QNP2024 - The 10th International Conference on Quarks and Nuclear Physics

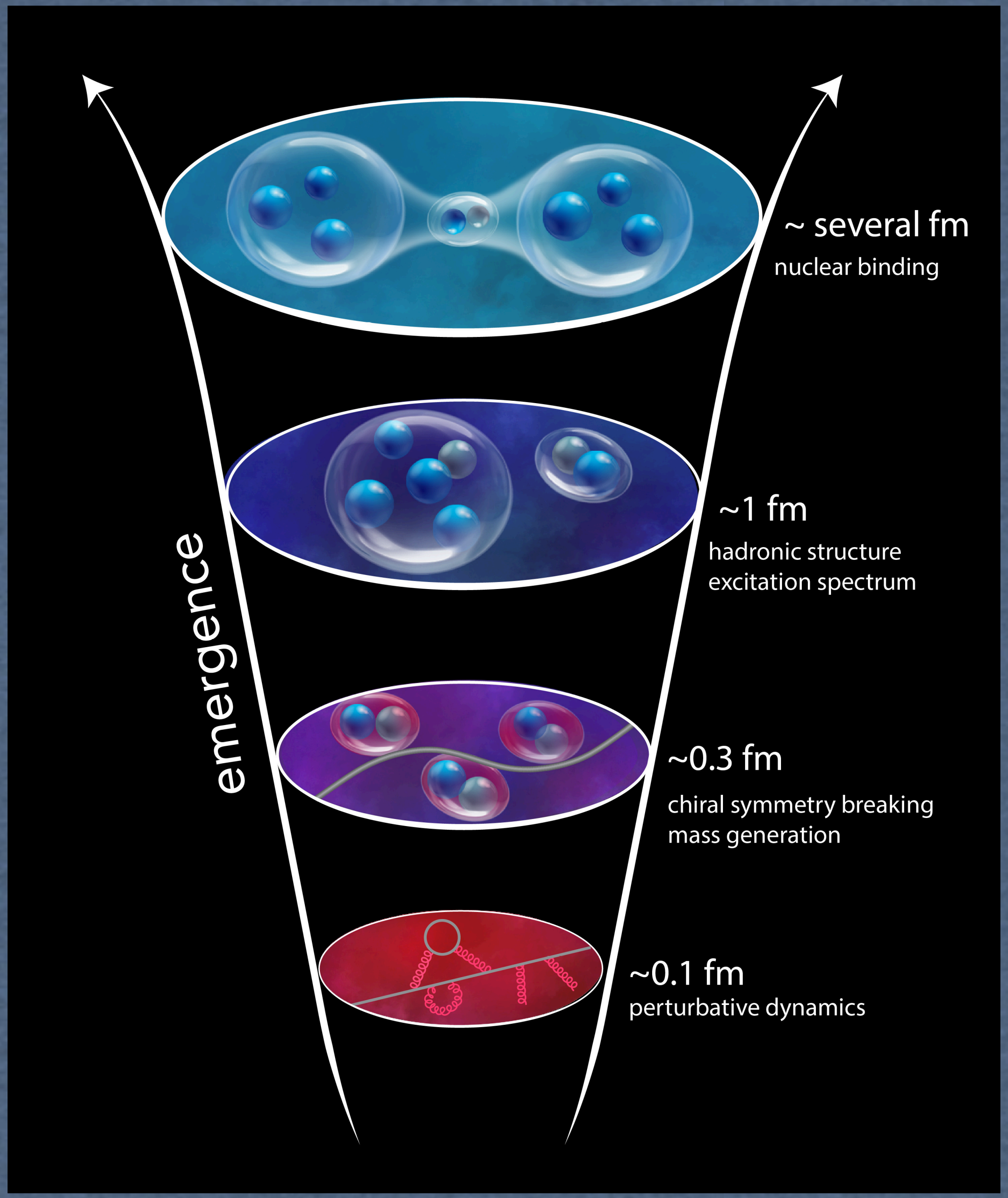
8–12 Jul 2024
Facultat de Biologia, Universitat de Barcelona

QNP 2024

# QCD at intensity frontier: 22 GeV electrons at Jefferson Lab

*M.Battaglieri (INFN)*

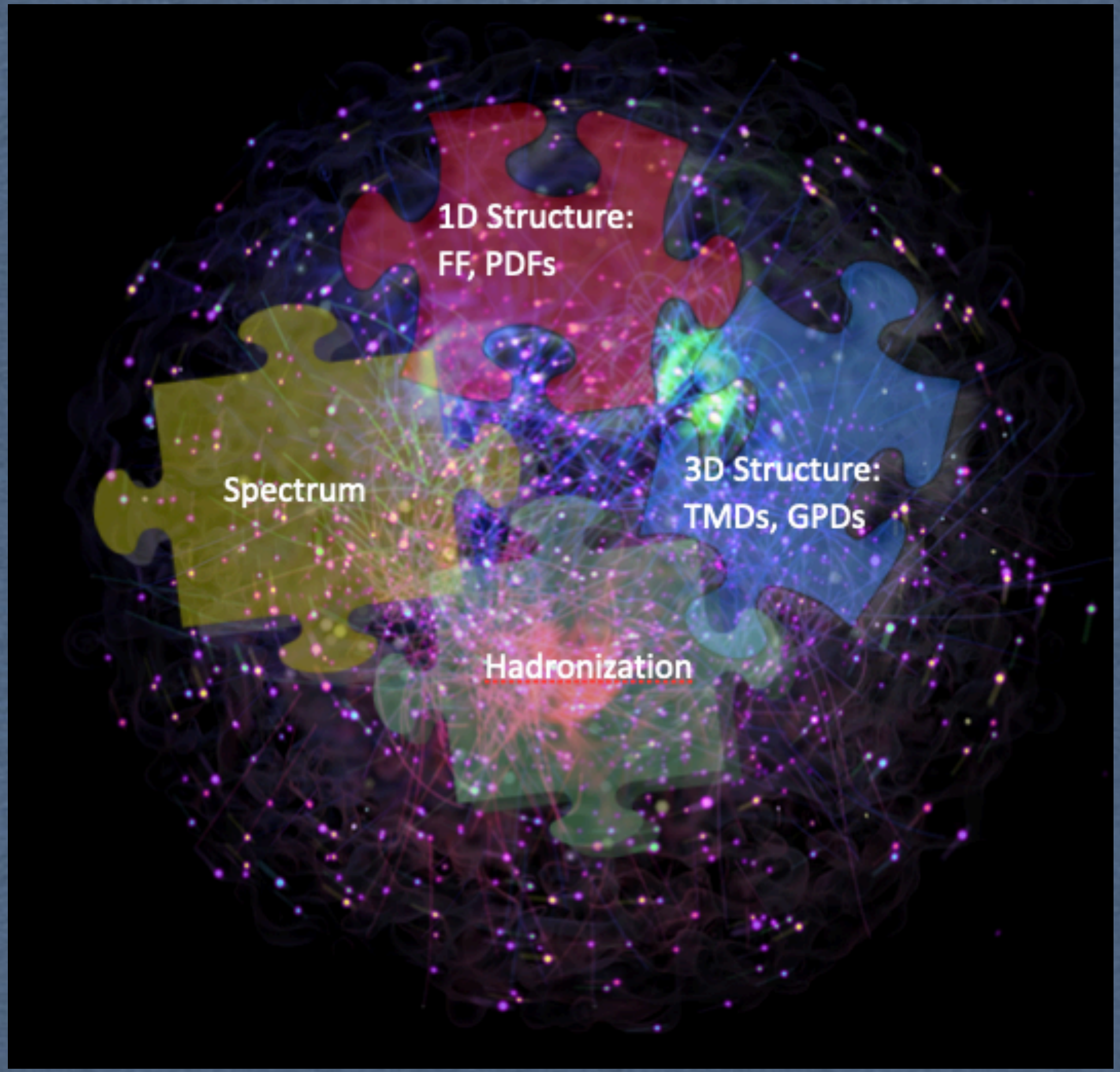
*Jefferson Lab's accelerator site*




# Emergent phenomena in QCD

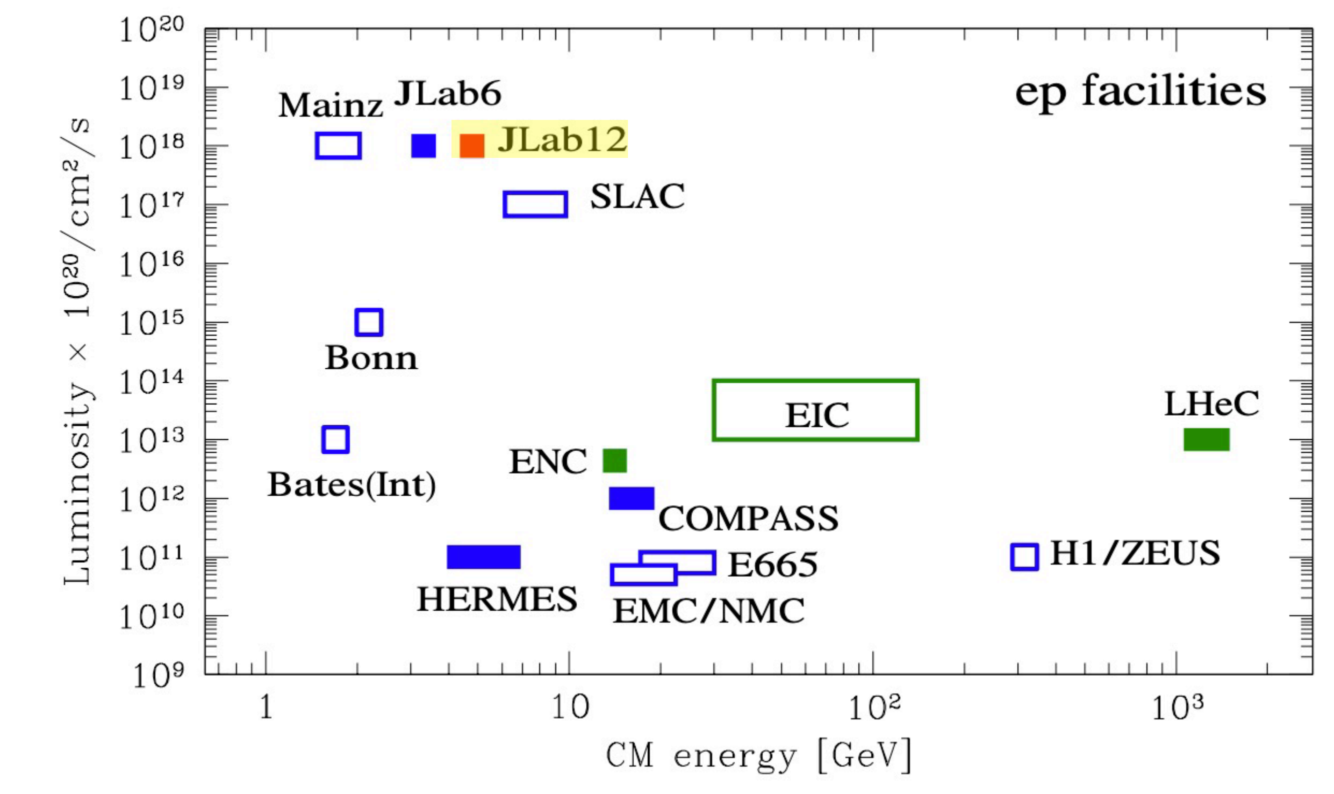
The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe." -- *More is different*, P. W. Anderson [Science 177, 393 (1972)].

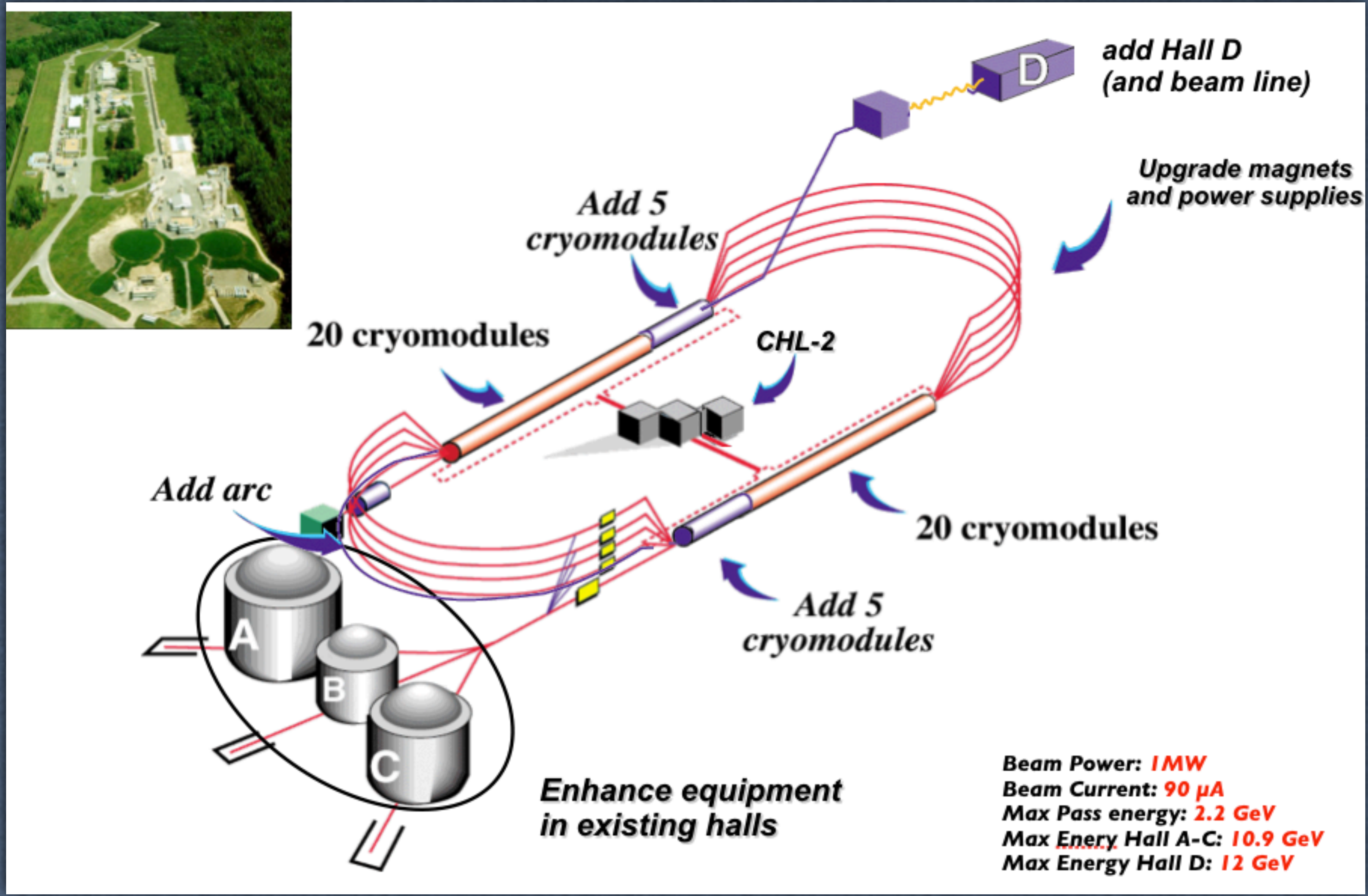
**Jefferson Lab's mission:**
**Study the emergence of hadron structure & the quarks and gluons <u>dynamics</u> in the non-pQCD regime**




- Complex and multi-faced problem requiring multiple observables sensitive to different characteristics of the hadron structure
- Keyword: **PRECISION →** **HIGH INTENSITY FRONTIER**

# Jefferson Lab
# The intensity frontier


✳Primary Beam: Electrons

✳ Beam Energy: 12 GeV

- 10 > λ > 0.1 fm
- nucleon → quark transition
- baryon and meson excited states

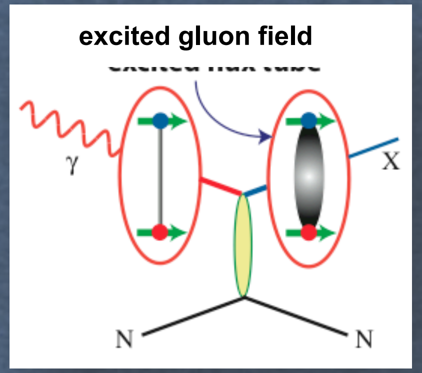
✳100% Duty Factor (CW) Beam

- coincidence experiments
- Four simultaneous beams
- Independent E and I

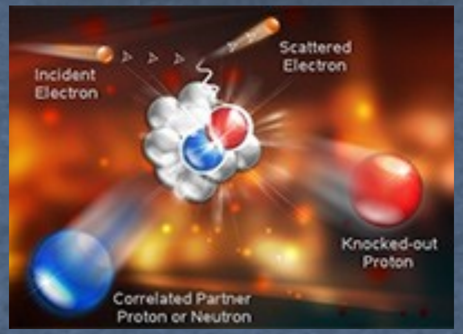
✳ Polarization

- spin degrees of freedom
- weak neutral currents

# Open questions in non-pQCD

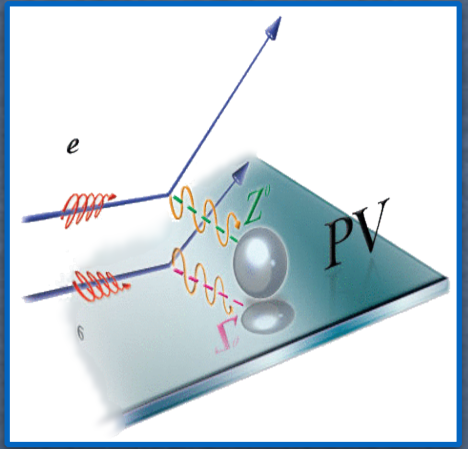



- What is the role of gluonic excitations in the spectroscopy of light mesons?
- Where is the missing spin in the nucleon? Role of orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?




**12 GeV experimental program is in full swing**

- 33 experiments completed out of 91 approved
- ~8 years of physics ahead (~30 weeks/year)



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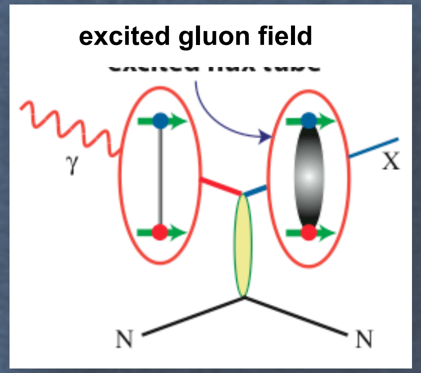


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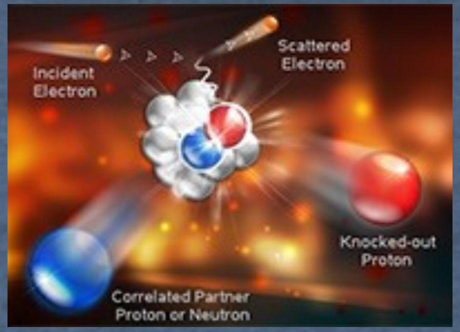
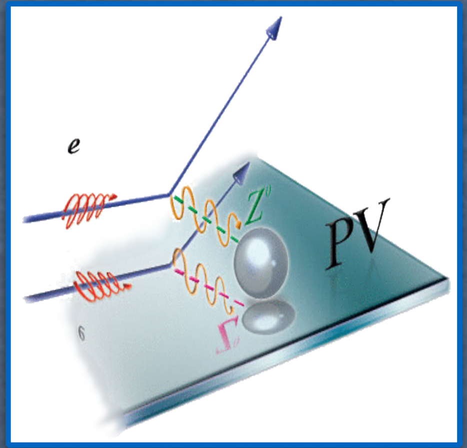



**Future opportunities at CEBAF**

| | |
|---|---|
| • High luminosity | 12 GeV era |
| • Higher Energy | This talk |
| • Positron beam | Not discussed |



# Why JLab@22 GeV?

CEBAF delivers the world's highest intensity and highest precision multi-GeV electron beams and has been do so for more than 25 years

- **A new territory to explore**
  - charm + light quarks in the same experiment
- **A better insight into our current program**
  - enhancement of the phase space
- **A bridge between JLab @ 12GeV and EIC**
  - low to high energy theory validation with high precision

- Leverage the uniqueness of JLab at 12 GeV
- Utilize largely existing or already-planned experimental halls equipment
- Take advantage of recent novel advances in accelerator technology

CEBAF $E_{beam}$ upgrades: 4 GeV and 6 GeV soon later. 12 GeV program undergoing
22 GeV will be the next step

# The (long) way to JLab @ 22 GeV

# J-FUTURE

March 28, 2022 - March 30, 2022 • Messina, Italy

TOPICS

- Physics opportunities
- Hadron spectroscopy
- Nucleon structure
- Nuclear structure
- Detector developments
- Accelerator infrastructures

ORGANIZERS

ABSTRACT

While the JLab 12 GeV program is runnin
time to plan the future developments for

A new round of upgrades to CEBAF are u
development. One of these is a potential
to 24 GeV using novel magnet designs in
recirculation arcs. Another is a potential
polarized beams of electrons or positrons
allow for new measurements in nucleon
provide precision extraction of contributi
order electromagnetic currents, and allov
the standard model. In addition, it is poss
research lines using secondary beams.

The workshop will gather theorists and e
to discuss the physics opportunities for e
scenarios.

Jefferson Lab

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Program and abstract submission on: htt

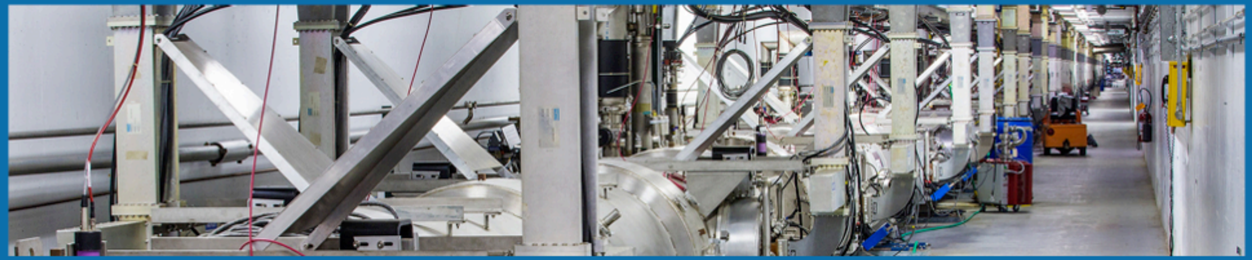
## HIGH ENERGY WORKSHOP SERIES 2022

We are pleased to announce an upcoming series of summer workshops being organized jointly between the laboratory and the Jeffe
Organization (JLUO) to probe the science that would be opened up by a higher energy electron beam (~20-24 GeV) at Jefferson Lab.
interested in identifying key measurements that are not possible to access at 12 GeV, that initially utilize largely existing or already-pla
and that leverage the unique capabilities of luminosity and precision possible at Jefferson Lab in the EIC era.

**Organizing Committee:**

Ed Brash, JLUO Chair - David Dean - Carlos Munoz Camacho - Thia Keppel - Bob McKeown - Kent Paschke - Jianwei Qiu - Patrizia Ro

## SCIENCE AT THE LUMINOSITY FRONTIER: JEFFERSON LAB AT 22 GEV



## APCTP Focus Program in Nuclear Physics 2022: Hadron Physics Opportunities with JLab Energy and Luminosity Upgrade

Jul 18 – 23, 2022
APCTP, Pohang
Asia/Seoul timezone

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- Overview
- Call for Abstracts
- Timetable
- Contribution List
- Registration
- Participant List
- Invited Speakers
- Transportation
- Regarding COVID-19 & Visa (updated at May)
- Link to APCTP Workshop: Physics of excited hadrons

Contact

yongseok.oh@apctp.org

The electroproduction of mesons and photons has been shown to be a powerful tool for studies of the interaction of elementary particles and their dynamics at short and long distances. In particular, studies of the orbital motion of partons encoded in transverse space and momentum distributions of partons, like Generalized Parton Distributions (GPDs) and Transverse Momentum Distributions (TMDs), have been widely recognized as key objectives of the JLab 12 GeV program. Studies of azimuthal distributions of hadrons and photons in exclusive and semi-inclusive DIS (SIDIS) provide access to variety of observables widely recognized as key objectives of the COMPASS measurements, various activities at RHIC and KEK, the LHC fixed target projects (LHC spin, SMOG2@LHCb) and a driving force behind the construction of the future Electron Ion Collider (EIC). Studies of the ground and excited nucleon state structure in terms of nucleon elastic form factors, PDFs, and the $N \to N^*$ (nucleon to nucleon resonances) transition electro-excitation amplitudes offer a unique complementary opportunity to explore the evolution of active components in the structure of the ground and excited state nucleons at distances where the transition from quark-gluon confinement to the perturbative QCD regime is expected and where the dominant part of hadron mass emerges. These studies are of particular importance to address key open problems of the Standard Model on emergence of hadron mass and quark-gluon confinement. The upgraded to 24 GeV JLab, with much wider kinematical coverage, in particular at large $Q^2$, will be crucial to extend all ongoing projects at JLab, in particular studies of the 3D structure of hadrons and hadronization, pin down interaction dependent parts, providing missing deeper access to quark-gluon dynamics and opening new opportunities on studies of the charm sector and significant improvement in secondary beam capabilities.

## OPPORTUNITIES WITH ENERGY AND LUMINOS UPGRADE

26 September 2022 — 30 September 2022

**ECT* - Villa Tambosi**

Strada delle Tabarelle, 286
Trento - Italy

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The Jefferson Lab upgraded to 24~GeV, will supersede HERMES, which even after being closed already 10 years still defines the landscape of the nucleon 3D structure, collecting years of HERMES data in days. Energy upgrade of JLab will provide access to the full range of kinematics where the non-perturbative sea is expected to be significant, also opening up the phase space to access large momentum transfer and large transverse momenta of final state particles. In addition, near-threshold charmonium photoproduction will enable studies of the gluonic properties of the proton, and an extensive program at the intensity frontier will cover light and heavy quark hadron spectroscopy in a single experiment. The possibility of a positron beam with the same properties and qualities as the electron beam will be a tremendous benefit for the physics program and the production of secondary beams at JLab, for instance, $K$-long beams will also benefit enormously from the energy upgrade, providing access to much wider kinematic domains.

Science at the Luminosity Frontier: JLab at 22 GeV – JLab January 2023

# The Physics case (I)

ELSEVIER
Progress in Particle and Nuclear Physics
Volume 127, November 2022, 103985

Review

## Physics with CEBAF at 12 GeV and future opportunities

J. Arrington [a], M. Battaglieri [b o], A. Boehnlein [b], S.A. Bogacz [b], W.K. Brooks [j], E. Chudakov [b], I. Cloët [c], R. Ent [b], H. Gao [d], J. Grames [b], L. Harwood [b], X. Ji [e f], C. Keppel [b], G. Krafft [b], R.D. McKeown [b h], J. Napolitano [g], J.W. Qiu [b h], P. Rossi [b n], M. Schram [b], S. Stepanyan [b]...X. Zheng [k]

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https://doi.org/10.1016/j.ppnp.2022.103985

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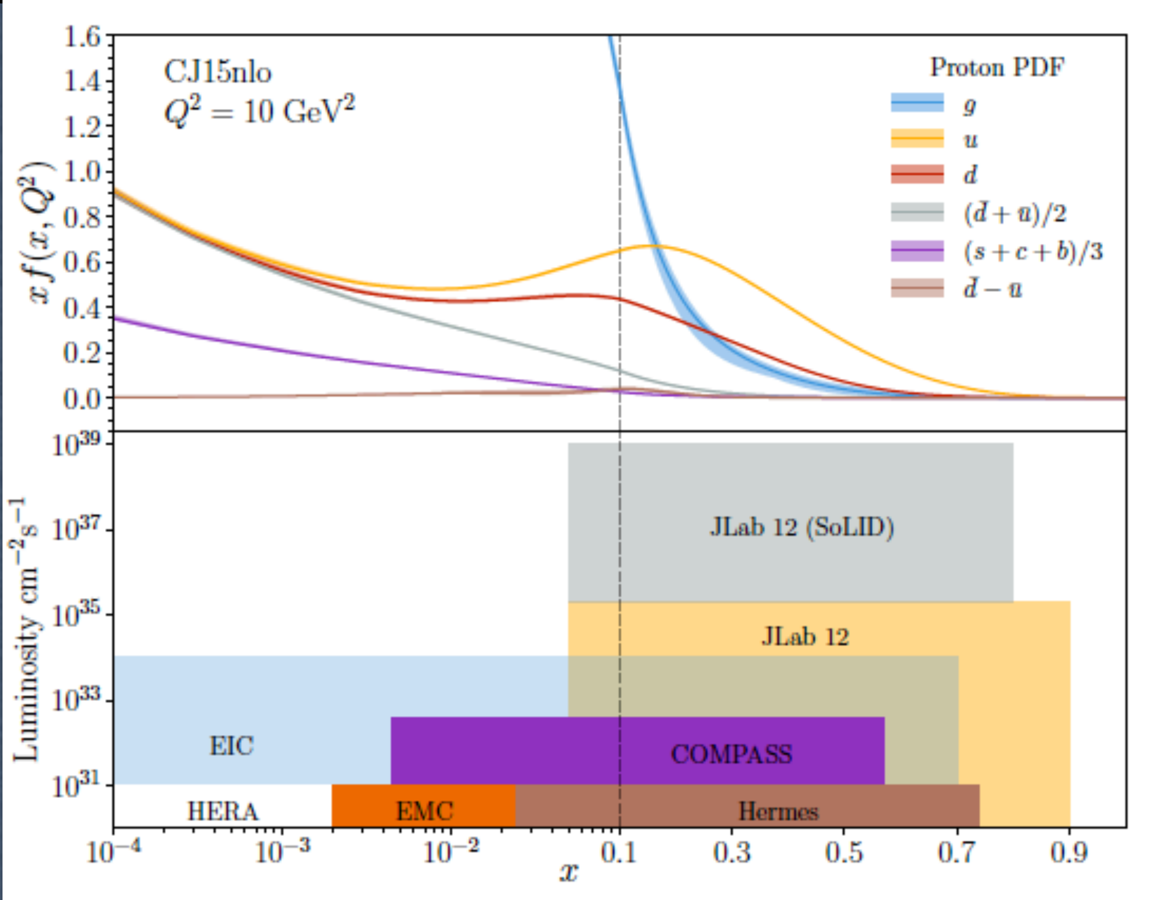
### Abstract

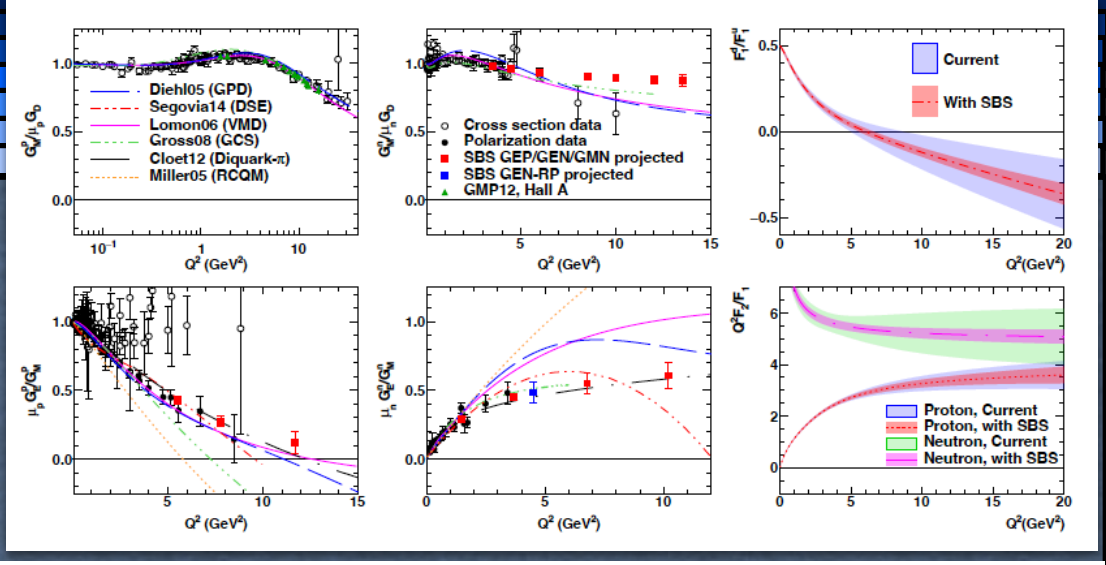
We summarize the ongoing scientific program of the 12 GeV Continuous Electron Beam Accelerator Facility (CEBAF) and give an outlook into future opportunities. The program addresses important topics in nuclear, hadronic, and electroweak physics, including nuclear femtography, meson and baryon spectroscopy, quarks and gluons in nuclei, precision tests of the standard model and dark sector searches. Potential upgrades of CEBAF and their impact on scientific reach are discussed, such as higher luminosity, the addition of polarized and unpolarized positron beams, and doubling the beam energy.

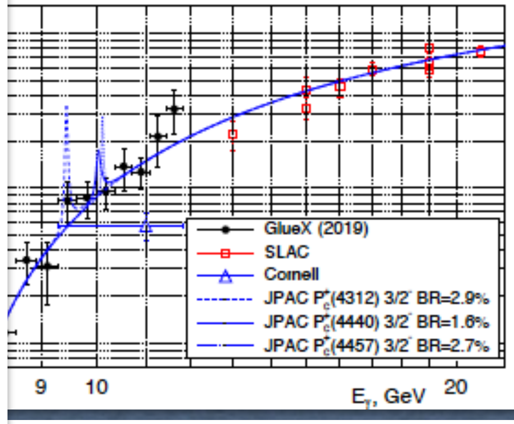
### Section snippets

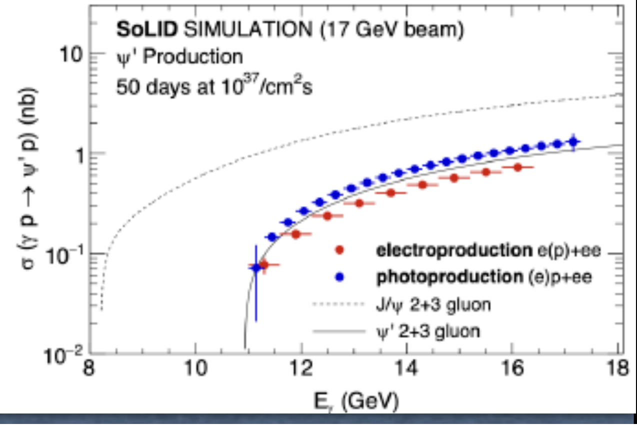
### Overview

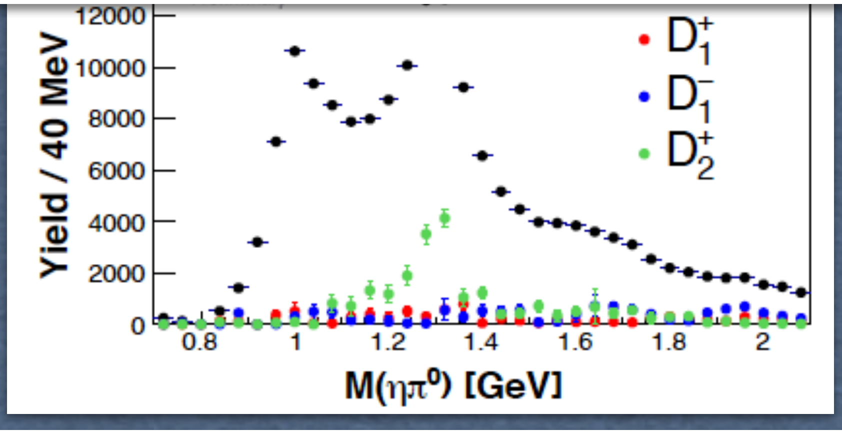
The ability to predict and understand the properties of nucleons and atomic nuclei from the first principles of Quantum Chromodynamics (QCD) with quarks and gluons as the underlying degrees of freedom is one of the goals of modern nuclear physics. Electron scattering at multi-GeV energies – with resolutions ten times or more smaller than the size of the proton – is a powerful microscope for probing the partonic structure and QCD dynamics of the nucleons and nuclei. With recent advances in...

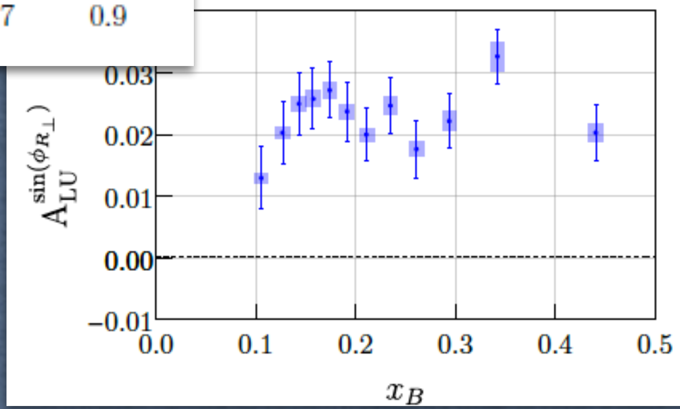


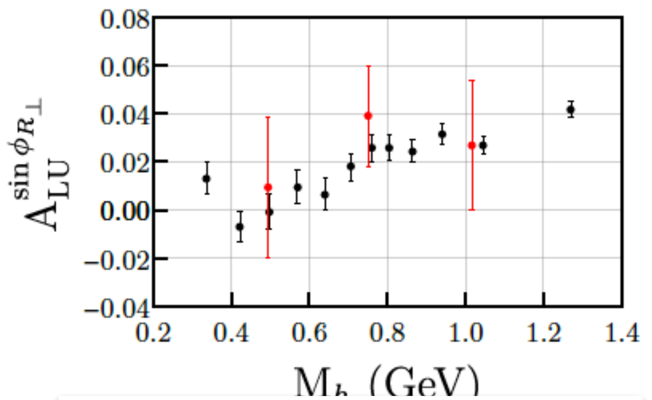



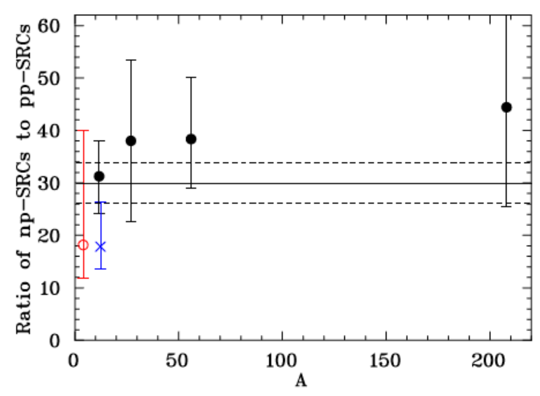



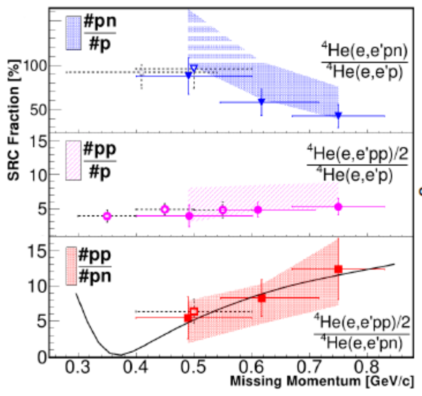



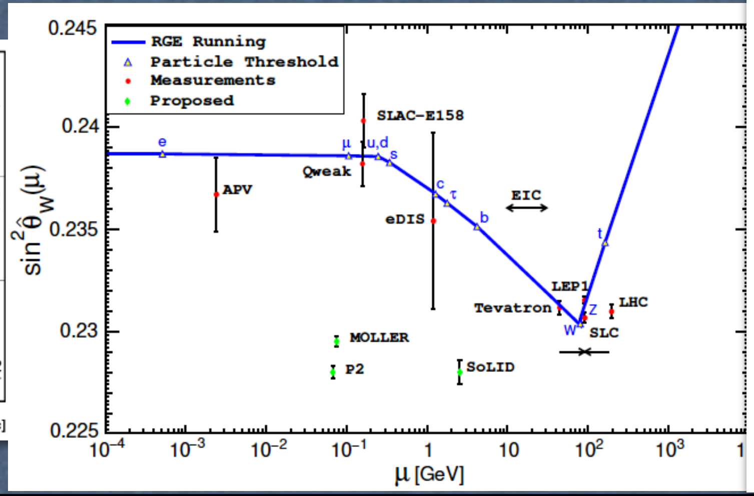



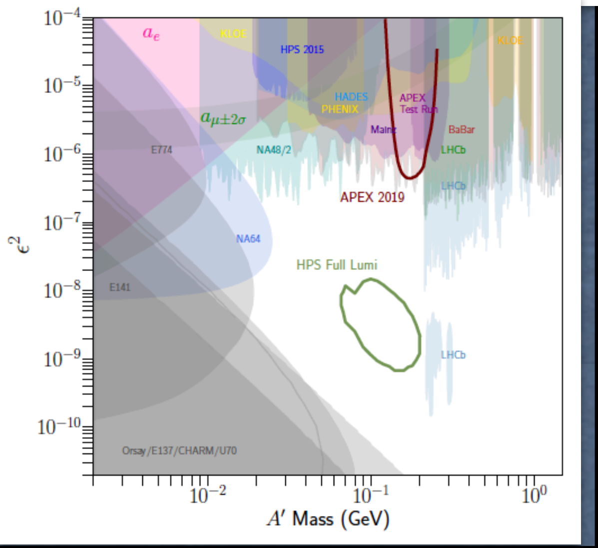



# The Physics case (II)

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

**2306.09360 [nucl-ex] *444 authors***


Cornell University

We gratefully acknowledge support from the Simons Foundation, member institutions, and all contributors. Donate

arXiv > nucl-ex > arXiv:2306.09360

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Nuclear Experiment

[Submitted on 13 Jun 2023 (v1), last revised 24 Aug 2023 (this version, v2)]

**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. ... 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. Christy, E. Chudakov, E. Cisbani, I. C. Cloët, J.J. Cobos-Martinez, O. Cohen, P. Colangelo, P.L. Cole, M. Constantinou, M. Contalbrigo, G. Costantini, W. Cosyn, C. Cotton, A. Courtoy, S. Covrig Dusa, V. Crede, 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 et al. (344 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 or planned facilities. In summary, this document provides an exciting rationale for the energy upgrade of CEBAF to 22 GeV, outlining the transformative scientific potential that lies within reach, and the remarkable opportunities it offers for advancing our understanding of hadron physics and related fundamental phenomena.

Comments: Updates to the list of authors; Preprint number changed from theory to experiment; Updates to sections 4 and 6, including additional figures

Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

Report number: JLAB-PHY-23-3840

Cite as: arXiv:2306.09360 [nucl-ex]

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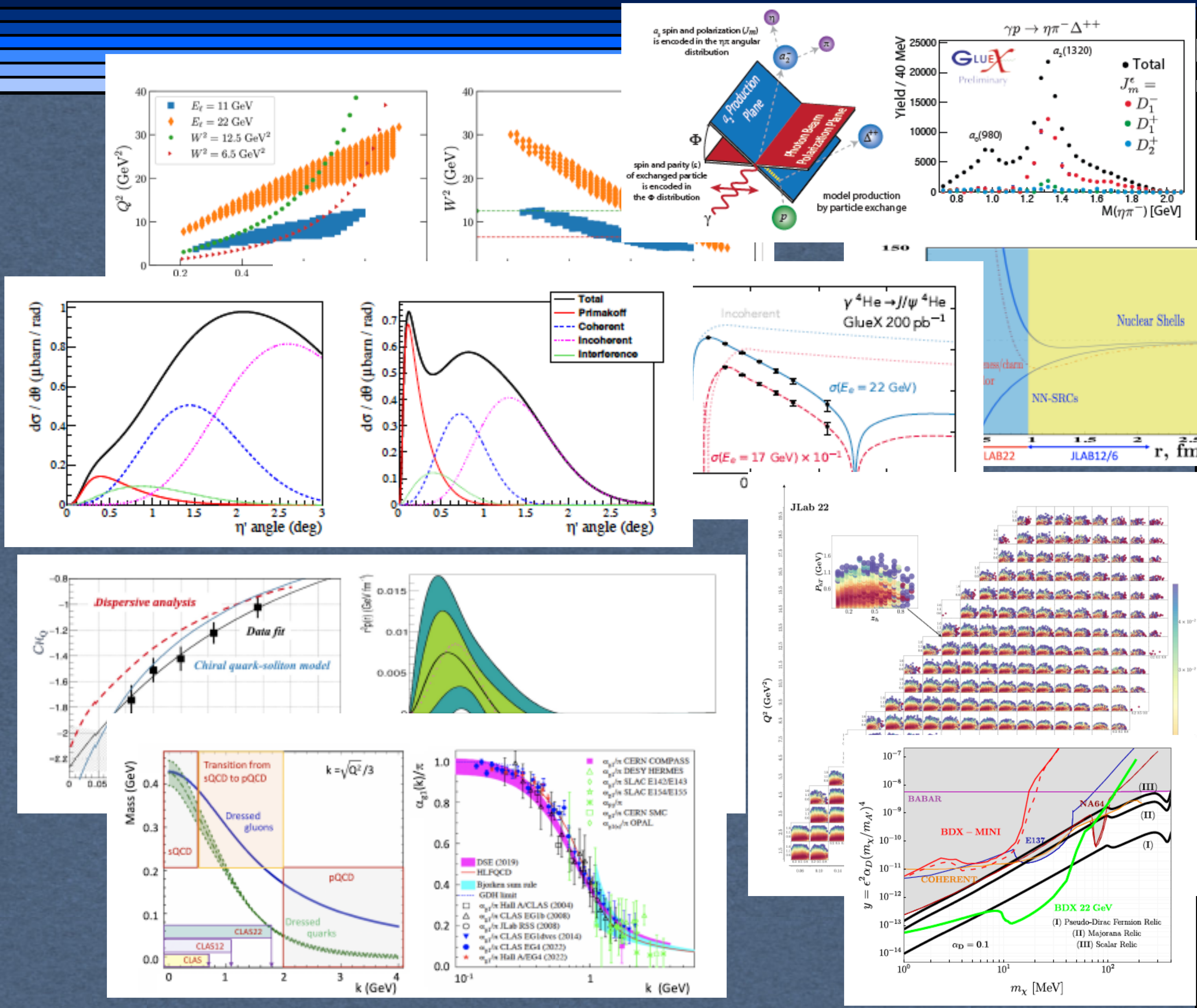
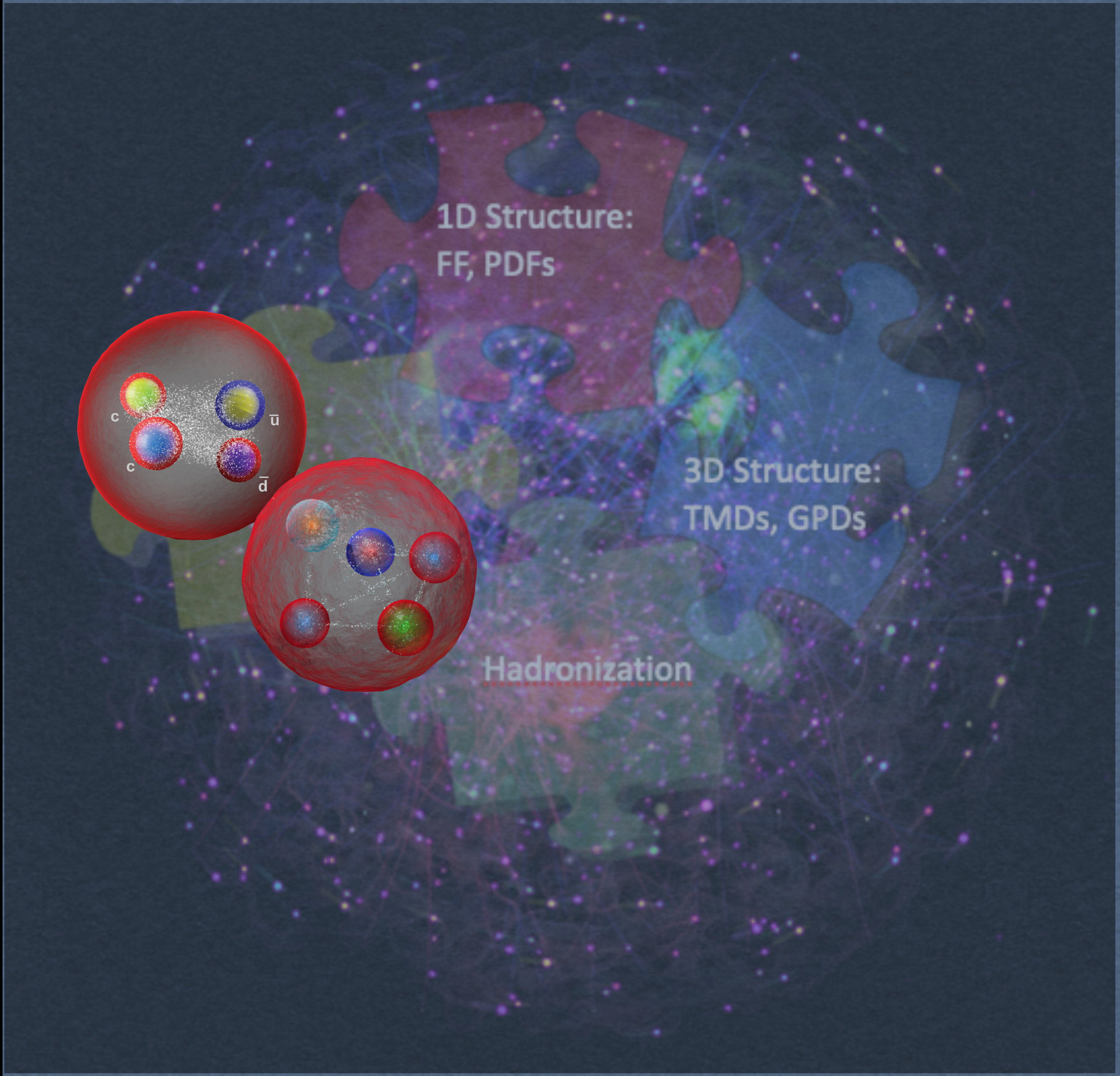


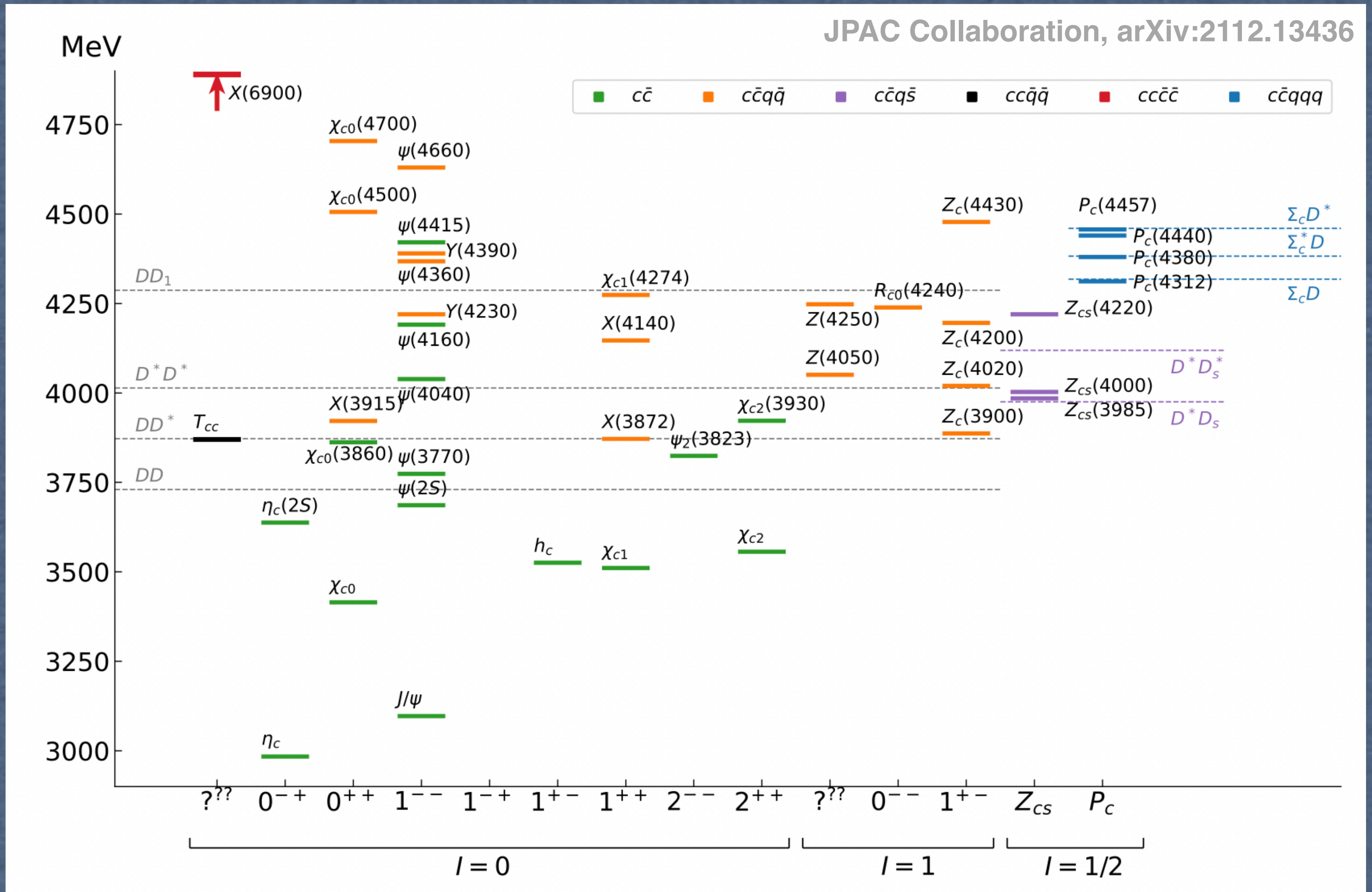


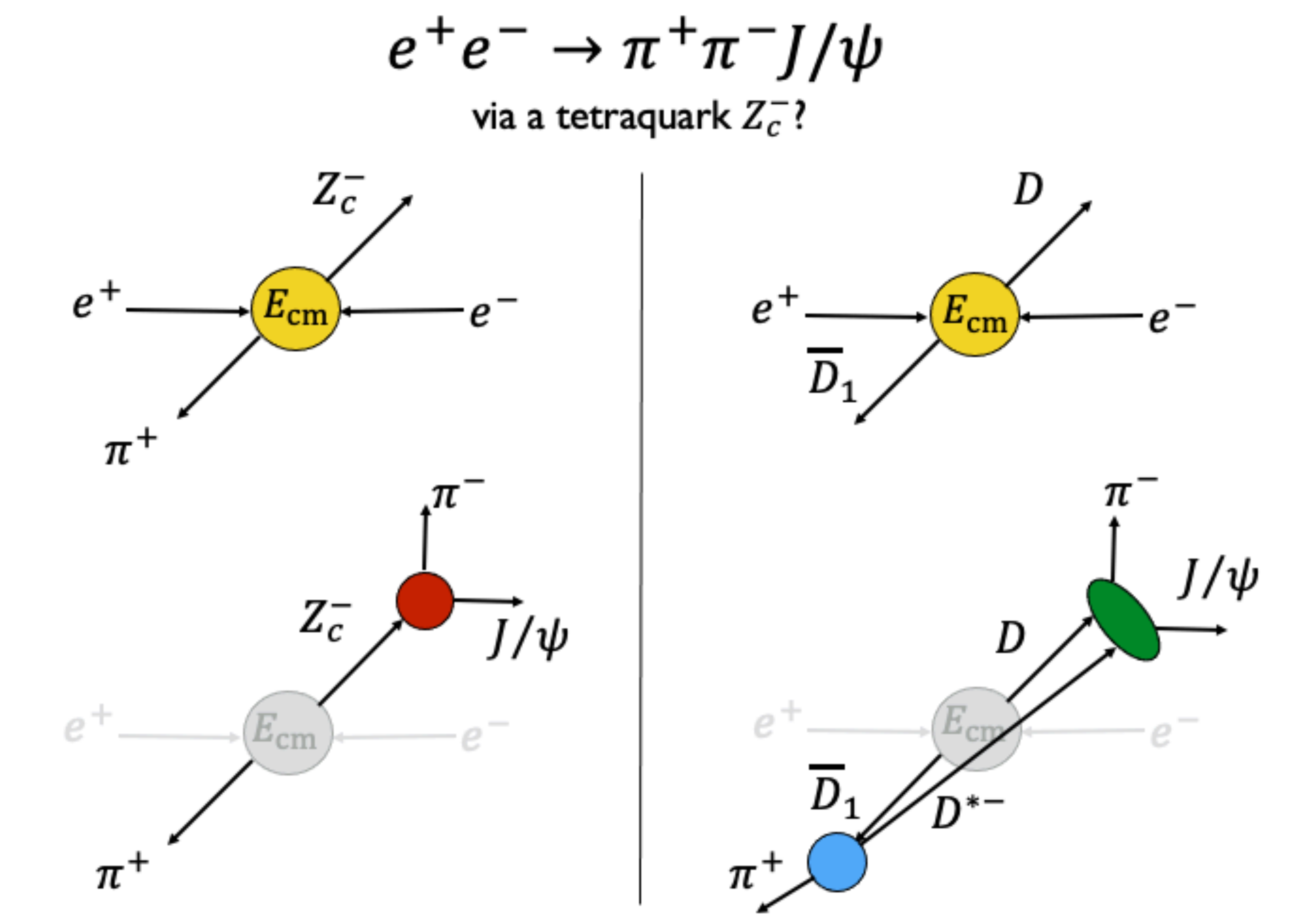

## Hadron spectrum

- Unique opportunity to study light and charm quarks together
- High-intensity electron and photons beams
- Polarisation, cross sections, decay matrix elements
- Hadron production/decay mechanisms
- Elastic and transition form factors via $Q^2$ evolution
- Unveil the nature of multi-q states (XYZ, exotics, tetra-q, penta-q, …)

# Photoproduction of Hadrons with Charm Quarks

## Potentially decisive information about the nature of some 5-quark and 4-quark (XYZ) candidates



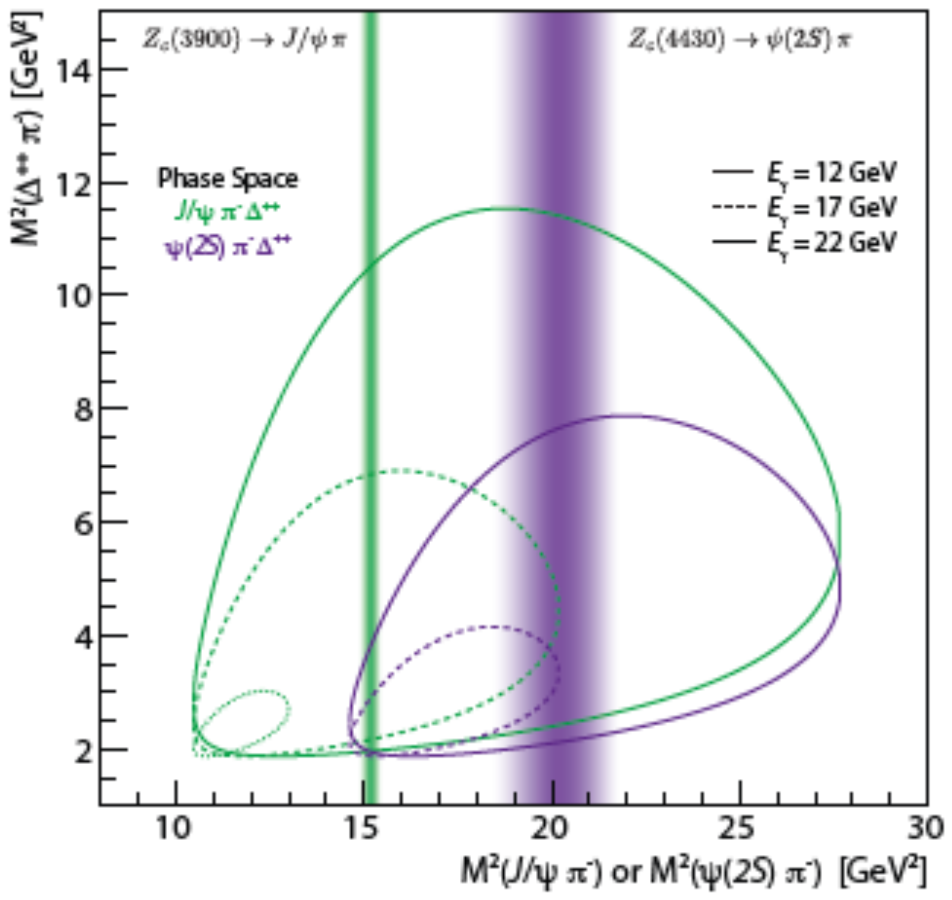



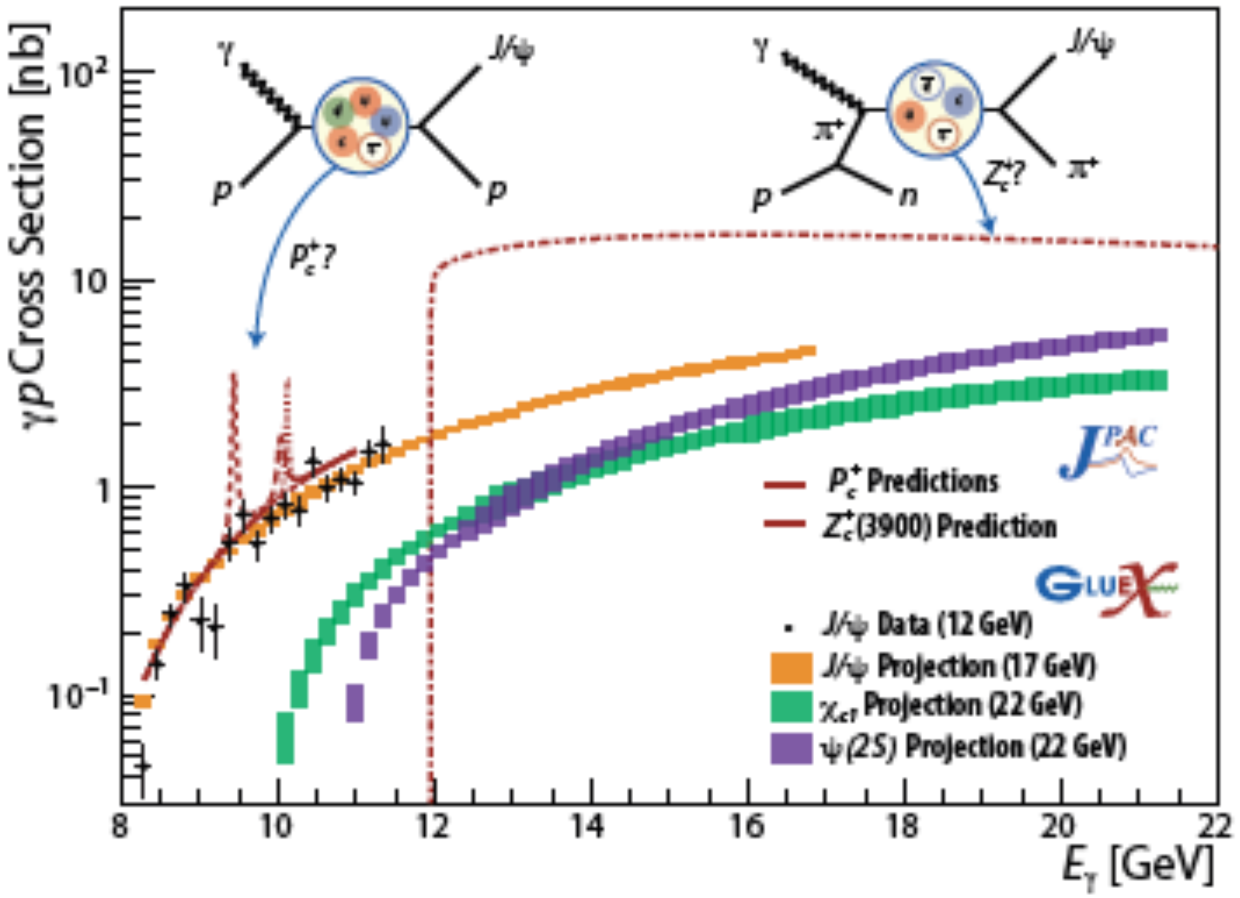

Interpretation of data is complicated by nonresonant $D^{*-}D \to J/\psi\pi^-$ scattering that can produce peaks in invariant mass spectra for certain choices of $E_{cm}$ and $\pi^+$ momentum that result in a $D^{*-}D$ interaction. These peaks are effects of initial state kinematics and do not require a resonance in $\pi^- J/\psi$.

- Many "XYZ" states observed in B decays, $e^+e^-$ colliders
- Scarce consistency between various production mechanisms
- Significant theoretical interest and progress, but internal structure not understood yet

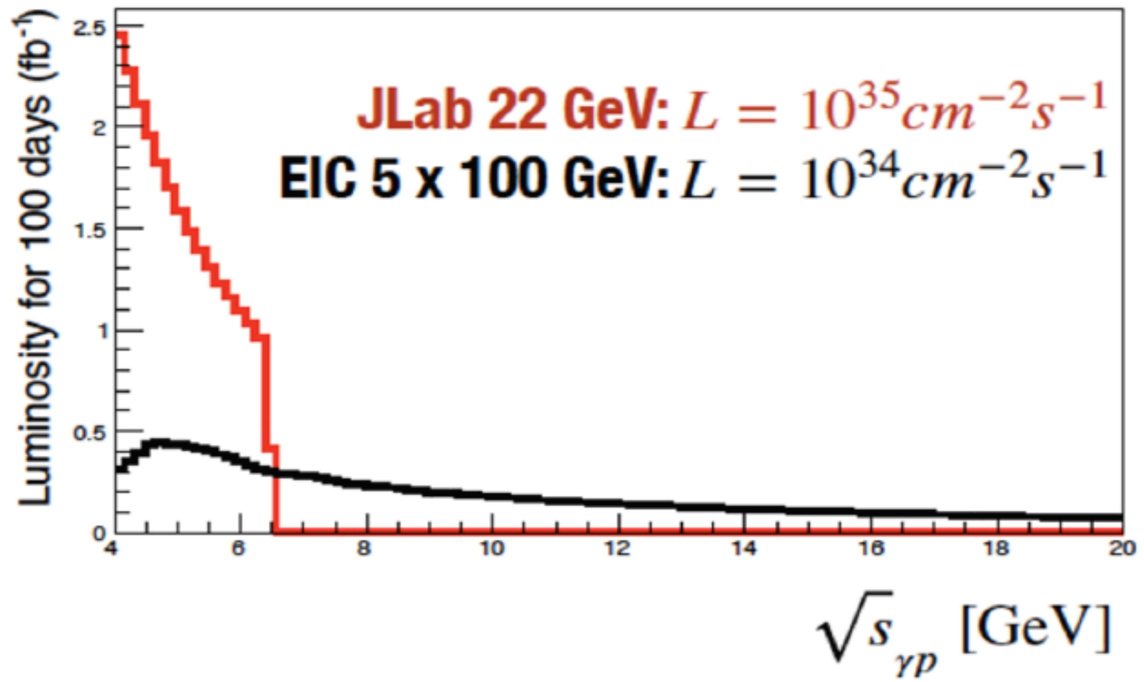
# Spectroscopy of Exotic States with $c\bar{c}$

- Never directly produced using γ/lepton beam
- Direct probe of the $Z_c \rightarrow J/\Psi\pi$ coupling without re-scattering effects
- Photoproduction tool already used to validate the existence of charmed pentaquark
- With an energy upgraded CEBAF, this line of investigation can be extended to other exotic candidates




GlueX-Hall D




Luminosity for 100 days running

# Spectroscopy of Exotic States with $c\bar{c}$

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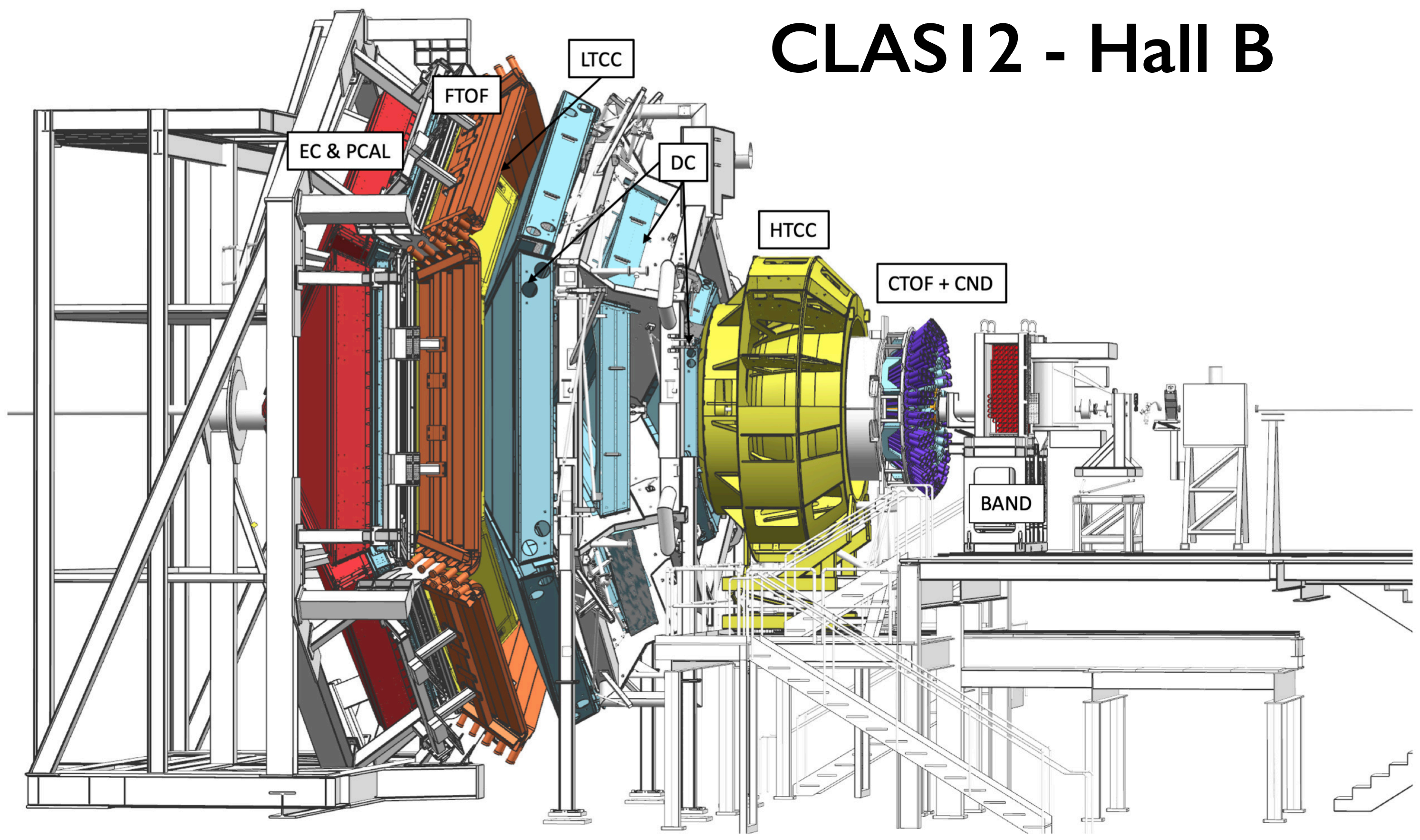
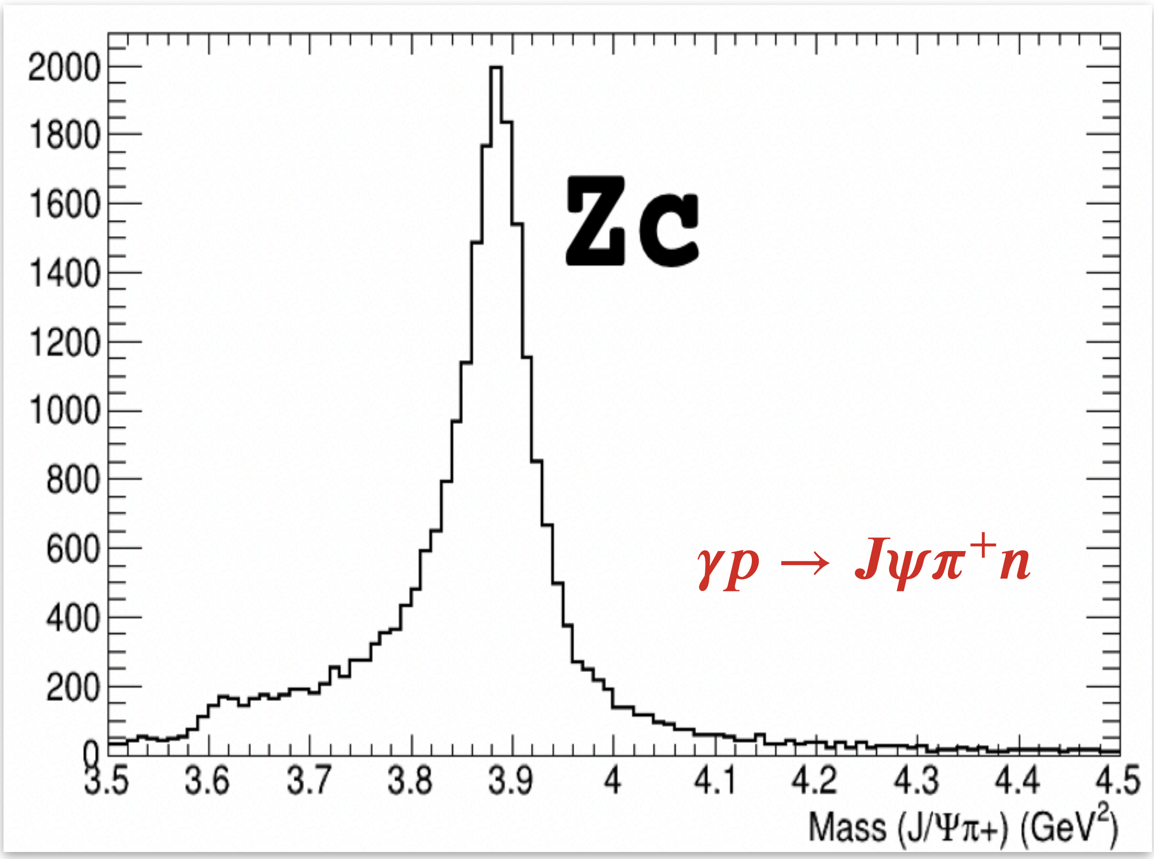
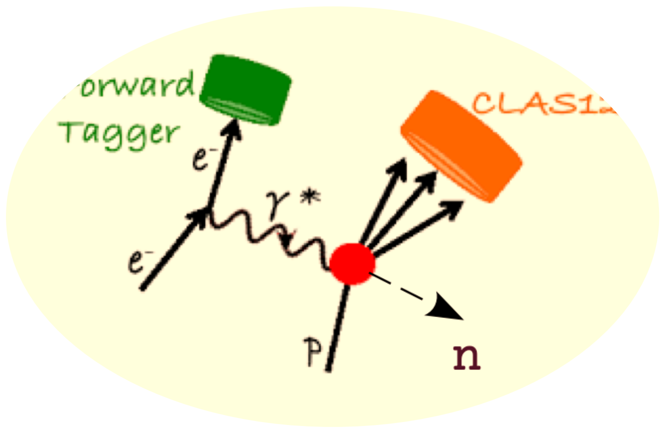
CLAS12 - Hall B



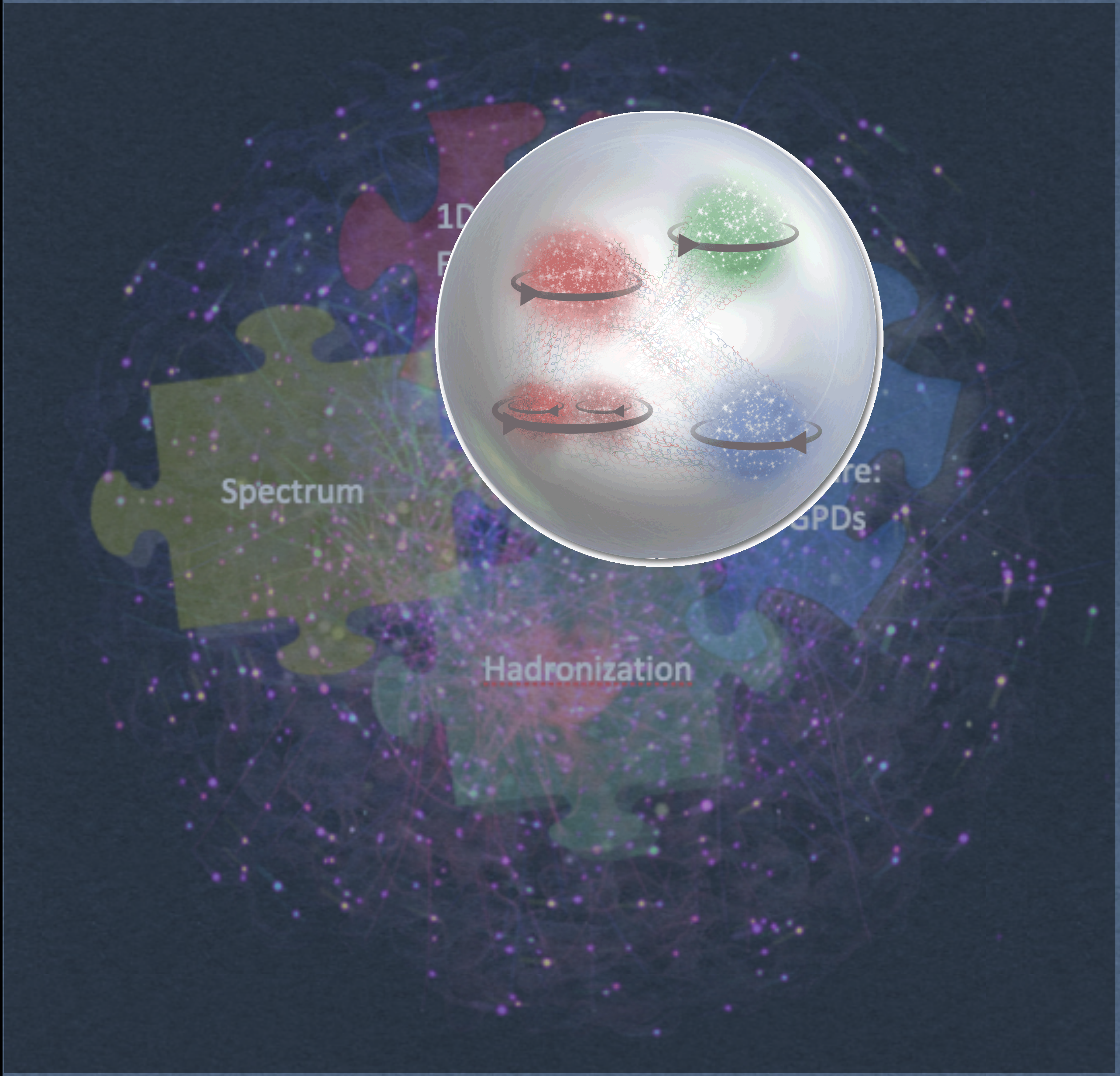

Full CLAS12 signal MC simulation with EXISTING detector




$e^-$ detected 2.5-4.5°
→ $Q^2<0.03$ (GeV/c)$^2$




$Q^2$ evolution of any new state produced

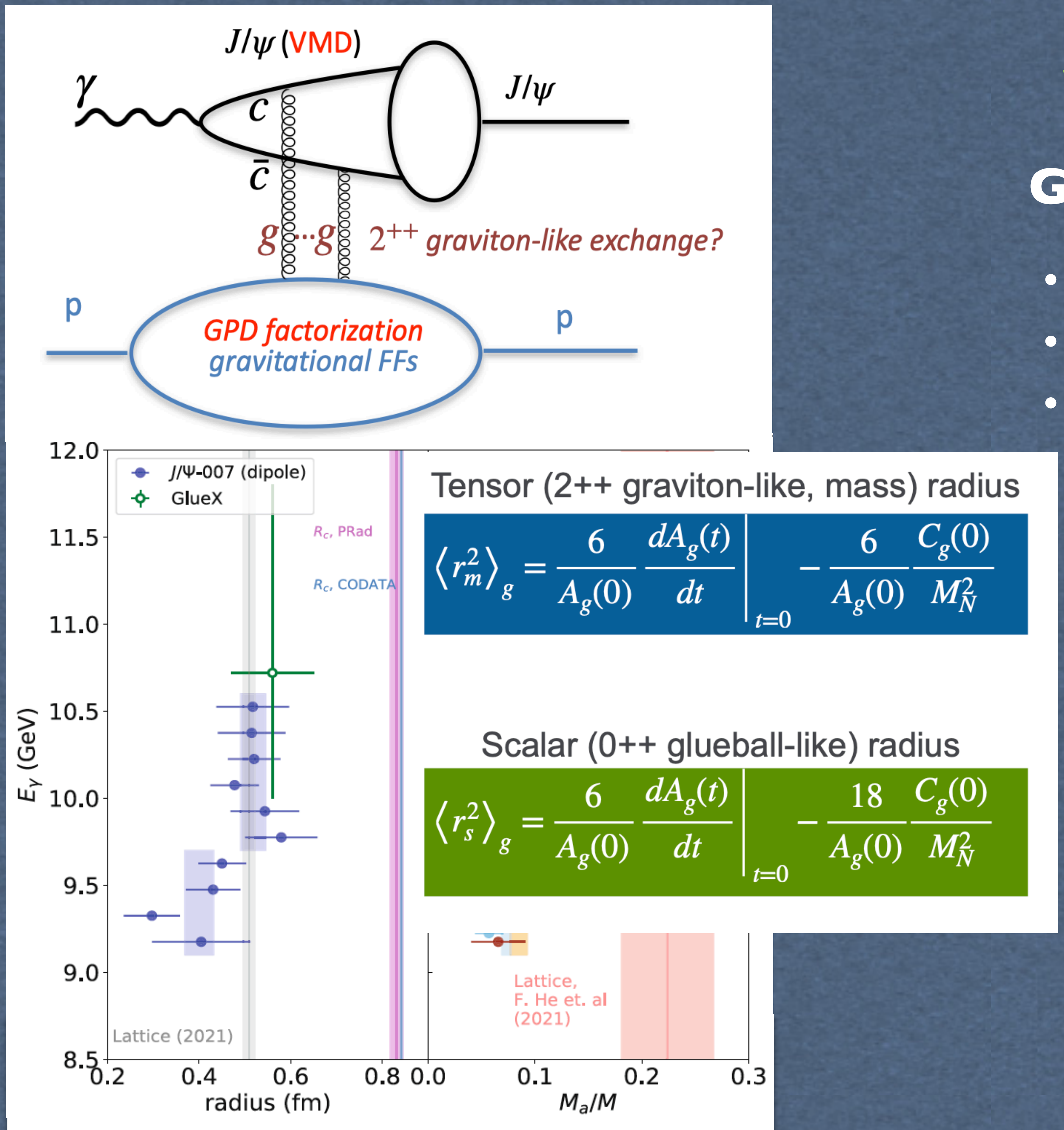



# Nucleon structure

**Better Insights into Quarks and Gluon Dynamics**

- **Mass distribution**
- **Force and pressure distribution**
- **Transverse structure of the nucleon**

# J/Ψ production near threshold




Tensor (2++ graviton-like, mass) radius

$$\langle r_m^2 \rangle_g = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{6}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

Scalar (0++ glueball-like) radius

$$\langle r_s^2 \rangle_g = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{18}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

*Nature* **volume 615**, pages 813–816 (2023)

## Gluonic properties of the nucleon

- Nucleon gravitational form factor (via gGPD D-term)
- EMT trace anomaly and nucleon mass
- Proton mass radius (different from charge radius)

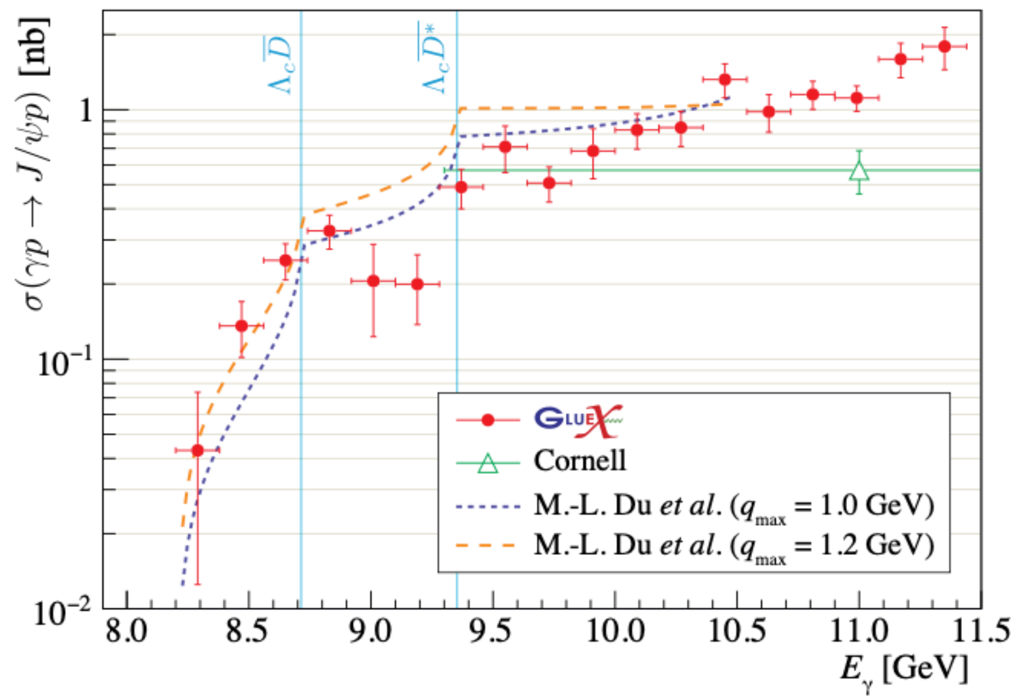
… under certain assumptions

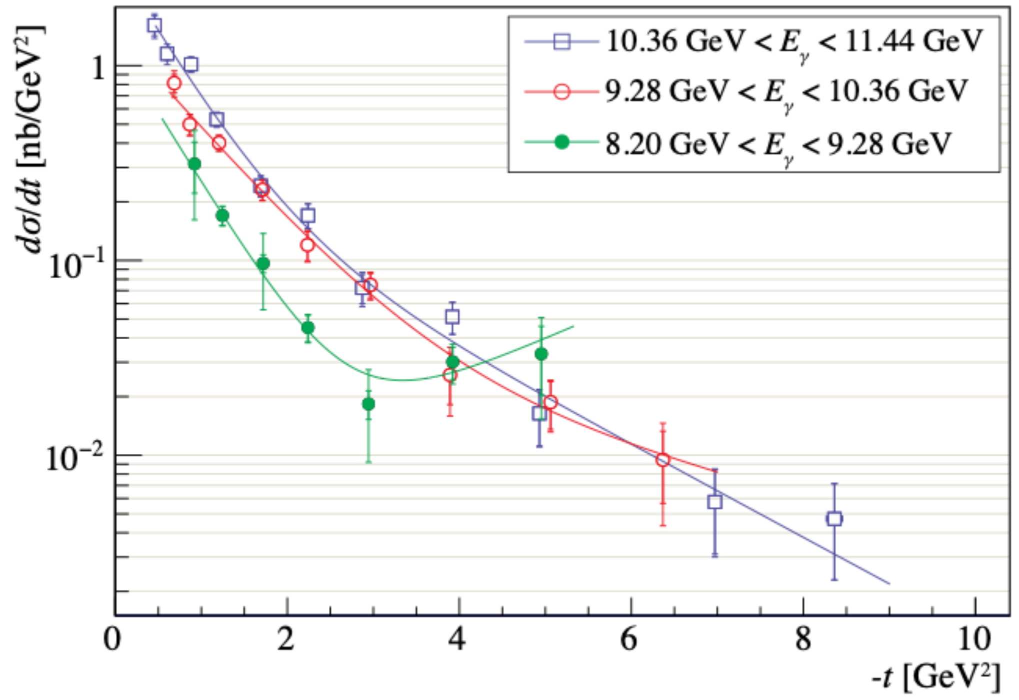
- VMD relates γp → J/ψp to elastic J/ψp → J/ψp
- $m_C \to \infty$ interaction via gluon exchange
- GPD factorization valid at threshold

**Detailed studies of the reaction γ*p* → *J*/ψ*p* are needed to verify the validity of the assumptions**

# J/Ψ production near threshold with GLUEX

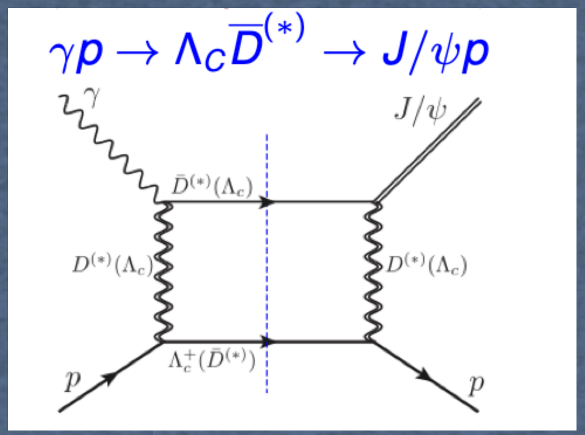
PHYSICAL REVIEW C 108, 025201 (2023)



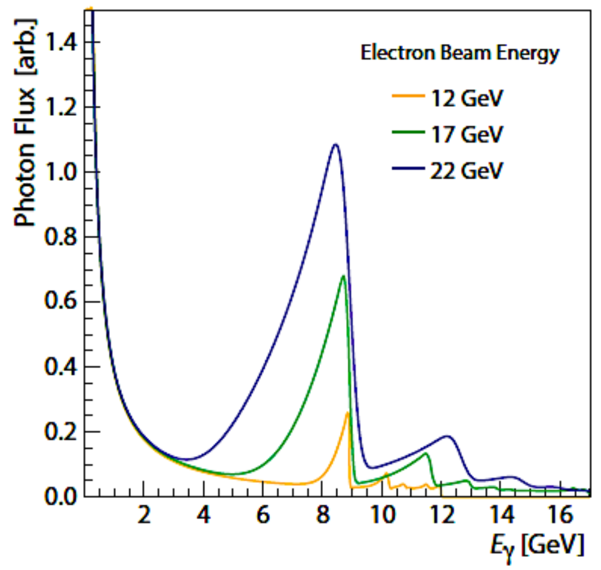



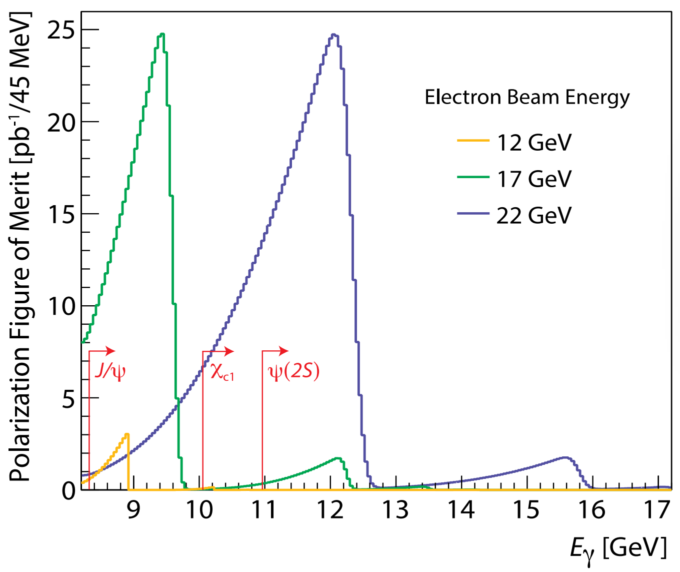

- Exponential slopes indicating t-channel generally consistent with the gluon-exchange mechanism
- Enhancement of $d\sigma/dt$ for lowest energy -> other mechanisms into the game

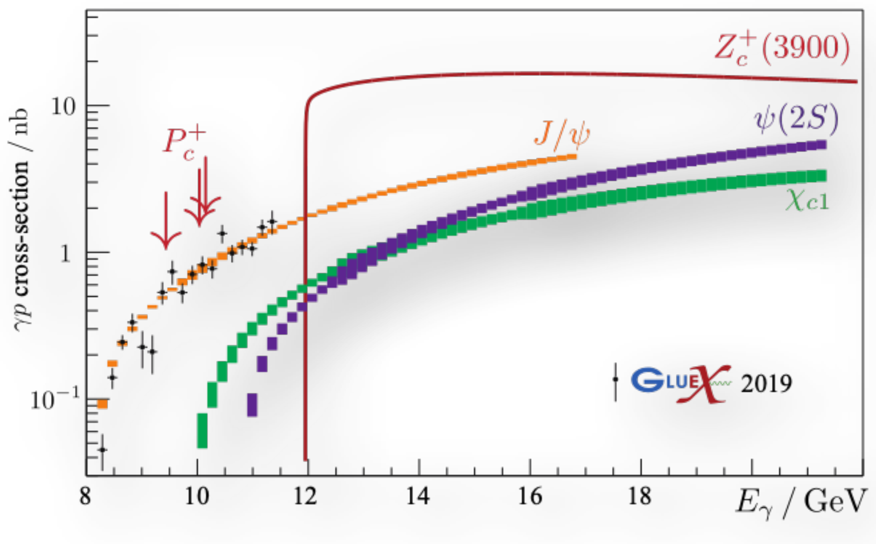
- Cusps at the thresholds of $\Lambda_c D$, $\Lambda_c D^*$
- Production via open-charm and rescattering?
  - This mechanism is not a 2-gluon exchange and may invalidate the relation between $\gamma p \to J/\psi p$ and GFF of the nucleon




# J/Ψ production at JLab@20+ GeV



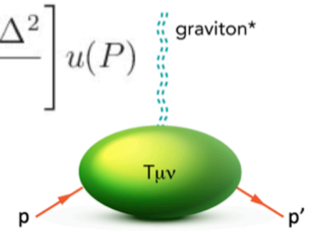



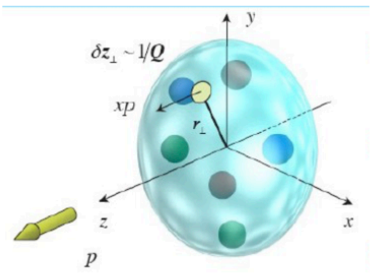

- Increasing the electron beam energy results in a larger fraction of useful high-energy photons
- The Energy upgrade gives a significant increase of polarization FOM, allowing unique studies of the gluon exchange for J/ψ and higher charmonium states

# Nucleon gravitational FF and GPDs

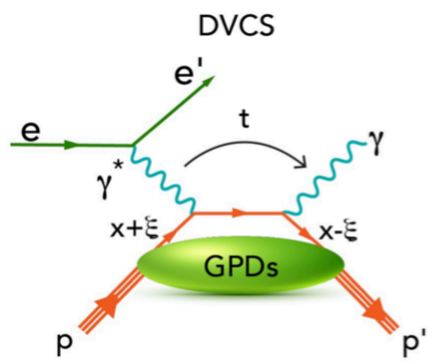
- **Matrix elements of QCD EMT** $\langle P'|T^{\mu\nu}|P\rangle = \bar{u}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\nu)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M}\right]u(P)$




For a spin ½ hadron there are 3 independent Form Factors associated with scattering off a graviton



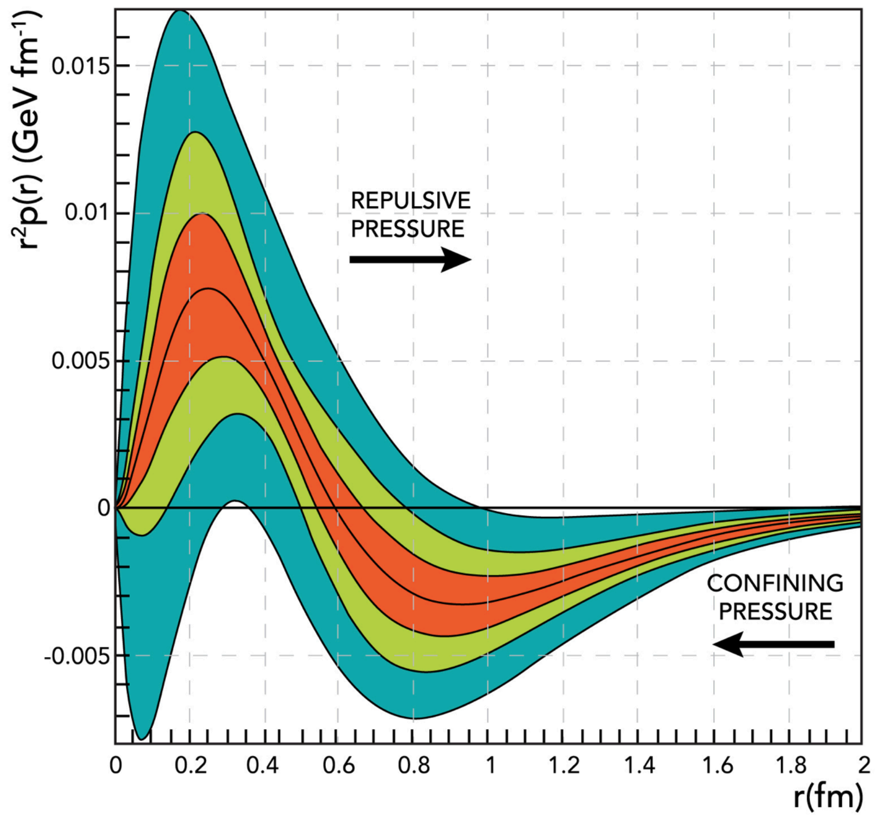

- **Generalized Parton Distributions:** multidimensional description of nucleon structure (longitudinal momentum versus transverse position) **H, E, H̃ , Ẽ**
  - A massless spin-2 field would couple to the stress–energy tensor in the same way that gravitational interactions do → **D –term accessible through DVCS measurements**




$$\mathrm{Re}\mathcal{H}(\xi,t) + i\mathrm{Im}\mathcal{H}(\xi,t) = \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] H(x,\xi,t)$$

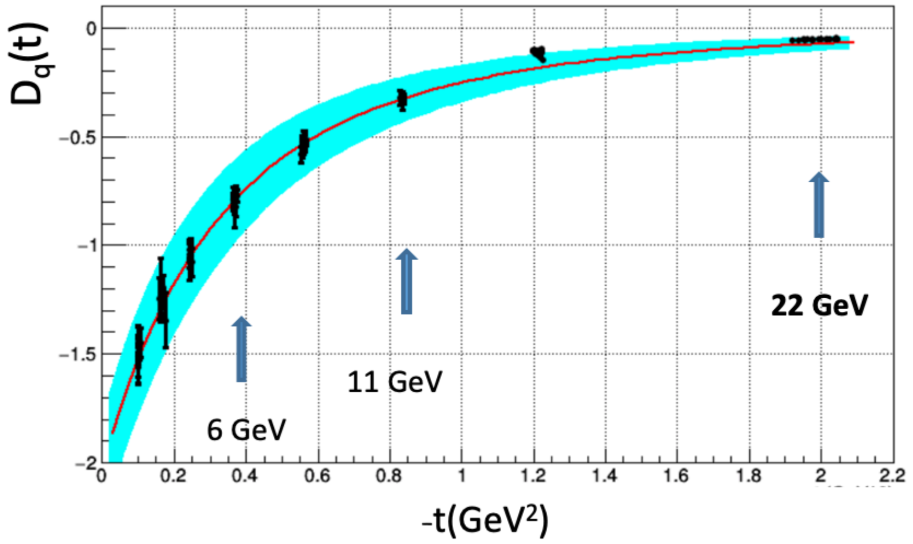
$$\mathrm{Re}\mathcal{H}_q(\xi,t) = \frac{1}{\pi}\int_{-1}^{1} dx \mathrm{P}\frac{\mathrm{Im}\mathcal{H}_q(x,t)}{\xi - x} + 2\int_{-1}^{1} dz \frac{D_q(z,t)}{1-z}$$

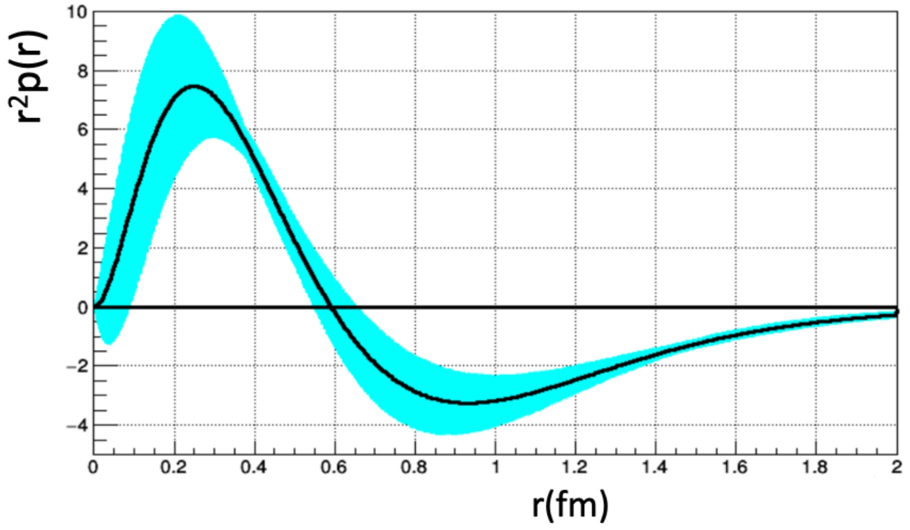
- D-term related to the subtraction constant in the dispersion relation (at fixed t) for the Compton Form Factor




- (quark) D(t) term and determination of the pressure distribution inside the proton from JLab-CLAS DVCS data @ 6 GeV

**JLab @ 22 GeV**



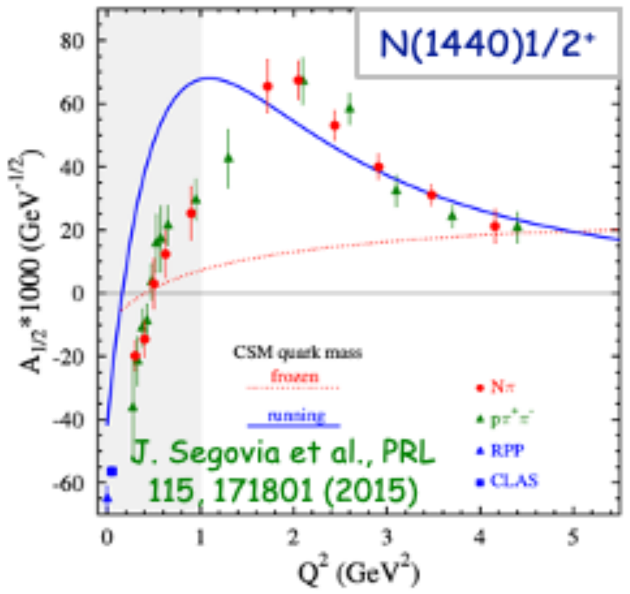



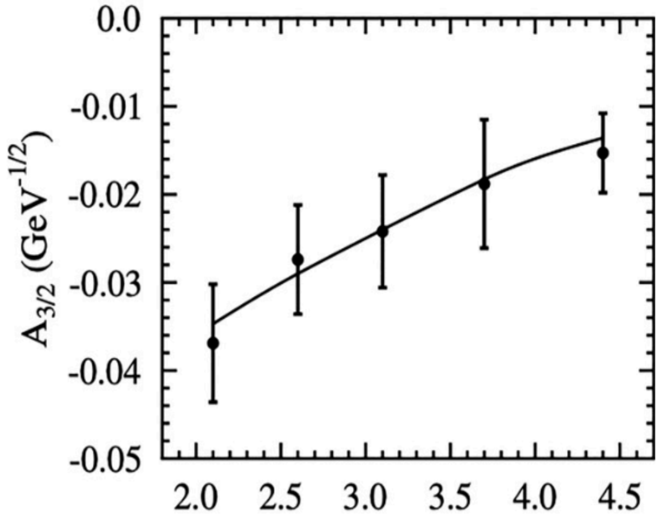

- **A larger -t range is required to perform the Fourier transform with controlled uncertainties ➜ high luminosity**

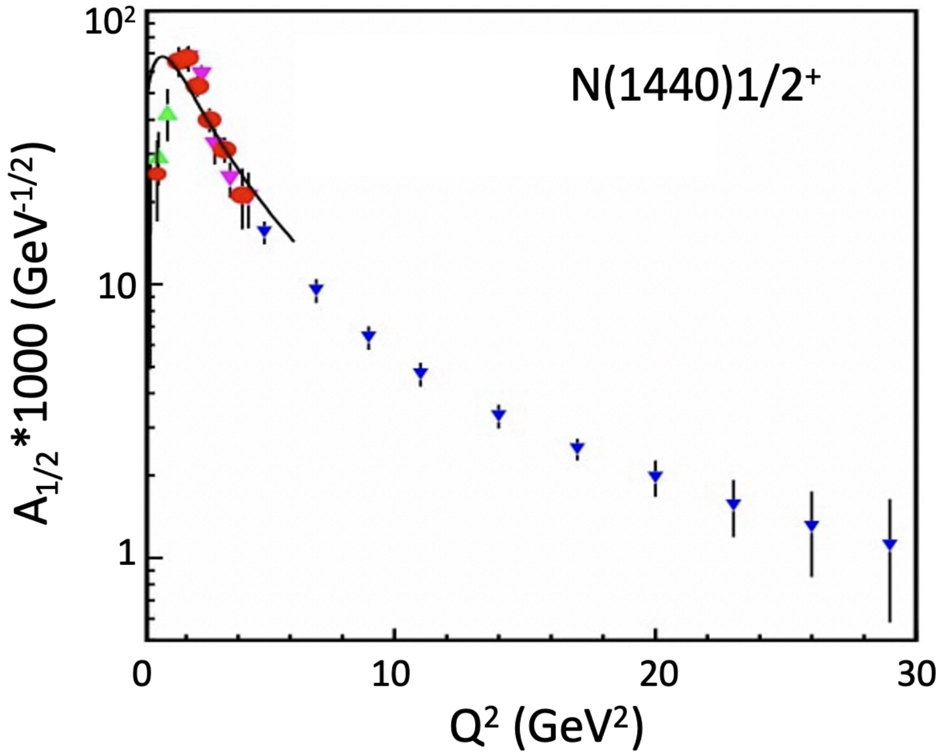
# Bound 3 Quark Structure of N*s and Emergence of Mass

*V.I. Mokeev et al. PRC 108, 025204*

## CLAS results



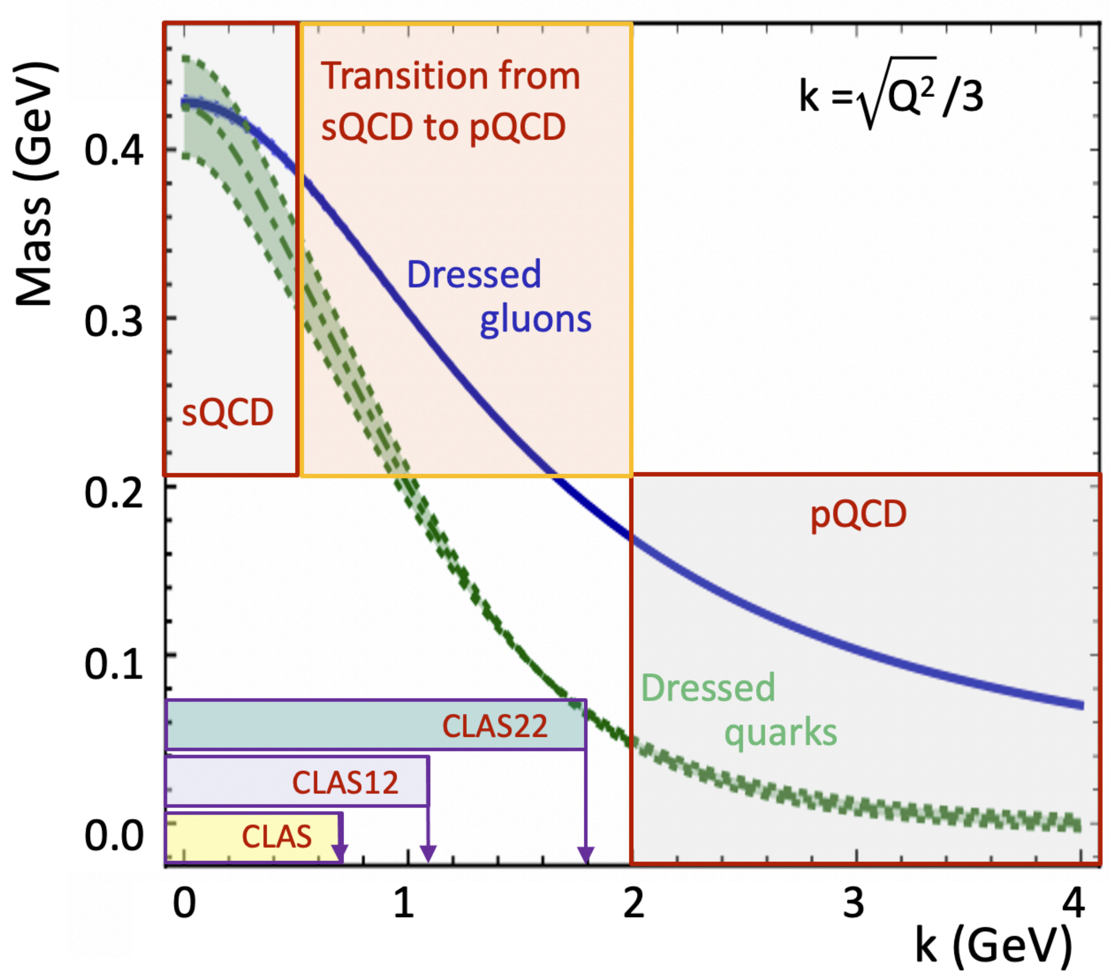




- $Q^2$ evolution of the $\gamma_v pN^*$ electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD

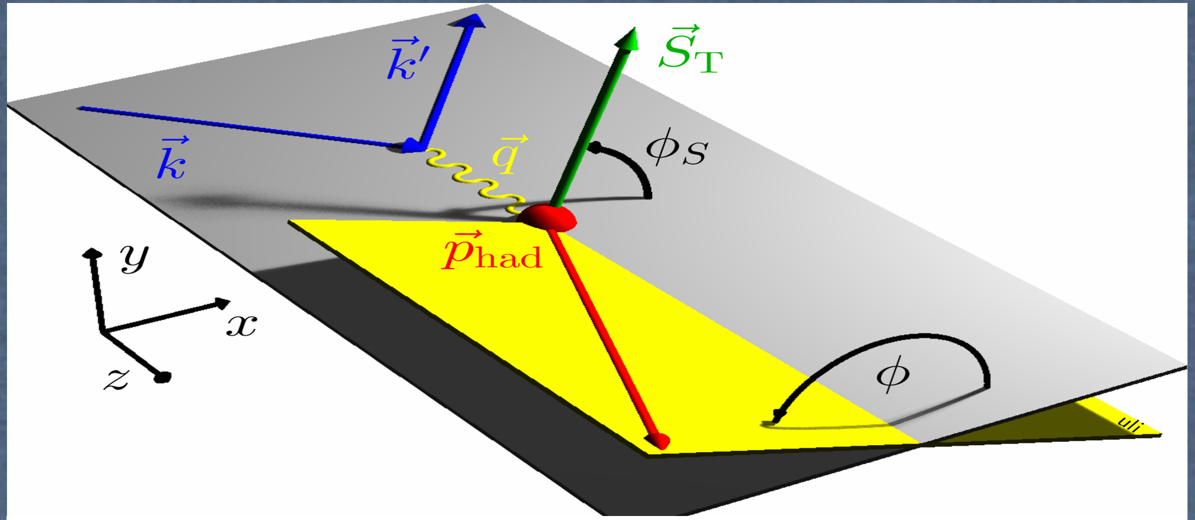
## Continuum Schwinger Method

- The solution of the QCD equations of motion for q/g fields reveals the existence of dressed q/g with momentum-dependent masses.




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

# 3D Picture of the Nucleon in Momentum Space (TMD)




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

- At large x fixed target experiments are sensitive to ALL Structure Functions

## Semi-Inclusive Deep Inelastic Scattering (SIDIS)

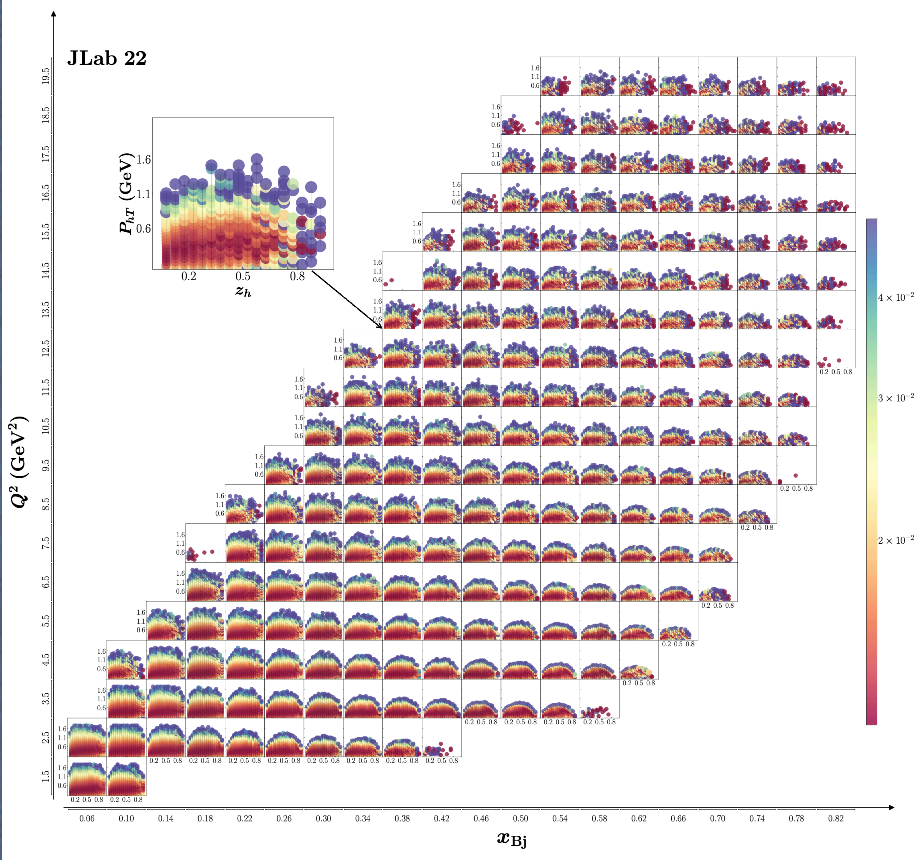
A more complete picture of the nucleon …
but there is no free lunch

- **More functions in the x-section**
- **More variables for each function**

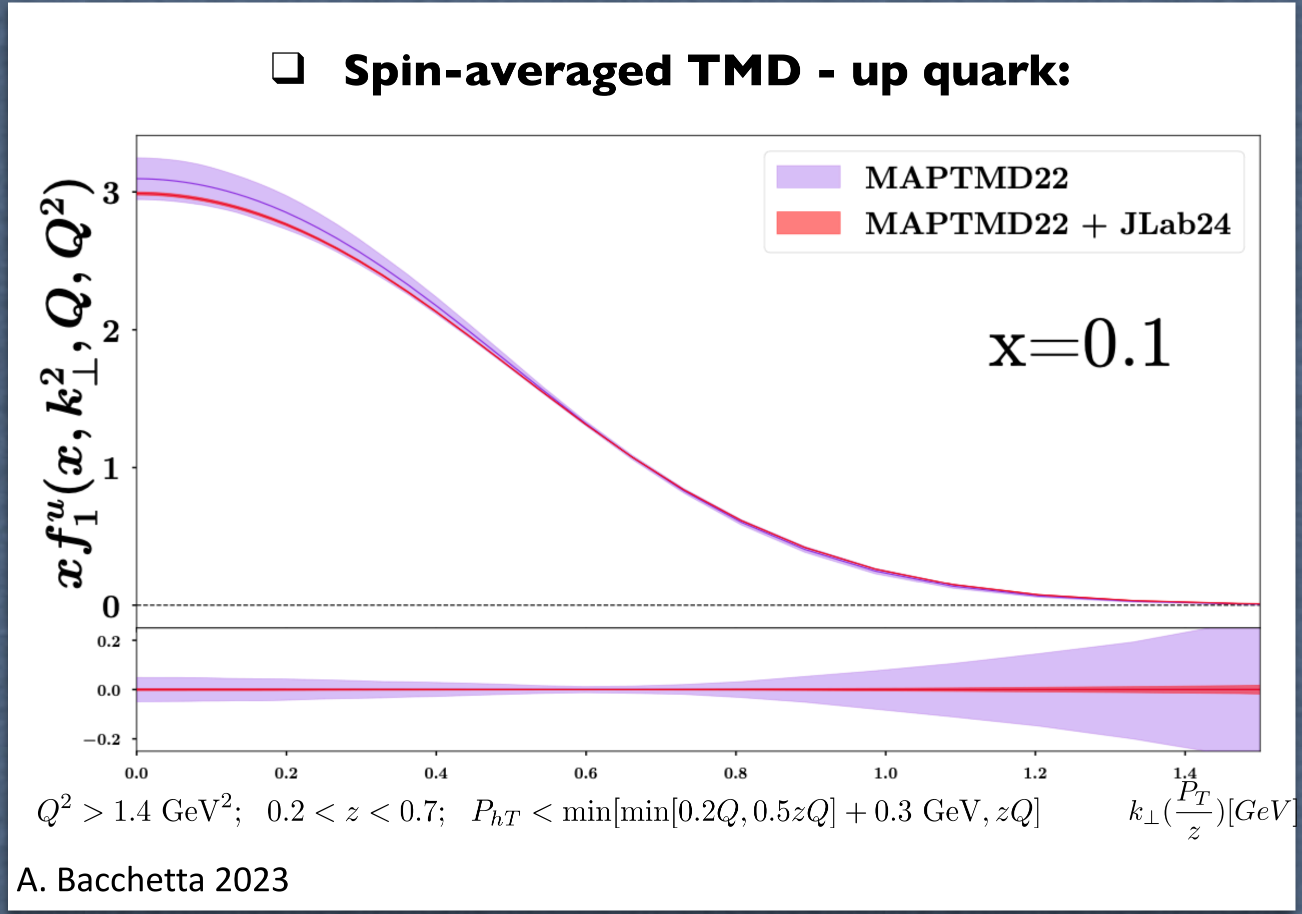
**Complexity in the extraction**

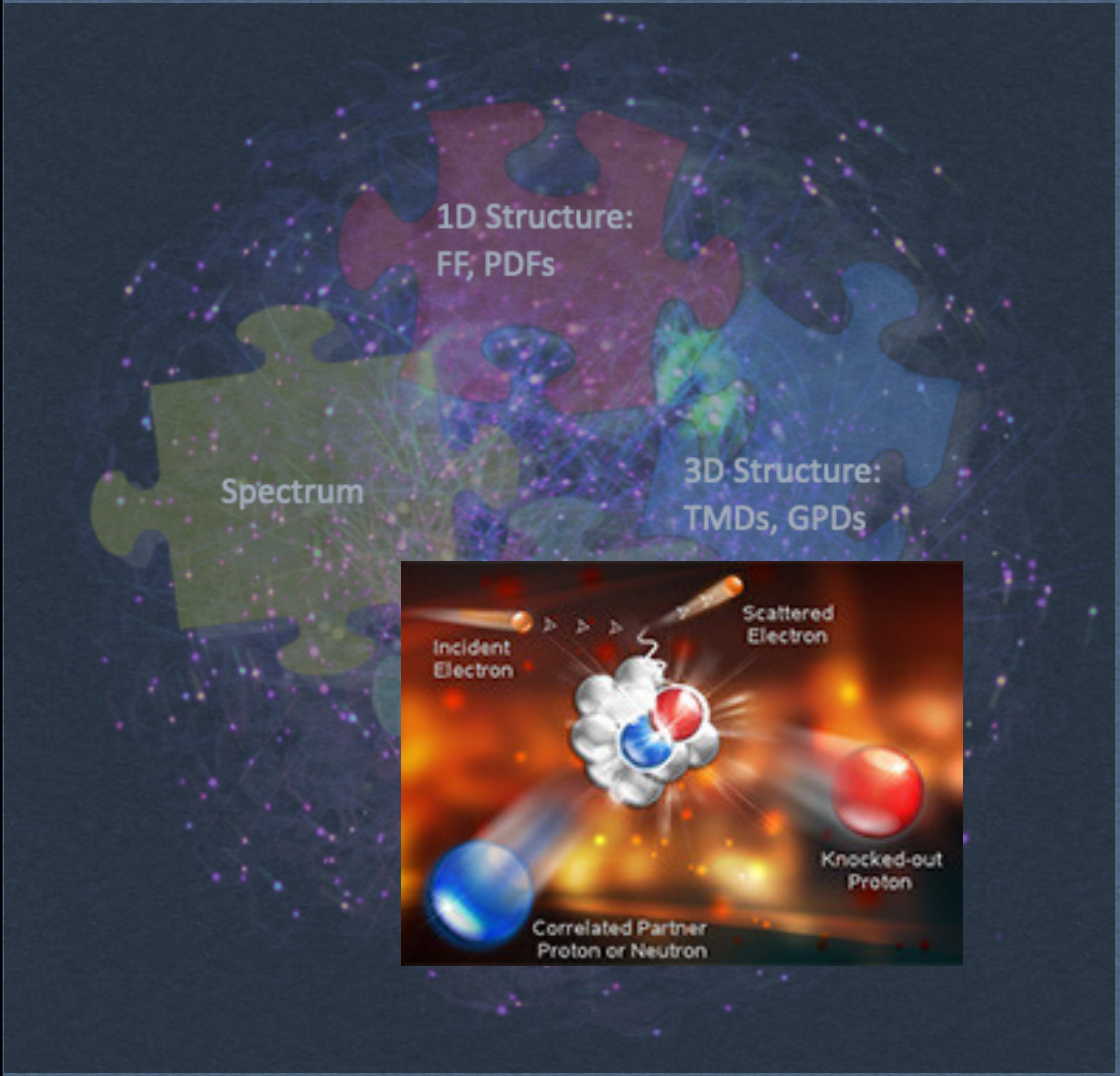
**High statistics**
**Wide kinematical range**

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




**Impact of SIDIS data at 22 GeV**



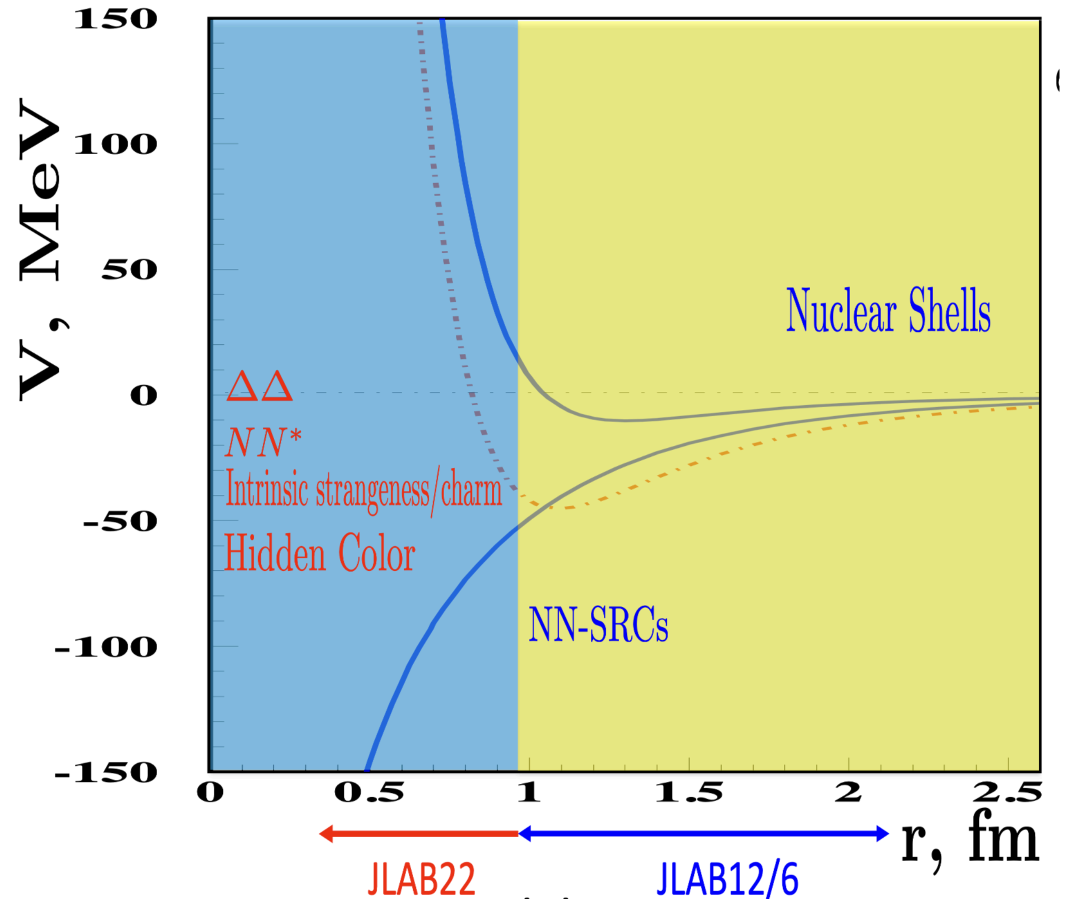



# Nuclear dynamics

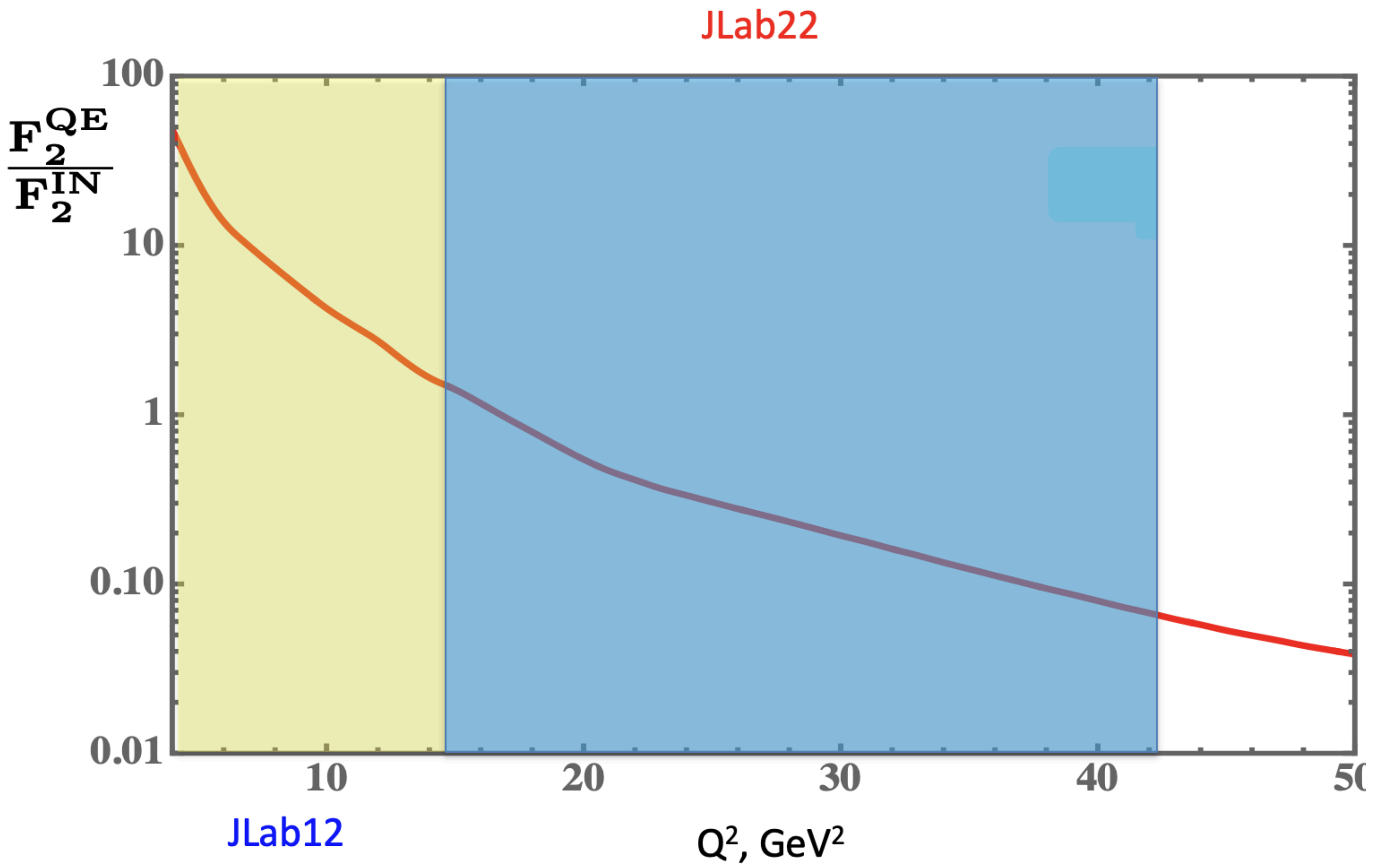
- **Exploring nuclear forces dominated by nuclear repulsion**
- **Investigation of nuclear-medium effects**
- **Short Range Correlations**
- **Hadronization and Color Transparency**

# 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**




Crucial for understanding the dynamics of transition between hadronic to quark-gluon phases of matter

→ evolution of the universe

→ dynamics of superdense matter at the core of neutron stars

## Superfast Quarks

- The high $Q^2$ reach will allow
  - the suppression of quasi-elastic contribution,
  - the first-ever direct study of nuclear DIS structure function at Bjorken x > 1.2 (r~ 0.5 fm)

# The Physics case (II)

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

**2306.09360 [nucl-ex] *444 authors***



Nuclear Experiment

*[Submitted on 13 Jun 2023 (v1), last revised 24 Aug 2023 (this version, v2)]*

**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. ... 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. Christy, 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, A. Courtoy, S. Covrig Dusa, V. Crede, 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 et al. (344 additional authors not shown)

Screenshot

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 or planned facilities. In summary, this document provides an exciting rationale for the energy upgrade of CEBAF to 22 GeV, outlining the transformative scientific potential that lies within reach, and the remarkable opportunities it offers for advancing our understanding of hadron physics and related fundamental phenomena.

Comments: Updates to the list of authors; Preprint number changed from theory to experiment; Updates to sections 4 and 6, including additional figures

Subjects: **Nuclear Experiment (nucl-ex)**; High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-ph); Nuclear Theory (nucl-th)

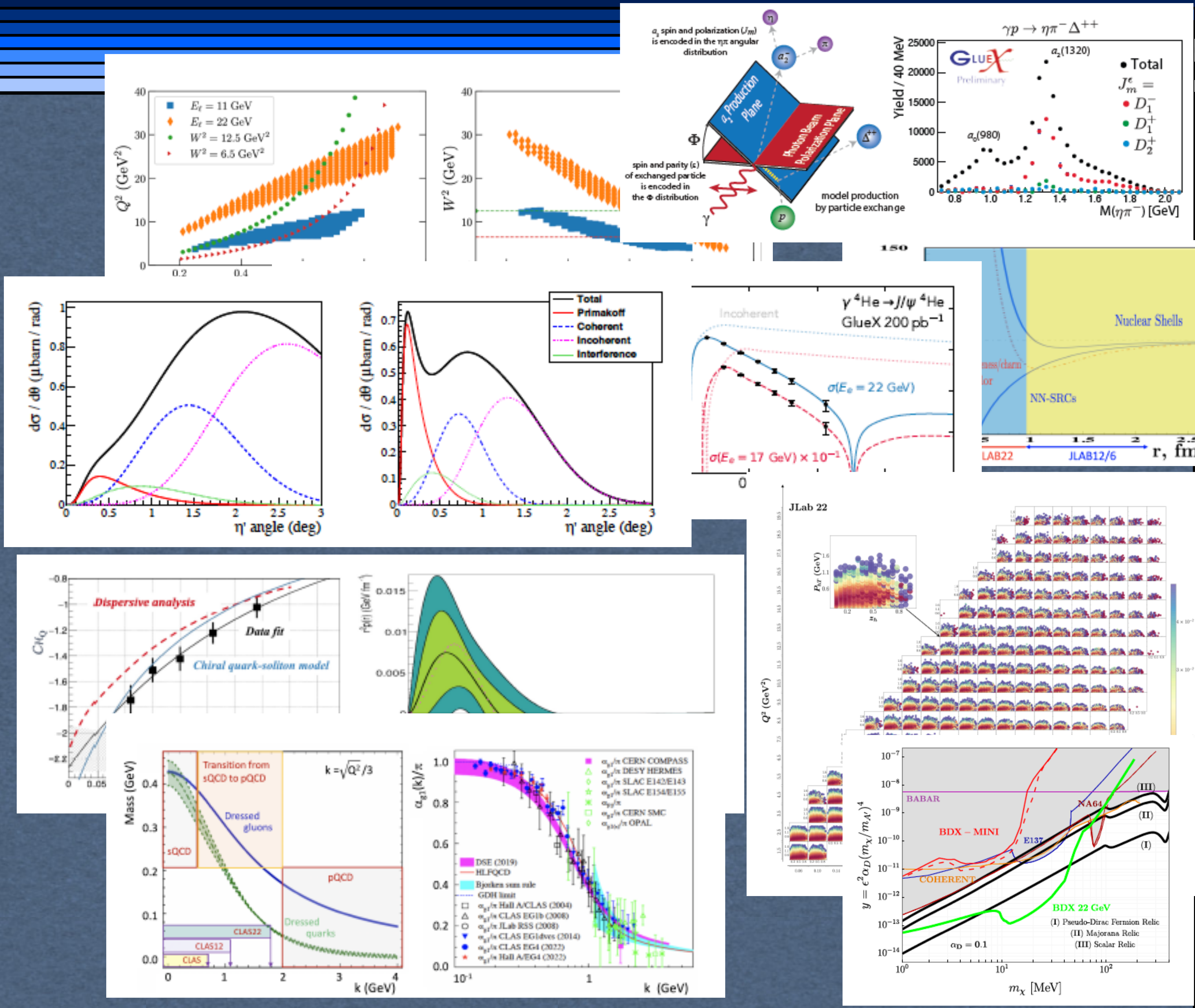
Report number: JLAB-PHY-23-3840

Cite as: arXiv:2306.09360 **[nucl-ex]**

(or arXiv:2306.09360v2 **[nucl-ex]** for this version)

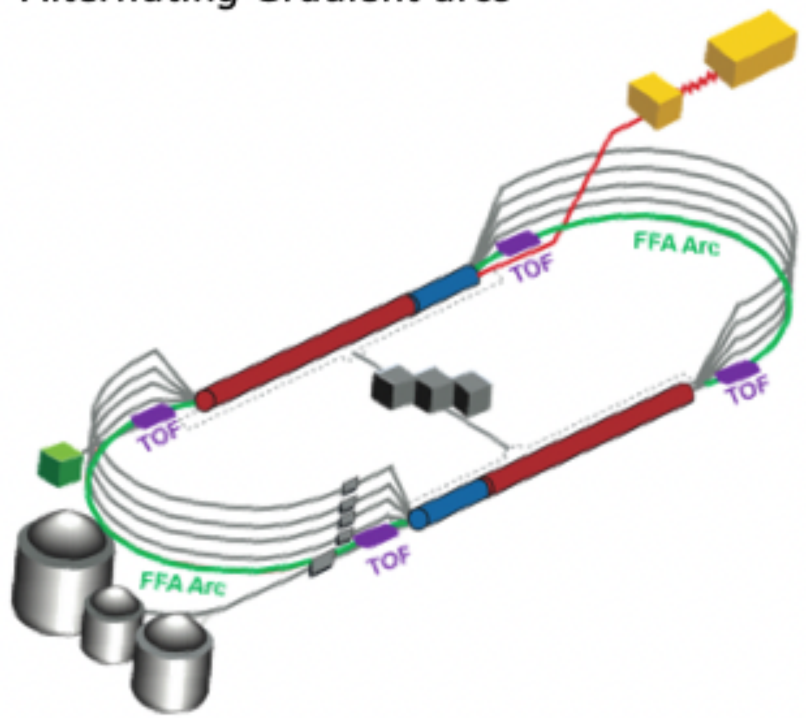
https://doi.org/10.48550/arXiv.2306.09360





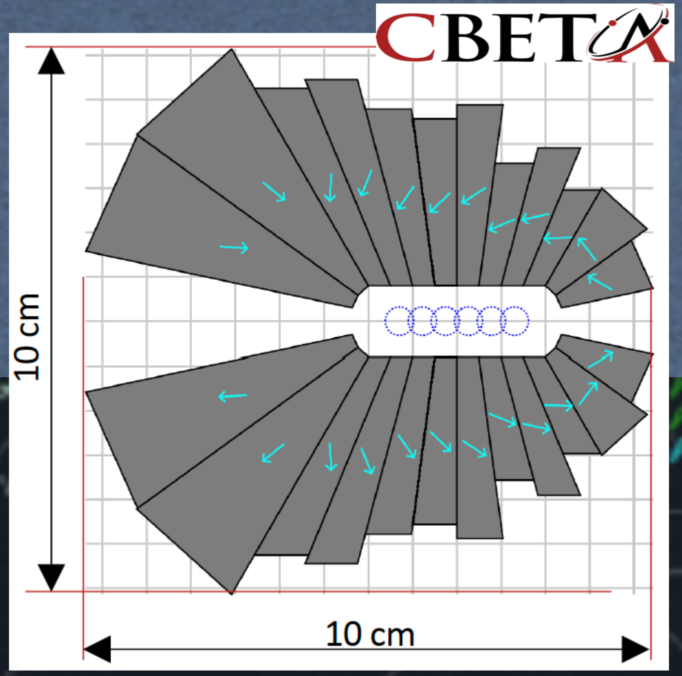
# CEBAF @ 22 GeV Infrastructures

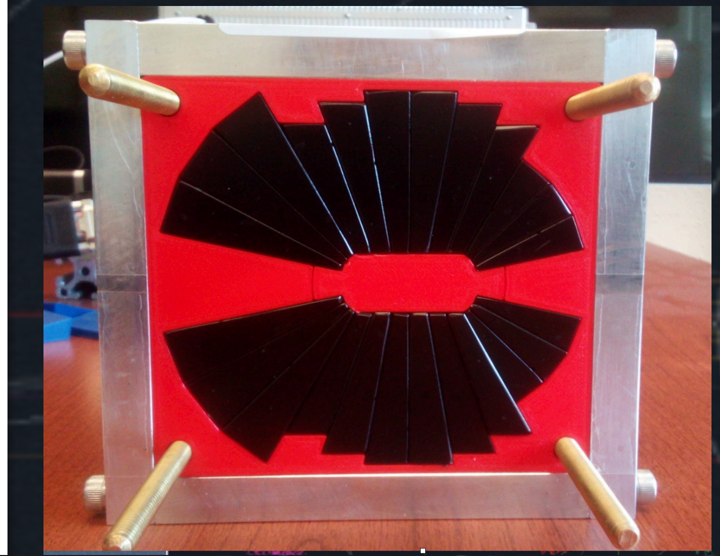
*Cost-effective path to doubling CEBAF energy based on Fixed-Field Alternating Gradient arcs*




- Starting with 12 GeV CEBAF
- NO new SRF
- NEW 650 MeV injector
- Remove the highest recirculation pass and replace them with **two FFA arcs** including TOF chicane
- Recirculate 4 + **6.5** times to get to **22 GeV**

**Enabling Technology:**
Novel permanent magnets



- FFA (fixed field alternating gradients) recirculation technique: multiple beam energies confined and recirculated in the same beam line
- No new SRF (1.1 GeV per LINAC), replace the highest recirculation passes with FFA arcs
- 11 passes to reach 22 GeV
- High energy beam delivered to Hall-D and Hall B suitable for an HS physics program
- **Hi-Lumi + Hi-E operations**


# The US NP 2023 Long Range Plan

- The 2023 LRP report was presented to the NP community a few months ago
- Set priorities (recommendations) to DOE for the next 7-8 years cycle
- Recommendations 1 & 4 strengthen the current CEBAF ops and future upgrade

**RECOMMENDATION 1**

**The highest priority of the nuclear science community is to capitalize on the extraordinary opportunities for scientific discovery made possible by the substantial and sustained investments of the United States. We must draw on the talents of all in the nation to achieve this goal.**

RECOMMENDATION 2

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

RECOMMENDATION 3

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

**RECOMMENDATION 4**

**We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.**

*… The staged upgrade plan for CEBAF foresees a first phase to establish intense polarized positron beam capability at 12 GeV, allowing for new measurements in nucleon tomography and providing precision extraction of contributions from higher order electromagnetic processes. The nontrivial operation with positron beams (polarized and unpolarized) will open a new area of study for CEBAF in the future. The subsequent phase is 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.*

# The JLAB@22 GeV upgrade: study group and community involvement

## Lab managed

- Beginning of a lengthy process which includes physics and technical planning
- White Papers for positron and the higher energy programs already available
- Appointed a study group (11 people from JLab Management, Physics Division, Accelerator Division, Users) for the S&T of 12 GeV positrons, and 22 GeV energy upgrade

- Understand requirements for e+ beam (e.g., polarizability, energy, intensity, fast switching between e+ and e- beams) and translating into source and machine ops requirements
- Define a roadmap for tech development
- Define the R&D path to reach polarized positrons and 22 GeV beams
- Report to JSA board, S&T Mission Committee, DOE/NP

## Community managed

- Digging deep about the importance of JLab science and its energy upgrade
- Developing, refining, and sharpening the White Paper's physics arguments
- Validate with extensive simulation projected results
- Develop new key topics not included in the White Paper

- Preparatory work for the pre-CDR: 35-40 "distillate" pages with a scientifically accurate story most accessible and interesting to people in the broader particle/nuclear community without an over-simplified propaganda

**The outcome shall be the upgrade pre-CDR**

# 22 GeV Upgrade: Next Workshop

## SCIENCE AT THE LUMINOSITY FRONTIER: JEFFERSON LAB AT 22 GEV


**Conference Date**
December 09, 2024 to December 13, 2024

**Conference Location**
LNF-INFN in Frascati (Italy)

- **Web Page under development**
- **Organization on-going**
- **Plan to send out an initial announcement by the end of June**

# Conclusions and outlook

★ QCD manifests fascinating complexity

★ Large research facilities like CEBAF are required to understand the implications of QCD in experiments

★ CEBAF will remain the prime facility for fixed target electron scattering at the luminosity frontier

★ A groundbreaking experimental program has been developed stretching well into the 2030s with existing or planned new equipment

★ A new round of upgrades to CEBAF are presently under technical development: an energy upgrade to 22 GeV and an intense polarized positron beams

★ JLab@22 GeV scientific program can provide a unique insight into the non-pQCD dynamics
- complementary to the envisioned EIC program
- presented and well received (!) in the NP 2023 Long Range Plan
- strong support from a broad community

**The lab and the users community are building the (bright) future of Jefferson Lab**

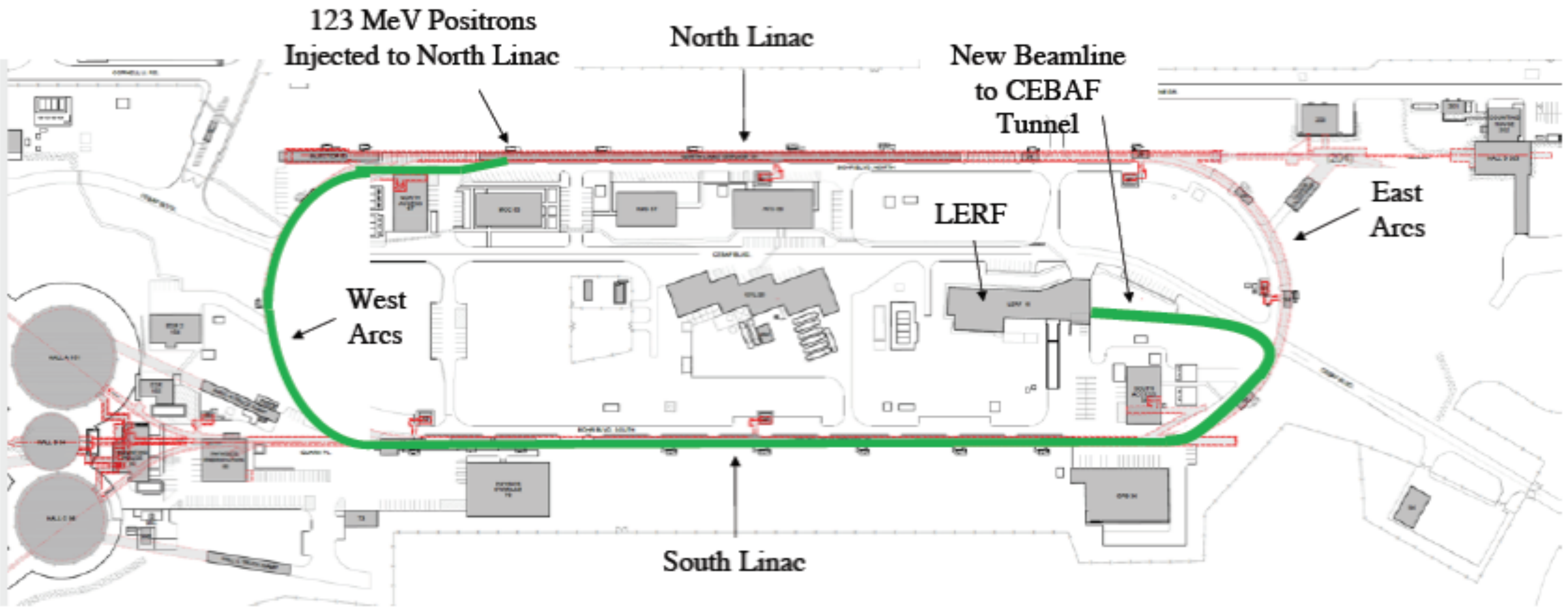
# CEBAF @ 22 GeV phased upgrade

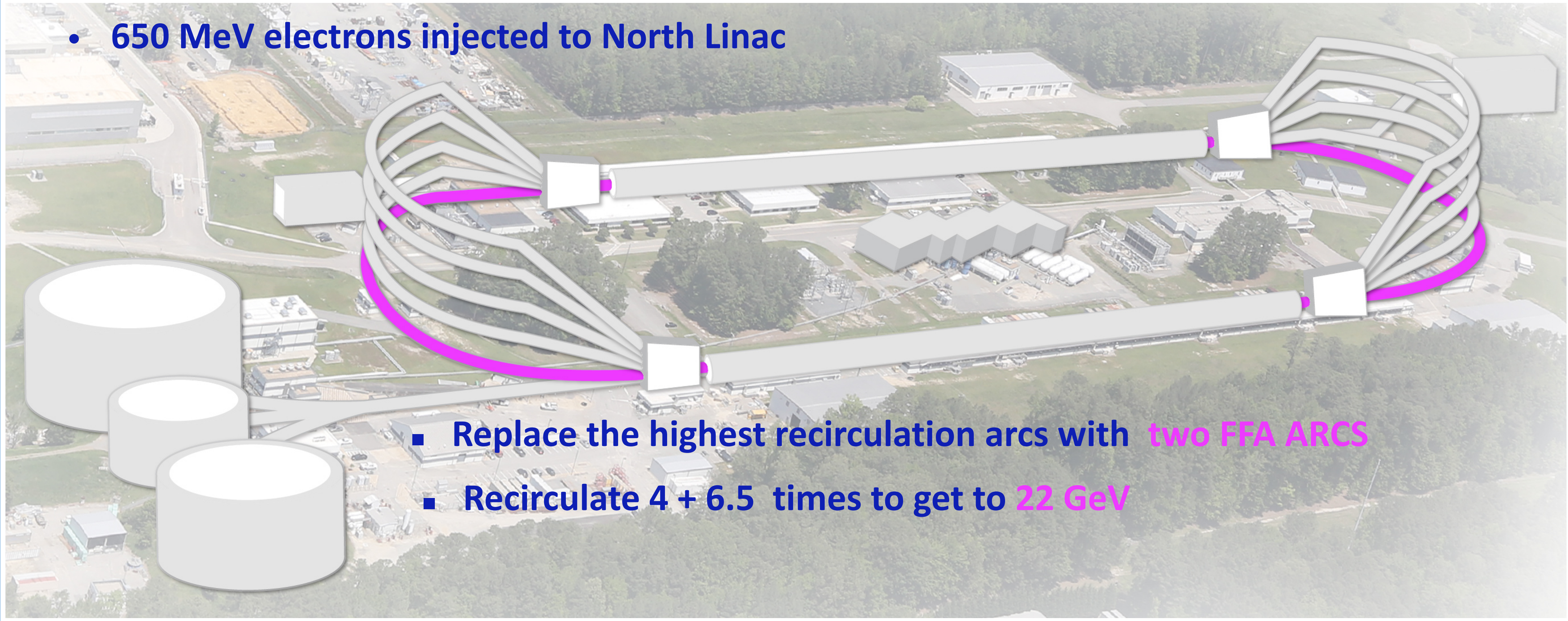
**Phase 1:**

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

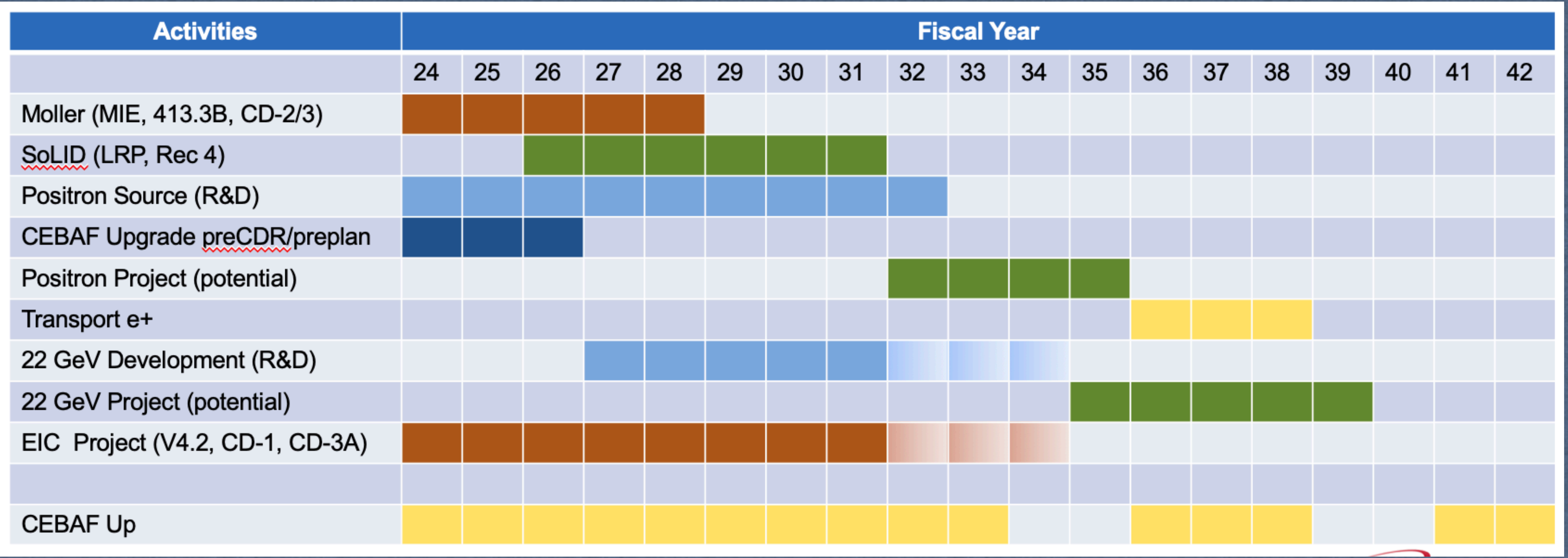
**Phase 2:**

- 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!



# VERY ROUGH timeline




Phase 1 includes building the positron source and the tunnel & beamline connecting the source to main machine
Phase 2 includes the new permanent magnets to allow 22 GeV within current CEBAF footprint

NOTE: Plan was formulated so that these projects are ramping up as the EIC project cost is ramping down