Exploring Hadronic Structure: Precision Rosenbluth Separation for the Pion Form Factor at Jefferson Lab

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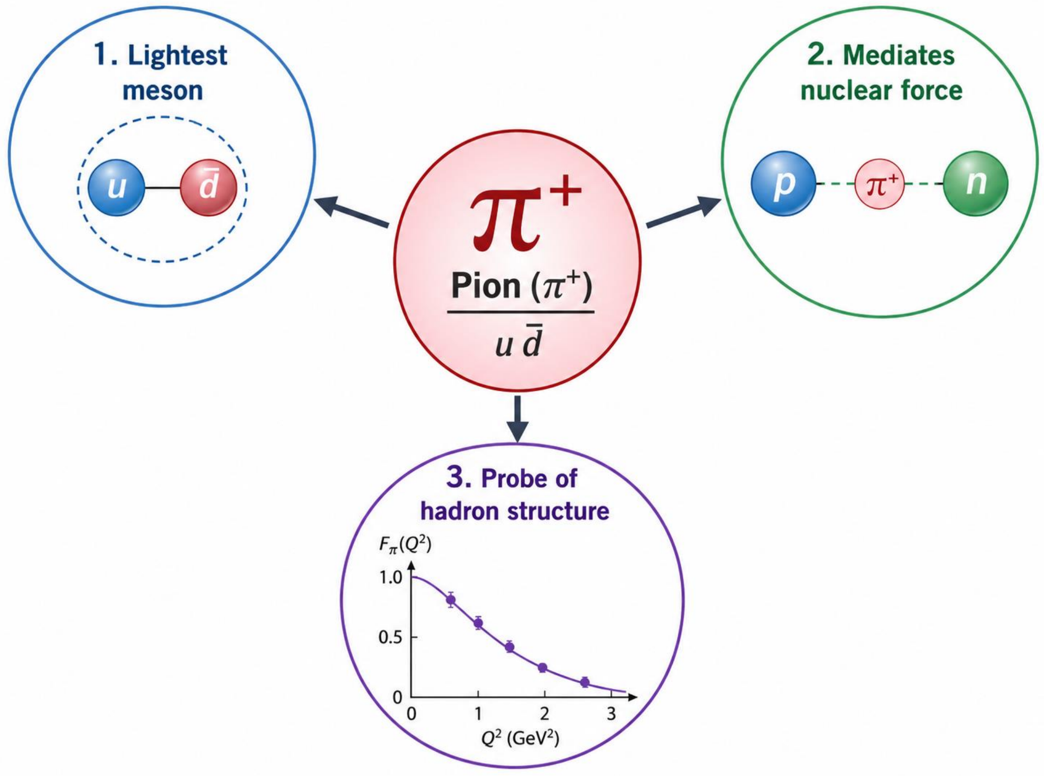
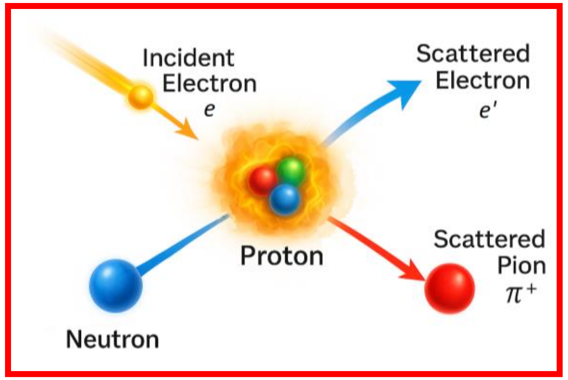
Scientific Motivation

- The 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.**
- **Pion** is the lightest meson and provides an ideal testing ground for our understanding of the bound $q\bar{q}$ hadronic system.
- **Pions mediate the residual strong force that helps bind nucleons inside the nucleus.**
- **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 $8.5\,\mathrm{GeV}^2$) checks the validity of QCD-based theories, including the transition region between perturbative and non-perturbative approaches**.



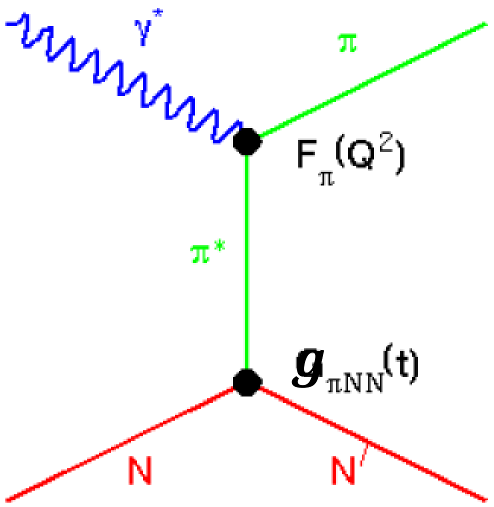
Pion Form Factor Measurement

- 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, CKY and PKT Models for $F_\pi^2(Q^2, t)$ extraction.

Rosenbluth Separation Technique

- **Rosenbluth separation required to isolate σ_L for L/T separation.**

- The physical cross-section for the electroproduction process is given by;

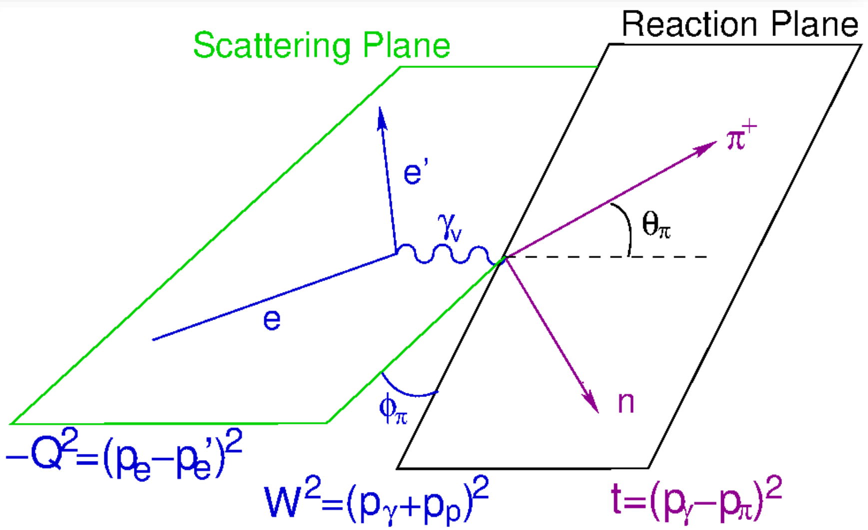
$$2\pi \frac{d^2\sigma}{dt d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$

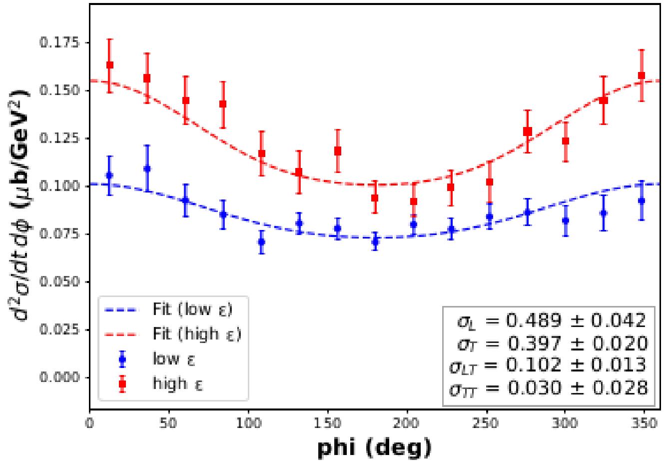
- Here "ϵ" is polarization of virtual photon.

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

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

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





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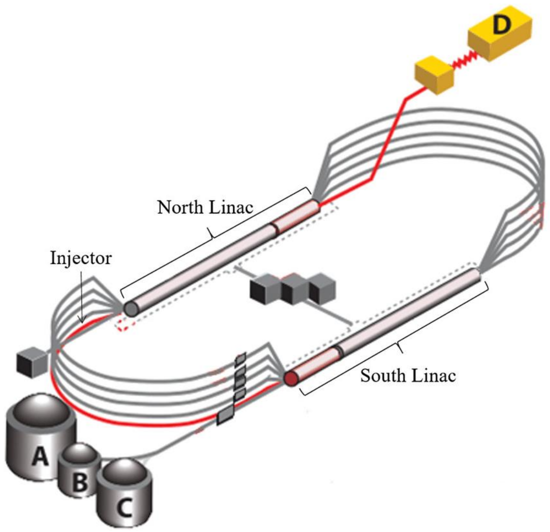
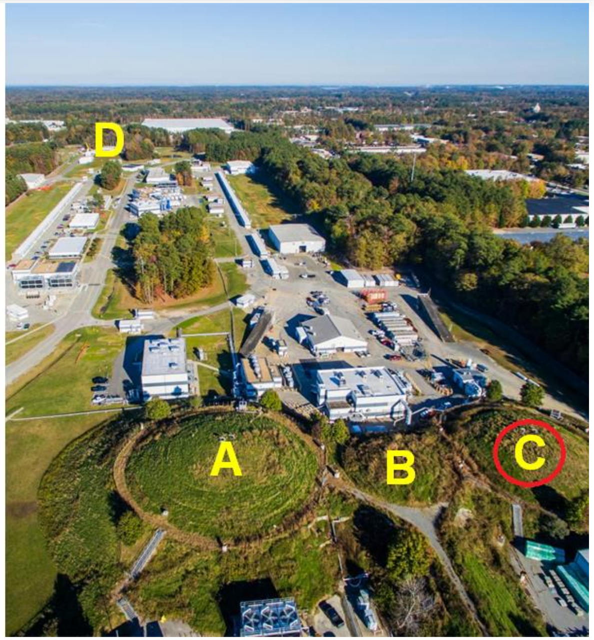
Pion-LT Experiment at JLab

- Located at Newport News, Virginia, USA.
- 2 Superconducting LINACs configured as "Racetrack".
- Continuous Electron Beam Accelerator Facility (CEBAF).
- Capable of $12 GeV$ beam up to $200 \mu A$.
- Four experimental halls, all running unique experiments and capable of running simultaneously.





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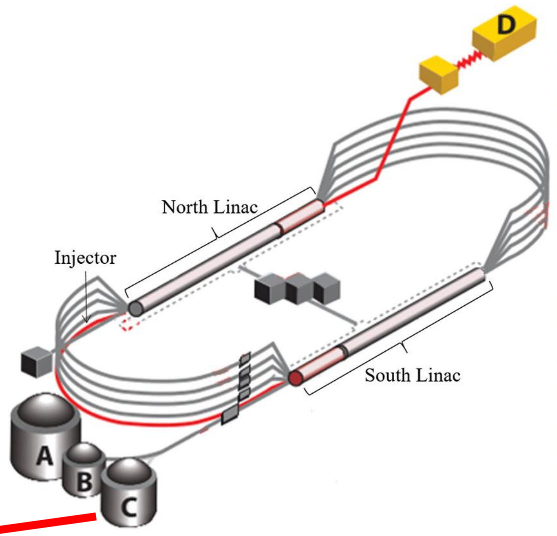
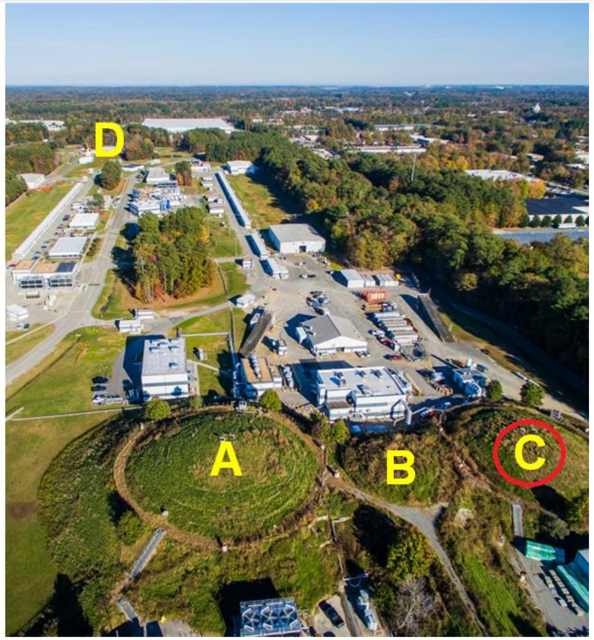
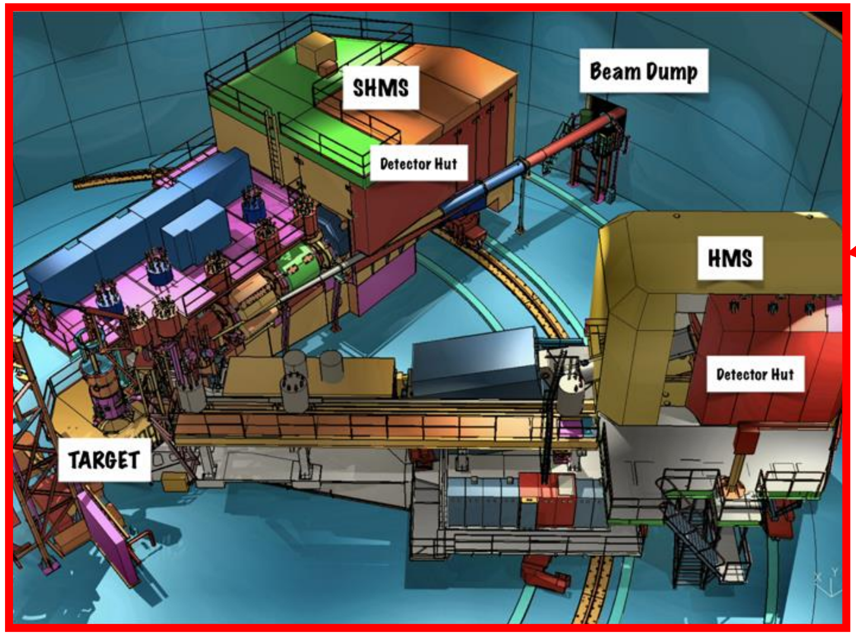






- Specially designed to measure precise cross-sections and form factors for mesons.
- Hall C has a target and two detector arms.
- Target can be Liquid H_2, Liquid D_2or solid targets.
- Two detectors are;
  - High Momentum Spectrometer (HMS)
  - Super High Momentum Spectrometer (SHMS)

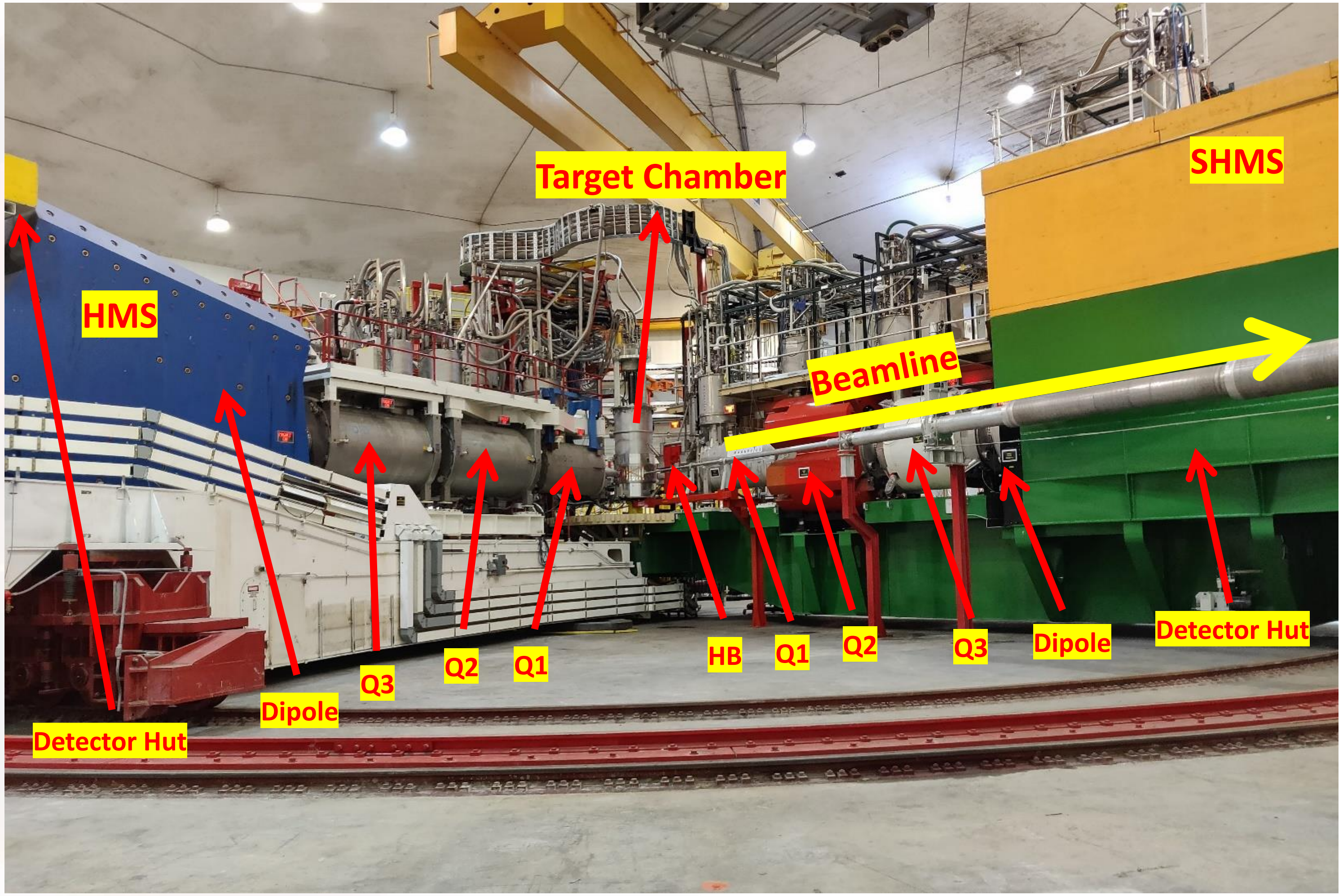
Hall C Spectrometers

- Both spectrometers are movable and have sets of quadrupole (Q), dipole (D) superconducting magnets and a Detector Hut.

- Both spectrometers are rotatable and contain similar detector packages.

Spec	Angle range (deg)	Momentum range
HMS	10.5 – 90	0.5 – 7 GeV
SHMS	5.5 – 40	0.5 – 11 GeV

- Took coincidence data; simultaneously detected **electrons in HMS** and **pions in the SHMS**



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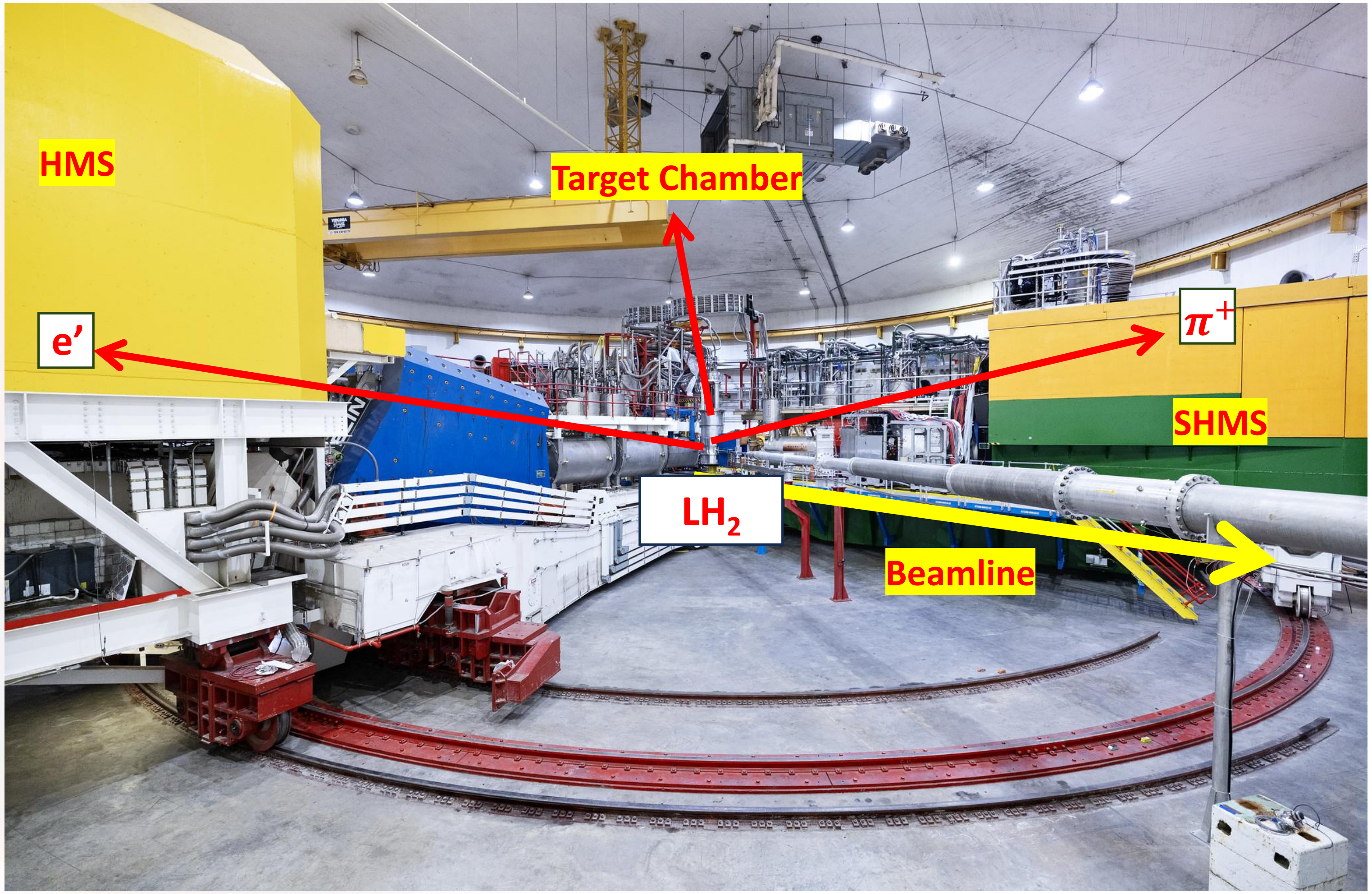
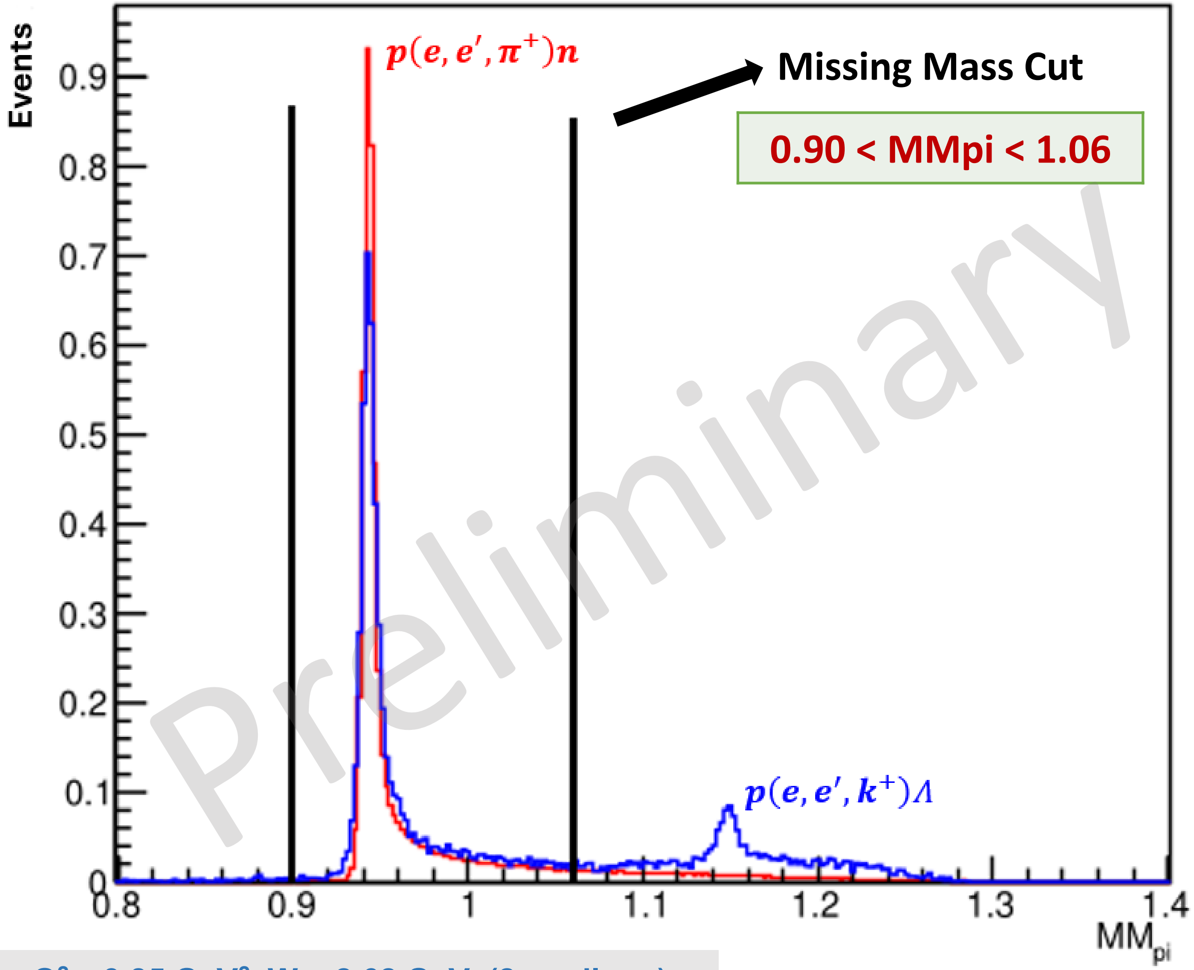


Selection of Event Sample

- Selected electrons in HMS in coincidence with pions in the SHMS.
- Missing particle reconstruction (neutron).

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

- 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 goal is to calculate the experimental cross-sections using the ratio method.

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

- 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.

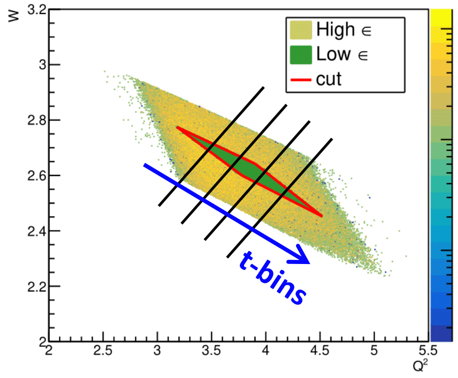
- Fit the Rosenbluth equation to extract the cross-section components.

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

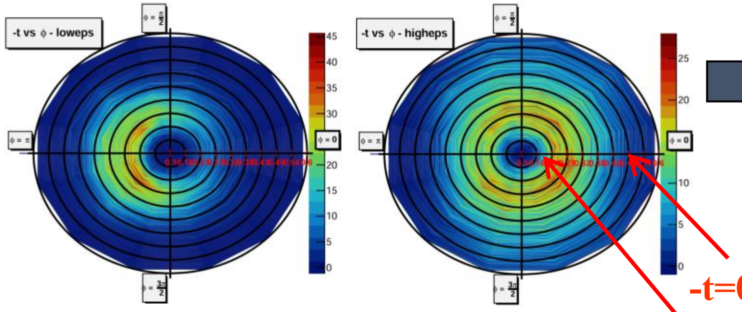
- Need to iteratively tune L/T/LT/TT empirical model until Monte Carlo reproduces experimental data.

L/T Separation Iteration Procedure

Diamond cut



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



-t=0.5

-t=0.16

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

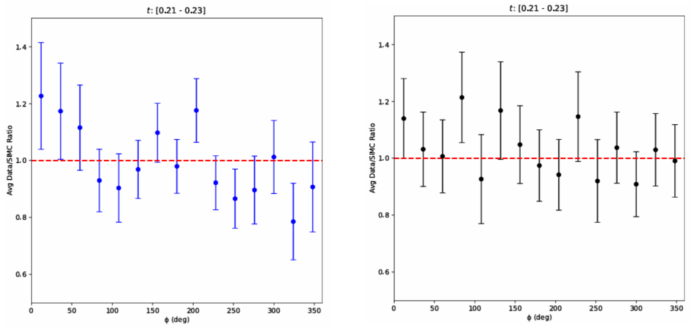
Q^2 = 3.85 GeV², W = 2.62 GeV (2 epsilons)

For each π HMS setting, form ratio:

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

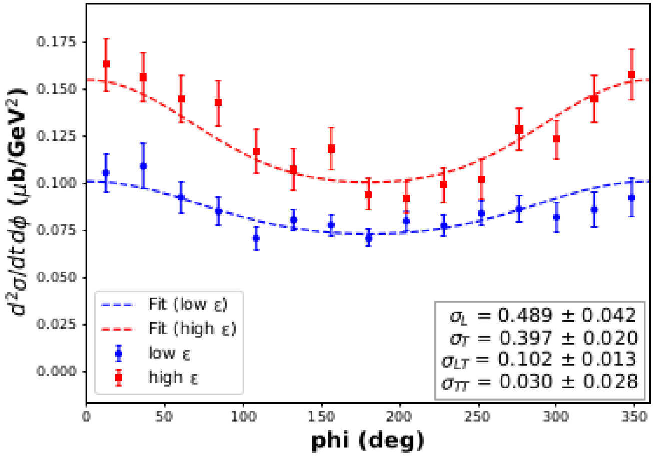
Combine ratios for π settings together, propagating errors accordingly.

Ratios



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

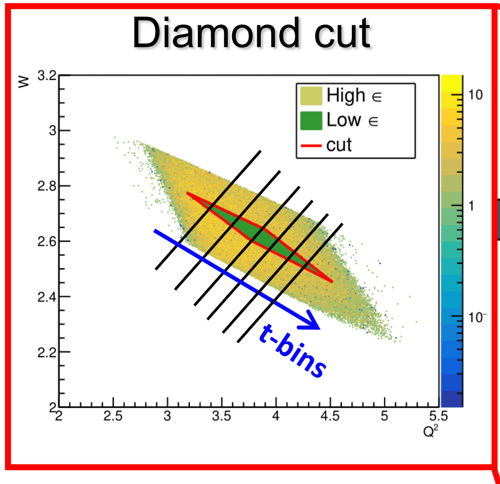
$$2\pi\frac{d\sigma}{dt d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$



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

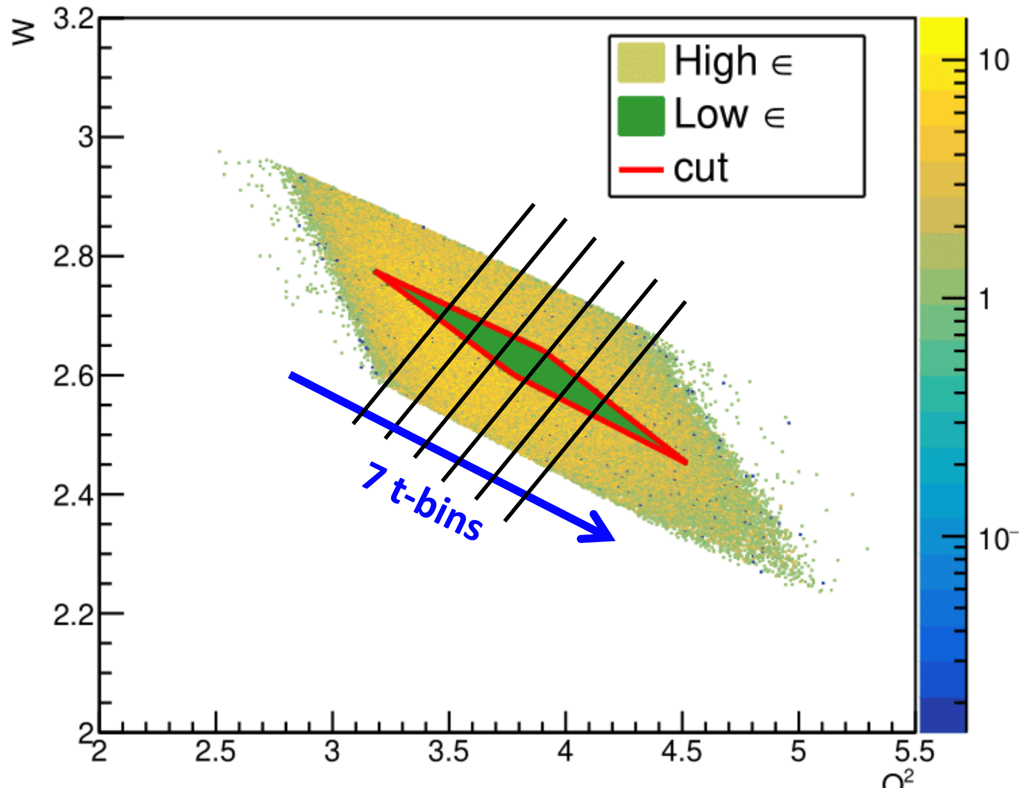
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Importance of Diamond Region



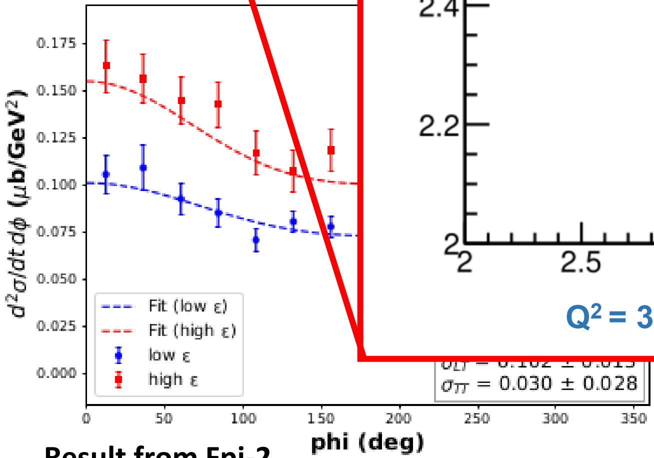
Improve φ coverage by taking data at

For each π HMS setting, form ratio:



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

- **Electron spectrometer acceptance is larger for high ϵ.**
- **Selected an overlapped phase-space region.**
- **Divided data into 7 t-bins based on data statistics.**
- **Purpose is to ensure consistency across different kinematic settings and measure the t-dependence**



Result from Fpi-2

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

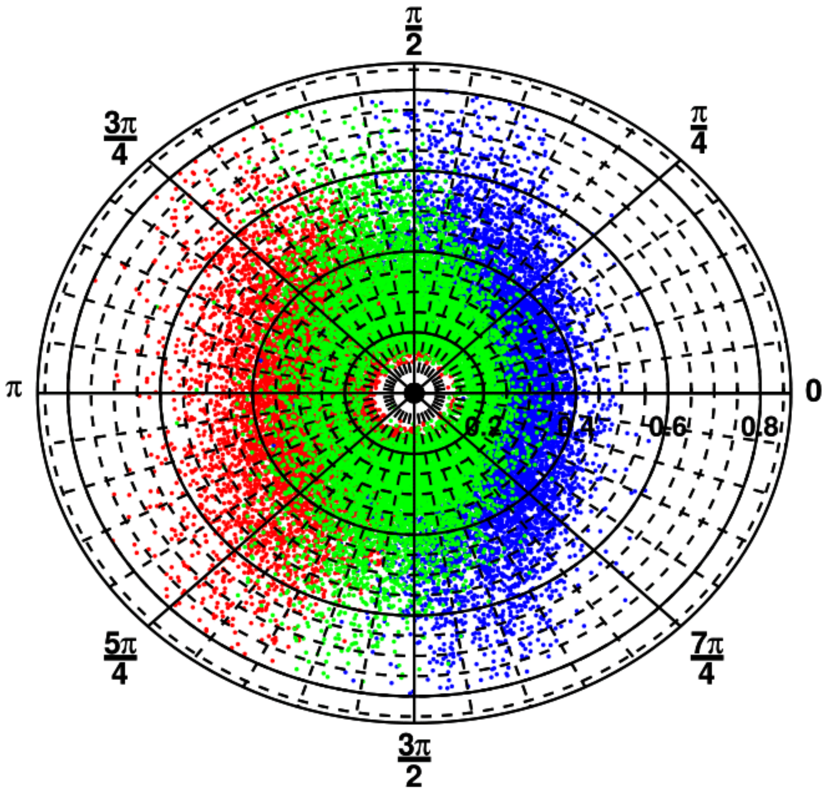
University of Regina

Full ϕ-Coverage

Diamond cut

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

For each ε HMS setting, form ratio:



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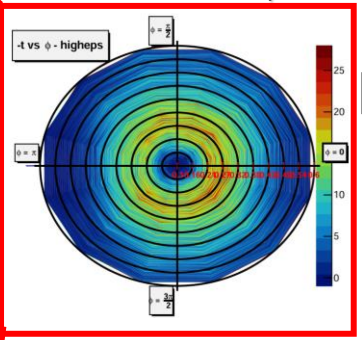
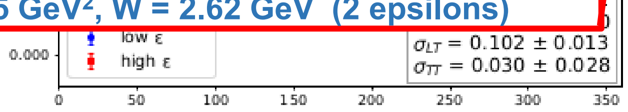


$\theta_{\pi q}=+2$

2.62, t = 0.21 (2 epsilons)



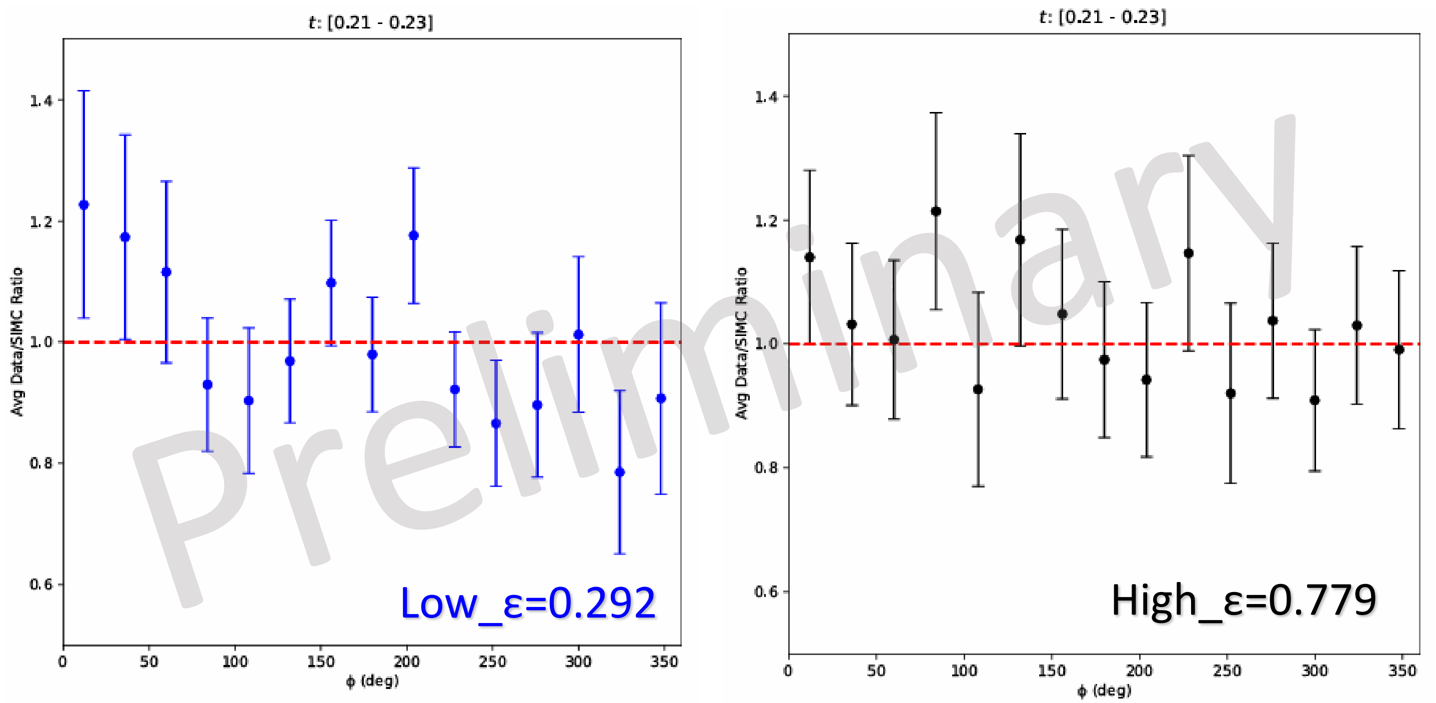
Result from Fpi-2

- 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.

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

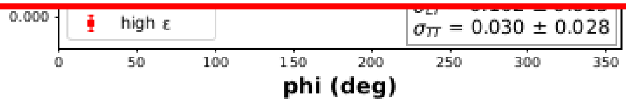
Low and High Epsilon Data/MC Ratios

Improve φ coverage by taking data at



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

Ratios are consistent



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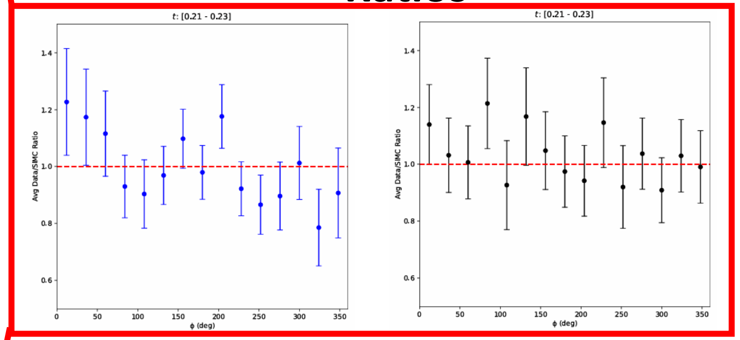

$$\left(\frac{d^2\sigma}{dtd\varphi}\right)_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\left(\frac{d^2\sigma}{dtd\varphi}\right)_{SIMC}$$

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

L/T Separa... ts

In
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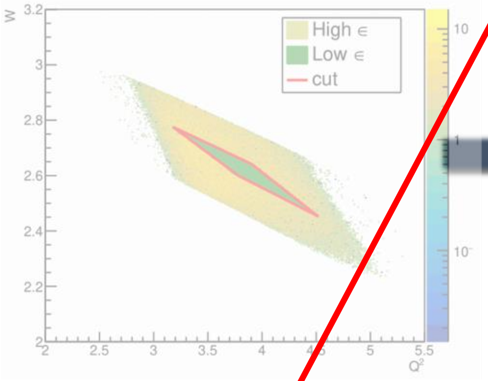
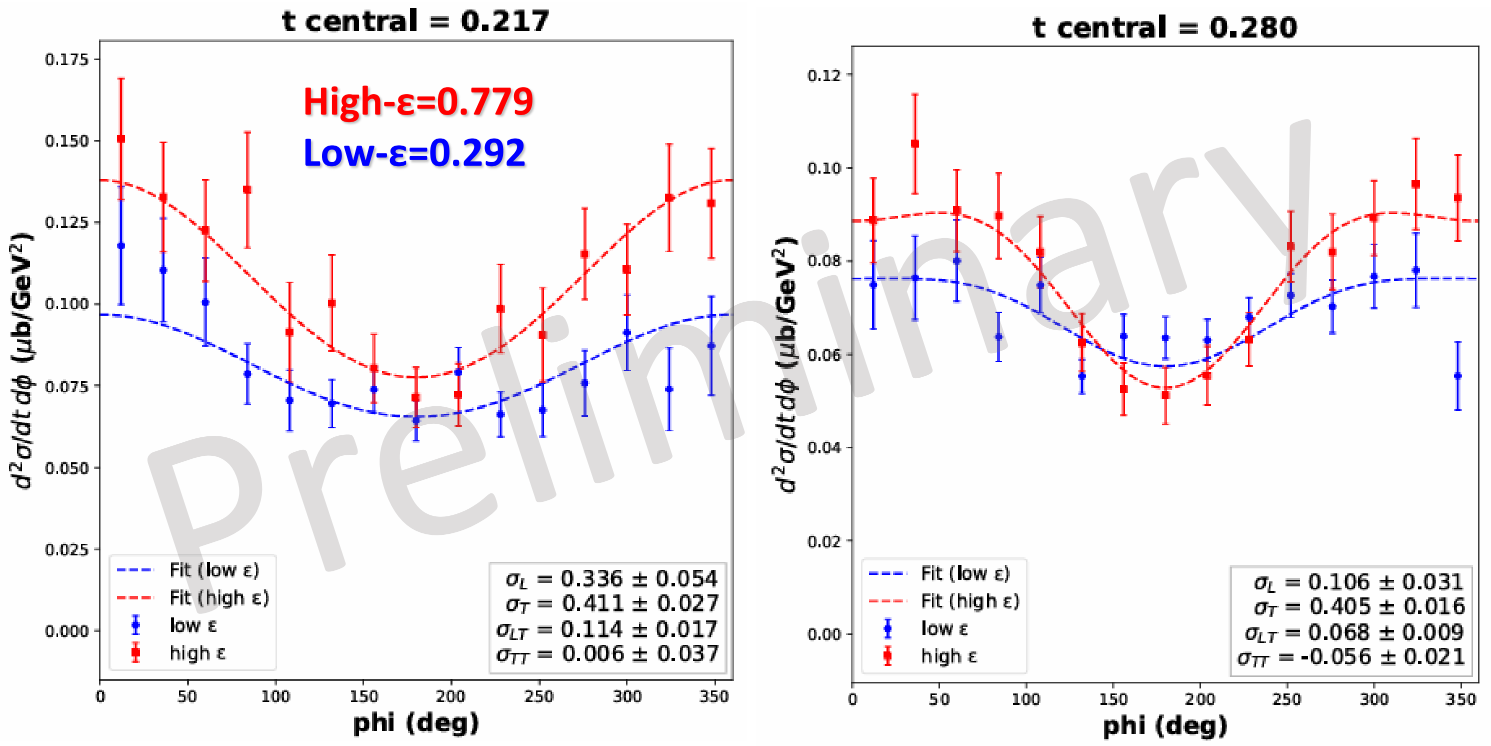
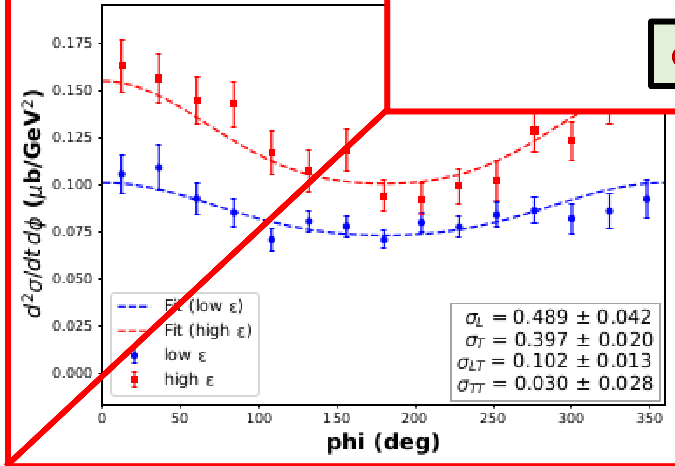




σ_L drops as we go to higher t

Q^2 = 3.85 GeV², W = 2.62 GeV (2 epsilons)



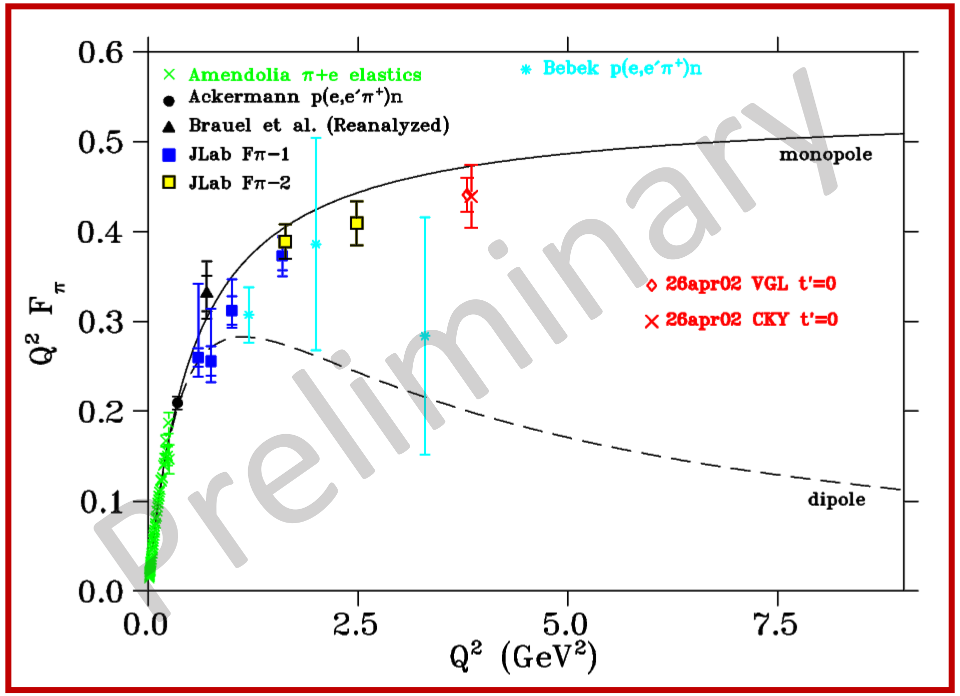
Extract via simultaneous fit of L,T,LT,TT

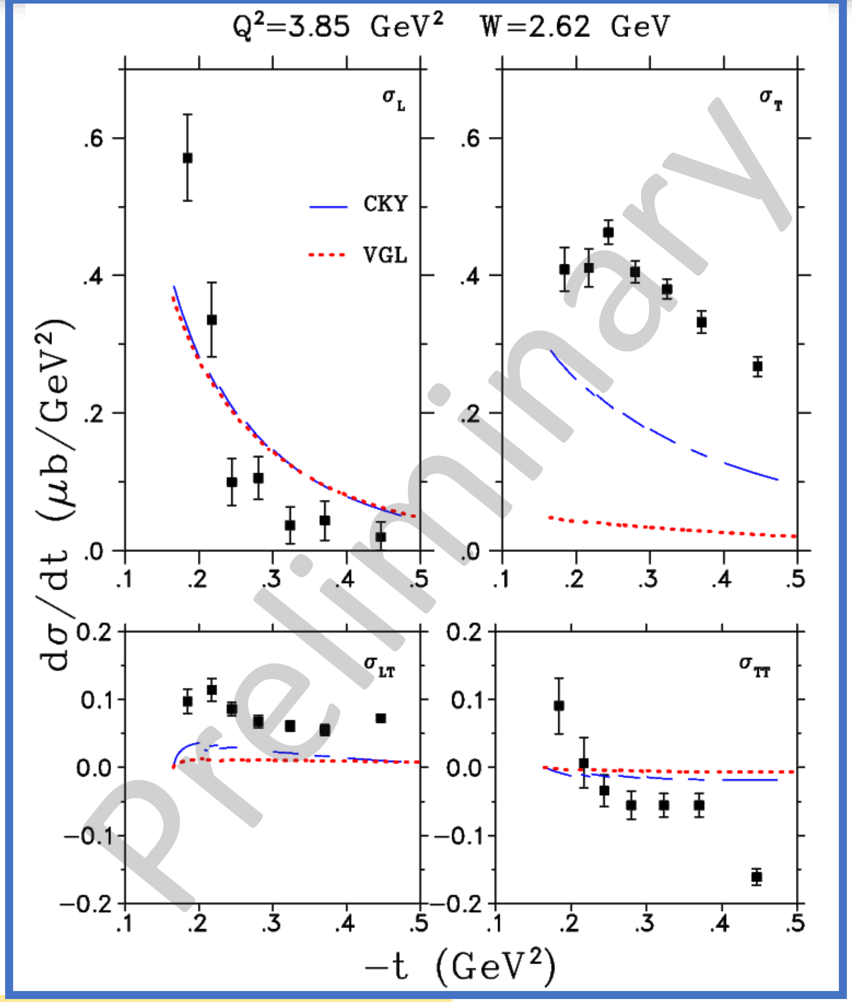
$$\frac{d^2\sigma}{dt\,d\varphi}_{EXP} = \left(\frac{Y_{EXP}}{Y_{SIMC}}\right)\frac{d^2\sigma}{dt\,d\varphi}_{SIMC}$$

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

Results from Moderate-Q^2 Pion-LT Experiment

- The VGL model struggles to describe the t-dependence of σ_L well, and dramatically underestimates T/L ratio.
- The CKY model also struggles to describe the t-dependence of σ_L well, but has a better T/L ratio.
- Comparison with PKT Model is in progress.

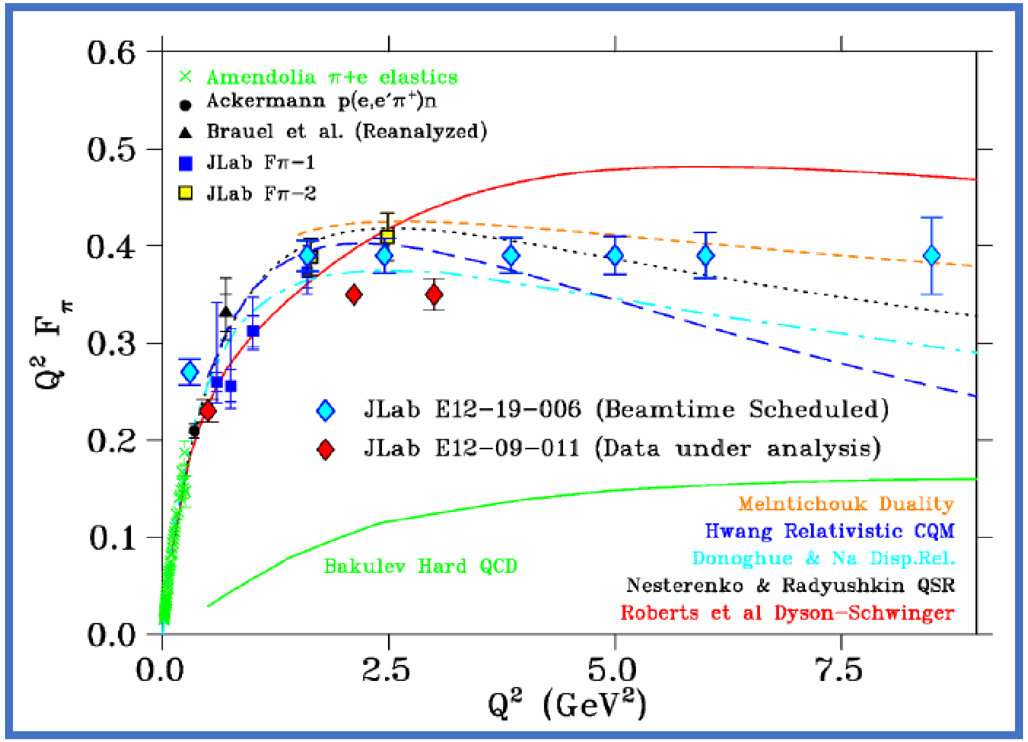




Model is evaluated at precise kinematics of data. Discontinuities indicate change in (Q^2,W) for each t-bin.

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, CKY, and PKT theoretical models.**
- **Results will help to understand the dependence of the Form factor and in validating theoretical models.**



Projected Results

Acknowledgement

- **Spokespersons:**
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  Nathan Heinrich (URegina), Muhammad Junaid (URegina),
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THANKS

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JSA
A SURA Company

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BACKUP

Literature

Scientific Motivation

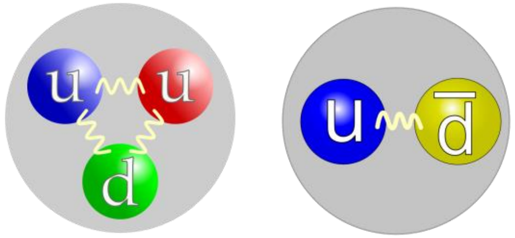
- Understanding the origin of the masses of protons and neutrons, as > 99% of the visible mass of the universe resides in atomic nuclei.

- Proton consists of two up-quarks (**u**) and one down-quark (**d**).

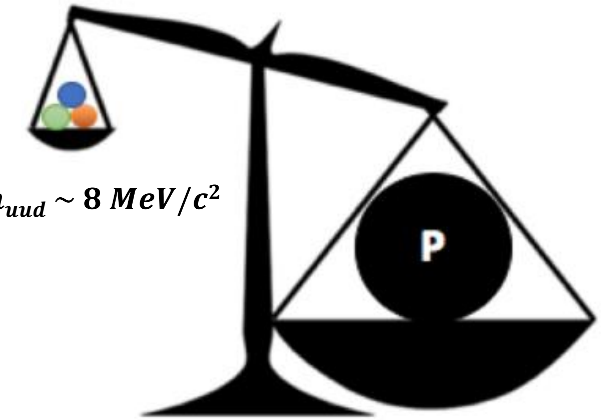
$$m_p \approx 938\ \text{MeV}/c^2$$

$$m_u \approx 2\ \text{MeV}/c^2 \text{ and } m_d \approx 4\ \text{MeV}/c^2$$

Total mass = (2 x 2 + 4) MeV/c² = 938 MeV/c² ?



- The Higgs mechanism, through which fundamental particles acquire mass, can explain only a small fraction of the nucleon mass.
- The majority of the mass comes from the strong interactions that bind the quarks and gluons together.
- We do not adequately understand the mass generation mechanisms of the strong interaction.

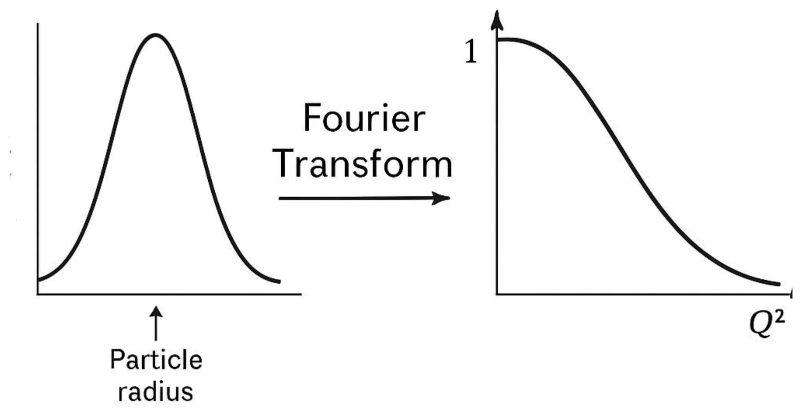


- To address the emergence of hadronic mass, one can examine internal structure of the lightest mesons i.e pions, kaons.
- **Form factor** can be studied to understand the internal structure of hadrons.

What is Form Factor?

- Form Factor ($F(Q^2)$) describes the transverse spatial position of partons within hadrons.
- $F(Q^2)$ is the Fourier transform of the particle's spatial charge density ($\rho(r)$).

$$F(Q^2) = \int \rho\,(r) e^{iQ\cdot r} d^3 r$$



- At low Q^2, the form factor directly relates to particle's charge radius $\langle r^2 \rangle$.

$$\langle r^2 \rangle = -6 \left. \frac{dF(Q^2)}{dQ^2} \right|_{Q^2=0}$$

- At high Q^2, form factor follows predictions from perturbative QCD and helps to understand nature of the quark-gluon coupling constant renormalization.

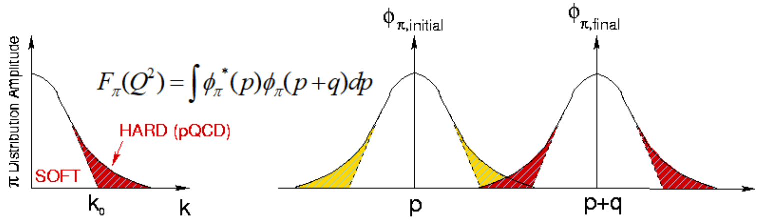
$$Q^2 F_\pi(Q^2) \rightarrow 16\pi\alpha_s(Q^2) f_\pi^2 \qquad (Q^2 \rightarrow \infty)$$

- Measuring the pion form factor at various Q^2 checks the validity of QCD-based theories, including the transition between region between perturbative and non-perturbative approaches.

Pion Form Factor

- Mesons give an ideal testing ground for our understanding of bound quark-antiquark system.
- Form Factor describes transverse spatial position of partons within hadrons.

- The Form Factor of a particle is defined in Quantum Field Theory as an overlap integral;



- where φ is the wave function is an important variable to study as it allows for comparison with theory:

Experiment Comparison Charge Density

$$\frac{d\sigma}{d\Omega} \rightarrow |F(q^2)| \leftrightarrow F(q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \leftarrow$$

Theory Dirac/ Schrodinger Equation

- The meson wave function can be separated into $\varphi_\pi^{\text{soft}}$ with only low momentum contributions $(k < k_0)$ and a hard tail $\varphi_\pi^{\text{hard}}$. While $\varphi_\pi^{\text{hard}}$ can be treated in pQCD, $\varphi_\pi^{\text{soft}}$ cannot.
- From a theoretical standpoint, the study of the Q^2–dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.

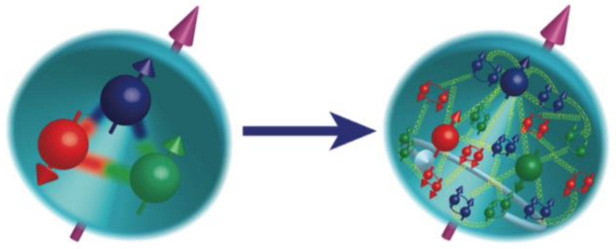
Scientific Motivation

- QCD is an extremely successful theory, but it struggles to predict the internal structure of hadrons.

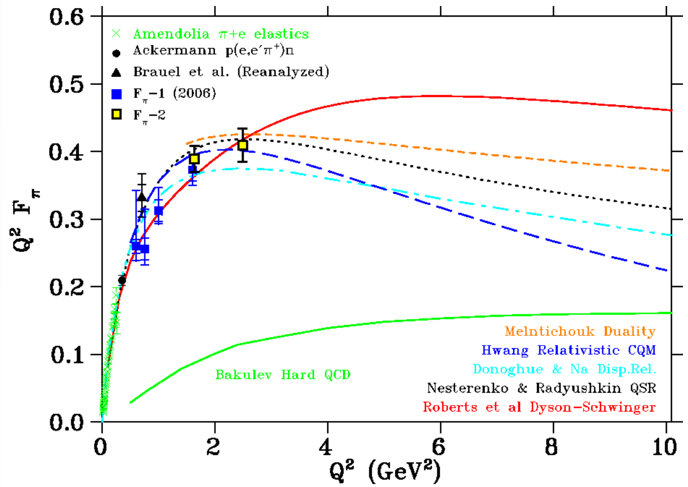
- In QCD, there are two main domains of the strong interaction.
  - Perturbative Quantum Chromodynamics (pQCD) corresponds to short-range quark-gluon interaction part (asymtotic freedom)
  - Non-Pertubrbative Quantum Chromodynamics (non-pQCD) corresponds to long-range quark-gluon interaction part (confinement).

- pQCD predicts the F_π at very high Q^2 (i.e $Q^2 \rightarrow \infty$) and it is well understood.
- In non-pQCD region, various theoretical models struggle to predicts F_π at low Q^2 (i.e $Q^2 \approx 1 - 10\ \text{GeV}^2$).

- **These QCD-based models disagree on how quickly the transition between pQCD and non-pQCD should occur.**
- **Pion Form factor** is an important observable that can be studied to understand the transition region between pQCD and non-pQCD.

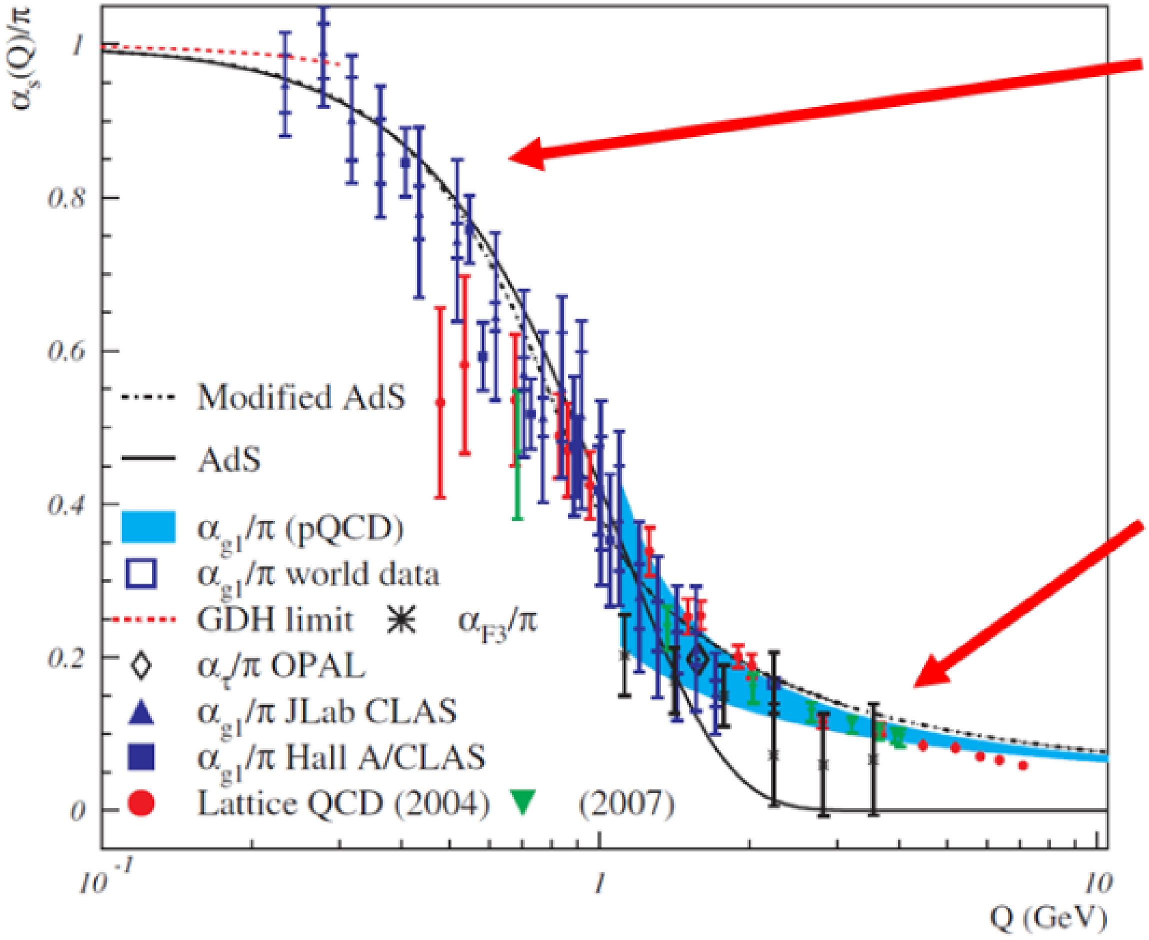


$x \approx 0.3$ $x \approx 0.0001$



University of Regina Go far, Together.

Dual Nature of QCD



Long Distance (Low Energy) Interaction:

- Quarks strongly bound within hadrons
- Color Confinement
- Quantitative QCD description of hadron properties remains a puzzle
- Unfortunately, this is the regime under which we live!

Short Distance (High Energy) Interaction:

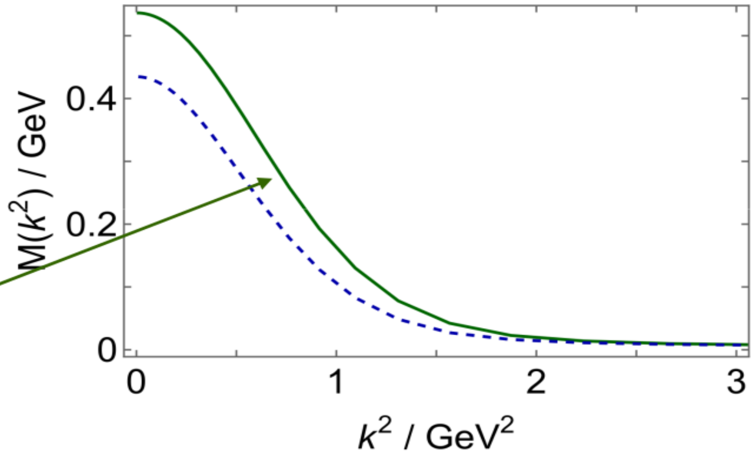
- Short range interaction is weak
- Quarks insoide hadrons behave as though they are nearly unbound
- Can understand behaviour using perturbative QCD (pQCD)
- Asymtotic Freedom

F_π sensitivity to Emergent Mass

- At emperically acessible energy scales, $\boldsymbol{F_\pi}$ is sensitive to emergent mass scale in QCD.

- Two dressed-quark mass functions distinguished by amount of DCSB

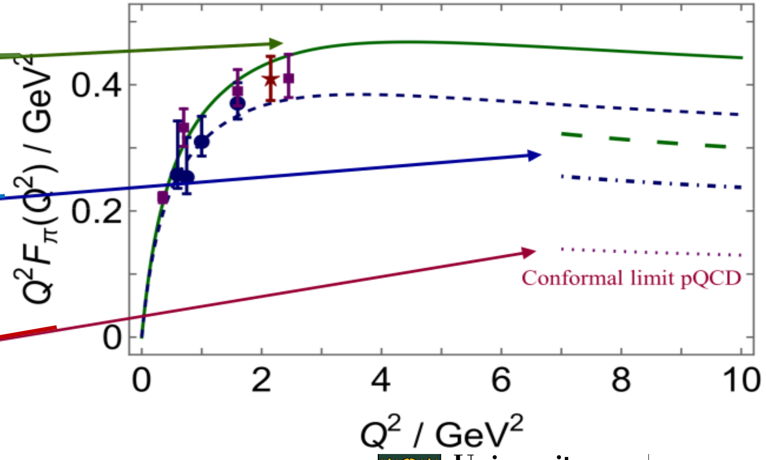
  - DCSB emergent mass generation is 10% stronger in system characterized by solid green curve, which is more realistic case.



- $\boldsymbol{F_\pi(Q^2)}$ obtained with these mass functions.
  - $r_\pi = 0.66$ fm with solid green curve
  - $r_\pi = 0.73$ fm with solid dashed blue curve

- $\boldsymbol{F_\pi(Q^2)}$ predicts from QCD hard scattering formula, obtained with related, computed pion PDAs
- QCD hard scattering formula, using conformal limit of pion's twist-2 PDA

$$\phi_\pi(x) = 6x(1-x)$$

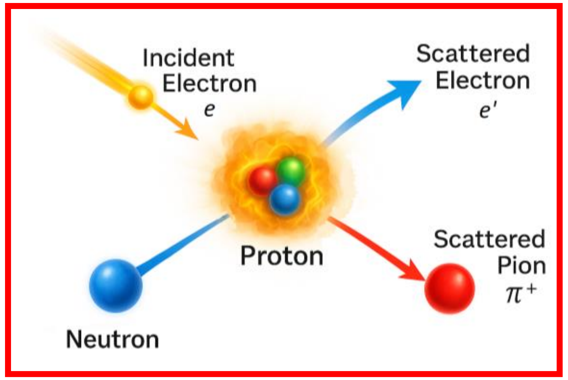


Chen, et al., PRD **98**(2018)091505(R); Aguilar et al, EPJA **55**(2019)190

Pion Form Factor Measurement

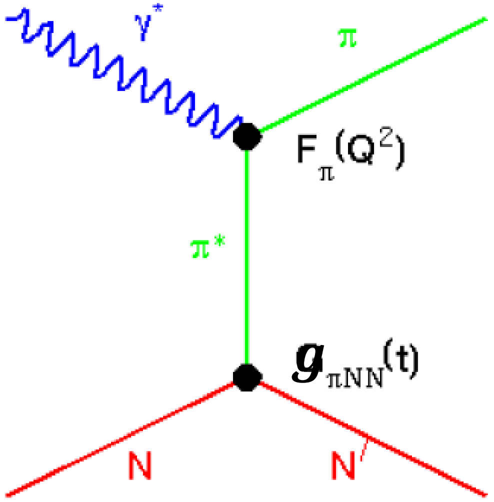
❑ Direct Measurement:

- Elastic Scattering of electrons from pions gives
$$e + \pi^+ \rightarrow e' + \pi^{+\prime}$$
- **Limitation:** Pion ($\pi^{\pm}$) targets not possible due to short lifetime ($\sim 2.6 \times 10-8$s)
- 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:

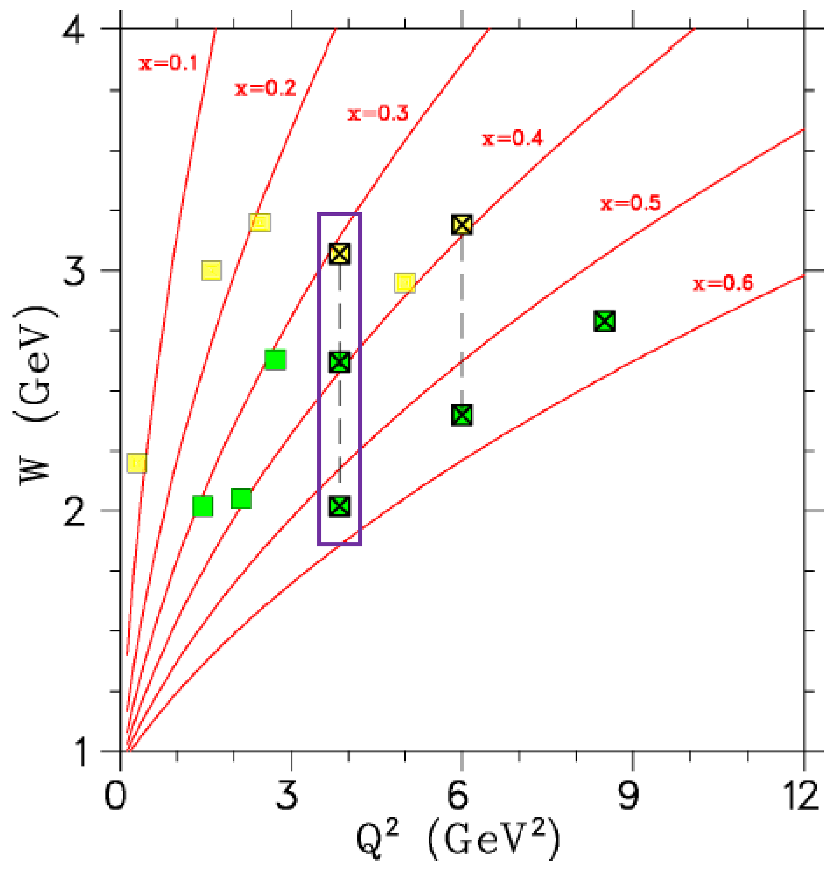
- Above $Q^2 > 0.3\text{GeV}^2$, F_π is measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e, e'\pi^+)n$
- Indirect measurement – Form factor extraction requires a model.
- As an illustration of how σ_L connects to $F_\pi^2(Q^2, t)$, we consider a simple Born Term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



Jefferson Lab
Thomas Jefferson National Accelerator Facility

Pion-LT Experiment

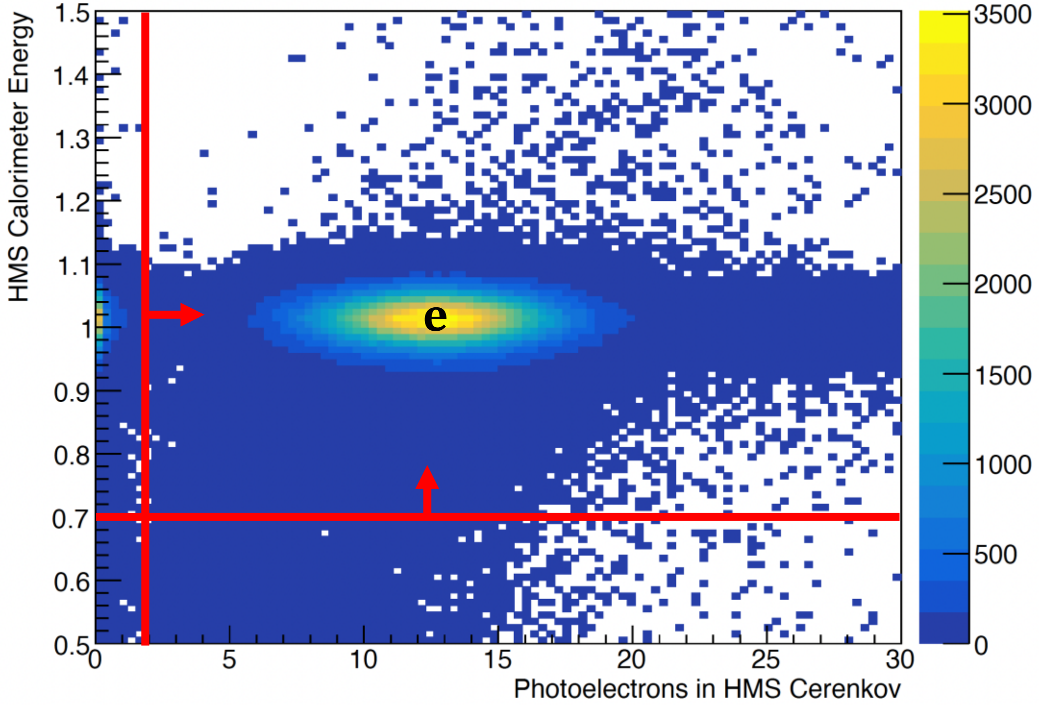
- The Pion-LT experiment was conducted over a wide kinematic range at the Hall C facility, JLab.
- **Green points represent the Pion Form Factor Study.**
- **Yellow points represent the Pion Scaling Study.**
- Vertical black dashed lines shows W-scan at fixed $\boldsymbol{Q^2}$.
- Points marked with 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.



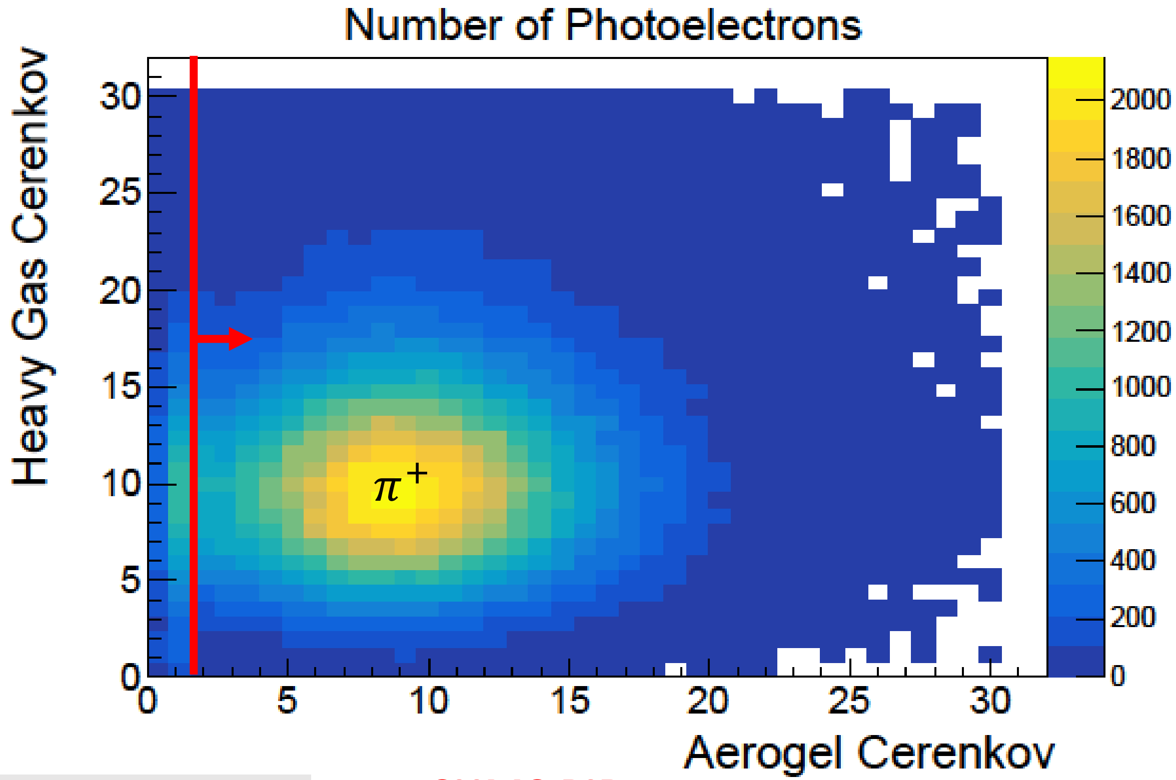
PID Study

Event Selection Criteria

- Purpose is to select the clean pion events sample in coincidence with the electrons to measure the cross-sections.
- Cuts must be tight, but not so close as to sacrifice efficiency across the acceptance.
- Overall, detector efficiencies are greater than ~98%.



HMS PID



SHMS PID

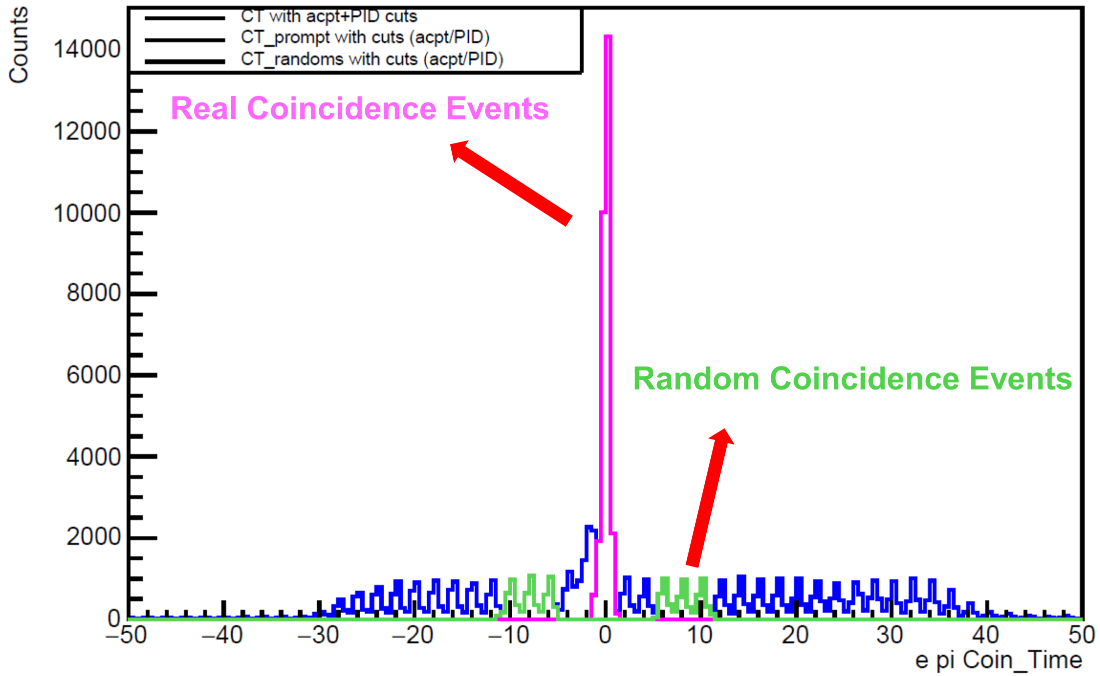
Q2 = 3.85, W = 2.62, t = 0.21 (2 epsilons)

Event Selection Criteria

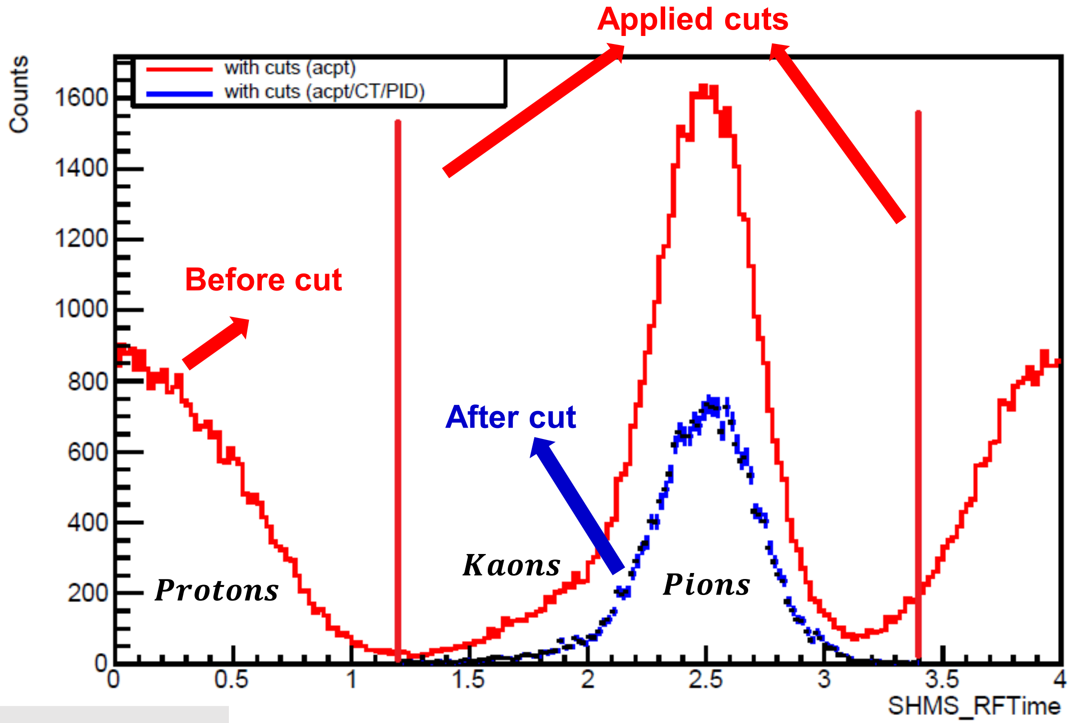
- CoinTime (CT) is given as:

$$t_{coin} = t_{HMS} - t_{SHMS}$$

- Used to eliminate random background caused by random coincidences.



- RF time refers to the time difference between a detected event and the nearest preceding RF signal of the electron linac.
- Enables the differentiation between pions, kaons, and protons due to their distinct velocities.



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

Efficiency Study

Tracking Efficiency Study

- The purpose of this study is to determine the tracking efficiency to account for the loss in the experimental normalized yields due to the bad track reconstruction by the Hall C analyzer (HCANA).
- The tracking efficiency can be expressed as;

$$\epsilon_{track} = \frac{N_{did,track}}{N_{should,track}}$$

- $N_{should,track}$ is the events where at least one track was expected after cuts (Acceptance + HMS PID +SHMS PID)
- $N_{did,track}$ is the events where at least one track formed by tracking process after cuts ($N_{should,track}$ + DC tracks > 0).

- The tracking efficiency error calculation can be expressed as;

$$\delta\epsilon_{track} = \sqrt{\frac{(N_{should,track} \times N_{did,track}) - (N_{did,track} \times N_{did,track})}{(N_{should,track})^3}}$$

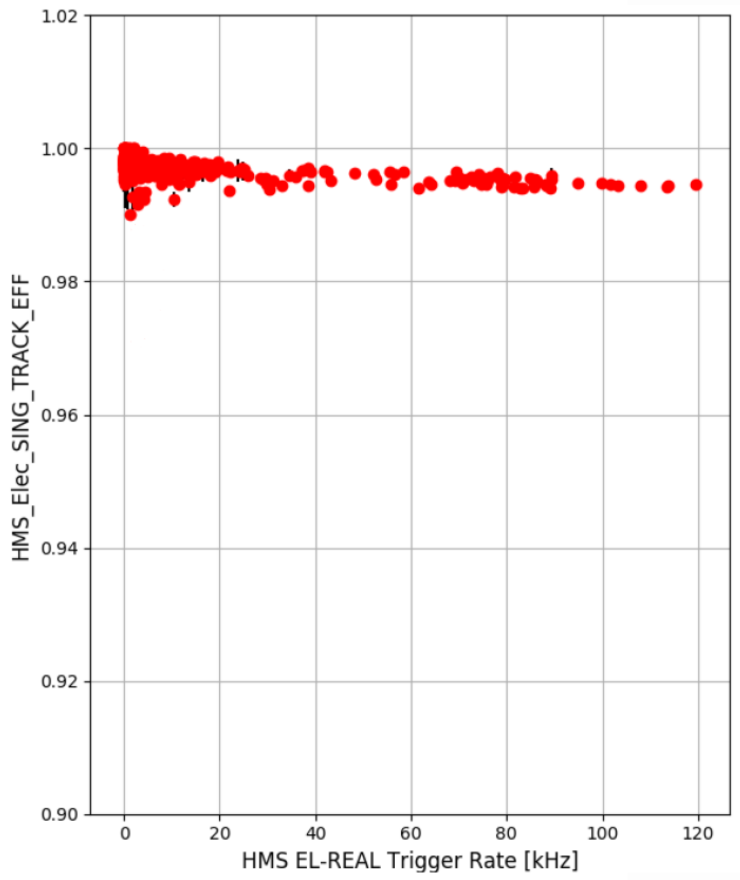
HMS Acceptance Cuts*	SHMS Acceptance Cuts
$-8.0\% \geq \delta \geq 8.0\%$	$-10.0\% \geq \delta \geq 20.0\%$
$-0.08 \geq x'_{tar} \geq +0.08$	$-0.08 \geq x'_{tar} \geq +0.08$
$-0.045 \geq y'_{tar} \geq +0.045$	$-0.04 \geq y'_{tar} \geq +0.04$

HMS PID Cuts (Electrons)
HMS Gas Cerenkov (NPE) > 1.5
HMS Calorimeter (Energy) > 0.7

SHMS PID Cuts (Pions)	SHMS PID Cuts (Protons)
HGC Cerenkov (NPE) > 1.0	HGC Cerenkov (NPE) > 1.0
Aerogel (NPE) > 1.5	Aerogel (NPE) > 1.5
Calorimeter (Energy) > 0.05	Calorimeter (Energy) > 0.05

- δ is the deviation of particle momentum from the spectrometer central momentum
- x'_{tar} and y'_{tar} are the angle of the particle trajectory at the target.
- NPE (Number of Photoelectrons) corresponds to the number of photoelectrons detected by a photomultiplier tube (PMT) when a charged particle passes through a detector.

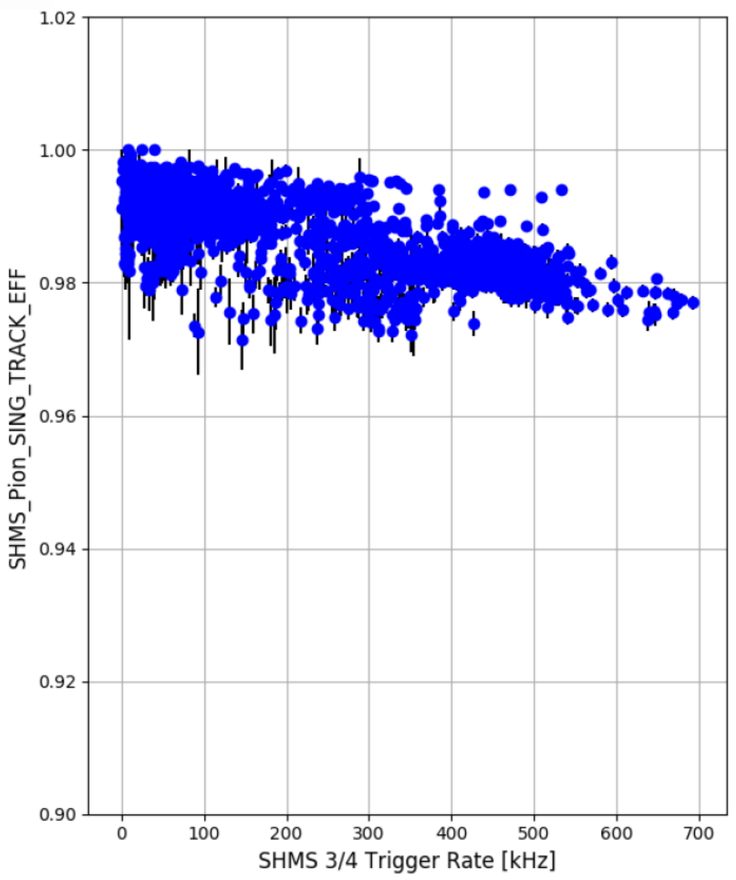
Tracking Efficiency Study



HMS Electron Tracking Efficiency

Tracking Efficiency plots from physics data.

- Both electron and pion tracking efficiencies are plotted against the detector trigger rates to check the rate dependence.
- Overall, the pion and electron tracking are looking good.
- The electron tracking is consistently near 100% ($\gtrsim$ 99%).
- The pion tracking has a bit of rate dependence and maintained above ~ 97%.

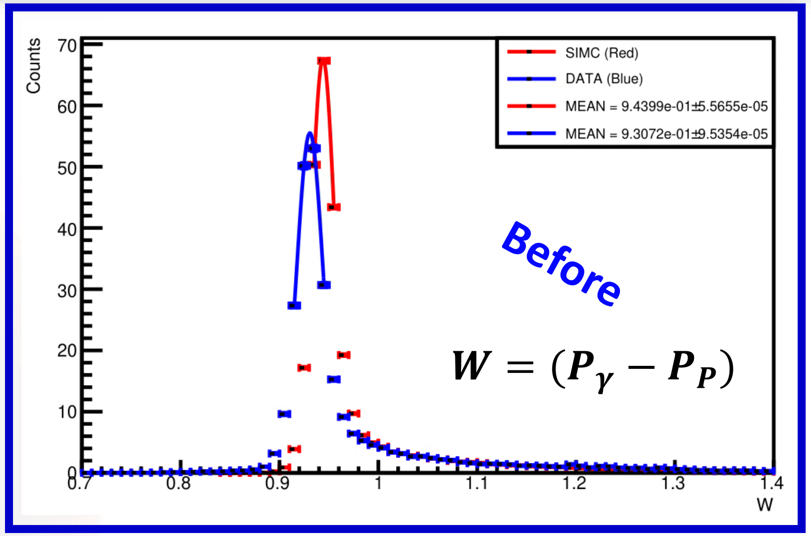


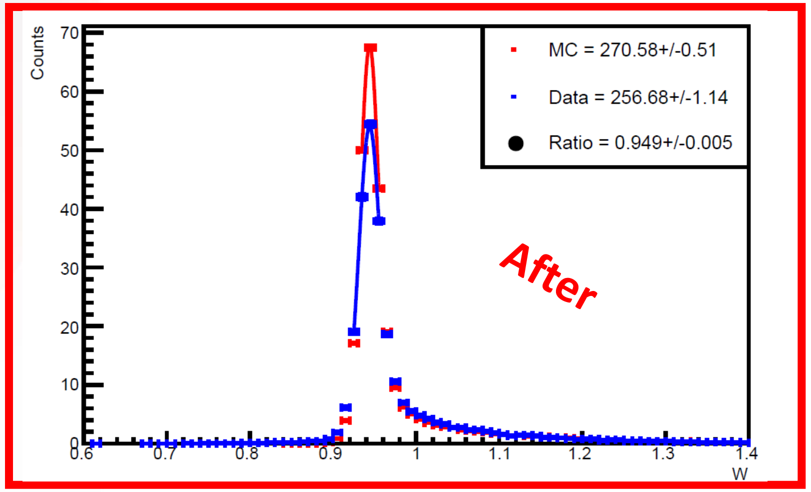
SHMS Pion Tracking Efficiency

HeeP Study

HeeP Offset Study

- looked at distributions of the missing variables ($E_M, \overrightarrow{P_M}, W$) to find deviations from expected values based on kinematics.
- The E_M , the components of $\overrightarrow{P_M}$, and W are correlated to different spectrometer quantities (momentum , angle, beam energy), and thus offsets can be extrapolated from them.
- By adjusting the beam energy, momentum and angles, missing variables $(E_M, \overrightarrow{P_M}, W)$ can be moved to better agree between data and SIMC.
- Red is SIMC and Blue is data.
- Offsets are doing a good job and peaks are matching with each other.
- Applied the determined HeeP offsets to the physics data for cross-section measurement.

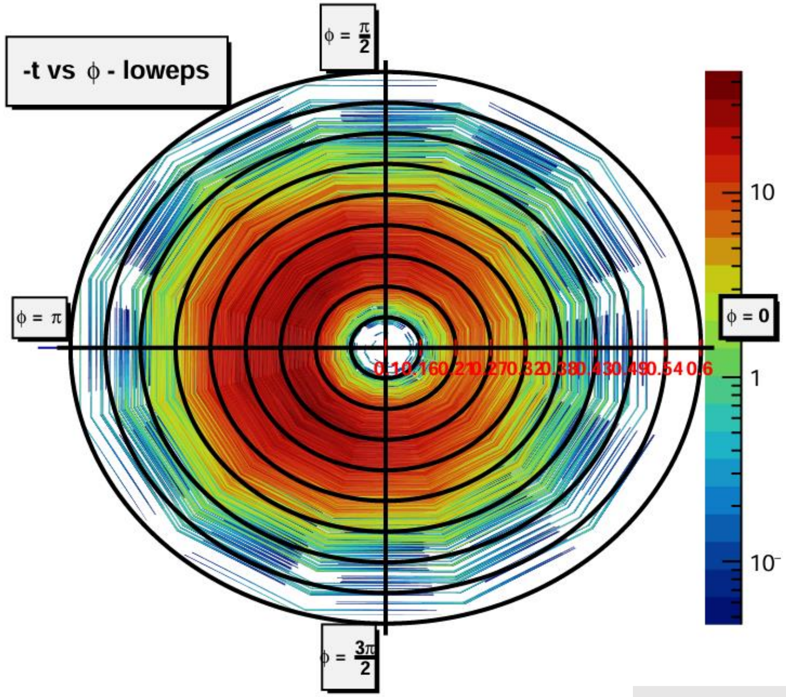


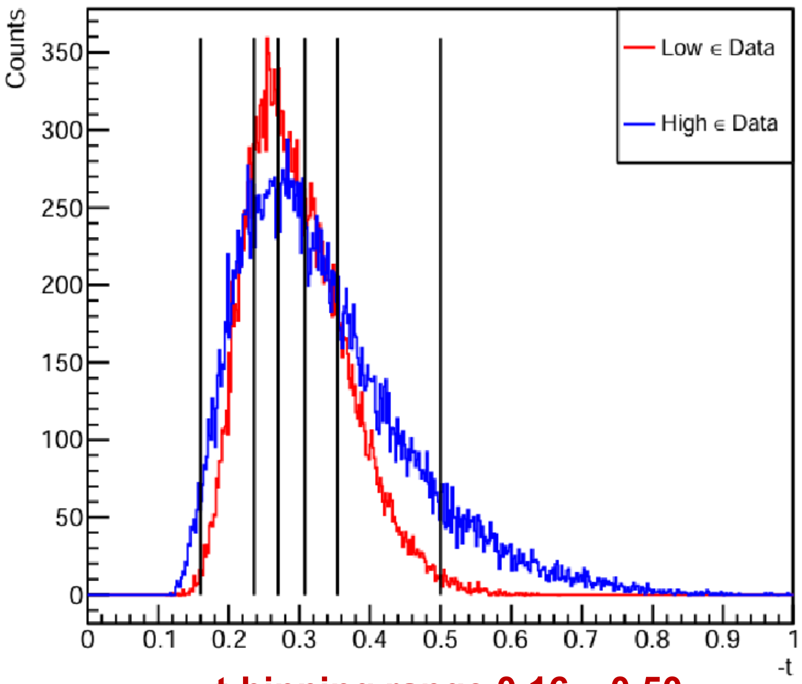


L/T-Separation Analysis

Determination of t-binning

- Purpose of t-bining is to maintain both statistical consistency and physical reliability in the extraction of the separated cross-sections.
- t-range is determined by looking at tvsphi polar plot of **Q^2=3.85 GeV^2, W=2.62 GeV (low-epsilon) physics setting.**
- **Divided "t" into 5 bins for Q^2=3.85 GeV^2, W=2.62 GeV (2-epsilon) physics setting.**
- **Tried to keep the number of events consistent between each bin (>2500).**
- **Red represents the low-epsilon experimental data.**
- **Blue represents the low-epsilon experimental data.**





t-binning range 0.16 – 0.50

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

Yield Calculations

- Calculated normalized bin-by-bin data yield.

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

where,

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

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

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

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

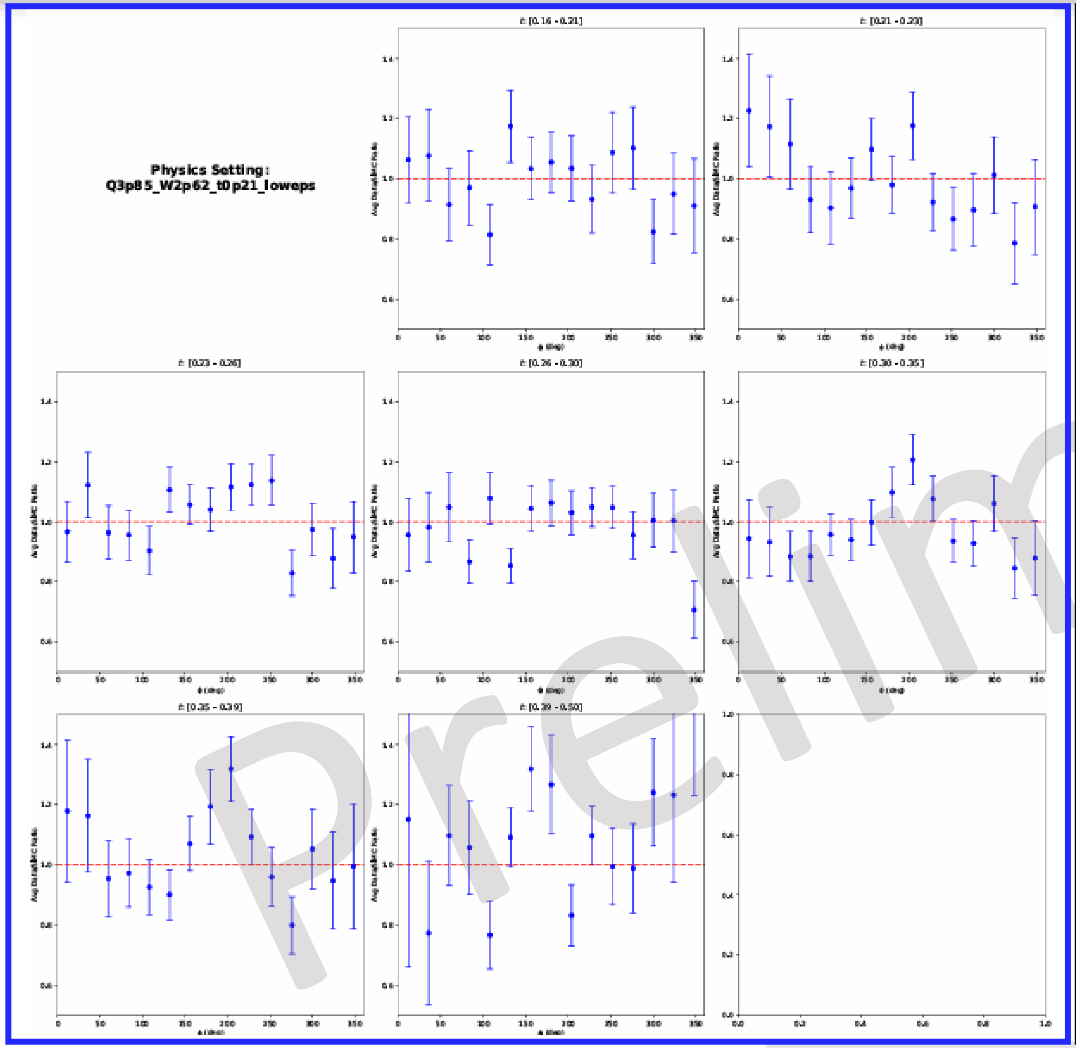
Normalization Factors	Comments
Charge	Calculated run-by-run
HMS & SHMS Tracking Efficiencies	> 98%
Live Time Correction	>98%
HMS Cerenkov Efficiency	>99%
HMS Calorimeter Efficiency	>99%
SHMS Aerogel Efficiency	>98%
HMS & SHMS Hodoscope Efficiency	>98%
RF Efficiency	>99%
Boiling Correction Factor	Calculated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

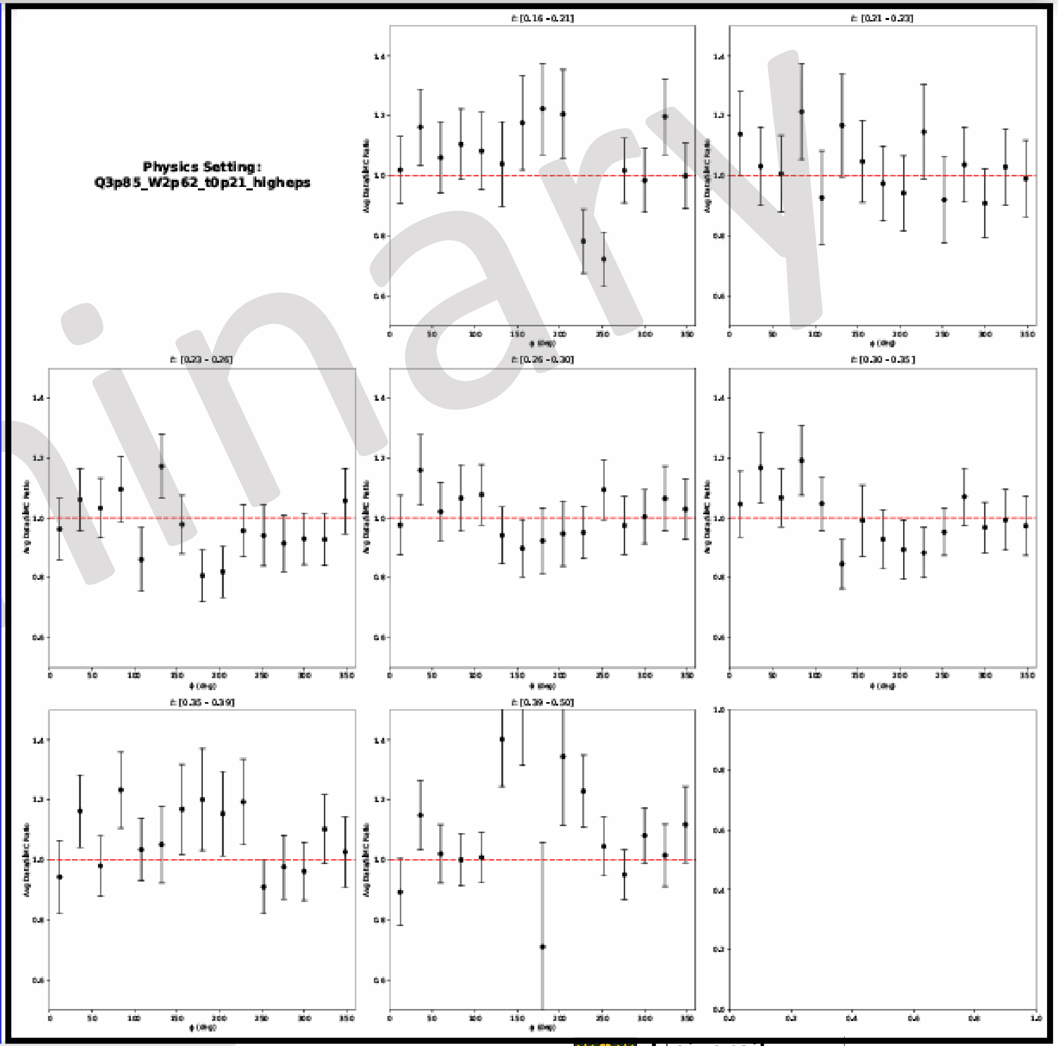
High & Low-epsilon Data/MC Ratios

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

Low_ε=0.292

High_ε=0.779

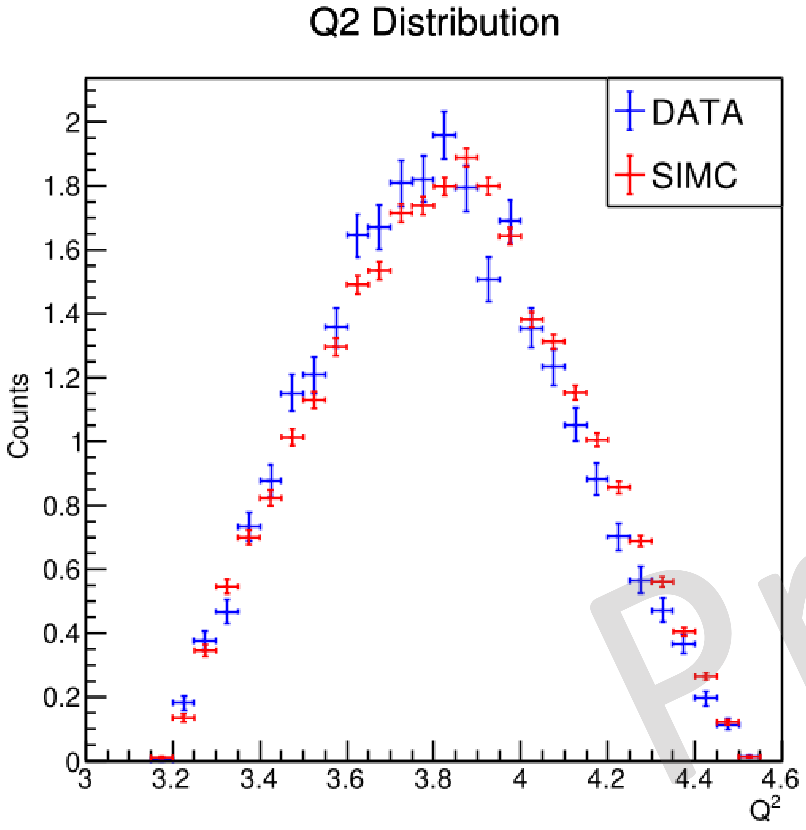


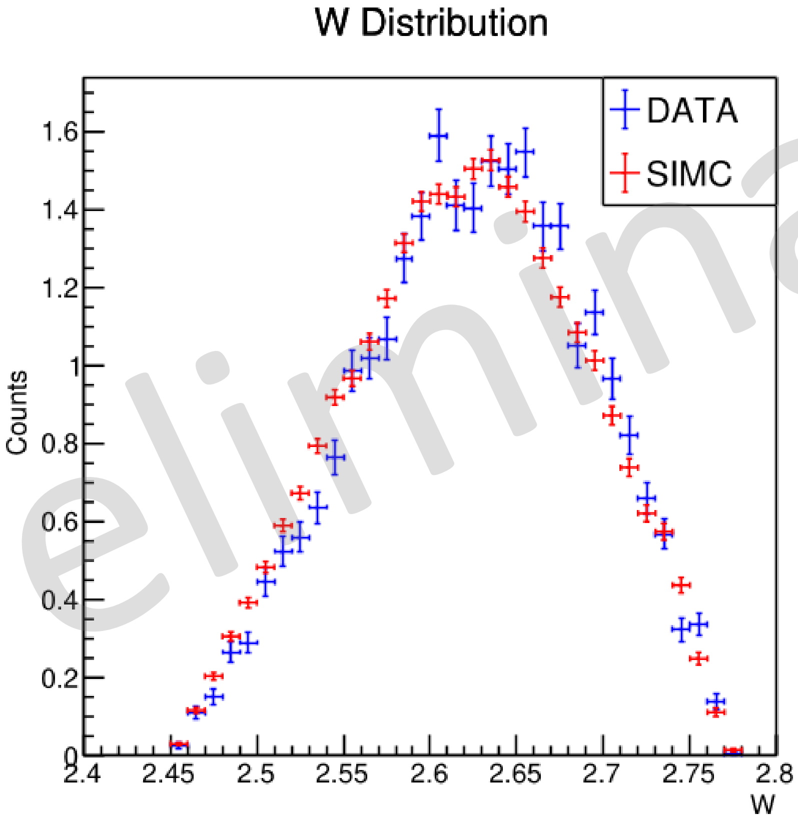


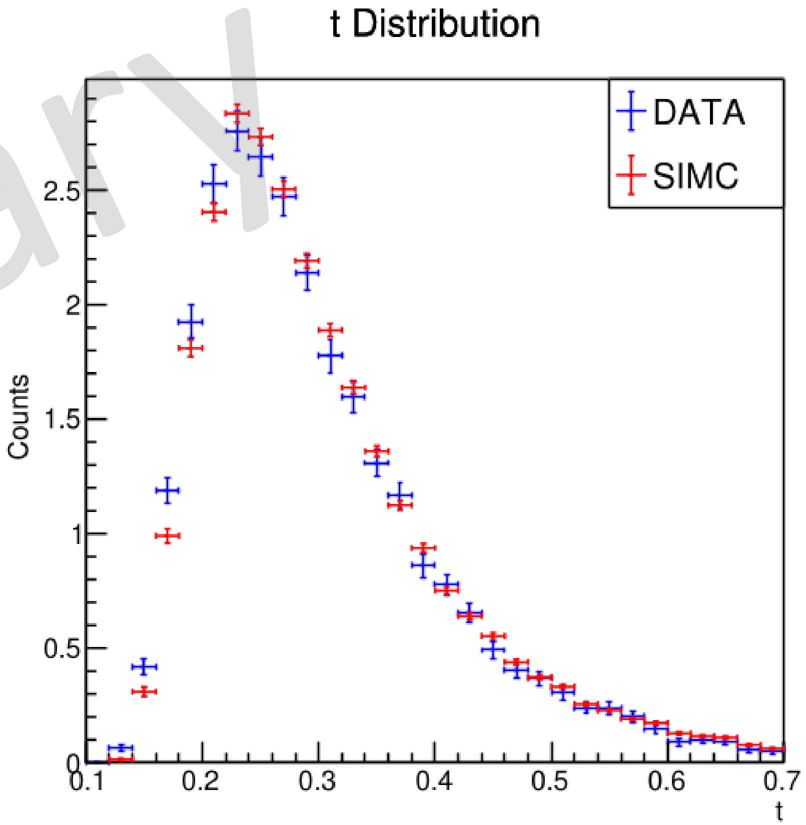
Q^2 = 3.85 GeV^2, W = 2.62 GeV (low-epsilons)

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)

SIMC Empirical Model for Cross-sections

- Final SIMC L/T/LT/TT functional forms:

$$\frac{d\sigma_T}{dt} = \left(\frac{p1}{Q^2}\right) \cdot e^{(p2\, Q^2)} \cdot e^{(p3\, |t|)}$$

$$\frac{d\sigma_L}{dt} = (p4 + p5/Q^2) \cdot \frac{|t|}{(|t| + m_\pi^2)^2} \cdot Q^2 e^{(p6|t|)} F_\pi^2$$

Where, $F_\pi = \frac{1}{(1+p7 \cdot Q^2 + p8 \cdot Q^4)}$

$$\frac{d\sigma_{LT}}{dt} = \left(\frac{p9}{Q^2} + e^{(p10/|t|)} \cdot \frac{p11}{|t|^{p12}}\right) \cdot \sin(\theta^*)$$

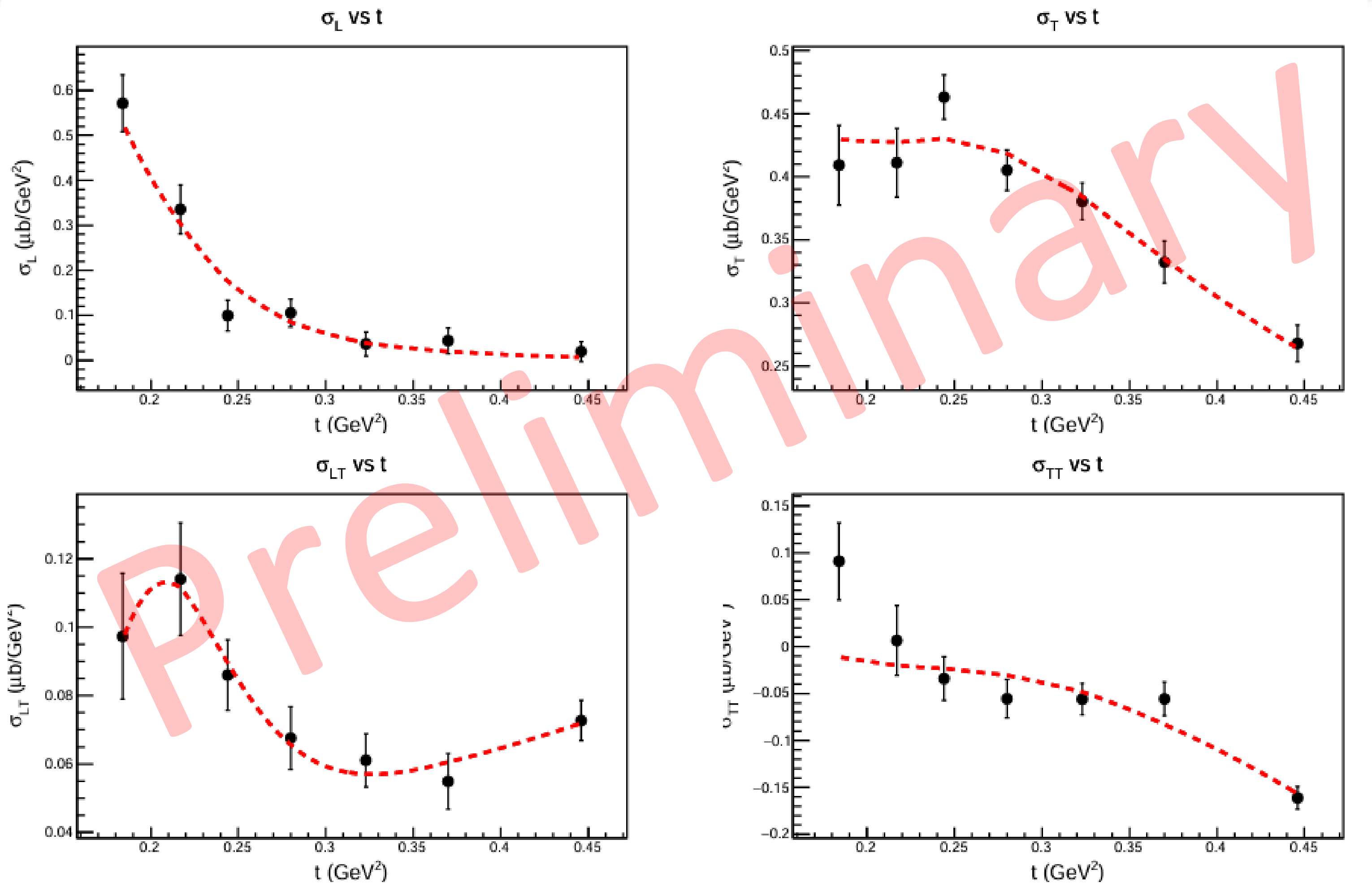
$$\frac{d\sigma_{TT}}{dt} = \left(\frac{p13}{Q^2} + \frac{p14}{|t|^{p15}}\right) \cdot \sin(\theta^*)^2$$

Parameter	Final Values	Paramete r	Final Values
p1	20.93	p9	41.42
p2	0.11	P10	-4.8
p3	-2.55	P11	1.1e-7
p4	-2861.81	P12	26.98
p5	12153.41	p13	2696.06
p6	-9.22	P14	-661.19
p7	1.77	P15	0.14
p8	0.05		

- Did 13 iterations to get optimized parameters.

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

L/T Separated Cross-sections



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

Model Comparison & F_π Extraction

Model Dependence & Future Extraction of F_π

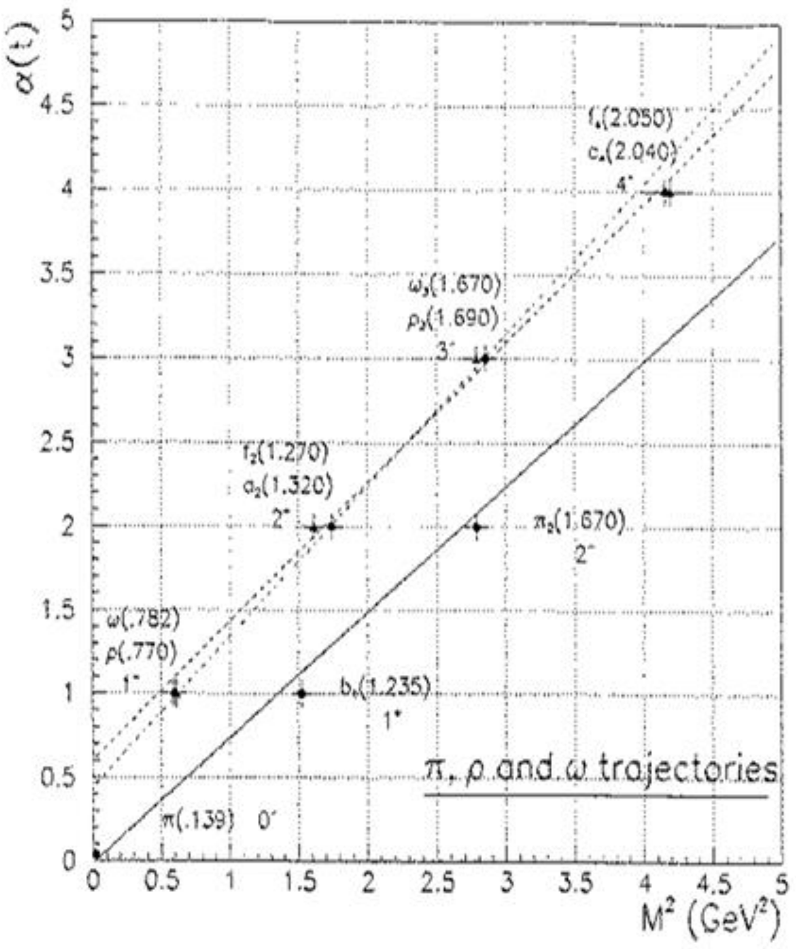
- **Our philosophy is to publish our experimentally measured $\frac{d\sigma_L}{dt}$, so that updated values of $F_\pi(Q^2)$ can be extracted as improved theoretical models become available.**
- Jefferson Lab F_π experiments have primarily used three models for form-factor extraction:
  - **VGL Regge Model** — Vanderhaeghen, Guidal, Laget, PRC 57, 1454 (1998)
    - VGL model has proven to give a **reliable description of σ_L** over a across a wide kinematic domain.
    - However, VGL **significantly underestimates** σ_T, indicating the need for improved models to fully describe the separated cross-section data.
  - **CKY Regge Model** — Choi, Kong, Yu, JKPS 67, L1089 (2015)
    - **This motivated the development of the CKY model**, aimed at improving the description of σ_T without degrading the successful description of σ_L.
  - **PKT Model** — Perry, Kizilersu, Thomas, PLB 807, 135581 (2020)
    - A **modern pion electroproduction model** was developed to improve theoretical consistency and study model dependence in the extracted $F_\pi(Q^2)$.
    - The PKT model provides an alternative framework for comparing how different reaction models affect the form-factor extraction.

- **More theoretical models are welcome**, especially those capable of describing both σ_L and σ_T consistently.

VGL Model to extract F_π from σ_L

- Feynman Propagator is given as; $\left[\frac{1}{t-m_\pi^2}\right]$ replaced by π and ρ Regge propagators.
- It represents the exchange of a series of particles, compared to a single particle.
- Model parameters fixed from pion photoproduction.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).
- ρ exchange does not significantly influence σ_L at small $-t$.
- Pionform factor is a free parameter in the model, parameterized as:

$$F_\pi = \frac{1}{1 + Q^2/\Lambda_\pi}$$



[Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]

Fit σ_L to the model which gives F_π at each Q^2.

Comparison with VGL Regge Model

VGL Regge Model

Phys Rev C 57(1998)1454

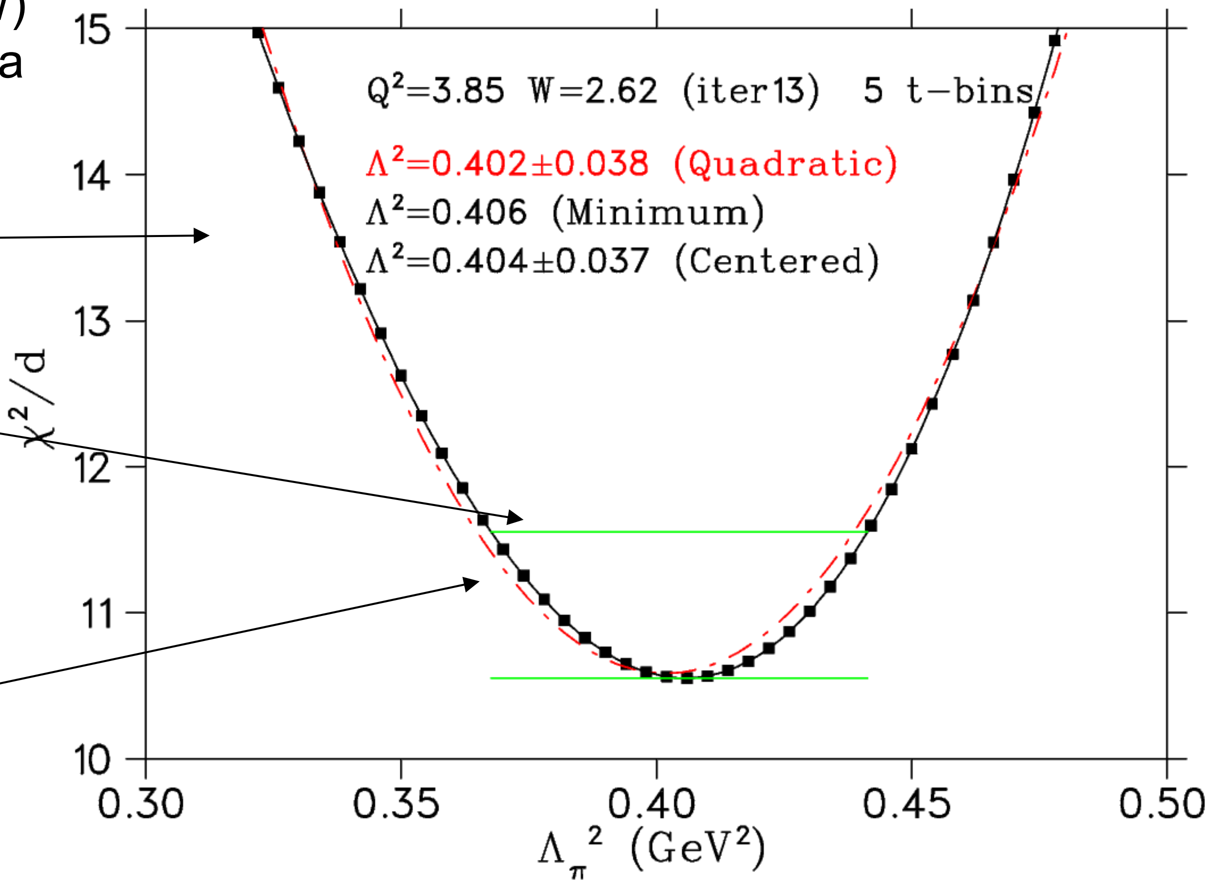
- The first model written for our data
- As the t-channel π exchange diagram is by itself not gauge invariant, the s-channel (for π^+ production) or u-channel (for π^- production) nucleon exchange diagram was also Reggeized, to ensure gauge invariance of their sum
- Two model parameters: σ_L sensitive to Λ_π^2, much less sensitive to Λ_ρ^2

Determine best fit Λ_π^2 value

- Calculate VGL model for many Λ_π^2 using precise (Q^2, W) values for each t-bin and compute χ^2 deviation from data
- Results depend on how many t-bins are used in the fit, #bins used shown here

Green line indicates increase in χ^2 by 1 unit, used to estimate in the uncertainty in Λ_π^2

Red fit is a symmetric parabola, the difference from the black line indicates whether the uncertainty is asymmetric

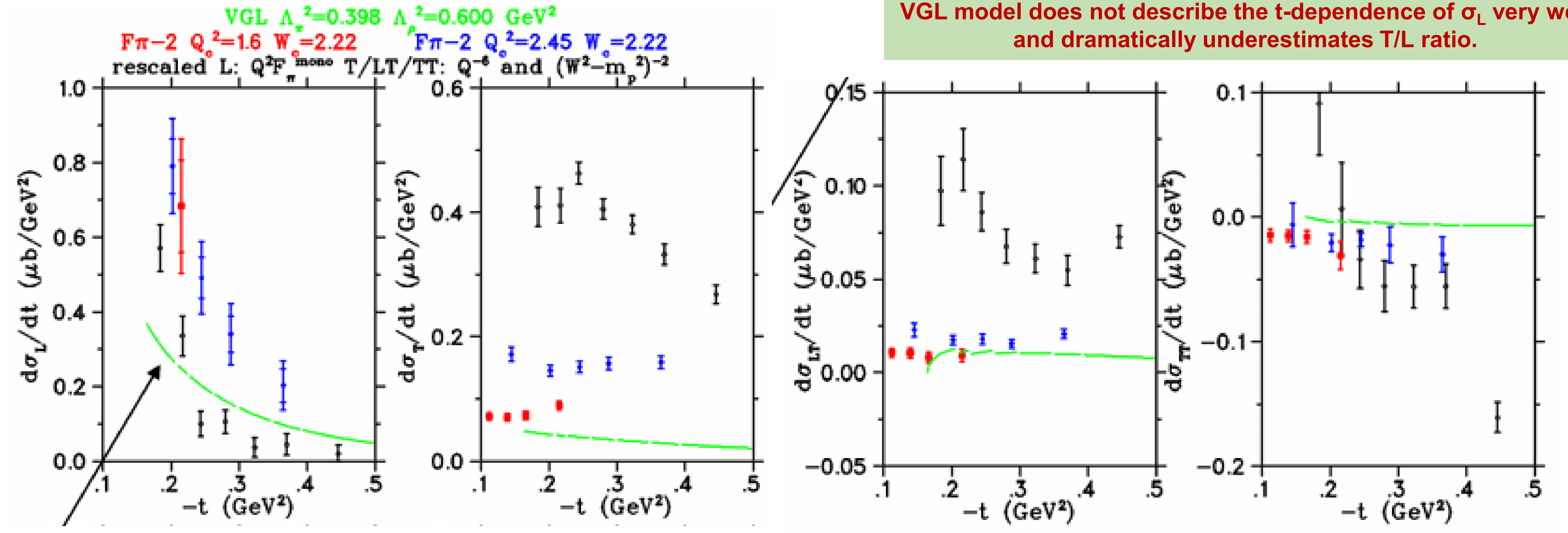


Λ_ρ^2=0.600 for all calcs

Comparison with VGL Model

- Jefferson Lab F_π experiments use the Vanderhaeghen–Guidal-Laget (VGL) 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].
- **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 Regge Model

CKY Regge Model

J Korea PhysSoc 67(2015)L1089

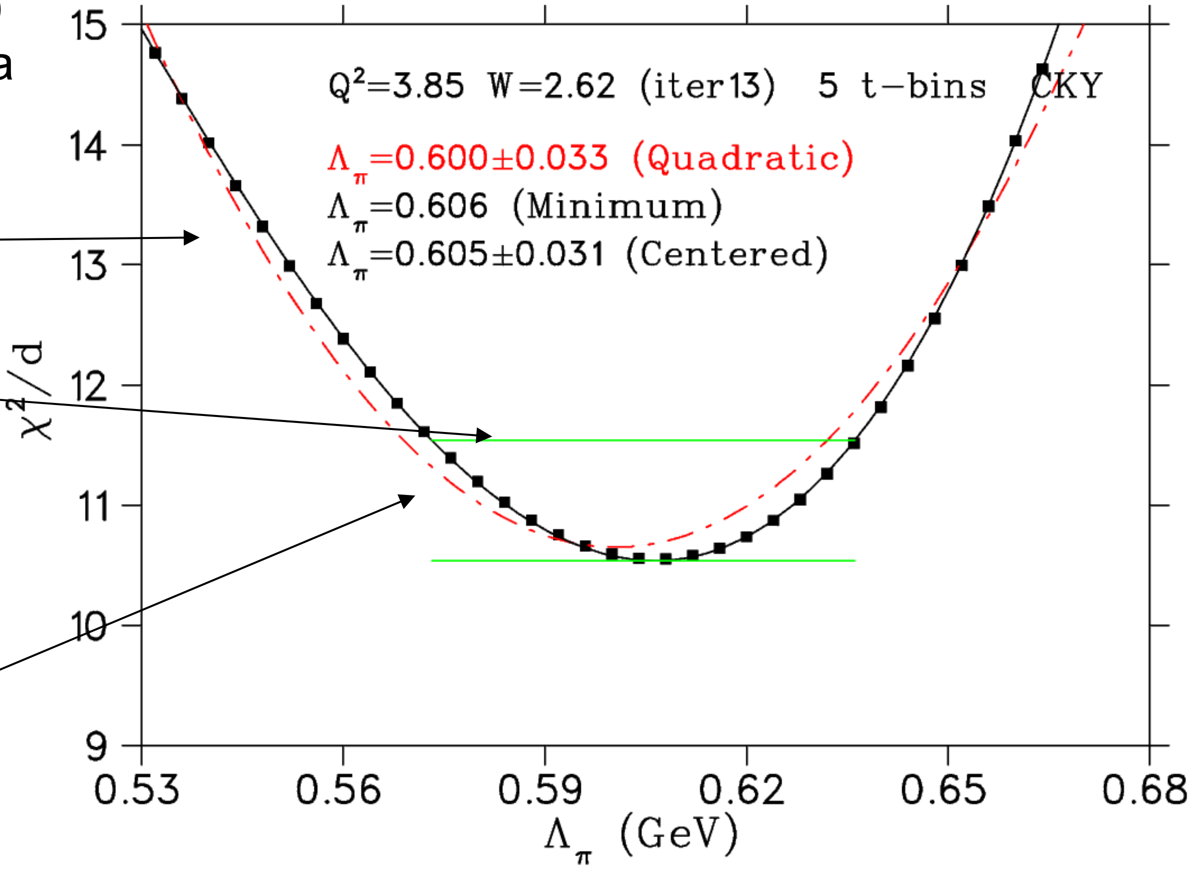
- The fact that VGL dramatically underestimates σ_T while doing a much better job on σ_L led to new model development, with the goal of increasing σ_T without degrading σ_L description
- The Kaskulov-Mosel and Vrancx-Ryckebusch models include intermediate (DIS-like) processes on the recoil nucleon, leading to the same final state. The CKY model is an extension of this work
- Third model parameter, Λ_N, for proton exchange in s-channel, is added to restore gauge invariance and plays a role in σ_T

Determine best fit Λ_π value

- Calculate CKY model for many Λ_π using precise (Q^2, W) values for each t-bin and compute χ^2 deviation from data
- Results depend on how many t-bins are used in the fit, #bins used shown here

Green line indicates increase in χ^2 by 1 unit, used to estimate in the uncertainty in Λ_π

Red fit is a symmetric parabola, the difference from the black line indicates whether the uncertainty is asymmetric

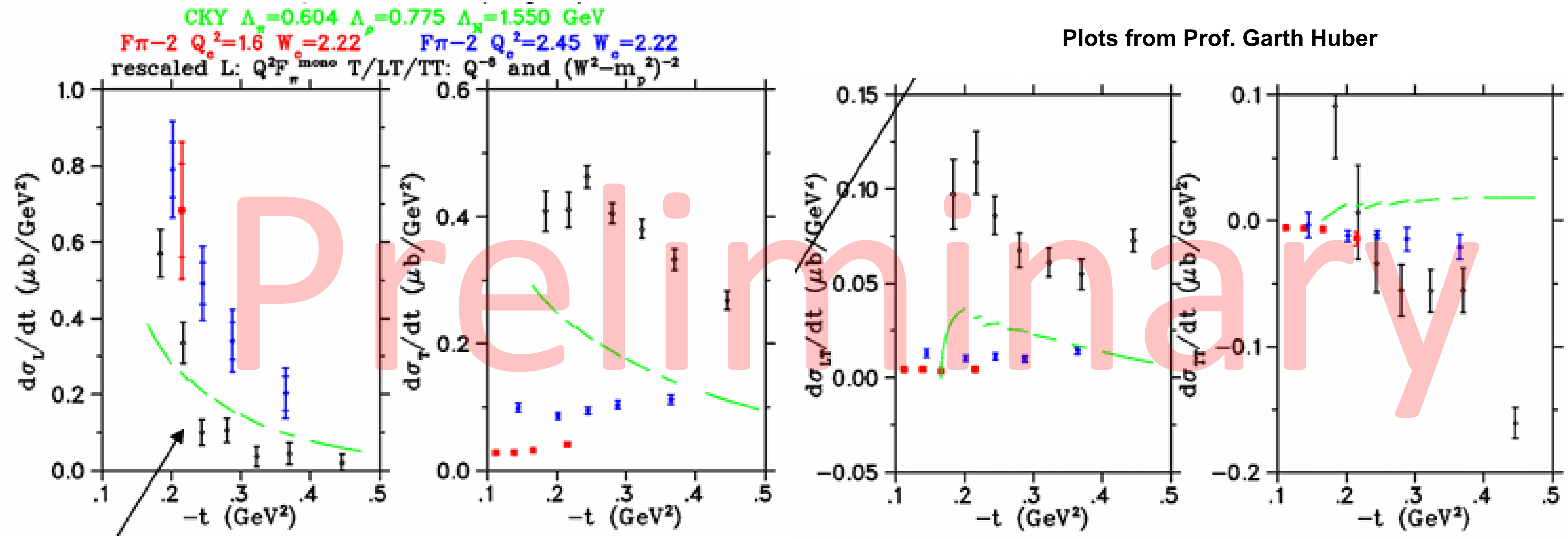


Λ_ρ=0.600, Λ_N=1.550 for all calcs

Comparison with CKY Model

- The VGL dramatically underestimates σ_T while doing a much better job on σ_L led to new model development CKY, with the goal of increasing σ_T without degrading σ_L description [*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.**
- **σ_{LT} somewhat higher than VGL, but still lower.**

Plots from Prof. Garth Huber



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