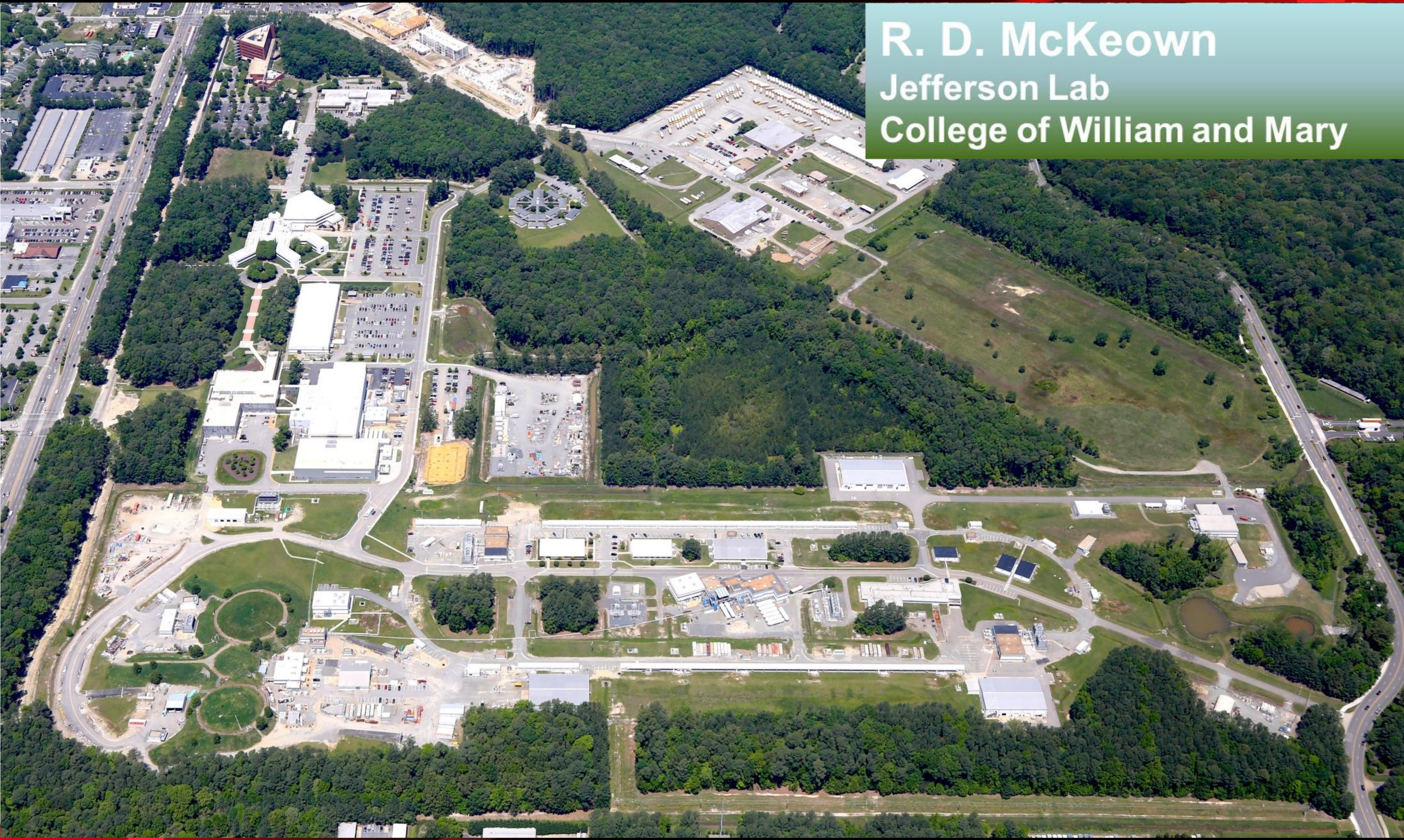
A New Era of Science at Jefferson Lab



R. D. McKeown
Jefferson Lab
College of William and Mary

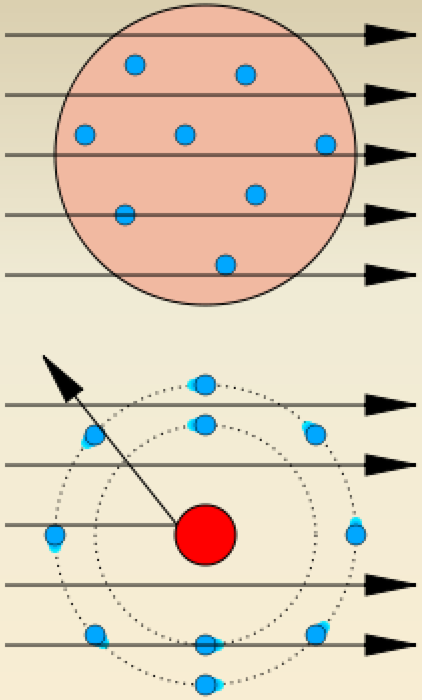
Columbia Univ.
September 11, 2017

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Outline

- Historical Introduction
- JLab Science Program at 12 GeV
- Future Electron Ion Collider
- Conclusion and Outlook

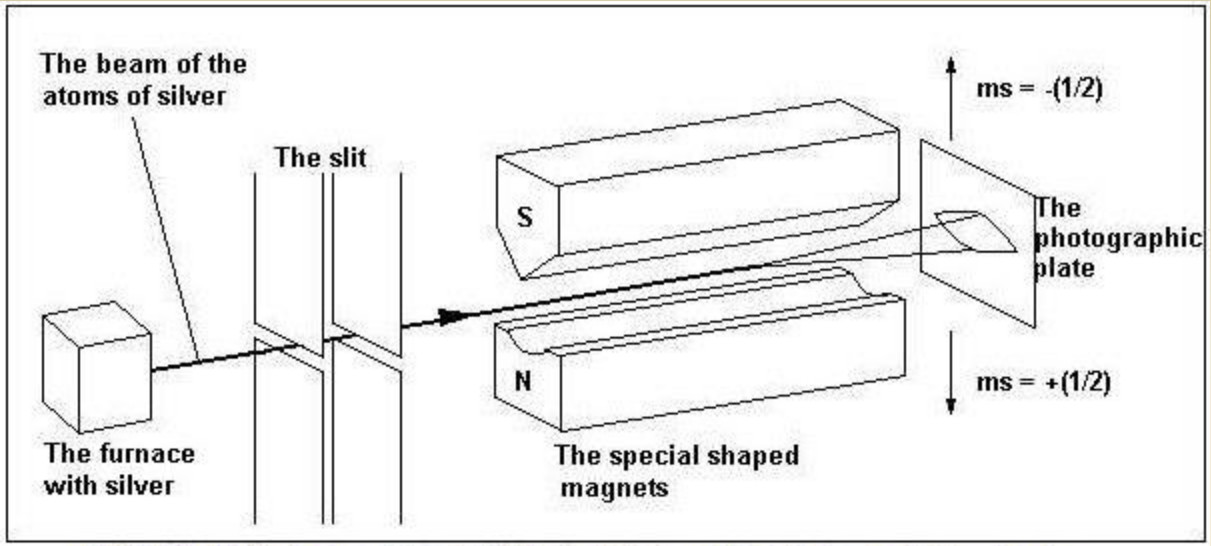
1911 – Rutherford Atom



$$\frac{d\sigma}{d\Omega} = \left(\frac{\alpha\hbar c}{2mv_0^2}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

- Revolutionized our view of the atom
- The power of charged particle scattering

1920's – Otto Stern

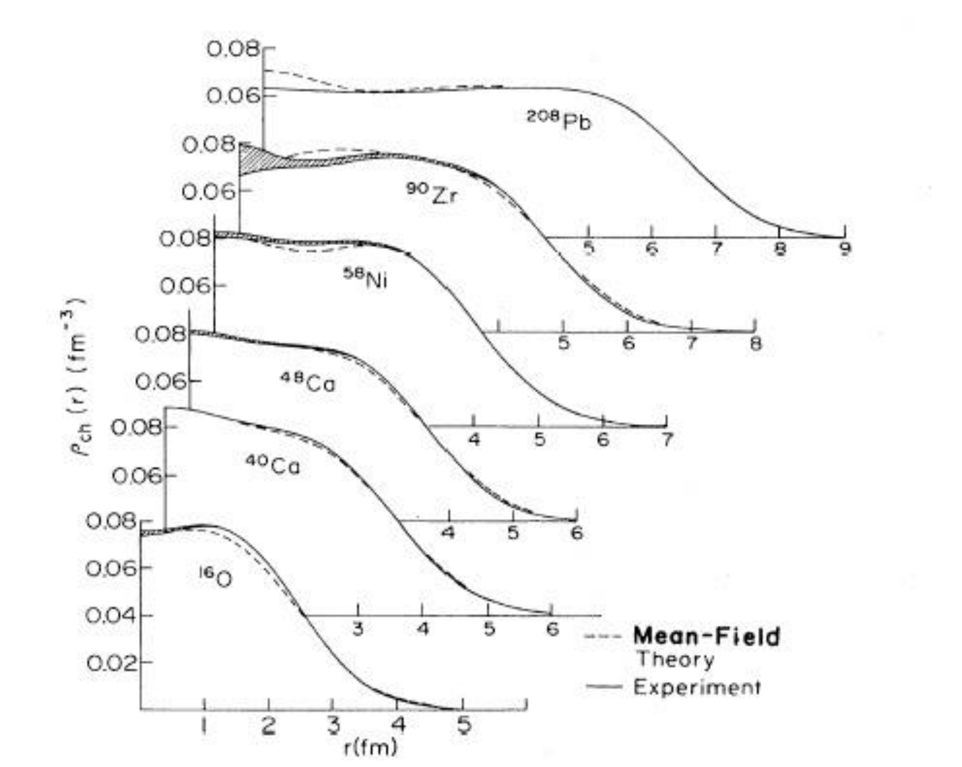


The Stern-Gerlach experiment. On the photographic plate are two clear tracks.

"for his contribution to the development of the molecular ray method and his discovery of the magnetic moment of the proton".

→ proton is not a point particle

1950's – Robert Hofstadter



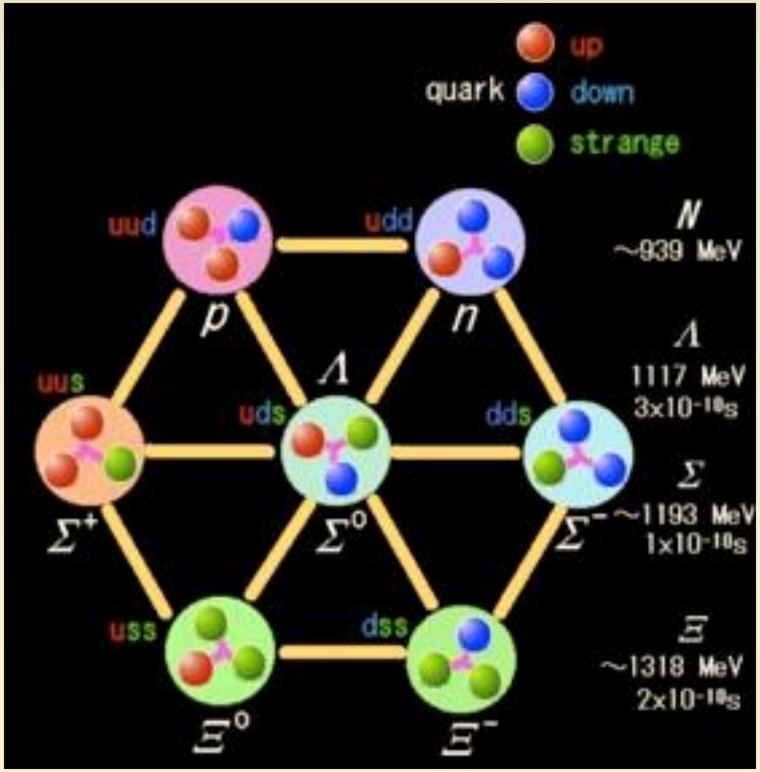
"for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

$$\frac{d\sigma}{d\Omega} = \sigma_{\text{point}} |\rho(q)|^2$$

$$\rho(q) = \frac{4\pi}{q} \int_0^\infty \rho(r) \sin(qr) r dr$$

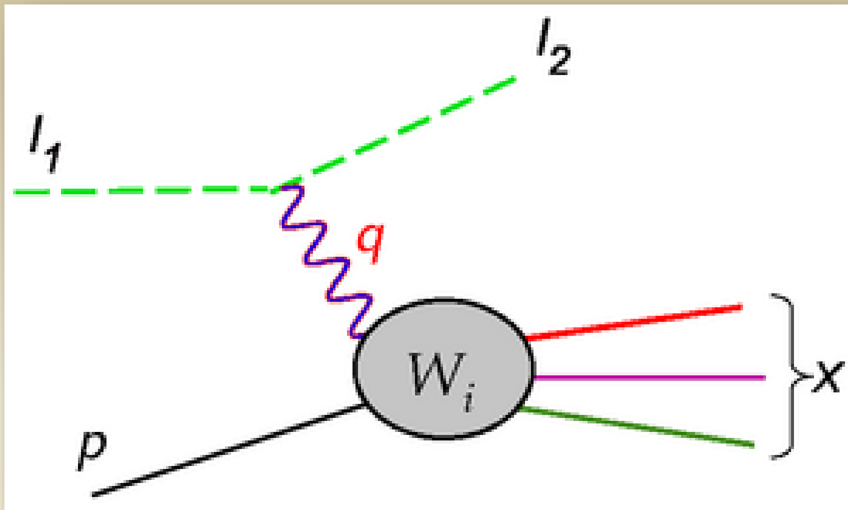
The Quark Model – M. Gell-Mann

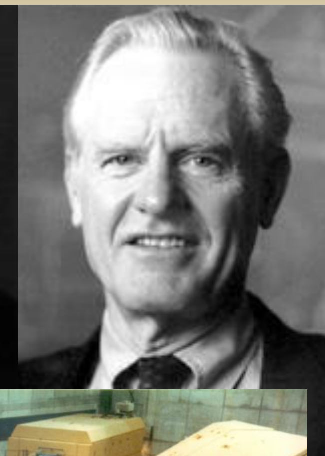
- Finite size of nucleon
- Patterns of known baryons and mesons



"for his contributions and discoveries concerning the classification of elementary particles and their interactions"

1960’s - Discovery of Quarks

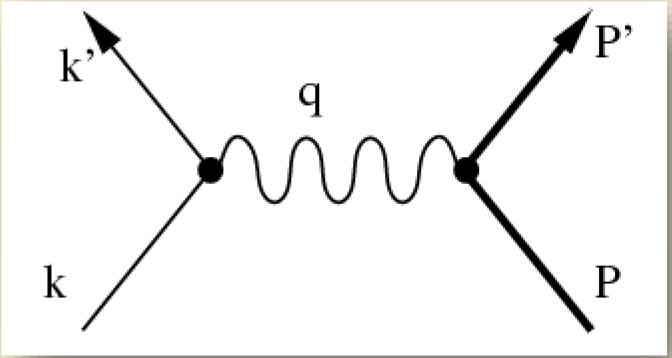


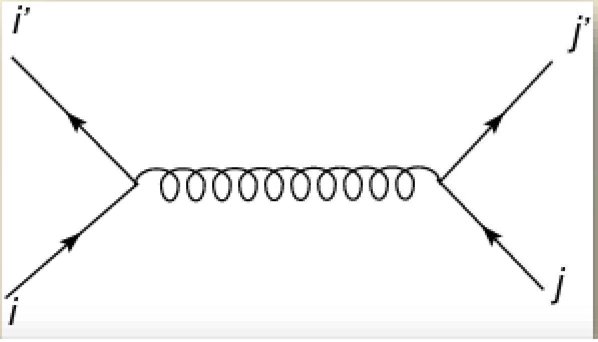


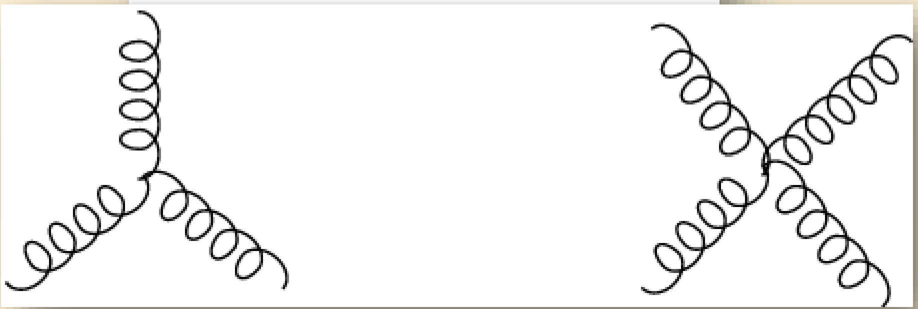
The Nobel Prize in Physics 1990 was awarded jointly to
Jerome I. Friedman, Henry W. Kendall and Richard E. Taylor
"for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics".

Quantum Chromodynamics (QCD)

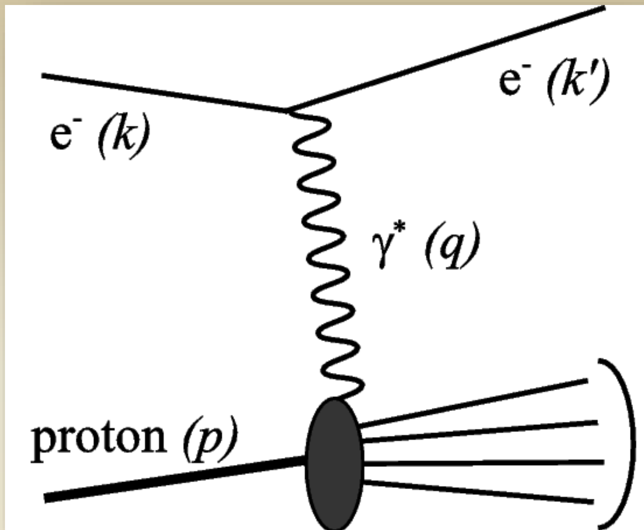
- 1960's – SLAC electron scattering results show small point-like constituents in the proton
- 1970's – theoretical development of QCD, analogous to QED







Deep Inelastic Scattering

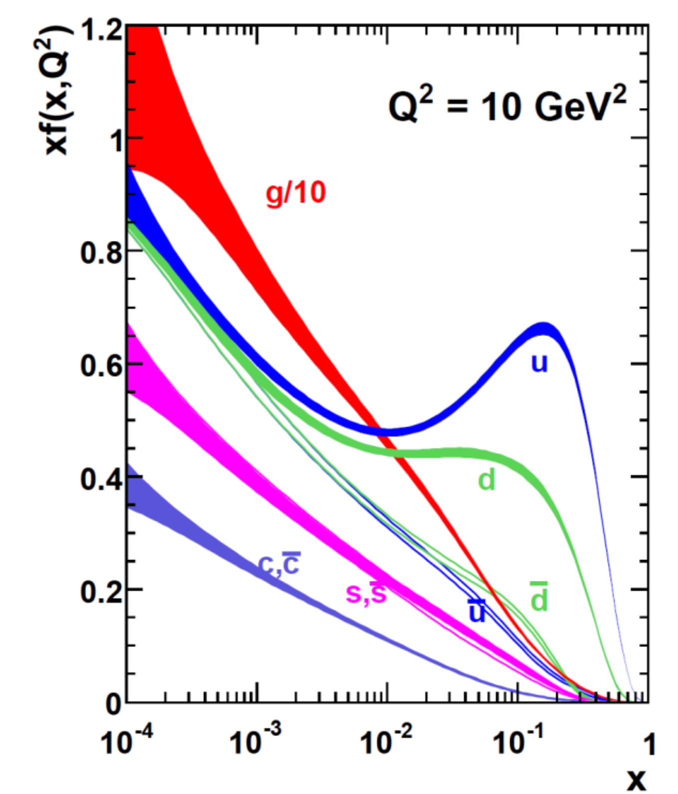


Detect only scattered electron

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^4}\left(W_2\cos^2\frac{\theta}{2} + 2W_1\sin^2\frac{\theta}{2}\right)$$

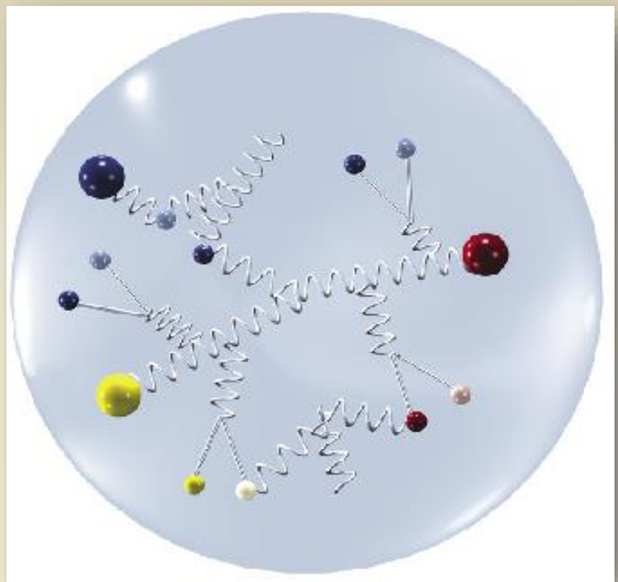
$$(k-k')W_2 = F_2(x) = \Sigma\, e_i^2\, xf_i(x)$$

- $x = Q^2/2M(k-k')$
  = parton momentum fraction
- "scaling" (point constituents)



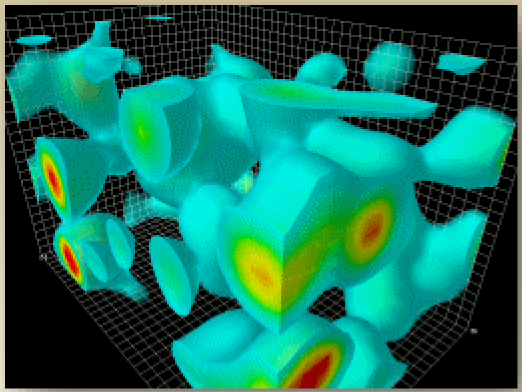
Modern View of the Proton

- Extended object (1 fm ~ 10^{-13}cm)
- Quarks (charged) & gluons (neutral)
- Quark-antiquark pairs (from gluons)
- Spin, orbital angular momentum

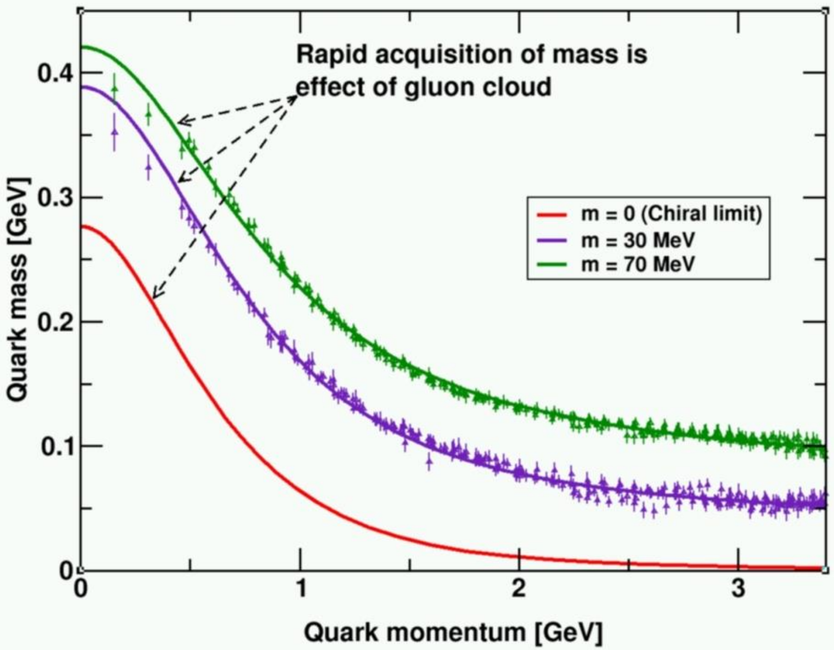


Sum of quark masses « proton mass (~2%)

QCD and the Origin of Mass



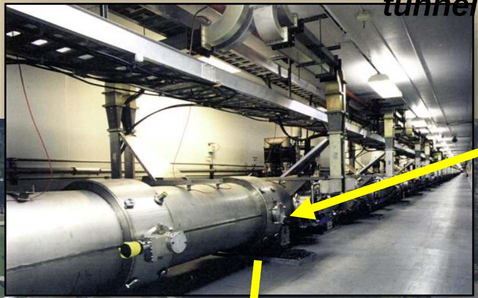
C.D. Roberts, Prog. Part. Nucl. Phys. 61 (2008) 50-65



- 99% of the proton's mass/energy is due to the self-generating gluon field
  - Higgs mechanism has almost no role.
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Quarks contribute almost nothing.
- Lattice and model calculations now explicitly display dynamical breaking of chiral symmetry

Jefferson Lab Accelerator Complex

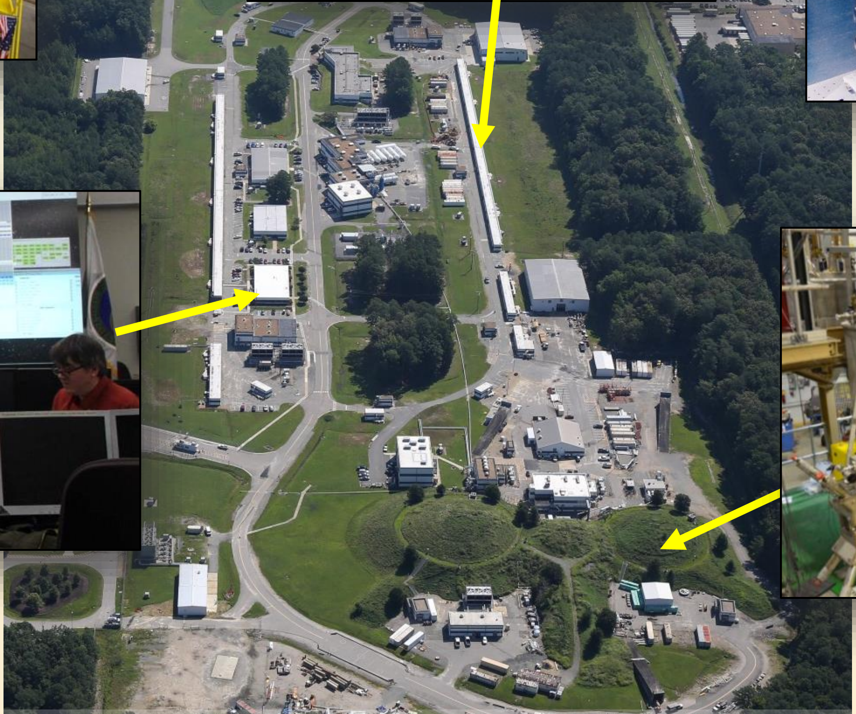
Cryomodules in the accelerator tunnel



Superconducting radiofrequency (SRF) cavities

Hall D

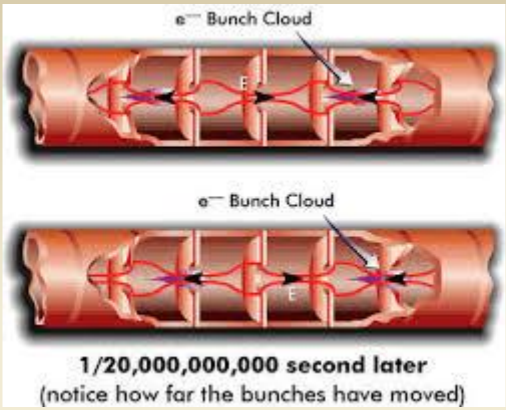
Machine Control Center



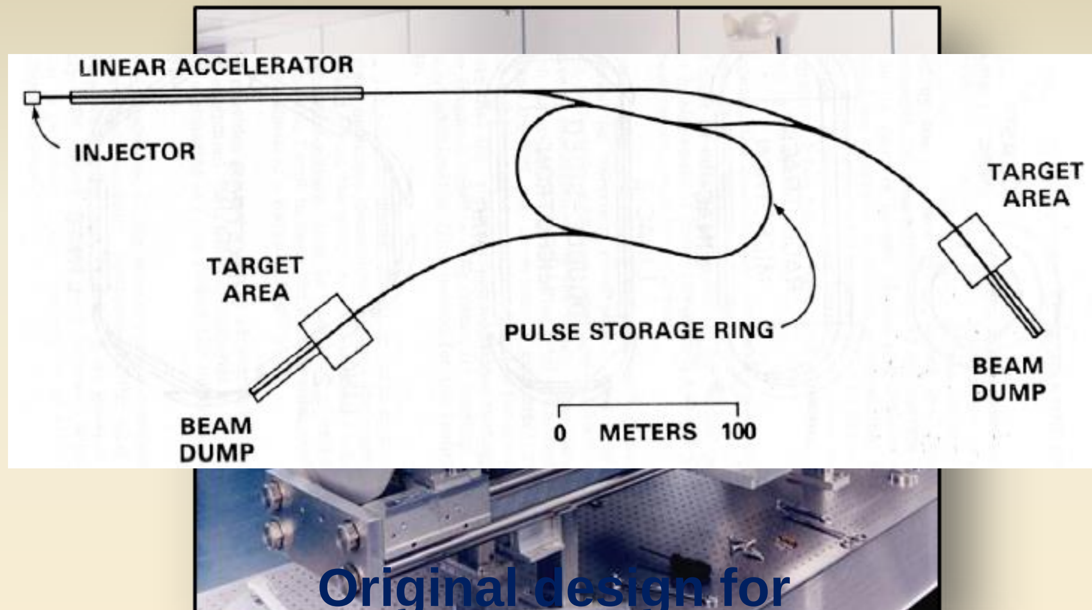
An aerial view of the recirculating linear accelerator and 4 experimental halls.

Hall C

Accelerator Technology: From SLAC to CEBAF



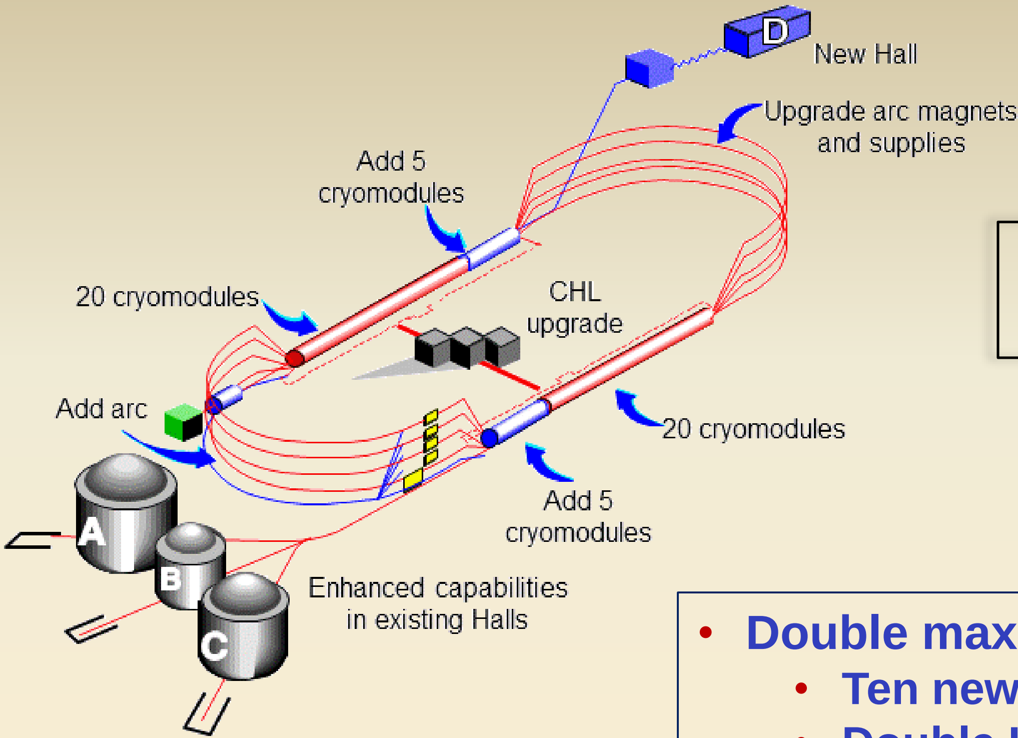
SLAC (1960's)
Water-cooled Cu



Original design for
"continuous wave" (CW) beam

CEBAF (1980's)
LHe cooled superconducting Nb

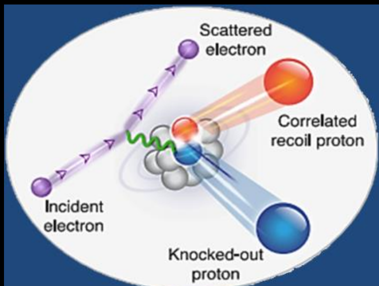
12 GeV CEBAF Upgrade



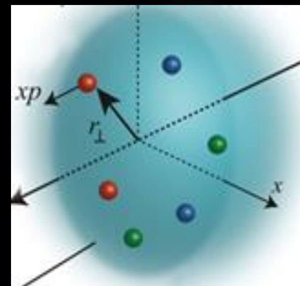
Total Project Cost = $338M
Estimate to Complete < $1M

- **Double maximum Accelerator energy to 12 GeV**
  - **Ten new high gradient cryomodules**
  - **Double Helium refrigerator plant capacity**
  - **Civil construction and upgraded utilities**
- **Add 10th arc of magnets for 5.5 pass machine**
- **Add 4th experimental Hall D**
- **New experimental equipment in Halls B, C, D**

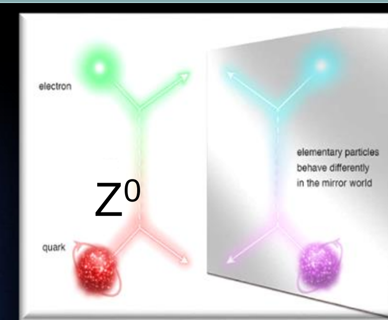
JLab: A Laboratory for Nuclear Science



Nuclear Structure

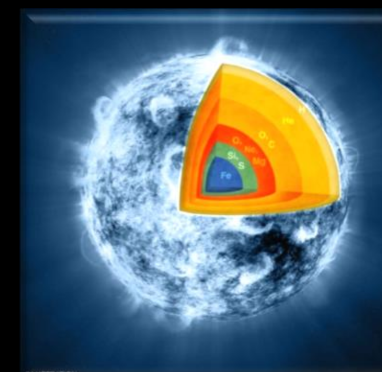


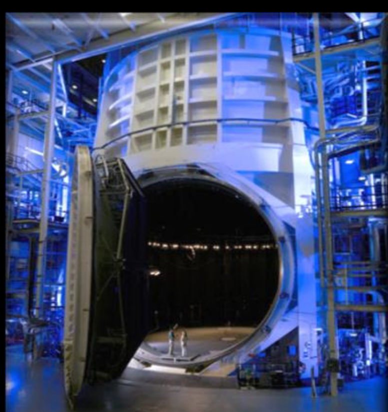
Structure of Hadrons



Fundamental
Forces & Symmetries


Medical Imaging


Nuclear Astrophysics

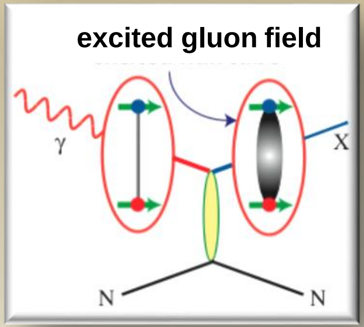

Cryogenics


Accelerator S&T


Theory & Computation

Jefferson Lab @ 12 GeV Science Questions

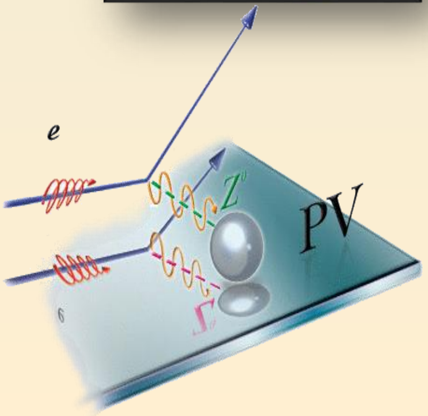
- What is the role of gluonic excitations in the spectroscopy of light mesons?



- Where is the missing spin in the nucleon? Role of orbital angular momentum?

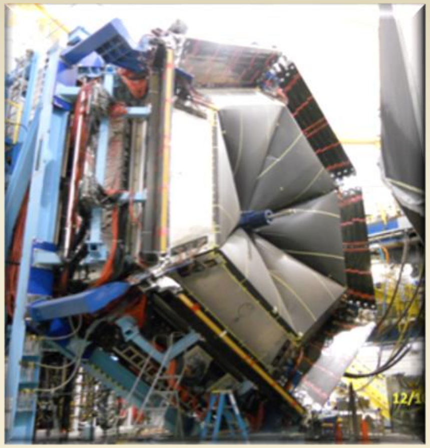
- Can we reveal a novel landscape of nucleon substructure through 3D imaging at the femtometer scale?

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



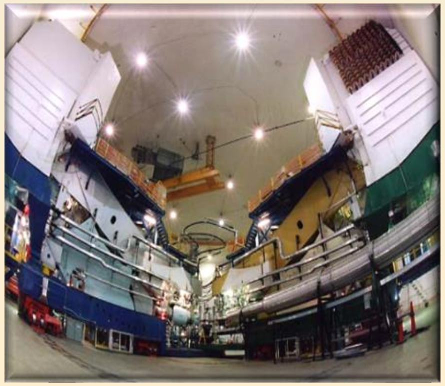
12 GeV Scientific Capabilities

Hall D – exploring origin of 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 – short range correlations, form factors (SBS), hyper-nuclear physics, future new experiments (e.g., SoLID and MOLLER)

12 GeV Project: University Detector Work

Hall	University	Activity	Status
B	**Idaho State U**	Drift Chamber	**Complete**
B	**Old Dominion U**	Drift Chamber	**Complete**
B	**U South Carolina**	TOF Counters	**Complete**
B	Moscow State U (RU)	SVT Testing	**Complete**
C	**Michigan State U**	HB Magnet	**Complete**
C	**U Virginia**	Noble Gas Cerenkov	**Complete**
D	U Athens (GR)	Monitoring BCAL, FCAL	**Complete**
D	**Carnegie Mellon U**	Central Drift Chamber	**Complete**
D	**Catholic U**	Tagger Hodoscope	**Complete**
D	**U Connecticut**	Tagger Microscope	**Complete**
D	**Florida Internat'l U**	Start Counter	**Complete**
D	**Florida State U**	TOF Counters	**Complete**
D	**Indiana U**	Forward Calorimeter	**Complete**
D	U Regina (CA)	Barrel Calorimeter	**Complete**
D	U Santa Maria (CH)	SiPM, Lightguides for BCAL	**Complete**
B, C, D	**U Massachusetts**	Electronics Testing	**Complete**

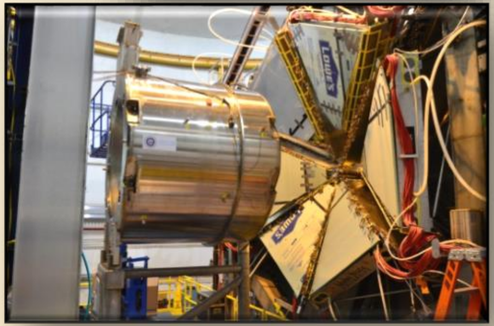
NSF-MRI funded (Hall B):
- **PCAL Detector**
- **Long. Polarized Target**

NSF-MRI funded (Hall C):
- **Drift Chambers**
- **Trigger Hodoscopes**
- **Aerogel**

Internat'l contributions for detectors beyond base equipment.

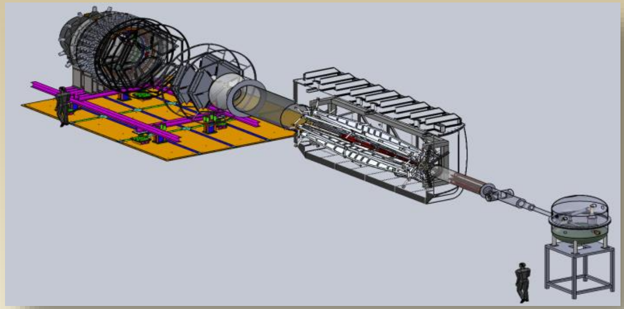
12 GeV Upgrade – Path to Completion

- **Accelerator**
  - Full 12 GeV energy achieved
  - Full luminosity demonstrated
  - Simultaneous multi-hall beam delivery achieved
- **Hall C** – Key Performance Parameter demonstrated
  - SHMS installed, commissioned with beam
  - March 2017
- **Hall B** – Key Performance Parameter demonstrated
  - CLAS12 installed, commissioned with beam
  - February 2017
- **Remaining Scope** = Solenoid Magnet for Hall B
  - Final phase of assembly at vendor completed in June 2017
  - Delivered to Jefferson Lab June 27
  - Installation and acceptance tests underway



Project Completion September 2017

Future Projects



- MOLLER experiment
  (Possible MIE – FY19-23)
  - CD-0 approved
    (project paused due to budget uncertainty)
  - Standard Model Test
  - DOE science review (September 2014) – strong endorsement
  - Director's review held December 15-16, 2016
    Technical, cost & schedule

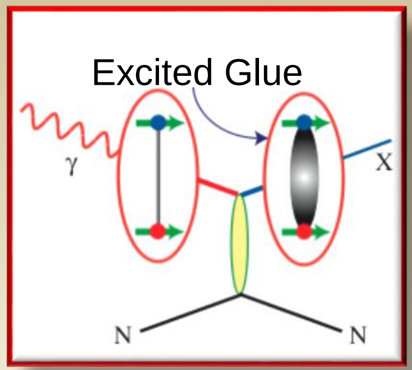
- SoLID
  - SIDIS and PVDIS
  - CLEO Solenoid ✓
  - International collaboration
  - Director's review (Feb. 2015)
    → new pre-CDR almost complete

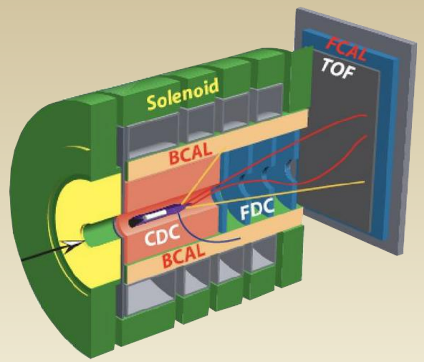
12 GeV Approved Experiments by Physics Topics

Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD	0	3	1	3	0	**7**
The transverse structure of the hadrons	6	4	3	1	0	**14**
The longitudinal structure of the hadrons	2	3	6	0	0	**11**
The 3D structure of the hadrons	5	9	6	0	0	**20**
Hadrons and cold nuclear matter	8	4	7	0	1	**20**
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1	0	1	1	**6**
Total	**24**	**24**	**23**	**5**	**2**	**78**
Total Experiments Completed	**2.5**	**1.1**	**0**	**0.4**	**0**	**4.0**
Total Experiments Remaining	**21.5**	**22.9**	**23.0**	**4.6**	**2.0**	**74.0**

A Decade of Experiments

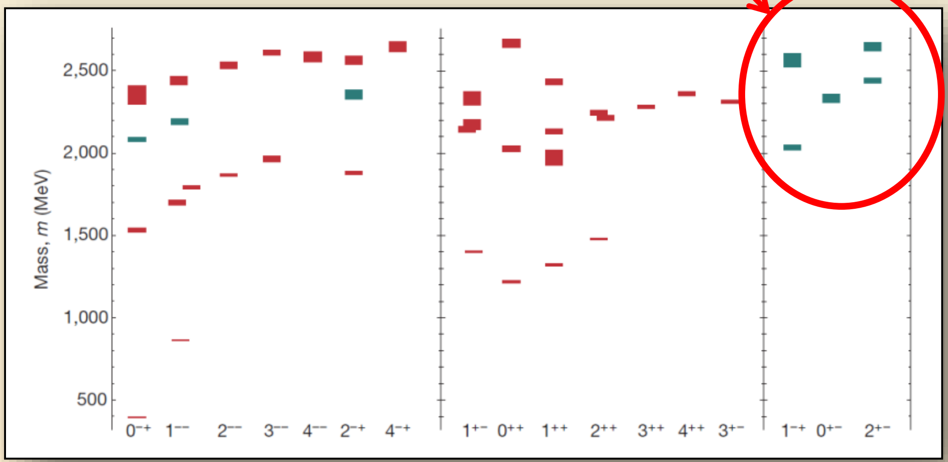
Gluonic Excitations and the Mechanism for Confinement





Hall D@JLab

States with Exotic Quantum Numbers



nature International weekly journal of science

Searching for the rules that govern hadron construction

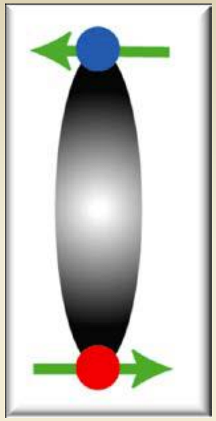
M. R. Sheperd, J. J. Dudek, R. E. Mitchell

Quantum Numbers of Hybrid Mesons

Quarks $\oplus$ **Excited Gluon Field** $\rightarrow$ **Hybrid Meson**

$$S = 0$$
$$L = 0$$
$$J^{PC} = 0^{-+}$$

like π, K

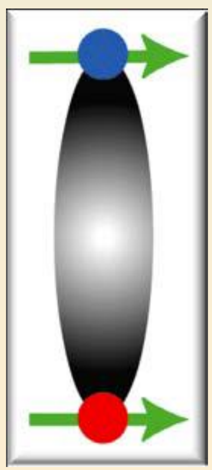


$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

$$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$$

$$S = 1$$
$$L = 0$$
$$J^{PC} = 1^{--}$$

like γ, ρ



$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

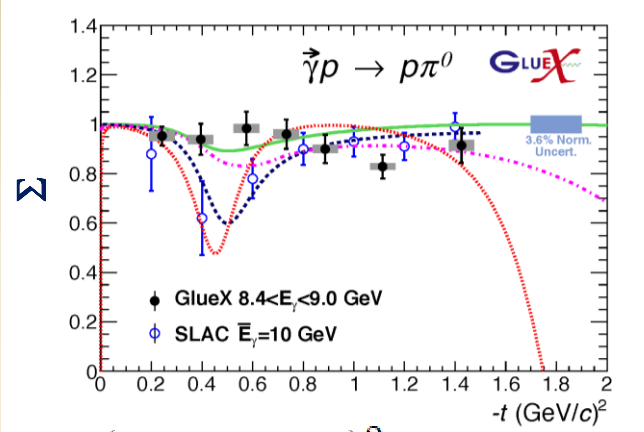
Exotic

$$J^{PC} = \begin{cases} 0^{-+} \quad 1^{-+} \quad 2^{-+} \\ 0^{+-} \quad 1^{+-} \quad 2^{+-} \end{cases}$$

Gluonic excitation (and parallel quark spins) lead to exotic J^{PC}

First Published Results from 12 GeV CEBAF

The first experimental results, from data collected in the GlueX engineering run, have been published in Phys. Rev. C.



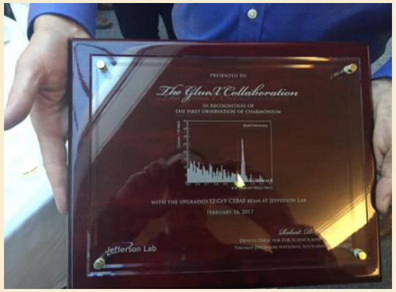
$$t = (p_{\mathrm{target}} - p_{\mathrm{p}})^2$$

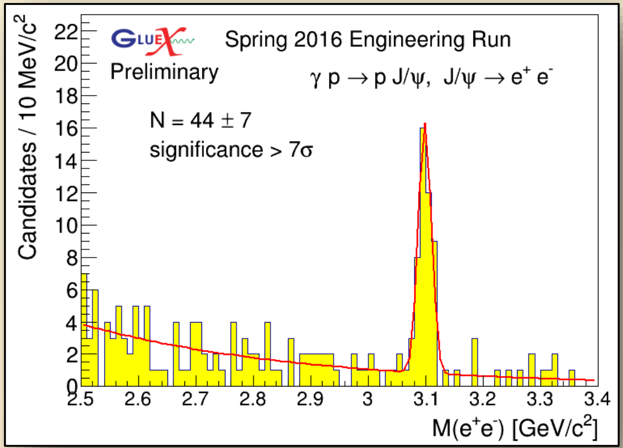
The new GlueX results show:

- For neutral pions, the reaction mechanism is dominated by pure vector coupling.
- The first data for beam asymmetry for η production >3 GeV.
- **The GlueX experiment in Hall D can produce timely results.**

GlueX will search for hybrid mesons, particles in which the strong gluonic field contributes directly to their properties. From the spectrum of these particles, we can learn about the gluonic field in QCD.

Bonus:

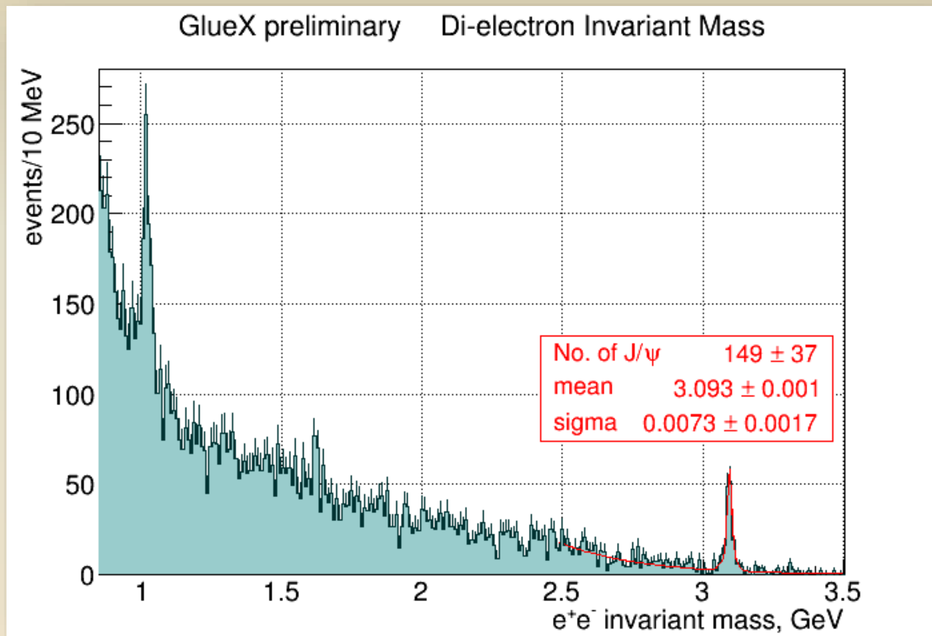


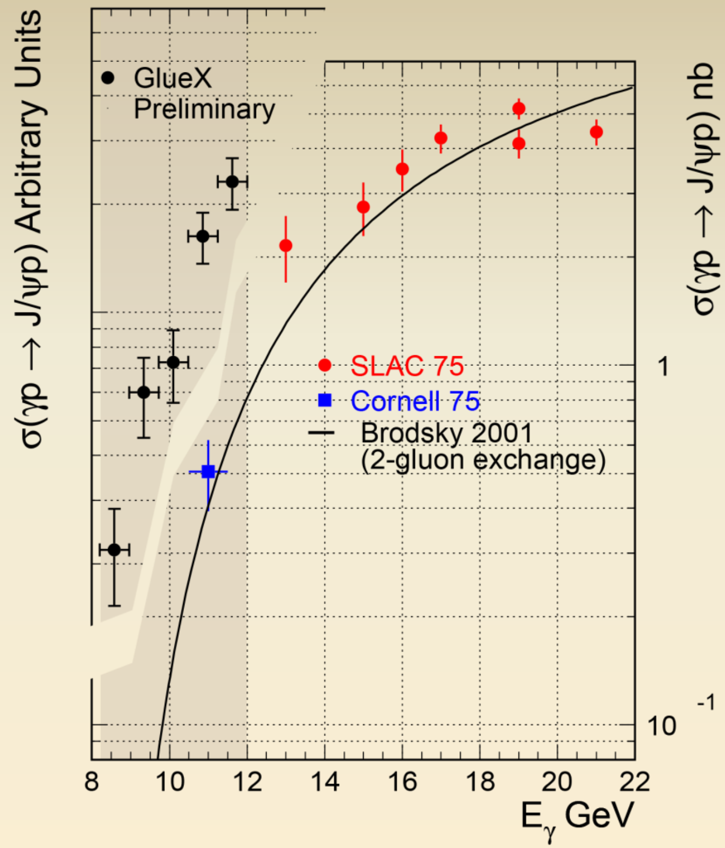


First observation of charmonium at JLab!

Planned Publication (II)

$$\gamma p \to pJ/\psi$$

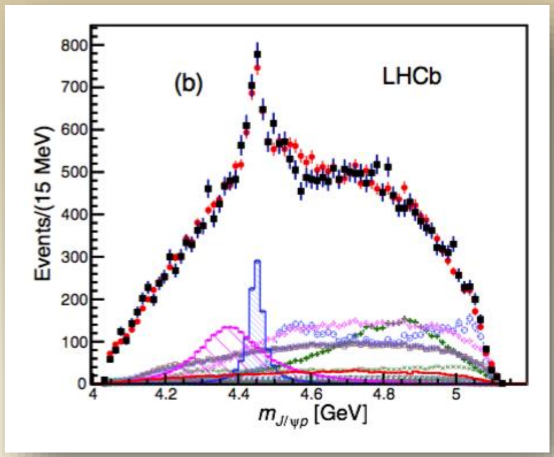




Statistics from the spring 2017 physics run will allow us to measure the cross section down to threshold.

The overall normalization of the GlueX data will shift the black points up or down, but the size of the errors is preserved on the log scale.

Charmonium Pentaquark



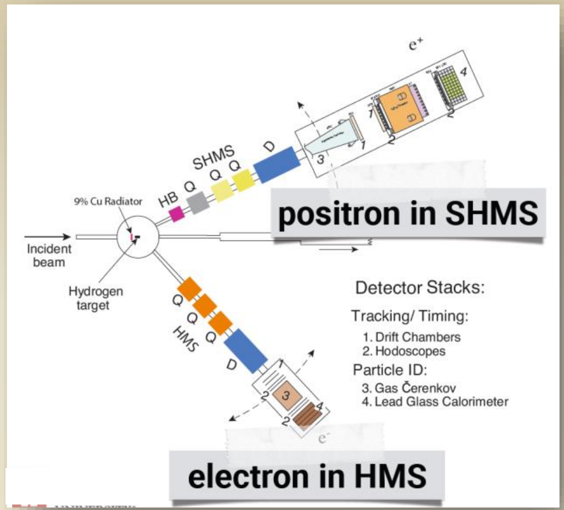
LHCb

2 P_c states needed to describe results:

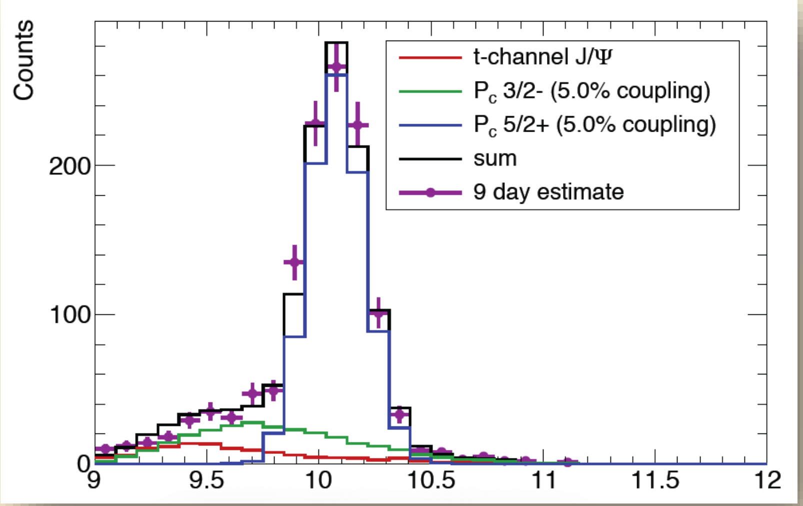
narrow: $P_c(4450)$

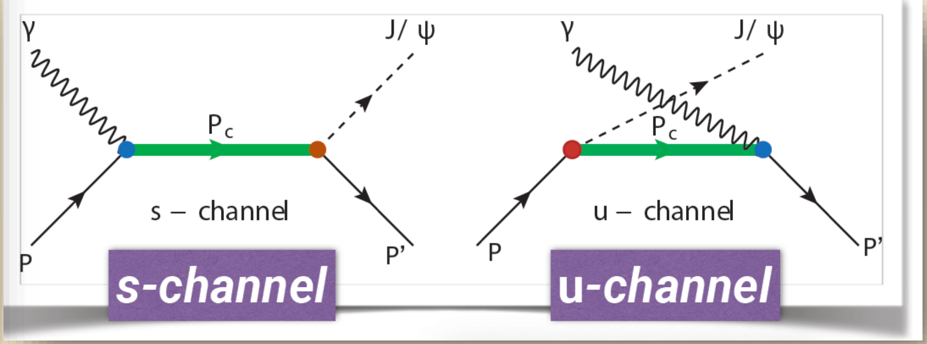
wide: $P_c(4380)$

JLab E12-16-007

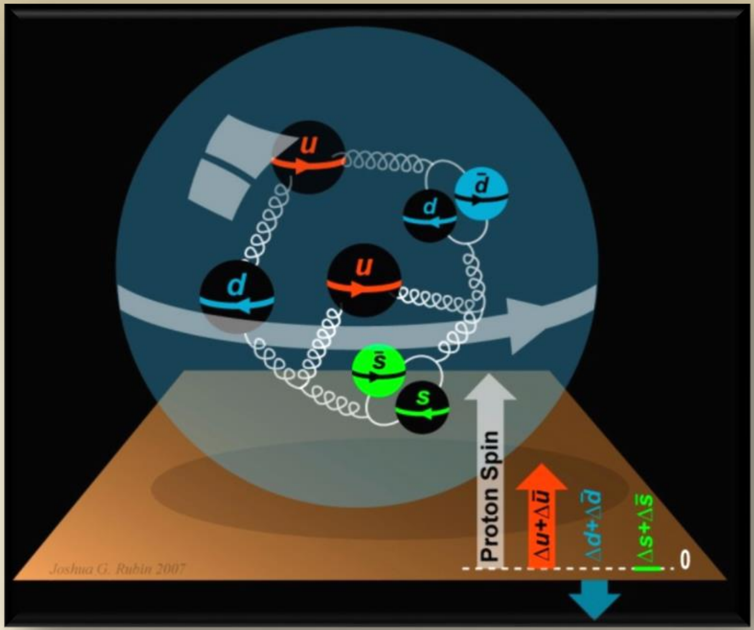


$$\gamma p \to P_c \to J/\psi p$$





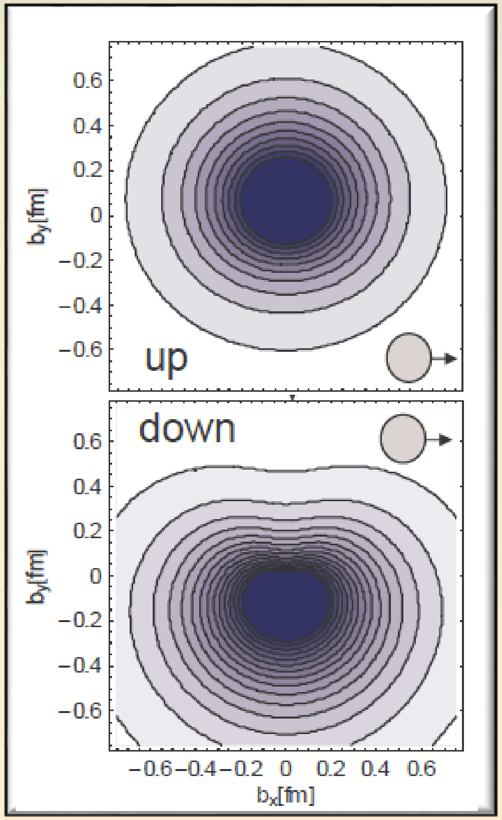
The Incomplete Nucleon: Spin Puzzle



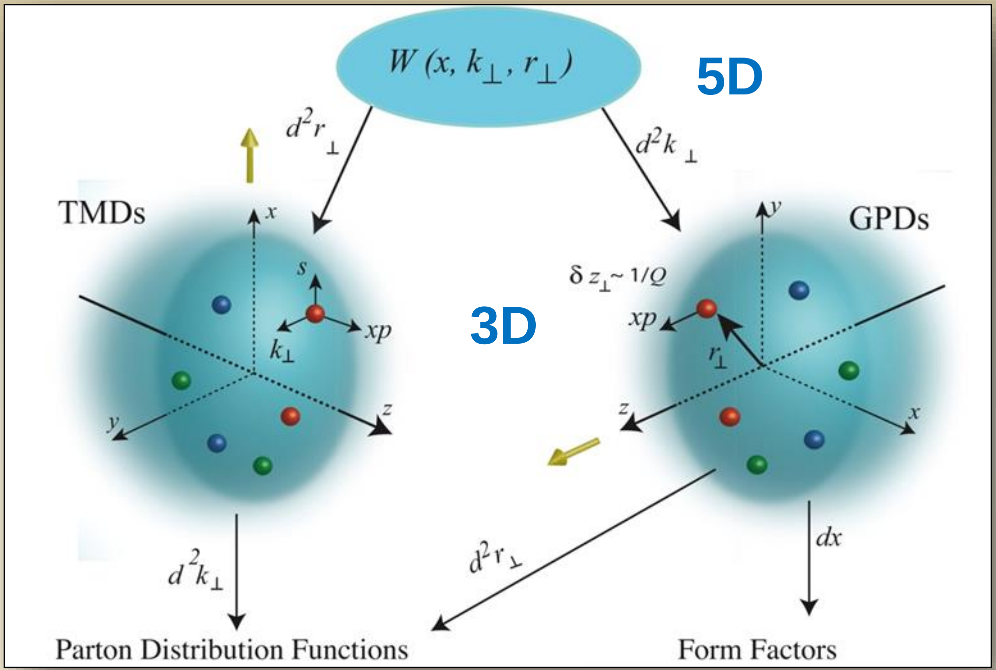
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

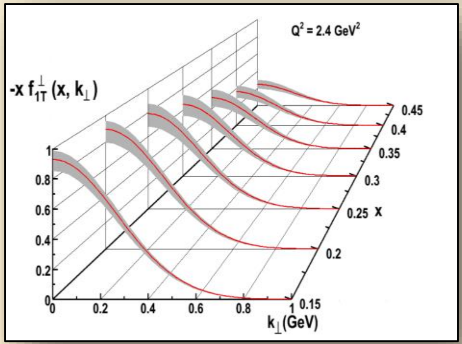
[X. Ji, 1997]

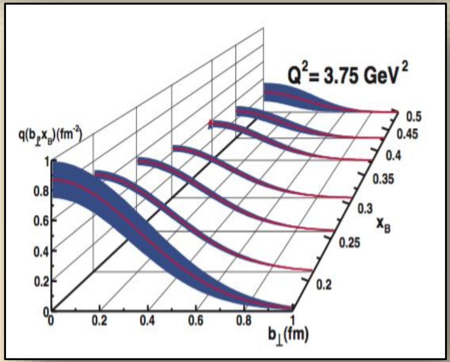
- DIS → $\Delta\Sigma \cong 0.25$
- RHIC + DIS → $\Delta G \sim 0.2$
- → L_q



"Nuclear Femtography"







- Transverse Momentum Dist. (TMD)
  - Confined motion in a nucleon (semi-inclusive DIS)
- Generalized Parton Dist. (GPD)
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets
  - Sophisticated detector systems

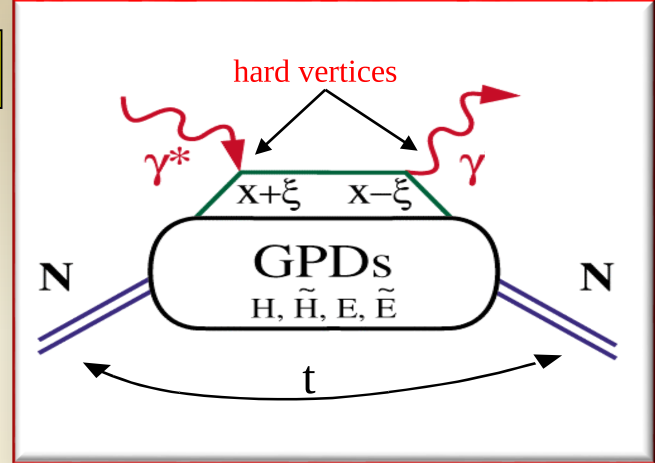
Major new capability with JLab @ 12 GeV

Extraction of GPD's

Cleanest process: Deeply Virtual Compton Scattering

$$A = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\Delta\sigma}{2\sigma}$$

$\xi = x_B/(2-x_B)$



Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}d\phi$ ⇒ $H(\xi,t)$

Unpolarized beam, longitudinal target:

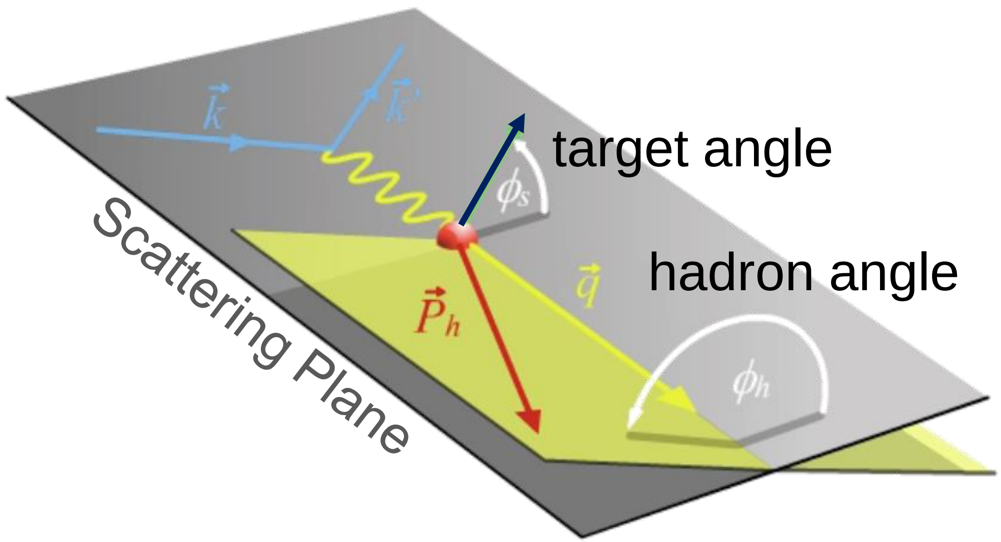
$\Delta\sigma_{UL} \sim \sin\phi\{F_1\tilde{H} + \xi(F_1+F_2)(H + \xi/(1+\xi)E)\}d\phi$ ⇒ $\tilde{H}(\xi,t)$

Unpolarized beam, transverse target:

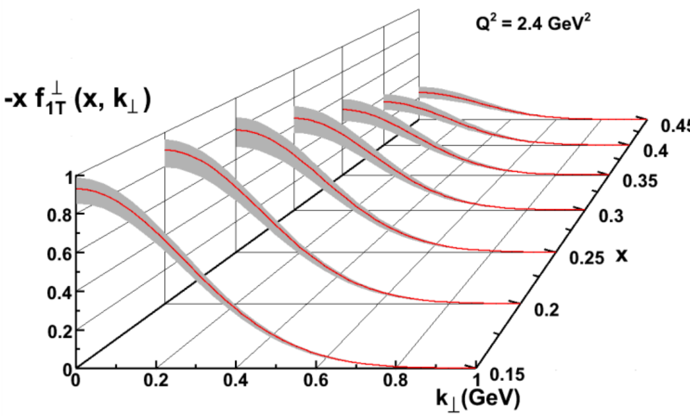
$\Delta\sigma_{UT} \sim \sin\phi\{k(F_2 H - F_1 E)\}d\phi$ ⇒ $E(\xi,t)$

SIDIS Electroproduction of Pions

- Separate Sivers and Collins effects



- Previous data from HERMES,COMPASS
- New landscape of TMD distributions
- Access to orbital angular momentum

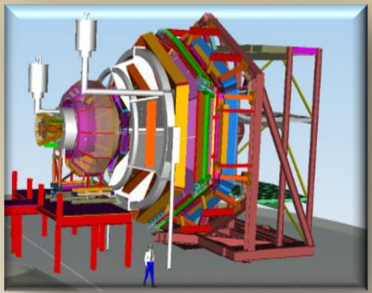


- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$

SIDIS Studies with 12 GeV at JLab

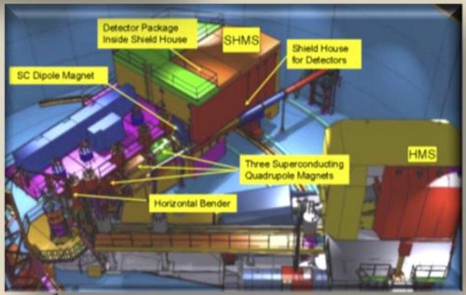
- **CLAS12 in Hall B**

  General survey, medium lumi



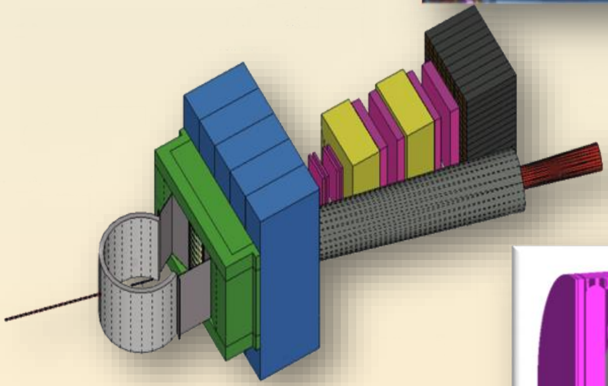
- **SHMS- HMS in Hall C**

  L-T studies, precise π^+/π^- ratios



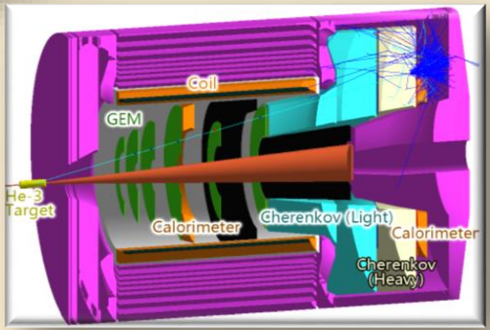
- **SBS in Hall A**

  High x, High Q^2, 2-3D



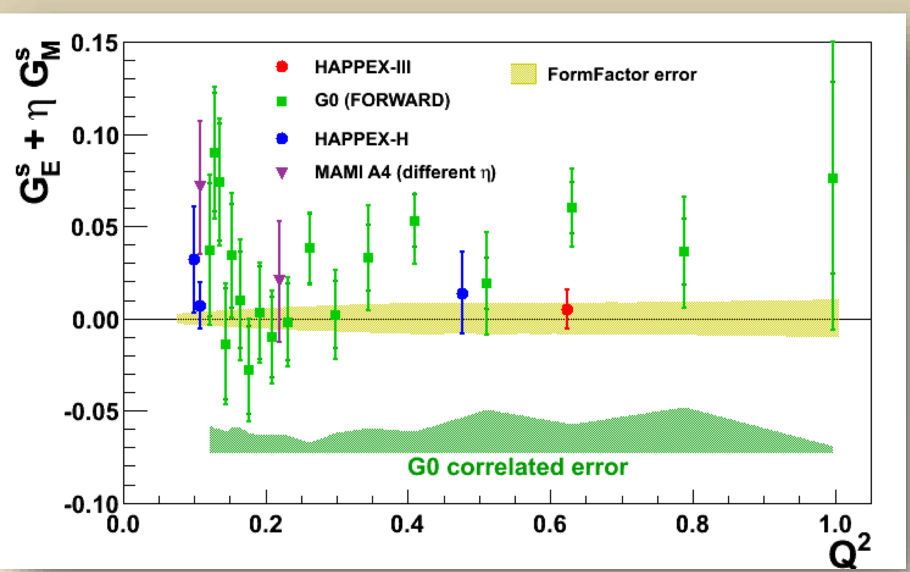
- **SOLID in Hall A**

  High Lumi and acceptance – 4D



Parity Violation at JLab

- Nucleon Strangeness Form Factors (complete)
  - HAPPEX (Hall A)
  - G0 (Hall C)



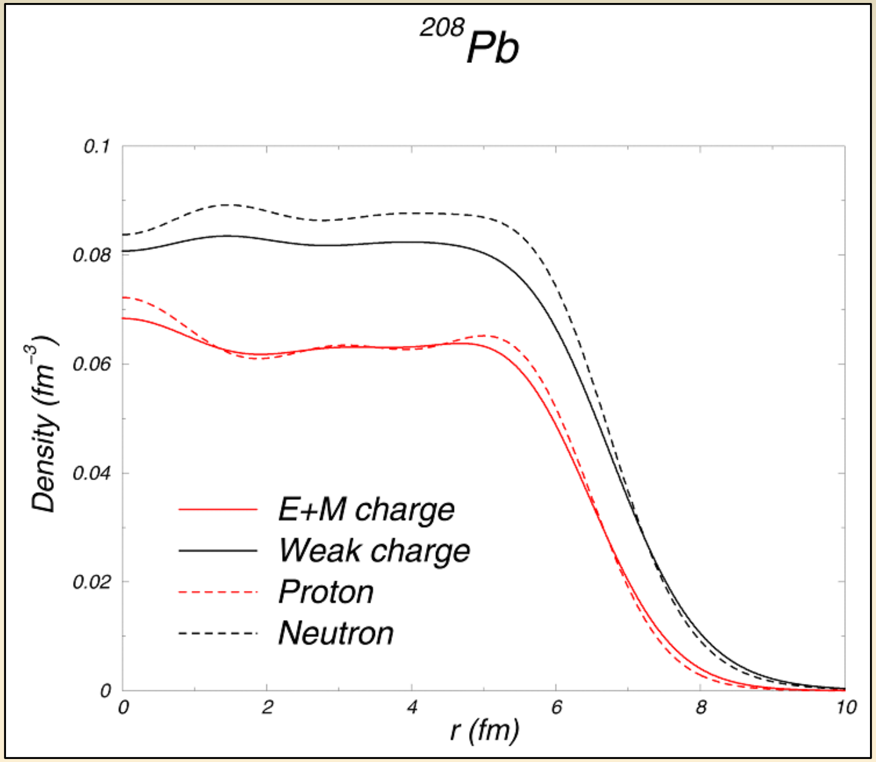
- Neutron Skin
  - PREX
  - CREX

- Precision Tests of Standard Model
  - Qweak (Under analysis)
  - MOLLER
  - SoLID

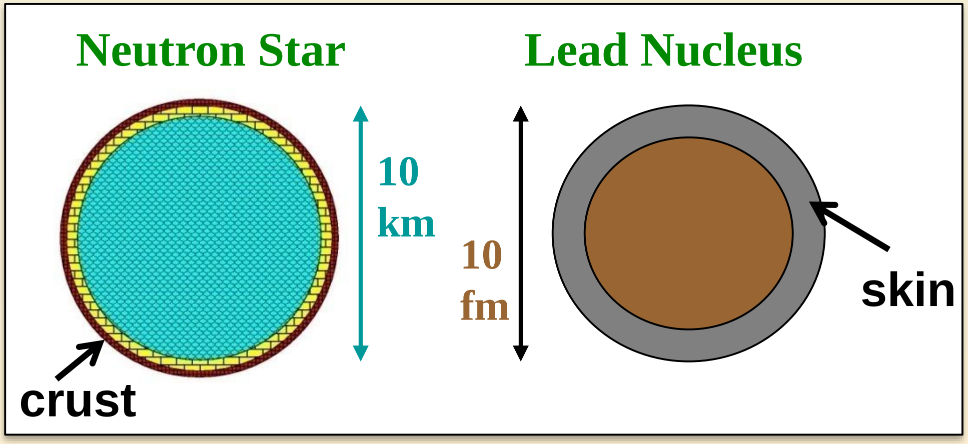
Measuring the Neutron “Skin” in the Pb Nucleus

$Q_W^p = (1 - 4\sin^2\theta_W)$
$Q_W^n = -1$

Weak interaction selects neutrons



- Parity violating electron scattering
- Sensitive to neutron distribution

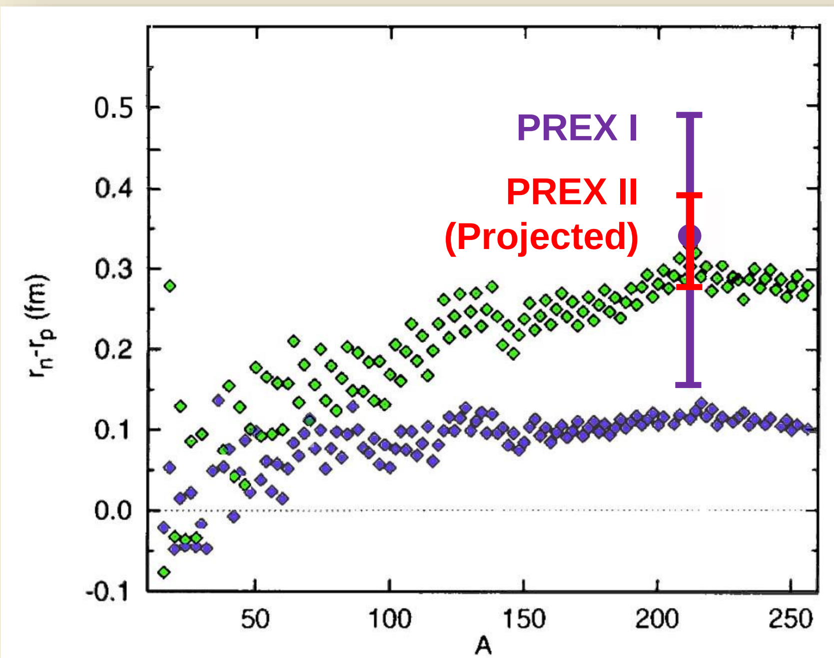


Applications: Nuclear Physics, Neutron Stars, Atomic Parity, Heavy Ion Collisions

Lead (^{208}Pb) Radius Experiment: PREX

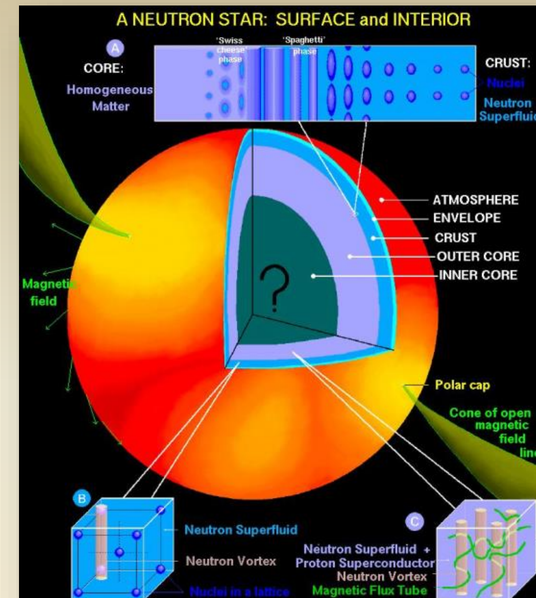
First measurement: clear indication of neutron skin

Future measurement: constrain symmetry EOS



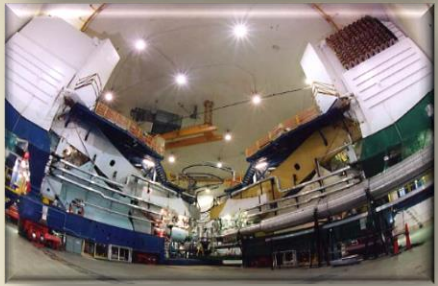
Relativistic mean field

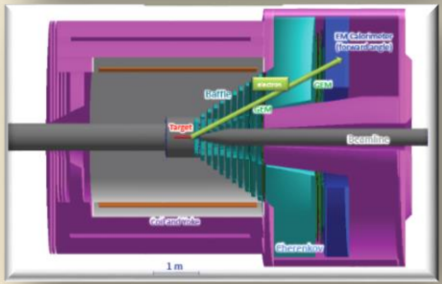
Nonrelativistic skyrme

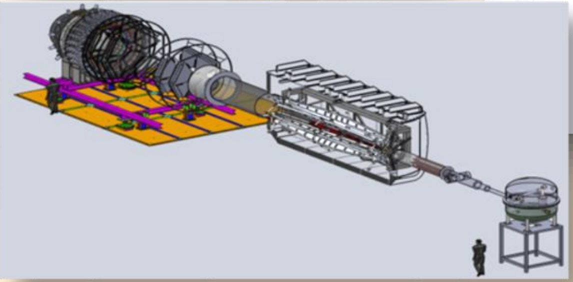


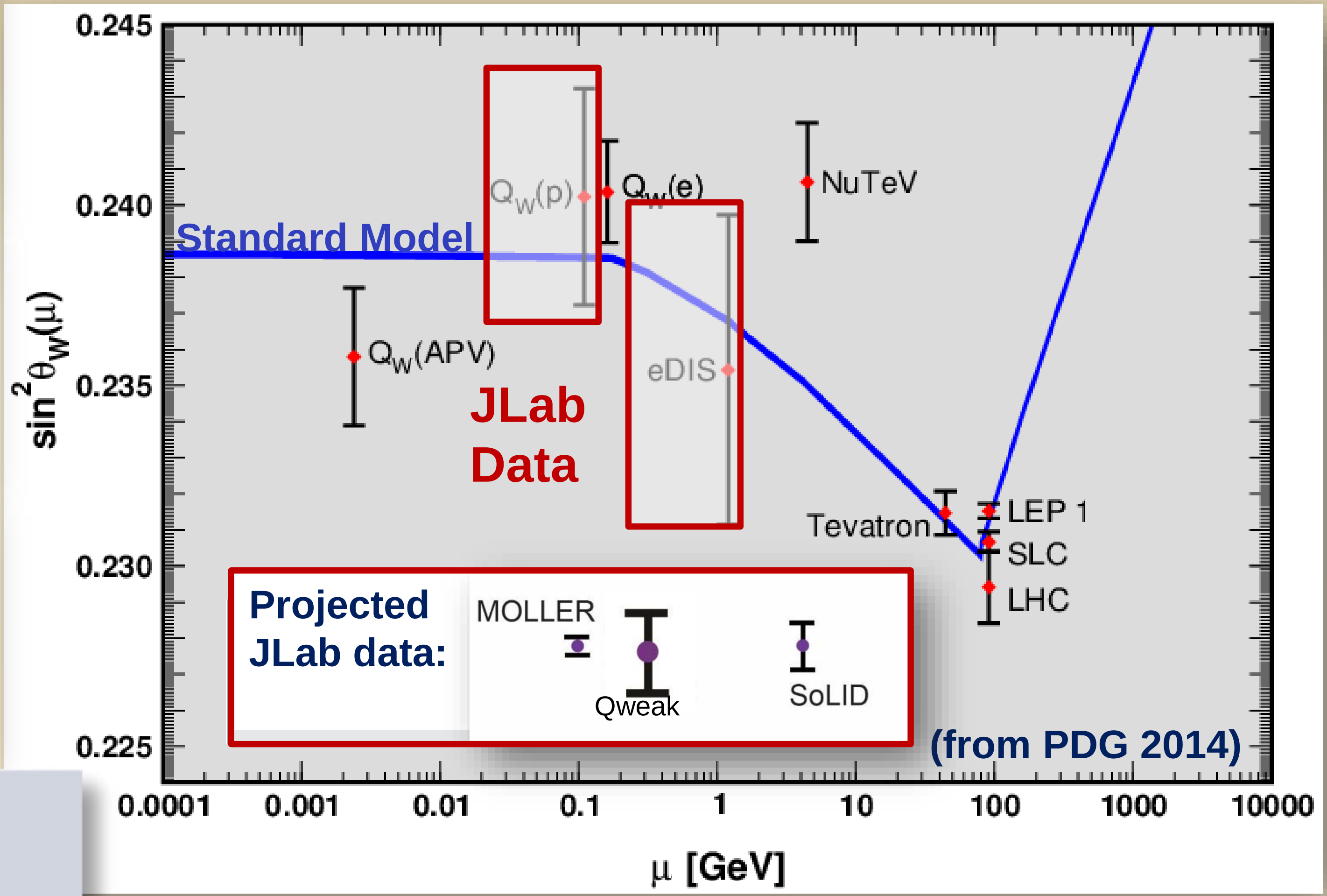
A neutron skin of 0.2 fm or more has implications for our understanding of neutron stars and their ultimate fate.

Testing the Standard Model at JLab







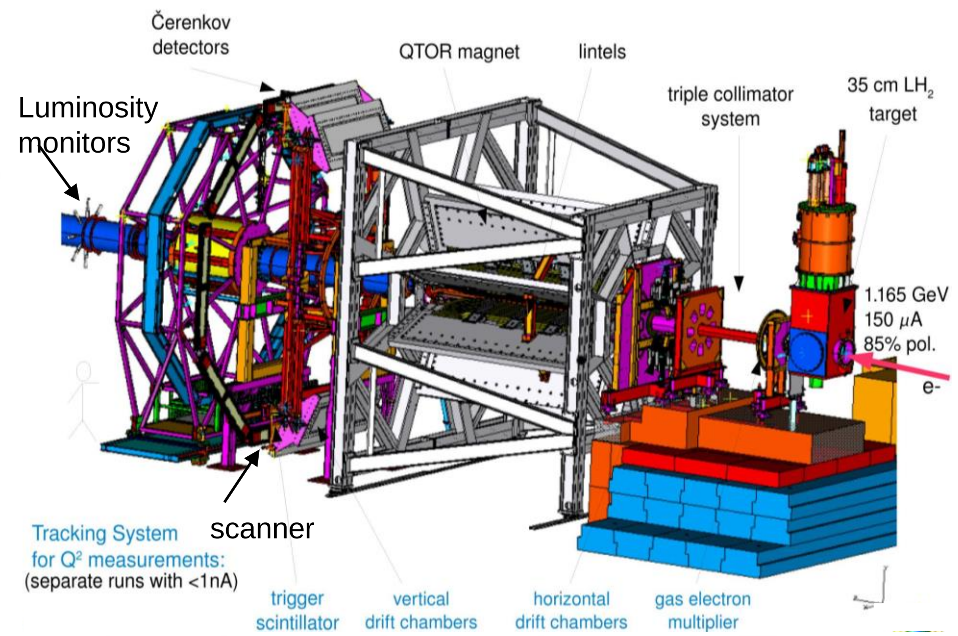


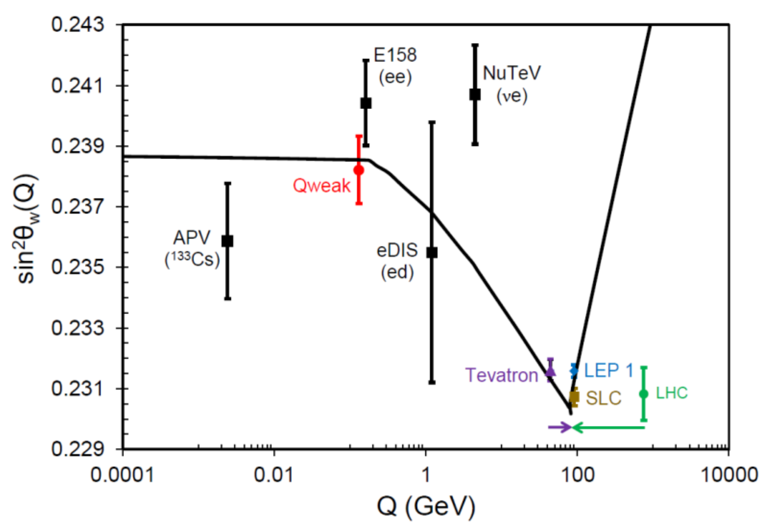
New Qweak Result

Precise determination of the weak charge of the proton

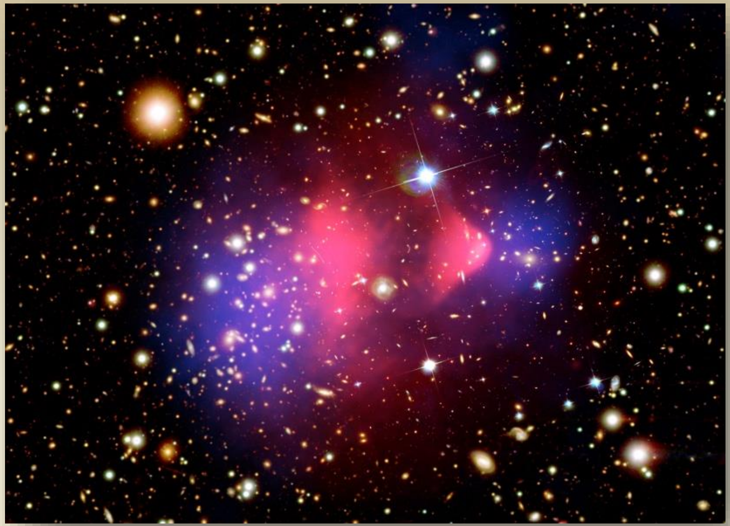
$$Q_w = -2(2C_{1u}+C_{1d})$$
$$=(1 - 4\sin^2\theta_W)$$

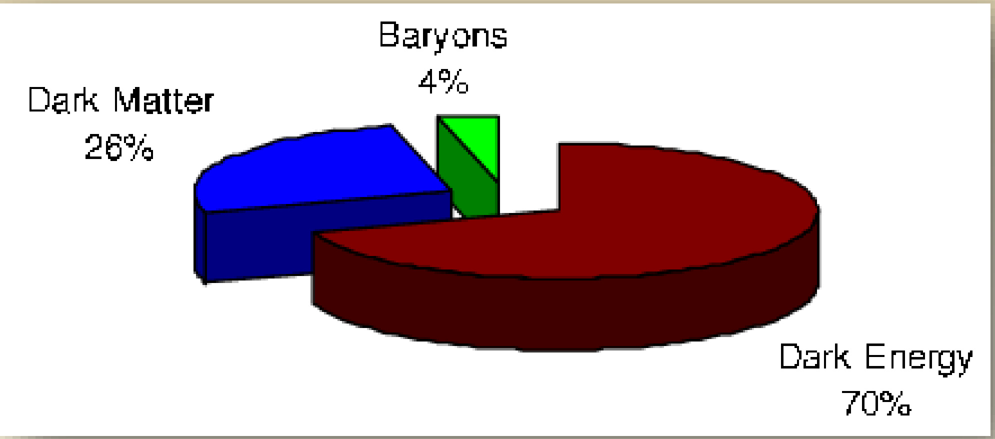
- Result unblinded March 2017
- In preparation for submission to Nature





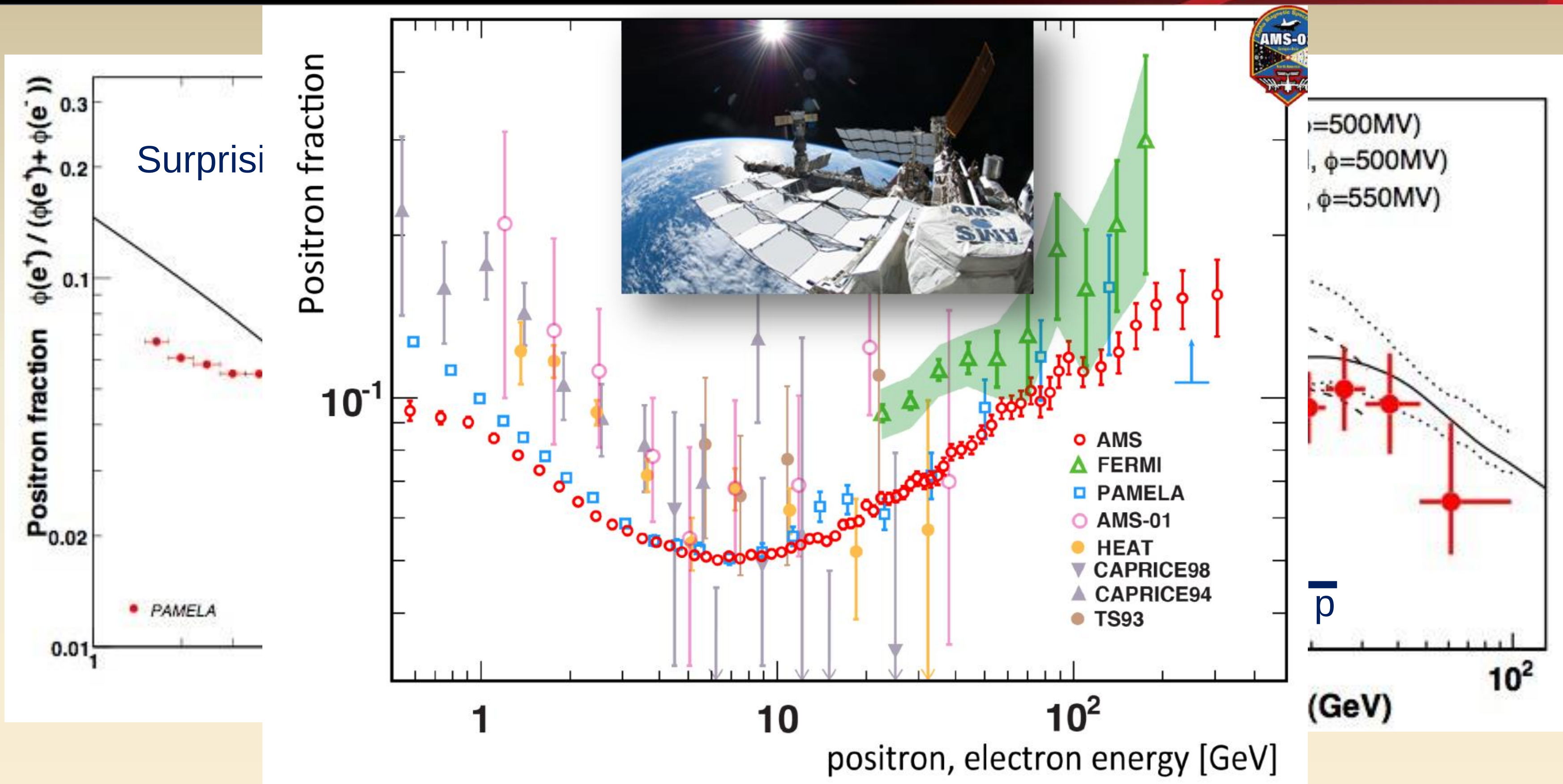
Cosmology and Dark Matter



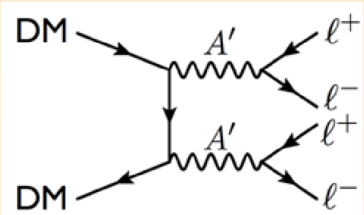


- *Dark sector is new physics, beyond the standard model*
- *Many direct searches for dark matter interacting with sensitive detectors (hints, no established signal yet…)*
- *Controversial evidence for excess astrophysical positrons…*

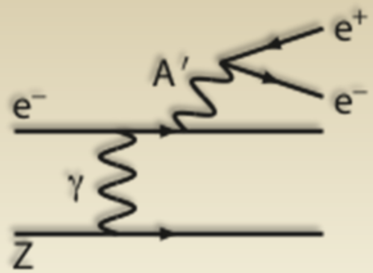
PAMELA Data on Cosmic Radiation

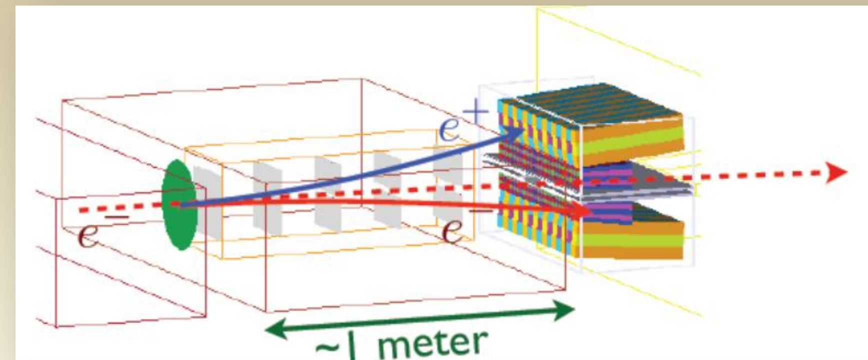


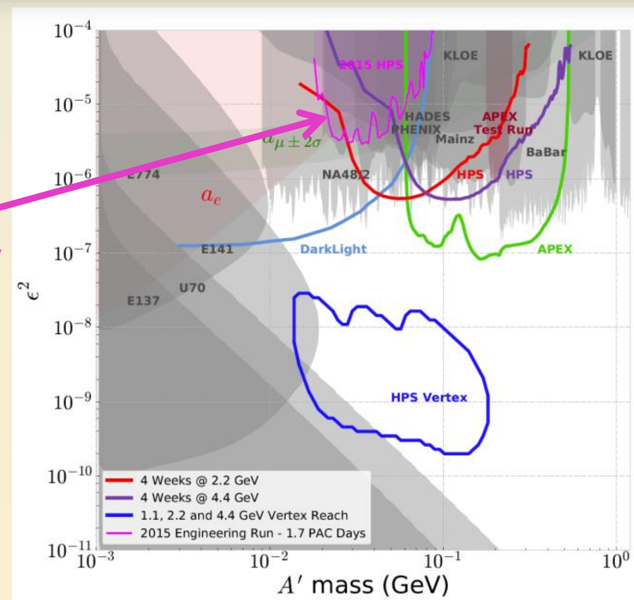
- Could indicate low mass A’ ($M_{A'} < 1$ GeV)
  - Or local astrophysical origin??



Heavy Photon Search – First Results



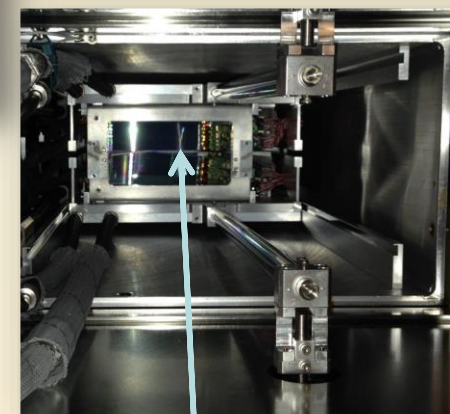




2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2 GeV data taken in 2016, under analysis

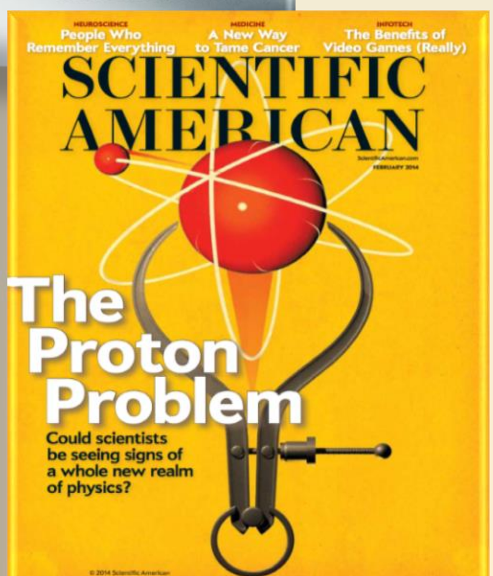
- NP-HEP Collaboration

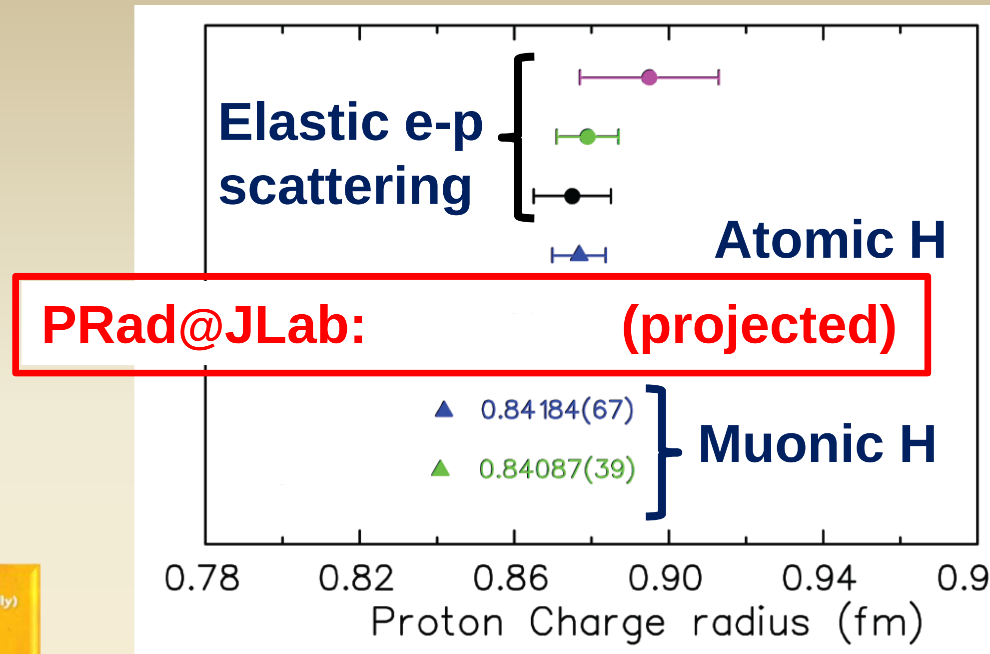


1 mm gap between Si tracker detectors for passage of electron beam

Future Program: more HPS, APEX, DarkLIGHT

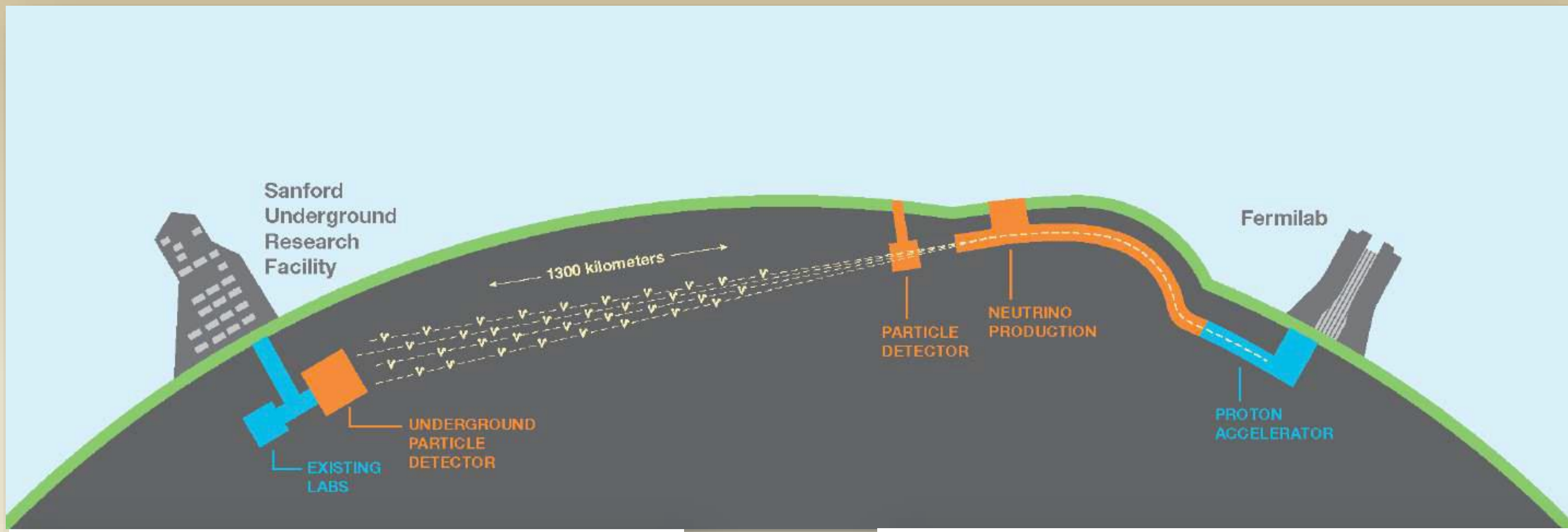
Solving the Proton Radius Puzzle

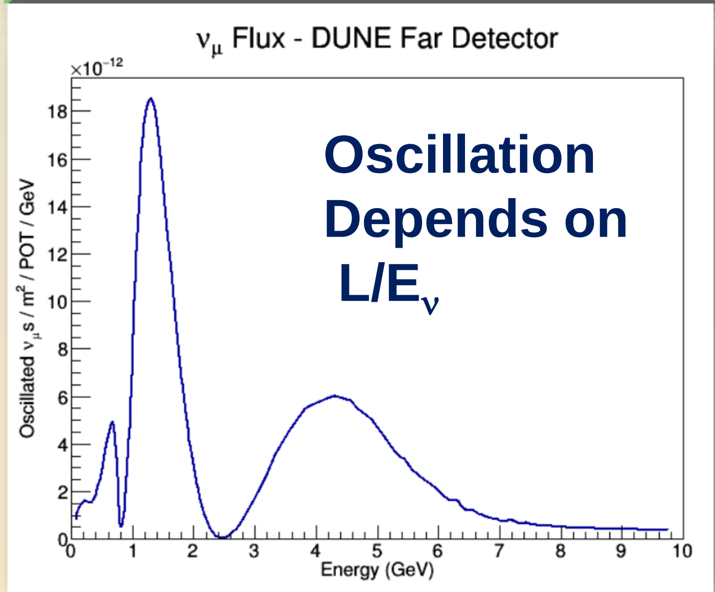




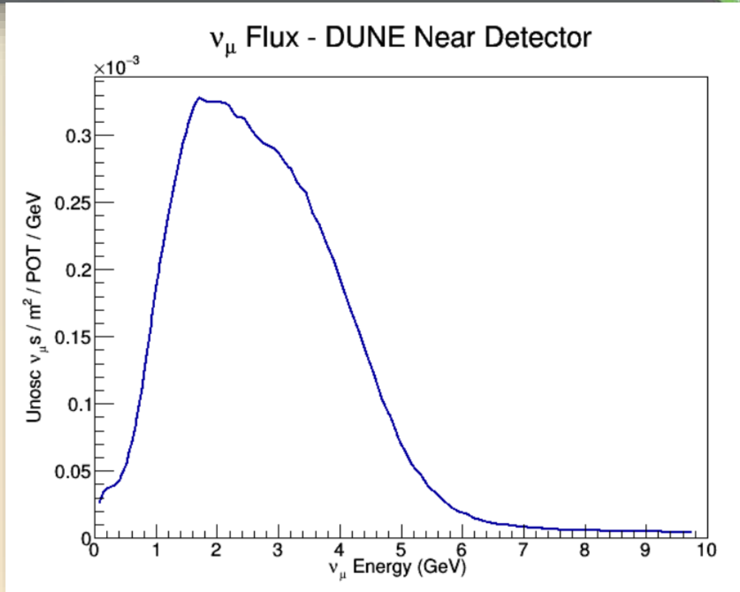
- **PRad: new experiment to address proton radius @ JLab**
- **NSF MRI: H_2 gas target**
- **DOE GEM tracking detectors**
- **Successful run in summer 2016!**

Contribution to Neutrino Physics

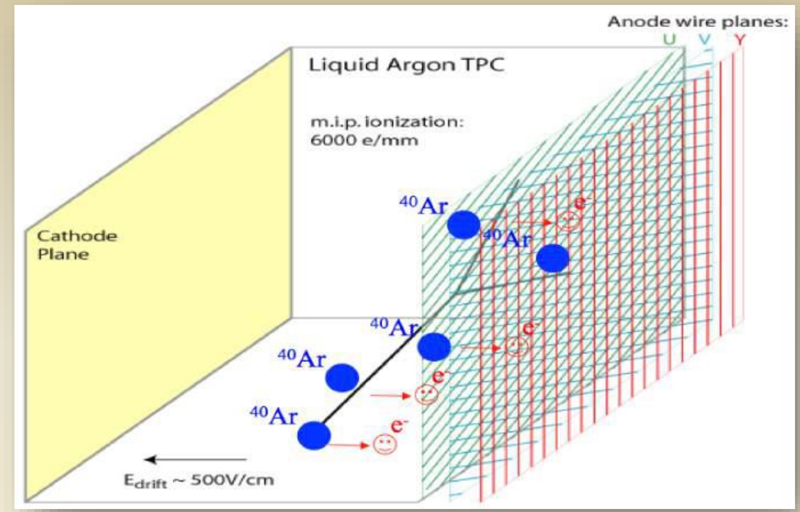


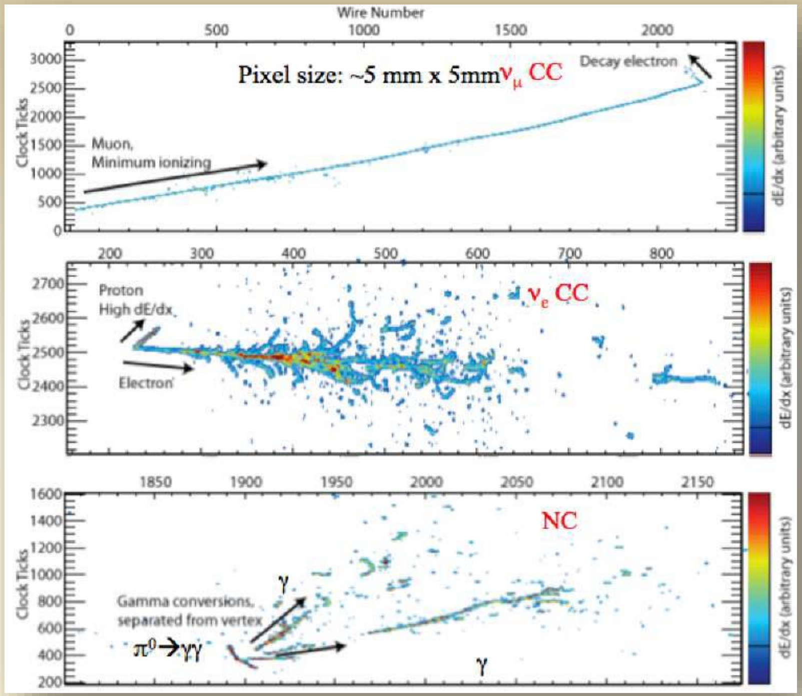


Oscillation Depends on L/E_ν



DUNE Detector

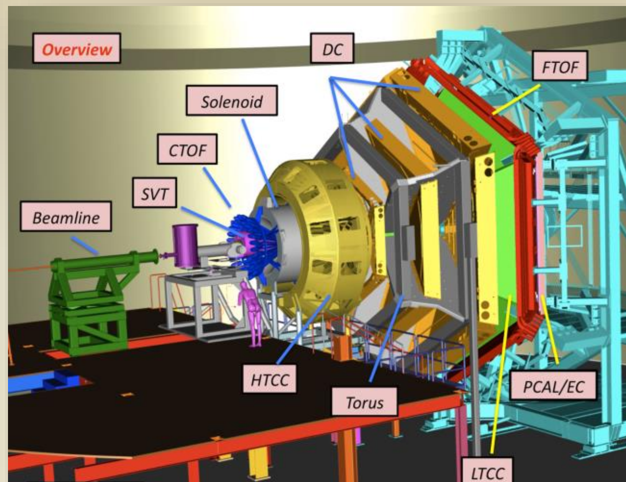


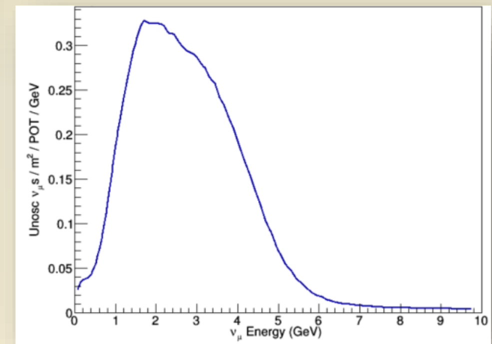


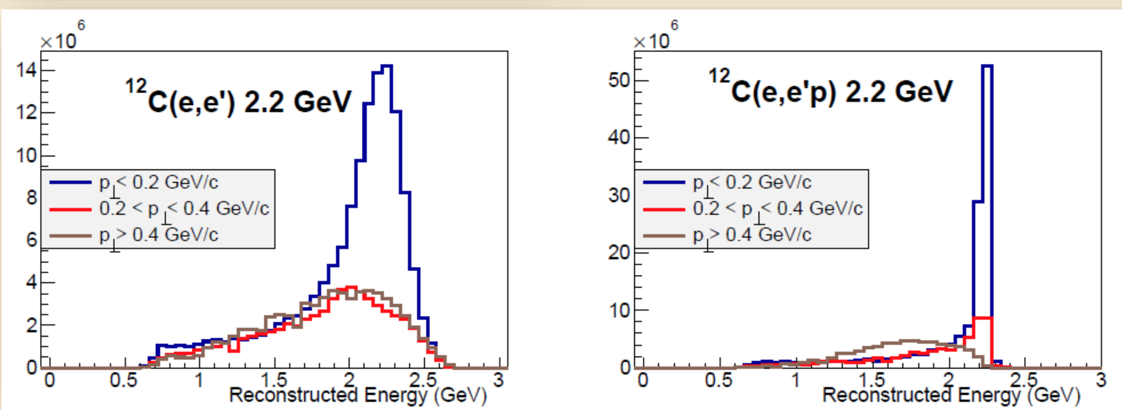
MicroBooNe Simulation

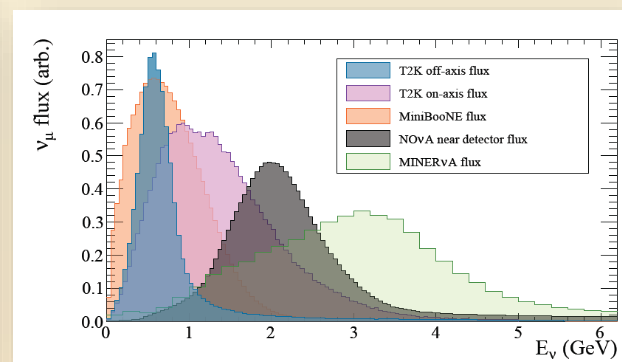
- Lot's of detailed information on detected events
- BUT not on incident neutrino energy (note need L/E_ν)!
- Also – the target is a complex atomic nucleus ^{40}Ar

Use Electron Data to “Train” Neutrino Analysis

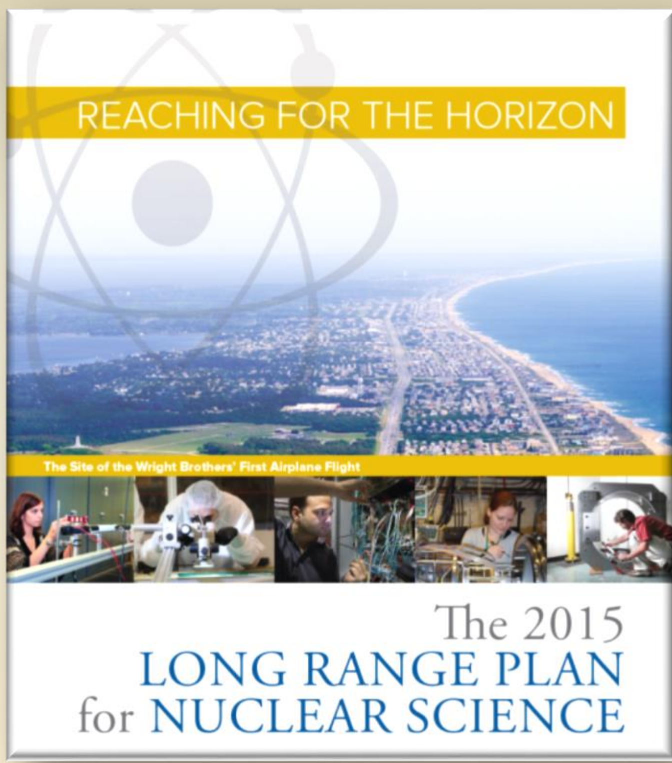








2015 NSAC Long Range Plan

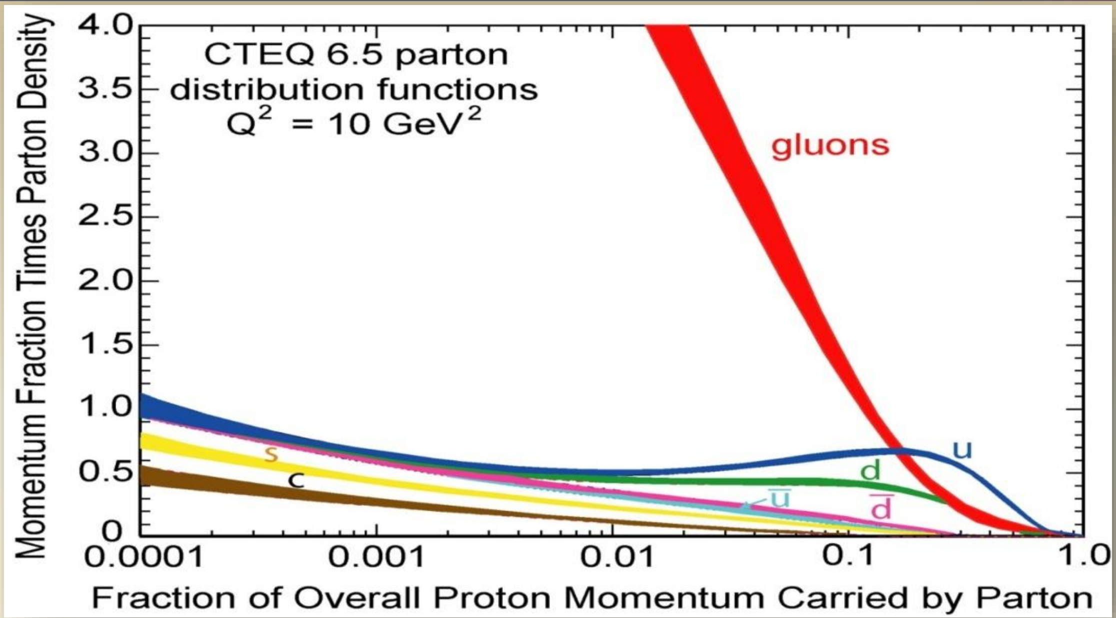


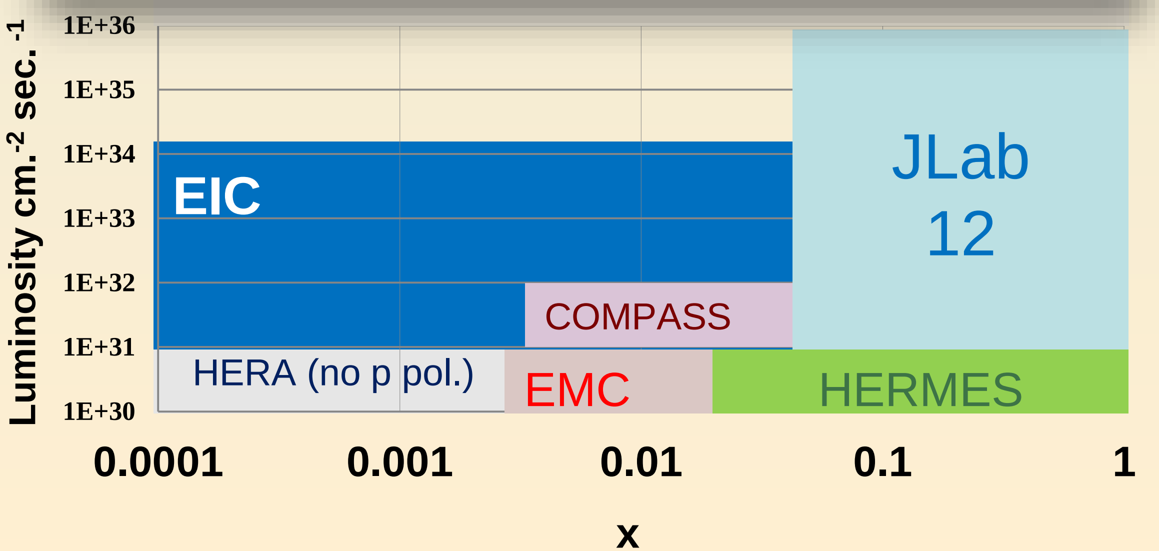
RECOMMENDATION III

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

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

The New Landscape Enabled by EIC





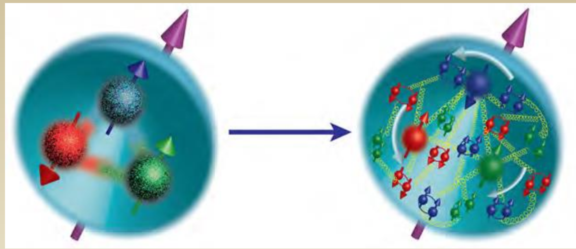
- High Luminosity
  → $10^{34}\ cm^{-2}s^{-1}$
- Low x regime
  x → 0.0001
- High Polarization
  → 70%

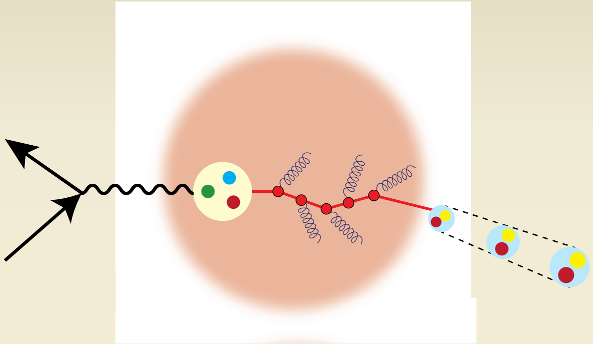
Discovery Potential!

A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?

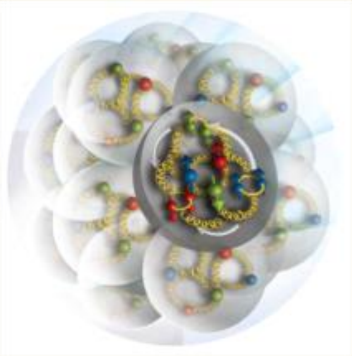




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

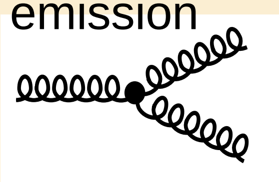
How do the quark-gluon interactions create nuclear binding?



How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

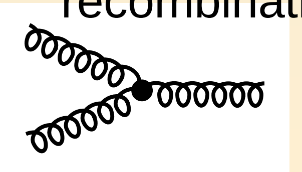
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission



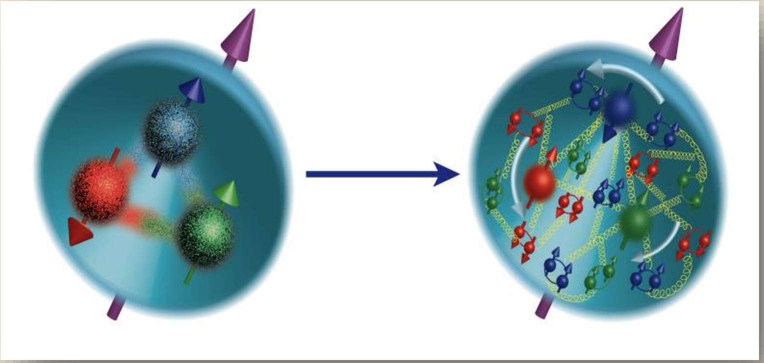
?
=

gluon recombination



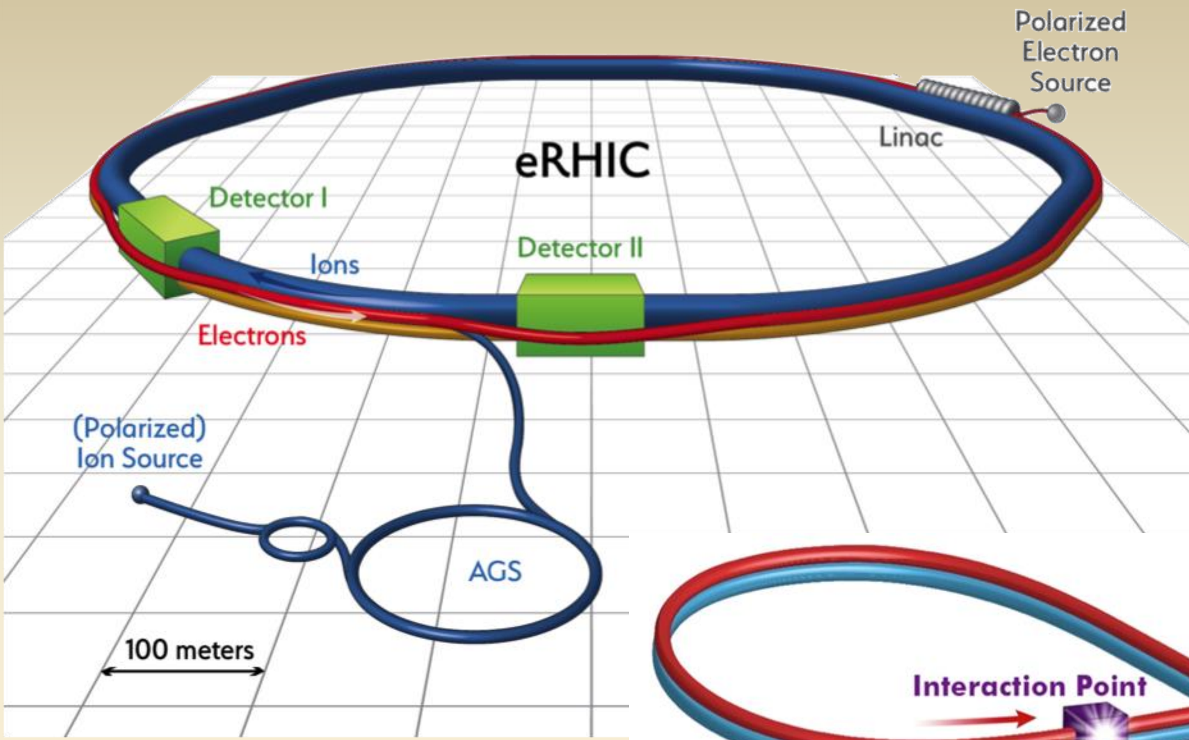
The World's First Polarized Electron-Proton Collider

Polarized proton as a laboratory for QCD

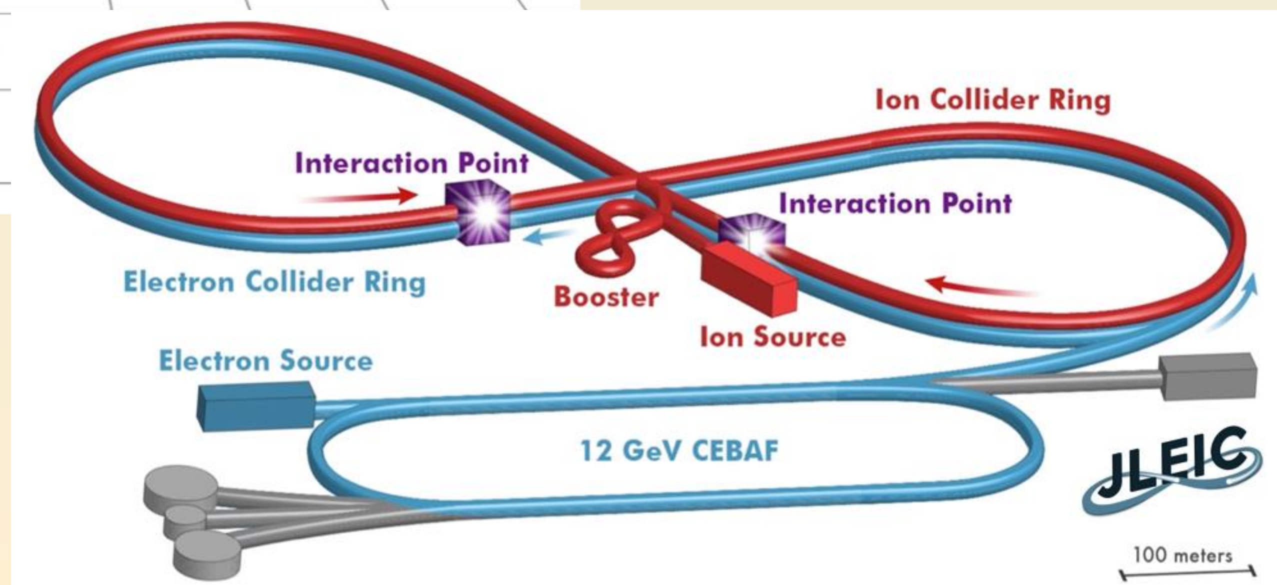


- Nucleon femtography for sea quarks and gluons.
- How do the *nucleon properties such as* ***spin and mass emerge*** from them and their interactions?

US-Based EIC Proposals



Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

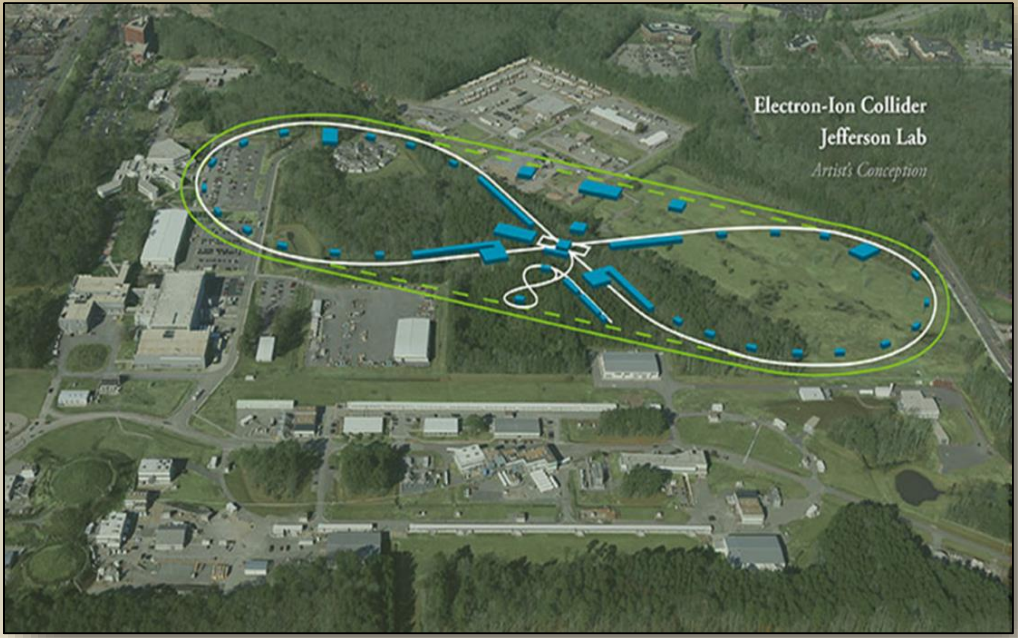
EIC at Jefferson Lab

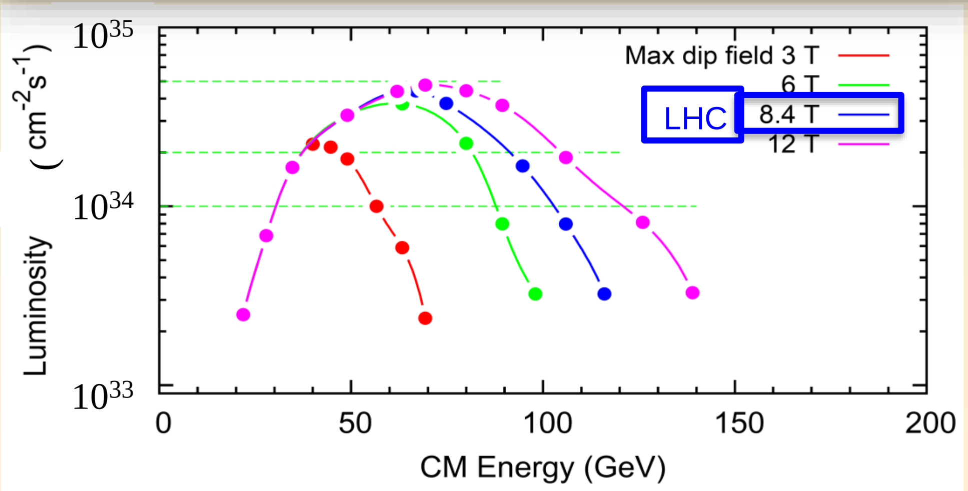
JLab EIC Figure 8 Concept

- High Polarization
- High Luminosity
- Low technical risk
- Flexible timeframe for construction consistent w/running 12 GeV CEBAF
- Cost effective operations

➢ Fulfills White Paper Requirements

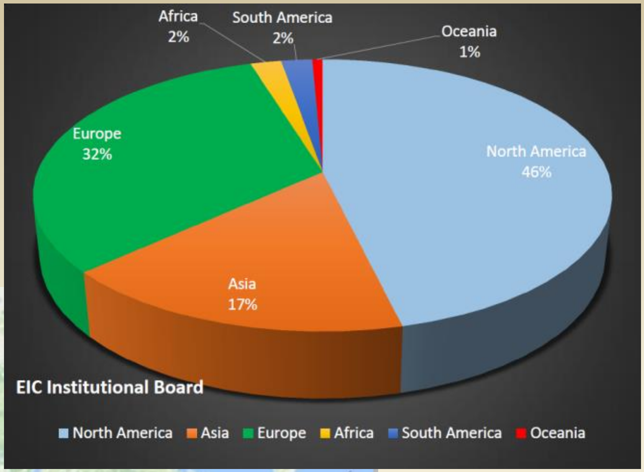
- Collaboration with SLAC, LBNL, ANL, BNL
- Site evaluation (Virginia funds)
- User group organizing (charter, meetings)
- NAS study underway
- DOE-NP accelerator R&D program (FY17-18)





EIC Users Group and International Interest

Formed 2016, currently: 705 members
162 institutions, 29 countries



Jefferson Lab: Today and Tomorrow

- The Jefferson Lab electron accelerator is a unique world-leading facility for hadron and nuclear physics research

- 12 GeV upgrade ensures at least a decade of excellent opportunities for discovery
  - New vistas in QCD
  - Growing program Beyond the Standard Model
  - Additional equipment: MOLLER, SoLID, plus smaller projects

- EIC moving forward:
  - Strong science case, much builds on JLab 12 GeV program
  - JLEIC design well developed – time scale following 12 GeV program is “natural”
  - NSAC 2015 Long Range Plan recommendation