New Opportunities with Jefferson Lab at 22 GeV: Science at the Luminosity Frontier

Cynthia Keppel

XVIth Quark Confinement and the Hadron Spectrum Conference

August 18-24, 2024

Cairns, Queensland, Australia

22 GeV is a rather new opportunity at Jefferson Lab….

The community did a lot of work (science workshops, accelerator studies, cost estimating, profile development,…) to quickly prepare for the US NSAC Long Range Plan

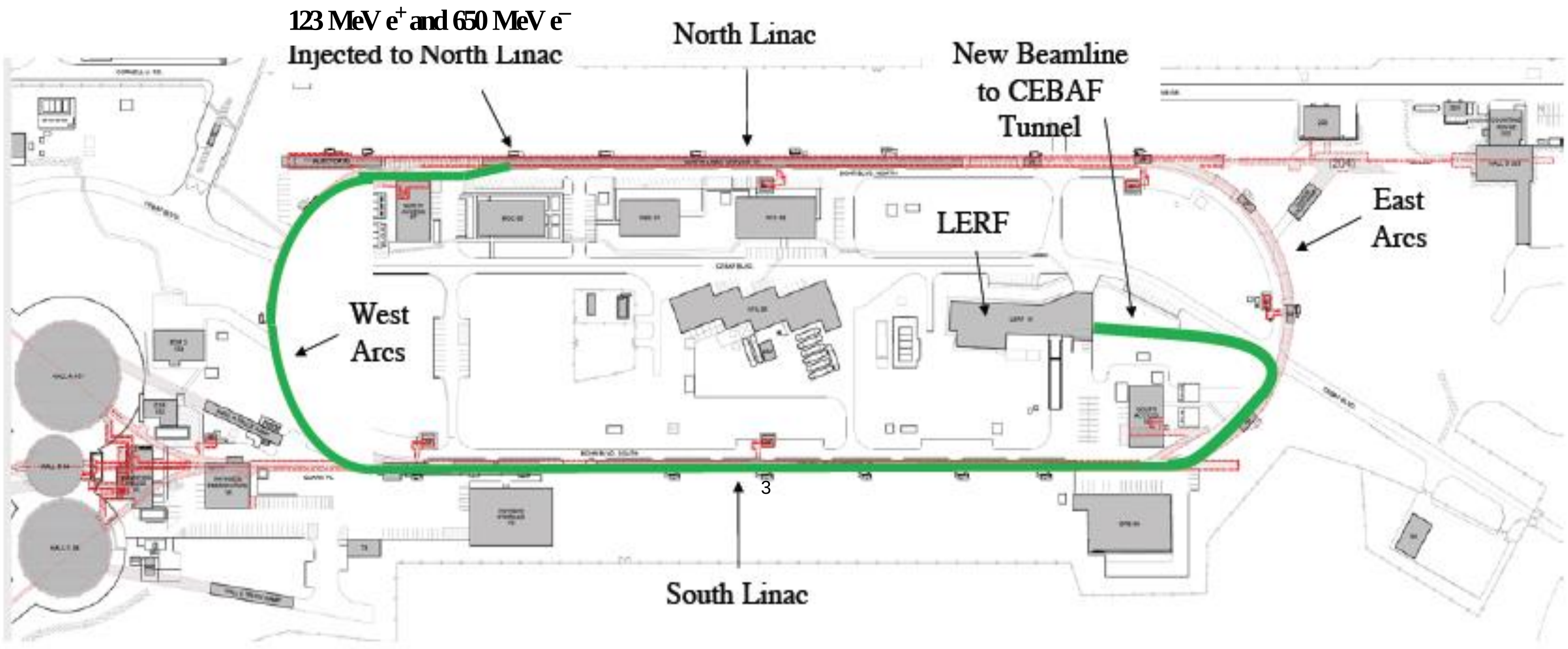
- *Critical just to be mentioned favorably!*

"To investigate the other XYZP states, higher beam energy is required; the tetraquark candidate Z_c states would be copiously produced at a high-luminosity, fixed-target electron machine operating above 20 GeV."

"The staged upgrade plan for CEBAF foresees...[]…an energy upgrade of CEBAF to more than 20 GeV. Recently, the Cornell Brookhaven Electron Test Accelerator (CBETA) facility demonstrated eight-pass recirculation of an electron beam with energy recovery employing arcs of fixed-field alternating gradient magnets. This exciting new technology could enable a cost-effective method to double the energy of CEBAF, allowing wider kinematic reach for nucleon femtography studies in the existing tunnels and with no new cryomodules required."

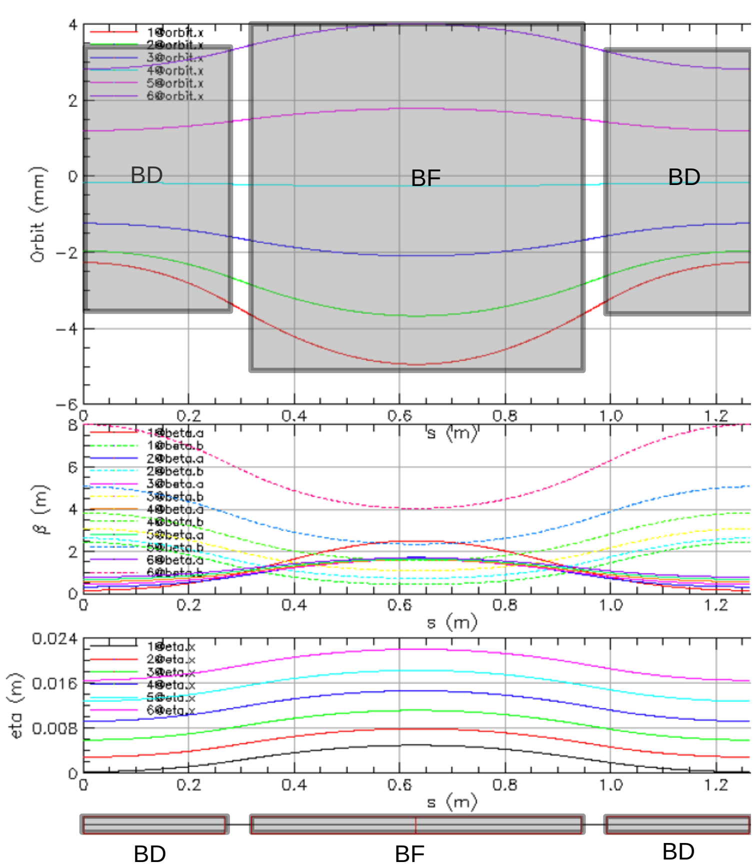
JEFFERSON LAB ACCELERATOR PHASED UPGRADE

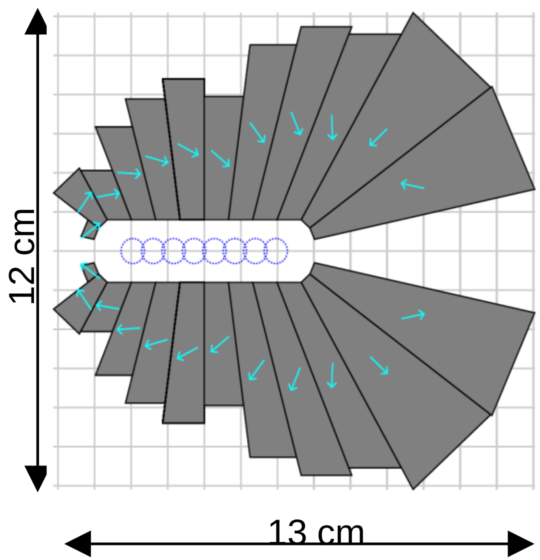
- A staged upgrade program at the luminosity frontier (up to 10^{39} e-N /cm^2/ s), capitalizing on novel accelerator science and technology
- Phase 1: Polarized positrons in a former FEL ("LERF") with transport to CEBAF (proposed 12 GeV science program)
- Phase 2: Recirculating injector energy upgrade 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!***



Compact FFA Cell – How Does it Work?

- Large momentum acceptance FFA (Fixed Field, Alternating Gradient) cell is configured with combined function permanent magnets capable of transporting multiple energy beams through the same string of magnets **(six beams with energies spanning a factor of two)**





Focusing Magnet BF

G_F= -41.13 T/m

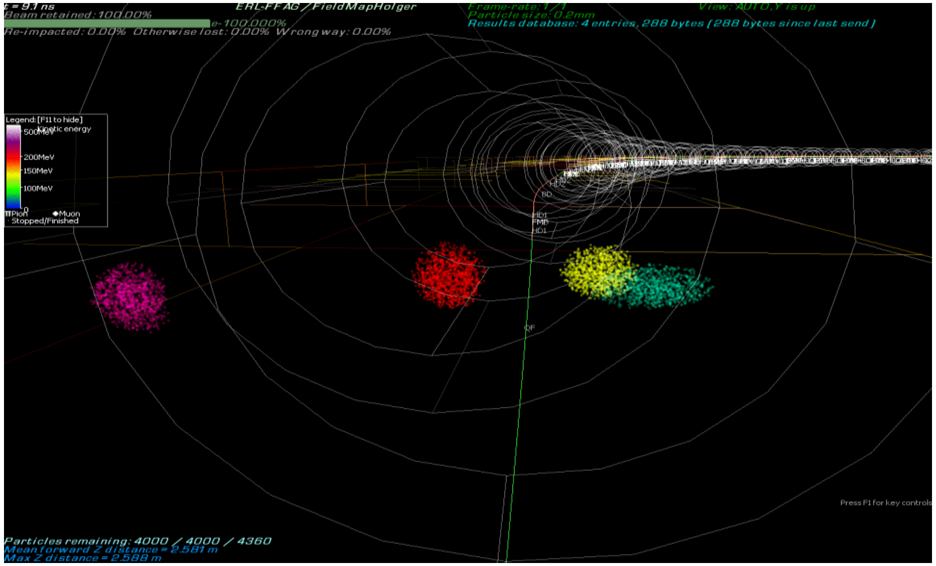
L_{QF}= 1.67 m

B_F= -0.812 T

- Closely spaced orbits for all six beams (~ 1 cm)
- Extremally low dispersion (a few mm) in a combined function lattice – virtue of FFA technology
- Self similar beta functions for different energy beams
- Arc composed of 75 cells, L_{cell} = 3.15 m

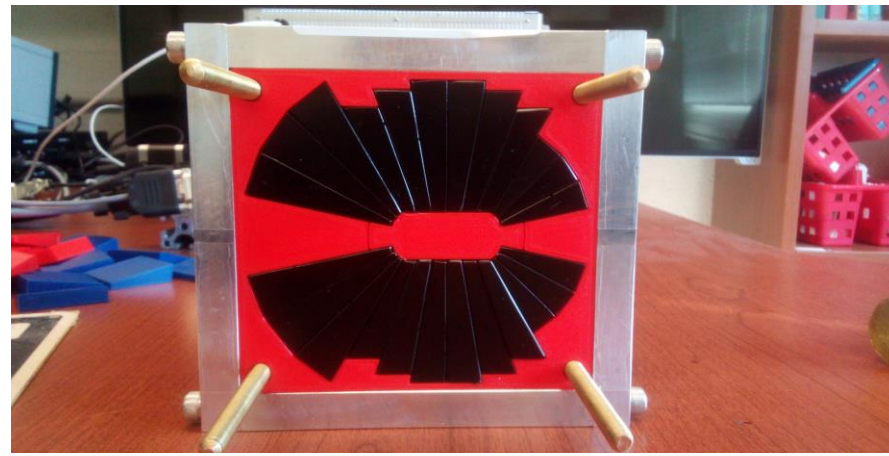
Multi-Energy Beam Dynamics in FFA Arc

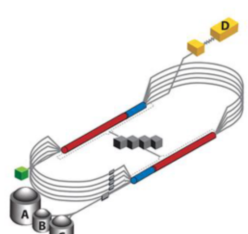
CBETA 2019-2022 the first multi-turn SRF ERL (150 MeV)



Stephen Brooks, BNL

Scaling to higher energy at Jlab…





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CEBAF 22 GeV FFA ENERGY UPGRADE*

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Abstract

Extending the energy reach of CEBAF by increasing the number of recirculations, while using the existing linacs is explored. This energy upgrade is based on the multi-pass acceleration of electrons in a single non-scaling Fixed Field Alternating Gradient (FFA) beam line, using Halbach-style permanent magnets. Encouraged by the recent successful demonstration of CBETA, a proposal was formulated to nearly double the energy of CEBAF from 12 to 22 GeV by replacing the highest energy arcs with FFA transport. The new FFA arcs would support simultaneous transport of an additional 6 passes spanning roughly a factor of two in energy.

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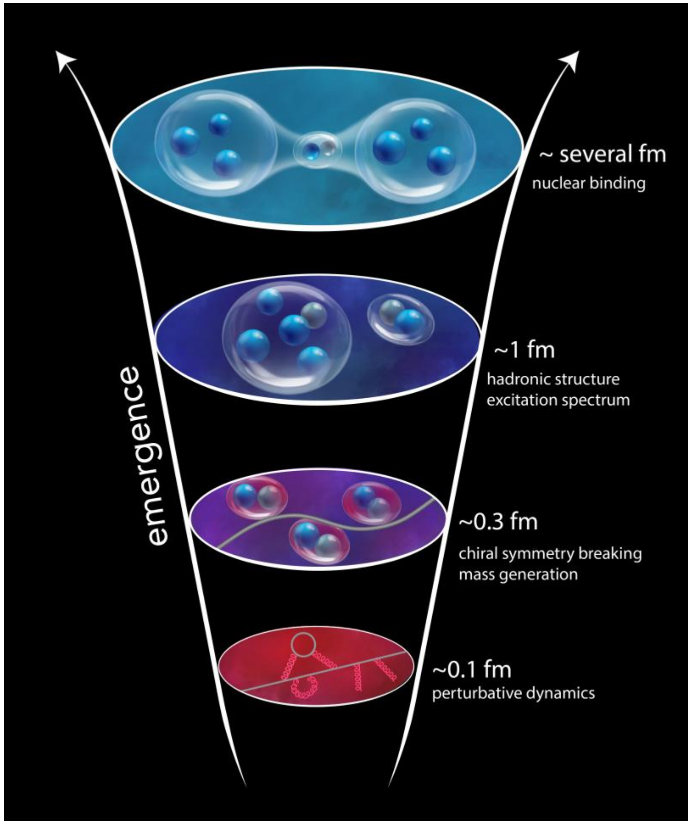
A prototype open midplane BF magnet was built and evaluated for mechanical integrity. Magnetic measurement confirmed a robust design with >1.5 Tesla in good field region, 10^{-3} field accuracy. JLab radiation resilience tests in CEBAF began October 2023.

Why CEBAF @ 22 GeV?

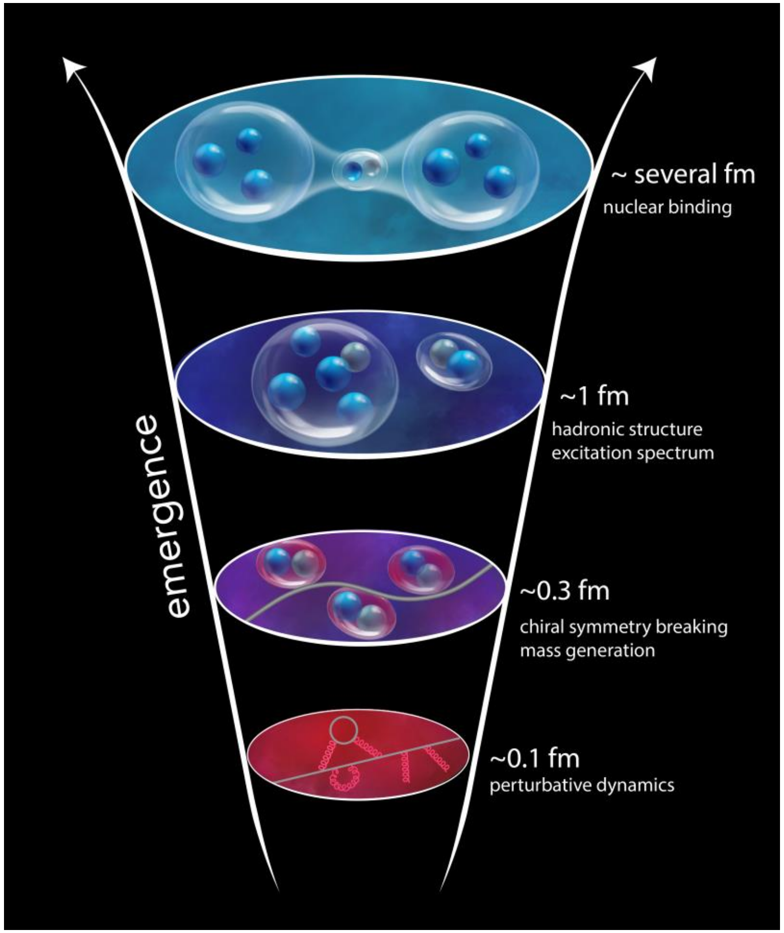
"The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe."
-- *More is Different*, P. W. Anderson [Science 177, 393 (1972)]



In this landmark paper P.W. Anderson established complexity as a fundamentally important subject of inquiry. He highlighted profound limitations of reductionist approaches in understanding nature's complexity, and he set in motion new lines of investigation that have led to, for instance, condensed matter physics and systems biology.

Levels at which different processes occur require our close and careful attention: understanding the dynamics at a given level often requires more than simply being able to characterize the dynamics at lower levels. Complexity is fundamentally important in its own right.

Why CEBAF @ 22 GeV?



Studying the Complexity in Quantum Chromodynamics

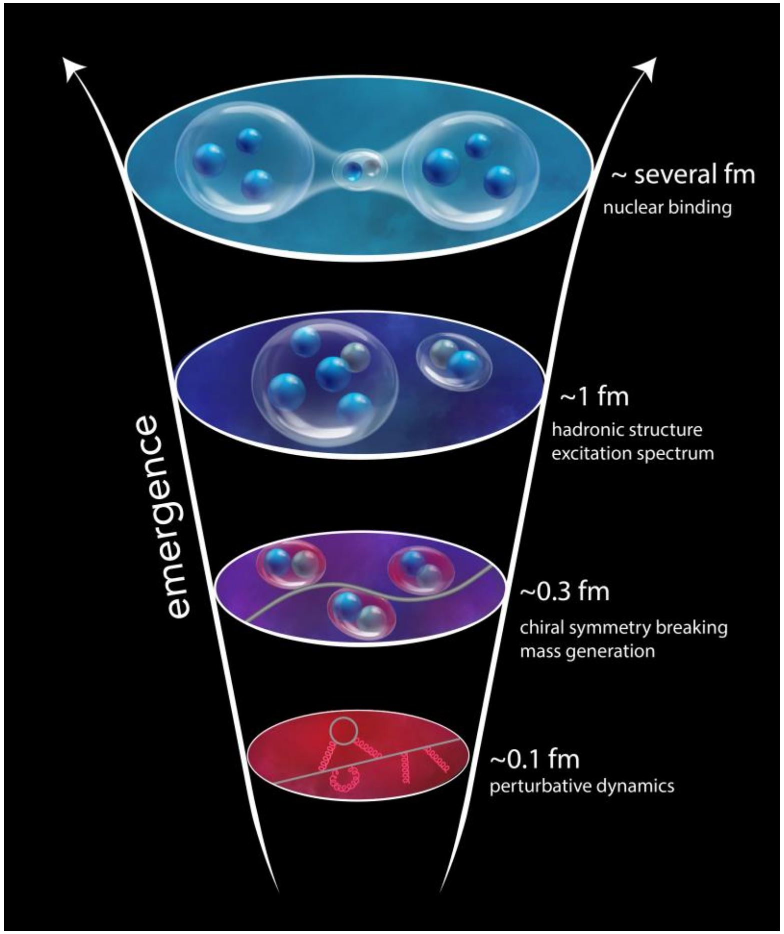
Need to understand strong interaction dynamics *at multiple levels*, from asymptotically free fundamental quark and gluon constituents to

- the structure of (bound) nucleons, to
- nucleon-nucleon interactions, and to
- the nuclear medium

Understanding the dynamics at each level is a complex, non-pQCD problem which demands different approaches and measurements to access multiple observables across multiple scales

Jefferson Lab

What a 22 GeV Upgrade Brings



A NEW territory to explore ➜ cross the critical threshold into the region where $c\bar{c}$ states can be produced in large quantities, and with additional light quark degrees of freedom

A BRIDGE between JLab @ 12 GeV and EIC ➜ testing and validation of QCD from lower to higher energy, through multiple phenomena, and with high precision

A BETTER insight into our current program ➜
enhancement of the phase space

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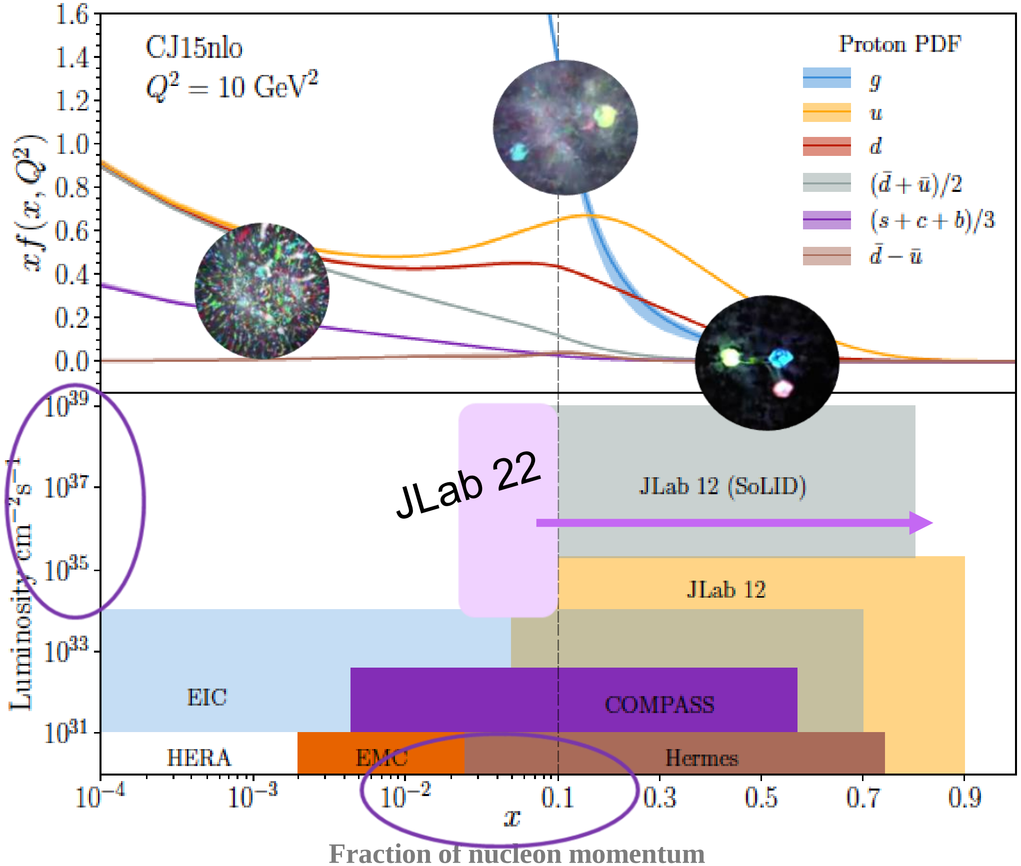
JLab 12 to 22 GeV:
Probing Nucleon Valence Structure at High Luminosity



Physics with CEBAF at 12 GeV and Future Opportunities
Prog. Part. Nucl. Phys. 127 (2022) 103985

The valence region *defines* the hadron

- Baryon number, charge, flavor content, total spin, …

- Large x, low Q^2 evolves to low x, high Q^2 via pQCD, extract parton distribution shape and strength ***from data***

Precision measurements (2D,3D) in the valence regime requiring high luminosity are the purview of JLab, providing overlap with EIC into the low x region

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at JLab

arXiv:2306.09360v2 [nucl-ex], accepted to EPJA

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Nuclear Experiment

[Submitted on 13 Jun 2023]

Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

A. Accardi, P. Achenbach, D. Adhikari, A. Afanasev, C.S. Akondi, N. Akopov, M. Albaladejo, H. Albataineh, M. Albrecht, B. Almeida-Zamora, M. Amaryan, D. Androić, W. Armstrong, D.S. Armstrong, M. Arratia, J. Arrington, A. Asaturyan, A. Austregesilo, H. Avagyan, T. Averett, C. Ayerbe Gayoso, A. Bacchetta, A.B. Balantekin, N. Baltzell, L. Barion, P. C. Barry, A. Bashir, M. Battaglieri, V. Bellini, I. Belov, O. Benhar, B. Benkel, F Benmokhtar, W. Bentz, V. Bertone, H. Bhatt, A. Bianconi, L. Bibrzycki, R. Bijker, D. Binosi, D. Biswas, M. Boër, W. Boeglin, S.A. Bogacz, M. Boglione, M. Bondí, E.E. Boos, P. Bosted, G. Bozzi, E.J. Brash, R. A. Briceño, P.D. Brindza, W.J. Briscoe, S.J Brodsky, W.K. Brooks, V.D. Burkert, A. Camsonne, T. Cao, L.S. Cardman, D.S. Carman, M Carpinelli, G.D. Cates, J. Caylor, A. Celentano, F.G. Celiberto, M. Cerutti, Lei Chang, P. Chatagnon, C. Chen, J-P Chen, T. Chetry, A. Christopher, E. Chudakov, E. Cisbani, I. C. Cloët, J.J. Cobos-Martinez, E. O. Cohen, P. Colangelo, P.L. Cole, M. Constantinou, M. Contalbrigo, G. Costantini, W. Cosyn, C. Cotton, S. Covrig Dusa, Z.-F. Cui, A. D'Angelo, M. Döring, M. M. Dalton, I. Danilkin, M. Davydov, D. Day, F. De Fazio, M. De Napoli, R. De Vita, D.J. Dean, M. Defurne, M. Deur, B. Devkota, S. Dhital et al. (335 additional authors not shown)

This document presents the initial scientific case for upgrading the Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLab) to 22 GeV. It is the result of a community effort, incorporating insights from a series of workshops conducted between March 2022 and April 2023. With a track record of over 25 years in delivering the world's most intense and precise multi-GeV electron beams, CEBAF's potential for a higher energy upgrade presents a unique opportunity for an innovative nuclear physics program, which seamlessly integrates a rich historical background with a promising future. The proposed physics program encompass a diverse range of investigations centered around the nonperturbative dynamics inherent in hadron structure and the exploration of strongly interacting systems. It builds upon the exceptional capabilities of CEBAF in high-luminosity operations, the availability of existing or planned Hall equipment, and recent advancements in accelerator technology. The proposed program cover various scientific topics, including Hadron Spectroscopy, Partonic Structure and Spin, Hadronization and Transverse Momentum, Spatial Structure, Mechanical Properties, Form Factors and Emergent Hadron Mass, Hadron-Quark Transition, and Nuclear Dynamics at Extreme Conditions, as well as QCD Confinement and Fundamental Symmetries. Each topic highlights the key measurements achievable at a 22 GeV CEBAF accelerator. Furthermore, this document outlines the significant physics outcomes and unique aspects of these programs that distinguish them from other existing

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140+ pages, ~450 authors with many powerful experiments *using existing or planned equipment* - just a few examples….

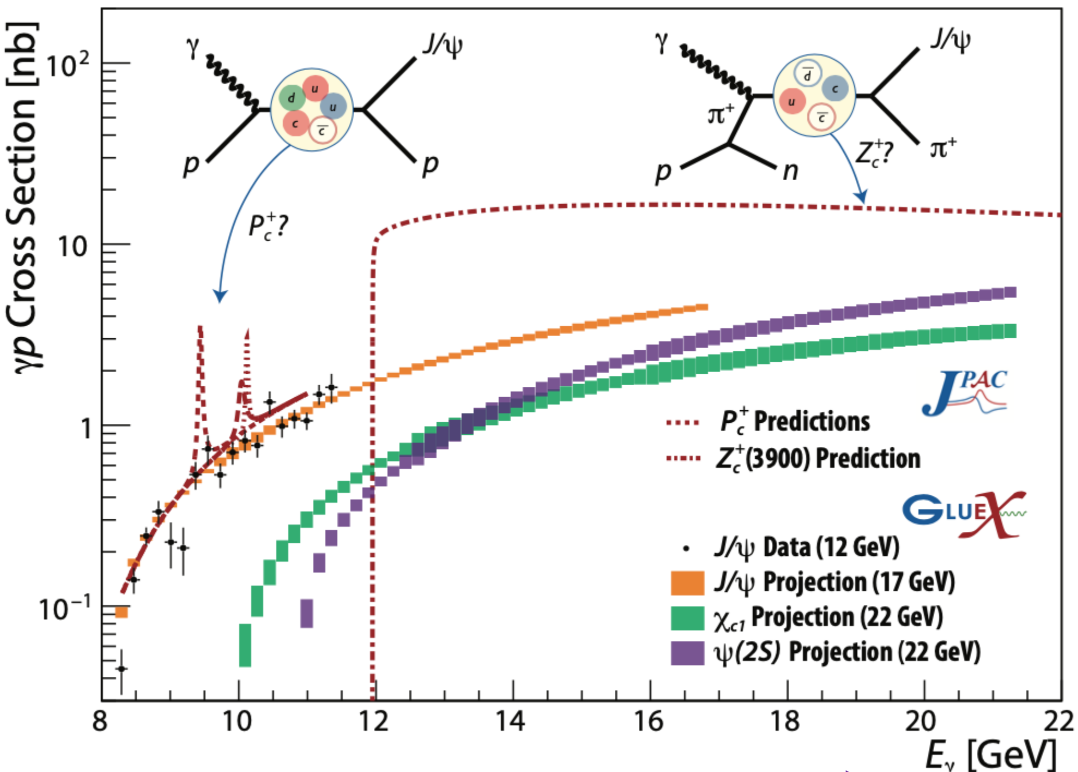
Jefferson Lab

Spectroscopy of Exotic States with charm

Photoproduction of hadrons with charm quarks: a <u>new tool for discovery in QCD</u>

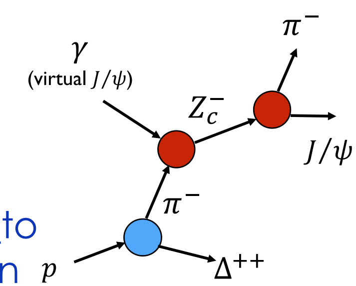
→ a unique method to probe the **gluonic structure of the proton**
→ potentially decisive information about the **nature of some 5-quark and 4-quark** candidates

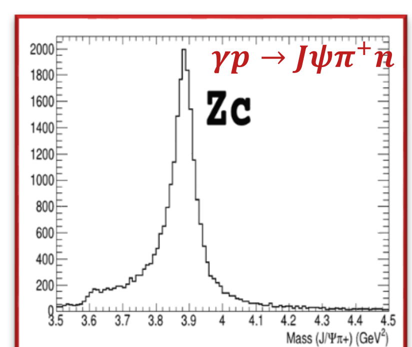
- Tetraquark candidates, **XYZ states**, observed in B decays, e^+e^- colliders but their internal structure is ***<u>not yet understood</u>***
- **Never direcly produced** using γ/lepton beams ➞ **Polarized photoproduction alternative mechanism to study such states**



Thresholds crossed and t range opens up at higher energy

Direct (photon) probe of the $Z_c \to J/\psi\pi$ coupling without rescattering effects provides <u>unique complementary data</u> to constrain interpretation of e^+e^- data.





Initial simulations demonstrate the **capabilities of the existing detectors to measure these reactions**

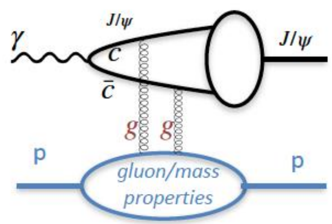
Jefferson Lab

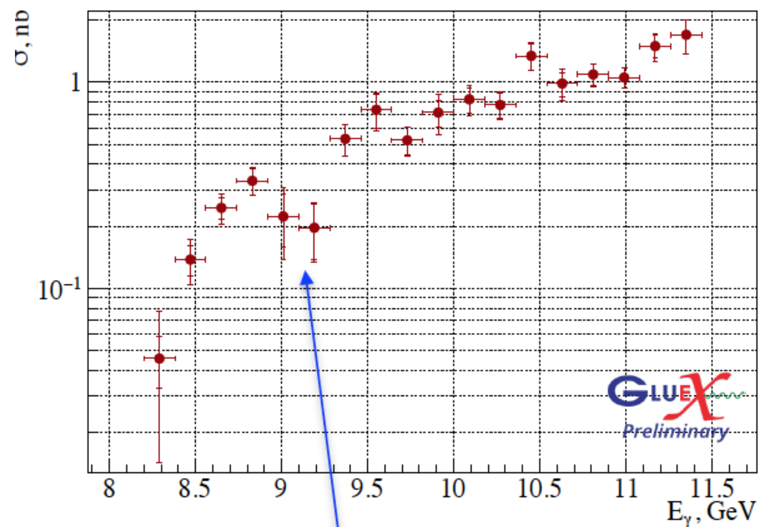
J/ψ photoproduction near threshold

Used to study important aspects of the gluonic structure of the proton

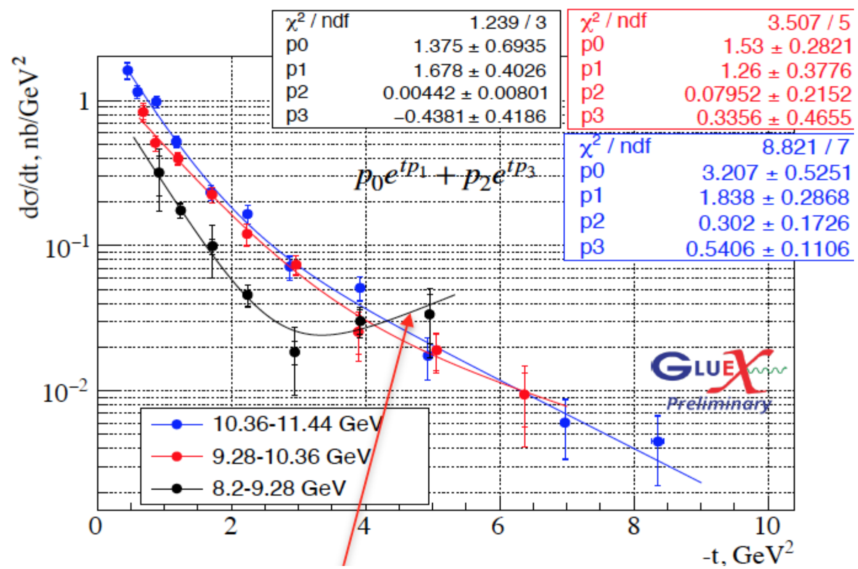
- **gluon GPD, gravitational FF**
- **mass radius of the proton,**
- **anomalous contribution to the proton mass.**

..based on some assumptions (mainly 2-g exchange)



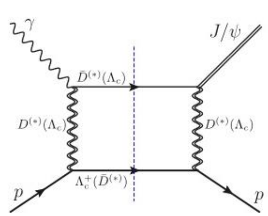


Possible structure at $\Lambda_c\overline{D}^{(*)}$ threshold σ(8.6-9.6) GeV



Enhancement of dσ/dt at high t for the lowest energy slice

- **CANNOT be explained by t-channel (GLUON EXCHANGE) alone**
- Can have contribution from open-charm exchange to both σ and $d\sigma/dt$ at high t



- **Can we interpret this as a possible evidence for a s-channel resonance (?) *Pc***

Phys. Rev. C 108 (2023) 2, 025201

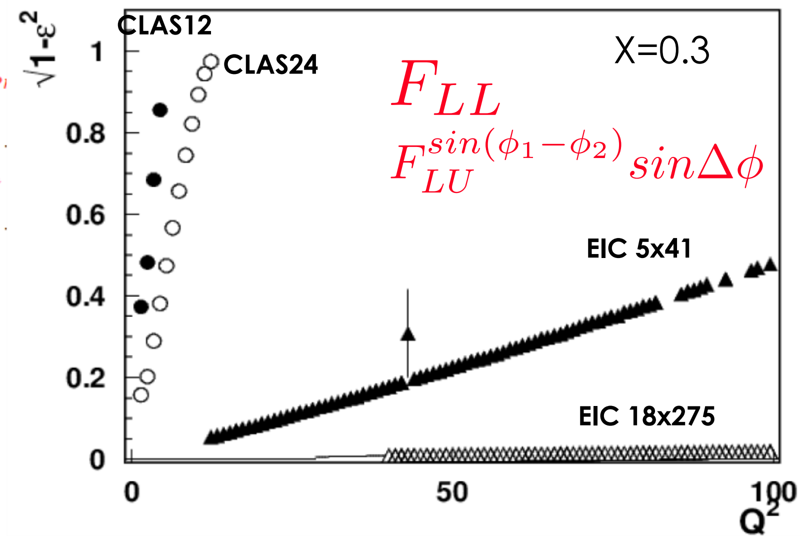
Nucleon Structure in 3D

SIDIS cross section

$\sigma = f\,(\,x\,,\,Q^2\,,\,z\,,\,P_T)$

$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} \\
&\quad + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + S_L\Big[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\Big] \\
&\quad + S_L\,\lambda_e\Big[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\Big] \\
&\quad + S_T\Big[\sin(\phi_h-\phi_S)\Big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\Big) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} \\
&\qquad + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} \\
&\qquad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] + S_T\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} \\
&\qquad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}
\end{aligned}
$$

- Separation of SFs highly non-trivial!

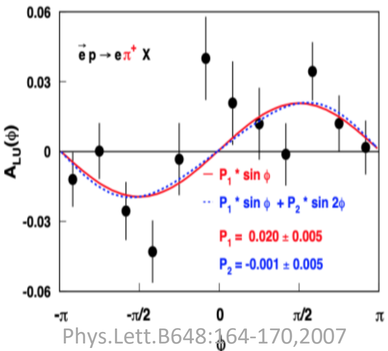


<u>A combined 11, 22 GeV and EIC SIDIS program</u>

will increase our ability to measure a variety of SIDIS SFs across an enhanced multidimensional phase space – the only way to test and validate our understanding and interpretation of SIDIS reactions.

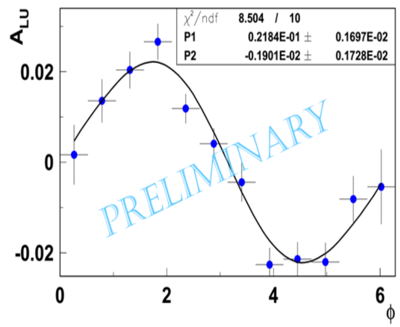
TMDs: High Statistics Crucial!

HERMES - 1996-2000



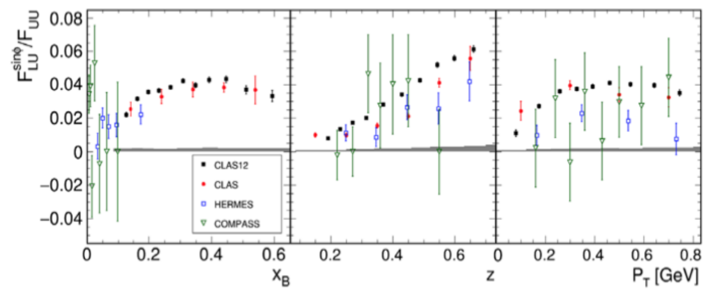
Phys.Lett.B648:164-170,2007

JLab – CLAS12 1 day

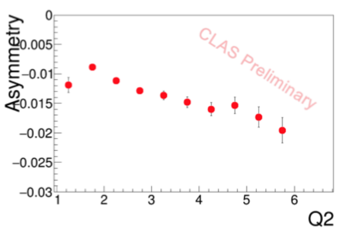


Phys. Rev. Lett. 128, 062005 (2022). (2022)

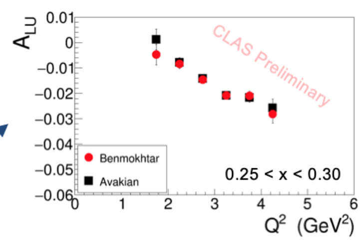
ep→e'π+ X

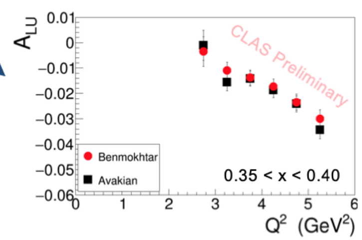


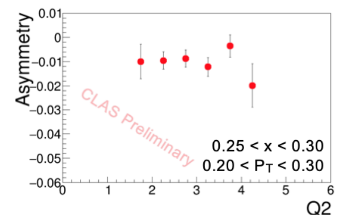
F_{LU} contains information on quark-gluon correlations

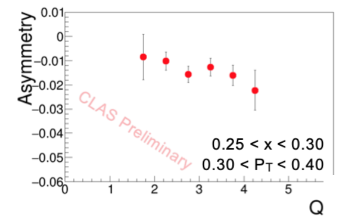


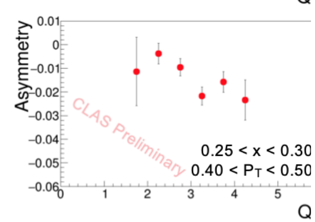
All plots $x_F < 0$.









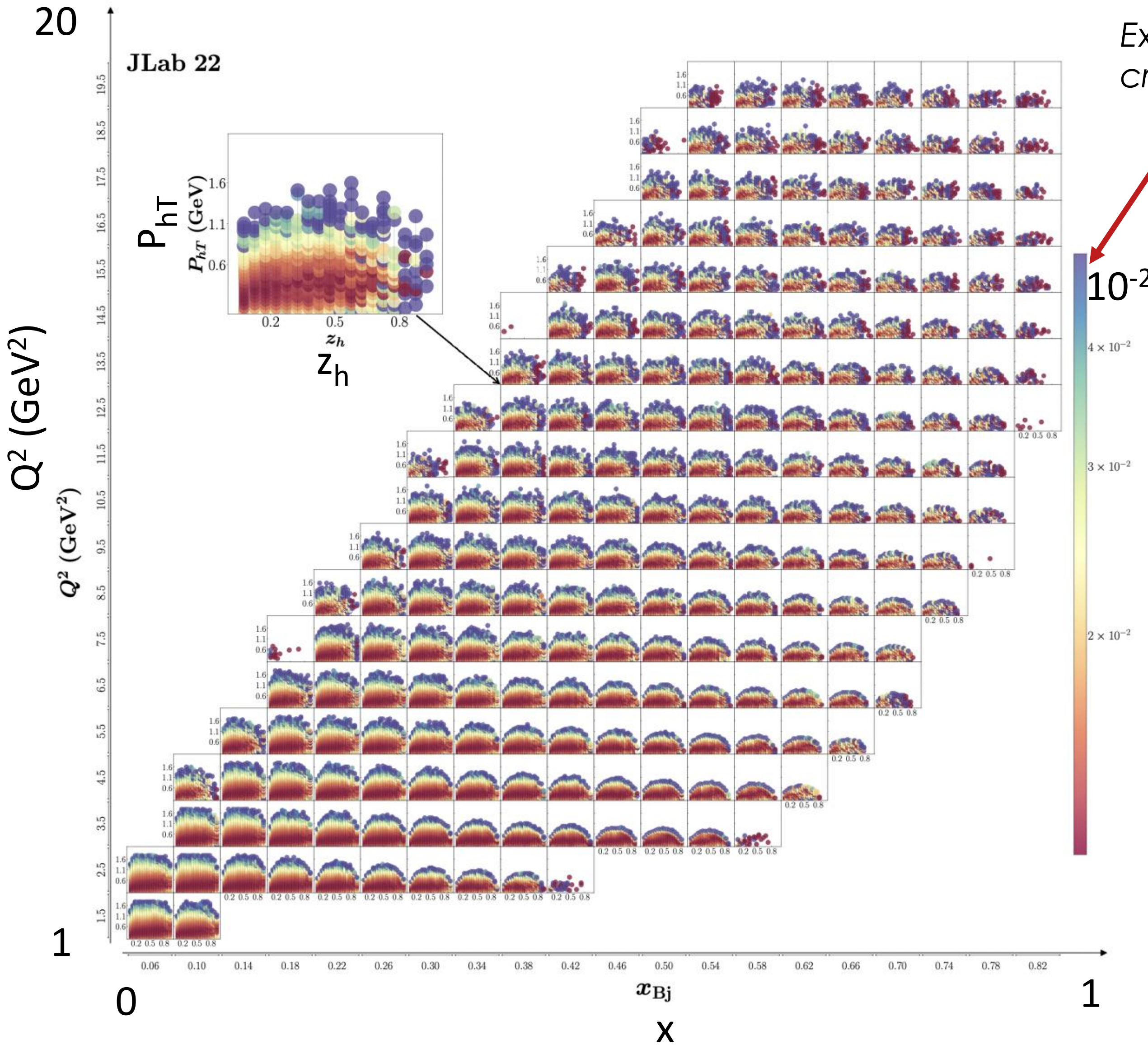


ep → e'pX

Onward to 4D

- QCD predicts only the Q^2 dependence
- Studies of the Q^2 behavior requires high precision multi-dimensional analysis

SIDIS Phase Space at 22 GeV



Expected uncertainties for SIDIS cross sections in 4D bins

Significantly increase the kinematic range to validate/test the theory/phenomenology

Multi-dimensional coverage of P_T gives access to fine binning of all observables

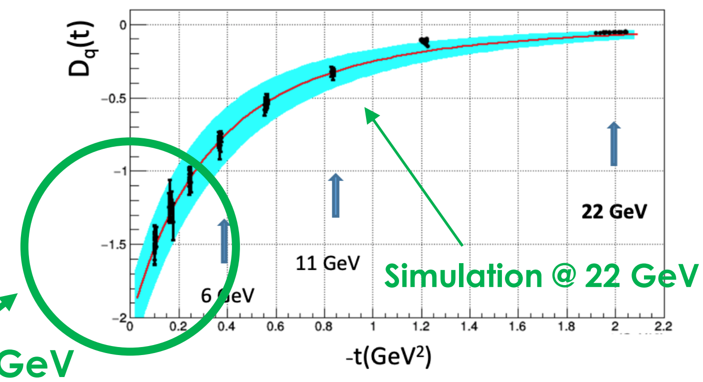
Projections using the existing CLAS12 simulation/reconstruction chain for 100 days of running with L= 10^{35} cm^2s^{-1}

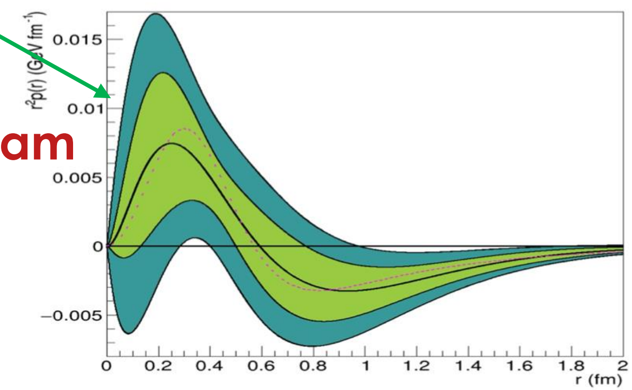
Spacial Structure & Mechanical Properties of the Proton

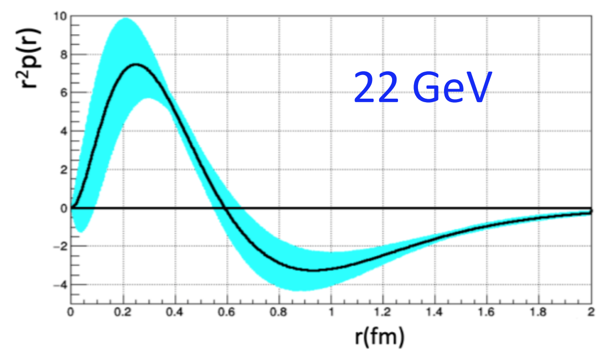
- Form Factors: source of information on hadron structure
- Gravitational FFs (GFFs) : describe how energy, spin, and various mechanical properties of hadrons are carried by q/g constituents.
- GFF D(t): describes the pressure distribution in the nucleon. It is accessible through measurements of the Compton FFs measured in **Deeply Virtual Compton Scattering**

- **A large -t range is required to perform the Fourier transform with controlled uncertainties ➜ high luminosity**

➜ **The 22 GeV beam energy is crucial to this program**







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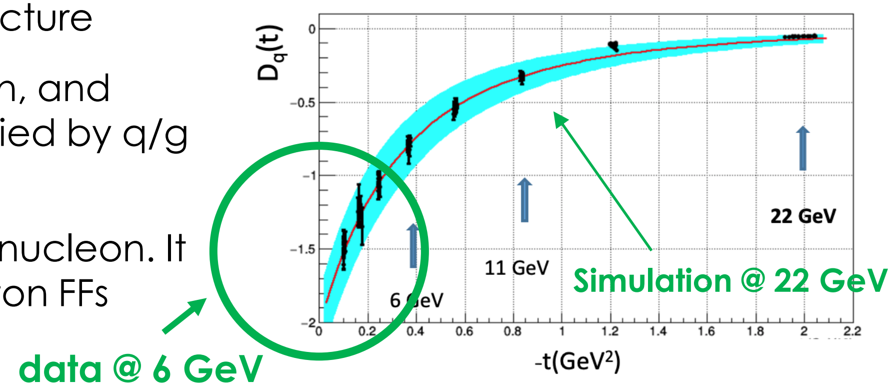
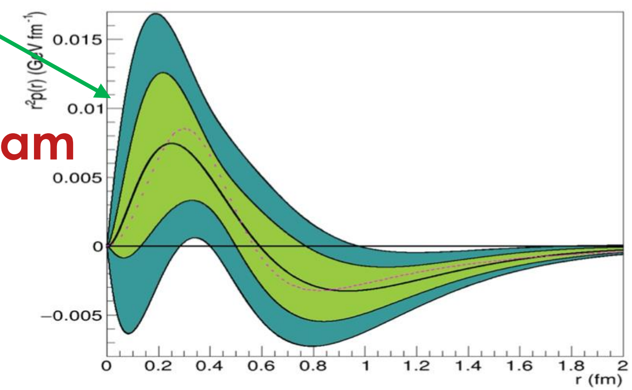
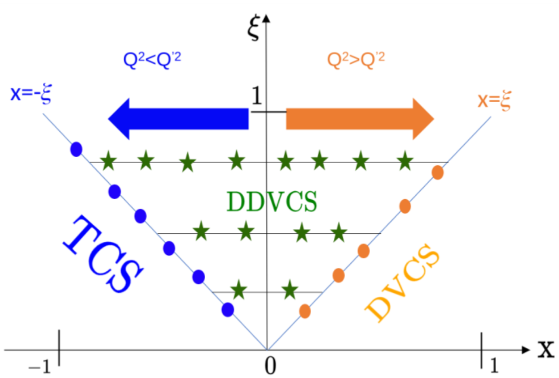


- **A large -t range is required to perform the Fourier transform with controlled uncertainties ➔ high luminosity**

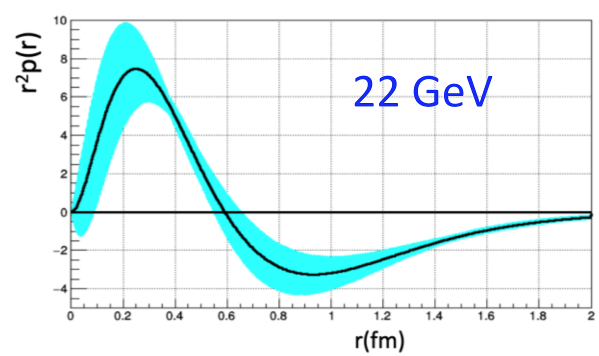


➔ The 22 GeV beam energy is crucial to this program

Double DVCS (DDVCS): e+p→e' +(l+l−)+p, l=e or μ



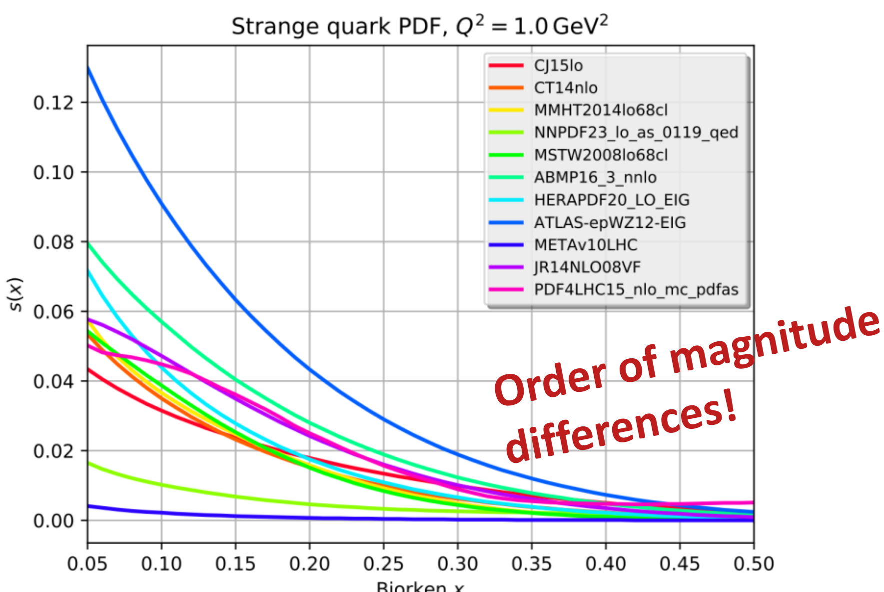
NEVER been measured (very small cross section).➔ **JLAB with high luminosity will be an excellent place to measure this reaction.**



Unambiguous Access to Strange Quarks

Current Situation

- **di-muon production in neutrino-nucleus scattering** – ***nuclear corrections introduce significant uncertainty***
- **W and Z rapidity distributions**
- **W+c production**
- **Semi-inclusive K production:** ***choice of fragmentation function negates inclusion in global fits***
- ***JLab12 Q^2 too low for PDF analysis***



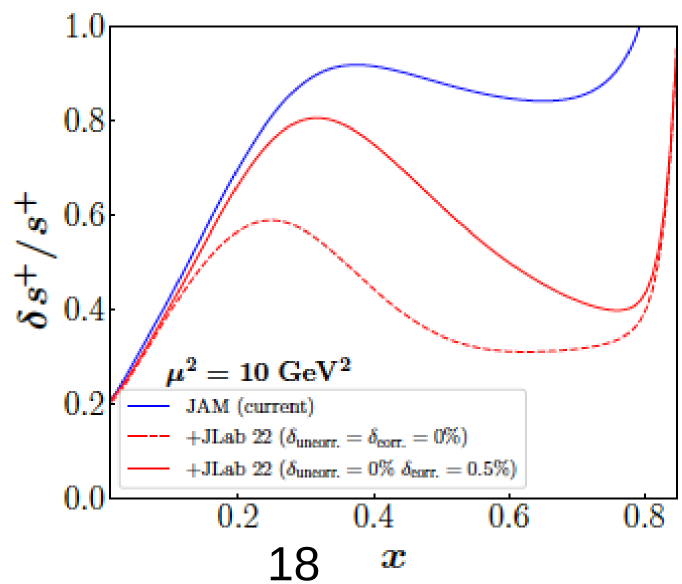
X

Parity-violating DIS

- **Parity-violating DIS allows strange contribution to be isolated from combined with p,n data**

$$s + \bar{s} \approx 3(5F_2^{\gamma Zp} - F_2^{\gamma p} - F_2^{\gamma n}) \qquad \text{LO}$$

- **Valence regime provides <u>strength and shape</u>**
- **Substantial improvement with a reduction in the uncertainty that can reach *<u>more than a factor two at large-x</u>***

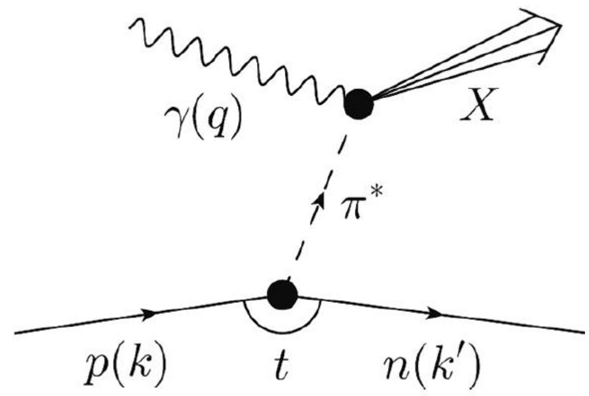


~100 days, 40 μA beam split between 40 cm D and H targets

Partonic Structure of Mesons

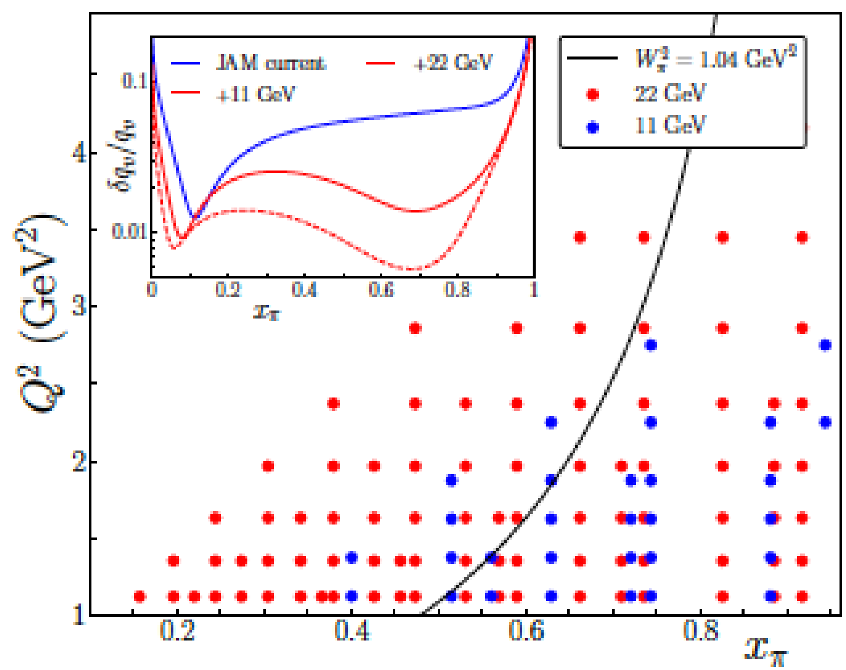
Meson structure

- Tagged deep inelastic scattering (TDIS) provides a mechanism to access the meson structure via the Sullivan process .
- A cut of $W^2_\pi > 1.04$ GeV^2 (to avoid contributions from resonances in a pion analysis,) eliminates most of the data at 11 GeV.

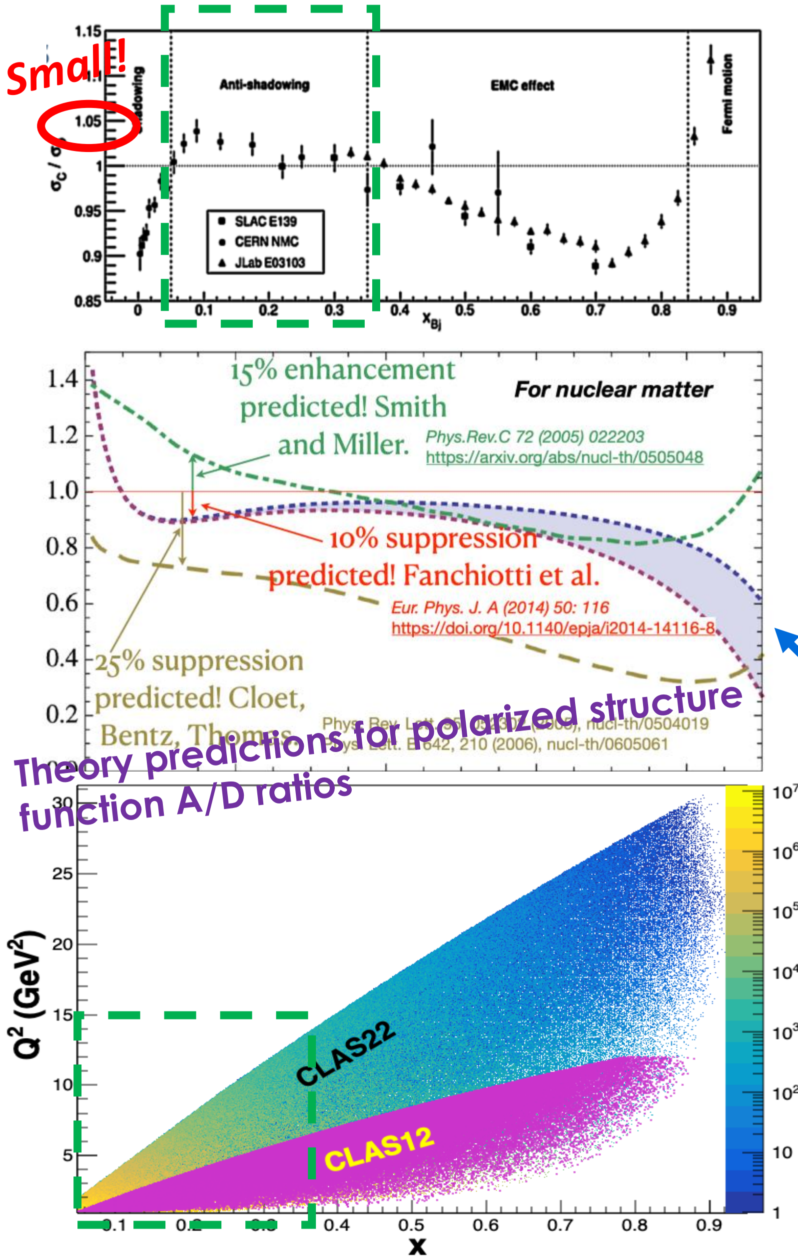


<u>At 22 GeV:</u>

- Available phase space significantly increased
  ➔ large improvement in the determination of the valence structure of the pion
  ➔ kin. coverage to smaller x_π region to probe the sea content of mesons
- Overlap the existing π induced DY data
  ➔ test the universality of PDFs in the mid to large x_π region
  ➔ pion PDF predicted to be broader than the proton PDF



Anti-shadowing: solving a multi-decade puzzle



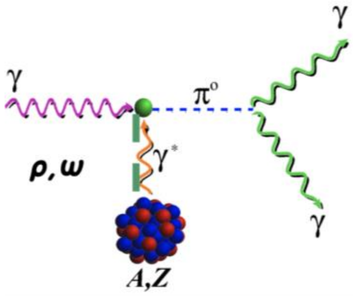
With a 22 GeV e- beam JLab can access the anti-shadowing region (x~0.1-0.3) at moderate Q^2

- Region extremely interesting, near-equally dominated by valence quarks, sea-quarks, and gluons → many many models!!

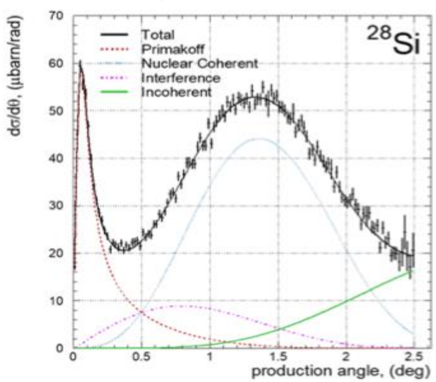
- Anti-Shadowing is the <u>*least studied*</u> nuclear structure function effect experimentally – ***small effect requiring precision and high luminosity***
  - flavor dependence essentially uncharted
  - spin dependence essentially uncharted (~50% differences in predictions)
  - no tagged measurements
  - no L/T separations

A rigorous testing ground between shadowing, EMC regimes – models and theory must describe **ALL**

QCD Confinement and Fundamental Symmetries



PrimEx-II: $\gamma + {}^{28}Si \rightarrow \pi^0 + {}^{28}Si$



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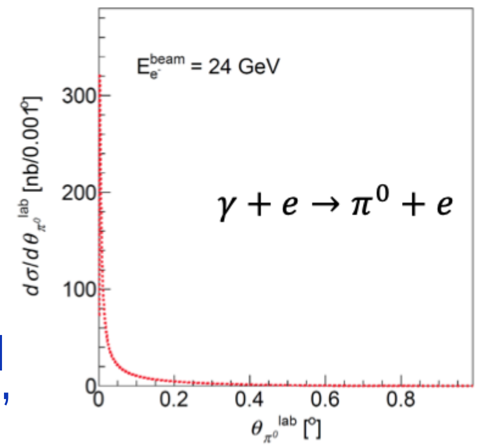
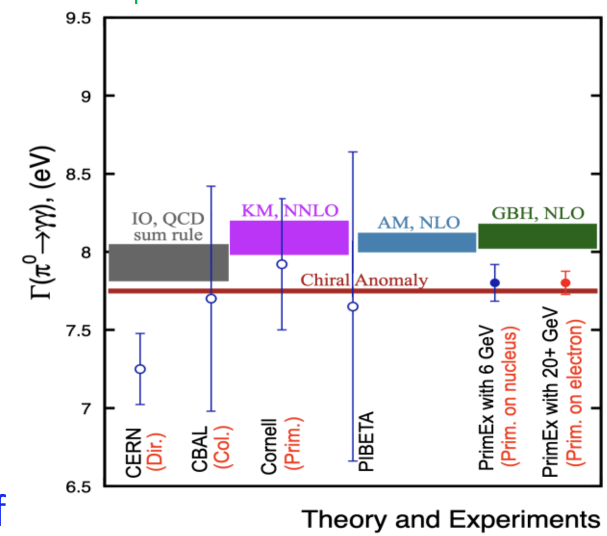
- **π^0 Primakoff production off an electron target**

Higher energy will allow for η'



The threshold for photo- or electroproduction of π^0 off an electron target is 18 GeV

$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ can be predicted at ≈ 1% precision



Stringent test of low-energy QCD

- **Primakoff production off nuclear target**

A 22 GeV upgrade will greatly enhance the Primakoff experiments for more massive mesons off nuclear target

➡ **first Primakoff measurement of Γ(η' → γγ)** with ~3.5% precision to study the U(1)A anomaly coupling to the gluon field,

➡ **improve the measurement of Γ(η → γγ)** to a 2% accuracy to determine the light-quark mass ratio

Science Outlook

- Understanding the strong interaction dynamics of non-pQCD and ``how'' hadrons/nuclei emerge from fundamental QCD principles, is a complex problem
- This complexity requires observation of the chromodynamic fields ``at work'' through multiple observables using different approaches and measurements
- With CEBAF at higher energy some important thresholds would be crossed and an energy window which sits between JLab @ 12 GeV and the EIC would be available. This, together with CEBAF uniqueness to run electron scattering experiments at the luminosity frontier, can provide powerful insight into non-pQCD dynamics.
- A very strong science case for such an upgrade is emerging – **join us at 22 GeV workshop at Frascati December 9-13, 2024**

Polarized gluon distribution, longitudinal/transverse separations, hadron formation in nuclei, meson form factors, probing the light quark sea,……. and more!

Near Term Strategy (next 3 years)

- Design focus for energy upgrade the next few years will be on:
  - Developing a pre-conceptual design for additional FFA racetrack in the existing CEBAF tunnel to reach the top energy of about 22 GeV (current baseline), more specifically:
    - Complete optics design for a pair of FFA arcs, including merger transitions to linacs
    - TOF Splitters design for NE and SW arc ends, including momentum compaction compensation and beta matching
    - Extraction system design capable of delivering all FFA passes (1-5) to A,B,C (same energy) and one pass above to D
    - Finalize multi-pass linac optics based on strongly focusing triplets
    - 650 MeV recirculating injector design (in the LERF vault)
    - Carry out S2E simulation including errors
    - Implement a robust correction system
    - Complete emittance dilution budget (longitudinal and transverse) via tracking studies

Near Term Strategy (next 3 years) – cont.

- Design focus for energy upgrade the next few years will be on:
  - Testing resilience of permanent magnets in CEBAF beam environment
  - Developing a prototype FFA FODO cell and testing its performance with multi GeV beams at CEBAF, more specifically:
    - Orbit mapping for different energies
    - Beam based optics measurement and validation
    - Validating effectiveness of orbit correction system
  - Designing and prototyping special magnets, more specifically:
    - Compact Splitter magnets
    - Vertical septa for extraction system
    - RF separator multi cell cavities

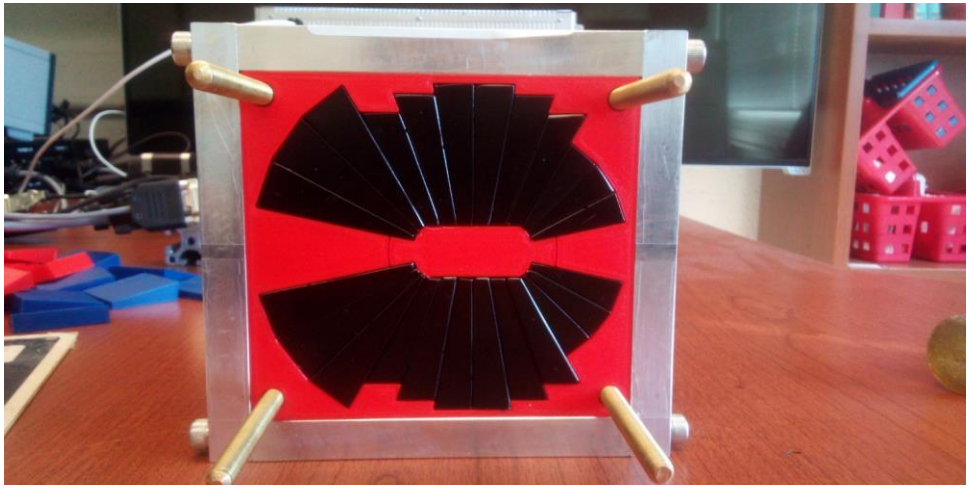
Thank you!

Thank you for listening, and thanks also to the scientific community working on developing this exciting science case

More info!

Prototype Magnet

- 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}
- Test of radiation resilience at CEBAF - LDRD project started Oct. 1, 2023

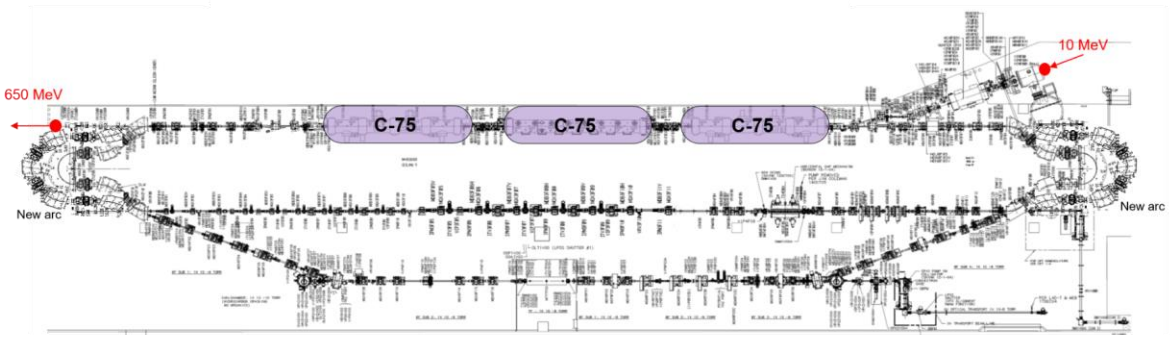


Parameter	Value	Unit
Dipole ($B(0)$)	-0.9512	T
Gradient (B')	55.54	T/m
x good field region (GFR)	±10.5	mm
$B_{\max}$ in GFR	$(-)1.536$	T
Magnet length	45	mm
Vertical aperture (GFR)	±7.5	mm
Minimum midplane gap	±3	mm
Material	NdFeB	
Grade	N42EH	
B_r	1.28–1.33	T
$\mu_0 H_{cJ}$	2.9	T

Injector Upgrade – 650 MeV Recirculating Injector based on LERF

With the present 123 MeV injector, the difference in the first and final pass energies in the North Linac is too large (1:175) to effectively control the beam.

650 MeV recirculating injector (3-pass) based on LERF will allow a manageable difference in energies (1:33)



Jefferson Lab

Energy loss, Emittance dilution and Energy spread

- Doubling the energy, while staying within current CEBAF footprint, makes the synchrotron radiation effects of paramount importance.

- Energy loss
- Emittance dilution
- Natural energy spread

$$\Delta E = \frac{2\pi}{3} r_0 \, mc^2 \, \frac{\gamma^4}{\rho}$$

$$\Delta \epsilon_N = \frac{2\pi}{3} C_q r_0 < H > \frac{\gamma^6}{\rho^2} ,$$

$$\frac{\Delta \epsilon_E^2}{E^2} = \frac{2\pi}{3} C_q r_0 \, \frac{\gamma^5}{\rho^2} ,$$

Maximize ρ, minimize H

$$H_x = g_x D_x^2 + 2a_x D_x D_x' + b_x D_x'^2$$

$$C_q = \frac{55}{32\sqrt{3}} \frac{\hbar}{mc}$$

- Quantum nature of a ‘recoil’ effect on electrons due to photon emission makes significant impact on both the transverse and longitudinal beam dynamics, leading to cumulative emittance growth (transverse and longitudinal).

- Cumulative emittance dilution (transverse and longitudinal) at 22 GeV (4 CEBAF + 6 FFA passes)

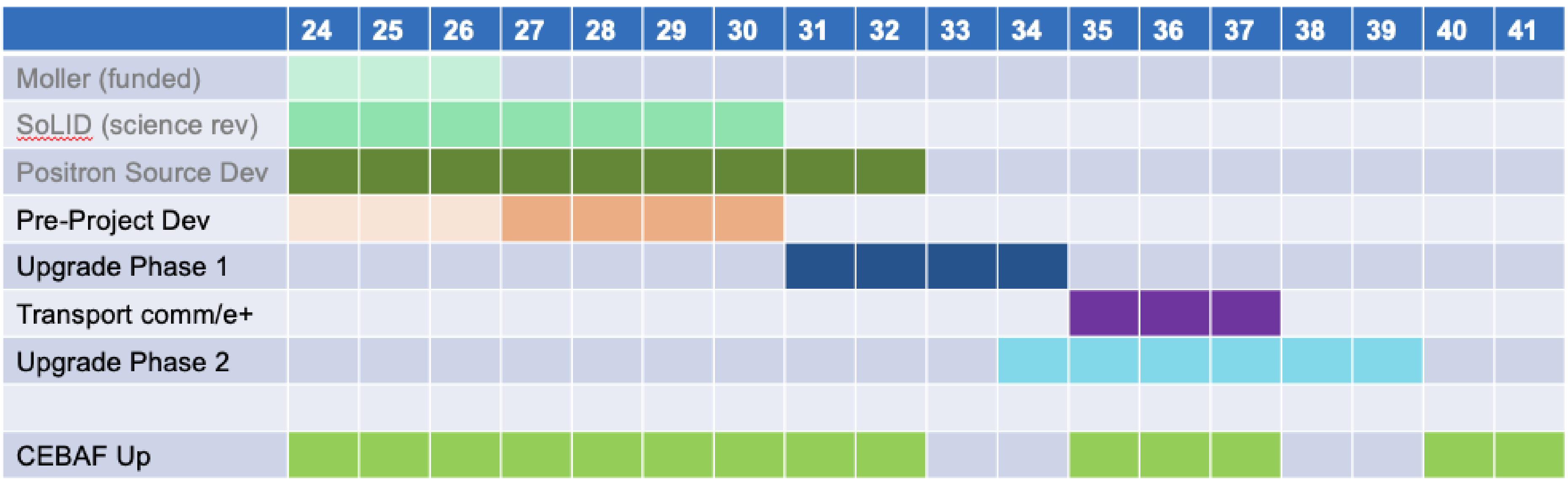
Beamilnes	$\Delta\varepsilon_N\,[m\ rad]$		$\Delta\sigma_{\Delta E/E}$
	horizontal	vertical	
Arcs	6.0E-05		9.0E-04
Spr/Rec		2.0E-05	3.0E-04
Splitters★	2.0E-05		3.0E-04
Total	8.0E-05	2.0E-05	1.5E-03

★ Projected value from the Spr/Rec contribution

Total Energy Loss [MeV]	990
Horizontal Emittance Dilution [mm mrad]	80
Natural Momentum Spread	1.5E-03

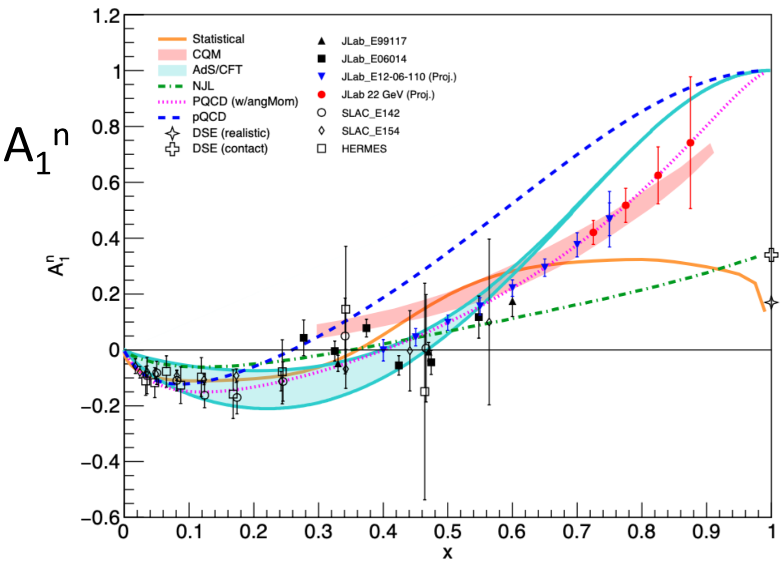
Notional CEBAF & upgrade schedule (FY24 – FY42)

- Accelerator and engineering team have 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 development also shown



Jefferson Lab

Polarized Structure Functions and α_s

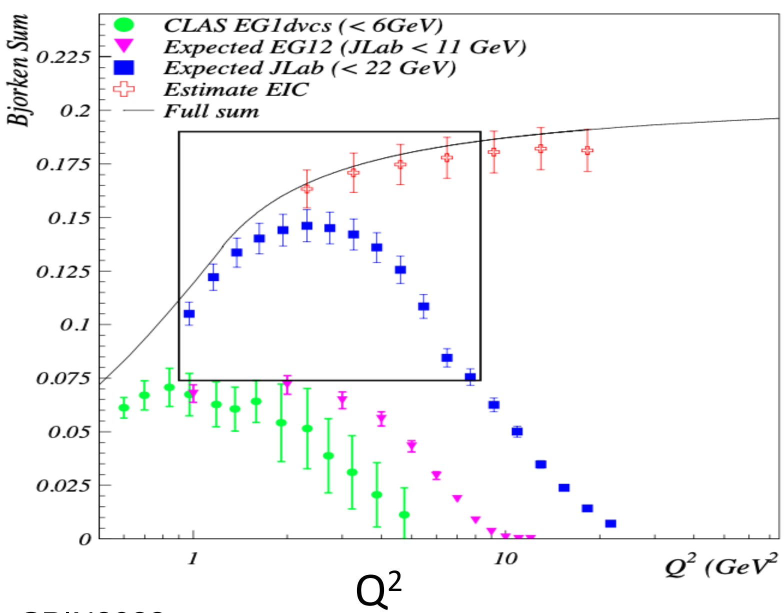


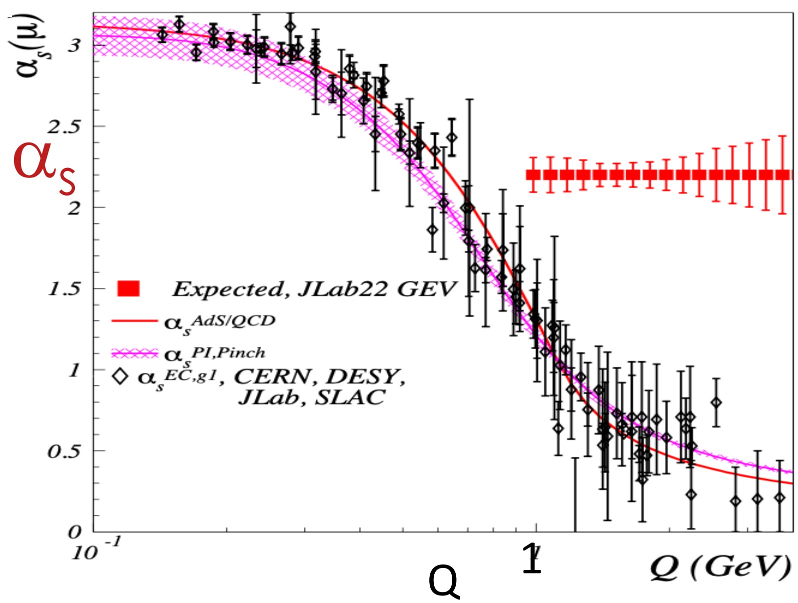
Extend the precision and kinematic reach of polarized structure functions

Bjorken Sum Rule $\Gamma_1^{p-n}(Q^2) \equiv \int \left(g_1^p(x,Q^2) - g_1^n(x,Q^2)\right) dx$

The strong coupling constant is a key parameter of the Standard Model

Its current uncertainty is the least precise among all fundamental couplings

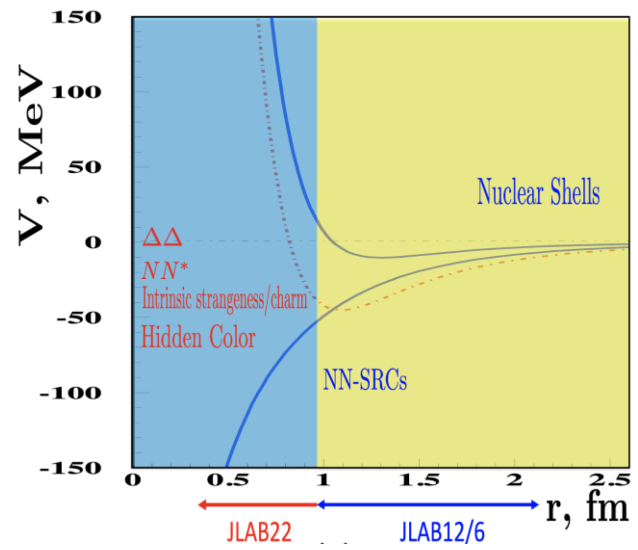




Nuclear Dynamics at Extreme Conditions

The dynamics of the nuclear repulsive core is still poorly understood

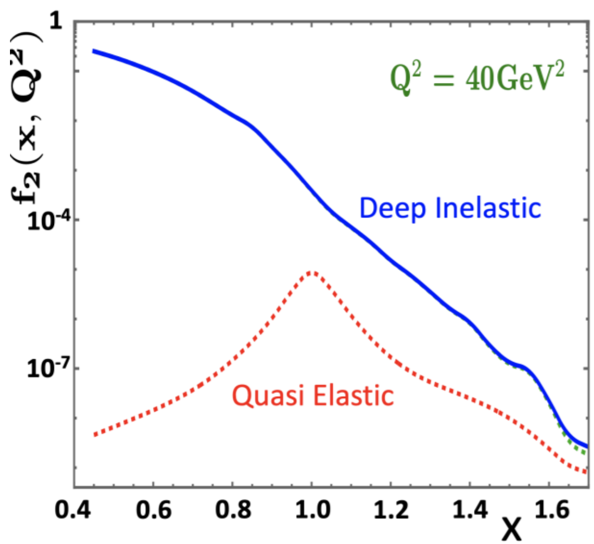
A 22 GeV upgrade will provide reach to the nuclear forces dominated by nuclear repulsion



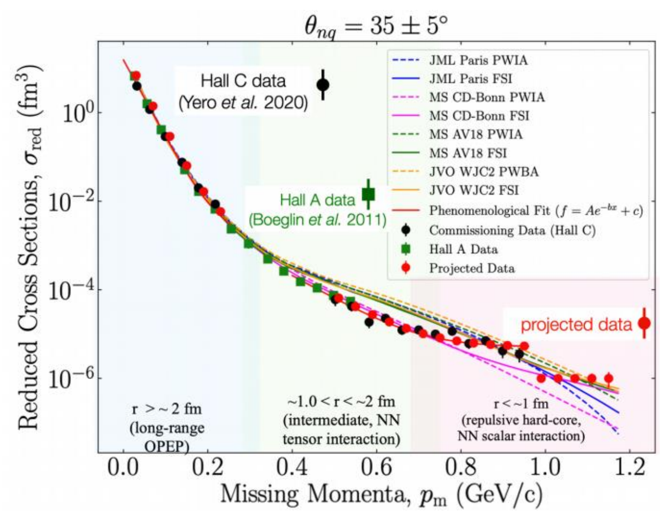
Superfast Quarks

The high Q^2 reach will allow

- the suppression of quasi-elastic contributions,
- the first-ever study of nuclear DIS structure function at Bjorken x > 1.2 (r~ 0.5 fm,)



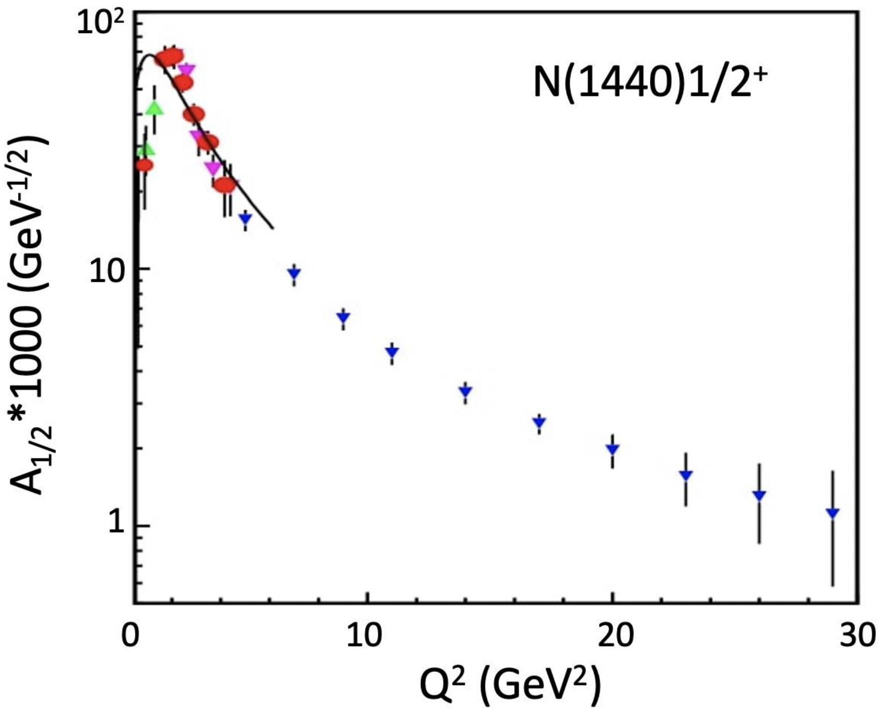
Exploring Deuteron at Very Large Internal Momenta (> 800 MeV/c – non-nucleonic & hidden color components)



- non-relativistic theory reproduces data up to pm ~ 0.7 GeV/c
- no model reproduces data (non-nucleonic degrees of freedom?, quarks?) pm > 0.7 GeV/c

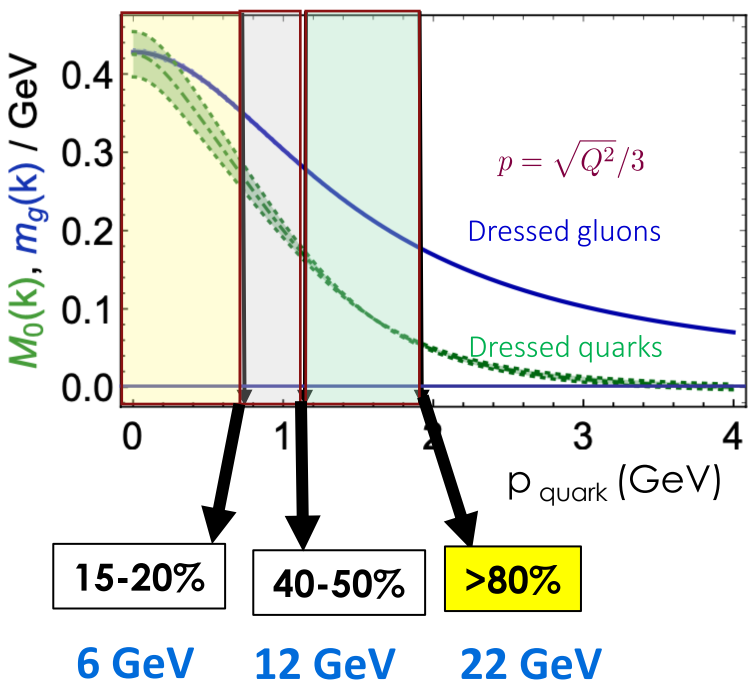
Jefferson Lab

Bound 3 Quark Structure of N*s and Emergence of Mass



Continuum Schwinger Method

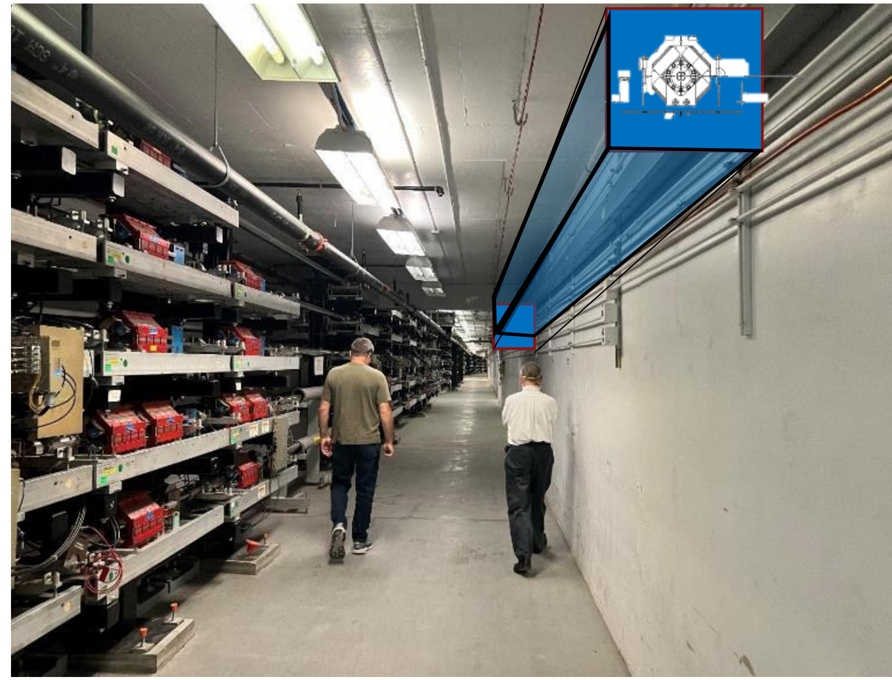
QCD equations of motion for q/g fields reveal existence of dressed q/g with momentum-dependent masses.



- Q^2 evolution of the γvpN* electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD
- **Simulations indicate JLab22 is the only foreseeable facility to extend these measurements up to 30 GeV^2**

Q^2 range(<35 GeV^2) where the dominant portion of hadron mass is expected to be generated

Transport and Upgrade CEBAF to 22 GeV

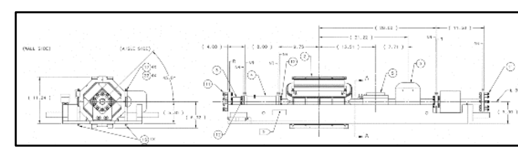


- Remove top pass of Dipoles and Quad girders
- All passes of Dipoles and Quad girders move up one level for FFA arc installation

- Running girder transport line at aisle side corner of tunnel
- Potential to use a “sit-in” style girder for smaller profile

after 6 FFA passes →

	E [GeV]	ρ [m]	ΔE [MeV]	<H> [m]		
FFA 20	21.88	70.6	144	4.0E-03	6.0E-05	1.9E-03



Final Energy [GeV]	22.3
Total Energy Loss [MeV]	920