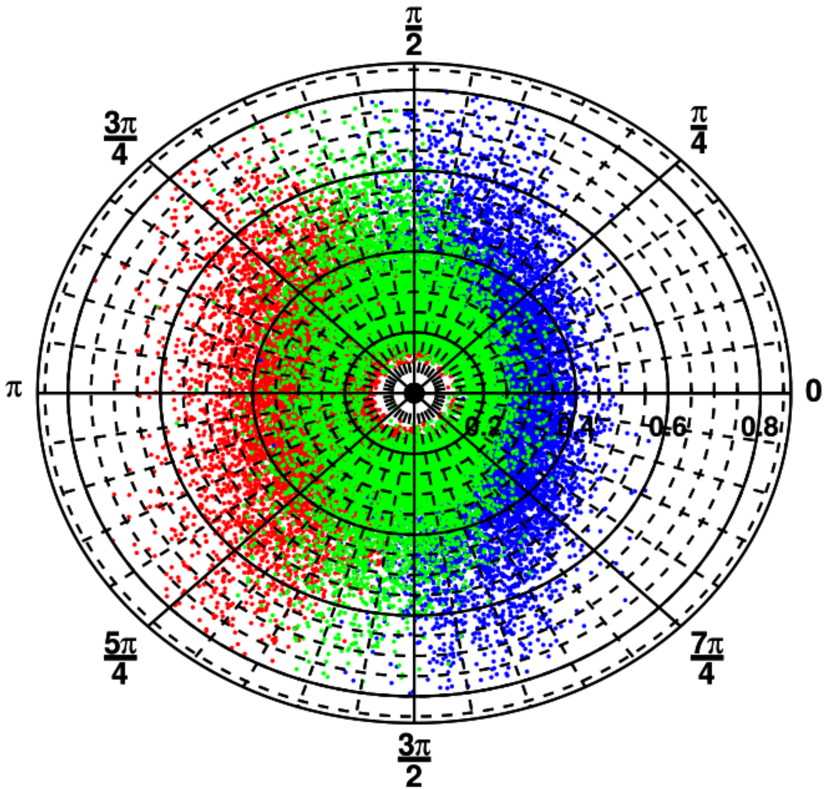
Result from Fpi-2

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

Full ϕ-Coverage

Diamond cut

Improve φ coverage by taking data at ...S) angles, $-2^o<\theta_{\pi q}<2^o$.



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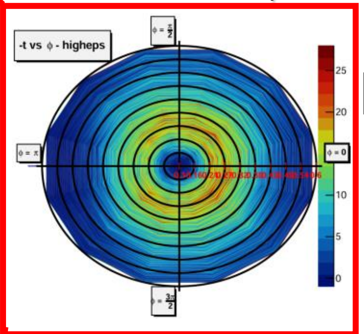

$\theta_{\pi q}$=+2

2.62, t = 0.21 (2 epsilons)

low ε
high ε
0.000
σ_{LT} = 0.102 ± 0.013
σ_{TT} = 0.030 ± 0.028
0 50 100 150 200 250 300 350
phi (deg)

Result from Fpi-2

For each ε HMS setting, form ratio:

- To get full-ϕ coverage, data is taken on two degrees on the right and left of the central angle by rotating the pion arm.

- **Red corresponds to the right angle pion arm setting**
- **Green corresponds to the central angle pion arm setting**
- **Blue corresponds to the left angle pion arm setting**

- Divided data into 15 ϕ-bins to measure the ϕ dependence.

$$2\pi\frac{d\sigma}{dt\,d\phi} = \epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos2\phi$$

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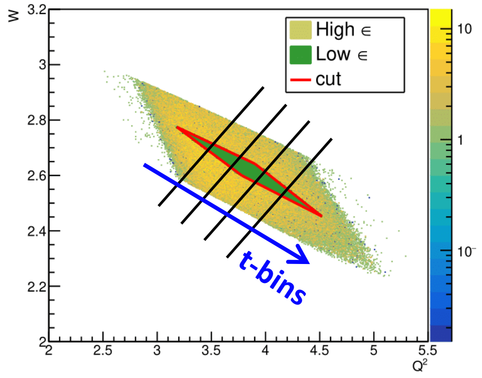

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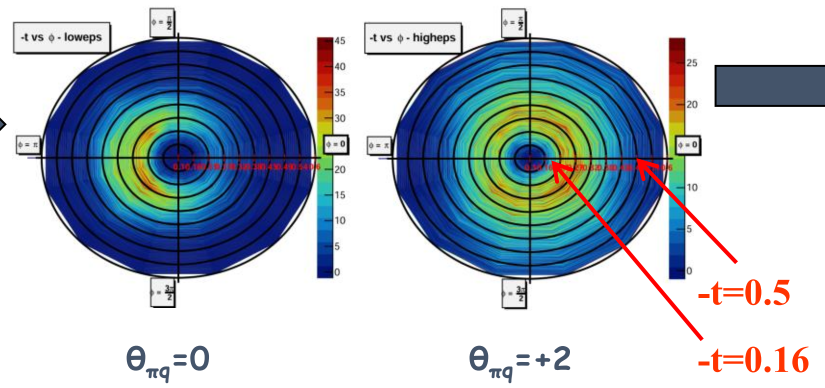


$\theta_{\pi q}=0$ $\theta_{\pi q}=+2$

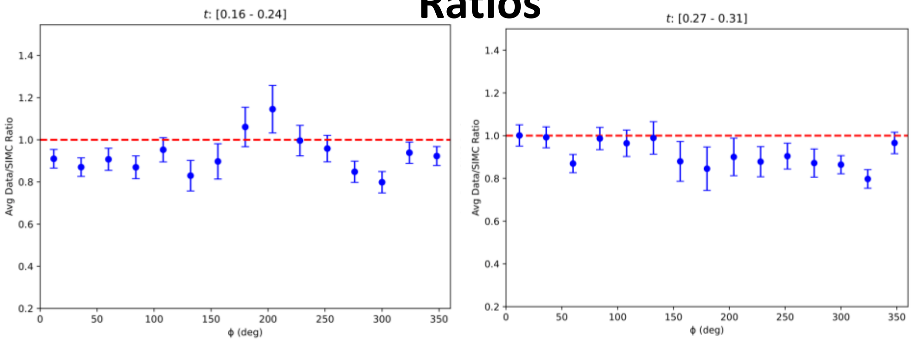
Q² = 3.85 GeV², W = 2.62 GeV (2 epsilons)

For each π HMS setting, form ratio:

$$R=\frac{Y_{EXP}}{Y_{SIMC}}$$

Combine ratios for π settings together, propagating errors accordingly.

Ratios



$$\frac{d^2\sigma}{dtd\varphi}_{EXP}=\left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dtd\varphi}_{SIMC}$$

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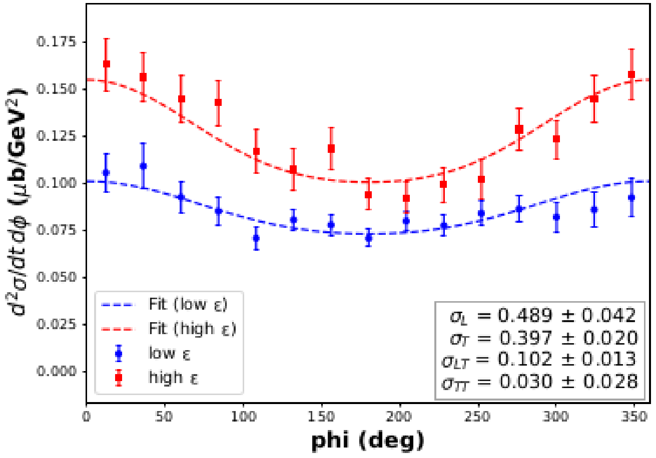

Yield Calculations

- Calculated normalized bin-by-bin data yield.

$$Y_{EXP} = \frac{N}{Q_{\text{eff}}}$$

where,

$$Q_{\text{eff}} = Charge \times Tracking\ Eff \times Detector\ Eff \times EDTM\ Live\ Time \times Boiling\ Corr \times other\ normalization\ factors \ldots$$

- Calculated normalized bin-by-bin MC yields.

Normalization Factors	Comments
Charge	Calculated run-by-run
HMS & SHMS Tracking Efficiencies	> 98%
Live Time Correction	>98%
HMS Cerenkov Efficiency	>99%
HMS Calorimeter Efficiency	>99%
SHMS Aerogel Efficiency	>98%
HMS & SHMS Hodoscope Efficiency	>98%
RF Efficiency	>99%
Boiling Correction Factor	Calculated run-by-run
Coin Blocking Correction	Calculated run-by-run
Pion Absorption Correction	~97%

Yield Calculations

- ❑ Calculated normalized bin-by-bin data yield.

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- ❑ Calculated normalized bin-by-bin MC yields.
- ❑ Calculated ratios (DATA/MC) for each t & phi-bin setting-by-setting, separately.

$$R(t, \varphi) = \frac{Y_{\text{EXP}}}{Y_{\text{SIMC}}}$$

- ❑ Combined data from each pion arm angle setting per ϵ by calculating their error-weighted average.

Normalization Factors	Comments
Charge	Calculated run-by-run
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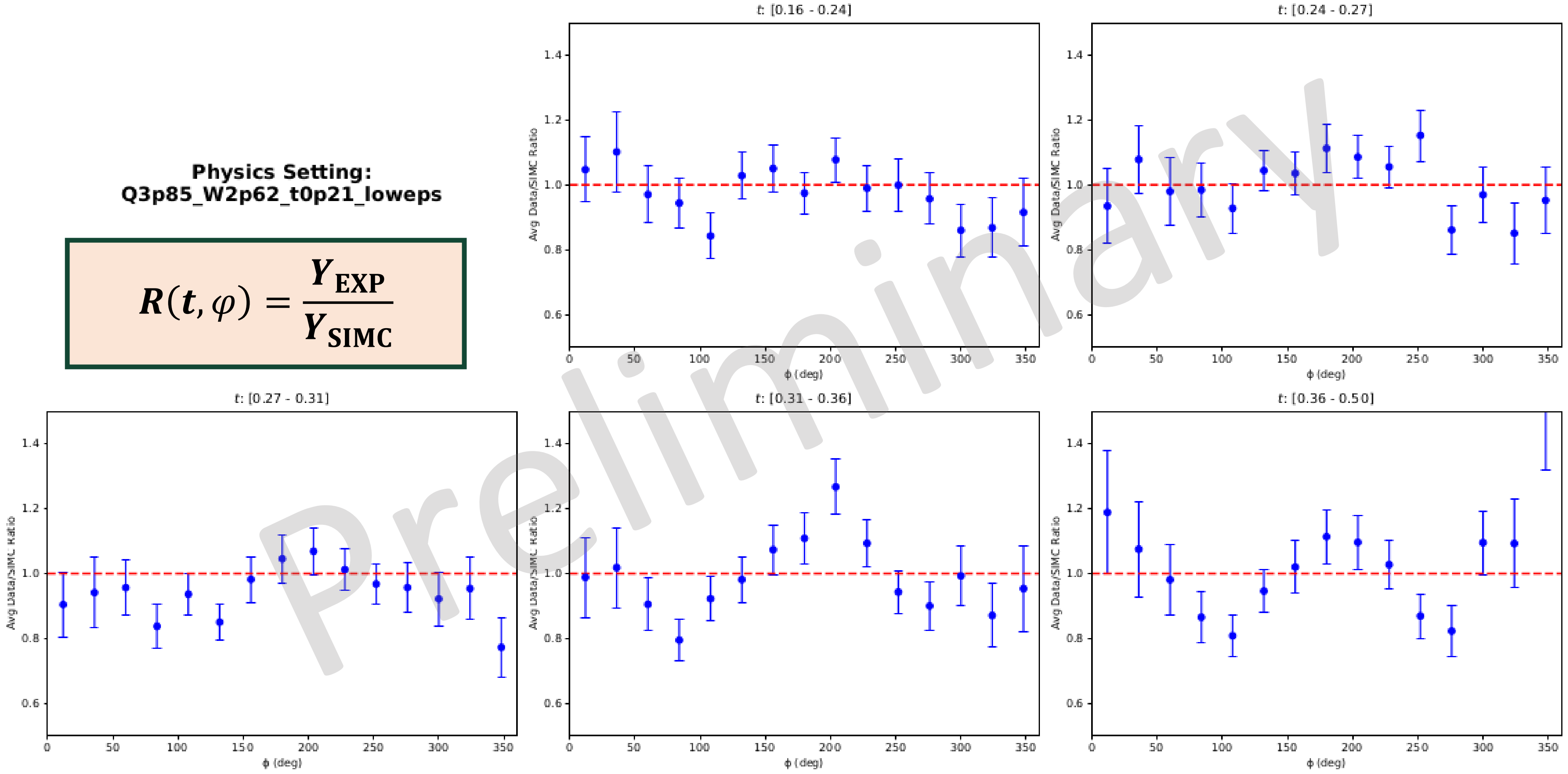
Coin Blocking Correction	Calculated run-by-run
Pion Absorption Correction	~97%

Low-epsilon Data/MC Ratios

Physics Setting:
Q3p85_W2p62_t0p21_loweps

$$R(t,\varphi) = \frac{Y_{\mathrm{EXP}}}{Y_{\mathrm{SIMC}}}$$

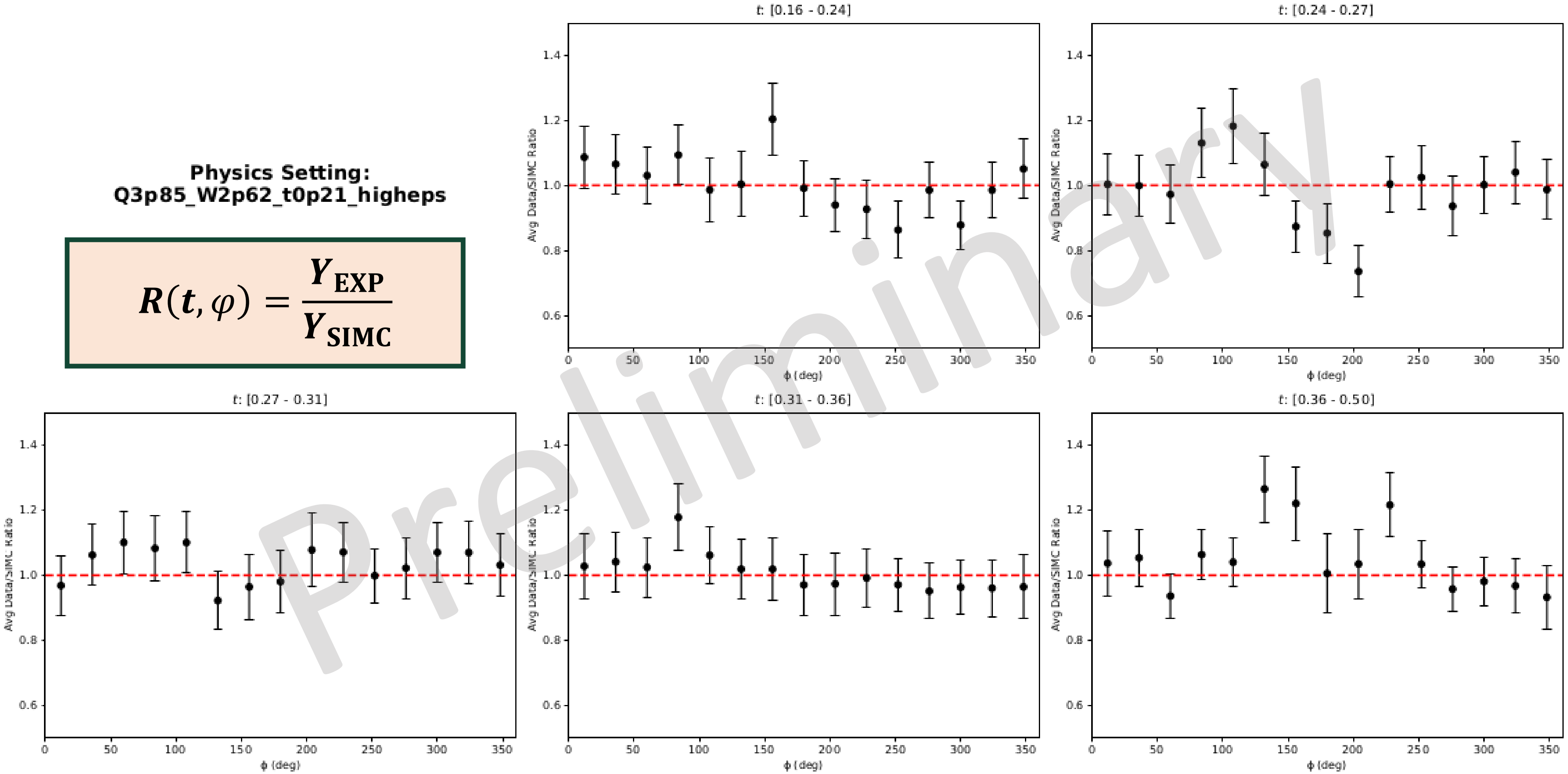


Q² = 3.85 GeV², W = 2.62 GeV (low-epsilons)

High-epsilon Data/MC Ratios

Physics Setting:
Q3p85_W2p62_t0p21_higheps

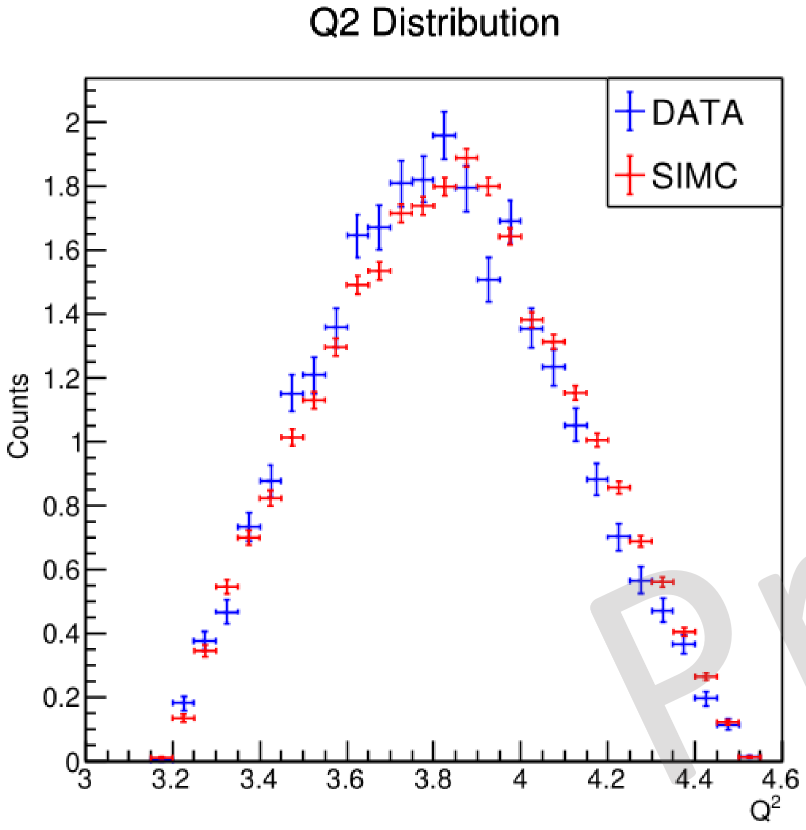
$$R(t,\varphi) = \frac{Y_{\text{EXP}}}{Y_{\text{SIMC}}}$$

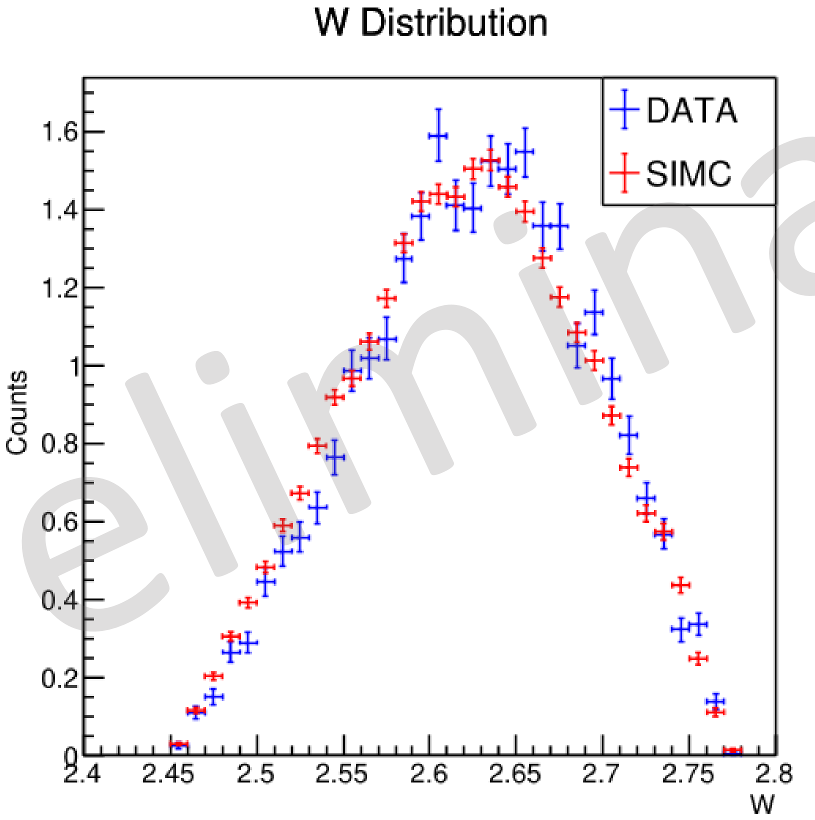


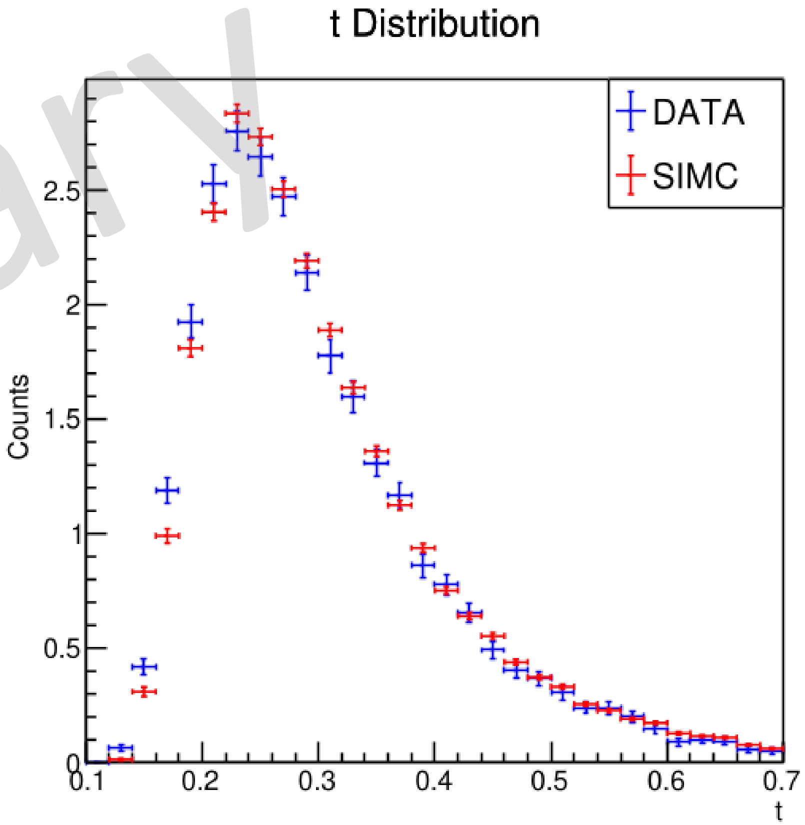
Q² = 3.85 GeV², W = 2.62 GeV (low-epsilons)

Data/MC Comparison Plots

- Compared kinematic and spectrometer variables between data and MC to verify that the SIMC model reliably reproduces the measured distributions.







Q^2 = 3.85 GeV^2, W = 2.62 GeV (low-epsilons Center Setting)

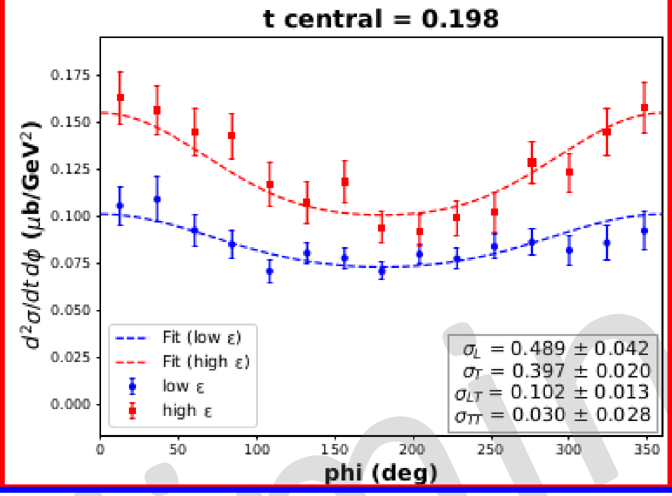
L/T Separated Cross-section Measurements

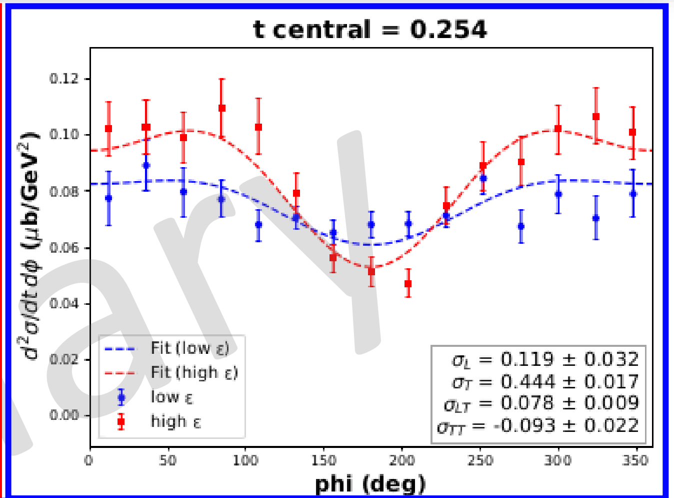
- Calculated unseparated cross-sections.

$$\frac{d^2\sigma}{dtd\phi}_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dtd\phi}_{SIMC}$$

- Calculated separated cross-sections.

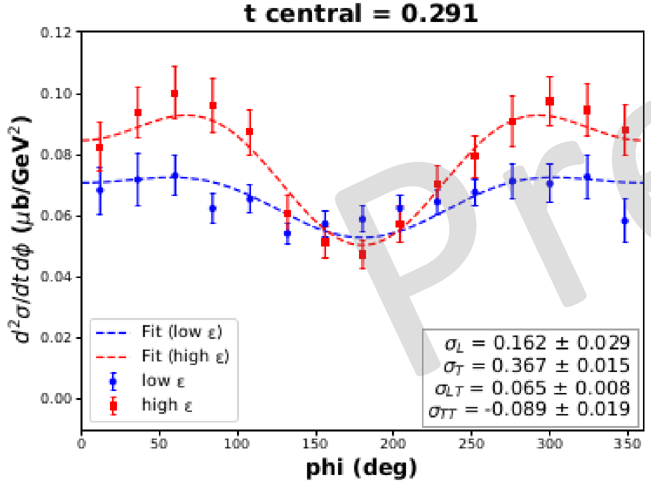
$$2\pi\frac{d\sigma}{dtd\varphi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\varphi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\varphi$$

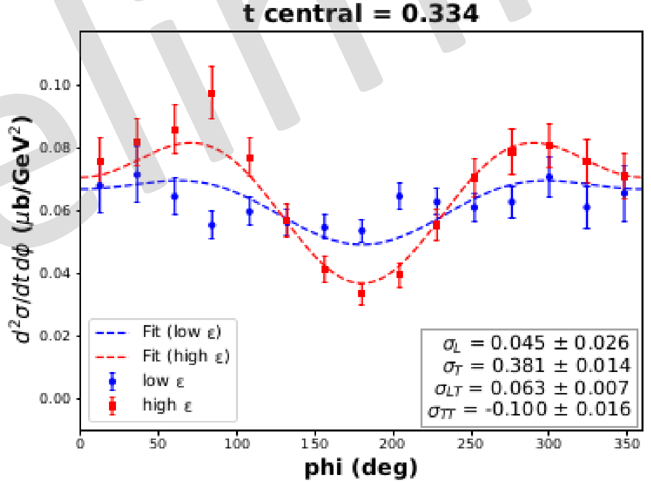


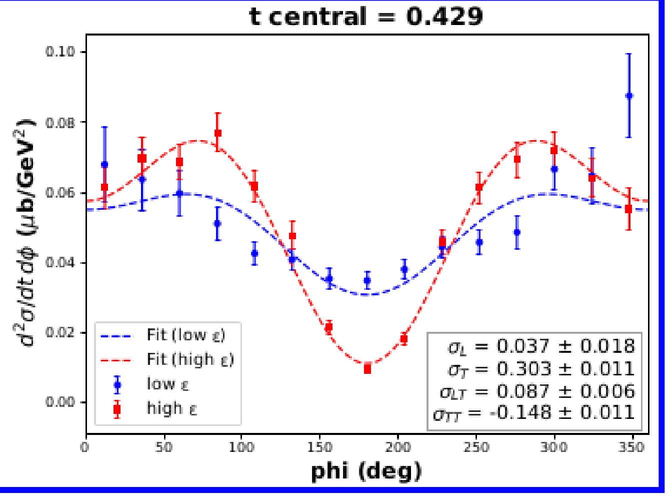


High-ε=0.779

Low-ε=0.292





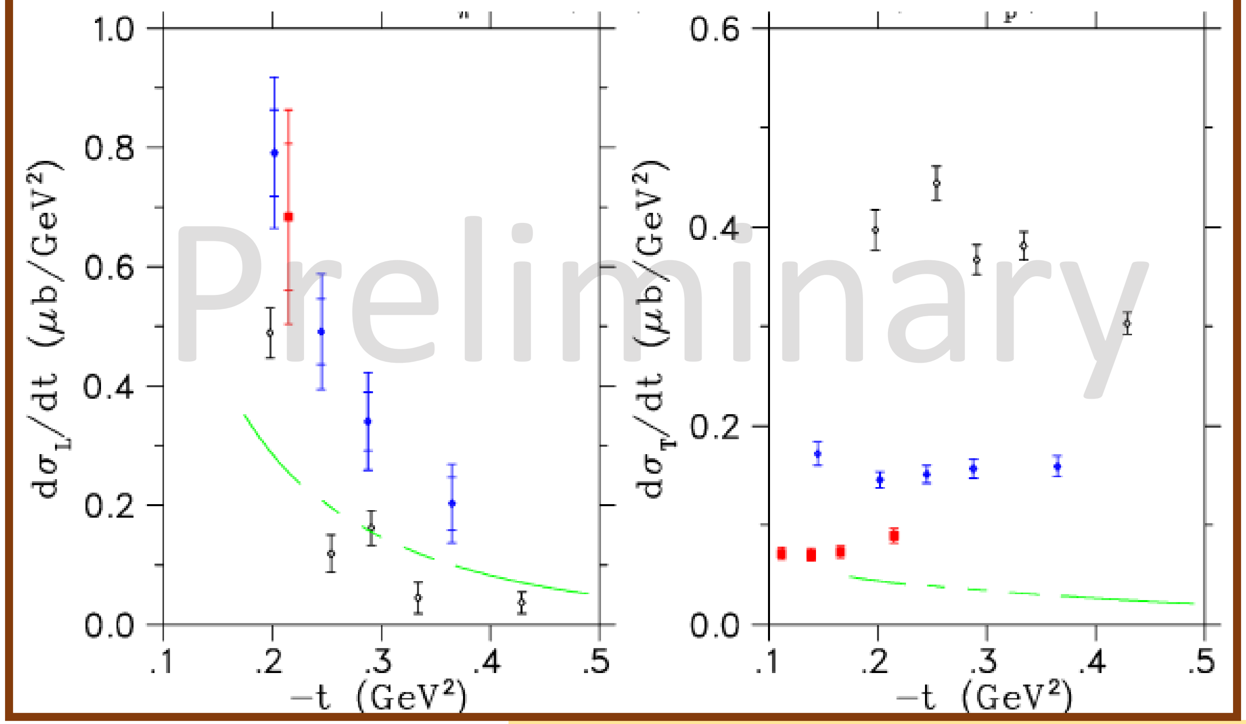


Preliminary

Physics Setting: Q^2=3.85 GeV², W=2.62 GeV

Comparison with VGL and CKY Model

- **VGL model gives a reliable description of σ_L across a wide kinematic domain [Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454].**
- **σ_L: results a little low compared to the previous Fpi-2 results.**
- **σ_T: surprisingly large as compared to previous Fpi results.**



Blue represents scaled Fpi-2 experiment results at Q^2 = 1.60 GeV^2

Red represents scaled Fpi-2 experiment results at Q^2 = 2.45 GeV^2

Black represents current experiment results at Q^2 = 3.85 GeV^2

Green curve shows the model fit.

Plots from Prof. Garth Huber

Model is evaluated at precise kinematics of data. Discontinuities indicate change in (Q^2,W) for each t-bin.

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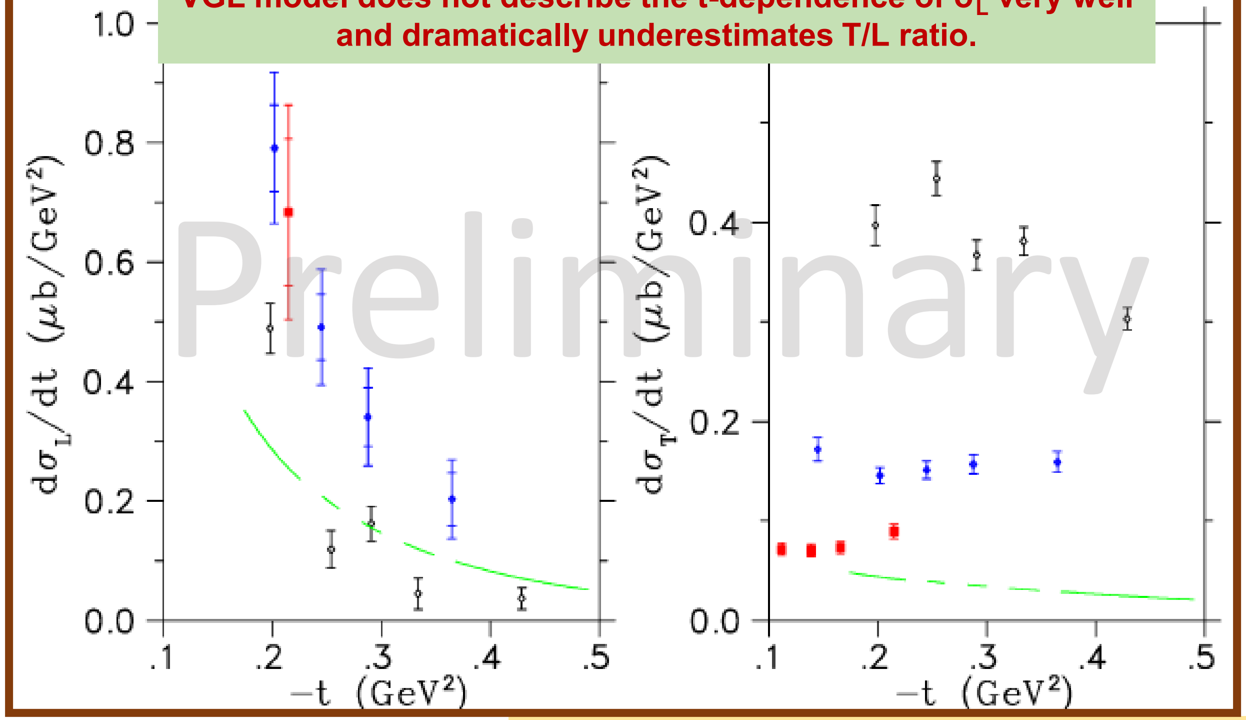
VGL model does not describe the t-dependence of σ_L very well and dramatically underestimates T/L ratio.



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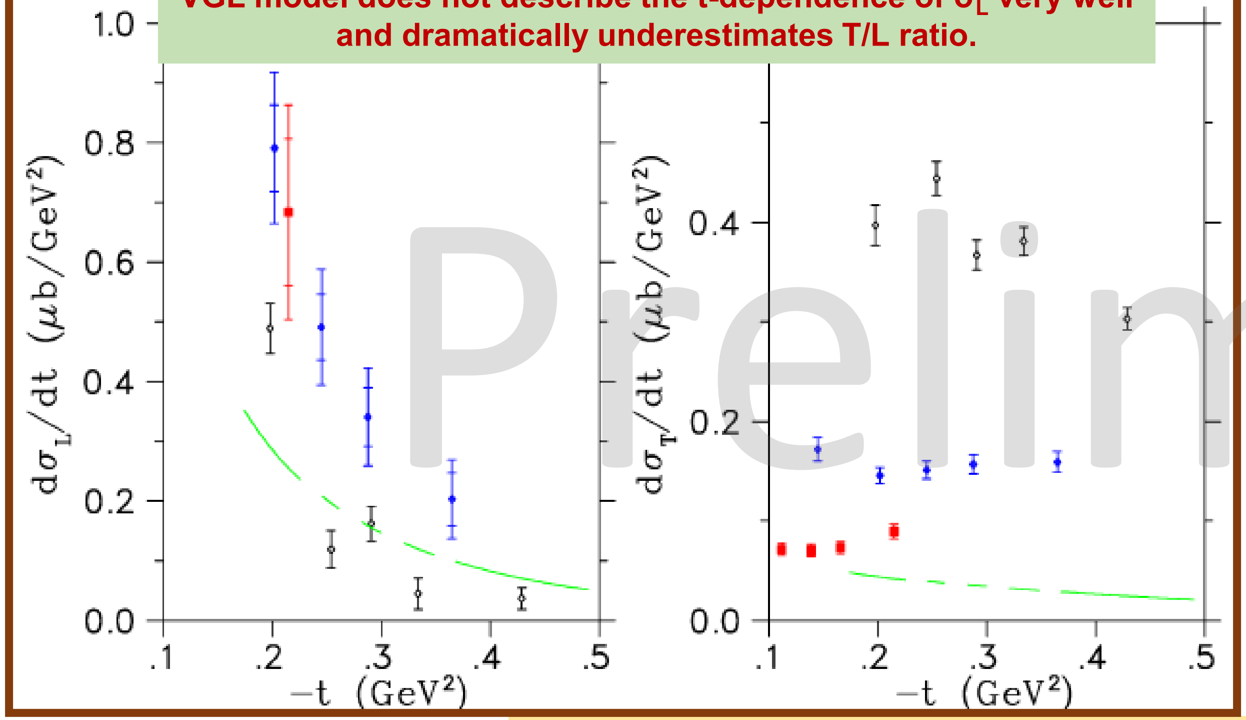
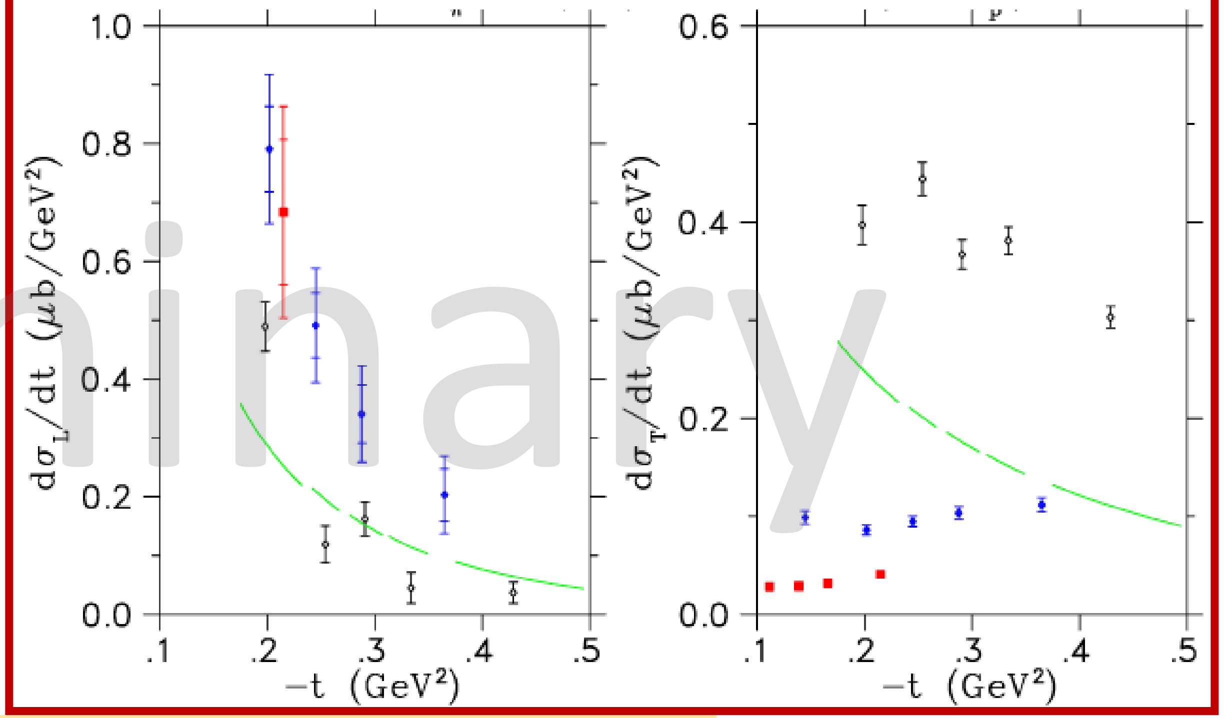


- **CKY developed with the goal of increasing σ_T without degrading σ_L [*T.K. Choi, K.J. Kong, B.G. Yu, J.Kor.Phy.Soc. 67(2015) L1089; arXiv: 1508.00969*].**
- **CKY model also does not describe t–dependence of σ_L very well.**
- **Much better T/L ratio, as expected, but still low.**



Plots from Prof. Garth Huber

Model is evaluated at precise kinematics of data. Discontinuities indicate change in (Q^2,W) for each t-bin.

Summary and Future Plans

- E12–19–006 (12 GeV Flagship Experiment) is expected to provide the definitive $p(e, e'\pi^+)n$ L/T–separation data set and will remain important for decades to come.
- Preliminary L/T separation is completed for Q^2=3.85 GeV^2, W=2.62 GeV physics setting.
- Systematic uncertainty studies still need to be done.
- Detailed comparison with existing VGL, YCK, and PKT theoretical models.
- Results will help to understand the dependence of the Form factor and in validating theoretical models.
- It is expected as many as 2 publications will come from this research.

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Canadian Institute of Nuclear Physics

Institut canadien de physique nucléaire

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