The π^+ electromagnetic form factor at Jefferson Lab and future EIC

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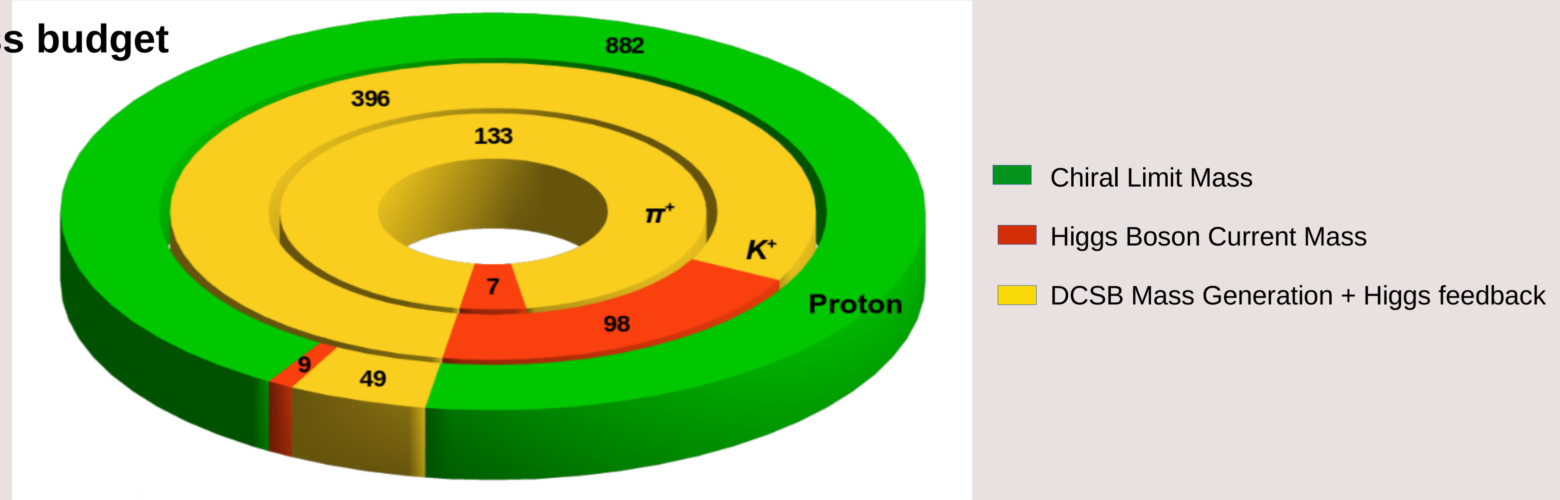
February 09, 2024

Dynamics of Gluons in QCD

- **How does the mass of nucleon arise?**
- **How does the spin of nucleon arise?**

Hope EIC answers

Hadron mass budget



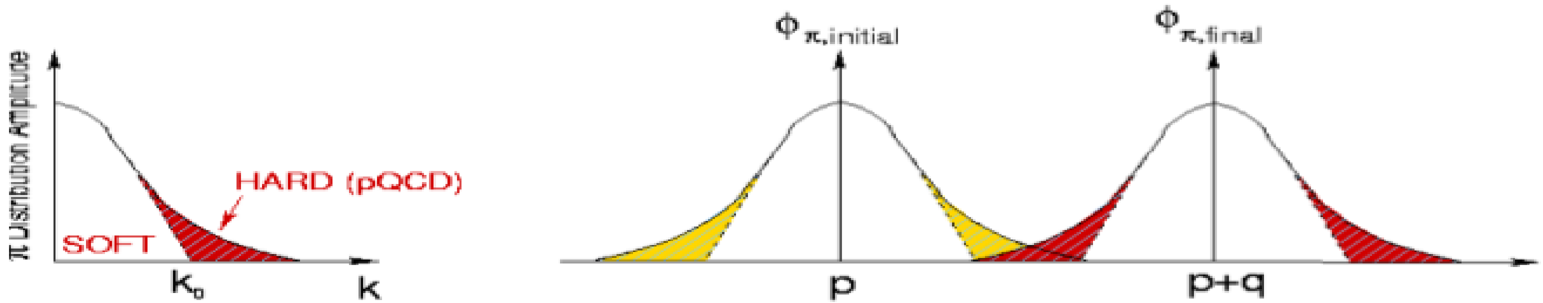
- **The Higgs mechanism is not sufficient to answer the questions!!!**
- Dynamical Chiral Symmetry Breaking (DCSB) is expected to provide most of the hadron mass.
- The π and K are pivotal to utilize in understanding DCSB.
  - π the lightest quark system, responsible for the long range character of the strong interaction.
  - K structure is involved with the strange quark.
  - π and K are connected to the Goldstone modes of DCSB.

Charged Meson Form Factors

Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

In quantum field theory, the form factor is the overlap integral:

$$F_\pi(Q^2) = \int \phi_\pi^*(p)\phi_\pi(p+q)dp$$



The meson wave function can be separated into φ_π^{soft} with only low momentum contributions ($k<k_0$) and a hard tail φ_π^{hard}.

While φ_π^{hard} can be treated in pQCD, φ_π^{soft} cannot.

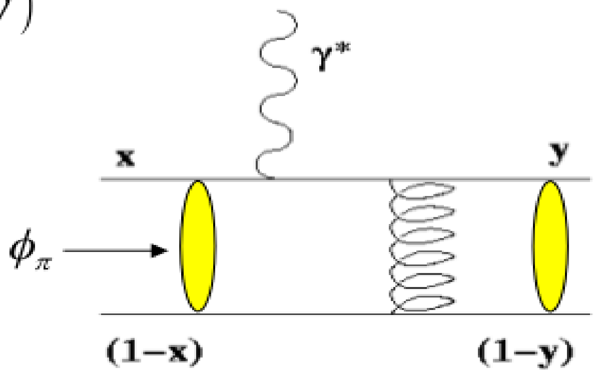
From a theoretical standpoint, the study of the Q^2–dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.

Slide's credit to Garth Huber

The Pion in Perturbative QCD

At very large Q^2, pion form factor (F_π) can be calculated using pQCD

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int dxdy \frac{2}{3} \frac{1}{xyQ^2} \varphi(x)\varphi(y)$$



at asymptotically high Q^2, the pion distribution amplitude becomes

$$\phi_\pi(x) \xrightarrow[Q^2\to\infty]{} \frac{3f_\pi}{\sqrt{n_c}} x(1-x)$$

and F_π takes the very simple form

$$Q^2 F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} 16\pi\alpha_s(Q^2) f_\pi^2$$

f_π=93 MeV is the $\pi^+ \to \mu^+\nu$ decay constant.

G.P. Lepage, S.J. Brodsky, Phys.Lett. **87B**(1979)359.

This only relies on asymptotic freedom in QCD, *i.e.* $(\partial\alpha_s/\partial\mu)<0$ as $\mu\to\infty$.

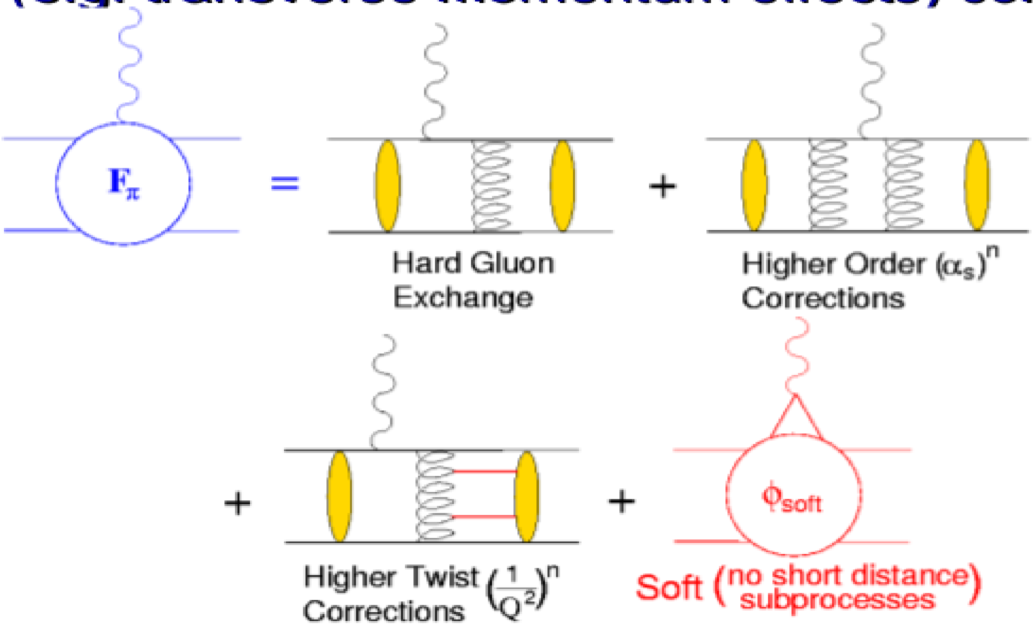
Q^2F_π should behave like $\alpha_s(Q^2)$ even for moderately large Q^2.

→ Pion form factor seems to be best tool for experimental study of nature of the quark–gluon coupling constant renormalization.
[A.V. Radyushkin, JINR 1977, arXiv:hep–ph/0410276]

Slide's credit to Garth Huber

The Pion Form Factor at Intermediate Q^2

At experimentally–accessible Q^2, both the "hard" and "soft" components (e.g. transverse momentum effects) contribute.

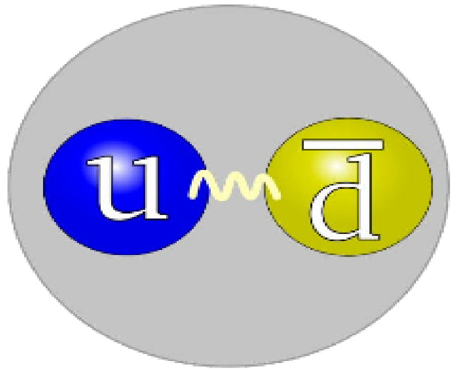


- **The interplay of hard and soft contributions is poorly understood.**
  → Different theoretical viewpoints on whether higher–twist mechanisms dominate until very large momentum transfer or not.

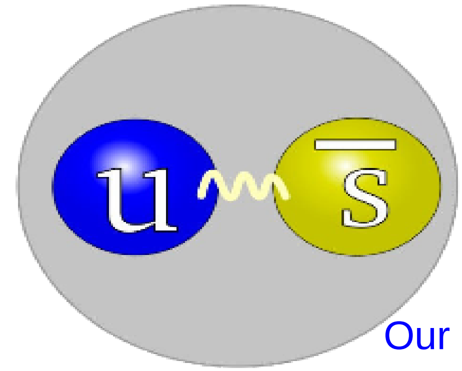
- **The pion elastic and transition form factors experimentally accessible over a wide kinematic range.**
  → A laboratory to study the **transition** from the soft to hard regime.

Slide's credit to Garth Huber

The Charged Kaon – a 2nd QCD Test Case



π^+



K^+

Our group has acquired experimental data for both π⁺ and K⁺ mesons. However, I will focus exclusively on the analysis of π⁺ in this talk.

- In the hard scattering limit, pQCD predicts that the π^+ and K^+ form factors will behave similarly

$$\frac{F_K(Q^2)}{F_\pi(Q^2)} \xrightarrow[Q^2 \to \infty]{} \frac{f_K^2}{f_\pi^{\;2}}$$

- It is important to compare the magnitudes and Q^2–dependences of both form factors.

Slide's credit to Garth Huber

Measurement of π^+ Form Factor – Low Q^2

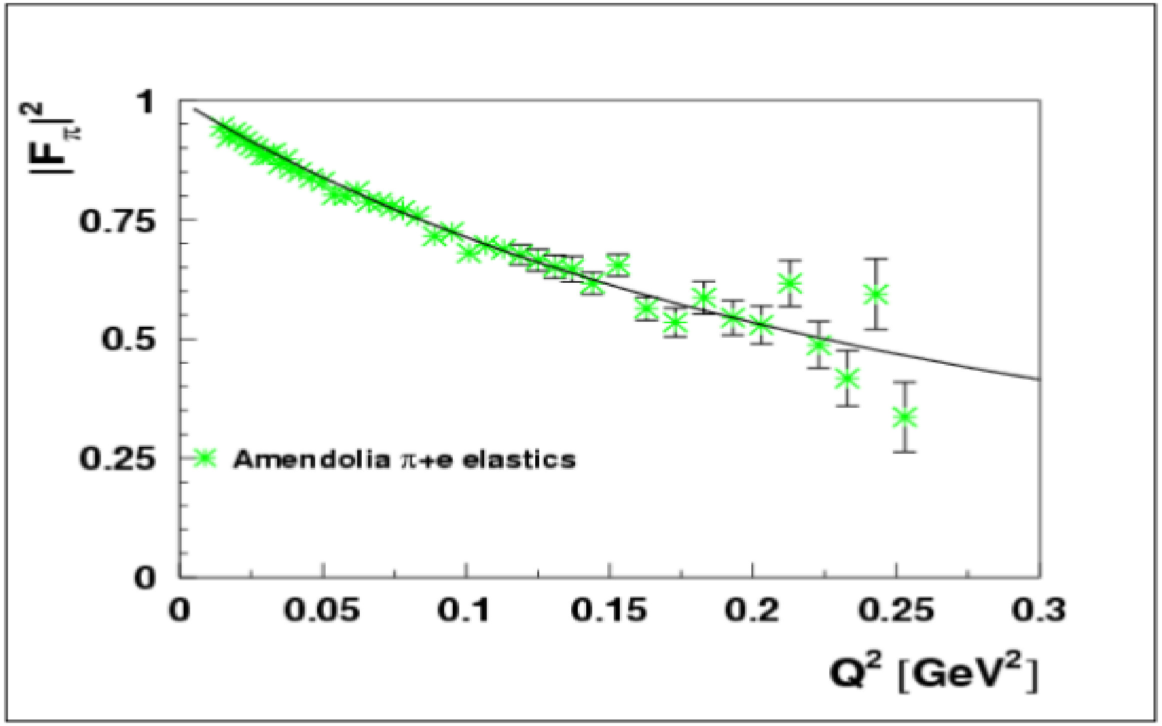
At low Q^2, F_π can be measured model–independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *[Amendolia, et al., NPB* ***277****(1986)168]*

- Data used to extract pion charge radius
  $r_\pi = 0.657 \pm 0.012$ fm

Maximum accessible Q^2 roughly proportional to pion beam energy

Q^2=1 GeV^2 requires 1 TeV pion beam



Slide's credit to Garth Huber

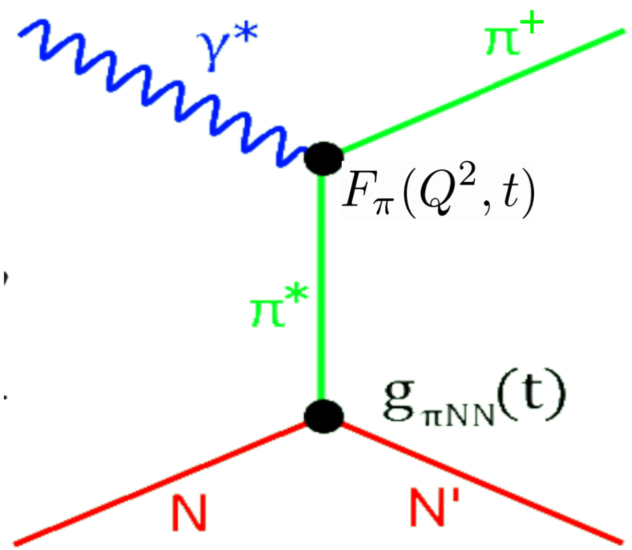
Measurement of F_π via Electroproduction (Indirect Technique)

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

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
- In Born term model, F_π^2 appears as

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



Drawbacks of this technique:

1. Isolating σ_L experimentally challenging.
2. The F_π values are in principle dependent upon the model used, but this dependence is expected to be reduced at sufficiently small $-t$.

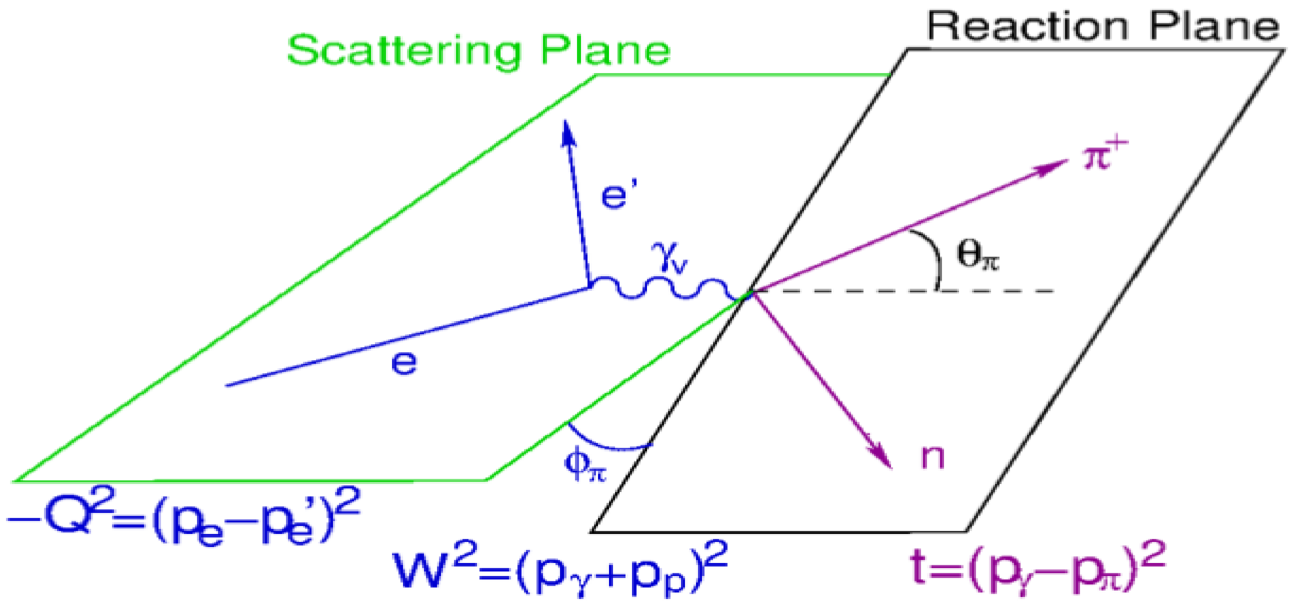
Slide's credit to Garth Huber

Rosenbluth (LT) Separation Technique

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

Virtual-photon polarization:

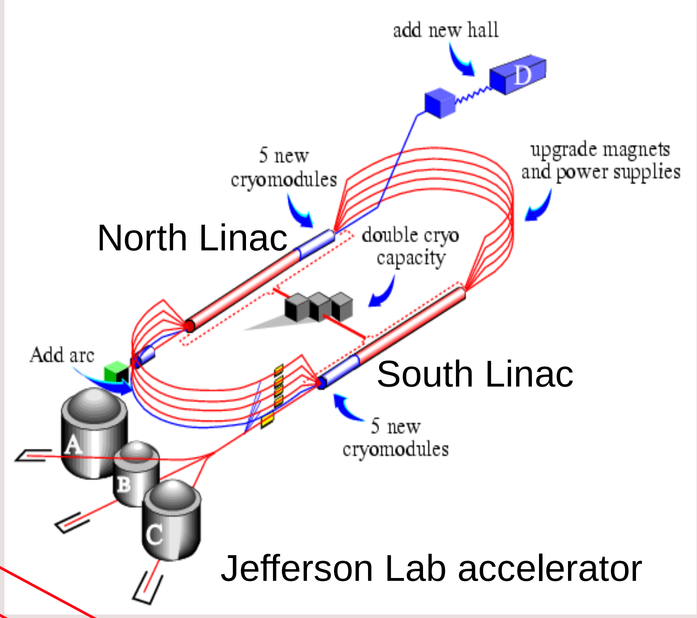
$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$



- **L-T separation required to separate σ_L from σ_T**
- **Need to take data at smallest available $-t$, so σ_L has maximum contribution from the π^+ pole**
- **Need to measure t–dependence of σ_L at fixed Q^2,W**

Slide's credit to Garth Huber

- Jefferson Lab has two 1.5 GHz Superconducting Linear Accelerators, which provide electron beam for Nucleon and Nuclear structure studies.

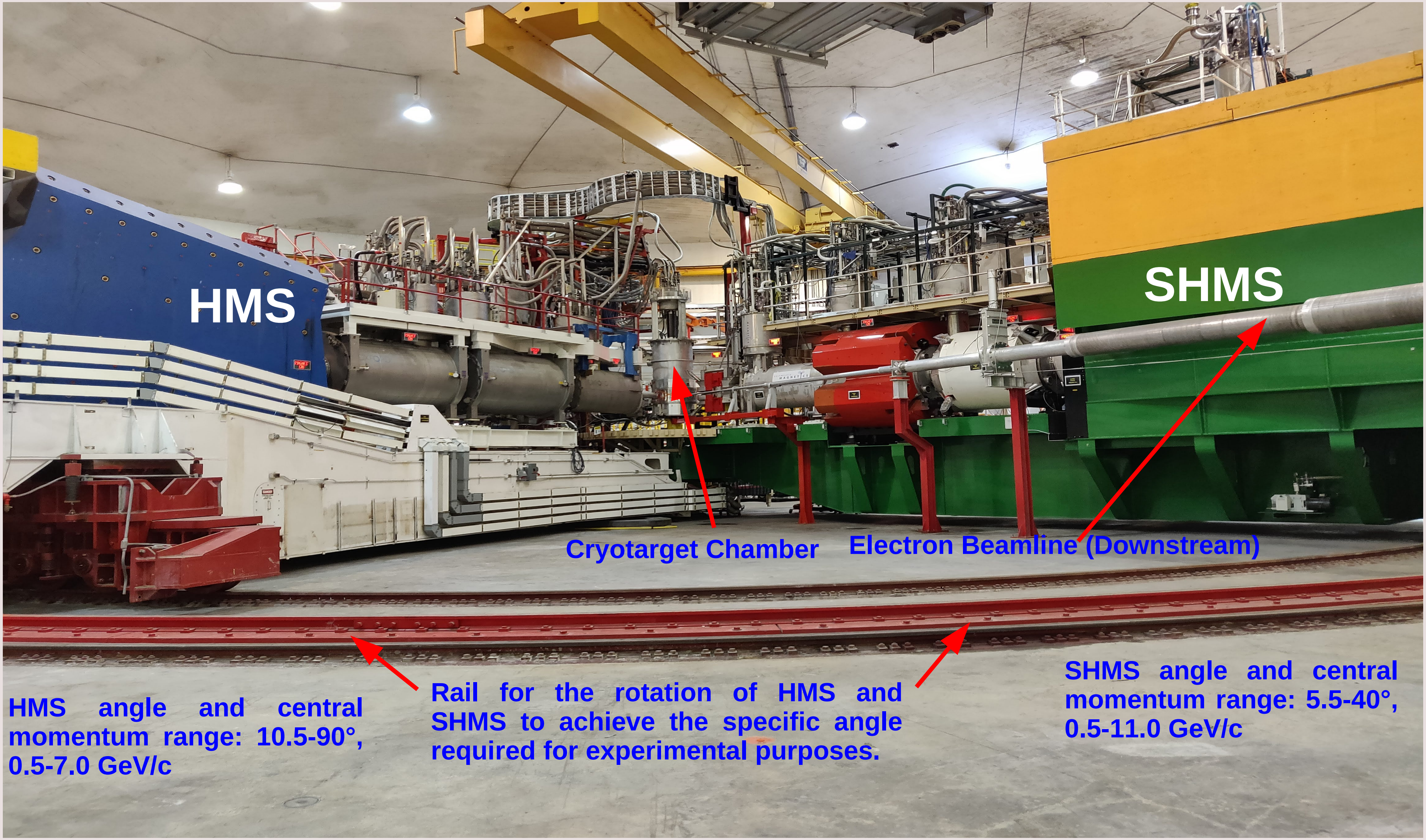


Four experimental Halls

- Beam energy up to ~12 GeV
- Beam current > 100 uA

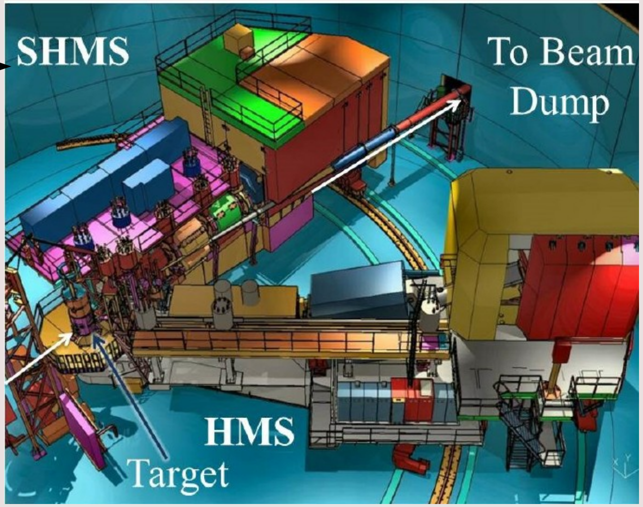
- All halls can receive electron beam simultaneously.

Experimental Hall C



PionLT Exclusive Experiment (E12-19-006)

- The experiment conducted in Hall C in three phases.
  - **First run period:** ran in summer 2019
  - **Second run period:** ran in fall 2021
  - **Third run period:** ran in fall 2022



- The reaction system of the experiment

$$e + p \rightarrow e' + \pi^+ + n$$

- The data acquired in first run period.

E_b (GeV)	Q^2 (GeV^2)	W (GeV)	x_B	ε
4.6/3.7/2.8	0.38	2.20	0.087	0.781/0.629/0.286
4.6/3.7/2.8	0.42	2.20	0.097	0.774/0.617/0.264

- Spokesperson of the experiment
  - Garth Huber (UofR) , Tanja Horn (CUA), and Dave Gaskell (JLab)

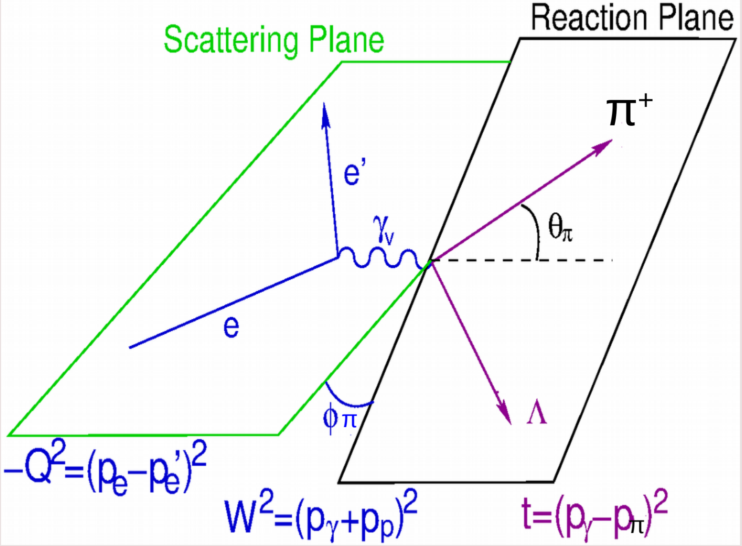
E12-19-006 LT Separation (Parallel Kinematics Case)

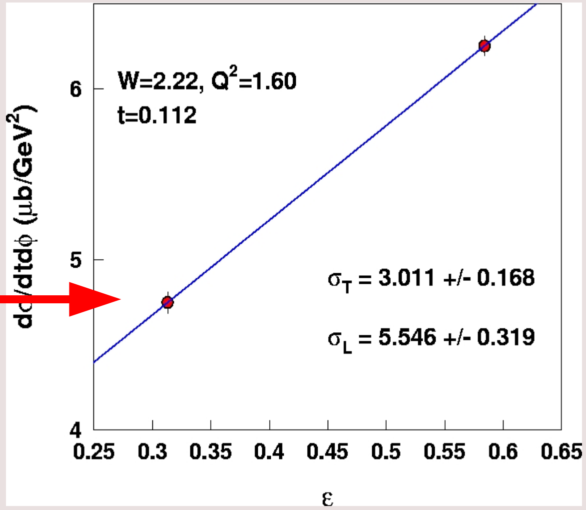
- The experimental data acquired for three ε at fixed Q^2, W and -t.
  - This is the first time data acquired for 3 ε with multiple settings (left1, left2, center, right1, right2) to maximize the full Φ coverage for the LT separation.
  - The -t range covers 0.001 - 0.07. Again, this is the first time data acquired to such lowest -t to maximize the pion pole contribution.
  - In parallel kinematics, $\theta_\pi = 0(\theta_\pi w.r.t \vec{q})$
    - σ_L and σ_T can be separated out.
    - It requires uniform detector acceptance.

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}$$

Virtual-photon polarization:

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



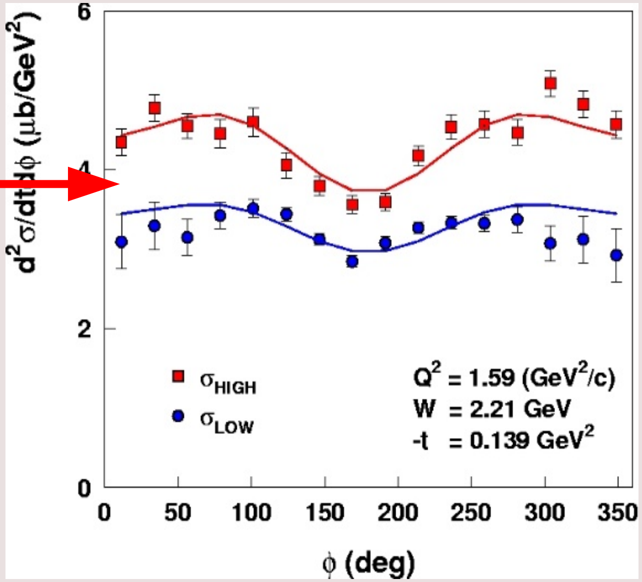


T. Horn, et al, PRL ***97*** *(2006)192001*

E12-19-006 Full LT Separation

- In non-parallel kinematics, $\theta_\pi \neq 0 (\theta_\pi w.r.t \vec{q})$

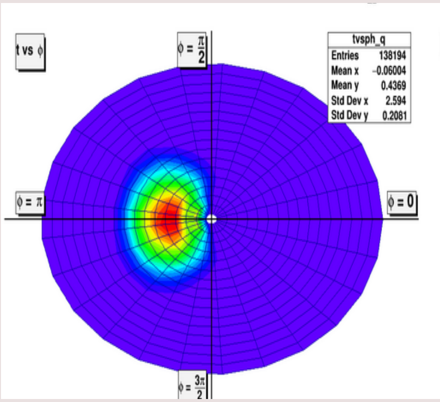
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$



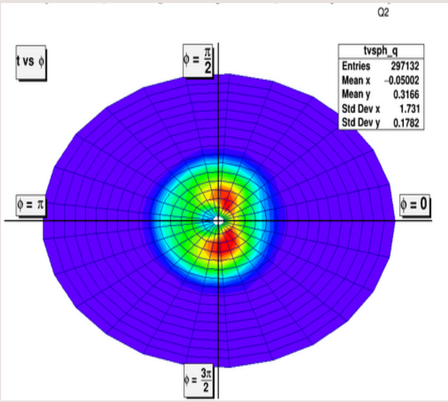
T. Horn, et al, PRL ***97*** *(2006)192001*

- An example of experimental settings (left, center & right) for the full φ coverage.

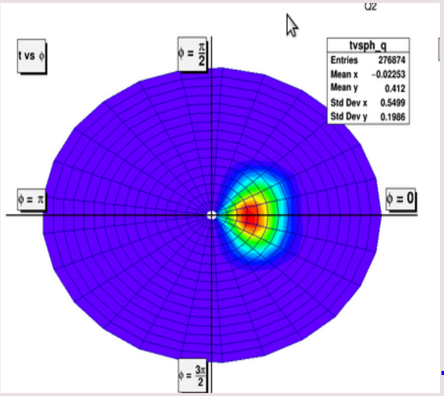
(left)



(center)

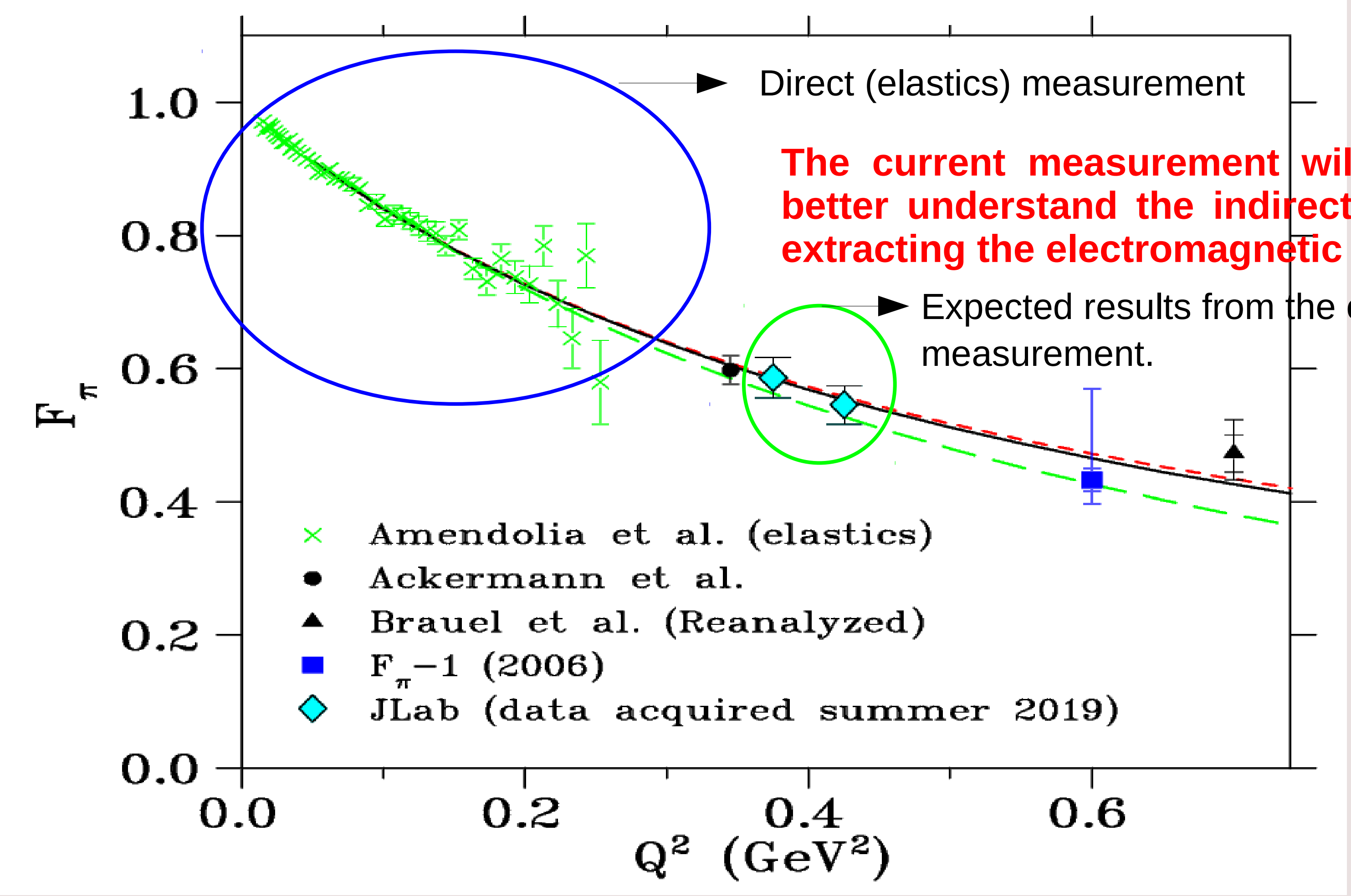


(right)



-t is radius

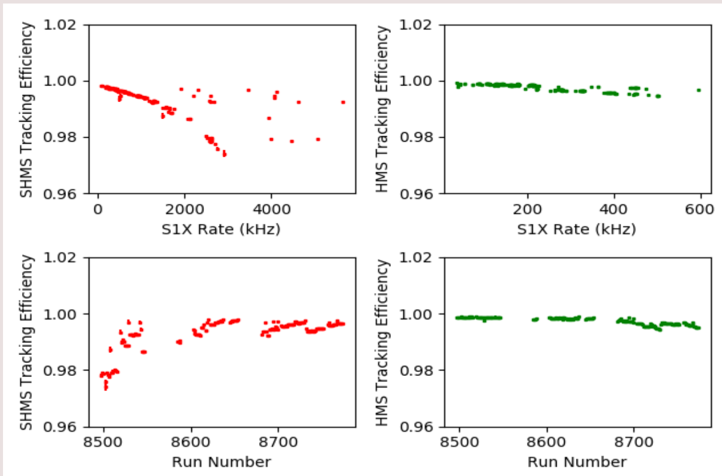
$e + p \to e' + \pi^+ + n$, Projected Results at Q^2 = 0.38 & 0.42 GeV^2

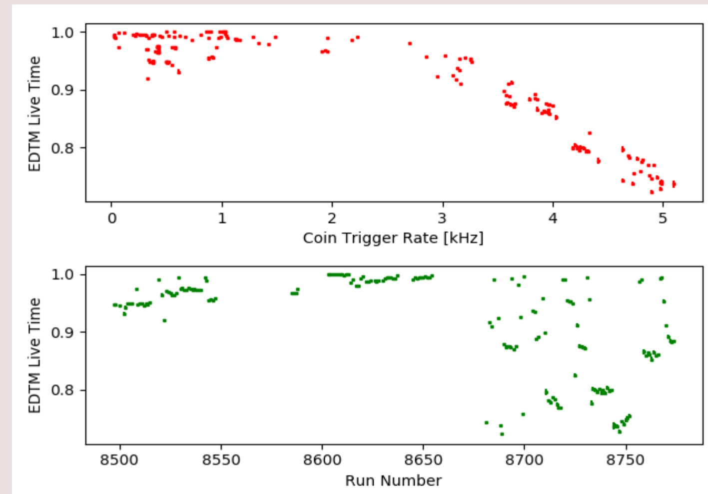


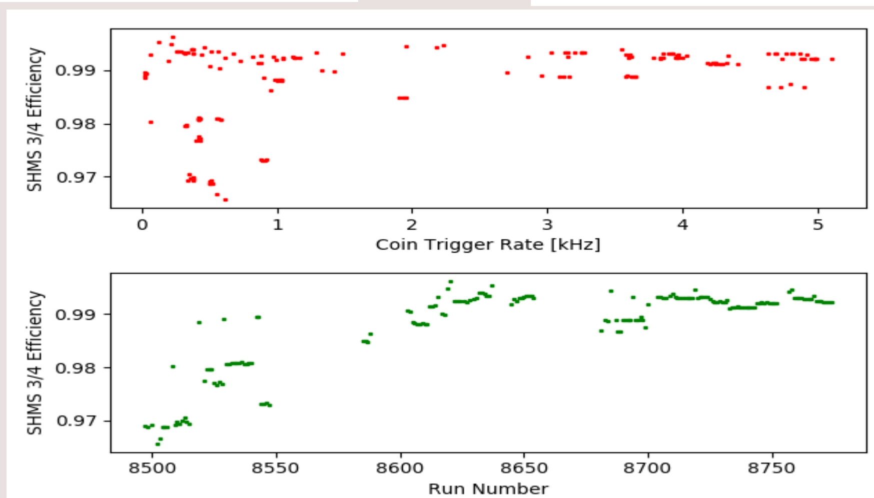
The current measurement will allow us to better understand the indirect technique of extracting the electromagnetic form factor.

The Data Analysis (Various Efficiency)

- The rate dependence study for all settings is of utmost importance to have correct experimental yield for the LT separation.
  - The experimental settings (left1, left2, center, right1 & right2) are acquired at different experimental rates.

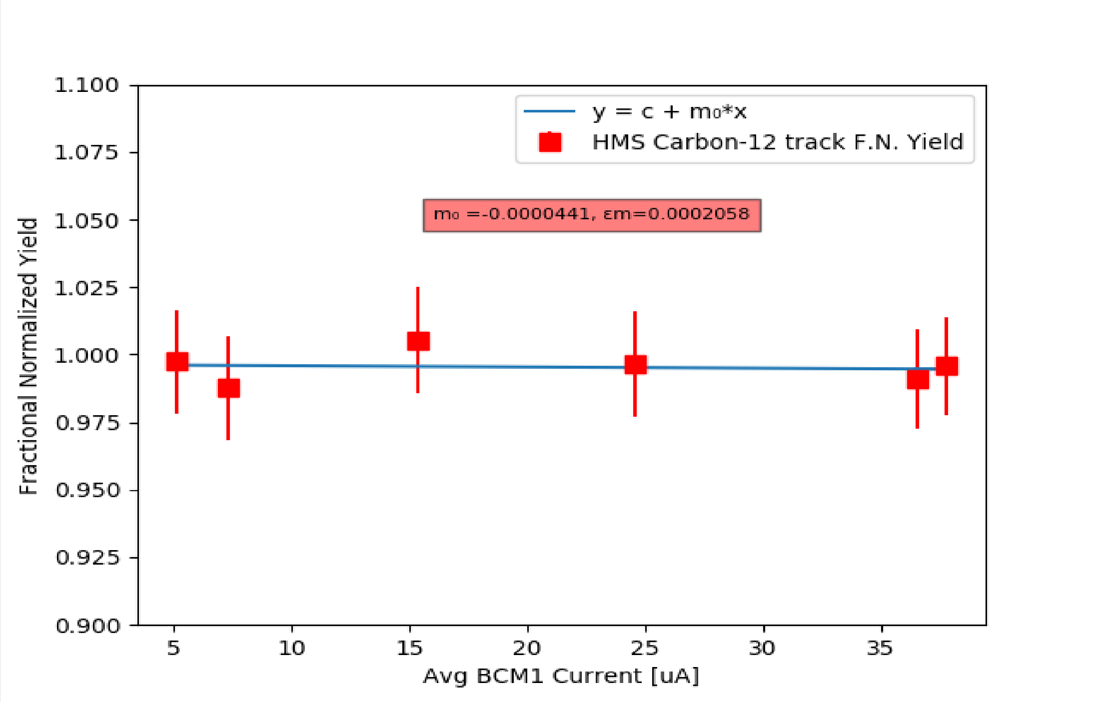


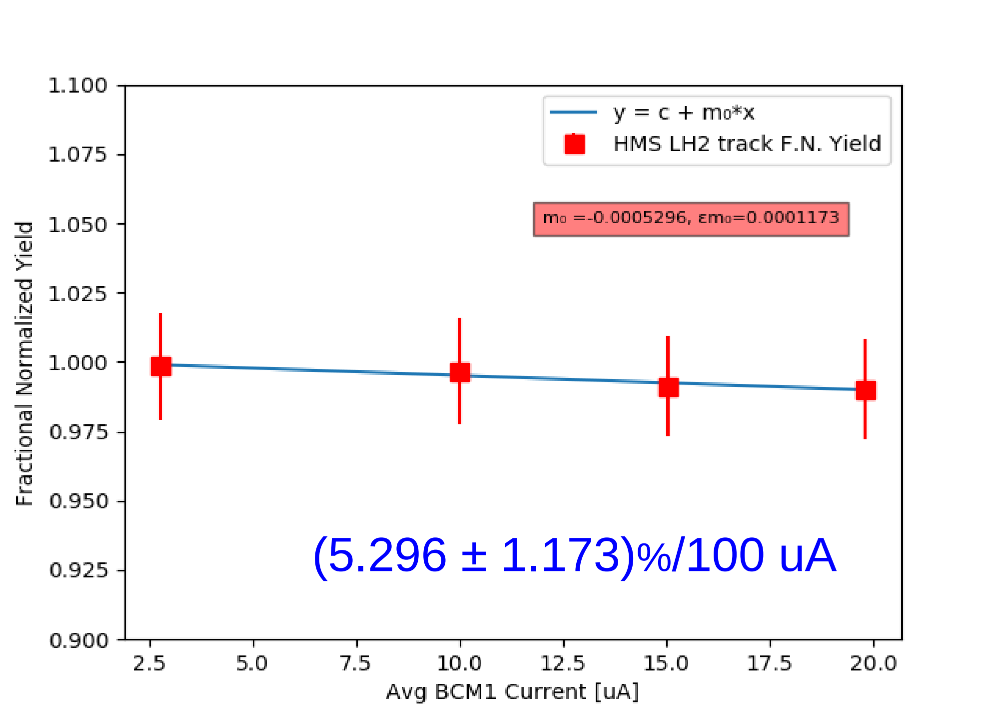




The Data Analysis (Luminosity Analysis)

- To check the rate dependence study and determine the LH_2 boiling correction factor the luminosity analysis is required.
  - Carbon does not boil at the Hall C experiments. Its yield at different currents (uA) should show no slope.
  - LH_2 could boil, and is required to determine the boiling correction factor for the LT separation.

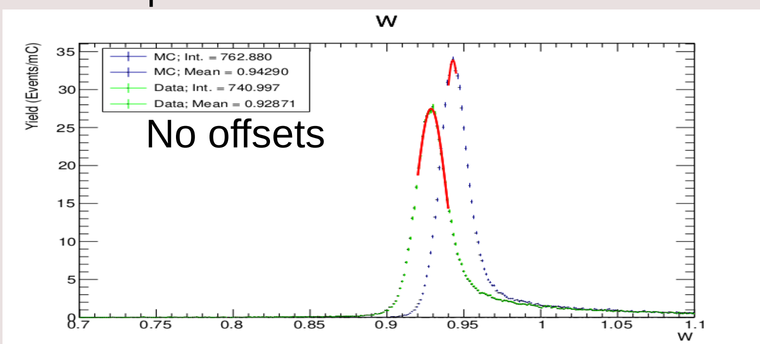


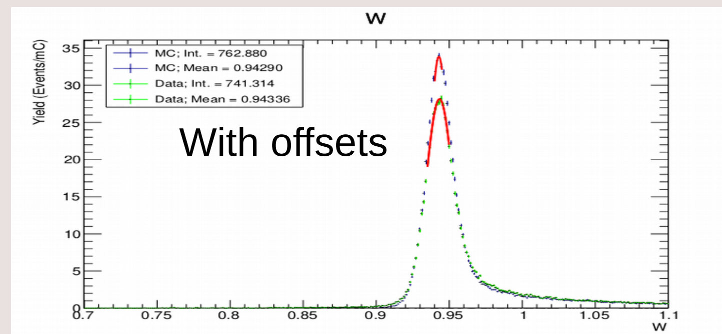


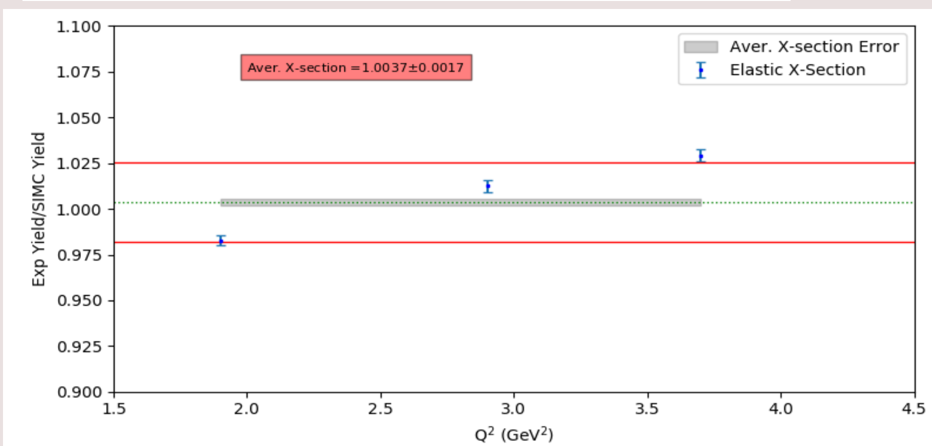
Error bars are statistical only.

‘Heep’, $e + p \rightarrow e' + p$, Analysis

- High quality L-T separation requires that we know the beam energy, spectrometer angles and momenta more accurately than what we know from the power supply calibrations and floor angle markings.
  - Heep reaction kinematically over-determined (detected both the e’ and p).
  - Missing energy, missing momentum and components of missing momentum must work out to zero.
  - W should ideally be equal to the proton mass.
  - We use the deviations between observed and physically-required values to determine the experimental offsets.



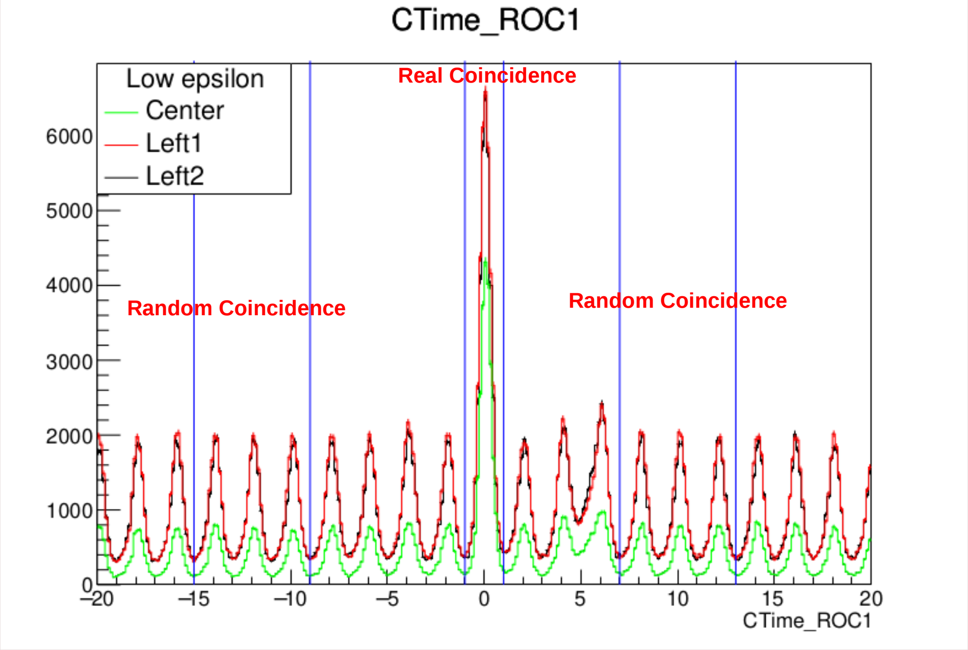


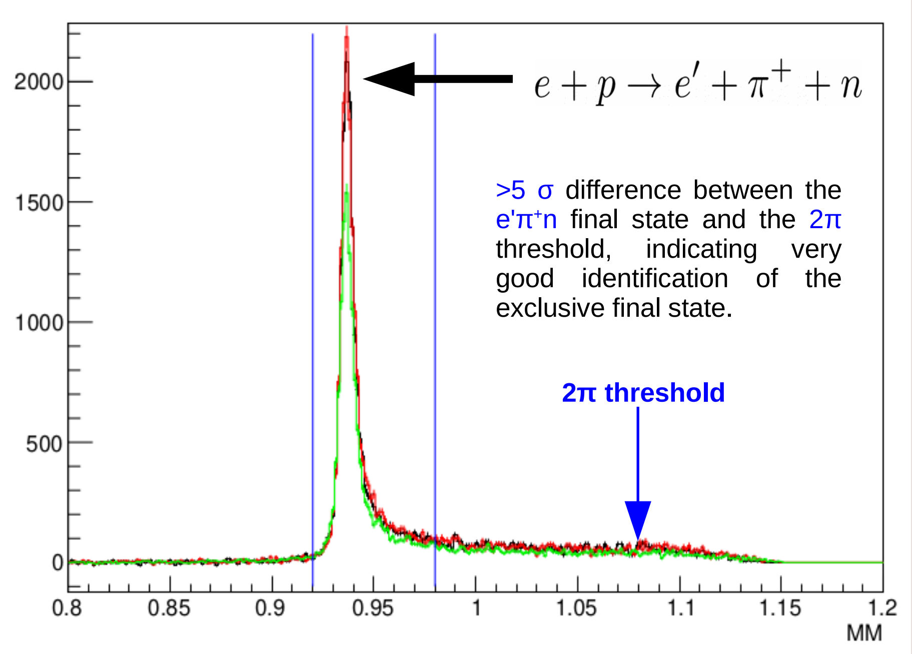


Quantity	SHMS	HMS
In-plane angle	2.8 mrad	1.2 mrad
Out-of-plane angle	0.0	0.99 mrad
Central Momentum	0.0	0.15%
Beam Energy	0.01% to 0.07%	

$e + p \rightarrow e' + \pi^+ + n$ Event Selection

- The experimental data acquired in the coincidence mode of DAQ.
  - The coincidence time is defined as, $t_{coin} = t_{HMS} - t_{SHMS}$.
  - Random coincidences: due to the RF structure of the electron beam, giving rise to accidental coincidences between a scattered electron from one beam burst and a pion from another.
  - Random coincidences are measured and subtracted from the real coincidences to give the real coincidences. The time spacing of bunches is 2 ns.
  - Also, we uniquely identify the exclusive final state with the missing mass technique.





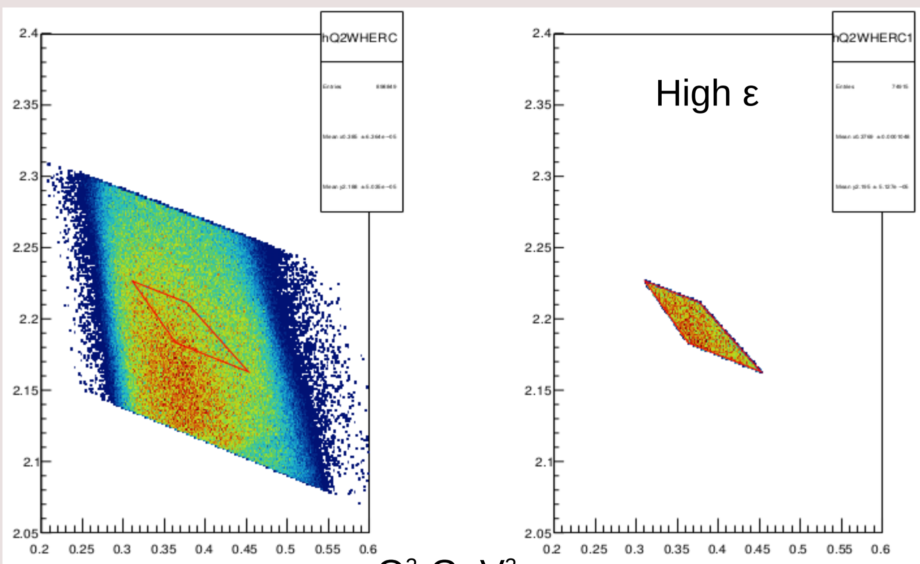
$$MM = \sqrt{((E_b + m_p - E'_e - E_{\pi^+})^2 - (\vec{P_e} - \vec{P_{e'}} - \vec{P_{\pi^+}})^2)}$$

$e + p \rightarrow e' + \pi^+ + n$ Diamond Cut, -t binning & Φ binning

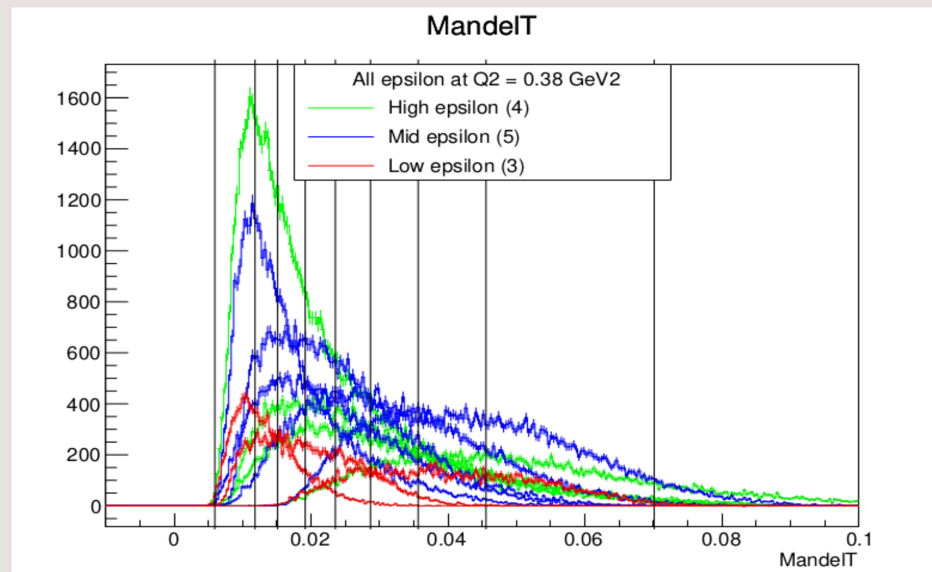
- To separate the individual cross-section terms through the Rosenbluth separation technique.
  - A diamond cut is required to match the phase space for all three ε data.
  - Diamond cut decides from the low ε data and applies the same cut to all three ε data.
  - -t and Φ binning: extract the cross section in -t and φ bins. In this study, 8 t bins and 16 Φ bins decided for a better converge the Rosenbluth separation equation.

$Q^2 = 0.38$ GeV²

W (GeV)



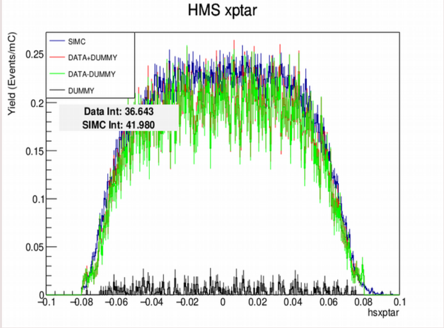
Q^2 GeV²



$t = (p_\gamma - p_\pi)^2$

$e + p \rightarrow e' + \pi^+ + n$ Cross-Section

- Monte Carlo (SIMC) is used to account for effects on the experimental acceptance, such as finite target length and beam spot, magnet field map and detector geometry.
  - It includes an empirical model, to compare the simulated event distributions with the observed distributions, for various experimental variables.

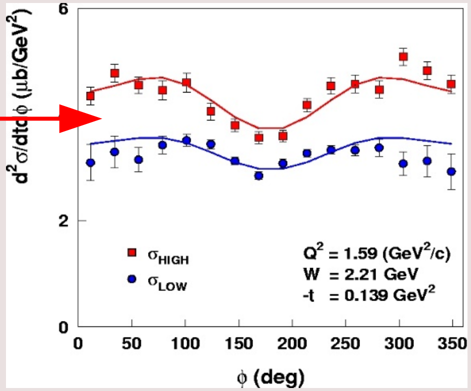


- The unseparated cross-section is calculated as,

$$\sigma_{exp}(\bar{W}, \bar{Q^2}, t, \phi; \bar{\theta}, \bar{\epsilon}) = \frac{Y_{exp}}{Y_{MC}} \sigma_{MC}(\bar{W}, \bar{Q^2}, t, \phi; \bar{\theta}, \bar{\epsilon}).$$

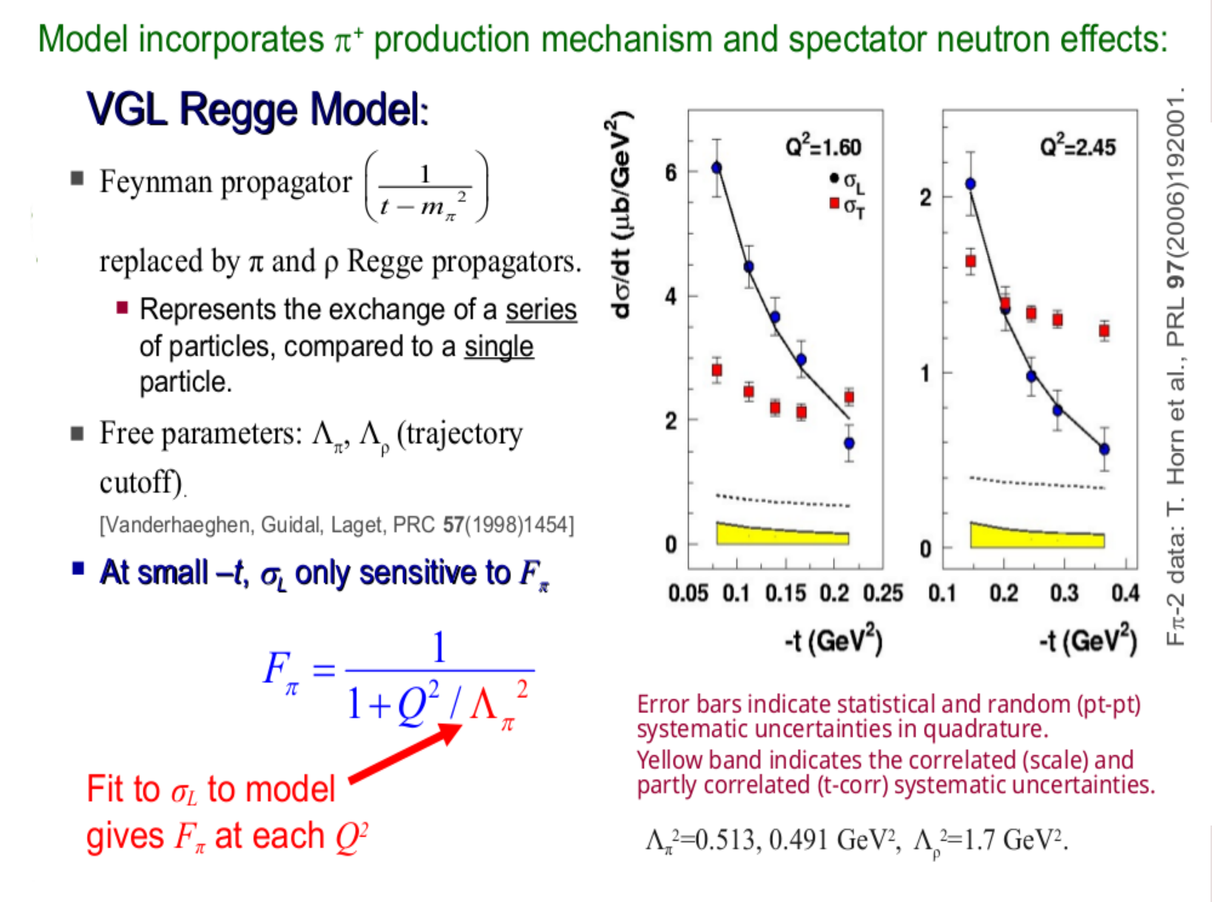
- The simultaneous fitting gives the individual cross-section terms.

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

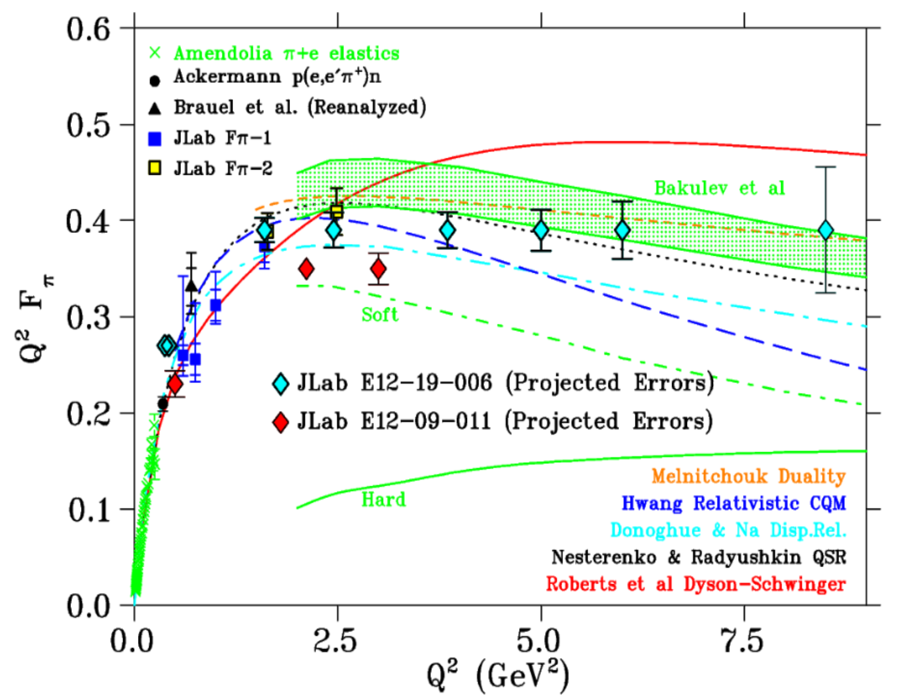


- The model input cross-section is then iterated to achieve the best agreement between the data and SIMC. The iteration process is continued until the experimental cross-section changes by less than 1 %.

Extract $F_\pi(Q^2)$ from JLab σ_L data



Previous measurements and projected results for the whole E12-19-006 experiment.



We now also have CKY model.

If anyone is working on developing cross-section models (σ_L & σ_T), please let me know. I would love to talk to you.

- Garth Huber (UofR), Tanja Horn (CUA) and Dave Gaskell (JLab).
- Proposal of the experiment: E12-19-006

Slide's credit to Garth Huber

The study at EIC

Extension of the Studies to EIC

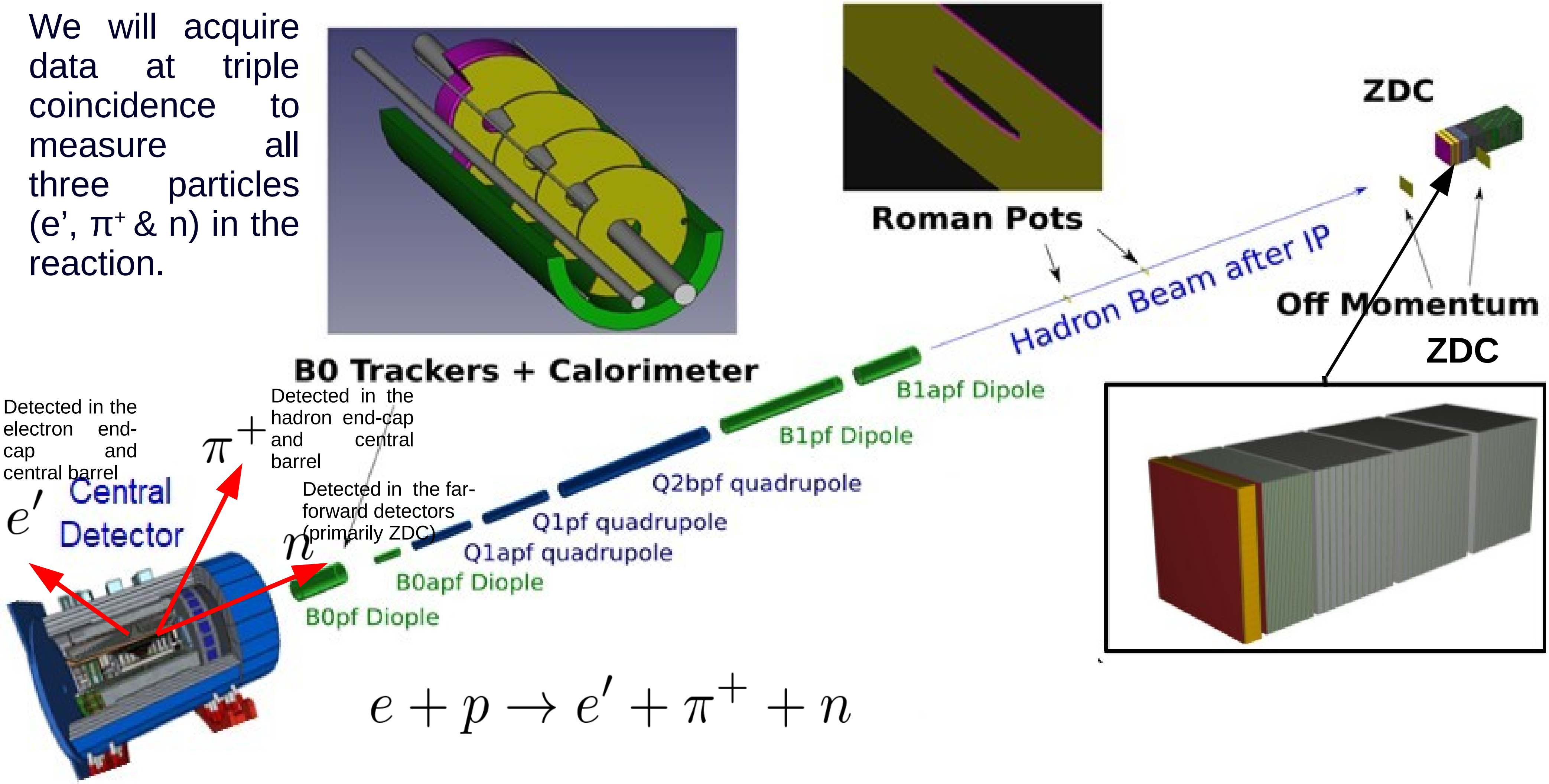
- **Physics Motivation:**
  - JLab measurements have shown the importance of π^+ and K^+ structure studies for understanding QCD's transition from "weak" and "strong" domains, and understanding DCSB's role in generating hadron properties.
  - Definite answers to these questions require high Q^2 data well beyond JLab's reach.
  - The Electron–Ion Collider (EIC) may provide this reach.

- **Experimental Issues:**
  - The cross section for the exclusive $p(e, e'\pi^+n)$ channel is small, can it be cleanly identified at EIC?
  - Is the detector resolution sufficient to reliably reconstruct (Q^2,W, t)? (work is being done)
  - How to measure the longitudinal cross section, $d\sigma_L/dt$, (LT separation is not possible at the EIC) needed for form factor extraction?

Extension of the Studies to EIC

Far-Forward Detectors:

We will acquire data at triple coincidence to measure all three particles (e', π^+ & n) in the reaction.



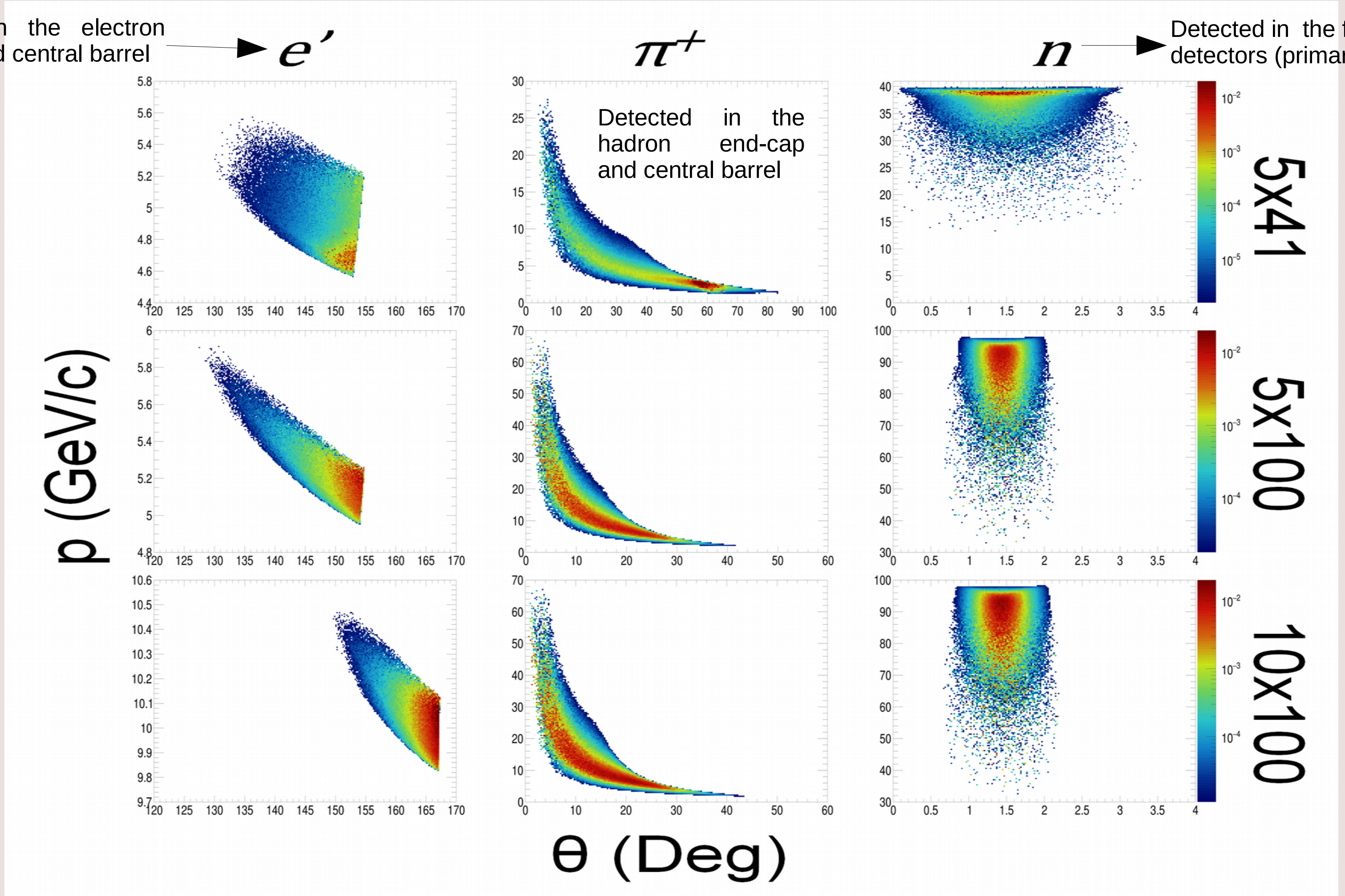
$$e + p \rightarrow e' + \pi^+ + n$$

$e + p \rightarrow e' + \pi^{+} + n$ at EIC

- The weighted spatial distribution study of p(e, e'π^+,n) reaction.
  - Used Deep Exclusive Meson Production (DEMP) event generator.

Detected in the electron end-cap and central barrel

Detected in the far-forward detectors (primarily ZDC)

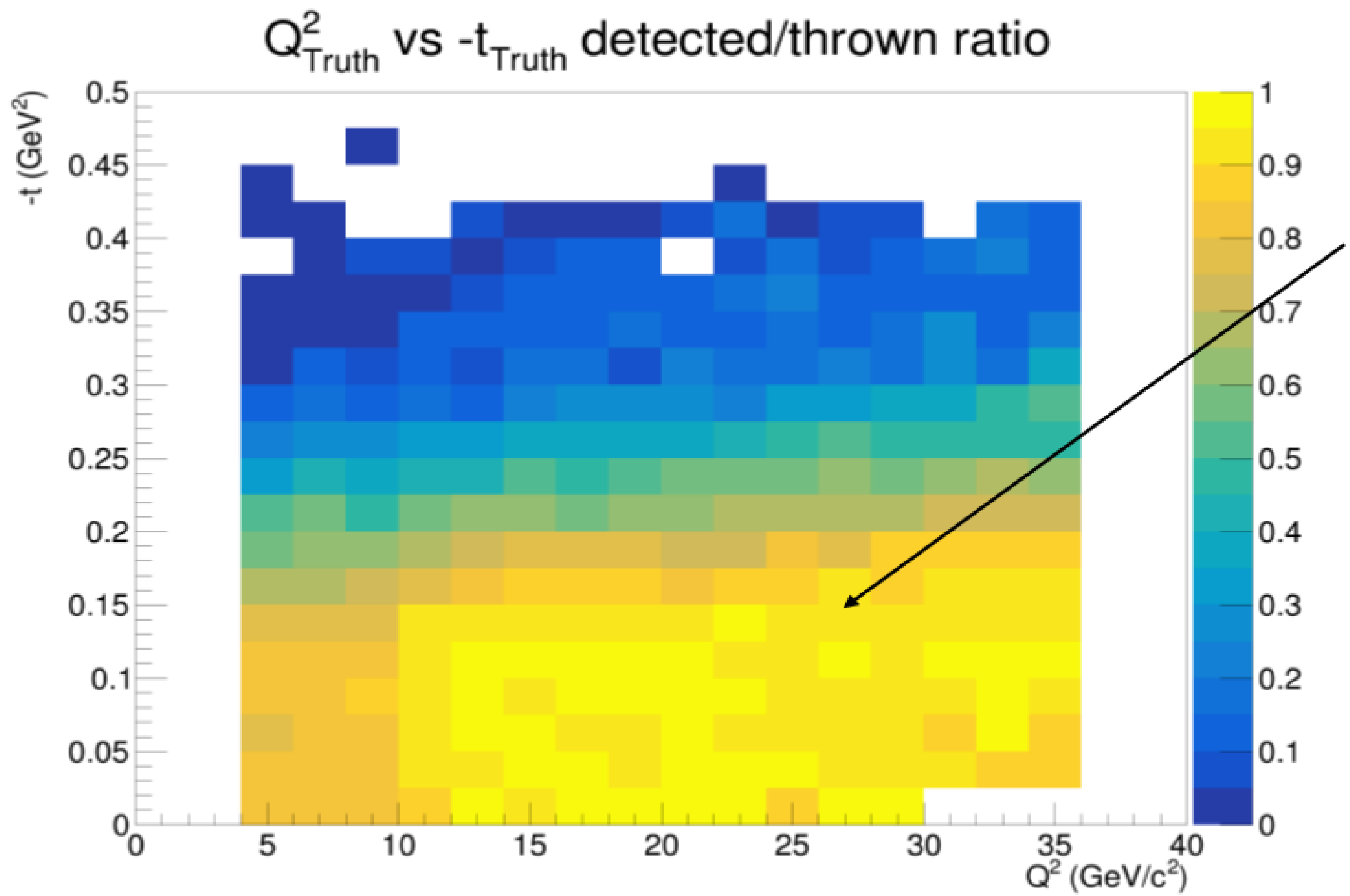


More details about simulation are in the ECCE NIM paper .

Plot's credit to Love Preet

Triple Coincidence Efficiency Study

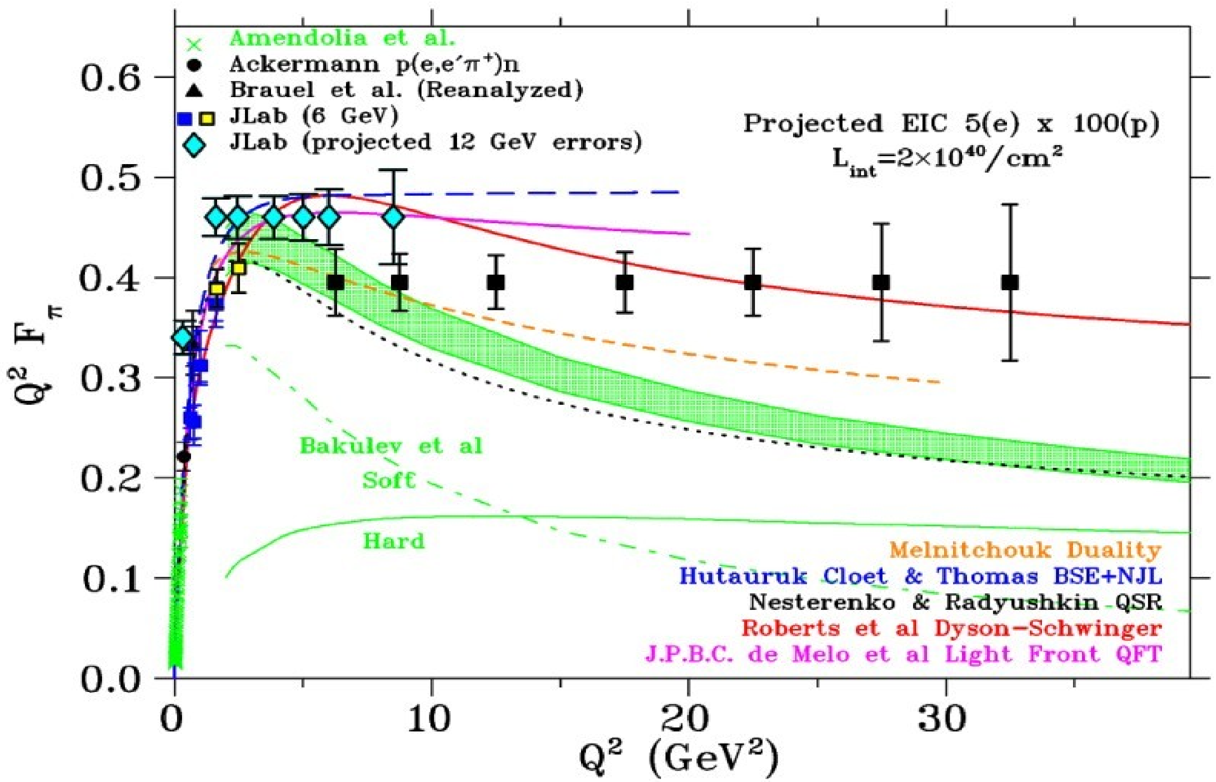
Detection efficiency per (Q^2,t) bin



Detection efficiency best in crucial low $-t$ region

Plot by Stephen Kay

The Projected F_π (Q^2) at EIC (5(e) x 100(p))



Assumptions:

- 5(e^-) x 100(p)
- Integrated L=20 fb^{-1}/yr
- Clean identification of exclusive $p(e,e'\pi^+n)$ events
- t reconstruction resolution based on ECCE detector design
- Syst. Unc: 2.5% pt–pt and 12% scale
- $R=\sigma_L/\sigma_T$ =0.013–0.14 at lowest $-t$ from VR model, and $\delta R=R$ syst. unc. in model subtraction to isolate σ_L.
- π pole dominance at small $-t$ confirmed in ^2H π^-/π^+ ratios.

Plot's credit to Garth Huber

Summary

- Our research focuses on advancing our comprehension of the electro-production reaction mechanism for pions and kaons, along with the investigation of their electromagnetic form factors. Jefferson Lab is the only facility for the LT separation.
- The pion data analysis at low Q^2 (0.38 & 0.42) would be the first measurement at the lowest -t, and the multiple experimental settings (left1, left2, center, right1 & right2).
- Unlike the pion pole, the dominance of the kaon pole at the lowest -t has not been previously tested. For the first time, our group is trying to understand the dominance of the kaon pole at the lowest -t.
- We are delving into understanding the validity of factorization, specifically how longitudinal and transverse cross-sections scale with Q^2.
- Our group is actively engaged in extending the study of pion and kaon structures at the Elecdtron-Ion Collider.

University of Regina

Center for Frontiers in Nuclear Science

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SAPIN-2021-00026

Thank You!

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