New Opportunities with Jefferson Lab at 22 GeV

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SPIN 2023

Duke University, September 24-28, 2023

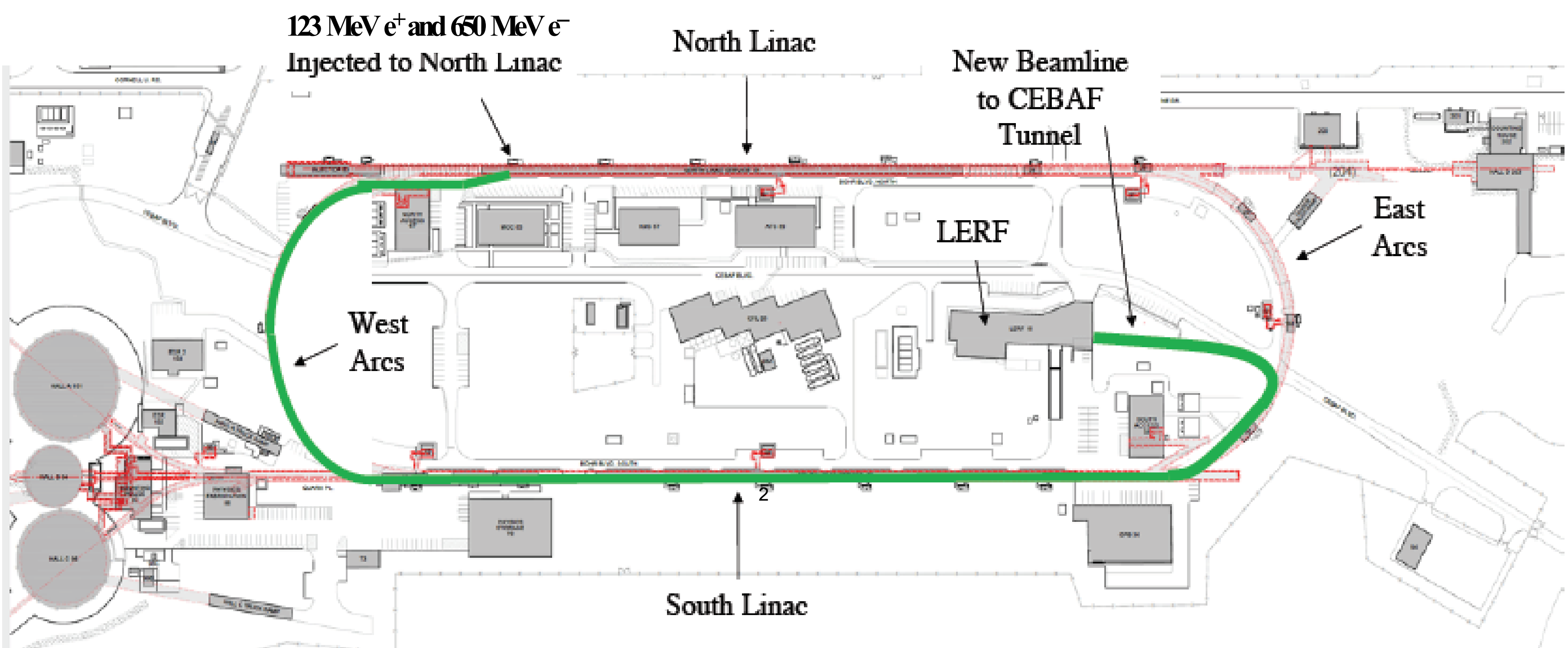
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

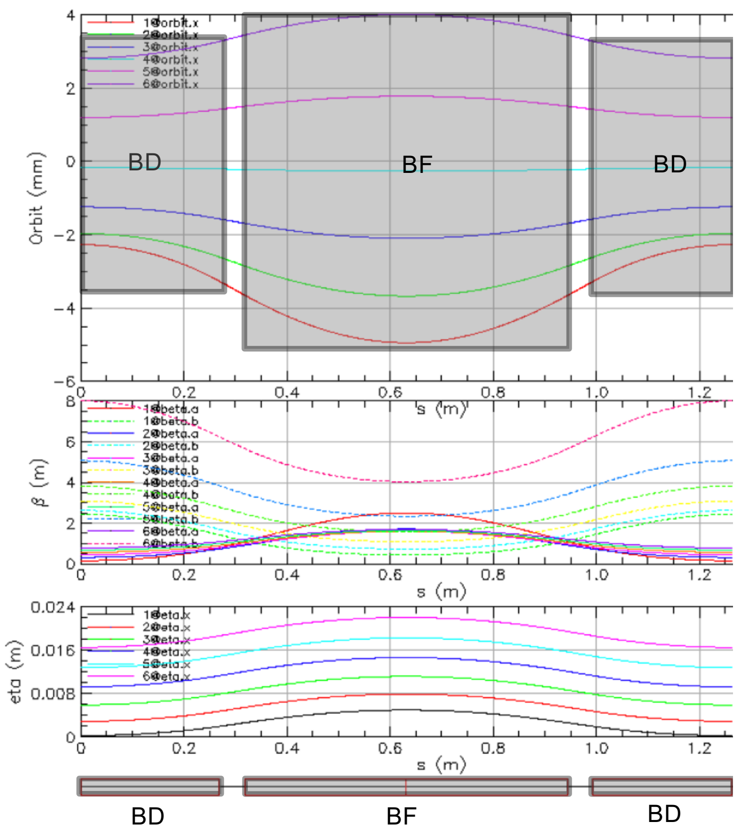
JEFFERSON LAB ACCELERATOR PHASED UPGRADE

- 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!***

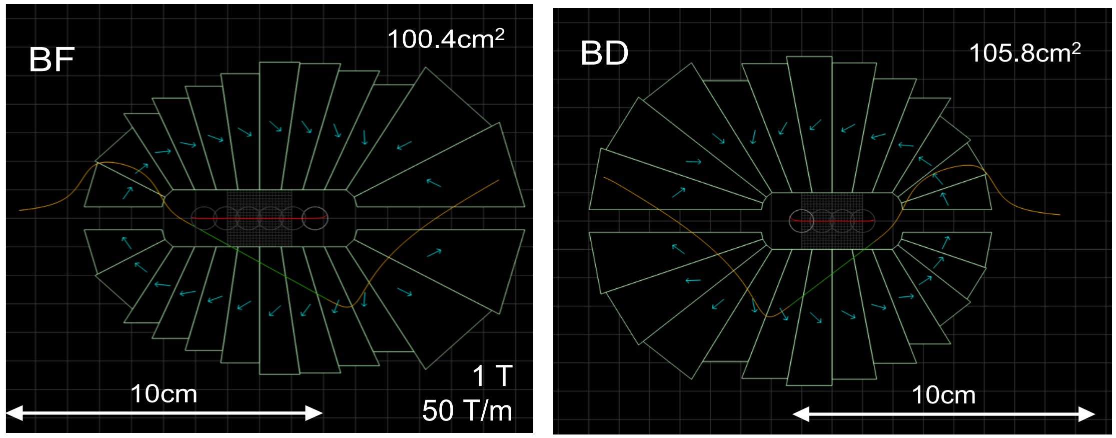


Compact FFA Cell – How Does it Work?

- Large momentum acceptance FFA 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)



CBETA magnets: from 38cm^2 to 78cm^2

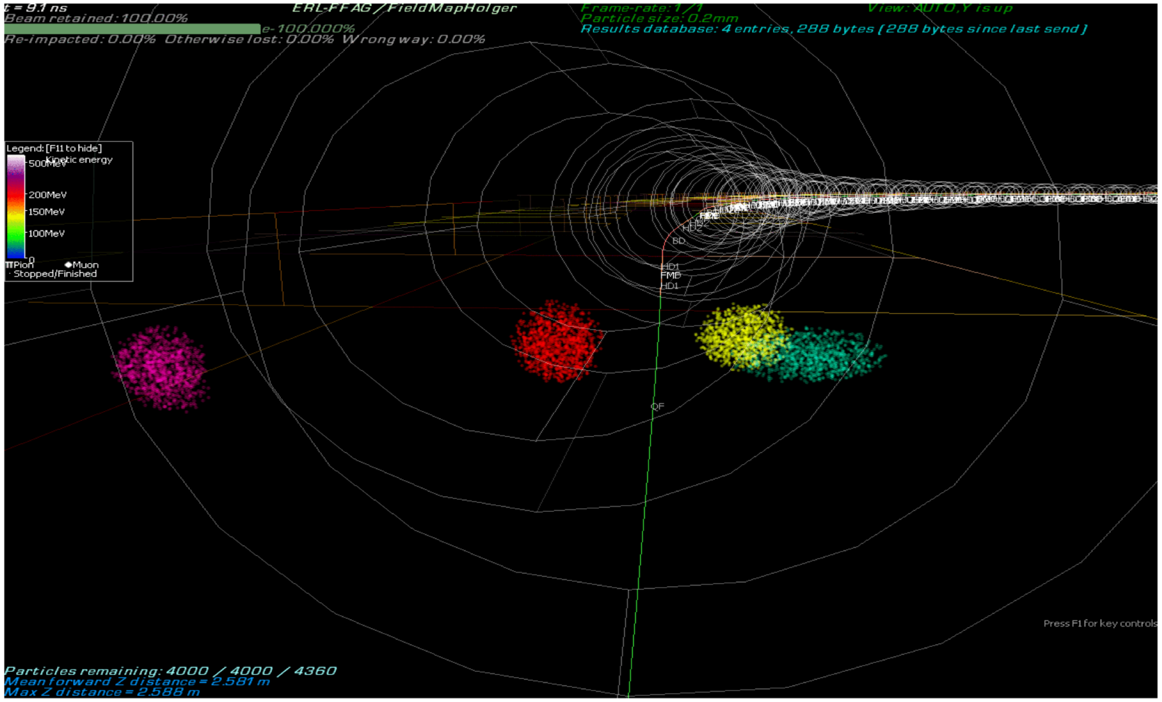


- Closely spaced orbits for all six beams (~ 1 cm)
- Extremally low dispersion (a few mm) in a combined function lattice
- Self similar beta functions for different energy beams

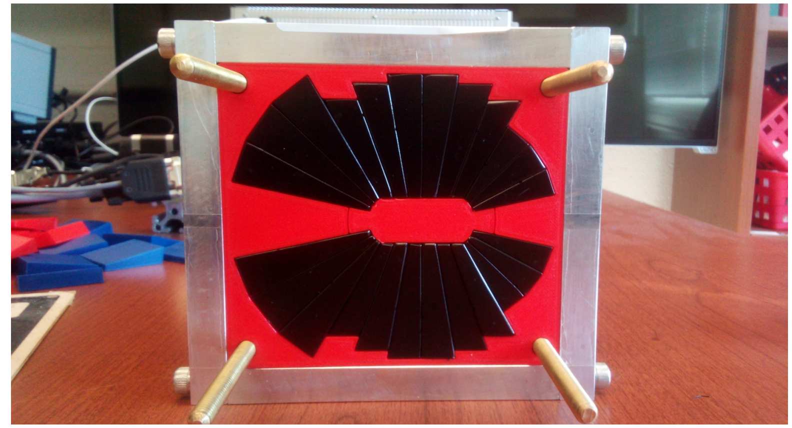
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Multi-Energy Beam Dynamics in FFA Arc

CBETA 2019-2022

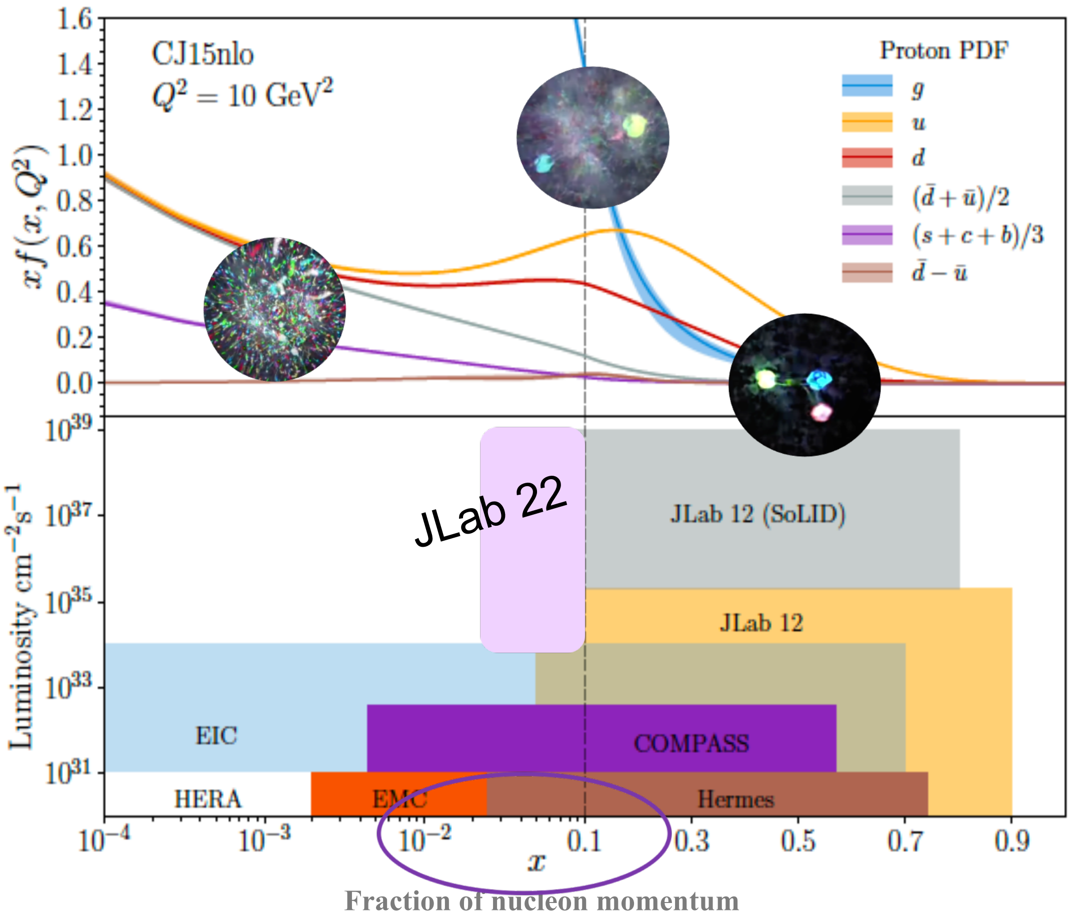


Stephen Brooks, BNL



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 LDRD for radiation resilience tests in CEBAF.

JLab 12 GeV:
Probing Nucleon Valence Structure at High Luminosity



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

Partonic structure in 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, shape and strength from data

Precision measurements in the valence quark regime requiring high luminosity are the purview of JLab, providing overlap with EIC into the sea quark region - keen discriminator of hadron structure models, test of QCD arXiv:2306.09360v2 [nucl-ex], submitted to EPJA

Nuclear Experiment

[Submitted on 13 Jun 2023]

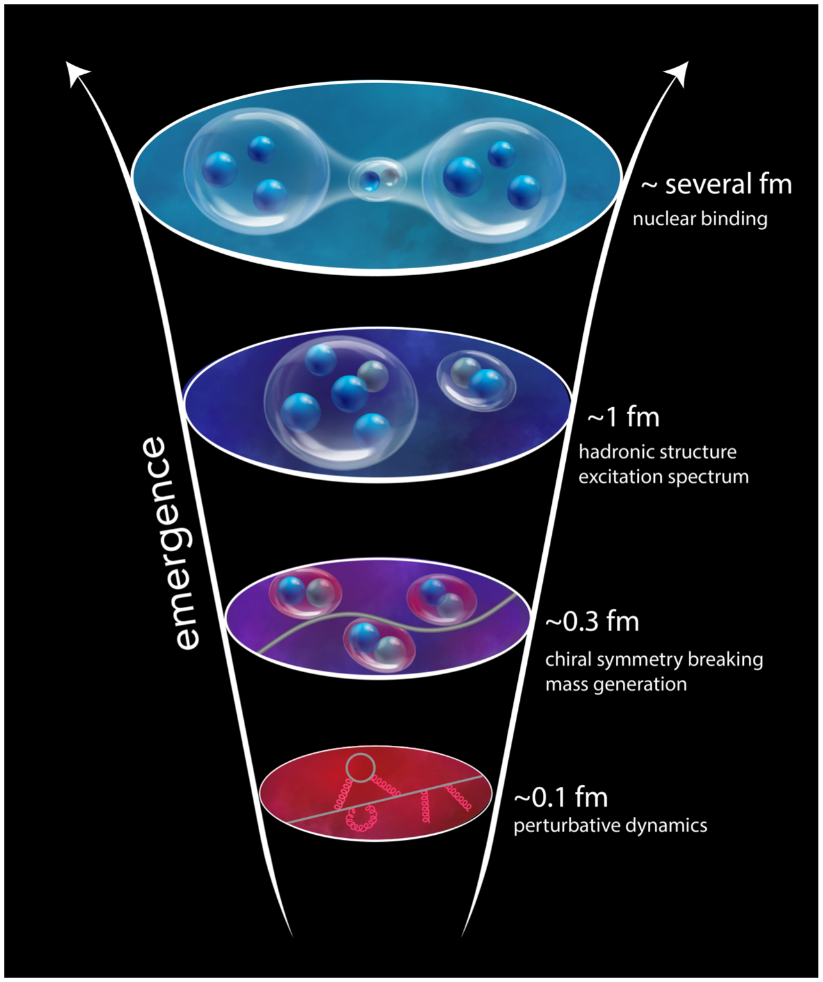
Strong Interaction Physics at the Luminosity Frontier with 22 GeV Electrons at Jefferson Lab

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

141 pages with many powerful experiments using existing or planned equipment - just a few examples....

Why CEBAF @ 22 GeV?

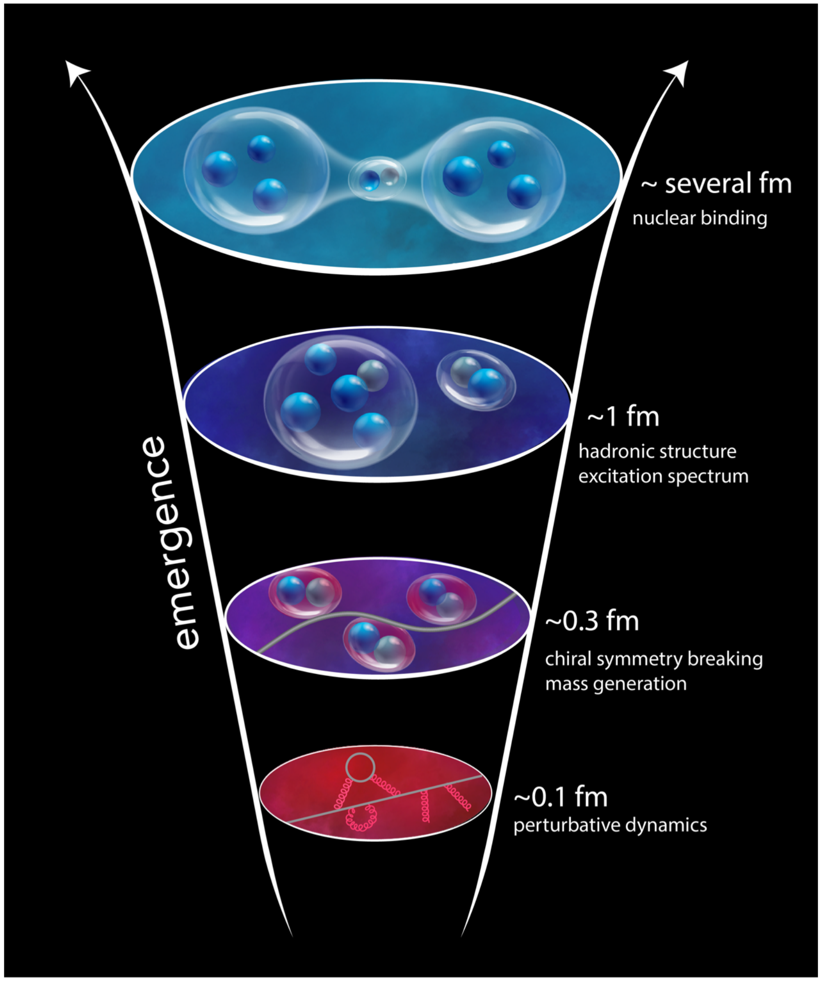


"The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe."
-- *More is Different*, P. W. Anderson [Science 177, 393 (1972)]

Need to understand strong interaction dynamics from asymptotically free fundamental quark and gluon constituents to the structure of bound nucleons to nucleon-nucleon interactions and the nuclear medium

Complex non-pQCD problem which demands different approaches and measurements to access multiple observables

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

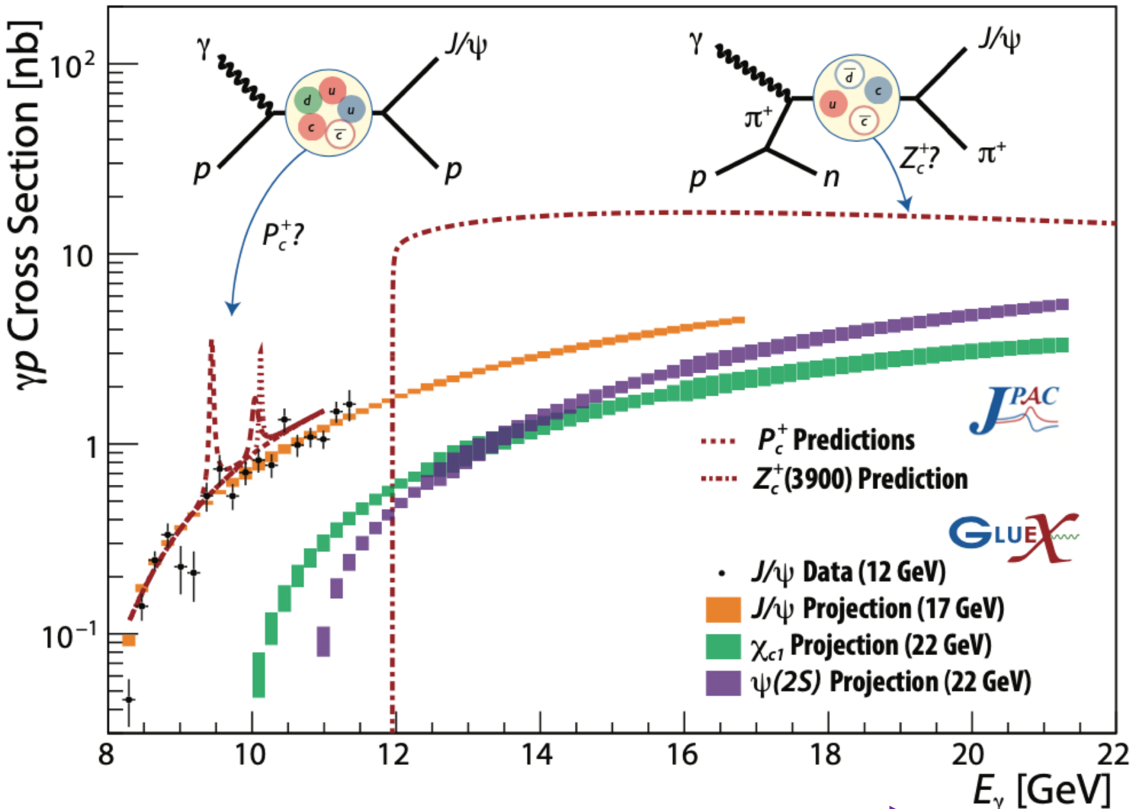
A BRIDGE between JLab @ 12 GeV and EIC ➜ testing and validation of QCD from lower to higher energy, through multiple phenomena, and with high precision

Spectroscopy of Exotic States with charm

Photoproduction of hadrons with charm quarks: a new tool for discovery in QCD

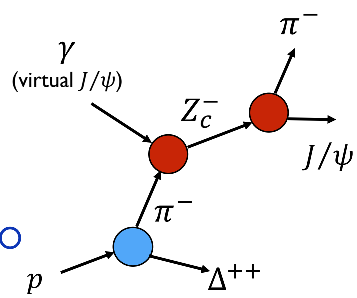
→ a unique method to probe the **gluonic structure of the proton**
→ potentially decisive information about the **nature of some 5-quark and 4-quark** candidates

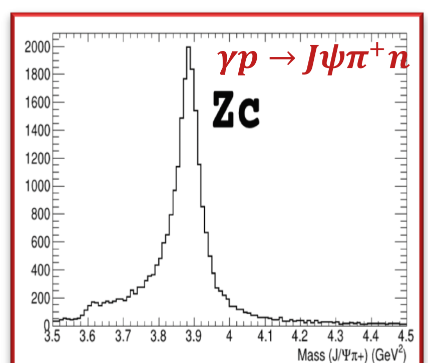
- Tetraquark candidates, **XYZ states**, observed in B decays, e+e- colliders but their internal structure is ***not yet understood***
- **Never direcly produced** using γ/lepton beams → **Polarized photoproduction alternative mechanism to study such states**



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 unique complementary data to constrain interpretation of e^+e^- data.





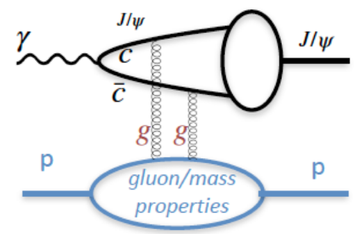
Initial simulations demonstrate the **capabilities of the existing detectors to measure these reactions**

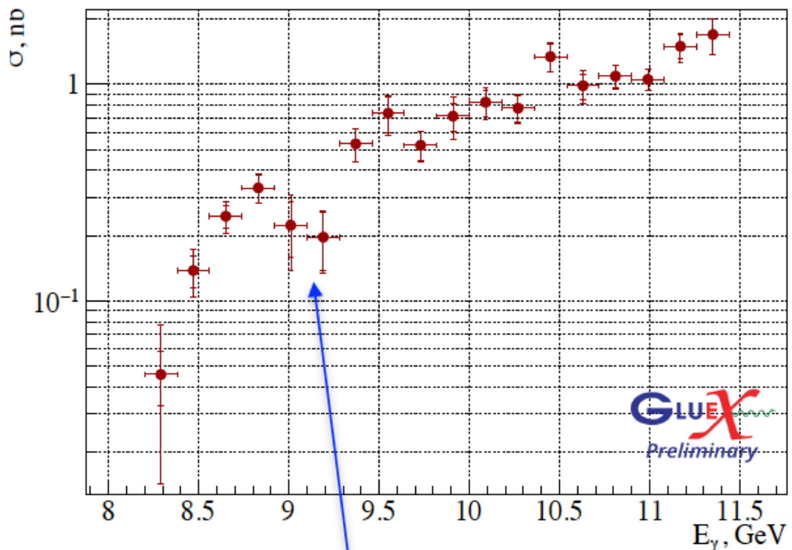
J/ψ photoproduction near threshold

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

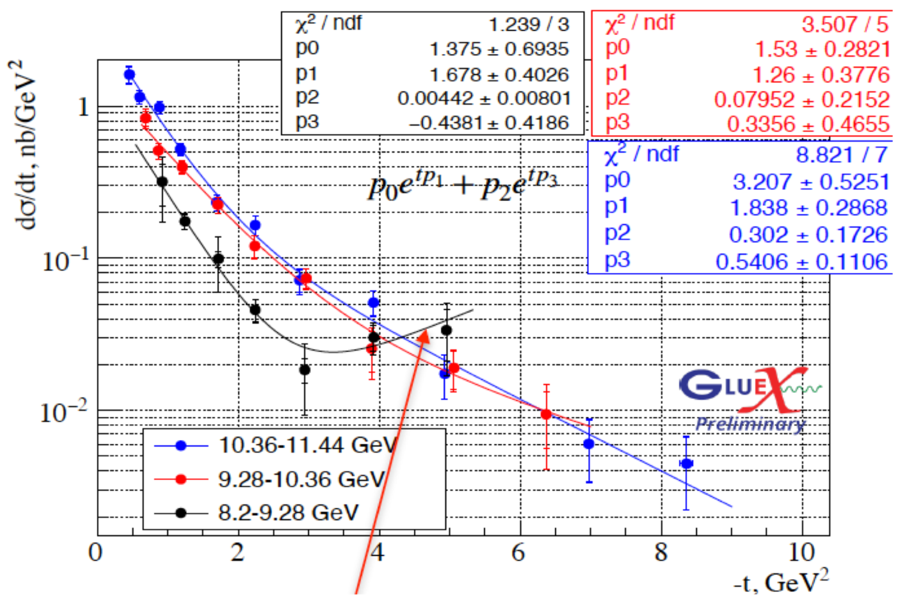
- **gluon GPD, gravitational FF**
- **mass radius of the proton,**
- **anomalous contribution to the proton mass**.

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



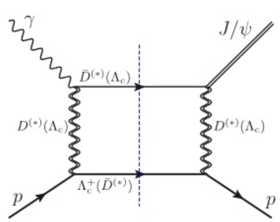


Possible structure at $\Lambda_c \overline{D}^{(*)}$ threshold σ(8.6-9.6) GeV



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

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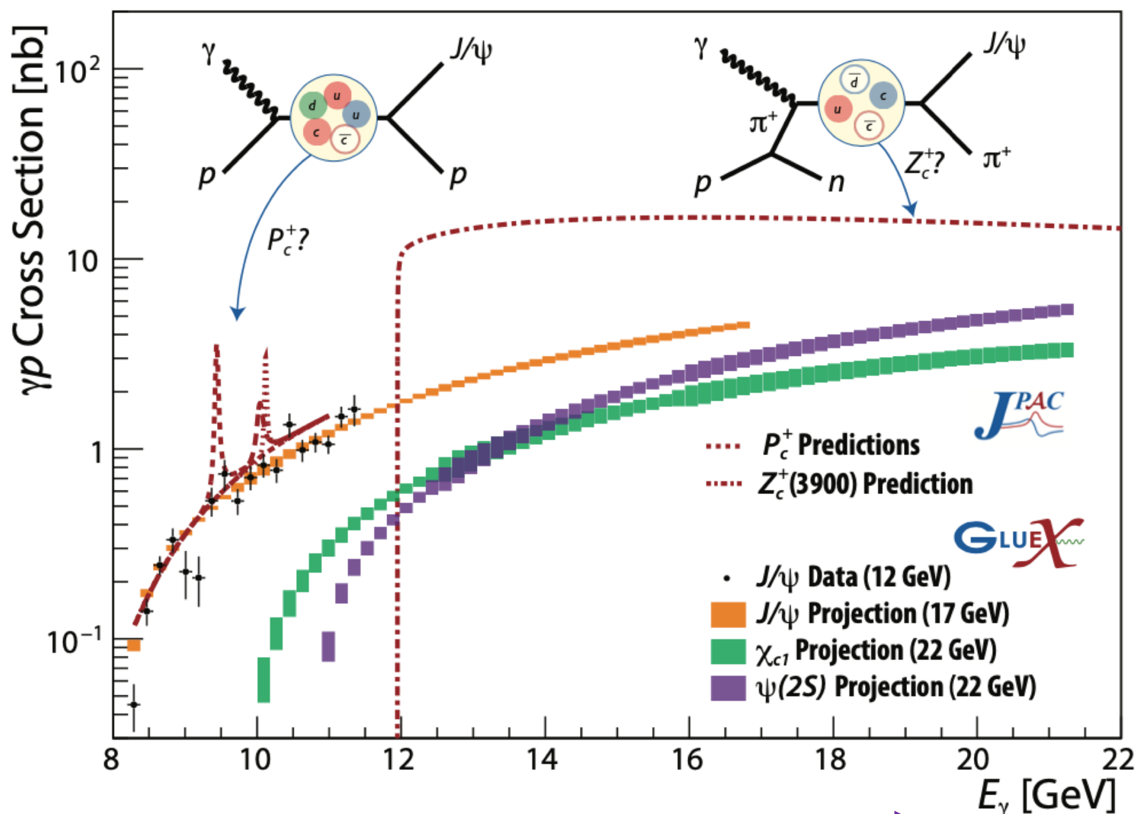

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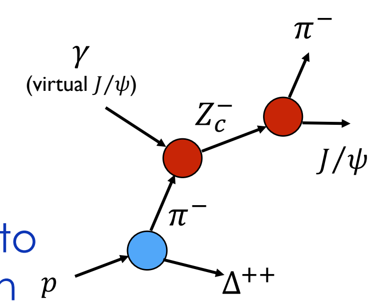

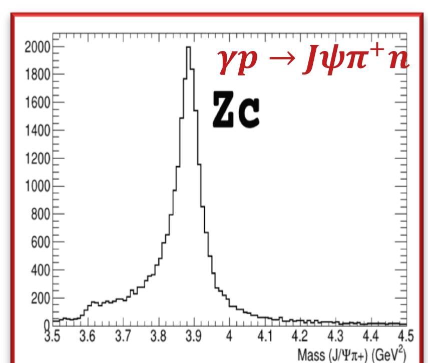

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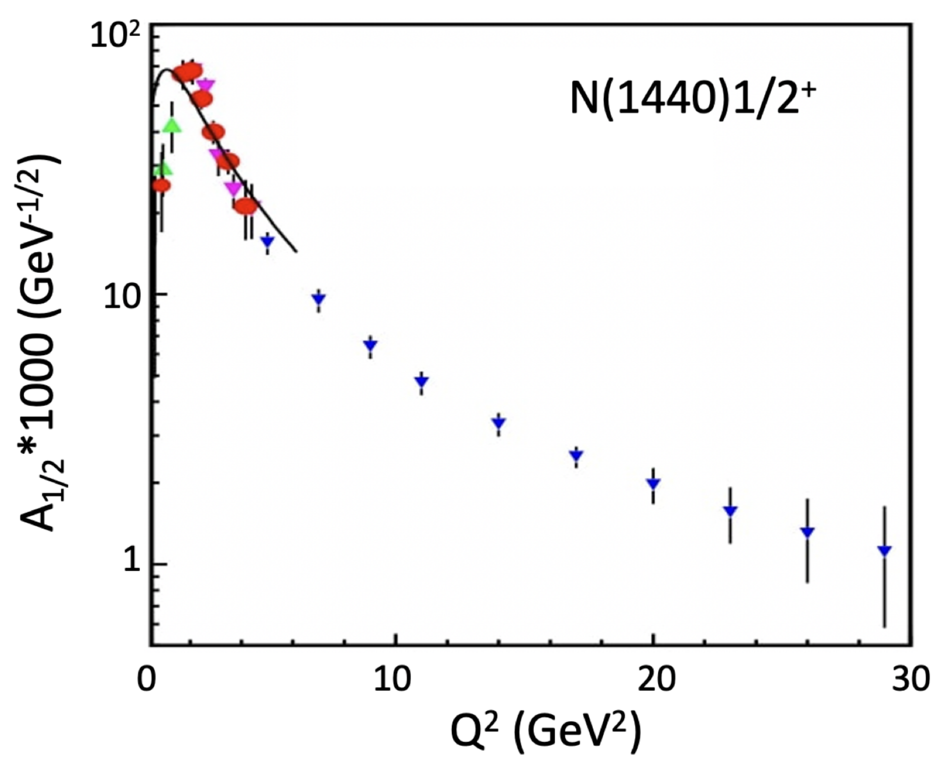
Bound 3 Quark Structure of N*s and Emergence of Mass

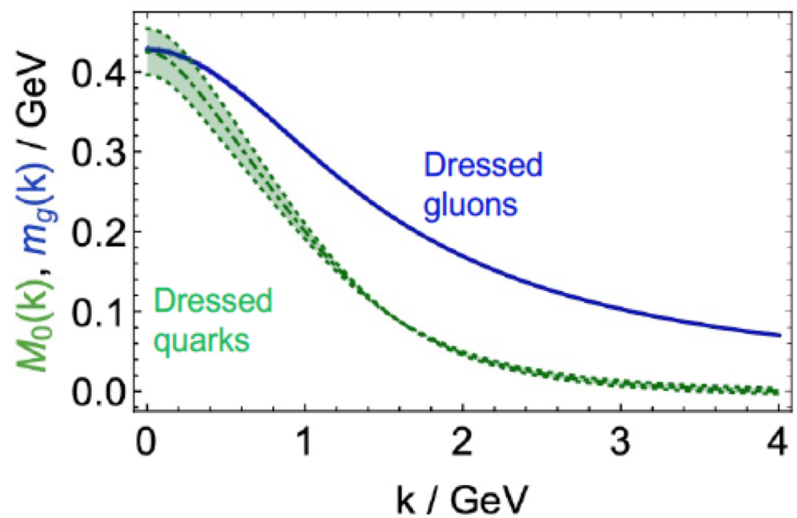


- Q^2 evolution of the $\gamma_v pN^*$ electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD

- **Simulations indicate JLab22 is the only foreseeable facility to extend these measurements up to 30 GeV^2**

Continuum Schwinger Method

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



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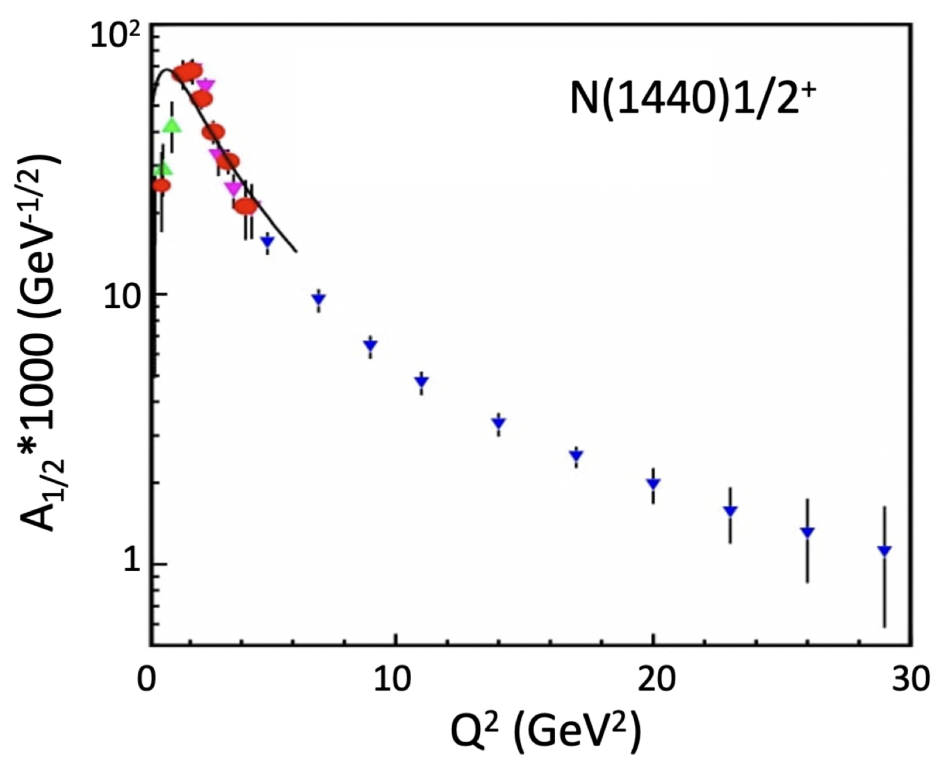

- Q^2 evolution of the γvpN* electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD

- **Simulations indicate JLab22 is the only foreseeable facility to extend these measurements up to 30 GeV²**

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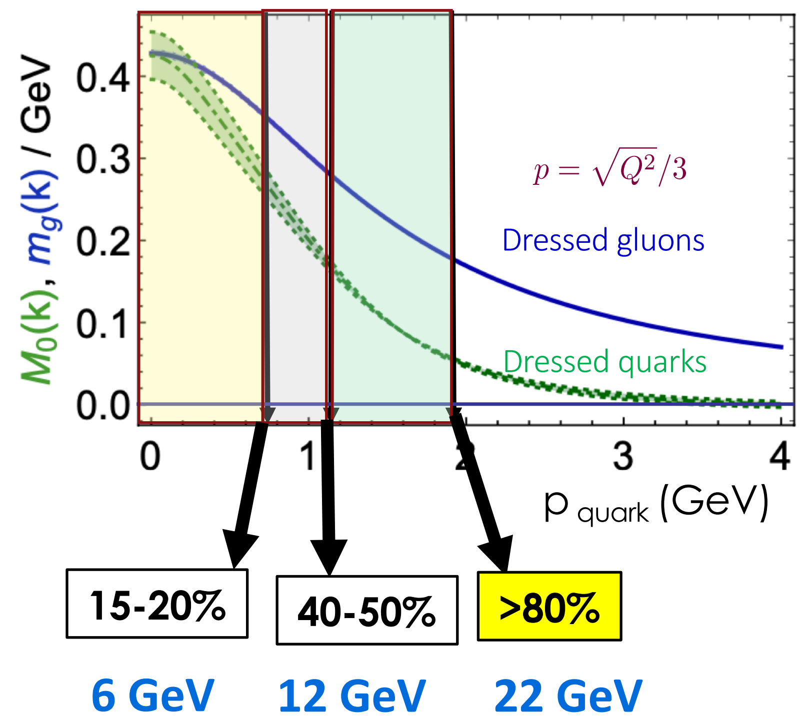


Q² range(<35 GeV²) where the dominant portion of hadron mass is expected to be generated

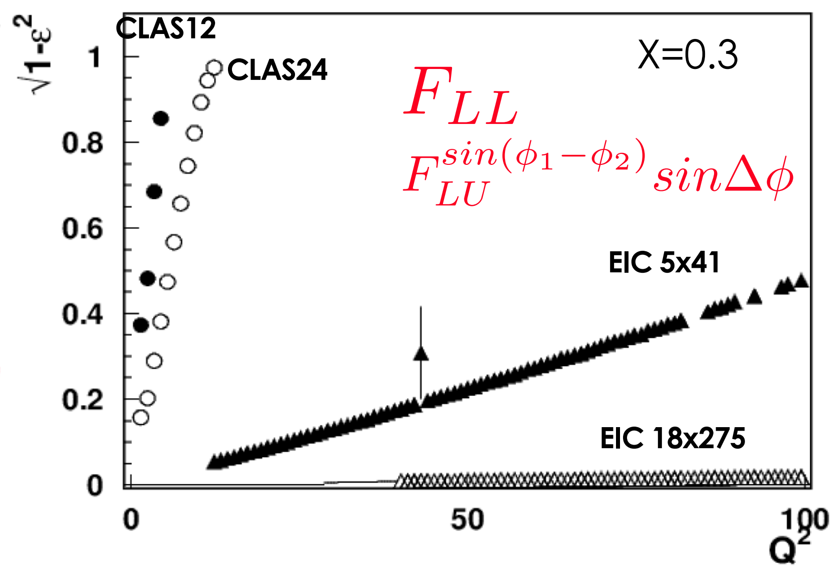
Nucleon Structure in 3D

SIDIS cross section

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

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

- Separation of SFs highly non-trivial!
- At large x fixed target experiments are sensitive to **ALL** structure functions



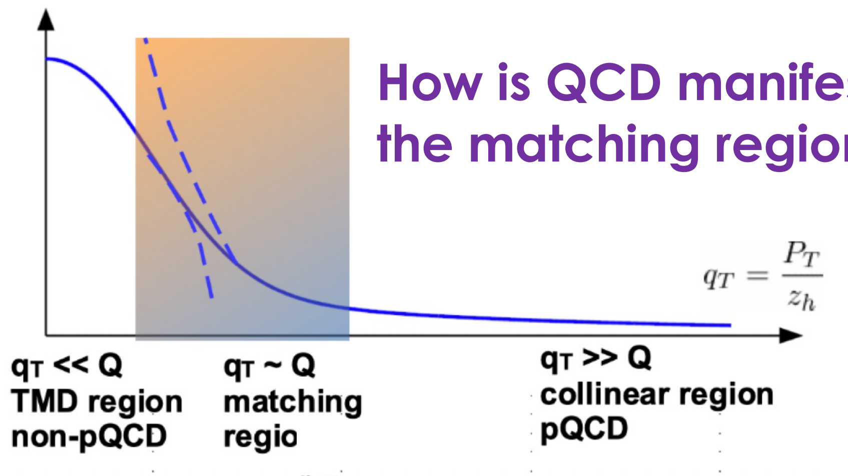
<u>A combined 11, 22 GeV and EIC SIDIS program</u>

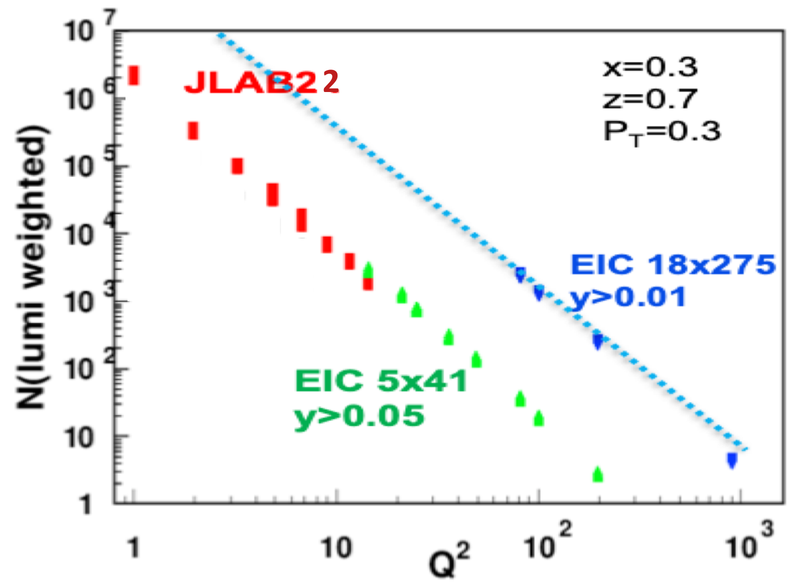
will increase our ability to measure a variety of SIDIS SFs across an enhanced multidimensional phase space – the only way to test and validate our understanding and interpretation of SIDIS reactions.

SIDIS Phase Space at 22 GeV

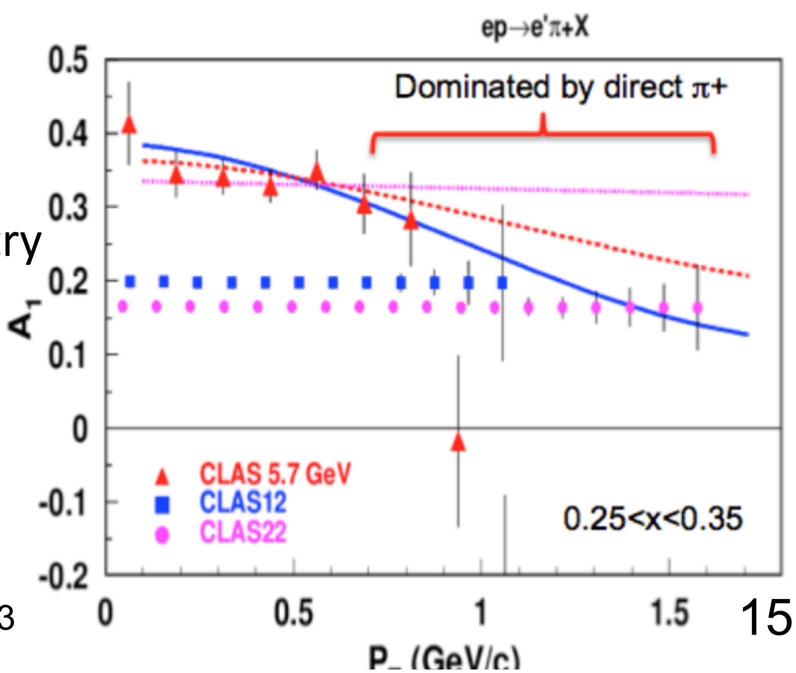
QCD predicts only the Q^2-dependence

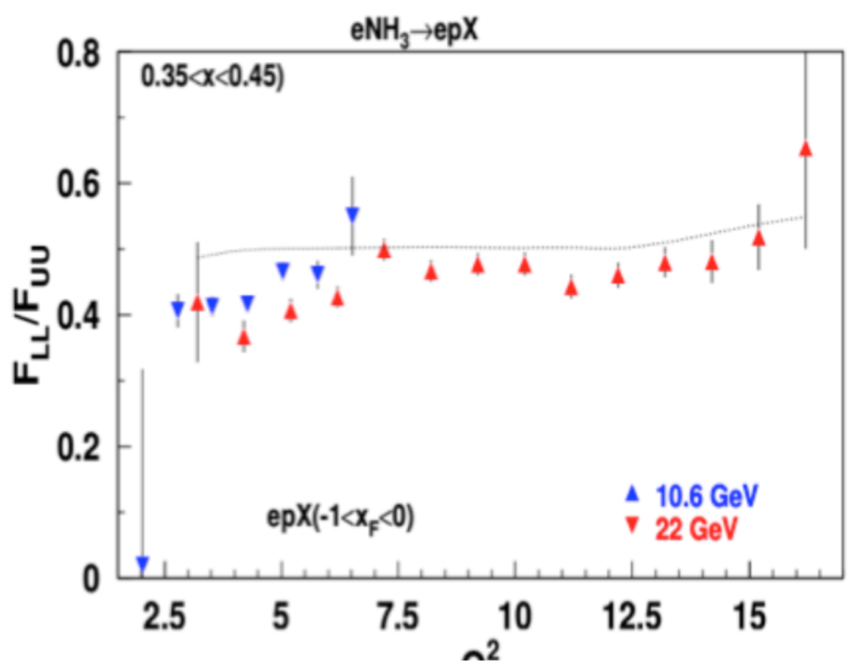
How is QCD manifested in the matching region?



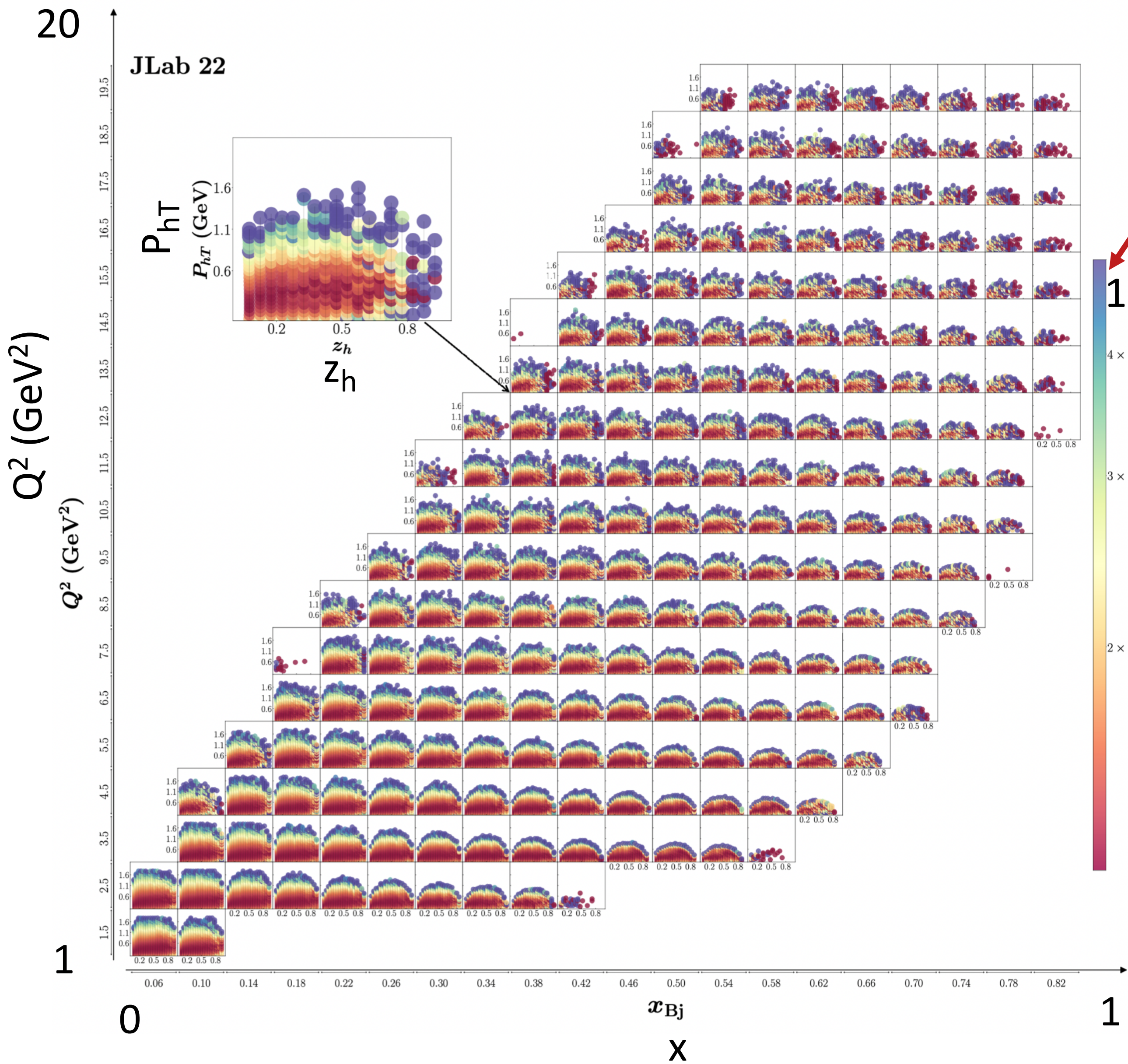


double spin asymmetry





SIDIS Phase Space at 22 GeV



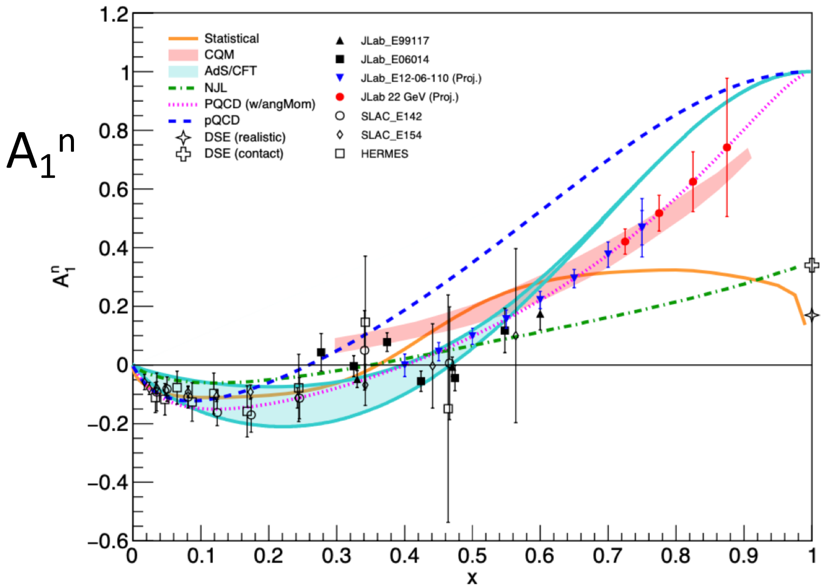
Expected uncertainties for SIDIS cross sections in 4D bins

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 $\mathcal{L}= 10^{35}$ cm^{2}s^{-1}

Polarized Structure Functions and α_s

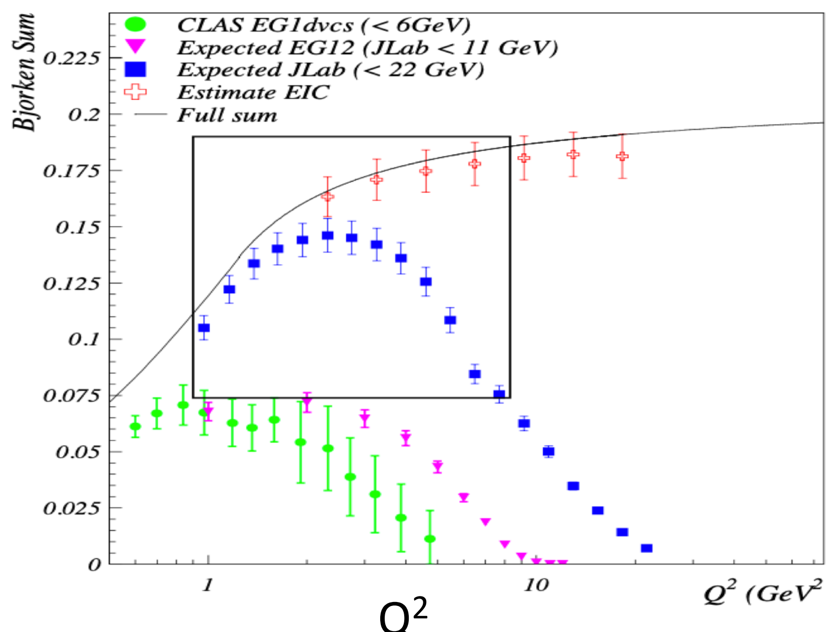


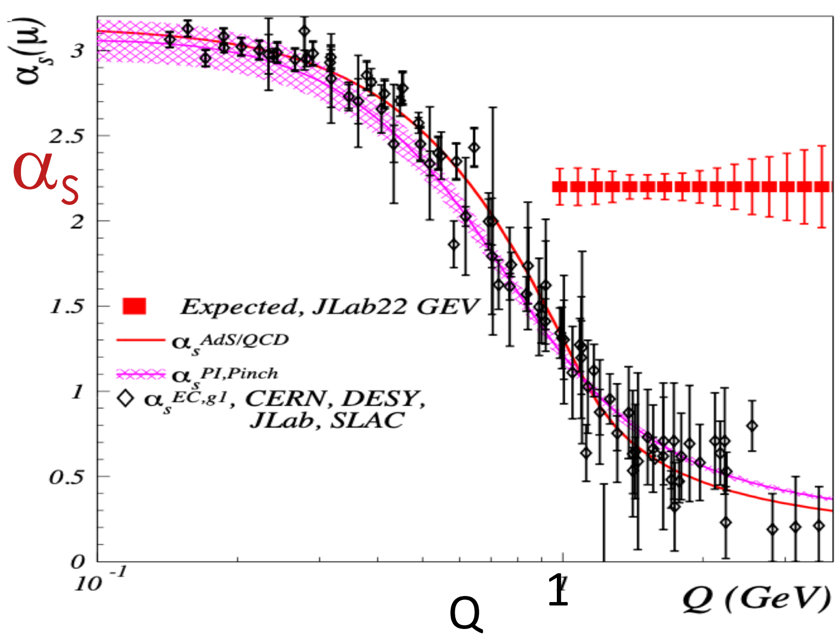
Extend the precision and kinematic reach of polarized structure functions

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



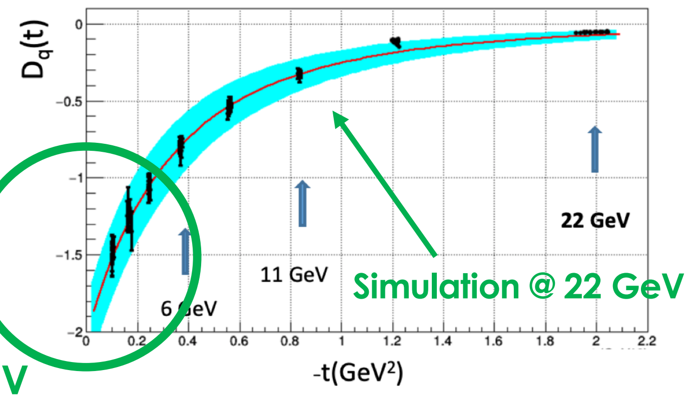


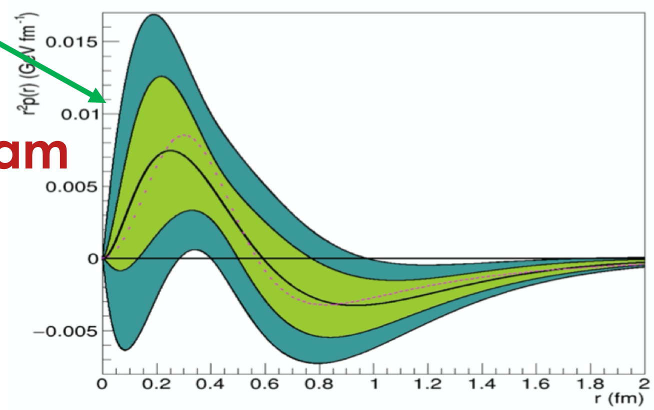
Spacial Structure & Mechanical Properties of the Proton

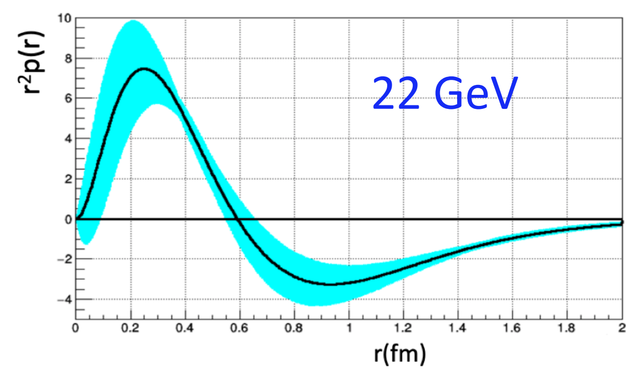
- Form Factors: source of information on hadron structure
- Gravitational FFs (GFFs) : describe how energy, spin, and various mechanical properties of hadrons are carried by q/g constituents.
- GFF D(t): describes the pressure distribution in the nucleon. It is accessible through measurements of the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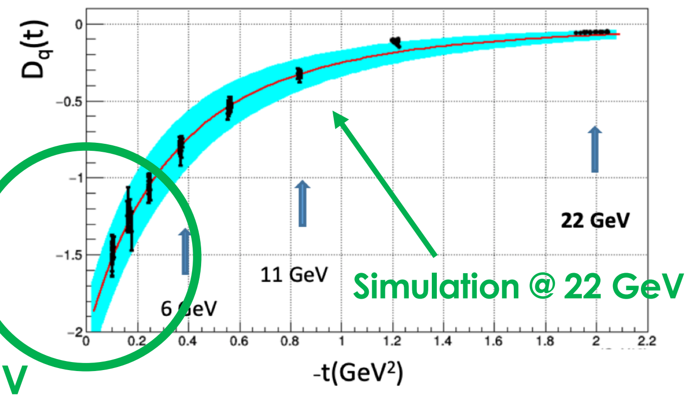

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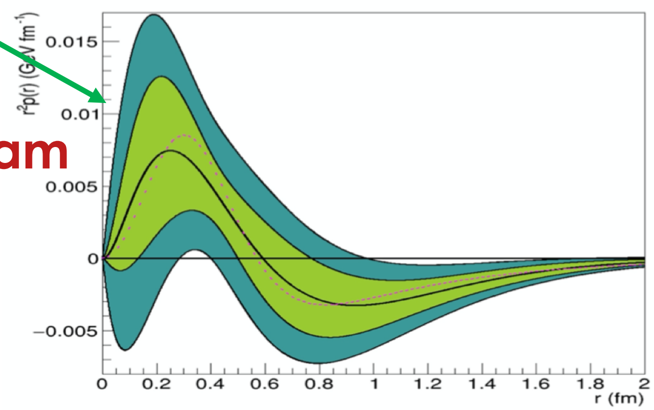
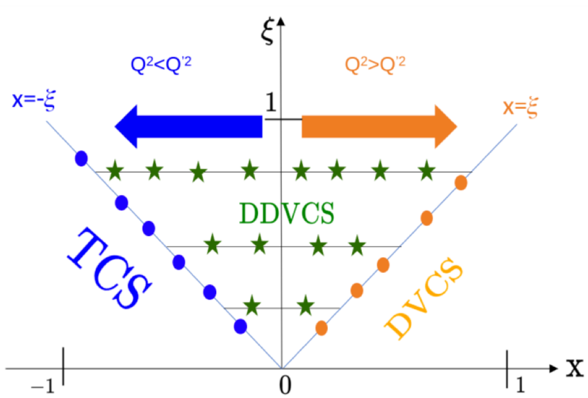
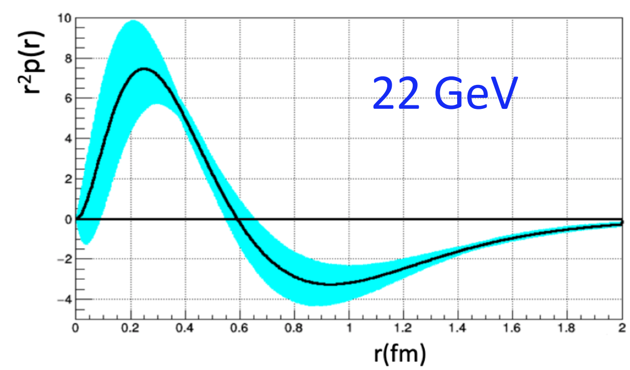


Double DVCS (DDVCS)



NEVER been measured (very small cross section).➜ **JLAB with high luminosity will be the only place to measure this reaction.**



Jefferson Lab

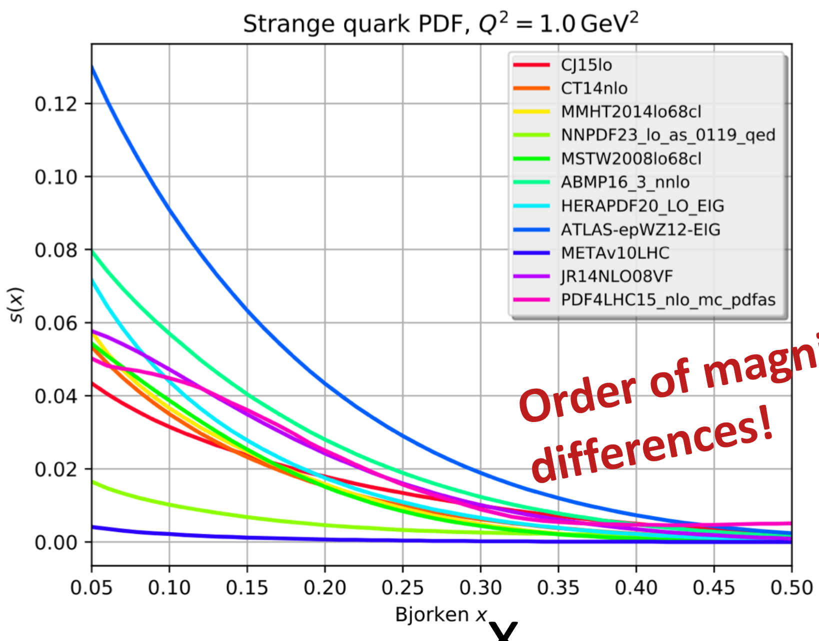
Unambiguous Access to Strange Quarks

Current Situation

- **di-muon production in neutrino-nucleus scattering** – *nuclear corrections introduce significant uncertainty*
- **W and Z rapidity distributions**
- **W+c production**

LHC results inconclusive

- **Semi-inclusive K production:** *choice of fragmentation function negates inclusion in global fits*
- ***JLab12 Q^2 too low for PDF analysis***



X

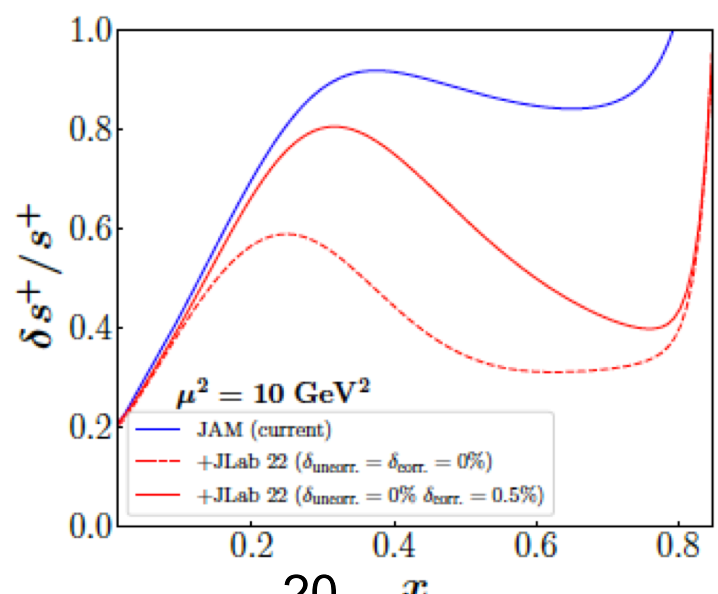
Order of magnitude differences!

Parity-violating DIS

- **Parity-violating DIS allows strange contribution to be isolated when 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 more than a factor two at large-x**



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

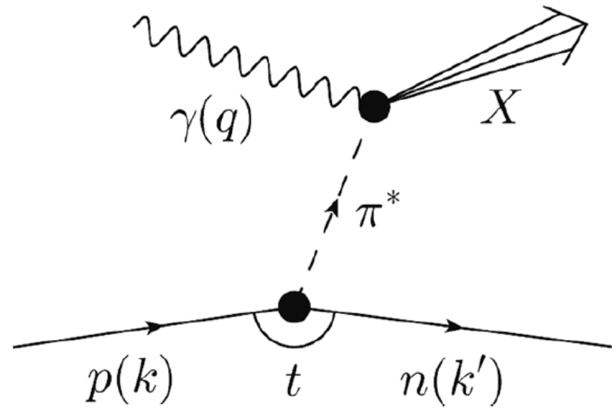
rson Lab

Partonic Structure of Mesons

Meson structure

- Tagged deep inelastic scattering (TDIS) provides a mechanism to access the meson structure via the Sullivan process .

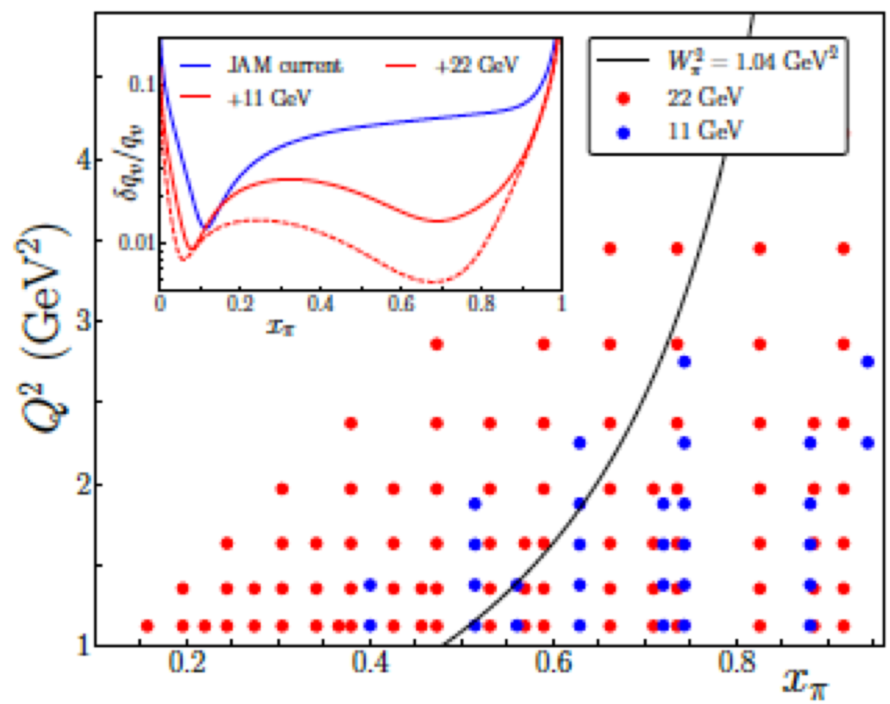
- A cut of $W^2\ \pi > 1.04\ \mathrm{GeV}^2$ (to avoid contributions from resonances in a pion analysis,) eliminates most of the data at 11 GeV.



<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

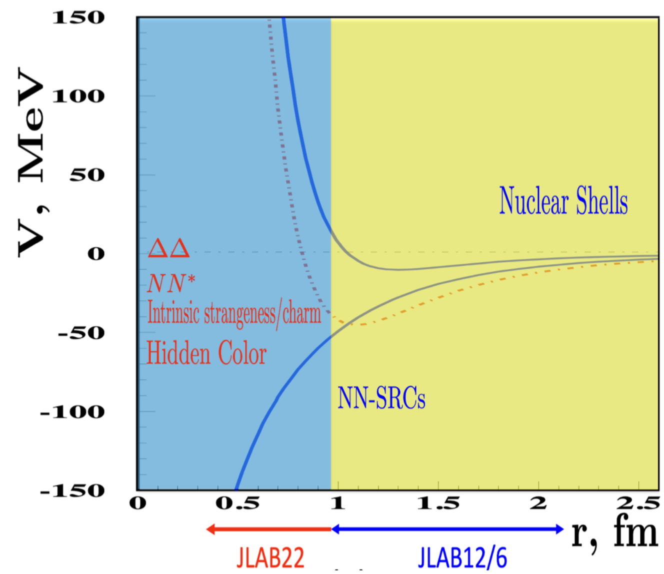
- Overlap the existing π induced DY data
  ➔ test the universality of PDFs in the mid to large x_π region
  ➔ pion PDF predicted to be broader than the proton PDF



Nuclear Dynamics at Extreme Conditions

The dynamics of the nuclear repulsive core is still poorly understood

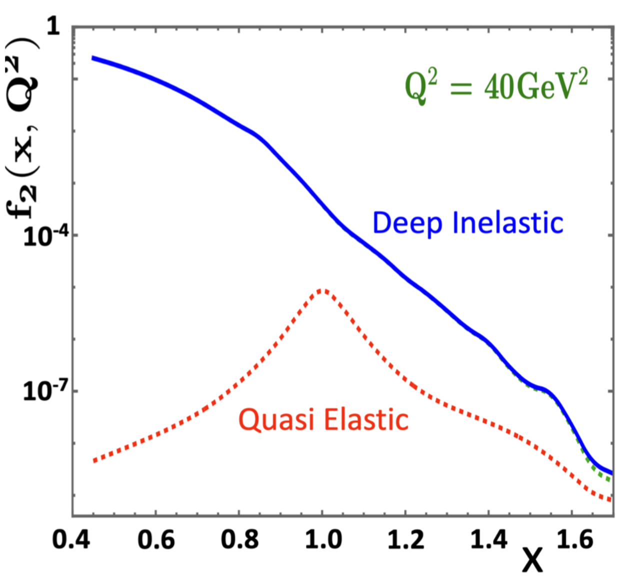
A 22 GeV upgrade will provide reach to the nuclear forces dominated by nuclear repulsion



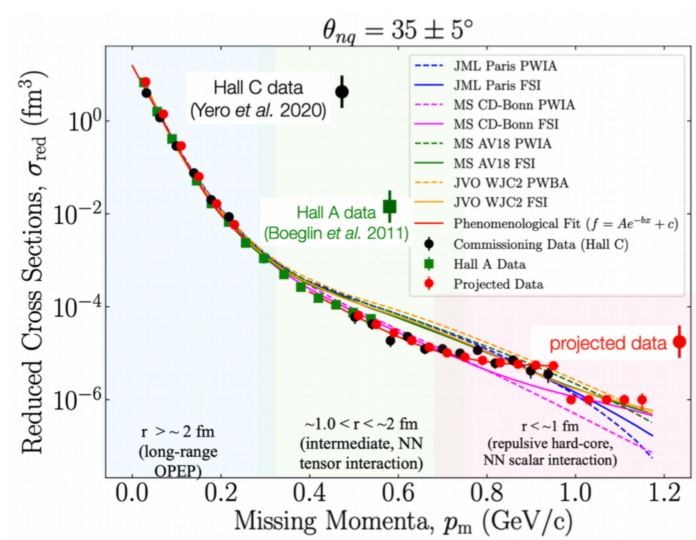
Superfast Quarks

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
- <u>no model</u> reproduces data (non-nucleonic degrees of freedom?, quarks?) pm > 0.7 GeV/c

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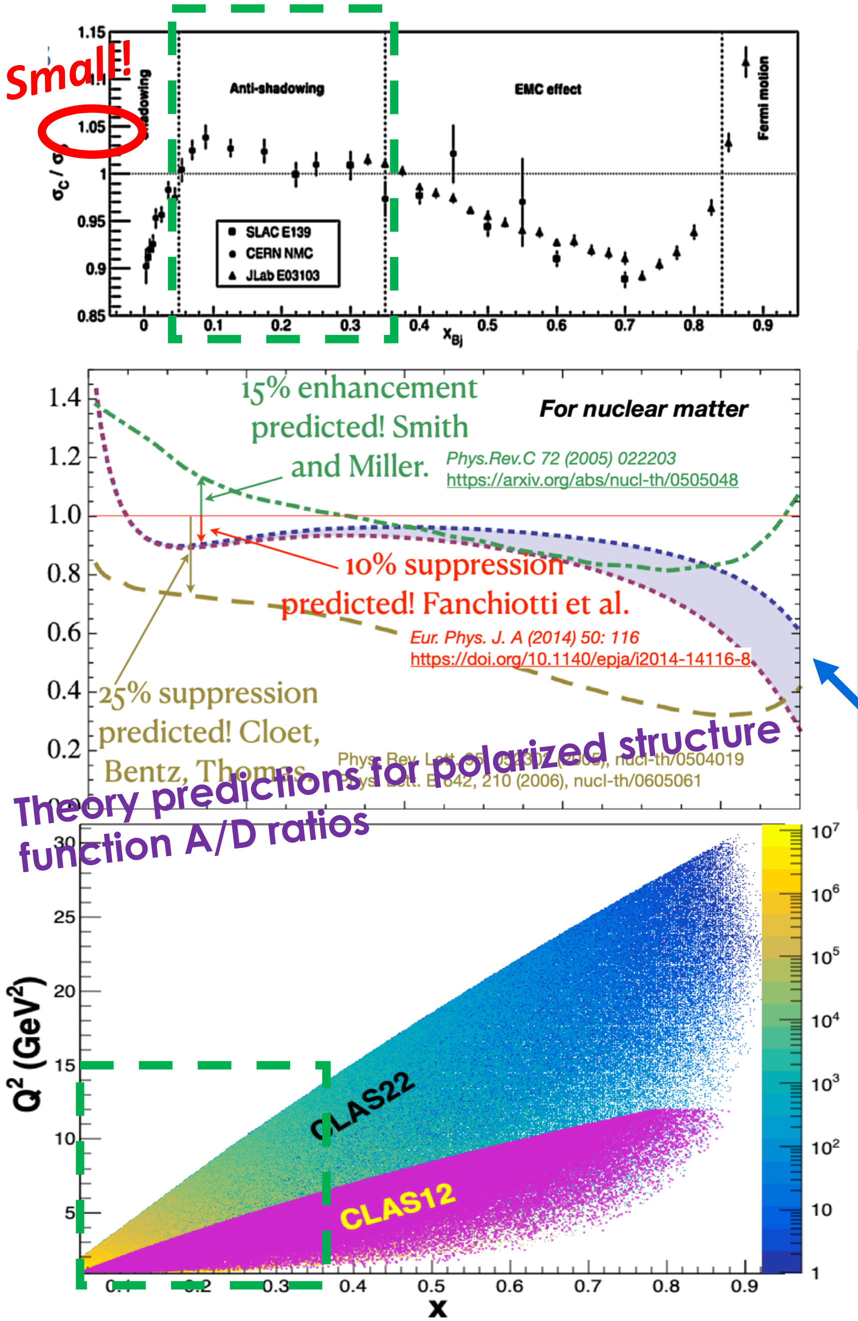
Anti-shadowing: solving a multi-decade puzzle

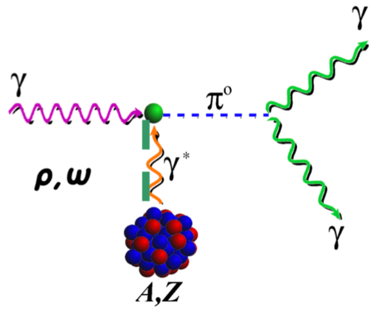


With a 22 GeV e- beam JLab can access the anti-shadowing region (x~0.1-0.3) at moderate Q^2

- 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

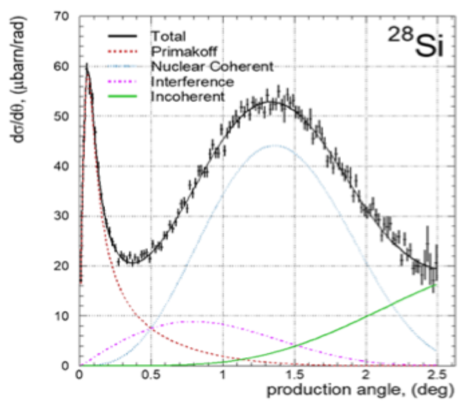
A rigorous testing ground between shadowing, EMC regimes – models and theory must describe **ALL**

QCD Confinement and Fundamental Symmetries



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

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



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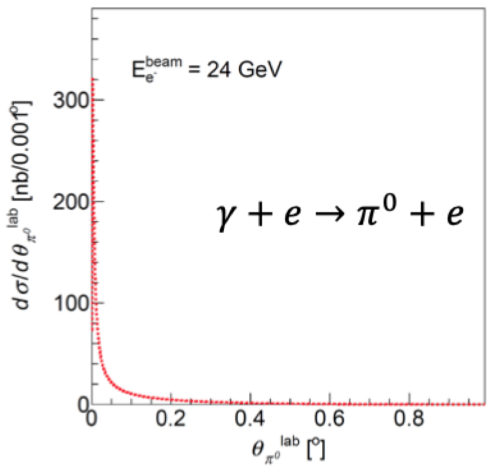
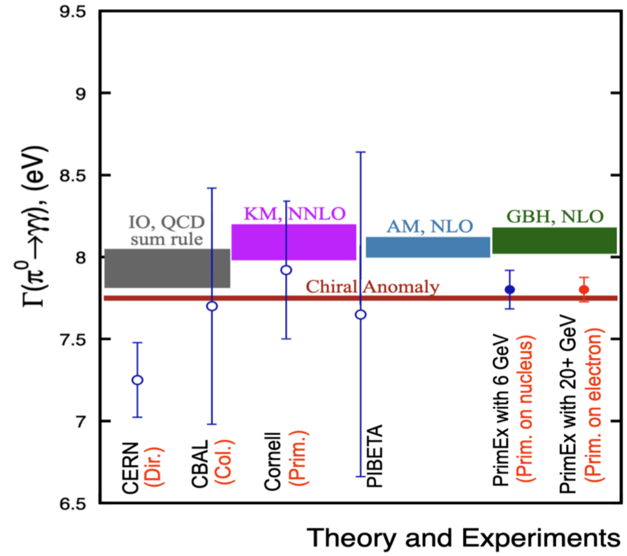
Higher energy will allow for η'



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 $\Gamma(\eta' \rightarrow \gamma\gamma)$** with ~3.5% precision to study the U(1)A anomaly coupling to the gluon field,

➡ **improve the measurement of $\Gamma(\eta \rightarrow \gamma\gamma)$** to a 2% accuracy to determine the light-quark mass ratio

Conclusions and 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

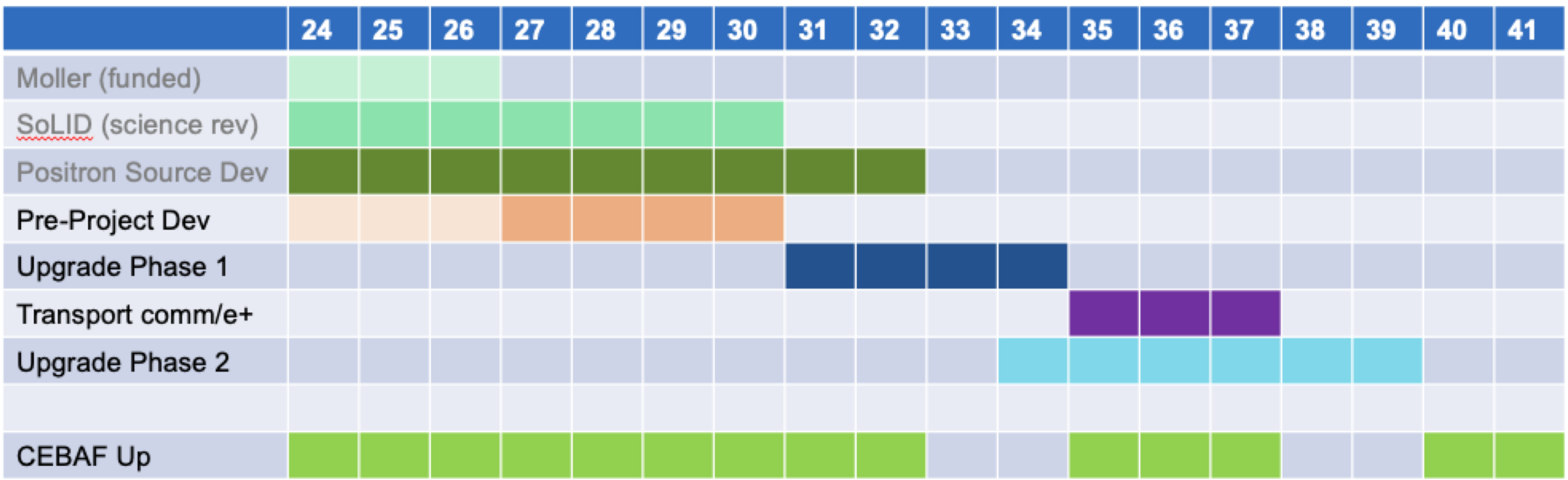
Polarized gluon distribution, longitudinal/transverse separations, hadron formation in nuclei, meson form factors, probing the light quark sea,……. and more!

Thank you!

Thank you for listening, and thanks also to the scientific community (400+) working on developing this exciting science case

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



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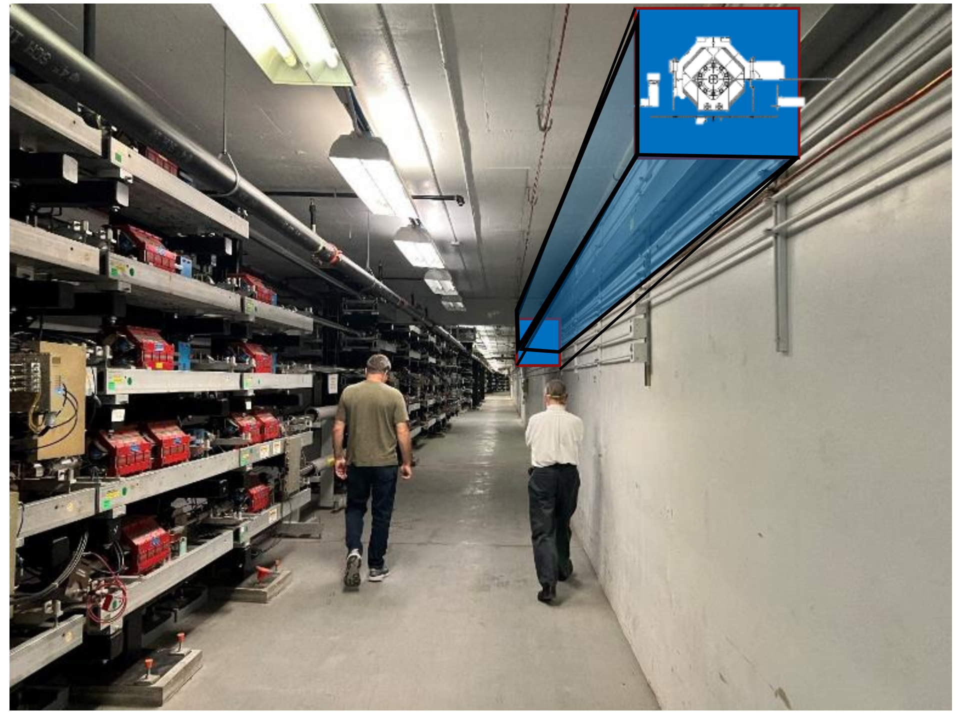
Transport and Upgrade CEBAF to 22 GeV

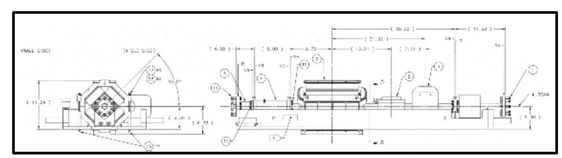
- Remove top pass of Dipoles and Quad girders
- All passes of Dipoles and Quad girders move up one level for FFA arc installation



- 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]	$\Delta\varepsilon_N^{arc}[m\ rad]$	$\Delta\sigma_{\Delta E/E}$
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