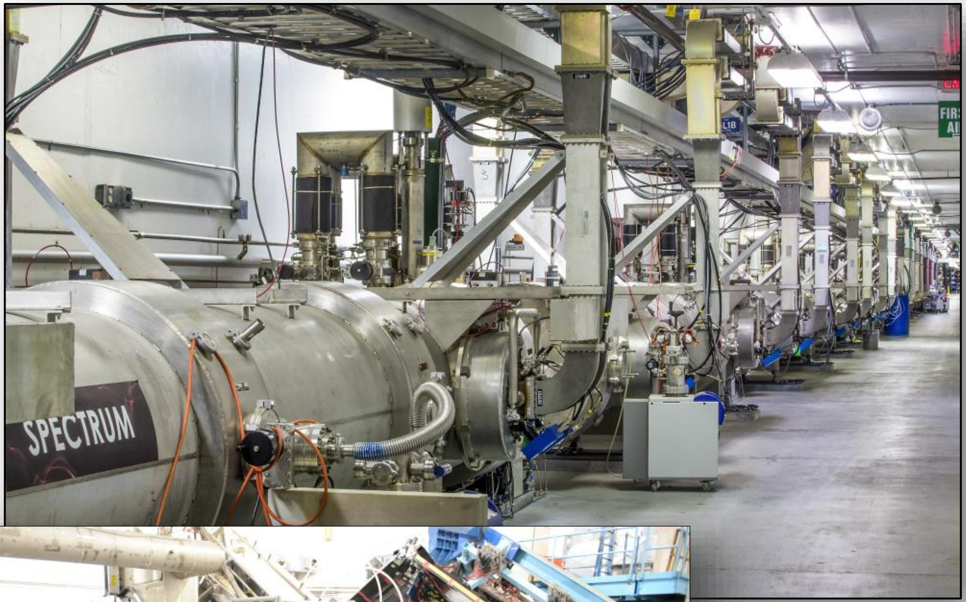
The 12 GeV Program at Jefferson Lab

Allison Lung

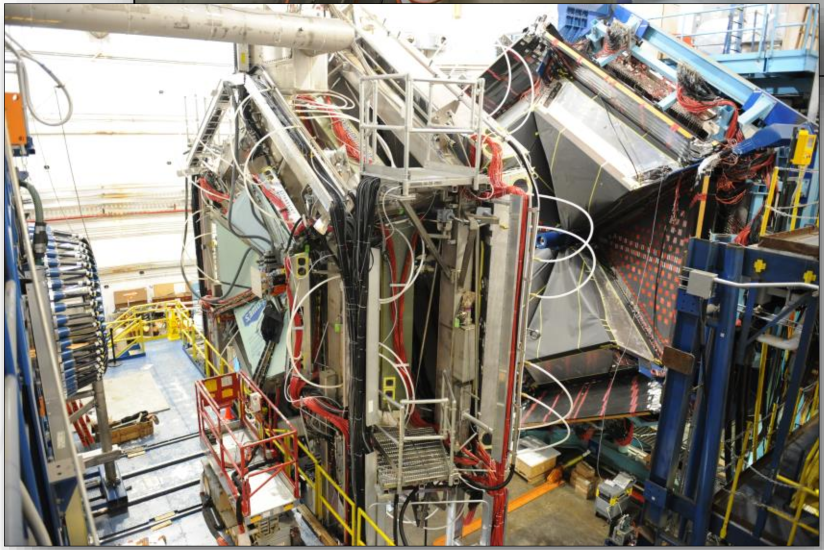
Chief Planning Officer



ICNFP

Lepton-Nucleus Scattering Workshop

August 23, 2019



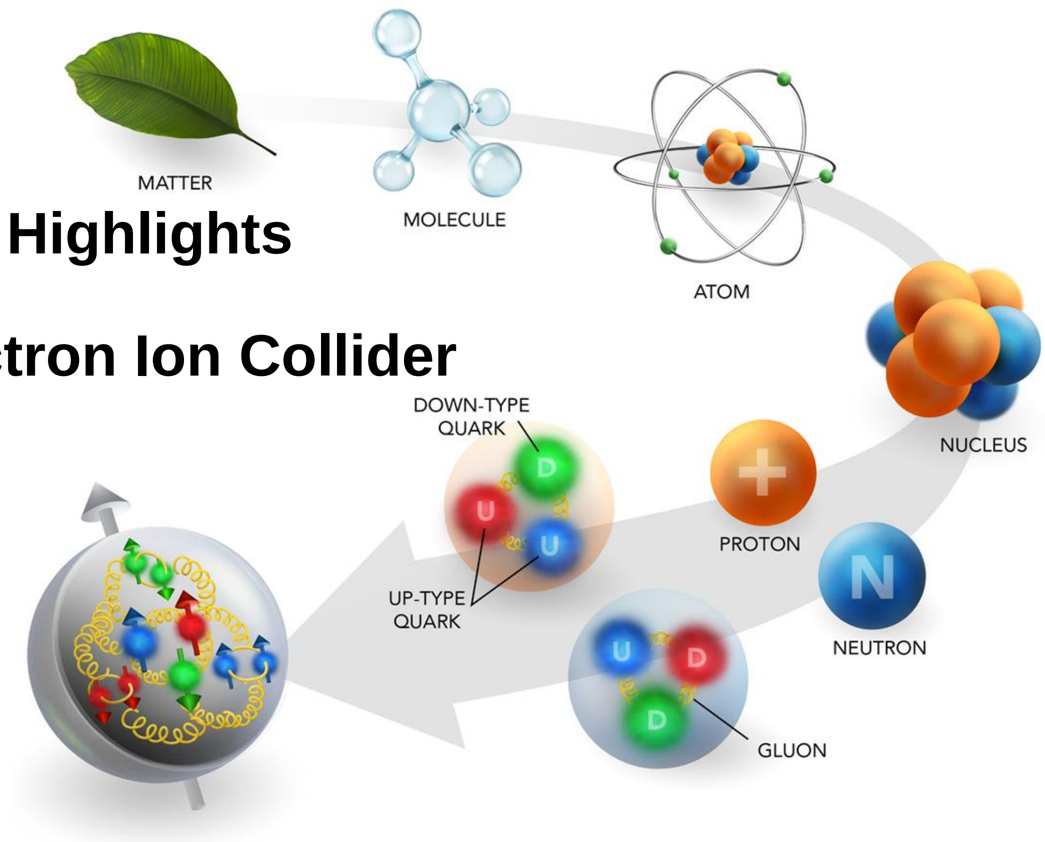
Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

OUTLINE

- **Jefferson Lab – Who are we & what do we do?**
- **Recent 12 GeV Upgrade**
- **Scientific Capabilities**
- **Quick Survey of Recent Highlights**
- **Look to the Future: Electron Ion Collider**
- **Summary**



Jefferson Lab

Jefferson Lab Overview

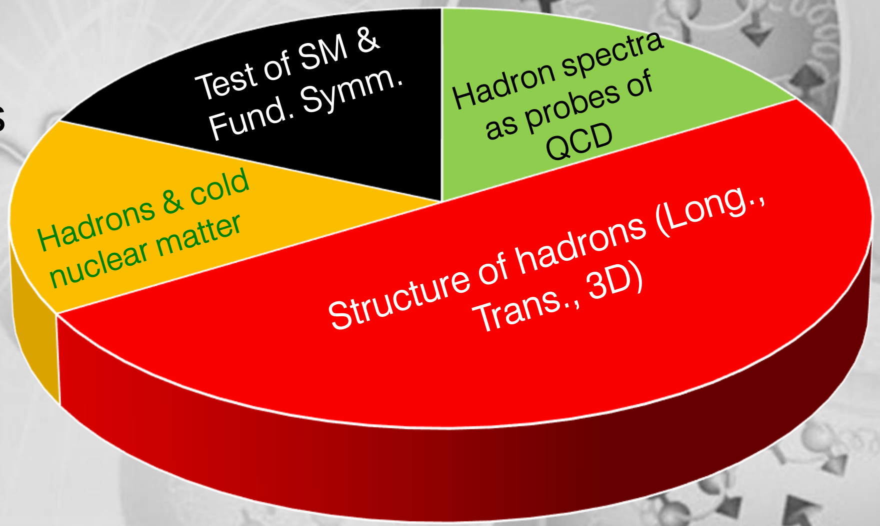
- Department of Energy, Office of Science Laboratory with a single program focused on Nuclear Physics.
- Mission is to gain a deeper understanding of the structure of matter:
  - Through advances in fundamental research in nuclear physics
  - Through advances in accelerator and nuclear science and technology
- Created to build and operate the Continuous Electron Beam Accelerator Facility (CEBAF), unique user facility for Nuclear Physics.
  - In operation since 1995
  - Major upgrade finished 2017

Jefferson Lab by the numbers:

- ~700 employees, 27 Joint faculty
- 1,630 Active Users
- Scientific users from 39 countries, 278 institutions (US: 124 institutions in 34 states)
- 630 PhDs granted to-date (212 in progress)
- K-12 programs serve more than 12,000 students and 950 teachers annually
- 169 acre site

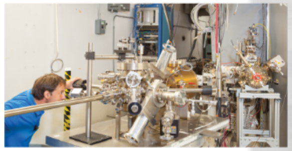
Jefferson Lab Mission

- **JLab's primary mission is to explore the fundamental nature of confined states of quarks and gluons**
  - How are quarks confined in nuclear matter?
  - What is the internal landscape of protons and neutrons?
  - How do the properties of protons and neutrons emerge from their constituent quarks and gluons?
  - How do the nuclear forces that lead to nuclei, arise from the basic interactions?



- Can we discover evidence for physics beyond the standard model ?

CEBAF at Jefferson Lab

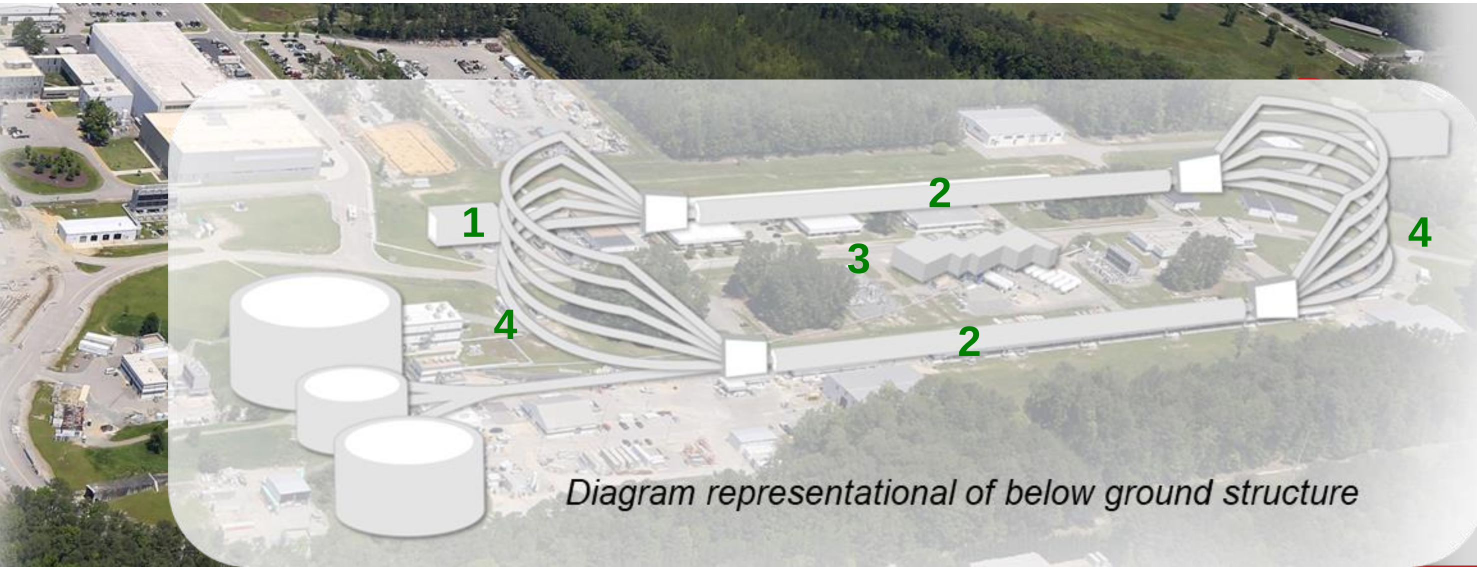


1 INJECTOR

The injector produces electron beams for experiments.

2 LINEAR ACCELERATOR

The straight portions of CEBAF, the linacs, each have 25 sections of accelerator called cryomodules. Electrons travel up to 5.5 passes through the linacs to reach 12 GeV.



3 CENTRAL HELIUM LIQUEFIER

The Central Helium Liquefier keeps the accelerator cavities at -456 degrees Fahrenheit.

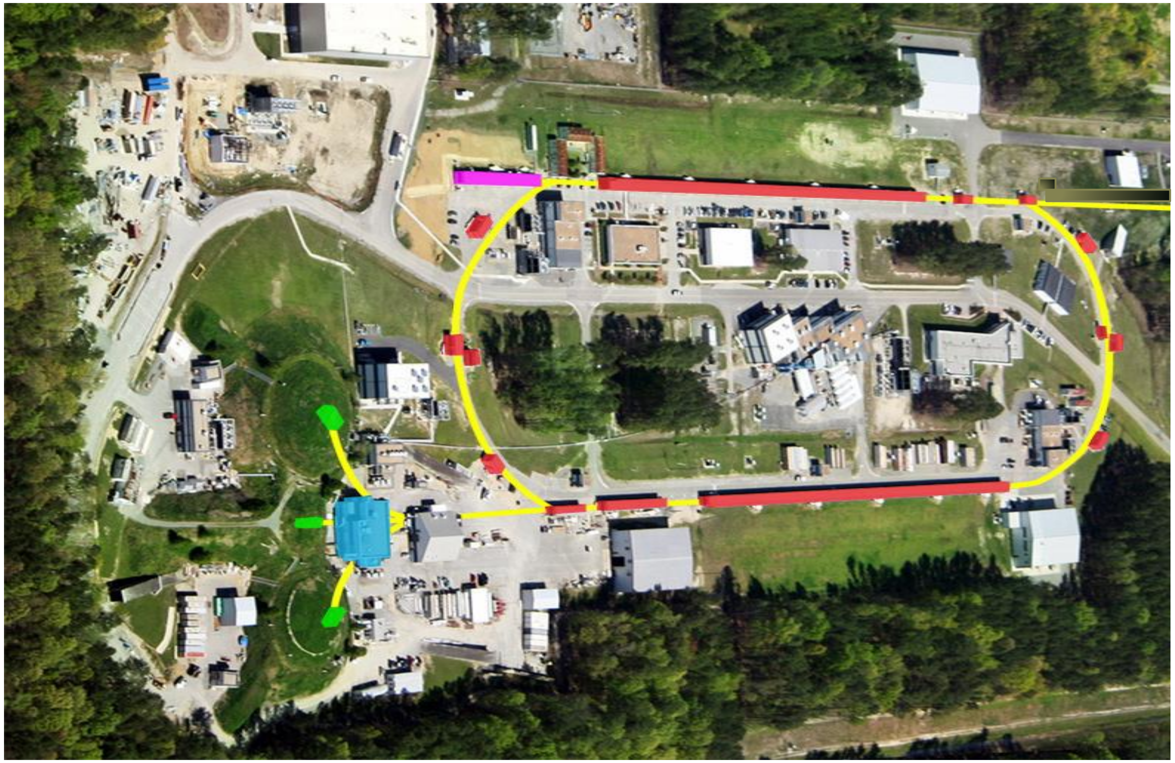
4 RECIRCULATION MAGNETS

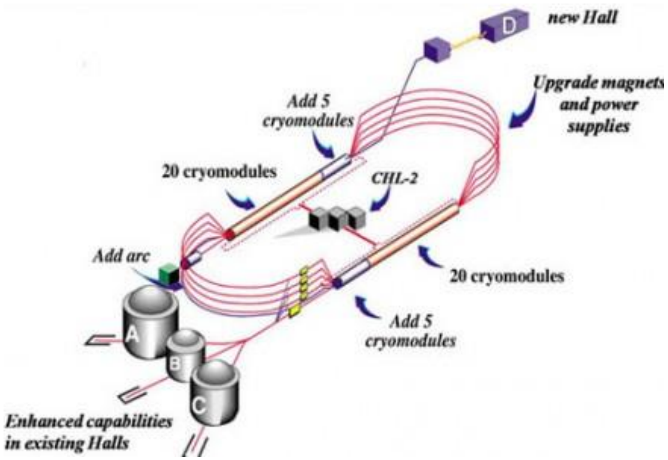
Quadrupole and dipole magnets in the tunnel focus and steer the beam as it passes through each arc.

CEBAF World-leading Capabilities

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/ s
- World-record polarized electron beams ~90%
- E_{max} = 12 GeV ; I_{max} = 90μA
- Highest intensity tagged photon beam at 9 GeV
- Unprecedented stability and control of beam properties ➔ Excellent for low energy SM tests
- **Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously**

12 GeV CEBAF Upgrade





- 12 GeV Upgrade Project Complete:
  - Total Project Cost of $338M
  - Double maximum accelerator energy to 12 GeV
  - Add 4th experimental Hall D
  - New experimental equipment in Halls B, C, D
- In full operation now with simultaneously beam deliver to all 4 experimental halls

Completed September 2017

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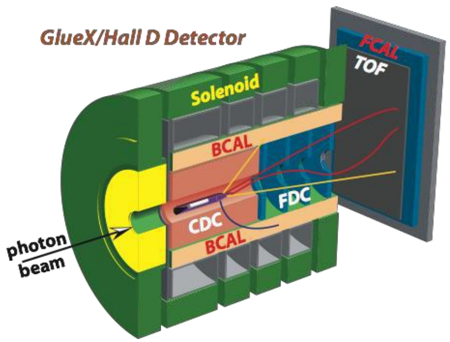
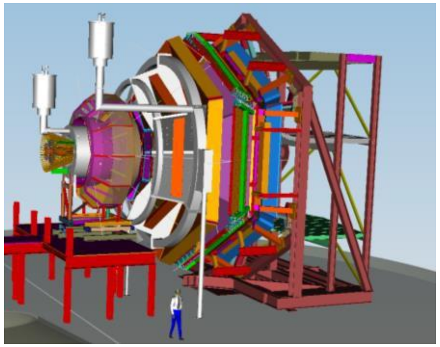
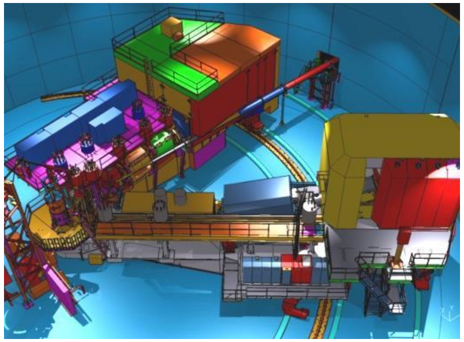
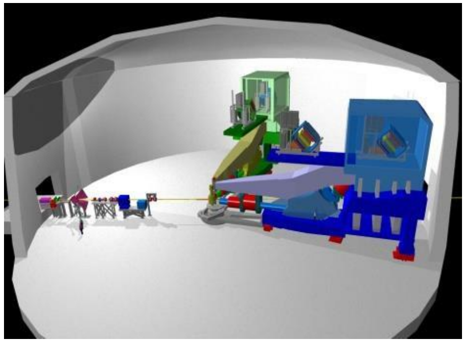
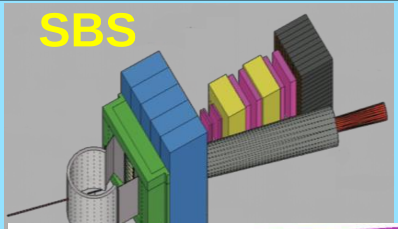
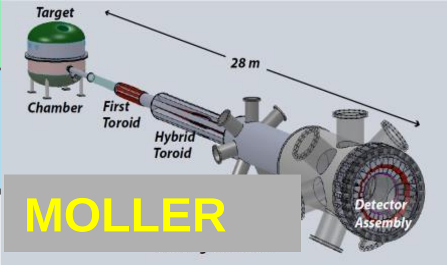
Detector Requirements: Complementarity



Hall D	Hall B	Hall C	Hall A
excellent hermeticity	luminosity 10^{35}	energy reach	
polarized photons	hermeticity	precision	
E_γ ~8.5-9 GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentu	
high multiplicity reconstruction		luminosity u	
particle ID			

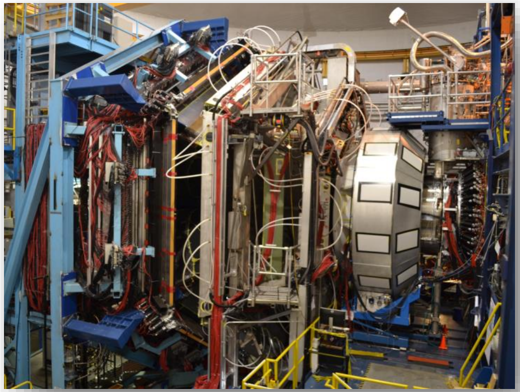




12 GeV Scientific Capabilities

Hall D

Exploring origin of quark **confinement** by studying **exotic mesons**

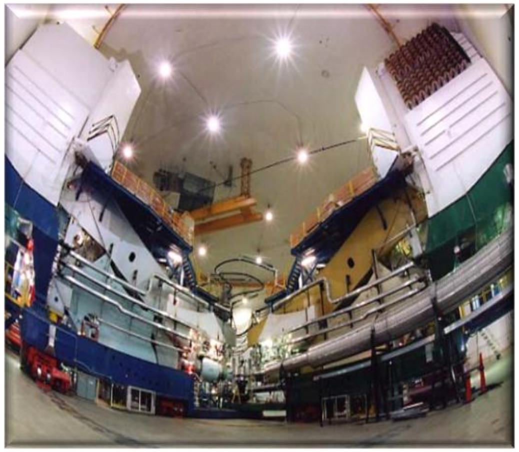


Hall B

Understanding **nucleon structure** via **generalized parton distributions** and **transverse momentum distributions**

Hall C

Precision determination of **valence quark** properties in nucleons and nuclei



Hall A

SRC, **form factors**, hyper-nuclear physics, **Physics BSM** (with **SoLID** & **MOLLER**)

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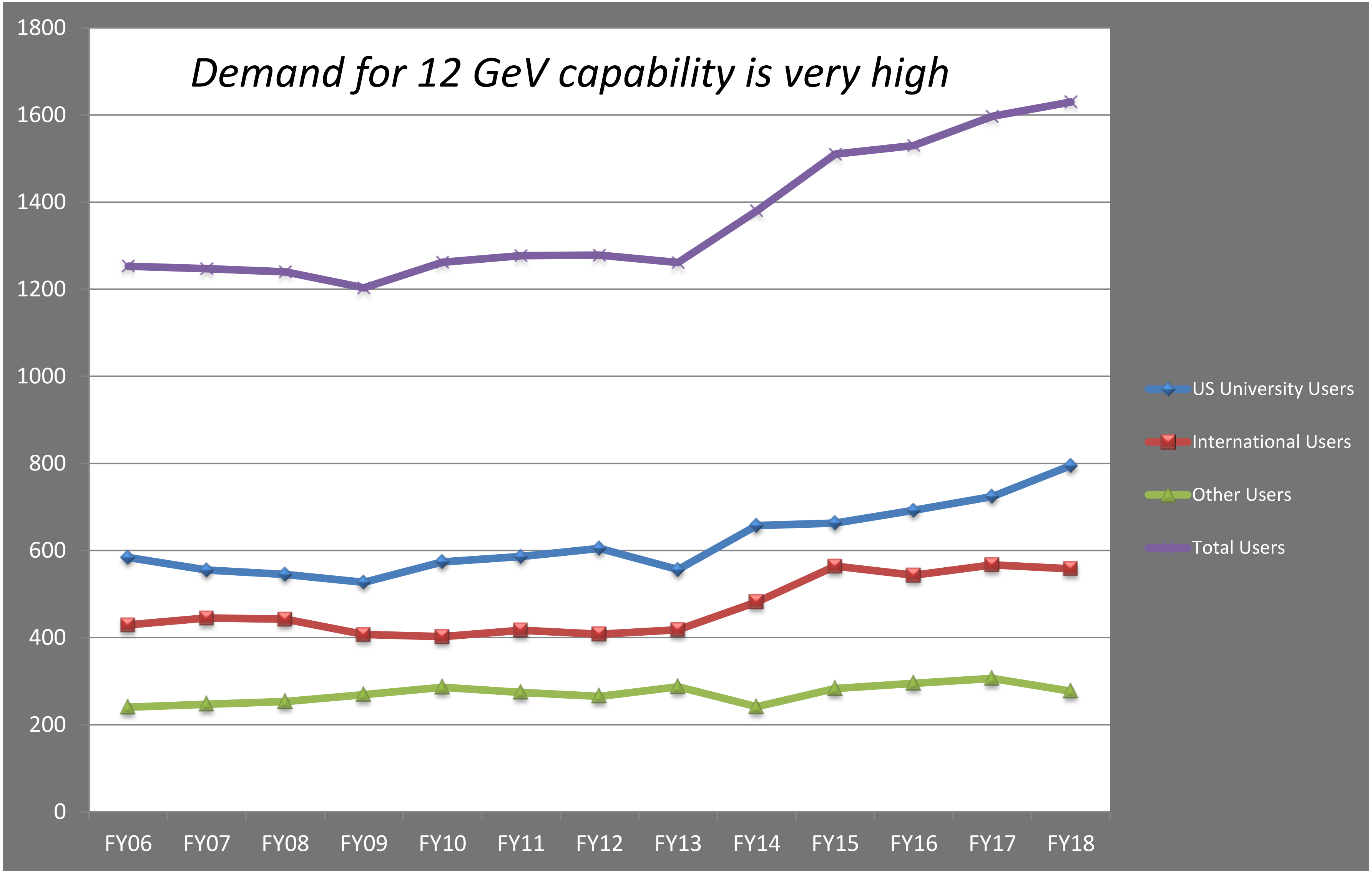
Approved Experiments by Science Topic

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
Hadron spectra as probes of QCD	0	2	1	3	0	**6**
Transverse structure of the hadrons	6	3	3	1	0	**13**
Longitudinal structure of the hadrons	2	3	7	0	0	**12**
3D structure of the hadrons	5	9	6	0	0	**20**
Hadrons and cold nuclear matter	8	5	7	0	1	**21**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	2	**7**
Total	**24**	**23**	**24**	**5**	**3**	**79**
Total Experiments Completed	**7.0**	**8.0**	**4.9**	**1.2**	**0**	**21.1**
Total Experiments Remaining	**17.0**	**15.0**	**19.1**	**3.8**	**3.0**	**57.9**

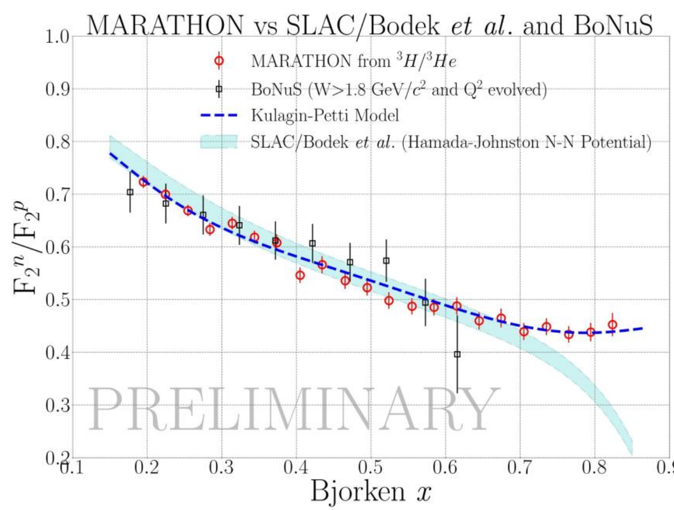
Program for ~7 to 10 years of exciting science

User community continues to grow (~1630 scientists)

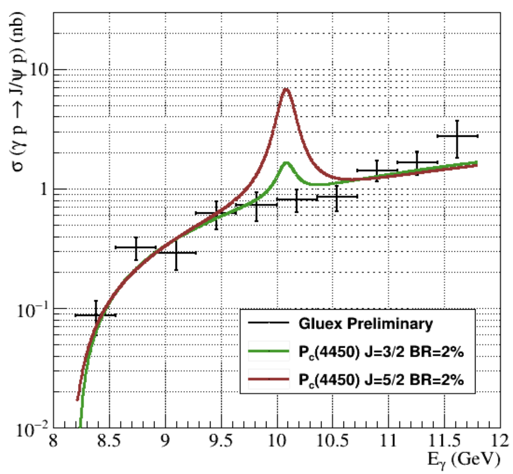


CEBAF 12 GeV Scientific Era is in Full Swing!

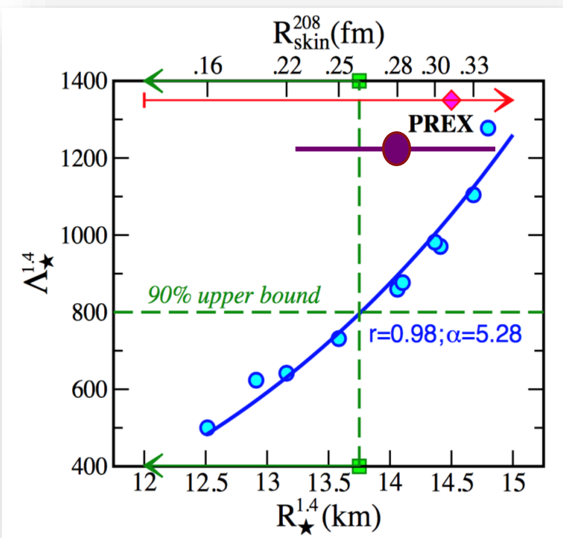
- **Mid-way through second full year of operation**
- **Completed several high-impact experiments; analysis in progress**
- **Delivered thesis data to nearly 50 graduate students**



Search for a pentaquark containing charm-type quarks



Measurement of Neutron skin constrains tidal polarizability of neutron stars



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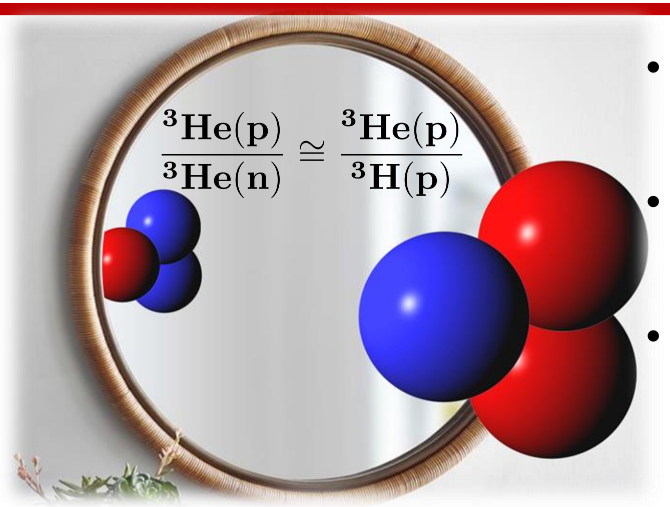
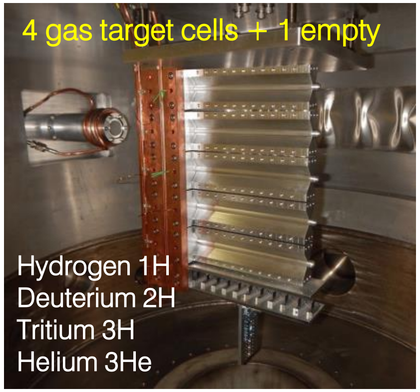
Hall A: Tritium Experiments

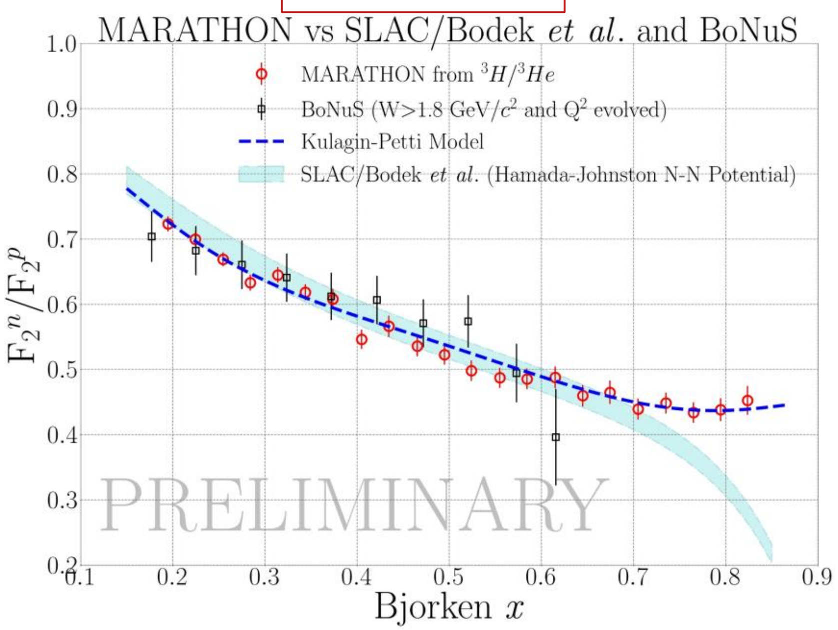
(see C. Keppel talk)



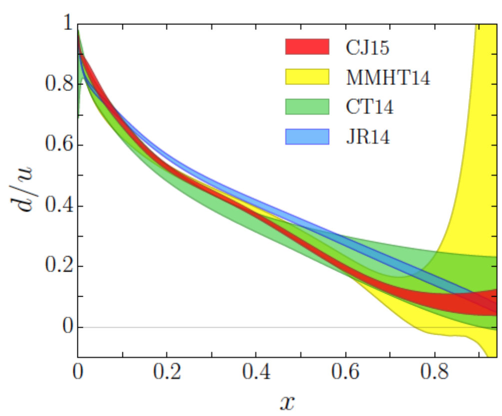
- Measurement of the F2n/F2p, d/u Ratios and A=3 EMC Effect in DIS
- Precision Measurement of the Isospin Dependence of two-nucleon SRC
- Determining the Unknown Λn Interaction by Investigating the Λnn Resonance



MARATHON



A. Accardi, et al. Phys. Rev. D 93 114017



- d/u at large x sensitive to valence quark dynamics
- High x determination of F^n_2/F^p_2 constrains d/u

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Hall A: MOLLER Project

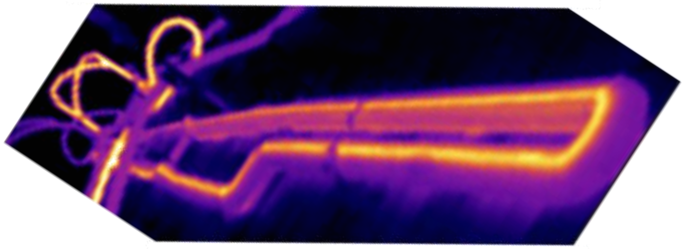
(see K. Kumar talk)

Fundamental Symmetries - Major Item of Equipment

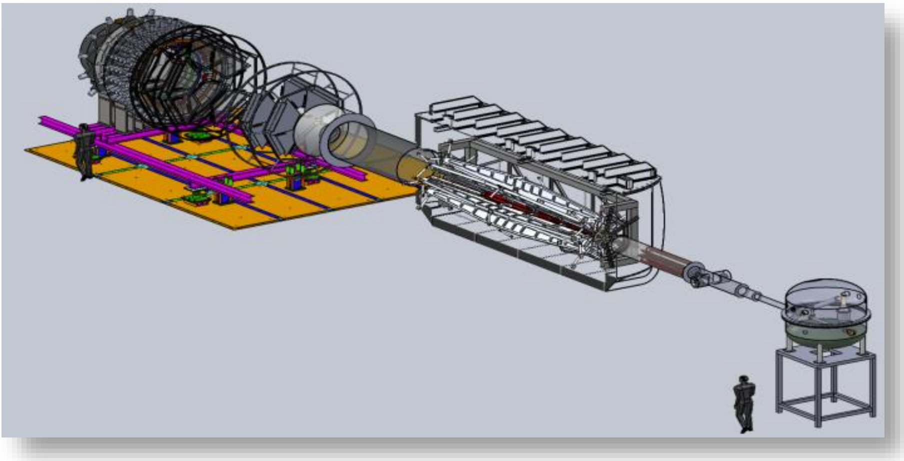
- Special opportunity with 12 GeV Upgrade to Search for New Flavor Diagonal Neutral Currents
- **Unique discovery space for new physics up to 38 TeV mass scale, with a purely leptonic probe**
- Most impact if run timely or in phase with initial HL-LHC runs that will add the complementary hadronic probe (FY25-28)
- **<u>Expecting FY20 Project Start</u>**

MOLLER main components:

- High-power target:
- High-Precision Polarimetry
- Moller-quality parity beam
- Spectrometer

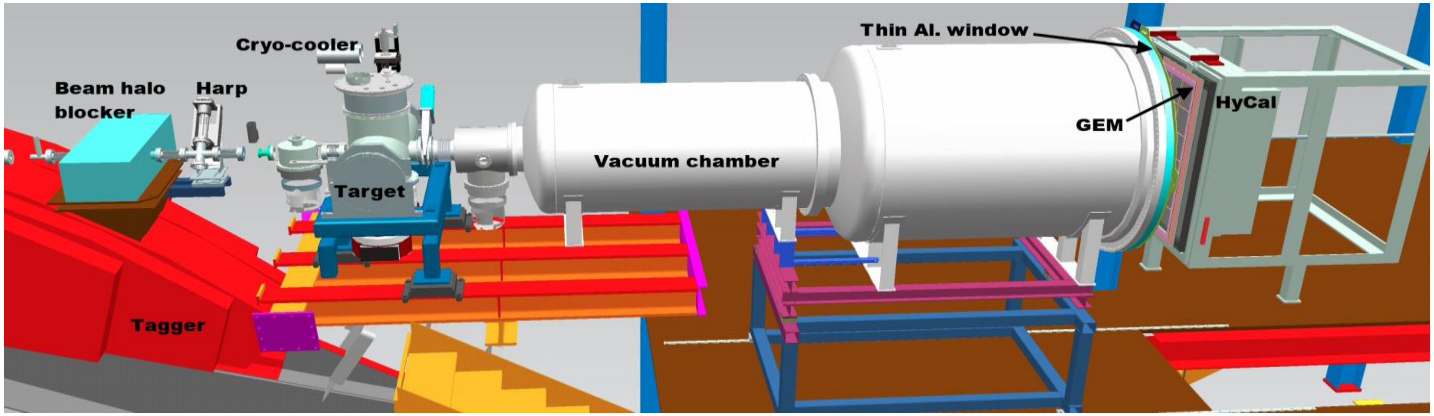


Prototype magnet coil test

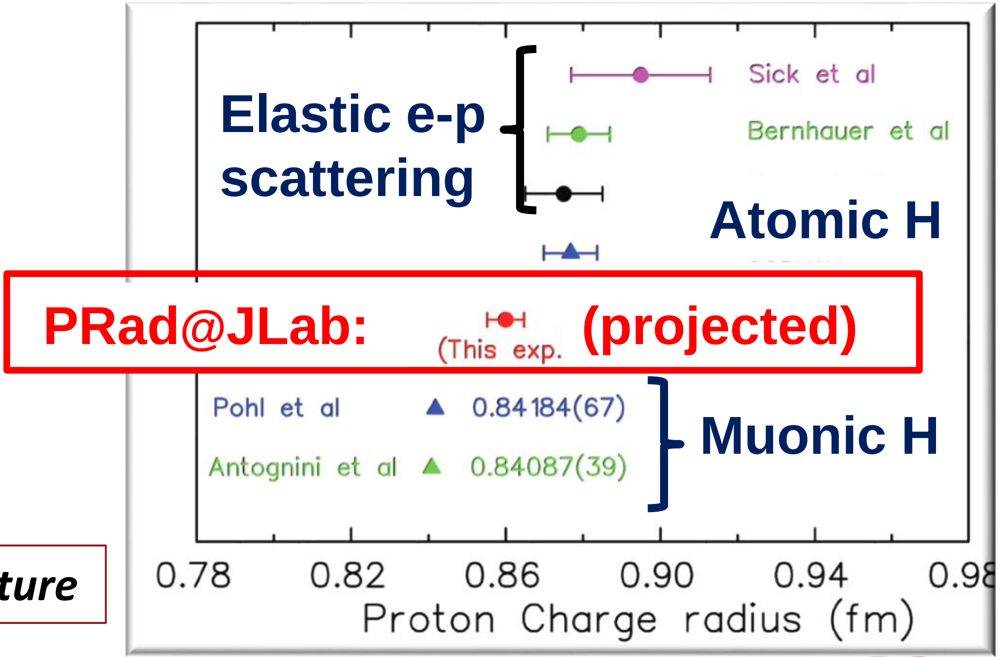


Hall B: PRad - Solving Proton Charge Radius Puzzle

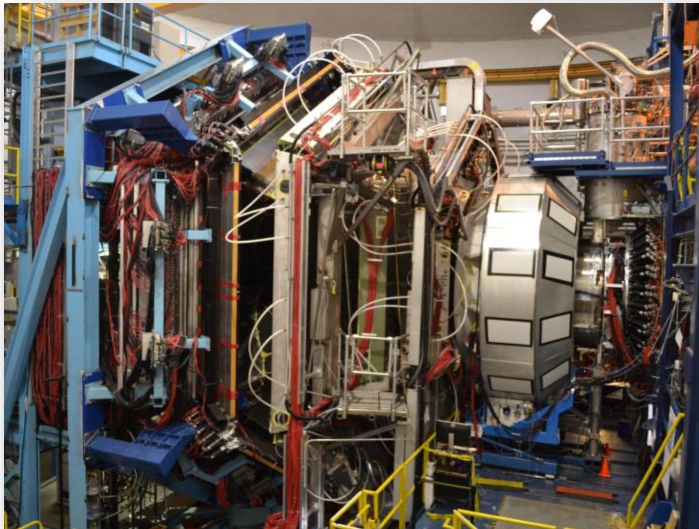
- e-p elastic cross section measured at very low Q^2 (10^{-4} to 10^{-2} GeV^2) by e.m. calorimetry only
- The e-p cross sections are normalized to the Møller cross sections measured simultaneously within the same detector acceptance → reach a sub-percent precision of r_p in an essentially model independent way.



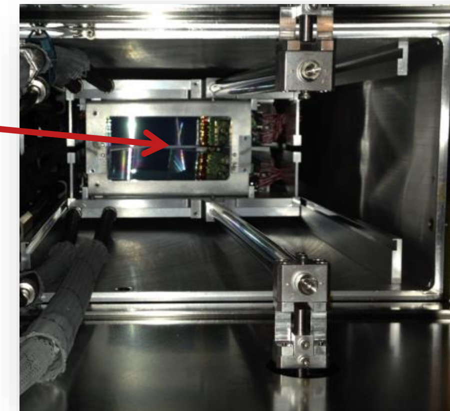
Results have been submitted to Nature



Hall B: Heavy Photon Search (HPS)



1 mm gap between Si tracker detectors for passage of electron beam



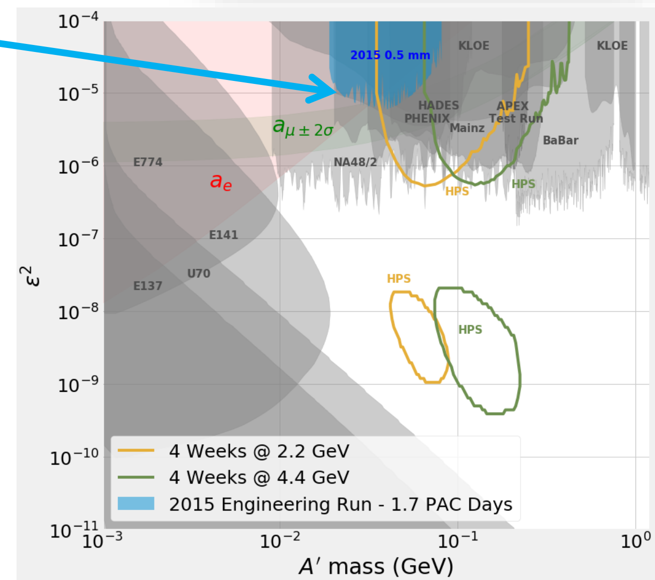
Hypothetical massive gauge boson A’ - force-mediator between the dark sector and the Standard Model - which couples to ordinary photons through a “kinetic mixing” mechanism.

2015 Run @ 1.05 GeV

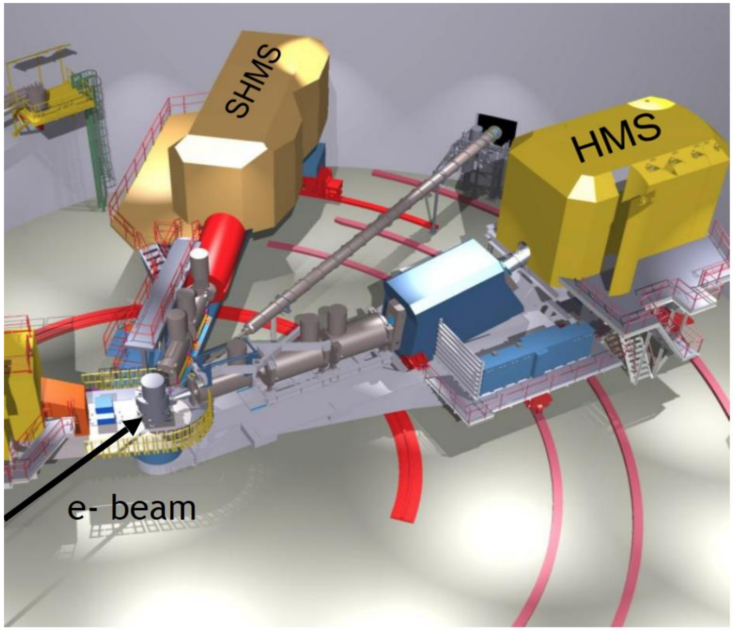
2016: 2 GeV data under analysis

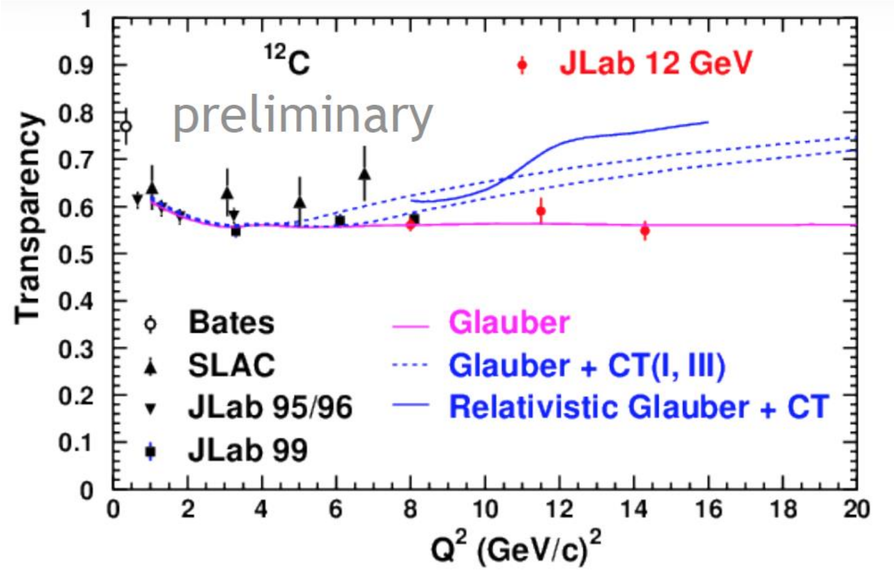
2019: Running now

- NP-HEP Collaboration
- Complementary run (APEX) in Hall A

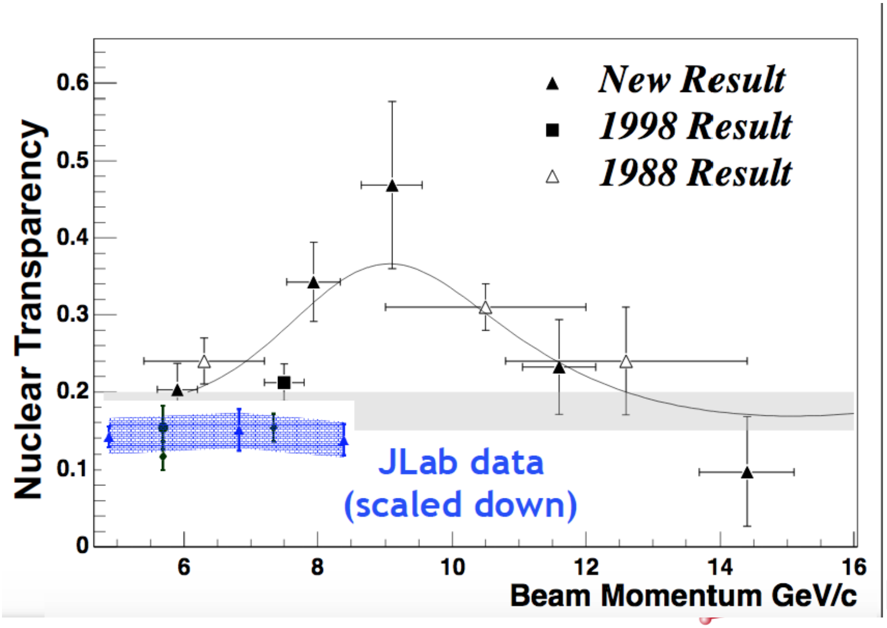


Hall C: Color Transparency



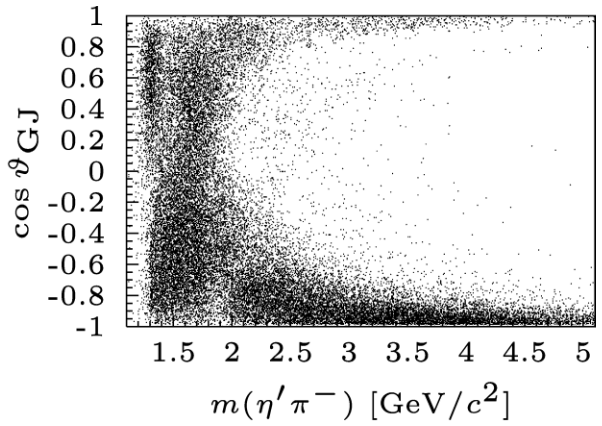


- Preliminary carbon transparency results do not show the onset of CT in protons
- BNL observations unlikely to be because of CT
- Places very stringent constraints on all existing CT models

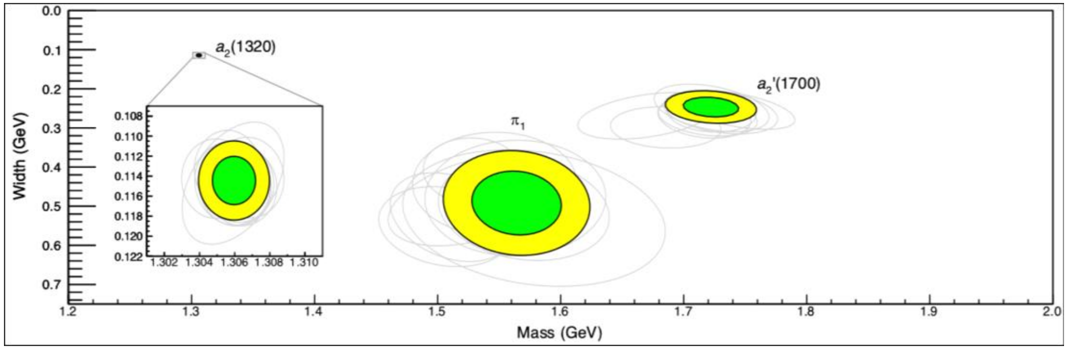


Lab

Hall D: Exotic Mesons on the Way



COMPASS: Phys. Lett. B 740, 303 (2015).

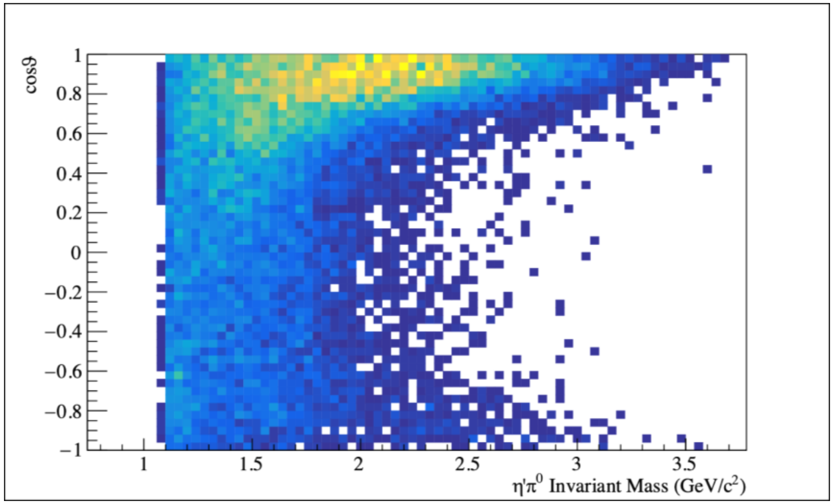


JPAC: Phys. Rev. Lett. 122, 042002 (2019).

- GlueX-I is complete
- 70% of data analyzed
- 3 papers in preparation
- Successful run of Primex-η
- Next is GlueX-II (with DIRC)

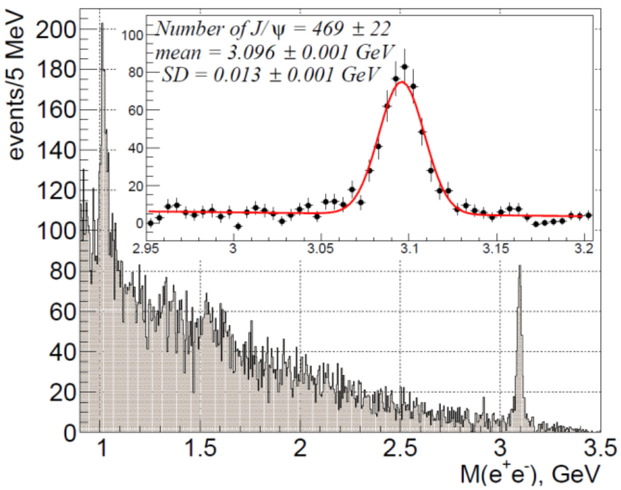
GlueX

$\gamma + p \rightarrow p\, \eta'\, \pi^0$

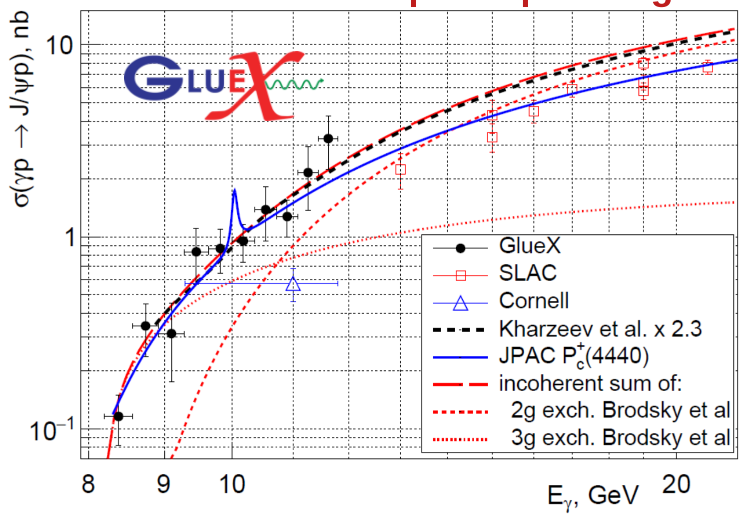


Hall C & D: Pentaquarks

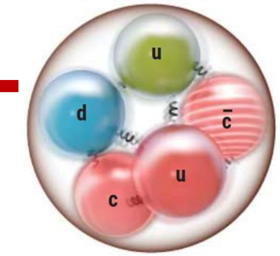
$$\gamma p \to P_c \to J/\psi p$$



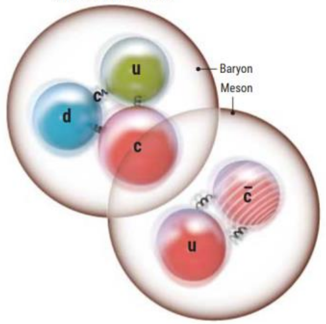
- No pentaquark signals

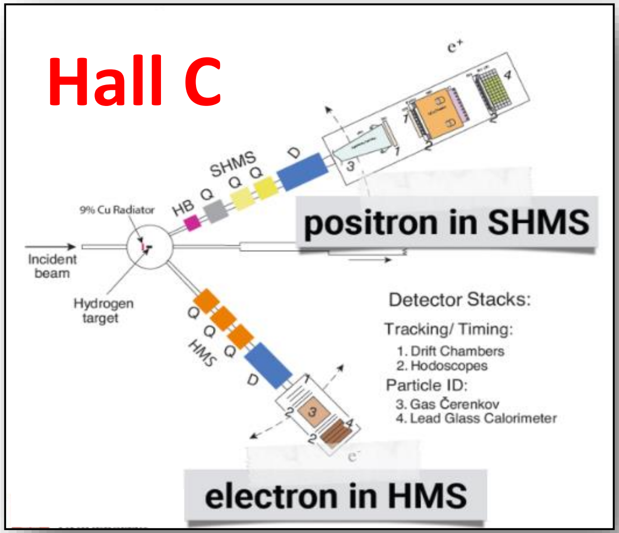


"Bag of quarks" pentaquark



"Molecule" pentaquark





- Largest data set of photoproduced J/ψ's (~2100)
Experiment completed - results soon
Absolute cross section ~5% precision

Science | AAAS

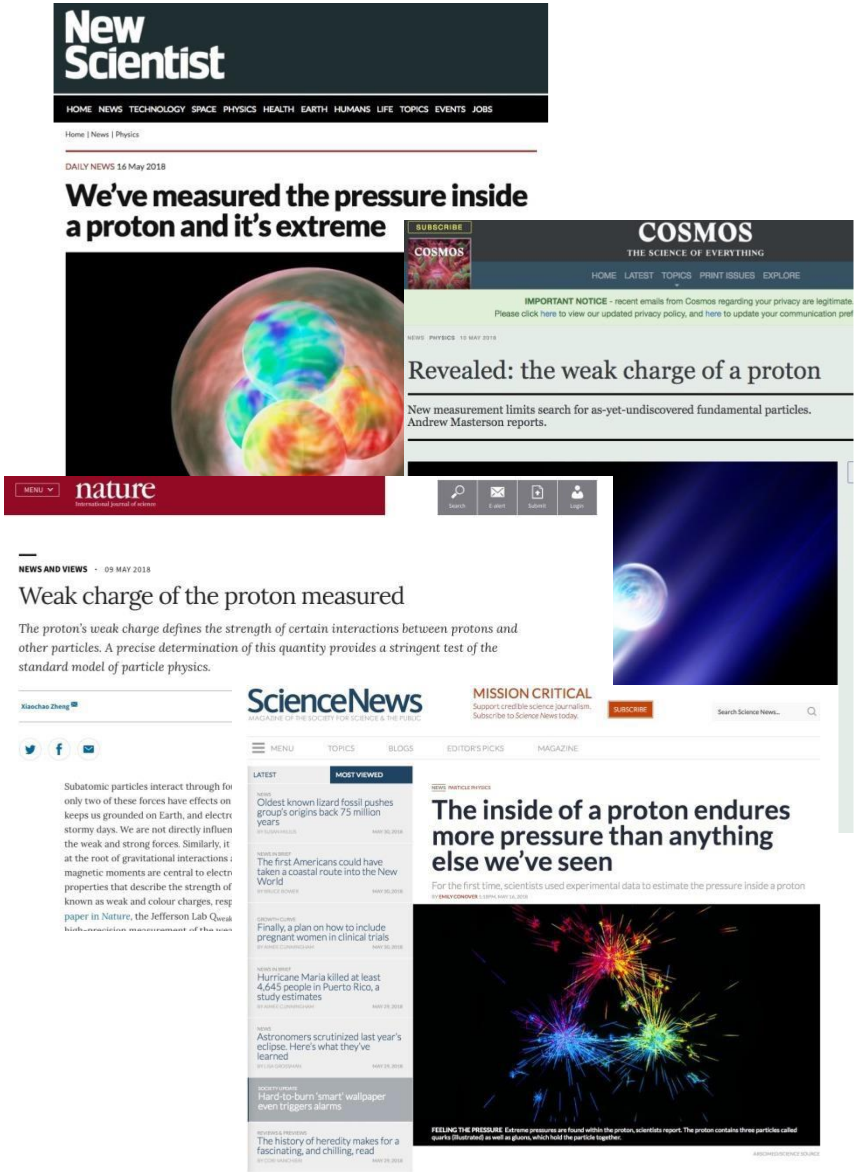
The Large Hadron Collider beauty experiment has discovered three new pentaquarks. PETER GINTER/CERN

Exotic particles called pentaquarks may be less weird than previously thought

Results Published in 2017/2018

nature
International weekly journal of science

- *Precision measurement of the weak charge of the proton*, Qweak collaboration, Published: Nature 557, 207–211 (2018)
- *The pressure distribution inside the proton,* Burkert, Elouadrhiri, Girod, Published: Nature 557 (2018) no.7705, 396-399
- *A per-cent-level determination of the nucleon axial coupling for quantum chromodynamics*, Berkowitz et. al., Published: Nature 558, 91-94 (2018)
- *Ultrafast Nucleons in Asymmetric Nuclei,* M. Duer et. al., CLAS Collaboration, Published: Nature 560 (2018) no.7720, 617-621
- *A glimpse of gluons through deeply virtual compton scattering on the proton*, Dufurne et. al., Published: Nature Communications 8, 1408 (2017)



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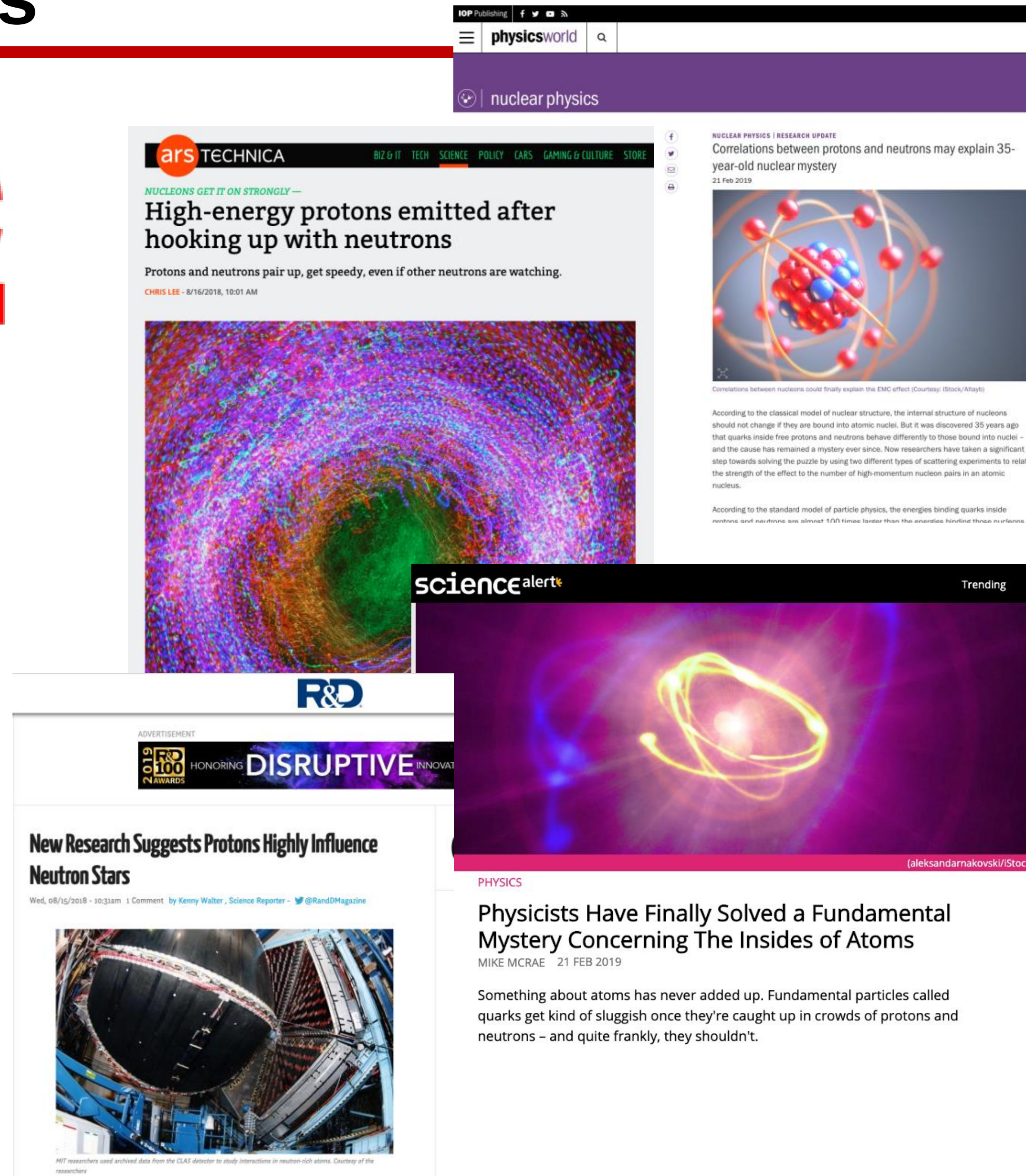
Recent Publications

nature
International weekly journal of science

- *Modified structure of protons and neutrons in correlated pairs*, The CLAS Collaboration, *Nature* **566**, 354–358 (2019).



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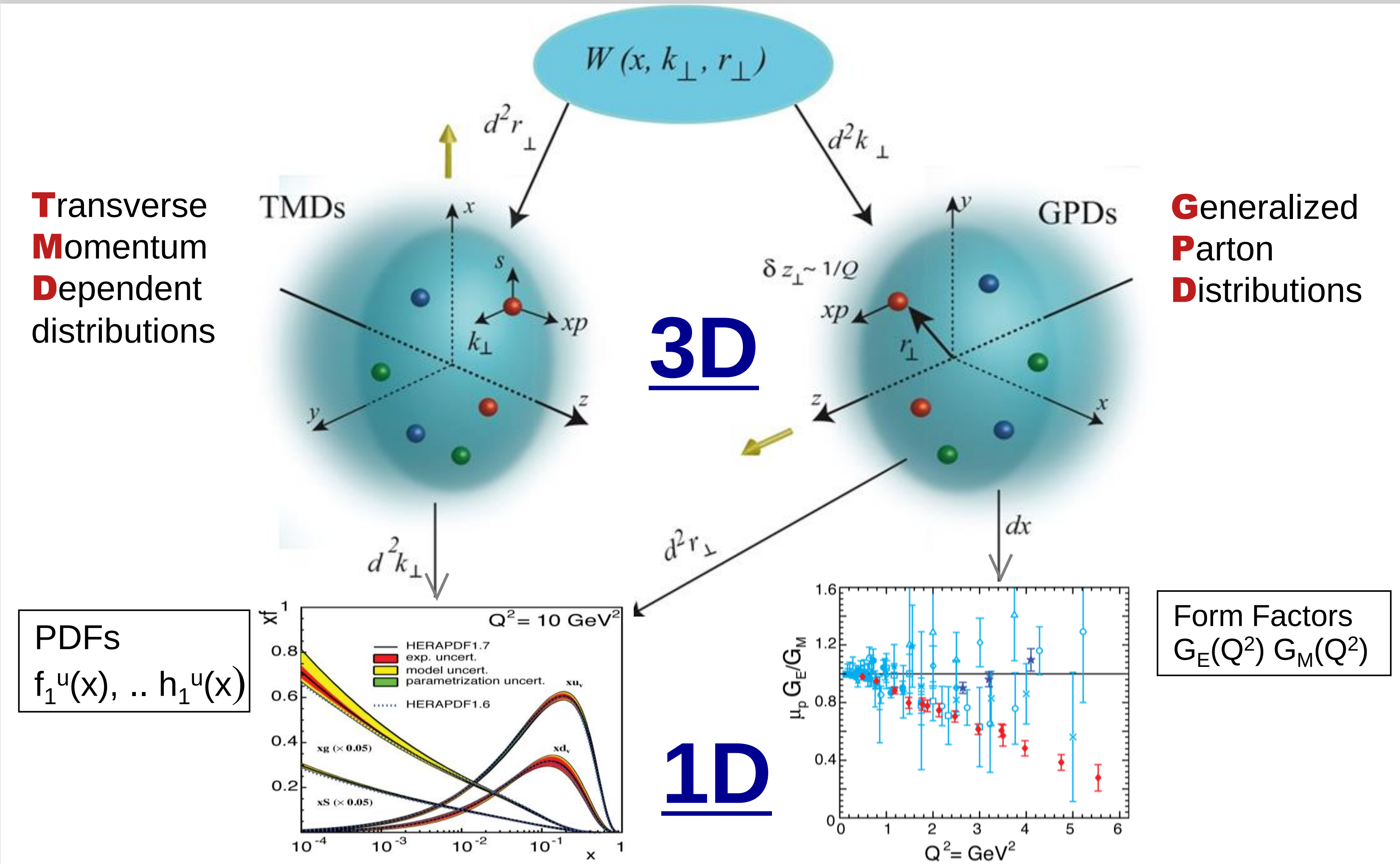
Unified View of Nucleon Structure



A NEW eye to study the nucleon: major capability with JLab @ 12 GeV

Nucleon femtography and comprehensive description of its internal dynamics.

Virginia Center for Nuclear Femtography

CENTER for
NUCLEAR FEMTOGRAPHY

- Funded by Commonwealth to "*…..to facilitate the application of modern developments in **data science** to the problem of imaging and visualization of sub-femtometer scale structure of protons, neutrons, and atomic nuclei*"
  - Seven (of fourteen) joint lab/university initiatives funded by the Commonwealth of Virginia
- Multi-disciplinary, bringing together *nuclear theorists and experimentalists, mathematicians, computer scientists,… … and architects and artists!*
- Workshop at University of Virginia

FEMTOGRAPHY 2018

Symposium on Imaging and Visualization in Science

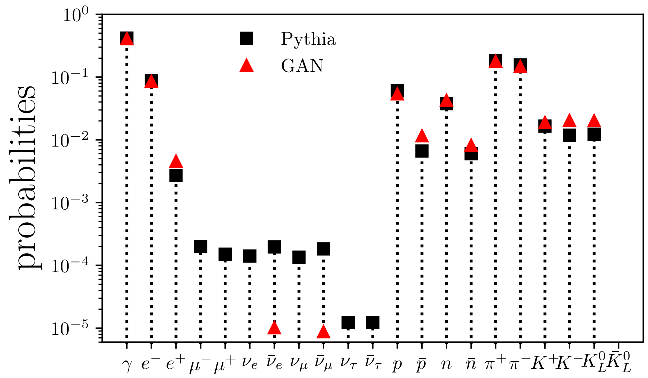
December 10-11, 2018, University of Virginia

The Symposium on Imaging and Visualization in Science will be held at the University of Virginia December 10-11, 2018. This symposium will bring together scholars and researchers from Virginia universities and research institutes to discuss recent developments and future opportunities in the imaging and visualization of scientific data.

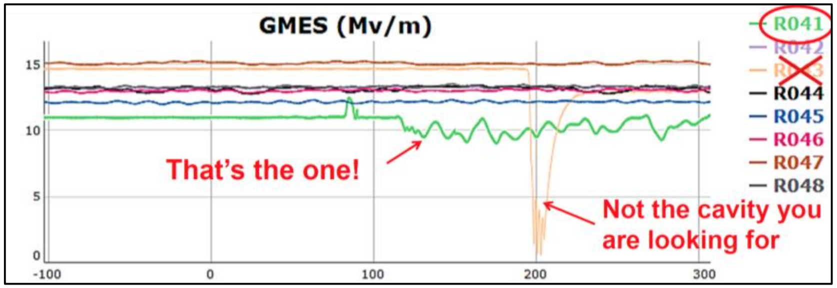
Machine Learning: Enabling Technology

Data Science is a component of all Advanced Computing Initiatives: recent progress

- Nuclear Femtography: Developing methods to derive physics observables from data samples
  - Initial tests using generated data as a control
- Accelerator: Use historical data from CEBAF to diagnose and improve operational performance
  - Significant progress applying machine learning to the problem of classifying C100 cavity faults



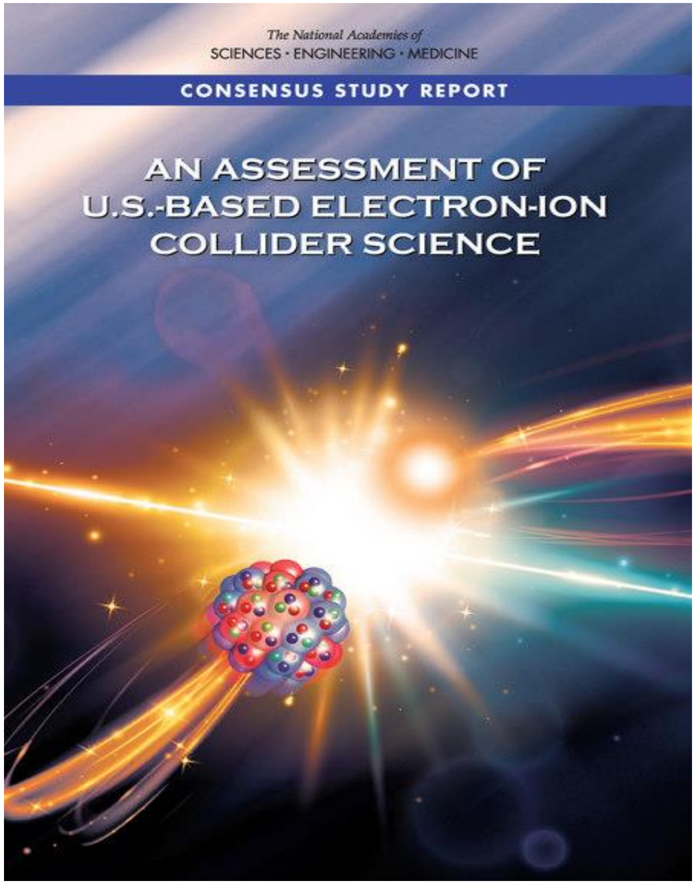
- Collaborations with universities and other labs
- Lunch and Learn Weekly Community of Practice
- Dedicated ML Developer hire in process
- Lab wide regular Machine Learning Challenge Contest
- Satellite Site for Pittsburgh Super Computing Center Big Data Training programs



Example of waveforms for several particular types of SRF cavity trips. There are 8 types of trips, and our ML already trained to recognize 4 of them with accuracy better than 86%

	Machine Learning			Deep Learning
Problem	Which Cavity?	Which Fault?		Which fault
Feature engineering	tsfresh	tsfresh	auto-regression	none
Model	Random Forest	Decision Tree	Random Forest	RNN-LSTM
Result	95.70%	96.60%	88%	86%

Future: Compelling Physics Questions for an EIC



An EIC is needed to address the picture of nucleons and nuclei as complex interacting many-body systems, and in particular to address three immediate and profound questions about neutrons and protons and how they are assembled to form the nuclei of atoms.

How does the mass of the nucleon arise?

In other words, how do the constituents of the nucleon, the valence quarks, the sea quarks, and the gluons, and importantly their interactions, lead to a mass some 100 times larger than the sum of the three constituent quarks alone?

How does the spin of the nucleon arise?

While nucleons are made of three quarks, each with spin ½ the spins of these quarks constitute only a small fraction of the nucleon's spin, the rest seemingly carried by the gluon spins, the sea quarks, and the orbital motion of the quarks.

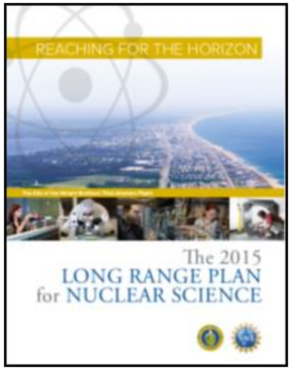
What are the emergent properties of dense systems of gluons?

Two questions concerning the gluons arise when nucleons are combined into nuclei: How is the gluon field modified in a nucleus to accommodate the binding of nucleons? And does a novel regime of nuclear physics emerge in the high-energy limit, a regime in which the complicated structure of the nucleus is radically simplified, leading to a state in which the whole nucleus becomes a dense gluon system?

Jefferson Lab

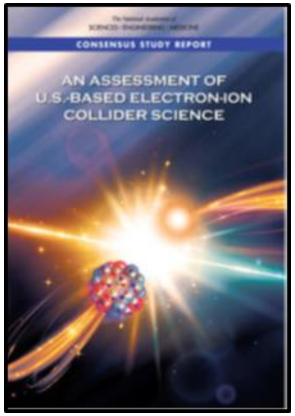
Electron-Ion Collider Planning

(see A. Deshpande talk)



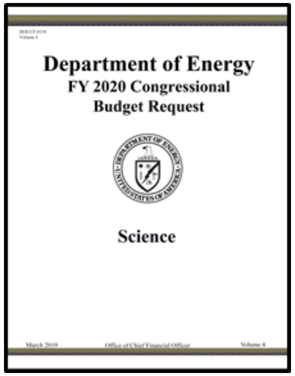
Federal Nuclear Science Advisory Cmte 2015 Long Range Plan

"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."



National Academy of Sciences – Assessment of U.S. Based Electron-Ion Collider Science (2018)

"…the committee finds a compelling scientific case for such a facility. The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

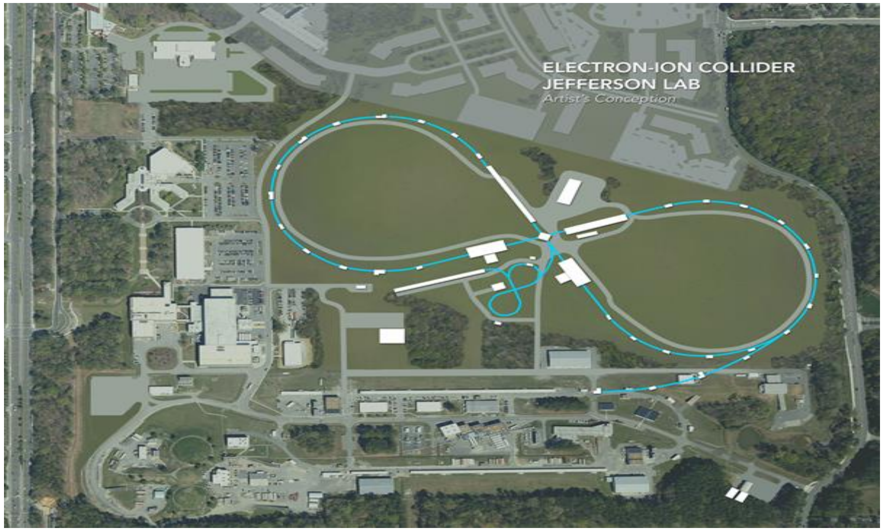


President's FY 2020 Budget Request to Congress (2019)

"Critical Decision-0, Approve Mission Need, is planned for FY 2019"

"The FY2020 Request will provide for the first year of Other Project Costs for the Electron Ion Collider, aimed at research to reduce technical risk and the development of a conceptual design."

Jefferson Lab Electron Ion Collider: Proposal



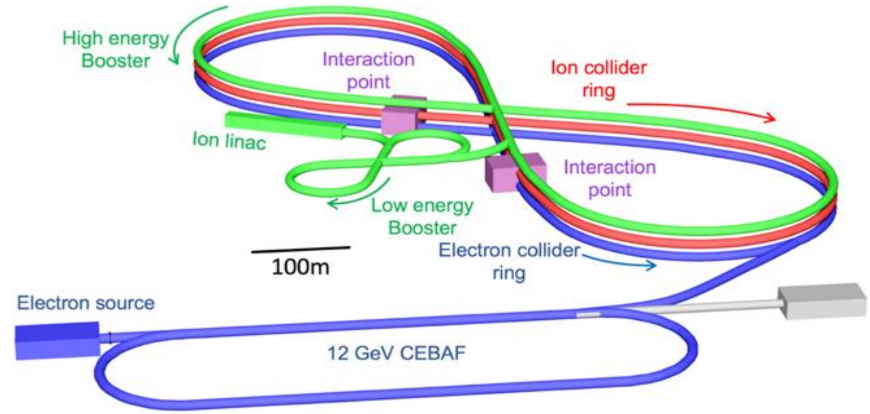


Figure 8 Concept

- High Luminosity of 10^{34} /cm^2/sec well-matched to requirements
- High Polarization (including deuterons)
- Energy Range: $\sqrt{s}$: 20 to 100 GeV upgradable to 140 GeV

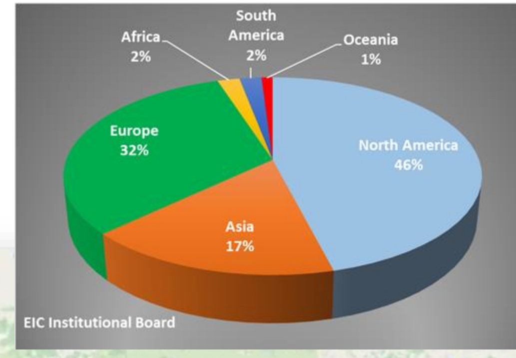
JLEIC

EIC^2 EIC Center at Jefferson Lab

https://www.eiccenter.org/

EIC Users Group and International Interest

- Formed in 2016; currently:
  - 864 members
  - 184 institutions
  - 30 countries



Jefferson Lab

SUMMARY

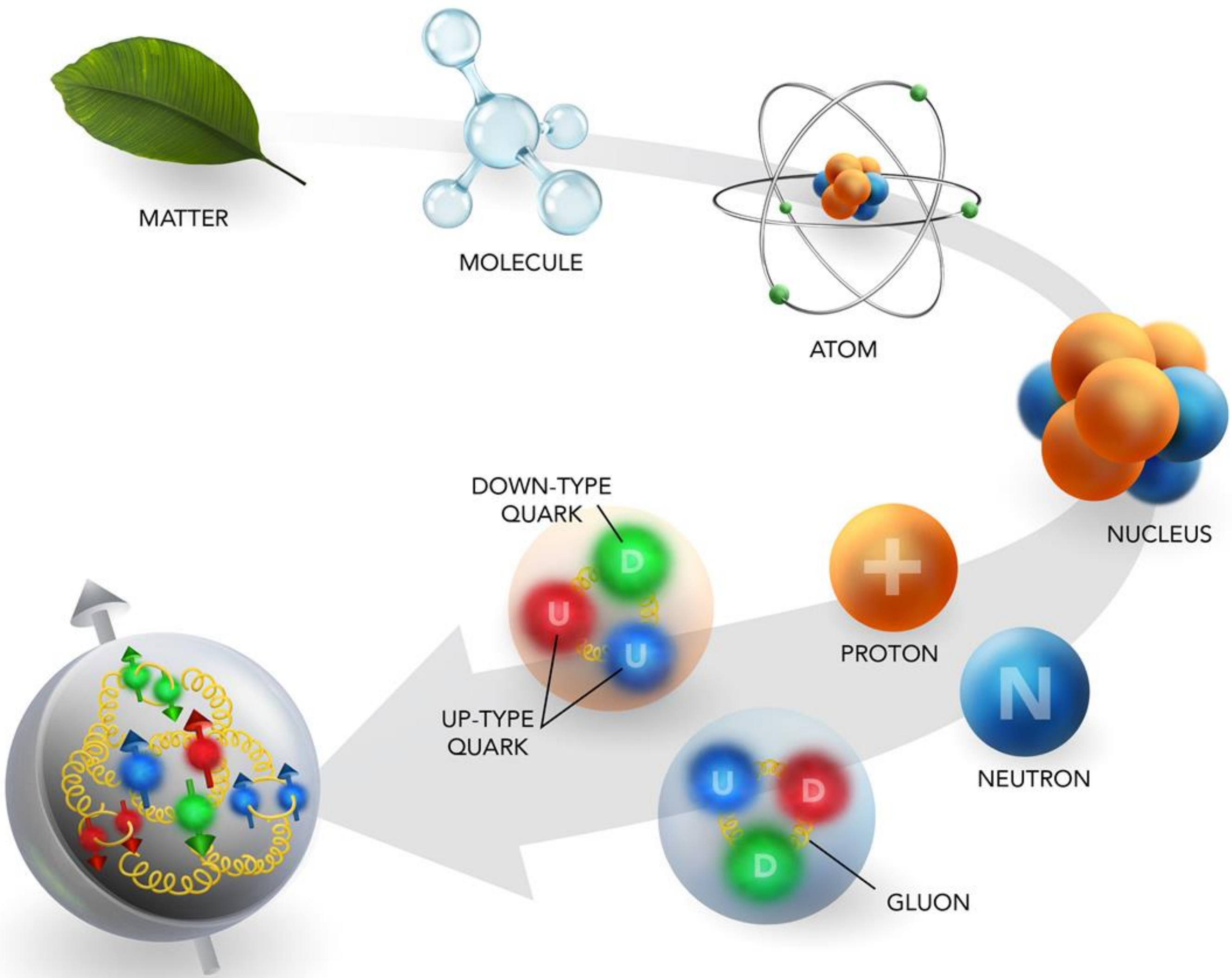
- **12 GeV Scientific era is in full-swing!**
  - Completed several high impact, high profile experimental programs including tritium program and Glue-X phase 1
  - Anticipating additional significant results from first set of 12 GeV experiments (~21 experiments complete)

- **Mid-way through second full year of CEBAF 12 GeV Operations**
  - Schedule delivers more than 30 weeks operations in FY19
  - Exciting program for next 7-10 years

- **Pushing on new frontiers for nuclear physics and tackling some 'old' frontiers with new techniques**

- **EIC Planning is moving forward jointly with BNL and Jefferson Lab**
  - Great opportunity for international collaboration

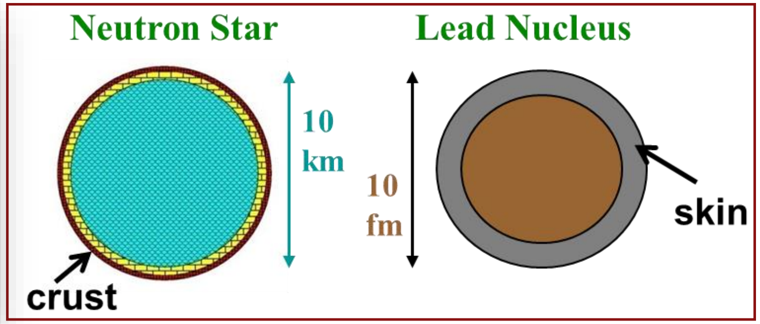
Thank you for the invitation to participate in ICNFP!



Thanks to many staff/collaborators for their contributions!

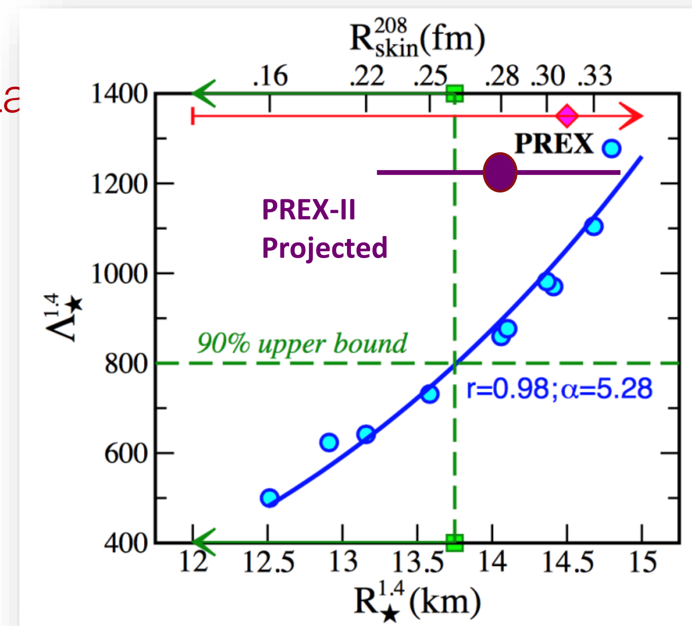
BACK-UP

The Neutron "Skin" in the ^{208}Pb Nucleus



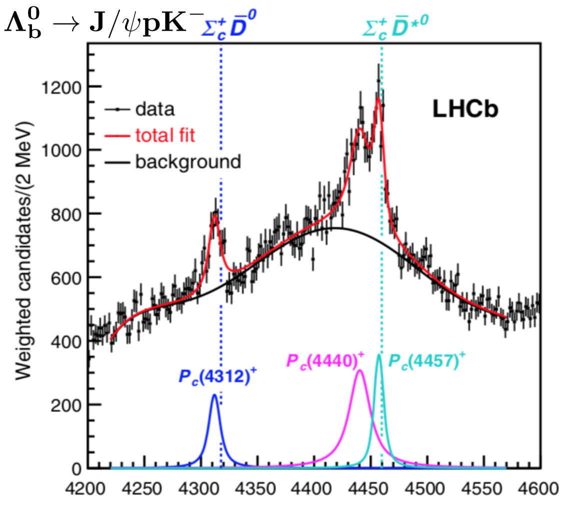
- Neutron star properties and neutron skins are both determined by the EOS of neutron-rich matter

- Measurement of neutron skin at JLa constrains tidal polarizability of neutron stars



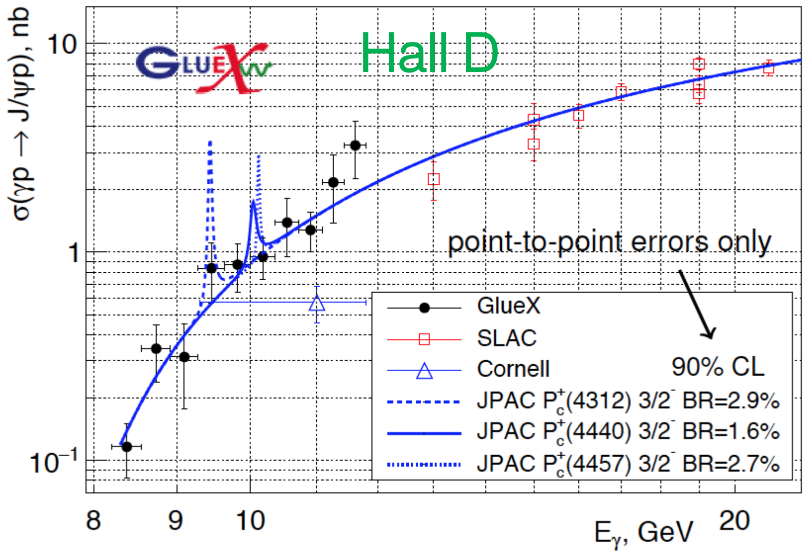
PRL120, 172702 (2018)

J/ψ & Charmonium Pentaquark



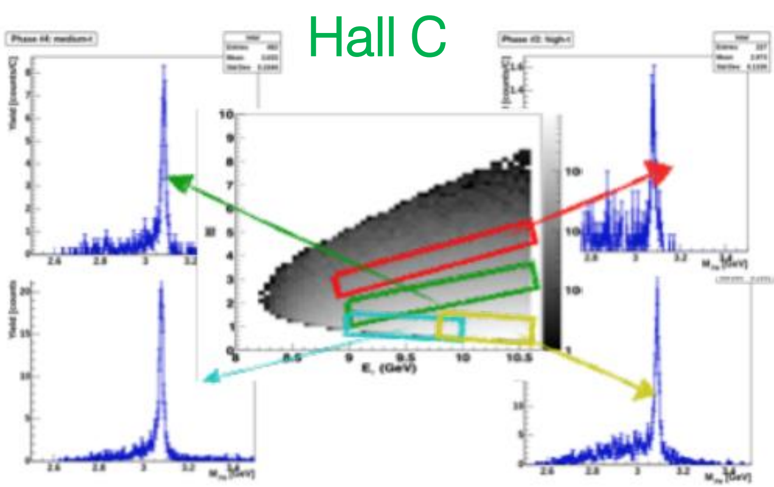
PRL 122, 222001 (2019).

- More experimental and theoretical scrutiny required



- No pentaquark signals
- Evaluation of
  BR ($P^+_c \to J/\psi\ p$)
  JPAC model PRD 94, 034002 for J = 3/2
  Limits at 90% CL

See J. Stevens' talk



- Largest data set of photoproduced J/ψ's (∼2100)
  Experiment completed - results soon
  Absolute cross section ∼5% precision

- Hall B J/ψ pentaquark taking data