Jefferson Laboratory: Plans for the 12 GeV Era and Beyond

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Presented To:
Baryons 2022

November 7, 2022

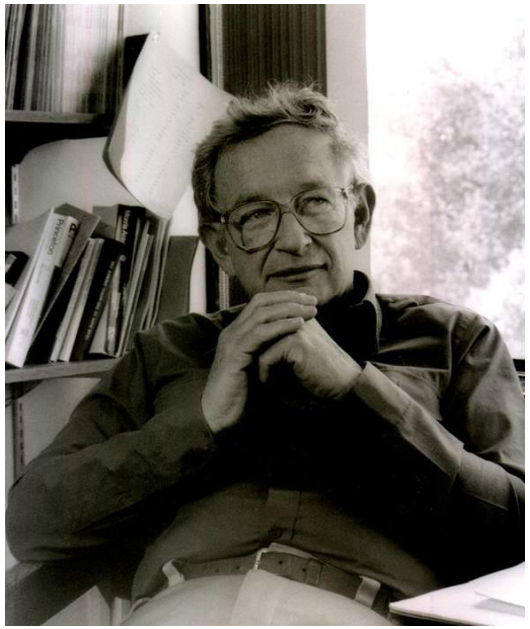
Outline

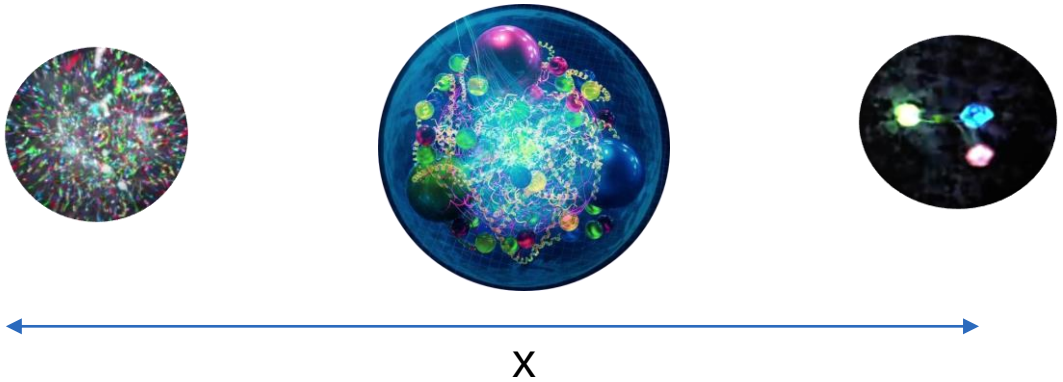
- Scientific questions and strategy
- The CEBAF 12 GeV program
  - Current outcomes
  - Future prospects
- A CEBAF energy upgrade
  - Toward 24 GeV – scientific case
  - Toward 24 GeV – technical feasibility

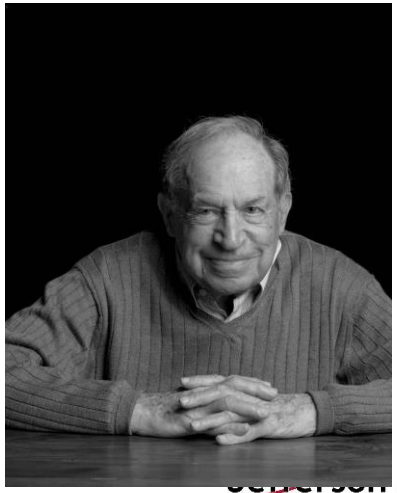
Scientific questions and strategy

Emergent phenomena…

- “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)].
- “When electrons or atoms or individuals or societies interact with one another or their environment, the collective behavior of the whole is different from that of its parts. We call this resulting behavior emergent. Emergence thus refers to collective phenomena or behaviors in complex adaptive systems that are not present in their individual parts.” -- D. Pines, Foundations & Frontiers in Complexity (2014)

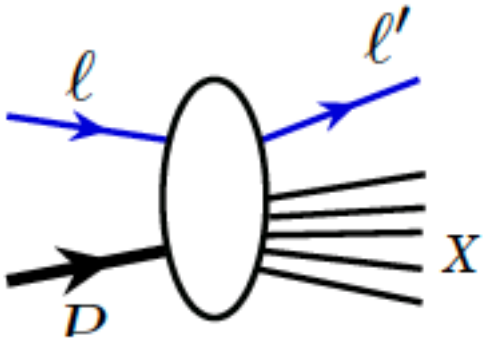


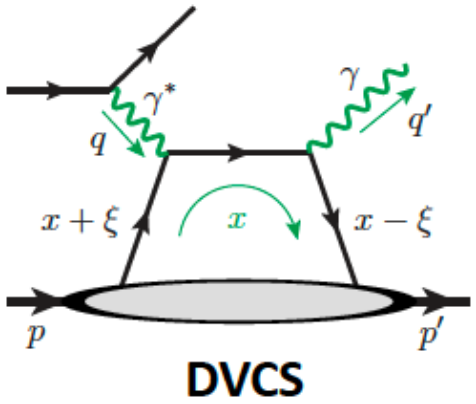


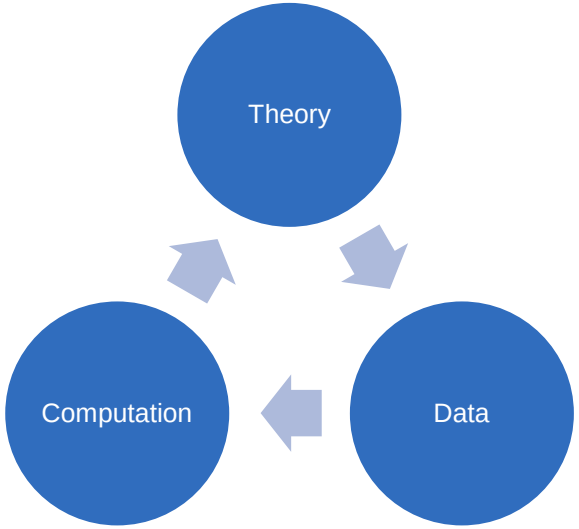


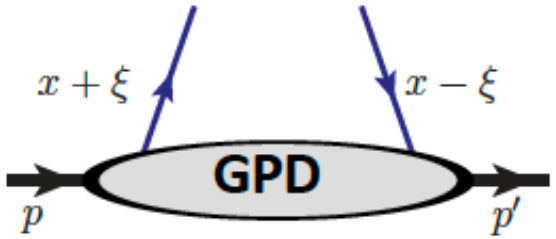
EXPERIMENTS MEASURE CROSS SECTIONS

- Quarks and gluons are ‘confined’ → experiments ‘see’ hadrons and infer an underlying quark and gluon structure and their dynamics

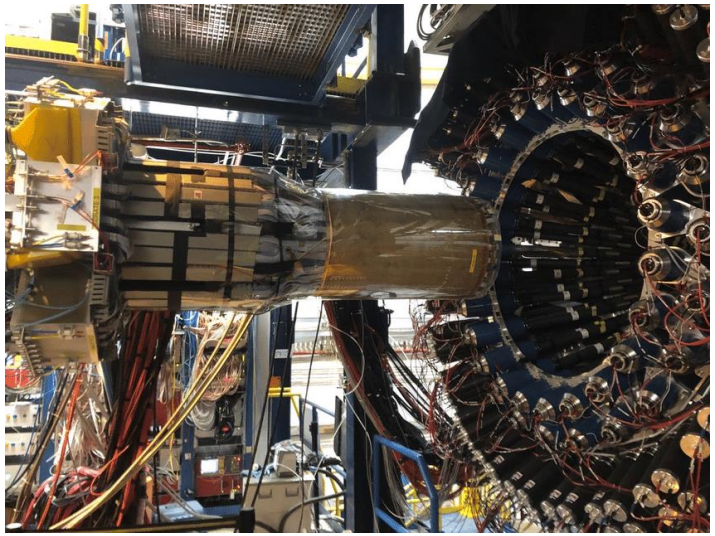






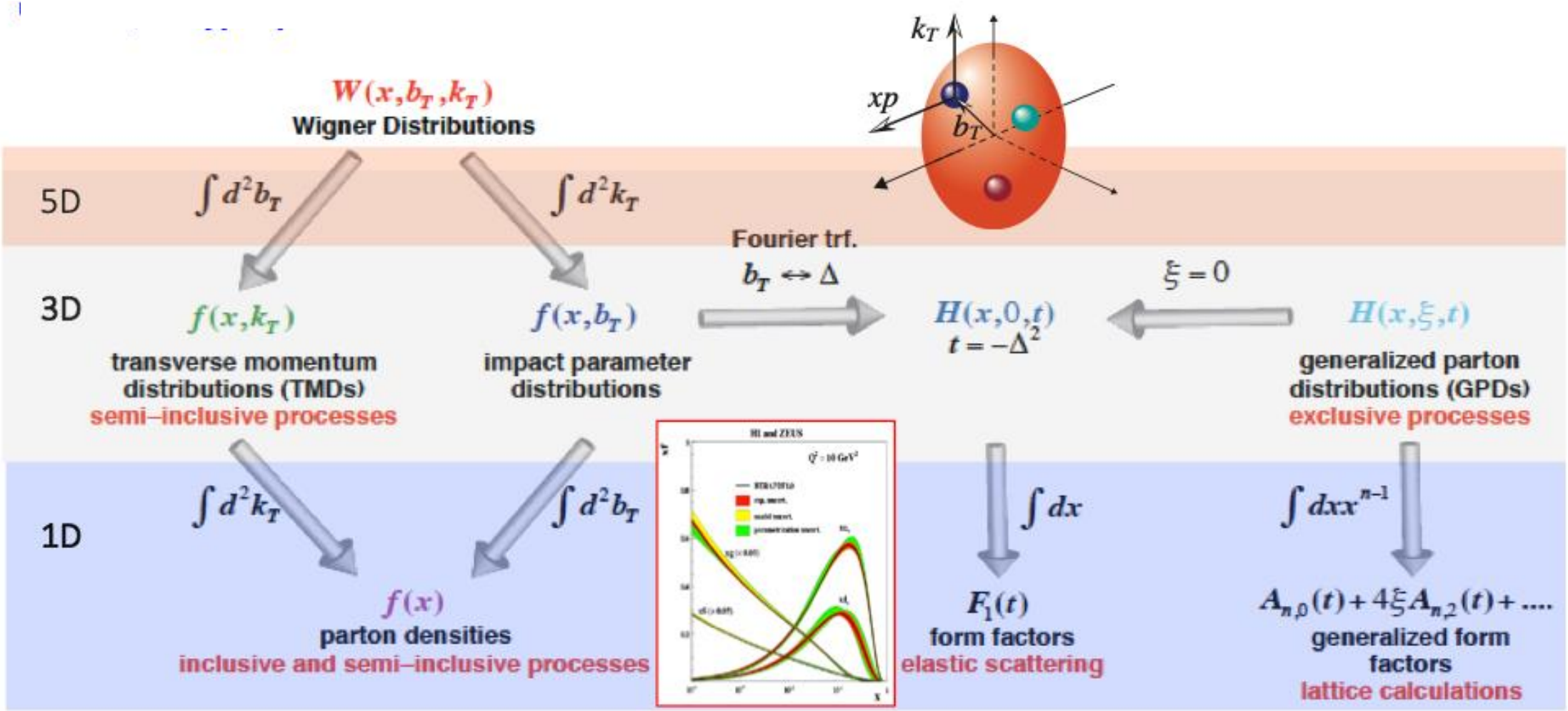


Experiments measure outgoing particles (hadrons and leptons)



Hall B BONUS detector

WIGNER FUNCTION CHARACTERIZES PARTONS IN THE NUCLEON



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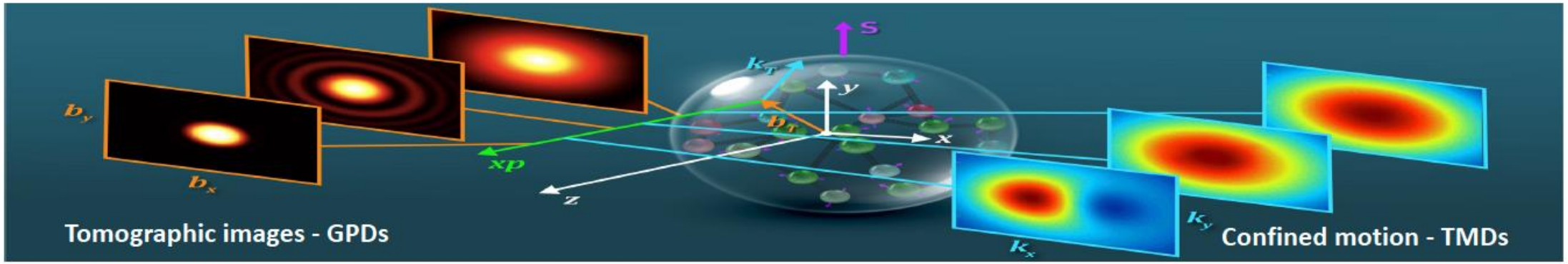
NO QUARKS AND GLUONS CAN BE SEEN IN ISOLATION

- 3D hadron structure:

NO quarks and gluons can be seen in isolation!

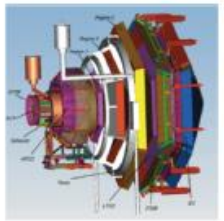


- QCD factorization – Matching hadrons to partons:

SciDAC5 – QuantOm Collab.

Lattice QCD data

Experimental data



Jefferson Lab, KEK, CERN, BROOKHAVEN, Fermilab

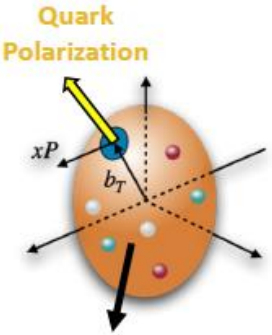
Factorization Theory

$$= \int \cdots \int$$

PQCD Calculation

$\otimes$

Quantum Correlation Functions Unknown



Bayesian inference
Theory/Phenomenology
AI/ML, Computation

Extract QCFs

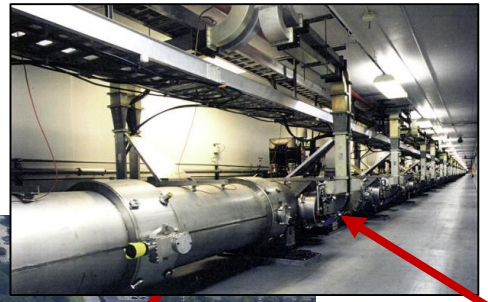
Slide courtesy Jianwei Qiu

The CEBAF 12 GeV program

CEBAF: A National Scientific User Facility

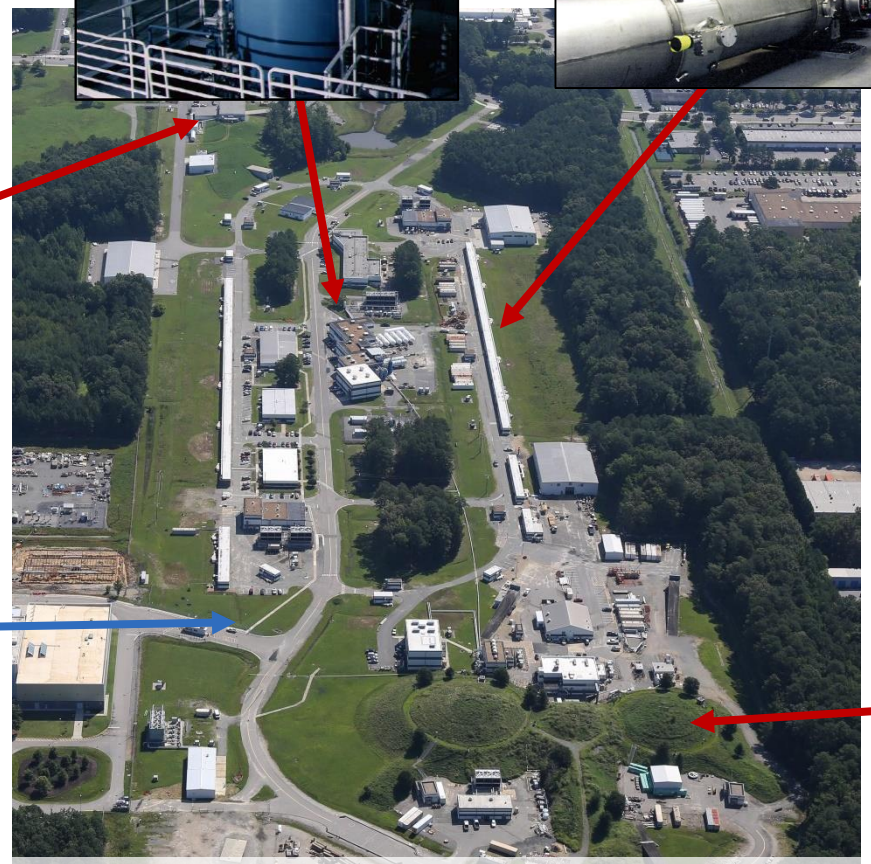
The world's most advanced high-energy electron microscope

Cryogenic Refrigeration Plant

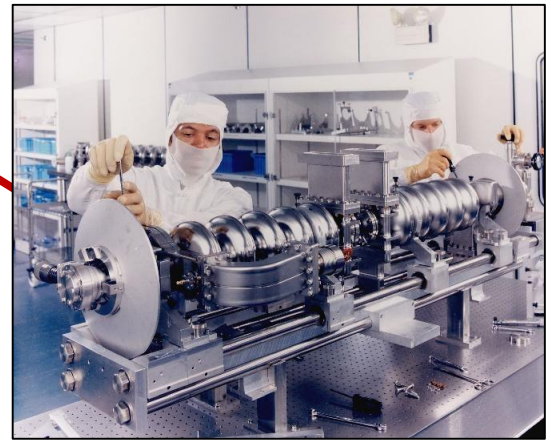


Cryomodules in the accelerator tunnel

Hall D



An aerial view of the recirculating linear accelerator and 4 experimental halls.



Superconducting Niobium radiofrequency cavities

Recirculation Arcs

Hall C

F_2^n/F_2^p – keen discriminator of fundamental models

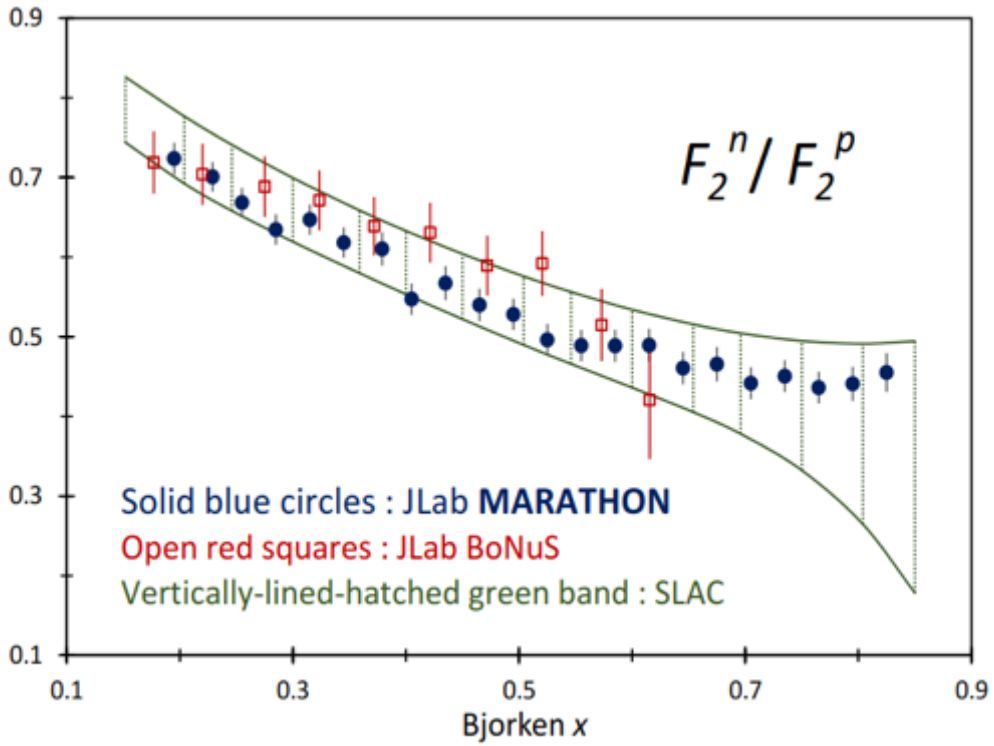
MARATHON results published March 31, 2022 in Phys. Rev. Lett. 128, 132003

Measured ^{3}He and ^{3}H cross sections in DIS kinematics using the LHRS and RHRS (last RHRS experiment!)

Extracted ratio of neutron to proton structure functions

$$\frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3He}/\sigma^{^3H}}{2\sigma^{^3He}/\sigma^{^3H} - R^*}$$

Assume R* is small (some theoretical uncertainty here)



SLAC deuteron data represented by green band since extraction sensitive to the NN potential used in the deuteron wave function

F_2^n/F_2^p predicted by models

Model	F_2^n/F_2^p
SU(6)	2/3
NJL	0.43
DSE-1	0.49
CQM	0.25
pQCD	3/7

Table from C. D. Roberts, R. J. Holt, S. M. Schmidt Physics Letters B, 727, 2013,p249-254

PROTONS OFFER SURPRISES IN ELECTROMAGNETIC STRUCTURES

ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

ALL TOPICS LIFE HUMANS EARTH

NEWS PHYSICS

Protons may be stretchier than physics predicts

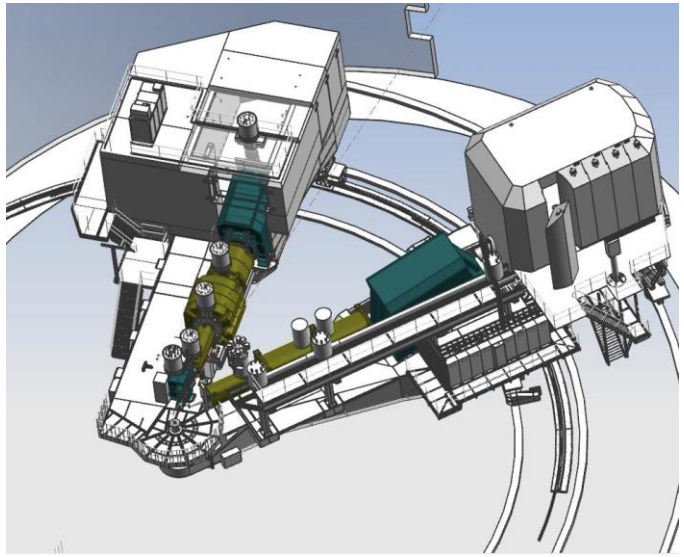
Quarks inside the particles seem to move more than they should in an electric field

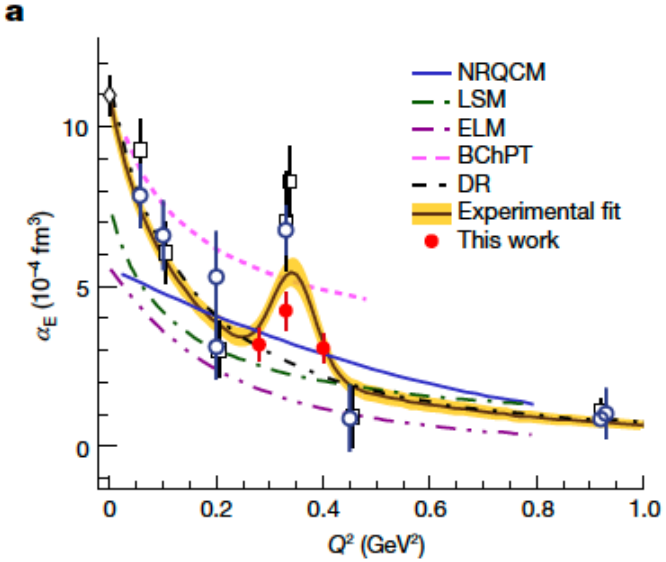
Proton's stretchiness is a puzzle for particle physicists

The particles inside a proton move around when exposed to electric and magnetic fields, causing it to deform, but this behaviour isn't well understood

PHYSICS 19 October 2022

By Alex Wilkins

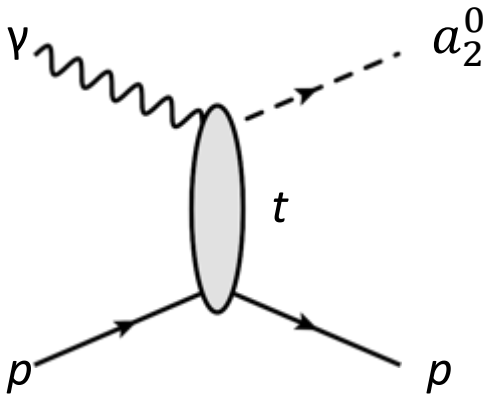


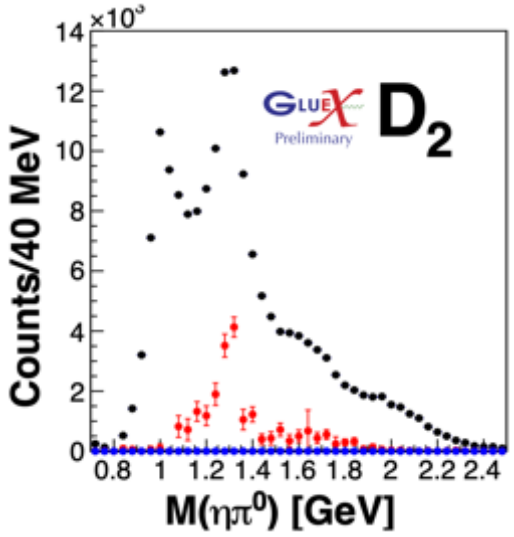


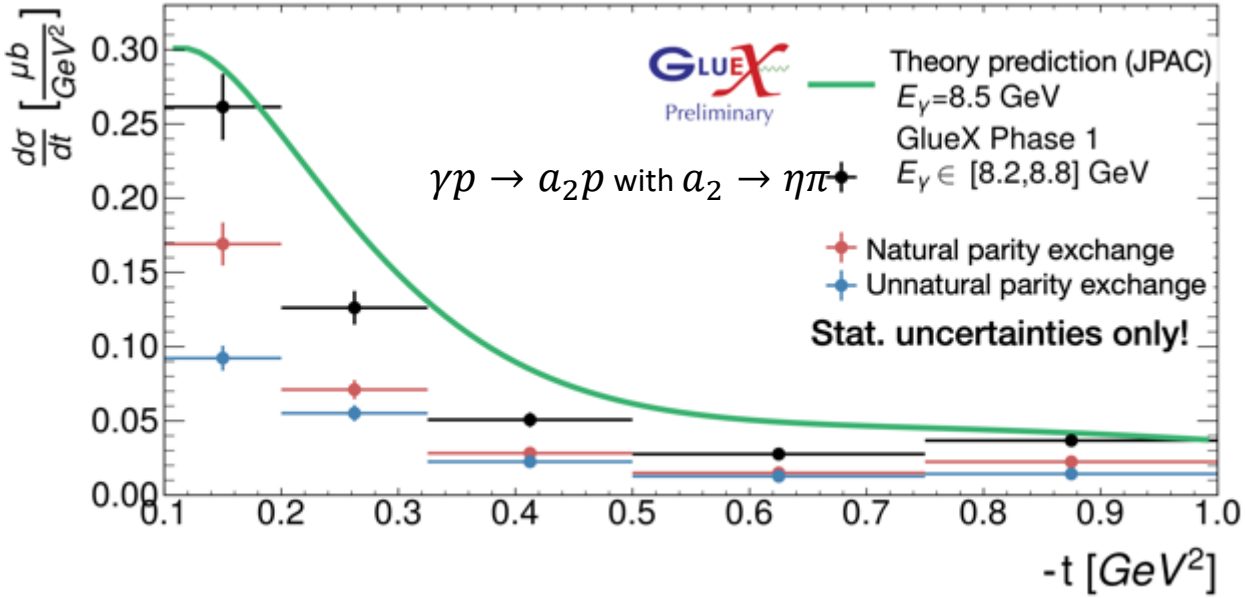
"Although steady progress has been made in recent years, we have yet to achieve a good understanding of how the nucleon properties emerge from the underlying dynamics of the strong interaction."

Measured proton electromagnetic structure deviates from theoretical predictions, R. Li et al., Nature (2022), *https://doi.org/10.1038/s41586-022-05248-1*

RESULTS ON PATH TOWARDS EXOTIC SEARCHES: $a_2(1320)$







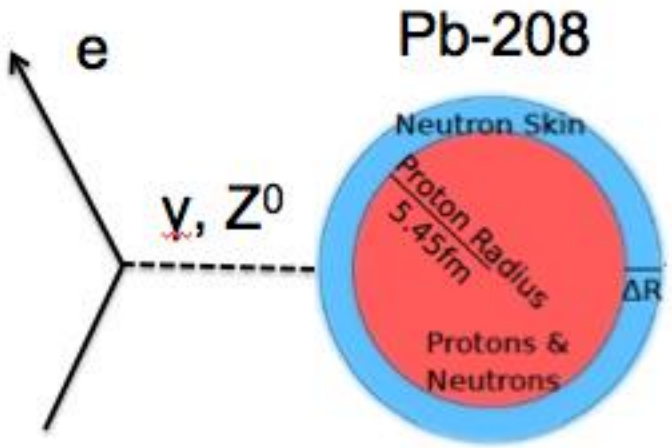
- Prioritize channels for searches including exotic $\pi_1(1600)$ decays to $\eta\pi$ and $\eta'\pi$ – review committee on $\eta\pi$ results:

  "The D waves show impressive signals for the a_2 meson. This indicates that there is a well-functioning analysis capable of extracting meaningful signals... The Committee endorses the collaboration's goal of presenting results on cross sections and mechanisms for $a_2(1320)$ photoproduction in one year's time"

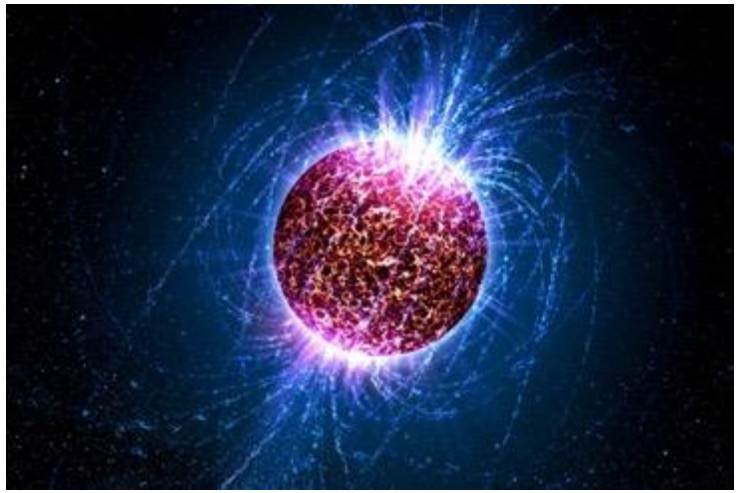
- **Relevance to exotic search:**
  - Validates theoretical amplitudes and analysis techniques with a known resonance
  - Forms a benchmark "standard candle" needed to analyze $\eta'\pi$, which is more sensitive to exotics than $\eta\pi$

- **Status:**
  - Preliminary results for a_2^0 shown at JLUO Meeting
  - Technical challenges with a_2^- remain
  - Advanced preliminary results expected by Fall 2022

Connections Across the Sciences

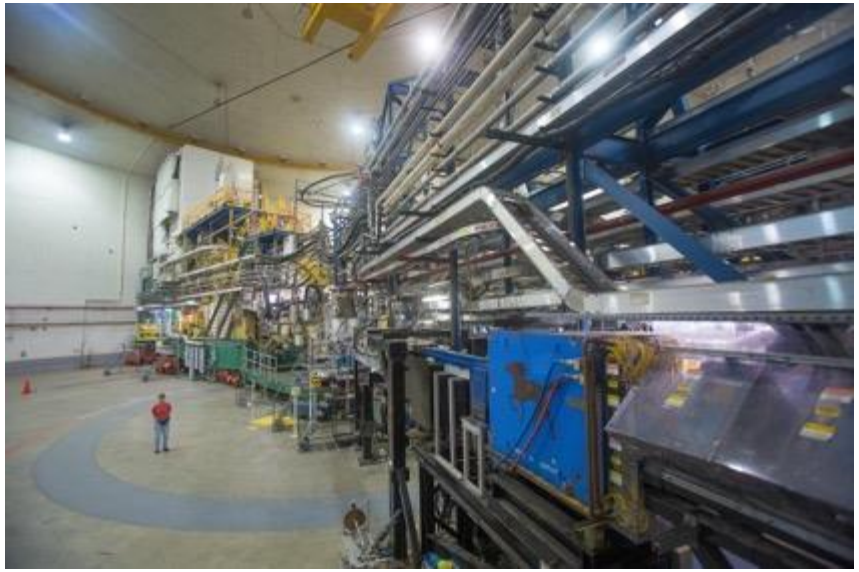


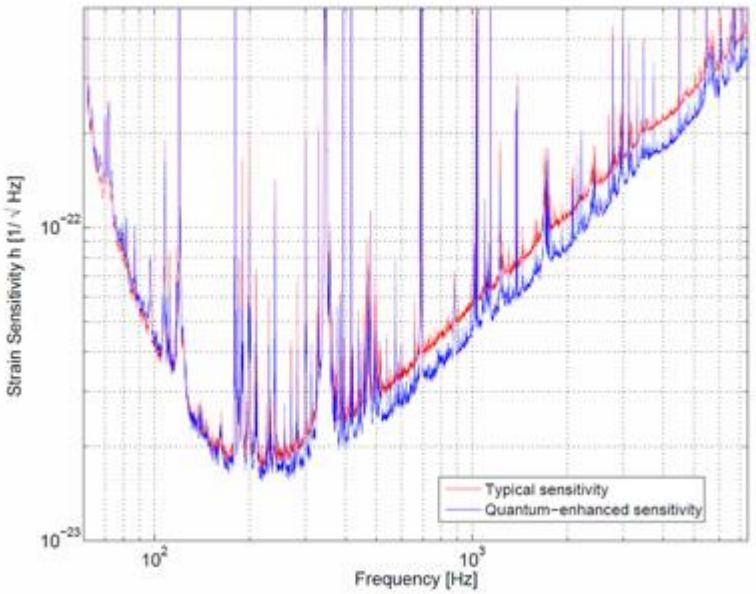
PREX: Phys Rev Lett 126, 172502 (2021)

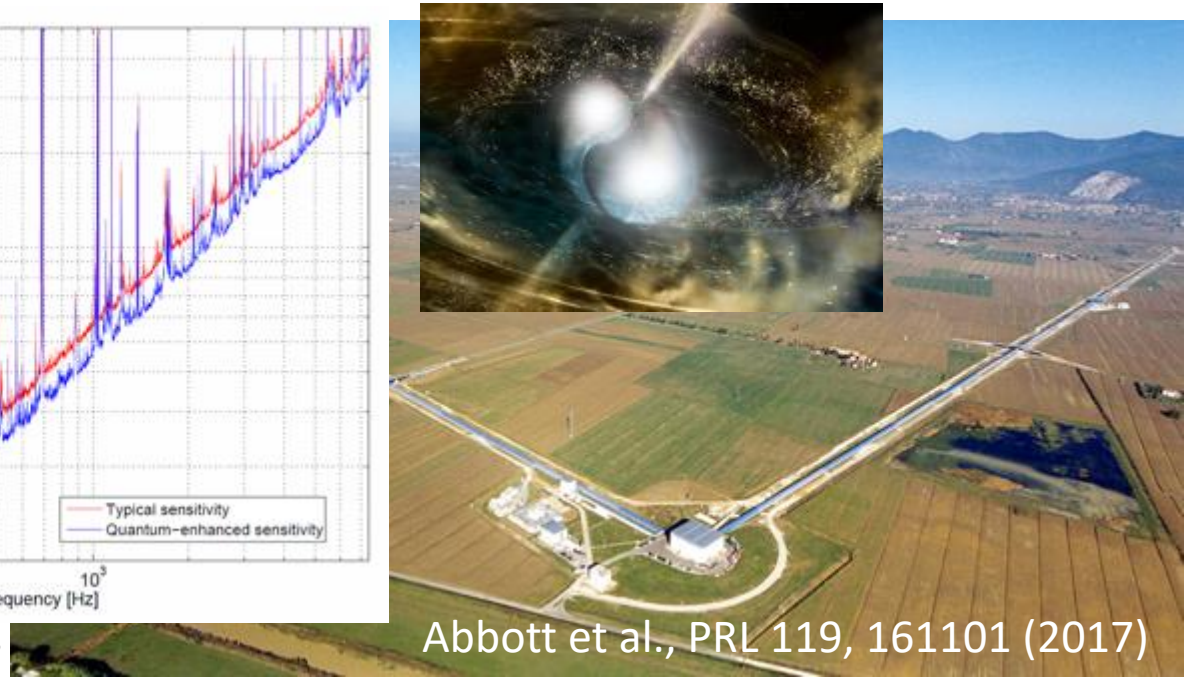


Amazing technology yields amazing insights

- Probing nuclear forces
- Implication for neutron star skins
- Squeezed light used to enhance LIGO
- LIGO sees neutron star mergers using squeezed light (a quantum sensing enhancement)







Abbott et al., PRL 119, 161101 (2017)

PROBING THE STANDARD MODEL TO 27 TEV

Elastic scattering of longitudinally polarized electrons on unpolarized electrons

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \qquad \vec{e} + e \rightarrow e' + e'$$

Parity violating asymmetry:

A_{PV} ~ 33×10^{-9} or 33 ppb (parts per billion)

δA_{PV} ~ ± 0.8 ppb (2.4% precision)

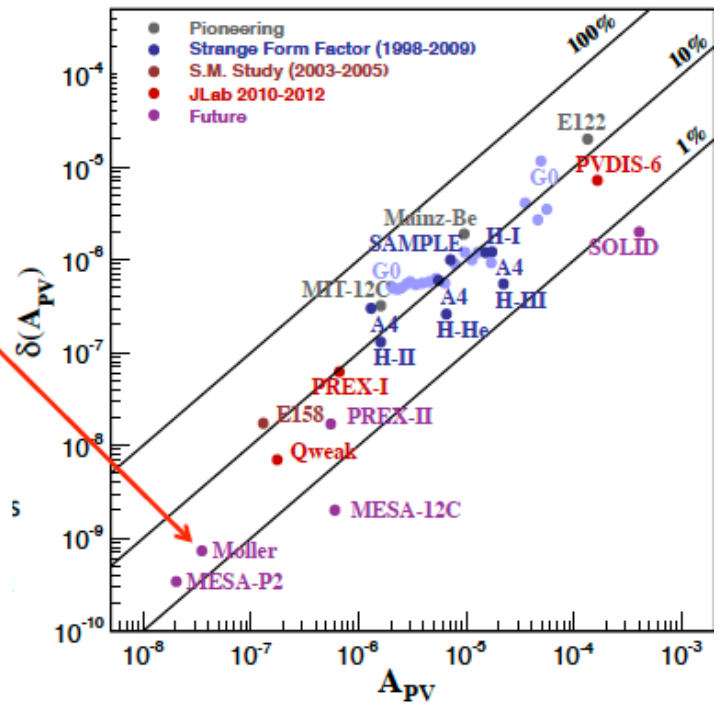
⟶ next generation in size and precision of asymmetry for parity-violating electron scattering experiments

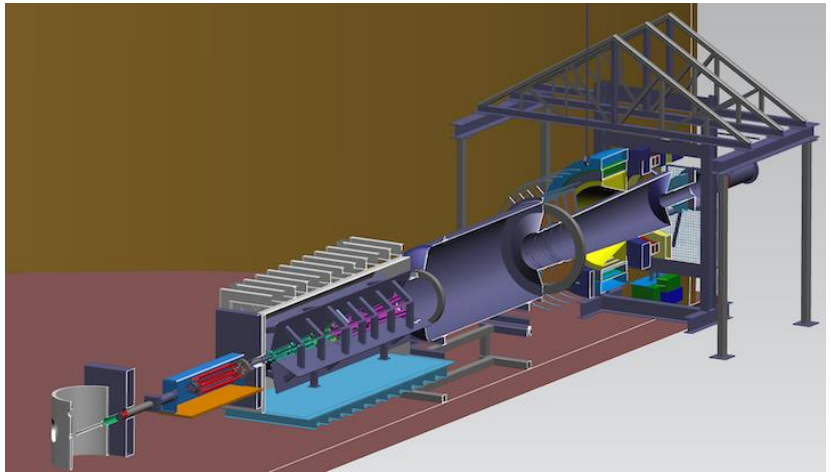
proportional to the electron's weak charge Q^e_W
- precisely predicted in Standard Model

At tree level $Q^e_W = -\left(1 - 4\sin^2\theta_W\right)$

2.4% precision on Q^e_W 0.1% on $\sin^2\theta_W$

From Mark Pitt



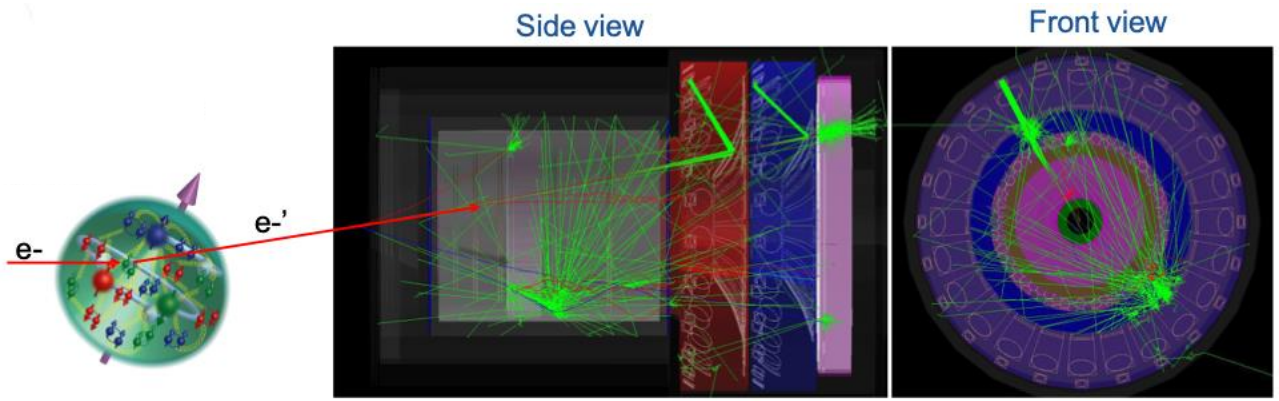


Moller will probe energy regions for Beyond Standard Model Physics to ~27 TeV in this Q-weak sector

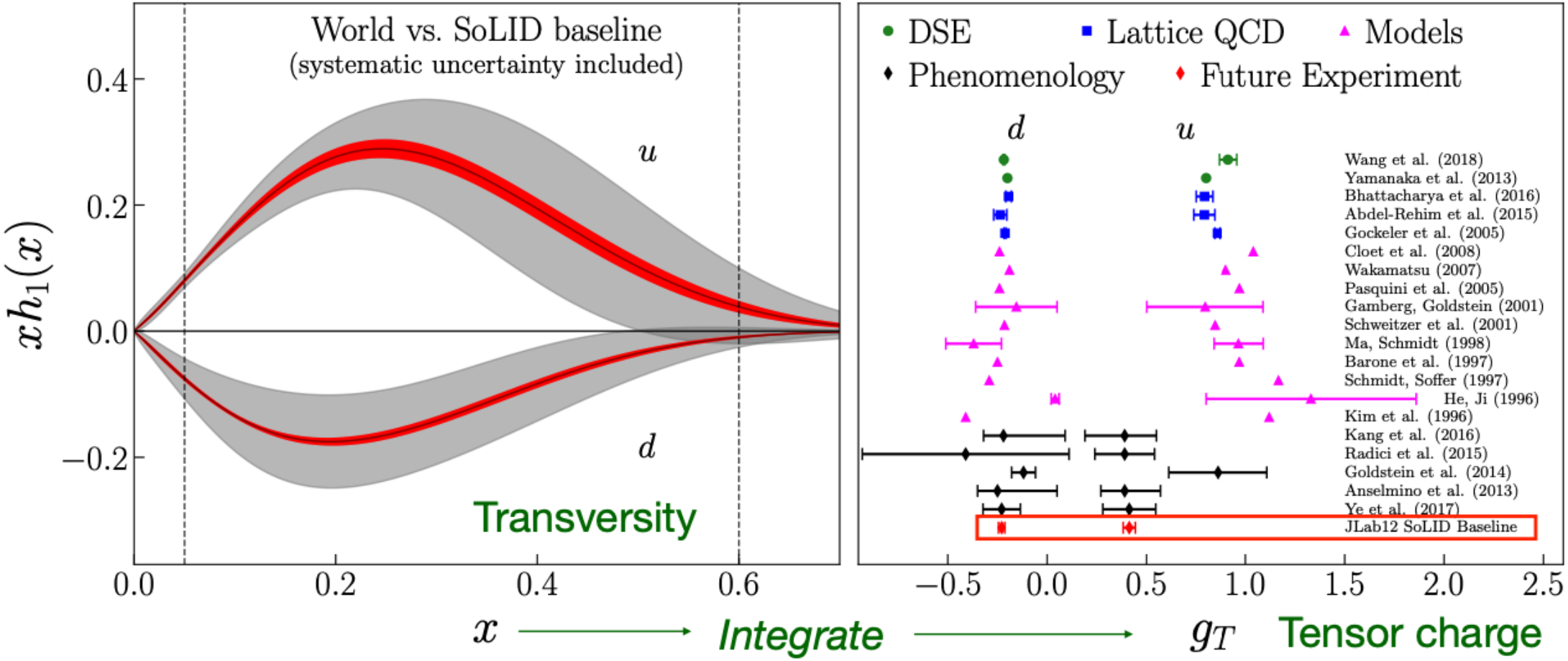
LHC energies: 13 TeV

SoLID fully enables CEBAF 12 GeV at the intensity frontier

- Nucleon spin, proton mass, BSM experiments require precision measurements of small cross sections and asymmetries, combined with multiple particle detection
- There is a critical need for a high luminosity 10^{37}-10^{39} $cm^{-2}s^{-1}$ and large acceptance working in tandem (12 GeV can reach 10^{35} $cm^{-2}s^{-1}$ today)
- Science reach
  - Precision 3D momentum imaging in the valence quark region
  - Exploring the origin of the proton mass and gluonic force in the non-perturbative regime
  - Beyond Standard Model searches in tandem with Moller



SIMI INCLUSIVE DEEP INELASTIC SCATTERING (SIDIS) AT 12 GEV WITH SOLID



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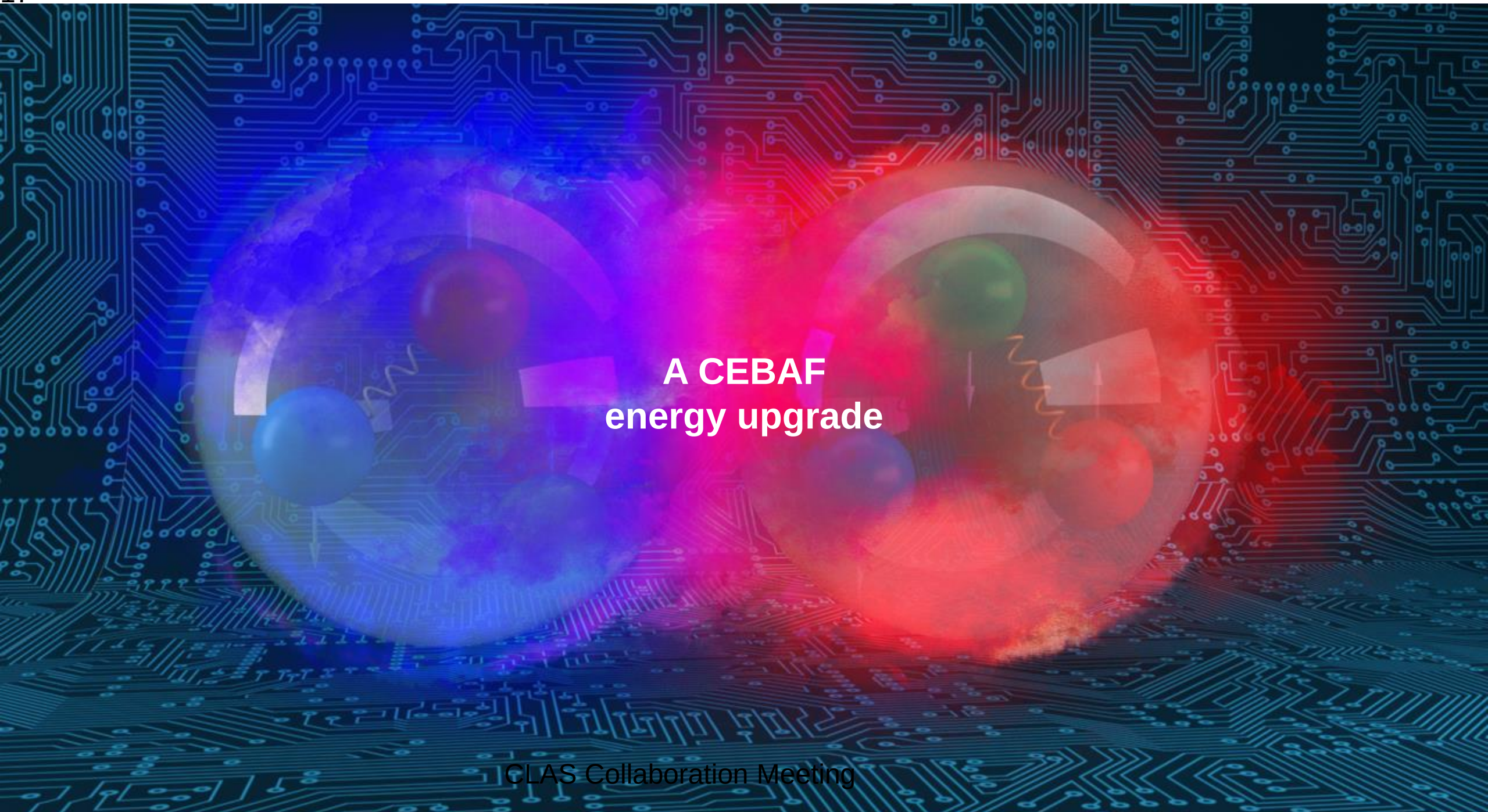
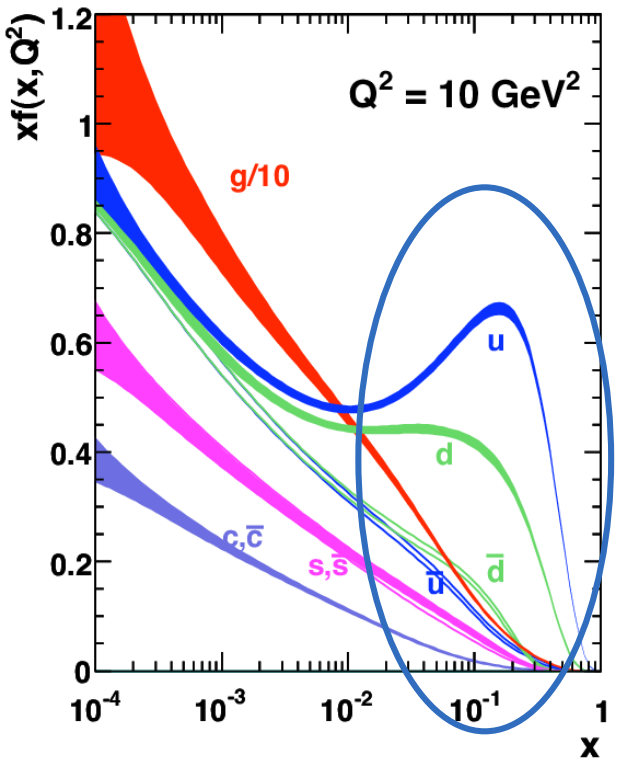


A CEBAF energy upgrade

A CEBAF Energy Upgrade – the Big Picture

- How do hadrons emerge from QCD?
- Study of the quark-gluon dynamics which determines the structure of hadrons and hadron-hadron interactions
  - Spectroscopy
  - Excited states
  - Hadron structure
  - TMDs, GPDs
  - Hadronization
- What an upgrade brings:
  - Builds upon a world-leading program of investigation in the valence region (x>~0.1)
  - Validation of theory (we rely on QCD inspired models in this regime)
  - Deeper access to and understanding of the structure of strongly-interacting quark gluon systems
  - Opens new opportunities on studies of the charm sector



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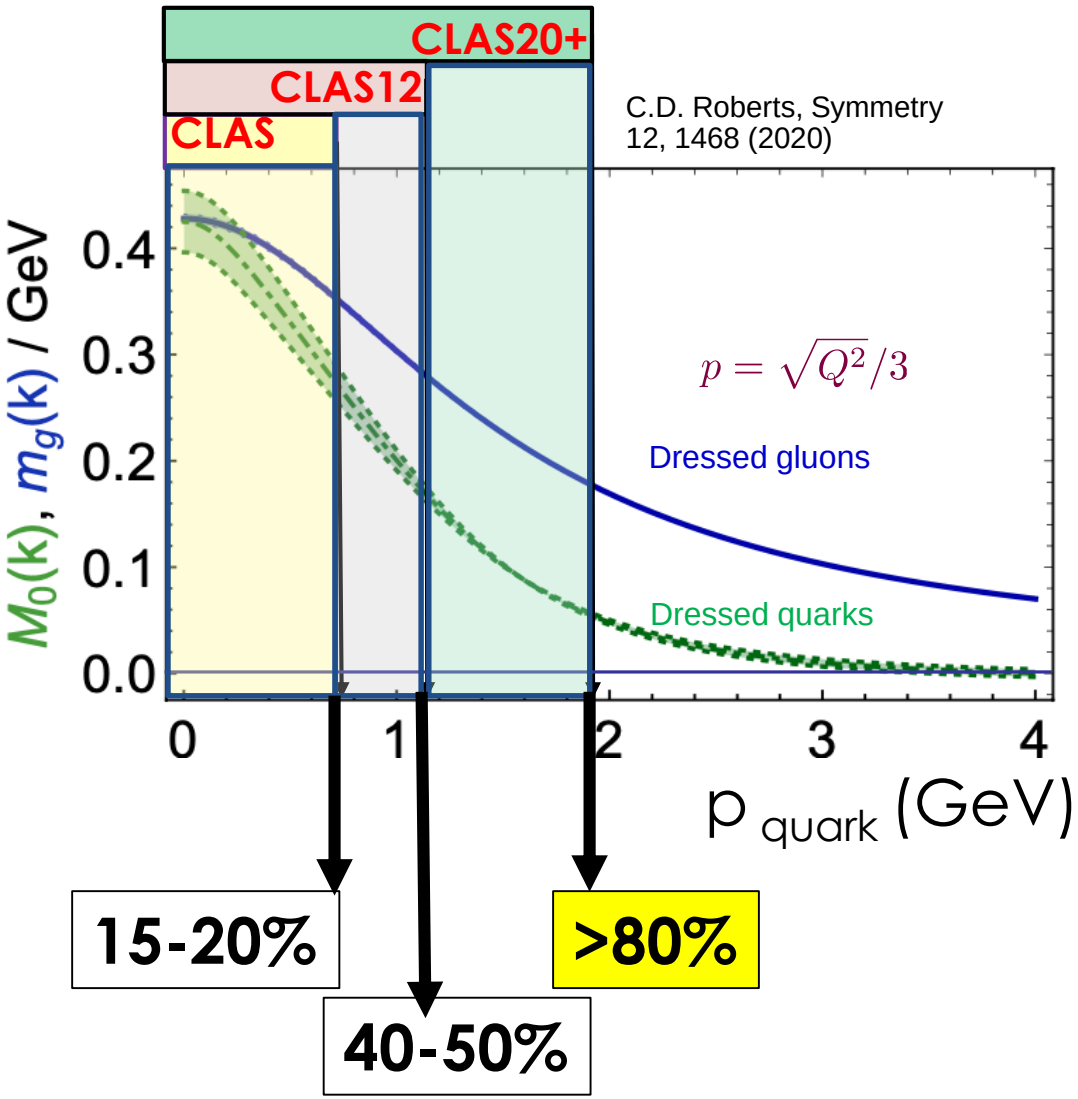
HOW DO HADRON STRUCTURES ORIGINATE IN QCD?



- We can increase our knowledge on running dressed quark mass from the results on $\gamma_v pN^*$ electrocouplings

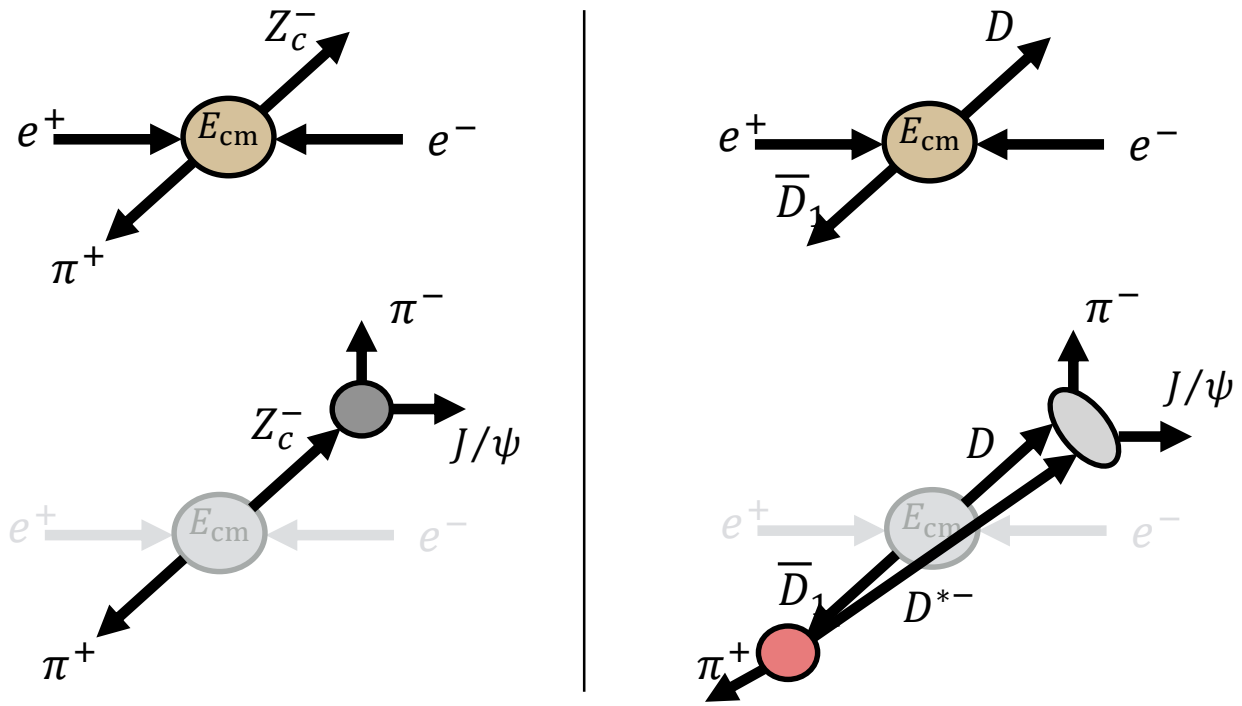
- $\gamma_v pN^*$ electrocouplings can be determined up to

- Q^2 ~30 GeV^2
- for $\mathcal{L}$ ~ 3 - 5×10^{35} $cm^{-2}s^{-1}$

- CEBAF 20+ GeV:
  <u>only foreseeable opportunity</u> to explore N* electroexcitation within the Q^2 range where the <u>dominant portion of hadron mass</u> is expected to be generated

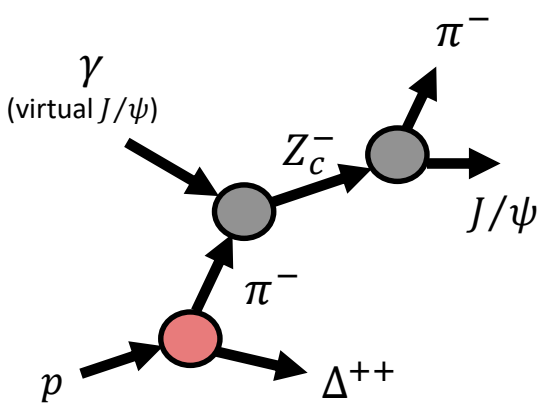
UPGRADE PROVIDES A CLEAN PRODUCTION MECHANISM FOR XYZ STATES

via a tetraquark Z_c^-?

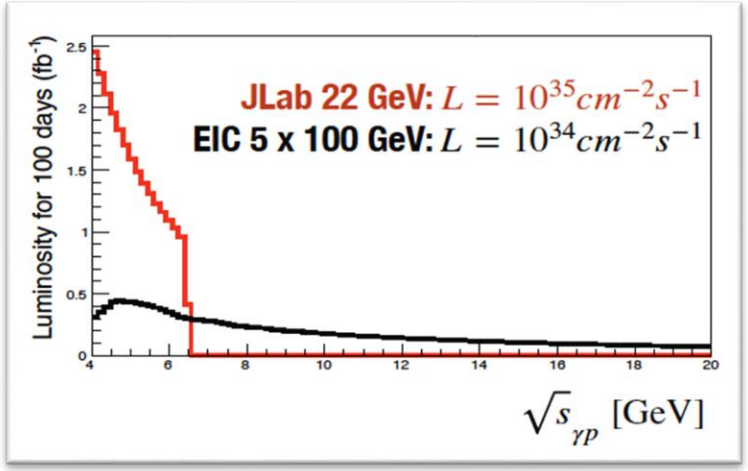


Interpretation of data is complicated by nonresonant $D^{*-}D \to J/\psi\pi^-$ scattering that can produce peaks in invariant mass spectra for certain choices of E_{cm} and π^+ momentum that result in a $D^{*-}D$ interaction. These peaks are effects of initial state kinematics and <u>do not require a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

$$\gamma p \to \pi^+ J/\psi \Delta^{++}$$

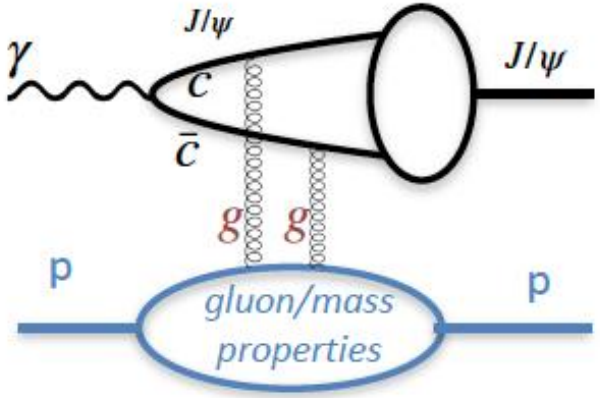


Direct probe of the $Z_c \to J/\psi\pi$ coupling without rescattering effects provides <u>unique complementary data</u> to constrain interpretation of e^+e^- data.

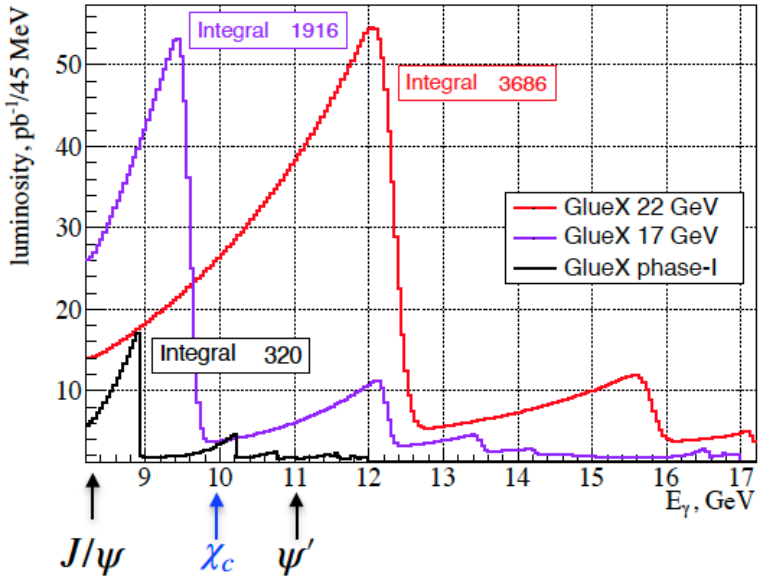


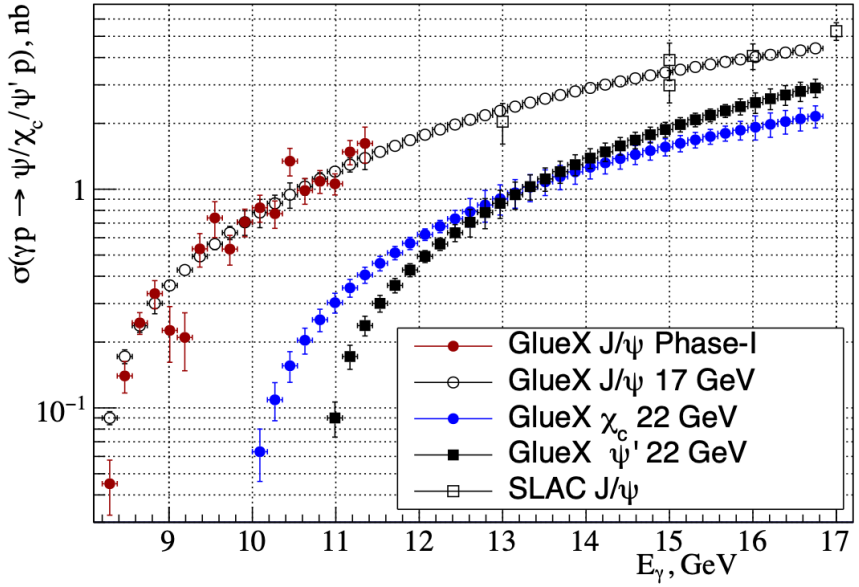
Courtesy Matt Shepherd

UPGRADE ENABLES DETAILED STUDIES OF CHARMONIUM THRESHOLD PHOTO-PRODUCTION

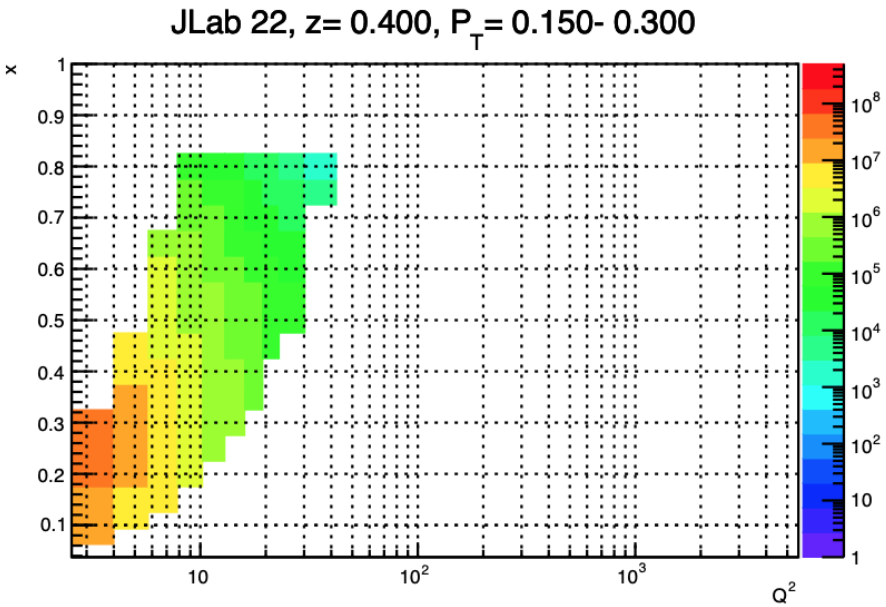


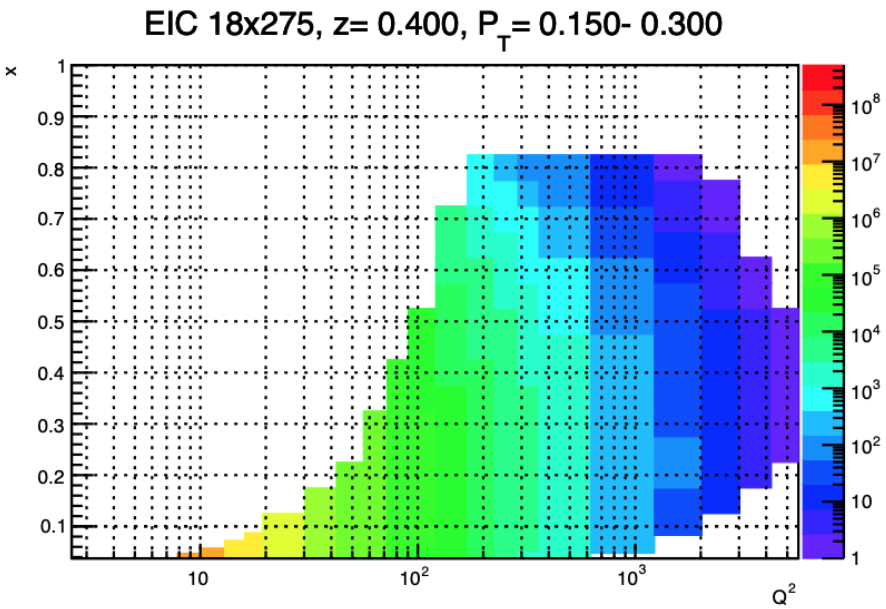
- Exclusive charmonium production near threshold probes gluon/mass properties of proton (mass radius, gravitational form factors, D-term, anomalous contribution to proton mass), however
  … assuming factorization
  … assuming two-gluon exchange

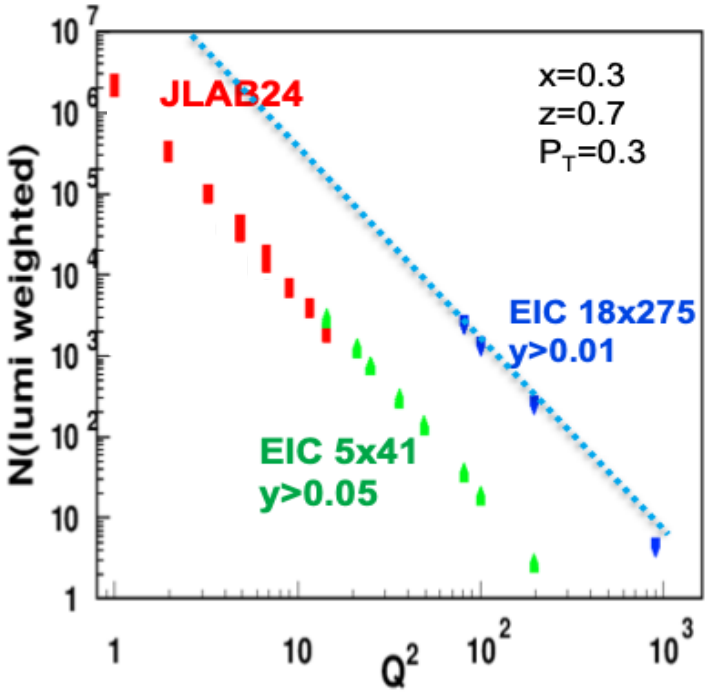




SIDIS AT LARGE X: COMPLEMENTARITY







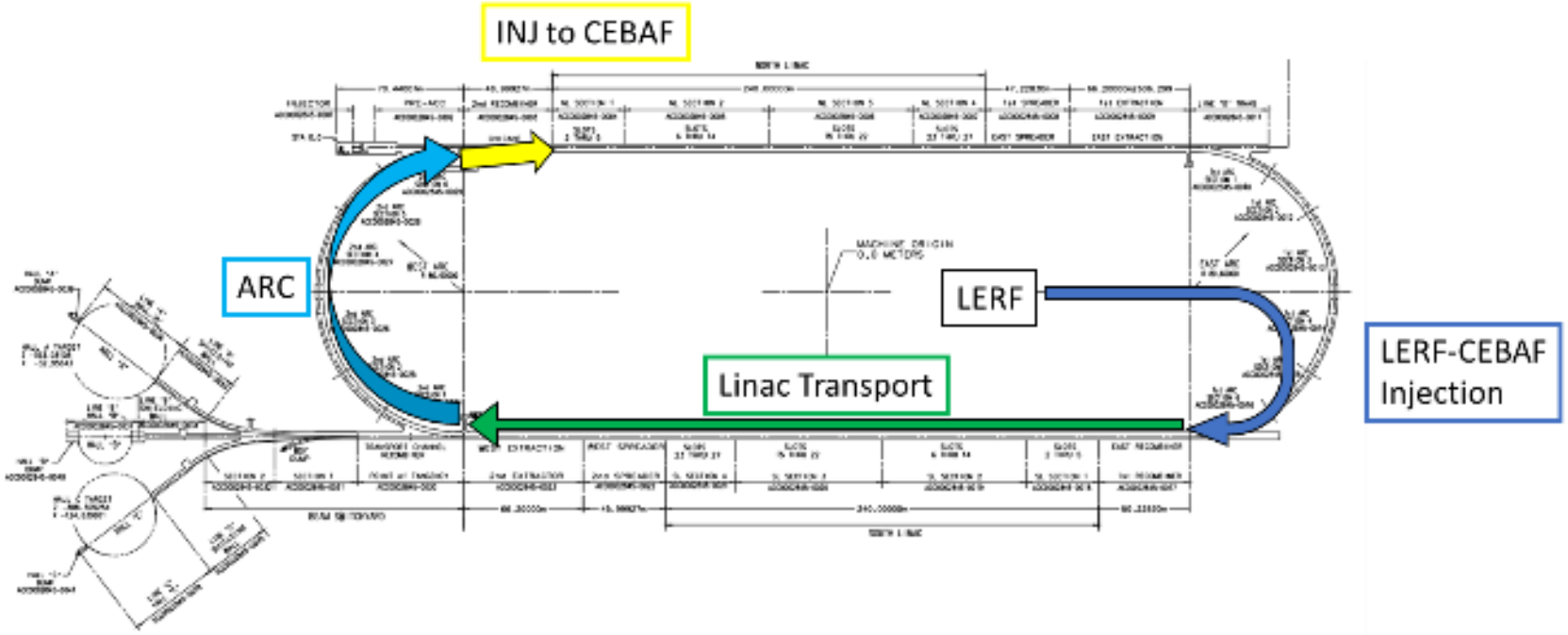
x-section from Bacchetta et al, 1703.10157

SIDIS provides data for Transverse Momentum Dependent PDFs

Counts / year

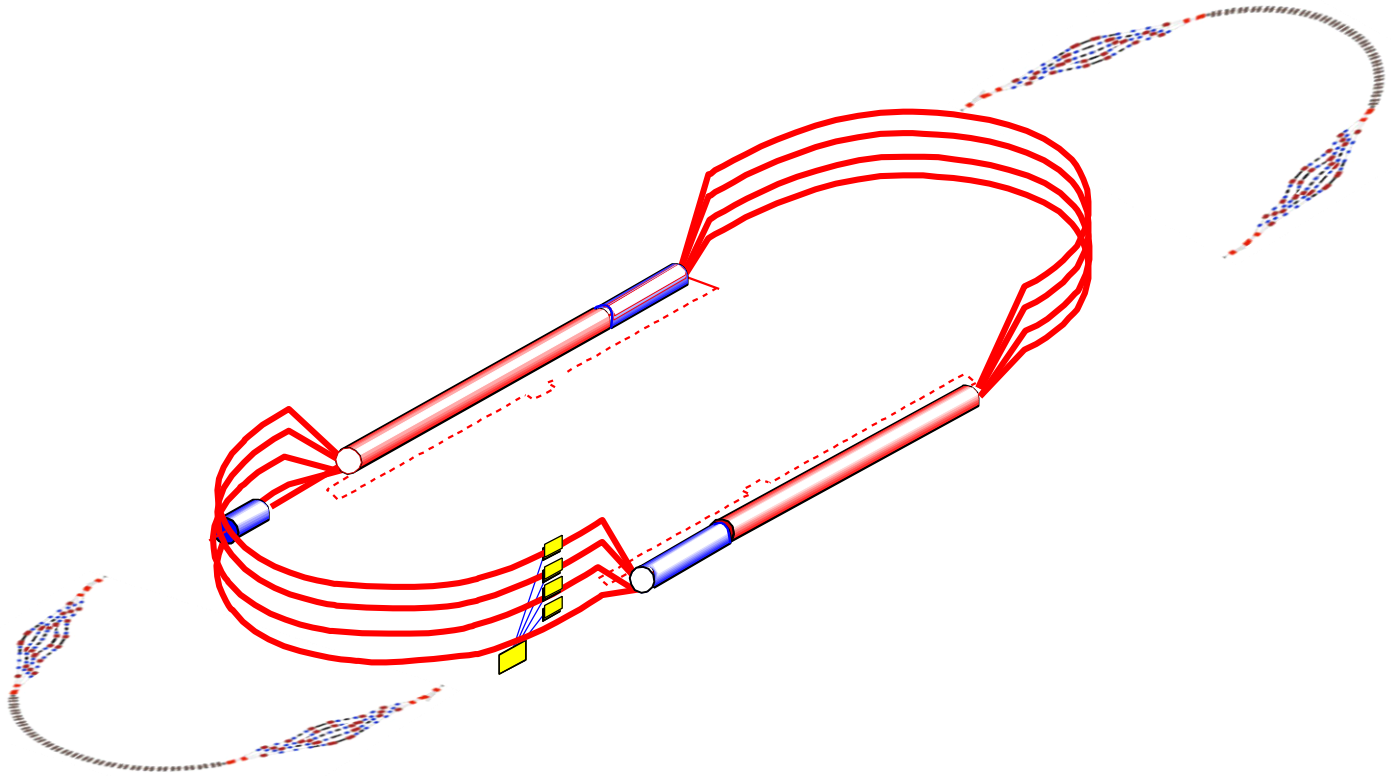
AN UPGRADE IS TECHNICALLY FEASIBLE

- *Capitalizing on recent science insights and US-led accelerator science and technology innovations, develop a staged program at the luminosity frontier*
- Positrons (e+) in the LERF (former FEL) with transport to CEBAF (validation of the scattering formalism)
- Energy Upgrade for 650 MeV Electron (e-) Injection in the LERF
- Replace arcs on each side with new FFA permanent magnet arcs to upgrade to 22 GeV



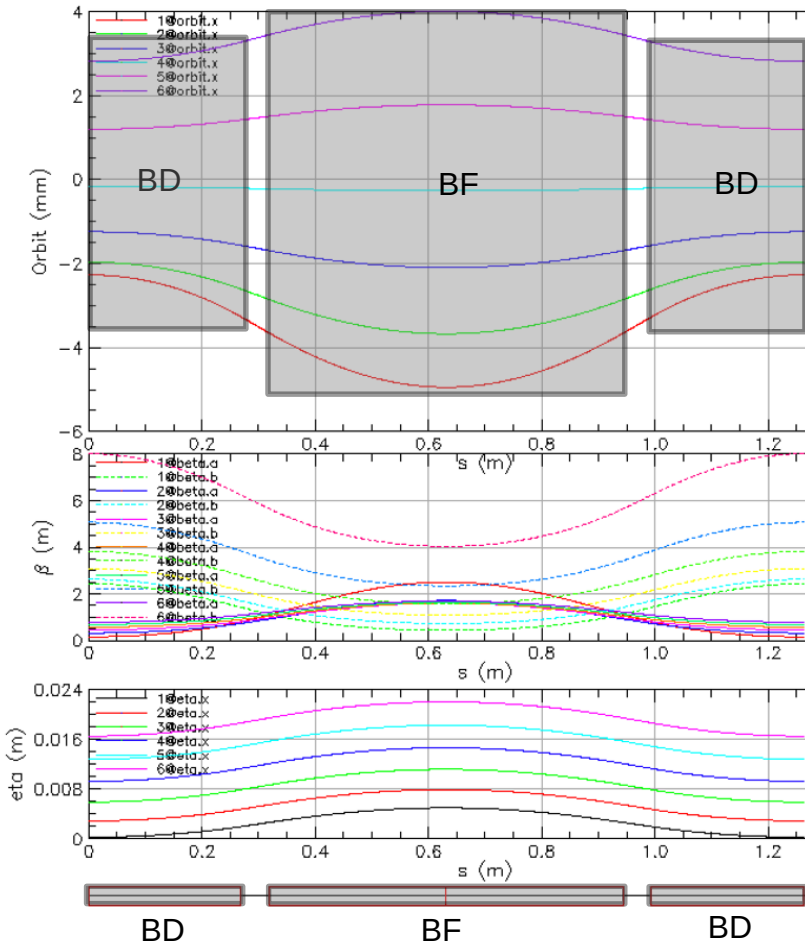
An energy upgrade: FFA CEBAF with CBETA-like Arcs

- Current status:
  - 1.1 GeV/linac
  - 120 MeV injector
  - Recirculate 5.5 times
- Replace one set of arcs with Fixed Field Alternating Gradient Arcs
- 650 MeV injector
- Recirculate up to 12 times

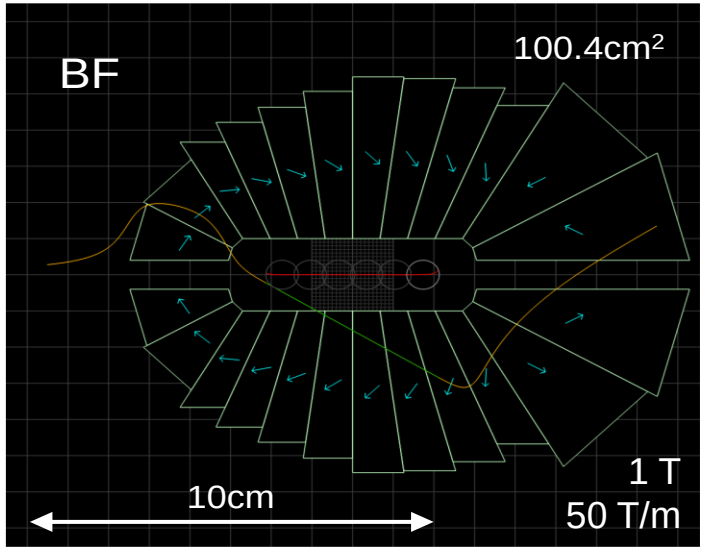


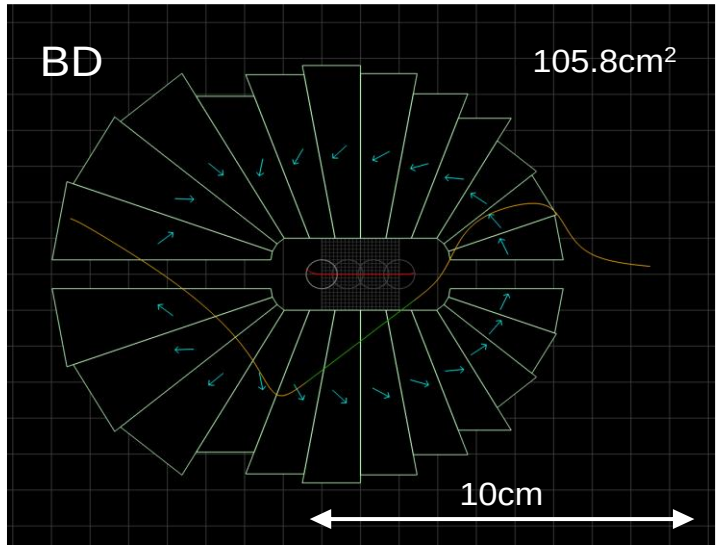
Compact FFA Cell – How Does it Work?

- Large momentum acceptance FFA cell, configured with combined function magnets capable of transporting multiple energy beams through the same string of permanent magnets (six beams with energies spanning a factor of two)



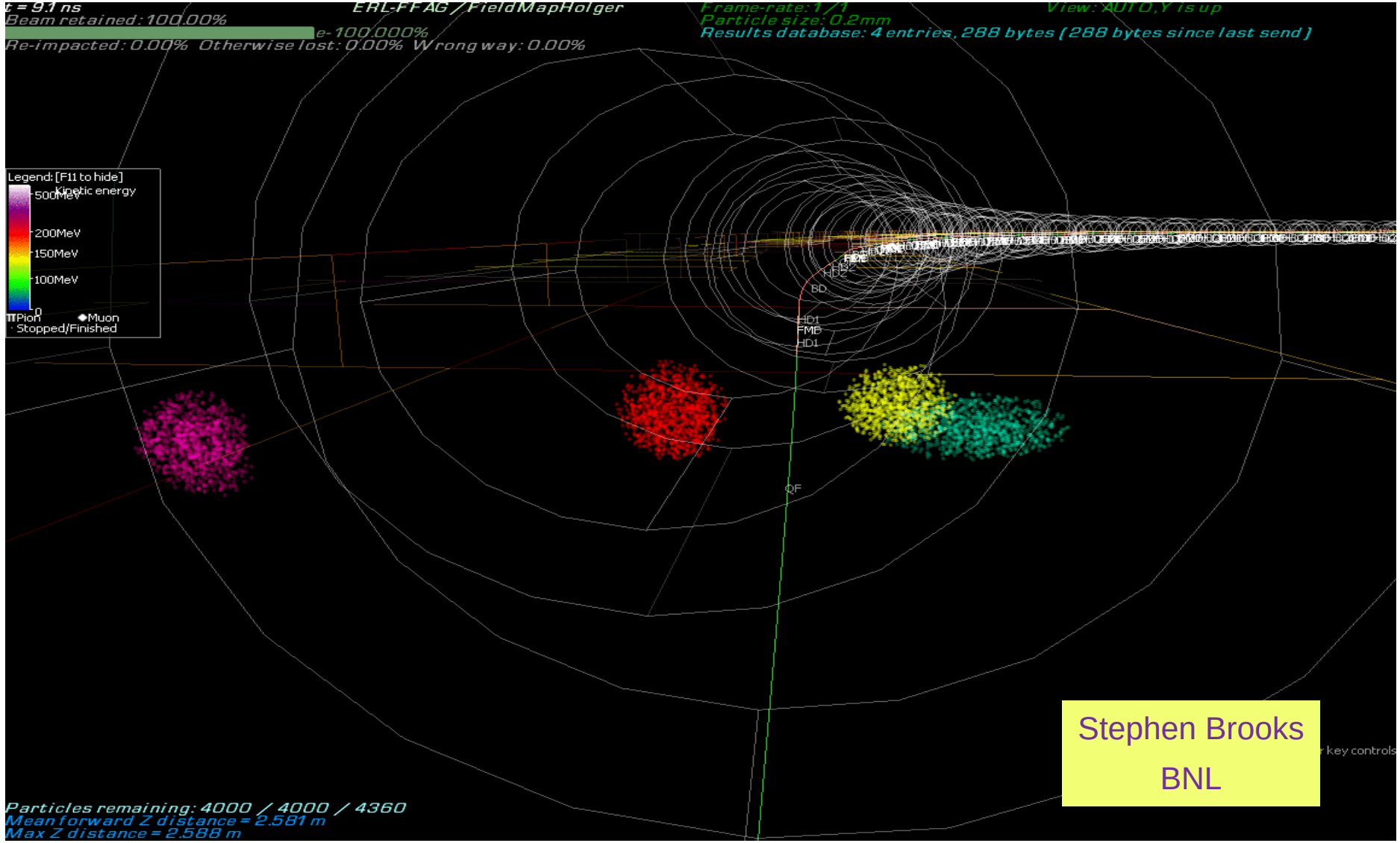
CBETA magnets: from 38cm² to 78cm²





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

Multi-Bunch Dynamics in CBETA FFA Arc



Stephen Brooks
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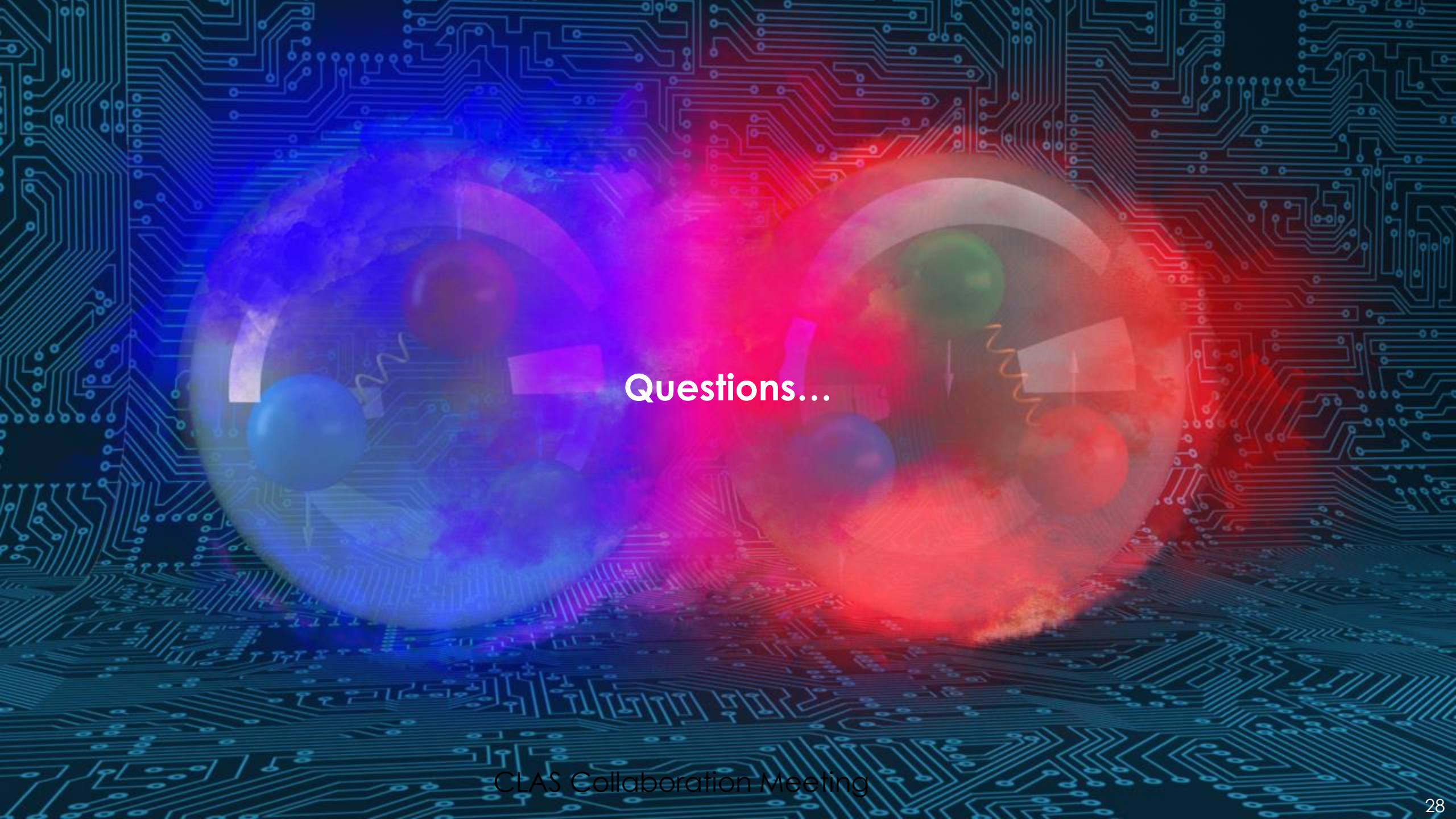
Jefferson Lab
Thomas Jefferson National Accelerator Facility

JLab Investigates quarks (larger x)…Conclusion

- CEBAF has a long program ahead that is complementary to the envisioned EIC program
- CEBAF will remain the prime facility for fixed target electron scattering at the luminosity frontier
- A groundbreaking experimental program has been developed stretching into the 2030s
- Moller is fully funded, SOLID enables CEBAF to reach its full intensity capability

We are developing both the science and technical case for moving beyond 12 GeV at high luminosity (white paper in development)

- Summer Workshops
- 23-25 January 2023 “Science at the Luminosity Frontier”



Questions…