Science at Jefferson Lab:Today and Future Plans

Patrizia Rossi

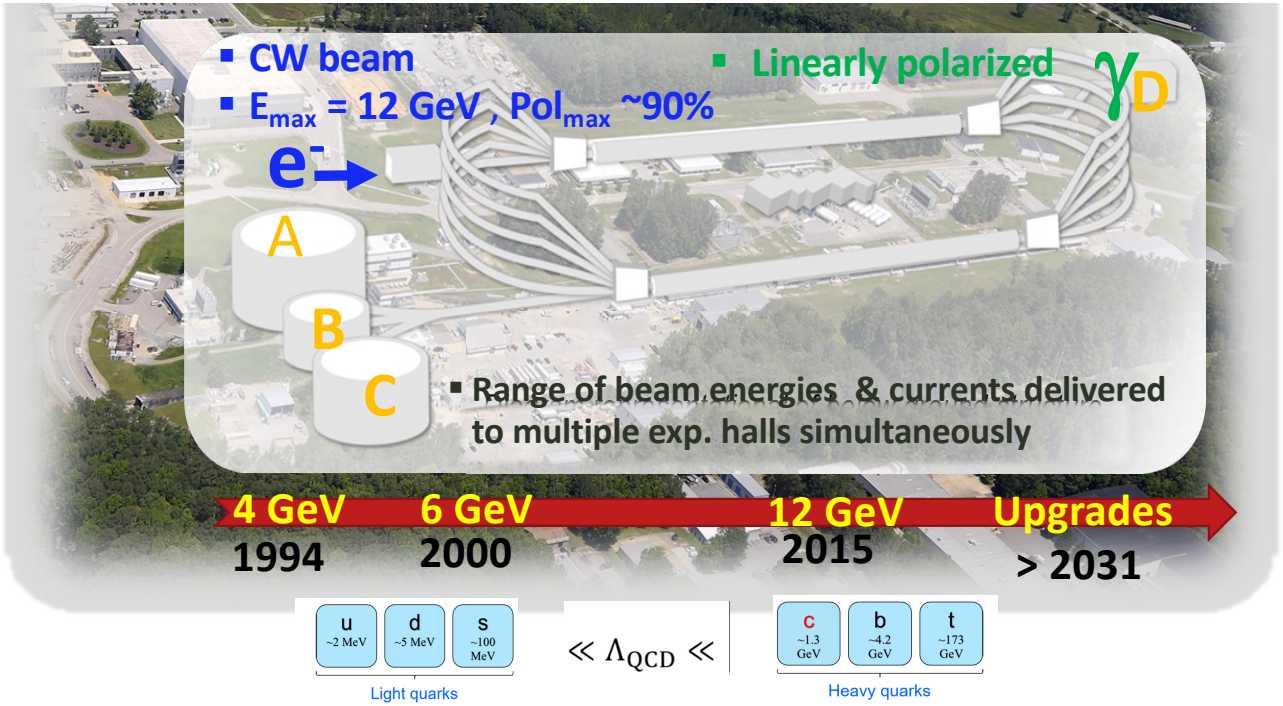
Physics Opportunities at an Electron-Ion Collider XI

Miami, Florida International University (USA) Feb 24 – 28, 2025

TJNAF is managed by Jefferson Science Associates for the US Department of Energy

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Jefferson Lab at a Glance



CEBAF @ 22 GeV
Positron Beam @ 12 GeV

A Facility at the LUMINOSITY Frontier

(up to 10^{39} cm^2 s^{-1})

World-Class Electron Beam

CEBAF provides a high-quality, 12 GeV continuous electron beam with::

- High Intensity
- High Polarization

Unique Experimental Facilities

CEBAF supports 4 cutting-edge experimental halls with:

- State-of-the-art detectors
- Versatile experimental setups
- Detection of multiparticle in the Final State

Impactful Research

CEBAF has a history of groundbreaking discoveries, including

❖ EIC will build upon this knowledge

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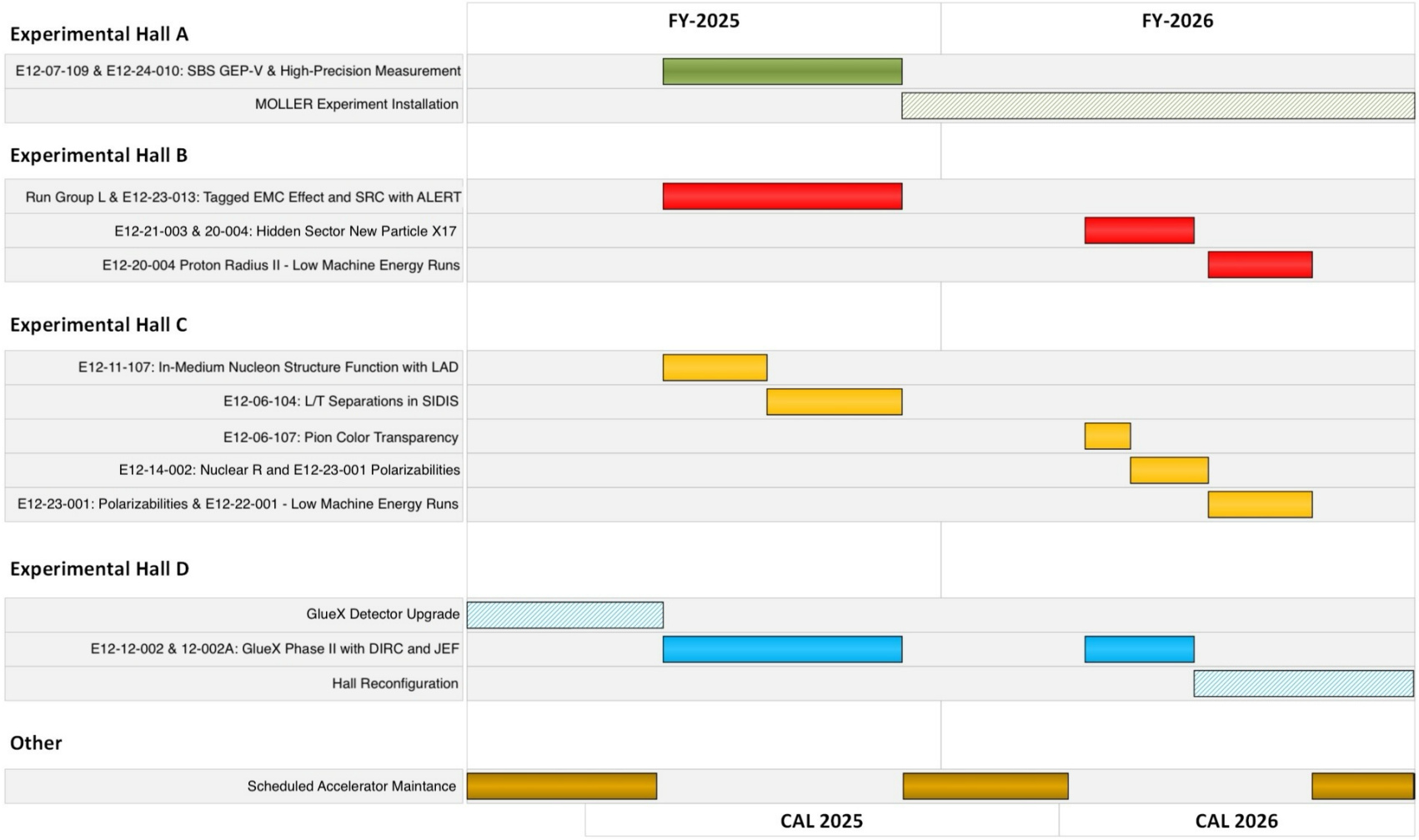
Today (and Tomorrow)



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Hall A – SBS: The Nucleon Form Factors Campaign

G_M^p

- Signature of a dominant contribution of TPE to the value of the Rosenbluth slope at Q^2 up to 15 $(GeV/c)^2$

G_M^n

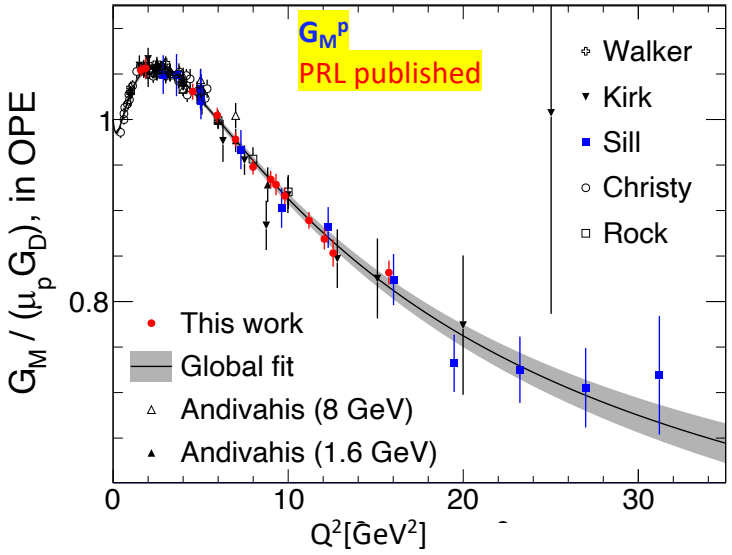
- Precision of the highest Q^2 data point (13.5 $(GeV/c)^2$) is expected to stay unmatched for years to come

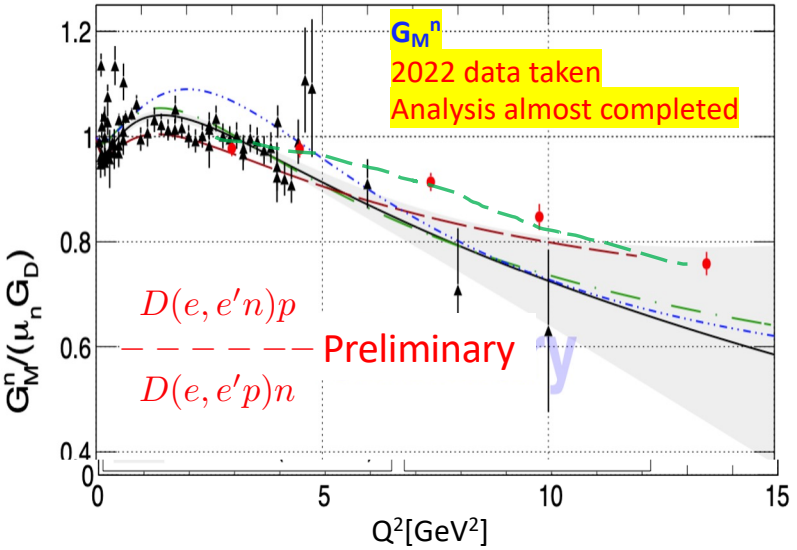
G_E^n / G_M^n

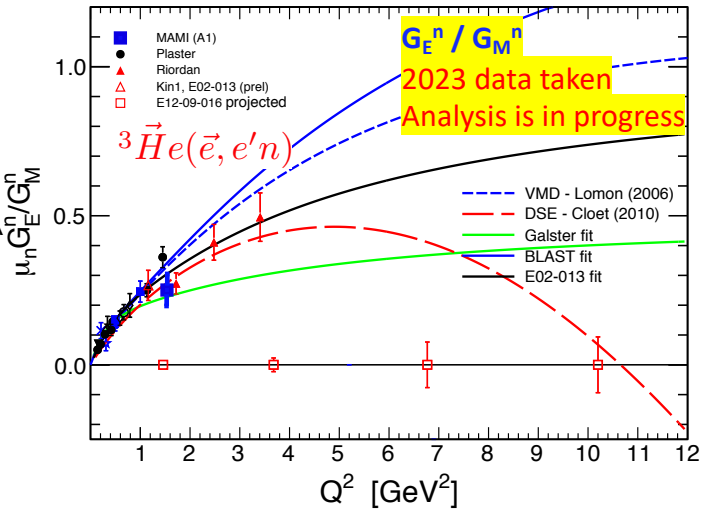
- This experiment will clearly differentiate between fundamental approaches to QCD.
- Polarized ^{3}He target – highest L to date!
  - First time 60 cm long target
  - 42 – 50% target polarization at 45mA

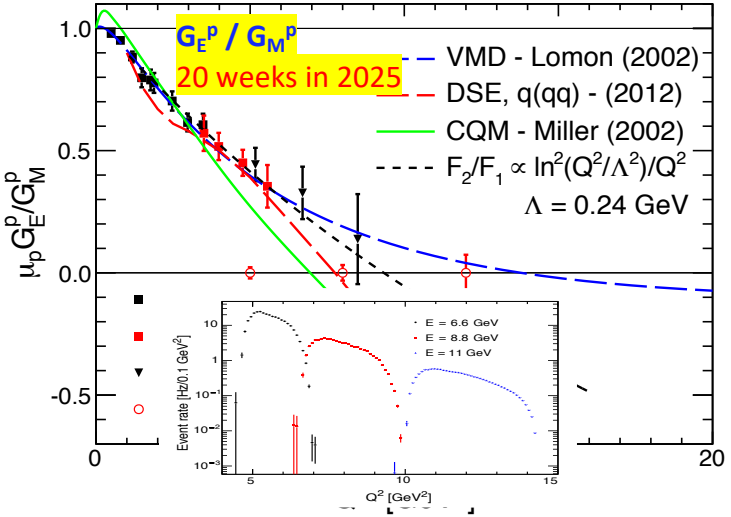
G_E^p / G_M^p

- This experiment will further extend the Q^2 range for GE/GM measurements, providing even deeper insights into the proton's structure.

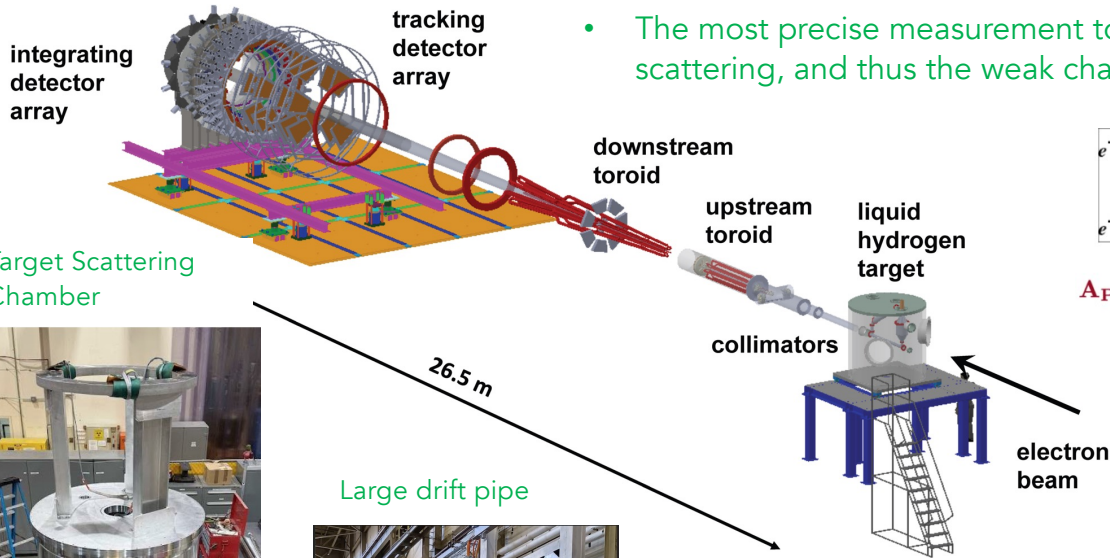




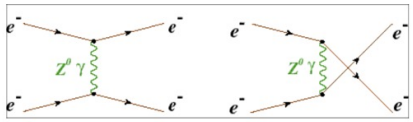




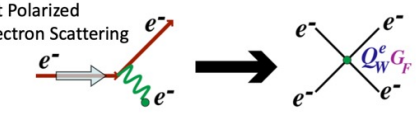
MOLLER World-leading Measurement of Lepton-Lepton Electroweak Reaction



- The most precise measurement to date of the **parity violating asymmetry, A_{PV},** in electron-electron scattering, and thus the weak charge of the electron, Q_W^e.



Fixed Target Polarized Electron-Electron Scattering



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

$$Q_W^e = 1 - 4\sin^2\theta_W \sim 0.075$$

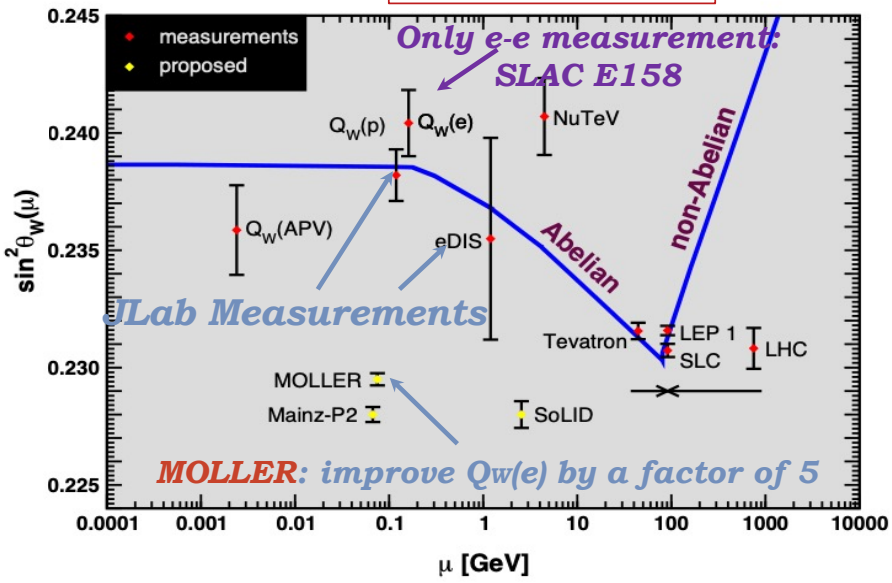
- The small APV requires an extremely high signal rate and very low noise

Large drift pipe

All coils for downstream magnet at JLab

A_{PV} ~ 26 ppb

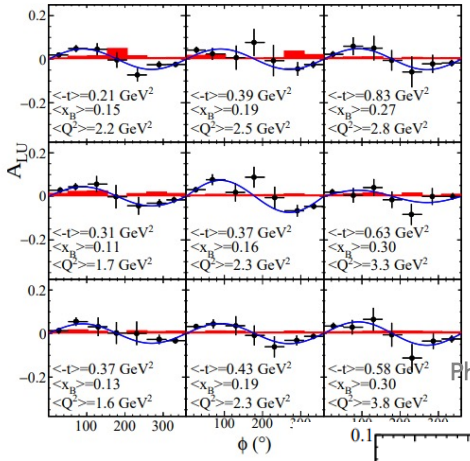
Combined $\frac{\delta A_{PV}}{A_{PV}} = 2.4\%$



- CD-2/CD-3 approved in May 2024
- Assembly starts August 2025
- MOLLER assembly complete September 2026
- Early CD-4 February 2027

Hall B: Recent Result & Upcoming Experiments

First Measurement of DVCS on the Neutron with Detection of the Active Neutron

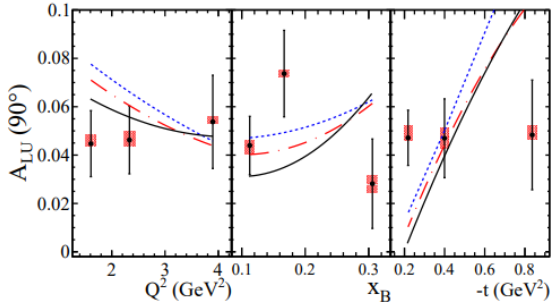


BSA versus Φ for bins in *-t*

Amplitude (few percent) is ~ a factor of 4 smaller than the pDVCS measured at these same kinematics

Phys. Rev. Lett. 133, 211903 (Nov. 2024

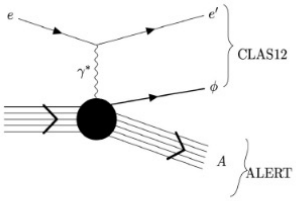
A_{LU} data compared with the VGG model



nDVCS : an important step toward the understanding of the contribution of the angular momentum of the quarks to the spin of the nucleon via Ji's sum rule, of which the GPD E is an essential, yet poorly known, ingredient.

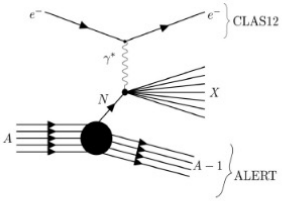
A comprehensive physics program to investigate the fundamental structure of the light nuclei

- What is the origin of the EMC effect?
- What is the partonic structure of a bound nucleon?
- How is the nucleon modified in nuclear medium?
- How are hadrons modified in nuclear medium?



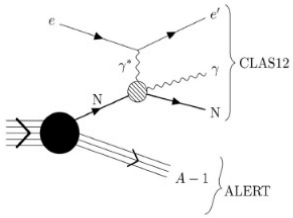
Coherent Processes on ^{4}He

- ^{4}He(e,e'γ)^{4}He
- ^{4}He(e,e'ϕ)^{4}He



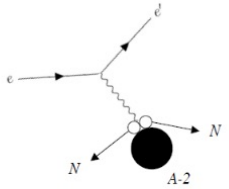
DIS on ^{4}He and ^{2}H: Tagged EMC Effect

- ^{4}He(e,e'^{3}H)X
- ^{4}He(e,e'^{3}He)X
- ^{2}H(e,e'p)X



Incoherent Processes on ^{4}He and ^{2}H

- ^{4}He(e,e'γp^{3}H)
- ^{4}He(e,e'γ^{3}He)n
- ^{2}H(e,e'γp)n



Short Range Correlations on ^{4}He

- ^{4}He(e,e'pd)n
- ^{4}He(e,e't)p
- ^{4}He(e,e'p)

This next generation nuclear measurements are realized by detecting low energy recoil nuclei

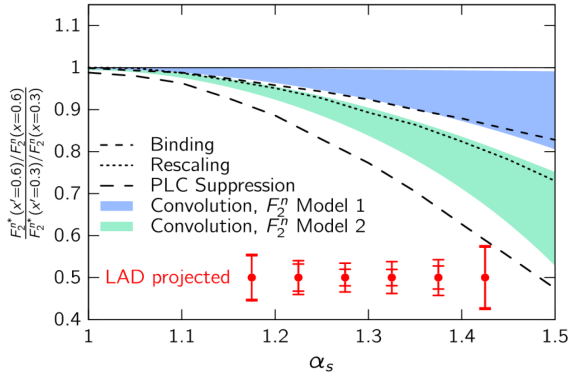
- A Low Energy Recoil Tracker (ALERT)
  - Hyperbolic drift chamber
  - Time-of-flight array
  - Target straw for H_2, D_2 & ^{4}He, - 30 cm active length, 6 mm Ø

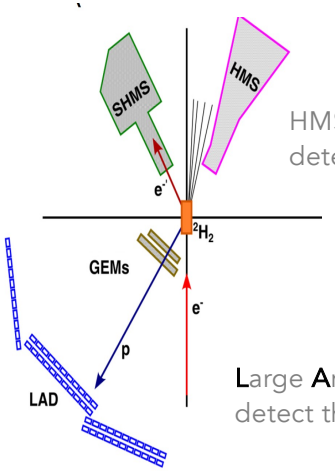
Hall C: Today & Tomorrow

E12-11-107 (EMC/SRC exp):
Does the EMC Effect depend on nucleon virtuality?

Measure Bound F2 by tagging the SRC proton in D(ee'p) DIS and look for nuclear effects

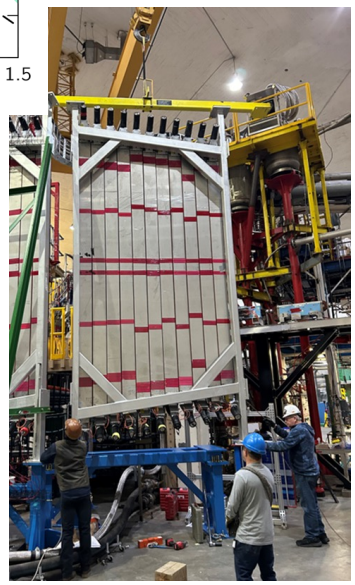
Hauenstein et al., EPJA (2024)



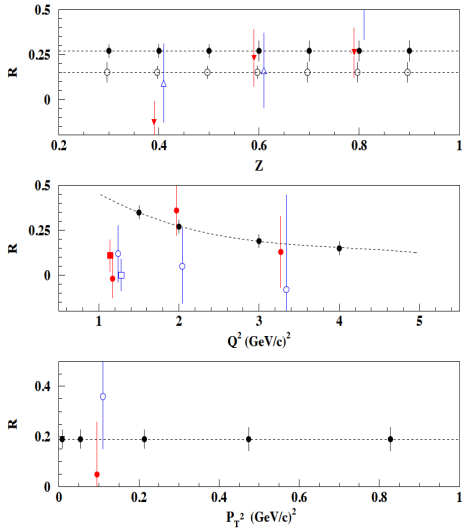


HMS or SHMS detect DIS electron

Large Angle Detector to detect the spectator proton



E12-06-104 (SIDIS exp):
Precise measurements of R=σ_L/σ_T in charged π and K SIDIS on H and D targets



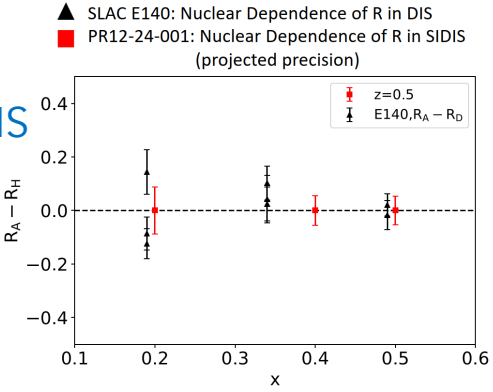
$$R_{SIDIS} = R_{DIS}?$$

$$R^{\pi^+}_{SIDIS} = R^{\pi^-}_{SIDIS}?$$

$$R^{\pi^+}_{SIDIS} = R^{K^+}_{SIDIS}?$$

$$R^{K^+}_{SIDIS} = R^{K^-}_{SIDIS}?$$

Projections for π SIDIS R on H (D) as solid (open) circles Red and blue are Cornell data



E12-24-001 (SIDIS exp):
Nuclear Dependence R in SIDIS

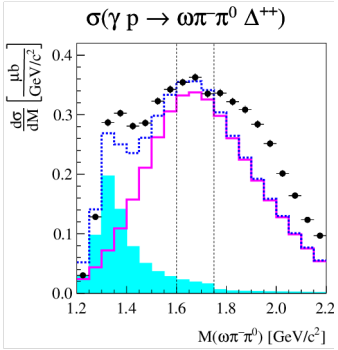
- NO existing measurements
- Potential Impact on SIDIS results (dilution factor for polarized target)
- **Exploratory** measurement

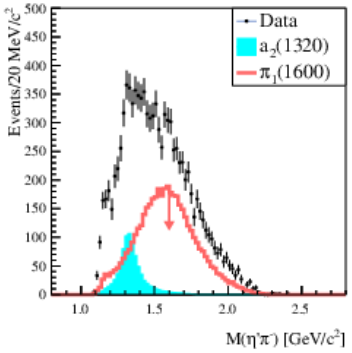
Hall D - GlueX-II+JEF

Gluex-II (E12-12-002) Spectroscopy

(46% done, 118 PAC days left)

- Upper limit for $\gamma p \rightarrow \pi_1(1600)p$ photoproduction



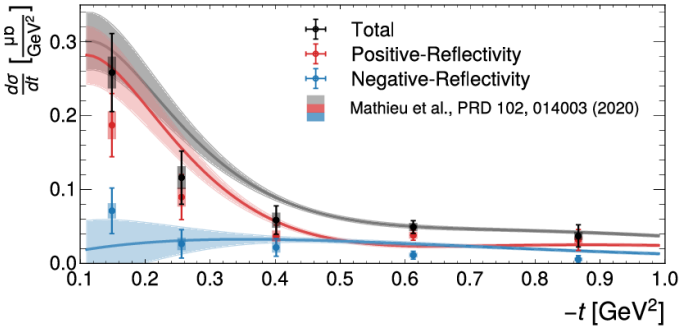


- Using LQCD prediction for $BR(\pi_1 \rightarrow b_1\pi)/BR(\pi_1 \rightarrow \eta'\pi)$
- Analysis of $\gamma p \rightarrow \omega\pi\pi p$, $\omega\pi^+\pi^0\Delta^{++}$ mass spectra
- Projection to $\gamma p \rightarrow \eta'\pi\, p$ (most promising for PWA)
- Limit of the cross section obtained is $\approx\sigma(a_2(1320))$

PRL133, 261903 (Dec 2024)

- Photoproduction of $\gamma p \rightarrow a_2(1320)^0 p$ cross section

  A milestone on the path toward search for hybrid mesons

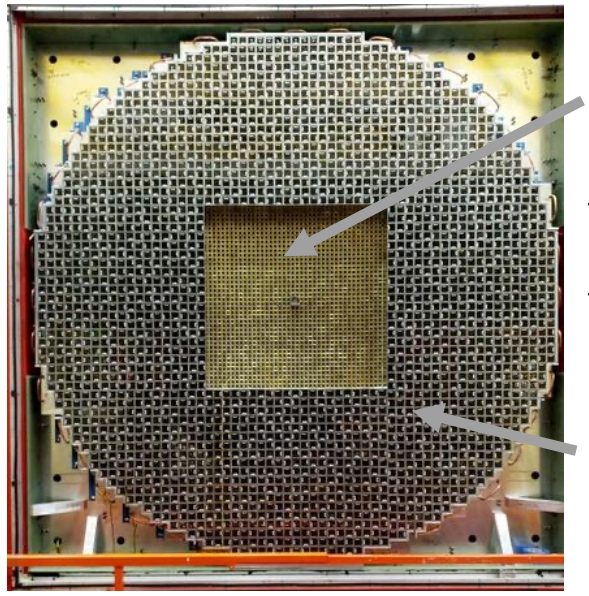


Submitted to PRL

JEF (E12-12-002A) Rare decays of η

Search for weakly-coupled new forces in neutral mode.

- 0% done, 100 PAC days approved
- Requires an upgrade of FCAL: a crystal insert



Removed 400 Lead Glass modules
Inserted 1600 $PbWO_4$ modules

- Twice better resolution than Lead Glass
- Radiation hardness

Lead Glass modules

A 1.5 year-long, major upgrade work

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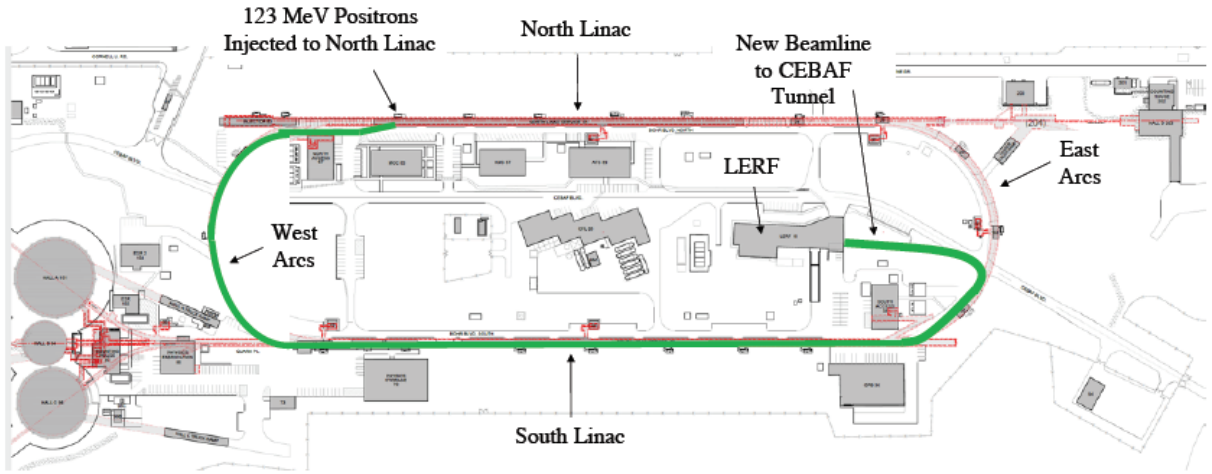
CEBAF Phased Upgrade

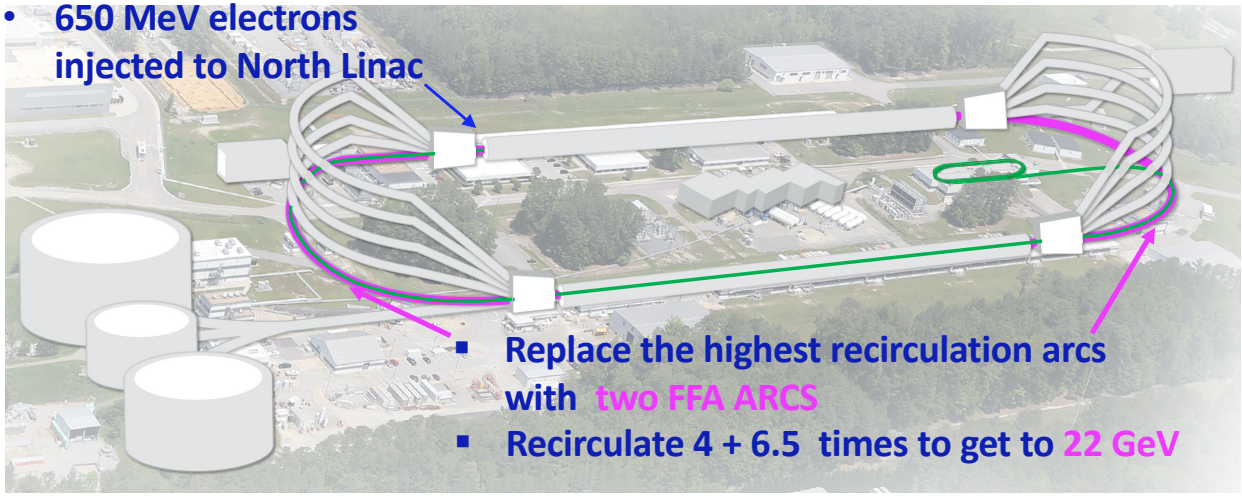
Phase 1:

- New injector (123 MeV e^+ & 650 MeV e^-) in a former FEL ("LERF")
- Polarized positrons transported to CEBAF (proposed 12 GeV science program)



Phase 2:

- Recirculating injector energy upgrade to 650 MeV electrons
- Replace one set of arcs on each side with new FFA permanent magnet arcs to upgrade to 22 GeV – no new RF needed! No new cryomodules needed!



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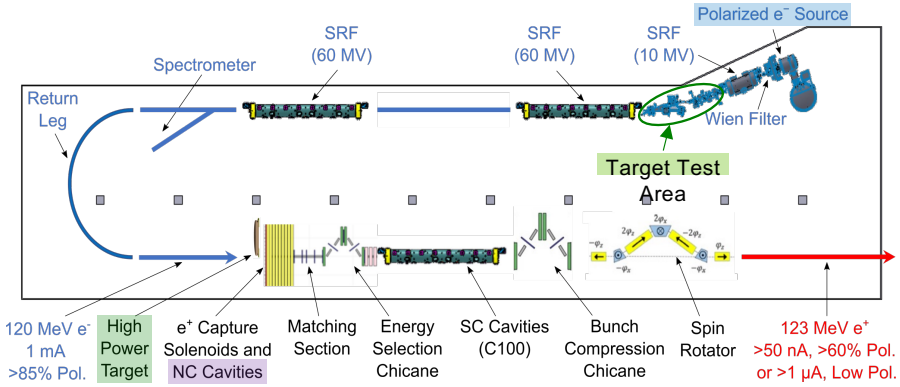
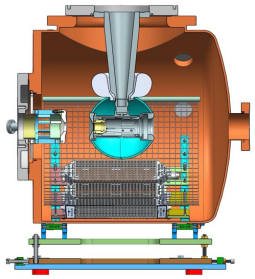
Ce+BAF: Realistic end-to-end Design & Funding Support

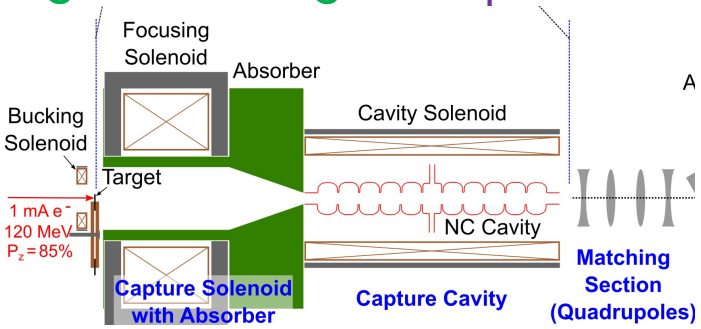


mA e⁻ Photogun

- High current e⁻ source (<10 mA @ 10 MeV)
- Up to 90% polarization
- Long life time

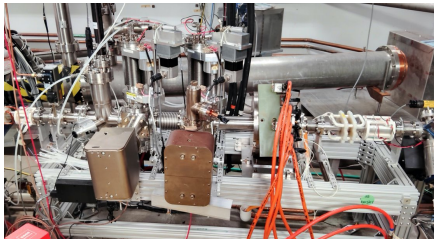


High Power Targets, Capture Cavity



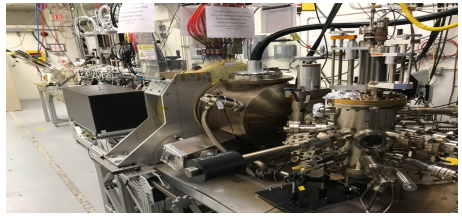
JLAB NP R&D

- 2.1 FTE across CASA, CIS, OPS, SRF
- 0.5 FTE in CASA (Distinguished Grunder fellow)
- Support Degrader (former LDRD) to quantify CEBAF acceptance



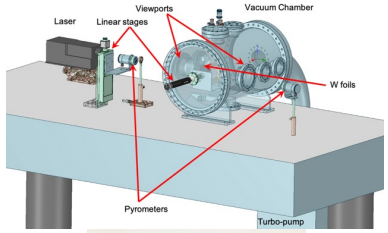
LDRD program

- 2-year - test improvements for high-intensity (mA) polarized photogun
- 3-year - strategic hire of positron model integrator role



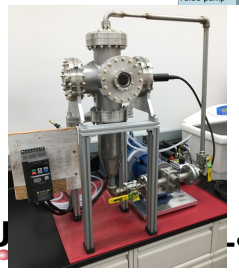
NP FOA

- 2-year - NP Futures concept of Tungsten Solid Target, CFD, Prototype Testing
- 2-year (SBIR) concept of GaInSn Liquid Target, Prototype Testing at LERF



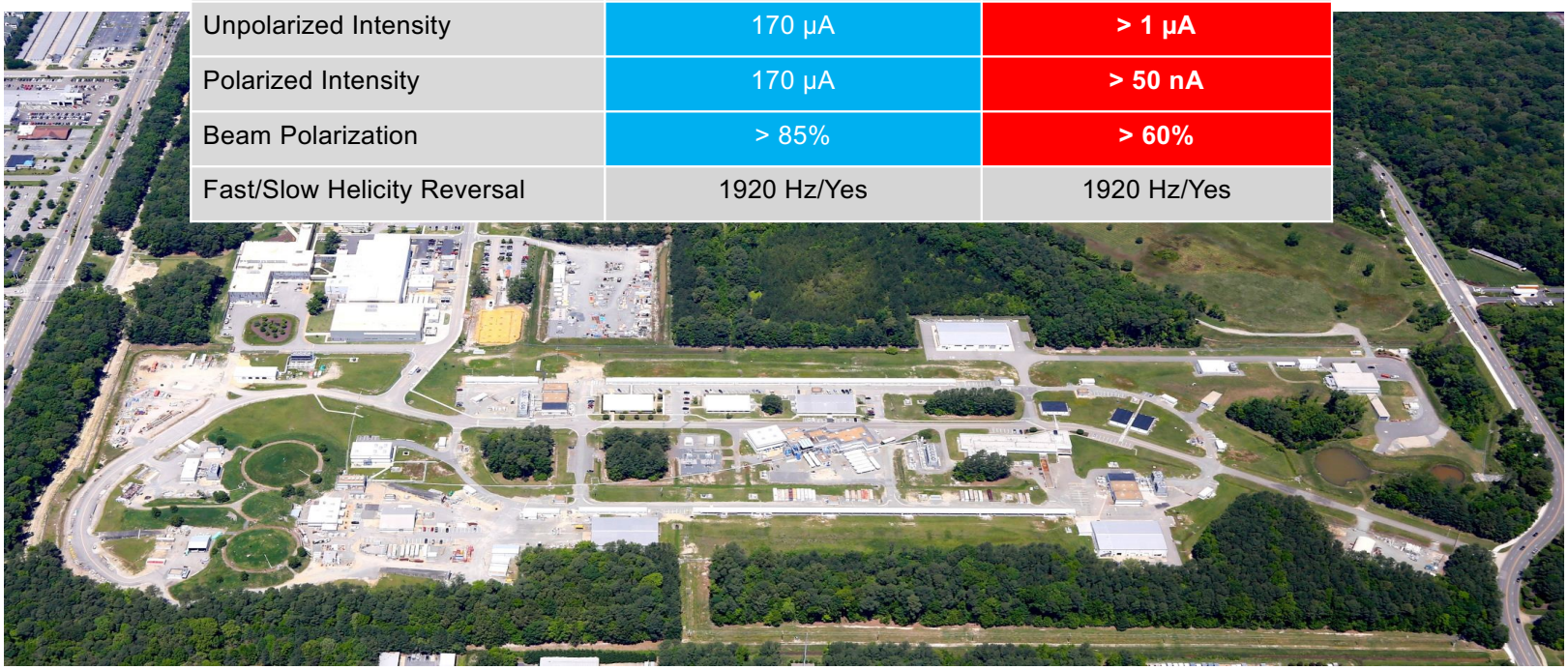
HEP FOA

- 3-year – US-Japan collaboration with SLAC/KEK to exchange e+/e- source concepts



12 GeV Ce+BAF: Polarized Positron Beams

Machine Parameter	Electrons	Positrons
Hall Multiplicity	4	**1 or 2**
Energy (ABC/D)	11/12 GeV	11/12 GeV
Beam Repetition	249.5/499 MHz	249.5/499 MHz
Duty Factor	100% cw	100% cw
Unpolarized Intensity	170 μA	**> 1 μA**
Polarized Intensity	170 μA	**> 50 nA**
Beam Polarization	> 85%	**> 60%**
Fast/Slow Helicity Reversal	1920 Hz/Yes	1920 Hz/Yes



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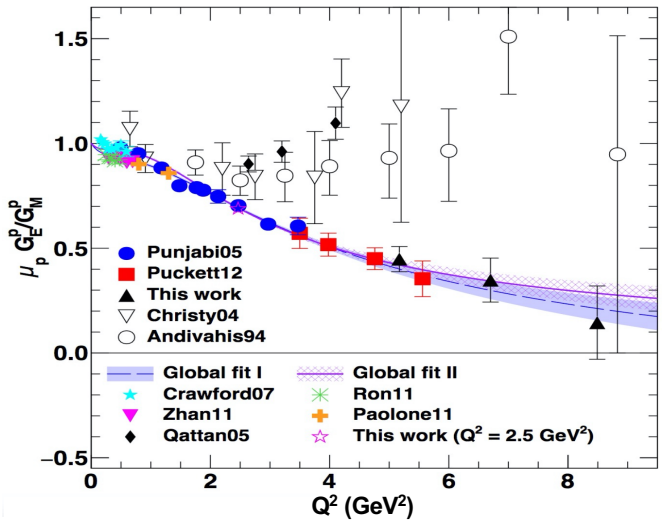
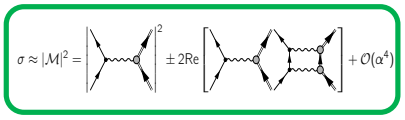
Physics Program with Ce+BAF



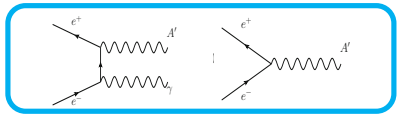
May the 2-γ exchange be the cause of the proton FF discrepancy?

$$R_{2\gamma} \equiv \frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 + 4\frac{\mathrm{Re}\left[\mathcal{M}_{1\gamma}\mathcal{M}_{2\gamma}\right]}{|\mathcal{M}_{1\gamma}|^2} + \ldots$$

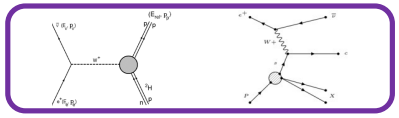
- Beam charge asymmetries
  - Two-photon exchange
  - Deeply Virtual Compton Scattering

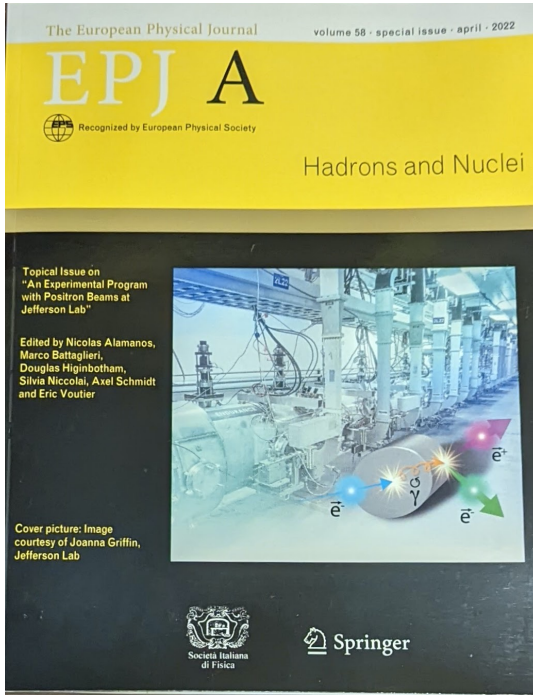


- Annihilation processes
  - Light dark matter searches



- Charged-current processes
  - Inverse beta-decay
  - Access strangeness with charm-tagging
  - Charged lepton flavor violation
  - Axial Form Factor





- Annual in person working group meeting
- Next March 24-26 at JLab

PAC approved experiments (as of Jan 2025)

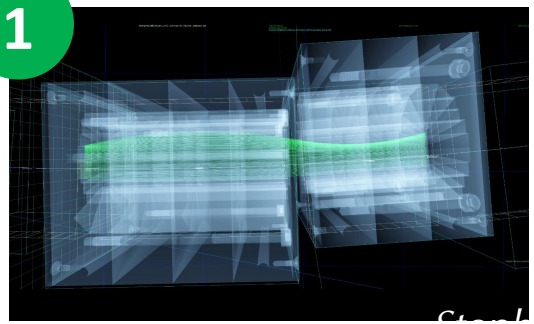
Approved 6 experiments for a total of 357 total PAC days (Hall A & C)

(PAC day = two calendar day)

Jefferson Lab

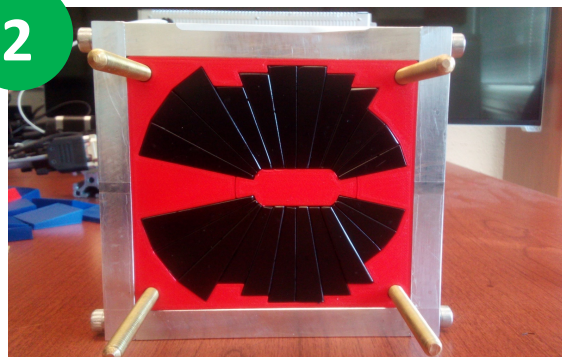
22 GeV Upgrade – Baseline under Study

1



- Imported a vendor's magnet mechanical design and overlaid it on the beam orbits to make sure there is **clearance**

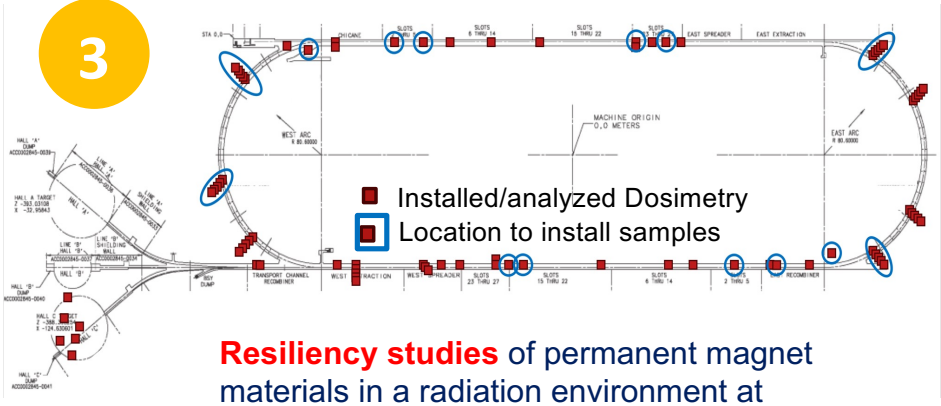
2



- Prototype open-midplane BF magnet successfully built and evaluated for **mechanical integrity**
- >1.5 Tesla measured in good field region
- Field accuracy of 10^{-3}

Installation map in CEBAF – 30 installation locations of varying dose and radiation type (gamma vs. neutron)

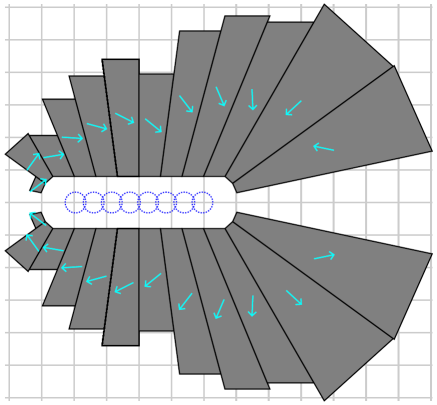
3



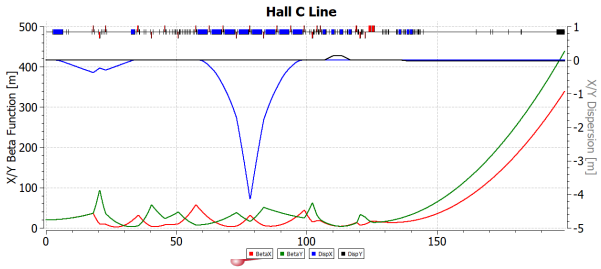
Resiliency studies of permanent magnet materials in a radiation environment at CEBAF resembling their intended operational one **(LDRD project started Oct. 1, 2023)**

4

Construction of a full-length permanent magnet (LoI to DOE)



Hall C - possible location of the **Test**



The 22 GeV Physics Program and the Project Development

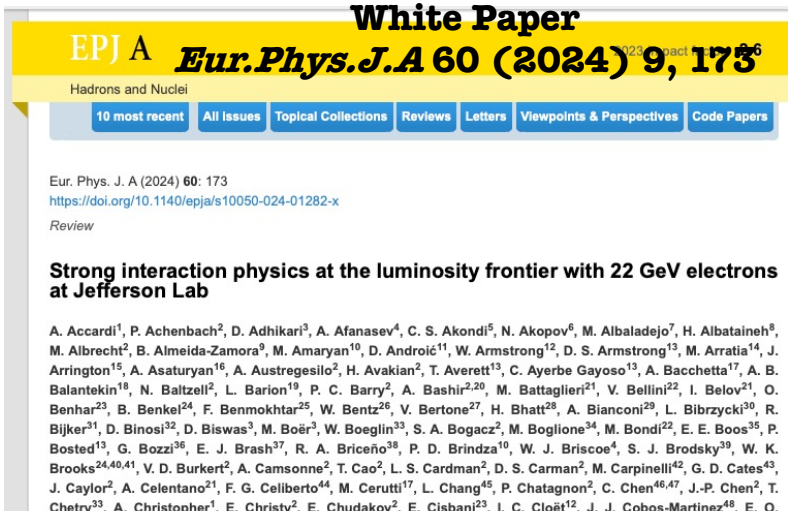
WHY 22 GeV?

- A NEW territory to explore
- A BRIDGE between JLab @ 12 GeV and EIC
- CRITICAL to some measurement @ EIC
- A BETTER insight into our current program

- Bi-weekly meetings to refine the scientific case (2024)
- LNF Workshop Dec 9-13, 2024 (91 participants, 62 plenary talks, 6 parallel sessions)

A document outlining the progress of the scientific case will be available within a few months

White Paper
***Eur.Phys.J.A* 60 (2024) 9, 173**


EPJ A
Hadrons and Nuclei
10 most recent | All Issues | Topical Collections | Reviews | Letters | Viewpoints & Perspectives | Code Papers

Eur. Phys. J. A (2024) **60**: 173
https://doi.org/10.1140/epja/s10050-024-01282-x
Review

Strong interaction physics at the luminosity frontier with 22 GeV electrons at Jefferson Lab

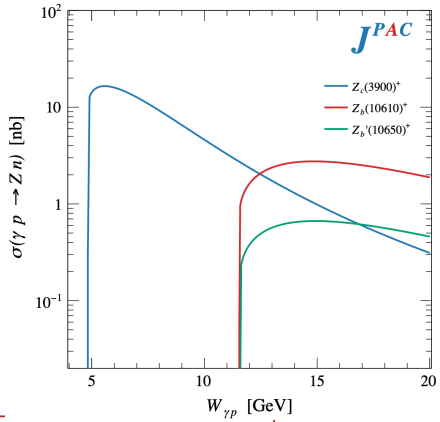
A. Accardi[1], P. Achenbach[2], D. Adhikari[3], A. Afanasev[4], C. S. Akondi[5], N. Akopov[6], M. Albaladejo[7], H. Albataineh[8], M. Albrecht[2], B. Almeida-Zamora[9], M. Amaryan[10], D. Androić[11], W. Armstrong[12], D. S. Armstrong[13], M. Arratia[14], J. Arrington[15], A. Asaturyan[16], A. Austregesilo[2], H. Avakian[2], T. Averett[13], C. Ayerbe Gayoso[13], A. Bacchetta[17], A. B. Balantekin[18], N. Baltzell[2], L. Barion[19], P. C. Barry[2], A. Bashir[2,20], M. Battaglieri[21], V. Bellini[22], I. Belov[21], O. Benhar[23], B. Benkel[24], F. Benmokhtar[25], W. Bentz[26], V. Bertone[27], H. Bhatt[28], A. Bianconi[29], L. Bibrzycki[30], R. Bijker[31], D. Binosi[32], D. Biswas[3], M. Boër[3], W. Boeglin[33], S. A. Bogacz[2], M. Boglione[34], M. Bondi[22], E. E. Boos[35], P. Bosted[13], G. Bozzi[36], E. J. Brash[37], R. A. Briceño[38], P. D. Brindza[10], W. J. Briscoe[4], S. J. Brodsky[39], W. K. Brooks[24,40,41], V. D. Burkert[2], A. Camsonne[2], T. Cao[2], L. S. Cardman[2], D. S. Carman[2], M. Carpinelli[42], G. D. Cates[43], J. Caylor[2], A. Celentano[21], F. G. Celiberto[44], M. Cerutti[17], L. Chang[45], P. Chatagnon[2], C. Chen[46,47], J.-P. Chen[2], T. Chetry[33], A. Christopher[1], E. Christy[2], E. Chudakov[2], E. Cisbani[23], J. C. Cloët[12], J. J. Cobos-Martinez[48], E. O.

- Established a small study group (11 people) from Jab management, Physics, Accelerator and Theory Divisions, and 3 representatives of the user community, meets monthly
- **Define the roadmap for the development of the positrons and the 22 GeV beams technology**
- **Ultimate outcome is a pre-CDR in ~2 years**

Jefferson Lab

22 GeV: A New Window into the World of XYZ States

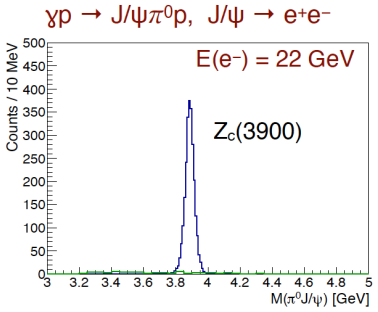
- This program suits perfect the 22 GeV upgrade: Thresholds for XYZ states open just above 12 GeV:
- Direct Production: Photons can directly produce XYZ states, unlike some other methods that rely on the decay of heavier particles.
- Complementary Information: Photoproduction can provide complementary information to what we learn about XYZ states from other production mechanisms, giving us a more complete picture.



Measurements of X(Y) Z states at JLab with 22 GeV e- are feasible!

Simulations from GlueX & CLAS12 with existing detectors

GlueX



- Assumes 1 year @ 500 pb^{-1}, Br($Z_c \to \pi J/\psi$) = 5%
  - N($Z_c \to J/\psi\pi$) ≈ 2500 from $\gamma p \to Z_c^- \Delta^{++}$
- Can compare charged and neutral Z_c production
  - Neutral production cross sections more uncertain

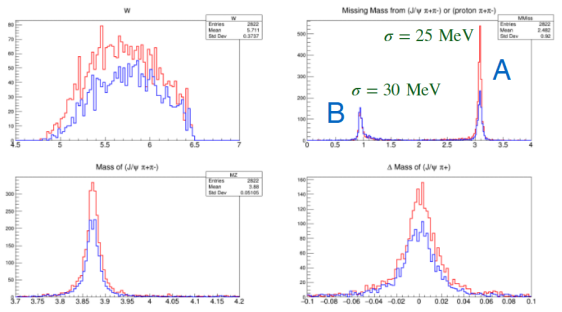
CLAS12

- CLAS12 has excellent PID
- Can measuring missing particles
- Simulations assuming 10^{35} cm^{-2}s^{-1} luminosity for 50 days, zero-degree tagger

Courtesy of D. Glazier

$X(3872) \to \pi^+\pi^- J/\psi$

A) Missing J/ψ B) Missing proton



Acceptances:
X(3872) ≈ 1%
Z_c(3900) ≈ 15%

Expected yields:
X(3872) = 2-3k
Z_c(3900) = 25k

Next steps:

- Develop reasonable non-resonant background models to include in the MC
- Evaluate the contribution of open charm channels

Jefferson Lab

Imaging Studies: the JLab Advantage

Jefferson LAB : IDEAL PLACE TO CARRY OUT IMAGING STUDIES in the non-perturbative region

High Luminosity + High Polarized beam and target + High Resolutions State-of-the-art detectors + Versatile experimental setup + Multiparticles FS detection

The increased energy will enable several advancements, including:

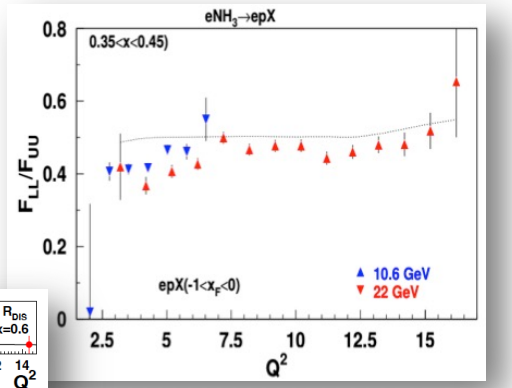
1. **Multidimensional** studies of the evolution of 3D observables with the energy scale (Q^2)

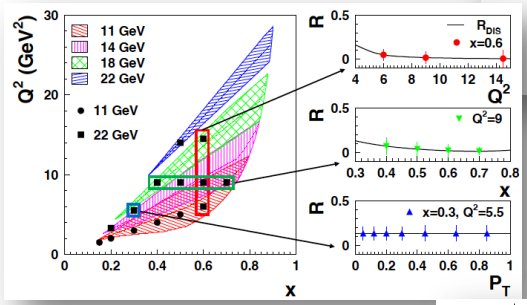
2. A unique opportunity to measure γ^*_L and γ^*_T contributions to observables at higher Q^2

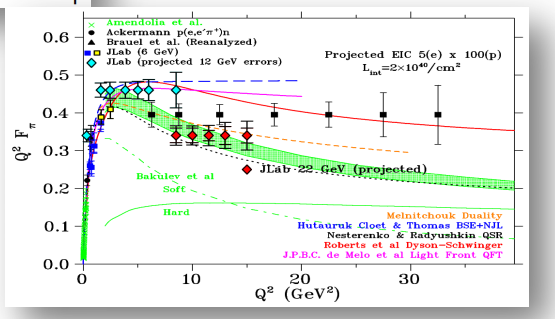
3. A unique opportunity to evaluate the contribution of various processes (i.e. diffractive ρ,..) at higher Q^2

→ All the above will enable us to evaluate the assumption of the TMD factorization

→ 2. & 3. will serve as a bridge between lower energy experiments and EIC, providing critical information for interpreting EIC results







Measurements of α_s with JLab@22 GeV

It is the most important quantity of QCD, key parameter of the SM, but (by far) the least known fundamental coupling: $\Delta\alpha_s/\alpha_s \simeq 10^{-2}$

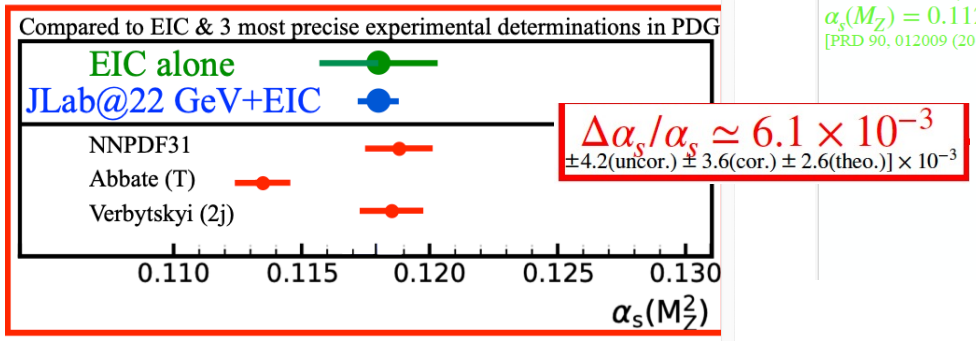
- Large efforts ongoing to reduce $\Delta\alpha_s/\alpha_s$
- No "silver bullet" experiment can exquisitely determine $\mathbf{a_s}$⇒ Strategy: combine many independent measurements

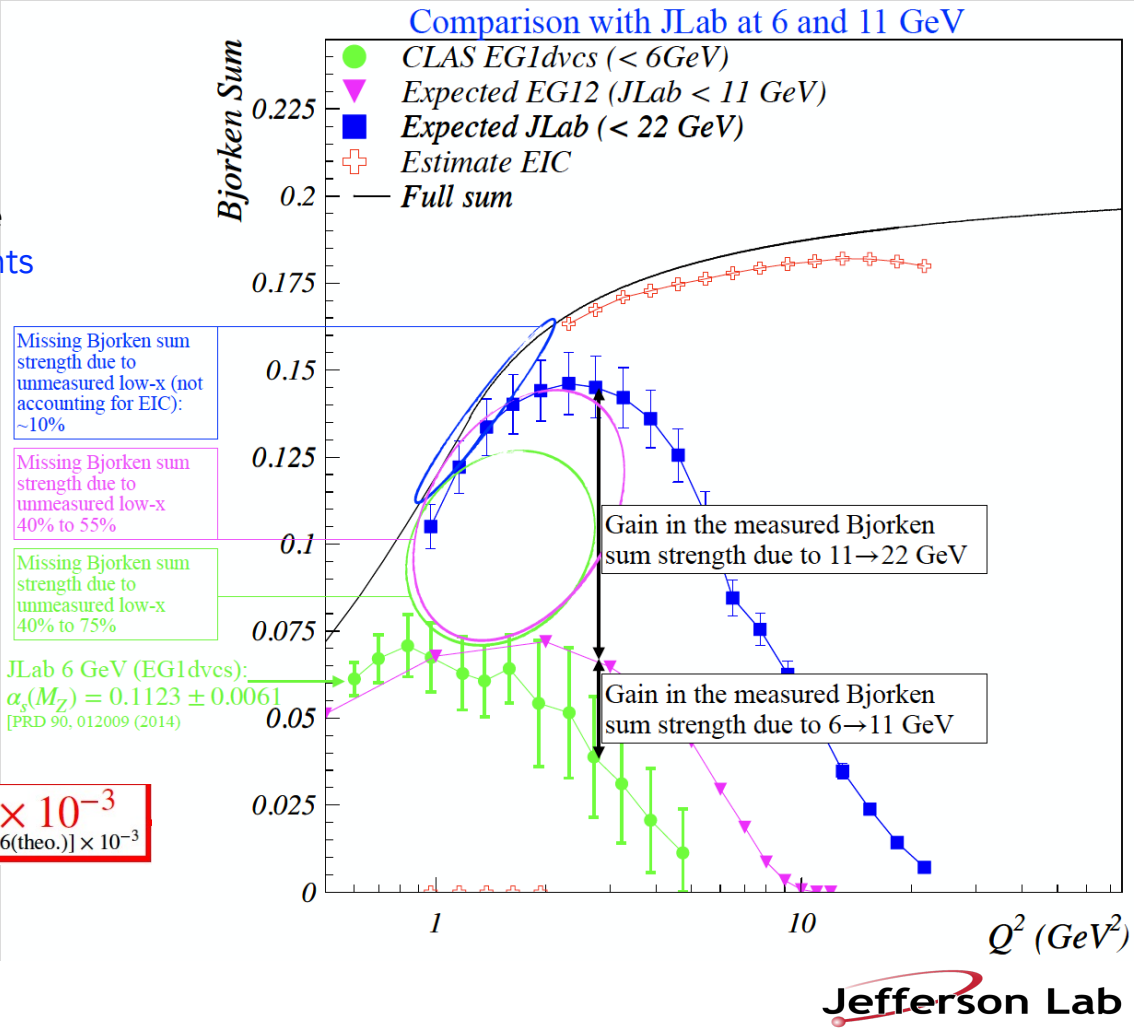
Good prospects of measuring precisely $\alpha_s\,(M_Z)$ at JLab@22 GeV with Bjorken sum rule:

Bjorken sum rule: $\Gamma_1^{p-n}(Q^2) \equiv \int g_1^{p-n}(x,Q^2)dx = \frac{1}{6}g_A\left[1-\frac{\alpha_s}{\pi}\cdots\right]$

Q^2-dependence of $\Gamma^{p-n}(Q^2)$ provides $\mathbf{a_s}$.

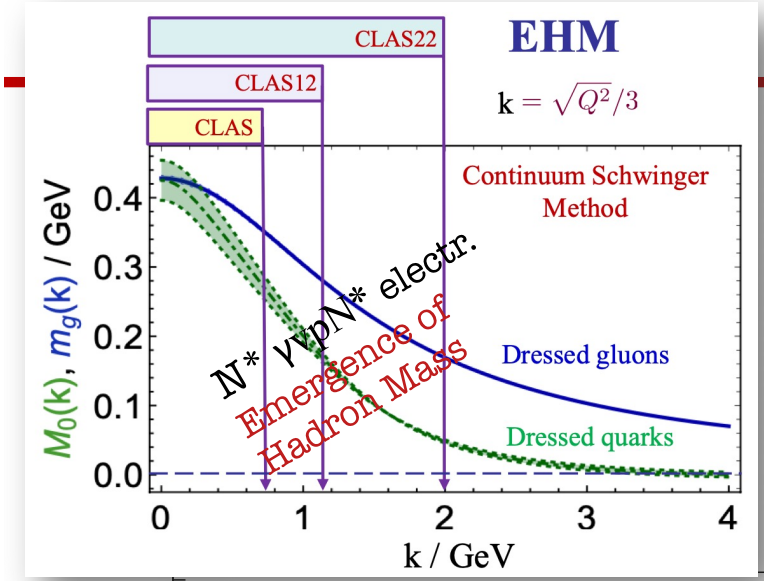
Uncertainties from pQCD truncation and Higher-Twists remain small

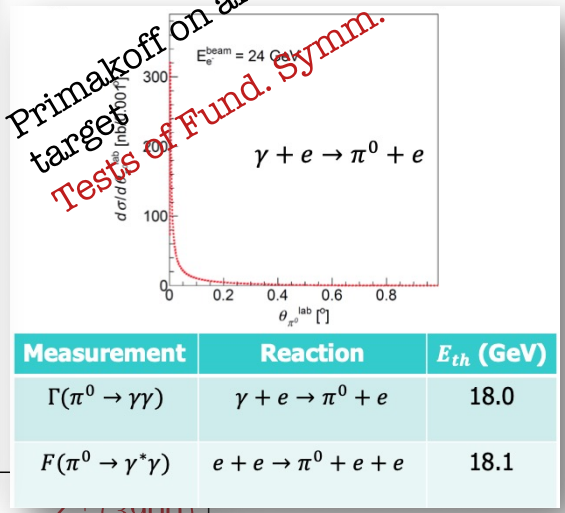




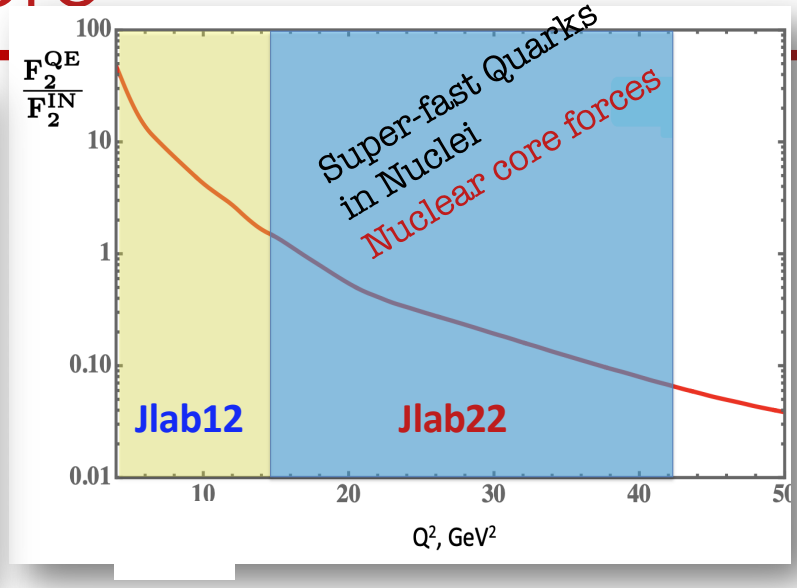
Jefferson Lab

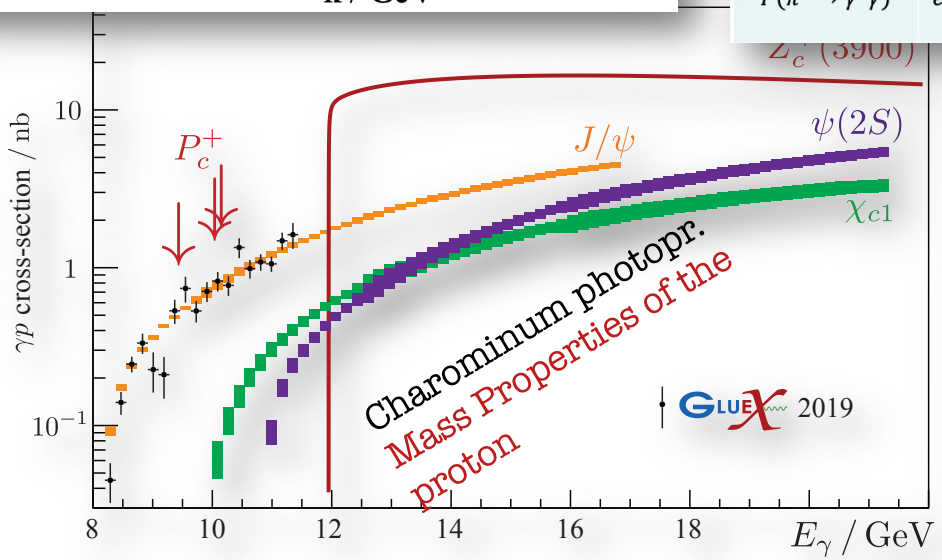
..And Many More

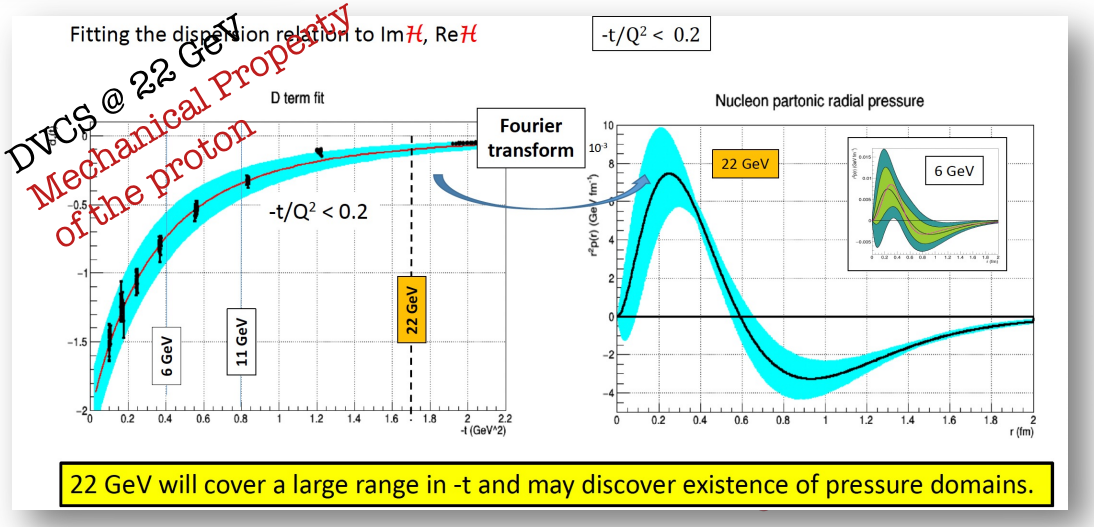




Measurement	Reaction	E_{th} (GeV)
$\Gamma(\pi^0 \to \gamma\gamma)$	$\gamma + e \to \pi^0 + e$	18.0
$F(\pi^0 \to \gamma^*\gamma)$	$e + e \to \pi^0 + e + e$	18.1







Conclusions

- The **CEBAF uniqueness** to run experiments at the **luminosity frontier** provides a powerful tool to understand the structure and dynamics of the strong interaction in the **non-pQCD regime**.

- An impactful experimental program is ongoing at 12 GeV which lays the foundation for future studies with even greater sensitivity.

- Jefferson Lab is indeed exploring future upgrades to CEBAF: a positron beam and an energy upgrade to 22 GeV.

- Proposals are being accepted by the Program Advisory Committee for positron science (6 approved and more to come!) and a strong science case for an energy upgrade is emerging which would allow for a deeper exploration of QCD, particularly in the valence quark region, and would provide crucial data for the upcoming Electron-Ion Collider (EIC).

Backup Slides

Notional CEBAF and EIC Efforts on One Chart

- Accelerator team has worked up an early schedule and cost estimate
  - Schedule assumptions based on a notional timing of when funds might be available (near EIC ramp down based on EIC V3 profile)
  - For completeness, Moller and SoLID (part of 12 GeV program) are shown; positron source dev shown
- EIC Project is shown