Charged π - Meson Studies at Jefferson Lab

Ali Usman[1], G. M. Huber[1], D. Gaskell[2], T. Horn[3], P. Markowitz[4], S. J. D. Kay[1], R. L. Trotta[3], V. Kumar[1]

On behalf of Hall C Collaboration

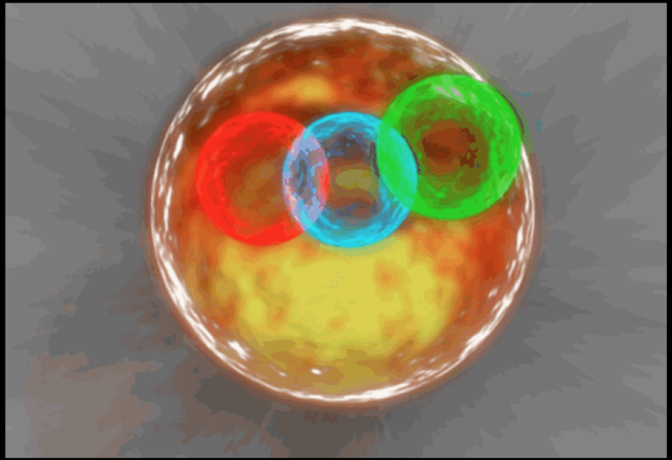
Scientific Motivation

- How do the properties of mesons arise from their constituents?

- What is the role of the form factor in the understanding of internal structure of meson?

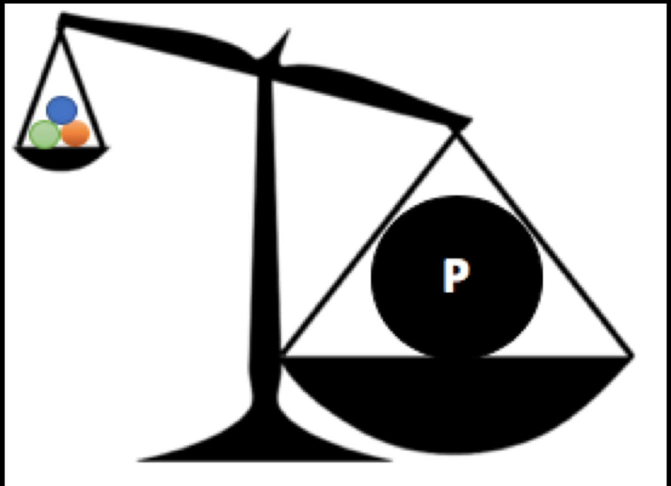
- Which theoretical model accurately predicts pion form factor at high Q^2 ?

Introduction



- Two well known hadronic states:
  - Baryons ($qqq\ or\ \bar{q}\bar{q}\bar{q}$)
  - Mesons ($q\bar{q}$)
- Mass Comparison

$m_{uud} \sim 9\ MeV/c^2$



$m_p \sim 938\ MeV/c^2$

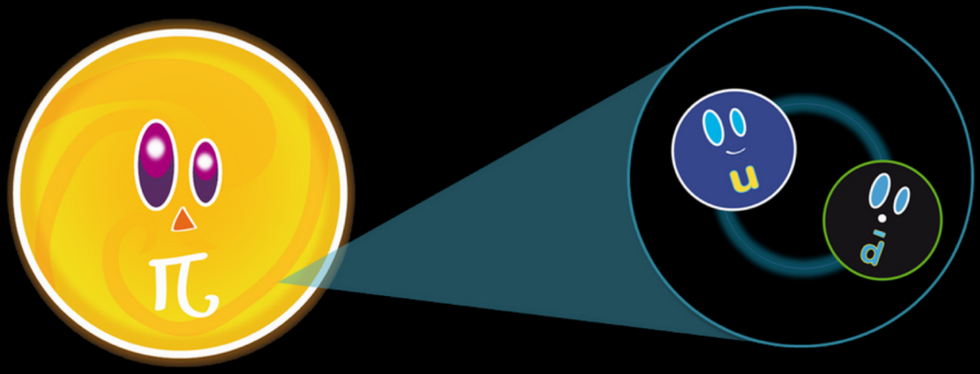
Reasons

- Parton interactions are different from nucleon interactions.
- Quark scale is smaller than the nucleon scale.

Pion – An ideal Candidate

- Pion is lightest meson with only two valence quarks (up and down).
- Pion is positronium atom of QCD.
- Crucial in the understanding of dynamical mass generation.
- The residual nuclear force is carried by pions inside a nucleus.
- Charged Pion decay

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$



Charge	+1e/-1e
Spin	0
Mass	139.57 MeV/c^2
Life Time	2.6 x 10^{-6} s
Charge Radius	0.659 ± 0.004 fm

Exclusive Pion Electroproduction

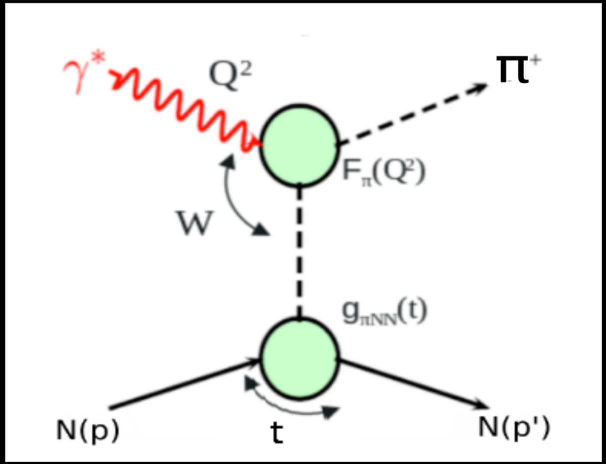
- Elastic scattering of electrons from pions gives

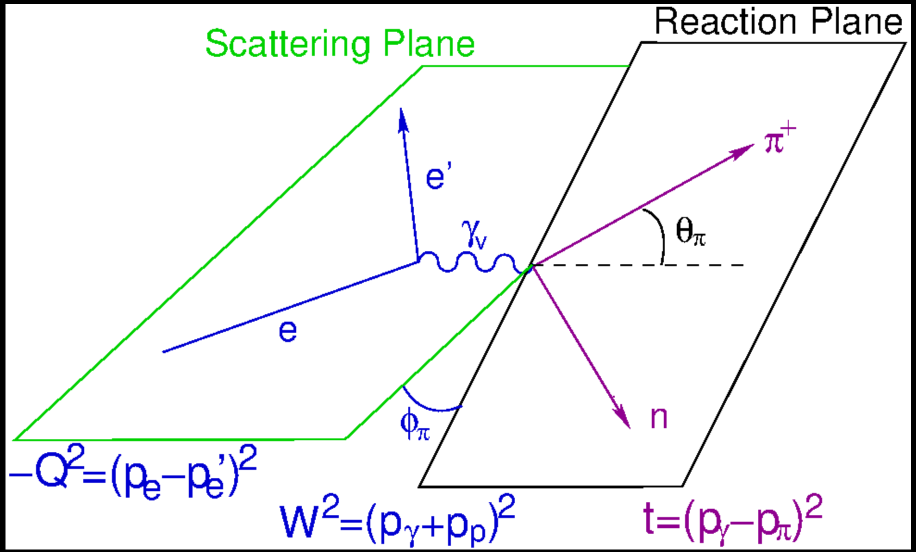
$$e + \pi^+ \rightarrow e' + \pi^{+\prime}$$

- No stable pion target for direct measurement.
- Scatter electrons off a proton target to produce pions.
- Reaction is

$$\boldsymbol{p + e^- \rightarrow e^{-\prime} + \pi^+ + n}$$

- Need a precise measurement of the cross-section of this reaction.





Cross-Section and L/T Separation

- The physical cross-section can be decomposed into four structure functions.

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

- These structure functions depend on “ϵ” → polarization of virtual photon.
- “Rosenbluth Separation technique” is used to separate the longitudinal and transverse cross-section terms.
- The successful separation requires a range of kinematic settings.

Pion Form Factor

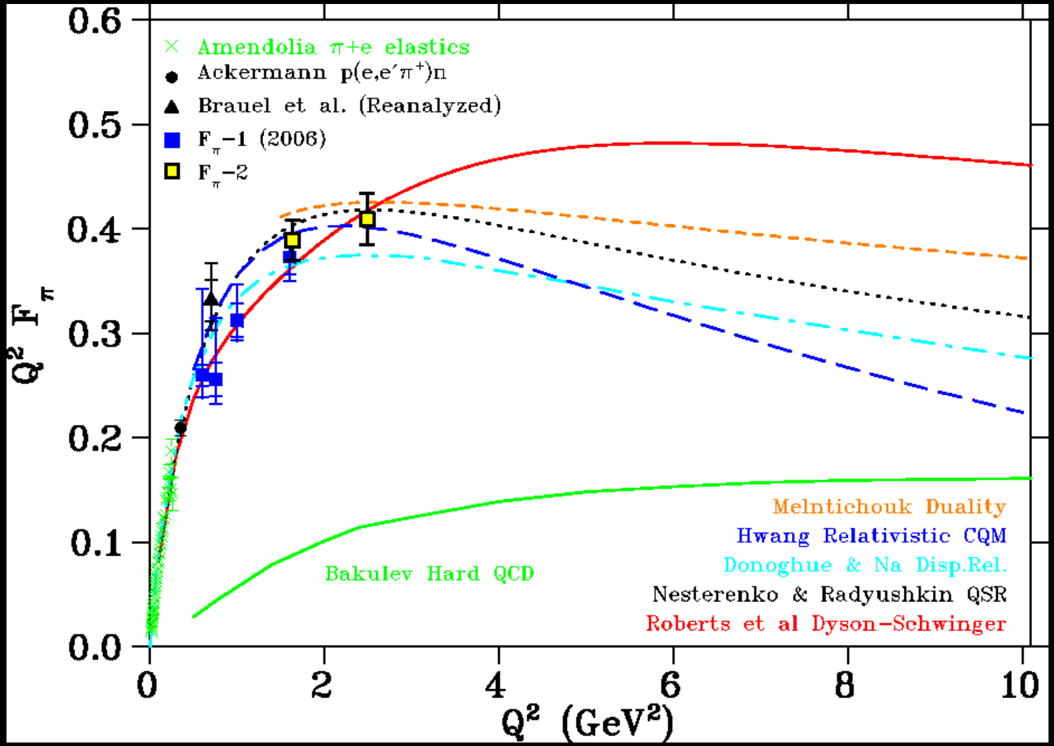
- Form factor describes the orientation of the momentum of the partons inside a hadron.
- Pion form factor, F_π, can be extracted from the longitudinal cross-section.
- In Born term model F_π appear as

$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} \underbrace{g_{\pi NN}(t)}_{\text{Coupling constant}} Q^2 \underbrace{F_\pi^2(Q^2, t)}_{\text{Form Factor}}$$

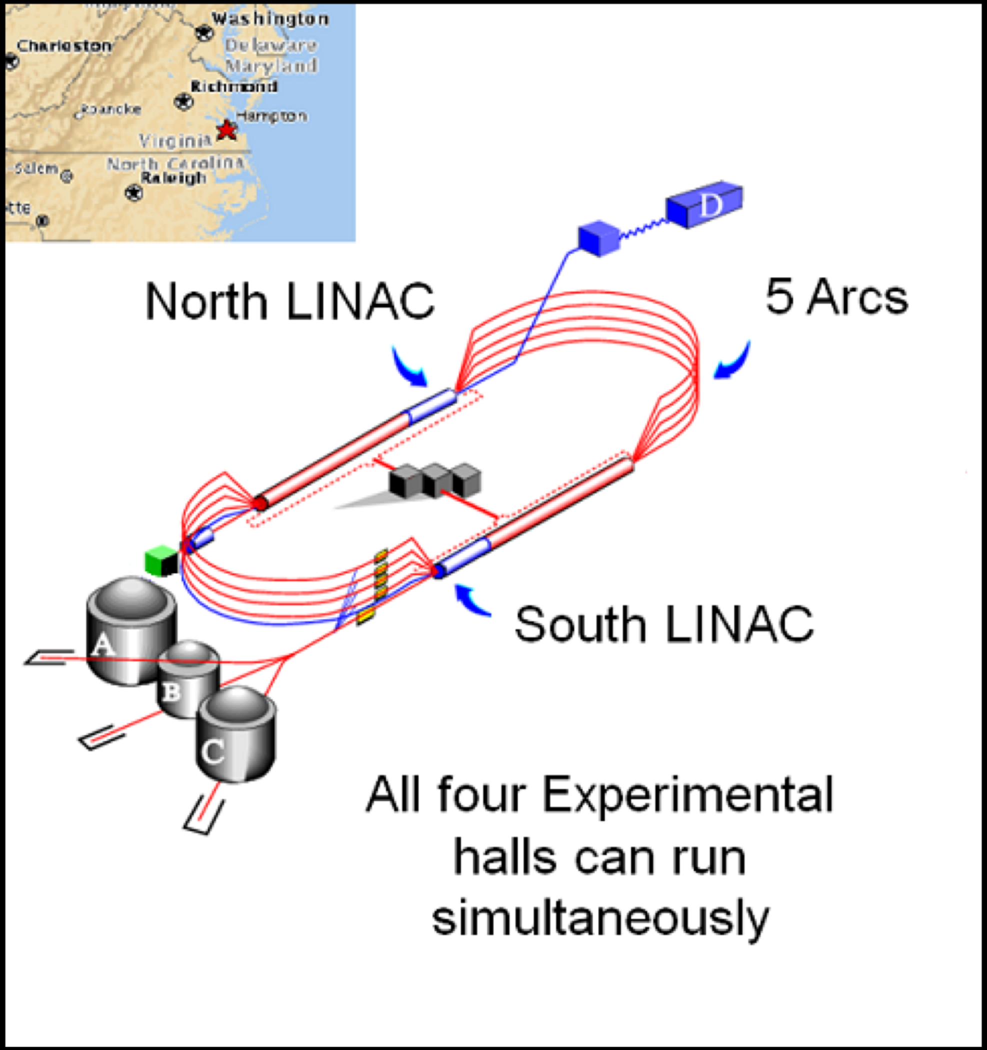
- F_π is cleanest case for studying transition from non-perturbative QCD to the perturbative QCD region.
- Previous experimental measurements are limited and don't give enough information.

Limitations of Previous Studies

- Only have experimental results at low Q^2.
- Difficult to validate theoretical predictions at low Q^2.
- At high Q^2, the theoretical predictions deviate from each other.
- Need experimental data to validate any of the predictions at high Q^2.
- Need a specific facility to study pions at high Q^2.



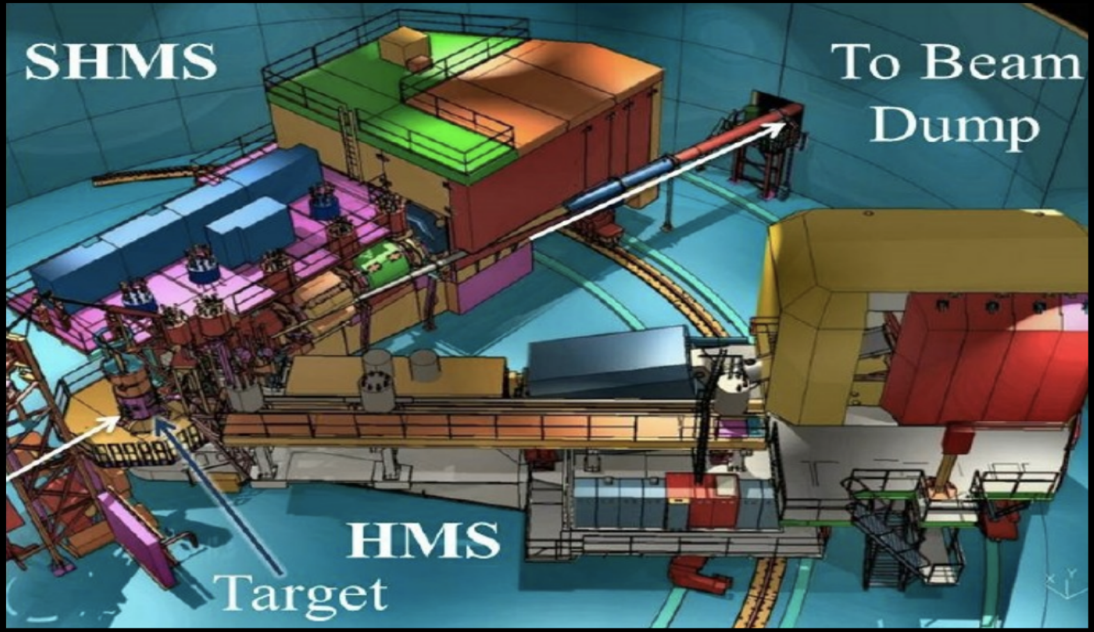
Jefferson Lab



- Located in Newport News, VA
- Continuous Electron Beam Accelerator Facility (CEBAF)
- Consists of two superconducting LINACs
- Capable of delivering a 12 GeV electron beam of up to 200 μA.
- Four Experimental Halls which perform unique experiments.
    - All four halls can run simultaneously

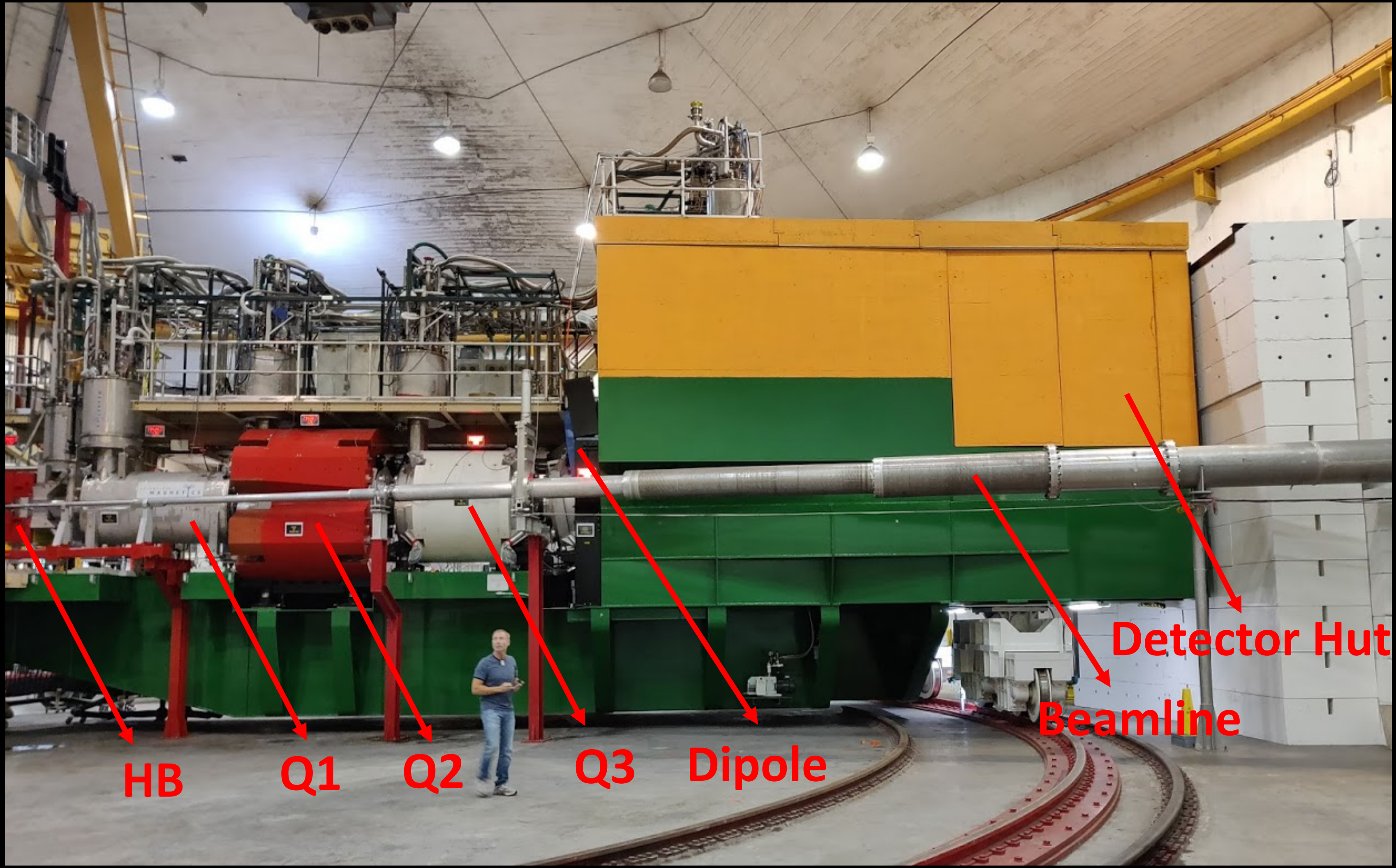
Experimental Hall C

- Specifically designed to measure precise cross-sections and form factors for mesons.
- Two advanced rotatable magnetic spectrometers.
  - High Momentum Spectrometer (HMS)
  - Super High Momentum Spectrometer (SHMS)
- Particles of specific momentum are studied by using a dipole.
- Capable of working at very high rates and different configurations.

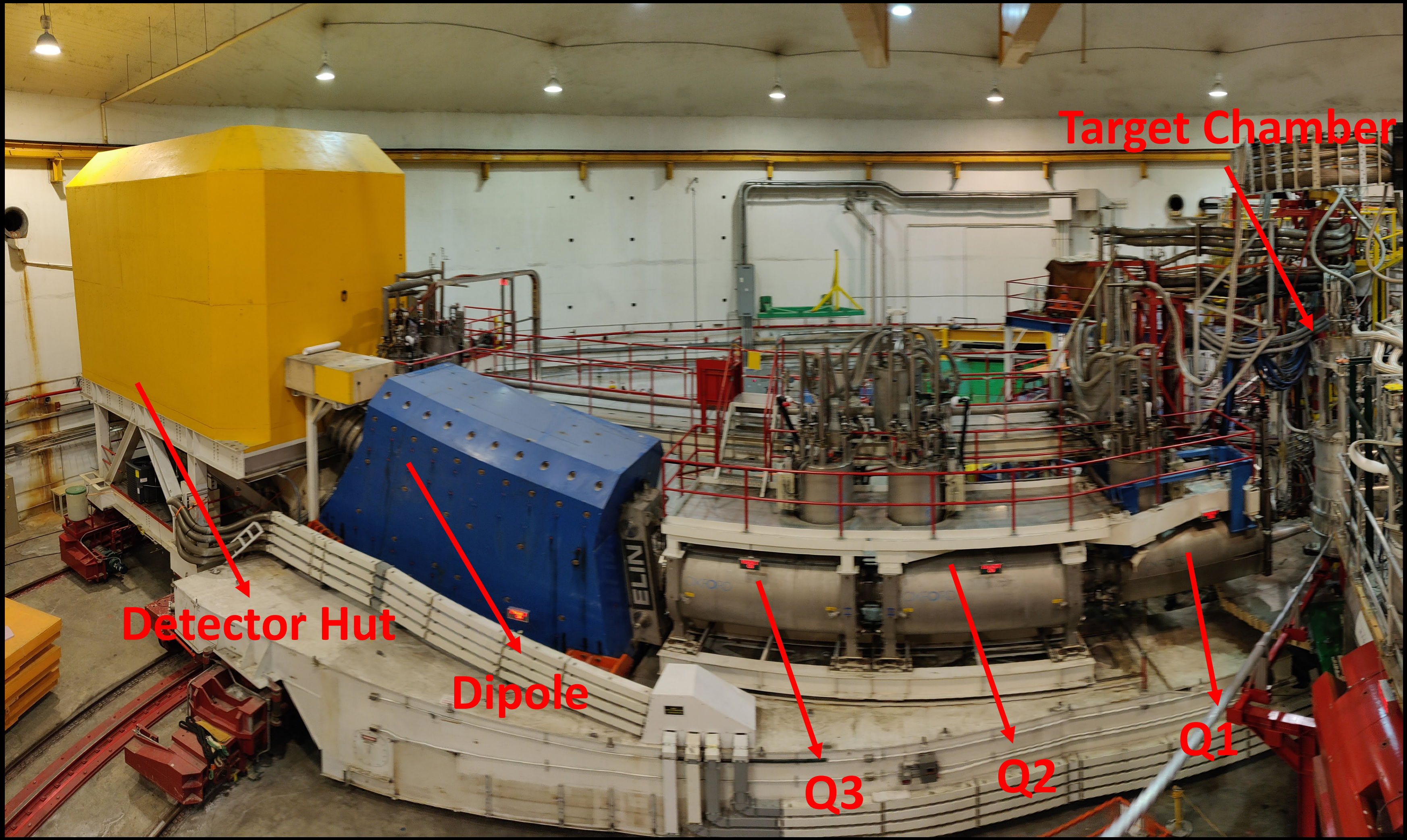


Spec	**Angle**	**Particle**	**Rate**	**Momentum range**
HMS	10.5 - 90	Electron	**< 1 MHz**	**0.5-7 GeV**
SHMS	5.5 - 40	Meson	**< 1 MHz**	**0.5-11 GeV**

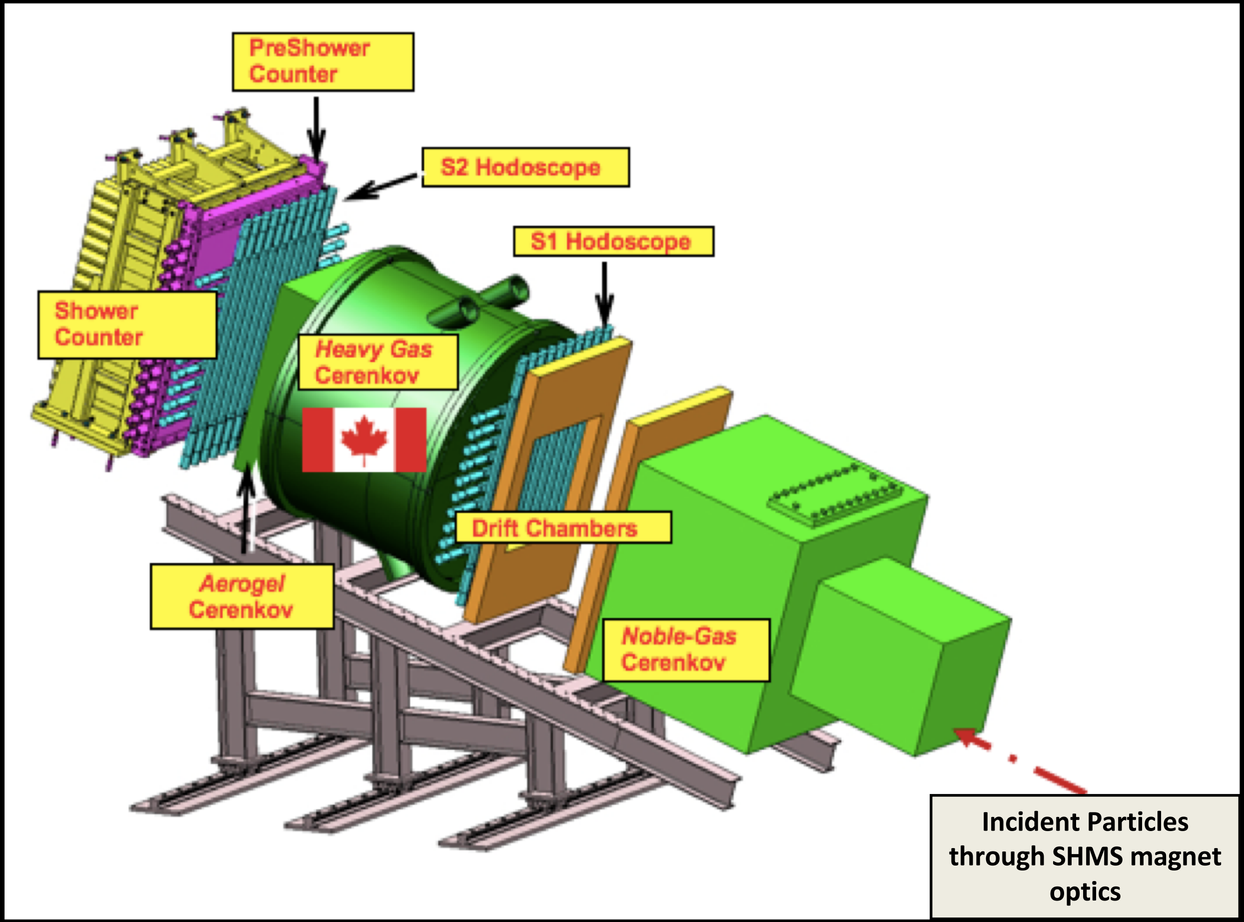
Super High Momentum Spectrometer (SHMS)



High Momentum Spectrometer (HMS)



SHMS Detector System

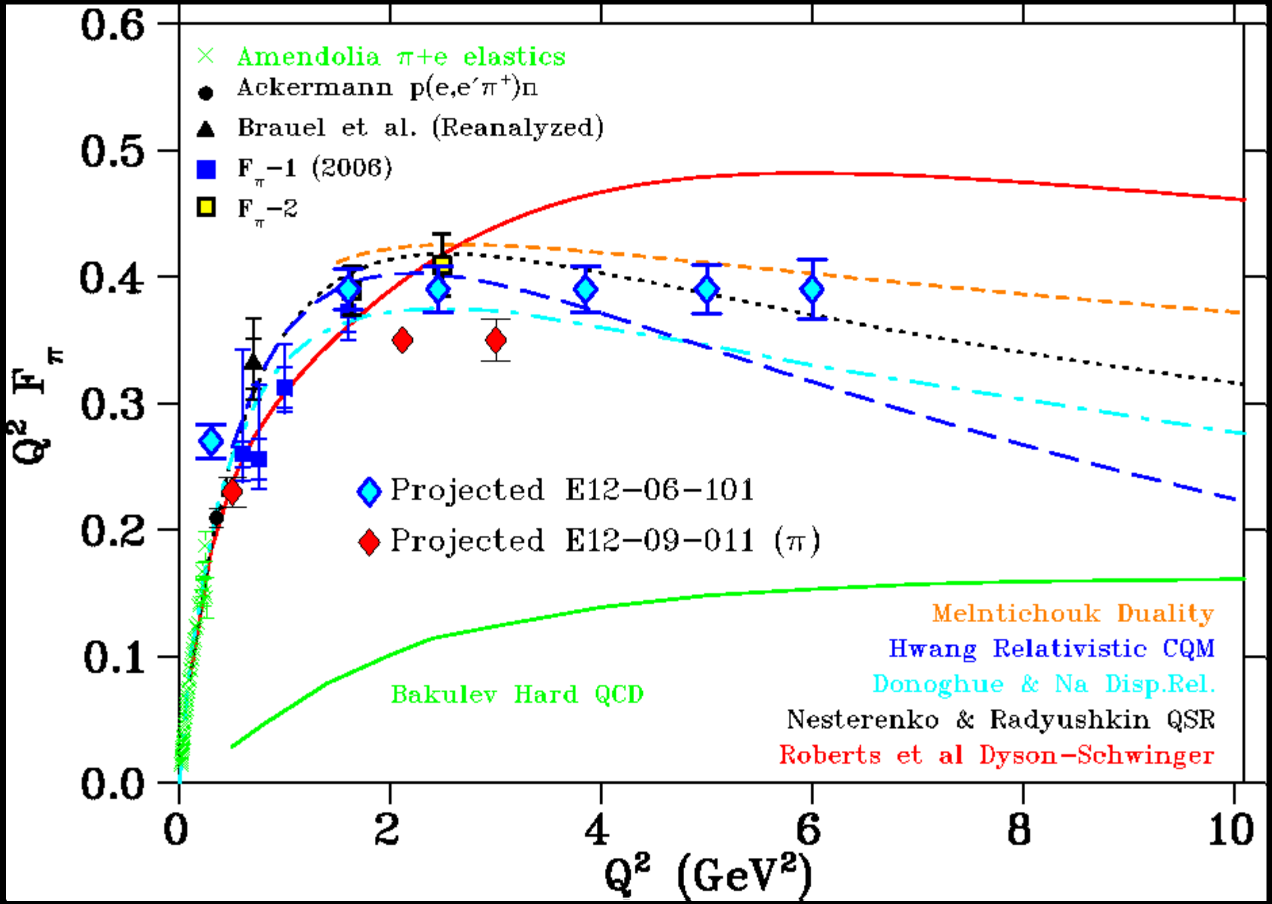


DETECTOR	PURPOSE	NOTES
S1XY, S2XY Hodoscopes	Lowest-level Trigger. Time reference	
Drift Chambers	Momentum Measurement. Tracking.	5mm max. drift 300 micron resolution
Noble-Gas Cérenkov	Particle ID, Trigger. $e^{\pm}/\pi^{\pm}$ at high momentum (replace by vacuum at low p)	Vary Ar/Ne mixture to set index at $\pi^{\pm}$ threshold.
Heavy-Gas Cérenkov	Particle ID, Trigger. $\pi^{\pm}/K^{\pm}$ discrimination	C_4F_8O – Vary pressure to set index at $K^{\pm}$ threshold
Aerogel Cérenkov	Particle ID, K+/p discrimination	n= 1.011,1.015, 1.03,1.05
Preshower / Shower Counters	Particle ID, Trigger. Electron tag	

Projected Results

- Two experiments were proposed for meson form factor studies for 12 GeV upgrade at Jefferson Lab.

E12-09-011
Mainly focused on Kaon studies but will also be used for pions due to high pion yield.



E12-06-101
(High Priority)
Actual pion form factor experiment which is planned to study high Q^2, up to 6 GeV^2.

Experiment Status

E12-09-011

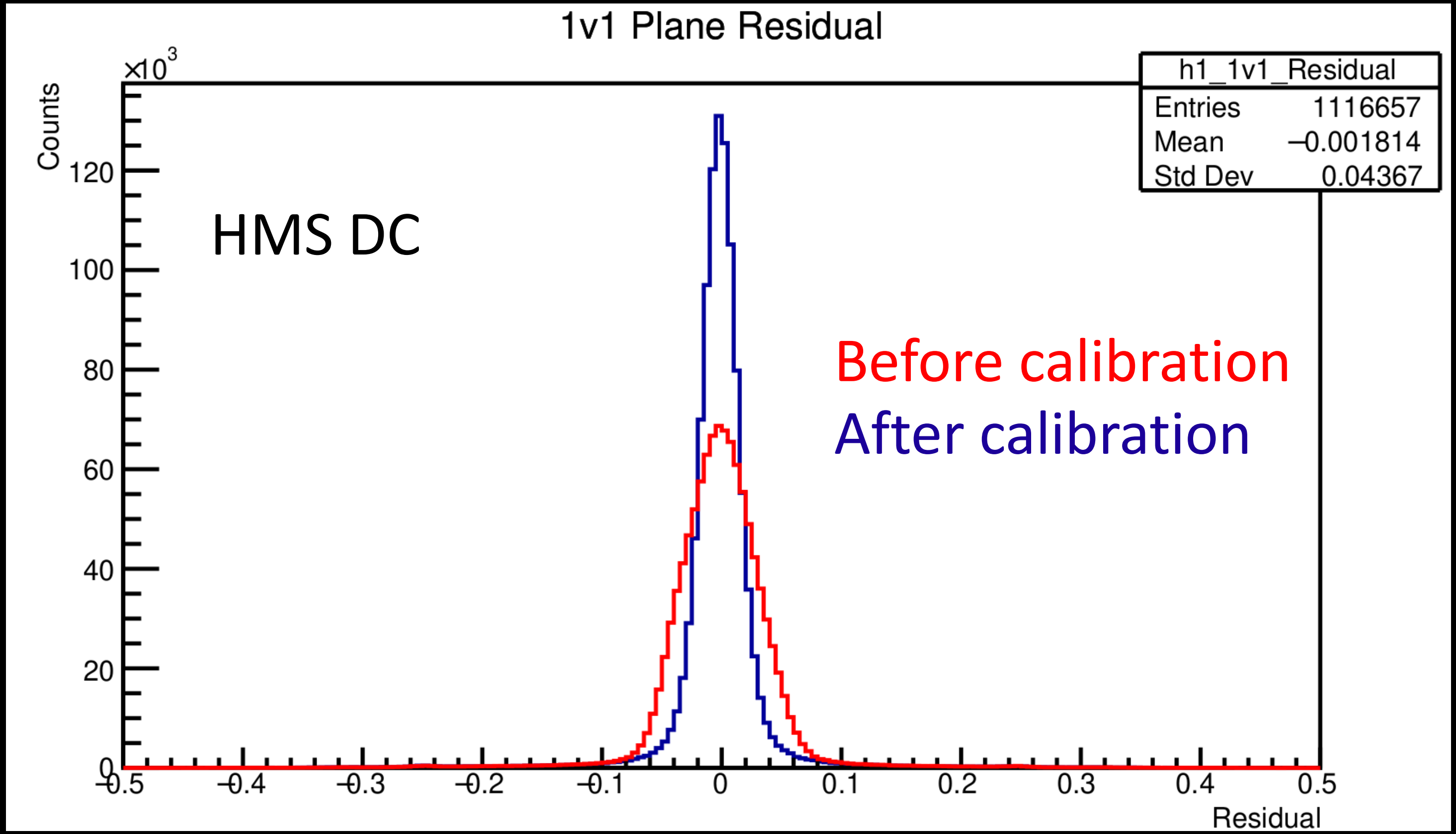
Data Collection	Done	Fall 2018 – Spring 2019
Calibrations	Done	Fall 2019
Efficiencies	In-Progress	Now
Cross-Section	Next	-
Form Factor	Next	-

E12-06-101

E_b = 2.8 GeV	Done	Summer - 2019
E_b = 3.7 GeV	Done	Summer - 2019
E_b = 4.2 GeV	Done	Summer - 2019
E_b = 4.5 GeV	Done	Summer - 2019
E_b = 6.0 GeV	Scheduled	Summer - 2021
E_b = 8.0 GeV	Scheduled	Summer - 2021
E_b = 9.9 GeV	Scheduled	Summer - 2021
E_b = 6.7 GeV	Planned	2023
E_b = 8.8 GeV	Planned	2023
E_b = 9.2 GeV	Planned	2023
E_b = 11.0 GeV	Planned	2023

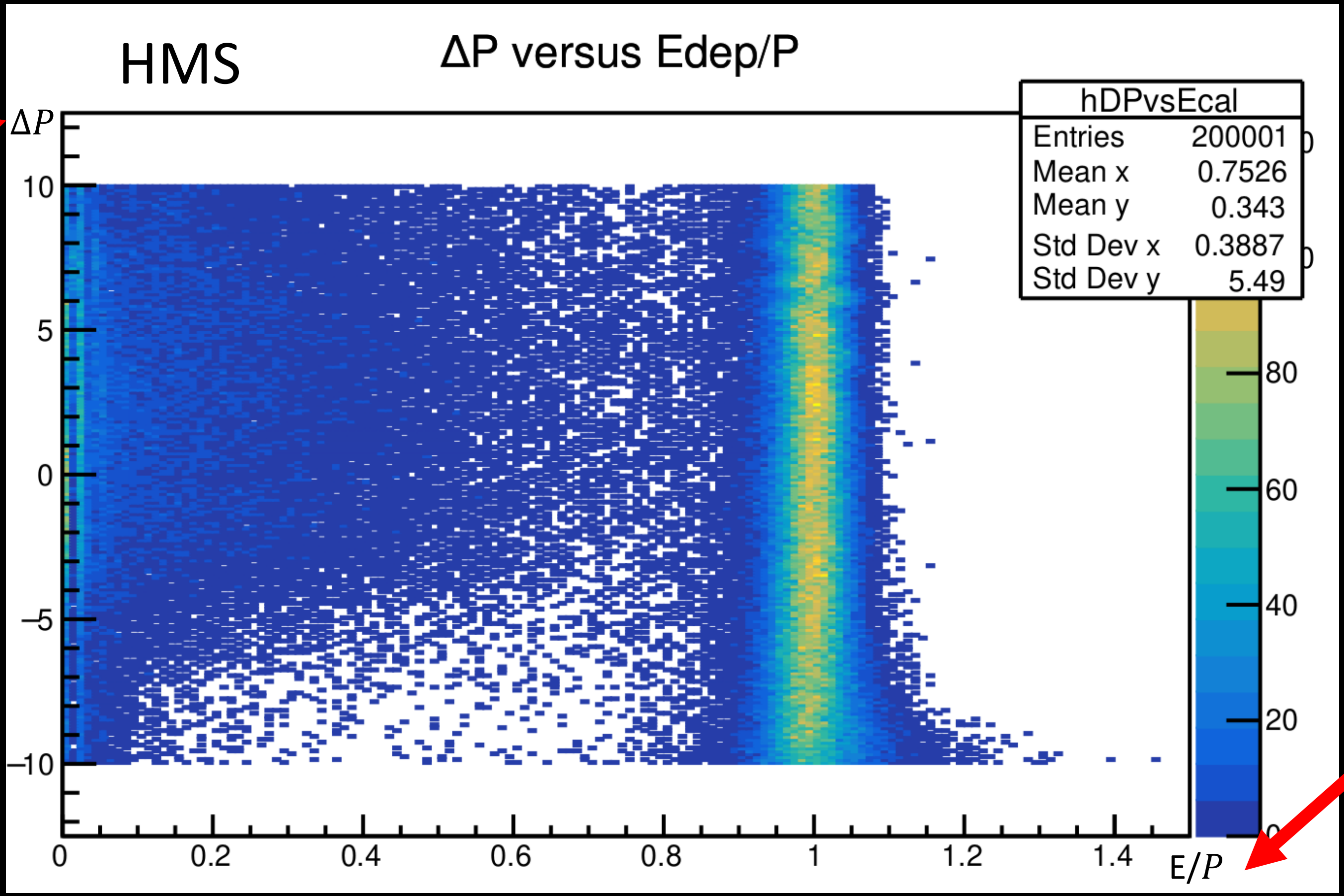
Calibrations - Drift Chambers

- Residual is the difference between final track position and the hit location obtained from individual drift chamber planes.



Calibrations - Calorimeter

- Momentum distribution for electrons.



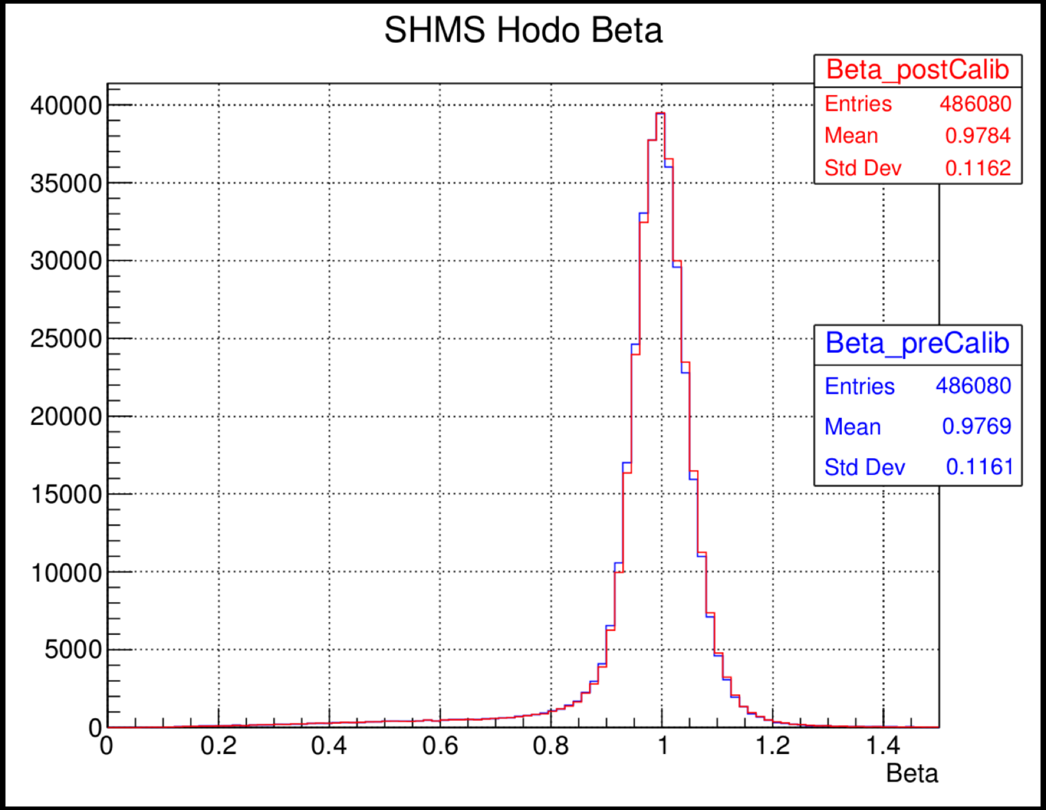
- Deviation of particle momentum from spectrometer central momentum

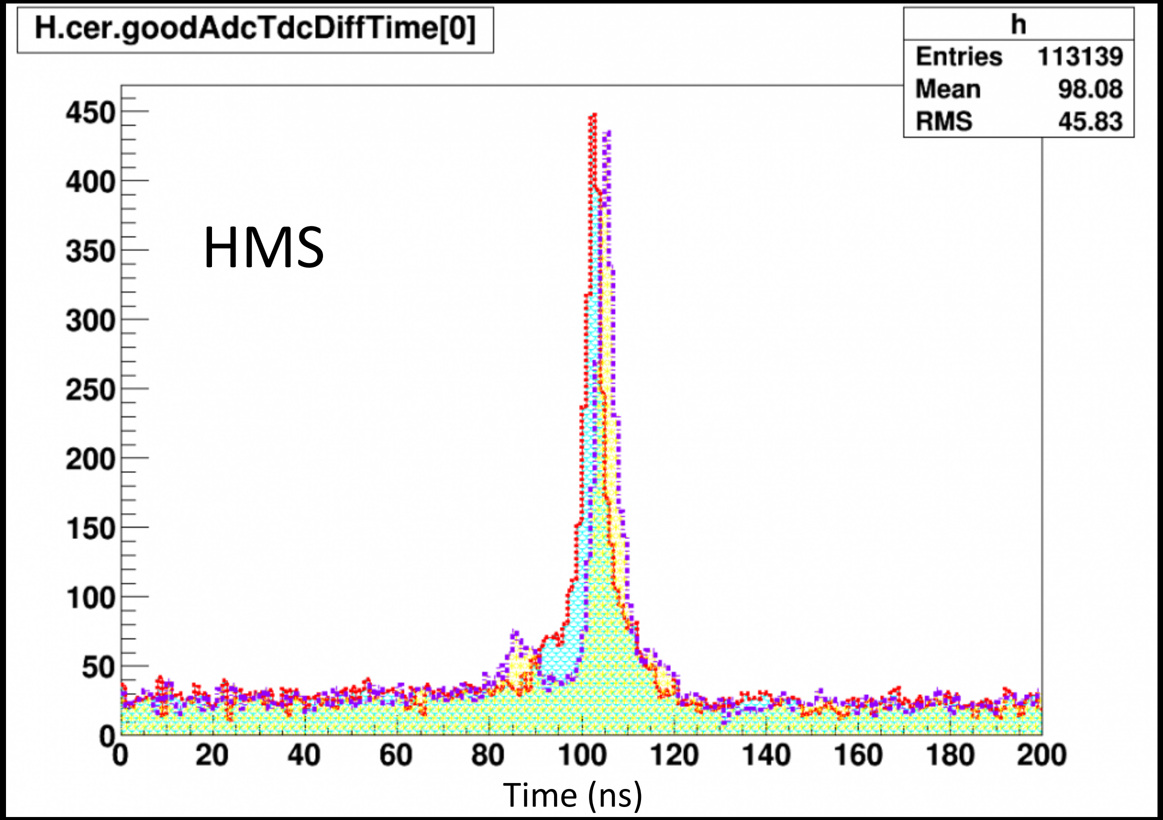
- E/p - Normalized energy
- Deposited energy/ particle momentum
- Expect E/p = 1 for e^-

Hodoscope & Cérenkov

$$\beta_{shms} = \frac{1}{c}\frac{\Delta l(h_2-h_1)}{\Delta t(h_2-h_1)}$$

$$t = t_{HMS\ trig} - t_{HMS\ Cer}$$





Summary and Outlook

- F_{π} is a key variable in our understanding of quark momentum distribution.
- Hall C at Jefferson lab is the only facility in the world which can measure F_{π} to a very high precision.

E12-09-011

- Data Collection → Done
- Analysis → In Progress

E12-06-101

- Data Collection → Partially Done
- Will continue in 2021-2023

- Results coming soon (hopefully)

Stay Tuned!!!

Collaborators

[1] University of Regina

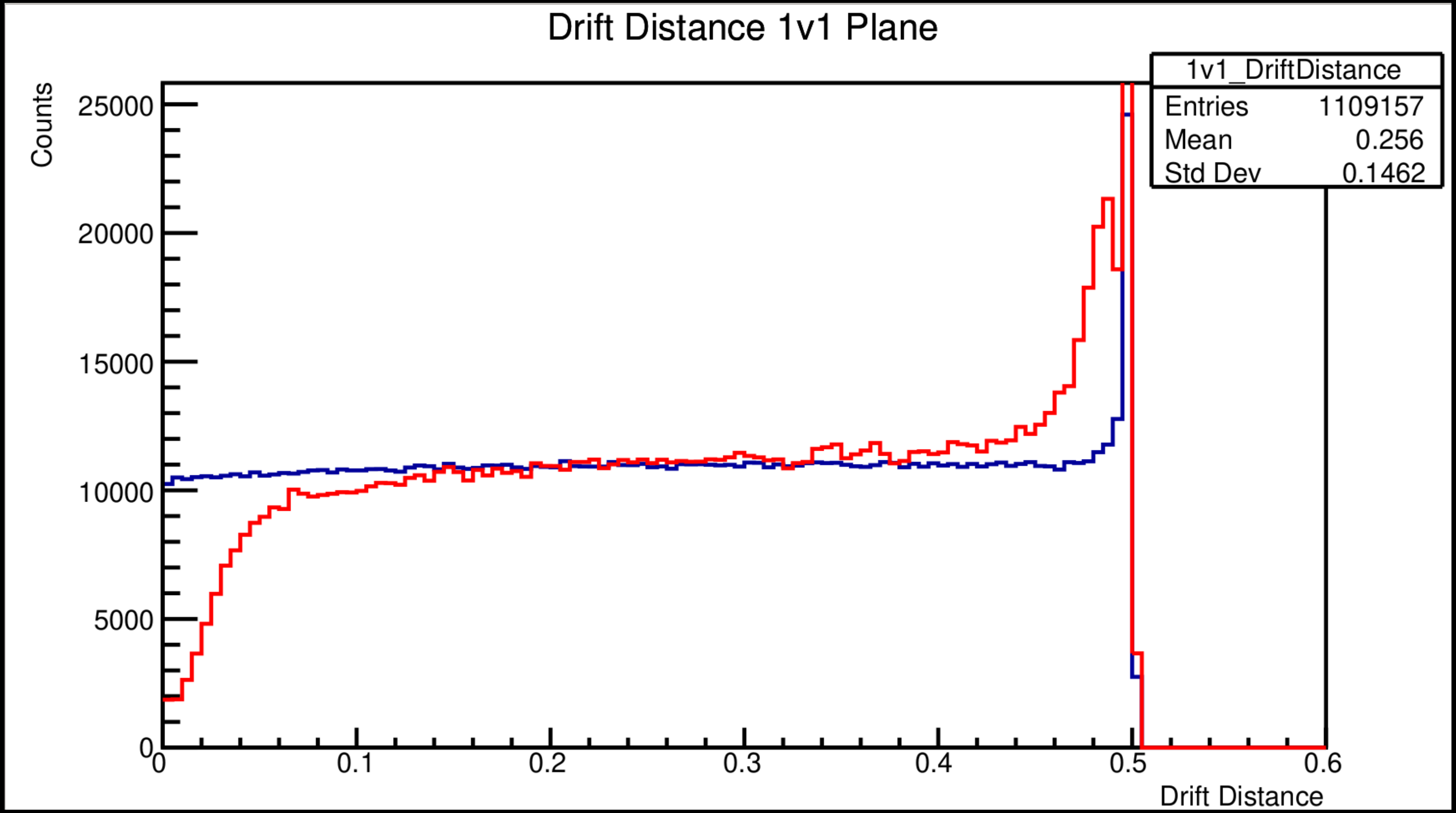
[2] Thomas Jefferson National Accelerator Facility (JLab)

[3] Catholic University of America

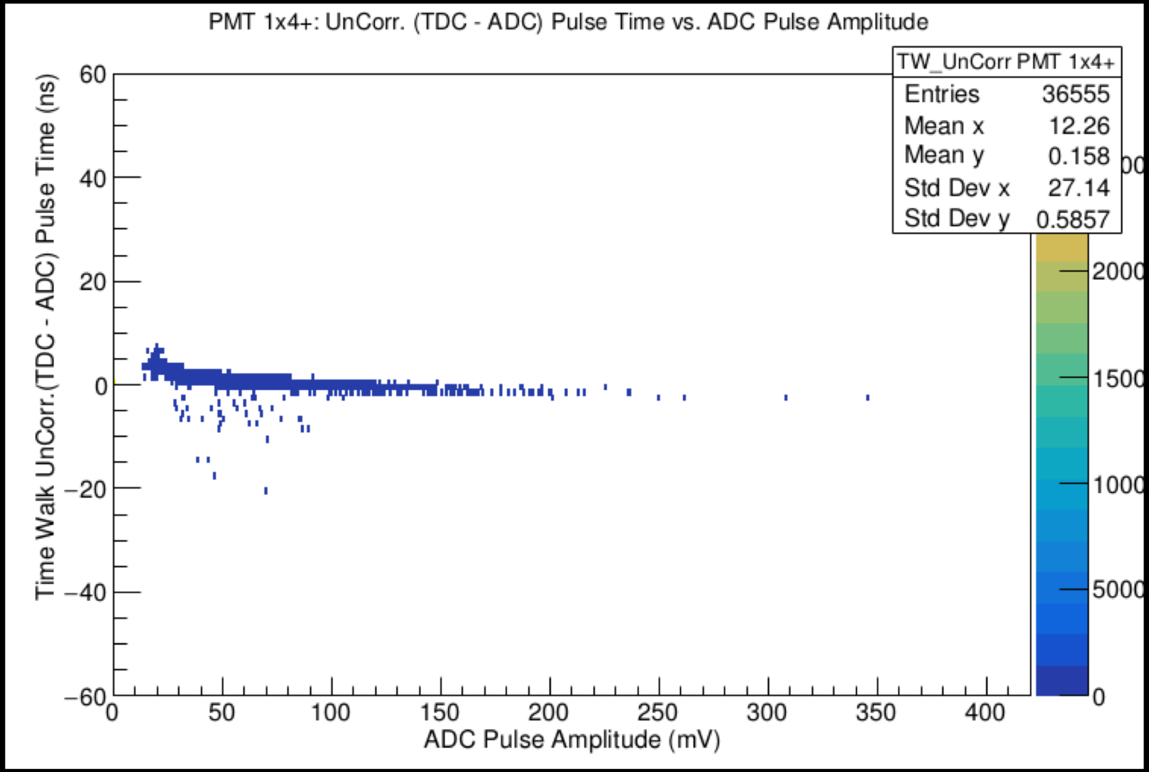
[4] Florida International University

Backup Slides

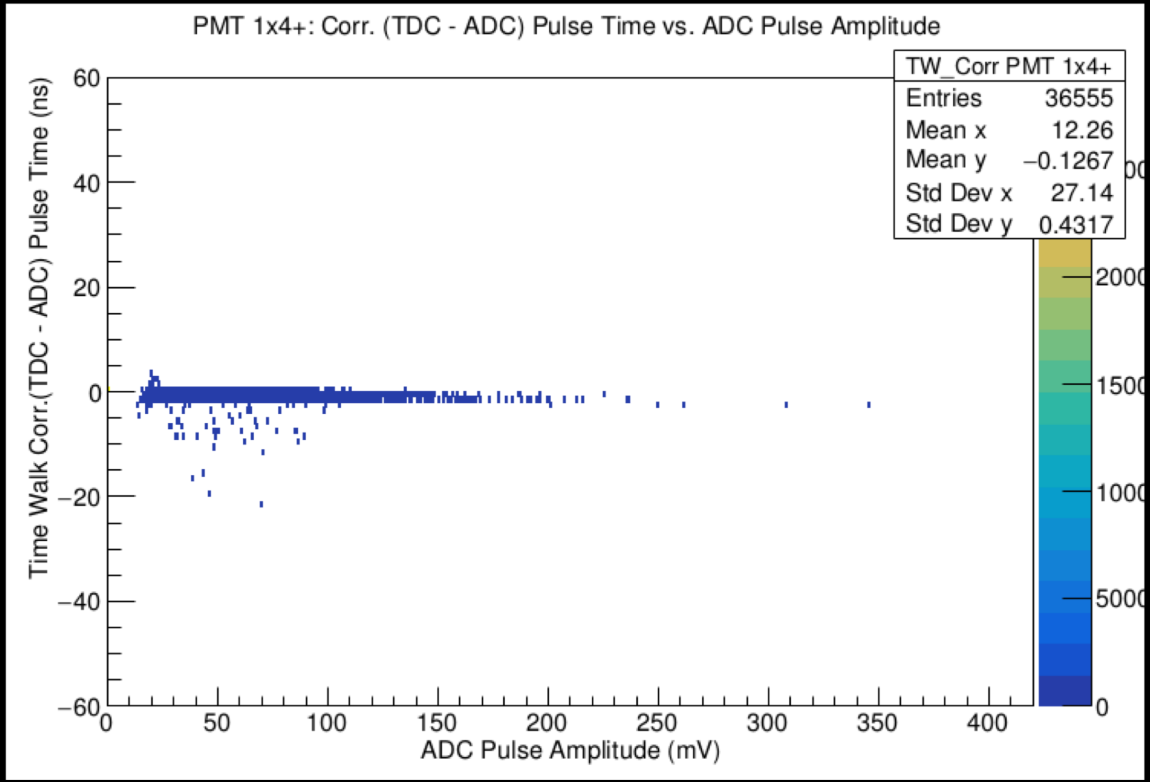
DC


Drift Distance 1v1 Plane
1v1_DriftDistance
Entries 1109157
Mean 0.256
Std Dev 0.1462
Counts
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
Drift Distance

Hodoscope

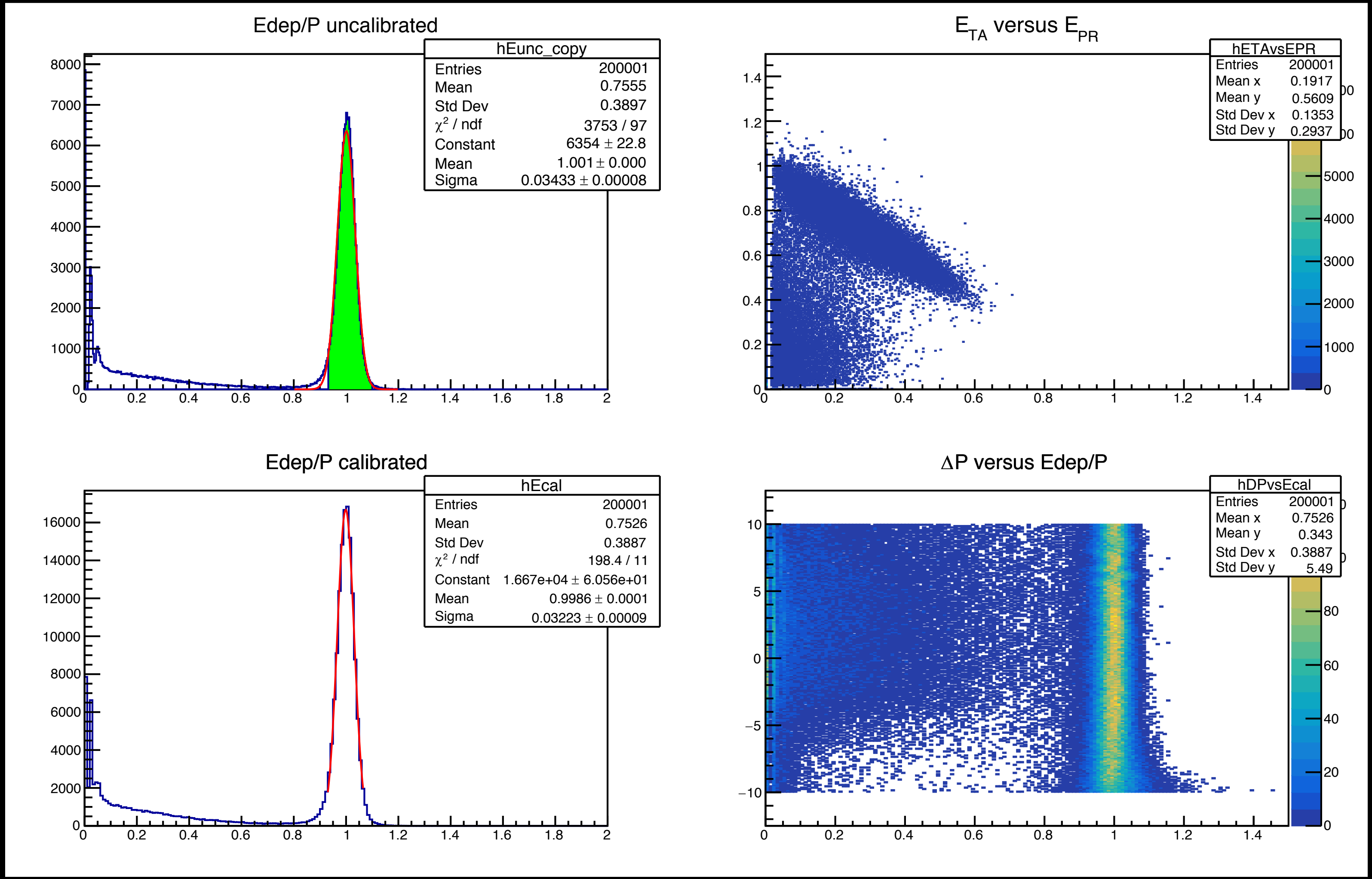


PMT 1x4+: UnCorr. (TDC - ADC) Pulse Time vs. ADC Pulse Amplitude
TW_UnCorr PMT 1x4+
Entries 36555
Mean x 12.26
Mean y 0.158
Std Dev x 27.14
Std Dev y 0.5857
Time Walk UnCorr.(TDC - ADC) Pulse Time (ns)
ADC Pulse Amplitude (mV)



PMT 1x4+: Corr. (TDC - ADC) Pulse Time vs. ADC Pulse Amplitude
TW_Corr PMT 1x4+
Entries 36555
Mean x 12.26
Mean y −0.1267
Std Dev x 27.14
Std Dev y 0.4317
Time Walk Corr.(TDC - ADC) Pulse Time (ns)
ADC Pulse Amplitude (mV)

Calorimeter



The Pion in perturbative QCD

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

$$F_\pi(Q^2) = \frac{4}{3}\pi\alpha_s \int_0^1 dxdy \frac{2}{3}\frac{1}{xyQ^2}\phi(x)\phi(y)$$

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

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

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.**
- Can study the renormalization of α_S quark-gluon coupling, and QCD's transition between asymptotic freedom and confinement.