





### Jefferson Lab - a Cornerstone of Hadron Physics Research

#### A Facility at the LUMINOSITY Frontier

(up to  $10^{39}$  cm- $^2$  s- $^1$ )



#### World-Class CW Electron Beam

- Max Energy 12 GeV
- High Intensity (up to 85μA @ 11 GeV)
- High Polarization (~80%)

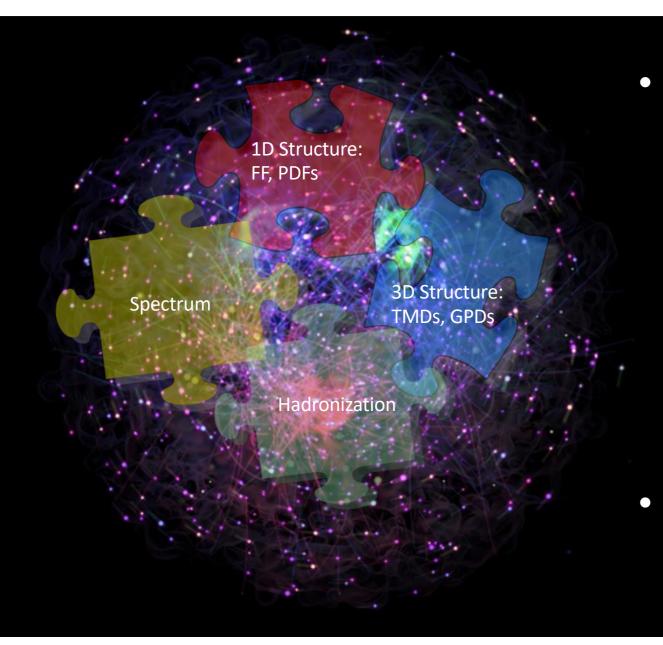
#### Four cutting-edge experimental halls

- State-of-the-art detectors
- Versatile experimental setups
- Detection of multiparticle in the Final State

#### **Fixed Targets**

- High Luminosity
- Variety and Flexibility
- Creation of secondary beams
- ❖ Explore the fundamental nature of confined states of quarks and gluons → Non-pQCD
- Discover evidence for physics BSM



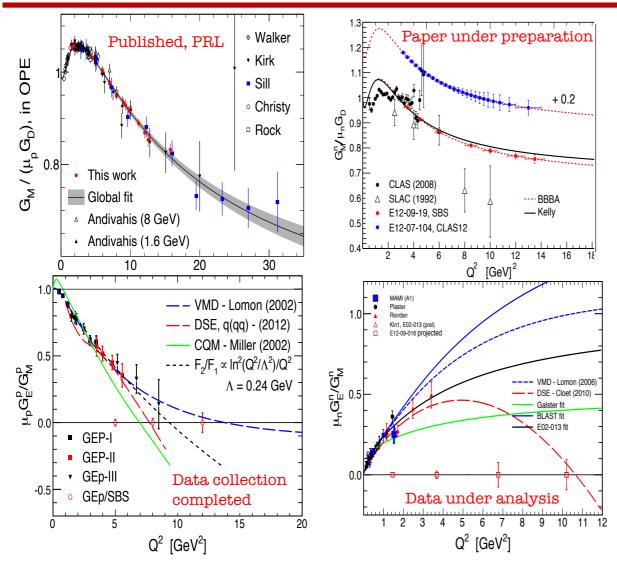


 Complex and multifaced problem requiring multiple observables sensitive to different characteristics of the hadron structure

- Precise measurements
  - → LUMINOSITY



### Hall A Program: access to ALL Nucleon e.m. FFs @ high Q<sup>2</sup>



#### The importance of nucleon e.m. form factors

- Are directly related to the spatial distributions of charge and magnetization
- Can be understood as the first moments of Generalized Parton Distributions (GPDs).
   Therefore, their measurements provide crucial constraints for the models used to interpret GPD data.
- Their measurements at different Q<sup>2</sup> provide a crucial test of our understanding of QCD at both low and high energies



## SBS G<sub>M</sub><sup>n</sup> Experiment

Statistical and Systematic errors have been added in quadrature

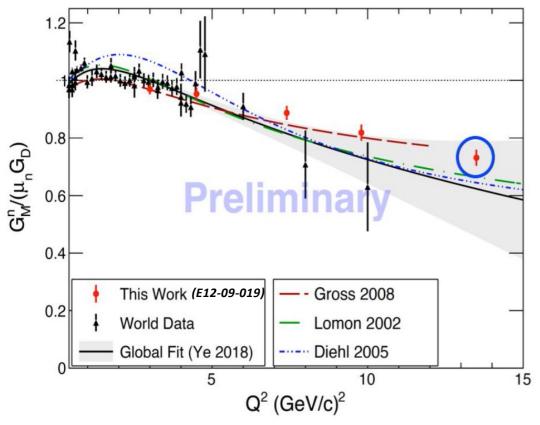


Figure from JSA thesis winner Provakar Datta's talk

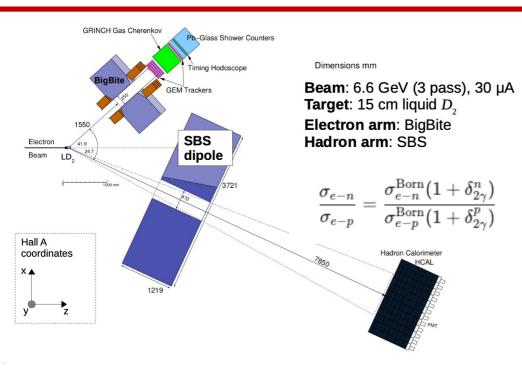
• Determine neutron  $G_M$  from ratio of quasifree deuteron neutron to proton knockout cross section

$$R' = \frac{\frac{d\sigma}{d\Omega}|_{\mathbf{n}(e,e')}}{\frac{d\sigma}{d\Omega}|_{p(e,e')}} \equiv \frac{\frac{\sigma_{Mott}}{1+\tau} \left(G_E^{n}^2 + \frac{\tau}{\epsilon} G_M^{n}^2\right)}{\frac{d\sigma}{d\Omega}|_{p(e,e')}}$$

- Precision of the highest Q<sup>2</sup> data point (13.5 (GeV/c)<sup>2</sup>) is expected to stay unmatched for years to come
- Paper in preparation

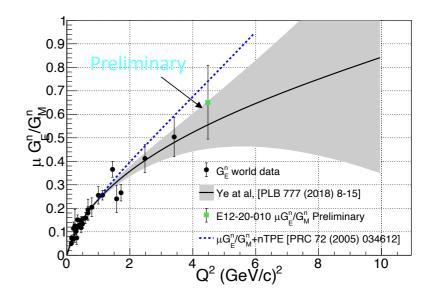


## **SBS Neutron TPE Experiment**



Kin	Q <sup>2</sup> (GeV/c) <sup>2</sup>	E (GeV)	E' (GeV)	$\theta_{_{BB}}$ (deg)	θ <sub>SBS</sub> (deg)	€
1	4.5	4.4	2.0	41.88	24.67	0.599
2	4.5	6.6	4.2	23.23	31.2	0.838

 G<sub>E</sub><sup>n</sup> obtained via Rosenbluth method provides first information on twophoton exchange in e,e'n



Paper in preparation

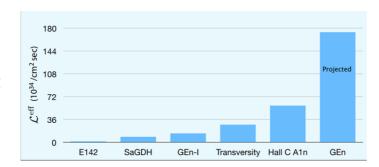


## SBS G<sub>E</sub><sup>n</sup> Experiment

Quasi-elastic Scattering of Polarized Electrons on Polarized He-3

## Polarized ${}^{3}$ He target – highest $\mathcal{L}$ to date!

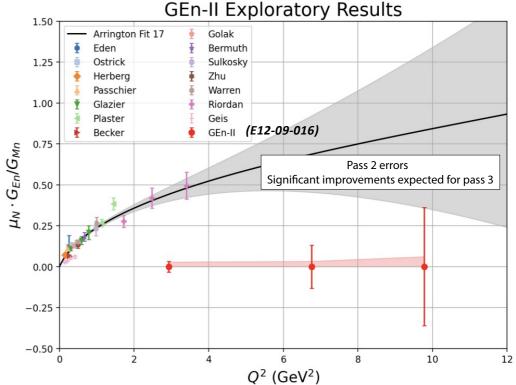
- First time 60 cm long target
- 42 50% target pol.



• Use double polarization to measure the Neutron Electromagnetic Form Factor Ratio  $G_F^n/G_M^n$  at High  $Q^2$ 

$$rac{G_E}{G_M} = -rac{A_{LT'}}{A_{LL}} imes rac{(1+ au) an^2(rac{ heta_e}{2})}{2\sqrt{ au(1+ au)} \sec^2(rac{ heta_e}{2}) an(rac{ heta_e}{2})}$$

Analysis on going



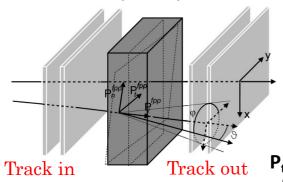


### SBS G<sub>E</sub><sup>p</sup> Experiment

• Polarization transfer method  $\, \vec{e} \, p 
ightarrow e \, \vec{p} \,$ 

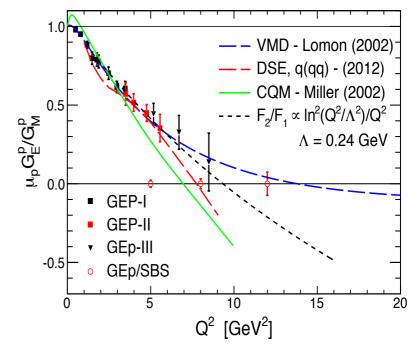


Recoil proton polarimeter

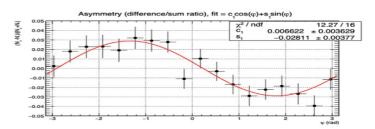


$$rac{G_E}{G_M} = -\sqrt{rac{ au}{\epsilon(1+\epsilon)}}rac{P_t}{P_t}$$

P<sub>t</sub> (P<sub>I</sub>) = transverse (longitudinal) polarization of the recoil proton.

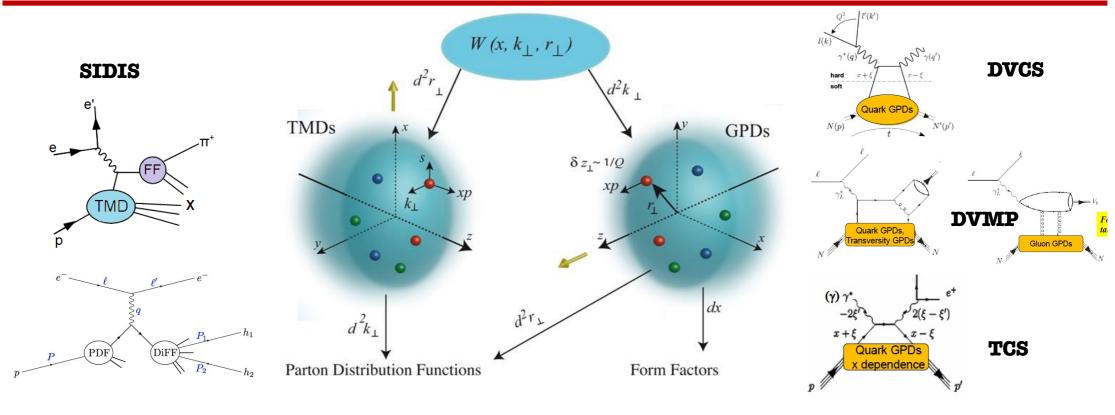


Online results for small subset of  $Q^2 = 5.6 \text{ GeV}^2$  data



Data collection just completed

#### **3D Nucleon Structure**



JLab: IDEAL PLACE TO CARRY OUT IMAGING STUDIES in the non-perturbative region

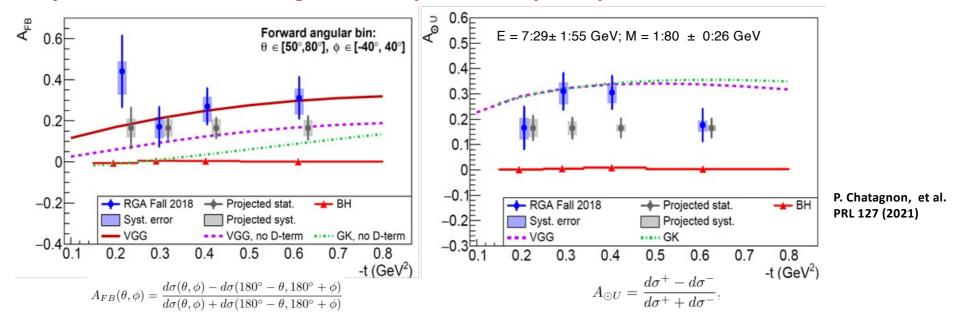
High Luminosity + High Polarized beam and target + High Resolutions State-of-the-art detectors + Versatile experimental setup + Multiparticles FS detection

Extensive Part of the JLab program (> 50% of approved PAC days)

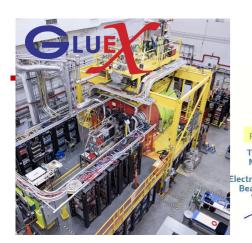
### First measurement of Timelike Compton Scattering (CLAS12)

 $\gamma {f p} 
ightarrow \gamma^* {f p} 
ightarrow ({f e}') {f e}^+ {f e}^- {f p}$  Quasi-real photo-production (Q2~0)

Very small cross section → high luminosity is necessary for a precise measurement

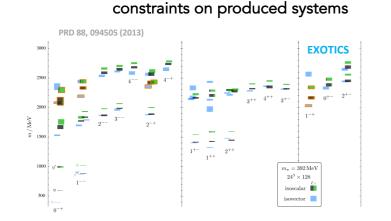


- Photon beam polarization asymmetry  $(A_{\odot U}) \rightarrow$  accesses the **imaginary part of the CFF** similar to the BSA in DVCS  $\rightarrow$  probes the **universality of GPDs**
- Forward-Backward asymmetry  $(A_{FB}) \rightarrow$  sensitive to the **real part of the CFF**  $\rightarrow$  direct access to the Energy-Momentum Form Factor dq(t) (linked to the D-term) that relates to the **mechanical properties of the nucleon**
- Imminent doubling of statistics thanks to data reprocessing with improved reconstruction (gray points)



 Experiment designed for light quark meson spectroscopy with nearly complete acceptance for all charged and neutral final state particles

 LQCD: Spectrum of exited states, several candidates with exotic composition at relatively low mass



Linear polarization provides

Forward Calorimeter

Forward Drift

Chamber

Central Drift

E<sub>y</sub> (GeV)

**▼ PARA** (0°)

PERP (90°) PARA (135°)

PERP (45°)

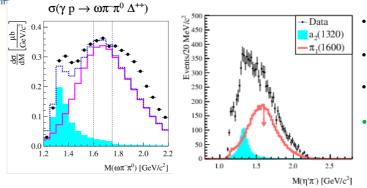
Time of Flight

**Barrel Calorimeter** 

Start Counter

#### Hall D - GlueX

Upper limit for  $\gamma p \rightarrow \pi_1(1600)p$  photoproduction

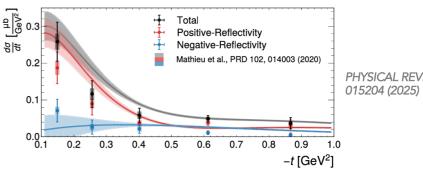


- Using LQCD prediction for  $BR(\pi_1 \rightarrow b_1 \pi)/BR(\pi_1 \rightarrow \eta' \pi)$
- Analysis of  $\gamma p \rightarrow \omega \pi \pi p$ ,  $\omega \pi^+ \pi^0 \Delta^{++}$ mass spectra
- Projection to  $\gamma p \rightarrow \eta' \pi p$  (most promising for PWA)
- Limit of the cross section obtained is  $\approx \sigma(a_2(1320))$

PRL133, 261903 (Dec 2024)

Photoproduction of  $\gamma p \rightarrow a_2(1320)^0 p$  cross section

#### A milestone on the path toward search for hybrid mesons



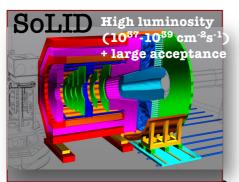
PHYSICAL REVIEW C 112.



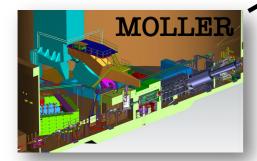
#### What's next with the 12 GeV beam: New Installations

BDX: Beam Dump exp.

- Precision nucleon 3D imaging
- Origin of the proton mass and gluonic force
- BSM searches & nucleon structure
- Ultra-precise measurement of the weak charge of the electron



R&D on-going

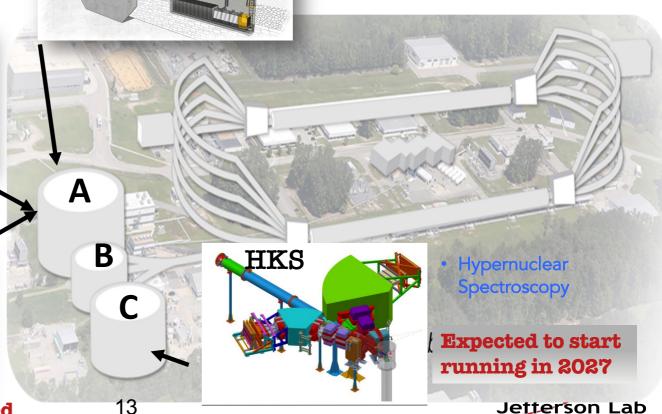


**Installation Just started** 

 Search for light dark matter particles

Engineering design studies for the the hall construction on-going

Jetterson Lab



### Pioneering the Future: New Beams from 12 GeV Electron Capabilities

#### KLF: High Intense Kaon beam Strangeness Spectroscopy 12 GeV e-BDX: Beam Dump exp. Beam 15.4 MHz KFM Spectrometer D Intense A secondary µ · e+ @ 12 GeV and v beams B • critical for resolving 2-y exchange issue A NEW territory to explore A BETTER insight into our current program • A BRIDGE between JLab @ 12 GeV and EIC 14

## **CEBAF Phased Upgrade**

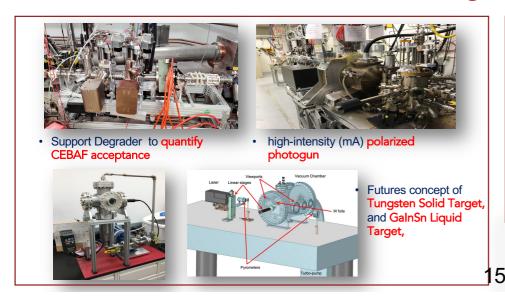
#### Phase 1:

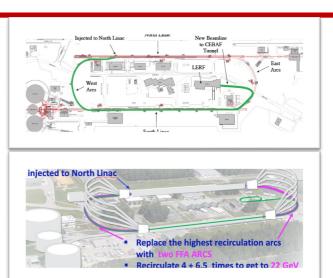
- New injector (123 MeV e<sup>+</sup> & 650 MeV e<sup>-</sup>) in a former FEL ("LERF")
- Polarized positrons transported to CEBAF (proposed 12 GeV science program)

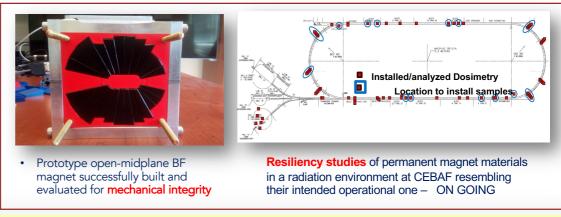
#### Phase 2:

- 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!

#### Accelerator R&D on-going







Goal: strong placement in the next Long Range Plan

Prepare TDR for ~2028, - Earlier pTDR prepared in ~2026

# Broad and Exciting Physics Program at 22 GeV

10 most recent All issues Topical Collections Reviews Letters Viewpoints & Perspectives Code Papers

~450 authors

Eur. Phys. J. A (2024) 60: 173

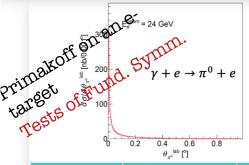
https://doi.org/10.1140/epja/s10050-024-01282-x

Review

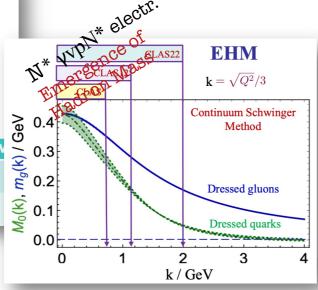
#### Strong interaction physics at the luminosity frontier with 22 GeV electrons at Jefferson Lab

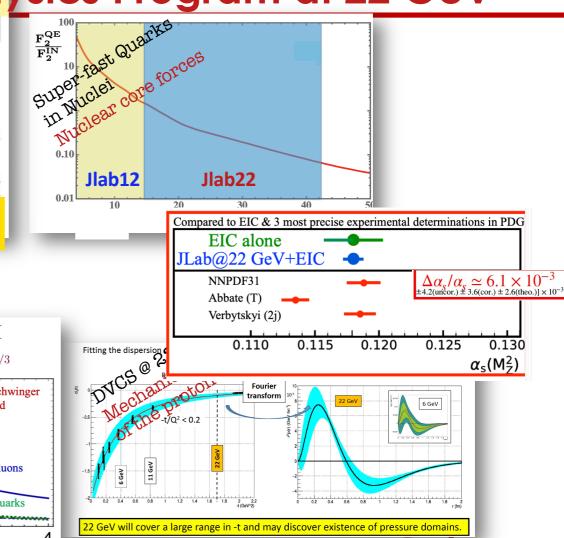
A. Accardi<sup>1</sup>, P. Achenbach<sup>2</sup>, D. Adhikari<sup>3</sup>, A. Afanasev<sup>4</sup>, C. S. Akondi<sup>5</sup>, N. Akopov<sup>6</sup>, M. Albaladejo<sup>7</sup>, H. Albataineh<sup>8</sup>, M. Albrecht<sup>2</sup>, B. Almeida-Zamora<sup>9</sup>, M. Amaryan<sup>10</sup>, D. Androić<sup>11</sup>, W. Armstrong<sup>12</sup>, D. S. Armstrong<sup>13</sup>, M. Arratia<sup>14</sup>, J.

A new document outlining the progress of the scientific case will be available soon



Measurement	Reaction	E <sub>th</sub> (GeV
$\Gamma(\pi^0 \to \gamma \gamma)$	$\gamma + e \rightarrow \pi^0 + e$	18.0
$F(\pi^0 \to \gamma^* \gamma)$	$e + e \rightarrow \pi^0 + e + e$	18.1





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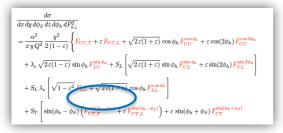
Jefferson Lab

### **Nucleon Structure @ 22 GeV**

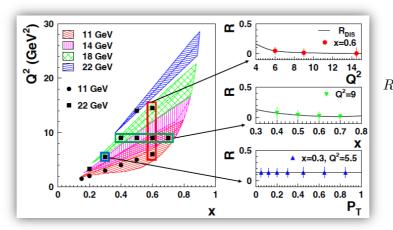
#### Several advancements @ 22 GeV, including:

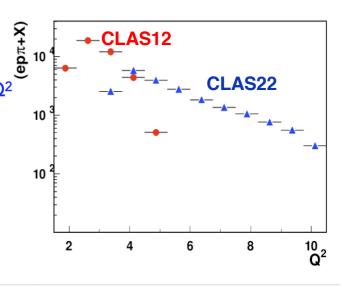
1. Multidimensional studies of the evolution of 3D observables with Q<sup>2</sup>

2. Unique opportunity to measure  $\gamma^*_L \& \gamma^*_T$  contributions to observables at higher  $Q^2$ 



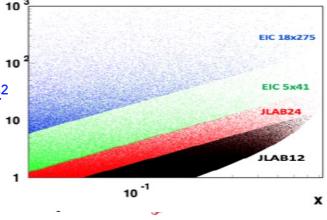
Neglecting  $\chi^*$  biases TMD extractions and factorization studies, limiting the accuracy of spin-dependent QCD insights





3. A unique opportunity to evaluate the contribution of various processes at higher Q<sup>2</sup>

All critical aspects for a deeper and better understanding of our current measurements and future measurements at EIC!

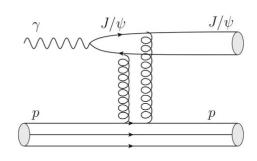


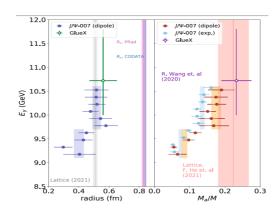
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## JLab delves into Proton's Mechanical Properties

• The interaction of a spin 2 particle with the nucleon's energy-momentum content, mimic the gravitational interaction → study the nucleon's gravitational FFs to access its mechanical properties.

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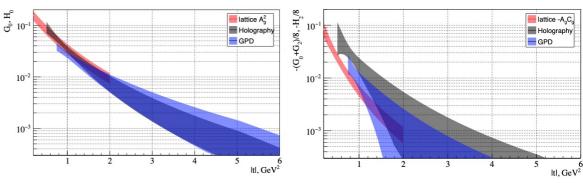


 J/ψ photoproduction at threshold: data from J/ψ-007 exp (hall C) used to estimate in a model-dependent way the mass radius of the proton

L. Pentchev. E. Chudakov arXiv:2404.18776v2

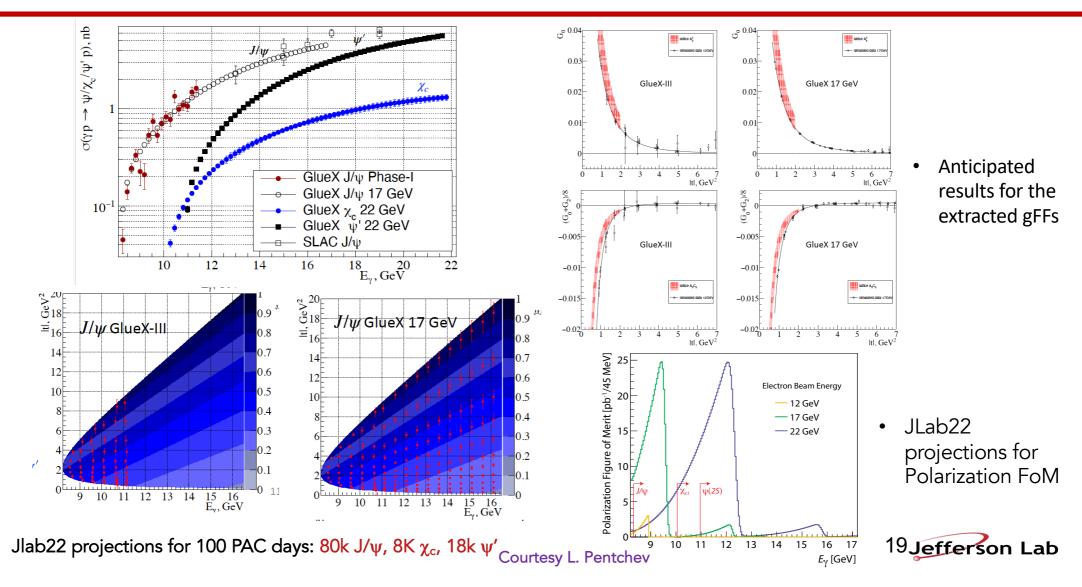
V.Burkert, L. Elouadrhiri, F.X. Girod, Nature 557 (2018) 7705, 396

- Two theoretical approaches used with very different domains of validity (GlueX and J/ψ-007 data)
- GPD  $\rightarrow$  requires high ltl and works for hard processes 1)  $(d\sigma/dt)_{VP \rightarrow J/\psi p} = F(E\gamma)\xi^{-4}[G_0(t)+\xi^2G_2(t)] + ...$
- Holographic → valid for soft processes 2) (dσ/dt)<sub>Vp→J/wp</sub> = N(Eγ)[H<sub>0</sub>(t)+η<sup>2</sup>H<sub>2</sub>(t)] + . .
- Leading terms in  $G_0(t)$ ,  $G_2(t)$ ,  $H_0(t)$ ,  $H_2(t)$  contain gGFFs  $A_q(t)$ ,  $B_q(t)$ ,  $C_q(t)$
- gGFFs extracted via Rosenbluth separation technique



General agreement in the extracted FFs using two diametric theories, and agreement with lattice

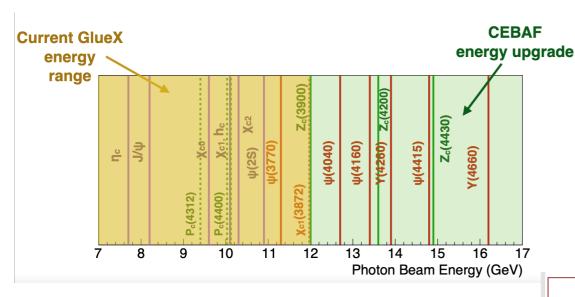
## Threshold J/Y Photoproduction at 22 GeV

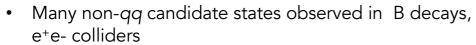


### 22 GeV: A New Window into the World of XYZ States

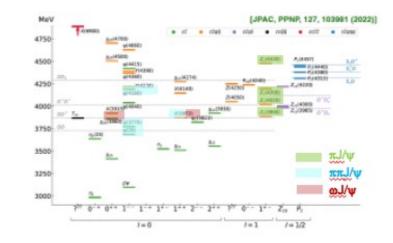
This program suits perfect the 22 GeV upgrade: Thresholds for XYZ states open just above 12 GeV

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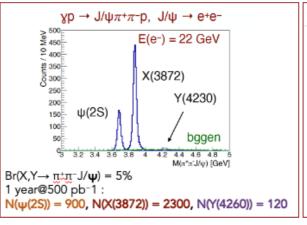


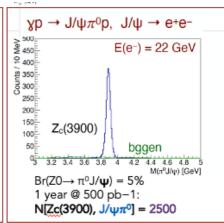


- No XYZ state uncontroversially seen so far (tetraquark, molecule, virtual state, triangle singularity, ... ?)
- Crucial to confirm these states in other production processes
- $\rightarrow$  never directly produced using  $\gamma$ /lepton beam  $\rightarrow$  free from re-scattering mechanisms



GlueX





# Measurements of $\alpha_s$ with JLab@22 GeV

Comparison with JLab at 6 and 11 GeV

 $CLAS\ EG1dvcs\ (< 6GeV)$ 

Expected JLab (< 22 GeV)

Estimate EIC Full sum

 $Expected\ EG12\ (JLab < 11\ GeV)$ 

It is the most important quantity of QCD, key parameter of the SM, but (by far) the least known fundamental coupling:  $\Delta \alpha_s / \alpha_s \simeq 10^{-2}$ Large efforts ongoing to reduce  $\Delta \alpha J \alpha_s$ 

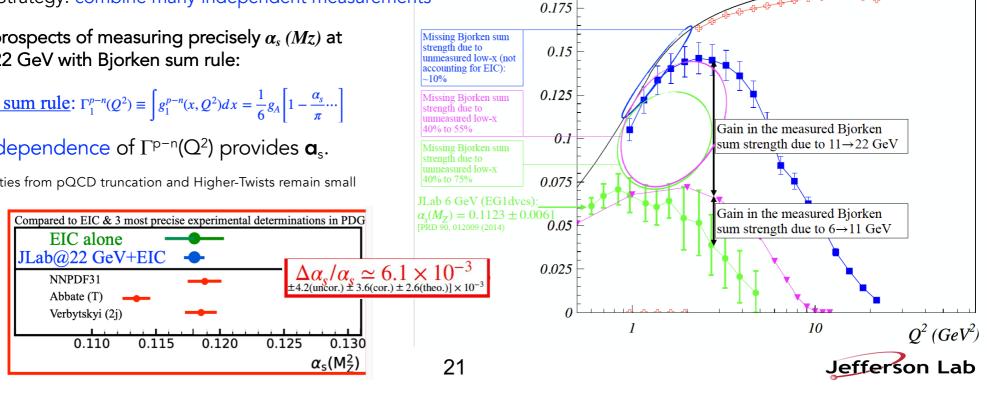
No "silver bullet" experiment can exquisitely determine **a**<sub>s</sub>⇒ Strategy: combine many independent measurements

Good prospects of measuring precisely  $\alpha_s$  (Mz) at JLab@22 GeV with Bjorken sum rule:

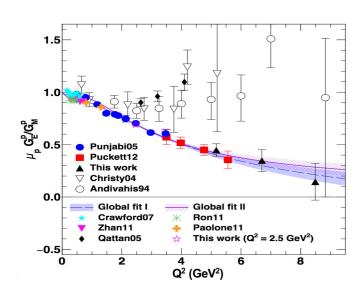
Bjorken sum rule:  $\Gamma_1^{p-n}(Q^2) \equiv \left[ g_1^{p-n}(x, Q^2) dx = \frac{1}{6} g_A \left[ 1 - \frac{\alpha_s}{\pi} \cdots \right] \right]$ 

 $Q^2$ -dependence of  $\Gamma^{p-n}(Q^2)$  provides  $\mathbf{a}_s$ .

Uncertainties from pQCD truncation and Higher-Twists remain small



## Physics Program with Ce+BAF



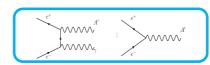
May the 2- $\gamma$  exchange be the cause of the proton FF discrepancy?

$$R_{2\gamma} \equiv \frac{\sigma_{e^+p}}{\sigma_{e^-p}} = 1 + 4 \frac{\text{Re} \left[ \mathcal{M}_{1\gamma} \mathcal{M}_{2\gamma} \right]}{|\mathcal{M}_{1\gamma}|^2} + \dots$$

- Beam charge asymmetries
  - Two-photon exchange
  - Deeply Virtual Compton Scattering

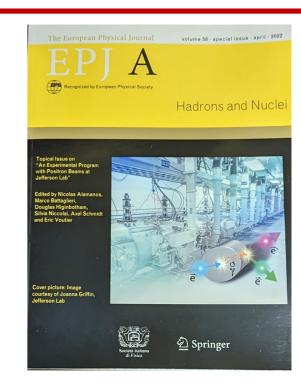
$$\sigma \approx |\mathcal{M}|^2 = \left| \sum_{\alpha \in \mathcal{M}} \int_{-\infty}^{\infty} d\alpha d\alpha \right|^2 + O(\alpha^4)$$

- Annihilation processes
  - Light dark matter searches



- Charged-current processes
  - Inverse beta-decay
  - Access strangeness with charm-tagging
  - Charged lepton flavor violation
  - Axial Form Factor





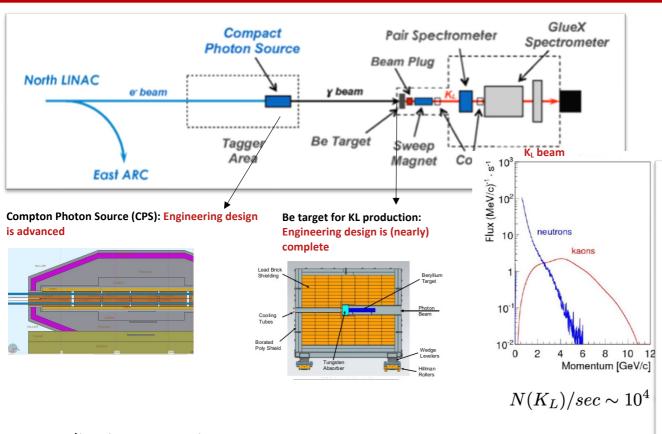
 Annual in person working group meeting

PAC approved experiments

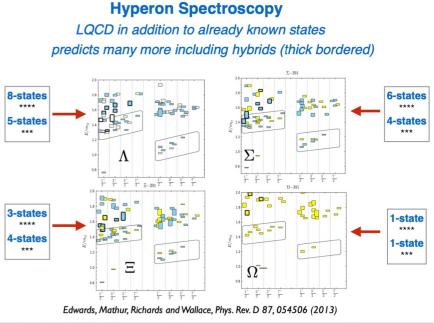
Approved 7 experiments for a total of 357 total PAC days (PAC day = two calendar day)



## K-Long Facility: Spectroscopy in K<sub>LONG</sub> beam

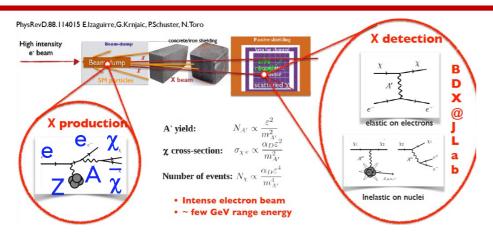


- Realization on going
- Big overhead: requires about 2 years for installation and >1 year for de-installation
- Schedule under discussion





## Beam Dump Experiment (BDX)

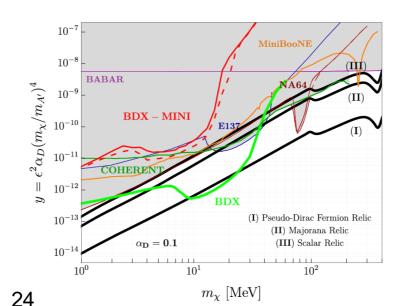


- A cutting-edge experiment designed to search for light dark matter
- Two step process
  - I) An electron radiates an A' and the A' promptly decays to a  $\chi$  (DM) pair
  - II) The  $\chi$  (in-)elastically scatters on a e-/nucleon in the detector producing a visible recoil (GeV)
- Experimental signature in the detector:
   X-electron → EM shower ~GeV energy

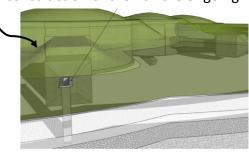
**BDX-MINI:** pilot experiment to prove the validity and feasibility of the BDX exp



Collected 4e21 EOT (40% BDX!) in ~4 months (+ cosmics)



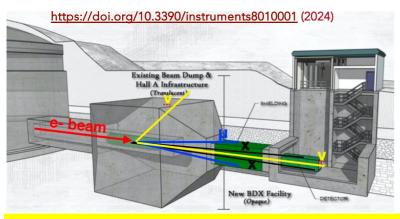
- Accumulating 10<sup>22</sup> EOT in ~2y BDX sensitivity is 10-100 times better than existing limits on LDM
- Funds for the construction of the first module of the calorimeter secured.
- Engineering design studies for the construction of the hall are ongoing.

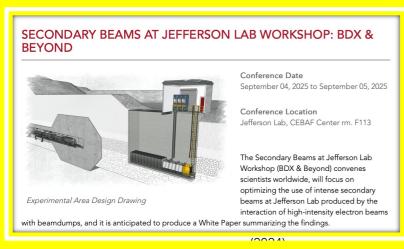


### Secondary Beams at Jefferson Lab

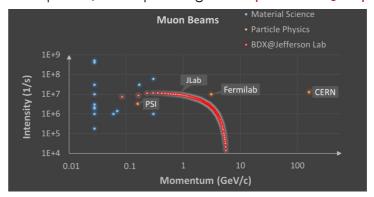
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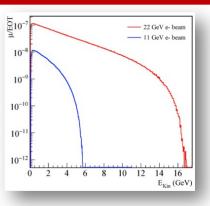
 High-intensity secondary beams are produced in the dump(s) fully parasitically with highintensity 10 GeV (22 GeV) electron beam



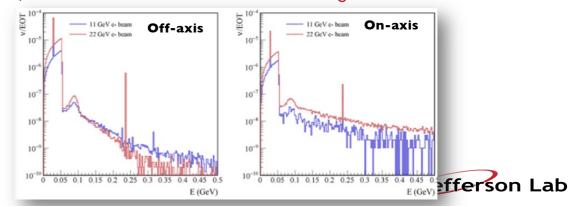


 A secondary muon beam with a bremsstrahlung-like energy spectrum extending up to 5 GeV could yield up to ~10<sup>-6</sup> μ/EOT, corresponding to 10<sup>8</sup> μ/s for an i<sub>e</sub> 50 μA





A secondary neutrino beam with a typical decay-at-rest (DAR) energy spectrum could provide up to  $\sim 7 \times 10^{-5}$  v/EOT when integrated over a 1 m<sup>2</sup> detector located 10 m above the beam dump; Considering a delivered charge of  $10^{22}$  EOT per year, the annual neutrino flux would be in the range of  $10^{18}$  v



### **Conclusions and Outlook**

- Jefferson Lab offers an exceptional environment for exploring QCD in the non-perturbative regime, combining high luminosity with state-of-the-art experimental facilities.
- Strategic upgrades, like the 22 GeV energy enhancement will allow to cross key energy thresholds, to expand the phase space for a better understanding of our current program, and to open a new window between Jefferson Lab at 12 GeV and the EIC.
- The development of positron beams is essential to isolating and quantifying two-photon exchange effects, while also enabling symmetry tests and rare process searches that deepen our exploration of the Standard Model and beyond.
- Innovative experiments such as MOLLER, SOLID, BDX, Hall C Hypernuclear and studies at the K-Long Facility will deepen our understanding of nucleon structure, dark sectors, and the role of strangeness in QCD.
- A new facility for muons and neutrinos is attracting new scientific communities to partner with the JLab community and nuclear physics.
- Together, these opportunities point toward a dynamic future that links precision measurements with bold exploration, and keeps Jefferson Lab at the forefront of discovery.