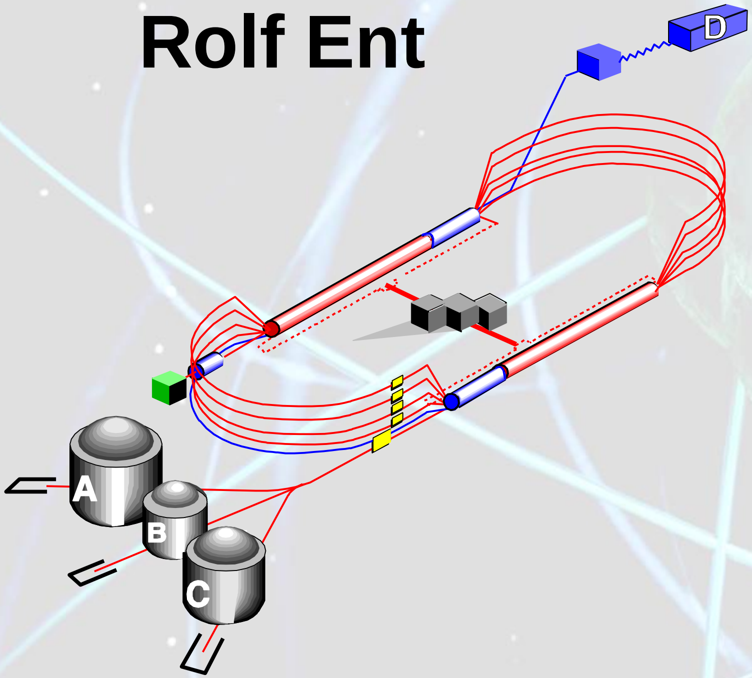
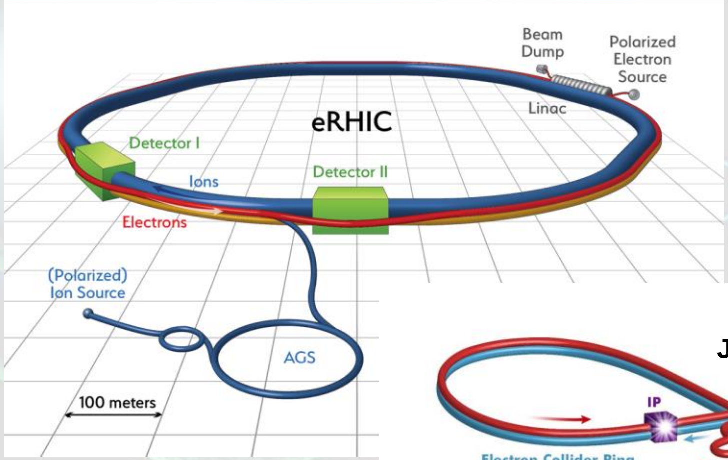
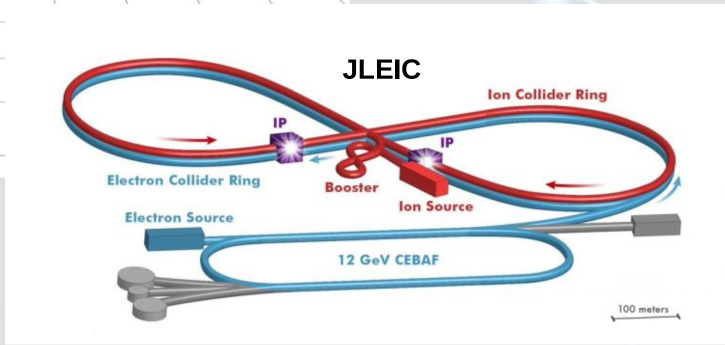
Perspective on Nuclear Physics at Jefferson Lab, from 12 GeV to EIC – Why Should We Be Excited?

Rolf Ent







Outline

Topics interspersed in this talk:

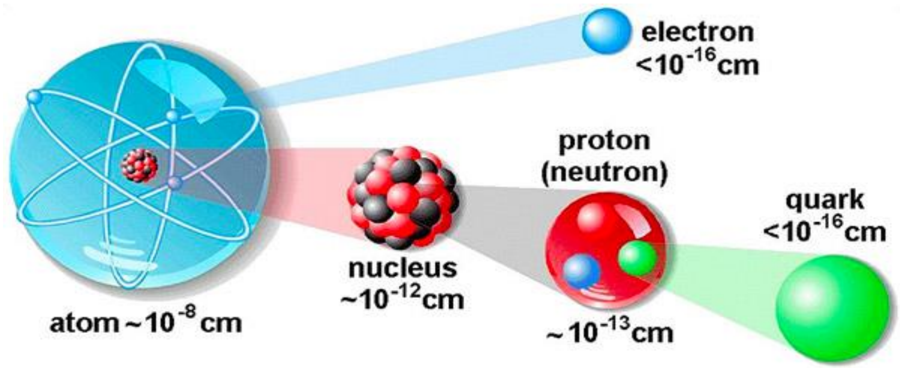
- Baryon and Light-Meson Spectroscopy
- Nucleon Form Factors and Low-Energy Hadron Structure
- Electroweak Studies – Searches for Physics BSM
- Partonic Structure of Nucleons and Nuclei
    - Parton Distributions
    - 3D Imaging
    - Nuclear Effects
- Spin and Helicity Parton Distributions
- Meson Structure
- Emergence of Hadrons
- Gluon Dynamics

The theme of this talk may be that while we may think we know a lot about the quark-gluon structure of nucleons and nuclei, there are many outstanding issues. Progress is good, and prospects are good, and we are in my view on the verge of a true transformation.

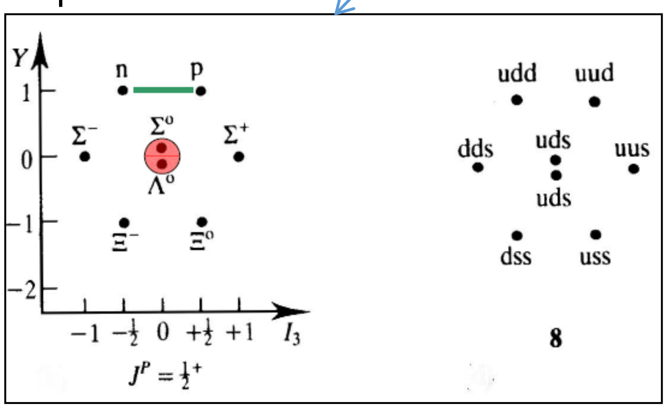
The low- and high-energy side of nuclei

The Low Energy View of Nuclear Matter

- nucleus = protons + neutrons
- nucleon ↔ quark model
- (valence) quark model ↔ QCD

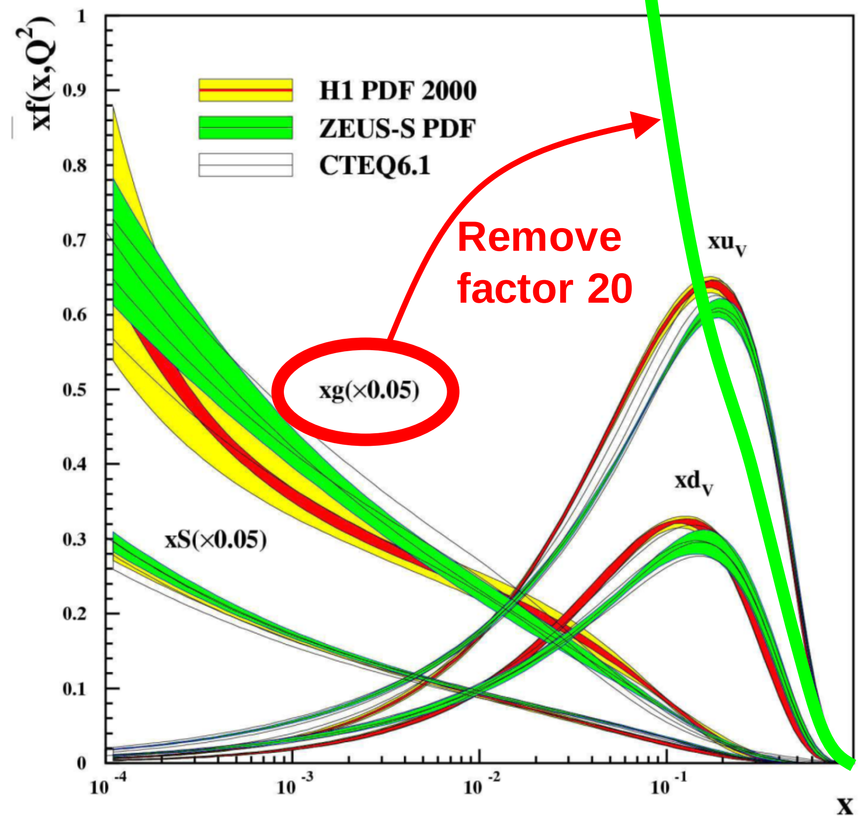


quark model

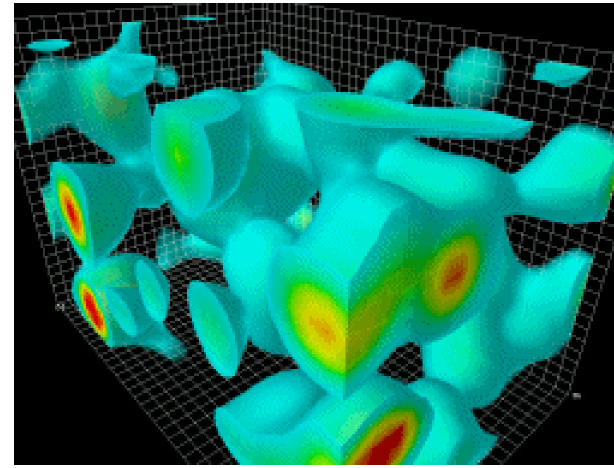


The High Energy View of Nuclear Matter

The visible Universe is generated by quarks, but dominated by gluons!
But what influence does this have on hadron structure?

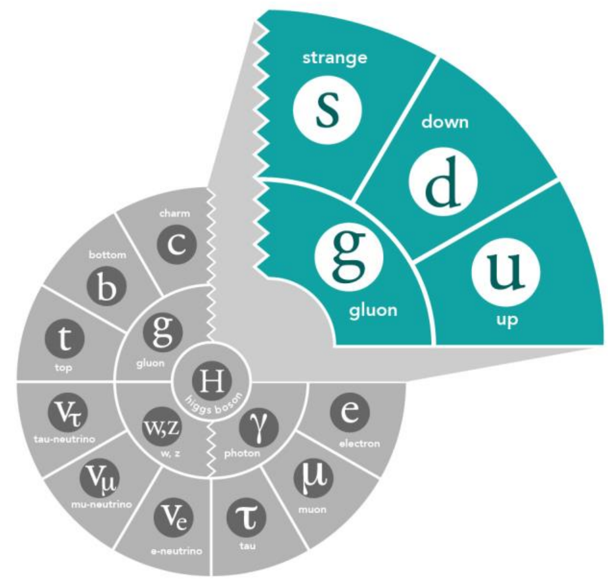


Gluons and QCD



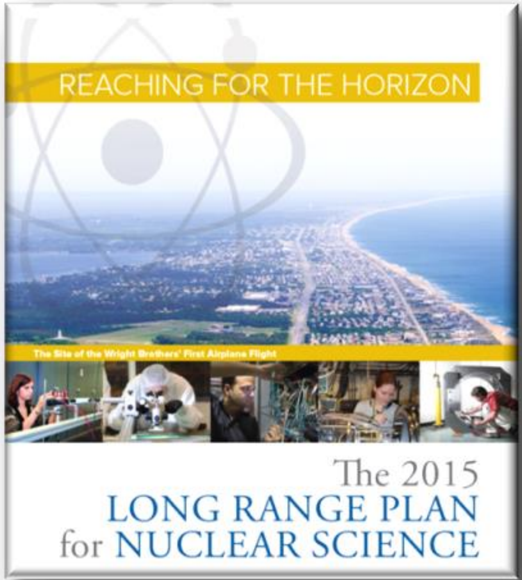
- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum

- Facts:
  - The essential features of QCD (e.g. asymptotic freedom, dynamical chiral symmetry breaking, and color confinement) are driven by gluons!
  - Unique aspect of QCD is the self interaction of the gluons
  - Mass from massless gluons and nearly massless quarks
    - Most of the mass of the visible universe emerges from quark-gluon interactions
    - The Higgs mechanism has almost no role here



Nuclear Science Long-Range Planning

Every 5-7 years the US Nuclear Science community produces a Long-Range Planning (LRP) Document

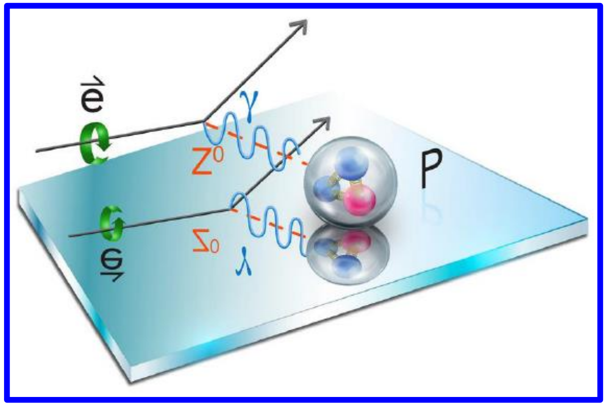


- **From Recommendation I:**

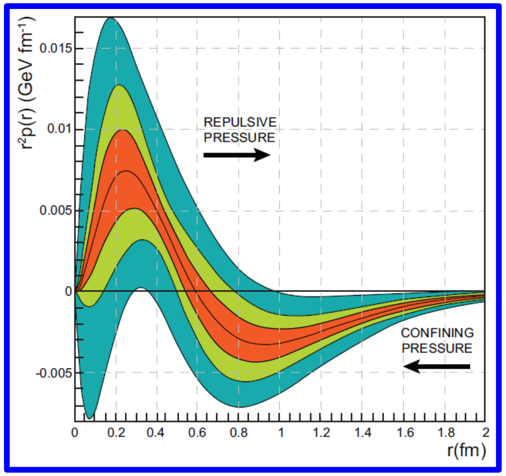
"With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized."

Still New Science Highlights of the 6-GeV Era

Final Qweak results accepted for publication in *Nature*



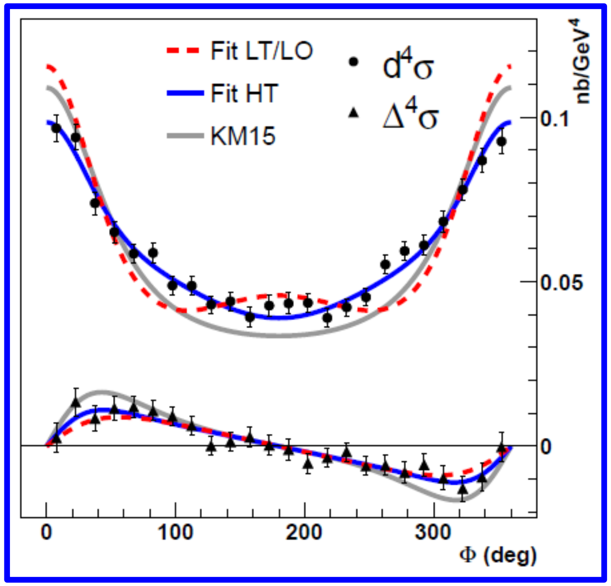
The weak charge of the proton – "Qweak", represents the (tiny) difference of the charge of the proton and it's mirror image



The pressure distribution inside the proton accepted for publication in *Nature*

A glimpse of gluons through deeply virtual compton scattering on the proton, published in *Nature Communications* 8, 1408 (2017).

doi:10.1038/s41467-017-01819-3

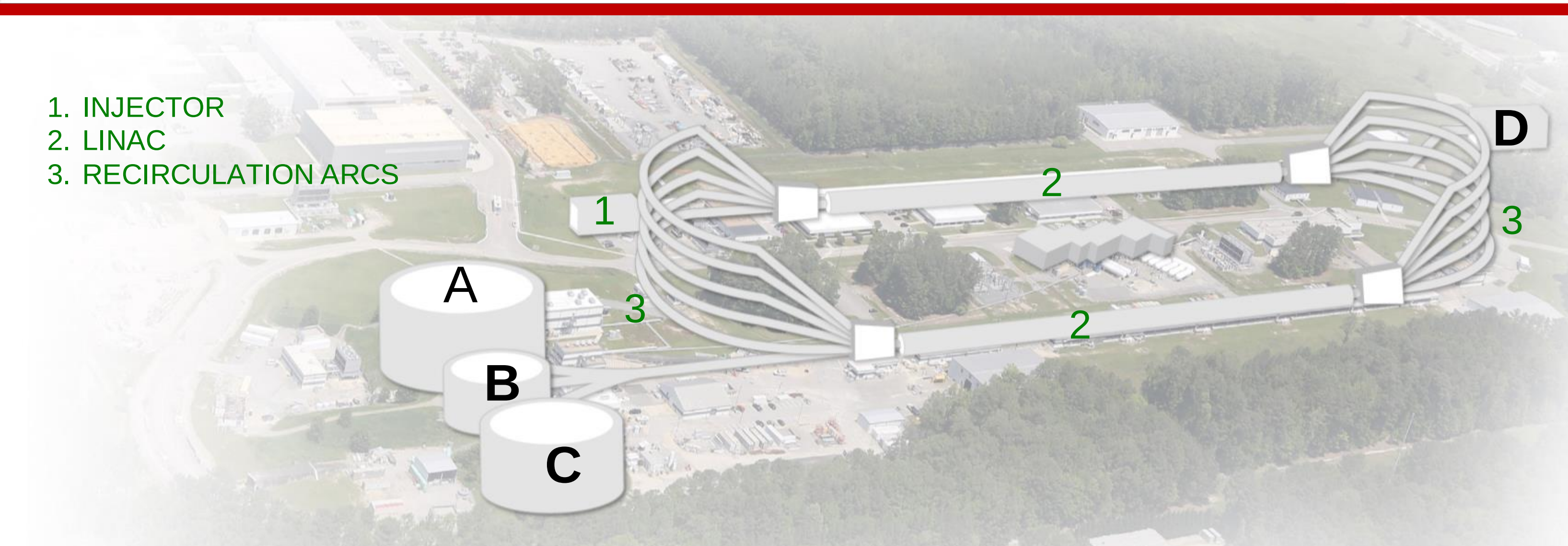


State N(mass)J^P	PDG pre 2012	PDG 2018*
N(1710)1/2⁺	***	****
N(1880)1/2⁺		***
N(1895)1/2⁻		****
N(1900)3/2⁺	**	****
N(1875)3/2⁻		***
N(2120)3/2⁻		**
N(2000)5/2⁺	*	**
N(2060)5/2⁻		**
Δ(2200)7/2⁻	*	***

- **** Existence is certain
- *** Existence is very likely
- ** Evidence of existence is fair
- * Evidence of existence is poor

Multiple nucleon resonances now confirmed; highlighted in Particle Data Group (PDG) tables.

CEBAF at Jefferson Lab

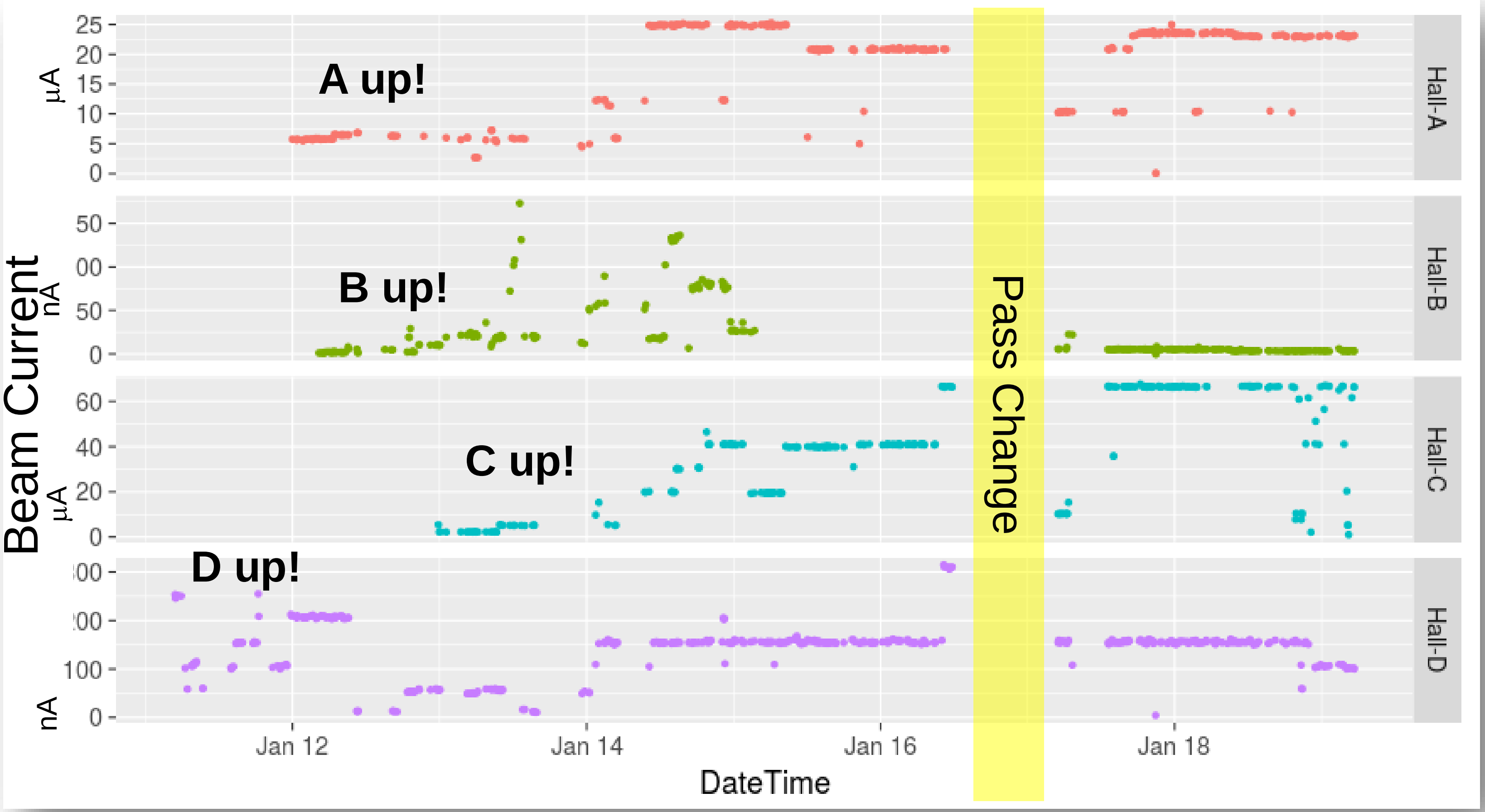


- CEBAF Upgrade completed in September 2017
  - CW electron beam
  - E_{max} = 12 GeV
  - I_{max} = 90 μA
  - Pol_{max} = 90%
- Commissioning:
  - April 2014: hall A
  - October 2014: hall D
  - February/March 2017: halls C & B

CEBAF World-leading Capabilities

- Nuclear experiments at ultra-high luminosities, up to 10^{39} electrons-nucleons /cm^2/ s
- World-record polarized electron beams
- Highest intensity tagged photon beam at 9 GeV
- Ability to deliver a range of beam energies and currents to multiple experimental halls simultaneously
- Unprecedented stability and control of beam properties under helicity reversal

Initiated Four Hall Operation

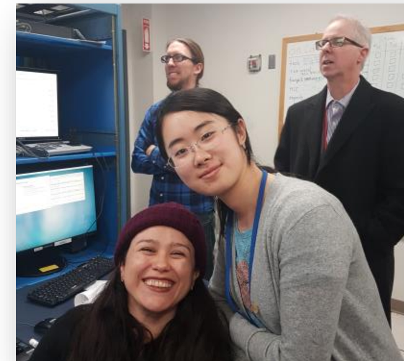


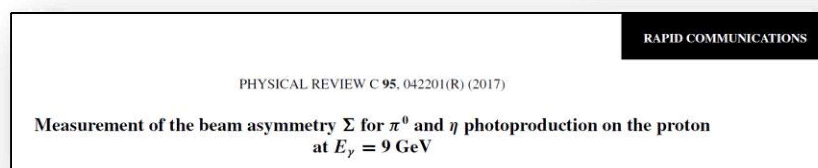
Simultaneous 4-Hall Beam Delivery since Jan 18, 2018

Now operating total 900 kW CW beam power to 4 Halls

12 GeV Science Era in all 4 Halls!

- **Hall A:** **In physics operations**
  - 4.5 Experiments completed to date
  - First 12 GeV era publications will be this year
  - December 15, 2017: First Beam on Tritium Target!
  - Series of measurements on nuclear structure & quark properties that use that Helium-3 (2p + n) and Tritium (2n + p) are (Isotope) Mirror Nuclei
- **Hall B:** **In physics operations**
  - Engineering run completed, up to nearly twice design luminosity
  - CLAS12 Physics data taking started February 5, 2018!
  - Hall B Proton Radius and Heavy Photon Search of pre-CLAS12 measurements publications anticipated
- **Hall C:** **In physics operations**
  - New spectrometer engineering run completed
  - Physics data taking started January 19, 2018!
  - Series of "simple" measurements on Nucleon and Nuclear Structure that can lead to early publications – 2 Experiments completed to date
- **Hall D:** **In physics operations (GlueX)**
  - Engineering Run Complete: Basis for > dozens papers at both American Physical Society (APS) Division of Nuclear Physics 2016 & 2017 Meetings
  - First 12 GeV era publication: 24 April, 2017!
  - Working on **several other publications**
  - First physics run (GlueX – search for exotic mesons) started in Spring 2017 and continuing in 2018

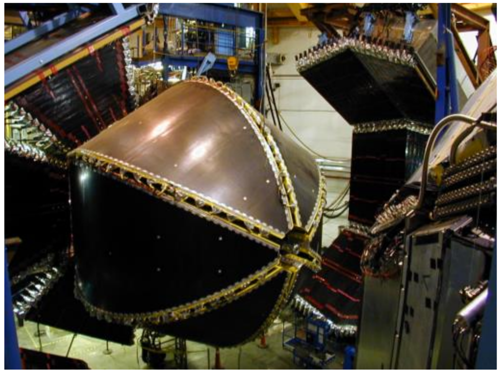



RAPID COMMUNICATIONS

PHYSICAL REVIEW C **95**, 042201(R) (2017)

Measurement of the beam asymmetry Σ for π^0 and η photoproduction on the proton at $E_\gamma = 9$ GeV

Solving the “missing resonances” puzzle



Star ratings of PDG before 2012 and projections for 2018, following a worldwide experimental and theoretical effort.

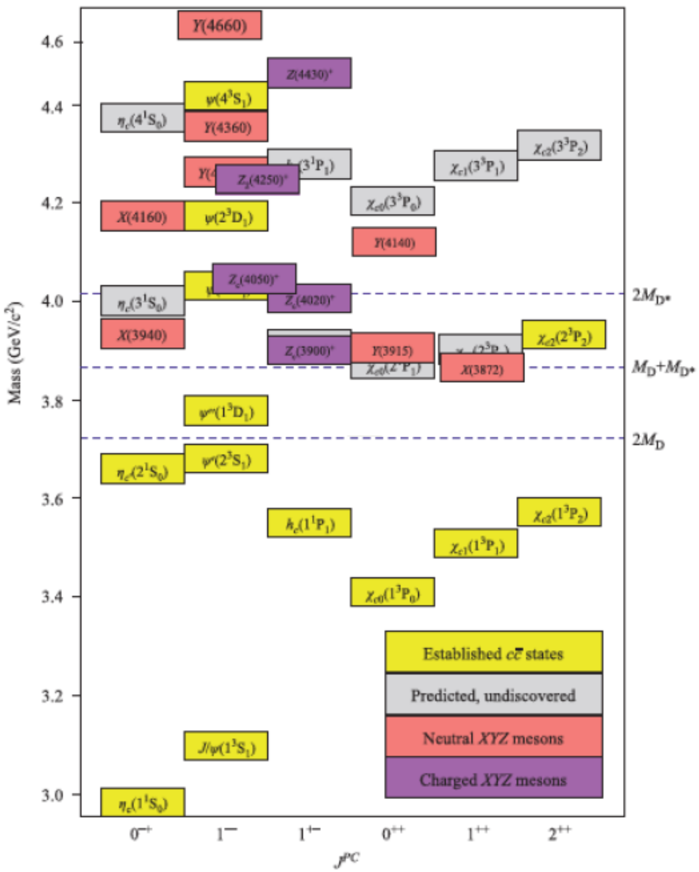
State $N(mass)J^P$	PDG pre 2012	PDG 2018*
$N(1710)1/2^+$	***	****
$N(1880)1/2^+$		***
$N(1895)1/2^-$		****
$N(1900)3/2^+$	**	****
$N(1875)3/2^-$		***
$N(2120)3/2^-$		**
$N(2000)5/2^+$	*	**
$N(2060)5/2^-$		**
$\Delta(2200)7/2^-$	*	***

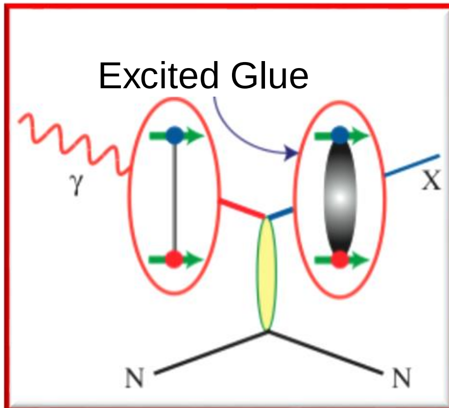
*) projected

****	Existence is certain
***	Existence is very likely
**	Evidence of existence is fair
*	Evidence of existence is poor

Hadron Spectroscopy in the 21st Century

Heavy quarks:
XYZ states in the charmonium sector



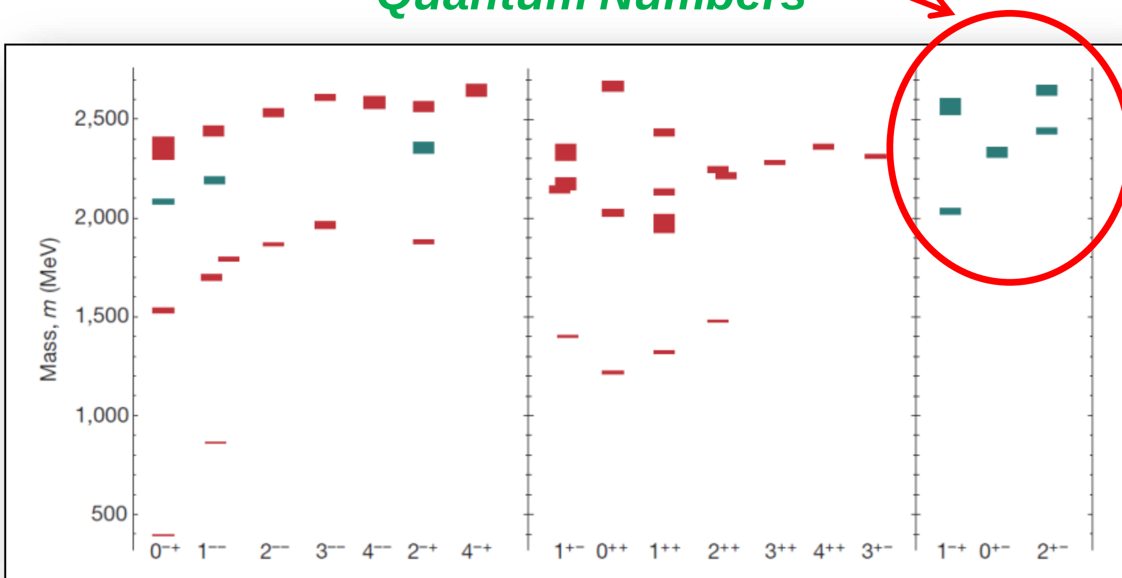


nature
International weekly journal of science

Searching for the rules that govern hadron construction

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

States with Exotic Quantum Numbers



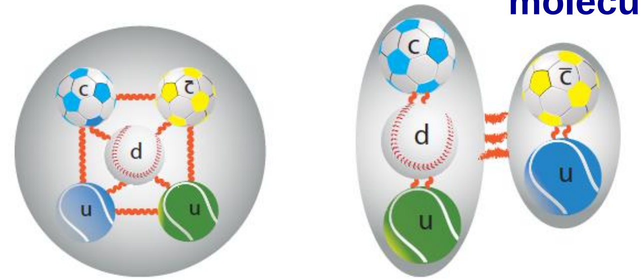
FY19 Halls C & B – nature of charmed pentaquark

What is the exact nature of the *charmed pentaquark* states discovered by the LHCb collaboration at CERN?

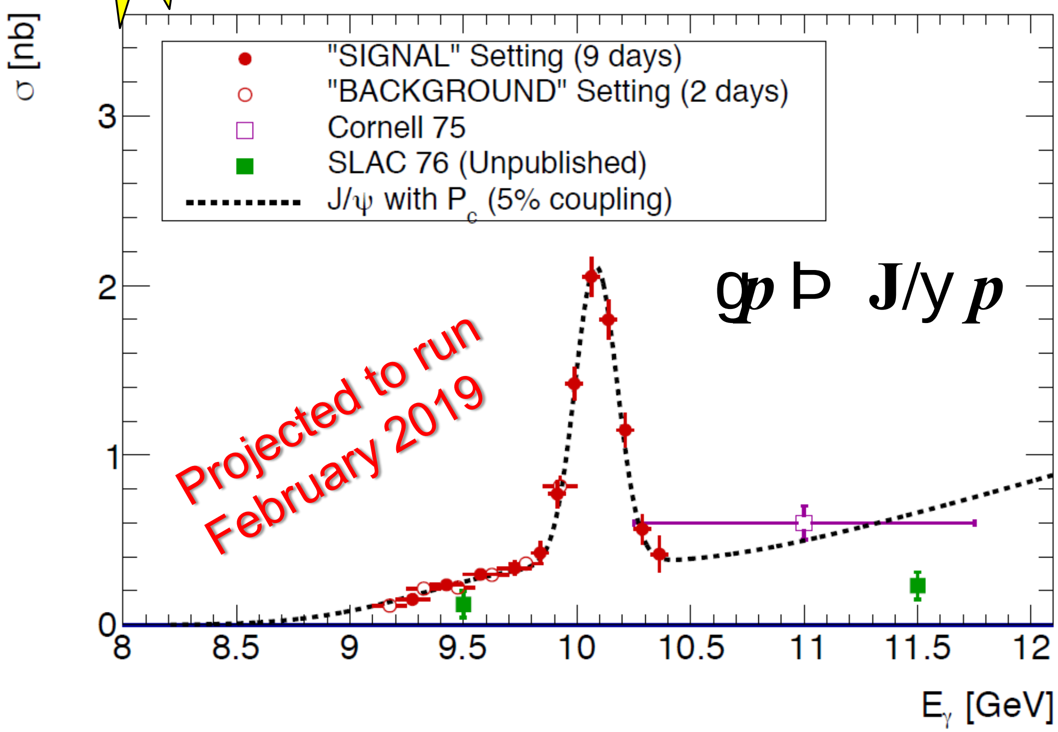
P_c Þ $J/$y p

high impact

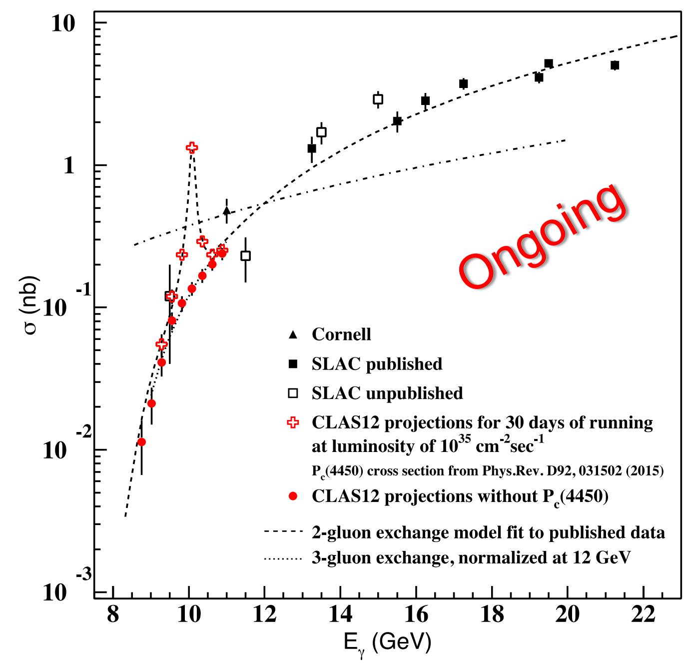
5-quark bound state | **Hadronic molecule**



Hall C



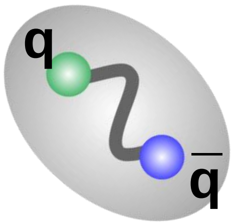
Hall B



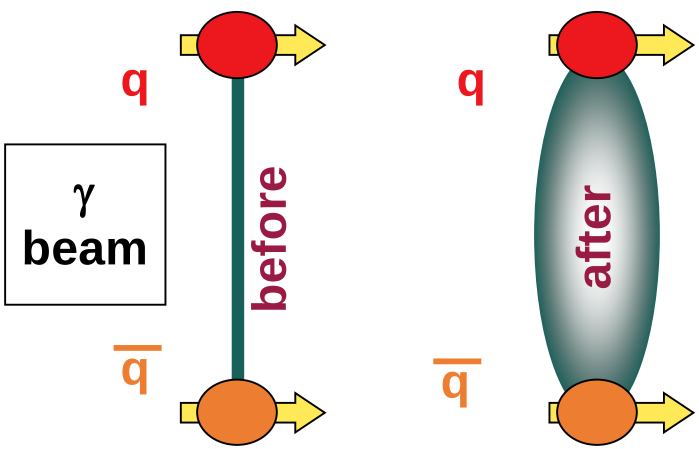
Gluonic Excitations and the mechanism for confinement

QCD predicts a rich spectrum of as yet to be discovered gluonic excitations - whose experimental verification is crucial for our understanding of QCD in the confinement regime.

With the upgraded CEBAF, a linearly polarized photon beam, and the GlueX detector, Jefferson Lab will be uniquely poised to:
- discover these states,
- map out their spectrum, and
- measure their properties

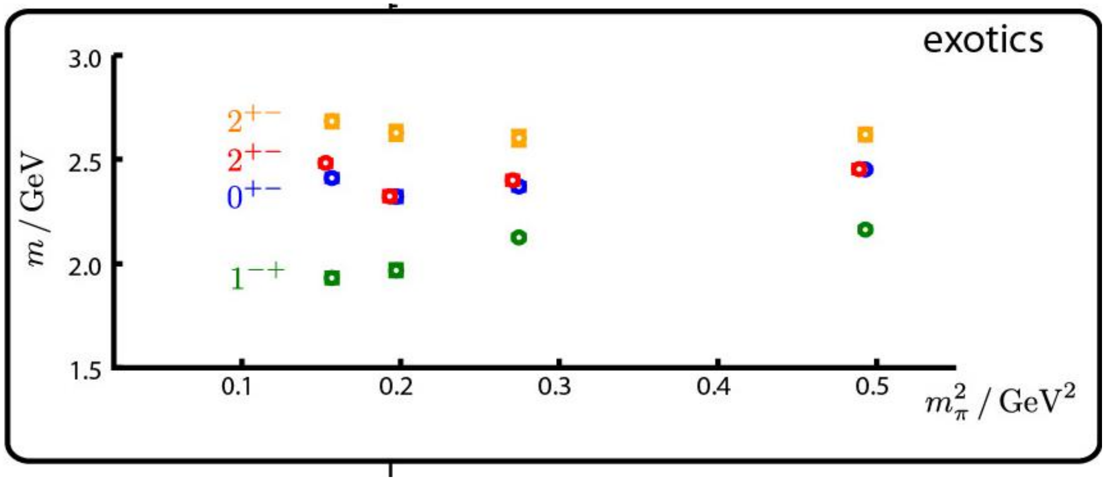


GlueX Phase I complete Fall 2018

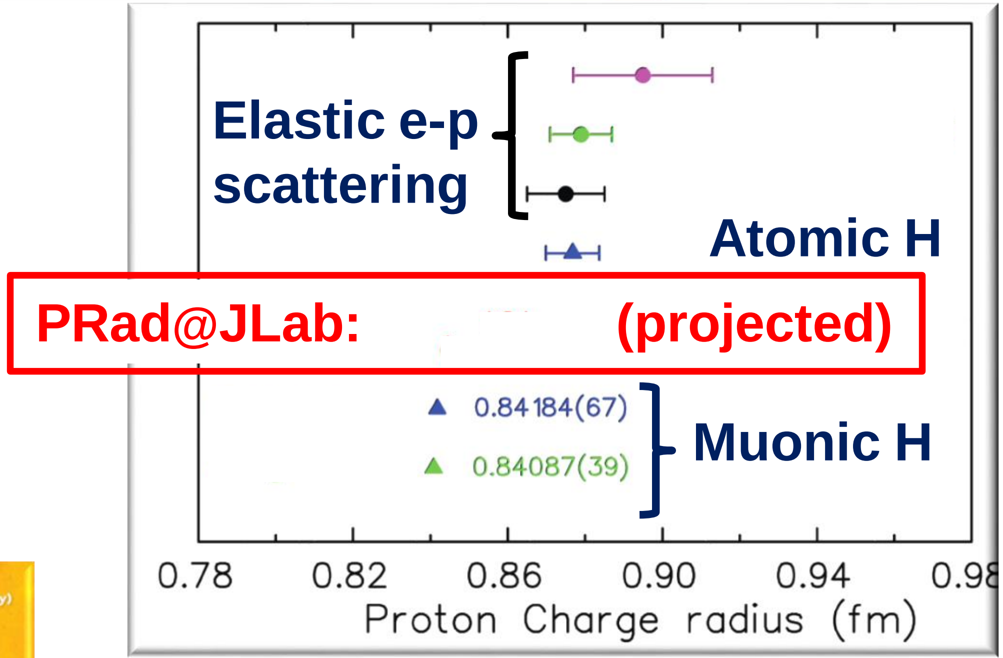


Dudek et al.

States with Exotic Quantum Numbers



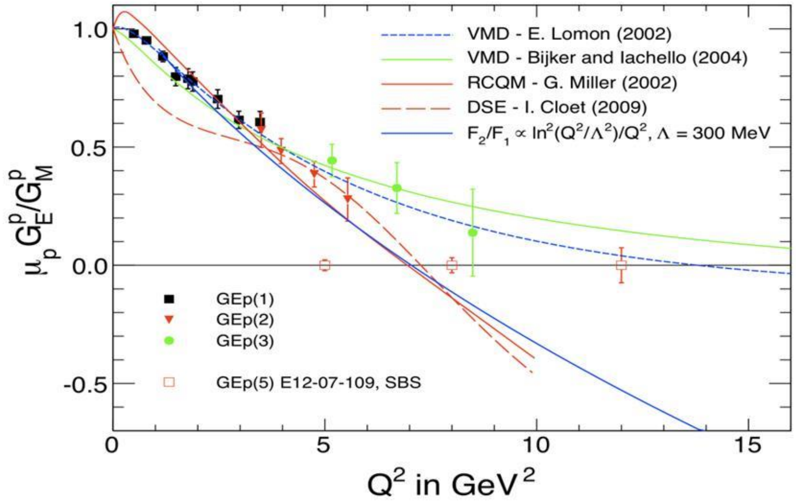
Solving the Proton Radius Puzzle

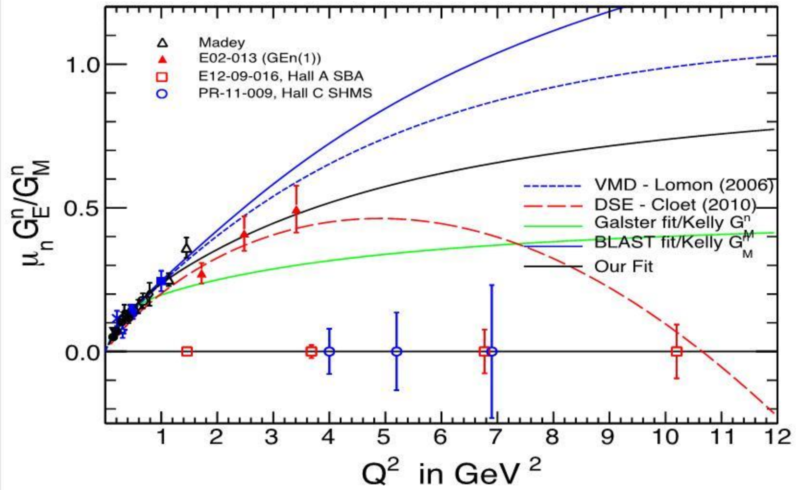


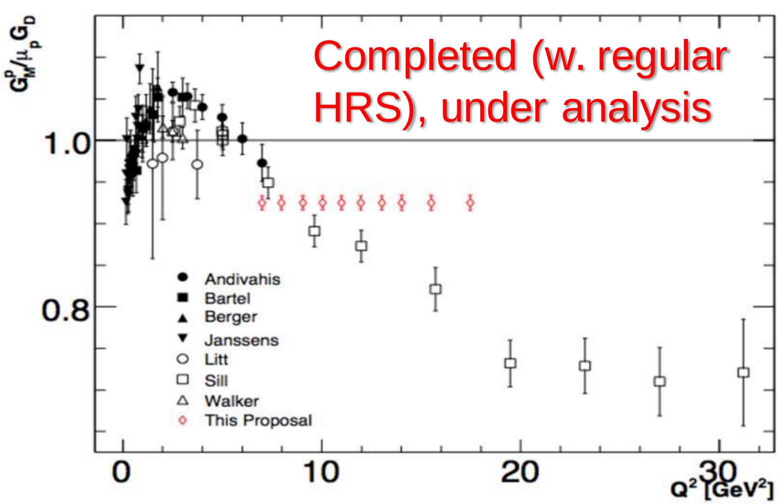
- PRad: new experiment to address proton radius @ Jefferson Lab
- NSF MRI: H_2 gas target,
  DOE: GEM tracking detectors
- Successful run in summer 2016
- Cross sections shown at DNP 2017
- Also MUSE @ PSI coming up

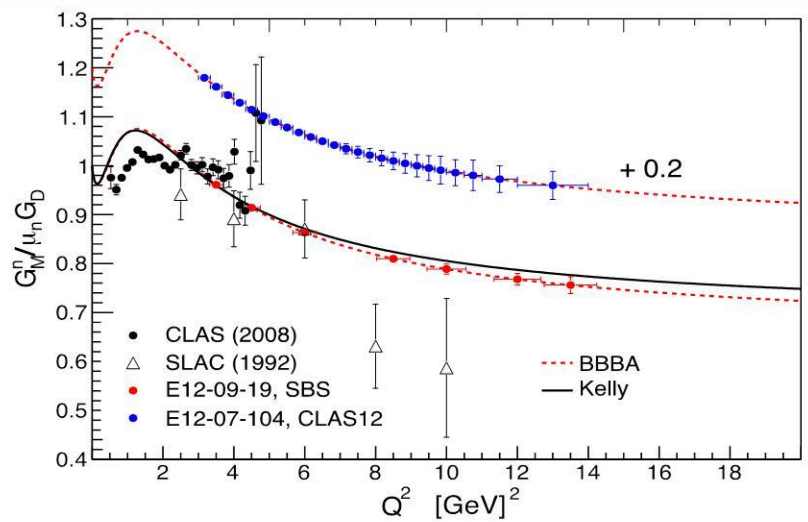
Extending Q^2 Range of Nucleon Form Factors

Physics reach extended to **$Q^2 > 10$ GeV^2** by SuperBigbite Spectrometer (SBS) in Hall A



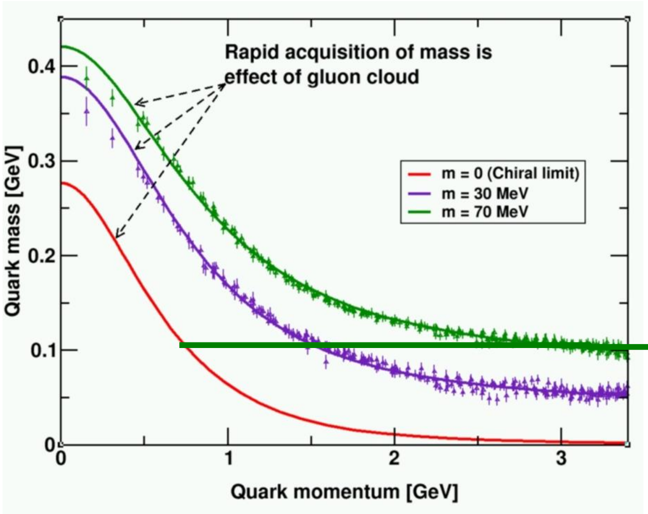


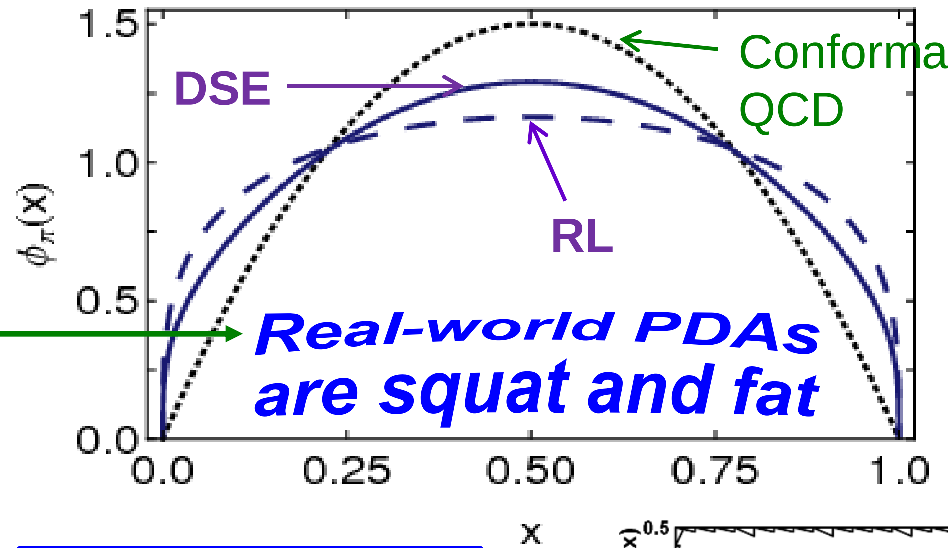


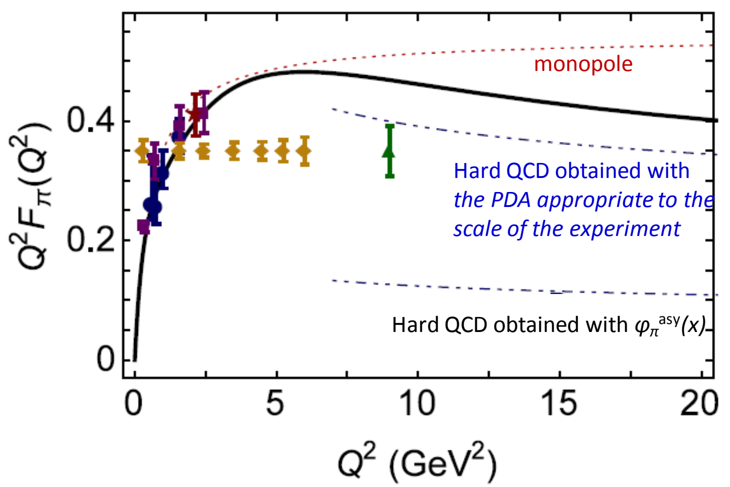


Allows for flavor decomposition to distance scales deep inside the nucleon

Pion Form Factor and Structure Function





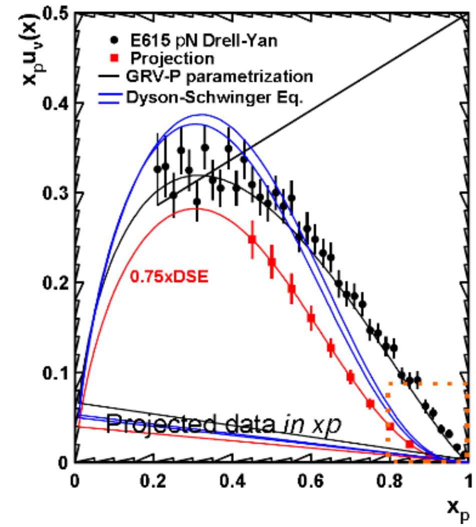


Pion FF – first quantitative access to hard scattering scaling regime?

Implications if so: two longstanding puzzles could be solved

1. Magnitude of pion form factor in hard scaling regime
2. Power of pion parton behavior at large x

Also implications for nucleon and N form factor interpretation (not shown here).*

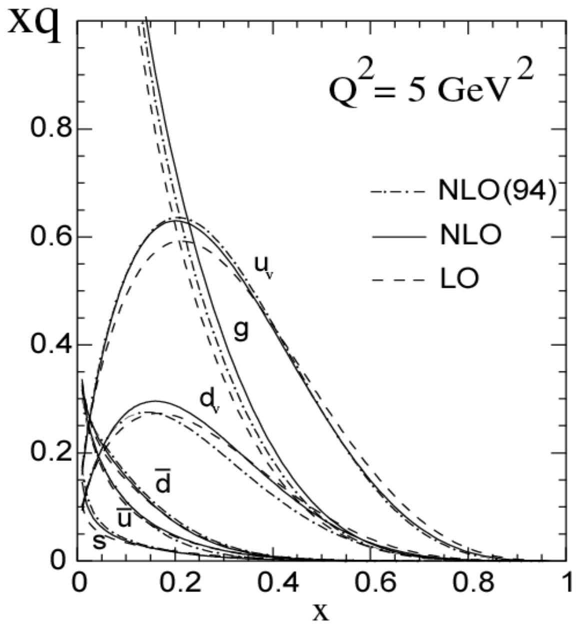


Pion SF – $(1\text{-}x)^{-1}$ or $(1\text{-}x)^{-2}$ dependence at large x?

Measuring High-x Structure Functions

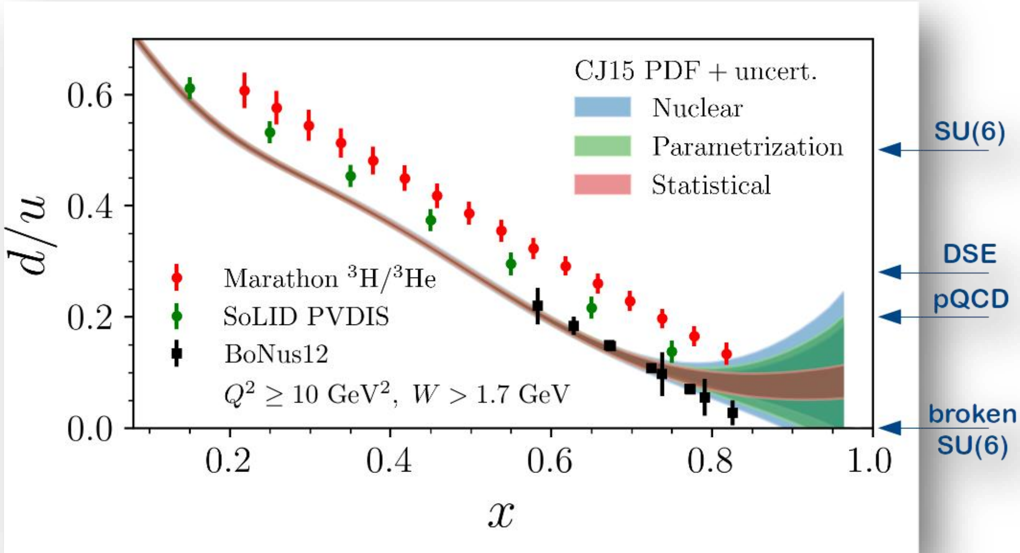
REQUIRES:

- High beam polarization
- High electron current
- High target polarization
- Large solid angle spectrometers



12 GeV will access the regime (x > 0.3), where valence quarks dominate

Projected JLab 12 GeV *d/u* Extraction



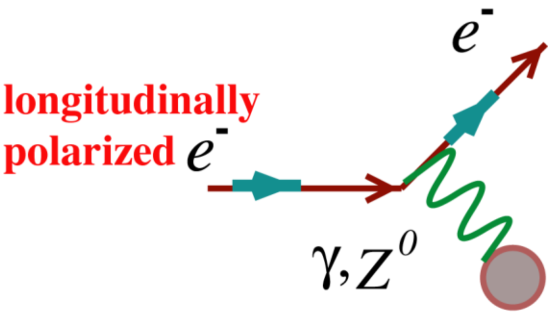
Marathon $^3H/^3He$ completed!

$x \to 1$ predictions	F_2^n/F_2^p	d/u	A_1^n	A_1^p
SU(6)	2/3	1/2	0	5/9
Diquark Model/Feynman	1/4	0	1	1
Quark Model/Isgur	1/4	0	1	1
Perturbative QCD	3/7	1/5	1	1
QCD Counting Rules	3/7	1/5	1	1

Parity-Violating Asymmetries

Weak Neutral Current (WNC) Interactions at $Q^2 << M_Z^2$

Longitudinally Polarized Electron
Scattering off Unpolarized Fixed Targets



$$\sigma \;\alpha\; | A_\gamma + A_{weak} |^2$$

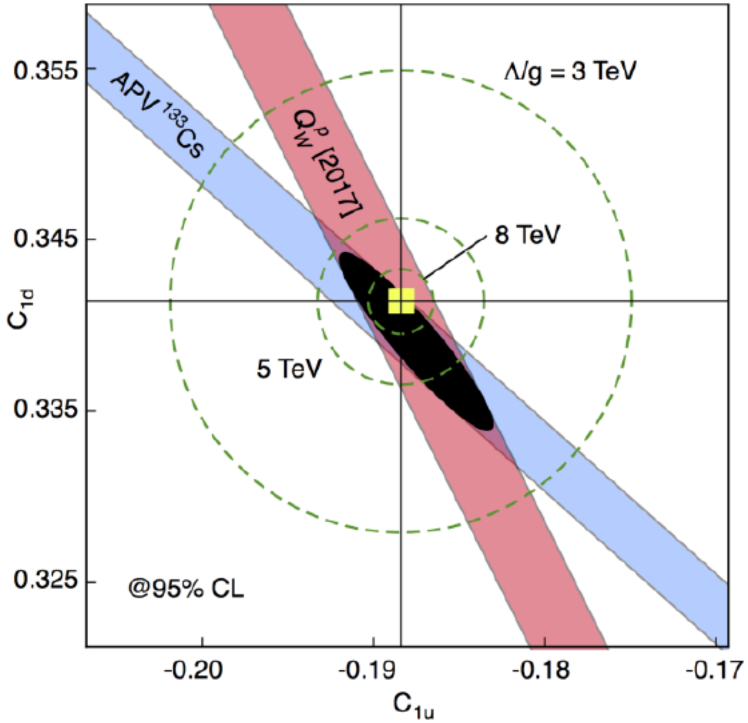
$$A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} \; (g_A^e g_V^T + \beta\, g_V^e g_A^T)$$

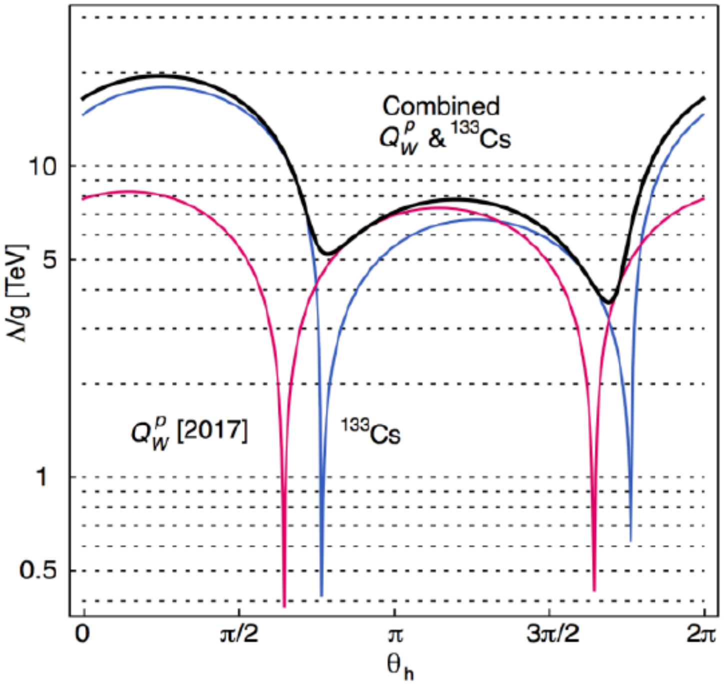
The couplings g depend on both electroweak physics and the weak vector and axial-vector hadronic current, and are functions of $\sin^2\Theta_W$

Mid 70s	goal was to show $\sin^2\Theta_W$ was the same as in ν scattering
1990-2010	target couplings probe novel aspects of hadron structure
Ongoing	precision measurements with carefully chosen kinematics to probe new physics at multi-TeV high energy scales

Qweak Results → Constraints

Qweak was one of the last 6-GeV era experiments to run, up to FY12

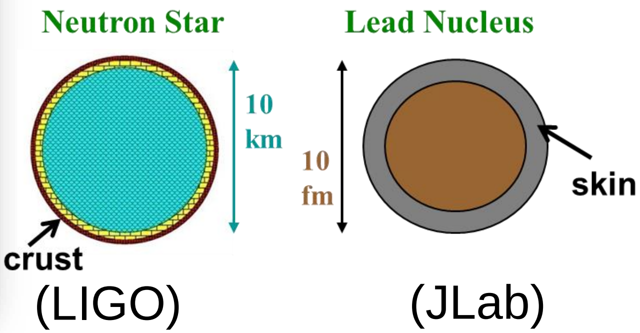


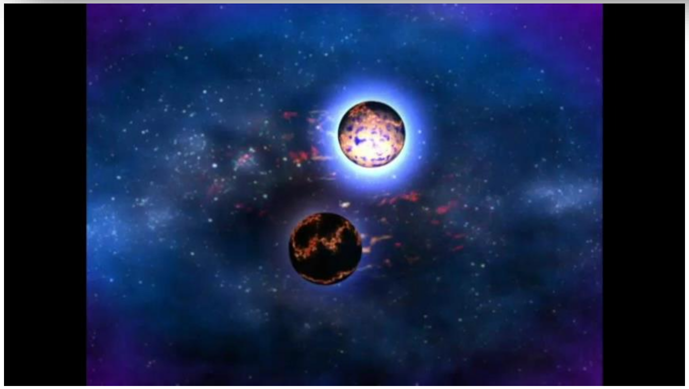


Constraints on the vector-quark, axial-electron weak coupling constants C_{1u} and C_{1d} provided by the Qweak and APV results.

Combined constraint raises the Θ_h-independent for generic new semi-leptonic Parity-Violating Beyond the Standard Model physics to 3.6 TeV (mass reach in Λ/g).

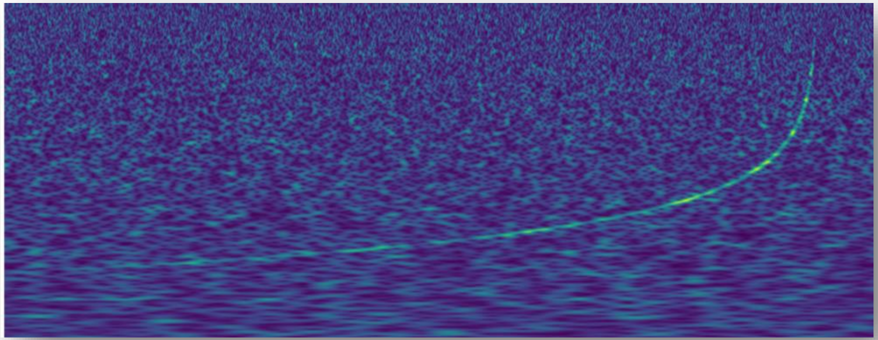
Hall A: Nuclear Physics and Neutron Stars

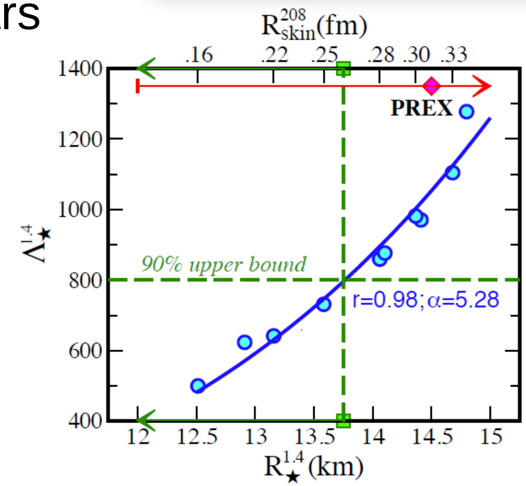




Courtesy of NASA/Goddard Space Flight Center

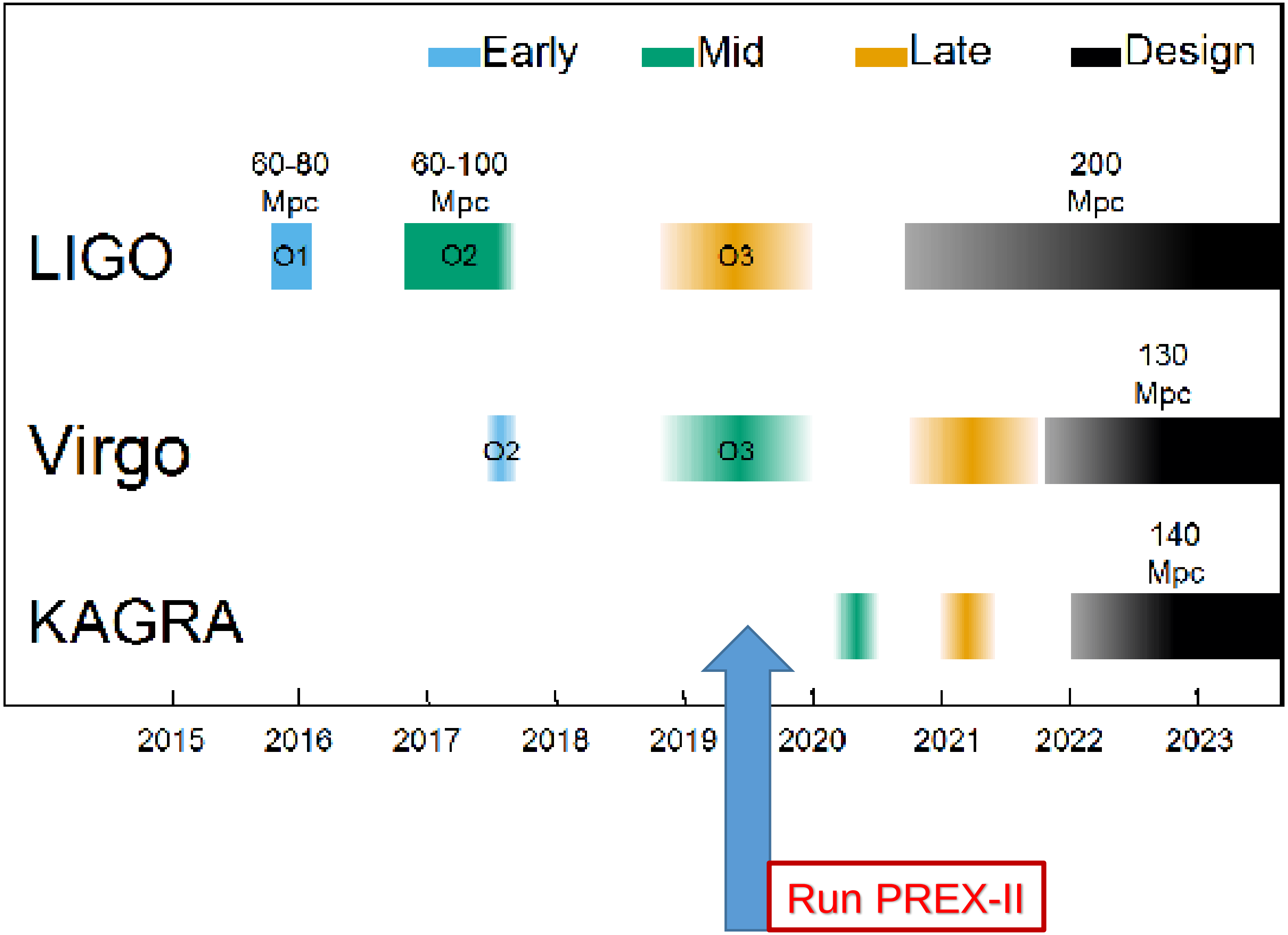
Measurement of neutron skin at JLab constrains tidal polarizability of neutron stars



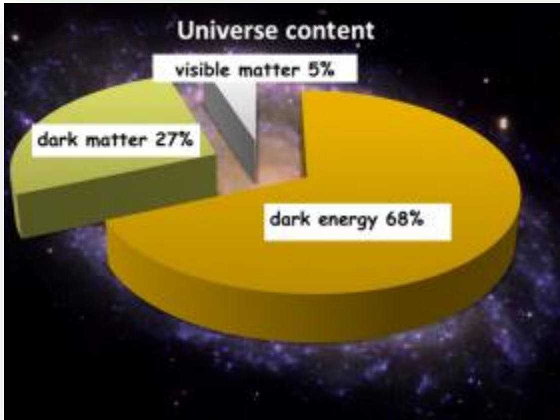


arXiv:1711.06615

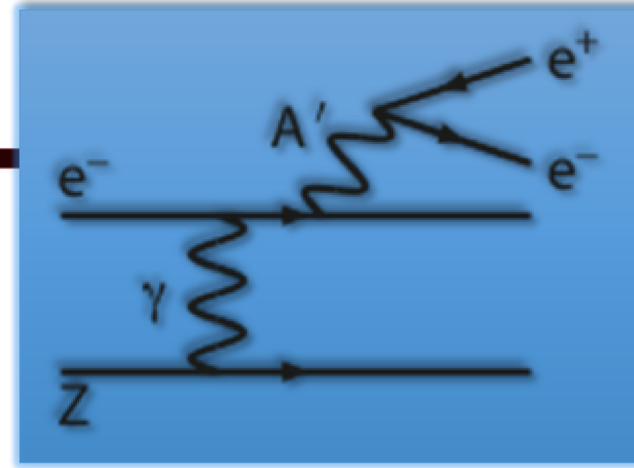
GW Astronomy Will Continue



Heavy Photon Search



Search for a U(1) Heavy Gauge Boson following up on cosmological observations (PAMELA, AMS)

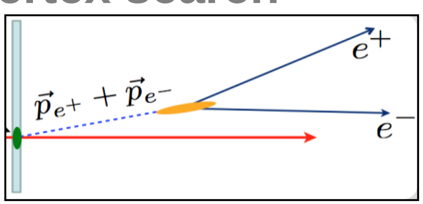


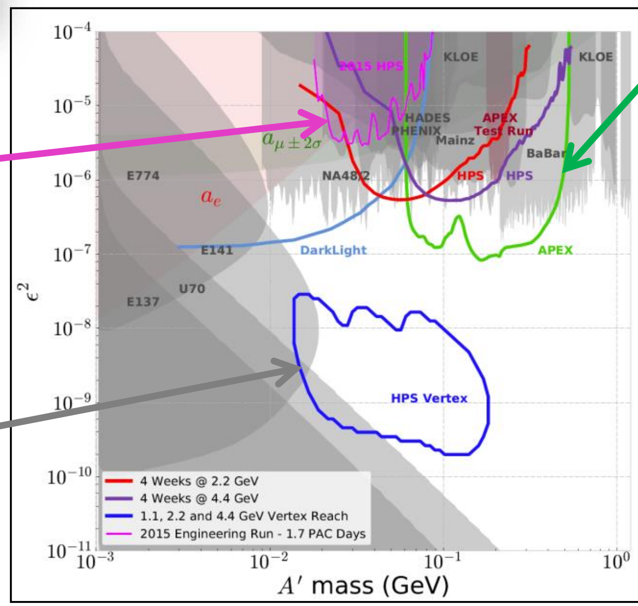
HPS (Hall B)

2015 Engineering Run
1.7 PAC days @ 1.05 GeV

2 GeV data taken in 2016, under analysis

Displaced decay vertex search





2019 Program: more HPS, APEX, also DarkLIGHT?

APEX (Hall A)
Search for 50-500 MeV A' decaying promptly to e^+e^- pairs

DARKLIGHT

Search for A' in "visible"

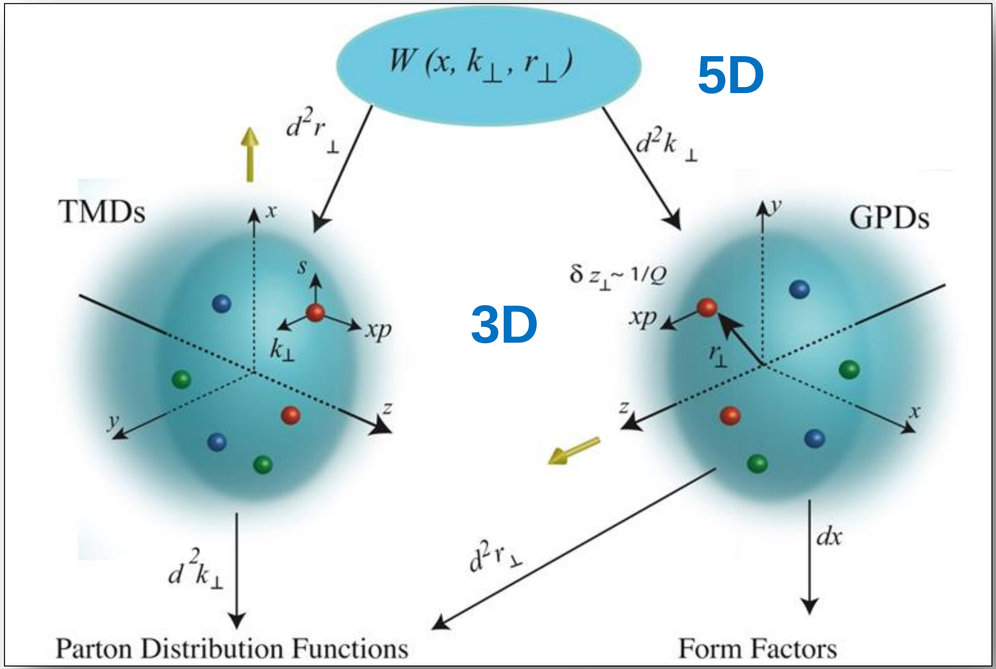
$$e^- p \rightarrow e^- p A',\ A' \rightarrow e^+ e^-$$

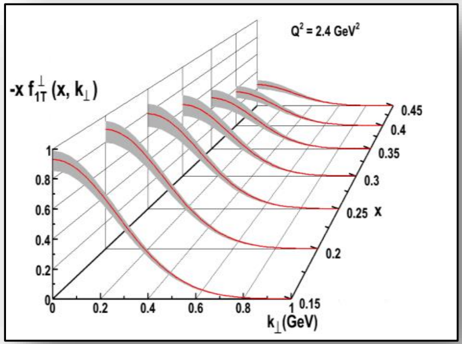
"invisible" decay modes

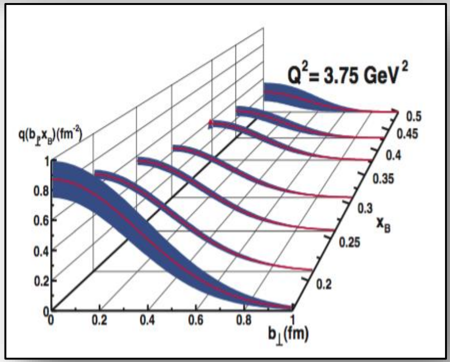
$$e^- p \rightarrow e^- p A',\ A' \rightarrow inv.$$

in region of ^{9}Be 17 MeV anomaly

New Paradigm for Nucleon Structure







- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets
  - Sophisticated detector systems

➡ **Major new capability with JLab12**

Exploring the 3D Nucleon Structure

- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to systematically move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
    - High luminosity, large acceptance experiments with polarized beams and targets.
    - Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions.

- **Deep Exclusive Scattering (DES)** cross sections give sensitivity to electron-quark scattering off quarks with longitudinal momentum fraction (Bjorken) x at a transverse location b.

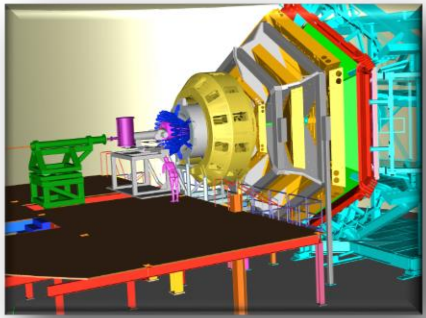
- **Semi-Inclusive Deep Inelastic Scattering (SIDIS)** cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum (k_T) of a parton and transverse momentum (p_T) created during the [parton → hadron] fragmentation process.

Nuclear Femtography

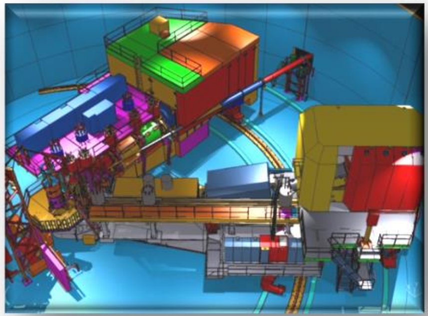
Imaging With JLab @ 12 GeV

Generalized Parton Distributions (GPDs) and Transverse Momentum Distributions (TMDs)

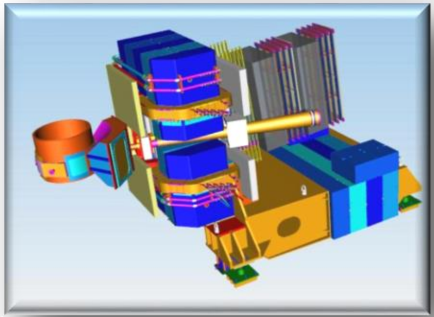
- CEBAF Large Acceptance Spectrometer (CLAS12) in Hall B: general survey experiments, large acceptance and medium luminosity



- SHMS, High Momentum Spectrometer (HMS) and Neutral-Particle Spectrometer (NPS) in Hall C: precision cross sections for L-T studies and ratios, small acceptance and high luminosity



- Super Bigbite Spectrometer (SBS) in Hall A : dedicated large-x TMD study medium acceptance and high luminosity

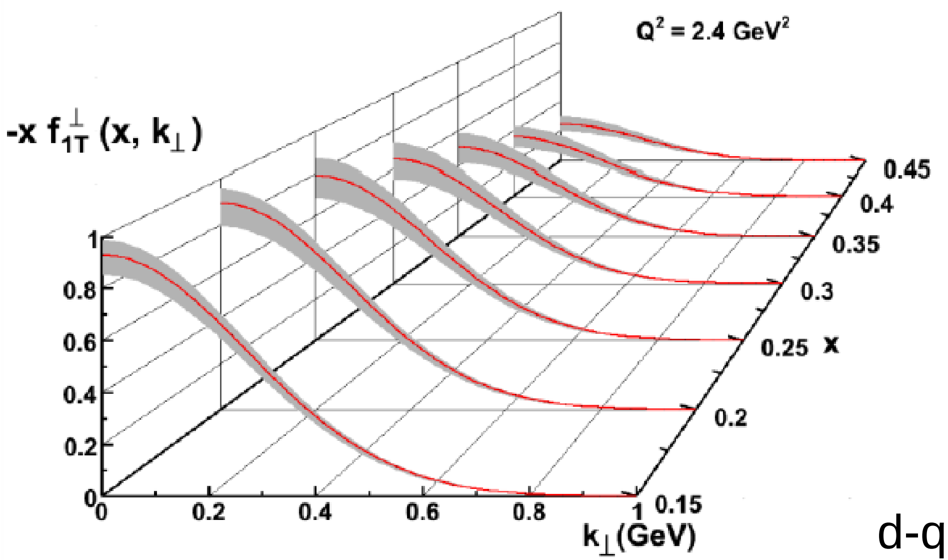


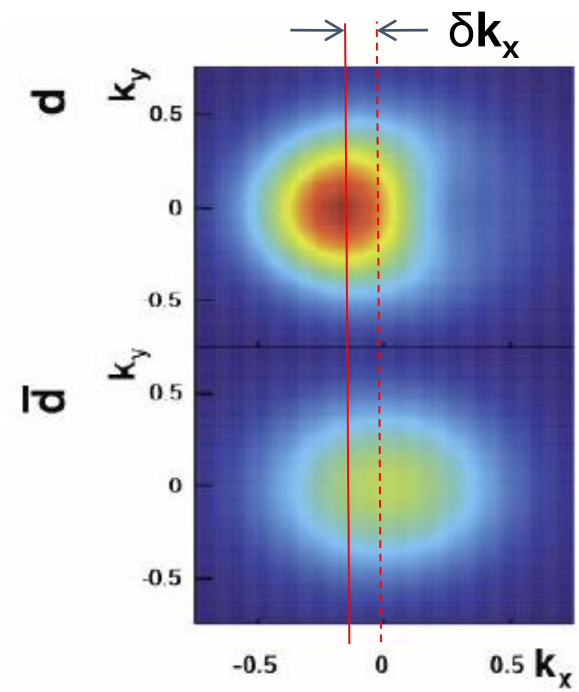
- Future: Solenoidal Large Intensity Device (SoLID) in Hall A: large acceptance and high luminosity

Momentum Tomography with TMDs @ 11 GeV

JLab/12 GeV Goal → Precision in 3D Momentum Imaging of the Nucleon!

Sivers function for d-quarks extracted from model simulations with a transverse polarized ^{3}He target.

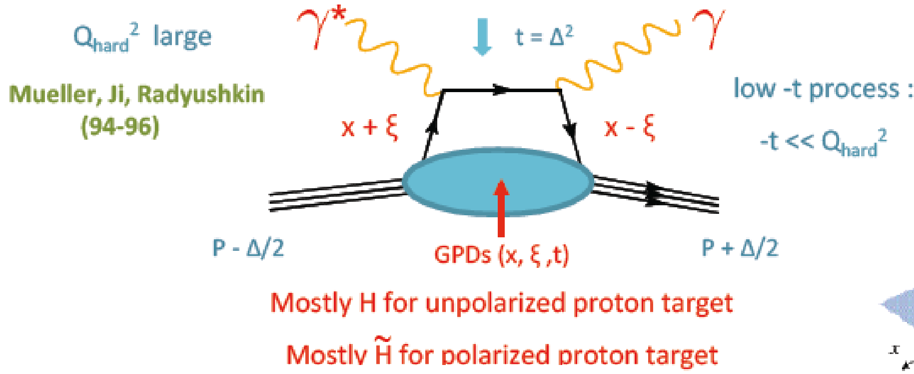


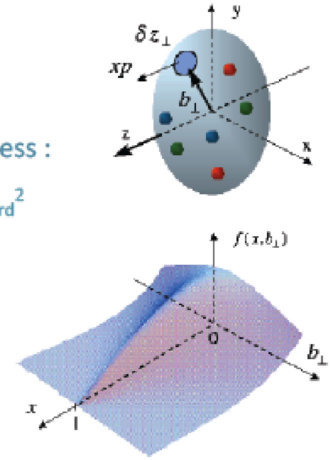


12 GeV ~ Valence Quark Region ($x > 0.1$)

d-quark momentum tomography for Sivers function. The d-quark momentum density shows a distortion and shift in $\mathbf{k_x}$. A non-zero $\mathbf{\delta k_x}$ value requires a non-zero orbital angular momentum.

Deeply Virtual Compton Scattering @ 11 GeV

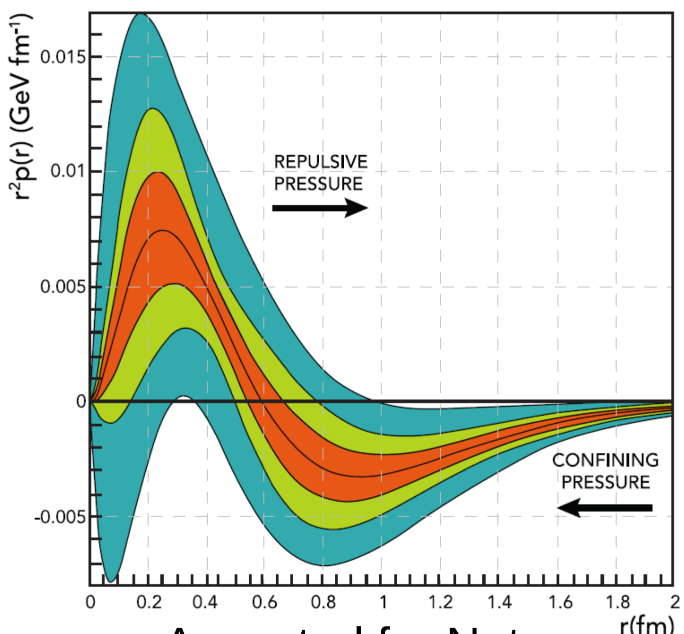




Hall A DVCS scaling check completed

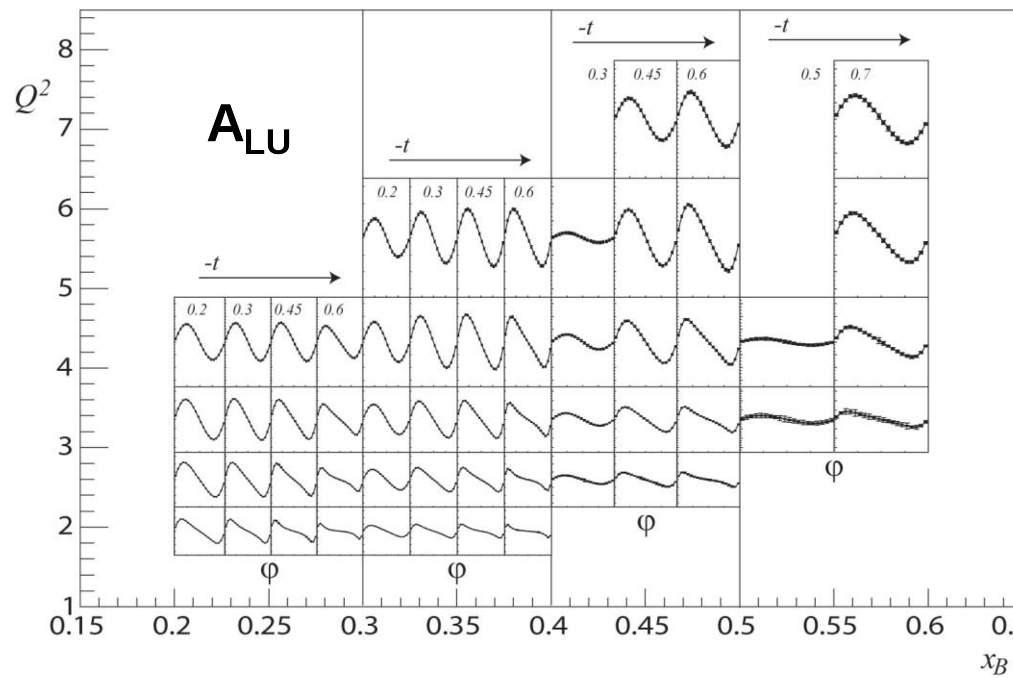
Hall B DVCS on H ongoing

CLAS DVCS data sample at 6 GeV

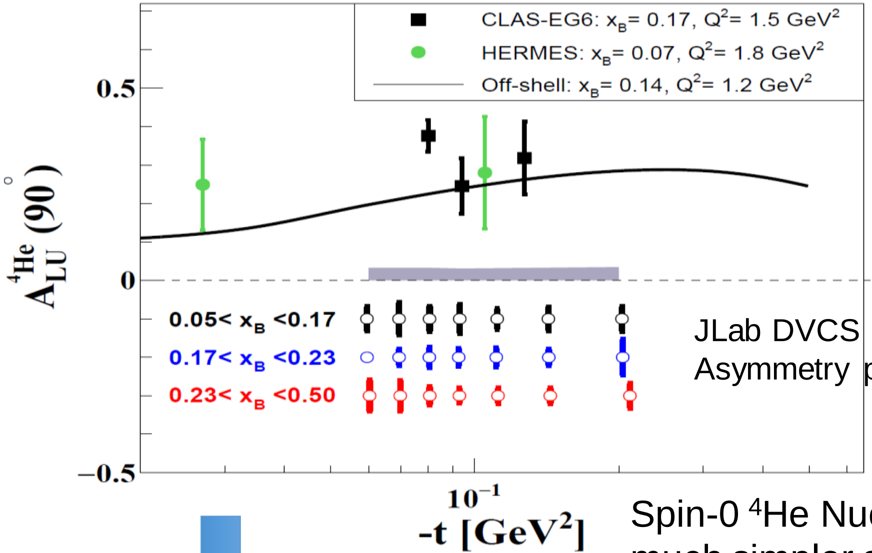


Accepted for Nature

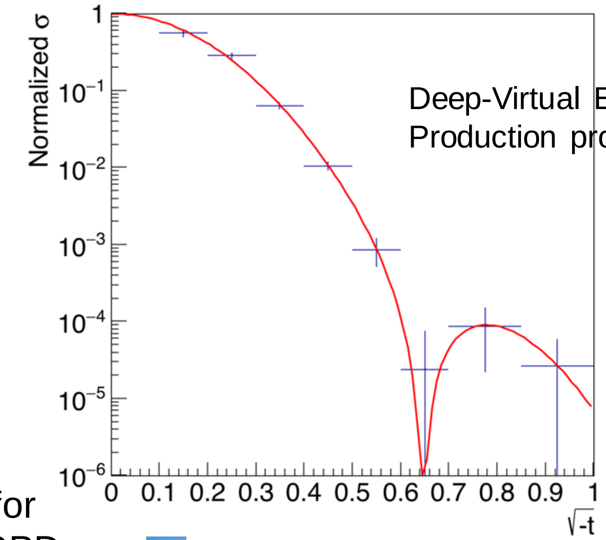
CLAS12 (projected)



Tomography of ^{4}He Nucleus @ 11 GeV



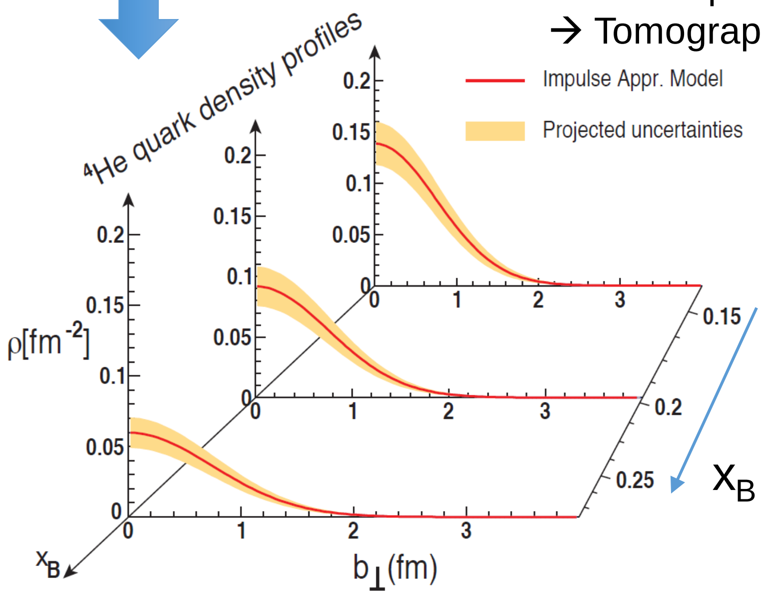
JLab DVCS Beam-Spin Asymmetry projections

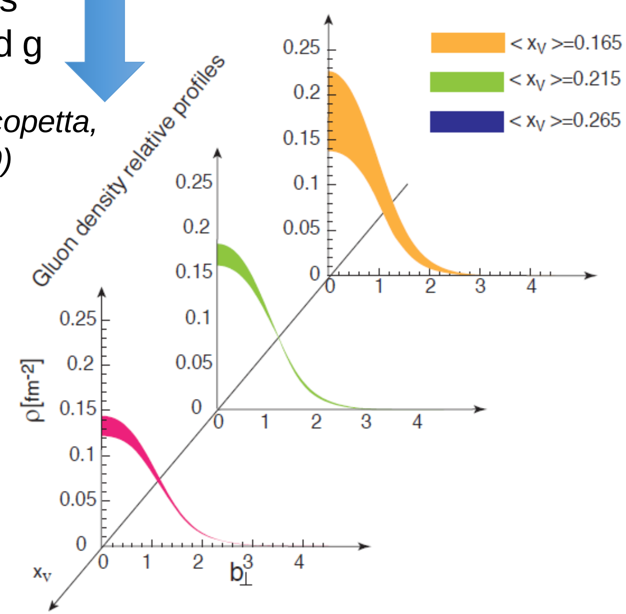


Deep-Virtual Exclusive φ Production projections

Spin-0 ^{4}He Nucleus makes for much simpler extraction of GPDs
→ Tomography in terms of q and g

(R. Dupre and S. Scopetta, EPJA 52 (2016) 159)

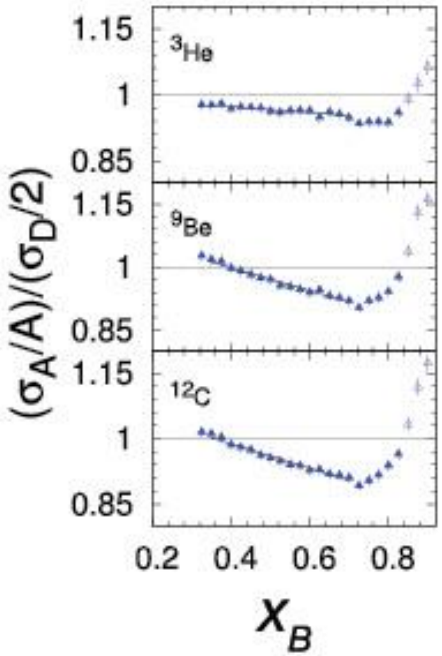


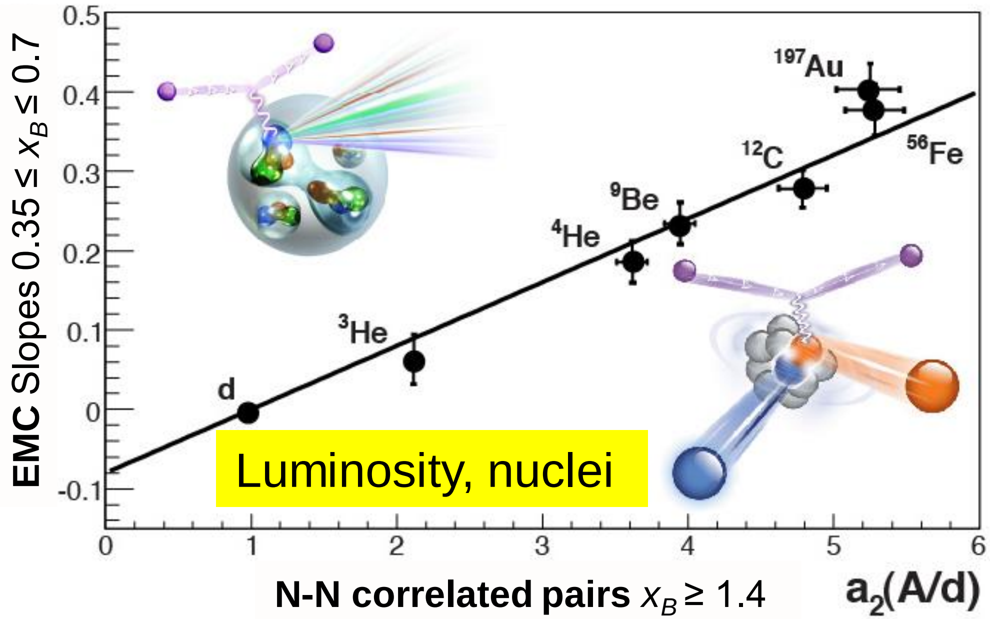


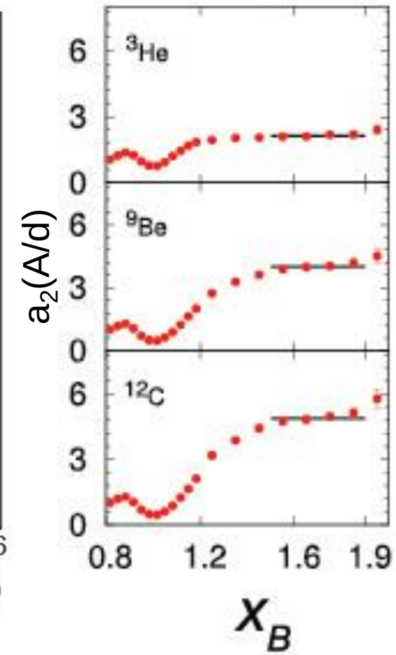
Parton Dynamics and N-N Correlations

EMC effect: quark momentum in nucleus is altered

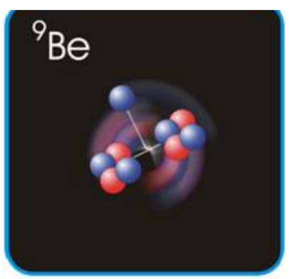
N-N Correlations: pairing due to tensor force and strong repulsive core





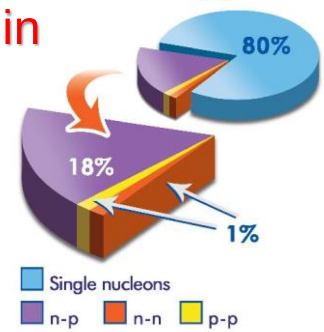


^{9}Be ~ $\alpha\alpha$n



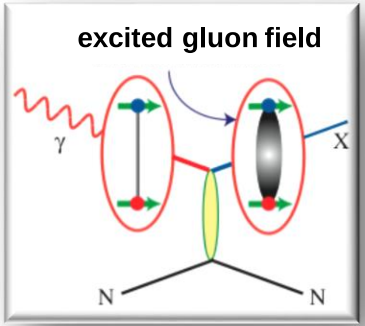
12 GeV science quest: Hall C ^{9}Be, ^{10,11}B data in

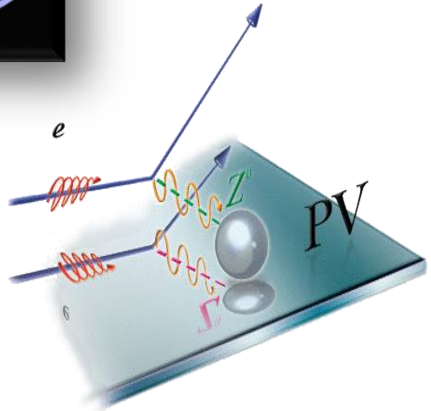
- isospin dependence: ^{3}H, ^{3}He, ^{6,7}Li, ^{9}Be, ^{10,11}B, ^{40,48}Ca
- spin dependence
- "tagged" deep-inelastic scattering off ^{2}H with both slow and fast protons



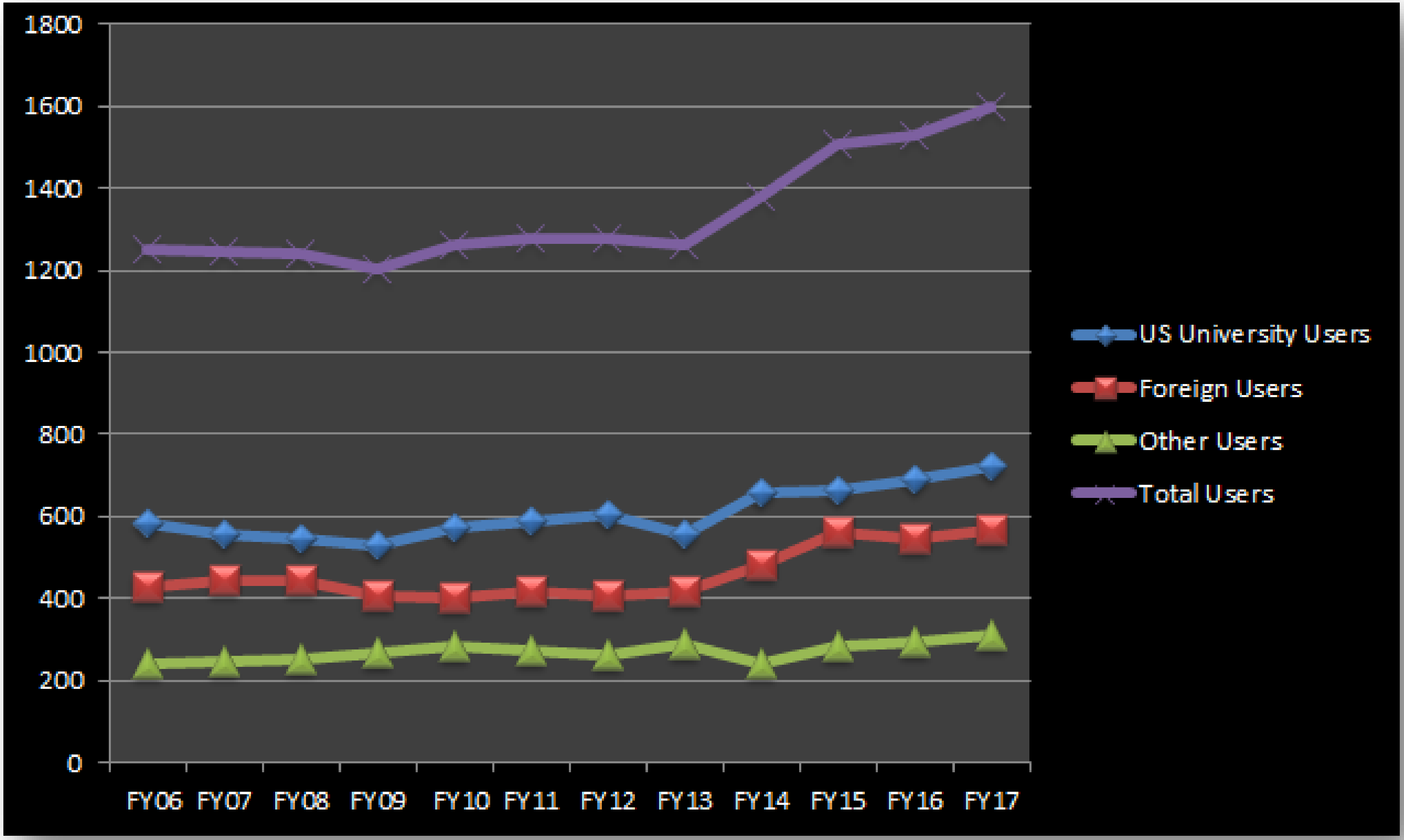
JLab: 21st Century Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range N-N correlations, the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?





Jefferson Lab User Growth

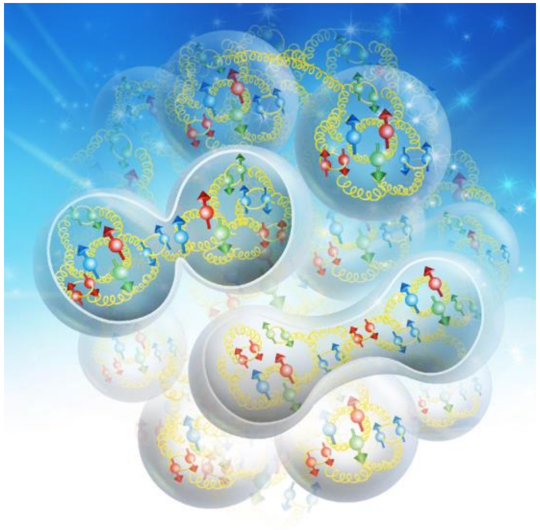


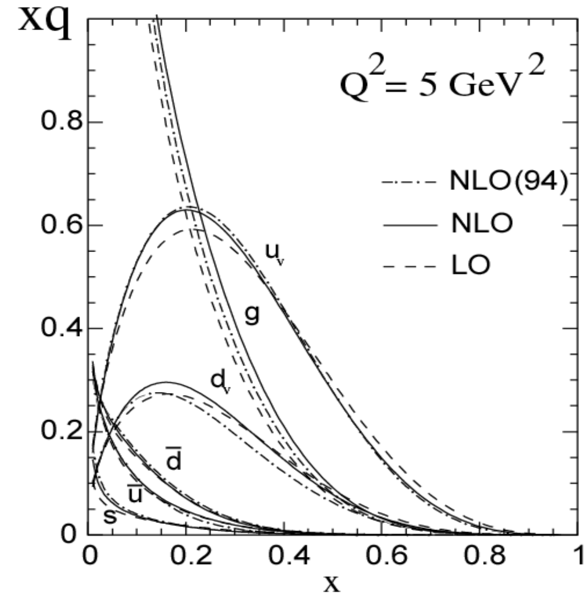
"Other Users" include US National Labs and Industry

Nuclear Femtography

Science of mapping the position and motion of quarks and gluons in the nucleus.

Artist's Conception
of Quark and Gluons
in a proton and nucleus





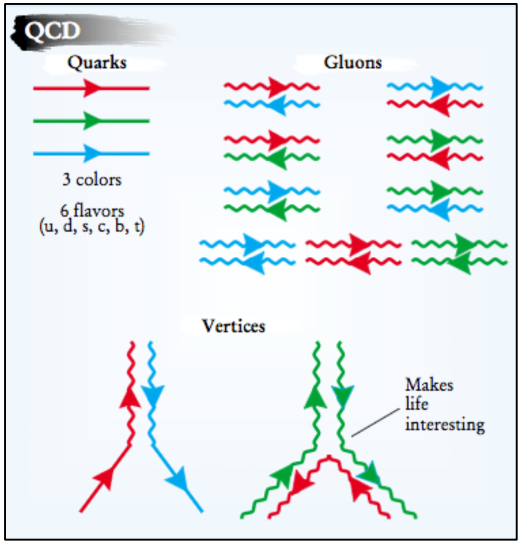
12 GeV

... is just beginning

REQUIRES:

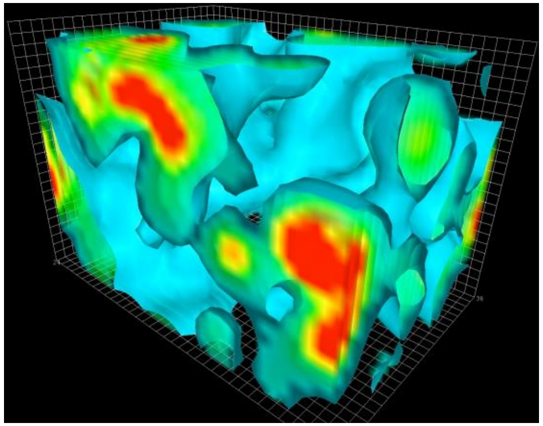
- *High beam polarization*
- *High electron current*
- *High target polarization*
- *Large solid angle spectrometers*

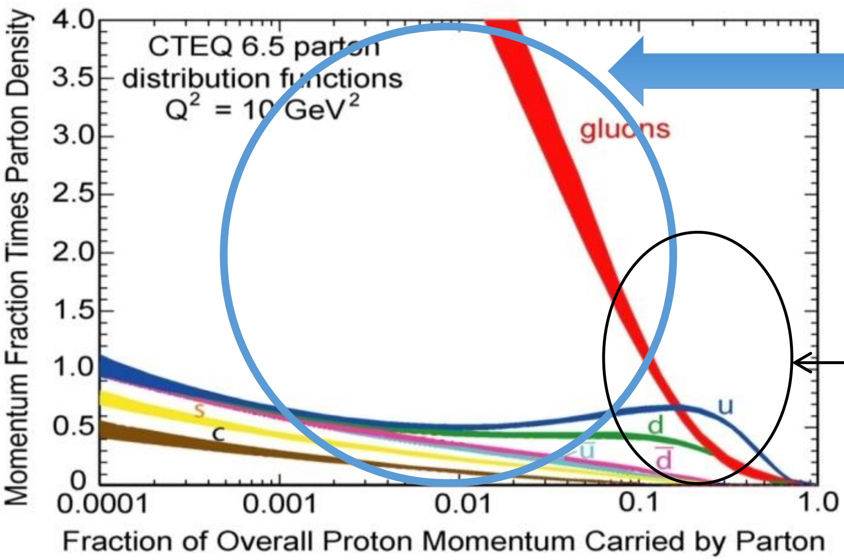
Cold Matter is Unique



Interactions and Structure are entangled
because of gluon self-interaction.

Observed properties such as mass and spin emerge from this complex system.

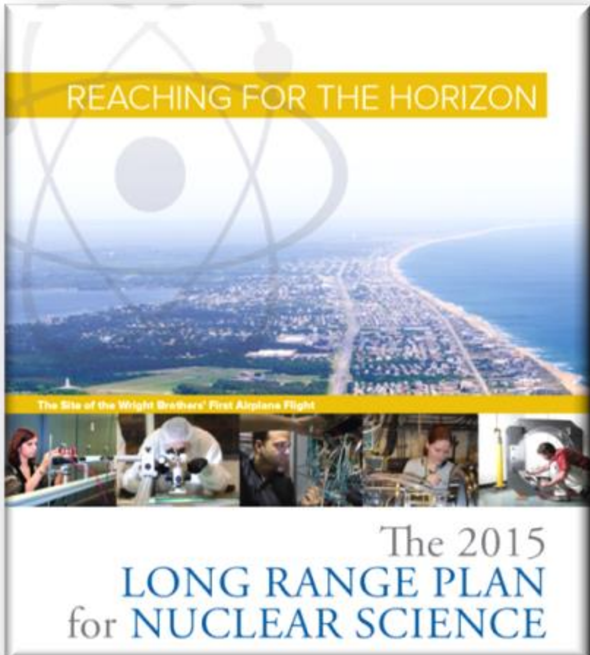




EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

EIC and the NSAC 2015 Long Range Plan

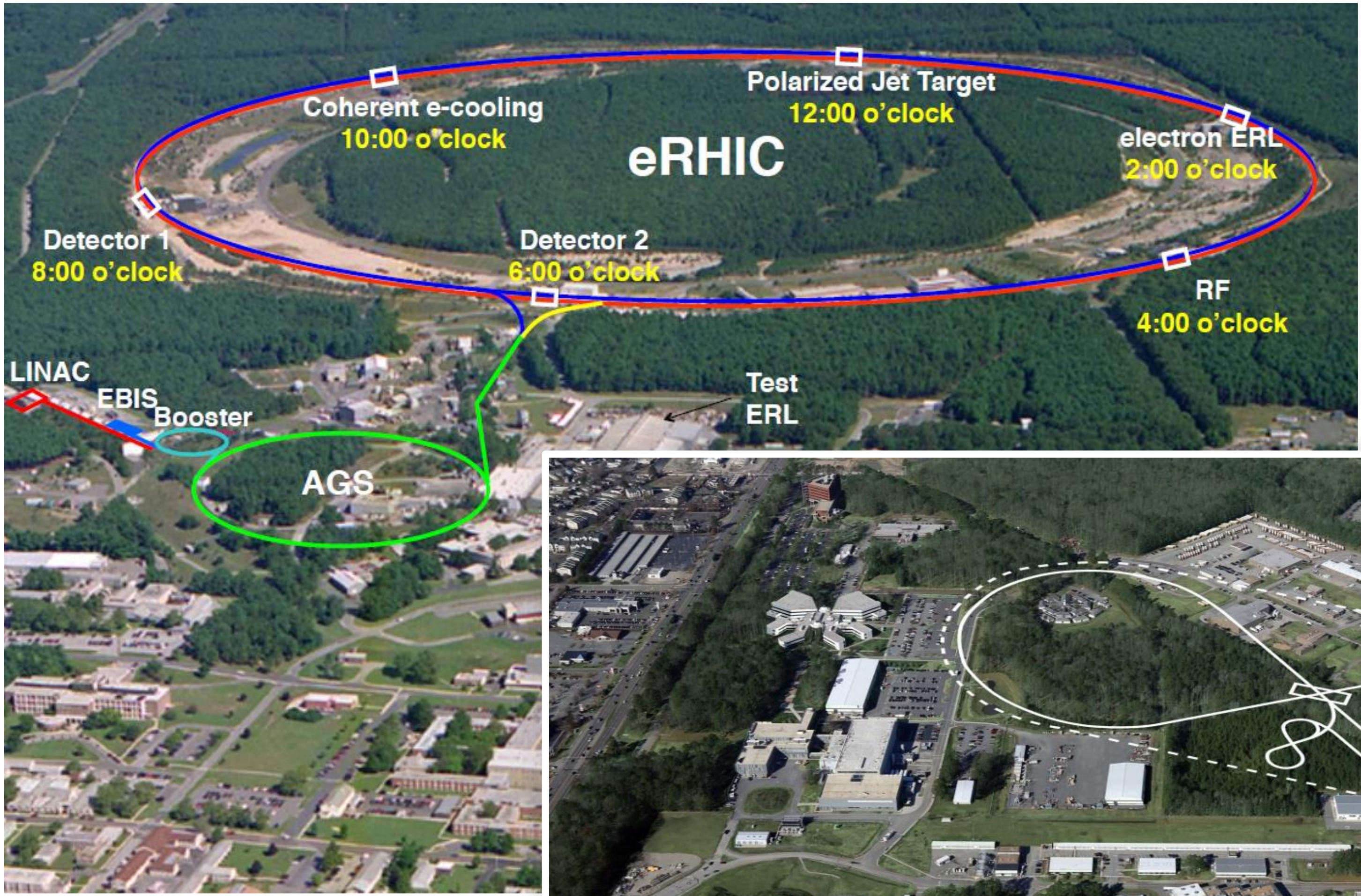


RECOMMENDATION III

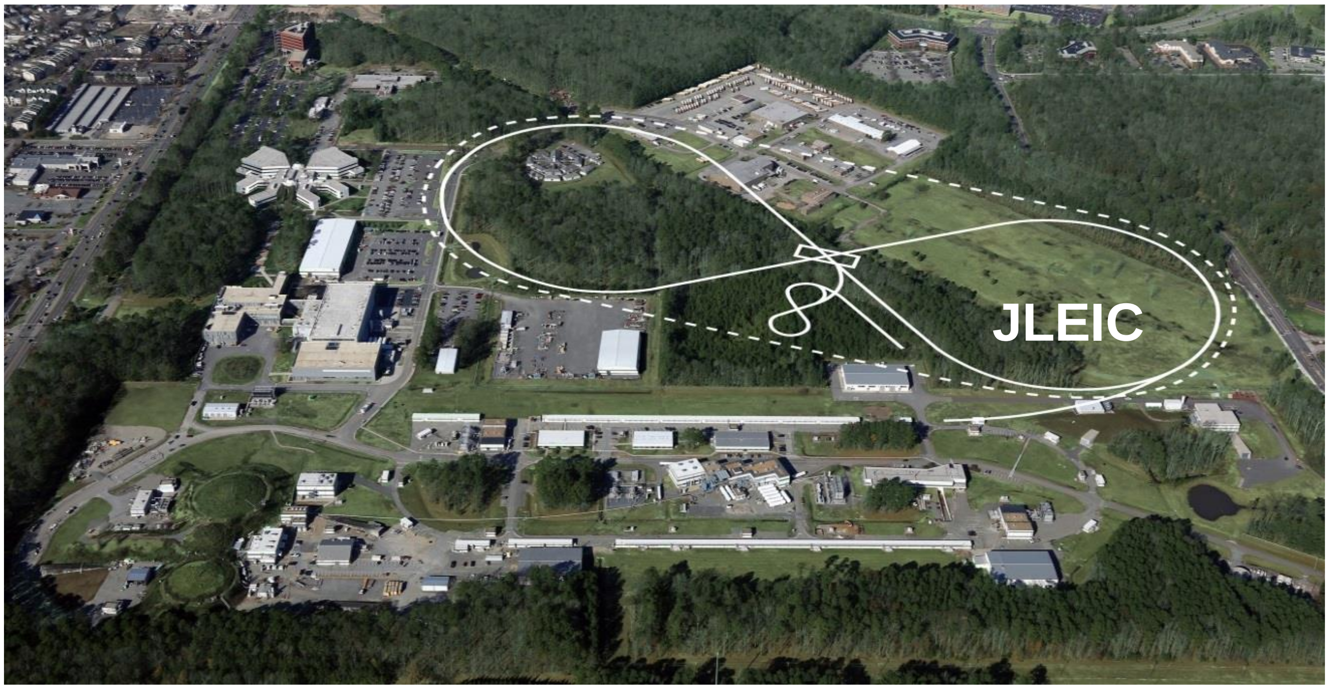
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with 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.

US-Based EICs

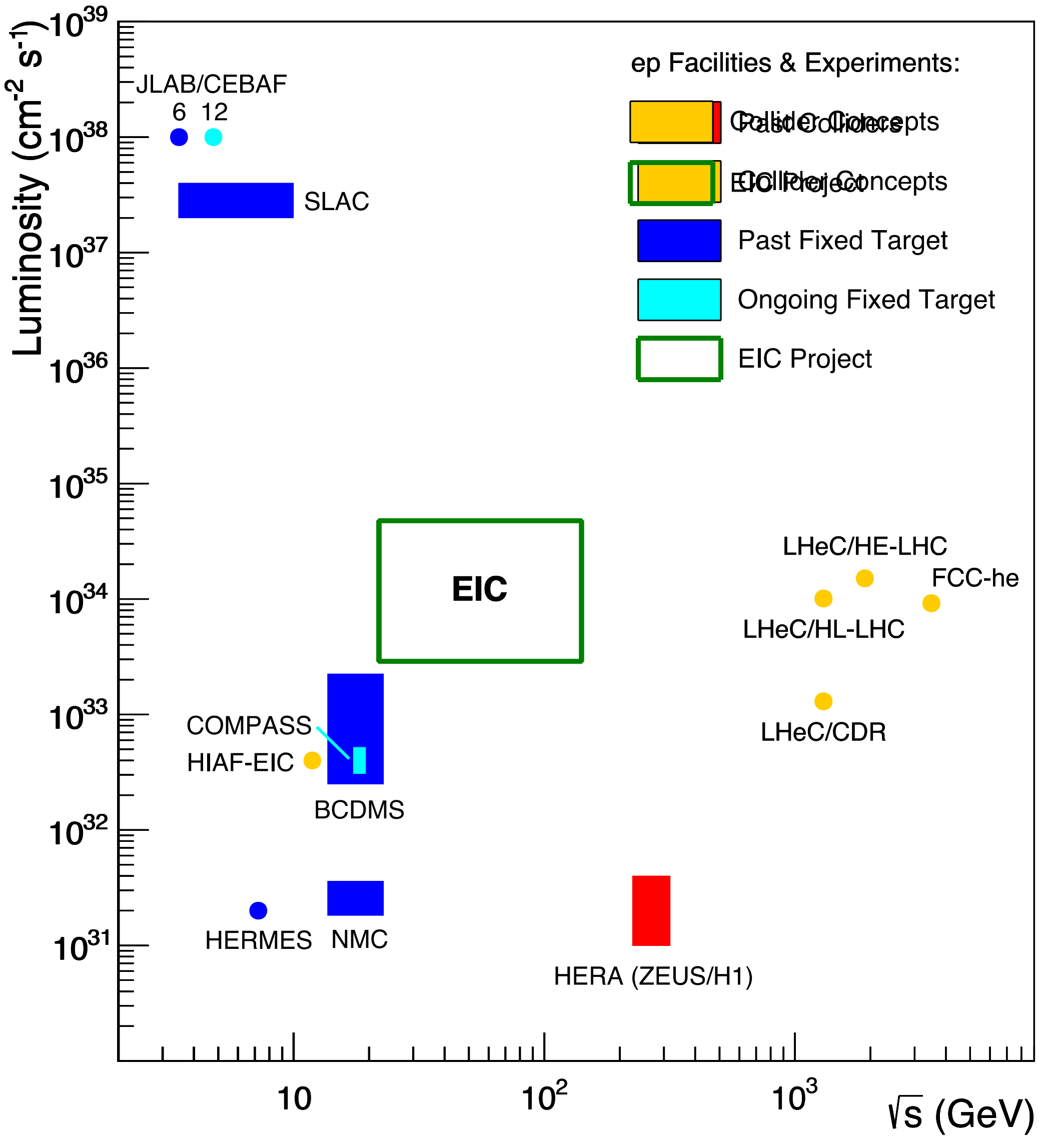


Brookhaven Lab
Long Island, NY



Jefferson Lab
Newport News, VA

Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

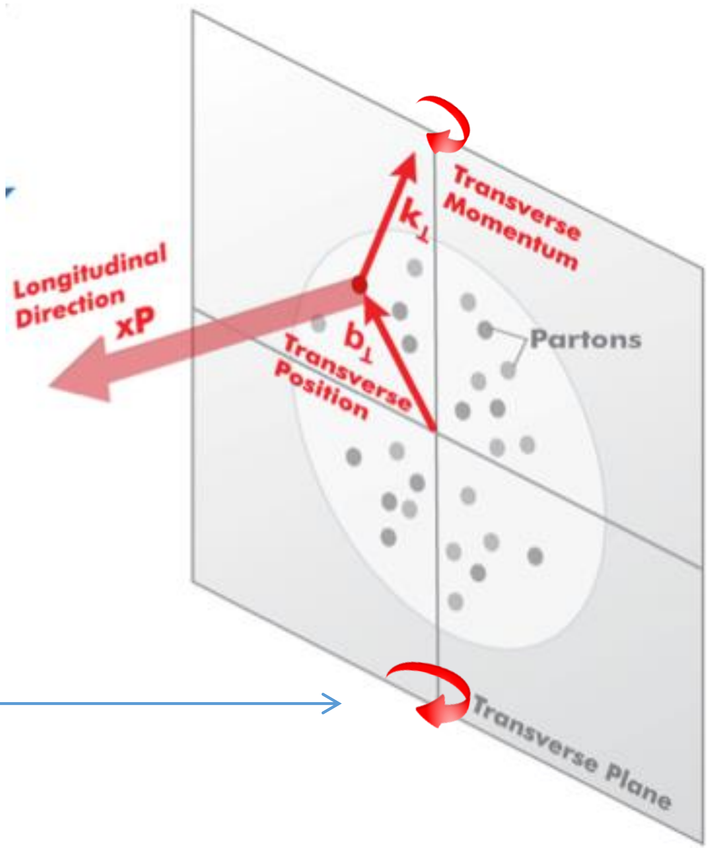
However,
if we ask for:

- high luminosity & wide reach in √s
- polarized lepton & hadron beams
- nuclear beams

EIC stands out as unique facility …

3D Structure of Nucleons and Nuclei

- EIC is a machine to completely map the 3D structure of the nucleons and nuclei
- We need to measure positions and momenta of the partons transverse to its direction of motion.
- These quantities (k_T, b_T) are of the order of a few hundred MeV.
- Also their polarization!



k_T, b_T (~100 MeV)

Proton and Ion Beam

Need to keep [100 MeV]$_T$/$E_{proton,Ion}$ manageable (~ >10^{-3}) ➔ E_{proton} ~< 100 GeV

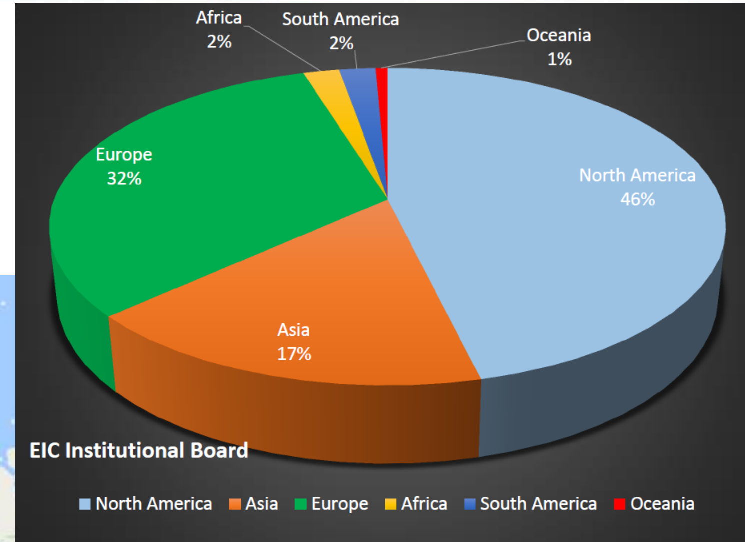
Electron-Ion Collider: Cannot be HERA or LHeC: proton energy too high

Worldwide Interest in EIC Physics

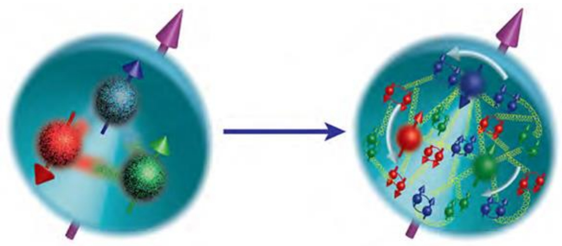
The EIC Users Group: EICUG.ORG

(students can be included now!)

Formed 2015 – now 794 collaborators, 29 countries, 169 institutions... (May 4, 2018)



EIC – World's First Polarized eN Collider

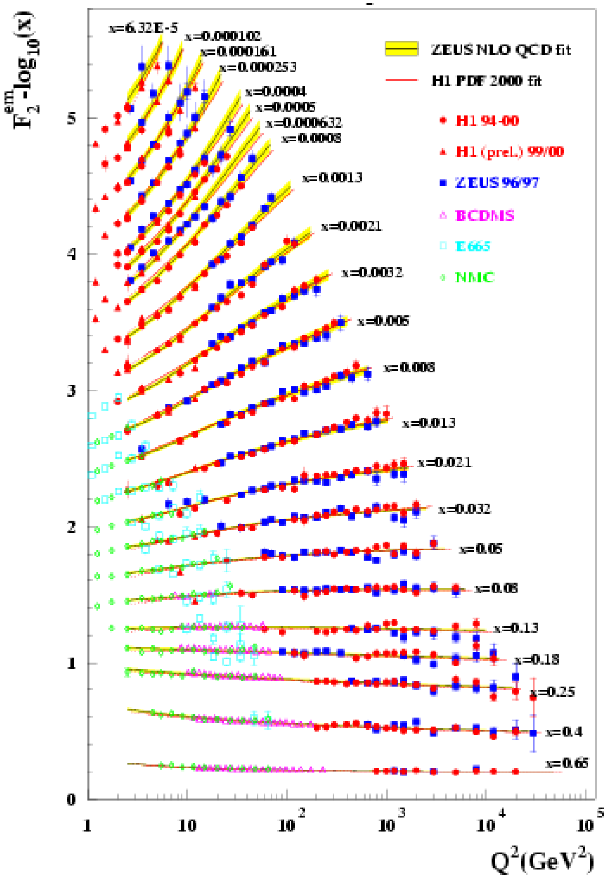


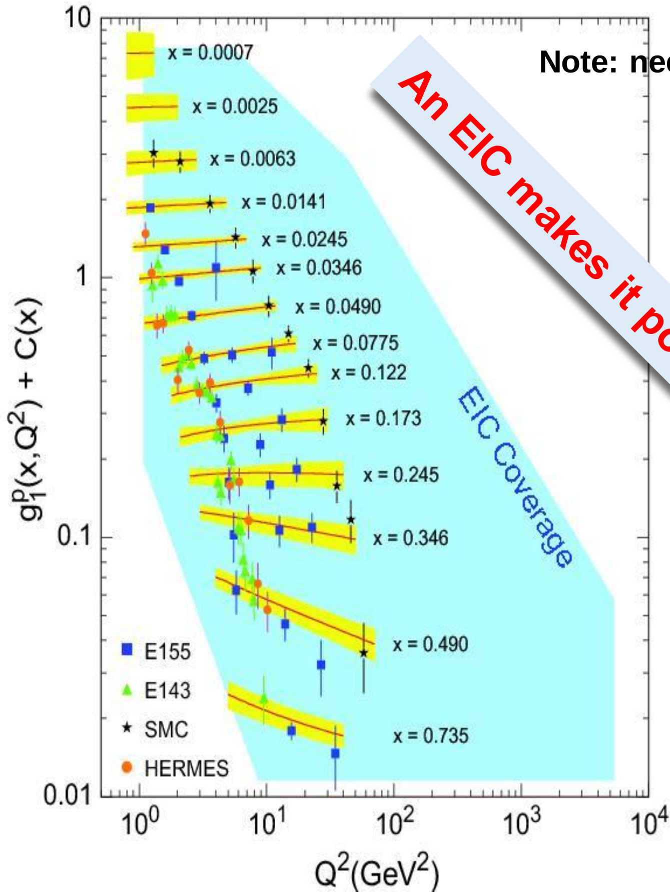
A spin factory of polarized electrons and polarized protons/light nuclei: imaging the quarks and gluons

- 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?

World Data on F_2^p World Data on g_1^p World Data on h_1^p

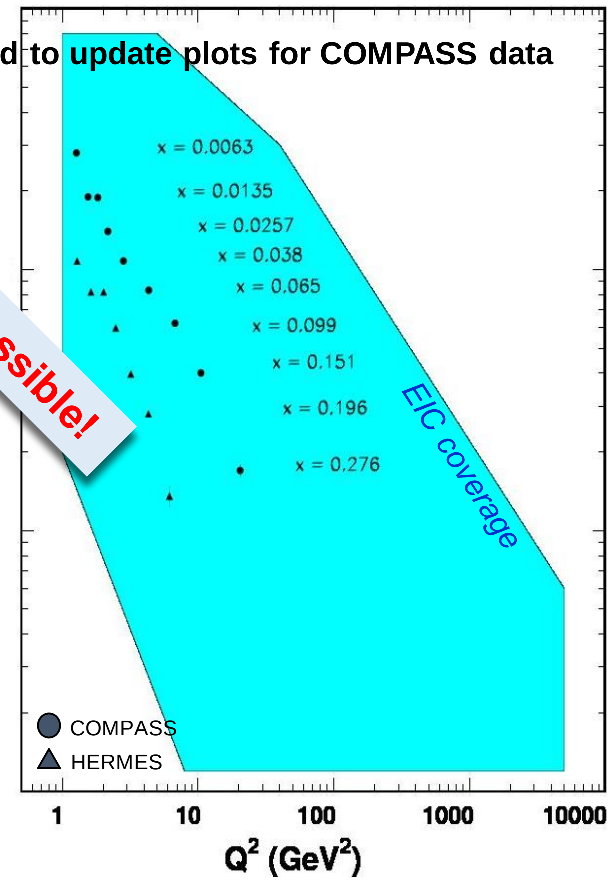
Similar for F_2^n **Similar for g_2^p, g_2^n (and b_1^d)** $F_{UT}^{\sin(\phi_h+\phi_s)}(x,Q^2) + C(x) \propto h_1$





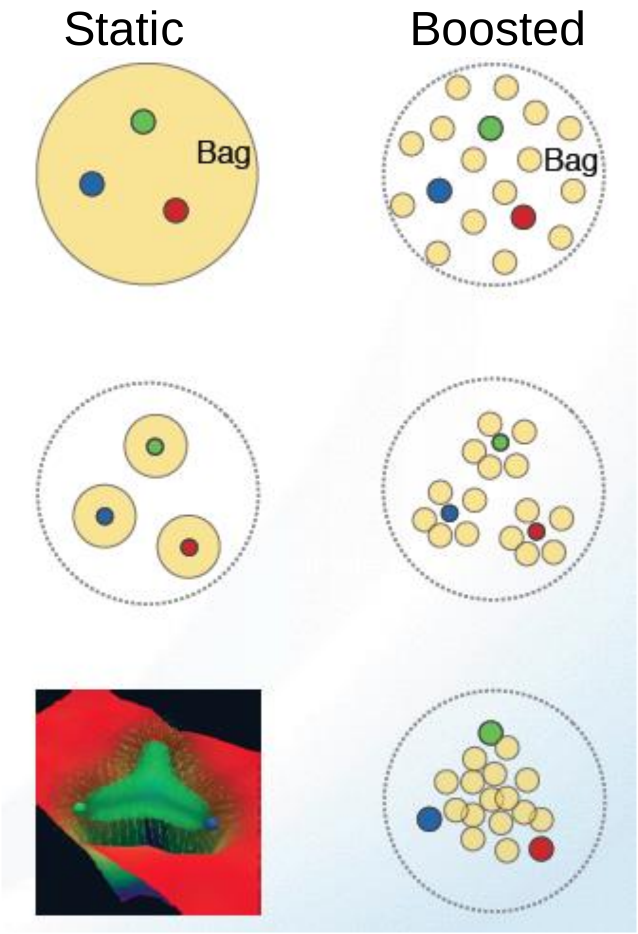
An EIC makes it possible!

Note: need to update plots for COMPASS data



momentum **spin** **transverse spin ~ angular momentum**

What does a proton or (nucleus) look like?



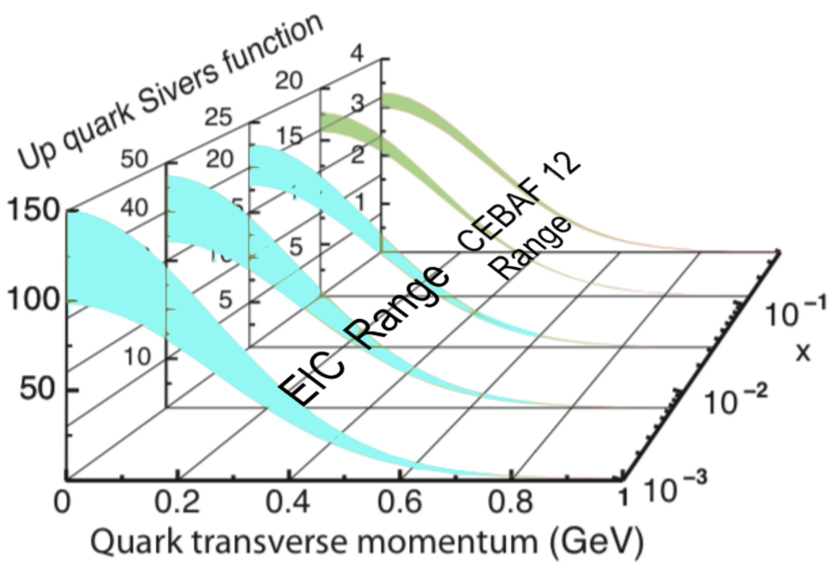
Bag Model: Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

Constituent Quark Model: Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

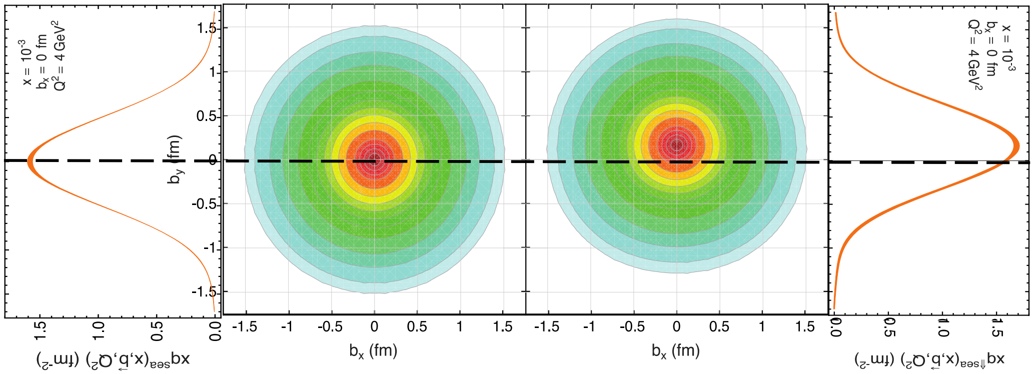
Lattice Gauge theory (with slow moving quarks), gluons more concentrated inside the quarks:
Gluon radius < Charge Radius

Need transverse images of the quarks *and gluons* in protons and nuclei

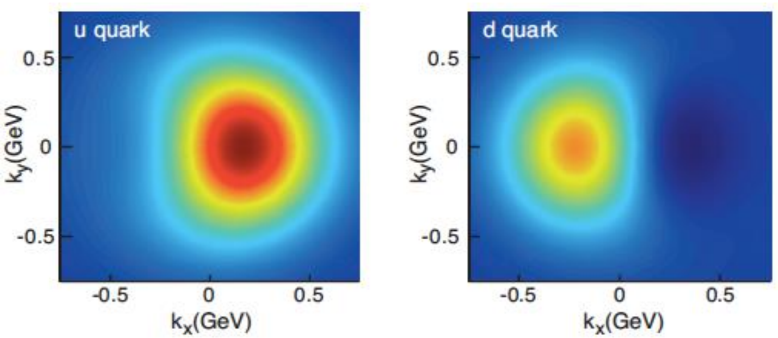
EIC Science: Imaging quarks and gluons in nucleons



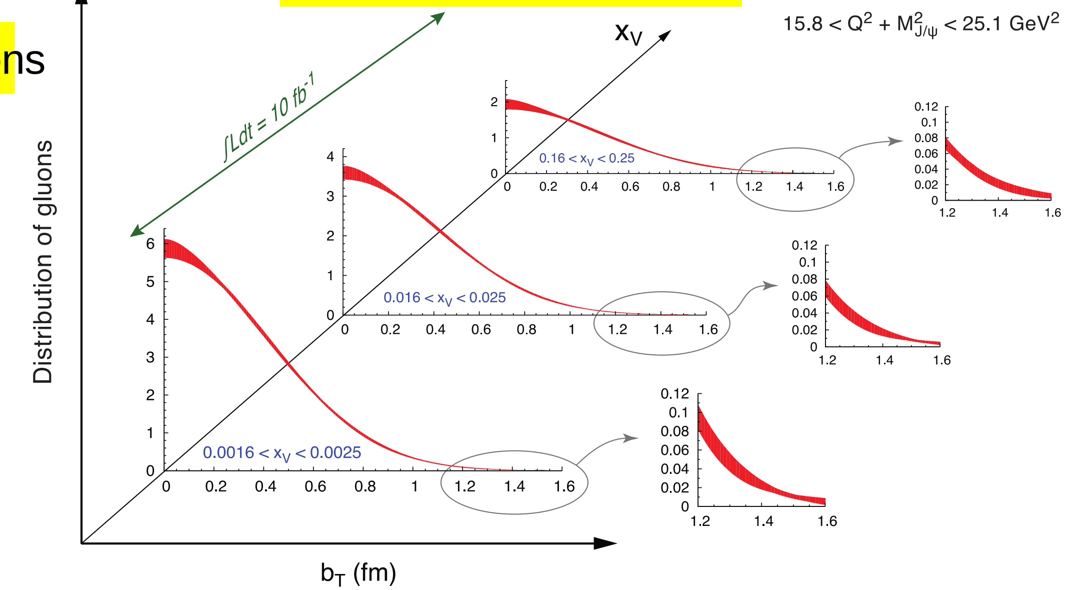
3D Sea Quark distributions unpolarized and polarized



Polarized Quark 3D Momentum distributions

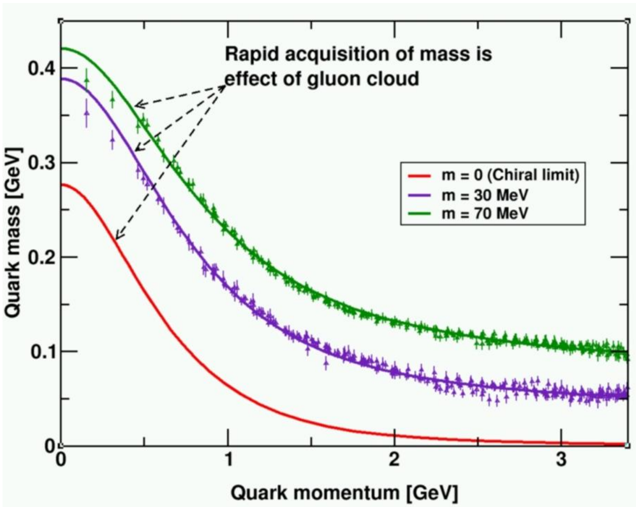


3D Gluon distributions



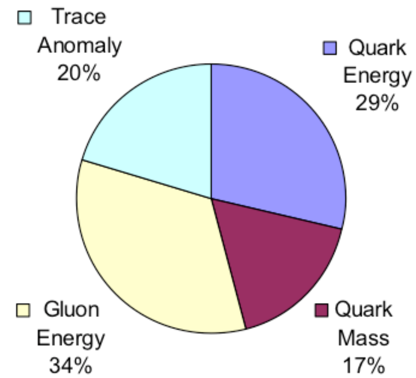
The Incomplete Nucleon: Mass Puzzle

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"



"Mass without mass!"

Bhagwat & Tandy/Roberts et al



Proton: Mass ~ 940 MeV

preliminary LQCD results on mass budget, or view as mass acquisition by DχSB

Kaon: Mass ~ 490 MeV

at a given scale, less gluons than in pion

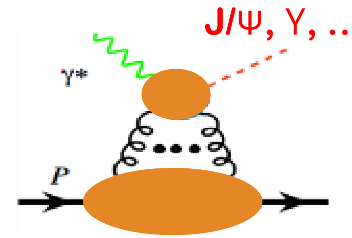
Pion: Mass ~ 140 MeV

mass enigma – gluons vs Goldstone boson

❑ EIC's expected contribution in:

✧ Trace anomaly:

Upsilon production near the threshold

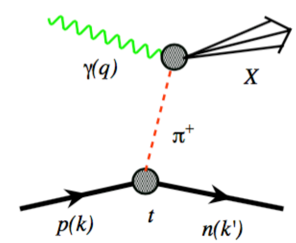


✧ Quark-gluon energy:

$\propto$ *quark-gluon momentum fractions*

In nucleon with DIS and SIDIS

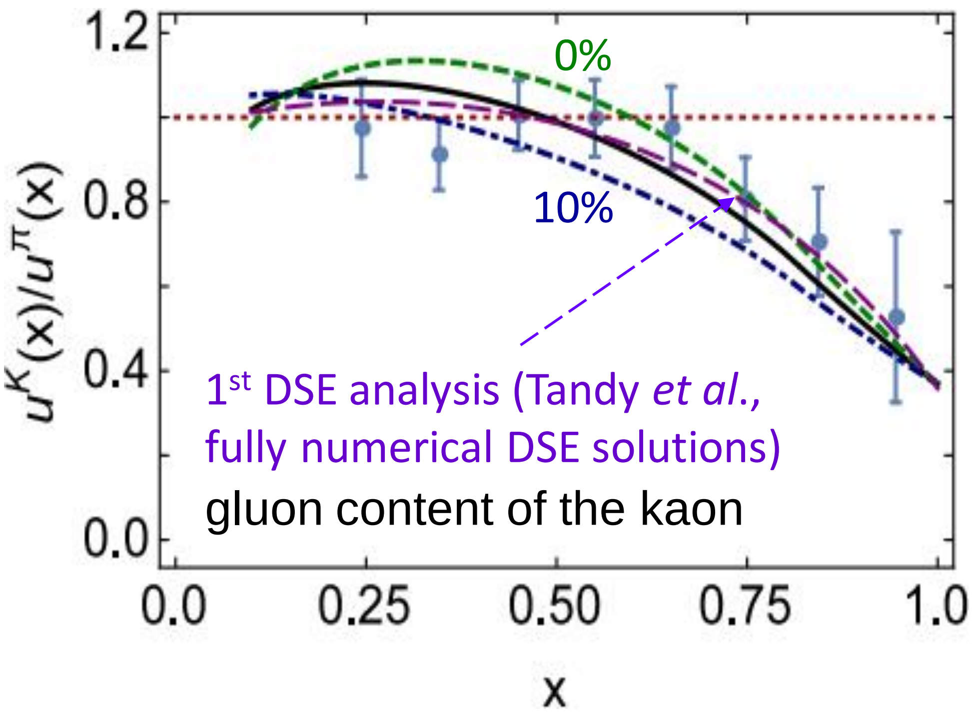
In pions and kaons with Sullivan process



Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

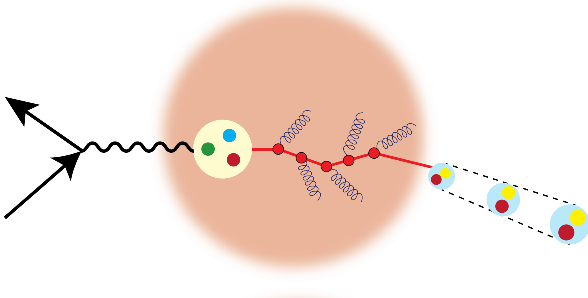
- Valence quarks carry some 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale

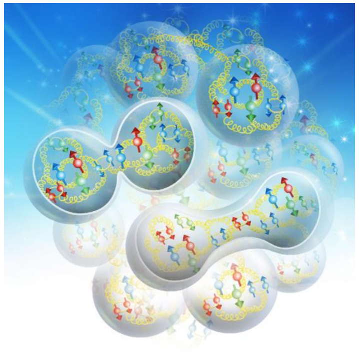


Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- ❑ heavier quarks radiate less readily than lighter quarks
- ❑ heavier quarks radiate softer gluons than do lighter quarks
- ❑ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ❑ Momentum conservation communicates these effects to the kaon's u-quark.

EIC – Versatility is Key





EIC: A Versatile Collider with a Hermetic Detector

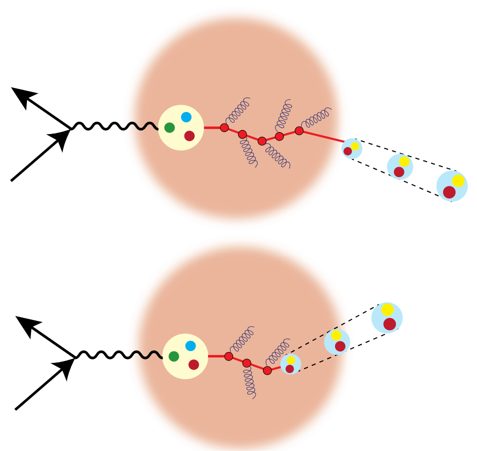
- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
- How do the confined hadronic states emerge from these quarks and gluons?
- How do the quark-gluon interactions create nuclear binding?

Emergence of hadrons from partons

Nucleus as a Femtometer sized filter

Unprecedented ν, the virtual photon energy range @ EIC : *precision & control*

$$\nu = \frac{Q^2}{2mx}$$

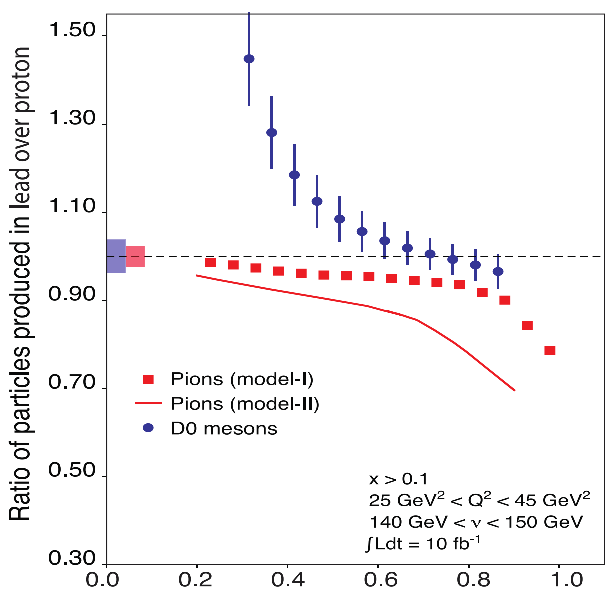


Control of ν by selecting kinematics;

Control the medium by selecting ions

Colored quark emerges as color neutral hadron ➔ What is nature telling us about confinement?

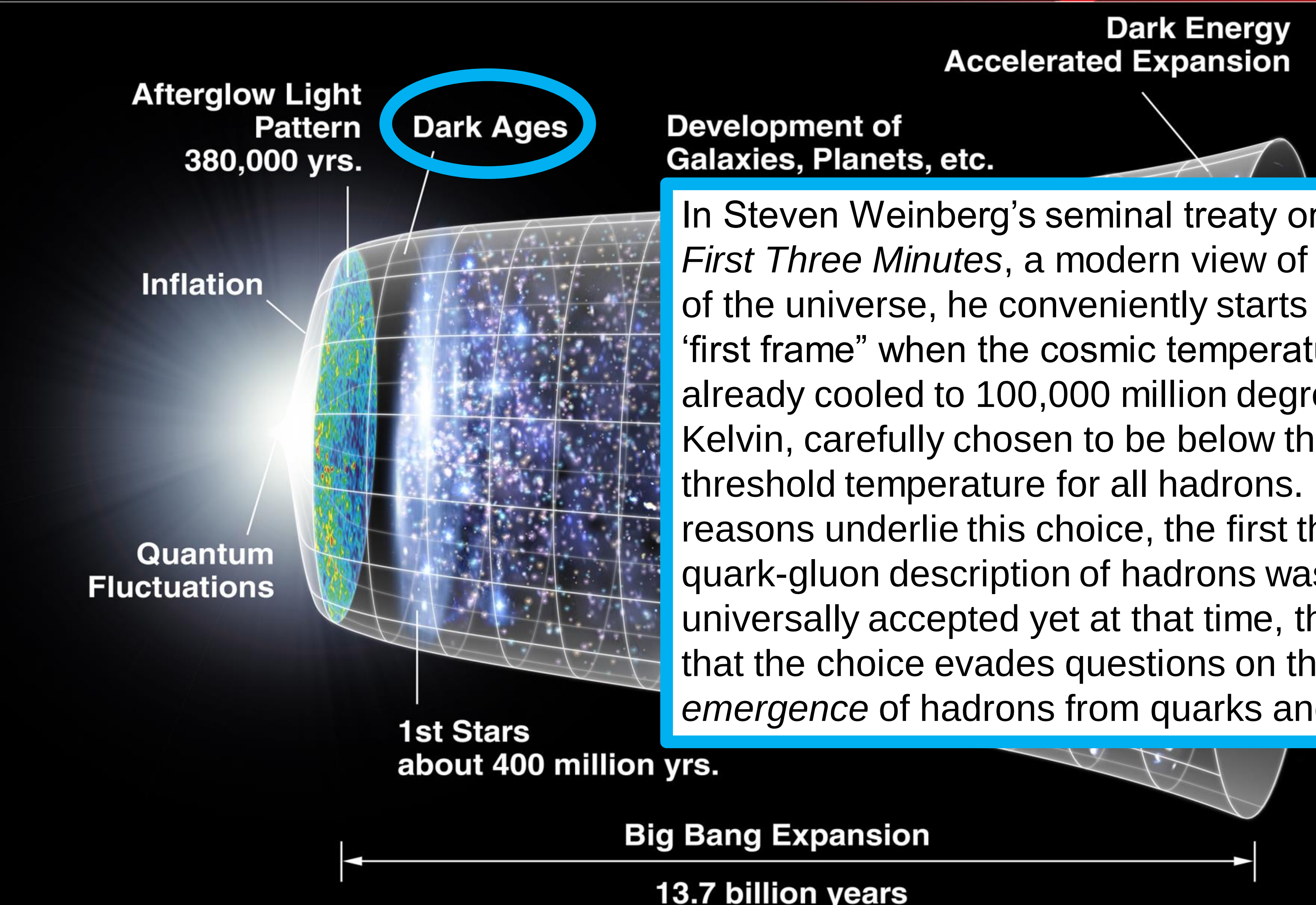
Energy loss by light vs. heavy quarks:



Identify π vs. D^0 **(charm)** mesons in e-A collisions: Understand energy loss of light vs. heavy quarks traversing nuclear matter

Need the collider energy of EIC and its control on parton kinematics

Timeline of the Universe



In Steven Weinberg's seminal treaty on *The First Three Minutes*, a modern view of the origin of the universe, he conveniently starts with a 'first frame" when the cosmic temperature has already cooled to 100,000 million degrees Kelvin, carefully chosen to be below the threshold temperature for all hadrons. Two reasons underlie this choice, the first that the quark-gluon description of hadrons was not universally accepted yet at that time, the second that the choice evades questions on the *emergence* of hadrons from quarks and gluons.

EIC Science: Nuclei and quarks/gluons (Deuterons)

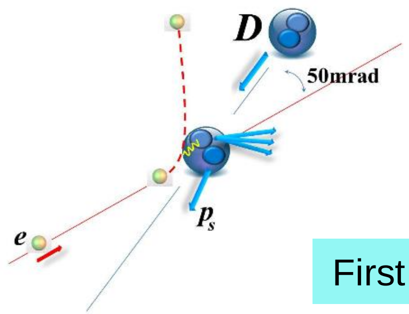
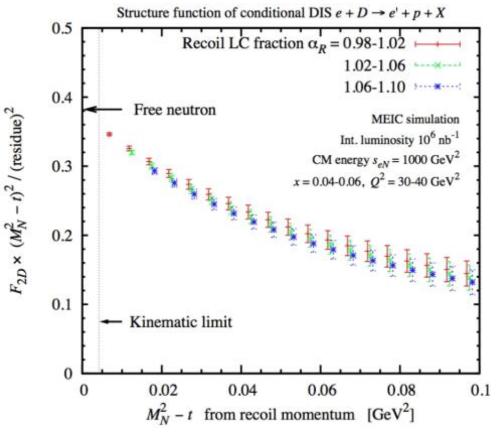


Figure-8 design enables polarized (vector and tensor) deuteron beams (>80% polarization).

Collider → allows a *precision measurement* of the spectator nucleon.

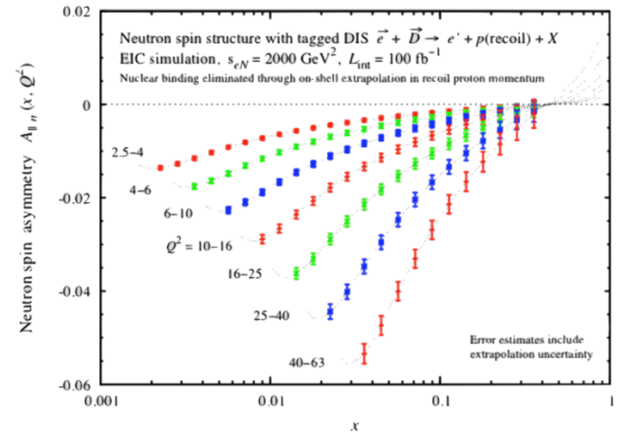
First precision measurement of *polarized* (and unpolarized) neutron is possible at EIC



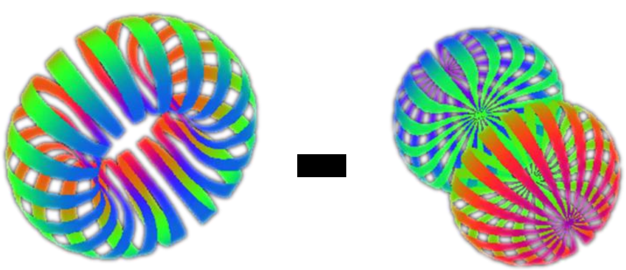
Extrapolation from bound to free neutron under control

F_2^n can be extracted at % level accuracy

Polarized Neutron Structure

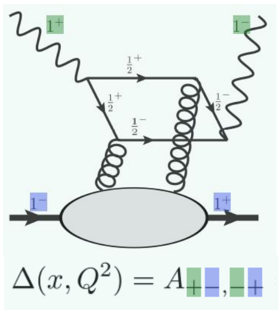


Investigate nuclear effects at the level of partons with Tensor Polarization Observables



Polarized Deuteron Structure Function b_1

Are quarks sensitive to the shape of the nucleus?



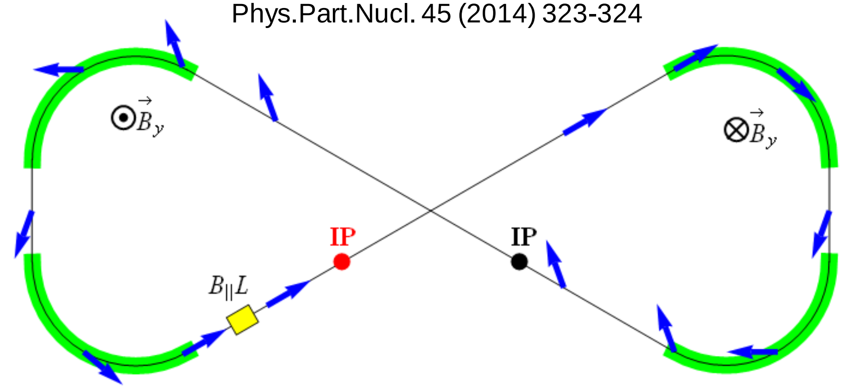
Double helicity-flip distribution $\Delta(x,Q^2)$
→ Gluon Transversity

- Non-nucleonic gluon component!
- Lattice results ≠ 0!

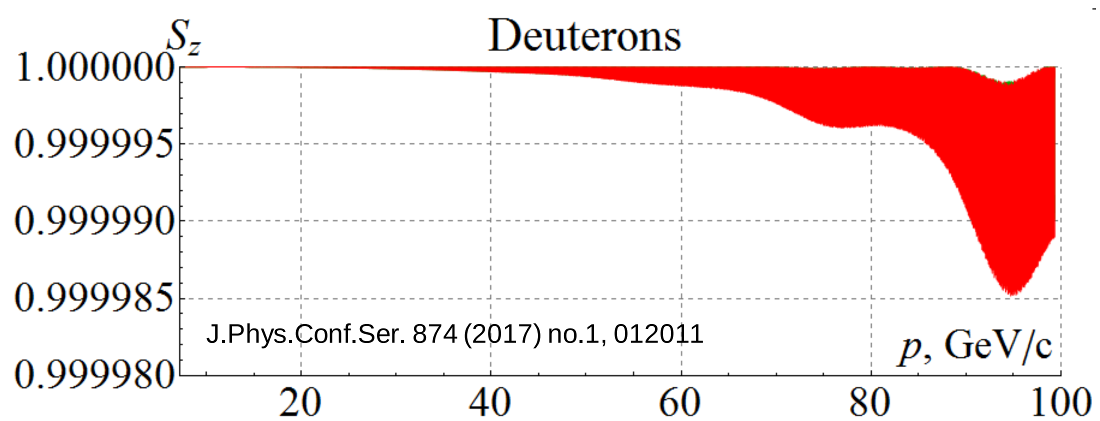
Polarized 2H Beams

- Properties of a figure-8 structure
  - Spin precessions in the two arcs are exactly cancelled
  - In an ideal structure (without perturbations) all solutions are periodic
  - The spin tune is zero independent of energy
- A figure-8 ring provides unique capabilities for polarization control
  - Local spin rotator determines spin tune and local spin direction
  - $B_{||}L$ of only 3 Tm provides deuteron polarization stability up to 100 GeV
  - A conventional ring at 100 GeV would require $B_{||}L$ of 1200 Tm or $B_{\perp}L$ of 400 Tm

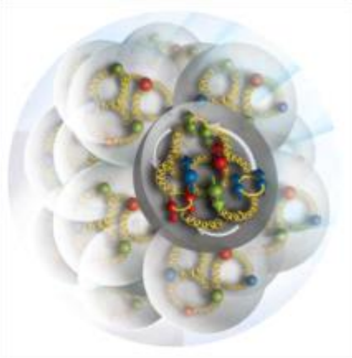
Phys.Part.Nucl. 45 (2014) 323-324

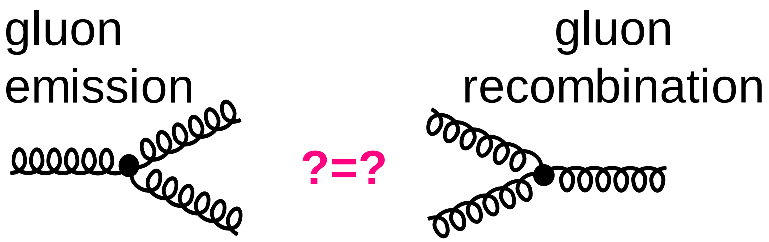


- Recent progress:
  - Start-to-end deuteron acceleration (folding in analytic-calculated spin tune requirement and orbit excursion due to magnet misalignments)
  - Deuteron spin is highly stable in figure-8 rings



EIC – World's First eA Collider



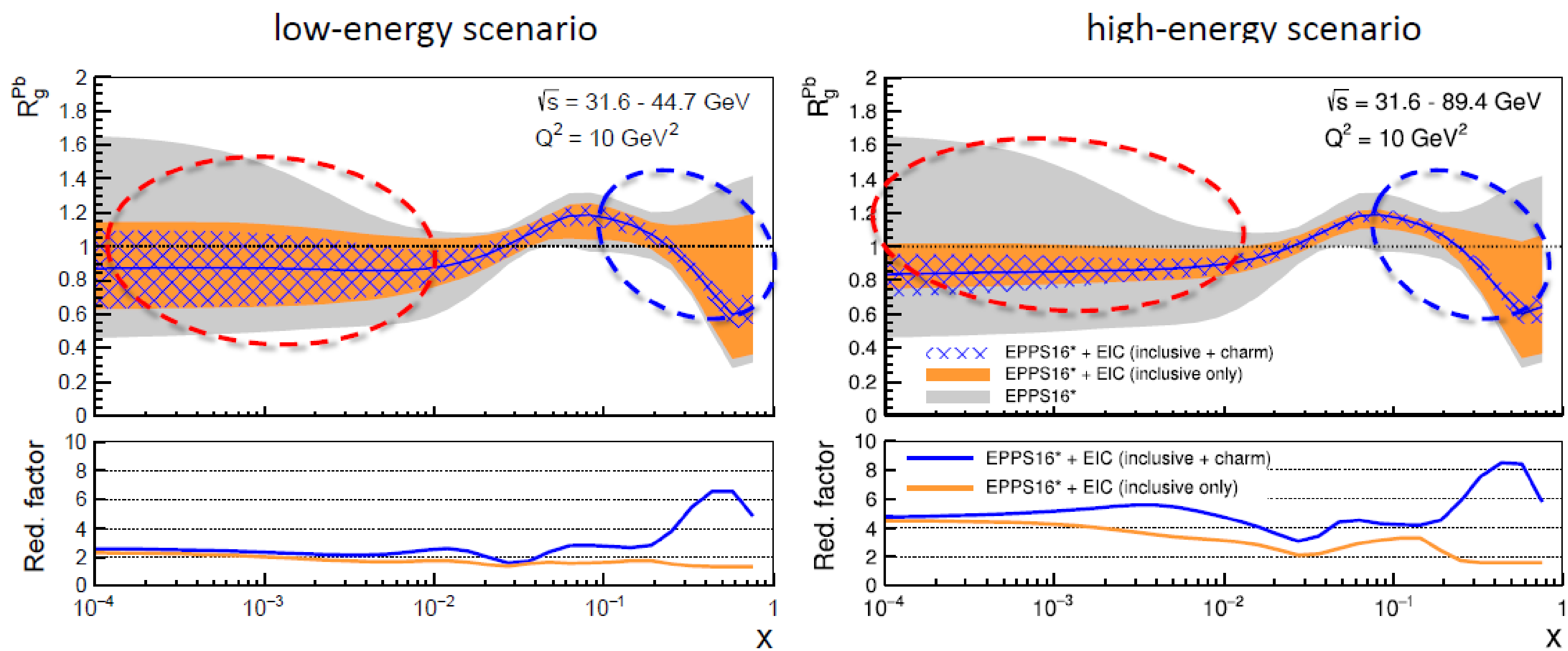


The Nucleus:
A laboratory for QCD

- 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?

Nuclear Parton Distributions

What do we know of gluons in nuclei? Essentially nothing!



Ratio of Parton Distribution Functions of Pb over Proton:

- Without EIC, large uncertainties in **nuclear (light) sea quarks and gluons**
- An EIC with projected F_L **and** F_L^{CC} will significantly reduce uncertainties
- Impossible for current and future pA data at RHIC & LHC data to achieve

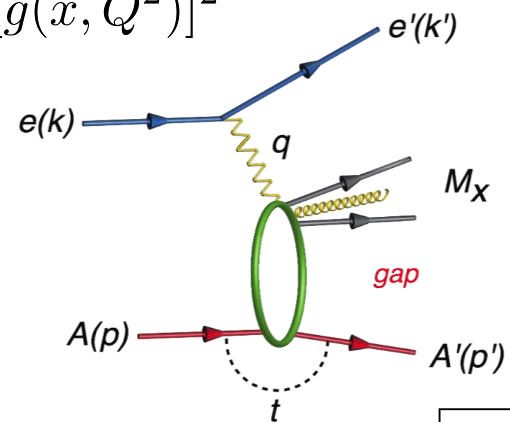
From: Salvatore Fazio talk at INT 2017-3 program, also arXiv:1709.00076

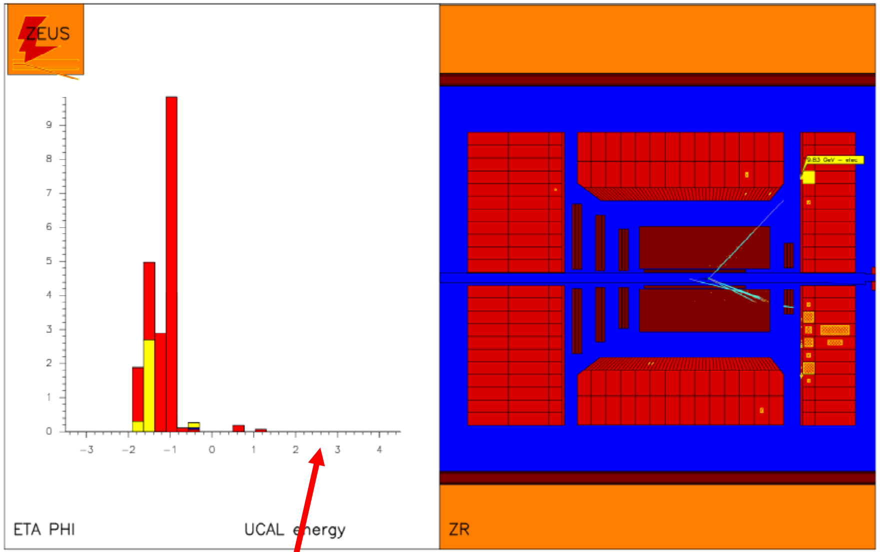
Gluon saturation – what to measure?

Many ways to get to gluon distribution in nuclei, but diffraction most sensitive:

Diffractive event

$$\sigma_{\mathrm{diff}} \propto [g(x, Q^2)]^2$$



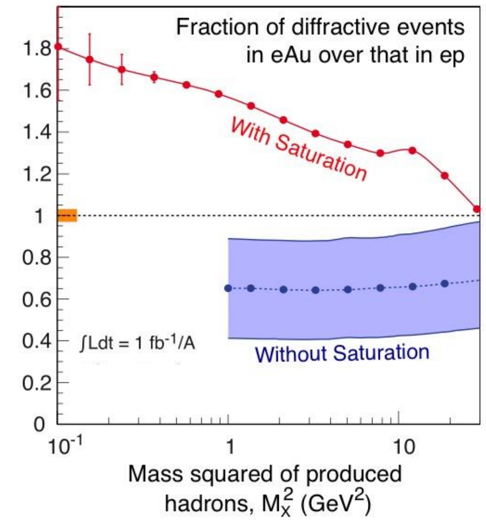


No activity in proton direction

A 7 TeV equivalent electron bombarding the proton …
but nothing happens to the proton in 10-15% of cases

Predictions for eA for such hard diffractive events range up to: 25-30%... given saturation models

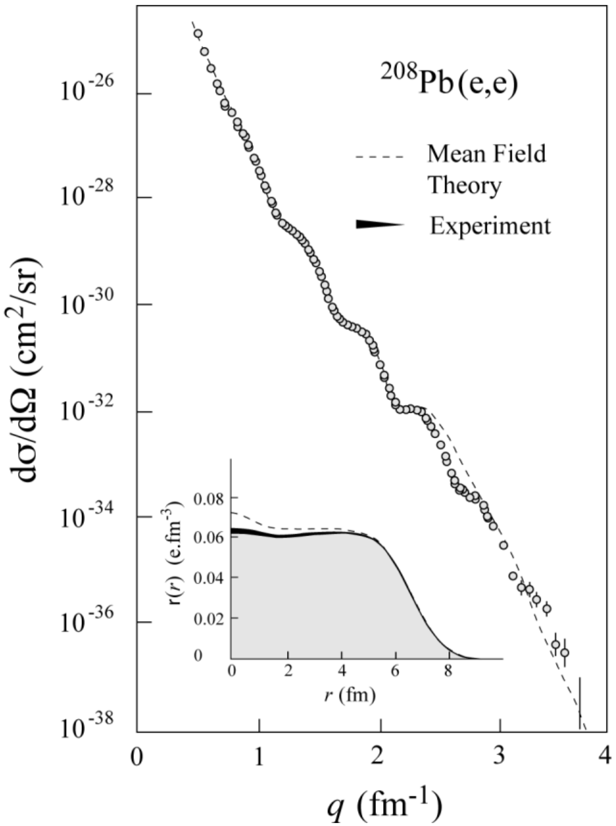
(EIC: utilize g ~ $A^{1/3}$ x $s^{0.3}$ to hunt for c.q. map onset of saturation)



Exposing different layers of the nuclear landscape with electron scattering

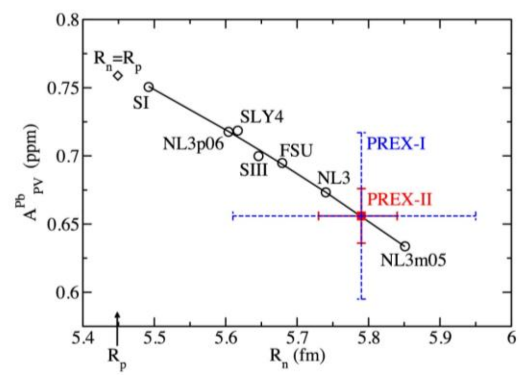
History:
Electromagnetic

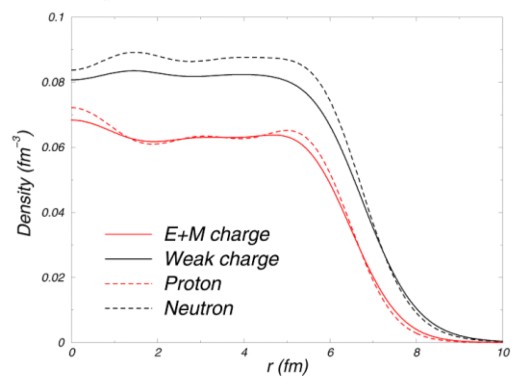
Elastic electron-nucleus scattering → charge distribution of nuclei



Present/Near-future:
Electroweak

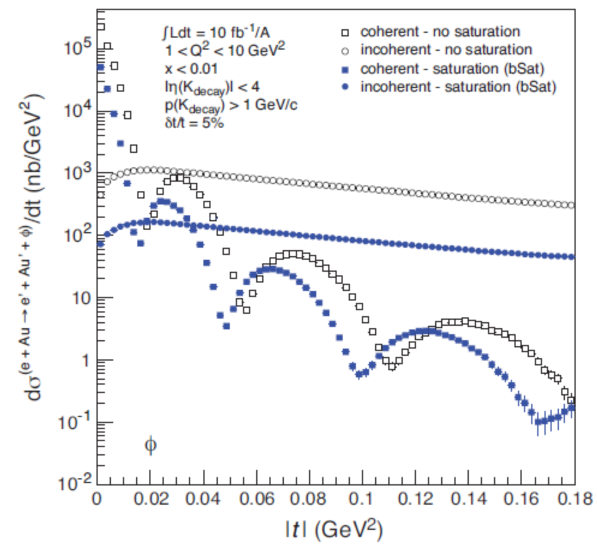
Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin





Future:
Color dipole

ϕ Production in coherent electron-nucleus scattering → gluon spatial distribution of nuclei



Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

EIC Realization Imagined

With a formal NSAC/LRP recommendation, what can we (or I) speculate about any EIC timeline?

- It seemed unlikely that a CD-0 (US Mission Need statement) would be awarded before completion of a National Academy of Sciences study
  - Indeed, a study was initiated and is ongoing
  - 1st meeting February 1-2, 2nd meeting April 19-20, 3rd meeting September 11-12, 4th meeting November 27-28
  - Report anticipated mid-2018 … assuming positive …
  - This would/could imply CD-0 Late 2018
- (critical) EIC accelerator R&D questions will not be answered until ~2019?
- Site selection may occur perhaps around 2019/2020?
- EIC construction has to start **after FRIB completion**, with FRIB construction anticipated to start ramping down near or in FY20

→ <u>Most optimistic</u> scenario would have EIC funds start in FY20, perhaps more realistic (yet optimistic) construction starts in FY22-23 timeframe

→ Best guess for EIC completion assuming NAS blessing would be 2025-2030 timeframe

EIC User Group Meeting

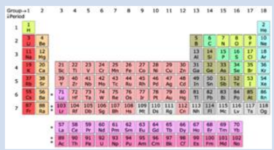
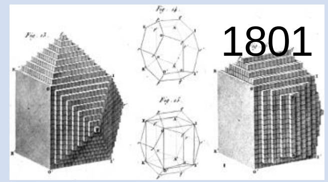
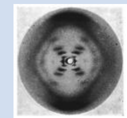
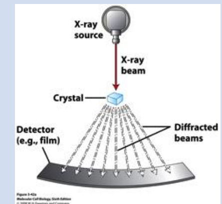
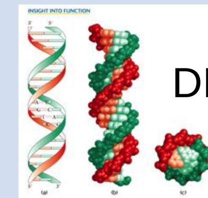
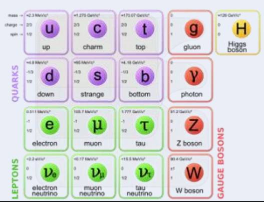
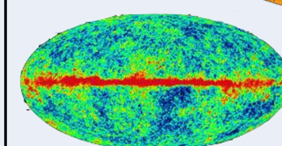
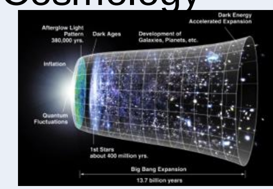
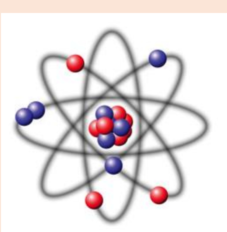
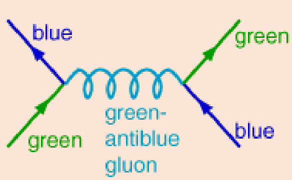
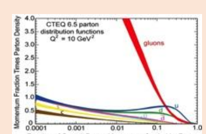
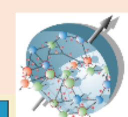
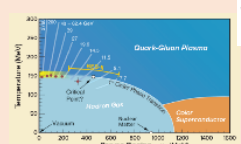
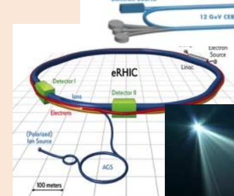
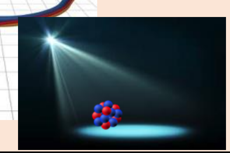
Electron - Ion Collider User Group Meeting 2018
July 30 - August 2, 2018
The Catholic University of America
Washington, D.C.
Further information about the EIC User Group.

Previous EIC User Group Meetings:
2017 - Trieste/Italy
2016 - Argonne National Laboratory
2016 - University of California/Berkeley
2014 - Stonybrook University

Local Organizing Committee
Fatiha Benmokhtar - Duquesne
Tanja Horn – CUA
Greg Kalicy – CUA
Ian Pegg – CUA
Alexei Prokudin – Penn State Berks

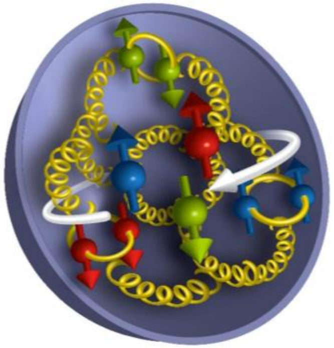
https://www.jlab.org/conferences/eicugm18/index.html

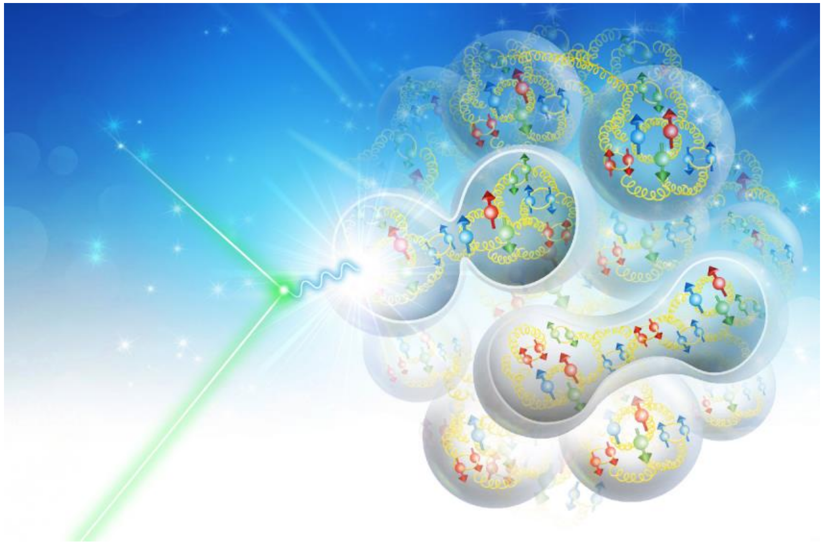
EIC: A Portal to a New Frontier

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure  CMB 1965	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \overline{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$ 	Non-perturbative QCD. Structure 2017   	Electron-Ion Collider (2025+)   	Structure & Dynamics in QCD 

Outlook – Proton Structure in the 21st Century

The theme of this talk may be that while we may think we know a lot about the quark-gluon structure of nucleons and nuclei, there are many outstanding issues. Progress is good, and prospects are good, and we are in my view on the verge of a true transformation.



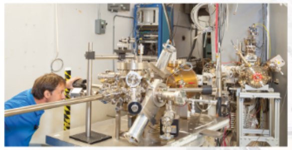


The electromagnetic structure of nucleons and nuclei is full of surprises and dynamics – there is much work to do but in a decade or so we can be in excellent shape to acquire a transformative view of the 3D quark-gluon structure of matter and the underlying strong QCD dynamics. These can become good and exciting times.

BACKUP

CEBAF AT JEFFERSON LAB

Jefferson Lab's Continuous Electron Beam Accelerator Facility (CEBAF) enables world-class fundamental research of the atom's nucleus. Like a giant microscope, it allows scientists to "see" things a million times smaller than an atom.

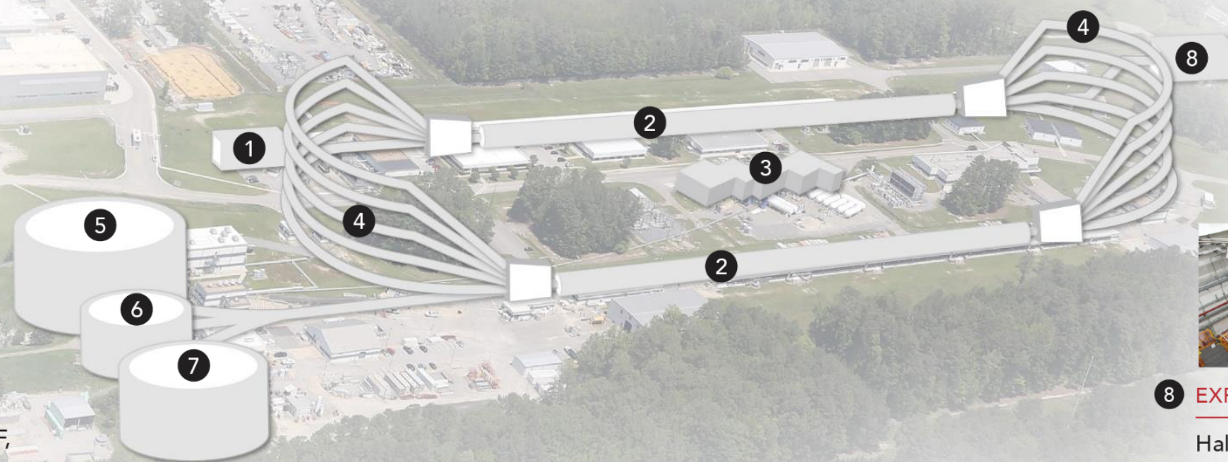


❶ INJECTOR

The injector produces electron beams for experiments.

❷ 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.



❽ EXPERIMENTAL HALL D

Hall D is configured with a superconducting solenoid magnet and associated detector systems that are used to study the strong force that binds quarks together.

Project Completion Approved September 27, 2017

❸ CENTRAL HELIUM LIQUEFIER

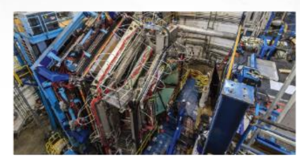
The Central Helium Liquefier keeps the accelerator cavities at -456 degrees Fahrenheit.

❹ RECIRCULATION MAGNETS

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

❺ EXPERIMENTAL HALL A

Hall A is configured with two High Resolution Spectrometers for precise measurements of the inner structure of nuclei. The hall is also used for one-of-a-kind, large-installation experiments.



❻ EXPERIMENTAL HALL B

The CEBAF Large Acceptance Spectrometer surrounds the target, permitting researchers to measure simultaneously many different reactions over a broad range of angles.

❼ EXPERIMENTAL HALL C

The Super High Momentum Spectrometer and the High Momentum Spectrometer make precise measurements of the inner structure of protons and nuclei at high beam energy and current.

The Structure of the Proton

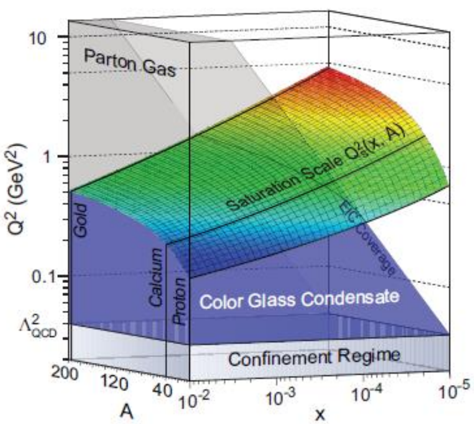
Naïve Quark Model: proton = uud (valence quarks)

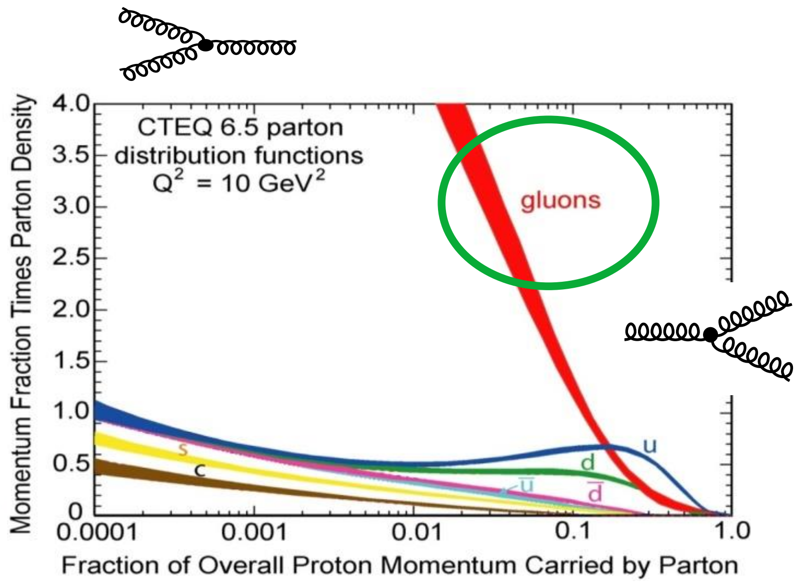
QCD: proton = uud + $u\bar{u}$ + $d\bar{d}$ + $s\bar{s}$ + …

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

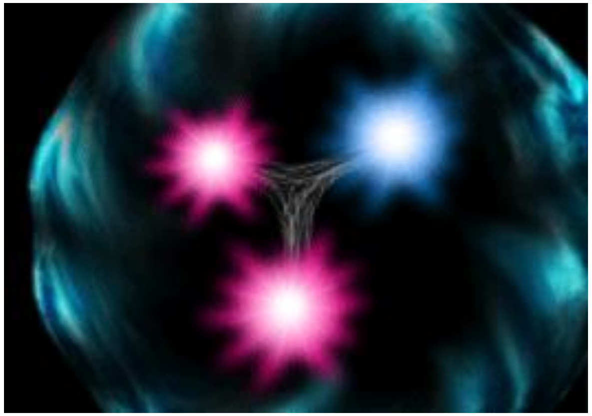
& gluons are abundant

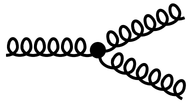
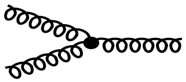
gluon dynamics



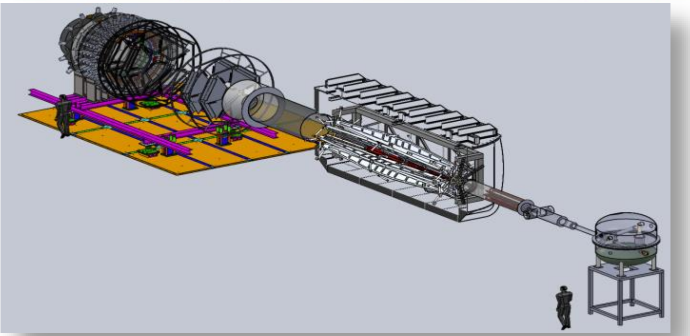


Non-trivial sea structure



- The proton is **far more** than just its up + up + down (valence) quark structure
- Gluon ≠ photon: Radiates  and recombines: 

Future Projects

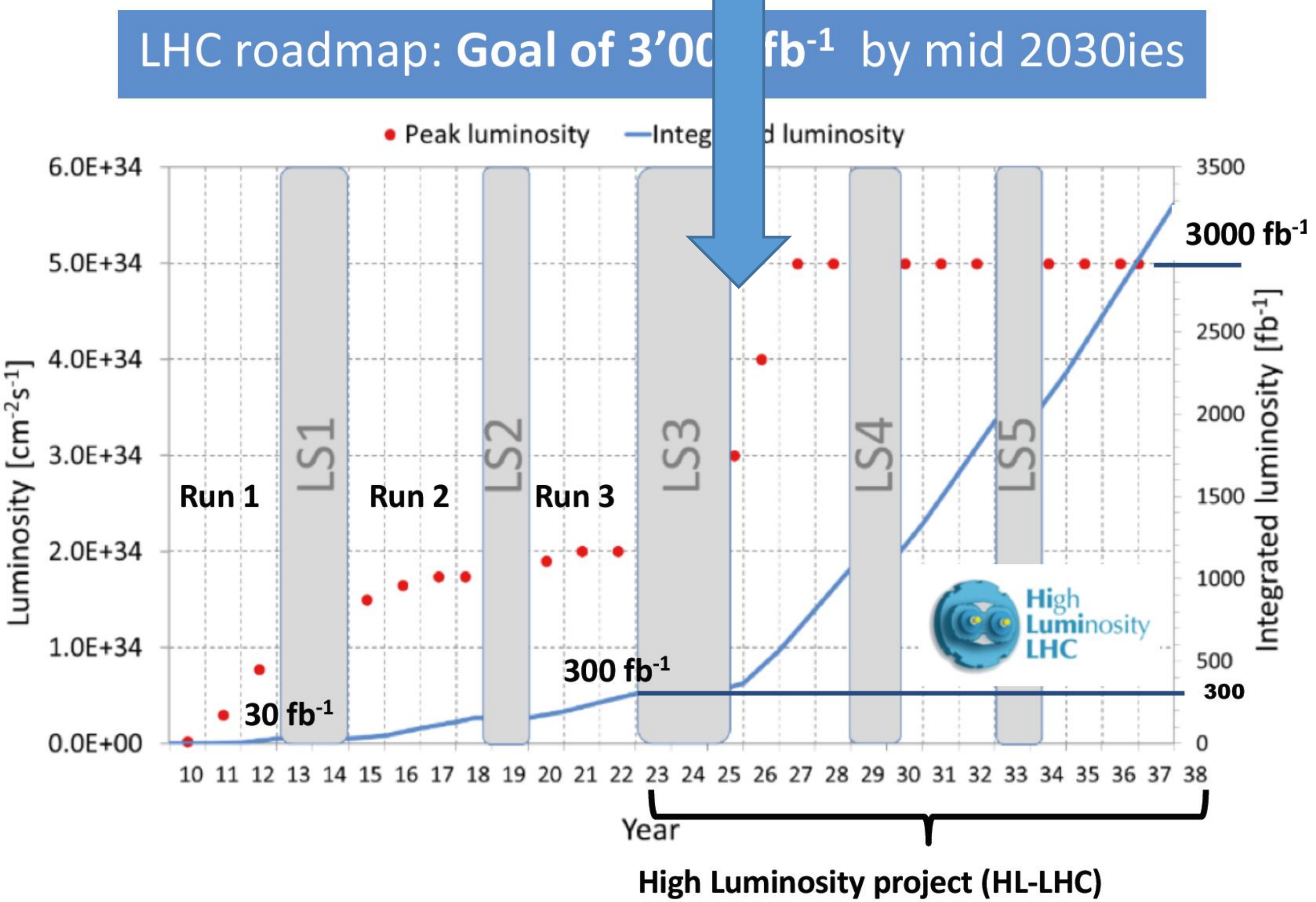


- MOLLER experiment
  (Possible MIE – FY19-23)
  - CD-0 approved
    (project paused due to budget)
  - Standard Model Test
  - DOE science review (September 2014) – strong endorsement
  - Director's review held December 15-16, 2016
  - Awaiting green light to proceed

- SoLID
  - Large acceptance, high lumi
  - SIDIS and PVDIS
  - CLEO Solenoid ✓
  - International collaboration
  - Director's review (Feb. 2015)
    → new pre-CDR complete
  - Awaiting science review from ONP

Timing with HL-LHC

MOLLER and SoLID start



Generalized Parton Distributions

(Quantum phase-space quark distribution in the nucleon)

5D

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle \; ,$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over transverse ***momentum*** space

Generalized Parton Distributions (GPD) H, $\tilde{H}$, E, $\tilde{E}$

3D

3D nucleon imaging in transverse coordinate and longitudinal momentum space

(Polarized) DVCS directly probes GPDs

Nucleon polarization		Sensitivity to GPD
	UP	H, $\tilde{H}$, E
	LP	$\tilde{H}$, H, E
	TP	E, H

DVMP is required for flavor separation

Transverse Momentum Structure of Nucleon – TMDs

(Quantum phase-space quark distribution in the nucleon)

5D

$$W_\Gamma(\mathbf{r},k) = \frac{1}{2M_N}\int \frac{d^3\mathbf{q}}{(2\pi)^3} e^{-i\mathbf{q}\cdot\mathbf{r}} \left\langle \mathbf{q}/2 \left| \hat{\mathcal{W}}_\Gamma(0,k) \right| -\mathbf{q}/2 \right\rangle$$

$$W_\Gamma(\mathbf{r},\mathbf{k}) = \int \frac{dk^-}{(2\pi)^2} W_\Gamma(\mathbf{r},k)$$

Integrate over ***spatial*** dimensions

Transverse Momentum-dependent Distributions (TMD)

3D

3D imaging of the nucleon in momentum space

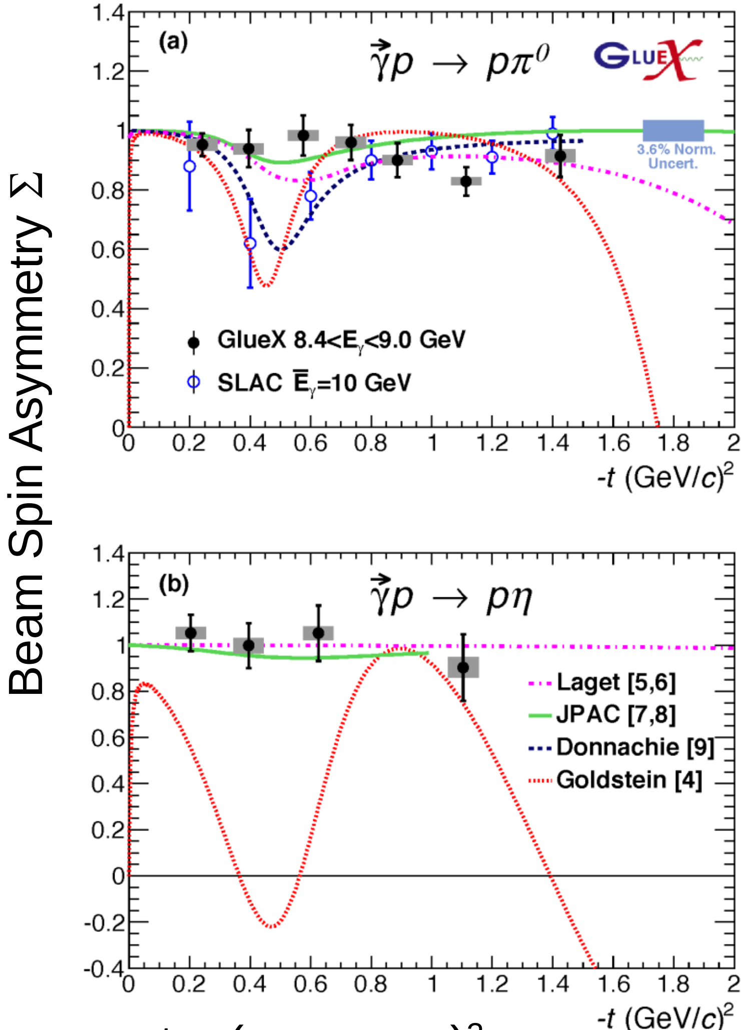
Quark spin polarization

Nucleon polarization

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

JLab has planned a complete SIDIS program with π/K to access quark TMDs, COMPASS can access sea quark region

1^{st} Results from 12-GeV JLab



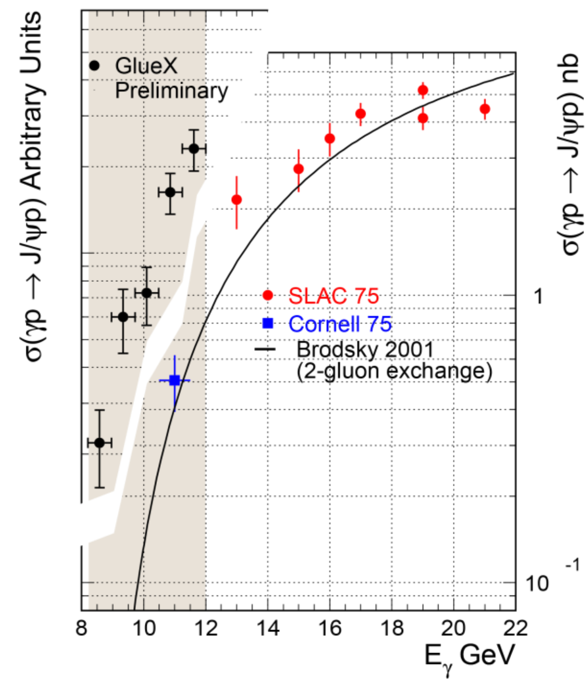
$t = (p_{target} - p_p)^2$

The new GlueX results (PRC 95 (2017) 042201) show:

- The reaction mechanism for neutral pions 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.

Next: $\gamma p \rightarrow pJ/\Psi$

- J/Ψ photoproduction at threshold
- Gives insight on J/Ψ production mechanism (2-gluon vs 3-gluon)
- Can also point to nature of charmed LHCb pentaquark

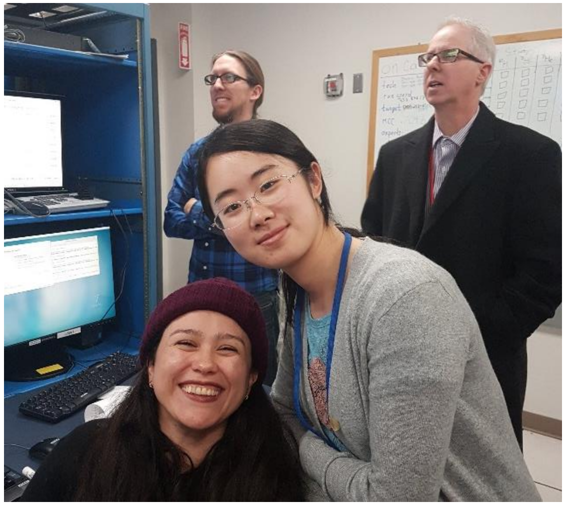


The overall normalization of the GlueX data will shift the black points up or down, but the size of the errors is preserved on the log scale.

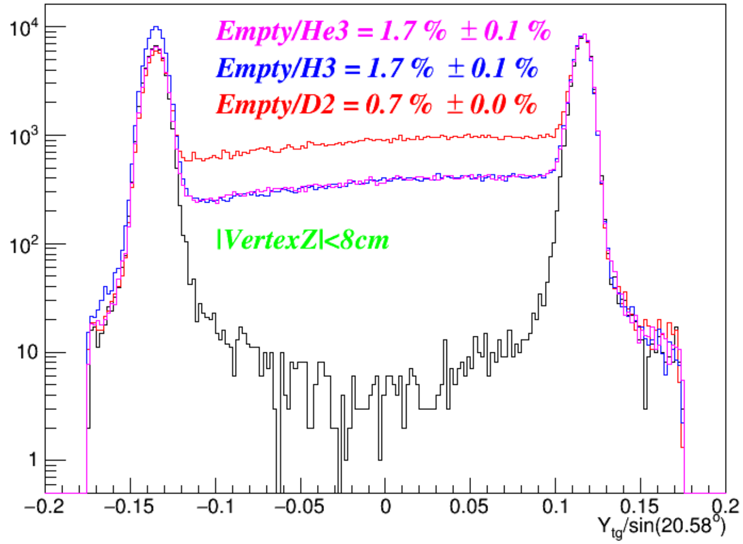
Hall A in Physics Production

First Beam On Tritium Target Cell

On 12/15/17 Hall A put first beam on a tritium target cell – facilitates 4 (3 high impact) experiments!



LEFT Image: Waiting for first beam on the Hall A tritium target: UNH Ph.D. students Nathaly Santiesteban and Shujie Li along with Jefferson Lab postdoc Evan McClellan and lab Director Stuart Henderson.



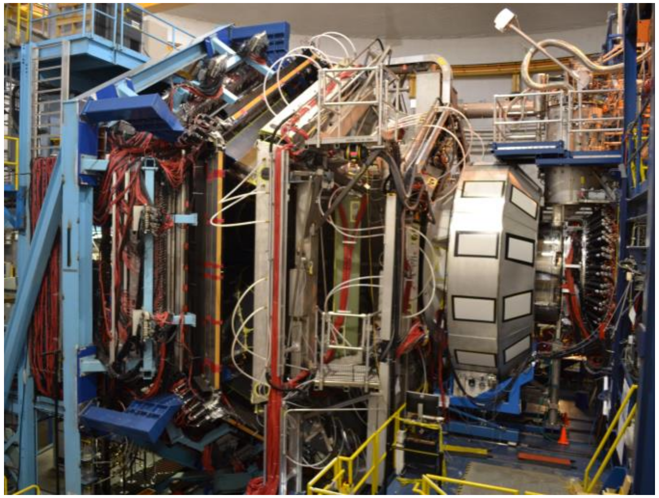
CENTER Image: Shown are the tritium, He, D target data as compared to running on an empty cell (black). The tritium and other gas targets are clearly visible between the aluminum entrance and exit windows of the target cell.

RIGHT Image: The target cell stack during installation in the Hall A scattering chamber.

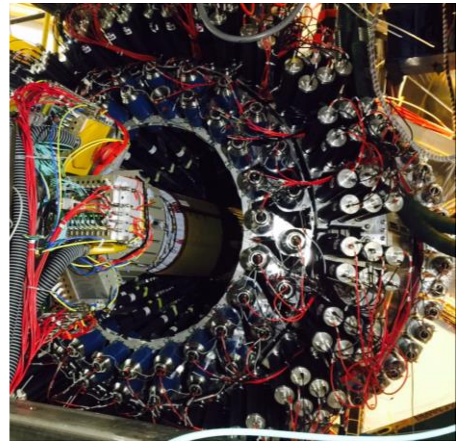
As the first Hall to receive beam in the 12 GeV era, Hall A has previously completed running for 2.5 non-tritium experiments.

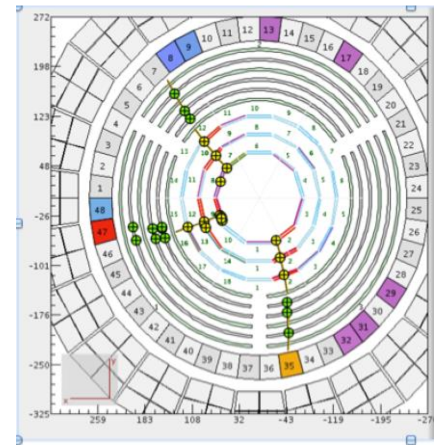
Hall B in Physics Production (since 02/05/18)!

CLAS12 Forward Detector

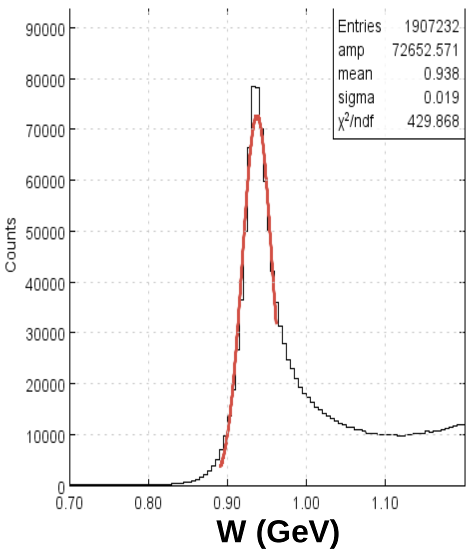


CLAS12 Central Detector with 3 charged particles

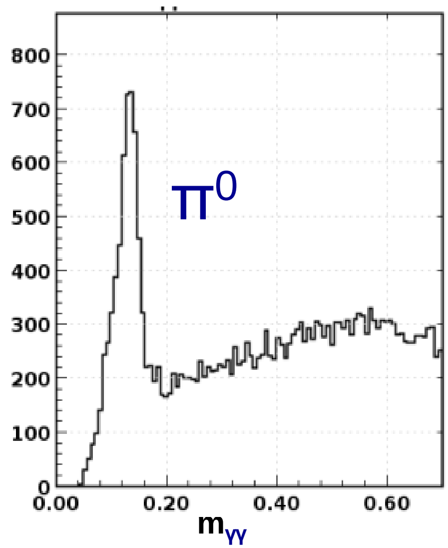




p(e,e')p @ 2.2 GeV



π⁰ @ 10.6 GeV

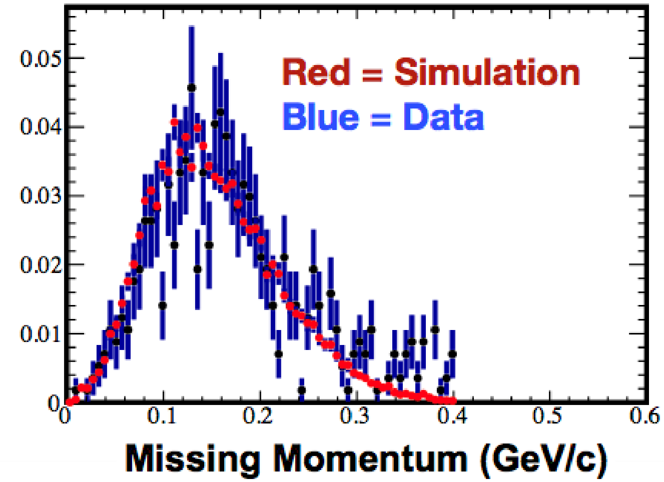


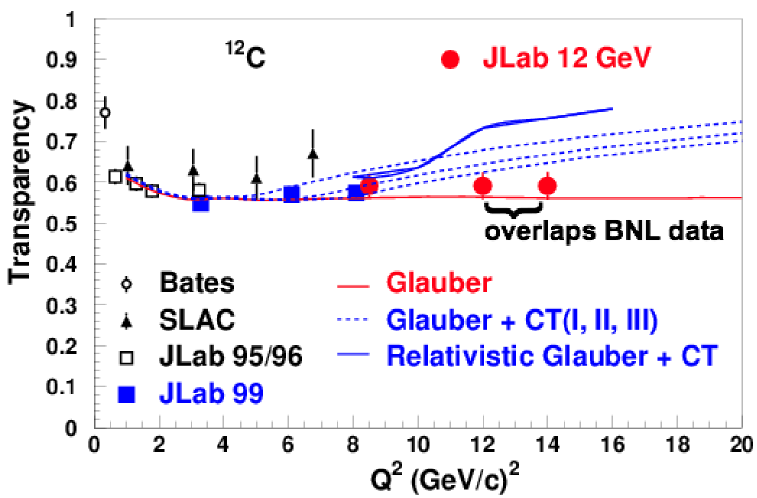
- Detectors were operated during engineering run at luminosities from 0.75 x 10^{34} to 1.75 x 10^{35}
- The latter is nearly twice the design luminosity!
- Physics production run started at a luminosity of 3 x 10^{34} to facilitate understanding of the detector efficiencies and calibrations.

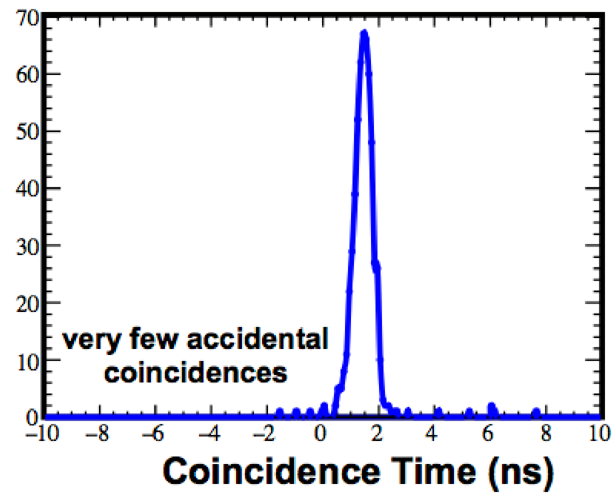
Hall C in Physics Production (since 01/20/18)!

- SHMS calibration data acquired
- Physics Program started:
  - $F_2^{H,D}$ structure functions
  - D(e,e'p) at high missing momentum
  - Color Transparency – ^{12}C(e,e'p)
    - Data for 2 of 3 points acquired.
    - Highest Q^2 is where BNL A(p,2p) saw rise in transparency

Online data quality excellent!



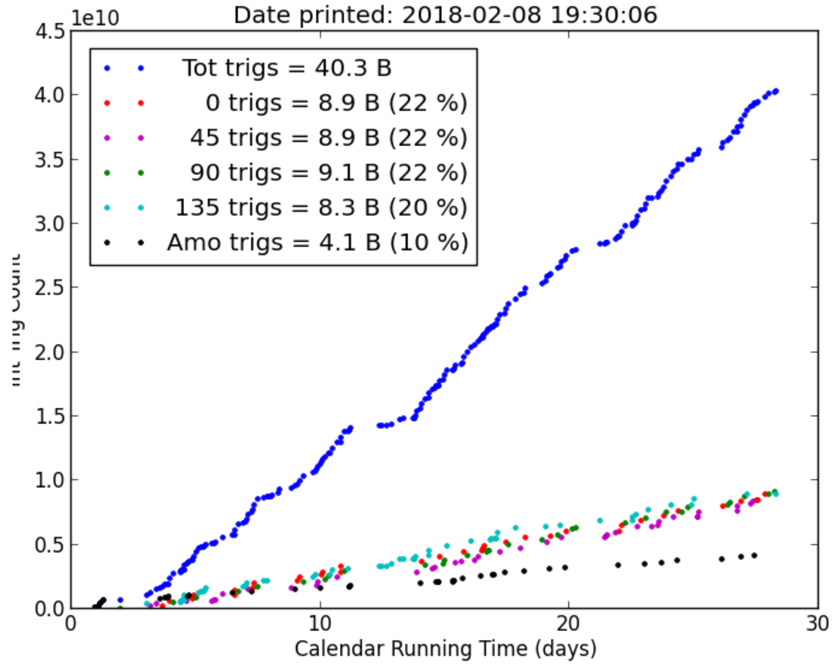




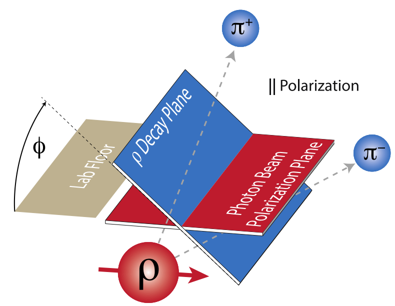
Hall D in Physics Production

Hall D is running GlueX-I (90 PAC days approved)

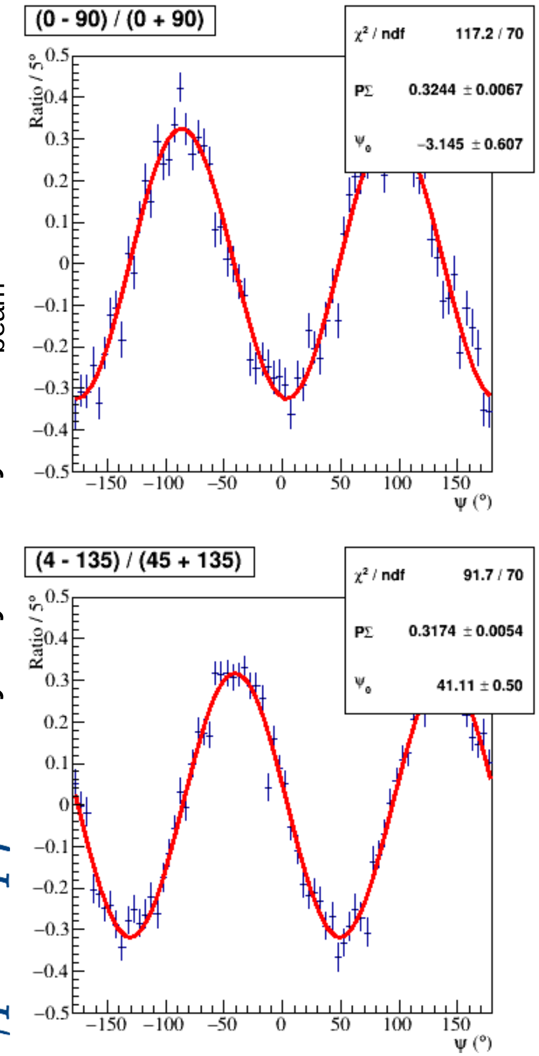
- Spring 2017: 20 PAC days accumulated, ~50B events collected.
- Spring 2018: as of Feb. 8, 14 PAC days, ~40B events collected.



Data quality monitoring

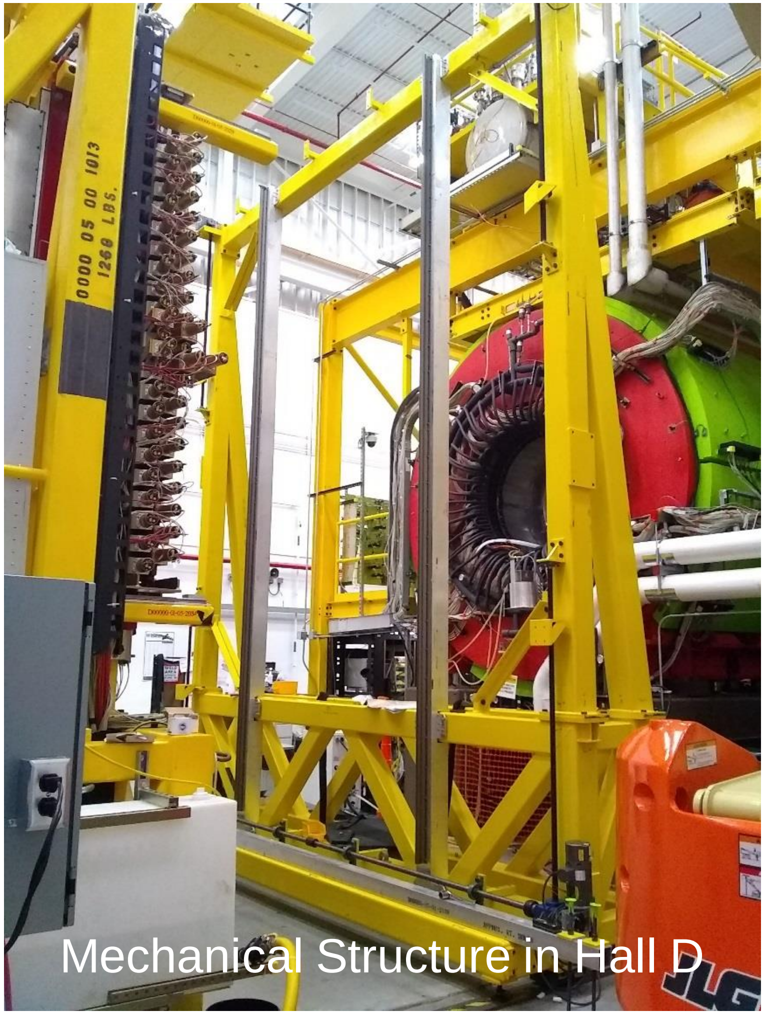


$\gamma p \to p\rho$ Decay asymmetry = ΣP_{beam}, $\Sigma \approx 1$

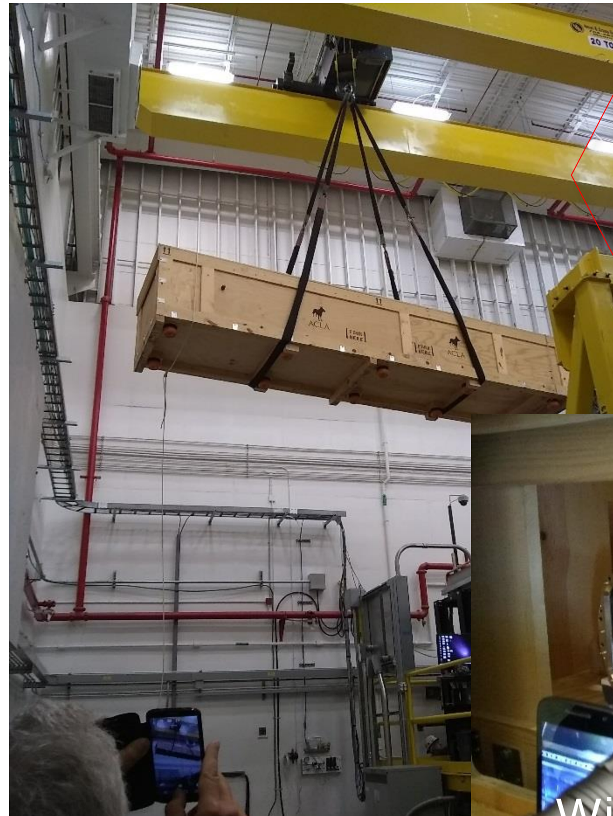


- Beam polarization P_{beam}~35%, similar to 2017
- Yields of known resonances are similar to 2017

DIRC detector – towards strange spectroscopy



Mechanical Structure in Hall D



- First bar box
- The remaining 3 bar boxes will be delivered 06/2018

Window of the bar box

- 30 MAPMTs on hand; order for the remaining MAPMTs was placed 1Q/FY18.
- All the electronics boards are at JLab.
- Components for the optical boxes are currently being machined at vendors and at MIT/Bates and the goal is for assembly to start soon. The target date for delivery is July 1.

1st test with beam: This Fall

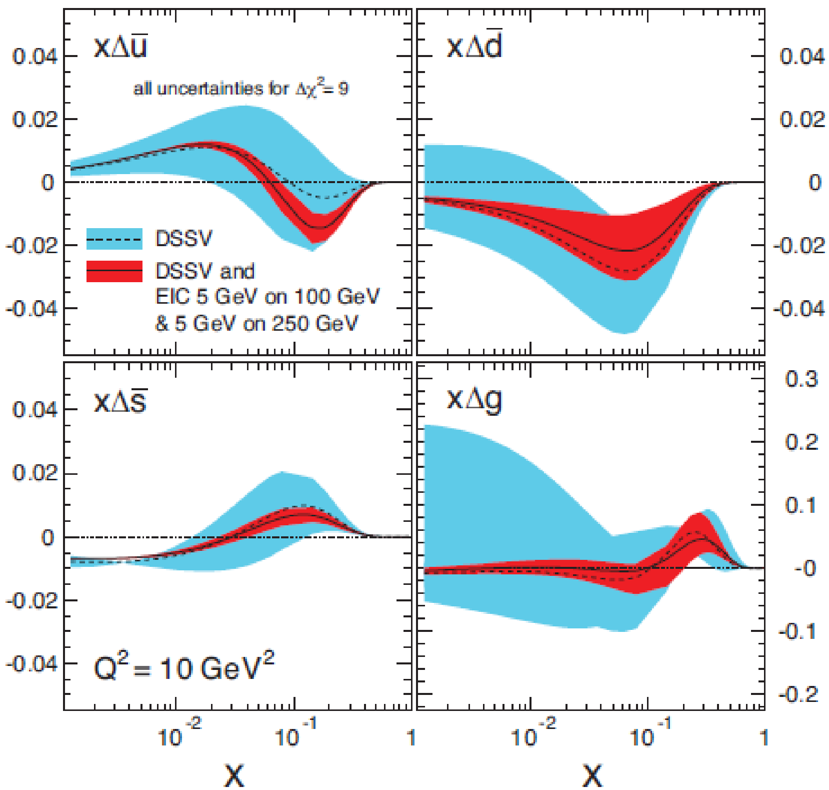
Helicity PDFs at an EIC

A Polarized EIC:

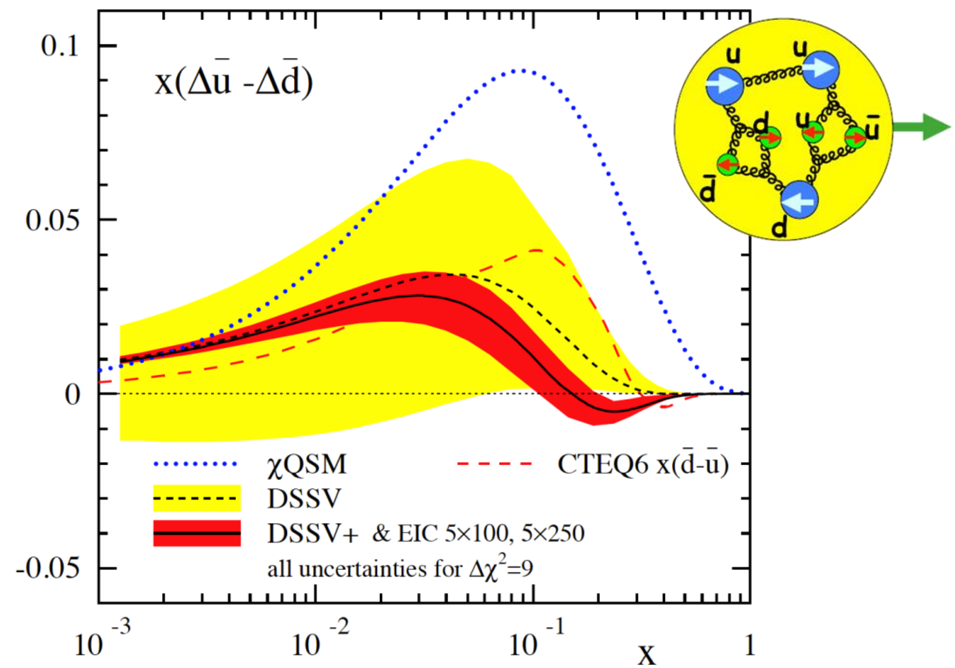
- Tremendous improvement on $x\Delta g(x)$
- Good improvement in $\Delta\Sigma$
- Spin Flavor decomposition of the Light Quark Sea

Many models predict $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

Needs range of √s, here from ~ 45 to ~ 70

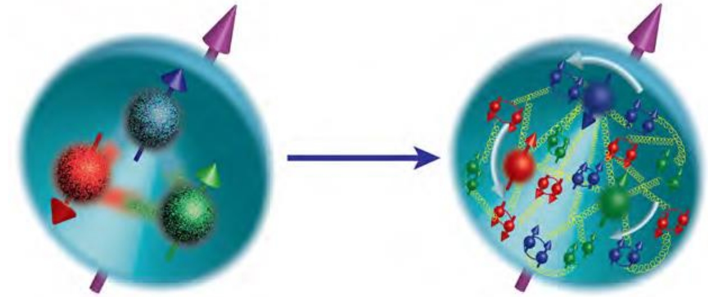


Needs range of √s ~ 30-70 (and good luminosity)

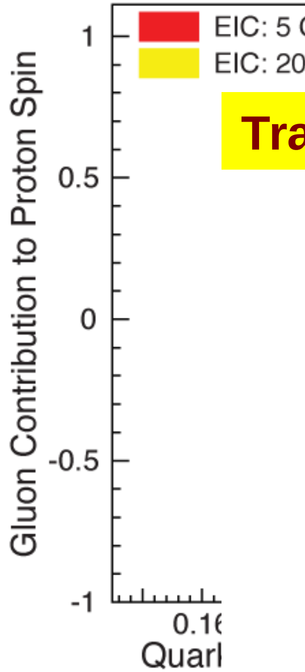


2+1 D partonic image of the proton@EIC

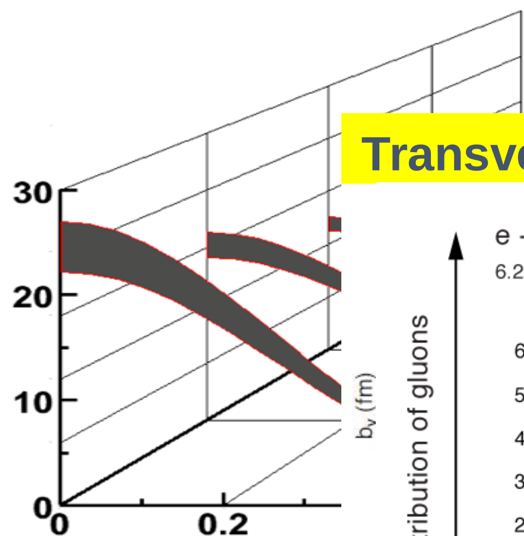
Spatial distance from origin X Transverse Momentum
→ Orbital Angular Momentum



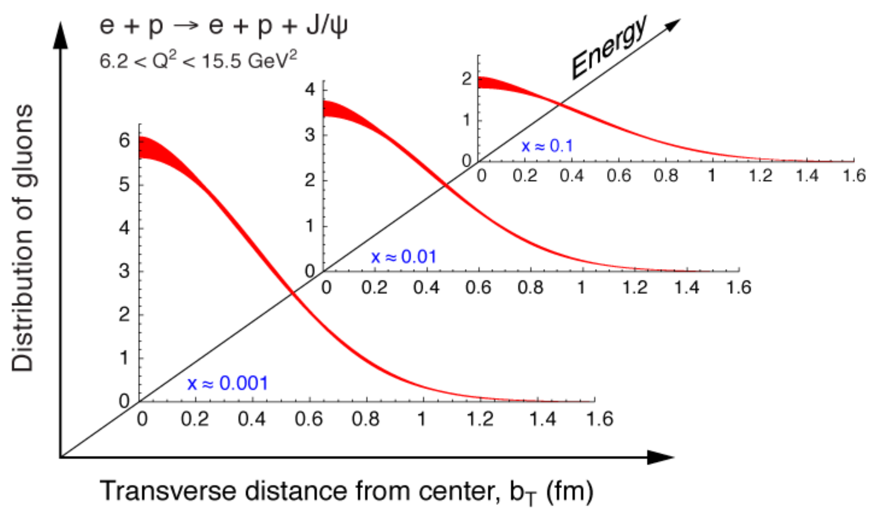
Helicity Distributions: ΔG and ΔΣ



Transverse Momentum Distributions



Transverse Position Distributions

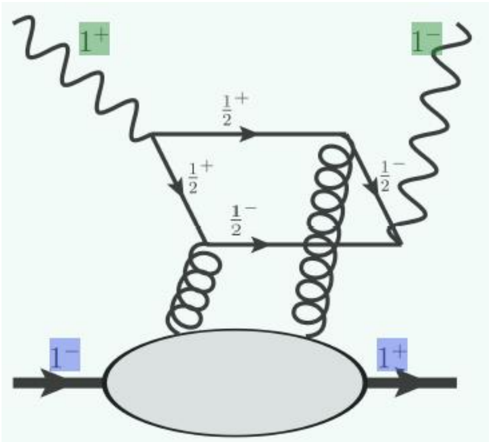


Exotic Glue in Nuclei

Exotic Glue in Nuclei =

- gluons **not** associated with individual nucleons in nucleus
- operator in nucleon = 0 & operator in nuclei ≠ 0

Targets with J ≥ 1 have leading twist gluon contribution
$\Delta(x,Q^2)$: double helicity flip (Jaffe and Manohar, 1989)
Changes both photon and target helicity by two units…



$$\Delta(x,Q^2) = A_{+-,-+}$$

Measurable in unpolarized Deep Inelastic Scattering with a **transversely polarized J ≥ 1 target like the deuteron** as azimuthal variation.

Parton model interpretation:
$\Delta(x,Q^2)$ informs how much more momentum of a transversely polarized particle is carried by a gluon with spin aligned rather than perpendicular to it in the transverse plane.

Shanahan, Detmold, et al.

LQCD calculation: gluon transversity distribution in the deuteron, m_π = 800 MeV
→ **First evidence for non-nucleonic gluon contributions to nuclear structure**

Many EIC Related Meetings

- EIC Users Group Meeting 2017, Trieste, Italy, July 18-22, 2017. Organizers A. Bressan, S. Dalla Torre et al. – Major focus was on engagement of EU community and funding agencies
- The Flavor Structure of the Nucleon Sea (INT-17-68W), October 2-13, 2017. Organizers C. Aidala, W. Detmold, J. Qiu, W. Vogelsang
- Physics Opportunities at an ElecTron Ion Collider (POETIC 2018), Regensburg, Germany, March 19-22, 2018. Organizer A. Schaefer
- 26th International Conference on Deep-Inelastic Scattering and Related Matters (DIS 2018), Kobe, Japan, April 16-20, 2018. Organizer Y. Yamazaki
- EIC Users Group Meeting 2018, Catholic University of America, Washington, D.C., July 30 – August 3, 2018. Organizer T. Horn - Major focus will be on steps after NAS report leading to anticipated CD0 EIC project award.
- Probing Nucleons and Nuclei in High-Energy Collisions (INT-18-3), October 1 – November 18, 2018. Organizers: Y. Hatta, Y. Kovchegov, C. Marquet, A. Prokudin

(not complete, also topical workshops and ECT meetings related to EIC science)*

In fact, essentially all conferences & workshops related to hadron physics have an EIC slot