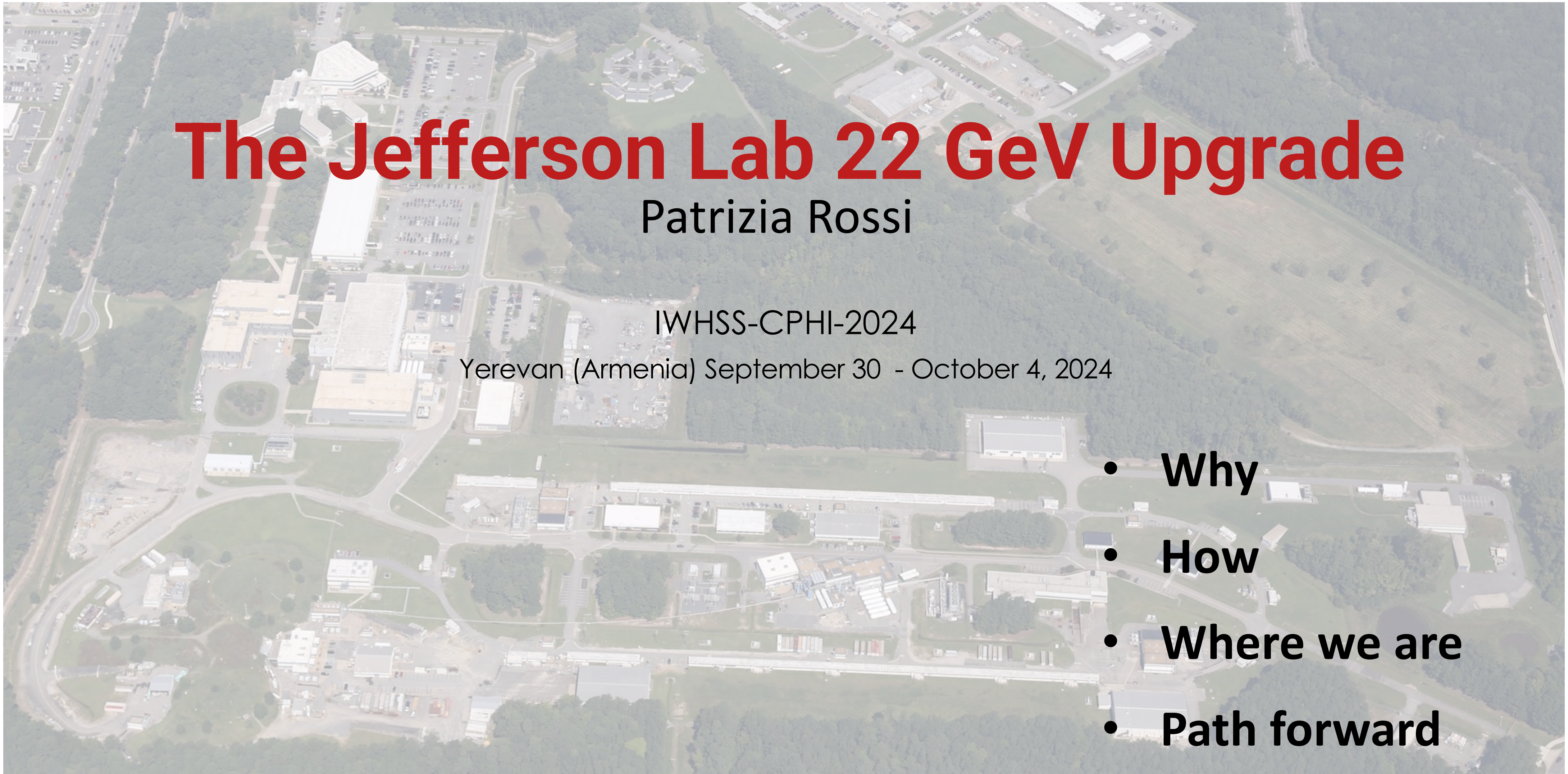


The Jefferson Lab 22 GeV Upgrade

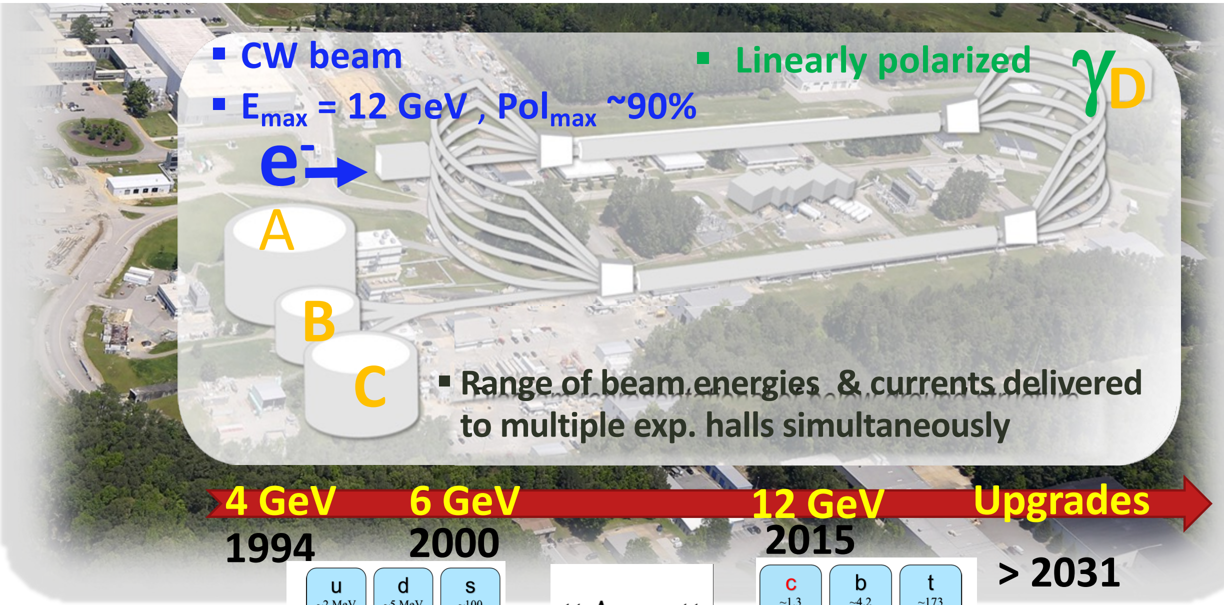
Patrizia Rossi

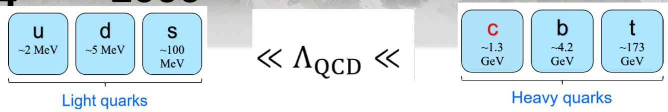
IWHSS-CPHI-2024

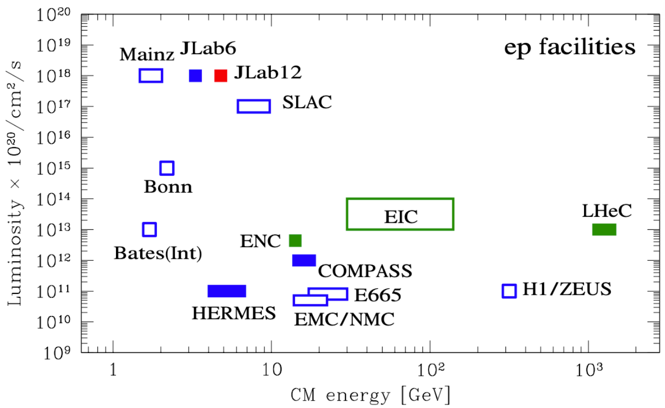
Yerevan (Armenia) September 30 - October 4, 2024

- **Why**
- **How**
- **Where we are**
- **Path forward**

CEBAF Today & Plans for the Future







- 12 GeV scientific program in full swing

- Fixed target experiments at the "luminosity frontier"
  (up to 10^{39} cm² s-¹)
- Large-acceptance precision detectors

UNIQUE facility !

CEBAF @ 22 GeV
Positron Beam @ 12 GeV

Prepare for the Future…

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

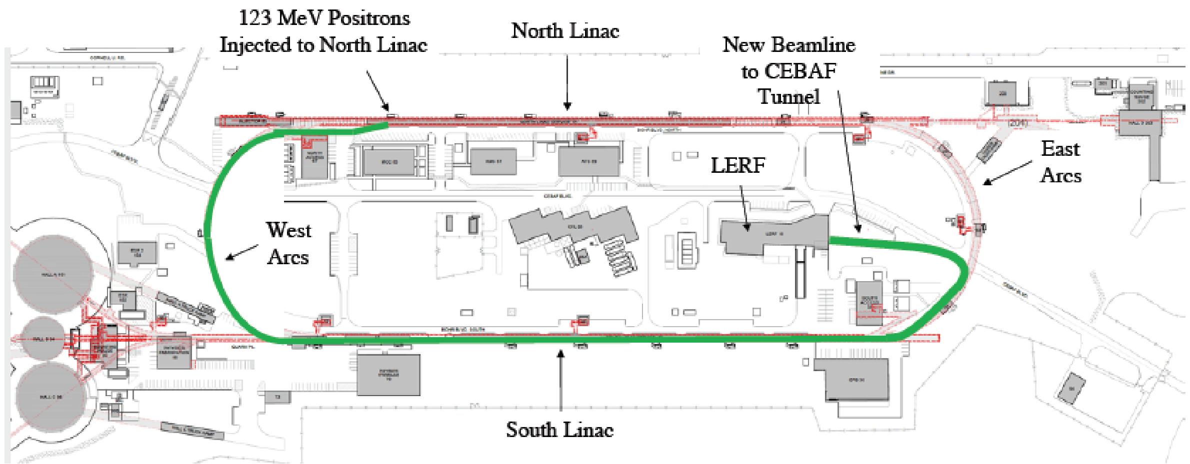
To investigate the other XYZP states, higher beam energy is required; the tetraquark candidate Zc states would be copiously produced at a high-luminosity, fixed-target electron machine operating above 20 GeV

"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."

CEBAF Phased Upgrade

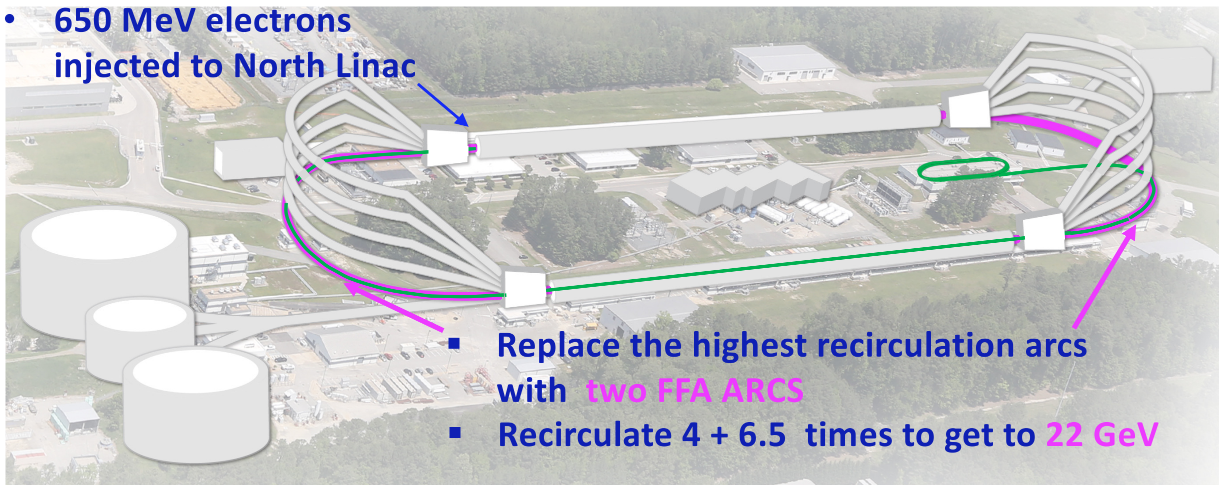
Phase 1:

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



Phase 2:

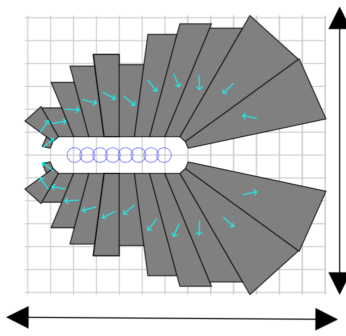
- Recirculating injector energy upgrade to 650 MeV electrons
- Replace one set of arcs on each side with new FFA permanent magnet arcs to upgrade to 22 GeV – no new RF needed! No new cryomodules needed!



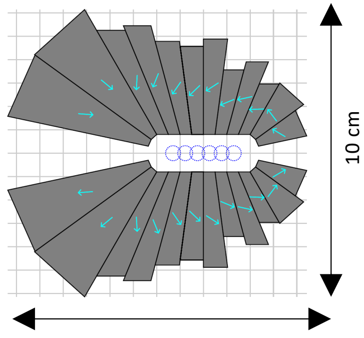
CEBAF FFA Upgrade – Baseline under Study

- 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)

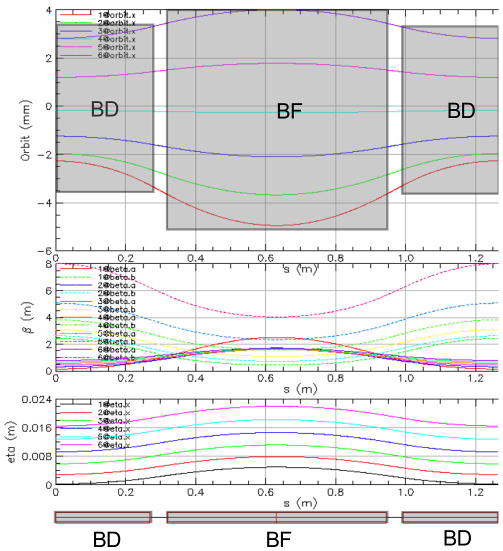
- Arc composed of 75 cells, Lcell = 3.15 m

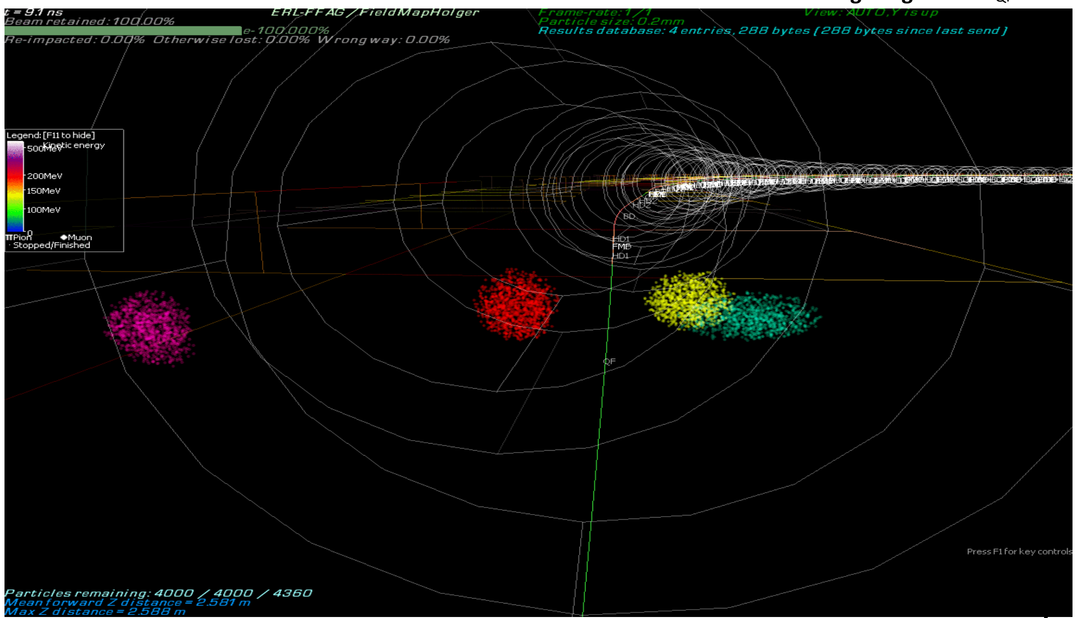


Focusing Magnet BF L_{QF}= 1.67 m

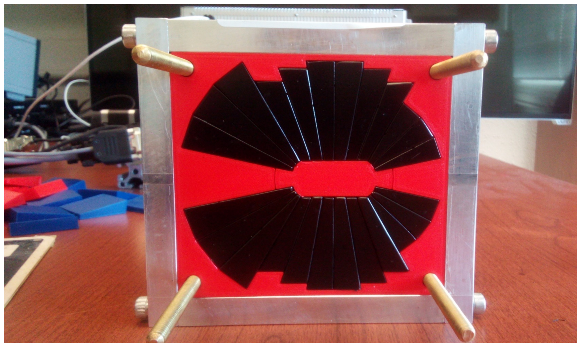


Defocusing Magnet BD L_{BD}= 1.24 m





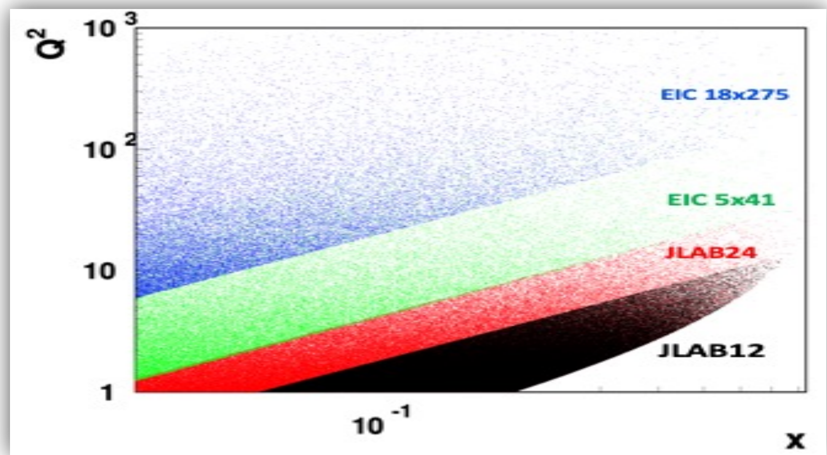
- Novel permanent magnets, CBETA-like used for power and cost savings



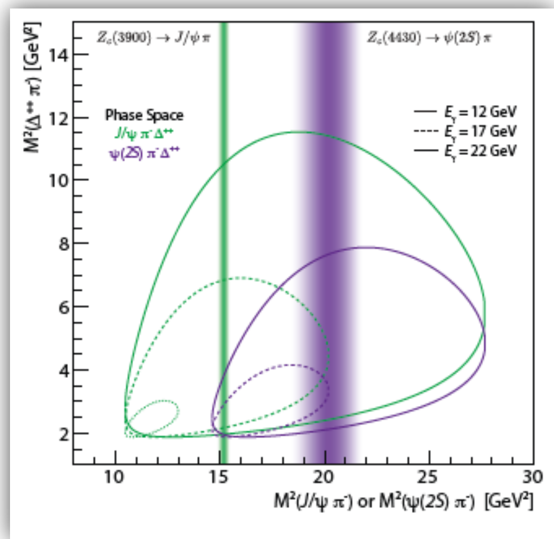
FFA@CEBAF Collaboration

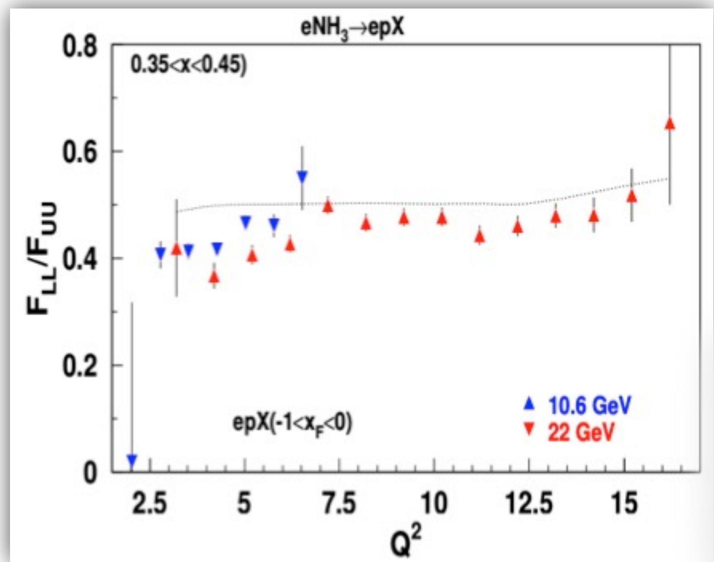
- A prototype open midplane BF magnet was built and evaluated for mechanical integrity
- Magnetic measurement confirmed a robust design with >1.5 Tesla in good field region, 10^{-3} field accuracy
- Testing magnetic materials for radiation resilience at CEBAF - LDRD project started Oct. 1, 2023

How can a 22 GeV upgrade help?



- **A BRIDGE between JLab @ 12 GeV and EIC**
- **CRITICAL for the interpretation of some measurements @ EIC**
- **A NEW territory to explore**
- **A BETTER insight into our current program**

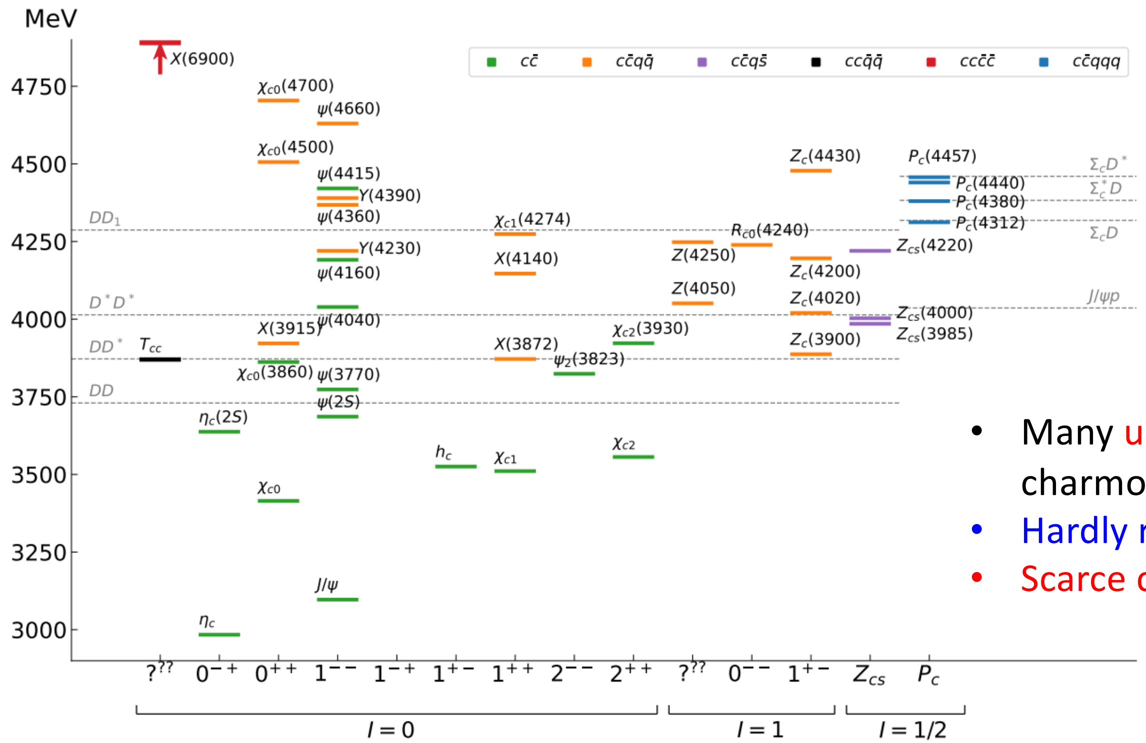




White Paper (~450 authors) ***Eur.Phys.J.A*** **60 (2024) 9, 173**

- Charmed and light hadron spectroscopy
- Structure of hadrons: Form Factors, PDFs, TMDs, GPDs, Fragmentation Functions, Fracture Functions
- QCD in Nuclei and associated Nuclear Modifications and Dynamics
- Low energy tests of the Standard Model and BSM physics

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



JPAC, PPNP, 127, 103981 (2022)

- Many unexpected resonances decaying mostly into charmonium + light quarks appeared in e+e- and B decays
- Hardly reconciled with usual $q\bar{q}$ pheno
- Scarce consistency between various production mechanisms

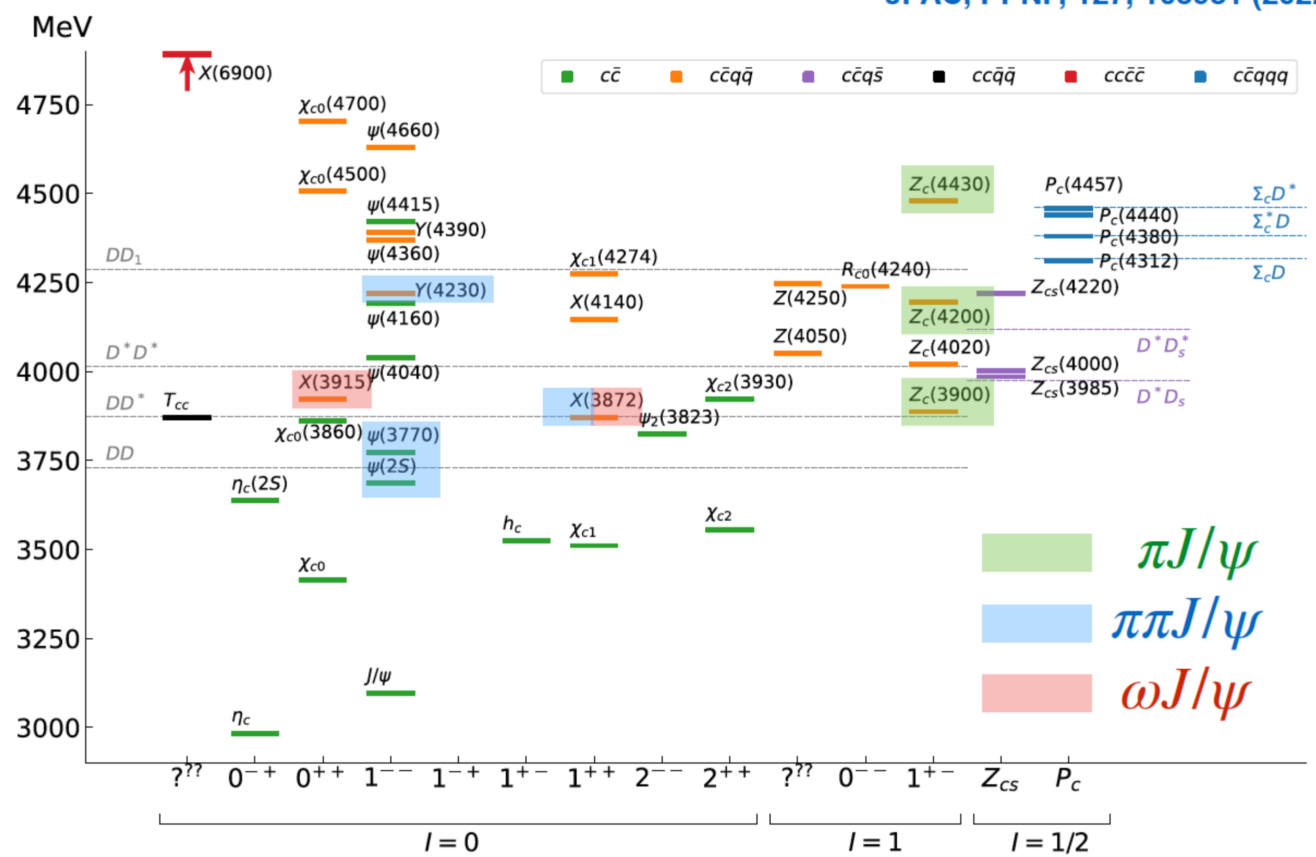
Why photoproduction?

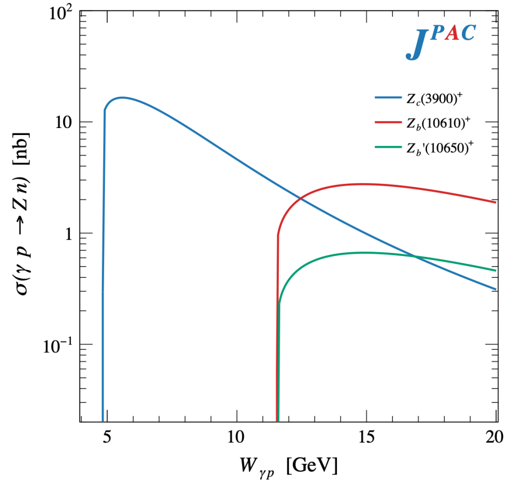
- It's new: no XYZ state has been uncontroversially seen so far
- It is free from rescattering mechanisms that could mimic resonances in multibody decays

Jefferson Lab

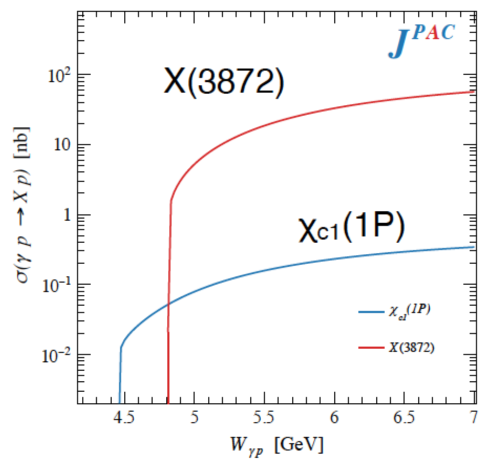
Spectroscopy of Exotic States with $c\bar{c}$

JPAC, PPNP, 127, 103981 (2022)



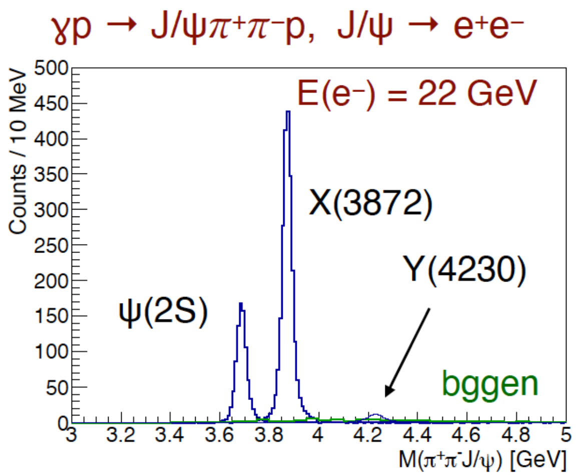


JPAC, PRD 102, 114010 (2020)



- Start looking at "discovery modes": $\pi J/\psi$, $\pi\pi J/\psi$
- Well matched for large acceptance detectors in Halls B and D

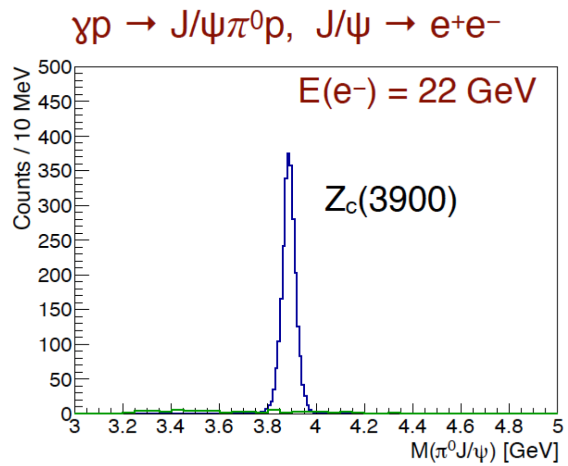
Projections for J/ψπ+π− & J/ψπ Photoproduction at GlueX



fully reconstructed events

- Performed simulations with nominal GlueX-II configuration
  - GlueX-III plans for twice GlueX-II luminosity
- Assumes 1 year @ 500 pb^{-1}, Br(X,Y→ $\pi^+\pi^-$J/ψ) = 5%
- Efficiencies around 10% (n.b. excl. J/ψ eff. around 20%)
- 22 GeV e^-: N(ψ(2S)) = 900, N(X(3872)) = 2300, N(Y(4260)) = 120

Courtesy of S. Dobbs



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

Spectroscopy of Exotic States with CLAS12

Courtesy of D. Glazier

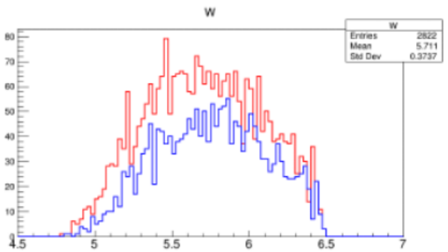
- CLAS12 has excellent PID
- Can measuring missing particles
- Simulations assuming 10^{35} cm^{-2}s^{-1} luminosity for 50 days, zero-degree tagger

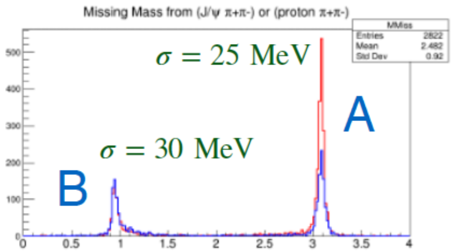
$$X(3872) \rightarrow \pi^+\pi^- J/\psi$$

A) Missing J/ψ

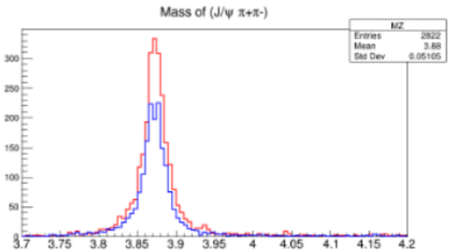
B) Missing proton

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

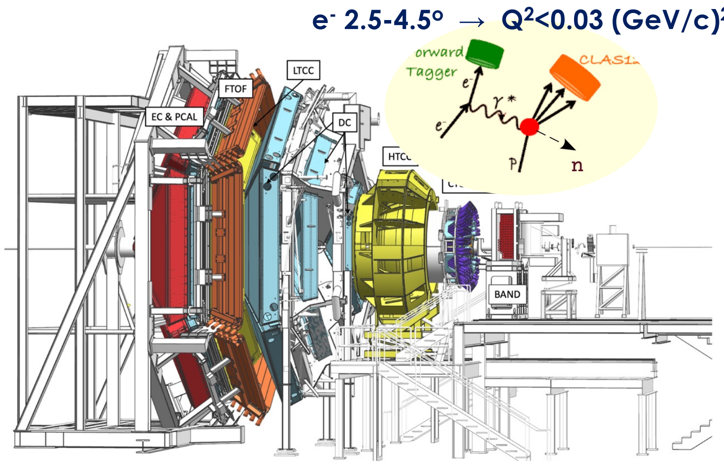




Red: positive particles outbending
Blue: negative particles outbending



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



- Once seen, Q^2 of transition form factors will give new observables crucial to assess the nature of these exotics

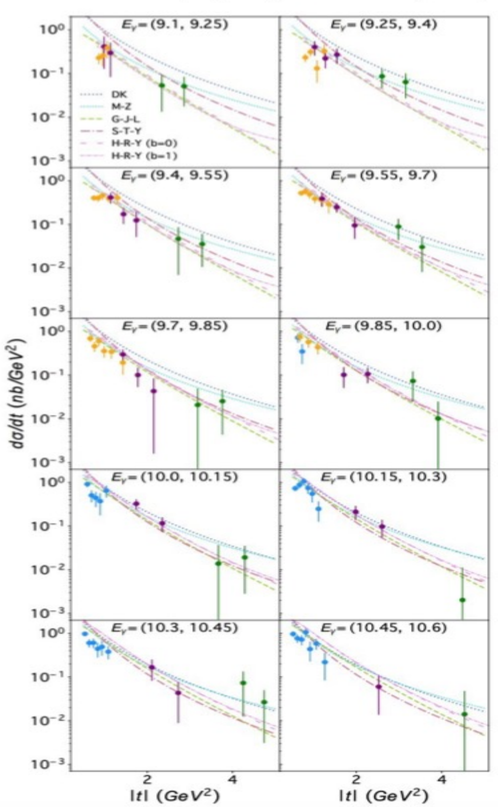
Measurements of X(Y) Z states at JLab with 22 GeV electrons are feasible

Charmonium Photoproduction & Mass Properties of the Proton

- Jlab @ higher energies is critical in justifying charmonium photoproduction near threshold as a method to study mass properties of the proton

HALL C EXPERIMENT E12-16-007

B. Duran et al. (J/ψ-007), Nature 615 (2023)



GRAVITATIONAL FORM FACTORS (GFFS)

$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle = \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

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

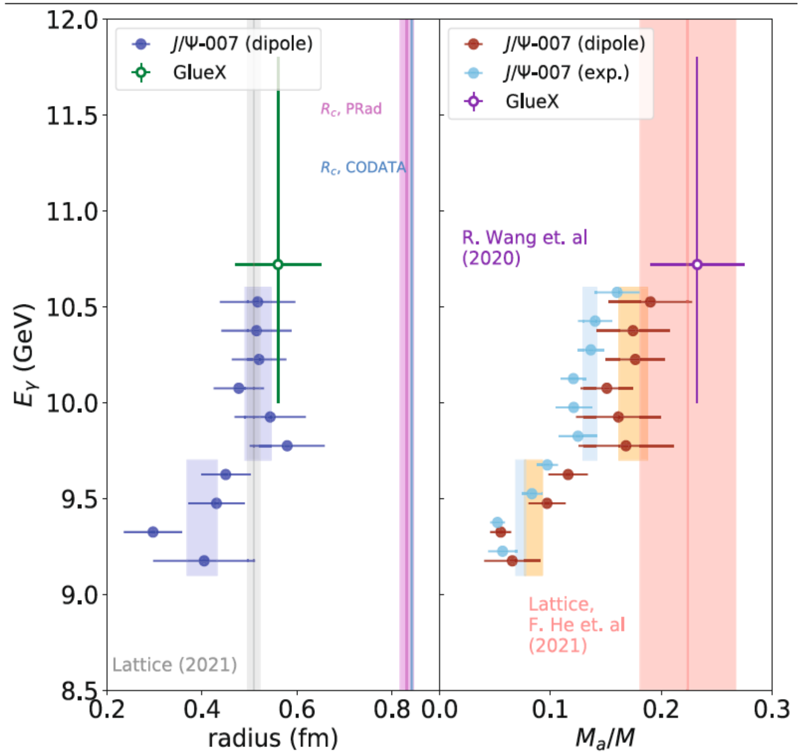
$$\langle r_m^2 \rangle_g = \frac{6}{A_g(0)} \frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{6}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

Scalar (0++ glueball-like) radius

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

Model assumptions & caveats →

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



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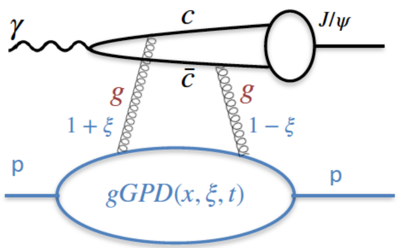
Threshold Charmonium Photoproduction

Model-dependent attempt to access the gluonic contribution to the mechanical properties of the proton (mass radius)

GPD



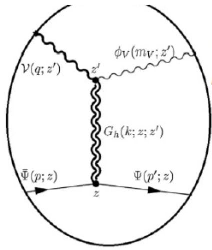
- Compton-like amplitudes $\mathscr{H}_{gC}(\xi,t)$, $\mathscr{E}_{gC}(\xi,t)$ and form-factors as in DVCS
- In contracts: threshold kinematics is very different: at high momentum transfer t and skewness ξ (hard process):

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p\to J/\psi p} = F(E_\gamma)\xi^{-4}[G_0(t)+\xi^2 G_2(t)]+\ldots$$

- Leading terms in $G_0(t)$ and $G_2(t)$ contain gGFFs $A_g(t), B_g(t), C_g(t)$
- Absolute calculations, but require knowledge of gGFFs

GPD analysis by Guo, Ji, Yuan PRD 109 (2024)

Holographic Approach



Witten diagram representation

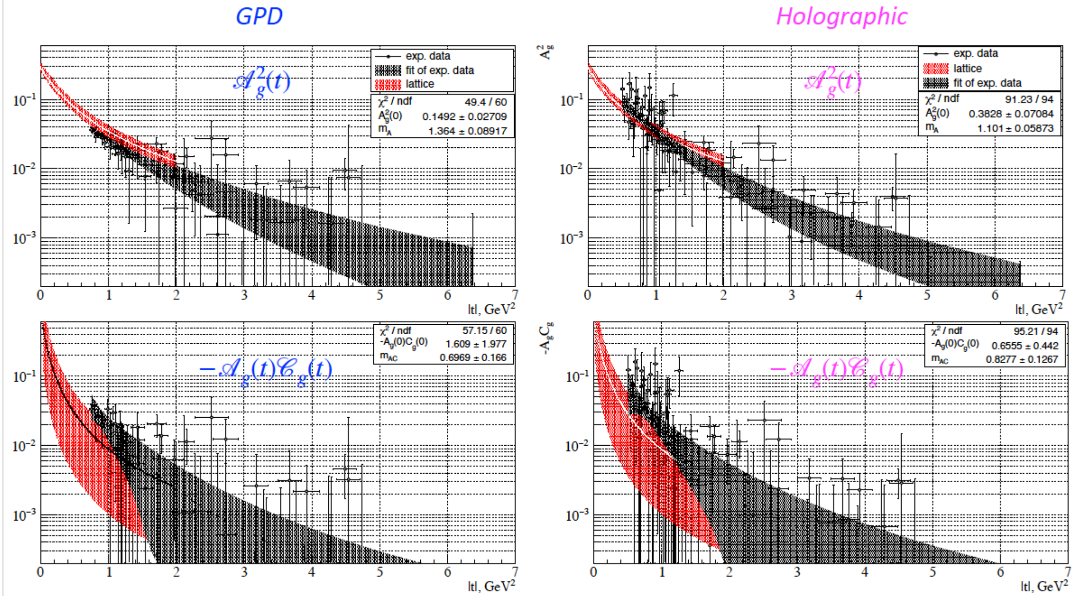
- Using gauge/string correspondence
- In the double limit of large N_c and strong gauge coupling (soft process):

$$\left(\frac{d\sigma}{dt}\right)_{\gamma p\to J/\psi p} = H(E_\gamma)[A_g^2(t)+\eta^2 8A_g(t)C_g(t)]+\ldots$$

- Approximate theory, requires $1/N_c$ corrections
- Relative calculations ($H(E_\gamma)$ normalized to GlueX total cross-sections), but predicts $A_g(t)$ and $C_g(t)$ shapes from Regge trajectories

Holographic analysis by Mamo and Zahed PRD 106 (2022), PRD, PRD 101 (2020), Hatta and Yang PRD 98 (2018)

Gluonic Form Factors - data vs lattice

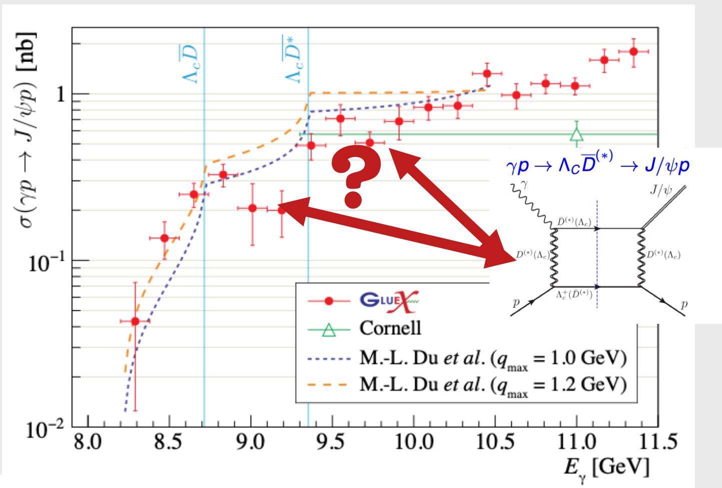


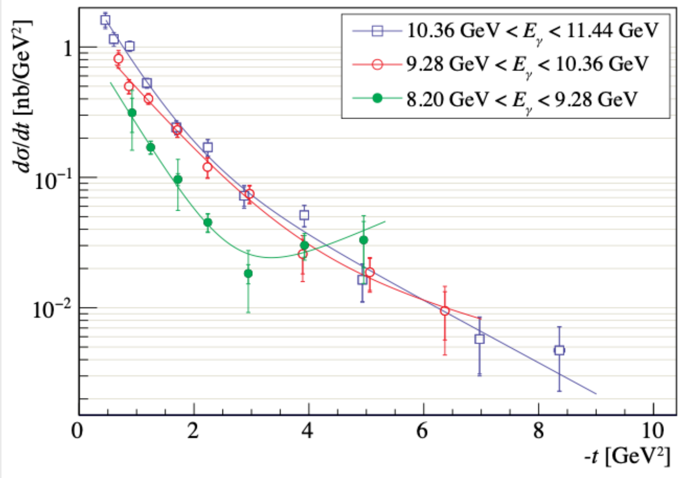
arXiv:2404.18776v1

Extraction of gluonic form factors from JLab J/Ψ data (GlueX + Hall C) **cannot distinguish between two diametric theories**, each with specific corrections (higher moments, 1/Nc)

J/y photoproduction near threshold with GlueX

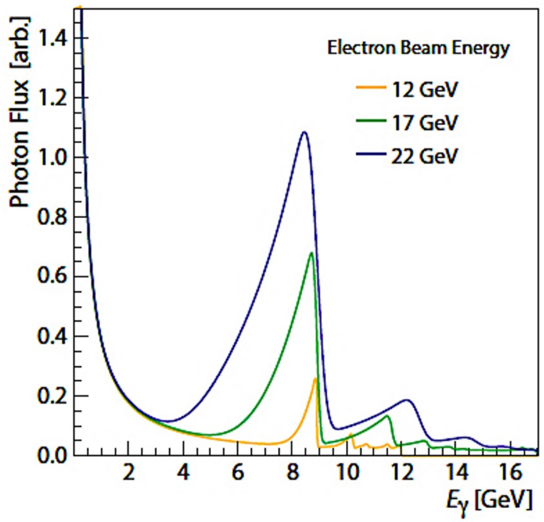
12 GeV

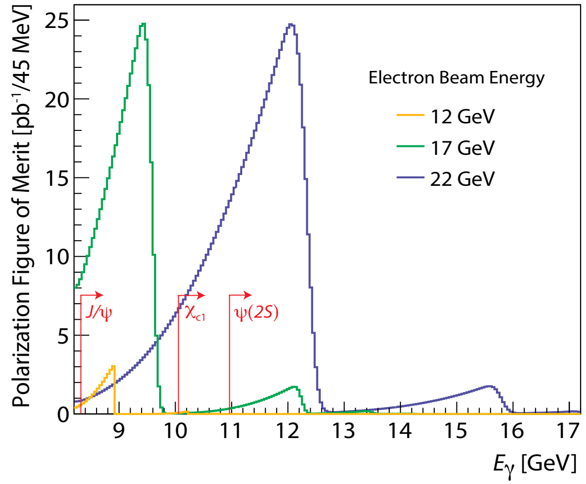


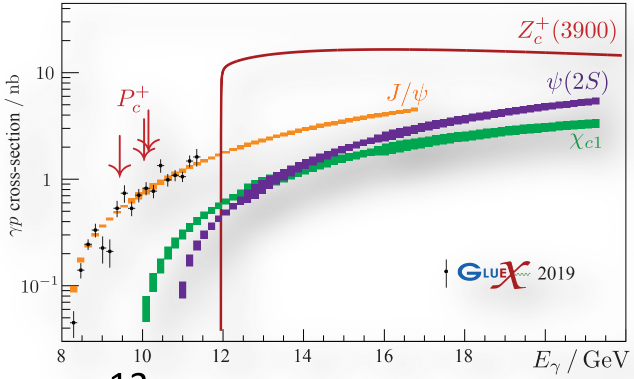


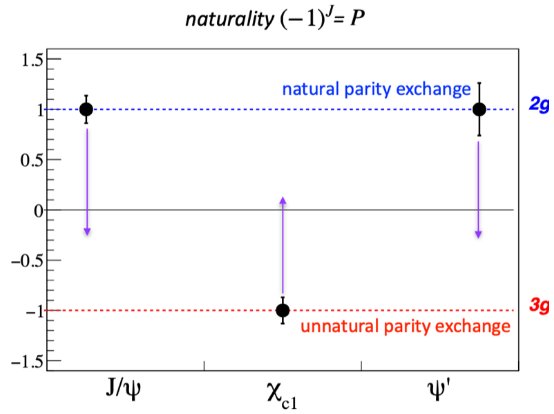
PHYSICAL REVIEW C 108, 025201 (2023)

Upgraded CEBAF









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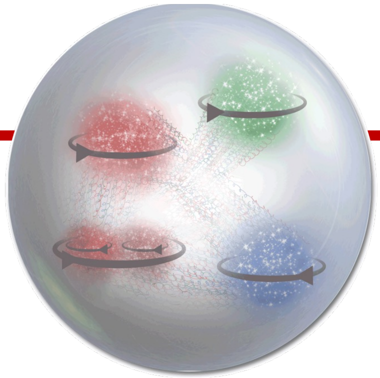
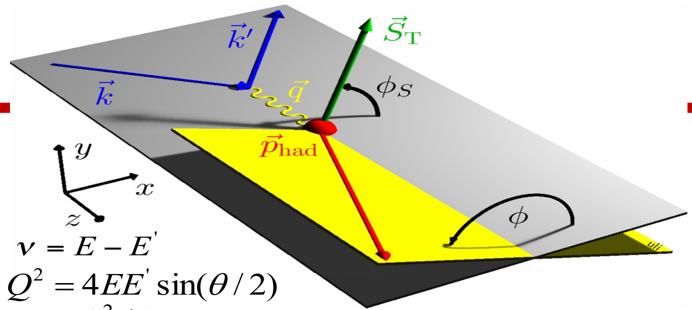
The Nucleon Structure in 3D





$\nu = E - E'$

$Q^2 = 4EE' \sin(\theta/2)$

$x = Q^2 / 2M\nu$

$z = E_h / \nu$

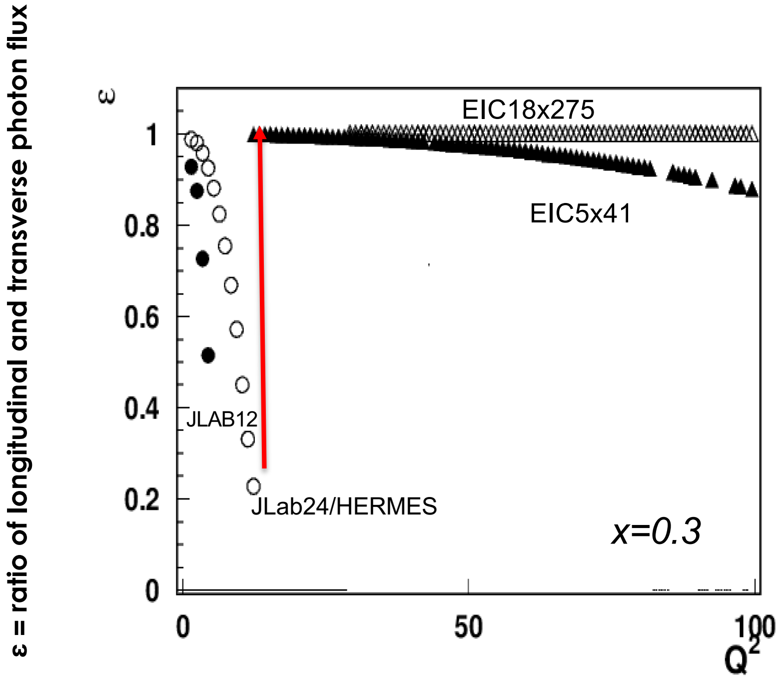
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,dP_{h\perp}^2} \\
&= \frac{\alpha^2}{x\,y\,Q^2}\,\frac{y^2}{2\,(1-\varepsilon)}\Big\{ F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}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

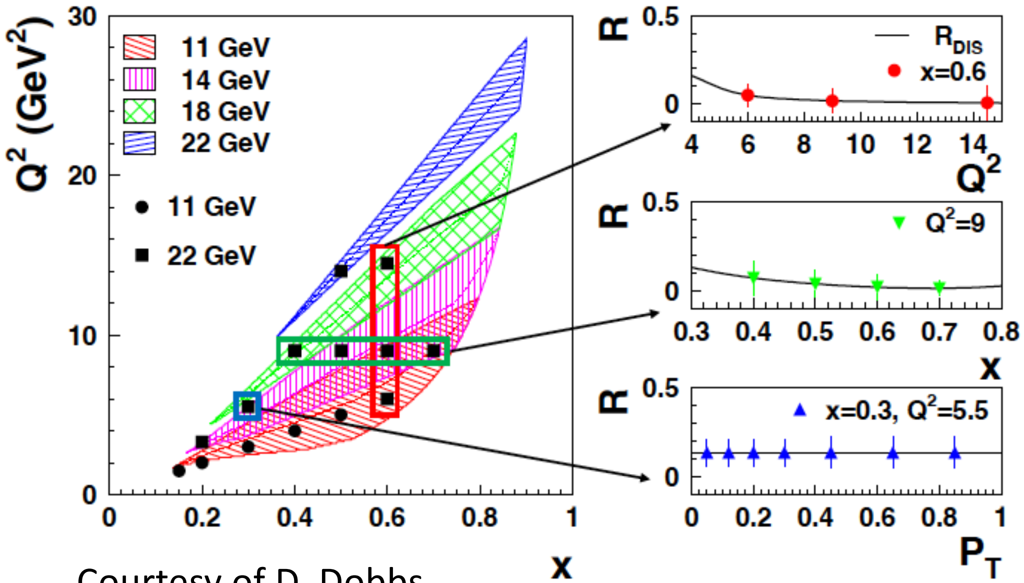
- Studies of azimuthal modulations in 6D (x,Q^2,z,P_T,f,f_S)
- Separate different contributions to x-section
- Separate different contributions to a given SF from different mechanisms
  - longitudinal photon contributions
  - exclusive.VMs

ALL Possible @ Jlab:

high luminosity, high precision, multi-dimentional and multiparticle detection

3D Structure of the Nucleon @ 22 GeV





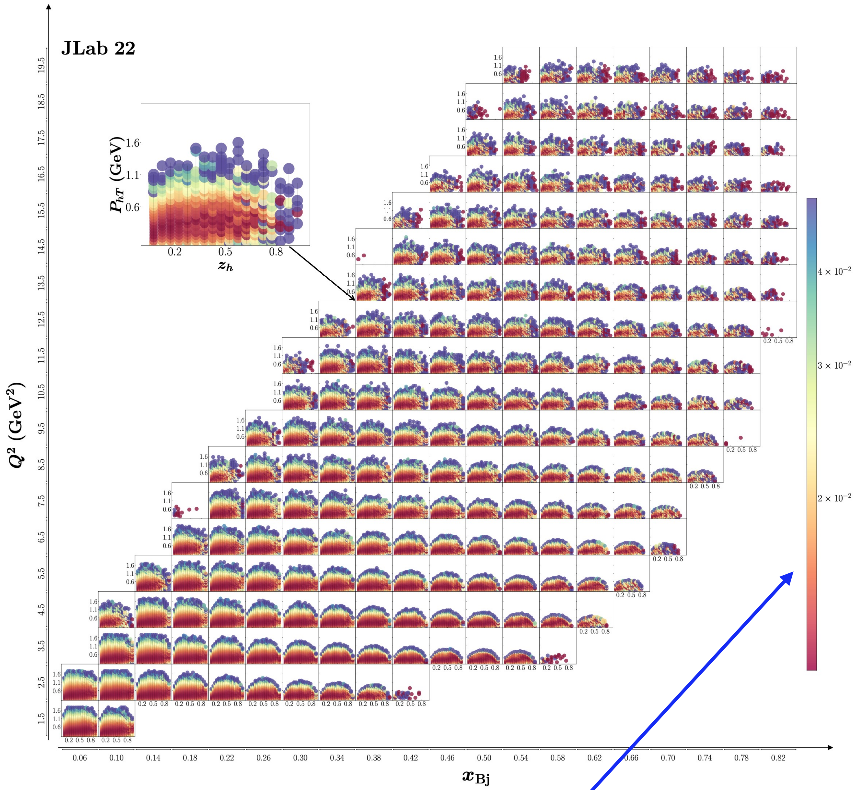
Courtesy of D. Dobbs

- For a given x&Q^2 contribution from longitudinal photon increases at higher energies (ex. at EIC 5 times bigger at Q^2~10, x~0.3 than at JLab)
- JLab studies of impact of longitudinal photons critical for interpretation of polarized SIDIS, including EIC data

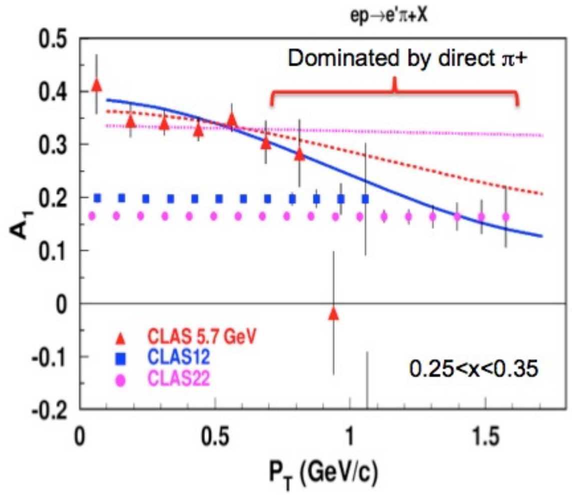
- Kinematic ranges accessible in Hall C with existing HMS and SHMS spectrometers
- Hall C can achieve two ε values separated by 0.2 with a minimum ε of 0.1

3D Structure of the Nucleon @ 22 GeV

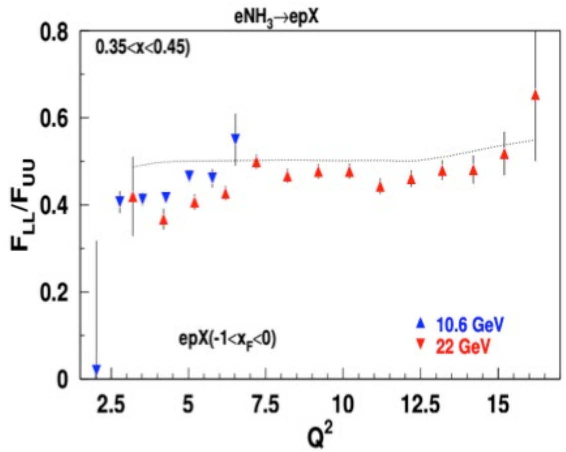
Projections for 100 @ L= 1035 cm−2s−1
using the existing CLAS12 sim/rec chain



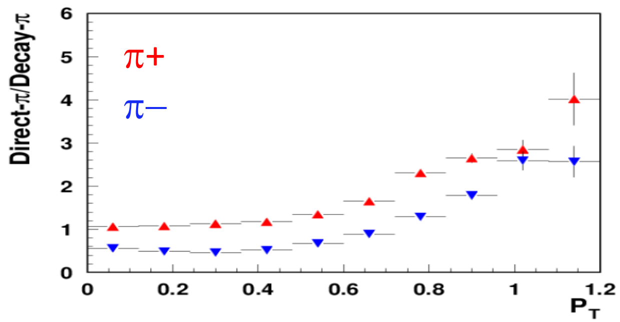
Expected uncertainties for SIDIS x-sections in 4D bins



- rho low P_T impact



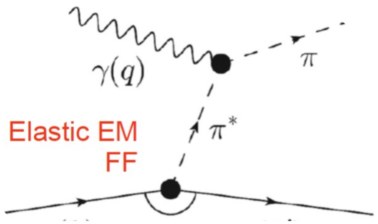
- Large P_T accessible @ CLAS12



- Q^2 evolution studies possible
  - QCD predicts only the Q^2-dependence of 3D PDFs
  - Studies of evolution properties
  - Validate/test the phenomenology

Jefferson Lab

Insights into Hadron Structure through Mesons

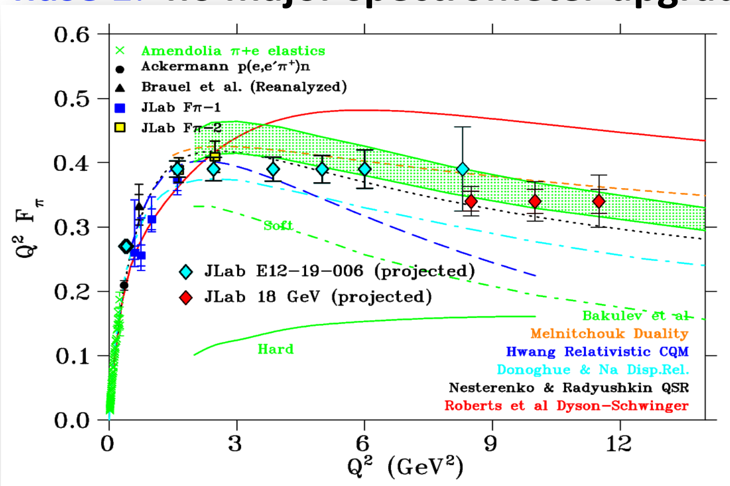


- **At small –t** the pion pole process dominates σ_L (in Born term model)

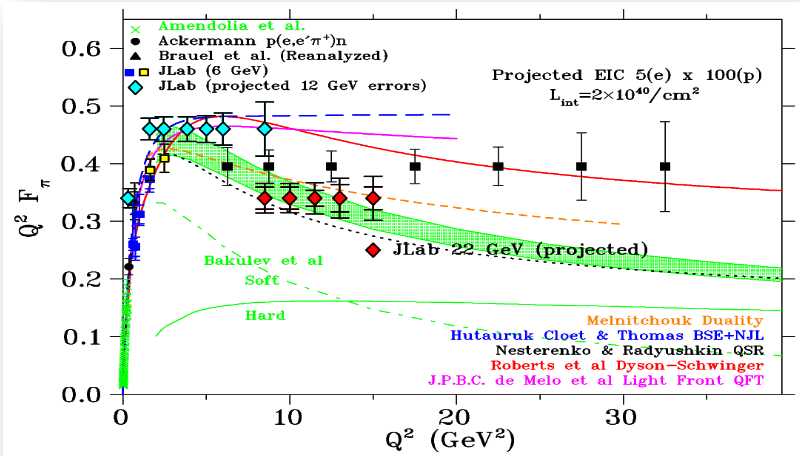
$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_\pi^2)}\, g_{\pi NN}^2(t)\, F_\pi^2(Q^2,t)$$

Quality L/T-separations needed

Phase 1: no major spectrometer upgrades

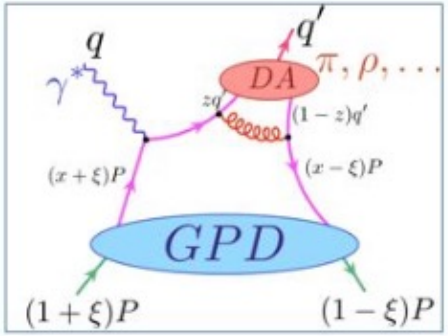


Phase 2: Replace HMS with VHMS

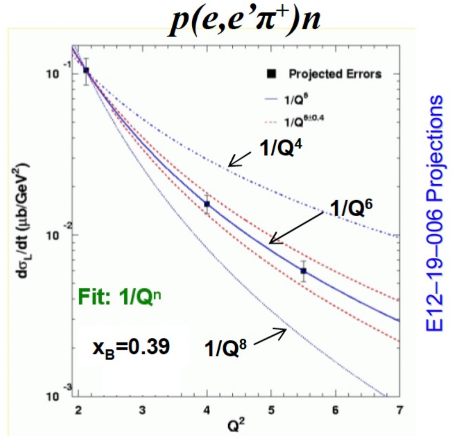


JLab will remain ONLY source of quality L–T separated data!

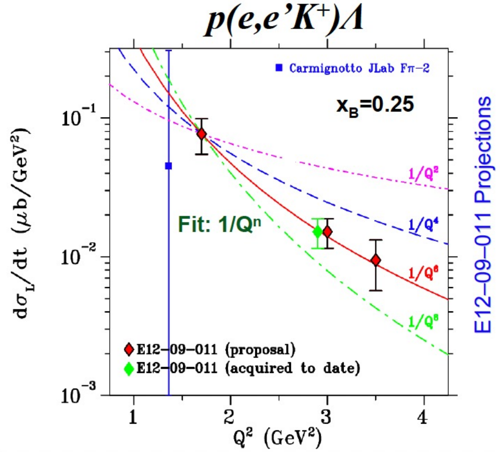
DVMP: L/T Separated Cross Sections



- Validate the understanding of the hard-exclusive reaction towards 3D imaging. **The key to this validation is precision longitudinal-transverse (L/T) separated data.**
- **The handbag factorization, tells us that for asymptotically large Q^2 longitudinally polarized photons dominate**
  - σ_L scales to leading order as Q^{-6}
  - σ_T does not, expectation of Q^{-8}
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$



x	Q^2 (GeV²)	W (GeV)	$-t_{min}$ (GeV²)
0.31	1.45–3.65	2.02–3.07	0.12
	1.45–6.5	2.02–3.89	
0.39	2.12–6.0	2.05–3.19	0.21
	2.12–8.2	2.05–3.67	
0.55	3.85–8.5	2.02–2.79	0.55
	3.85–11.5	2.02–3.23	



x	Q^2 (GeV²)	W (GeV)	$-t_{min}$ (GeV²)
0.25	1.7–3.5	2.45-3.37	0.20
	1.7–5.5	2.45–4.05	
0.40	3.0–5.5	2.32–3.02	0.50
	3.0–8.7	2.32–3.70	

PHASE 1 SCENARIO

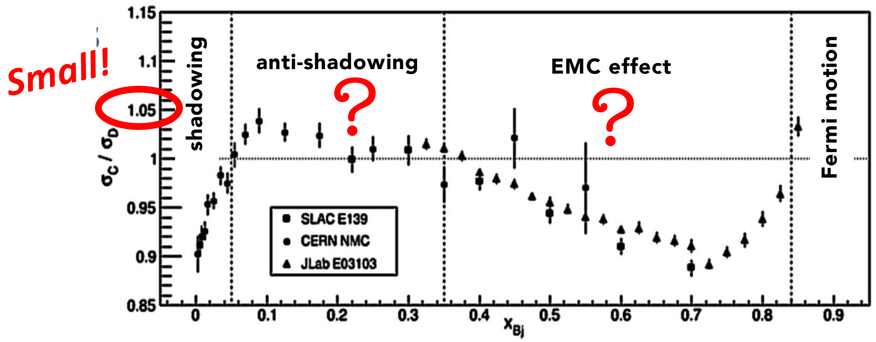
Q^{-n} scaling test range nearly doubles with 18 GeV beam

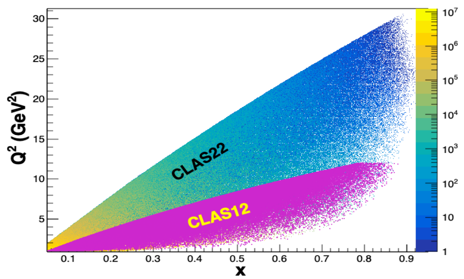
Experimental validation of onset of hard scattering regime is essential for reliable interpretation of JLab GPD program results

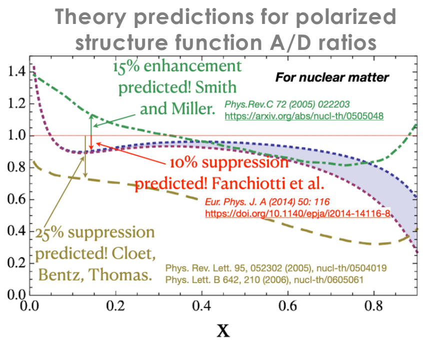
Jefferson Lab

Nuclear Medium Modification of Hadronic Structure @ 22 GeV

Accessing the **anti-shadowing** region



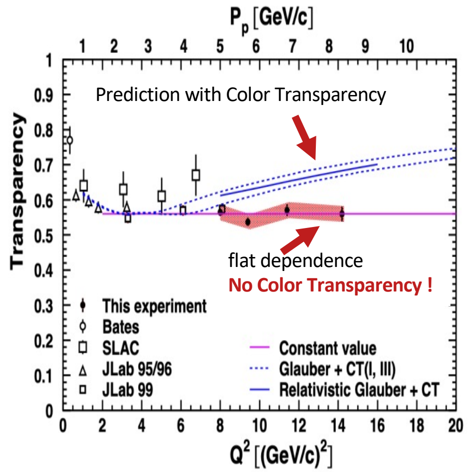




- least studied nuclear structure function effect experimentally – **small effect requiring precision and high luminosity**
  - flavor dependence essentially uncharted
  - no tagged measurements
  - no L/T separations
  - spin dependence essentially uncharted (~50% differences in predictions)

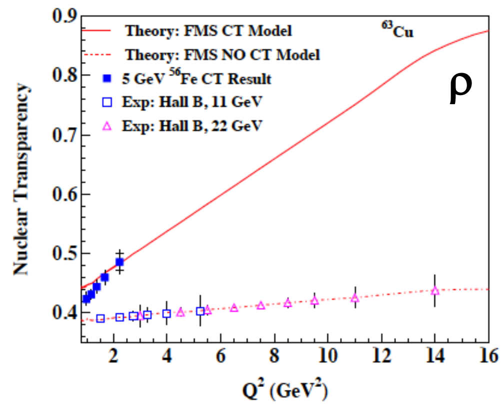
Color Transparency Studies

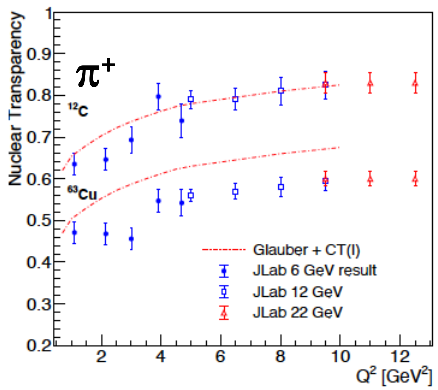
Ruling out color transparency in quasi-elastic $^{12}C(e,e' p)$ up to Q^2 of 14.2 $(GeV/c)^2$



JLAB HALL C
Phys. Rev. Lett. 126, 082301

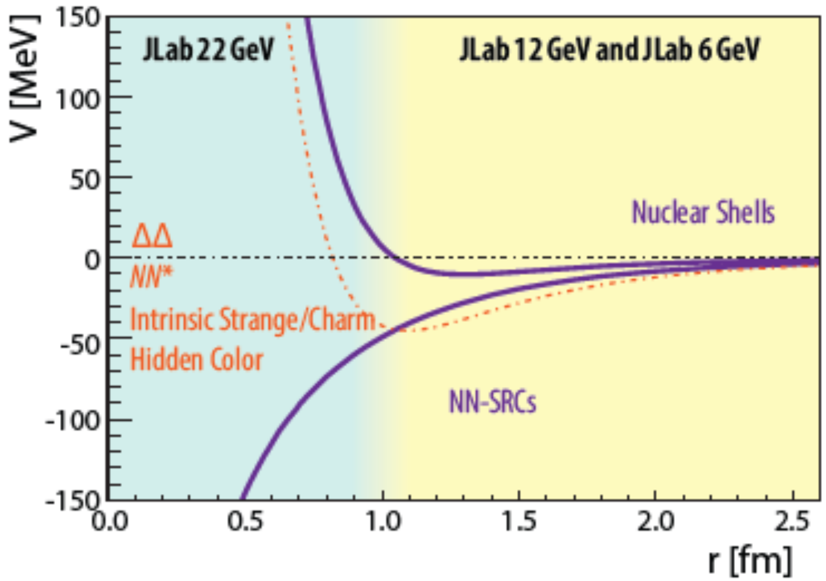
New nuclear data challenge theory!!



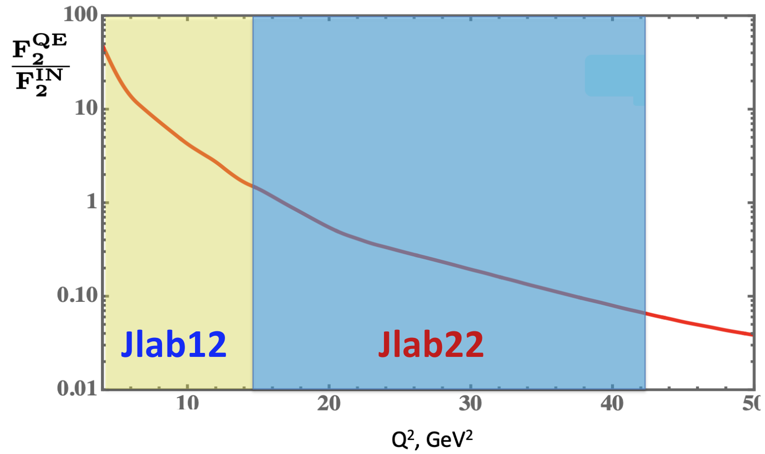


Nuclear Dynamics at Extreme Conditions

22 GeV: reach the **nuclear forces** dominated by **nuclear repulsion**



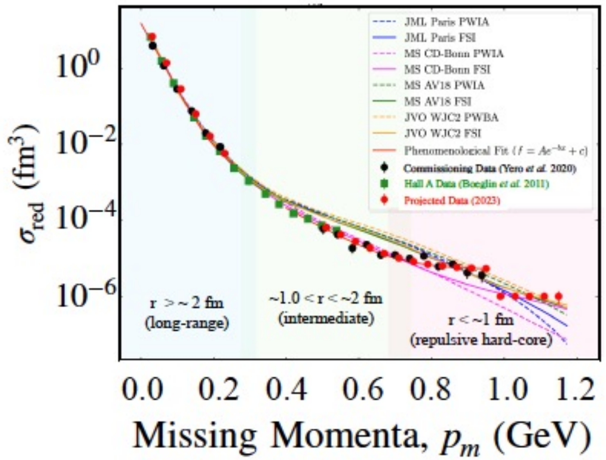
○ **Probing Superfast Quarks in Nuclei**



The high Q^2 reach will allow

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

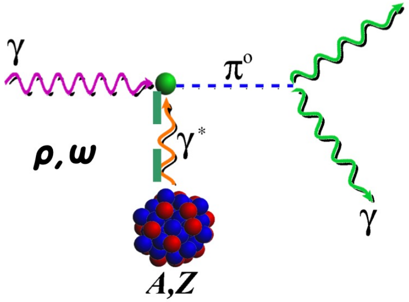
○ **Deuteron Structure at Sub-Fermi Distances**



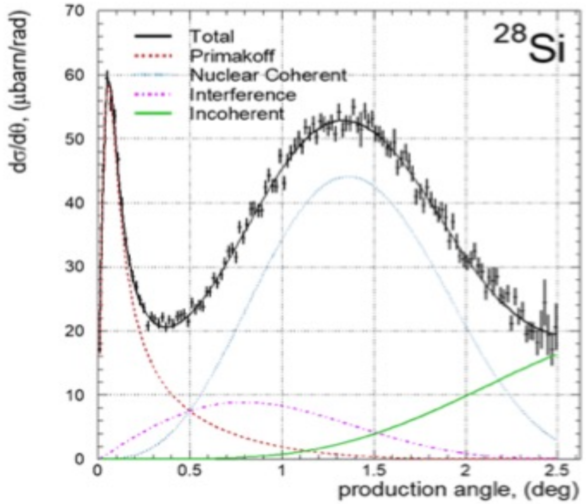
- Data in good agreement with theoretical calculations up to p_m of ~ 700 MeV
- None of the existing theor. calculations able to describe data > 700 MeV, indicating the possible onset of the existence of non-nucleonic components in the deuteron, including possible hidden-color states

QCD Confinement and Fundamental Symmetries

- γ/e-production of mesons in the Coulomb field of a target

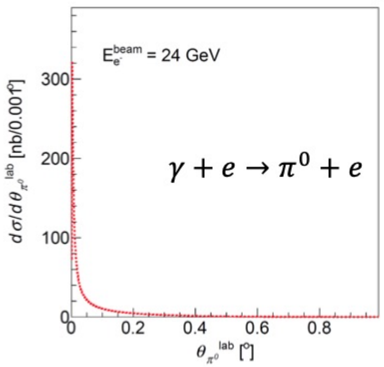


PrimEx-II: $\gamma + {}^{28}Si \rightarrow \pi^0 + {}^{28}Si$



Science 368, 506-509 (2020)

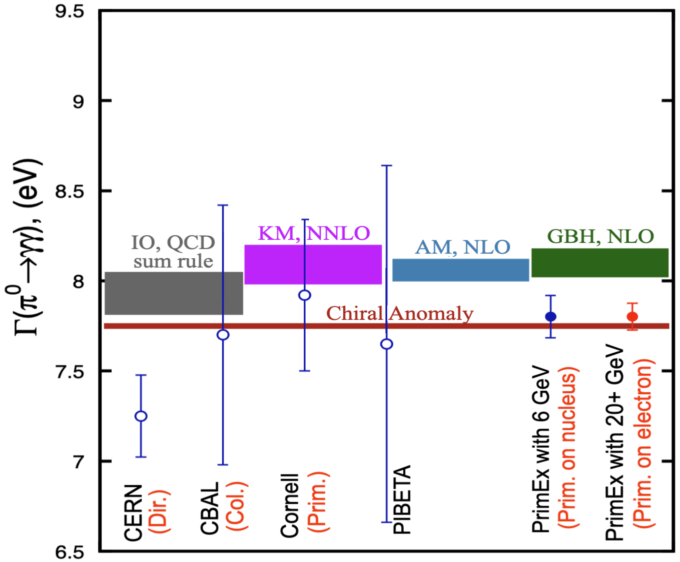
- 22 GeV: π^0 **Primakoff** production off **an e⁻ target**



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

π^0 Primakoff off an e- target: eliminate nuclear bkg

- **π^0 radiative decay width**: can be predicted at ≈ 1% precision in the low energy QCD



Theory and Experiments

2ND WORKSHOP SCIENCE AT THE LUMINOSITY FRONTIER: JEFFERSON LAB AT 22 GEV (LNF-INFN 2024)

The workshop will focus on the continuing development of the scientific case for a 22 GeV upgrade to CEBAF at Jefferson Lab.

As highlighted in the 2023 US Long Range Plan for Nuclear Science:

> *"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…"*
>
> *The 22 GeV energy upgrade "…will allow access to a new sector of hadron spectroscopy and offer an unprecedented view of the complex nucleon structure in the valence region, one not accessible at other machines."*

This workshop will showcase the continued staff and user community efforts to develop increasingly realistic projections for experiments that would become possible with an energy upgrade that maintains the world-leading luminosity of CEBAF. This is the second edition in a series with the previous workshop being in January 2023 at Jefferson Lab. The outcome of the 2023 workshop has been summarized in a white paper (e-Print: 2306.09360 [nucl-ex]) accepted for publication in EPJA.

The format of the workshop foresees invited and contributed talks that span the interests of the user community. We encourage our users and others interested to submit talks and ideas on the scientific topics listed below. The participation of young researchers interested in the field is very much encouraged.

Scientific topics:

- Charmed and light hadron spectroscopy
- Structure of hadrons: Form Factors, Parton Distribution Functions, TMDs, GPDs, Fragmentation Functions, Fracture Functions
- QCD in Nuclei and associated Nuclear Modifications and Dynamics
- Low energy tests of the Standard Model and beyond the Standard Model physics

Registrations are open and the deadline for abstract submission is October 15, 2024

Path Forward

- Continue to refine the scientific case through workshops and biweekly meetings
- Next workshop:
  https://www.jlab.org/conference/dec24luminosity22gev
- Continue the accelerator R&D
- Goal: pre-CDR in ~2 years

Jefferson Lab

Conclusions and Outlook

- The **CEBAF uniqueness** to run experiments at the **luminosity frontier** provides a powerful tool to understand the structure and dynamics of the strong interaction in the **non-pQCD regime**
- A CEBAF energy upgrade to 22 GeV is presently under technical development
- With CEBAF at higher energy some important thresholds would be crossed, a broader phase space will be available - important to understand better our current program, and an energy window which sits between JLab @ 12 GeV and EIC would be available.
- A strong science case for the upgrades is emerging – come join the fun!