Charged Pion Form Factor – A Unique Precision Experiment at Jefferson Lab

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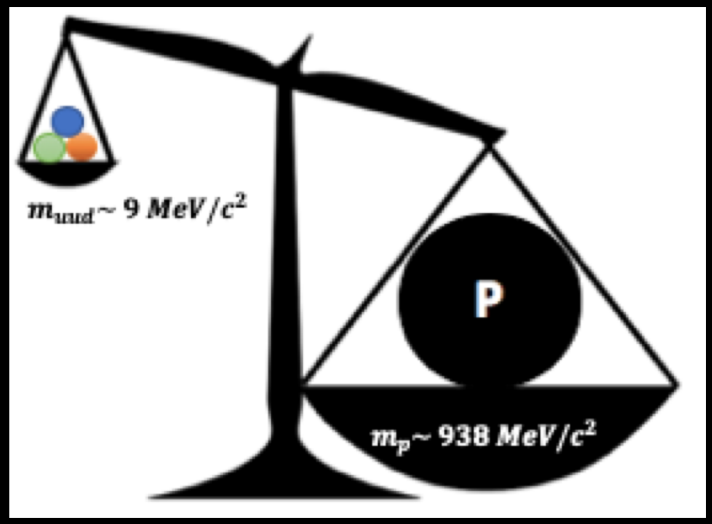
Physics Motivation

- Two well known hadronic states:
  - Baryons (qqq or $\bar{q}\bar{q}\bar{q}$)
  - Mesons ($q\bar{q}$)
- Interactions of quarks and gluons are described by Quantum Chromodynamics (QCD).



Open Questions

- ❑ How fundamental properties of hadrons arise from their constituent quarks and gluons?
- ❑ Which theoretical model precisely predicts the parton (quark-gluon) interactions in color confinement regime?

- Mesons give an ideal testing ground for our understanding of bound $q\bar{q}$ system.
- Form Factor describes transverse spatial position of partons within hadrons.

Pion Form Factor

- Pion is lightest meson with only two valence quarks (up and down).
- In pQCD, F_π can be written as

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

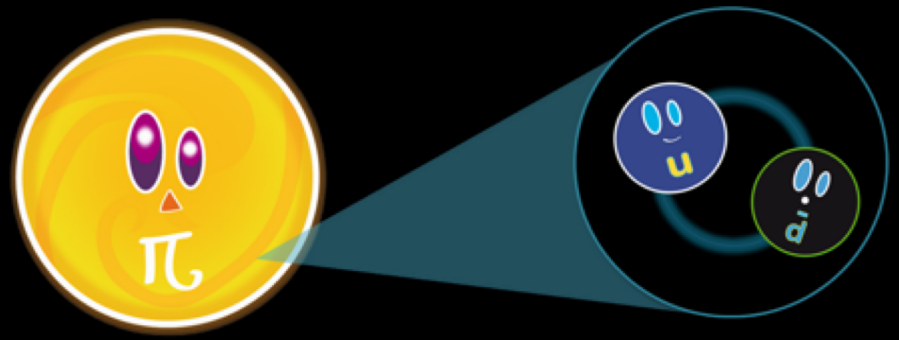
- At low Q^2, an experimentally accessible non-pQCD process dominates quark-gluon interactions.
- ***Exclusive Pion Electroproduction***

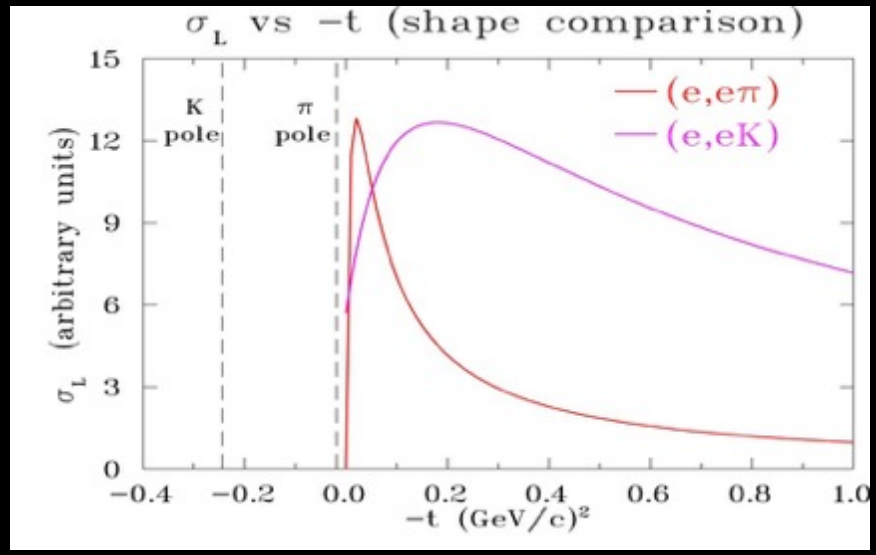
$$\boldsymbol{e^- + p \rightarrow e^{-\prime} + \pi^+ + n}$$

- In Born term model F_π appears as

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

- Scattering from virtual pion cloud dominates at low $-t$, need to measure σ_L through L/T separation.





Rosenbluth (L/T) Separation

- "Rosenbluth Separation technique" is used to separate σ_L and σ_T terms.
- **In parallel kinematics (i. e. $\theta_{\pi q} = 0$)**

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

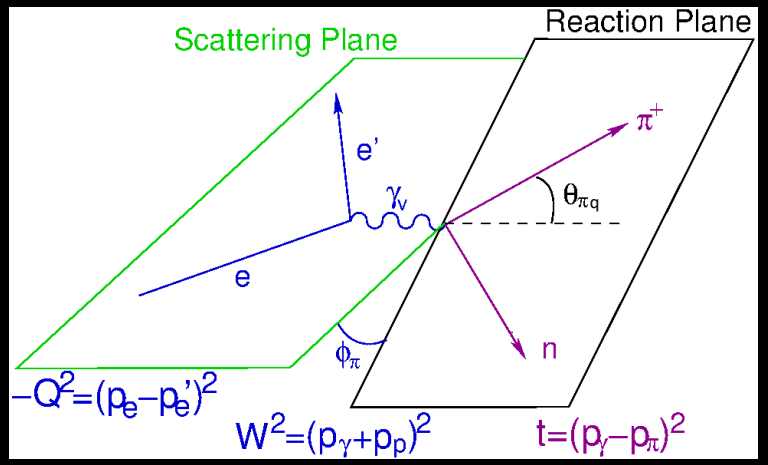
- Here "ϵ" is polarization of virtual photon

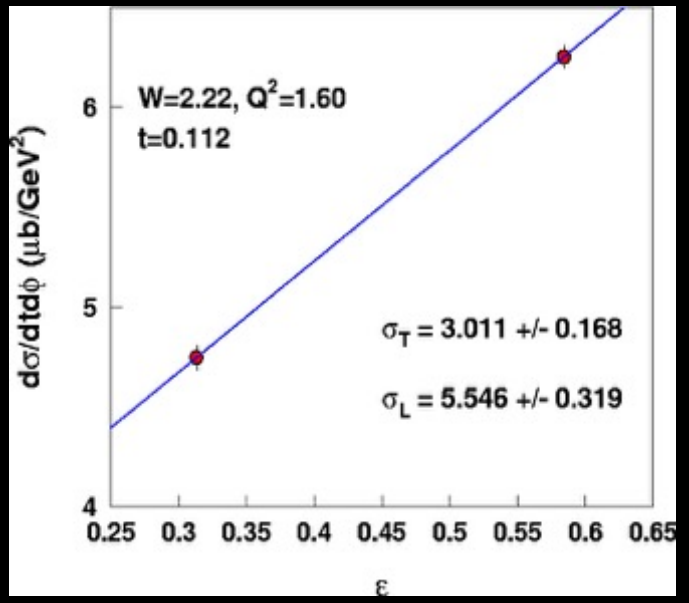
$$\epsilon = \left[1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2} . tan^2\frac{\theta_{e'}}{2}\right]^{-1}$$

- Cross-section is separated by performing two scattering measurements with different "ϵ" value.

Error Estimation

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





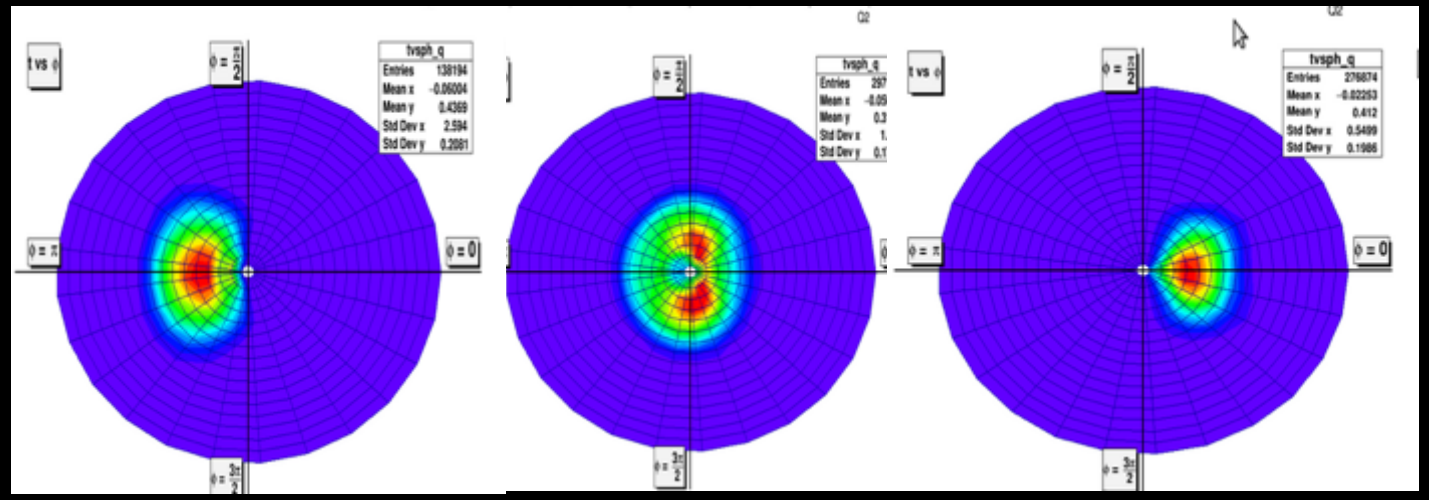
L/T/LT/TT Separated Cross-Section

- For $\boldsymbol{\theta_{\pi q} \neq 0}$, cross-section can be decomposed into four structure functions.

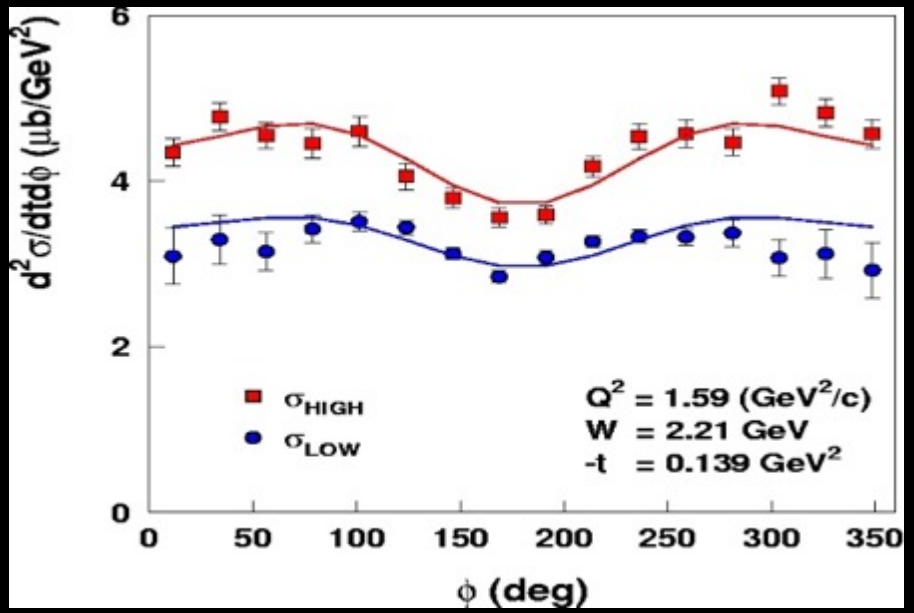
$$2\pi \frac{d^2\sigma}{dtd\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{LT}}{dt} cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} cos2\phi$$

- To study *t*-dependence of cross-section at fixed Q^2 and *W*, we need to take data at non-parallel kinematics.

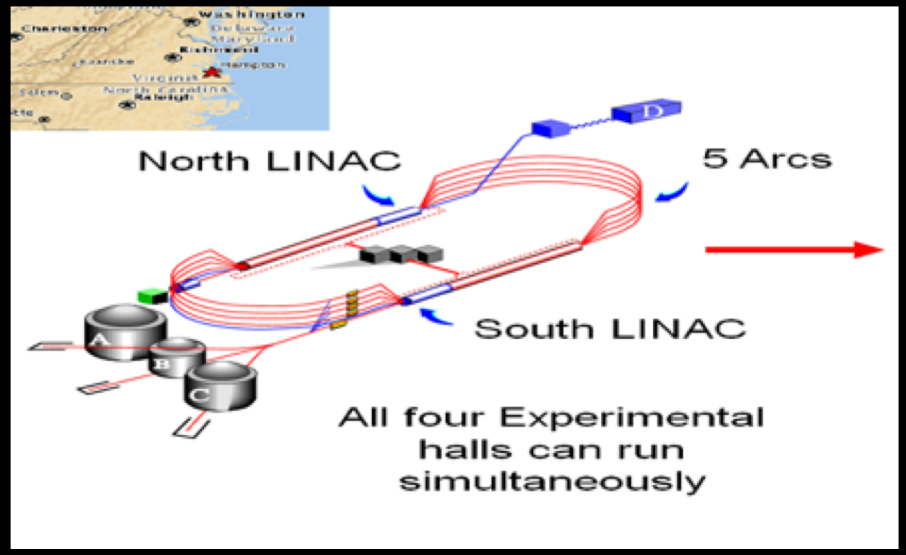
$E_e = 10.6\ GeV$ $Q^2 = 3.0\ GeV^2$ $W = 3.14\ GeV$



$\theta_{SHMS} = 12.42$ $\theta_{SHMS} = 9.42$ $\theta_{SHMS} = 6.65$



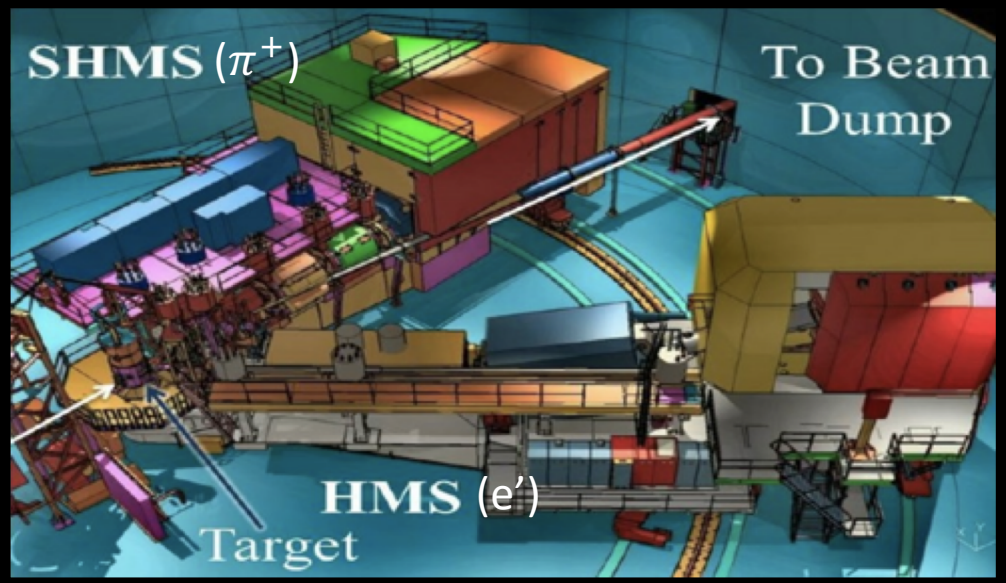
Thomas Jefferson National Accelerator Facility



- Located in Newport News, VA
- Consists of two superconducting electron LINACs.
- Capable of delivering a 12 GeV electron beam of up to 200 μA.

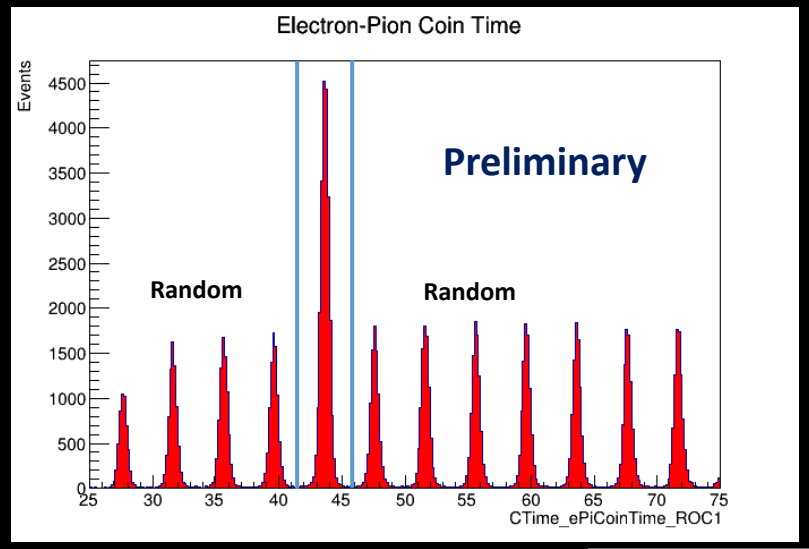
Hall C

- Specifically designed to measure precise cross-sections.
- Two advanced rotatable magnetic spectrometers (HMS and SHMS).
- Particles of specific momentum are studied by using a magnet system.

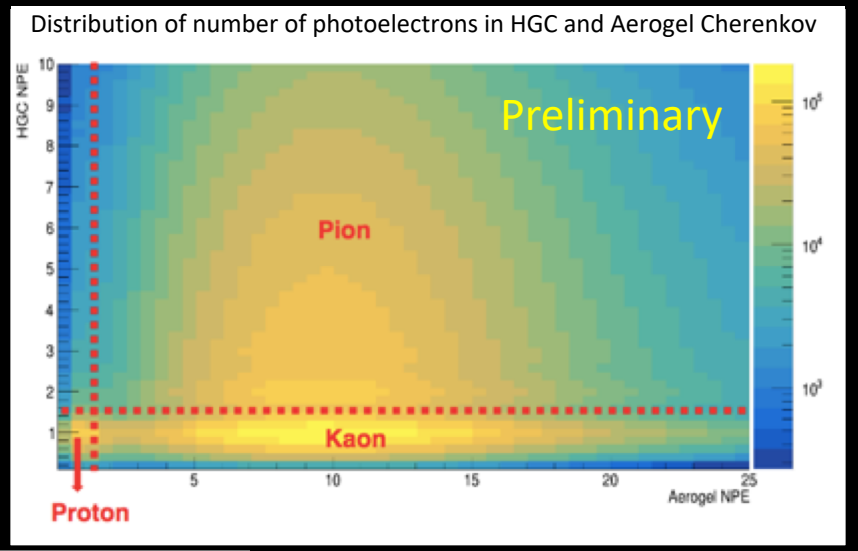


Data Analysis

➢ $e' - \pi^+$ Coincidence

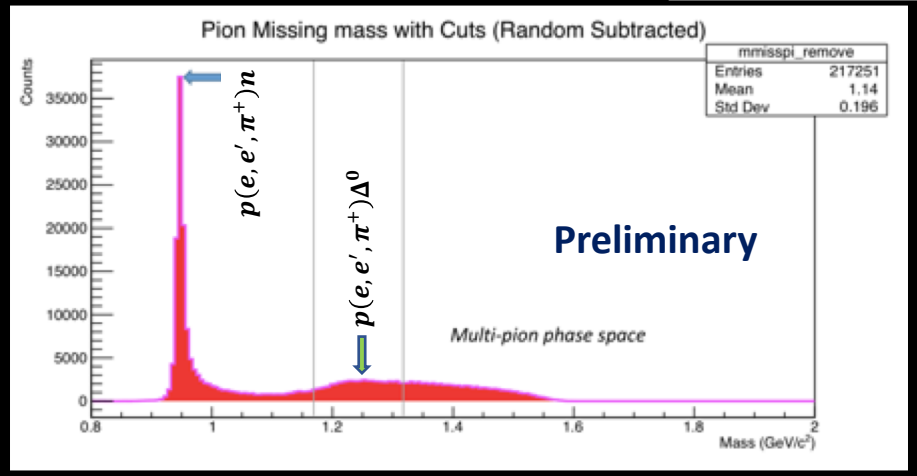


➢ Particle Identification



➢ Missing Mass

$E_e = 10.6\ GeV$
$Q^2 = 3.0\ GeV^2$
$W = 3.14\ GeV$



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

F_π Results and Projections

- F_π is a key variable in our understanding of strong QCD.
- Two proposed experiments at Jefferson Lab Hall C will extend current F_π results up to Q^2 of 8.5 GeV^2.

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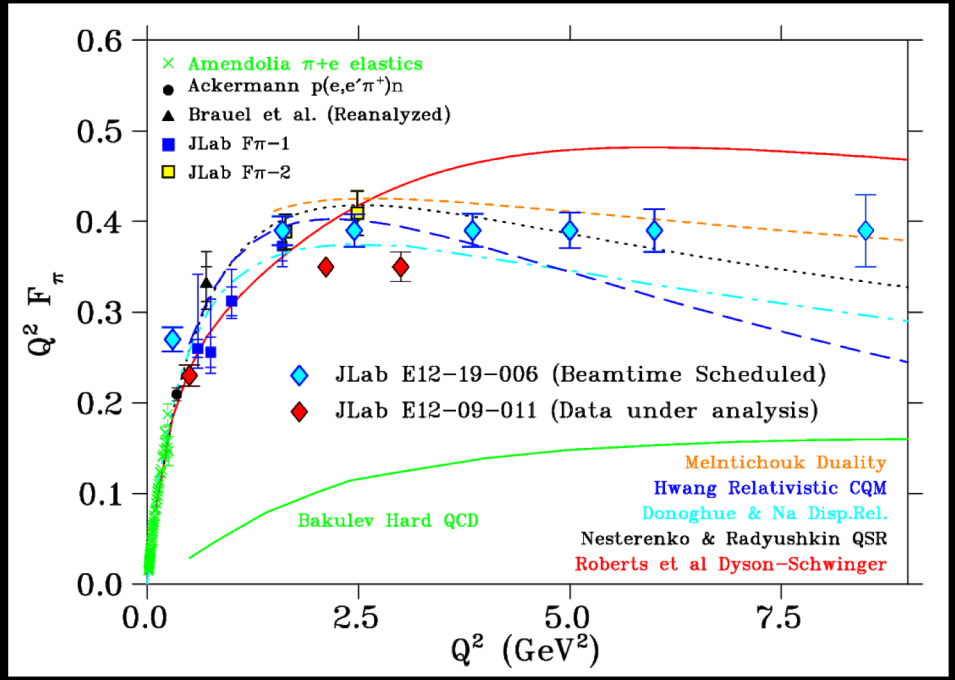
- Data Collected in 2018-19
- Analysis in progress
- Results expected in 2023-24



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- Data collection scheduled in 2021-22
- Results will be published in ~2025-26.

This is the beginning of exciting QCD physics era which extends beyond Jefferson Lab

Collaborators

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