Measurement of Charged Pion Form Factor at Q^2=3.85GeV^2 in Hall C of Jefferson Lab

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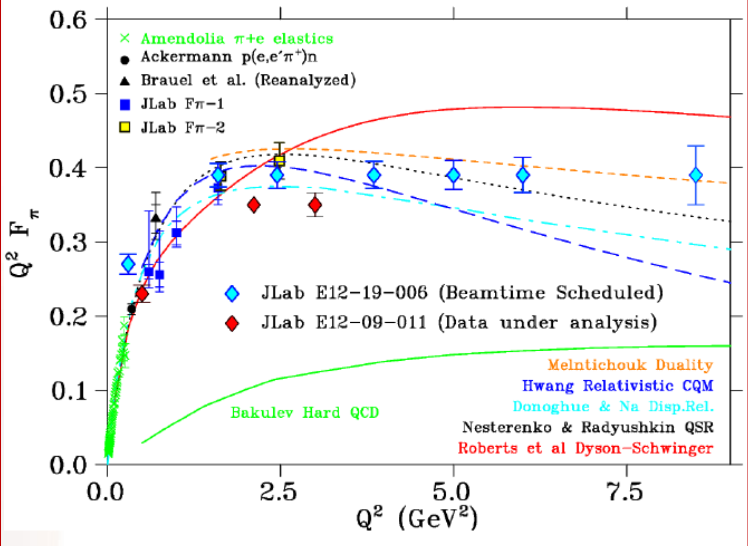
Pion Form Factor and Scaling Study

- Interaction of quarks and gluons is successfully described by **QCD.**
- **But unable to construct the quantitative description of hadrons in terms of the underlying constituents, quarks and gluons.**
- **Pion** is the lightest meson and gives an ideal testing ground for our understanding of the 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 between region between perturbative and non-perturbative approaches.**



Thesis topic of Muhammad Junaid

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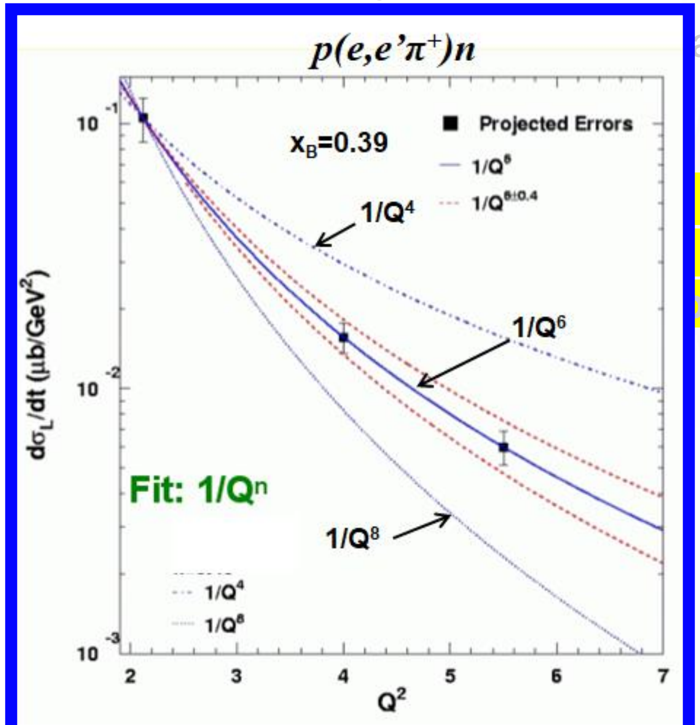
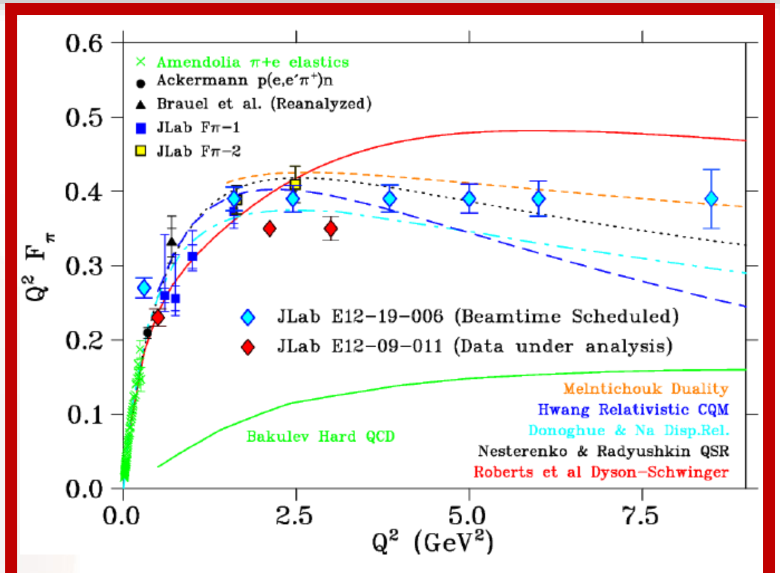


Thesis topic of Nathan Heinrich



Thesis topic of Muhammad Junaid

- **GPD encode quark position and momentum information.**
- Study hard-soft factorization is important for **GPD** extraction.
- Factorization regime predicts $1/Q^n$ dependence of $p(e,e'\pi^+)n$ cross-sections in Hard Scattering Regime.
- σ_L, to leading order, scales as $1/Q^6$
- σ_T scales as $1/Q^8$
- **Scaling Study** at fixed x = 0.31, 0.39, 0.55 as a function of Q^2.

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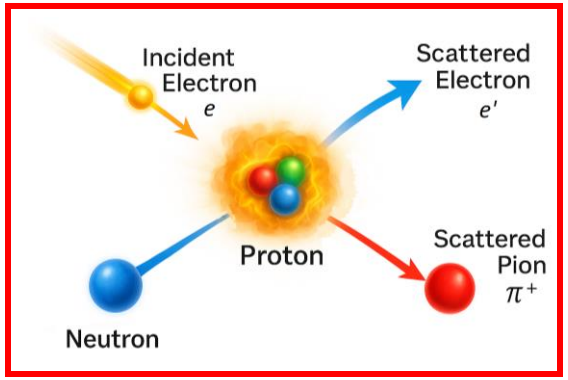
Pion Form Factor Measurement

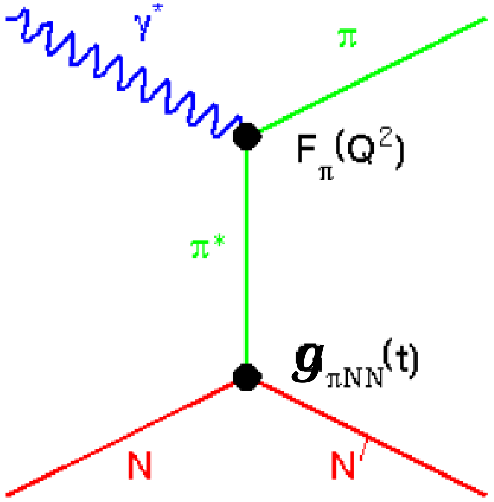
Direct Measurement:

- Elastic Scattering of electrons from pions gives
  $$e + \pi^+ \rightarrow e' + \pi^{+'}$$
- **Limitation:** Pion ($\boldsymbol{\pi}^{\pm}$) targets not possible due to short lifetime ($\sim$2.6 x 10 − 8s)
- Even scattering high energy pion beam (1 TeV, if some facility could be constructed) can access only $Q^2 \sim 1 GeV^2$



Indirect Measurement:

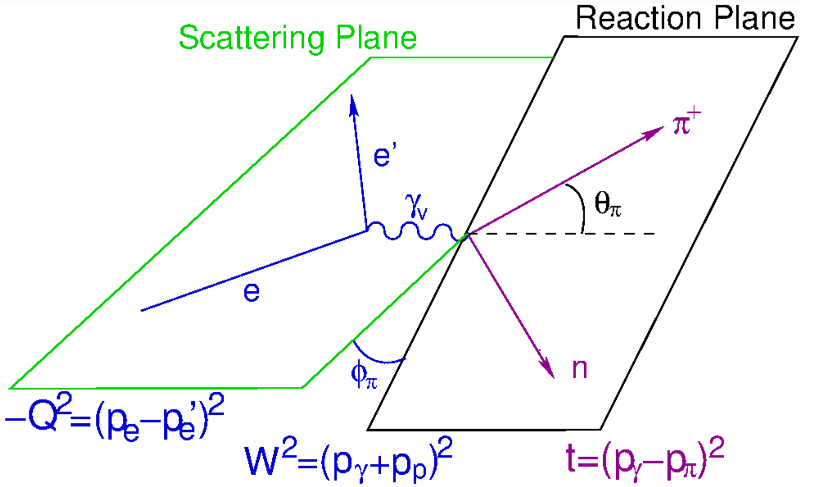
- Above $Q^2 > 0.3\text{GeV}^2$, $\boldsymbol{F_\pi}$ is measured indirectly using the "pion cloud" of the proton via pion electroproduction $\boldsymbol{p(e, e'\pi^+)n}$
- Indirect measurement – Form factor extraction requires a model.
- As an illustration of how $\boldsymbol{\sigma_L}$ connects to $\boldsymbol{F_\pi^2(Q^2, t)}$, 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 $\boldsymbol{F_\pi^2(Q^2, t)}$ 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.

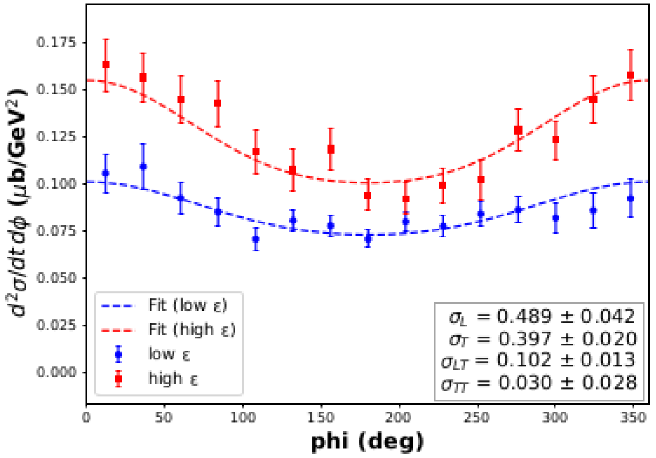
$$\epsilon = \left[1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} . \tan^2\frac{\theta_{e'}}{2}\right]^{-1}$$

- 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.

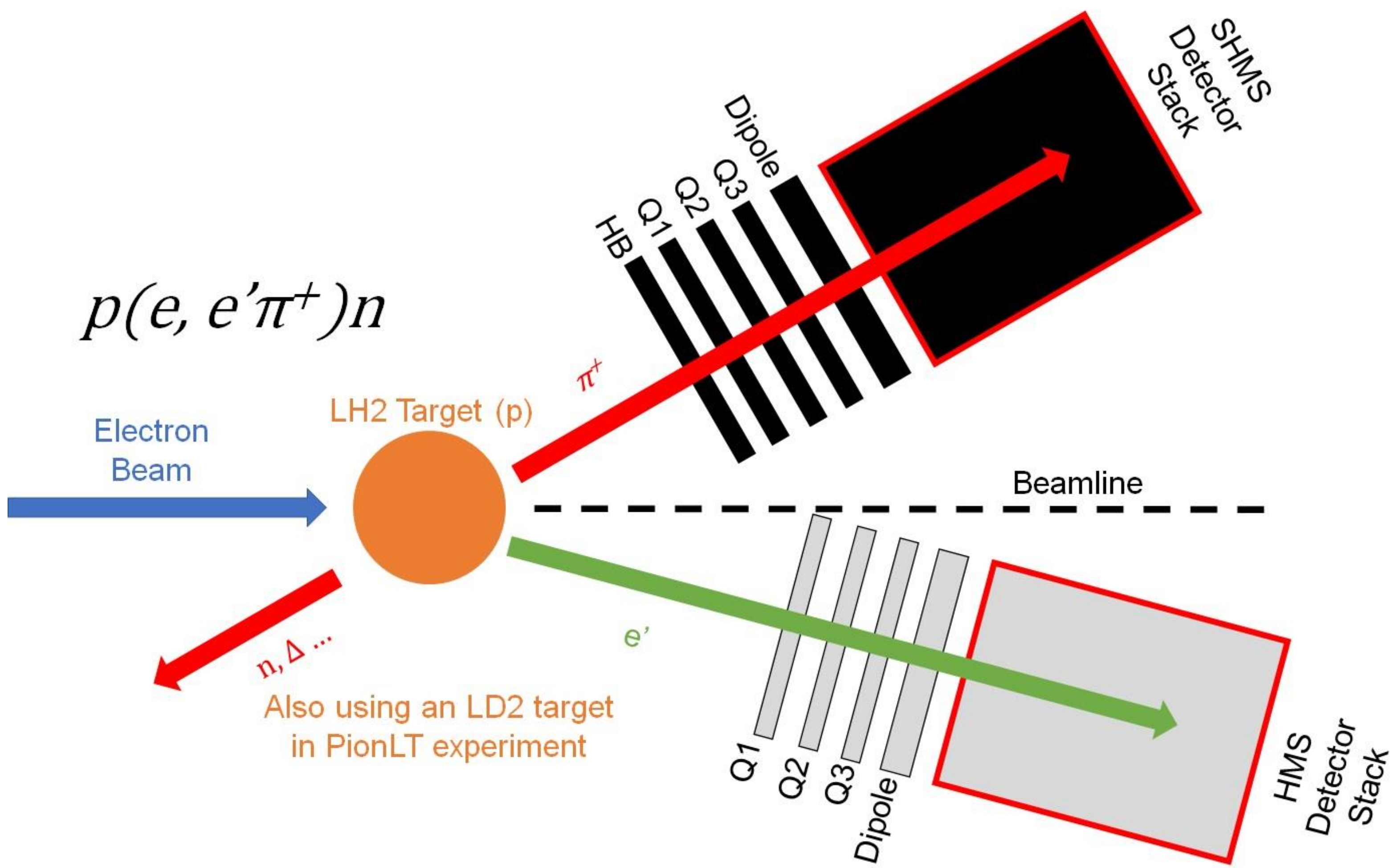
$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{\epsilon_1 - \epsilon_2} \frac{1}{\sigma_L} \sqrt{\Delta\sigma_1^2 + \Delta\sigma_2^2}$$

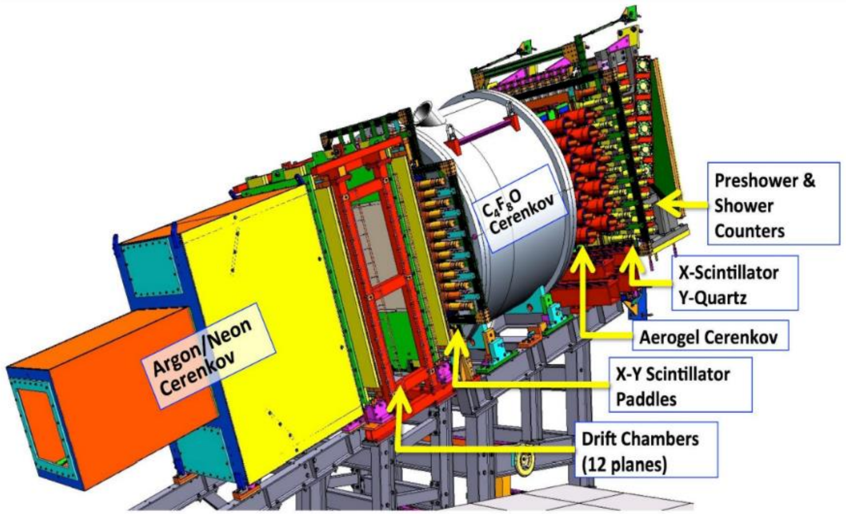
Where "$\sigma_1 = \sigma_T + \epsilon_1 \sigma_L$" and "$\sigma_2 = \sigma_T + \epsilon_2 \sigma_L$".

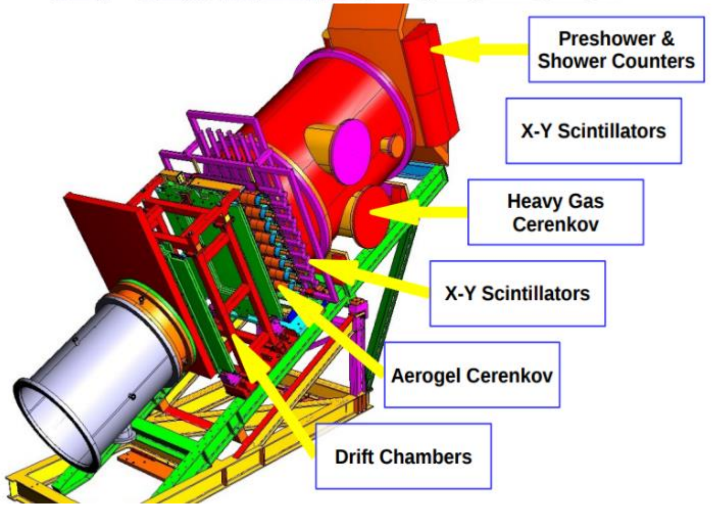


- Careful attention must be paid to systematic studies such as spectrometer acceptance, kinematics, efficiencies, etc.

Coincidence Experiment in Hall C



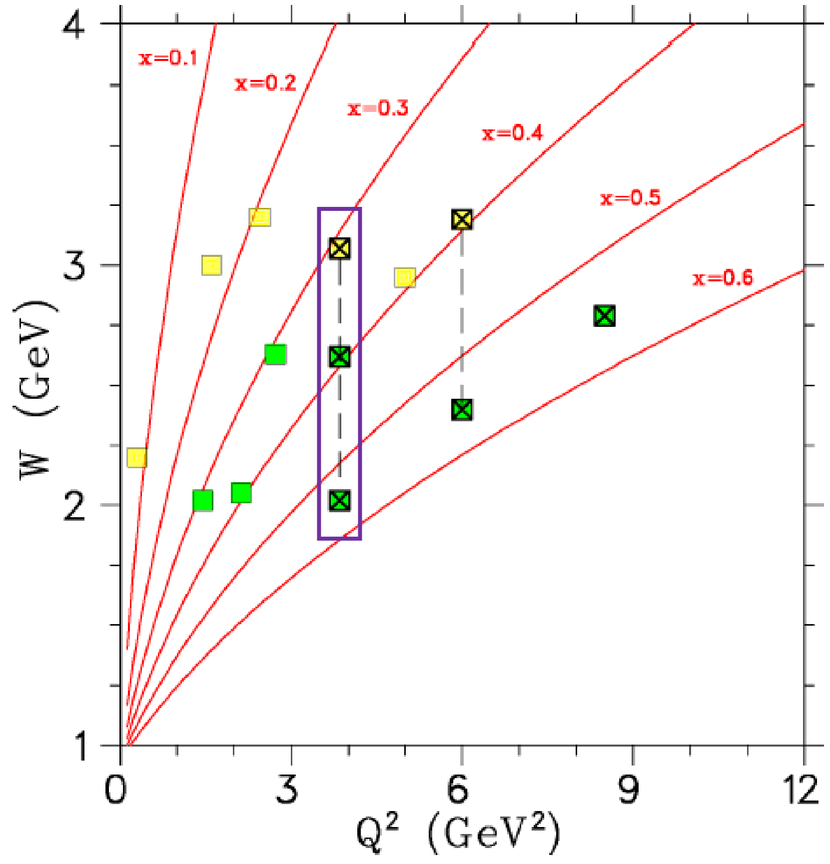




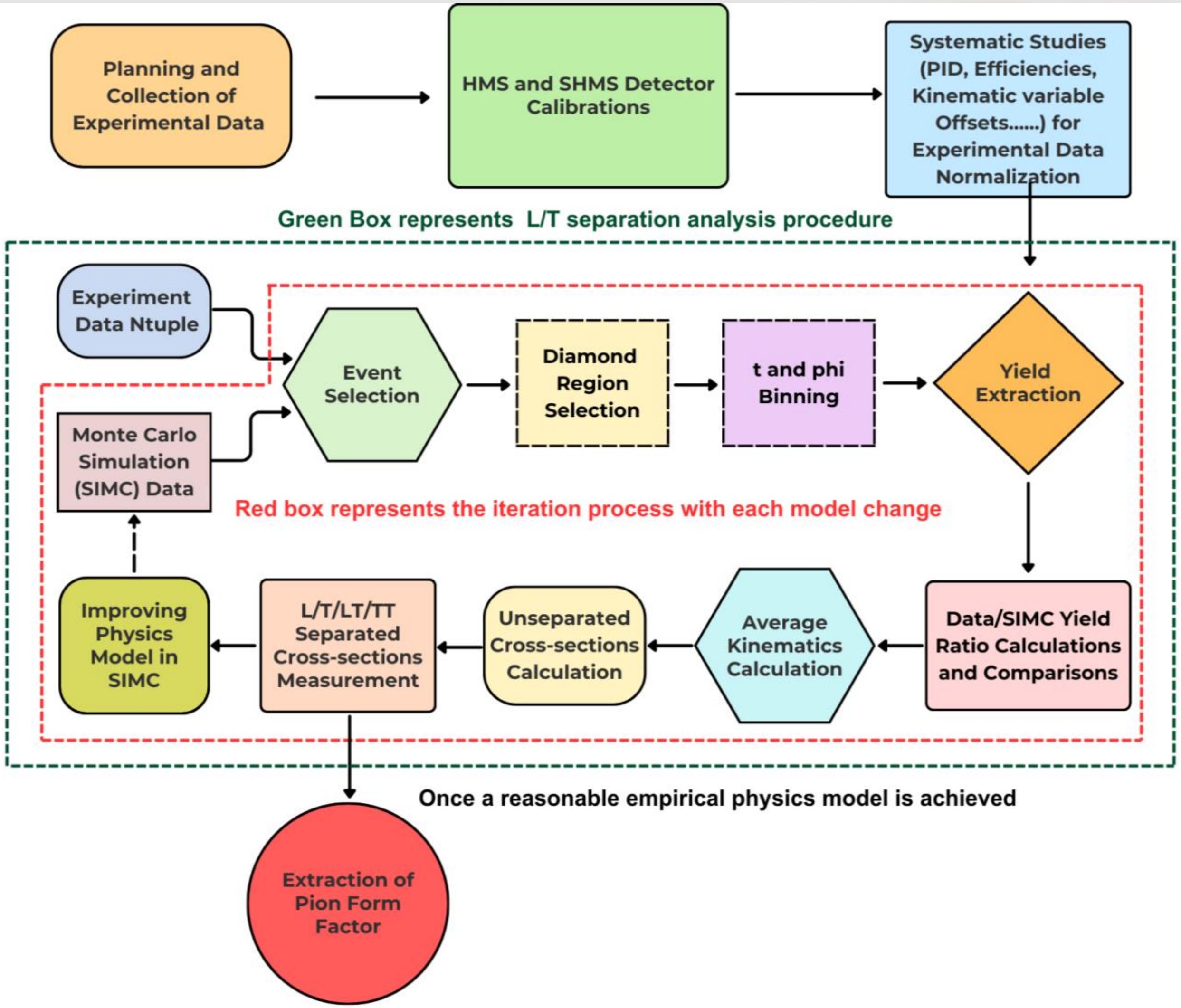
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Pion-LT Experiment

- The Pion-LT experiment was conducted over a wide kinematic range at the Hall C facility, JLab.
- **Green points represent the Pion Form Factor Study.**
- **Yellow points represent the Pion Scaling Study.**
- Vertical black dashed lines shows W-scan at fixed $\boldsymbol{Q^2}$.
- Points marked with an '**x**' are instrumental in higher $\boldsymbol{Q^2}$, $\boldsymbol{F_\pi}$ extraction
  - $\boldsymbol{Q^2 = 8.5\ GeV^2}$ is highest achievable extraction at JLab
- Red lines allow for $1/Q^n$ scaling study at fixed x = 0.31, 0.39, 0.55.
- Focusing on the physics settings highlighted in purple box.



Analysis Flowchart



- Planning and Experimental data collection were completed in 2021 and 2022.
- Detector Calibrations were completed in 2023.
- Systematic studies, including PID and efficiencies, offsets, were completed in 2024.
- L/T separation analysis for Q^2 = 3.85 GeV^2, W = 2.62 GeV (2-epsilon) physics setting is completed in 2025.

Lumi Analysis

- ➢ **This analysis seeks to identify and remove all rate dependence from the physics yields**
- ❑ **Sub Tasks in Order:**
- ❑ **Beam Current Monitor (BCM) Calibration and Zero Current Offset**
  - ❑ Remove rate dependence from Scalar Yields.
- ❑ **Analyzed Carbon Singles Data**
  - ❑ Remove Singles rate dependence.
- ❑ **Analyzed LH2 Elastic Singles Data**
  - ❑ Determine Target Boiling Correction
- ❑ **Analyzed LH2 Physics Coincidences Data**
  - ❑ Ensure physics yields do not have any remaining rate dependence

This work is done by Nathan Heinrich

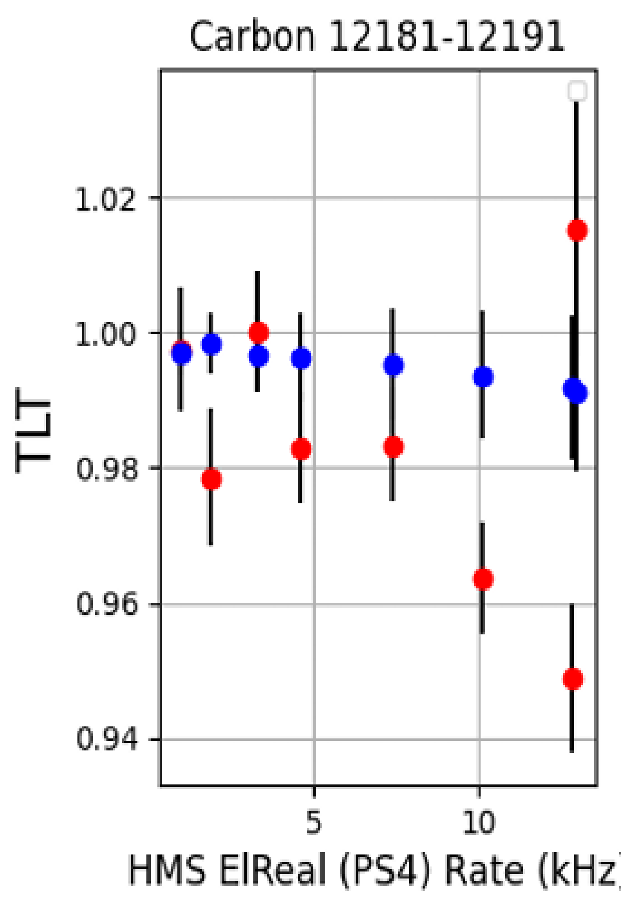
Carbon Singles - LiveTime

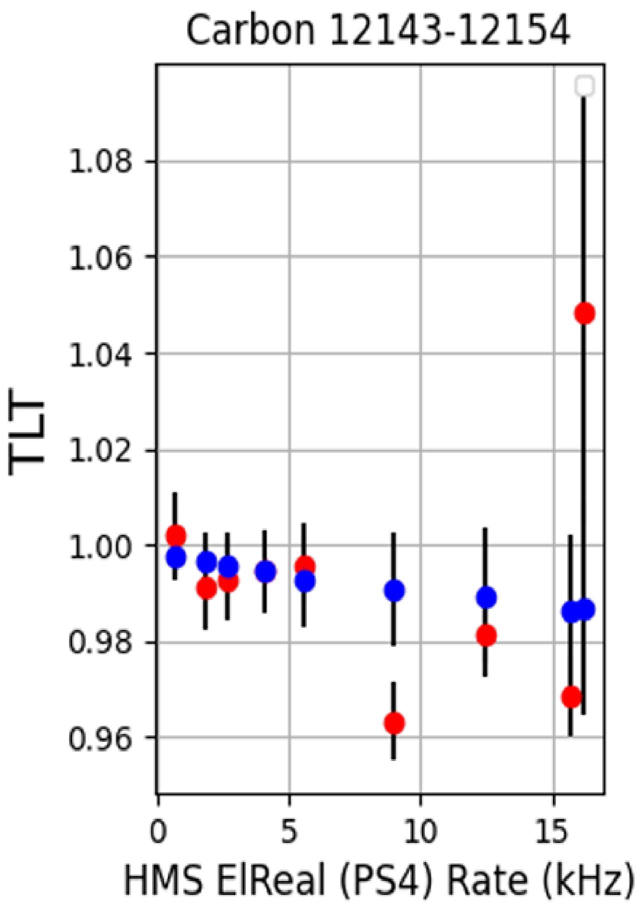
- Electronic Dead Time Monitor (EDTM) system is found to be an unreliable measure of Total Live Time. (See Jacob Murphy's report DocDB id 1177)
- **Instead use: Computer Live Time and Electronic Live Time (CPULT x ELT)**
- CPULT comes from scalers
- ELT estimated using the Hodoscope plane combinatorics (D. Mack's Method DocDB id: 1063)

  EDT = rate*GateWidth, ELT = 1 - EDT

so

LT3of4 = LT1*LT2*LT3*LT4 + DT1*LT2*LT3*LT4
+ LT1*DT2*LT3*LT4 + LT1*LT2*DT3*LT4
+ LT1*LT2*LT3*DT4





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Carbon Singles - Flat

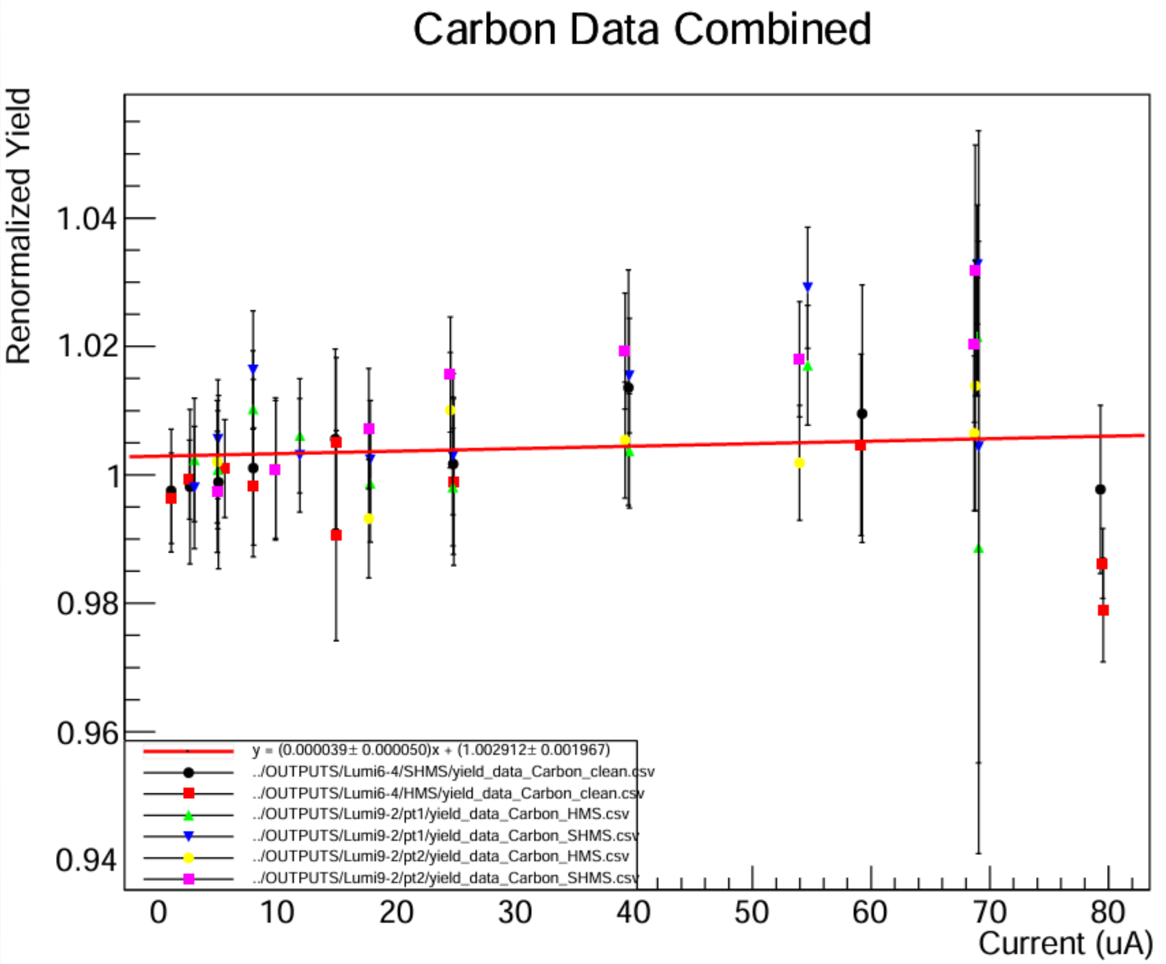
- Carbon Target shouldn't 'boil', so if detectors are understood, there will be no rate dependence in Yield:

$$Lumi\ Yield = \frac{Events}{(Charge) * (\prod Efficiencies)}$$

- With charge, tracking, and live time corrections applied slope of the combined Carbon singles settings:

0.39 ± 0.50 %/100uA

- Consistent with no slope,
- Data is well understood.



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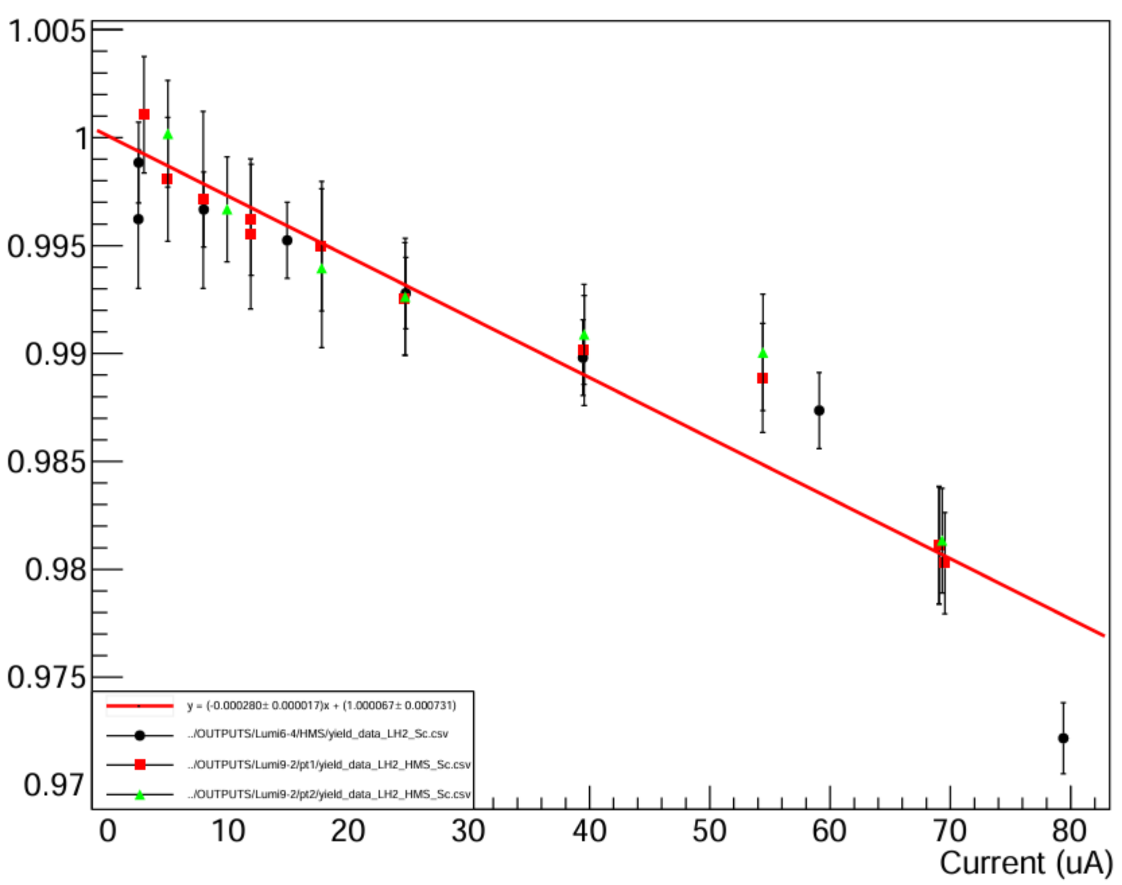
LH2 Singles Lumi - Boiling

- ❑ After ensuring that carbon data is understood, move to the Liquid Hydrogen target.
- ❑ Here, we expect "boiling" or a change in density with current (beam heating).
- ❑ Because of issues with live time approximation at a high rate, only use HMS data.
- ❑ Acquire boiling coefficient:

  2.8 ± 0.17 ± 0.69 %/100uA



Others get:

C. Yero	6.3 ± 0.6 %/100uA
H. Bhatt	3.2 ± 0.4 %/100uA
Deepak	3.2 ± 0.8 %/100uA
R. Trotta	7.9 ± 1.8 %/100uA

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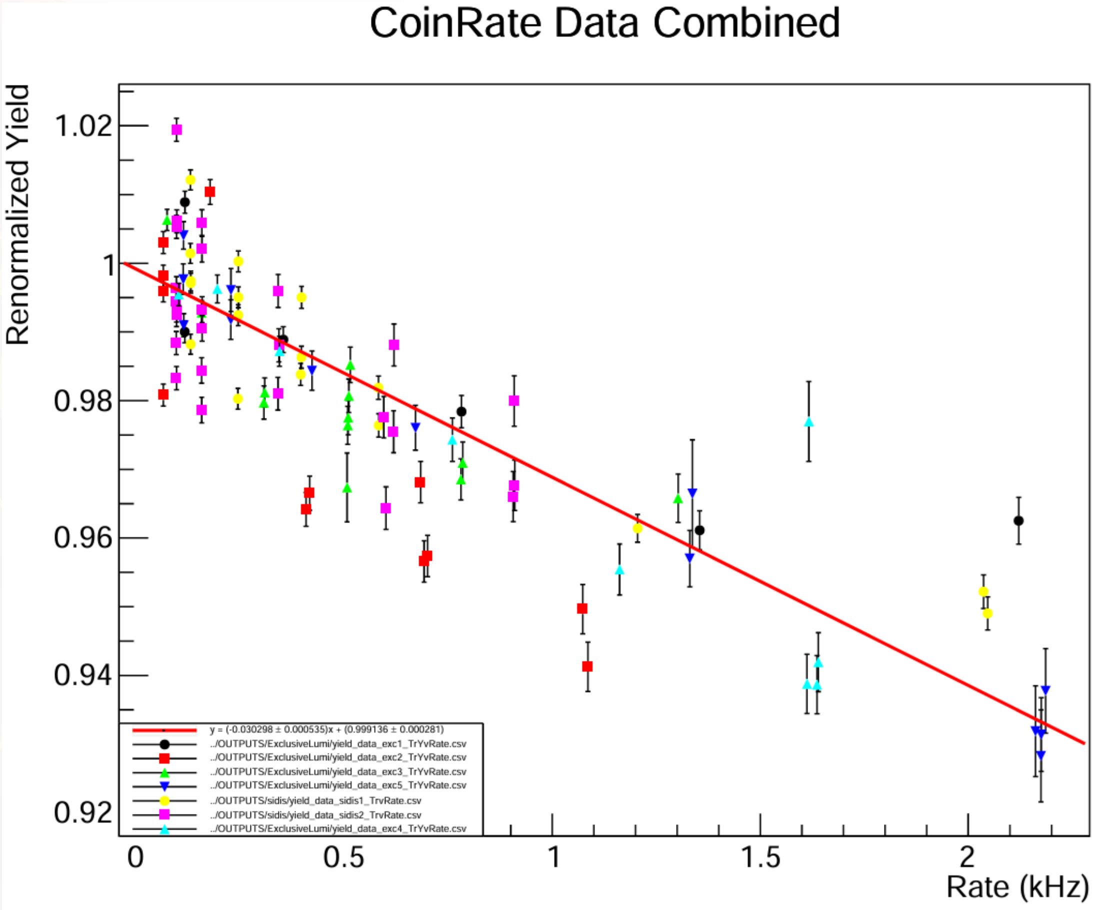
LH2 Physics Coin

- Moving to coincidence between HMS and SHMS spectrometers (called Coin), specifically using data similar to what is used for physics studies.
- EDTM issue that exists in singles does not exist for coin, as ALL Coin events are taken, rather than a fraction like with Singles
- With all corrections applied find additional rate dependence.
- Still find additional effect coming from Coincidence Blocking



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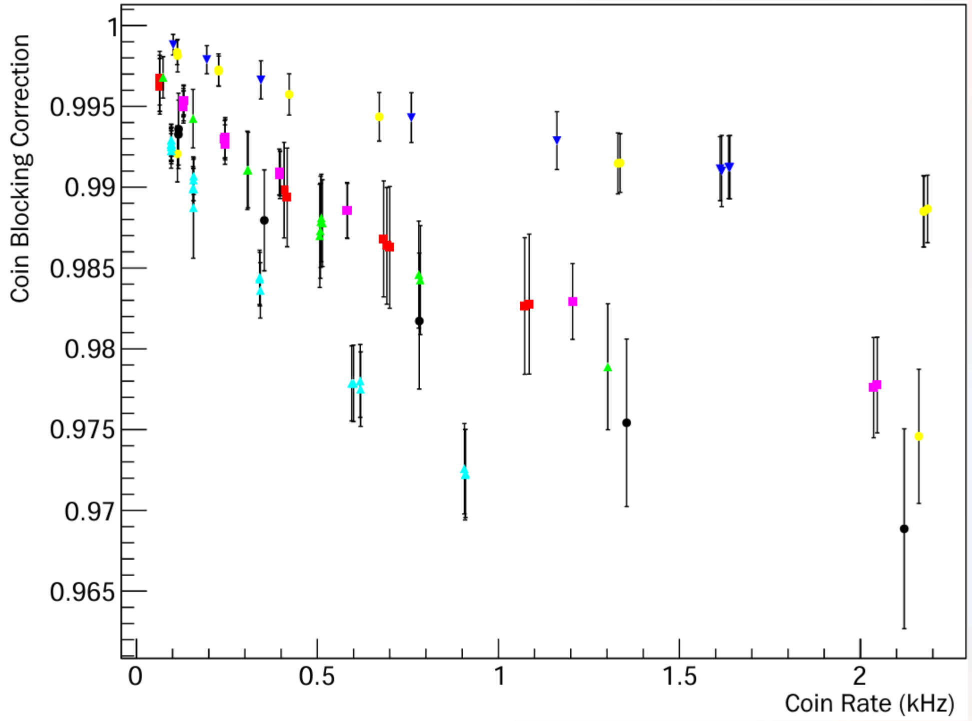
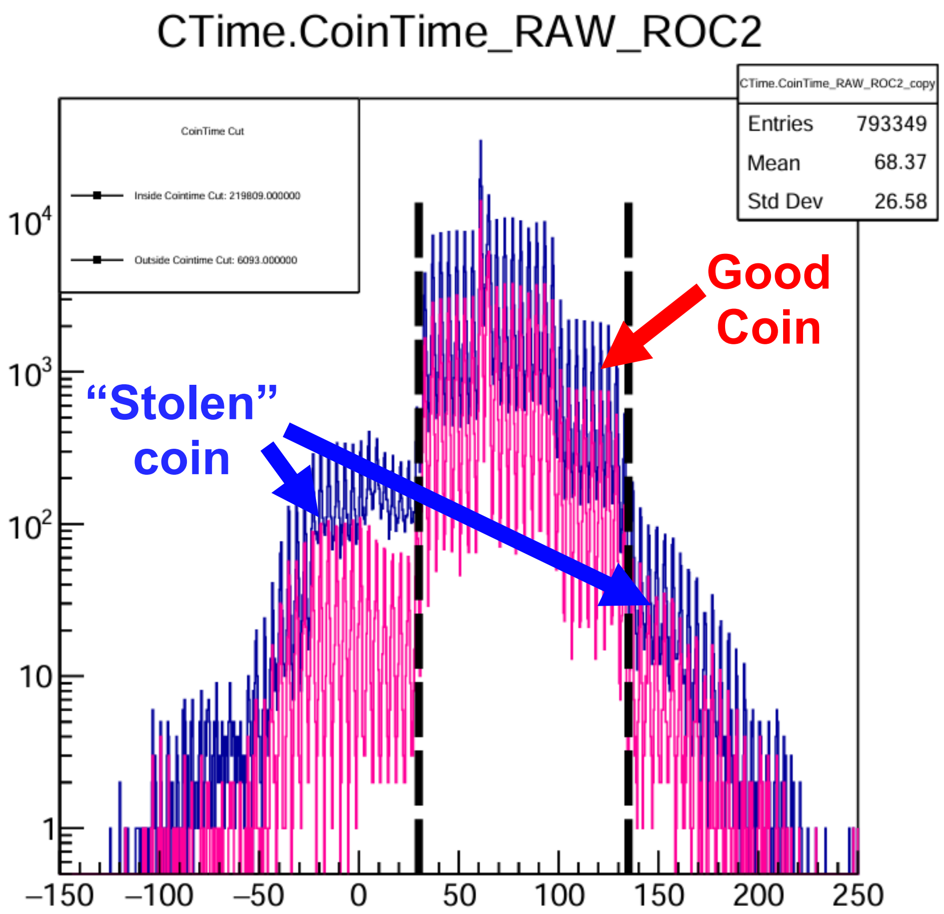
Coin Blocking Correction – 12 GeV Era

- ➢ **Coin Blocking is where noise events "steal" the coin time, Causing the event to be lost.**
- ➢ **Fixed with by cutting on raw coin time and correcting**





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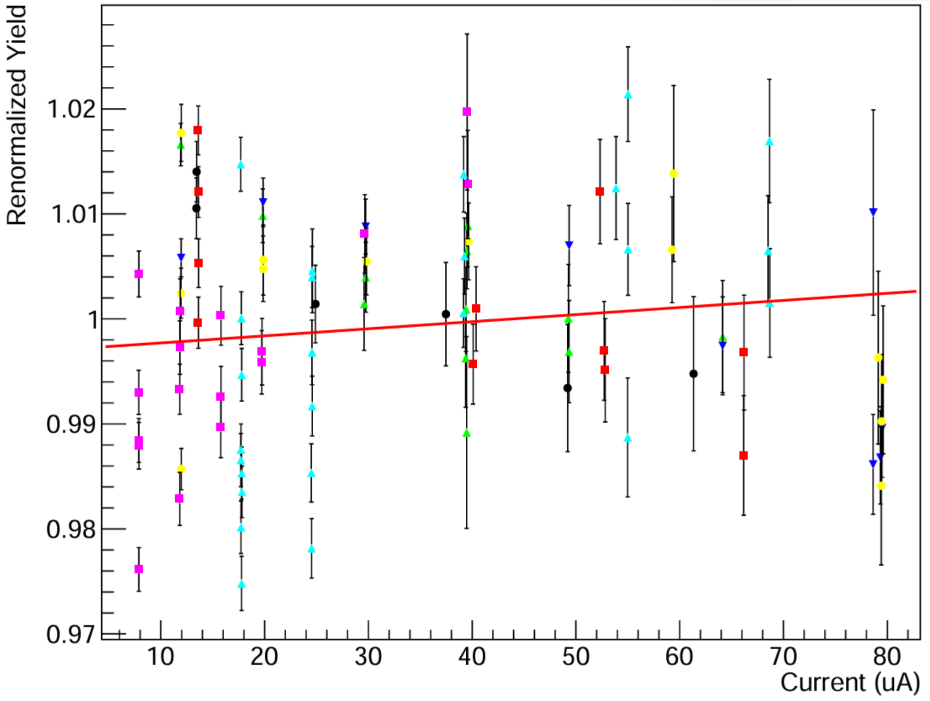
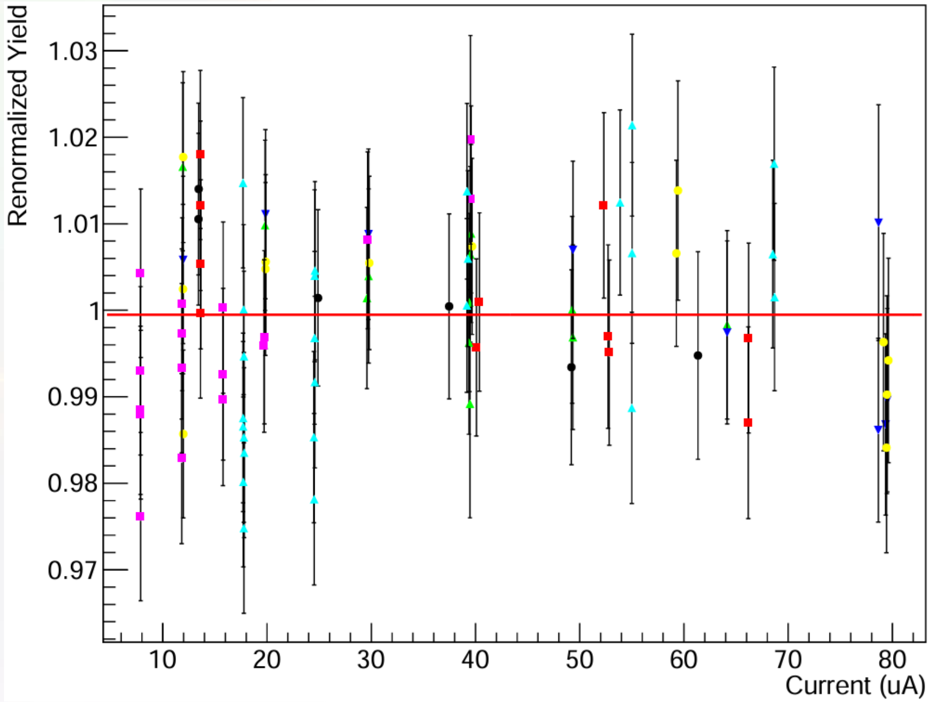
Coin Lumi Flat

- After correcting for Coin Blocking, it is very nearly flat, but not within the errors listed. So, uncertainty must be under-estimated.
- Added a small systematic uncertainty of 0.94% to EDTM Live Time so that a constant fit has $\chi^2 = \sim 1$.
- **Detailed report can be found on DocDB1307.**



Added Systematic



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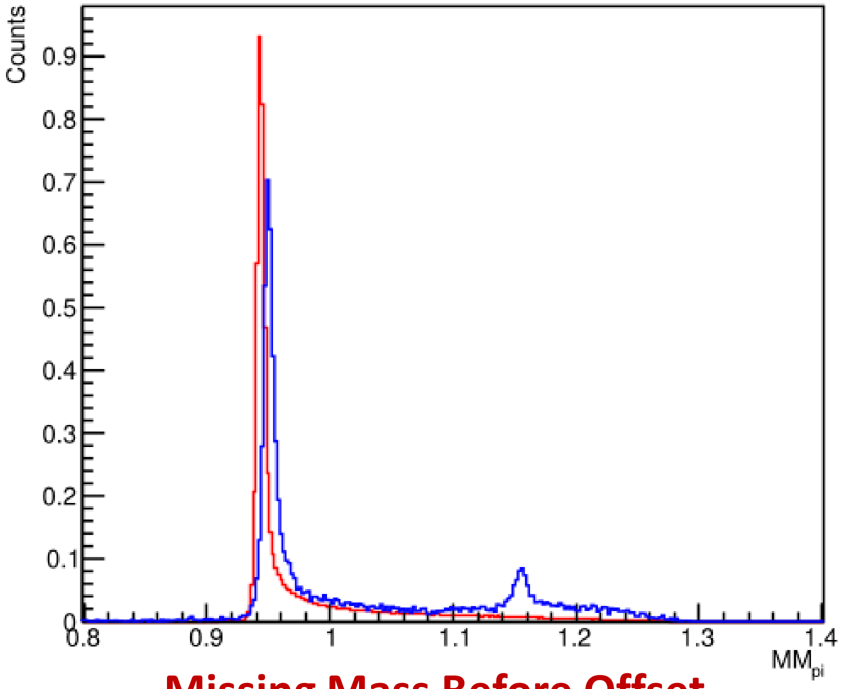
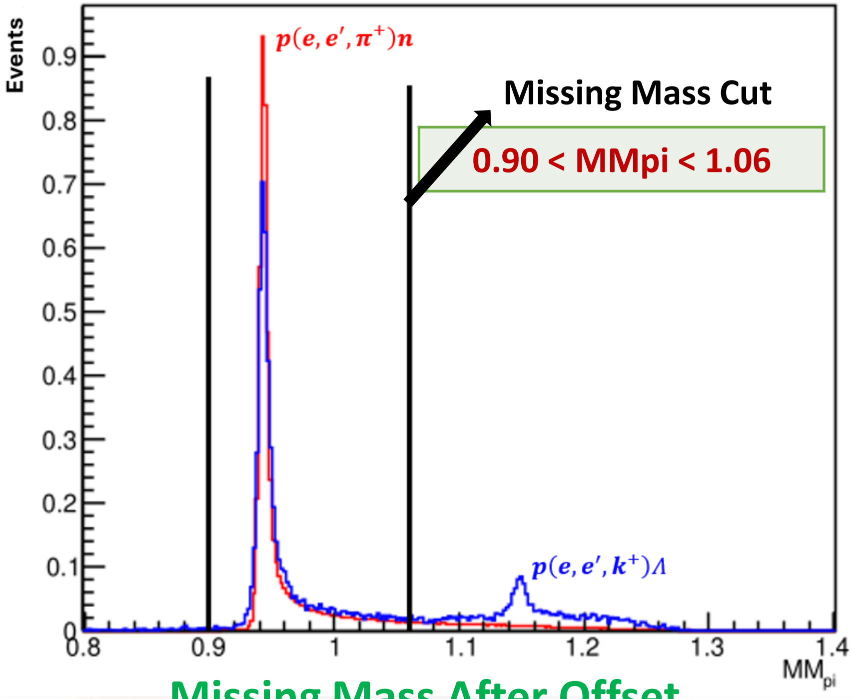
Missing Mass Offset and Cut Study

- **Purpose of the missing mass offset study is to improve the agreement between data and simulation and reduce systematic uncertainties in the extracted cross-sections.**
- **Blue represents the experimental data MM plot.**
- **Red represents the SIMC MM plot.**

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



Missing Mass Before Offset



Missing Mass After Offset

Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

Finalized PID and timings cuts

HMS Cuts (Electrons)
HMS_Cal_etottracknorm > 0.7
H_Cer_npeSum > 1.5

SHMS Cuts (Pions)
Aerogel (NPE) > 1.5
-2.25 > epiCoinTime > +2.25
1.2 > RFTime > 3.4

These cuts will be applied to physics data to select a clean sample of eπ events for further analysis.

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, binning, and kinematic selections are applied to both the data and the SIMC.
- This technique is model-dependent.
- Requires the SIMC empirical model to reproduce data.
- Only reliable if SIMC reproduces the data well in both shape and normalization.

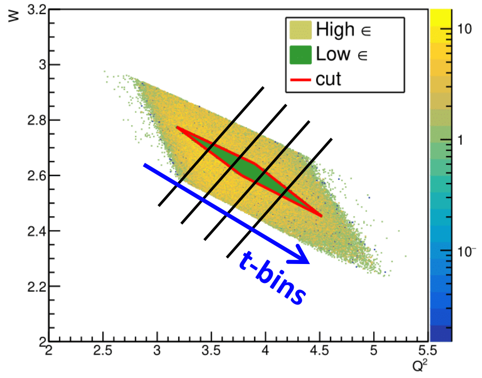
- Fit the Rosenbluth equation to extract the cross-section components.

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

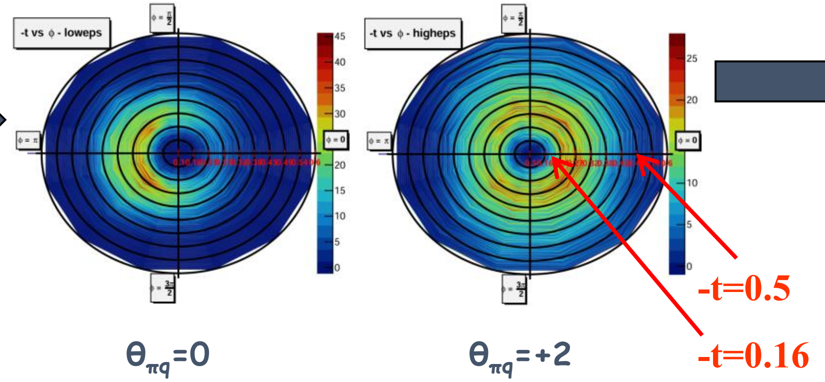
- Need to iteratively tune L/T/LT/TT empirical model until MC reproduces experimental data.

L/TSep Iteration Procedure

Diamond cut



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



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

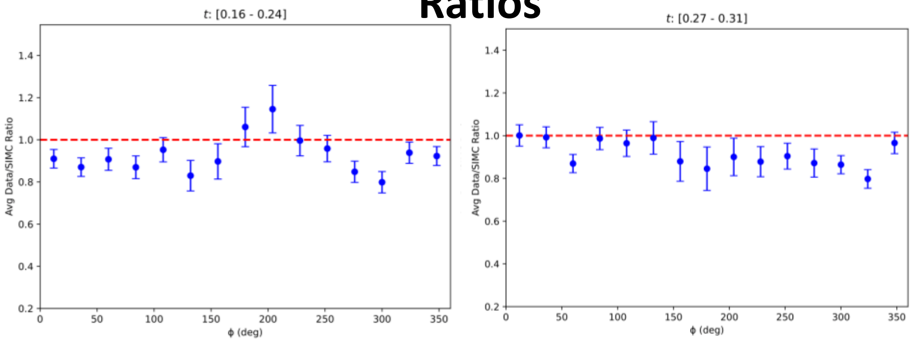
Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

For each π HMS setting, form ratio:

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

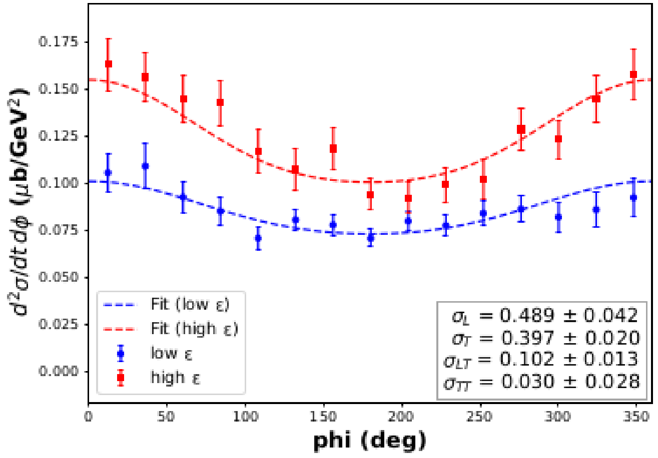
Combine ratios for π settings together, propagating errors accordingly.

Ratios



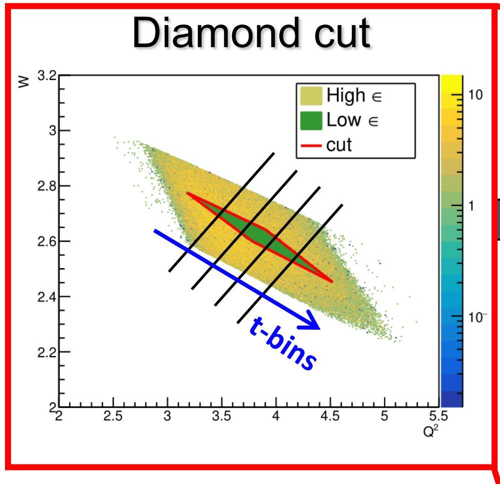
$$\left.\frac{d^2\sigma}{dtd\varphi}\right|_{EXP}=\left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\left.\frac{d^2\sigma}{dtd\varphi}\right|_{SIMC}$$

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



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

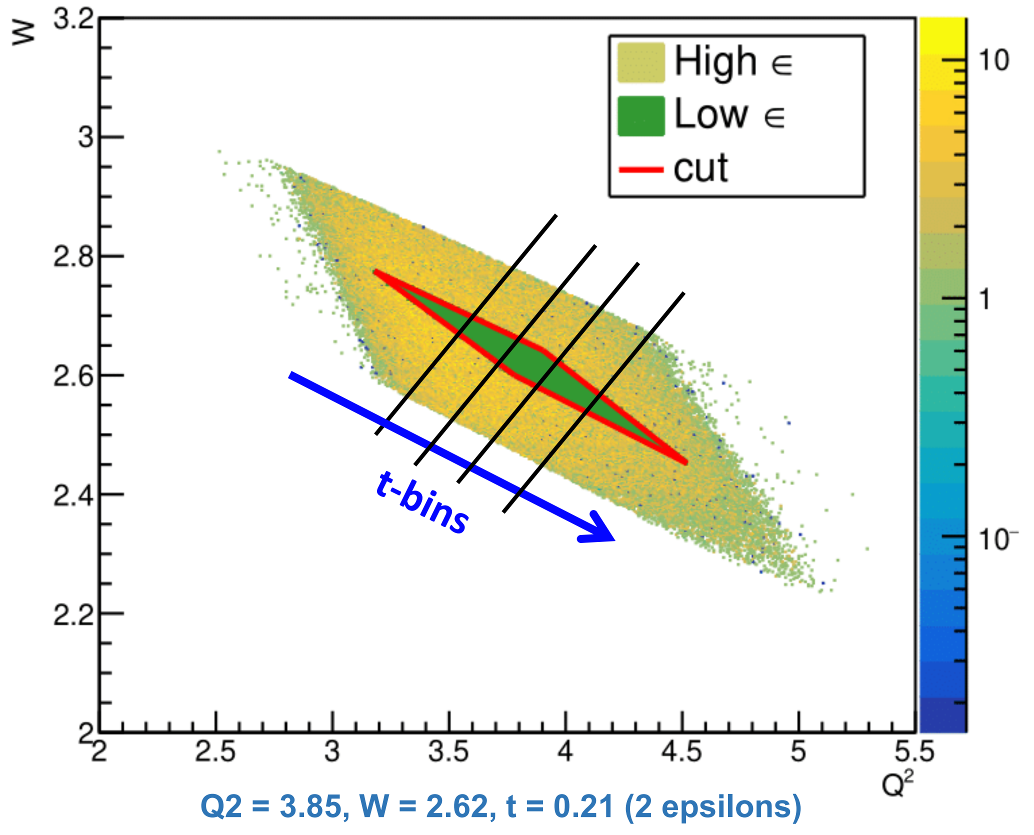
Diamond Region Selection



Improve φ coverage by taking data at

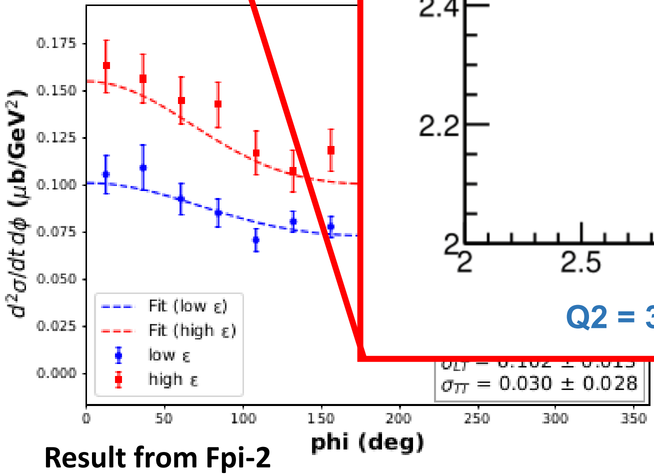
n

For each π HMS setting, form ratio:



Q2 = 3.85, W = 2.62, t = 0.21 (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

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

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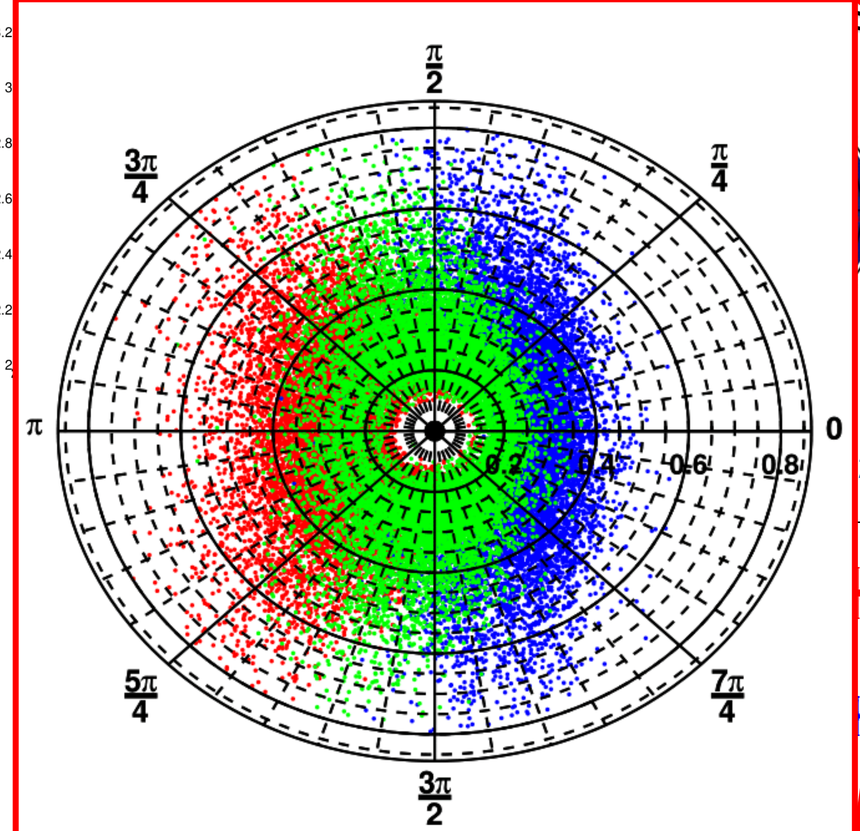
Full ϕ-Coverage

Diamond cut

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



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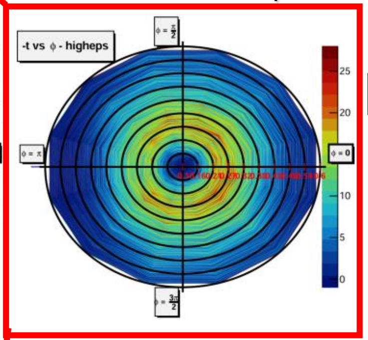


$\theta_{\pi q}$=+2

2.62, t = 0.21 (2 epsilons)

low ε
high ε
σ_{LT} = 0.102 ± 0.013
σ_{TT} = 0.030 ± 0.028
phi (deg)

Result from Fpi-2

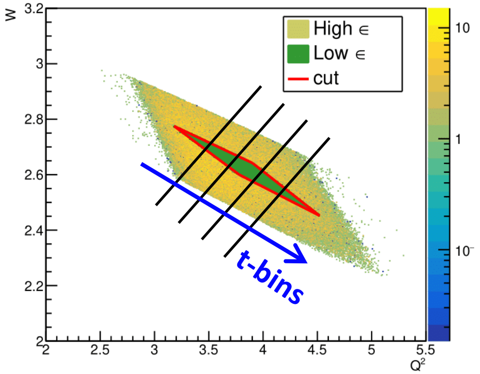
For each ... HMS setting, form ratio:

- 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.

$$2\pi \frac{d\sigma}{dt\,d\phi} = \ldots \frac{\ldots}{dt} + \ldots \frac{\ldots}{dt} + \sqrt{2\epsilon(\epsilon+1)} \ldots \frac{\ldots}{dt} \cos\phi + \epsilon \ldots \frac{\ldots}{dt} \cos 2\phi$$

L/TSep Iteration Procedure

Diamond cut



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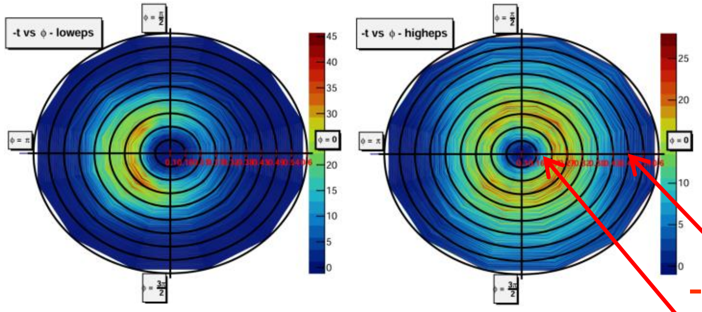


-t=0.5

-t=0.16

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

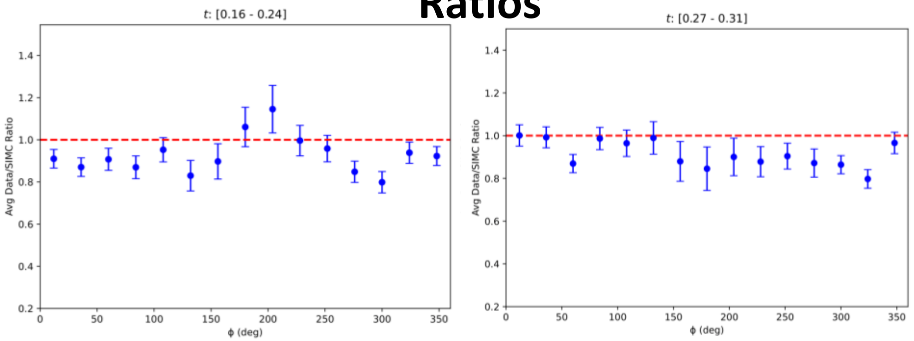
Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

For each π HMS setting, form ratio:

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

Combine ratios for π settings together, propagating errors accordingly.

Ratios



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

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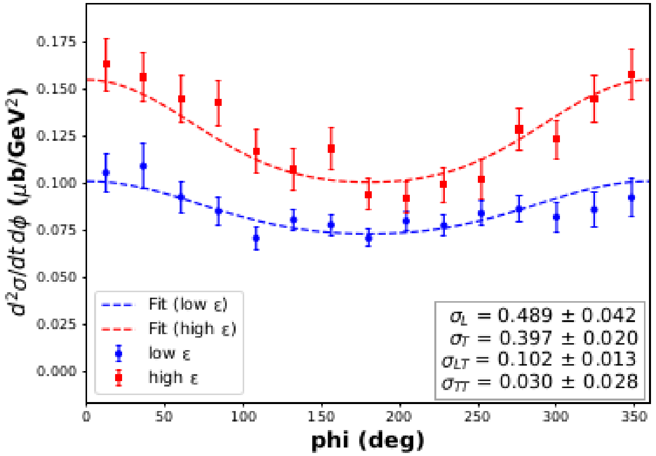


Yield Calculations

- Calculated normalized bin-by-bin data yield.

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

where,

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

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

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

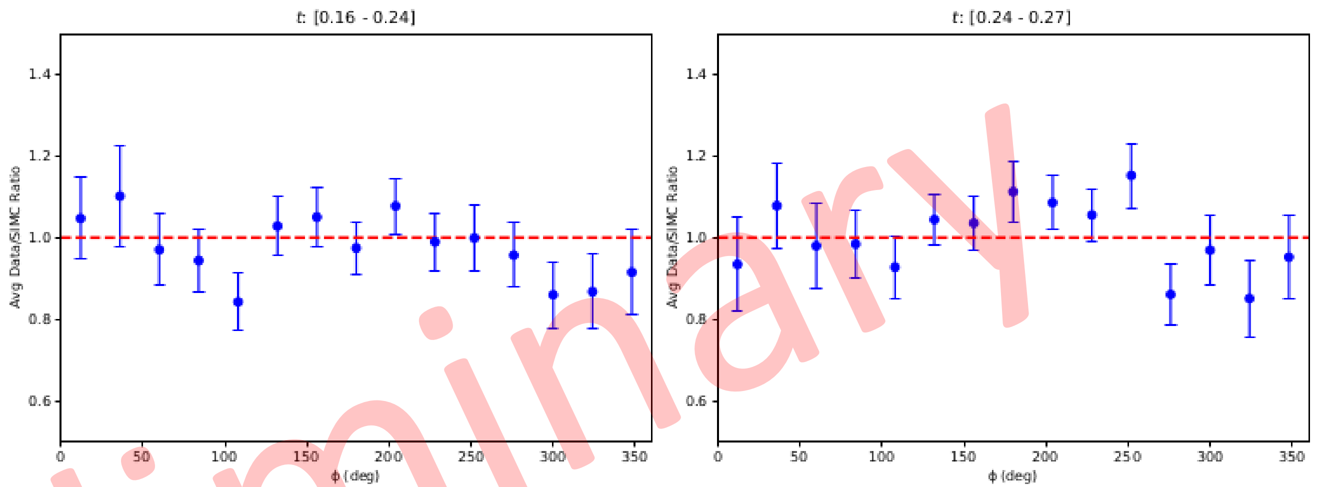
- Combined data from each pion arm angle setting per ϵ by calculating their error-weighted average.

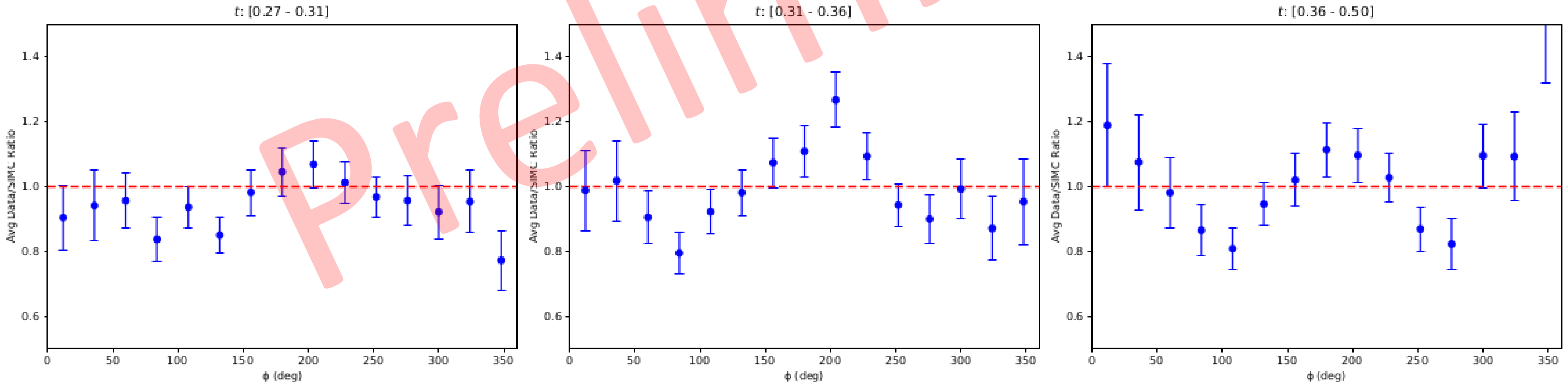
Normalization Factors	Comments
Charge	Calculated run-by-run
HMS & SHMS Tracking Efficiencies	> 98%
Live Time Correction	>98%
HMS Cerenkov Efficiency	>99%
HMS Calorimeter Efficiency	>99%
SHMS Aerogel Efficiency	>98%
HMS & SHMS Hodoscope Efficiency	>98%
RF Efficiency	>99%
Boiling Correction Factor	Calculated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

Low-epsilon Data/SIMC Ratios

Physics Setting:
Q3p85_W2p62_t0p21_loweps

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



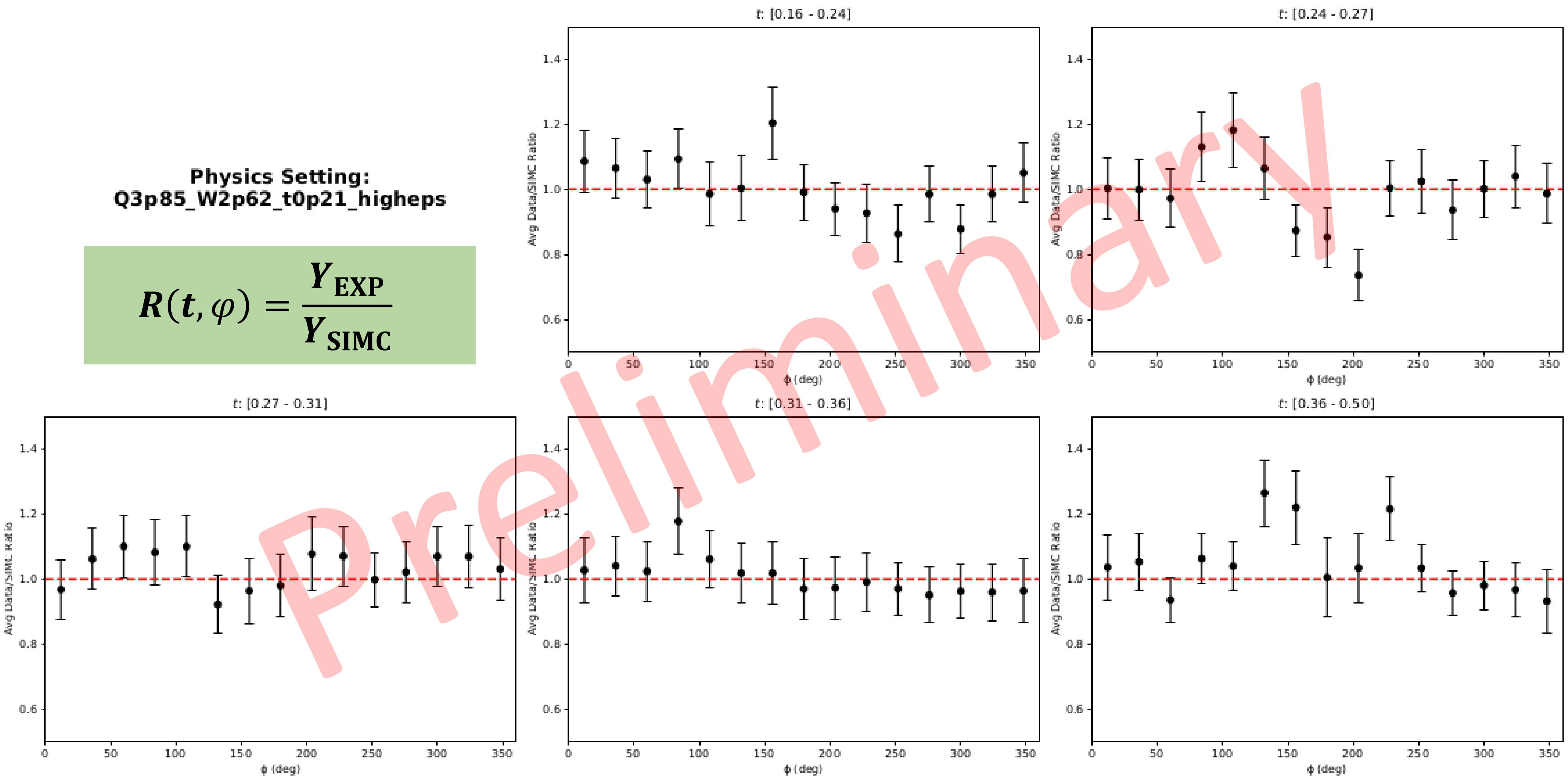


Physics Setting: Q^2=3.85 GeV^2, W=2.62 GeV

High-epsilon Data/SIMC Ratios

Physics Setting:
Q3p85_W2p62_t0p21_higheps

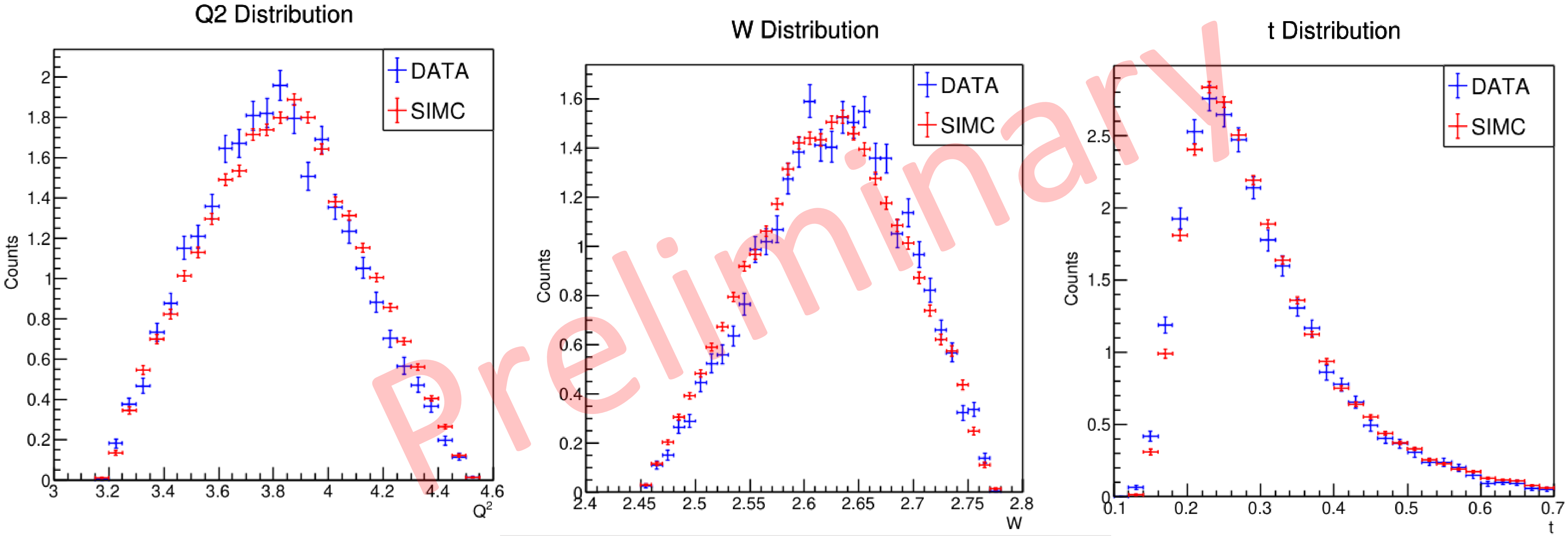
$$R(t,\varphi) = \frac{Y_{\mathrm{EXP}}}{Y_{\mathrm{SIMC}}}$$



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

Data/SIMC Comparison Plots

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



Physics Setting: Q^2=3.85 GeV^2, W=2.62 GeV low-eps Center

L/T Separated Cross-section Measurements

- Calculated unseparated cross-sections.

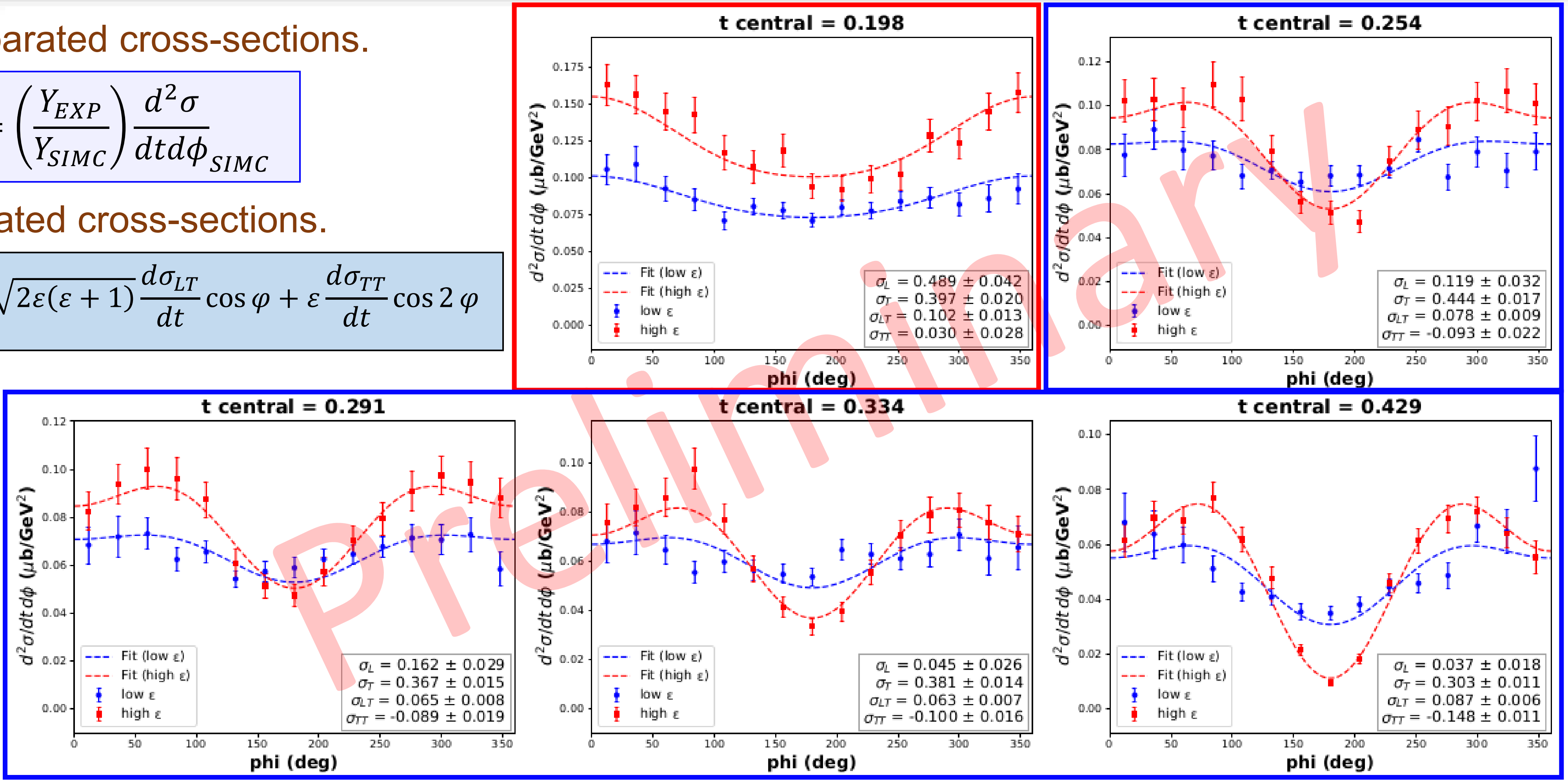
$$\frac{d^2\sigma}{dtd\phi}_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dtd\phi}_{SIMC}$$

- 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



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

Theoretical Model Comparison

- **Our philosophy is to publish our experimentally measured $\frac{d\sigma_L}{dt}$, so that updated values of $F_\pi(Q^2)$ can be extracted as better models become available.**

- Jefferson Lab F_π experiments use the Vanderhaeghen–Guidal-Laget (VGL) Regge model as it has proven to give a reliable description of σ_L across a wide kinematic domain.
  [Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]

- The VGL dramatically underestimates σ_T while doing a much better job on σ_L led to new model development, with the goal of increasing σ_T without degrading σ_L description.

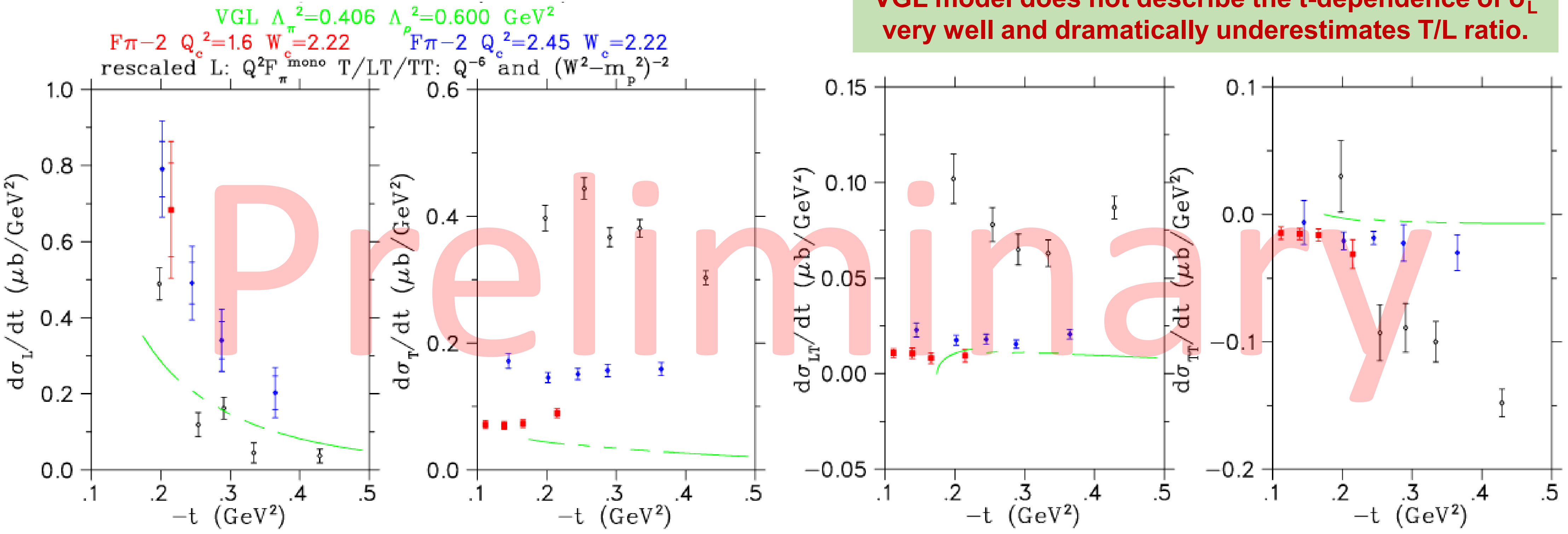
- Some recent model developments, more are welcome!
  - *T.K. Choi, K.J. Kong, B.G. Yu, J.Kor.Phy.Soc. 67(2015) L1089; arXiv: 1508.00969*
  - *T. Vrancx, J. Ryckebusch, PRC 89(2014)025203*
  - *M.M. Kaskulov, U. Mosel, PRD 81(2010)045202.*
  - *R.J. Perry, A. Kizilersu, A.W. Thomas, PLB 807(2020)135581*

- Compared results with VGL and CKY Models.

Comparison with VGL Model

- **σ_L:** results a little low compared to the scaled expectation from Fpi-2
  - If this is confirmed in our final analysis, it could indicate F_π is dropping more rapidly.
- **σ_T:** surprisingly large, an interesting rising trend from Q^2=1.6-2.45-3.85.
- **σ_{LT} & σ_{TT}:** also much larger than Fpi-2.

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



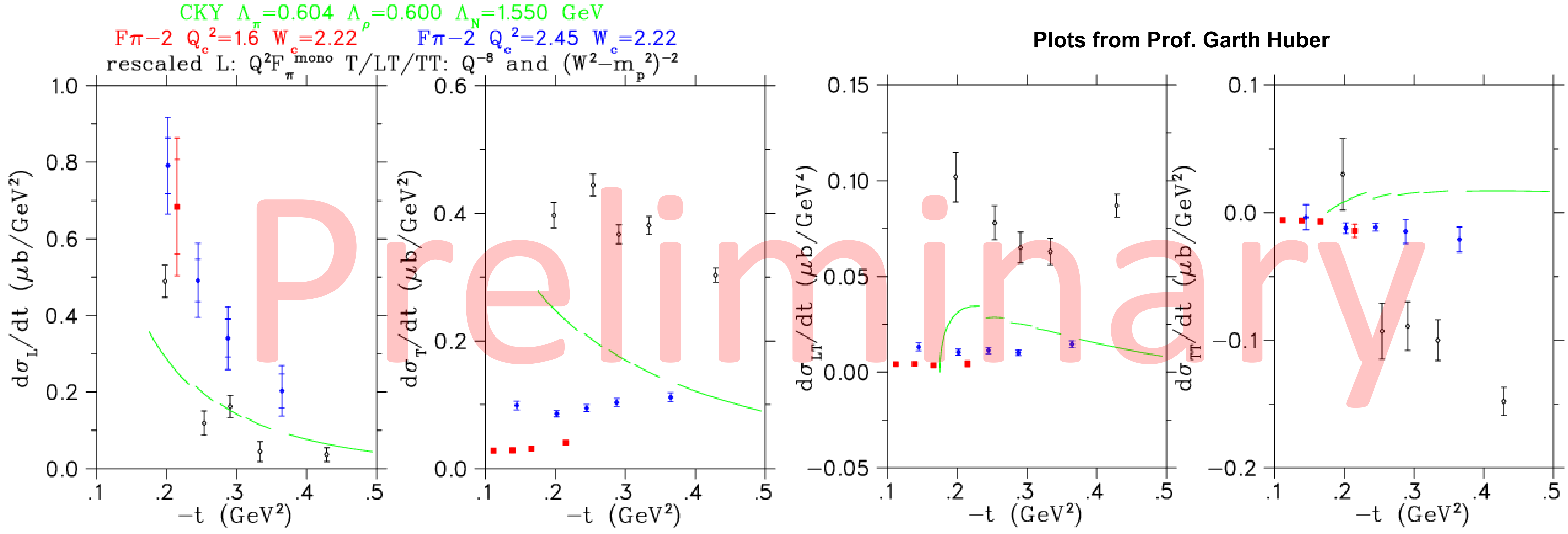
Plots from Prof. Garth Huber

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

Comparison with CKY Model

- **CKY model also does not describe t–dependence of σ_L very well.**
- **Much better T/L ratio, as expected, but still low.**
- **σ_{LT} somewhat higher than VGL, but still lower than**

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 $\mathrm{p}(\mathrm{e}, e'\pi^{+})\mathrm{n}$ 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.
- Next step will be to work on the other two physics settings to calculate the L/T separated cross-sections using the Rosenbluth technique and extract the pion form factor.
- Then will do a 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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