The JLab 22 GeV Upgrade

Patrizia Rossi

TOWARDS IMPROVED HADRON TOMOGRAPHY WITH HARD EXCLUSIVE REACTIONS

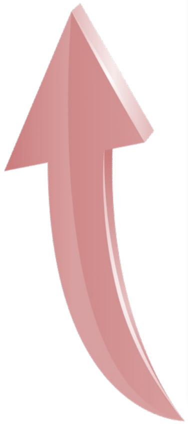
ECT* Trento (Italy), August 5-9, 2024

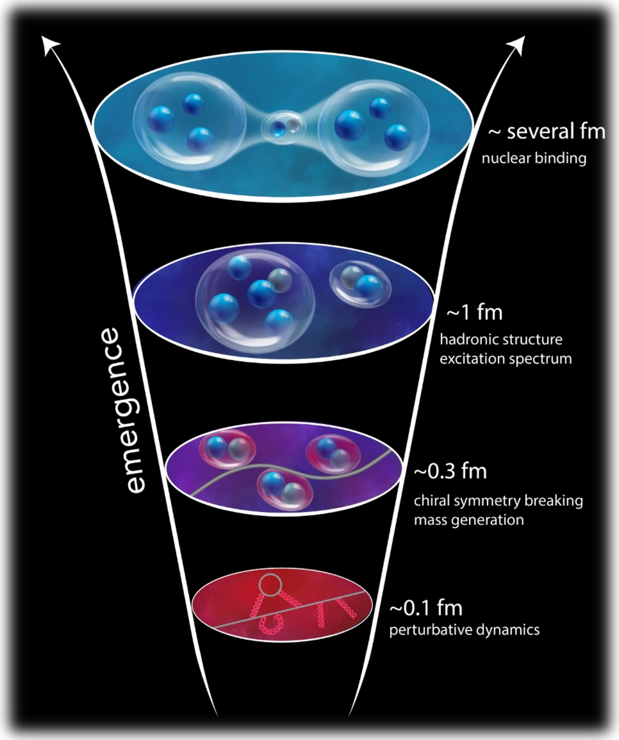
- **Why**
- **How**
- **Where we are**
- **Path forward**

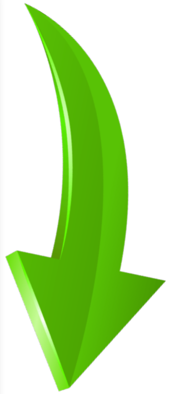
TJNAF is managed by Jefferson Science
Associates for the US Department of Energy

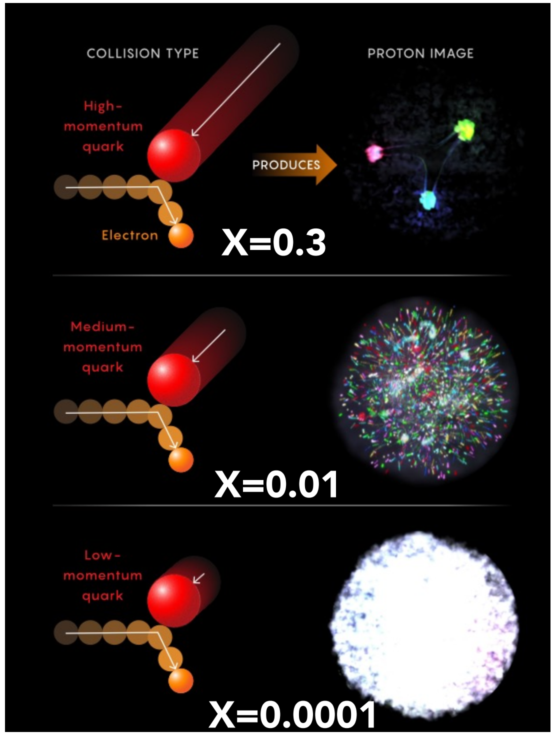
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Emergent Phenomena in QCD

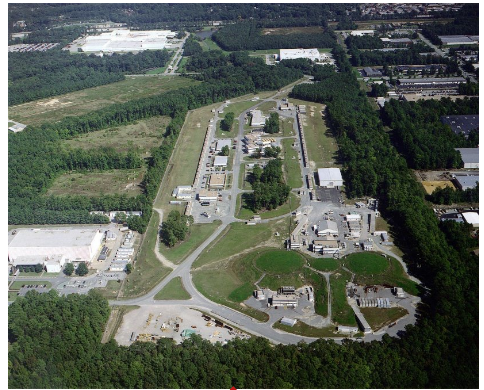






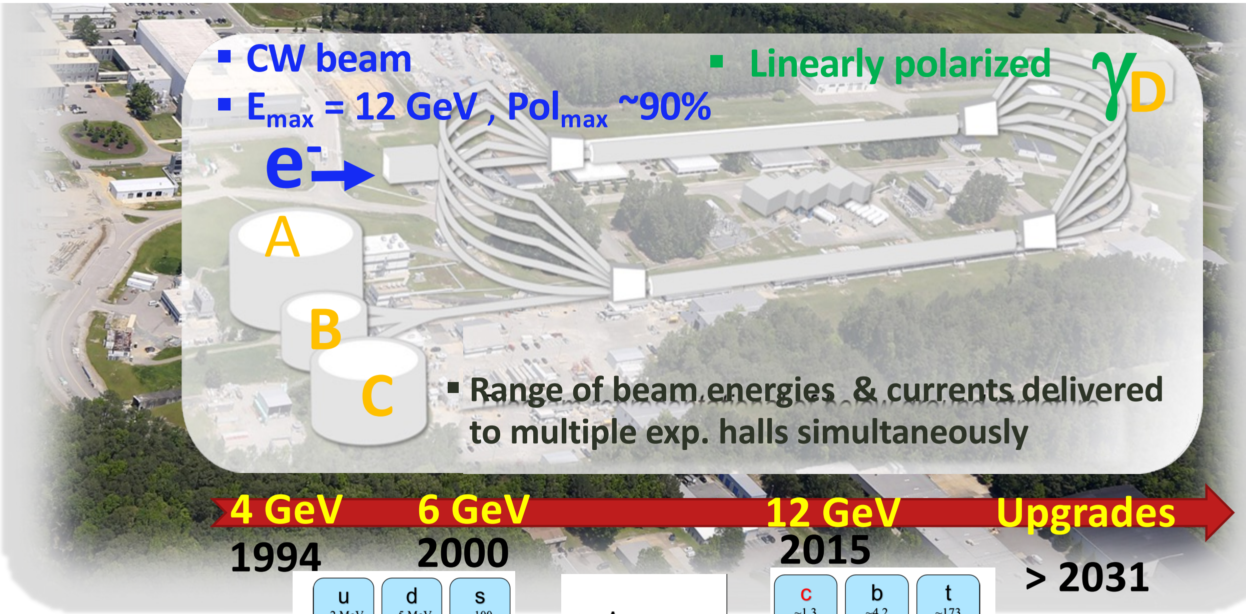


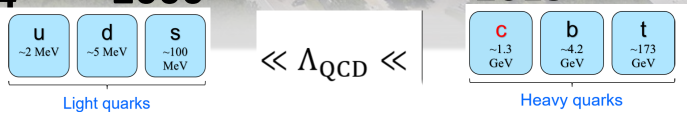
https://www.quantamagazine.org/inside-the-proton-the-most-complicated-thing-imaginable-20221019/

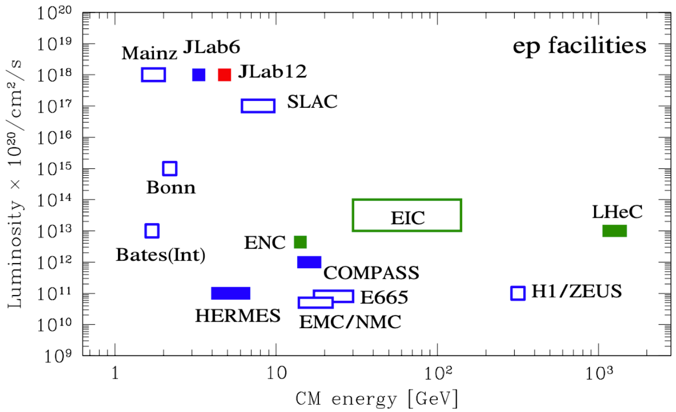


COMPLEMENTARY MACHINES

CEBAF Today & Plans for the Future







- **Fixed target experiments at the "luminosity frontier"** (up to 10^{39} cm² s-1)
- **12 GeV scientific era is in full swing**
- **We want to secure the future of this 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

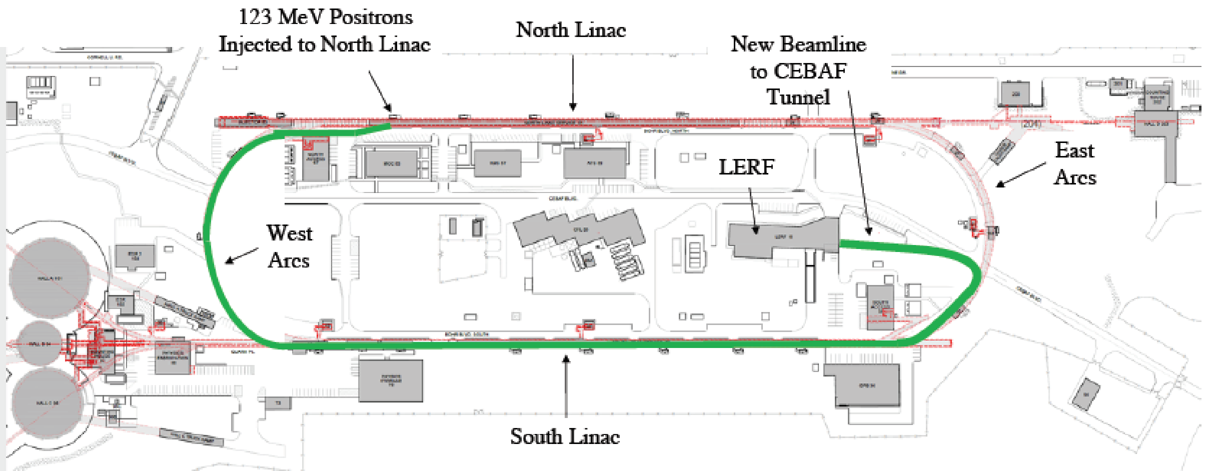
To investigate the other XYZP states, higher beam energy is required; the tetraquark candidate Zc states would be copiously produced at a high-luminosity, fixed-target electron machine operating above 20 GeV

"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

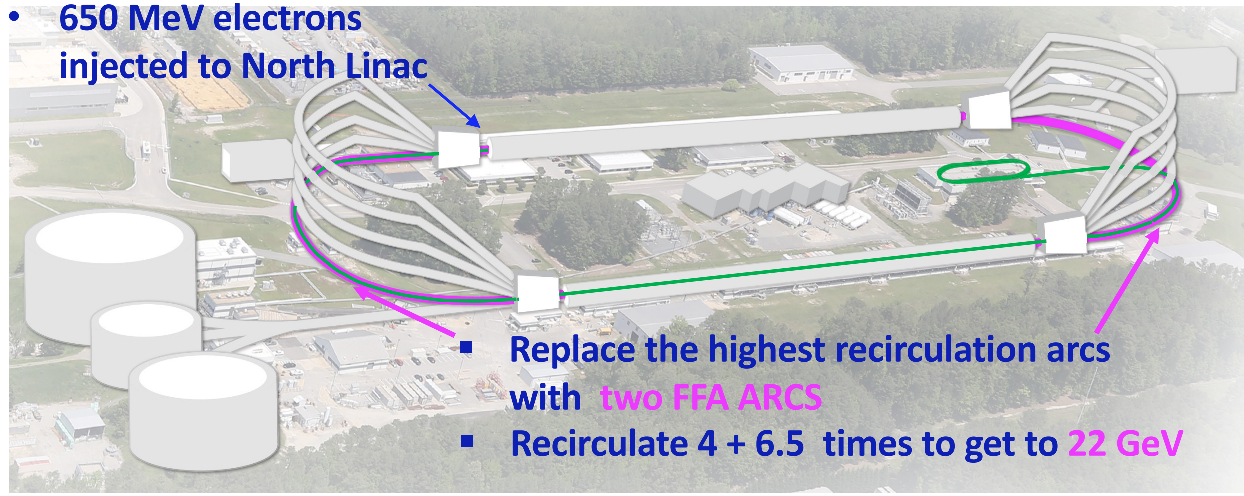
Phase 1:

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



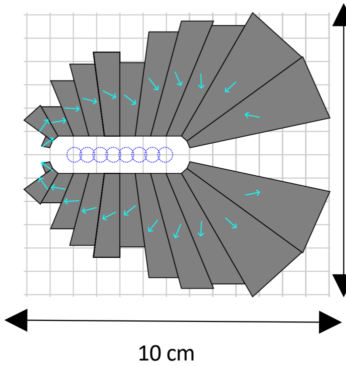
Phase 2:

- 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!

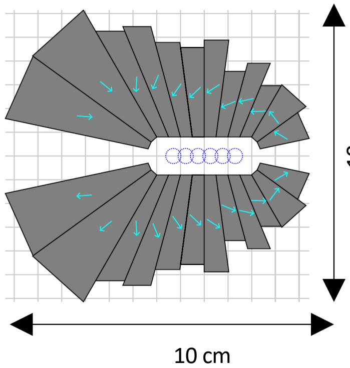


CEBAF FFA Upgrade – Baseline under Study

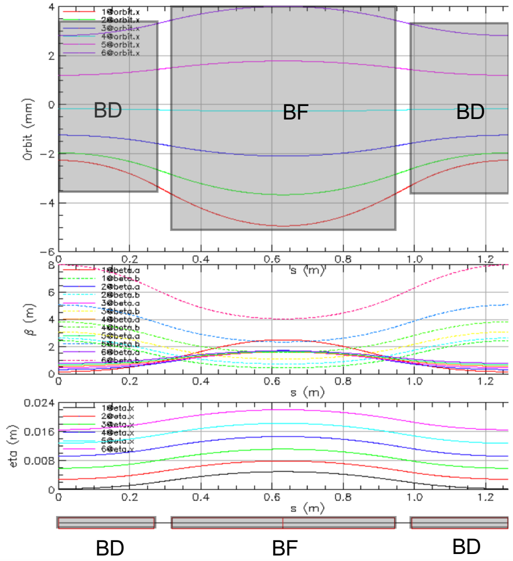
- Large momentum acceptance FFA (Fixed Field, Alternating Gradient) cell is configured with combined function permanent magnets capable of transporting multiple energy beams through the same string of magnets (six beams with energies spanning a factor of two)
- Arc composed of 75 cells, Lcell = 3.15 m

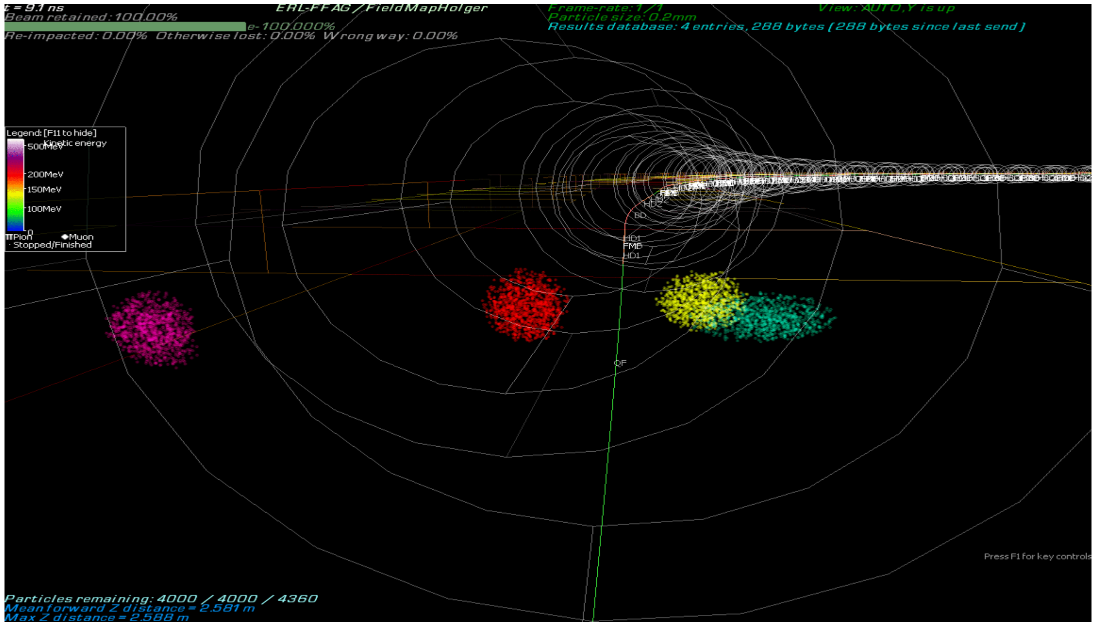


Focusing Magnet BF L_{QF}= 1.67 m

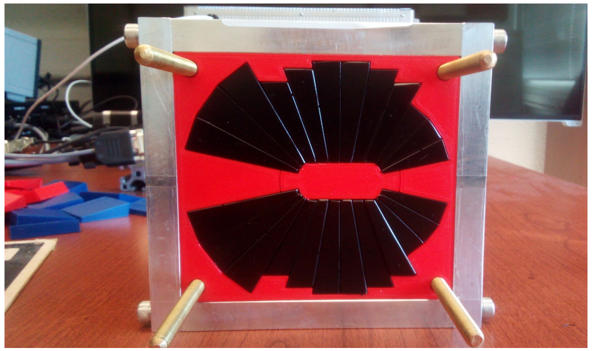


Defocusing Magnet BD L_{BD}= 1.24 m





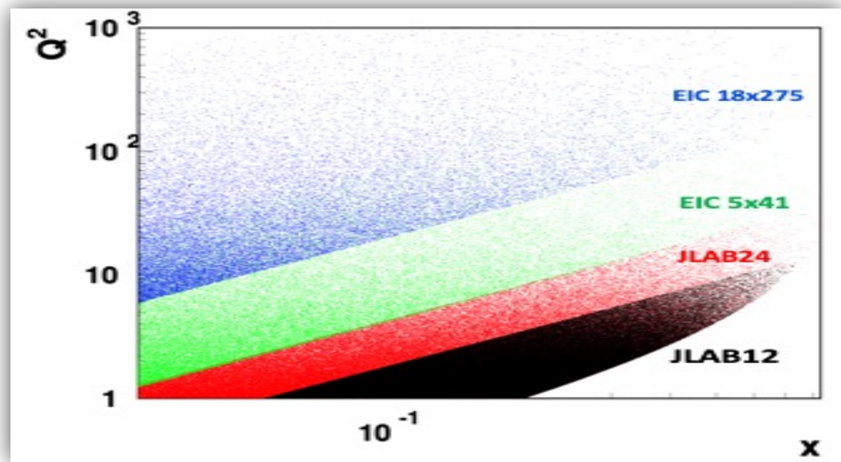
- Novel permanent magnets, CBETA.-like used for power and cost savings



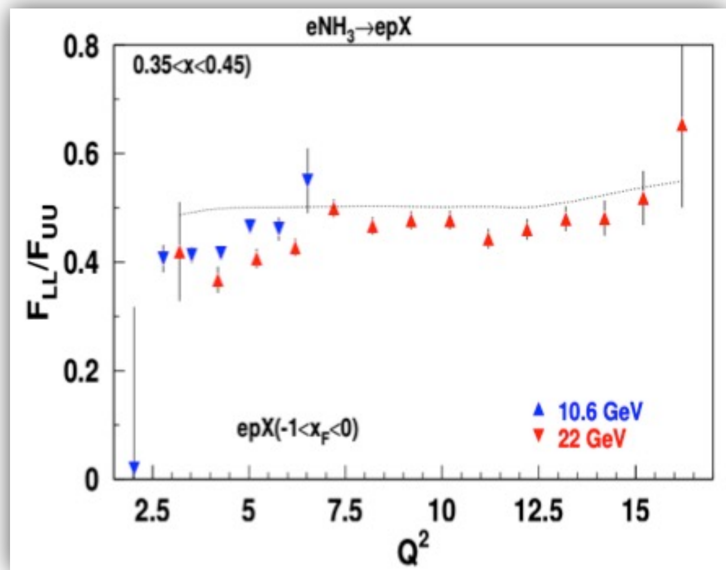
FFA@CEBAF Collaboration

- 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?

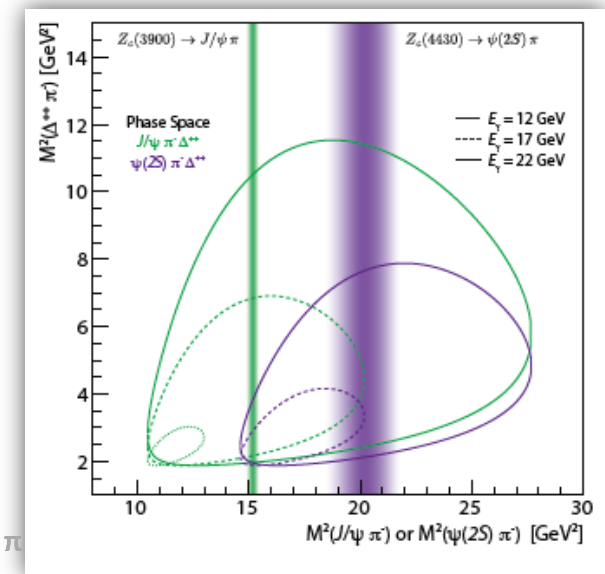


- **A BRIDGE between JLab @ 12 GeV and EIC**
- **CRITICAL for the interpretation of some measurements @ EIC**



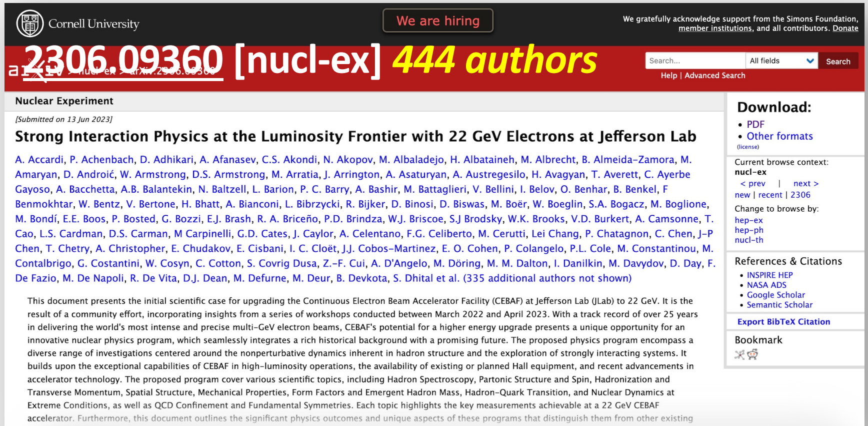
- **A BETTER insight into our current program**
- **A NEW territory to explore**

- Zc(3900) → J/ψ π
- Zc(4430) → ψ(2S) π



The <u>INITIAL</u> Physics case with 22 GeV

- Developed through a series of workshops started in summer 2022
- A white paper has been written and accepted for publication by 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

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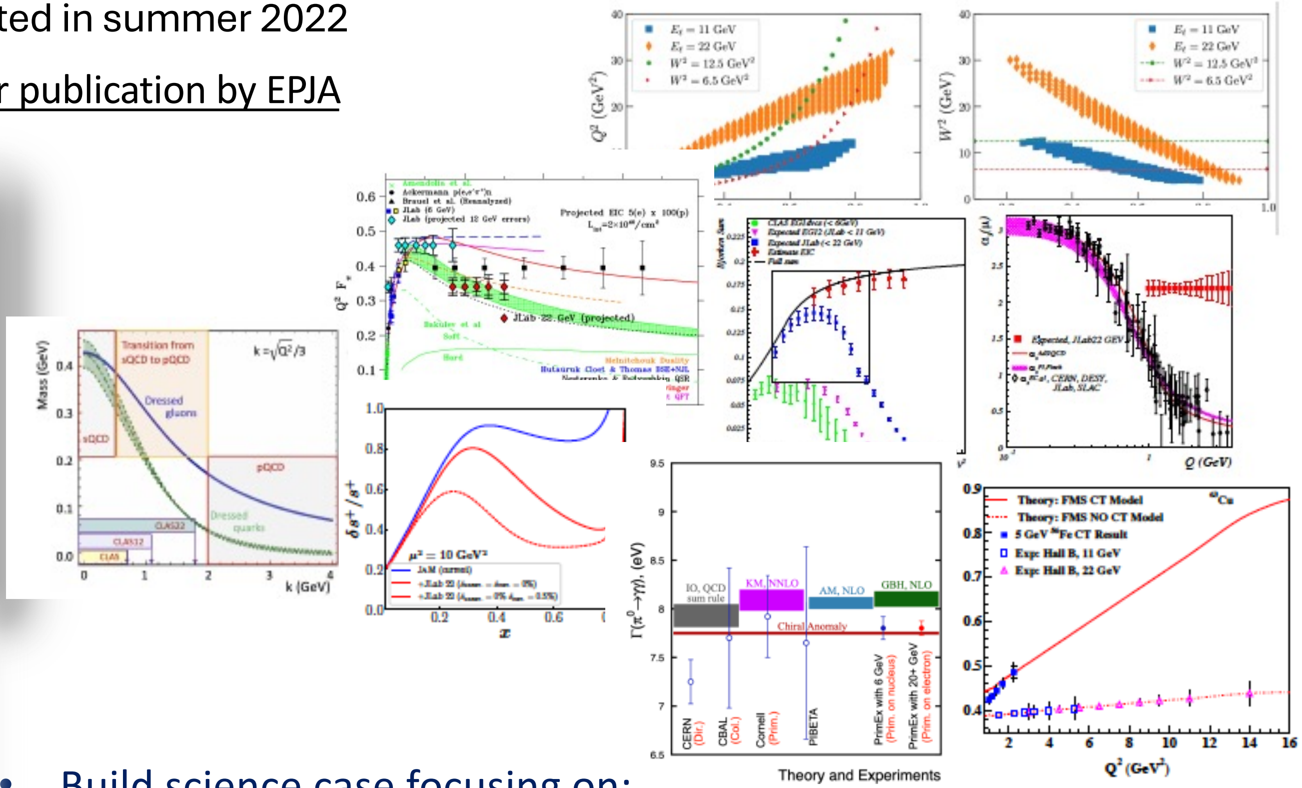

- Hadron Spectroscopy
- Partonic Structure and Spin
- Hadronization and Transverse Momentum
- Spatial Structure, Mechanical Properties, Emergent Hadron Mass
- Hadron-Quark Transition and Nuclear Dynamics at Extreme Conditions
- QCD Confinement and Fundamental Symmetries

- Build science case focusing on:
- Unique science (luminosity frontier, precision)
- Key science questions with 22 GeV
- Complementarity with EIC

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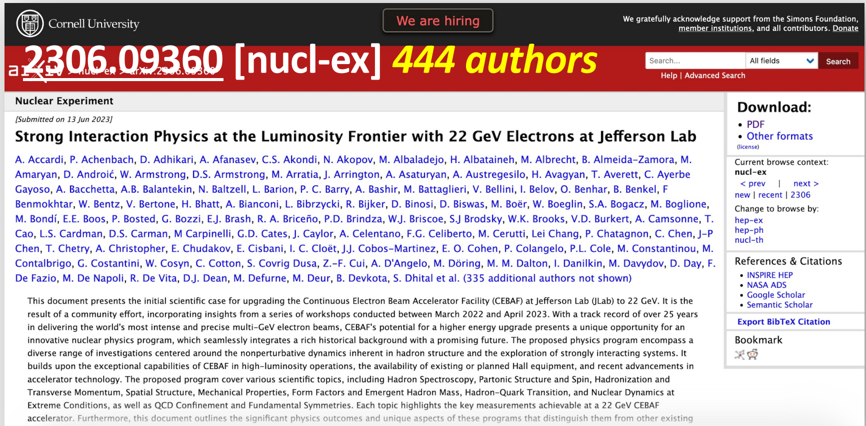

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Nuclear Experiment

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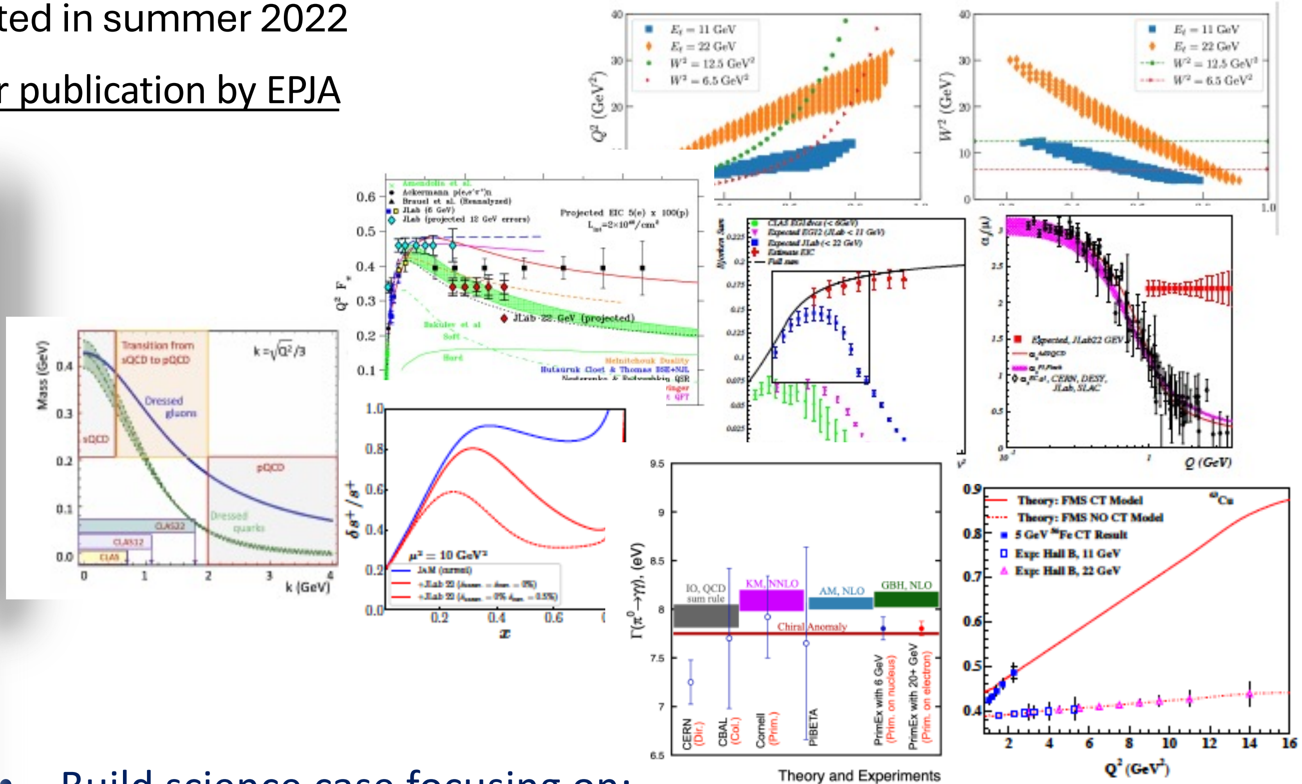

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Path Forward

- A small study group meets monthly to define the roadmap for development of the technology for the positrons and for the 22 GeV beams.
  - The ultimate outcome of this group would be the preCDR (~2 years)

- Bi-weekly meetings open to the whole community

  - The goal is to the refine the scientific case for the 22 GeV upgrade

- Next workshop https://www.jlab.org/conference/dec24luminosity22gev

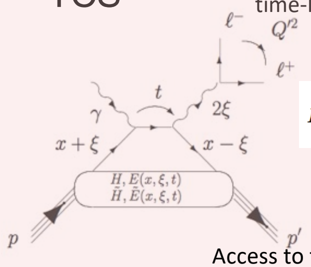
Closing the loop on virtual Compton scattering

S. Stepanyan

JLAB Flagship program – accessing GPDs through measurements of beam/target asymmetries and the cross sections of hard exclusive reactions

TCS

Hard scale is defined by time-like photons



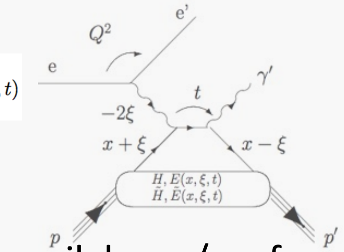
$$Re\ \mathcal{H}(\xi,t) = PV \int_{-1}^{1} dx\, C^{-}(\xi,x) H(x,\xi,t)$$

$$Im\ \mathcal{H}(\xi,t) = i\pi H(\xi,\xi,t)$$

Access to the Re-part of the Compton amplitude

DVCS

Hard scale is defined by space-like photon

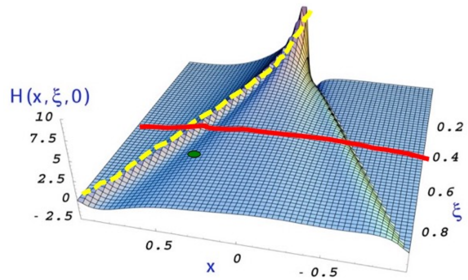


https://www.jlab.org/conference/dec24luminosity22gev

- Extracting information on GPDs from exp. observables is not straightforward

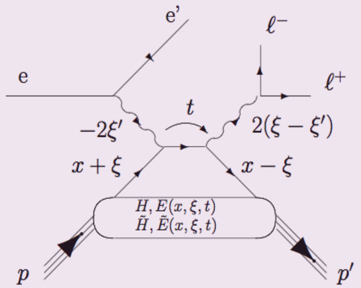
a. The exp. observables are parametrized by complex-valued CFFs:

b. Infer information on GPDs from CFFs, is challenging (x integrated out of the CFFs; no unique solution in going from CFFs to GPDs).



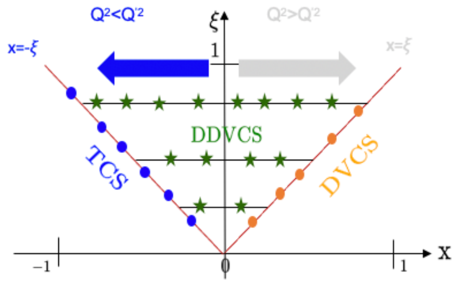
DDVCS

Both space-like and time-like photons can set the hard scale



$$\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-(2\xi'-\xi)+i\epsilon} + \ldots$$

$$H(2\xi'-\xi,\xi,t) + H(-(2\xi'-\xi),\xi,t)$$



σ-DDVCS is three orders of magnitude smaller than σ-DVCS

- **Jefferson Lab at the luminosity frontier is the <u>only place</u> in the world DDVCS can be measured!**
- **μCLAS12 in Hall B and SoLID in Hall A are the two proposed facilities capable of carrying out such measurements**

LOI12-16-004 (Hall B) LOI12-15-005 (Hall A)

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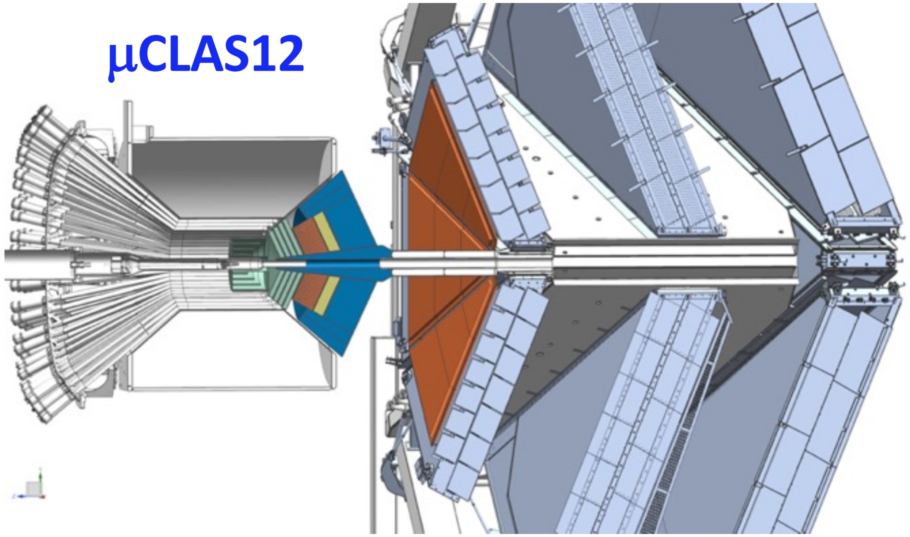
High luminosity μCLAS12 and projections @ 11 GeV

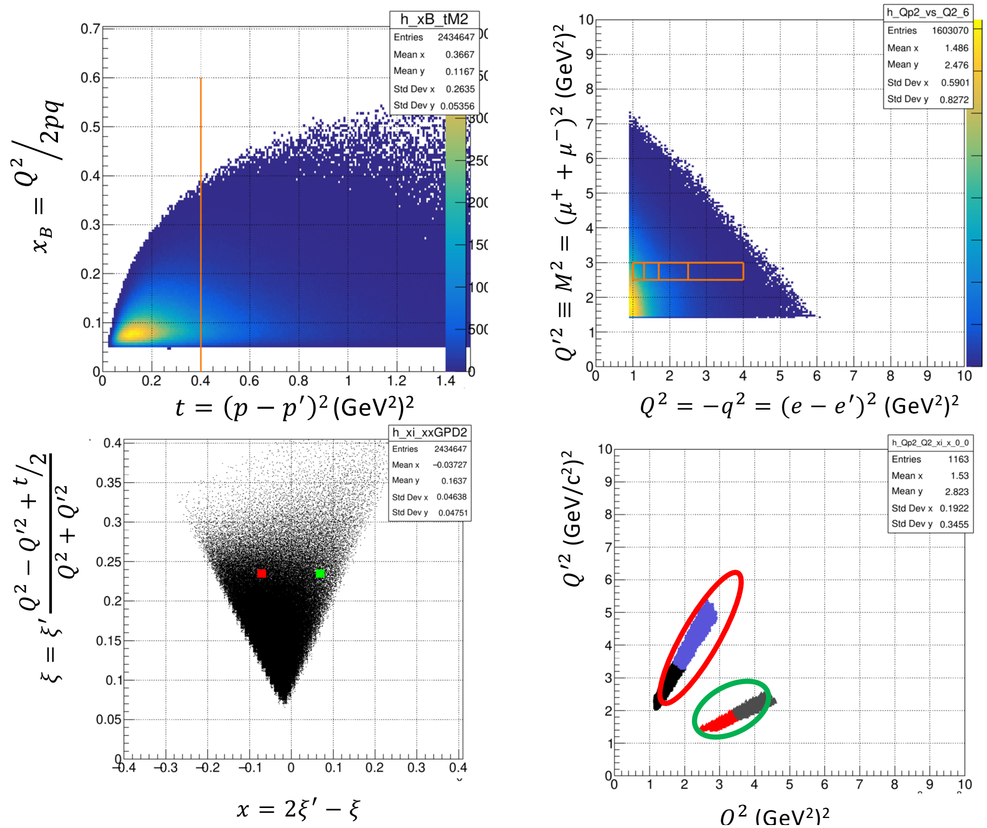
Di-muon electroproduction, using upgraded CLAS12



Detector capable of measuring
$ep \rightarrow e'p'\mu^+\mu^-$ @ $L > 10^{37} cm^{-2} sec^{-1}$

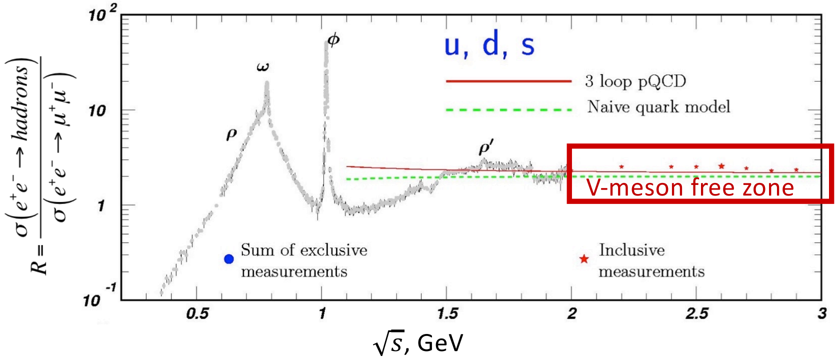
- Remove HTCC and block the CLAS12 forward with a W-shield and $PbWO_4$ calorimeter to prevent flooding of DC by EM background
- Scattered electrons will be detected in the calorimeter, while the shield will work as a pion filter
- Remove CVT, instead use a high rate MPGDs for the central and forward (in front of the calorimeter) tracking.

- GRAPE event generator, BH only.
- The whole region is measured simultaneously.
- At 11 GeV, the interesting region is $Q'^2 > 2$ (GeV/c²)².



- ξ - x bin fixes the ratio Q'^2/Q^2 while their values are unconstrained.
- For each ξ - x bin asymmetry can be measured at different Q'^2 and Q^2, can be a scaling test for GPDs.

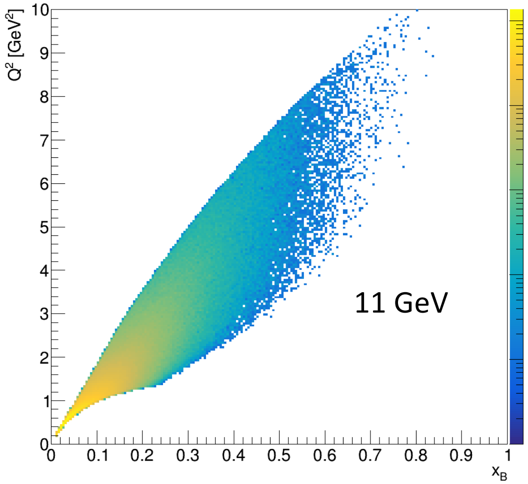
DDVCS at 22 GeV

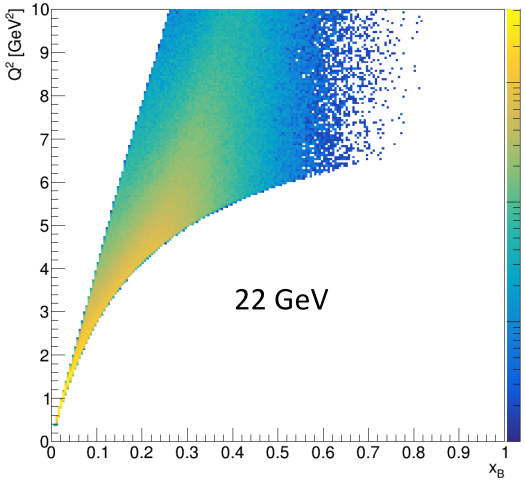


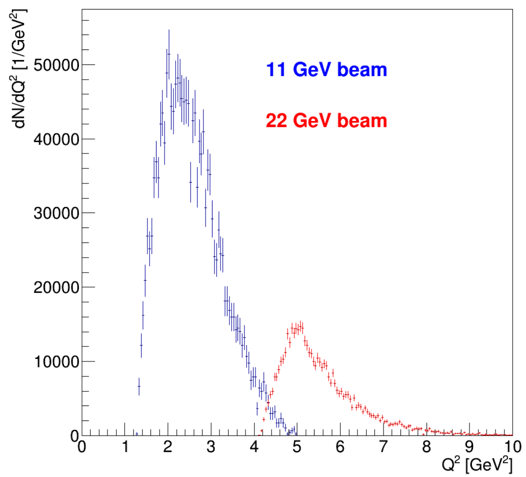
Expand measurements in spacelike, $Q^2 > Q'^2$, and timelike, $Q^2 < Q'^2$, regimes to the resonance free region $Q'^2 > 4$ (GeV/c^2)^2

$\mu CLAS12$ will perform with higher energy beams.

$ep \to e'p'\mu^+\mu^-$







Simulations from R. Paremuzyan

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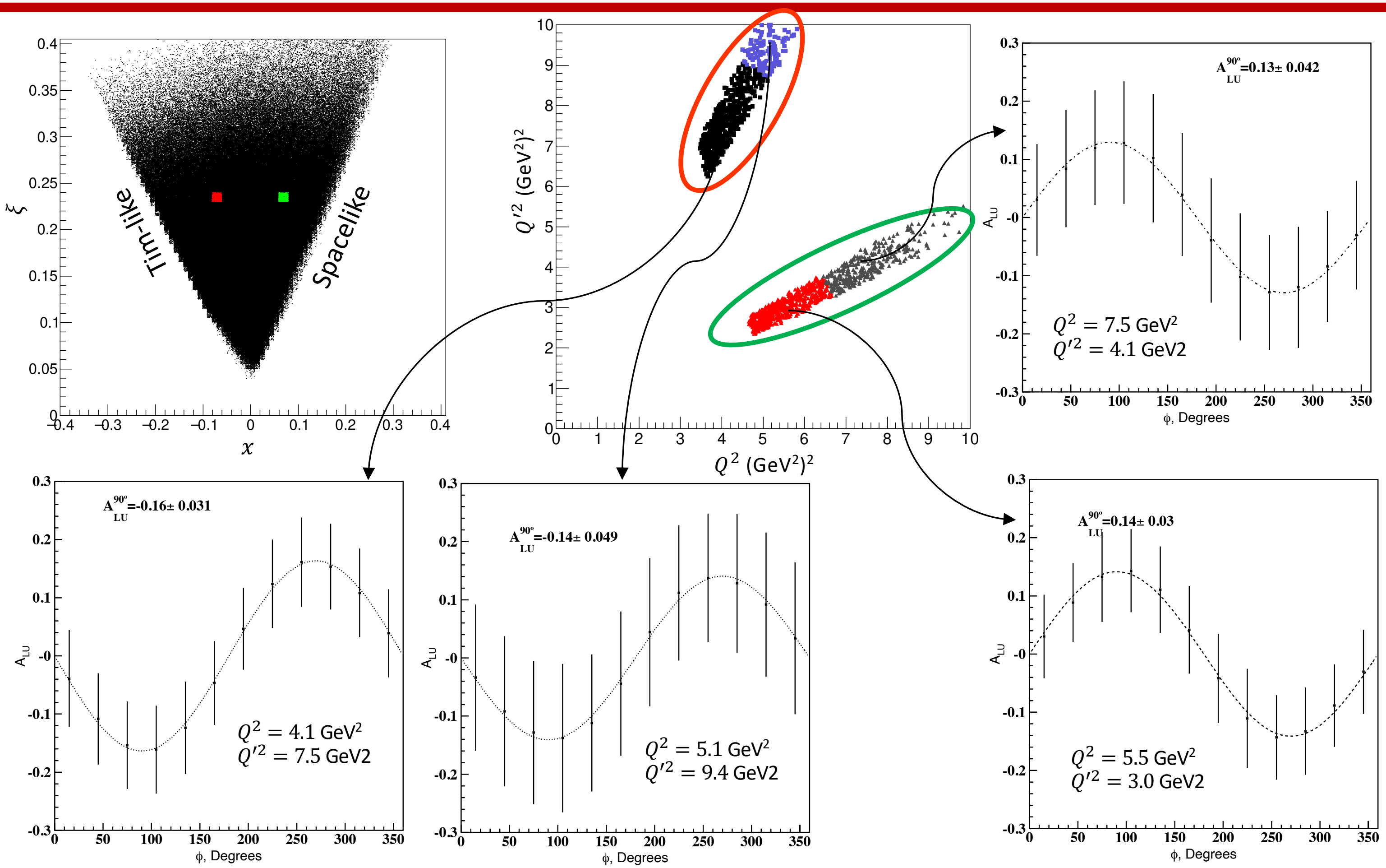
Projections: BSA 200 days @ $10^{37} cm^{-2} sec^{-1}$



Simulations from R. Paremuzyan

Statistics is from GRAPE, asymmetries is from VGG

Jefferson Lab

Pion and Kaon Form Factors

G. Huber

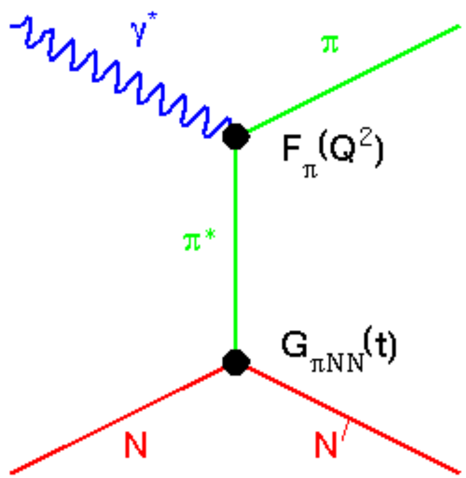
- Pion's structure: determined by two valence quarks and the quark-gluon sea → **attractive as QCD lab**
- Asymptotic behavior of F_π rigorously calculable in perturbative QCD; at experimentally accessible Q^2 less certain. Around which value of Q^2 the hard scattering part of the pion form factor will dominate?
- Kaon's structure: how does meson structure change when *s* quark is substituted for *d* quark?

At larger Q^2, F_π must be measured indirectly using the "pion cloud" of the proton via pion electroproduction $p(e,e'\pi^+)n$

At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L

In Born term model, F_π^2 appears as:

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



Drawbacks of this technique

1. Isolating σ_L experimentally challenging
2. Theoretical uncertainty in form factor extraction

Jefferson Lab

Measurement in Hall C – Phase 1

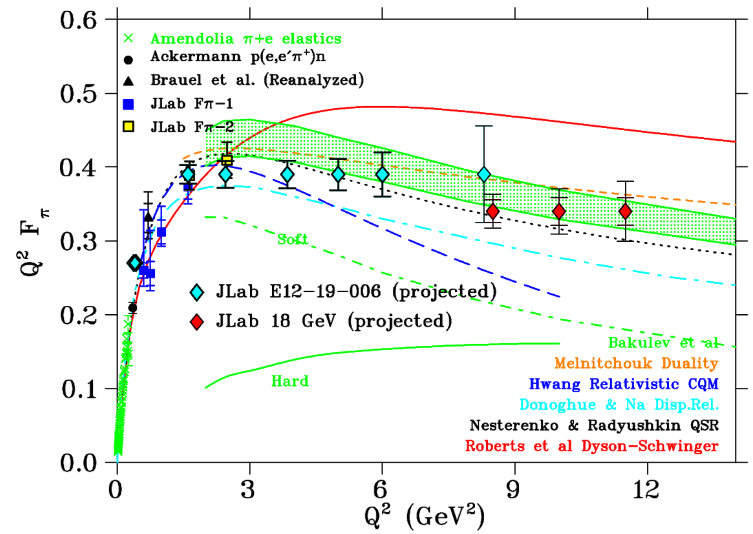
Phase 1: Maximum beam energy and higher Q^2 reach constrained by sum of HMS+SHMS maximum momenta (7.2 GeV/c HMS & 11.0 GeV/c SHMS) - **no major upgrades**

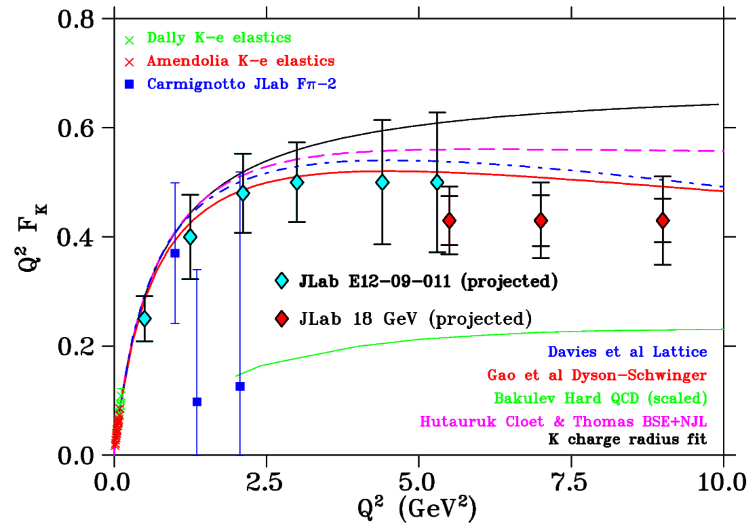
- Scattered electron and π^+/K^+ in coincidence with the two high performance spectrometers in Hall C
  - High momentum, forward angle (5.5°) meson detection is required, with **good Particle ID to separate π^+, K^+, p**
  - **Good momentum resolution** required to reconstruct crucial kinematics, such as M_{miss}, Q^2, W, t
  - Need to measure the **longitudinal cross section $d\sigma_L/dt$** needed for form factor extraction

	10.6 GeV	18.0 GeV	Improvement in δF /F
Q^2=8.5	Δε=0.22	Δε=0.40	16.8%→8.0%
Q^2=10.0	New high quality F data		
Q^2=11.5	Larger F extraction uncertainty due to higher $-t_{min}$		

Energy Upgrade

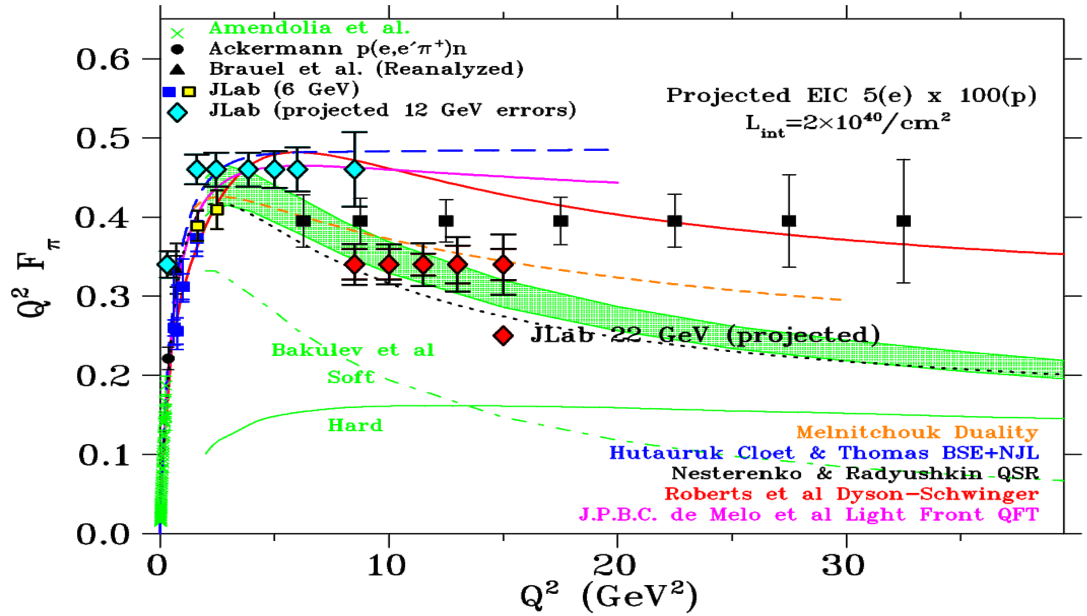
- Allows access to higher Q^2
- Expanded range of γ^* polarization $\Delta\varepsilon=(\varepsilon_{HI}-\varepsilon_{LO})$, leading to reduced errors in the extraction of $d\sigma_L/dt$ *(Uncertainty in σ_L~$1/\Delta\varepsilon$,)*





Measurement in Hall C – Phase 2

- **Replace HMS with VHMS for π^+, use SHMS for e'**
- Dramatic increase in upper Q^2 11.5 → 15.0 GeV^2
- Error bars for Q^2=8.5–11.5 GeV^2 substantially decrease due to smaller $-t_{min}$ (better $R=\sigma_T/\sigma_L$) and shorter running times
- Extends region of high quality F_π values to Q^2=13 GeV^2
- Highest Q^2 running time is "expensive" but would have very high scientific priority (even with larger errors)
- **Provides MUCH improved overlap of F_π data set between JLab and EIC**

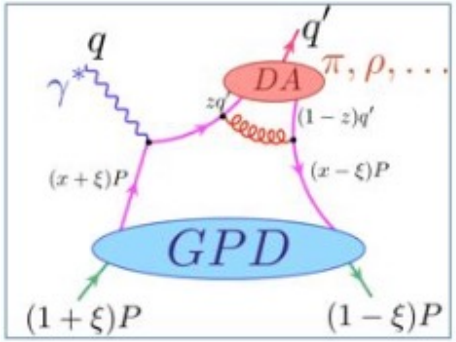


Quality L/T-separations impossible at EIC (can't access ε<0.95)

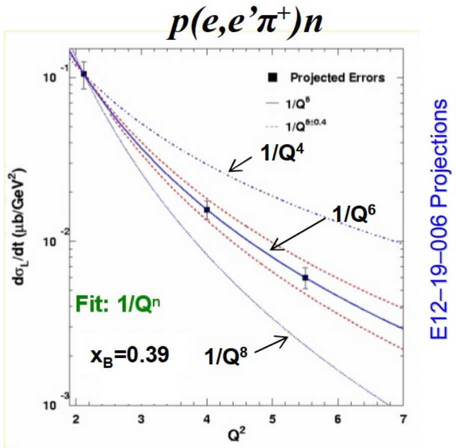
JLab will remain ONLY source of quality L–T separated data!

DVMP: L/T Separated Cross Sections

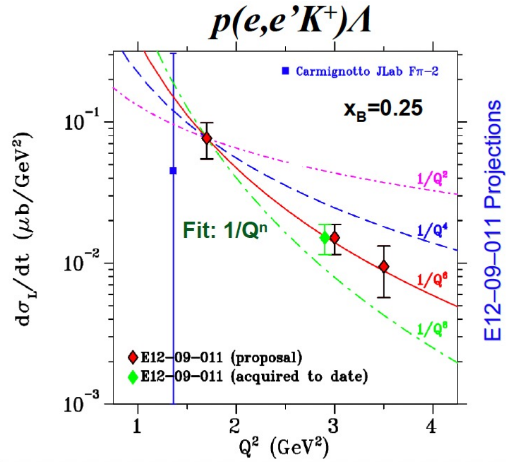
G. Huber



- 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 and HMS+SHMS

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

The proton's D(t) and pressure at 22 GeV

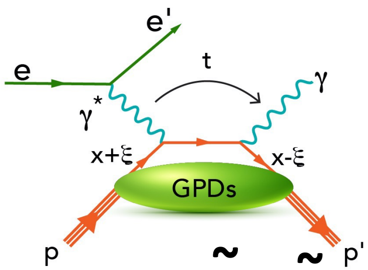
V. Burkert

- **Matrix elements of QCD EMT**

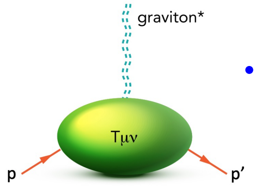
$$\langle P'|T^{\mu\nu}|P\rangle = \bar{u}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\nu)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M}\right]u(P)$$

Related to Pressure and Shear Forces

DVCS



H, E, $\tilde{H}$, $\tilde{E}$



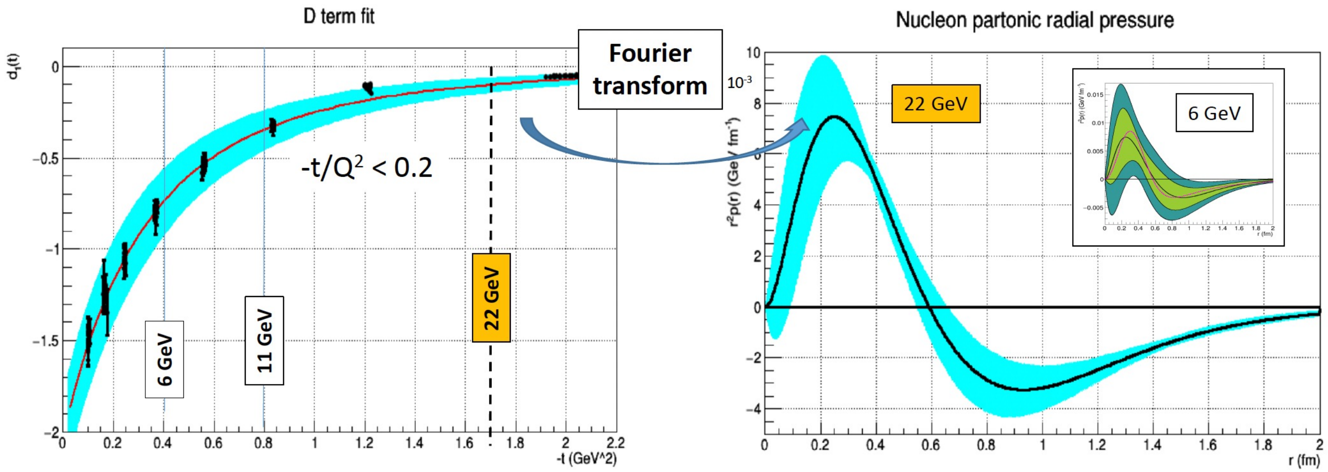
- A massless spin-2 field would couple to the stress–energy tensor in the same way that gravitational interactions do → **D –term accessible through DVCS measurements**

Polarized beam, unpolarized target

Unpol. DVCS x-section: Re $\mathcal{H}(\xi, t)$

$\Delta\sigma_{LU} \sim \sin\phi$ Im {F1 $\mathcal{H}(\xi, t)$ +…)

Fitting the dispersion relation to Im$\mathcal{H}$, Re$\mathcal{H}$ $-t/Q^2 < 0.2$



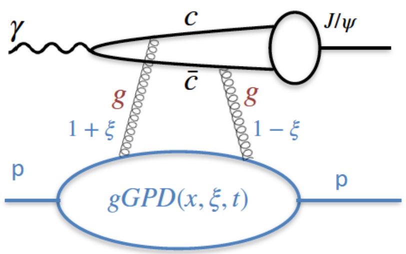
22 GeV will cover a large range in -t and may discover existence of pressure domains.

Threshold Charmonium Photoproduction

L. Pentchev

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

GPD



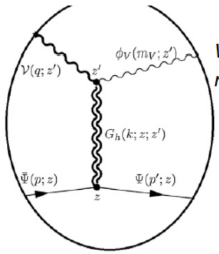
- Compton-like amplitudes $\mathscr{H}_{gC}(\xi, t)$, $\mathscr{E}_{gC}(\xi, t)$ and form-factors as in DVCS
- In contracts: threshold kinematics is very different: at high momentum transfer t and skewness ξ (hard process):

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

- 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



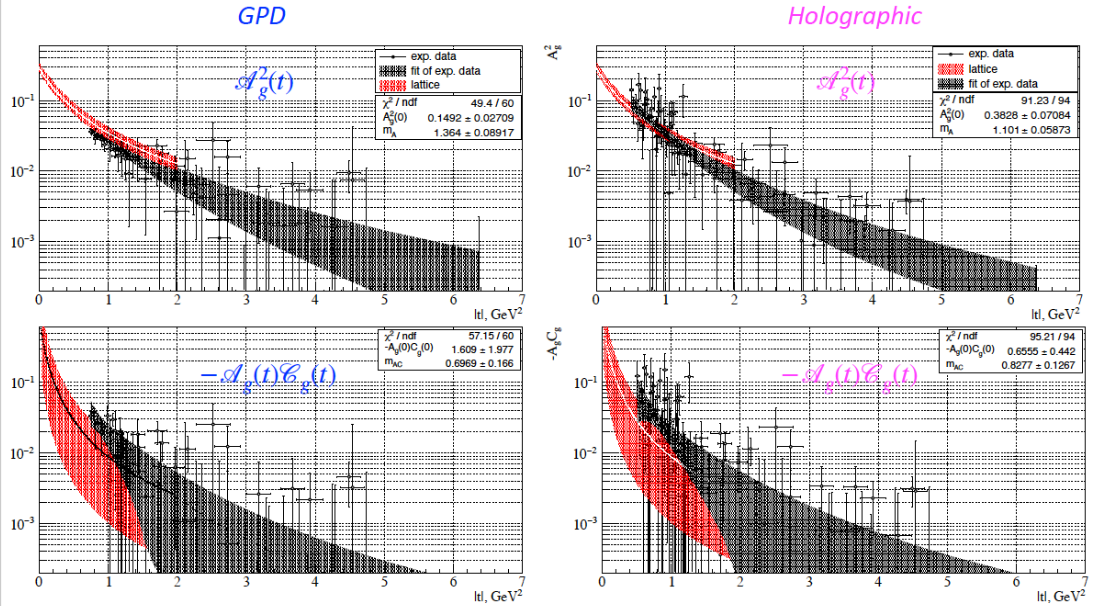
- Using gauge/string correspondence
- In the double limit of large N_c and strong gauge coupling (soft process):

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

- 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)

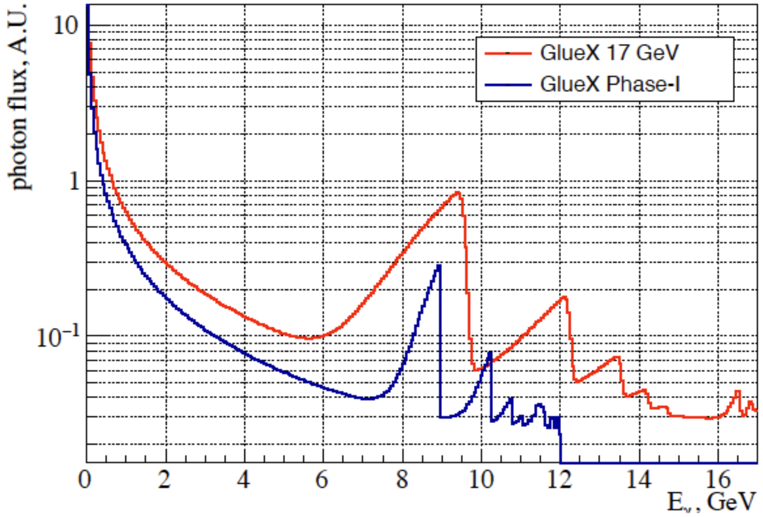
Gluonic Form Factors - data vs lattice



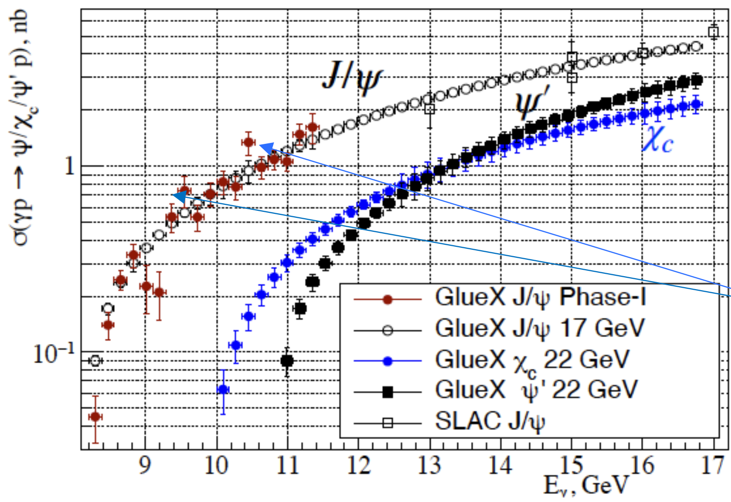
arXiv:2404.18776v1

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)

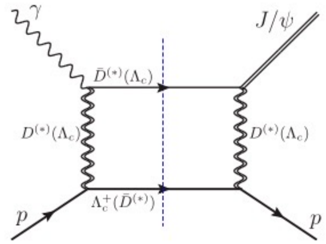
Threshold Charmonium Photoproduction at 22 GeV era

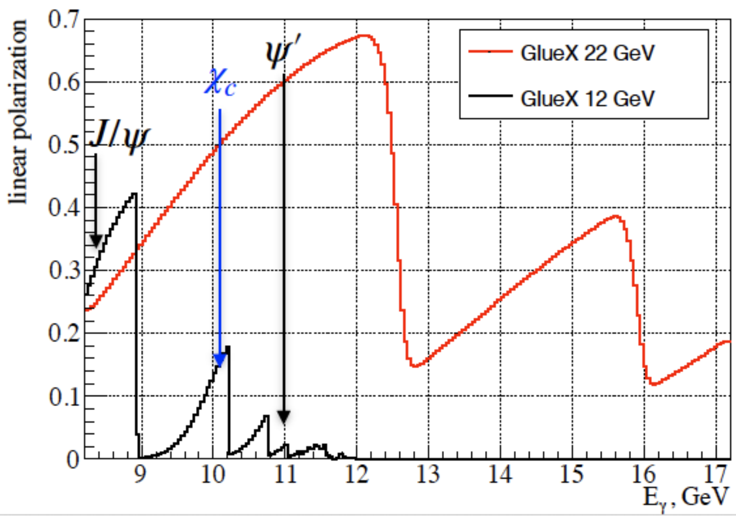


E_{el} = 22 GeV

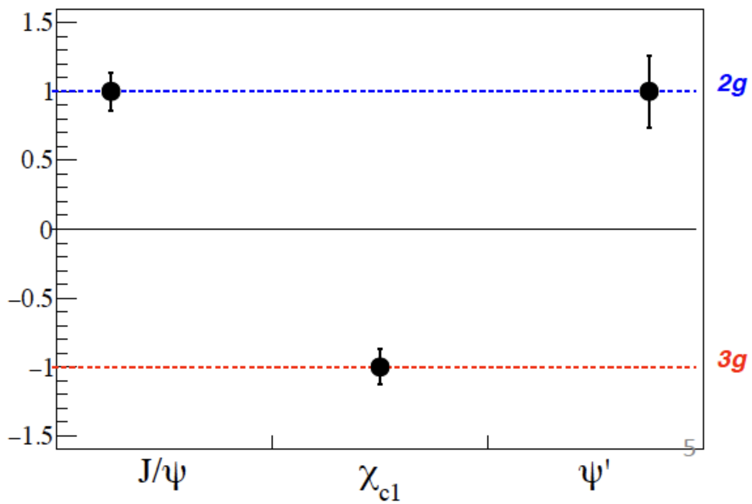


Possible structure at $\Lambda_c\overline{D}^{(*)}$ threshold σ(8.6-9.6) GeV



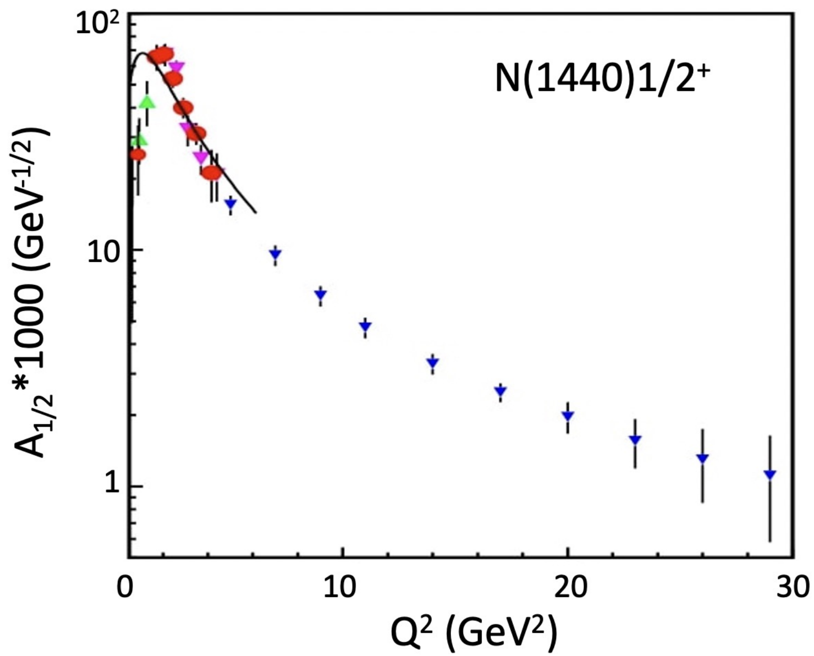


naturality $\times (-1)^J = P$



Jefferson Lab

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

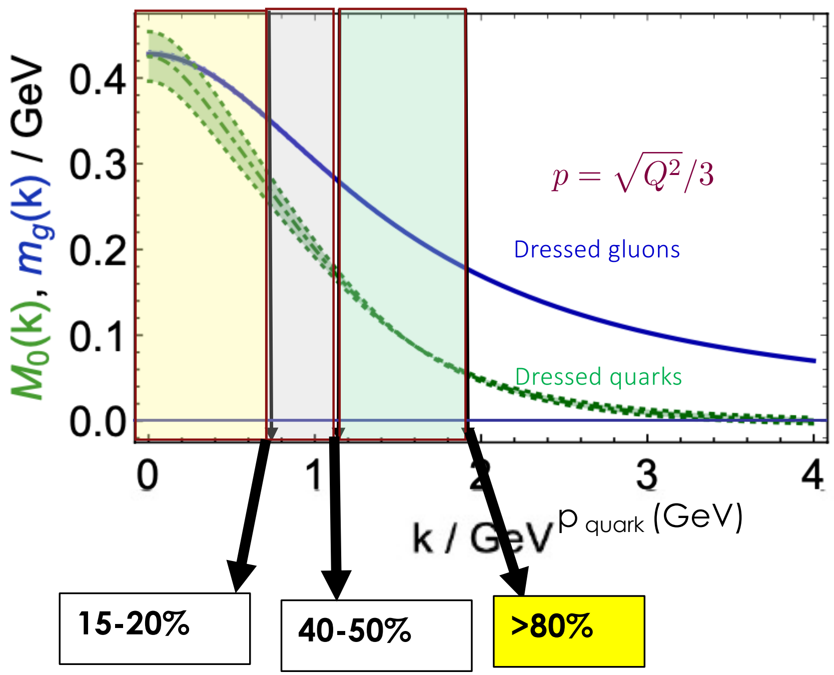


- Q^2 evolution of the $\gamma_v pN^*$ electrocouplings could offer an insight into hadron mass generation and the emergence of the N* structure from QCD

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

Continuum Schwinger Method

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



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

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!