Measurement of the Charged Pion and Kaon Form Factors to High Q^2 at JLab and the EIC

University of Regina

Garth Huber

(on behalf of PionLT and KaonLT Collaborations and EIC Canada)

Elucidating the structure of Nambu-Goldstone bosons
CFNS Workshop
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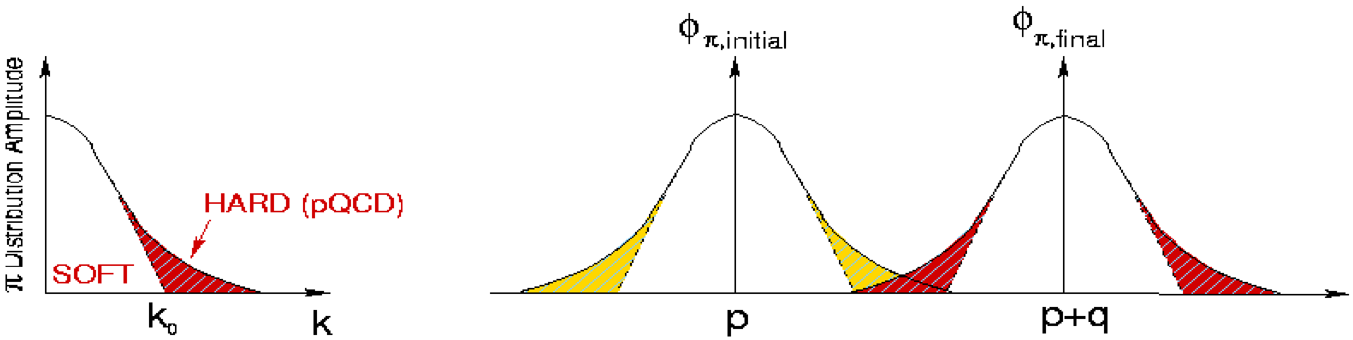
Charged Meson Form Factors

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.

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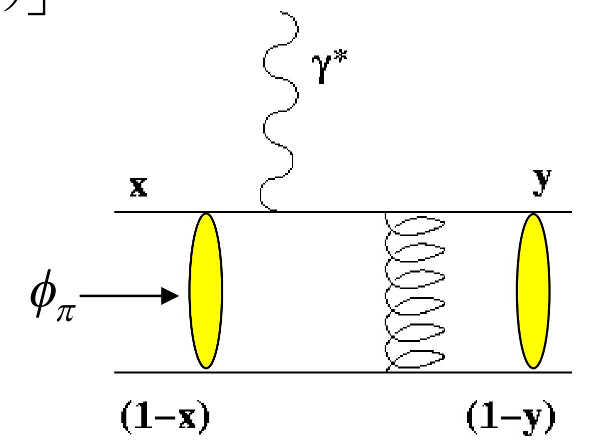
The Pion in perturbative QCD

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

$$F_\pi(Q^2) = \frac{4\pi C_F \alpha_S(Q^2)}{Q^2} \left| \sum_{n=0}^{\infty} a_n \left(\log\left(\frac{Q^2}{\Lambda^2}\right)\right)^{-\gamma_n} \right|^2 \left[1 + O\left(\alpha_s(Q^2), \frac{m}{Q} \right) \right]$$

At asymptotically high Q^2, only hardest portion of pion distribution amplitude contributes

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



and F_π takes the very simple form

$$Q^2 F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} 16\pi\alpha_s(Q^2) f_\pi^2$$

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 $\mu\to\infty$.

***$Q^2 F_\pi$* 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]

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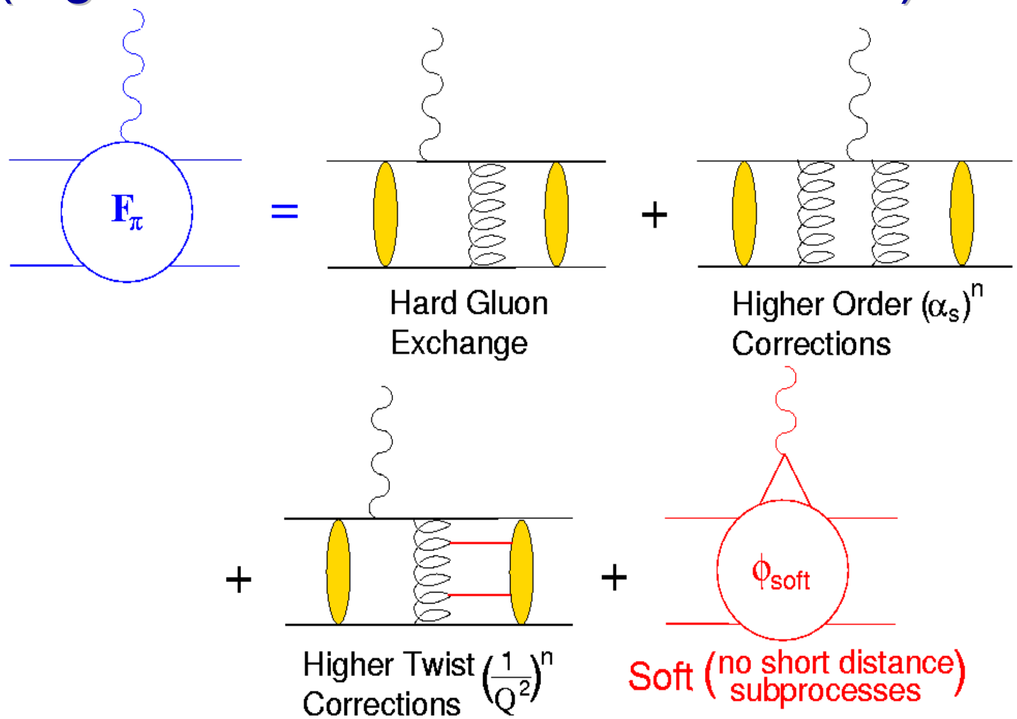
Pion Form Factor at Intermediate Q^2

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.

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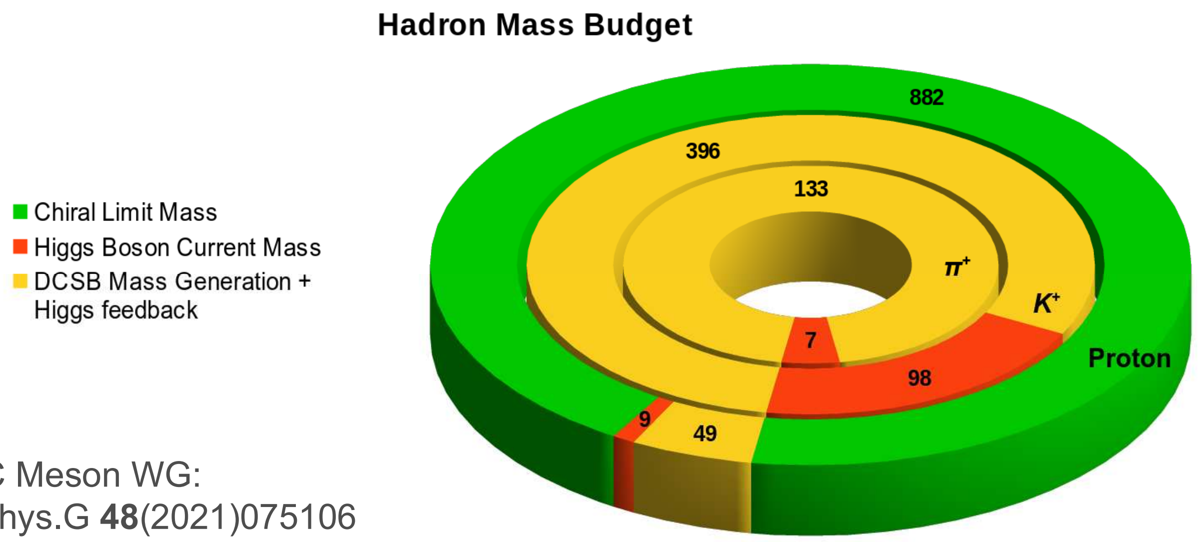
Contrasts in Hadron Mass Budgets



EIC Meson WG:
J.Phys.G **48**(2021)075106

Stark Differences between proton, K^+, π^+ mass budgets

- Due to Emergent Hadronic Mass (EHM), Proton mass large in absence of quark couplings to Higgs boson (chiral limit).
- Conversely, and yet still due to EHM and DCSB, *K* and π are massless in chiral limit (i.e. they are Goldstone bosons of QCD).
- The mass budgets of these crucially important particles demand interpretation.
- Equations of QCD stress that any explanation of the proton's mass is incomplete, unless it simultaneously explains the light masses of QCD's Goldstone bosons, the π and *K*.

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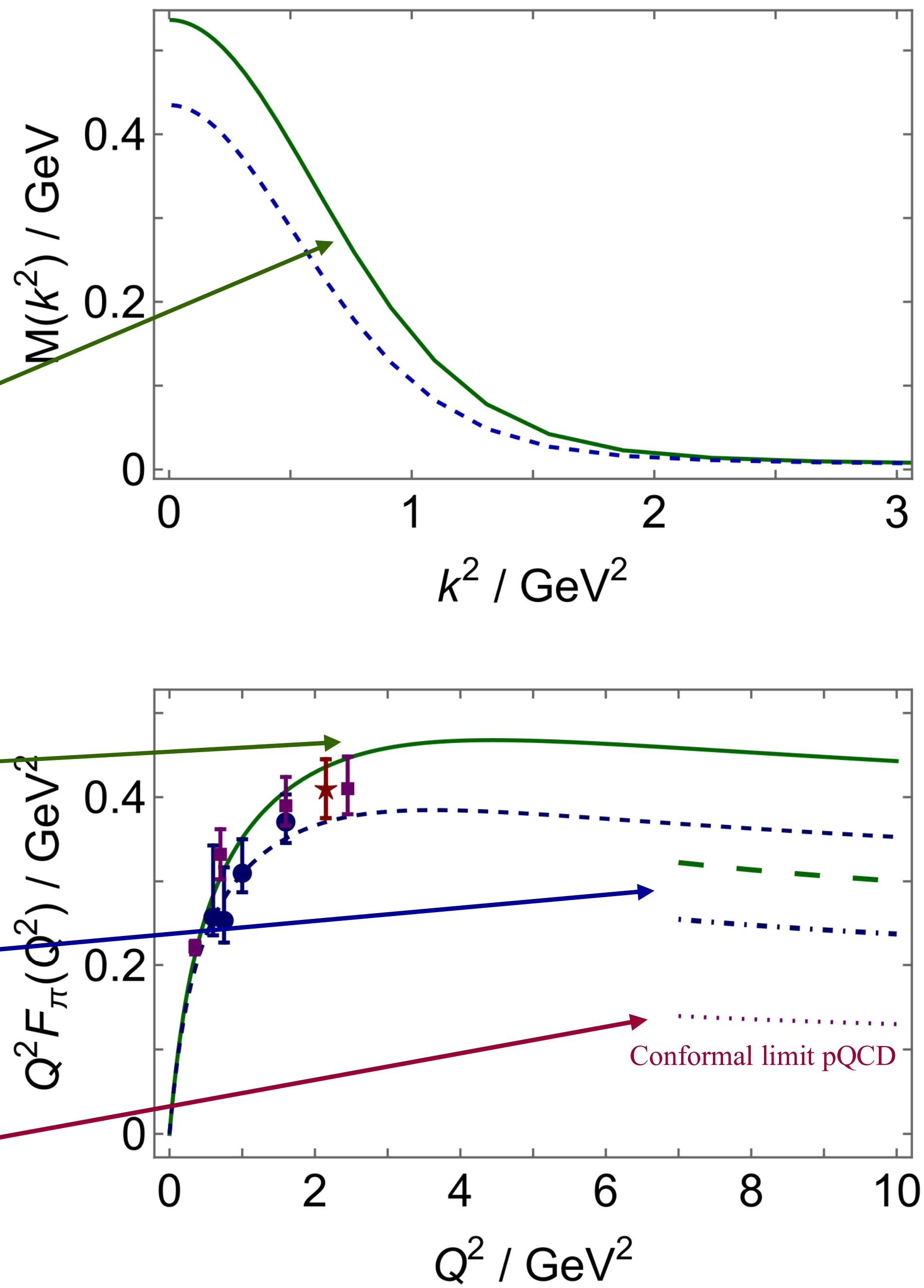
Synergy: Emergent Mass and π^+ Form Factor

At empirically accessible energy scales, π^+ form factor is sensitive to emergent mass scale in QCD

- **Two dressed–quark mass functions distinguished by amount of DCSB**
  - DCSB emergent mass generation is 20% stronger in system characterized by solid green curve, which is more realistic case
- **$F_\pi(Q^2)$ obtained with these mass functions**
  - r_π=0.66 fm with solid green curve
  - r_π=0.73 fm with solid dashed blue curve
- **$F_\pi(Q^2)$ predictions from QCD hard scattering formula, obtained with related, computed pion PDAs**
- **QCD hard scattering formula, using conformal limit of pion's twist–2 PDA**

$$\phi_\pi^{cl}(x) = 6x(1-x)$$



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

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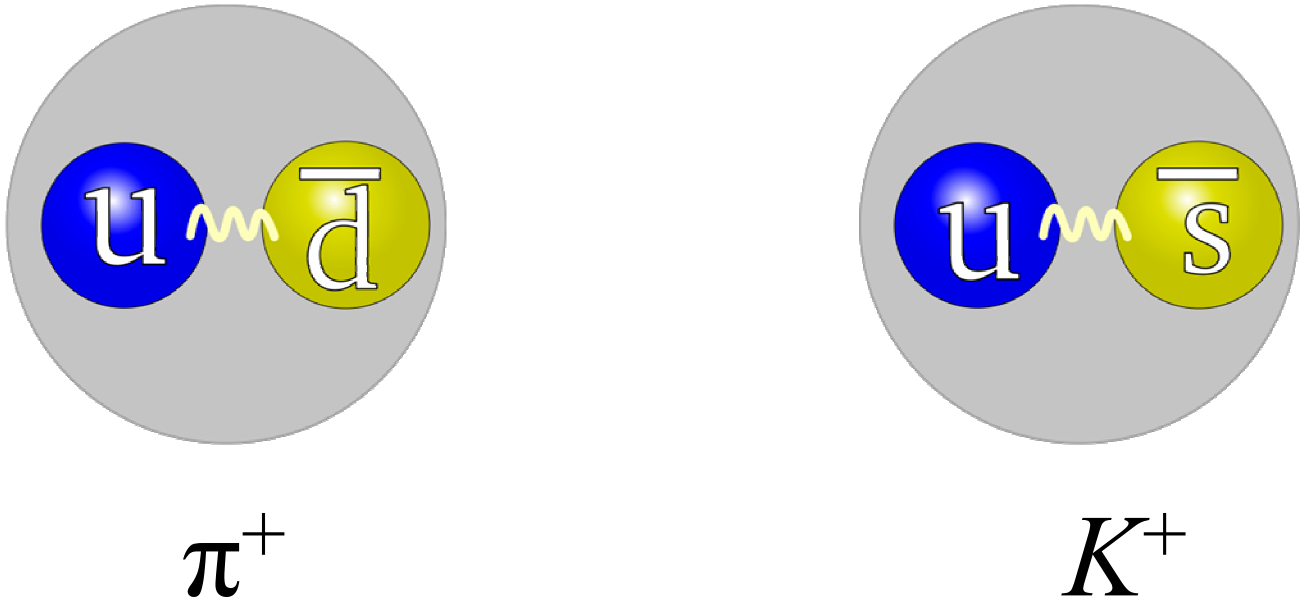
The Charged Kaon – a 2nd QCD test case



- 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.

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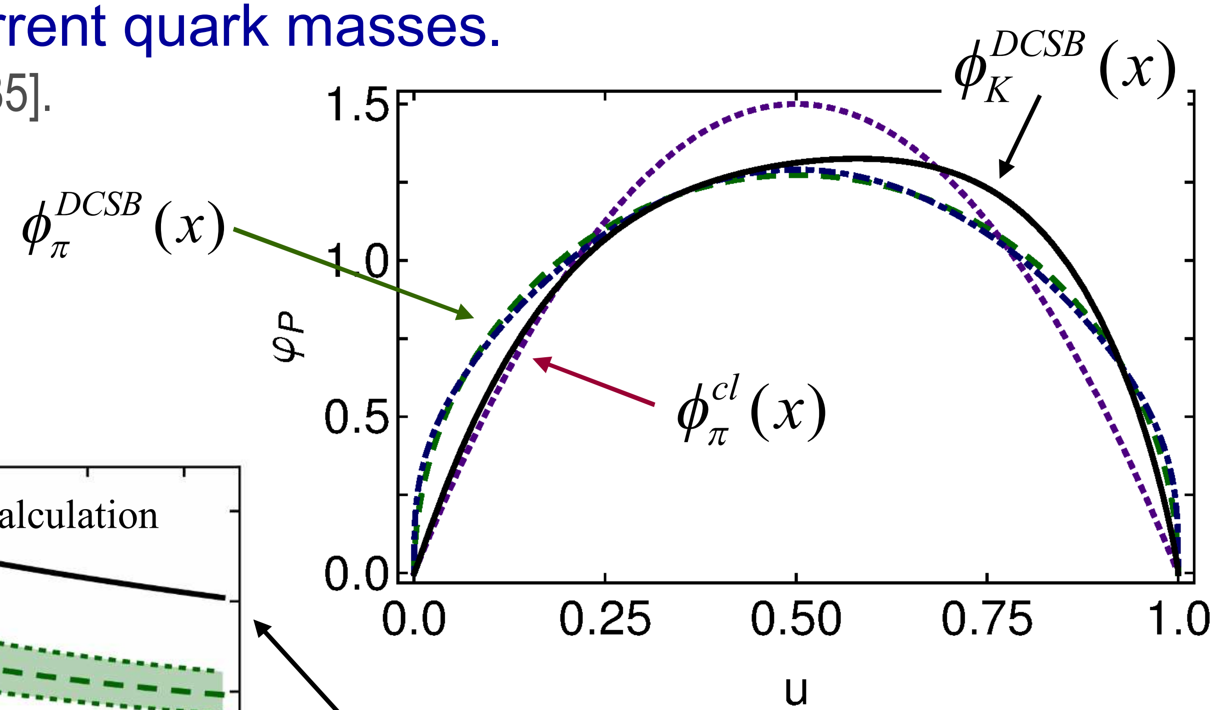
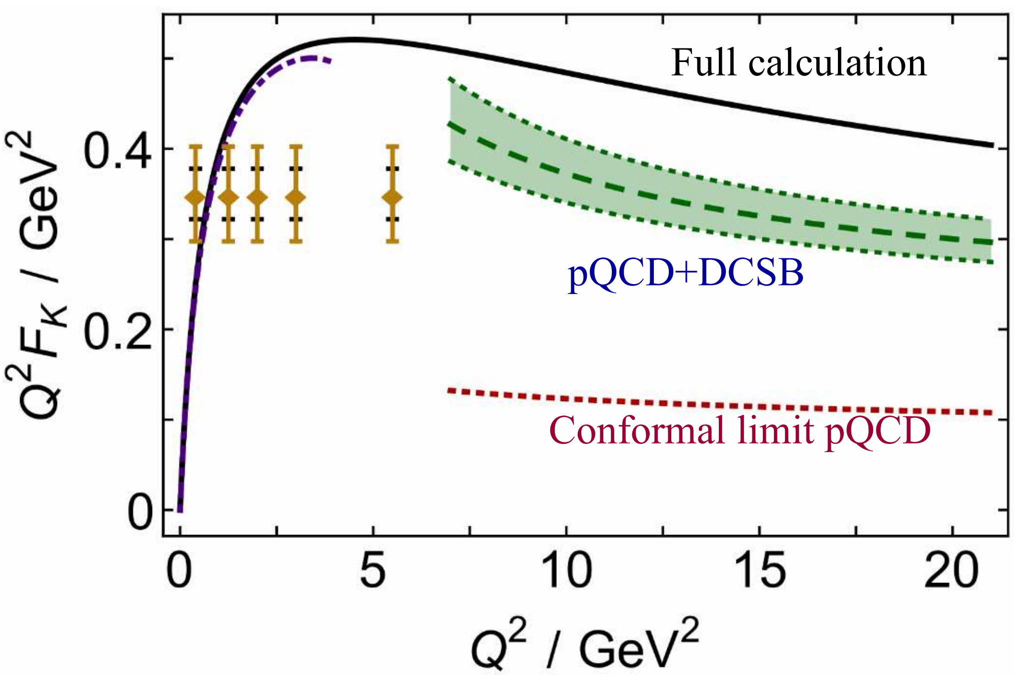
K^+ properties also strongly influenced by EHM

- **K^+ PDA also is broad, concave and asymmetric.**
- While the heavier s quark carries more bound state momentum than the u quark, the shift is markedly less than one might naively expect based on the difference of u, s current quark masses.
  [C. Shi, et al., PRD **92** (2015) 014035].





- **F_K DCSB model prediction for JLab kinematics**
  [F. Guo, et al., arXiv: 1703.04875].

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

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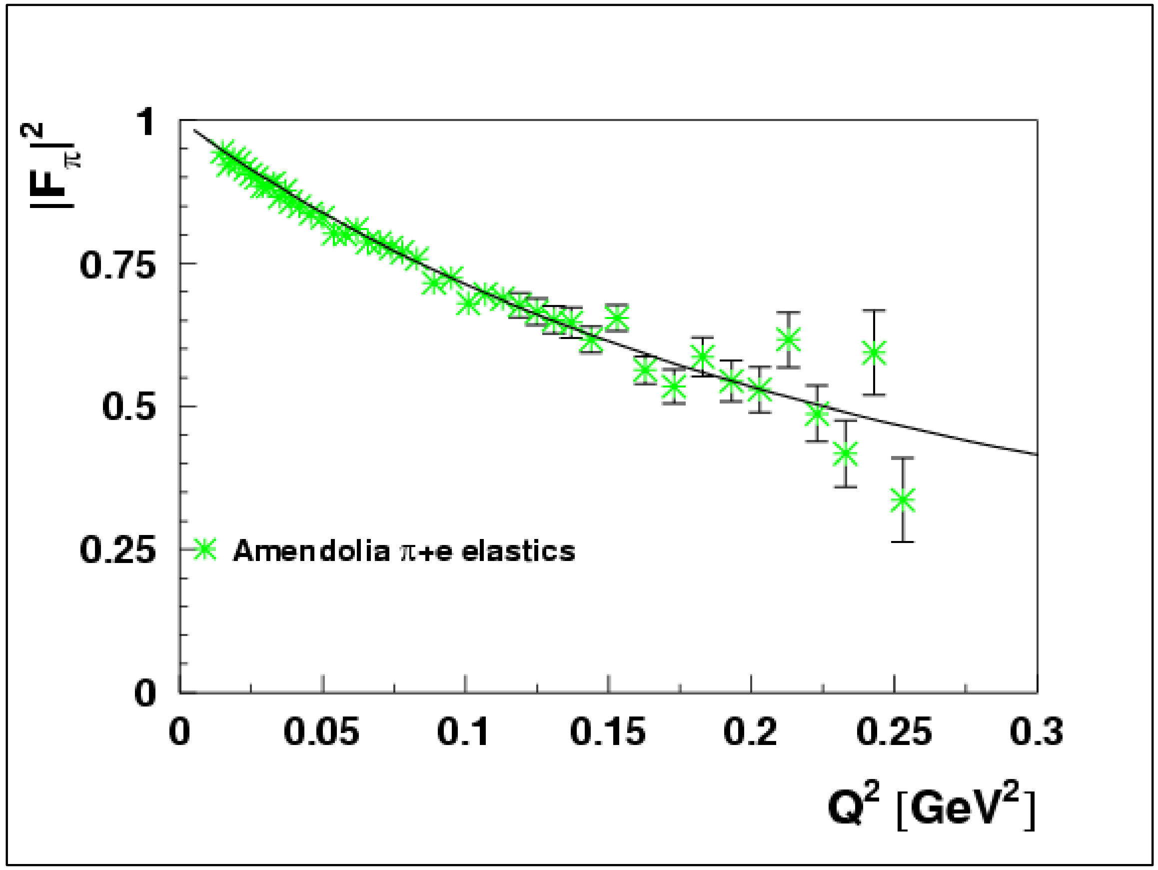
At low Q^2, F_π can be measured model–independently via high energy elastic π^- scattering from atomic electrons in Hydrogen

- 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



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

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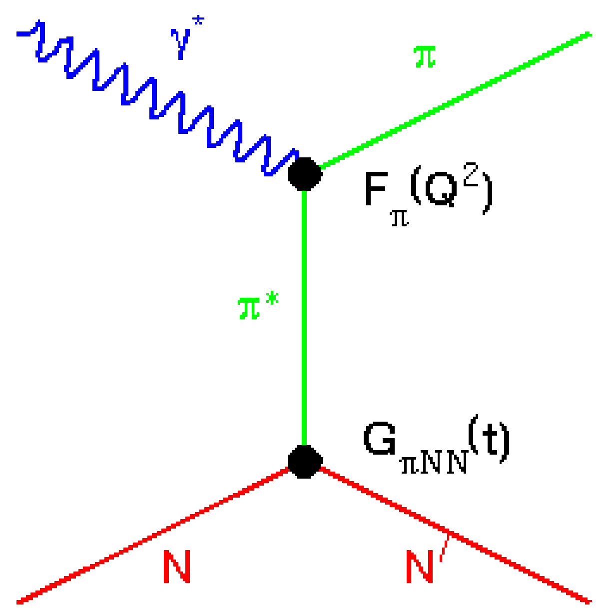
At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

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

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

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



Drawbacks of this technique
1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction.

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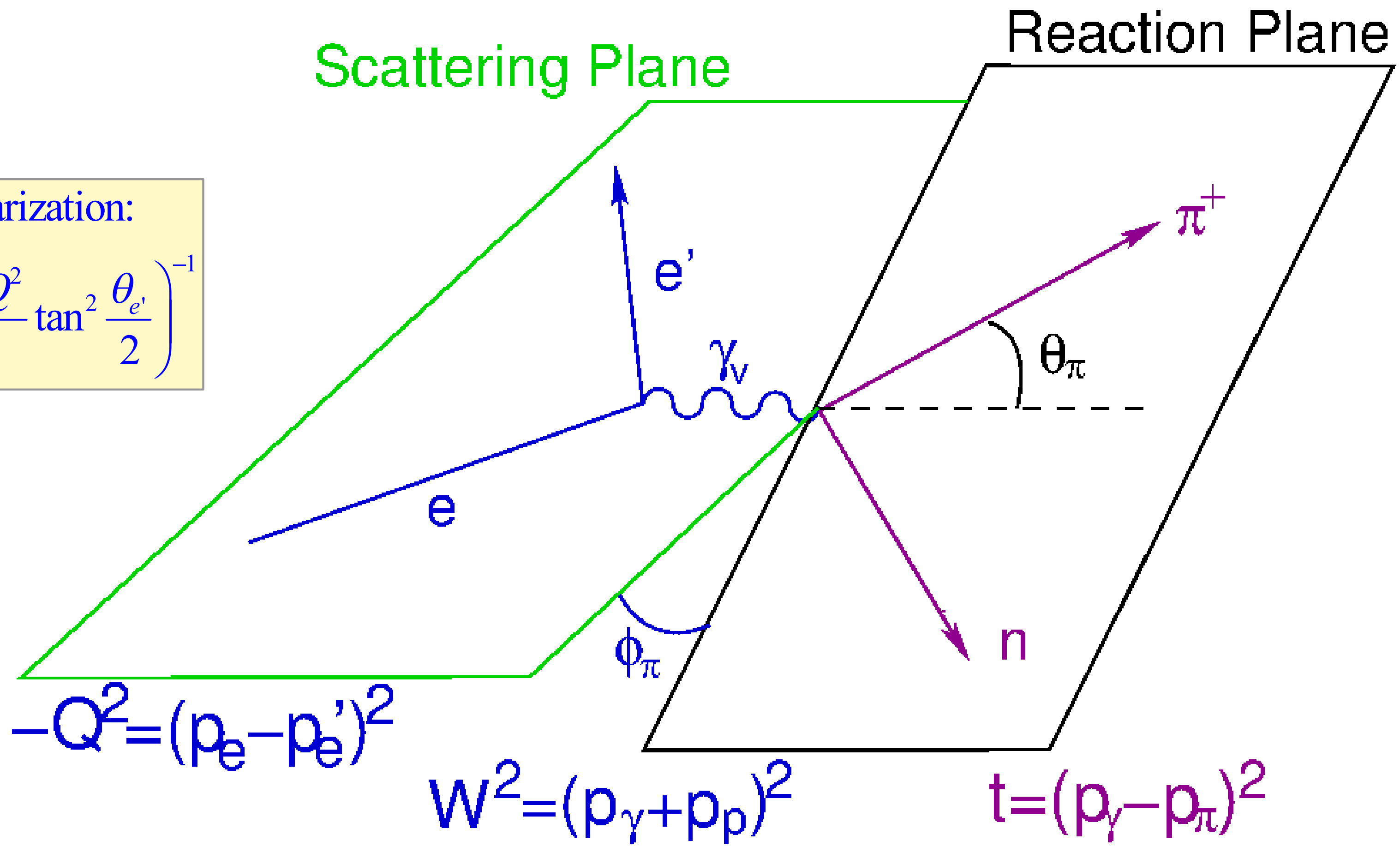
$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

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.**

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L/T–separation error propagation

Error in $d\sigma_L/dt$ is magnified by $1/\Delta\varepsilon$

→ To keep magnification factor <5x, need Δε>0.2, preferably more!

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

$$\frac{\Delta\sigma_L}{\sigma_L} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{(R+\varepsilon_1)^2+(R+\varepsilon_2)^2} \qquad \text{where } R=\frac{\sigma_T}{\sigma_L}$$

$$\frac{\Delta\sigma_T}{\sigma_T} = \frac{1}{(\varepsilon_1-\varepsilon_2)}\left(\frac{\Delta\sigma}{\sigma}\right)\sqrt{\varepsilon_1^{\,2}\left(1+\frac{\varepsilon_2}{R}\right)^2+\varepsilon_2^{\,2}\left(1+\frac{\varepsilon_1}{R}\right)^2}$$

The relevant quantities for F_π extraction are R and $\Delta\varepsilon$

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

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Chew–Low Method to determine Pion Form Factor

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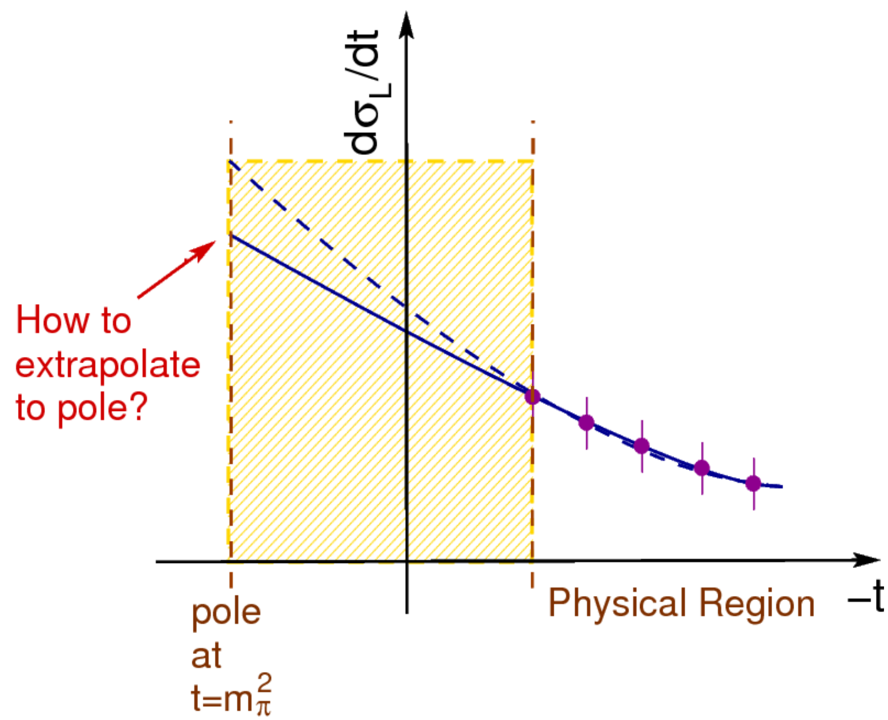
$p(e,e'\pi^+)n$ data are obtained some distance from the $t=m_\pi^2$ pole.

→ "Chew Low" extrapolation method requires knowing the analytic dependence of $d\sigma_L/dt$ through the unphysical region.

Extrapolation method last used in 1972 by Devenish & Lyth

- Very large systematic uncertainties.
- Failed to produce reliable result.

  → **Different polynomial fits equally likely in physical region gave divergent form factor values when extrapolated to $t=m_\pi^2$**



The Chew–Low Method was subsequently abandoned

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Only reliable approach is to use a model incorporating the π^+ production mechanism and the `spectator' nucleon to **extract** F_π from σ_L

- JLab F_π experiments have used 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]*
- **More models would allow a better understanding of the model dependence of the F_π result.**
- Some recent model developments, more are welcome!
  - *R.J. Perry, A. Kizilersu, A.W. Thomas, PLB **807**(2020)135581*
  - *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*

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

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JLab Hall C – 12 GeV Upgrade

SHMS:
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c **HMS**

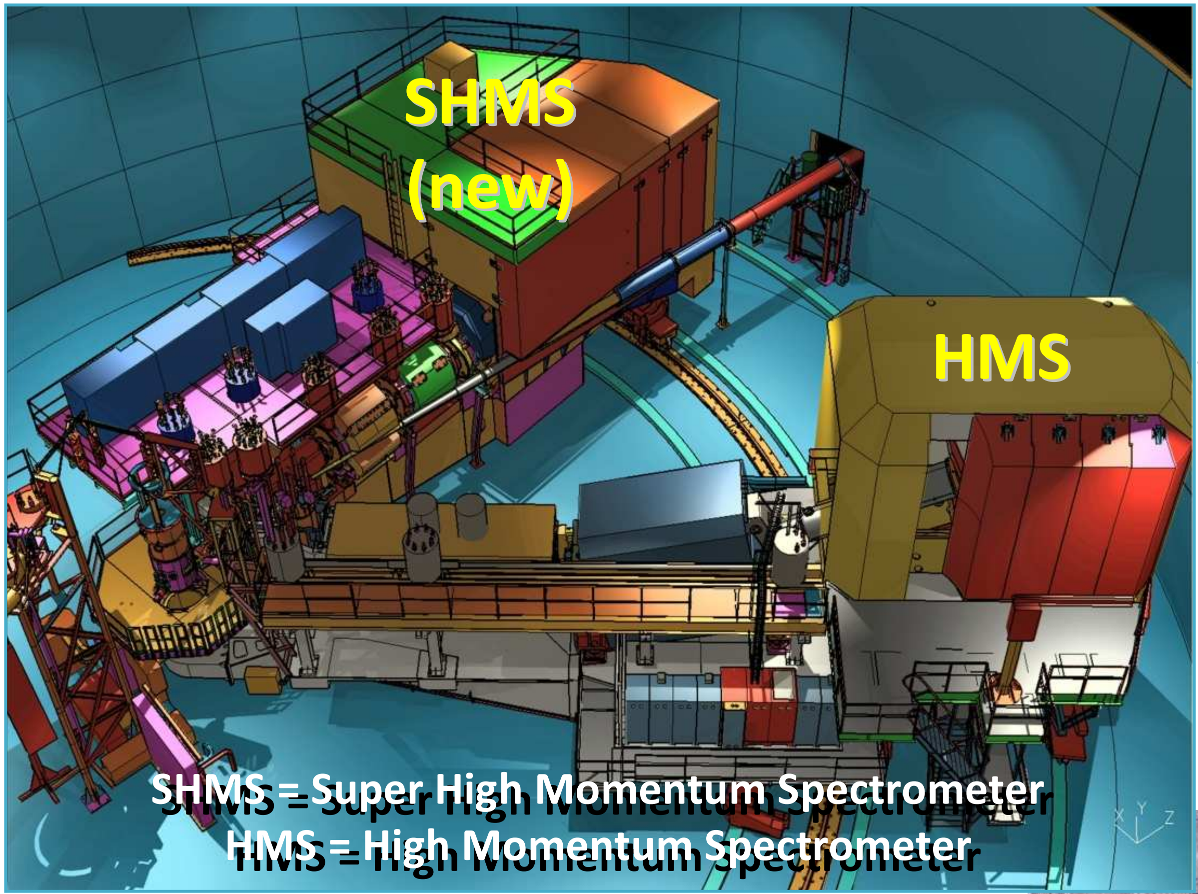
MAGNETIC OPTICS:
- Point-to Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

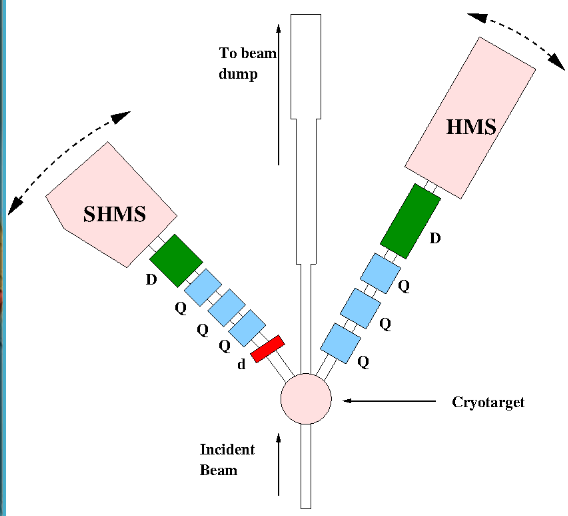
Detector Package:
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter

Well-Shielded Detector Enclosure

Rigid Support Structure
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

Luminosity
- ~4x10^{38} cm^{-2} s^{-1}

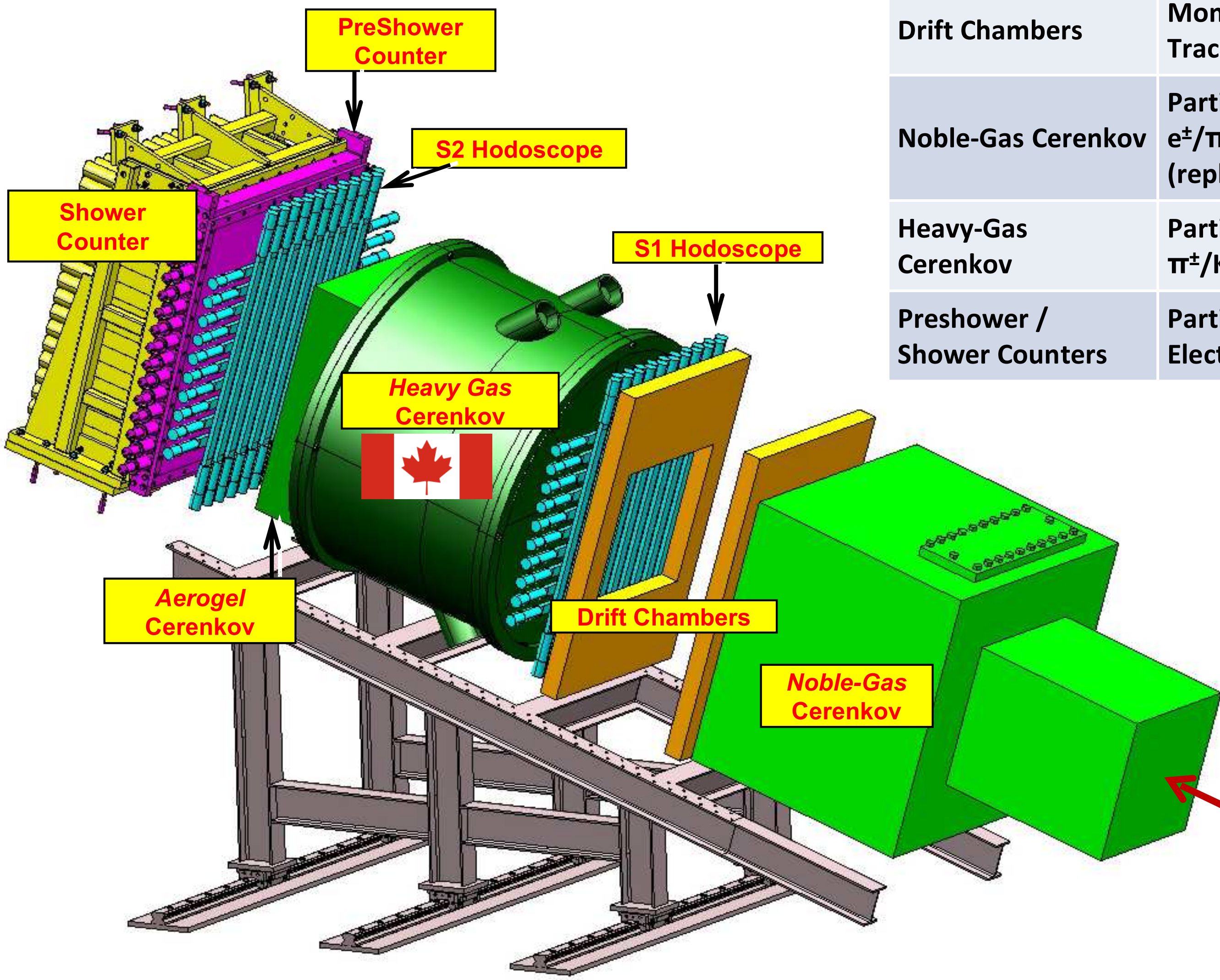




Upgraded Hall C has some similarity to SLAC End Station A, where the quark substructure of proton was discovered in 1968.

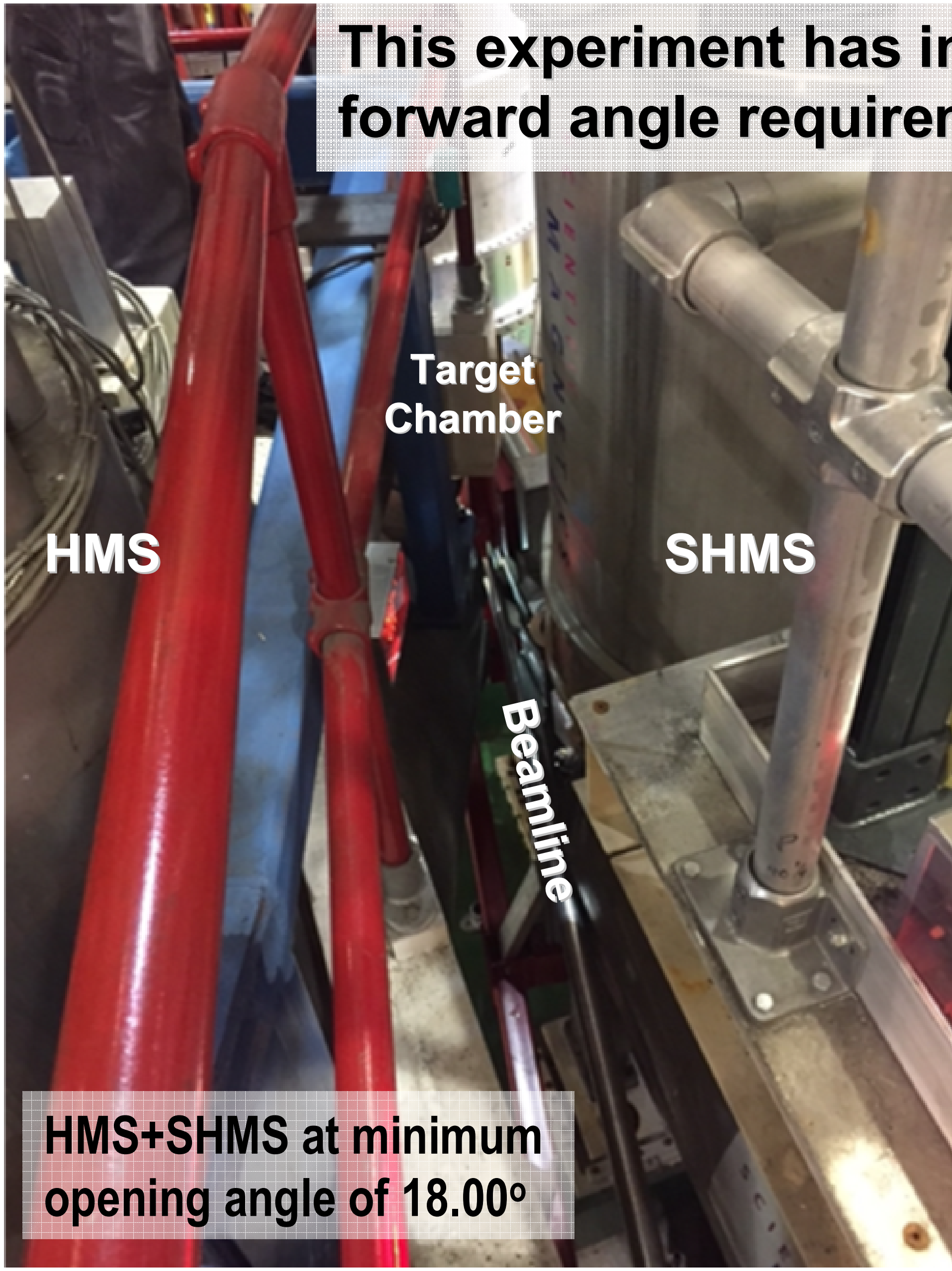
SHMS Focal Plane Detector System

DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cerenkov	Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^{\pm}$ threshold.
Heavy-Gas Cerenkov	Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination	C_4F_8O – Vary pressure to set index at $K^{\pm}$ threshold
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	



HMS and SHMS during Data Taking

This experiment has in large part driven the forward angle requirements of the SHMS+HMS



HMS+SHMS at minimum opening angle of 18.00°

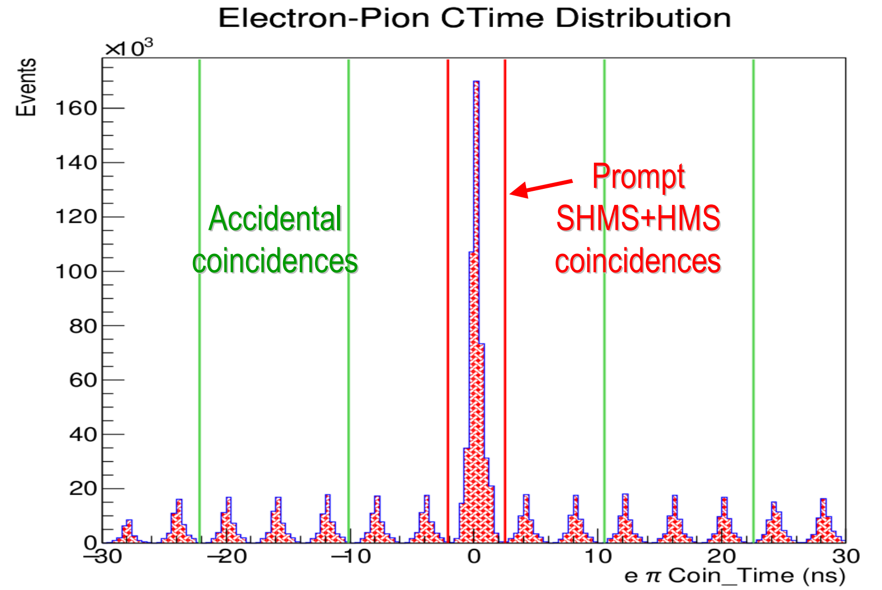
SHMS at 5.69°

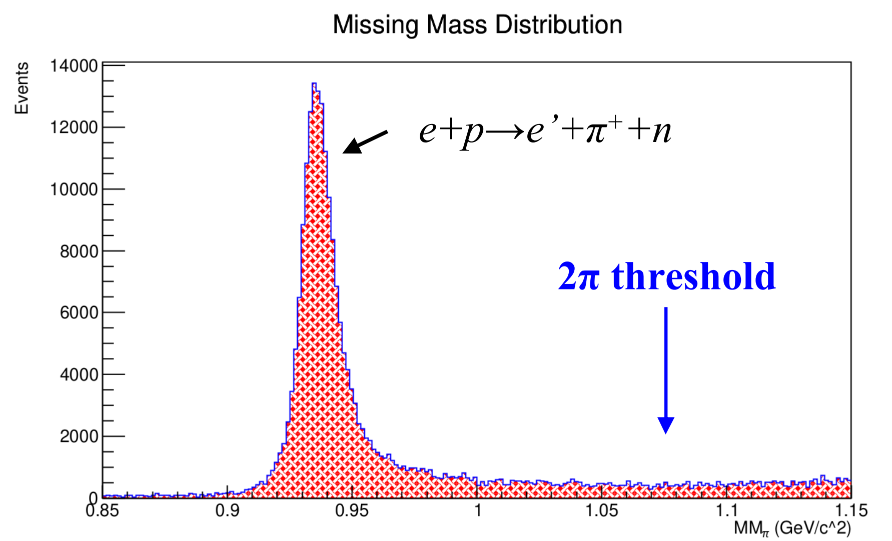
$p(e,e'\pi^+)n$ Event Selection

Coincidence measurement between charged pions in SHMS and electrons in HMS.

Easy to isolate exclusive channel

- Excellent particle identification
- CW beam minimizes "accidental" coincidences
- Missing mass resolution easily excludes 2–pion contributions





PionLT experiment E12–19–006 Data

Q^2=1.60, W=3.08, x= 0.157, ε=0.685

E_{beam}=9.177 GeV, P_{SHMS}=+5.422 GeV/c, θ_{SHMS}= 10.26° (left)

Plots by Muhammad Junaid (Regina)

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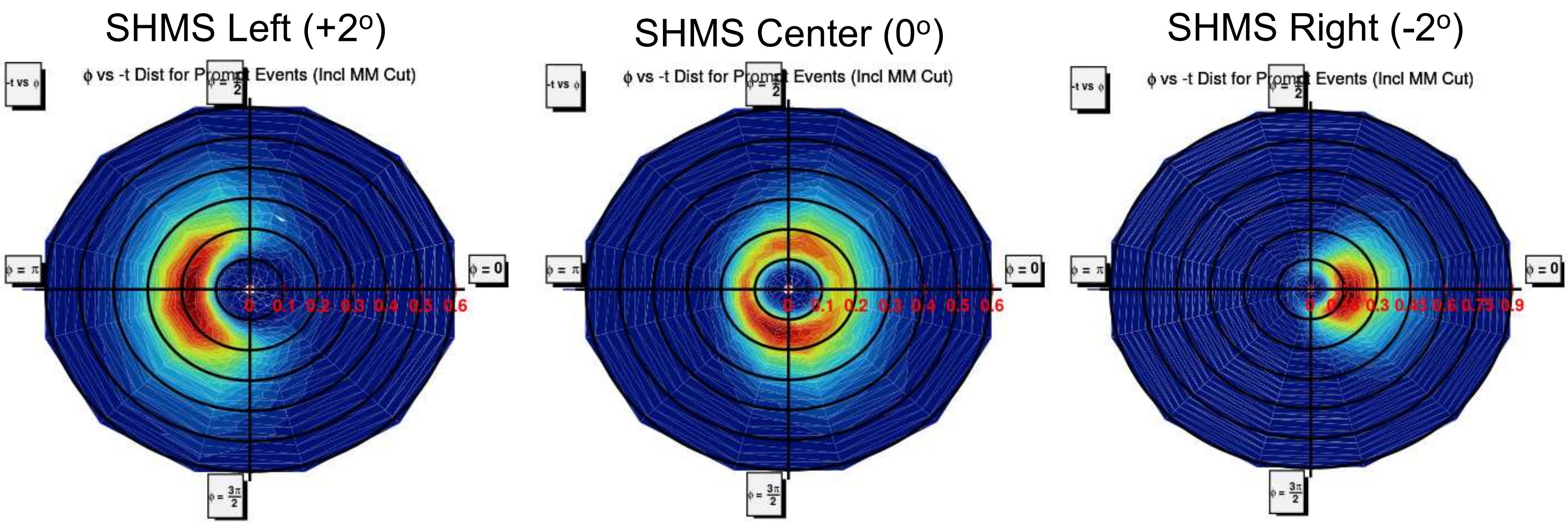
PionLT (E12–19–006) t–φ Coverage

- Measure σ_{LT}, σ_{TT} by taking data at three pion spectrometer (SHMS) angles, +2°, 0°, -2°, with respect to *q*–vector

Example t–φ plots from: Q^2=3.85, W=3.07, High ε



Plots by Nathan Heinrich (Regina)

- To control systematics, an excellent understanding of spectrometer acceptances is required
  - Over–constrained *p(e,e'p)* reaction, and inelastic e+^{12}C, used to calibrated spectrometer acceptances, momenta, kinematic offsets, efficiencies.
  - Control of point–to–point systematic uncertainties crucial due to 1/Δε error amplification in σ_L

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The different pion arm (SHMS) settings are combined to yield φ-distributions for each *t*-bin

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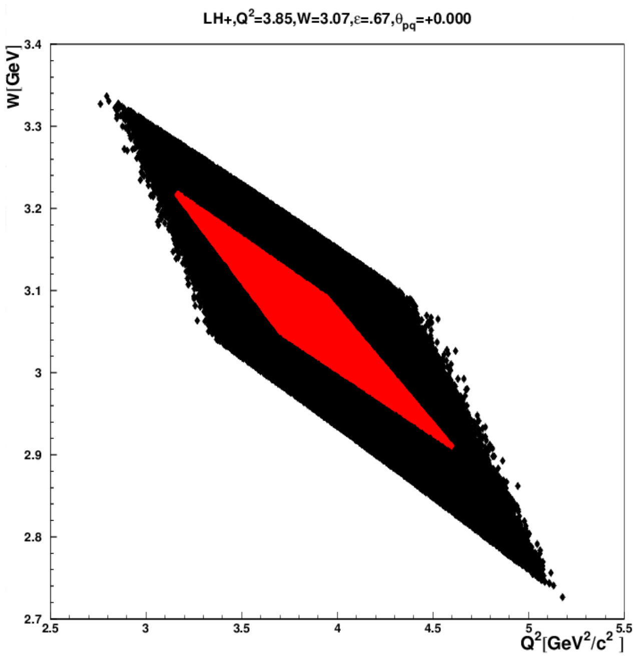
$$2\pi\frac{d^2\sigma}{dt\,d\phi}=\varepsilon\frac{d\sigma_L}{dt}+\frac{d\sigma_T}{dt}+\sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi+\varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

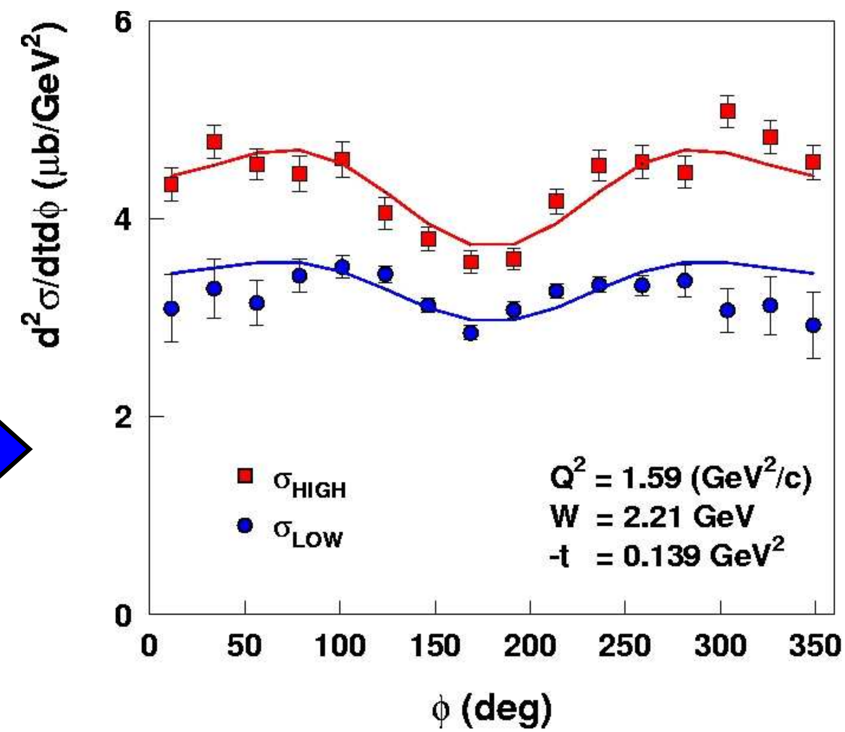


Diamond cuts define common (W,Q^2) coverage at both ε

Simulated SHMS+HMS acceptance at Q^2=3.85, W=3.07

■ High ε=0.67 ■ Low ε=0.30

- Extract σ_L by simultaneous fit of L,T,LT,TT using measured azimuthal angle (φ_π) and knowledge of photon polarization (ε)



Fπ-2 data: T. Horn, *et al*, *PRL* **97** (2006)192001

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

Model incorporates π^+ production mechanism and spectator neutron effects:

VGL Regge Model:

- Feynman propagator $\left(\frac{1}{t - m_\pi^2}\right)$

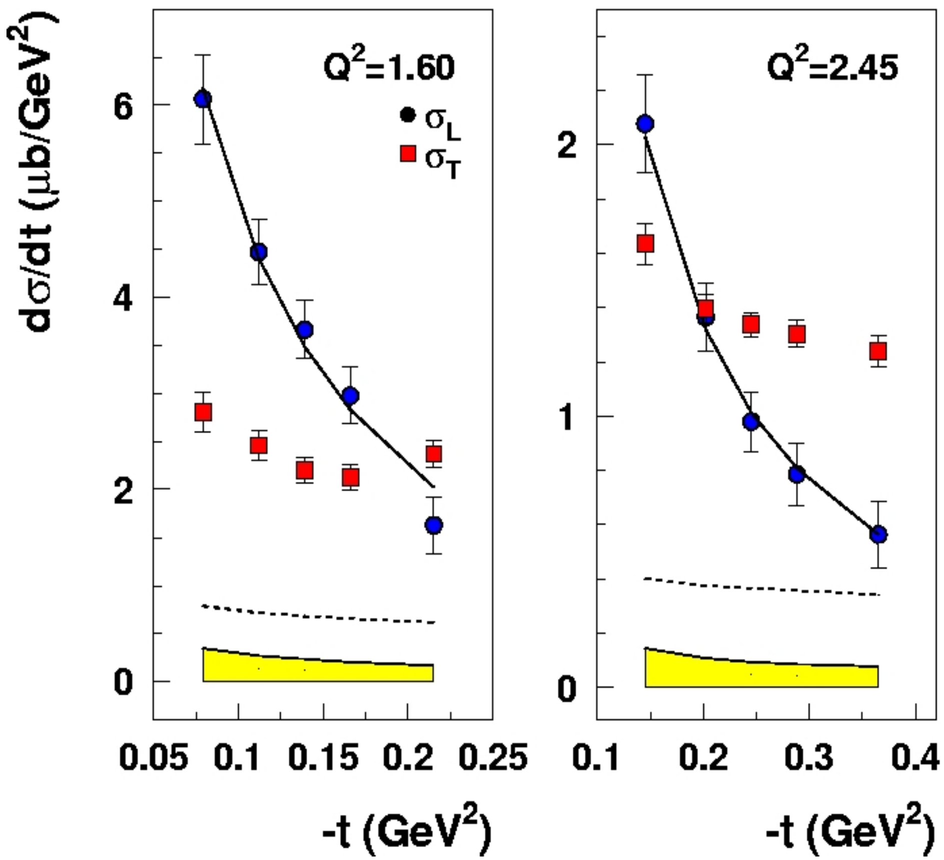
  replaced by π and ρ Regge propagators.
  - Represents the exchange of a series of particles, compared to a single particle.
- Free parameters: Λ_π, Λ_ρ (trajectory cutoff).

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

- At small $-t$, σ_L only sensitive to F_π

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

Fit to σ_L to model gives F_π at each Q^2



Fπ-2 data: T. Horn et al., PRL **97**(2006)192001.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature.
Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

Λ_π^2=0.513, 0.491 GeV², Λ_ρ^2=1.7 GeV².

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Current and Projected F_π Data

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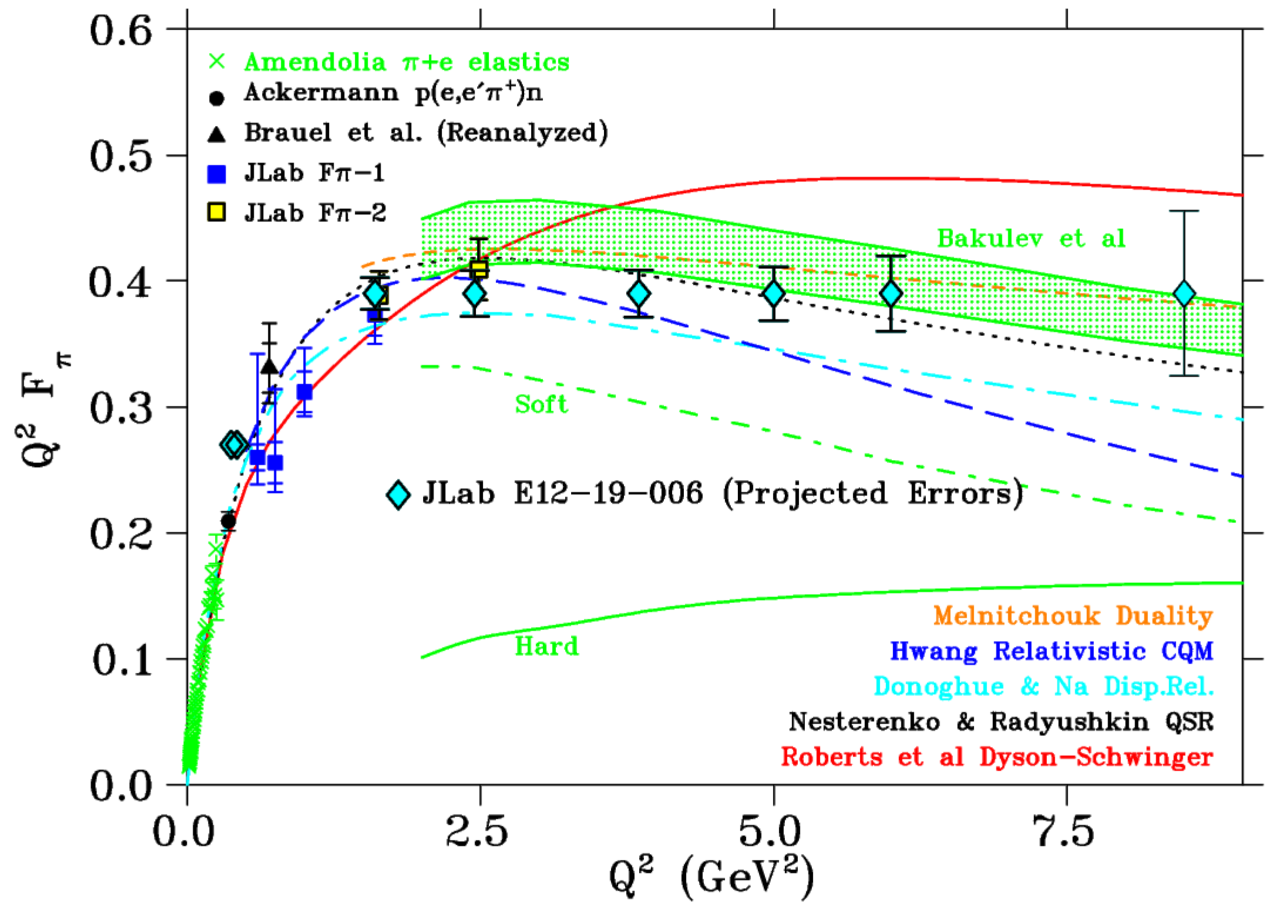
SHMS+HMS will allow measurement of F_π to much higher Q^2

No other facility worldwide can perform this measurement

Data taking completed September 2022 (E12–19–006: G. Huber, D. Gaskell and T. Horn, spokespersons)

y–positions of projected points are arbitrary

Error bars are calculated from obtained statistics and projected systematic uncertainties



The ~10% measurement of F_π at Q^2=8.5 GeV^2 is at higher $-t_{min}$=0.45 GeV^2

The pion form factor is the clearest test case for studies of QCD's transition from non–perturbative to perturbative regions

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Model / Intepretation Issues

- A common criticism of the electroproduction technique is the difficulty to be certain one is measuring the "physical" form factor.

> "What is at best measured in electroproduction is the transition amplitude between a mesonic state with an effective space-like mass $m^2=t<0$ and the physical pion. It is theoretically possible that the off-shell form factor $F_\pi(Q^2,t)$ is significantly larger than the physical form factor because of its bias towards more point-like $q\bar{q}$ valence configurations within its Fock state structure." --S.J. Brodsky, Handbook of QCD, 2001.

- What tests/studies can we do to give confidence in the result?
  - Check consistency of model with data.
  - Extract form factor at several values of $-t_{min}$ for fixed Q^2.
  - Test that the pole diagram is really the dominant contribution to the reaction mechanism.
  - Verify that electroproduction technique yields results consistent with π^+e elastic scattering at same Q^2.

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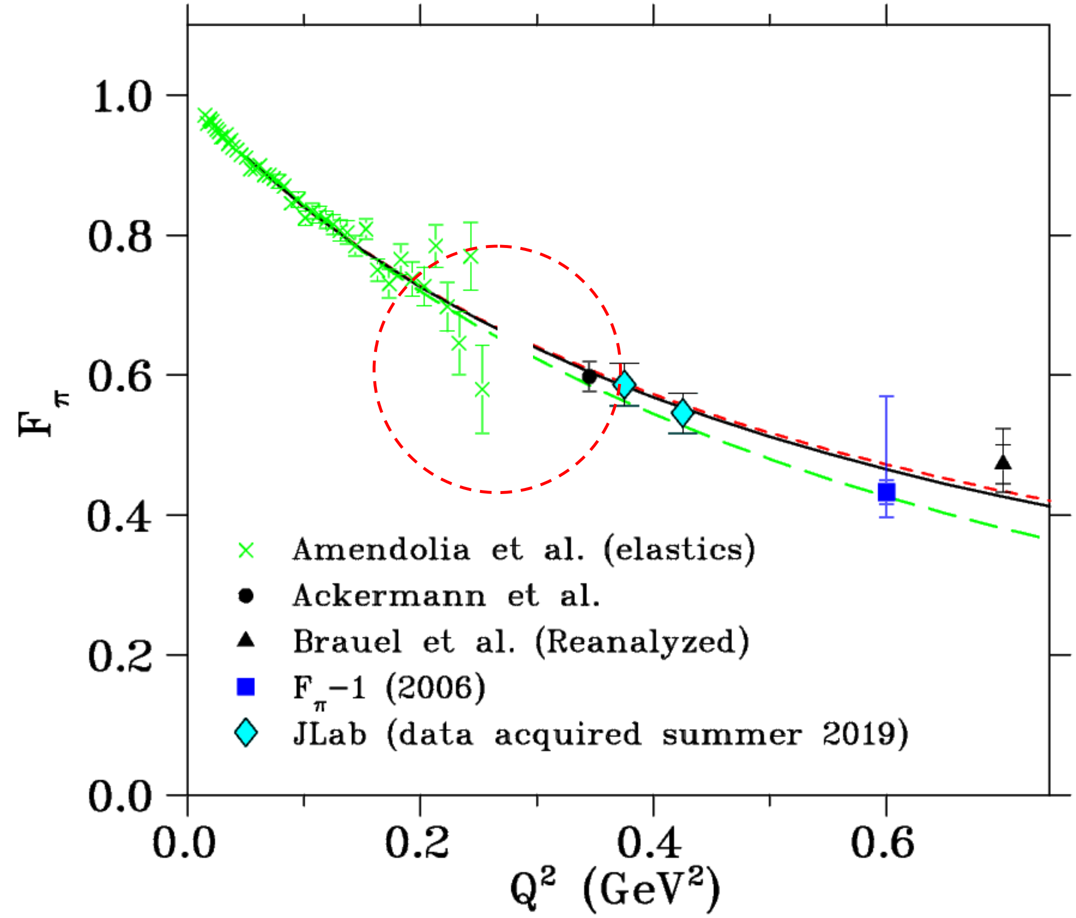
Check of Pion Electroproduction Technique

- Does electroproduction really measure the on–shell form–factor?
- Test by making $p(e,e'\pi^+)n$ measurements at same kinematics as π^+e elastics.
- ***Can't quite reach the same Q^2, but electro–production appears consistent with extrapolated elastic data.***



Data for new test acquired in Summer 2019:

- small Q^2 (0.375, 0.425) competitive with DESY Q^2=0.35
- $-t$ closer to pole (=*0.008* GeV^2) vs. DESY 0.013

Expecting results to be finalized soon — V. Kumar (Regina)

- **A similar test for F_{K+} (KaonLT) is under analysis — A. Hamdi (Regina)**

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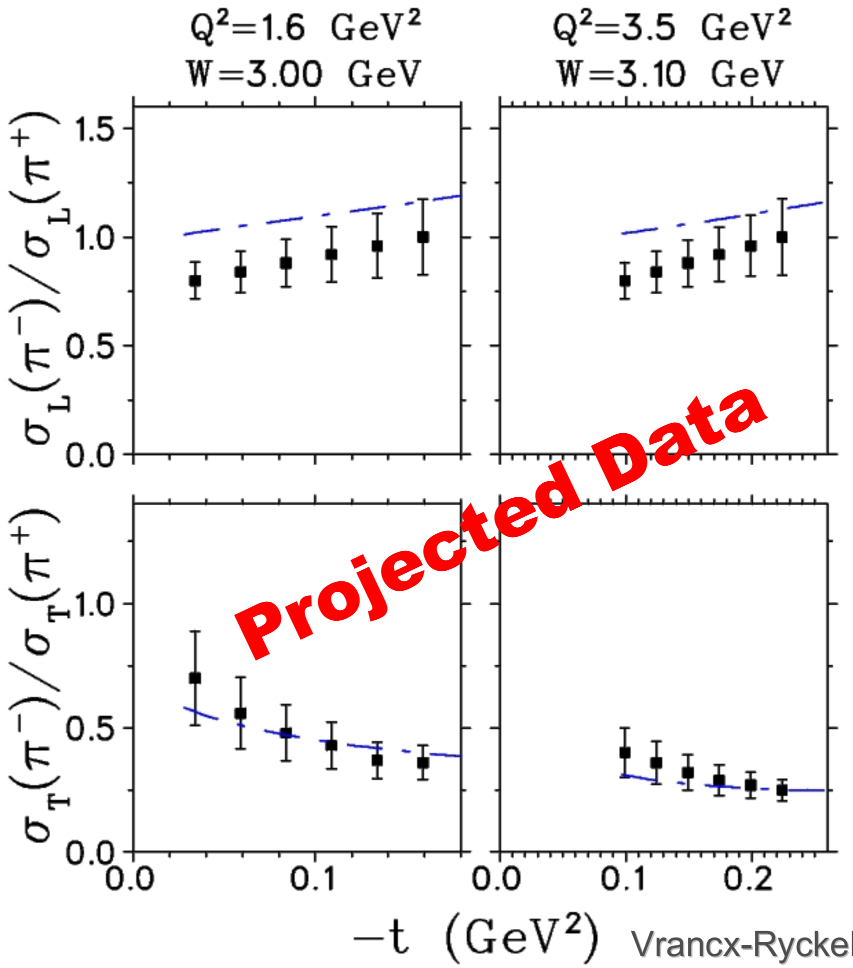
Verify that σ_L is dominated by t-channel process

- π^+ t-channel diagram is purely isovector.
- Measure

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

using a deuterium target.

- Isoscalar backgrounds (such as $b_1(1235)$ contributions to the t-channel) will dilute the ratio.
- We will do the same tests at Q^2=1.60, 3.85, 6.0 GeV^2.



Vrancx-Ryckebusch Regge+DIS Model [PRC **89**(2014)025203]

Because one of the many problems encountered by the historical data was isoscalar contamination, this test will increase the confidence in the extraction of $F_\pi(Q^2)$ from our σ_L data.

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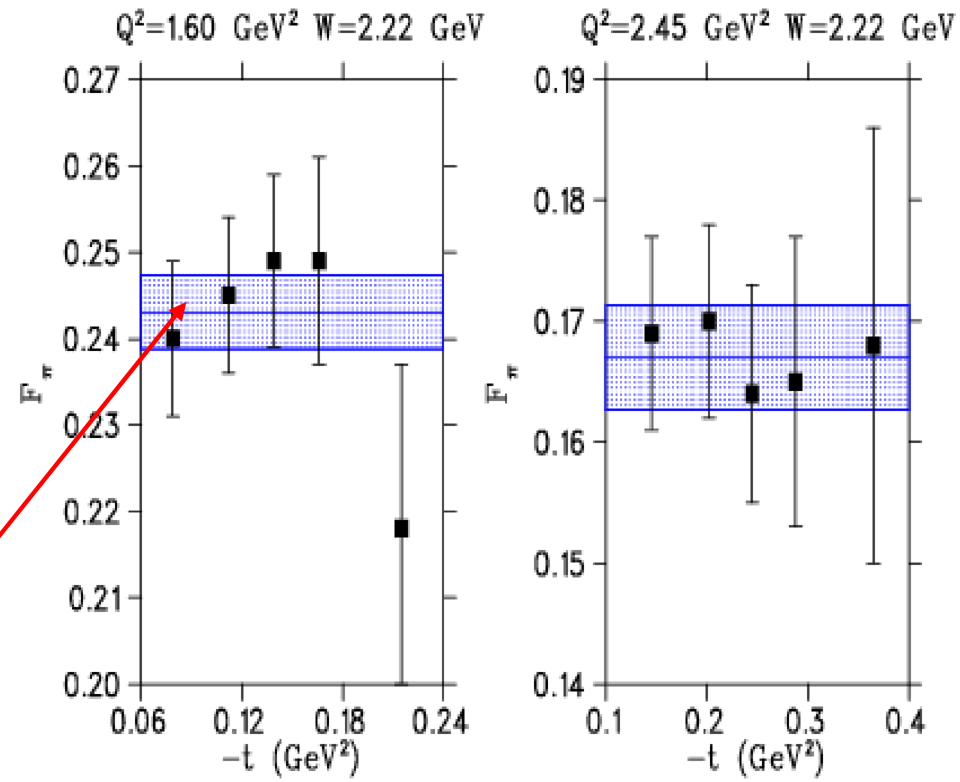
Fπ–2 VGL $p(e,e'\pi^+)n$ model check

- To check whether VGL Regge model properly accounts for:
  - π^+ production mechanism.
  - spectator nucleon.
  - other off–shell (*t*–dependent) effects.

  extract F_π values for each *t*–bin separately, instead of one value from fit to all *t*–bins.

Error band based on fit to all *t*-bins.



Fπ-2 data: G.M. Huber, et al., PRC **78** (2008) 045203

Only statistical and t–uncorrelated systematic uncertainties shown

- Deficiencies in model may show up as *t*–dependence in extracted $F_\pi(Q^2)$ values.
- Resulting F_π values are insensitive (<2%) to *t*–bin used.
- Lends confidence in applicability of VGL model to the kinematical regime of the JLab data, and the validity of the extracted $F_\pi(Q^2)$ values.

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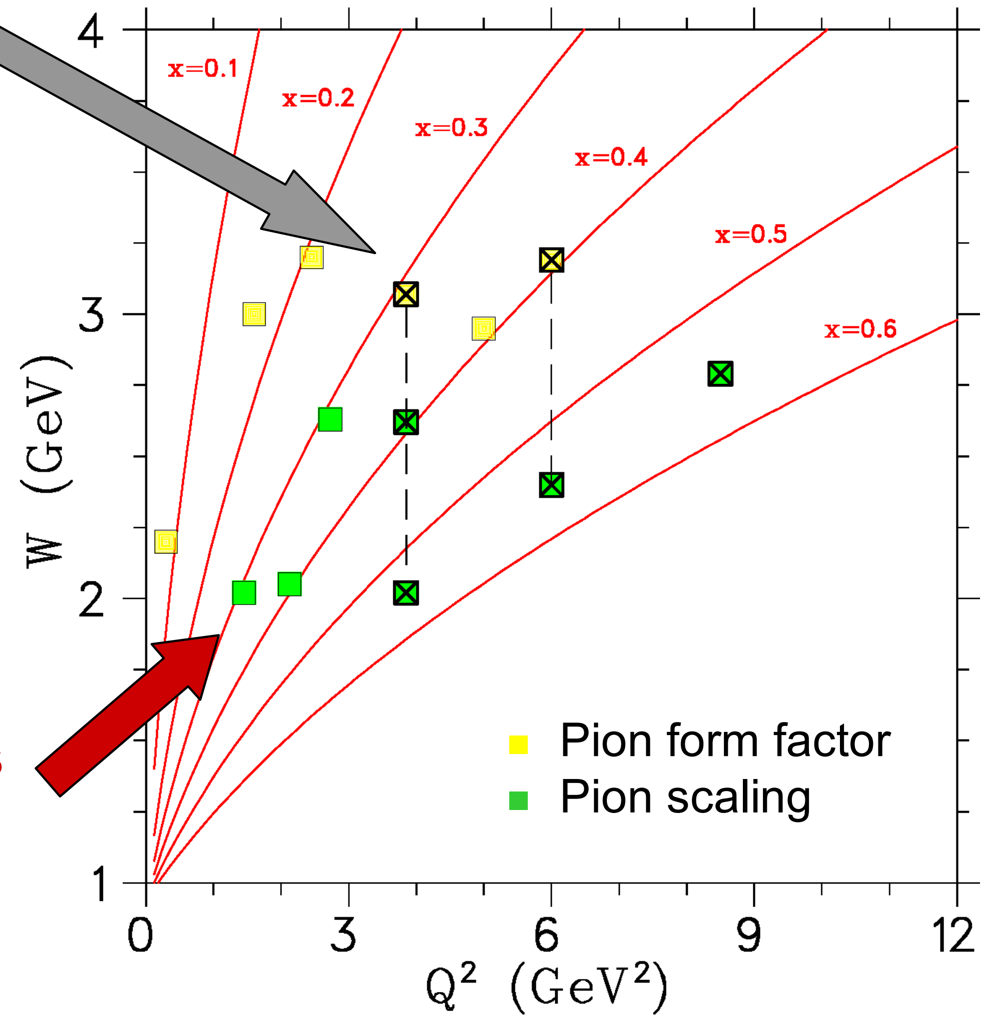
E12–19–006 Optimized Run Plan

Points along vertical lines allow F_π values at different distances from pion pole, to check model properly accounts for:

- **π^+ production mechanism**
- **spectator nucleon**
- **off-shell (*t*–dependent) effects**

Points along red curves allow $1/Q^n$ scaling tests at fixed x_B



For more details, visit Pion-LT RedMine: https://redmine.jlab.org/projects/hall-c/wiki/

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Measurement of K^+ Form Factor

- Similar to π^+ form factor, elastic K^+ scattering from electrons used to measure charged kaon form factor at low Q^2

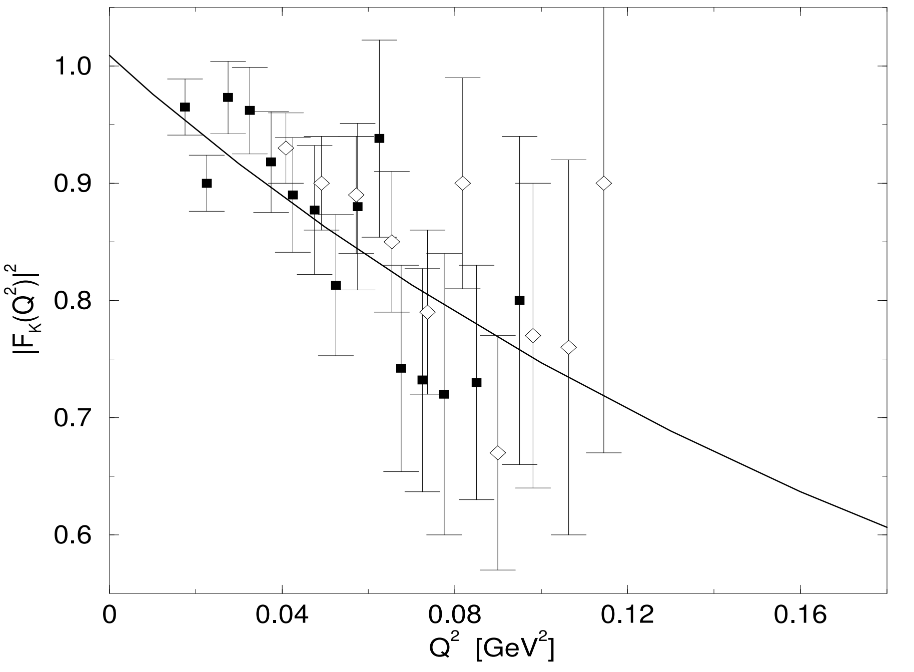
  [Amendolia, et al., PL **B178** (1986) 435]

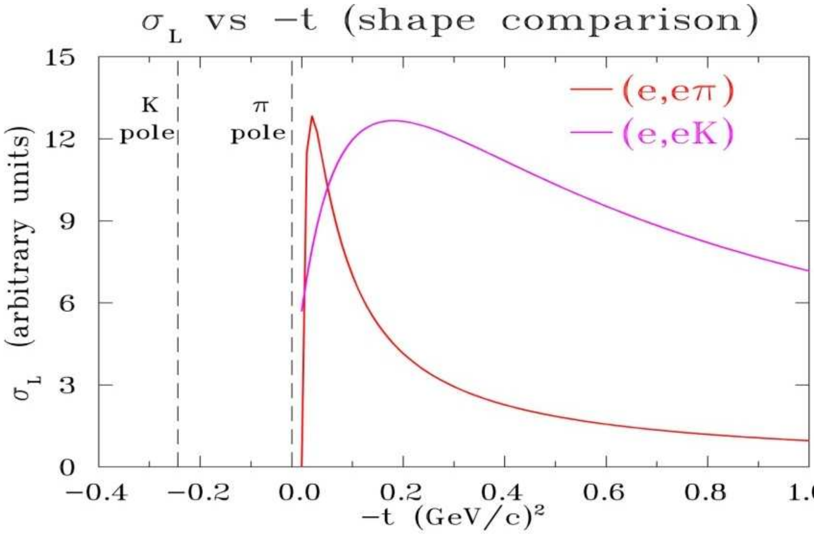
- Can "kaon cloud" of the proton be used in the same way as the pion to extract kaon form factor via ***p(e,e'K⁺)***Λ ?

- Kaon pole further from kinematically allowed region

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_K^2)} g_{K\Lambda N}^2(t) F_K^2(Q^2,t)$$

- Many of these issues are being explored in JLab E12–09–011





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Kaon Form Factor Experiment Goals

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- **Measure the $-t$ dependence of the $p(e,e'K^+)\Lambda,\Sigma^\circ$ cross section at fixed Q^2 and W>2.5 GeV to search for evidence of K^+ pole dominance in σ_L**
  - Separate the cross section components: L, T, LT, TT
  - First L/T measurement above the resonance region in K^+ production
- **<u>If warranted by the data</u>, extract the Q^2 dependence of the kaon form factor to shed new light on QCD's transition to quark–gluon degrees of freedom.**

- **<u>Even if we cannot extract the kaon form factor</u>, the measurements are important.**
  - $K^+\Lambda$ and $K^+\Sigma^\circ$ reaction mechanisms provide valuable information in our study of hadron structure
  - – Flavor degrees of freedom provide important information for QCD model building and understanding of basic coupling constants

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$p(e,e'K^+)\Lambda(\Sigma^0)$ Experiment

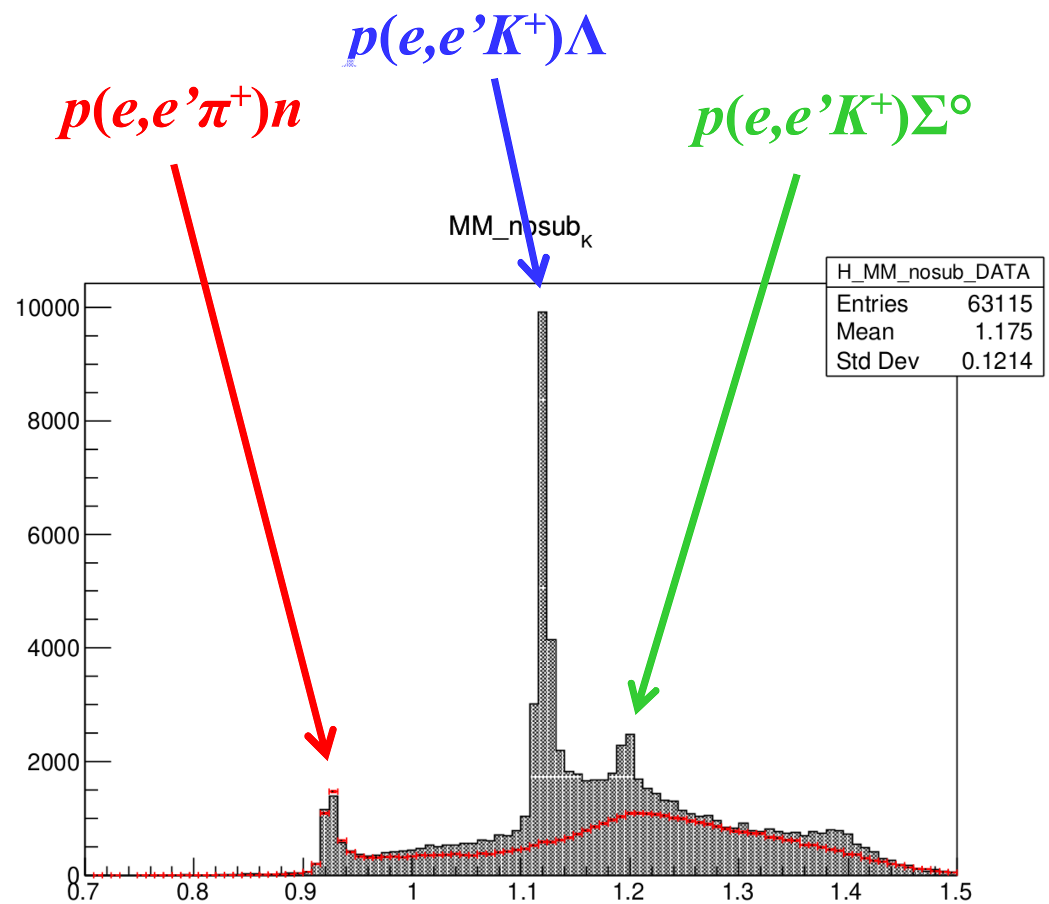
Isolate Exclusive Final States via Missing Mass

$$M_X = \sqrt{(E_{\det} - E_{init})^2 - (p_{\det} - p_{init})^2}$$

- Spectrometer coincidence acceptance allows for simultaneous studies of Λ and Σ° channels.
- Kaon-pole dominance test through

$$\frac{\sigma_L(\gamma^* p \to K^+\Sigma^0)}{\sigma_L(\gamma^* p \to K^+\Lambda^0)}$$

- Should be similar to ratio of $g^2_{pK\Lambda}/g^2_{pK\Sigma}$ coupling constants if t-channel exchange dominates.



Q^2=3.0 GeV^2 , W=3.14, low ε, θ_{Kq}=+0.0

Plot by Richard Trotta (CUA/Virginia)

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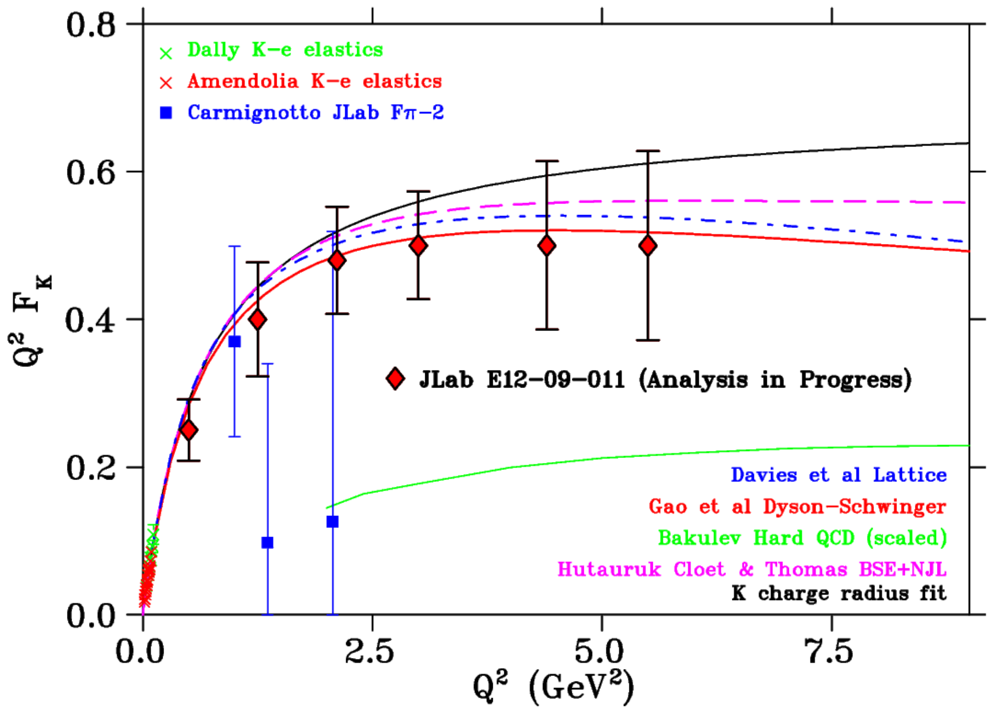
Projected Uncertainties for K^+ Form Factor

- First measurement of F_K well above the resonance region.
- Measure form factor to Q^2=3 GeV^2 with good overlap with elastic scattering data.
  - Limited by –t<0.2 GeV^2 requirement to minimize non–pole contributions.
- Data will provide an important second $q\bar{q}$ system for theoretical models, this time involving a strange quark.

$p(e,e'K^+)\Lambda$ W>2.5 GeV



Extraction of F_K from Q^2>4 GeV^2 data is more uncertain, due to higher $-t_{min}$

- ***Partially completed as an early SHMS commissioning experiment: LT–separation (E12–09–011: T. Horn, G. Huber and P. Markowitz, spokespersons)***
- ***Data under analysis, expecting final results next year***

— R. Trotta (CUA/Virginia)

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F_π and F_K Studies to Higher Q^2 at EIC

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- **Physics Motivation:**
  - π^+ and K^+ structure studies are important 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 EIC may provide these data
- **Experimental Issues:**
  - The DEMP cross section is small, can the exclusive $p(e,e'\pi^+)n$ and $p(e,e'K^+)\Lambda$ channels be cleanly identified?
    - Count rates, Detector Acceptances?
  - Is the detector resolution sufficient to reliably reconstruct (Q^2,W,t)?
  - How to measure the longitudinal cross section $d\sigma_L/dt$ needed for form factor extraction?

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DEMP π^+/K^+ Event Generator

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- Regge-based *p(e,e'π⁺)n* model of *T.K. Choi, K.J. Kong, B.G. Yu (CKY)* [J.Kor.Phys.Soc. 67(2015)1089]
  - Created a MC event generator by parameterizing CKY σ_L, σ_T for $5<Q^2$ (GeV^2)<35 $2.0<W$ (GeV)<10 $0<-t$ (GeV^2)<1.2
- Extended to $p(e,e'K^+)\Lambda[\Sigma^0]$ by parameterizing Regge-based model of M. Guidal, J.M. Laget, M. Vanderhaeghen (VGL) [PRC 61 (2000) 025204]
- New paper describing our generator arXiv:2403.06000

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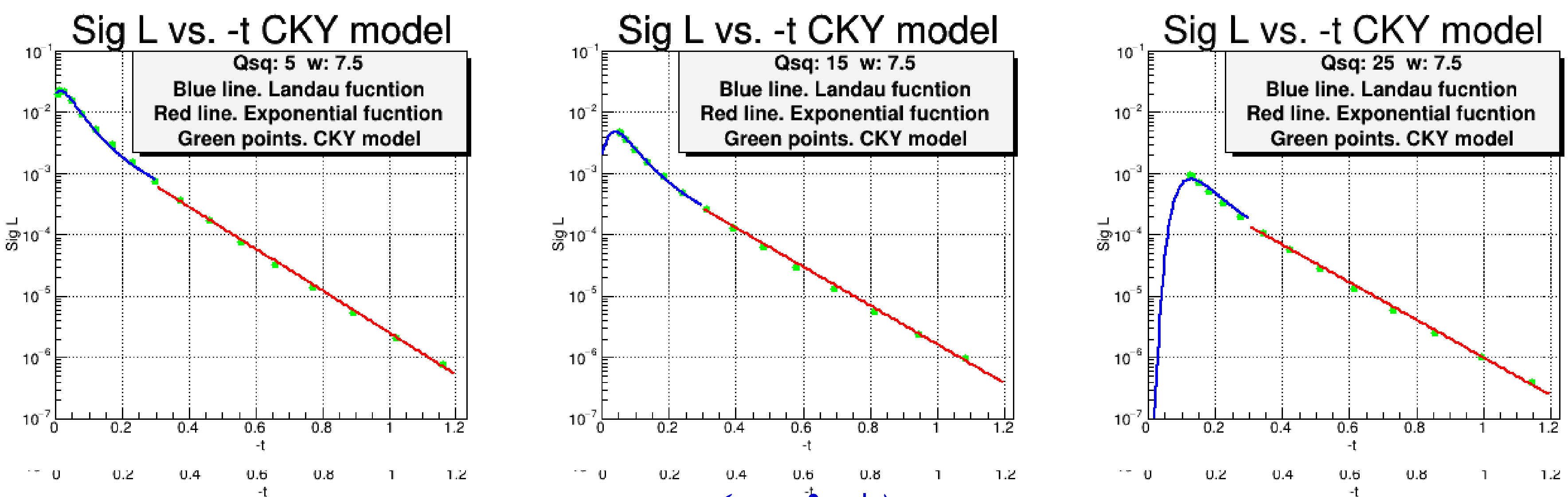


$p(e,e'\pi^+)n$

DEMP Particle Kinematics

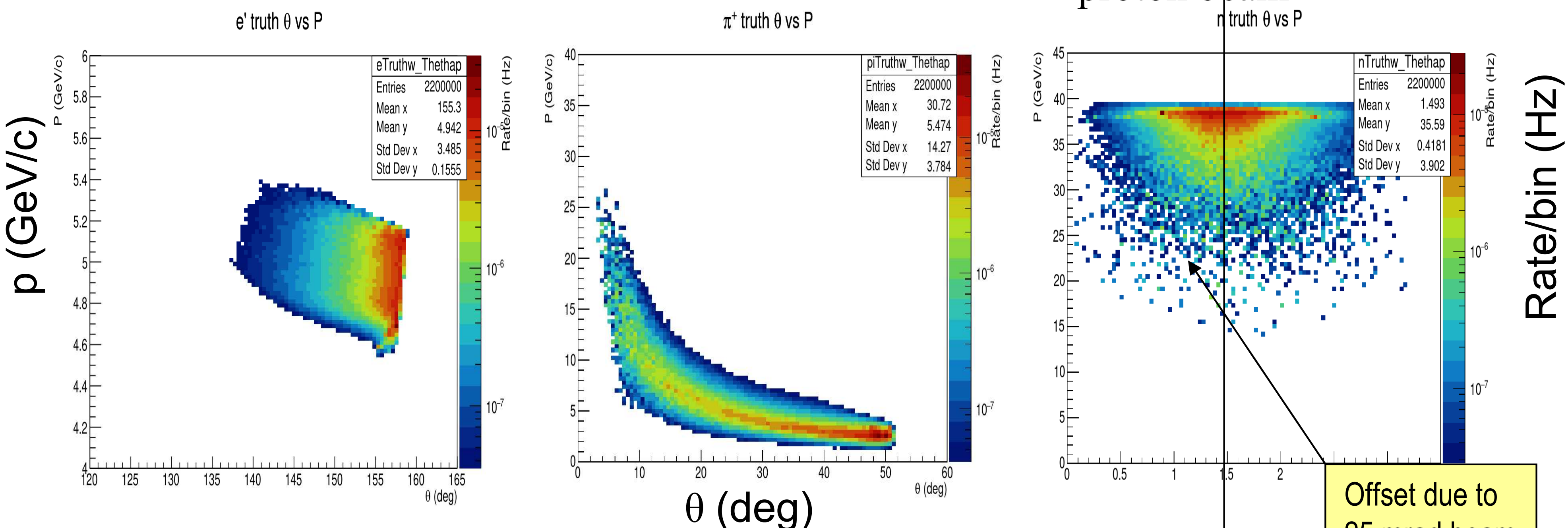
Assure exclusivity of *p(e,e'π⁺n)* reaction by detecting all 3 particles

IR6: 5(e^-) x 100(p) GeV Collisions → E_{cm}=44.7 GeV

Scattered electrons:
5–6 GeV/c,
25–50° from outgoing e beam

Pions:
3–40 GeV/c,
3–40° from p beam

Neutrons:
65–98 GeV/c
<0.7° of outgoing proton beam



Offset due to 25 mrad beam crossing angle

e–π–n triple coincidences, weighted by cross section, truth info

Plots by Love Preet (Regina)

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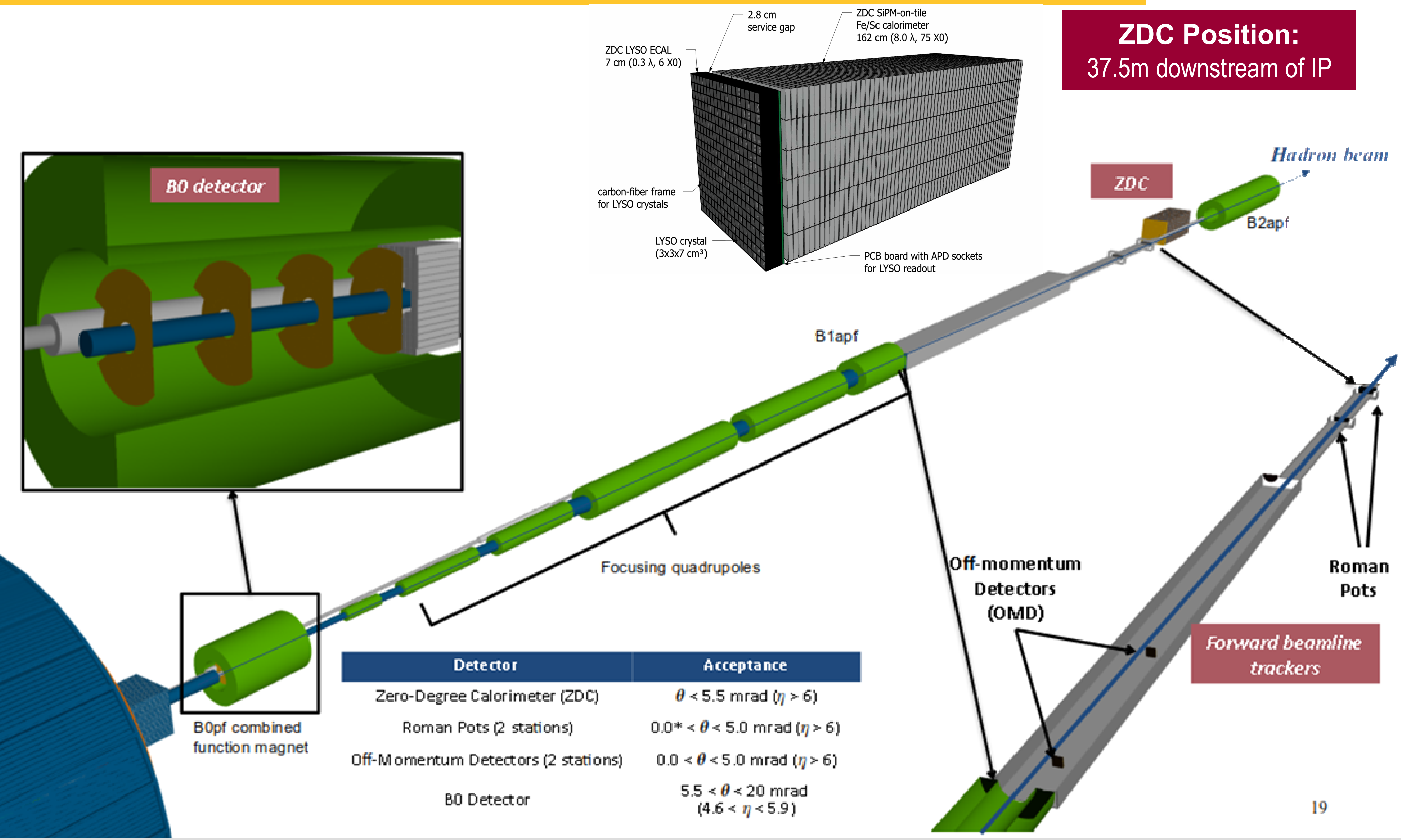
EIC Far Forward Detectors

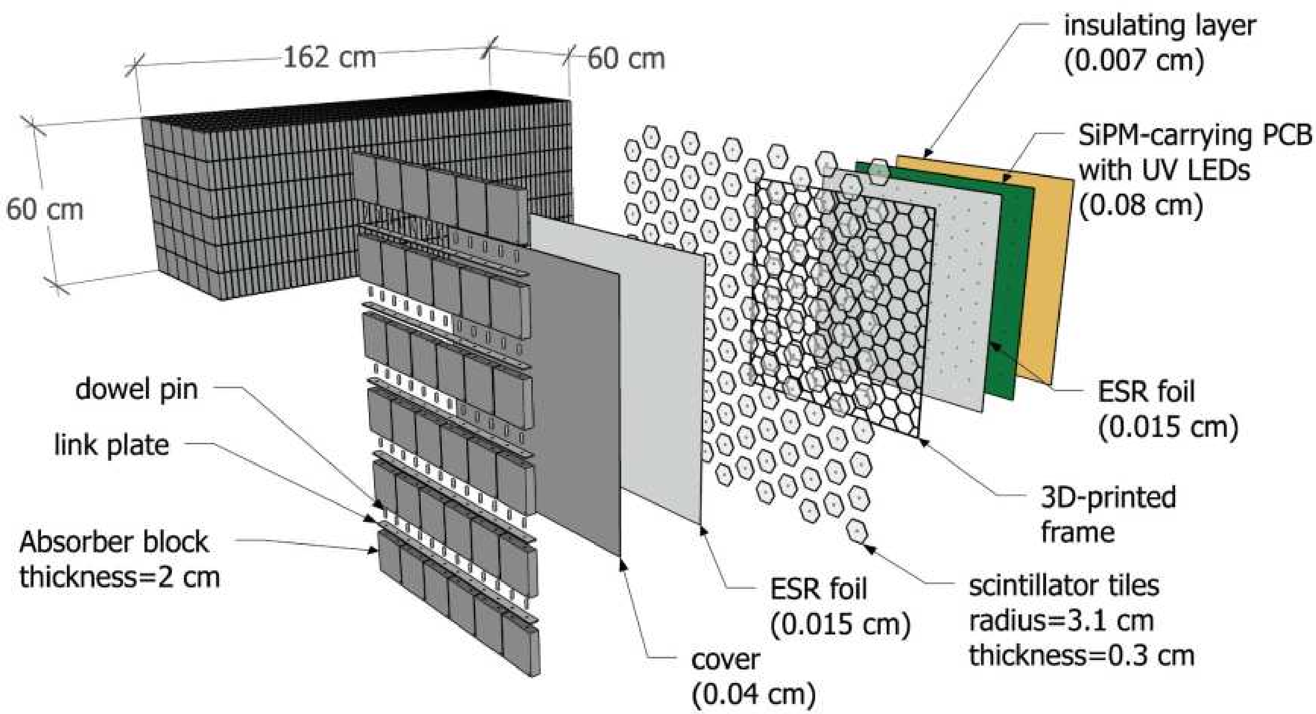
ZDC Position:
37.5m downstream of IP



Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	$\theta < 5.5$ mrad ($\eta > 6$)
Roman Pots (2 stations)	$0.0^* < \theta < 5.0$ mrad ($\eta > 6$)
Off-Momentum Detectors (2 stations)	$0.0 < \theta < 5.0$ mrad ($\eta > 6$)
B0 Detector	$5.5 < \theta < 20$ mrad ($4.6 < \eta < 5.9$)

- Vital to isolate exclusive $p(e,e'\pi^+n)$ process from competing inclusive reactions
- EIC measurement impossible unless recoil high momentum neutron is efficiently detected

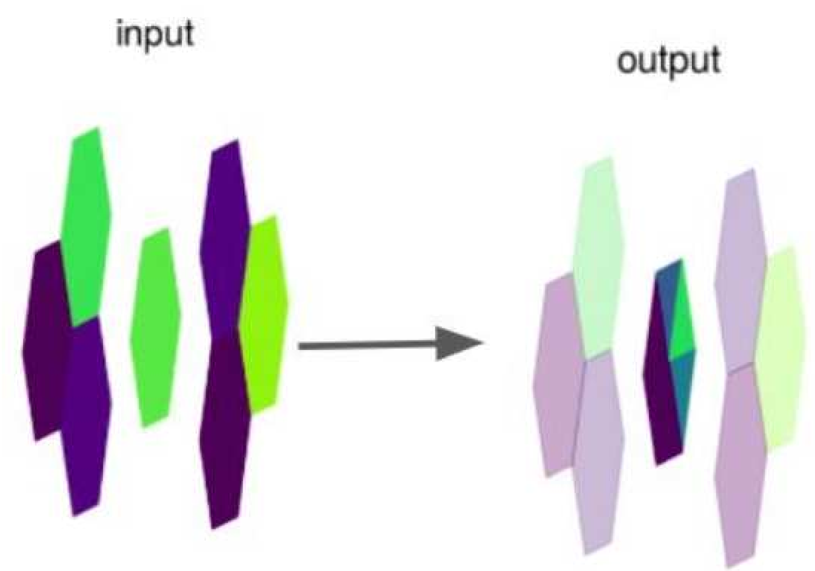
Neutron Reconstruction in ZDC



Figures courtesy of Miguel Arratia (UC Riverside)

- Proposed SiPM–on–Tile design of ZDC divides HCAL into hexagonal cells
- HEXSPIT algorithm defines cells with overlap, assigns weights according to overlap, uses this to reconstruct energy based on subcell energy

HEXPLIT Algorithm



S. Paul, M. Arratia arXiv:2308.06939

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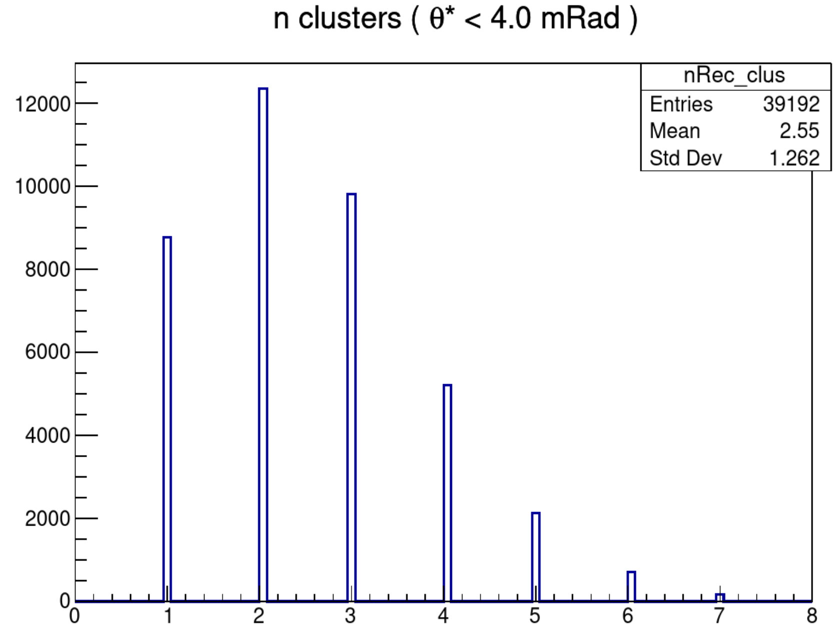
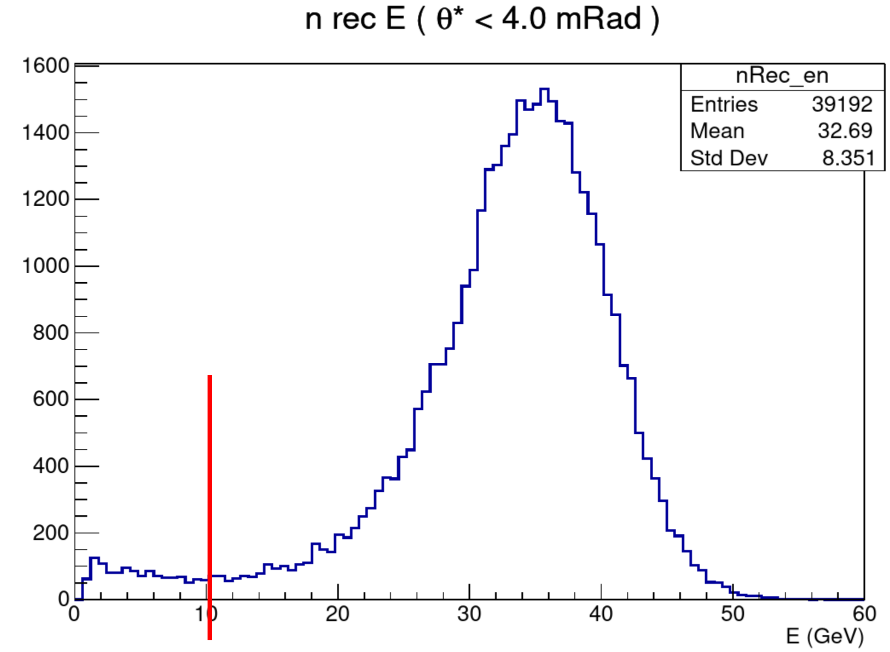
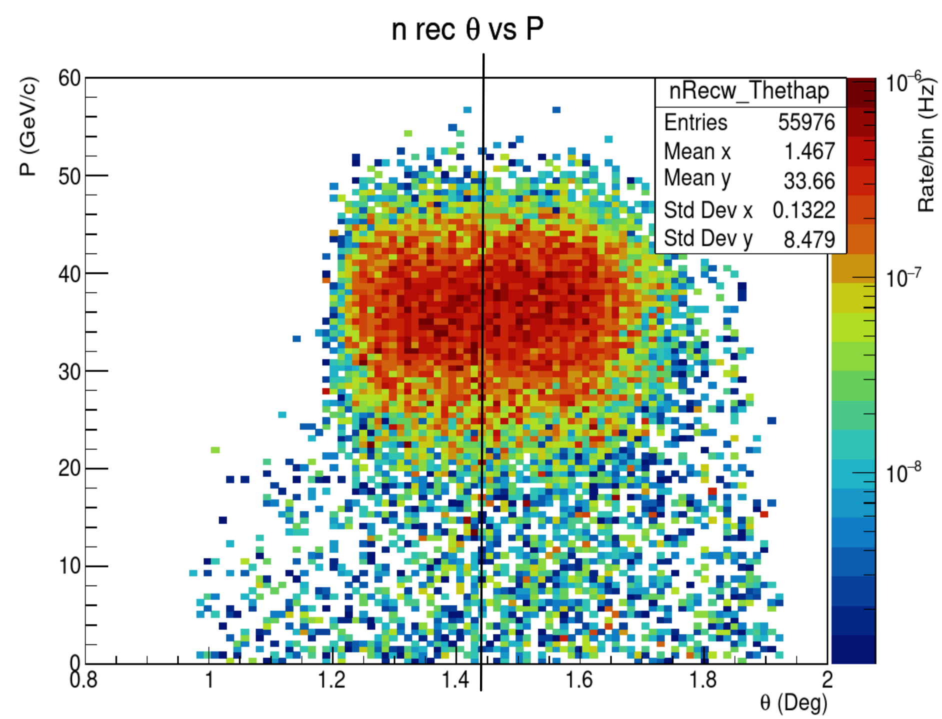
p(e,e'π⁺n) Neutron reconstruction in ZDC





- 5x41 e+p collisions w/ ePIC
- High proportion of neutron hits have multi–clusters
  - Results use latest ReconstructedFarForward ZDCNeutrons algorithm
- (x,y) acceptance of ZDC fully filled
- Apply >10 GeV/cluster cut to select good neutrons



Plots by Love Preet (Regina)

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

- **Can we isolate a clean sample of exclusive $p(e,e'\pi^+n)$ events by detecting the neutron, or are other requirements needed in addition?**
- For a source of background $p(e,e'\pi^+)X$ events we used the EIC SIDIS generator written by Tianbo
  - located on JLab farm at /work/eic/evgen/SIDIS_Duke/e5p100
- Since the generator does not output the neutron momentum, we use the missing momentum as a proxy

- The SIDIS and DEMP event generators are used to create LUND format files
- Generated events are fed into ECCE Geant4 simulation to study acceptance and resolution requirements

p_{miss} cut vs Q^2–bin

$$p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$$

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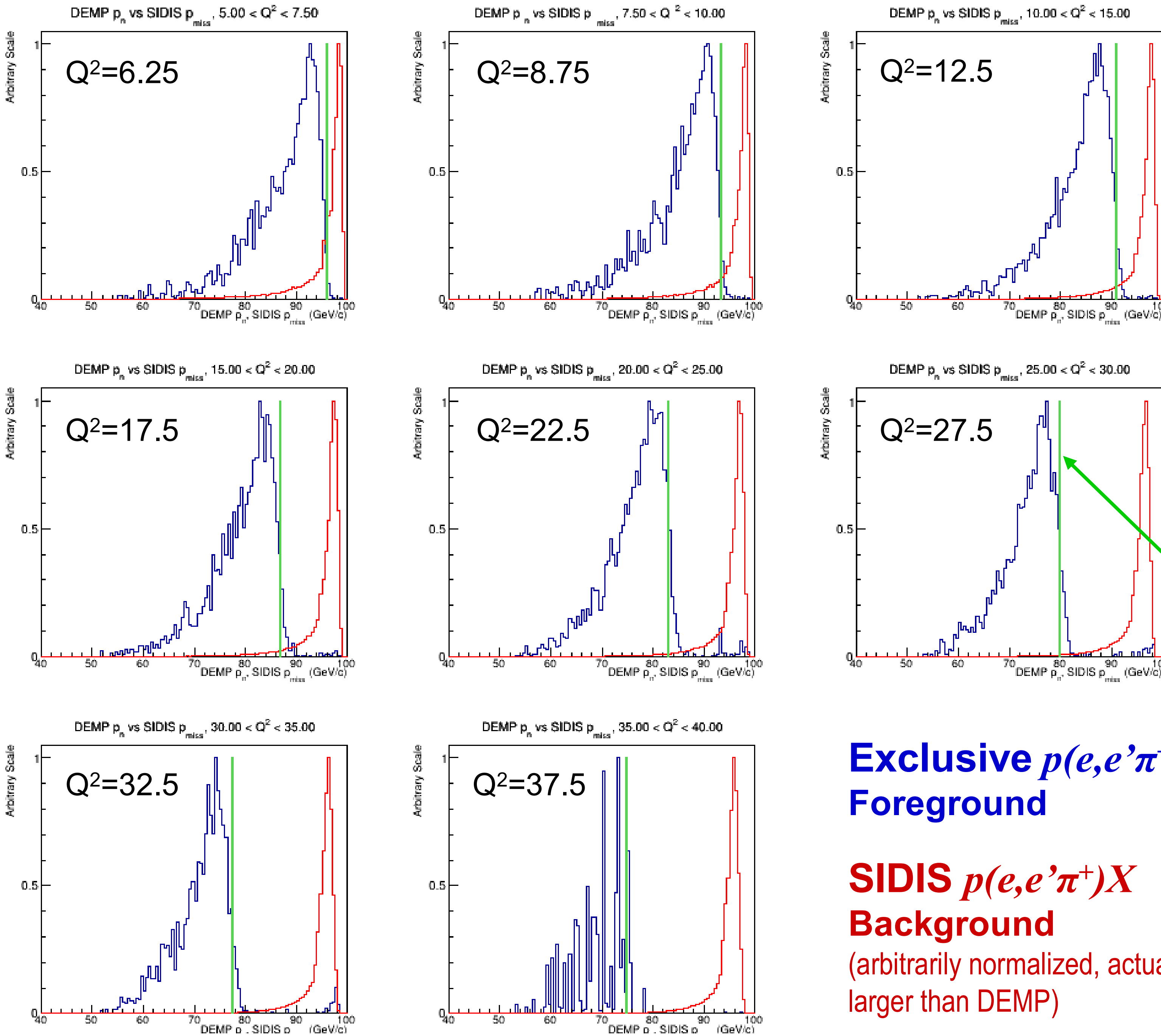

Plots by Stephen Kay (Regina/York)

Cut value
(varies w/Q^2)

Exclusive ***p(e,e'π⁺n)***
Foreground

SIDIS ***p(e,e'π⁺)X***
Background
(arbitrarily normalized, actually much larger than DEMP)

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Another Cut to Remove Background

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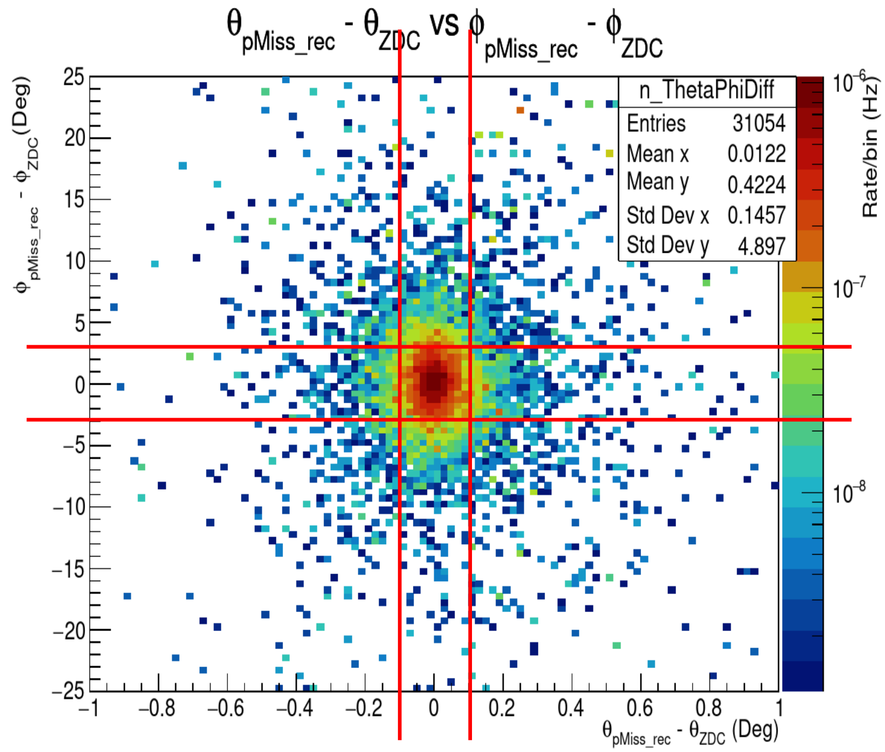
- **Make use of high angular resolution of Zero Degree Calorimeter (ZDC) to further reduce background events**
  - Compare hit (θ,φ) positions of energetic neutron on ZDC to calculated position from p_{miss}
  - If no other particles are produced (i.e. exclusive reaction) these quantities should be highly correlated
  - Energetic neutrons from inclusive background processes will be less correlated, since additional lower energy particles are produced

5x41 e+p collisions w/ ePIC



Differences between hit and calculated neutron positions on ZDC for DEMP events

Cuts applied: $|\Delta\theta|<0.1^o$ $|\Delta\varphi|<3.0^o$, in addition to triple coincidence and $\theta_n<4.0^o$, $E_n>10$ GeV cuts

Plot by Love Preet (Regina)

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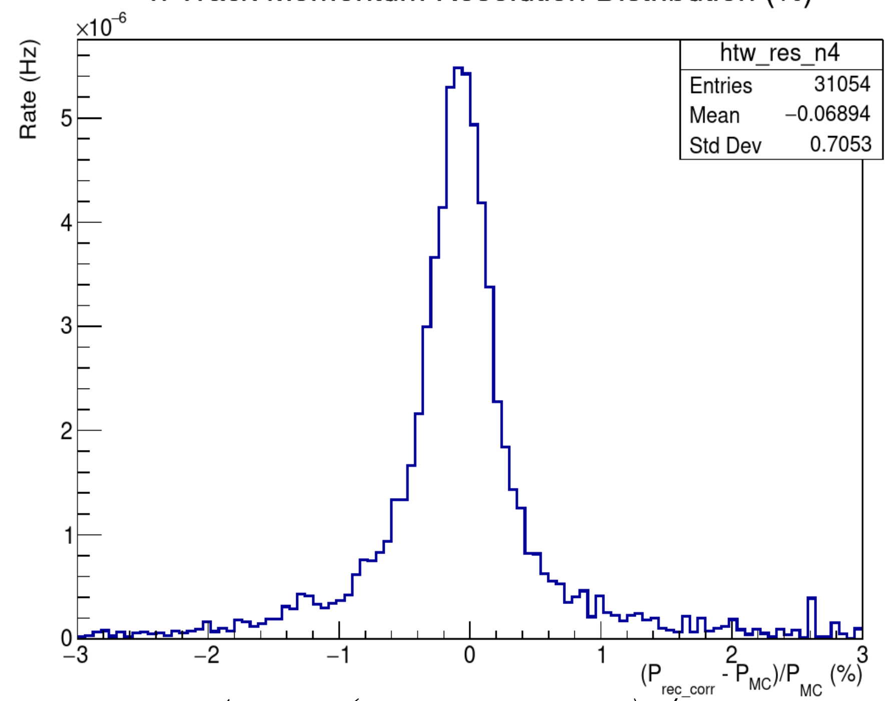
Improving *neutron* reconstruction resolution

- **Exclusive $p(e,e'\pi^+n)$ event selection requires exactly one high energy ZDC hit as a veto**
- Since the neutron hit position from ZDC is known to high accuracy, this information can be used to "correct" the missing momentum track $p_{miss} = \left| \vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+} \right|$
- **Use ZDC hit positions θ_{ZDC}, φ_{ZDC} instead of calculated θ_{miss}, φ_{miss} angles**
- E_{miss} also adjusted to reproduce neutron mass
- After these adjustments, the neutron track momentum was reconstructed to <1% of "true" momentum



$\Delta p_n = (p_{n\,track} - p_{n\,truth}) / p_{n\,truth}$

Plot by Love Preet (Regina)

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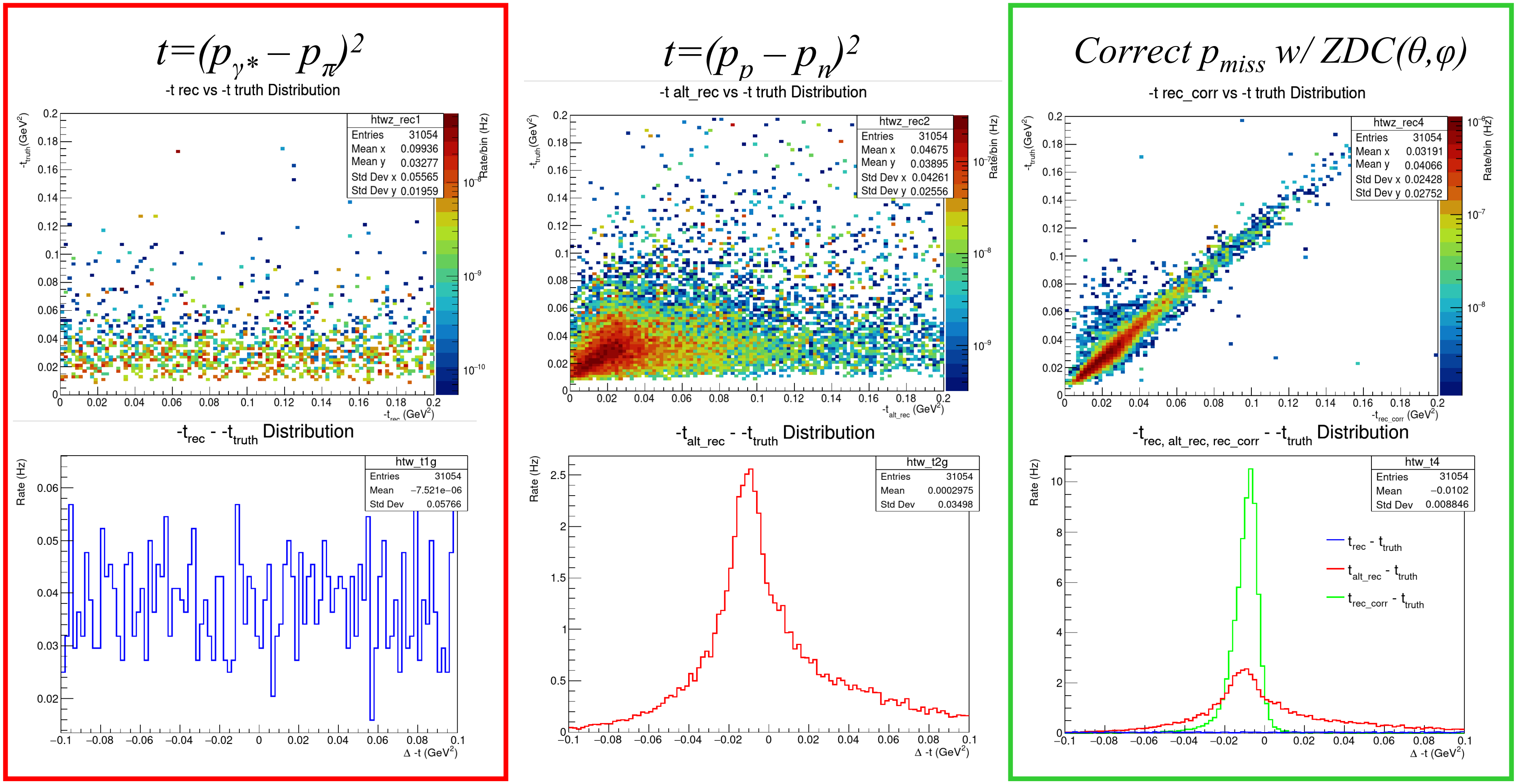
Reconstructing Mandelstam *t*

- Extraction of pion form factor from $p(e,e'\pi^+n)$ data requires *t* to be reconstructed accurately, as we need to verify dominance of the *t*–channel process from the dependence of $d\sigma/dt$ *upon t*

$t_{reconst}(x)$ vs $t_{truth}(y)$

$t_{reconstr} - t_{truth}$



5x41 e+p collisions w/ ePIC

Unusable *t* reconstruction
$\sigma_{t\ reconstr} = 3.4\ \text{GeV}^2$

Plots by Love Preet (Regina)

Best *t* reconstruction
$\sigma_{t\ reconstr} = 0.009\ \text{GeV}^2$

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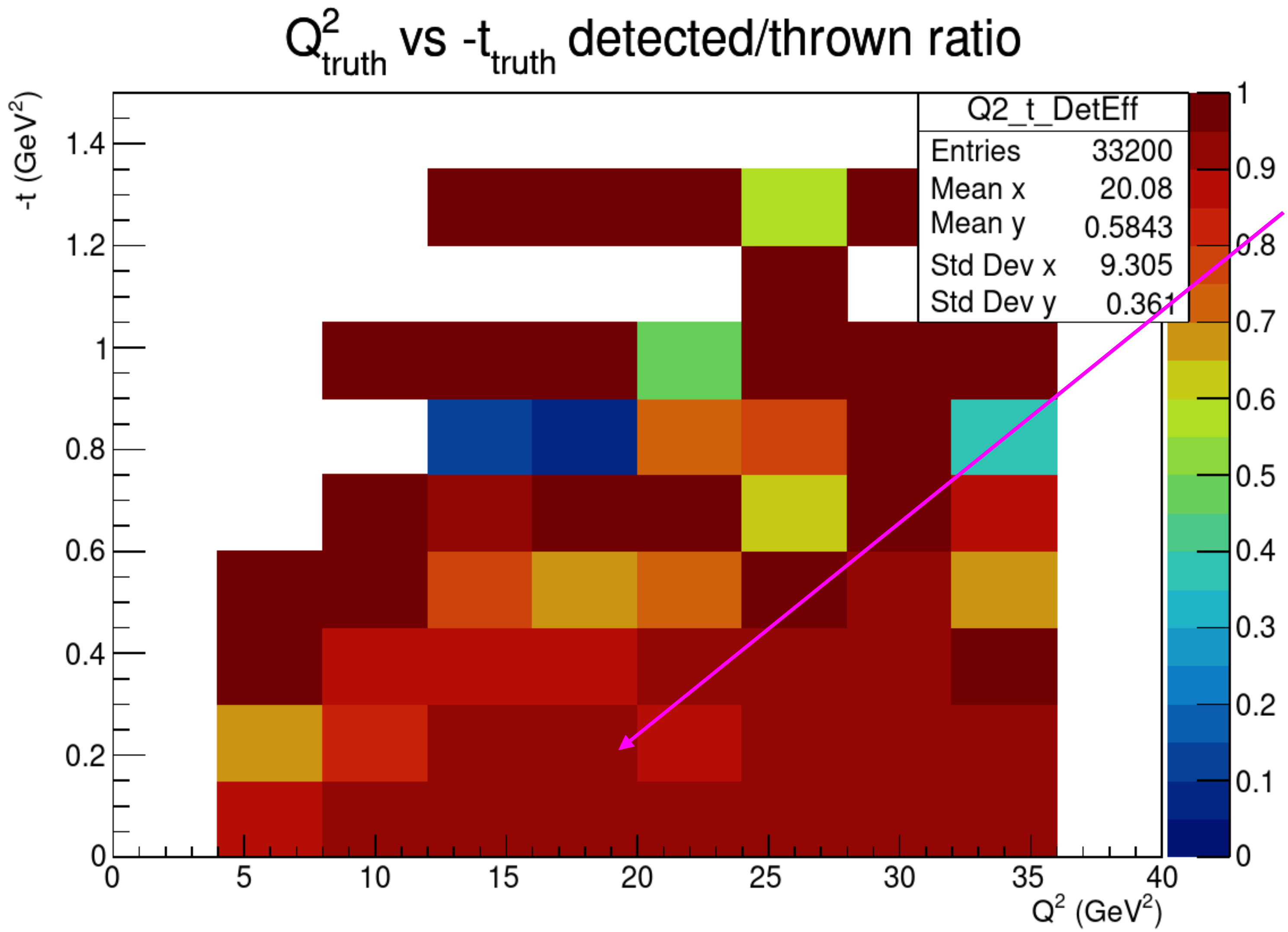
Detection efficiency per (Q^2,t) bin

5x41 e+p collisions with full ePIC simulation



Detection efficiency best in crucial low $-t$ region

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Plot by Love Preet (Regina)

Separating σ_L from σ_T in e–p Collider

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$$\varepsilon = \frac{2(1-y)}{1+(1-y)^2} \quad \text{where the fractional energy loss } y = \frac{Q^2}{x(s_{tot} - M_N^{\ 2})}$$

- Systematic uncertainties in σ_L are magnified by $1/\Delta\varepsilon$.
  - Desire $\Delta\varepsilon > 0.2$.
- **To access $\varepsilon < 0.8$, one needs $y > 0.5$.**
  - This can only be accessed with small s_{tot},

    i.e. low proton collider energies (5–15 GeV), where luminosities are too small for a practical measurement.
- **A conventional L–T separation is impractical, need some other way to identify σ_L**

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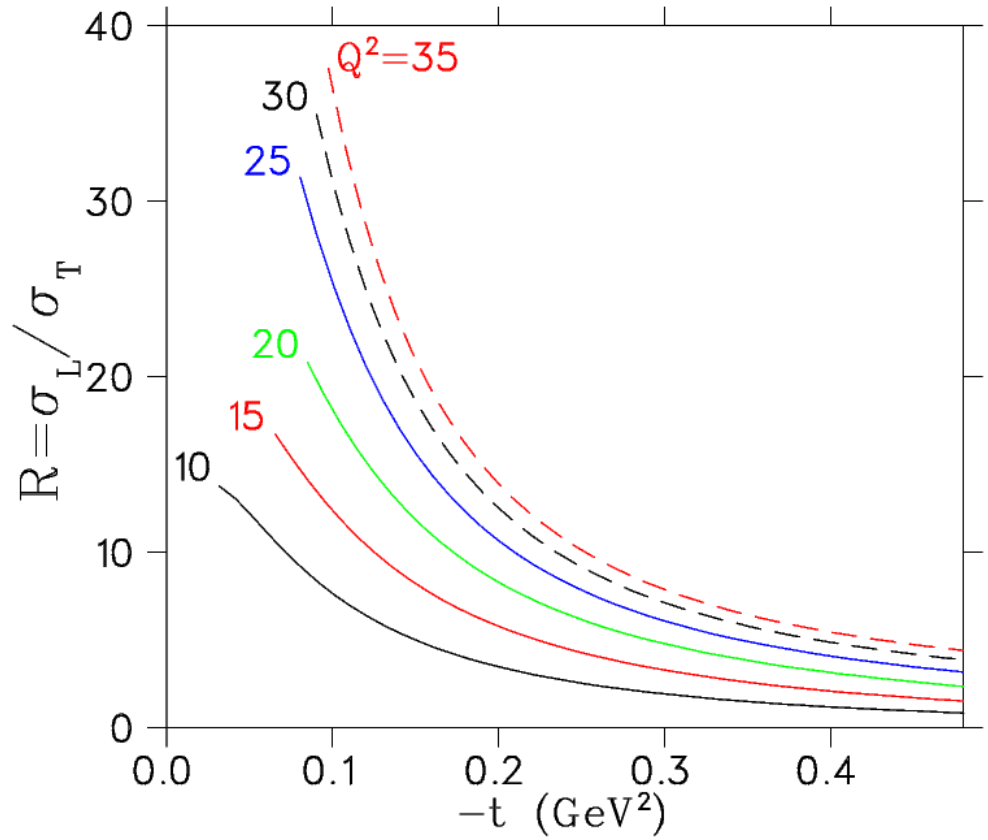
Isolate $d\sigma_L/dt$ using a Model

- In the hard scattering regime, QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$.
- At high Q^2, W accessible at EIC, phenomenological models predict $\sigma_L \gg \sigma_T$ at small $-t$.
- The most practical choice might be to use a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$.
- **In this case, it is very important to confirm the validity of the model used.**



- T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.
- Predictions are for ε>0.995 Q^2, W kinematics shown earlier.

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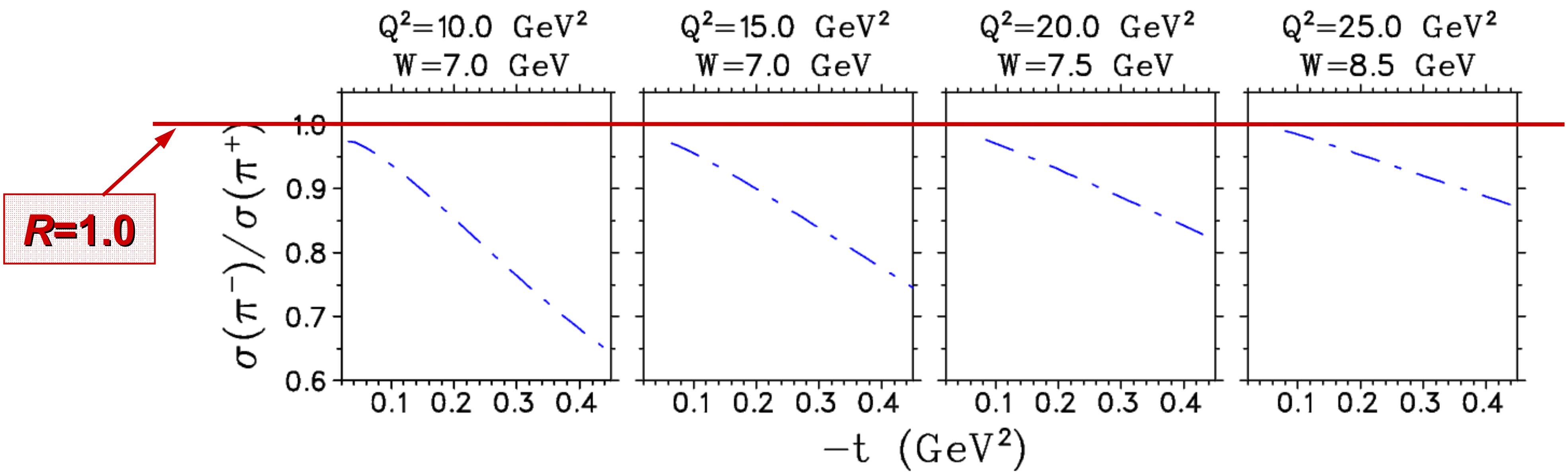
Using π^-/π^+ ratios to confirm $\sigma_L \gg \sigma_T$

- Exclusive $^2H(e,e'\pi^+n)n$ and $^2H(e,e'\pi^-p)p$ in same kinematics as $p(e,e'\pi^+n)$
- π *t*–channel diagram is purely isovector (G–parity conservation).

$$R=\frac{\sigma[n(e,e'\pi^-p)]}{\sigma[p(e,e'\pi^+n)]}=\frac{|A_V-A_S|^2}{|A_V+A_S|^2}$$

- **The π^-/π^+ ratio will be diluted if σ_T is not small, or if there are significant non-pole contributions to σ_L.**
- **Compare measured π^-/π^+ ratio to model expectations.**



T. Vrancx, J. Ryckebusch, PRC **89**(2014)025203.

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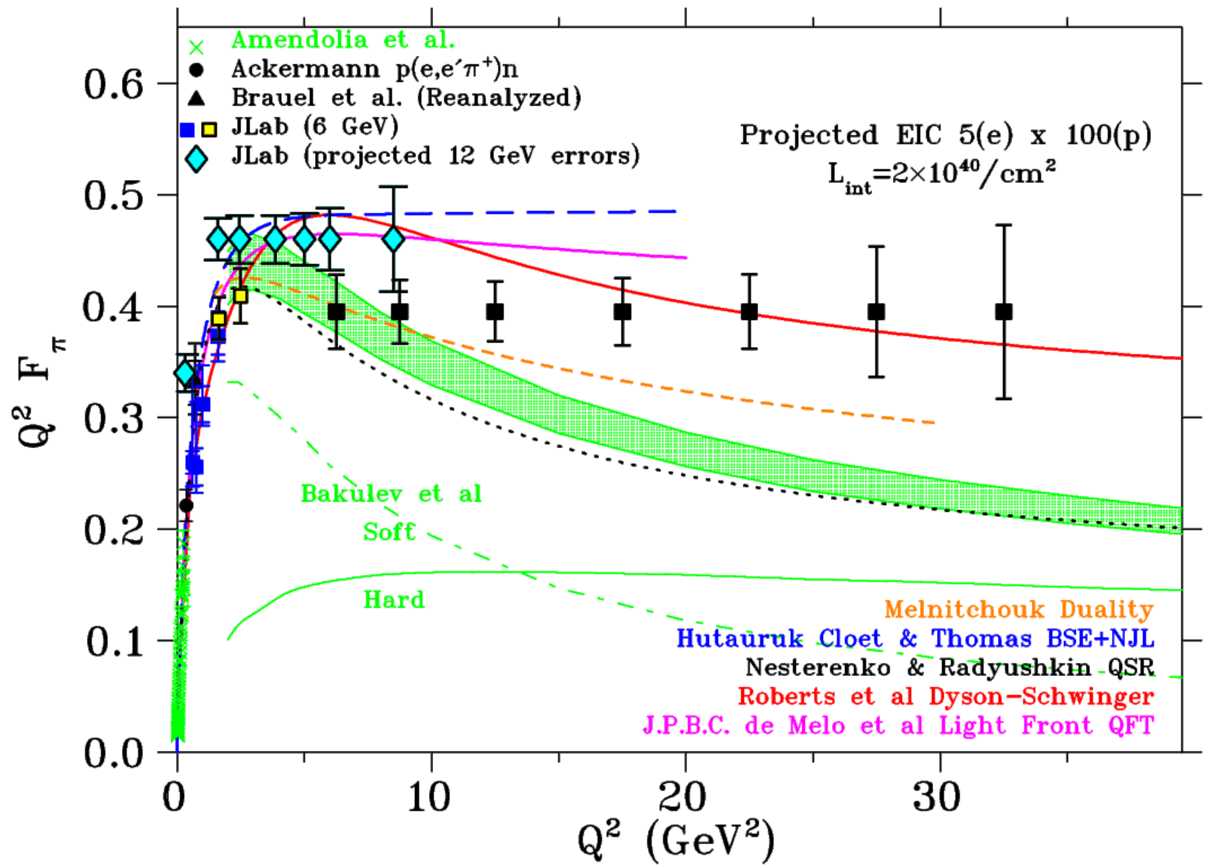
EIC Kinematic Reach (projection)



Assumptions:

- $5(e^-)$ x $100(p)$.
- Integrated L=20 fb^{-1}/yr.
- Clean identification of exclusive $p(e,e'\pi^+n)$ events.
- 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 ^{2}H π^-/π^+ ratios.

Dec 2022 ECCE projections shown

Projections to be updated soon using latest ePIC detector simulation

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$p(e,e'K^+\Lambda)$ Event Reconstruction

- Significantly more challenging than $p(e,e'\pi^+n)$ reconstruction
- Need to efficiently identify $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ decay (~33%)
  - Neutral products take straight line paths
  - Cleanly distinguishing n from γ clusters is main challenge
- Dominant $\Lambda \rightarrow p\pi^-$ channel (~67%) has its own challenges
  - Avoids issue of distinguishing n from γ clusters
  - Main issue is that p, π^- are deflected in opposite directions by proton ring magnetic elements. Can be detected in Off-Momentum Detectors, but detection efficiency needs study
- Additional reconstruction issue:
  - Do not know Λ decay vertex when reconstructing $\pi^0 \rightarrow \gamma\gamma$ decay
  - SiPM will provide enough information about spatial extent of showers to extract incident angle of γ on EMCAL to enable full 4–vector reconstruction of π^0. Is it sufficiently good?

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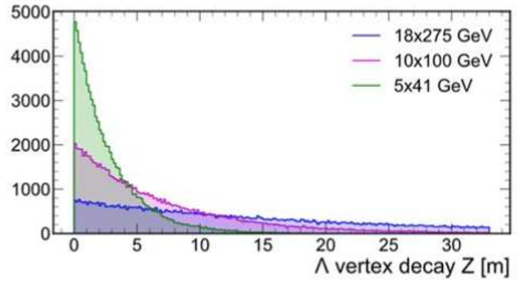
Some ZDC Design Choices

- $\Lambda \rightarrow n\pi^0 \rightarrow n\gamma\gamma$ reconstruction studies will inform ZDC design choices

1. **20cm EMCAL + SiPM–on–Tile:** E resolution is very good, but lose γ angular information needed for Λ reconstruction
2. **~10cm EMCAL + SiPM–on–Tile:** EMCAL can act as a sort of “pre–shower” while still enabling γ angular information
3. **SiPM–on–Tile ONLY:** Allows best γ angular reconstruction, but might lose low–E photon capability, potentially more difficult hadronic/EM shower separation



From: J Arrington *et al* 2021 *J. Phys. G: Nucl. Part. Phys.* **48** 075106

Yellow: crystal EMCAL
Blue: SiPM-on-Tile

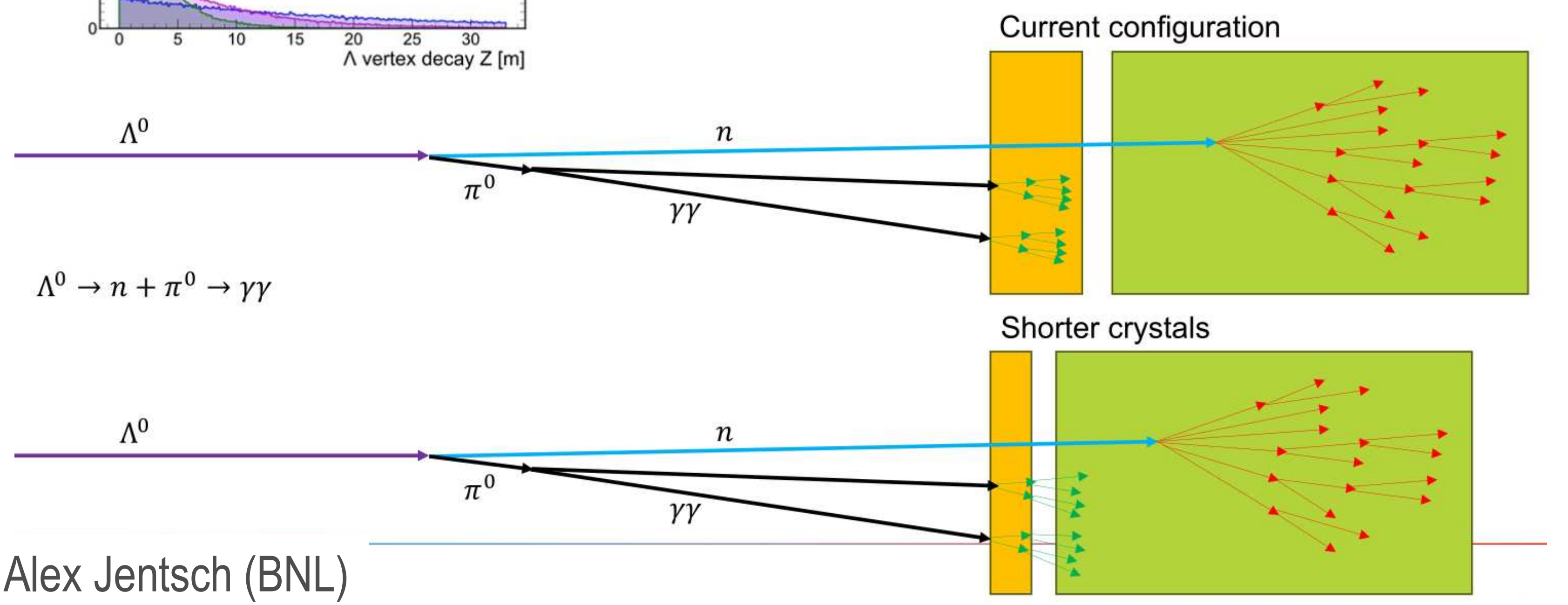


Figure courtesy of Alex Jentsch (BNL)

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Later Stage $p(e,e'K^+\Lambda[\Sigma^0])$ Reconstruction

- **Far Forward large acceptance is even more important for K^+ form factor than for π^+ form factor**
- Detection of $e'K^+\Lambda[\Sigma^0]$ triple coincidence over wide range of $-t$ essential for identification of K–pole process, needed for K^+ form factor extraction from data
  - $\Lambda\rightarrow n\pi^0\rightarrow n2\gamma$ and $\Sigma\rightarrow\Lambda\gamma\rightarrow n3\gamma$ identification over wide $-t$ only possible if ZDC calorimeter acceptance is extended with addition of a B0 calorimeter
  - Not only essential for F_K, but also would improve forward acceptance for u–channel DVCS, and nuclear coherent diffraction studies

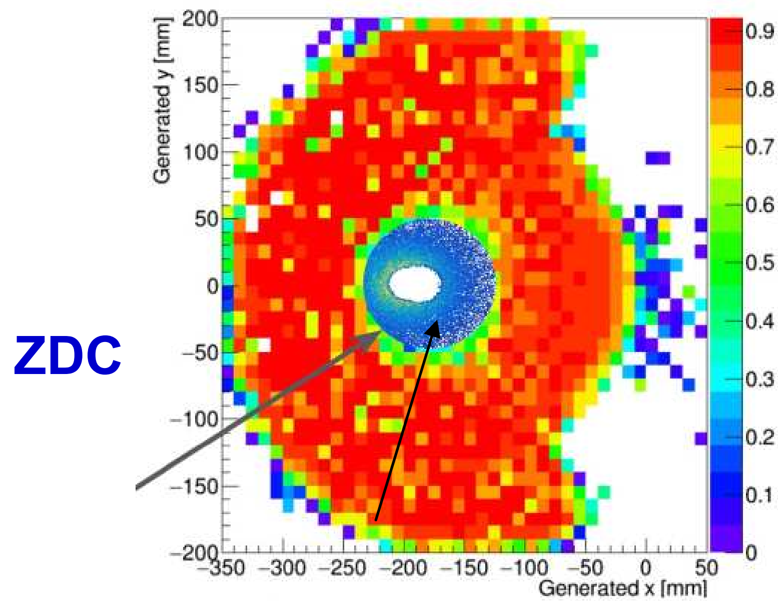

Figure courtesy of Wenliang Li (SBU)

Possible B0 Calorimeter
- **Greatly extends acceptance!**

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Summary

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- Higher Q^2 data on π^+ and K^+ form factors are vital to our better understanding of hadronic physics
  - Pion and kaon properties are intimately connected with dynamical chiral symmetry breaking (DCSB), which explains the origin of more than 98% of the mass of visible matter in the universe
  - F_π is our best hope to directly observe QCD's transition from confinement-dominated physics at large length–scales to perturbative QCD at short length-scales
- PionLT (E12–19–006) has for the first time, since the pioneering measurements at Cornell in 1970's, acquired the high quality data needed to test these theoretical developments with authority
- KaonLT (E12–09–011) partially completed. First results hopefully out next year
- Measurement of F_π at EIC seems feasible
  - Efficient identification of $p(e,e'\pi^+n)$ triple coincidences with sufficient resolution is feasible according to our simulations
- Measurement of F_K at EIC very challenging
  - Λ reconstruction studies are likely to inform ZDC design choices

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