Introduction to JLab science

Ciprian Gal

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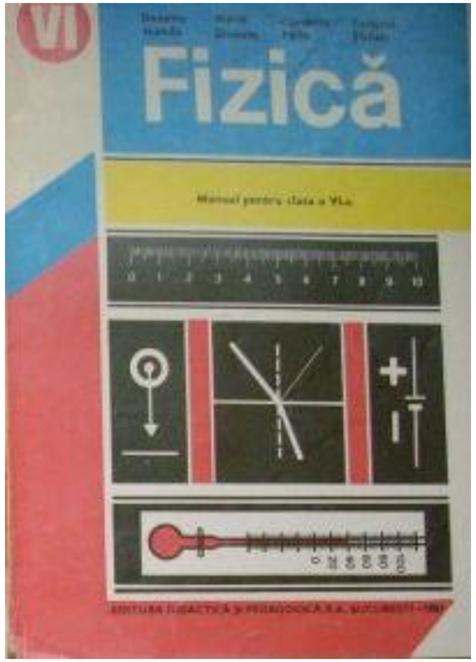
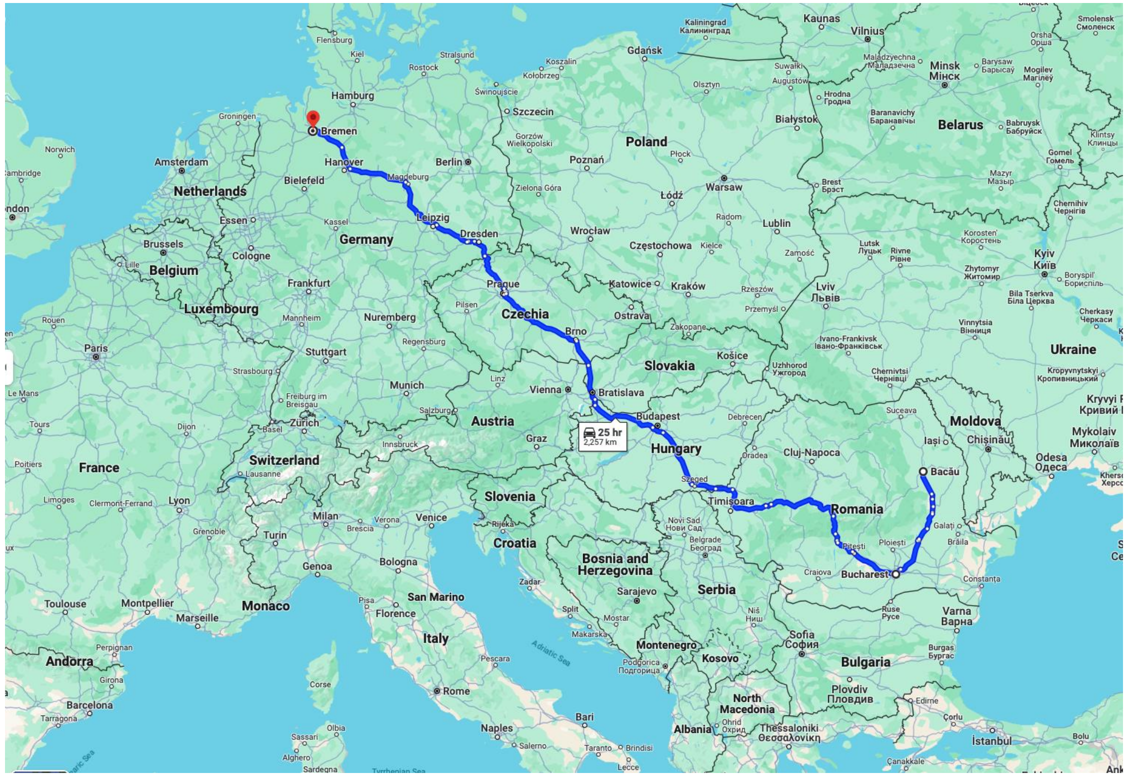
Jefferson Lab

Who am I and where did I come from?





- Started as hall A/C staff in Feb 2023 ☺
- My interest in physics started very early in life
- Studies have taken me to quite a few places: Bucharest -> Bremen -> Stony Brook -> Jefferson Lab

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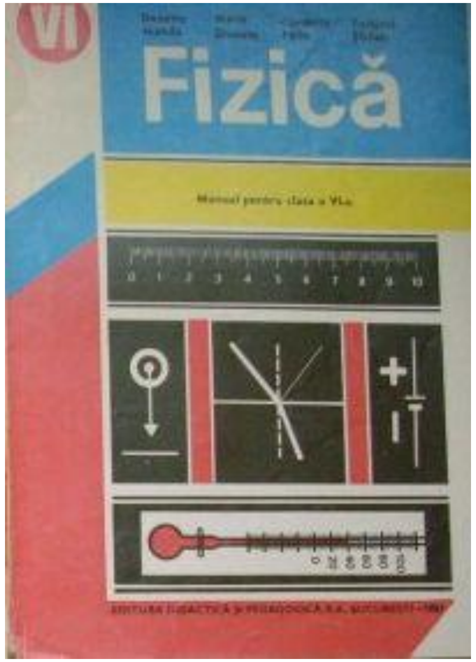

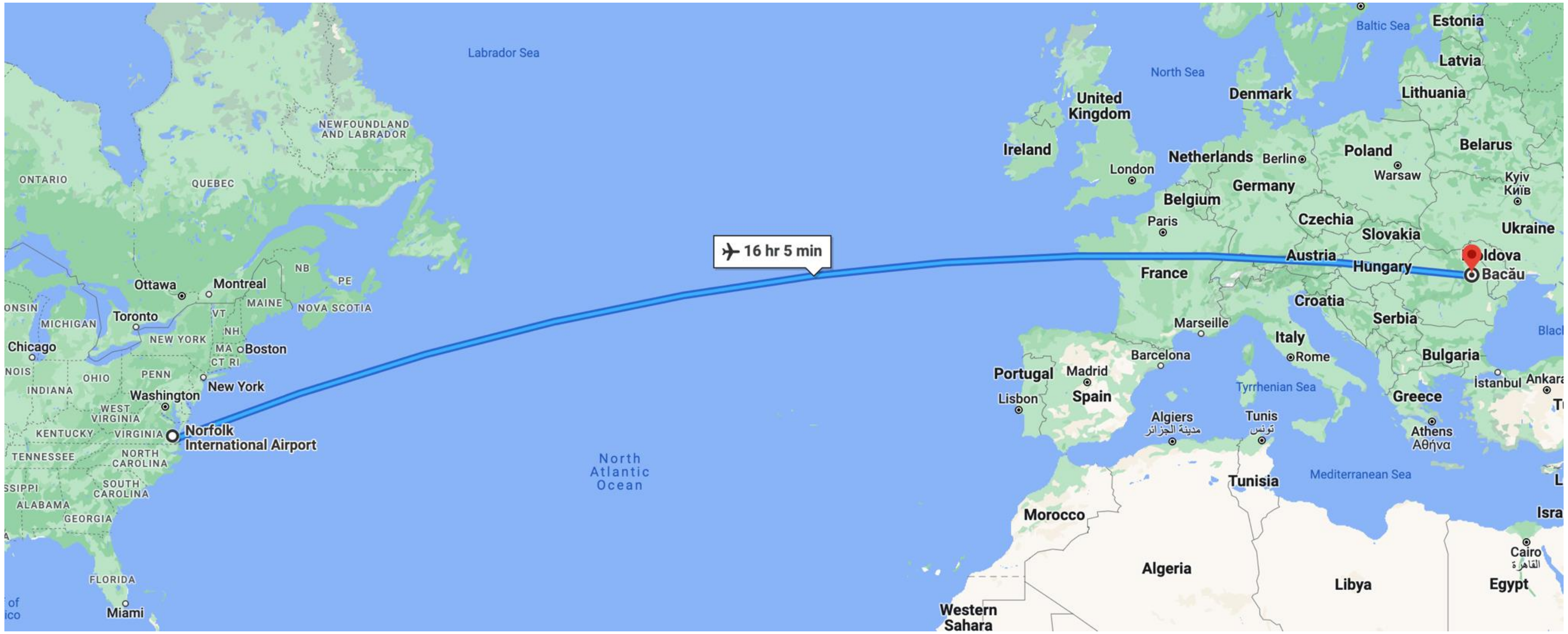

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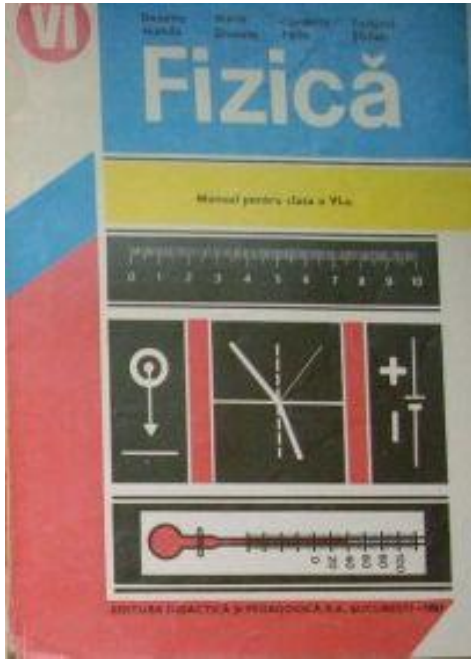
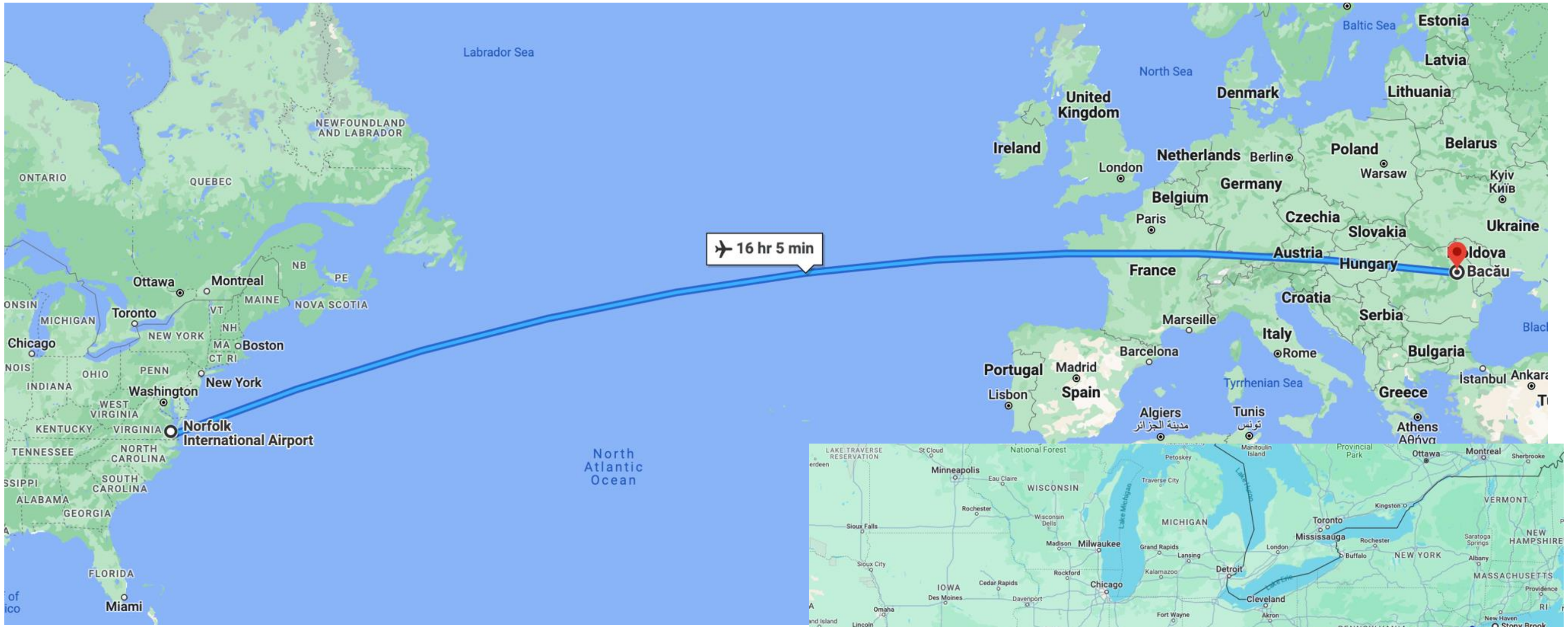
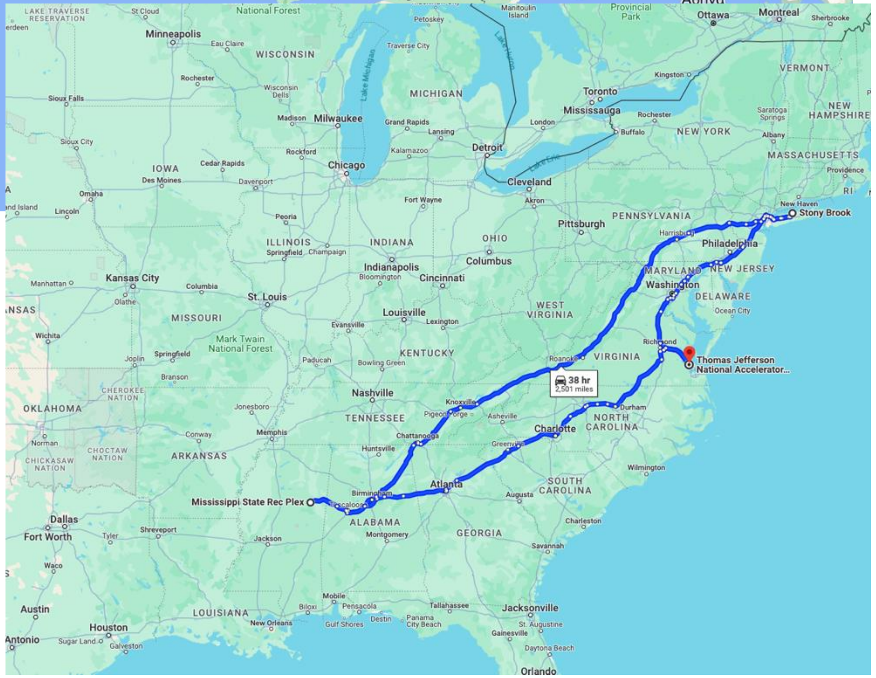






- Started as hall A/C staff in Feb 2023 ☺
- Search for a permeant position is a slog
- Interested in all sorts of physics, currently focused on PVES and EIC

Disclaimer

- Sorry to those who are well on their Physics learning journey
  - My guess is that some of you may not have had nuclear or particle physics courses at an advanced level and I want to make sure I don't lose you along the way
- As you go along you will find that quite a bit can be accomplished without perfect knowledge
  - I am shooting for a "big picture" understanding
- I am an experimentalist -> my slides will be focused on measurements
  - However, experiments are only half of the story -> theory the other
- The lectures are my attempt to weave together slides (lots of other summers schools out there), chapters, papers from a whole lot of different folks
  - Rolf End, Cynthia Keppel, Sanghwa Park, Krishna Kumar, Kent Paschke, …

The talking ”stick”

- Great tool for conversation invented by indigenous people of the Americas
- Rules:
  - You have the “stick”: no one can interrupt you
    - BUT you do have to answer
    - Guesses are more than welcome – we are going to exercise our physics intuition muscles and have some fun along the way
    - We will all learn from your answers (or questions) – even if they are “wrong”
  - You don’t have the ”stick”: you can listen and absorb what someone else is saying
    - Once they are done, we can continue the conversation respectfully

Talking stick test

- Question:
  - Where are you in your physics journey and what is something interesting about you?

Talking stick test

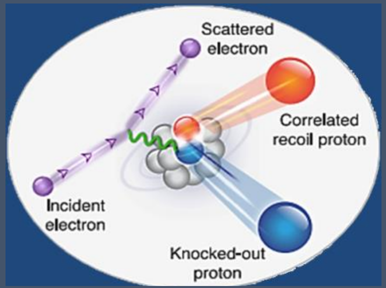
- Question:
    - What is something interesting about you?

Plan for the afternoon

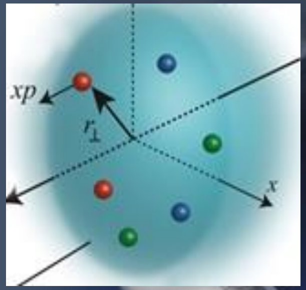
- Go through some scattering basics
- Get a firm grasp of what makes JLab special
- Highlight the diversity in experiments here by talking through some examples

- But most importantly: **<u>ask questions!</u>**
  - I don't have to go through all the material I collected since you will have in depth lectures throughout the school

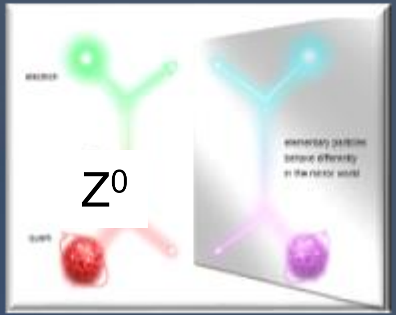
JLab: A Laboratory for Medium Energy Nuclear Science



Nuclear Structure



Structure of Hadrons



Fundamental Forces & Symmetries

Medical Imaging

Jefferson Lab is a state-of-the-art *user facility* for nuclear physics research and beyond.

Nuclear Astrophysics

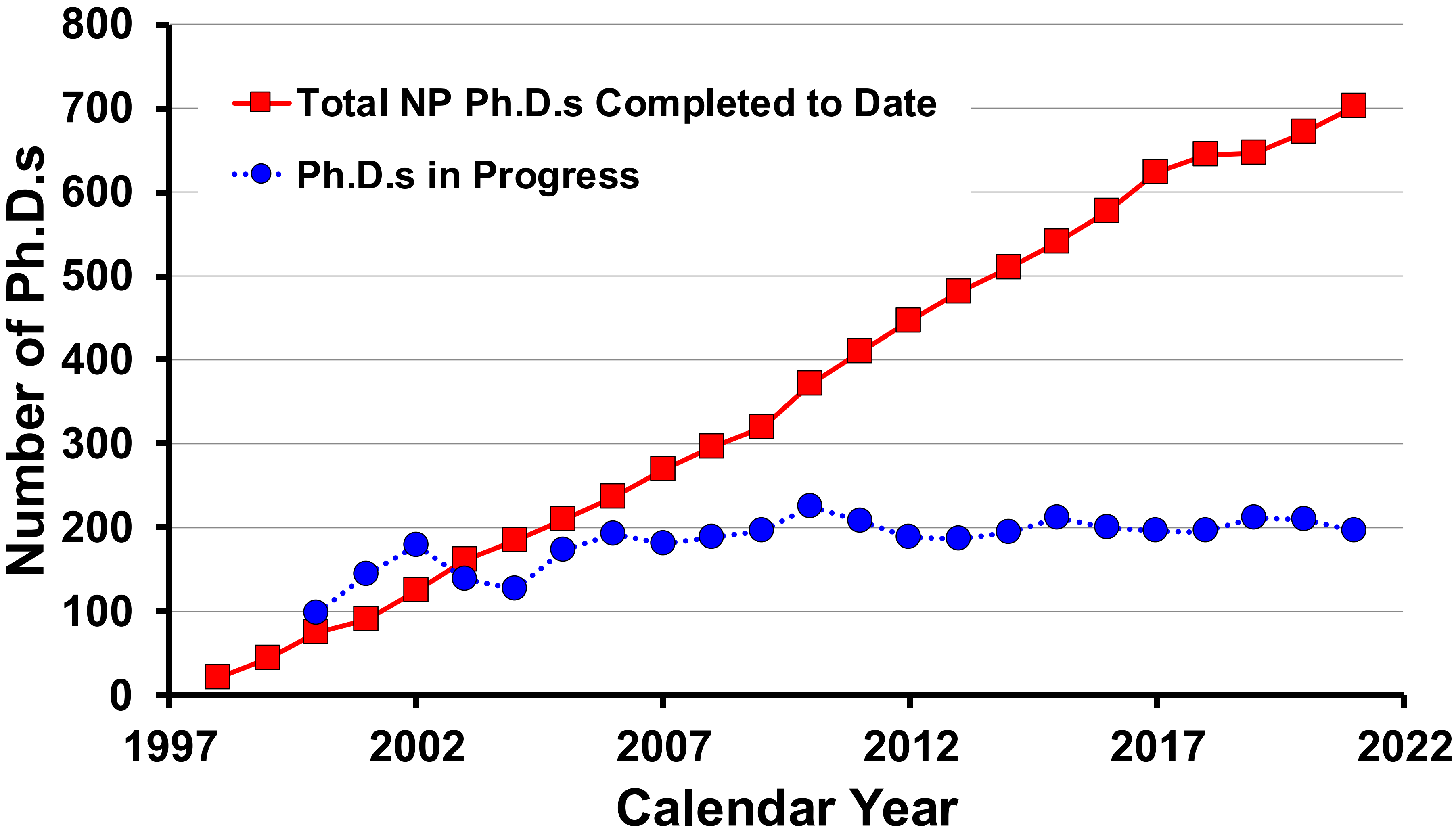
Cryogenics

Accelerator S&T

Theory & Computation

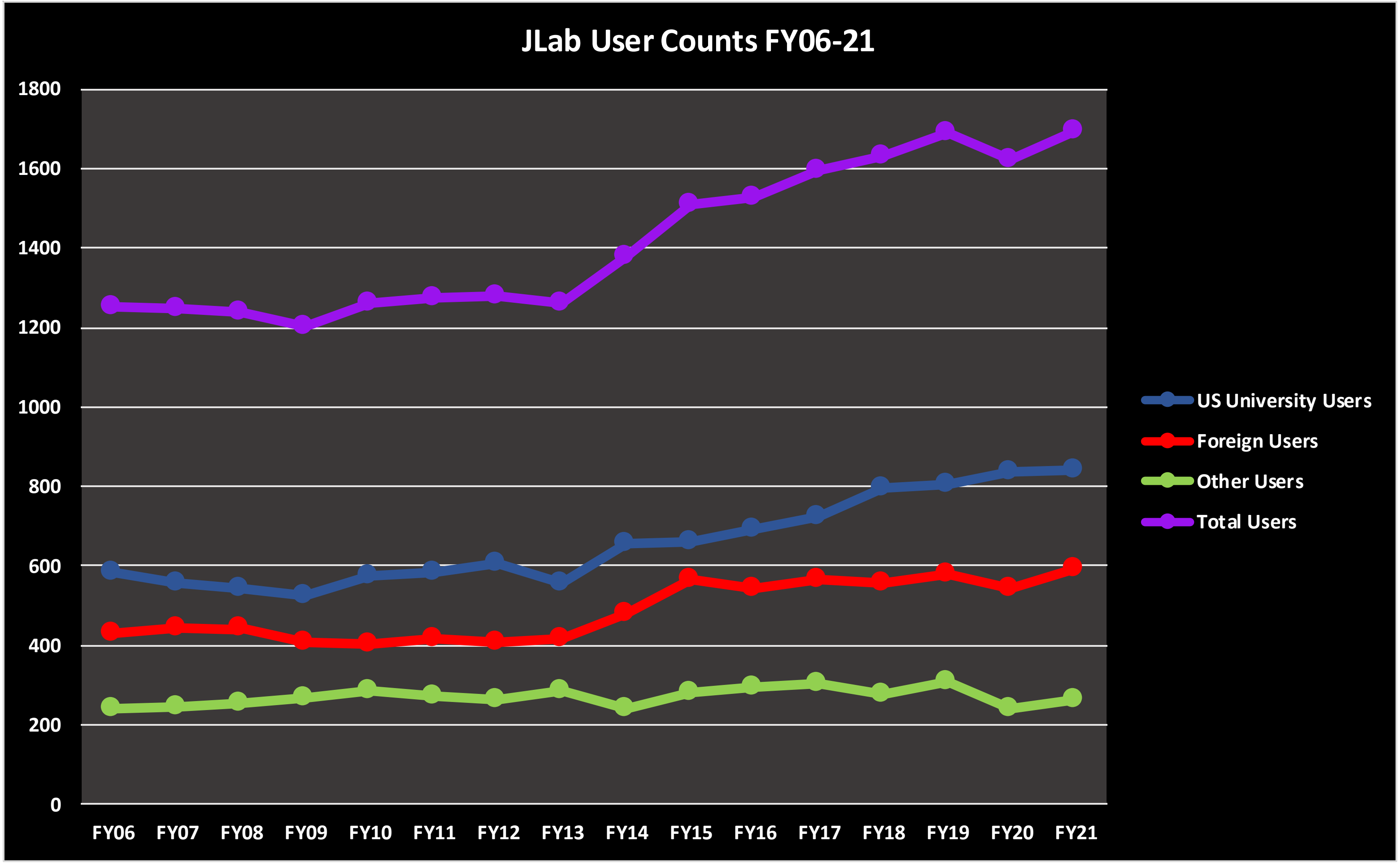
About 25% of NP PhDs

On average: 30 PhDs/year.
Typically, 200 PhD students annually engaged in Jefferson Lab research.



JLab's superpower: USERS

- FY21: 1694 users in 278 institutions from 38 countries worldwide.
- US: 144 US institutions in 34 states, including 6 HBCU and 12 HSI



Rutherford Scattering

- While working for Rutherford at the University of Manchester Geiger and his undergraduate student Marsden observed that alpha particles emitted from "A" (radium) reflected more than 90 degrees onto a reflected screen "S" from a series of targets (lead, gold, tin, aluminum, copper, silver, iron, and platinum)
  - higher A resulted in more scintillation

Ernest Rutherford | Hans Geiger | Ernest Marsden

[669] **1911**

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom.* *By* Professor E. RUTHERFORD, *F.R.S., University of Manchester* *.

§ 1. IT is well known that the α and β particles suffer deflexions from their rectilinear paths by encounters with atoms of matter. This scattering is far more marked

- Rutherford interpreted these results as being due to Coulomb scattering from the atomic nucleus

$$\sigma(\theta) = \frac{z^2 Z^2 e^4}{16E^2} \frac{1}{\sin^4 \frac{1}{2}\theta}$$

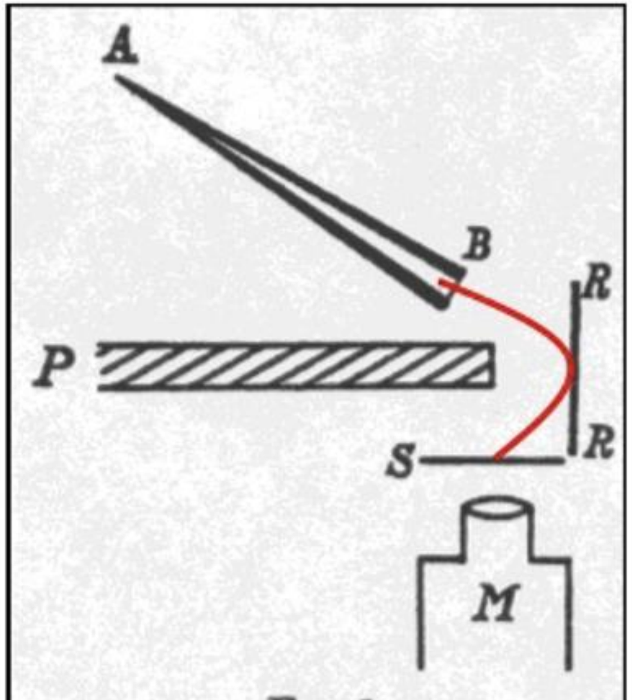
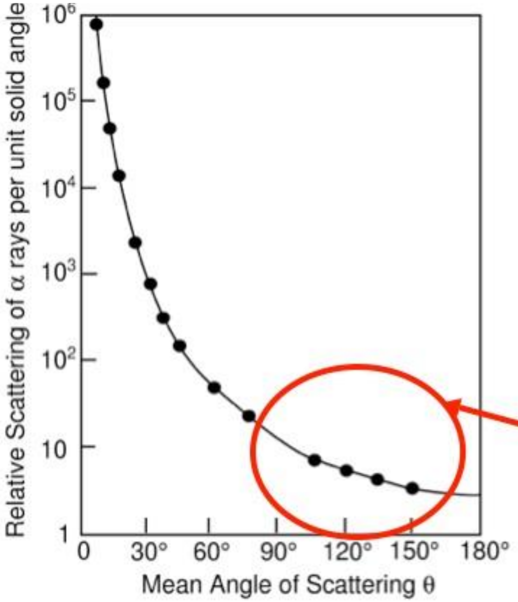


FIG. 1.

Rutherford Scattering

- Geiger and Marsden subsequently confirmed this prediction and concluded that the atom consists of a charged nucleus on the order of 10^{-14} m surrounded by a complement of electrons at about 10^{-10} m

Ernest Rutherford Hans Geiger Ernest Marsden



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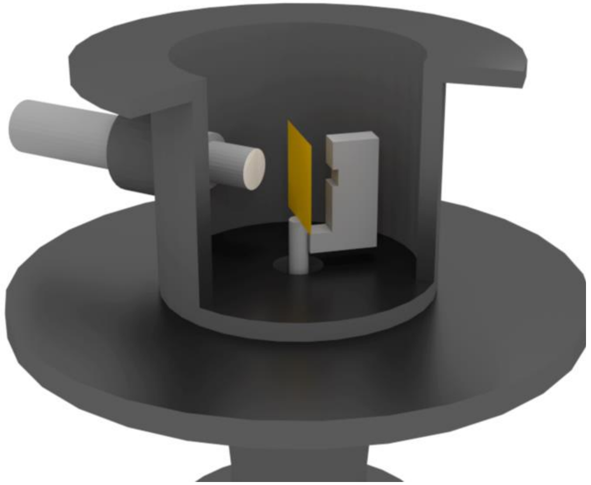
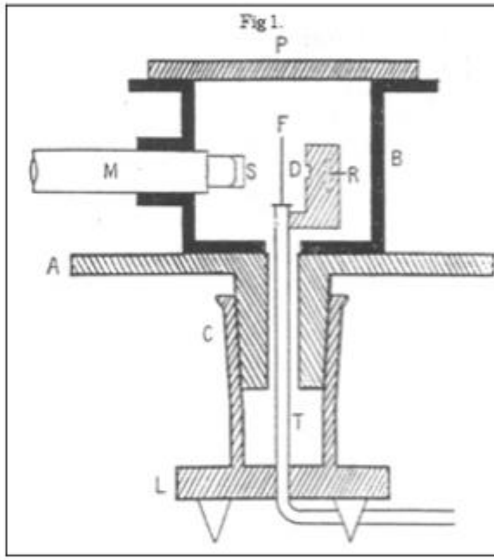
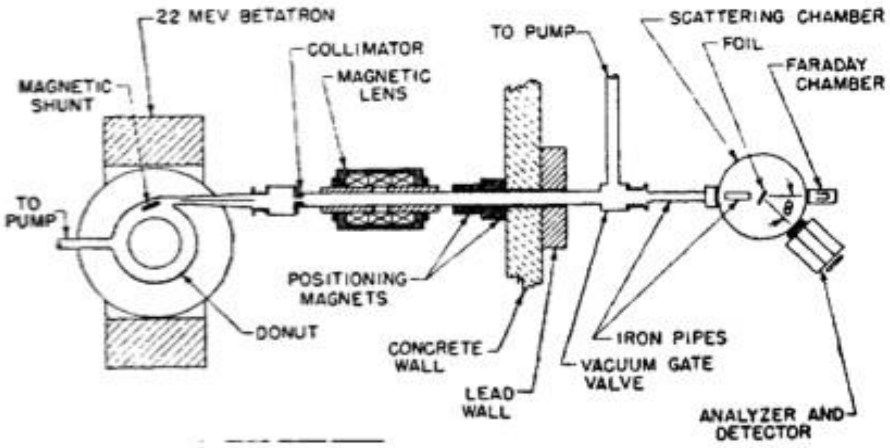




Electron scattering from nuclei

Scattering of 15.7-Mev Electrons by Nuclei*

E. M. LYMAN, A. O. HANSON, AND M. B. SCOTT†
Department of Physics, University of Illinois, Urbana, Illinois
(Received July 3, 1951)



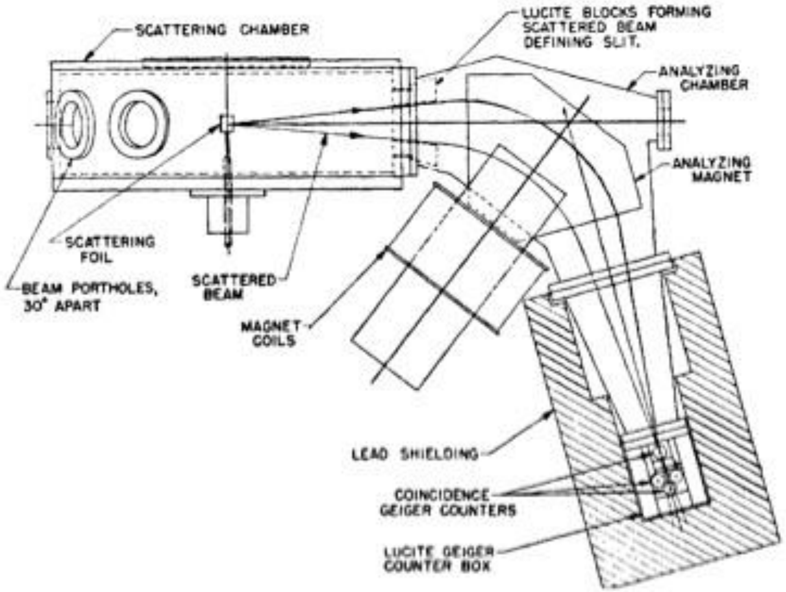
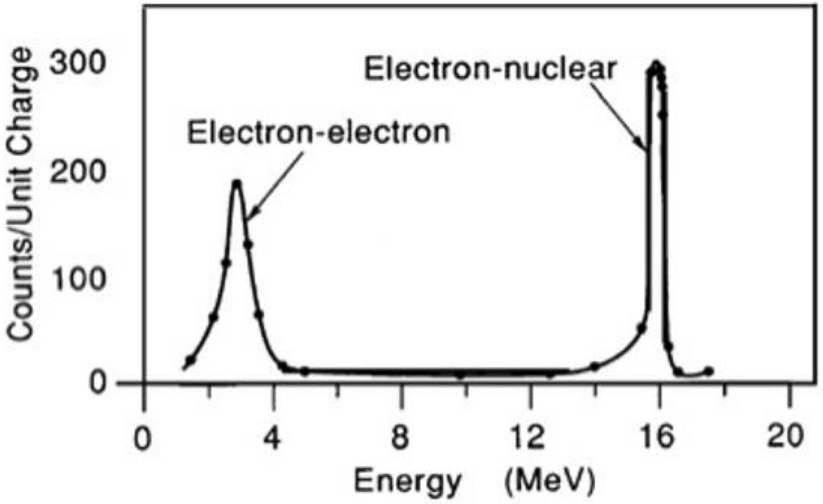


FIG. 2. Scattering chamber.


Alfred O. Hanson

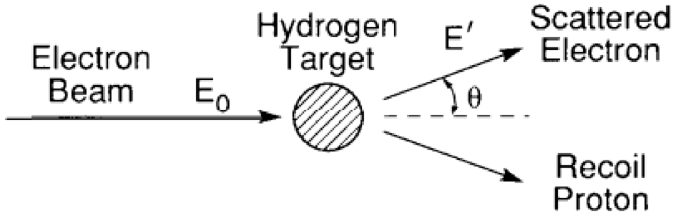

Ernest M. Lyman

- Lyman, Hanson, and Scott performed the first electron scattering from nuclei showing that the probing power of the electron was inversely proportional to its energy
  - The electron is a much cleaner probe than Rutherford's alpha particles



Does the proton have a radius?

1948-50 – Schiff, Rosenbluth: suggest use of **elastic electron-proton scattering** to probe the proton:



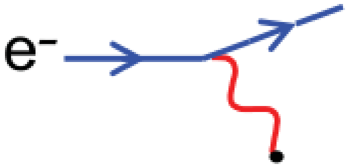
$q = (E_0 - E', \vec{q}\,)$

$$E' = \frac{E_0}{1 + \frac{2E_0}{M}\sin^2\frac{\theta}{2}}$$

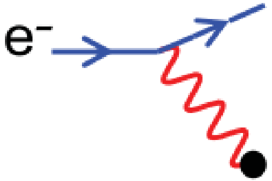
electron is left with less energy after meeting the proton

$$\boxed{Q^2 = 4E_0E'\sin^2\frac{\theta}{2}}$$

square of four-momentum transfer: connected to the probe's ability of resolving the structure of the proton



probe's ability of resolving structure $\sim \frac{\hbar}{Q}$



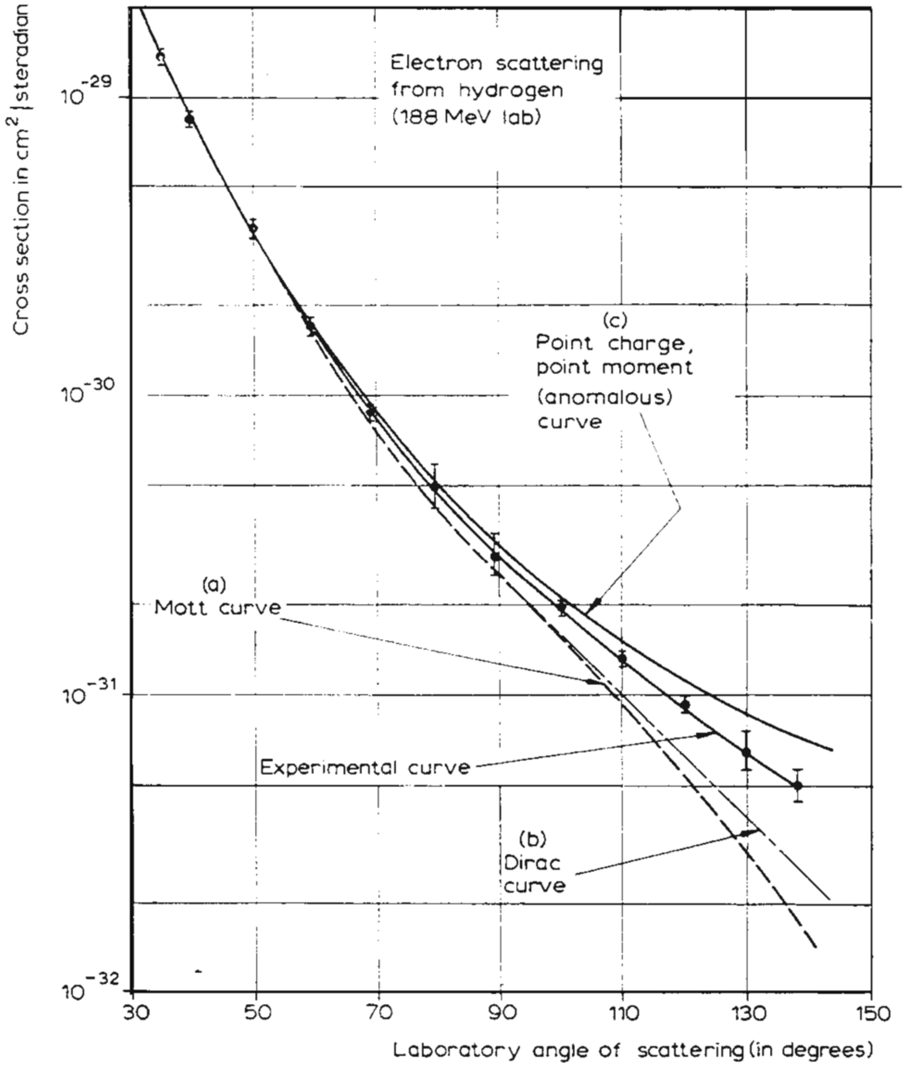
proton when $\frac{\hbar}{Q}$ >> than its size

same proton when $\frac{\hbar}{Q}$ $\sim$ its size

Does the proton have a radius?

Robert Hofstadter
Nobel Prize in Physics 1961

Photo from the Nobel Foundation archive.



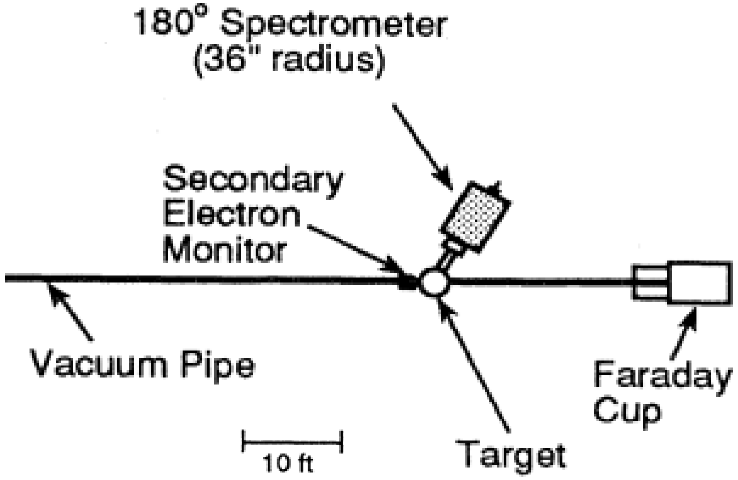


Fig. 9. Electron scattering from the proton at an incident energy of 188 MeV. *Curve (a)* shows the theoretical Mott curve for a spinless point proton. *Curve (b)* shows the theoretical curve for a point proton with a Dirac magnetic moment alone. *Curve (c)* shows the theoretical behavior of a point proton having the anomalous Pauli contribution in addition to the Dirac value of the magnetic moment. The deviation of the experimental curve from the Curve (*c*) represents the effect of form factors for the proton and indicates structure within the proton. The best fit in this figure indicates an rms radius close to $0.7 \cdot 10^{-13}$ cm.

https://www.nobelprize.org/uploads/2018/06/hofstadter-lecture.pdf

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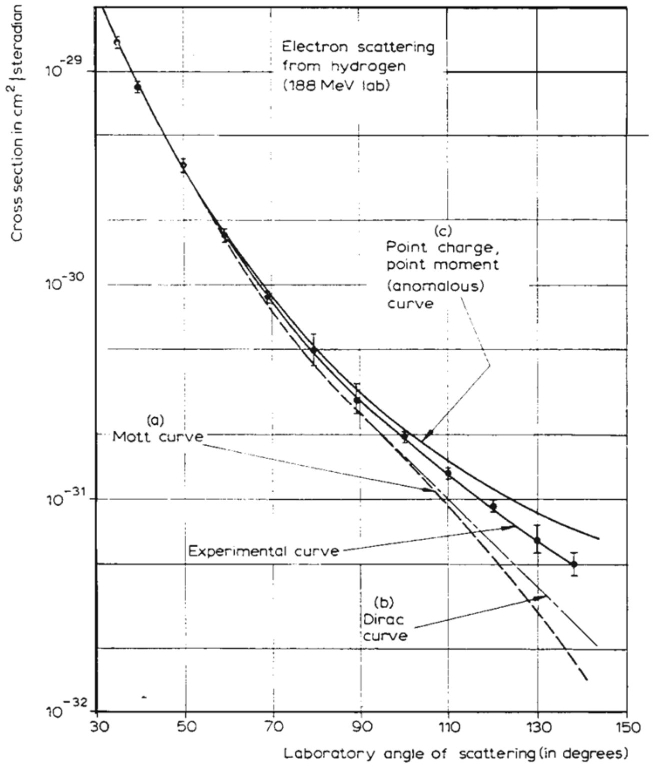
As we may see in Fig. 9, the experimental data fell below the expected theoretical curve for a proton possessing a point charge and a point magnetic moment. This behavior can be understood in terms of the theoretical scattering law developed by M. Rosenbluth[11] in 1950. This law described the composite effect of charge and magnetic moment scattering and is given by:

$$\frac{d\sigma}{d\Omega} = \sigma_{NS}\left\{F_1^2 + \frac{\hbar^2 q^2}{4 M^2 c^2}\left[2\left(F_1 + KF_2\right)^2 \tan^2 \theta/2 + K^2 F_2^2\right]\right\} \quad (7)$$

where σ_{NS} is taken from Eq. 2 with Z = 1. In the Rosenbluth equation the quantity $F_1(q)$ is the Dirac form factor, representing the proton's charge and its associated Dirac magnetic moment. The quantity $F_2(q)$ is the Pauli form factor and represents the anomalous magnetic moment of the proton. K in the above equation indicates the static value (1.79) of the anomalous magnetic moment in nuclear magnetons.



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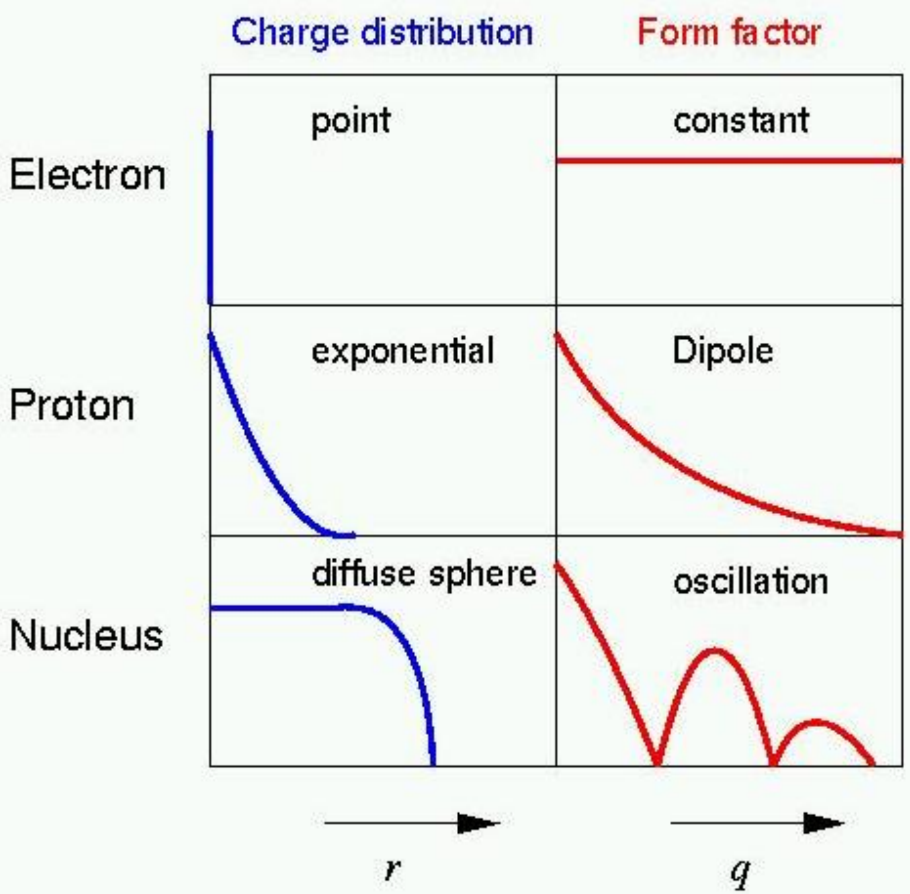
Form factors

Probability of elastic interaction: $\frac{d\sigma}{d\Omega} \Big/ \left(\frac{d\sigma}{d\Omega}\right)_{point} = \left[\frac{G^2{}_E(Q^2) + \tau G^2{}_M(Q^2)}{1+\tau} + 2\tau G^2{}_M(Q^2)\tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M^2}$



- Elastic cross section

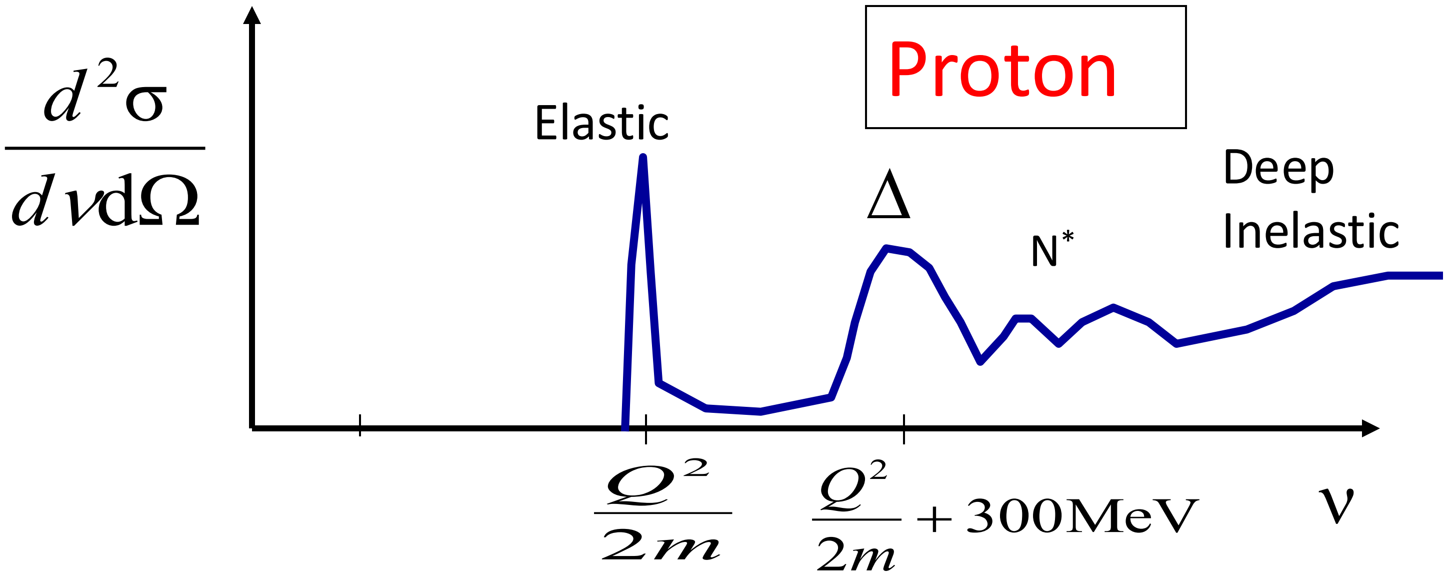
$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{exp}} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left|F(q^2)\right|^2$$

- Form factor

$$F(q^2) = \int e^{iqx/\hbar}\rho(x)d^3x$$

The form factor as a Fourier transformation of the charge distribution is a non-relativistic concept.

Electron scattering at fixed Q^2



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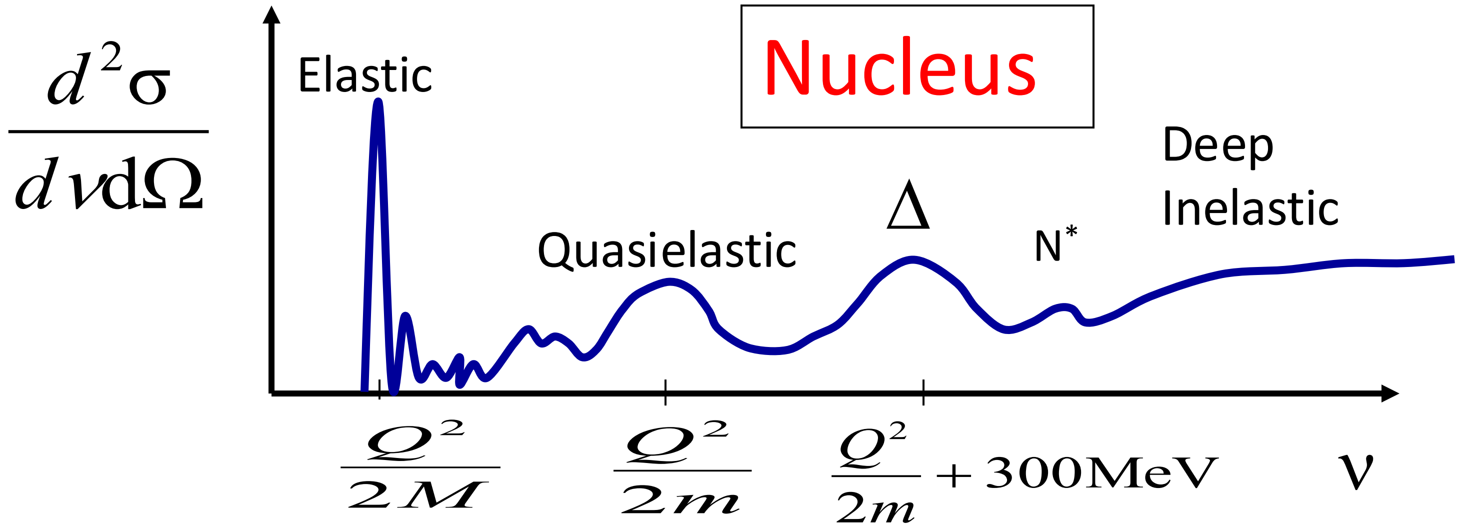
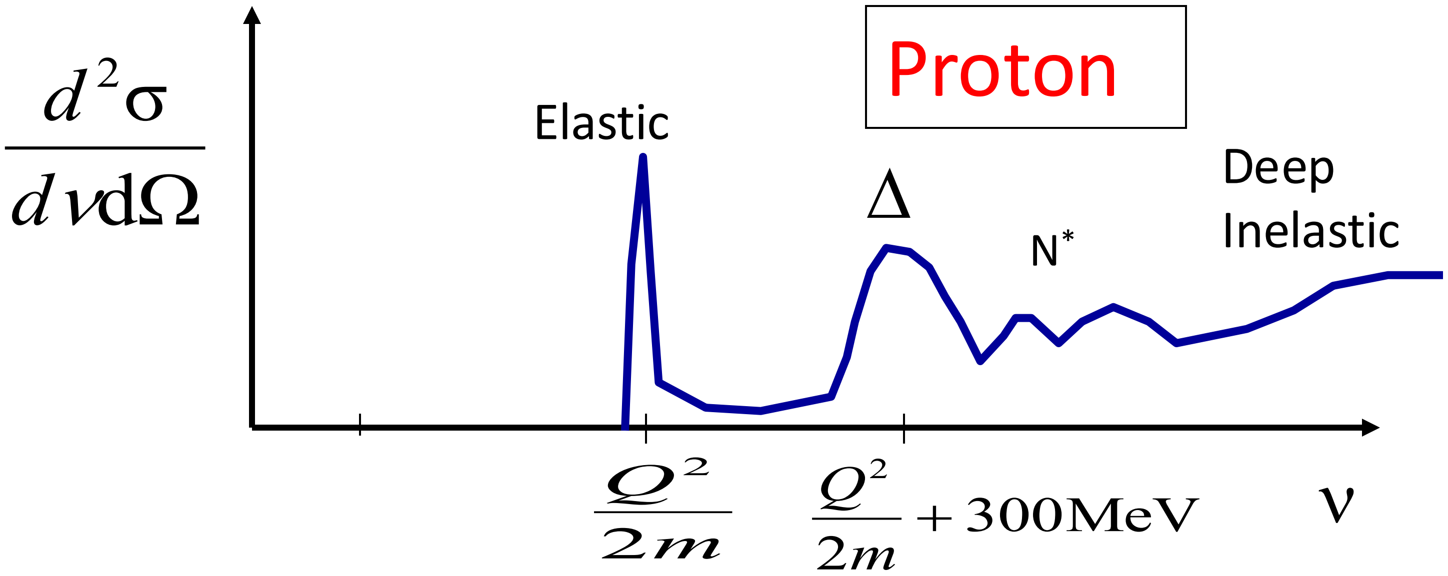
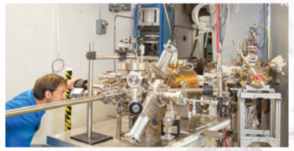




CEBAF AT JEFFERSON LAB

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.

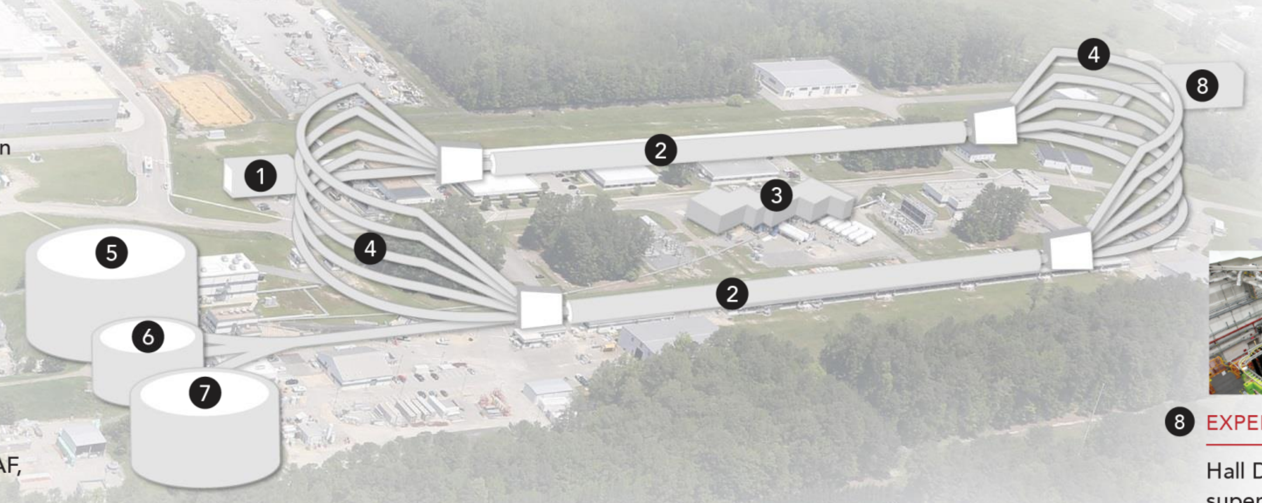
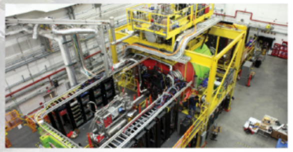


Diagram representational of below ground structure



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.

❸ CENTRAL HELIUM LIQUEFIER

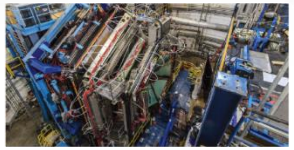
The Central Helium Liquefier keeps the accelerator cavities at -456 degrees Fahrenheit.

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.

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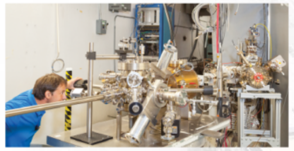


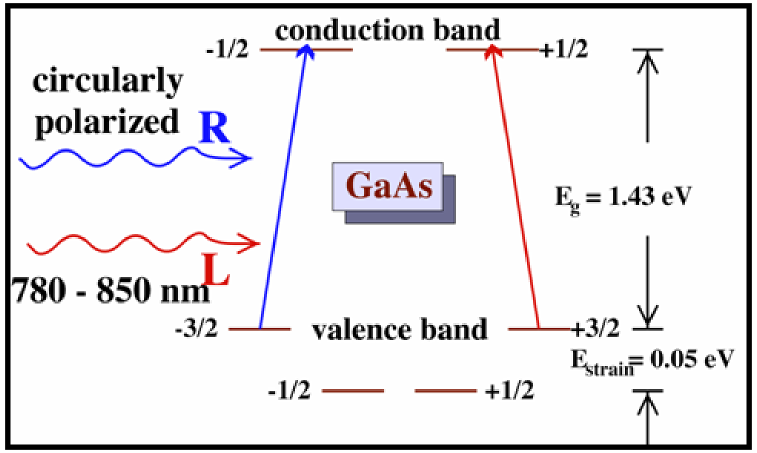
1 INJECTOR

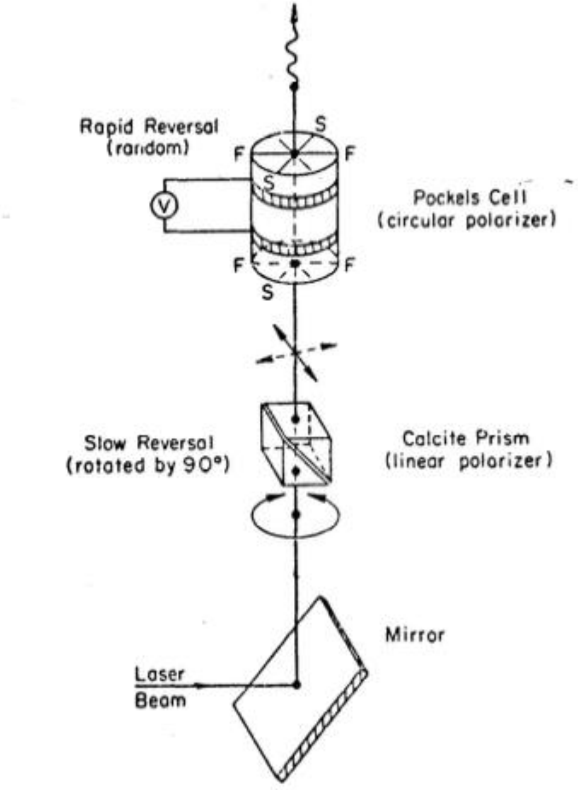
The injector produces electron beams for experiments.

Diagram representational of below ground structure

Injector setup

- The GaAs strained cathode acts as an analyzer and produces negative and positive helicity electrons with approximately 90% polarization
- The system relies on a Pockels Cell to produce quick changes between opposite circular polarization states
- Imperfections between the two polarization states will lead to beam asymmetries
  - Careful setup and constant monitoring is needed to mitigate any changes in the accelerator setup that introduce such asymmetries





OPTICAL REVERSAL SCHEME
Figure 3

Injector setup

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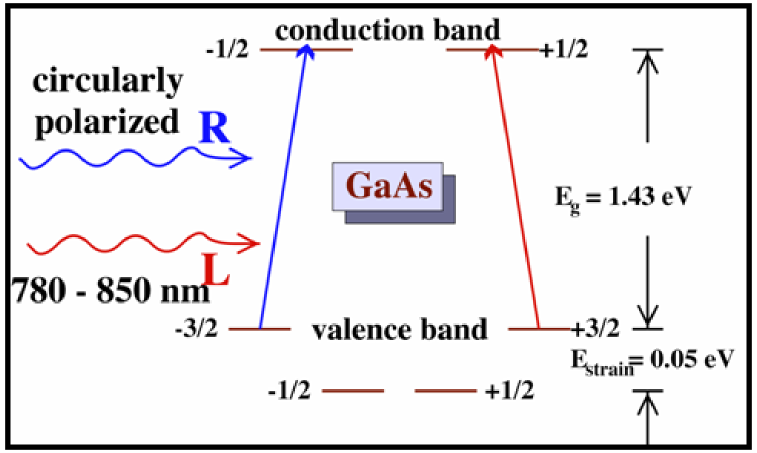

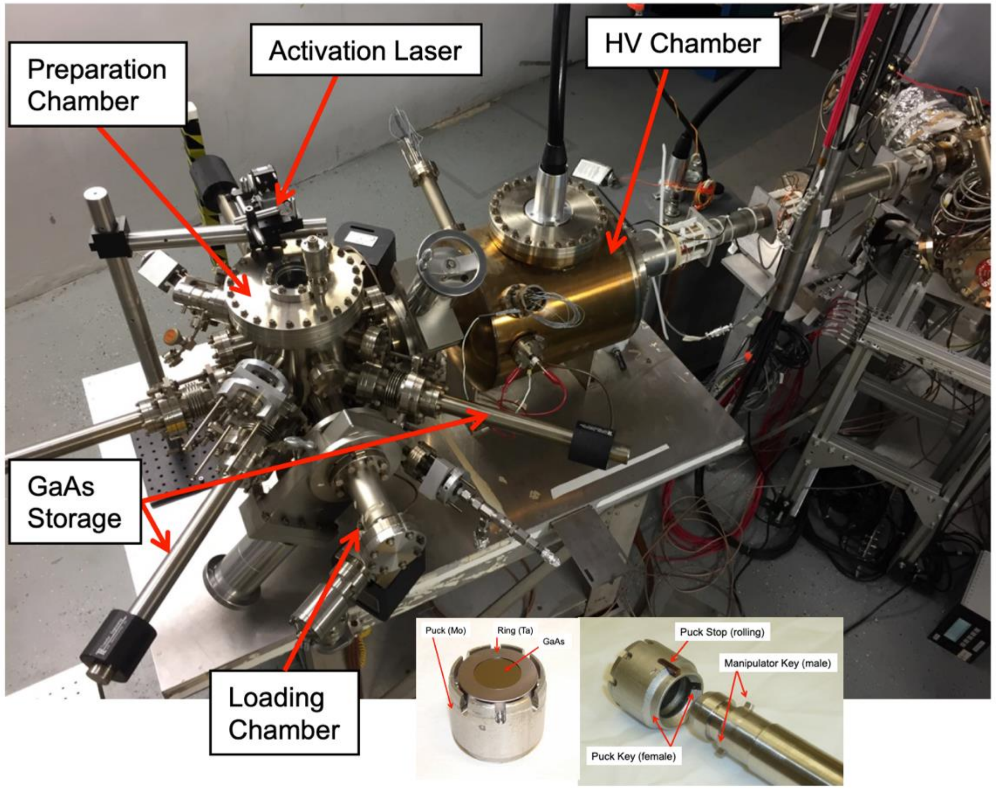

P. Adderley *et al.*, Phys. Rev. Accel. Beams **13**, 010101 (2010)

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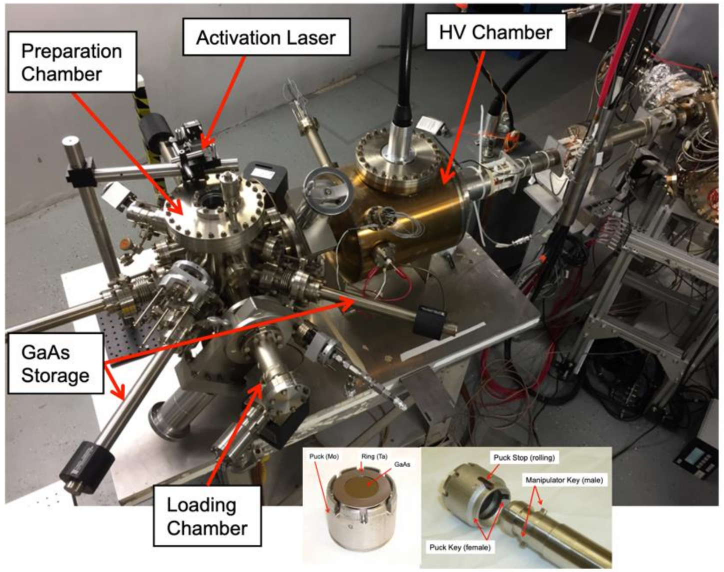
- Imperfections between the two polarization states will lead to beam asymmetries
  - Careful setup and constant monitoring is needed to mitigate any changes in the accelerator setup that introduce such asymmetries
- The double Wien allows us to change the helicity of the electron beam completely independently of the laser flips



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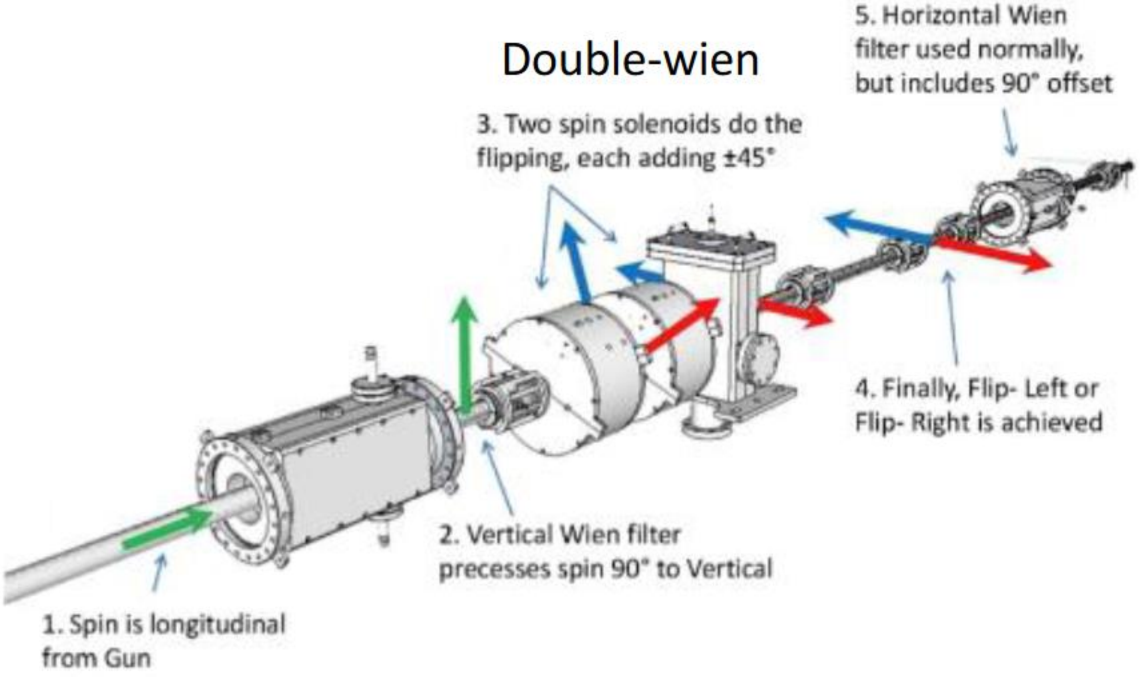
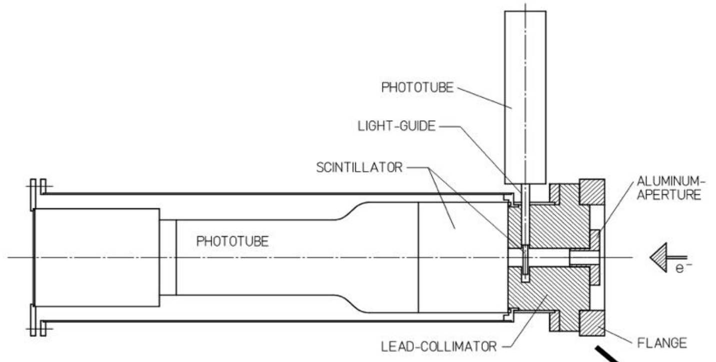
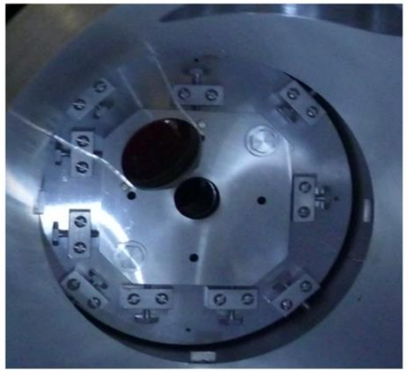


Injector setup – upgraded Mott polarimeter

Checked and repaired each detector package, comprised of both E (e-) and ΔE (photon veto) detector

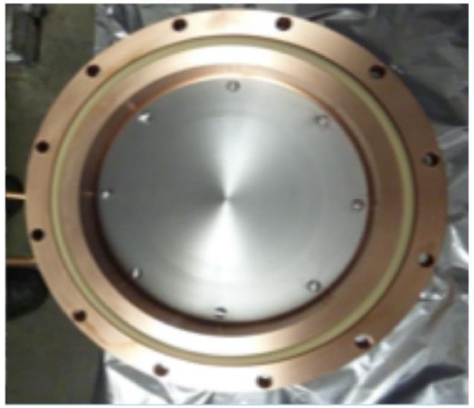


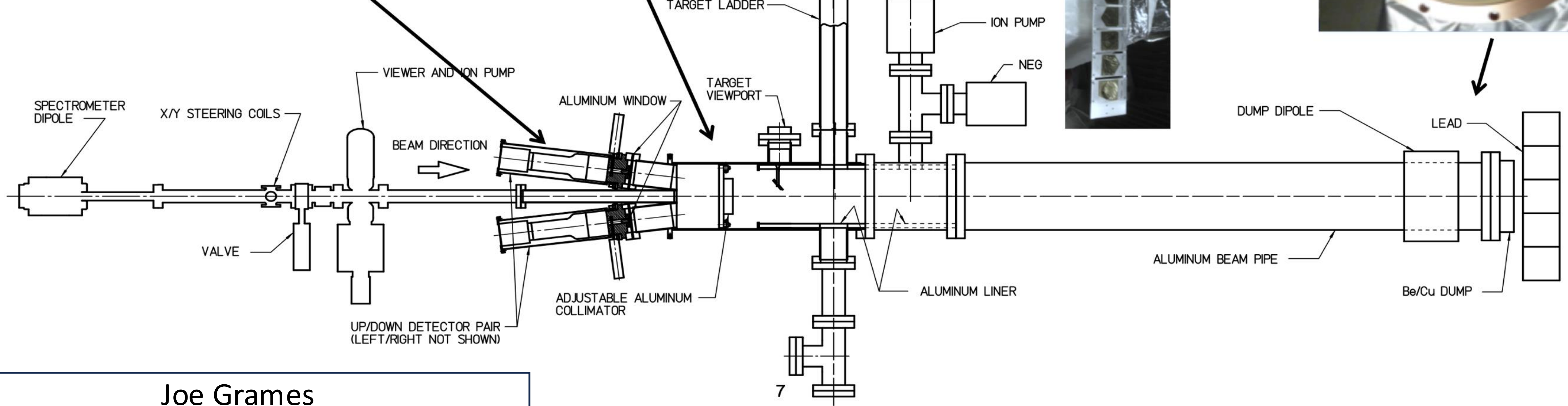
Re-surveyed adjustable collimator system



Loaded 10 gold foils, each with a sibling for thickness measurement

Replaced Al dump with Be plate to reduce e- backscatter and Cu radiator end flange





Joe Grames

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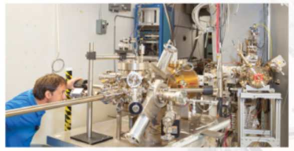

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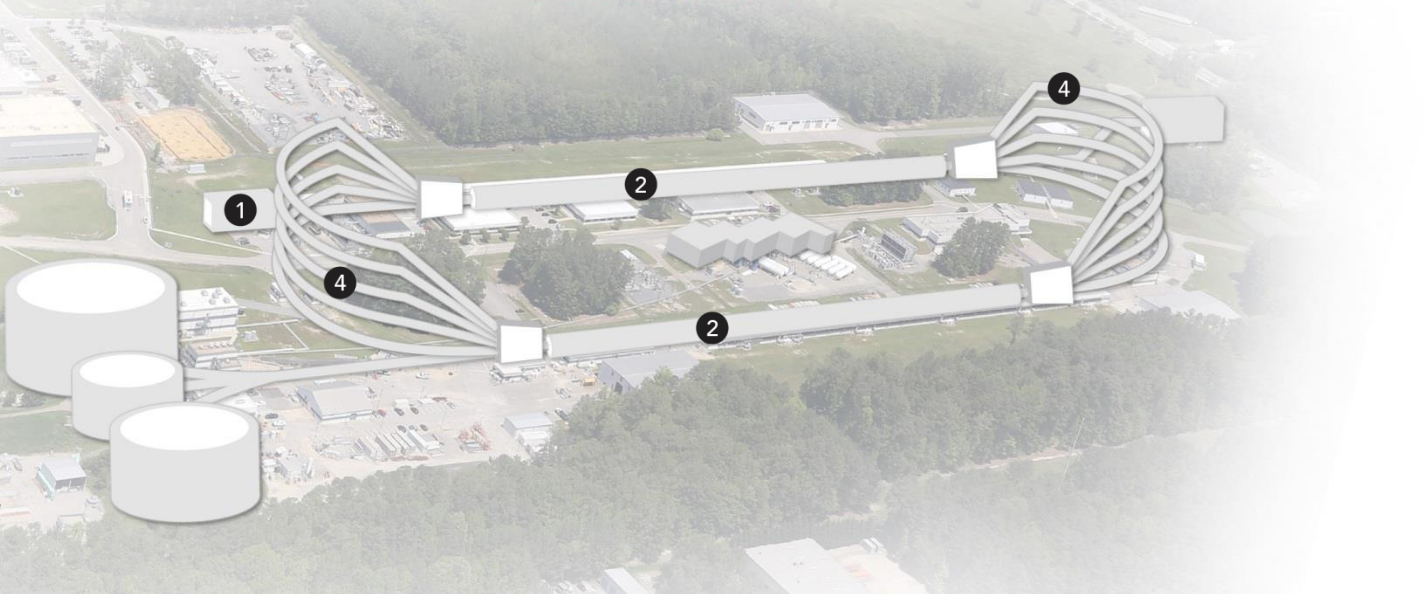
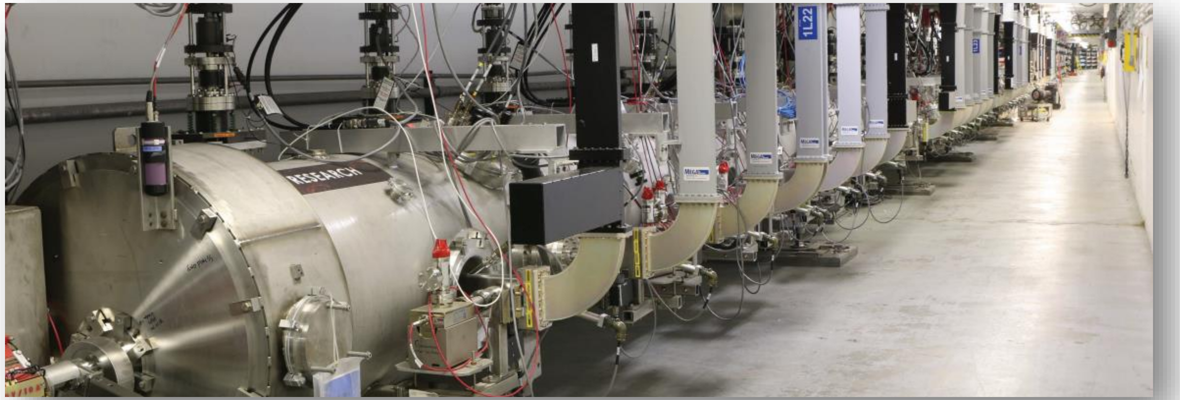


Diagram representational of below ground structure

❹ RECIRCULATION MAGNETS

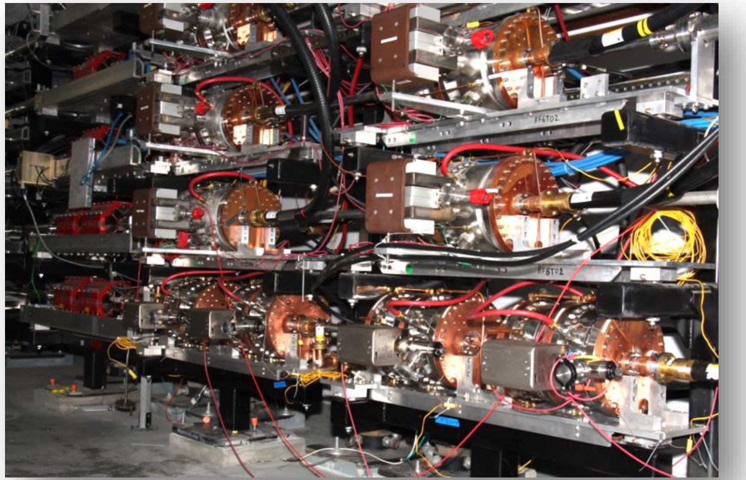
Quadrupole and dipole magnets in the tunnel focus and steer the beam as it passes through each arc.

Accelerator

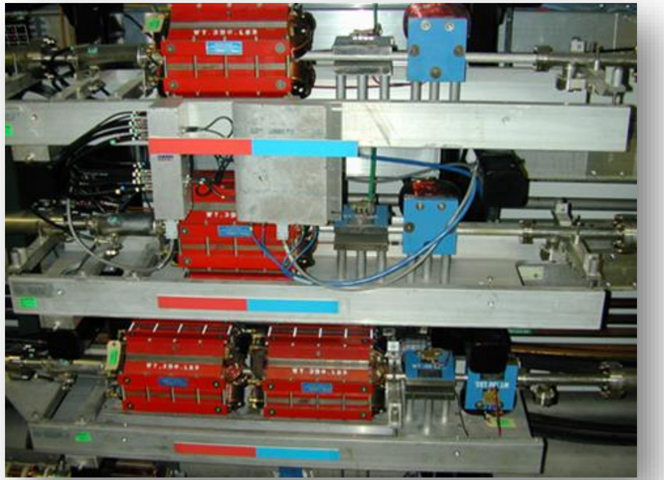


52-1/4 Cryomodules with 418 SRF Cavities to Accelerate Electrons in CEBAF

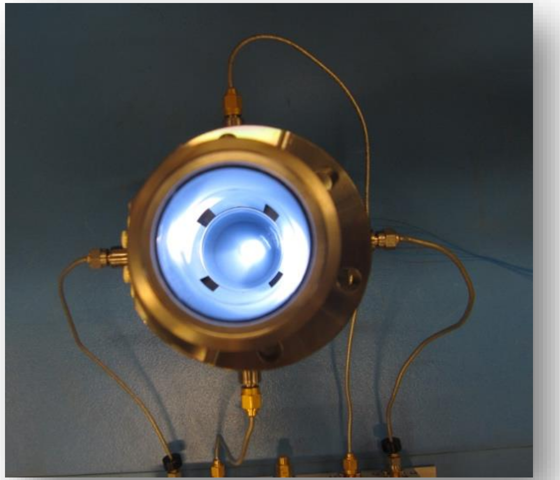
~500 Large Dipoles powered by >40 HVPS



16 RF Deflectors for Extracting Beams



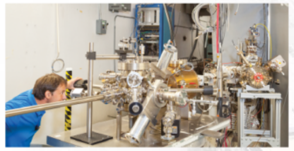
>2800 Magnets to Focus and Steer Beam



>800 Beam Position Monitors

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.



1 INJECTOR

The injector produces electron beams for experiments.

2 LINEAR ACCELERATOR

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

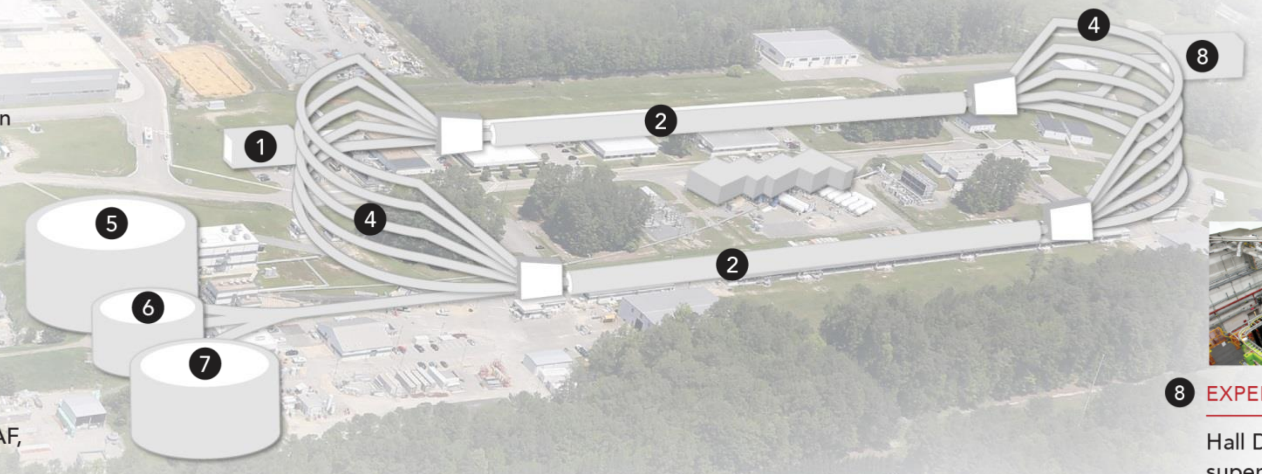
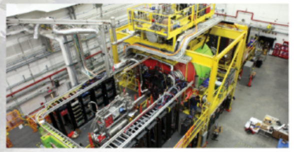


Diagram representational of below ground structure



8 EXPERIMENTAL HALL D

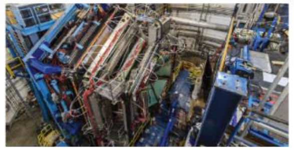
Hall D is configured with a superconducting solenoid magnet and associated detector systems that are used to study the strong force that binds quarks together.

4 RECIRCULATION MAGNETS

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

5 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.



6 EXPERIMENTAL HALL B

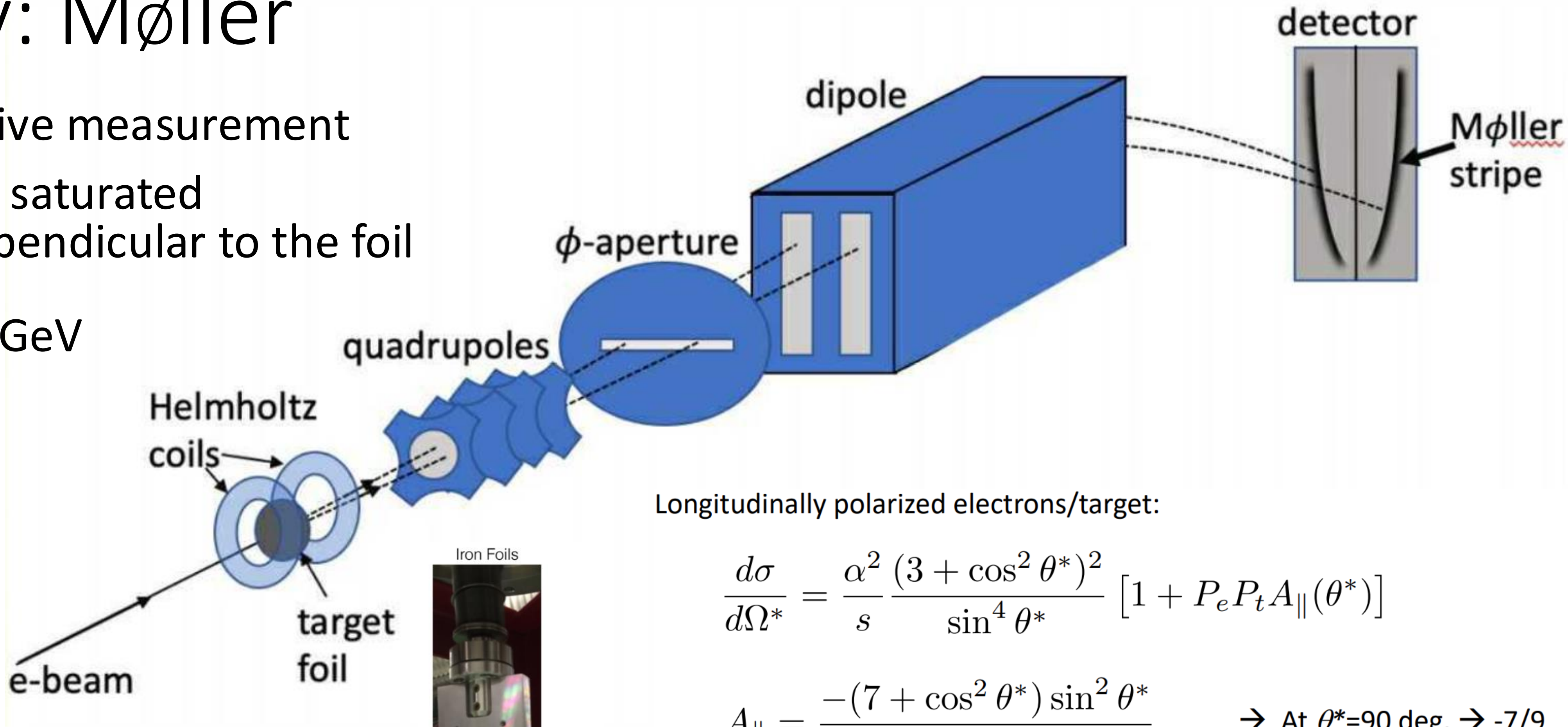
The CEBAF Large Acceptance Spectrometer surrounds the target, permitting researchers to measure simultaneously many different reactions over a broad range of angles.

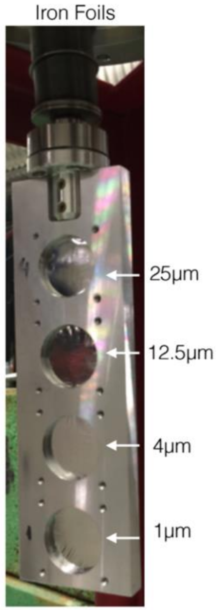
7 EXPERIMENTAL HALL C

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.

Polarimetry: Møller

- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Redesigned for 11 GeV running





Longitudinally polarized electrons/target:

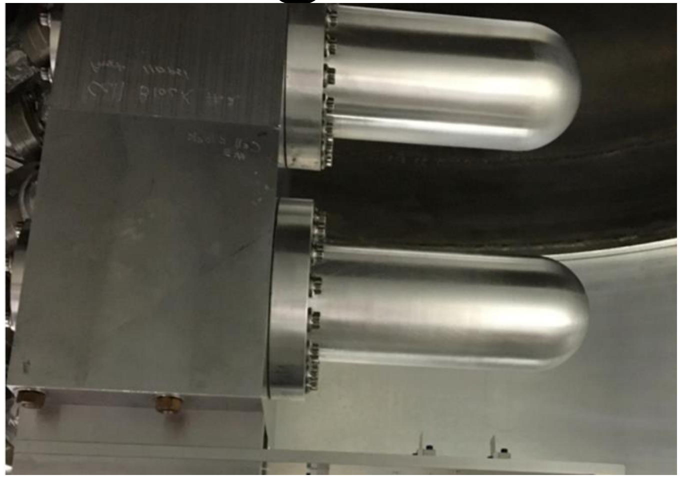
$$\frac{d\sigma}{d\Omega^*} = \frac{\alpha^2}{s}\frac{(3+\cos^2\theta^*)^2}{\sin^4\theta^*}\left[1 + P_e P_t A_{\parallel}(\theta^*)\right]$$

$$A_{\parallel} = \frac{-(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2}$$

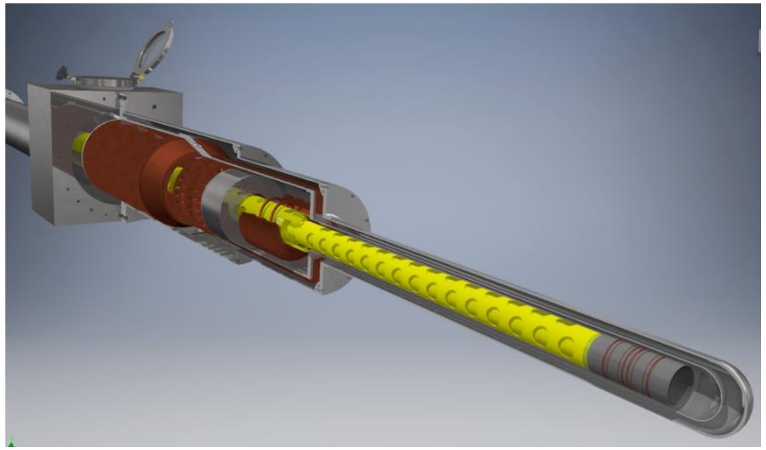
→ At θ^*=90 deg. → -7/9

Maximum asymmetry independent of beam energy

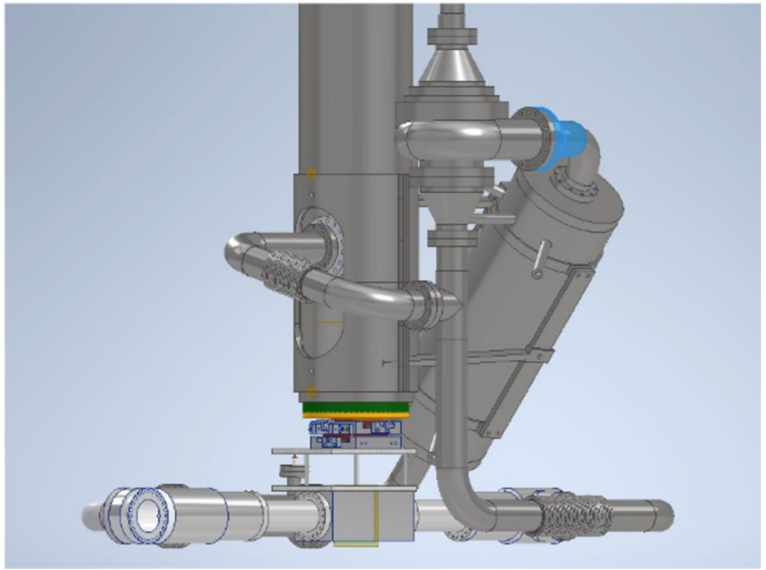
JLab targets



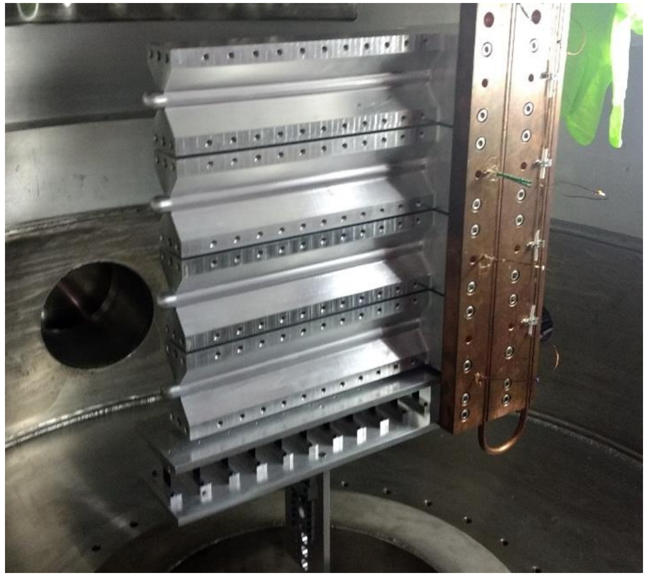
<1kW Liquid hydrogen/deuteron targets for hall A/C



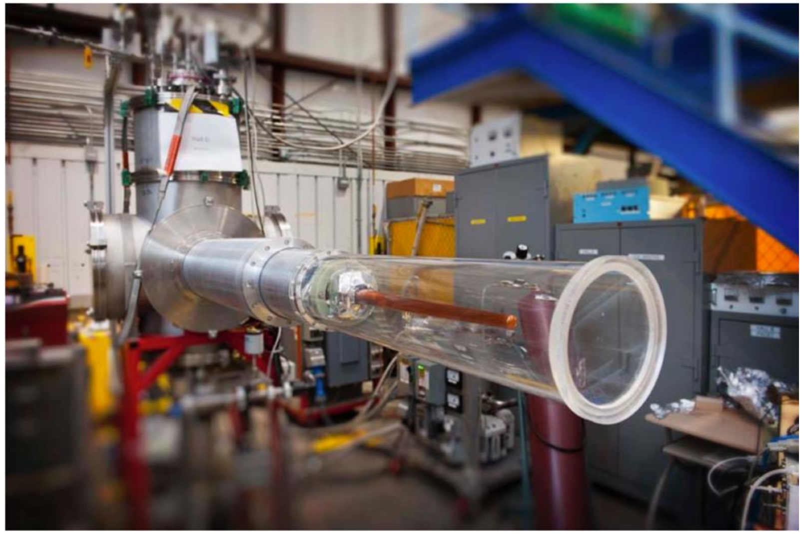
CLAS12 proton & deuteron polarized target



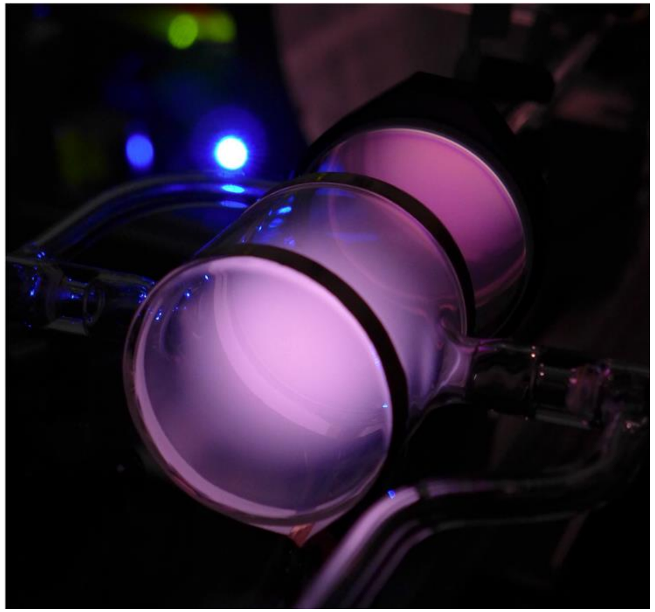
High power LH2 target (MOLLER)



H3 targets for Hall A (first in 30 years)



Liquid hydrogen target for Hall D

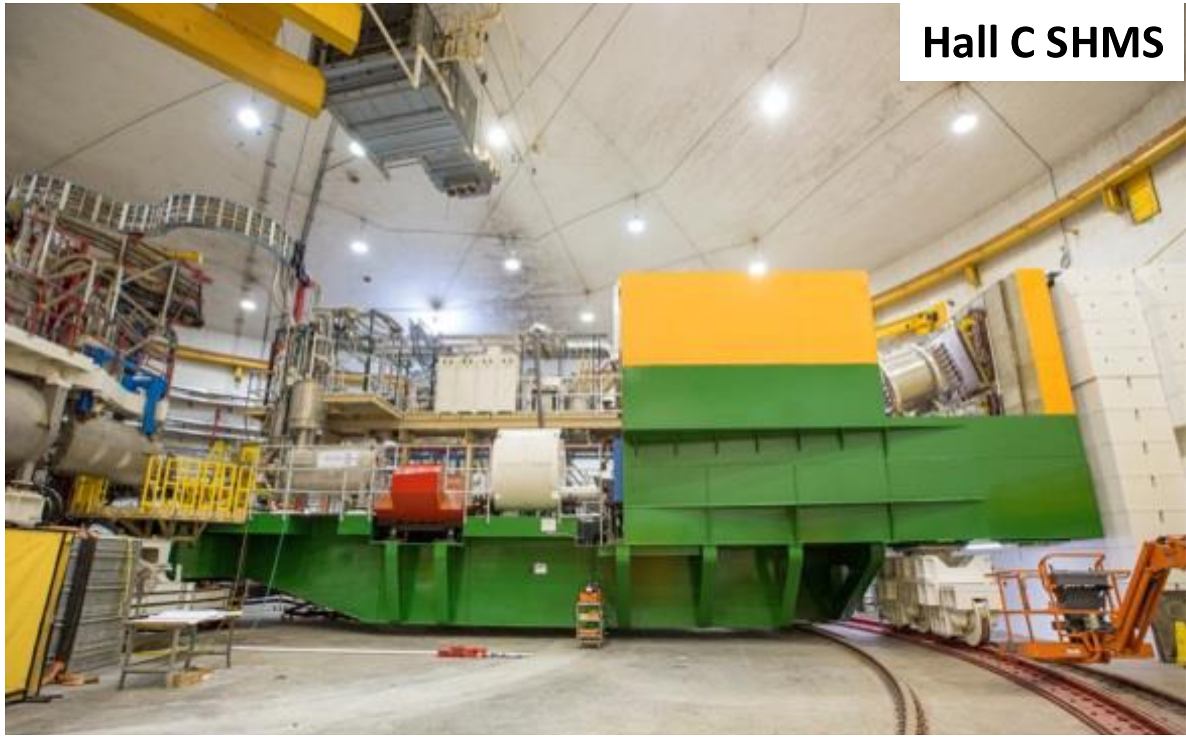


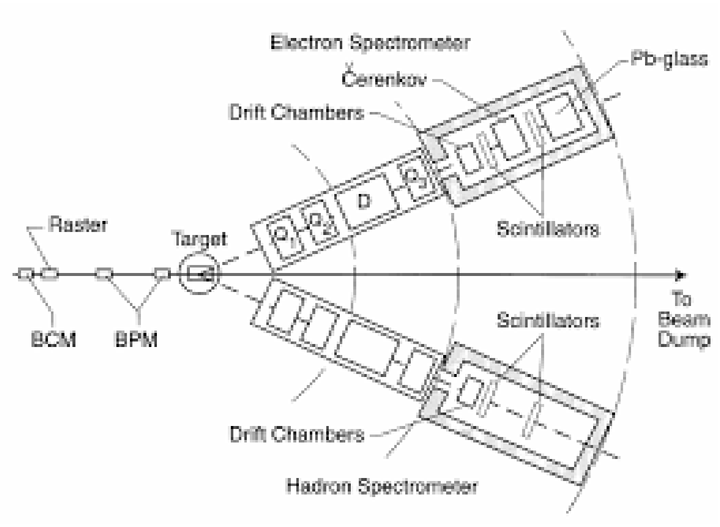
CLAS12 He3 polarized target

Spectrometers

- The spectrometer needs to prepare as clean as possible sample of scattered electrons
  - focus it on the detectors
  - remove as much background as possible
- Trade-offs: precision/flexibility - acceptance

Hall C SHMS





E122 sketch

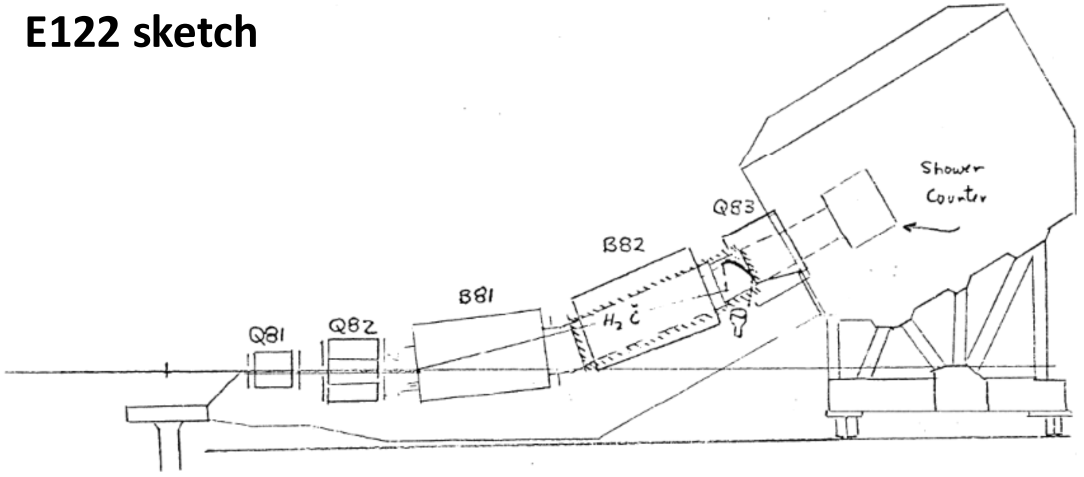
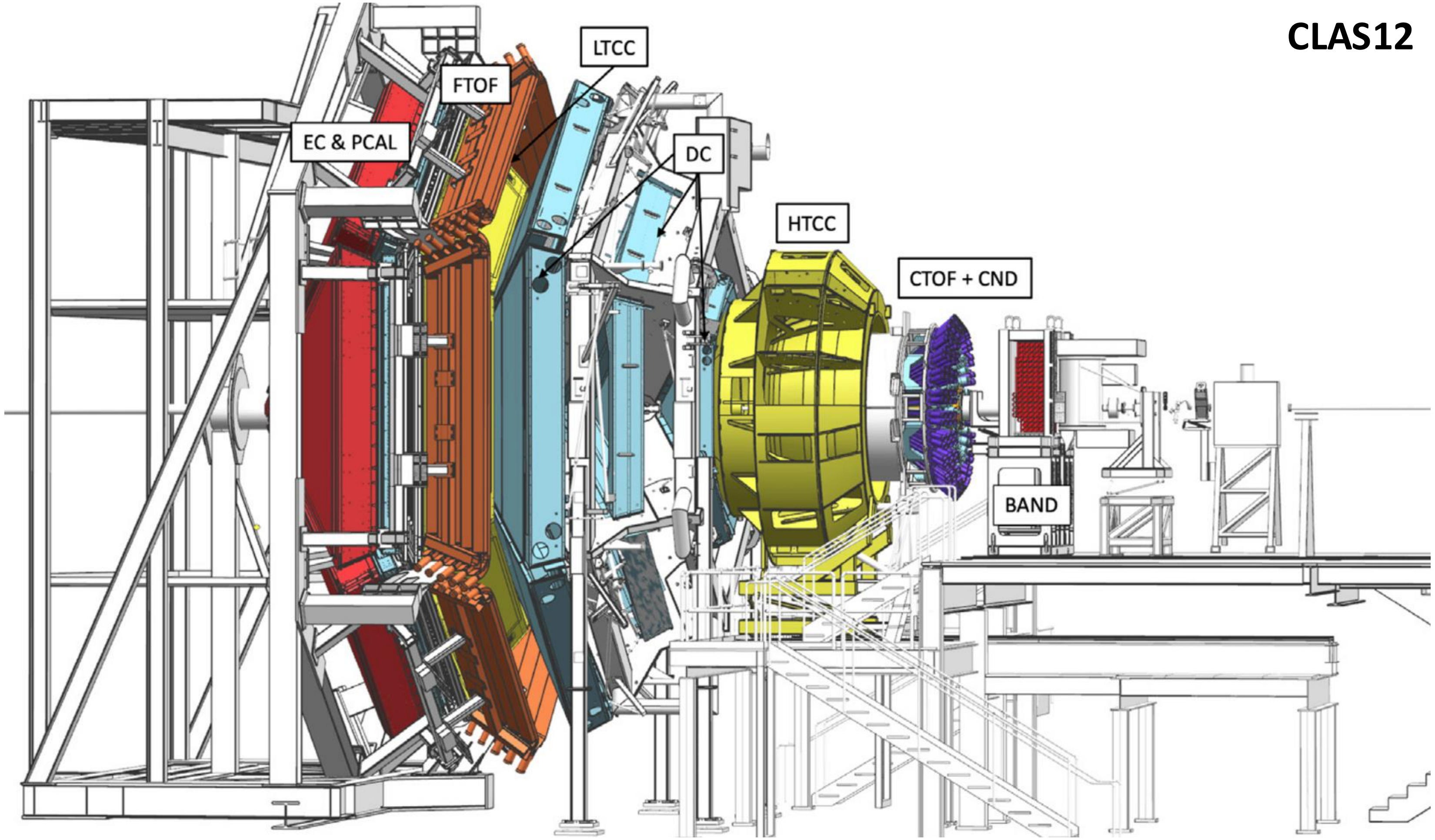


FIGURE 1b SKETCH OF 8 GeV Spectrometer

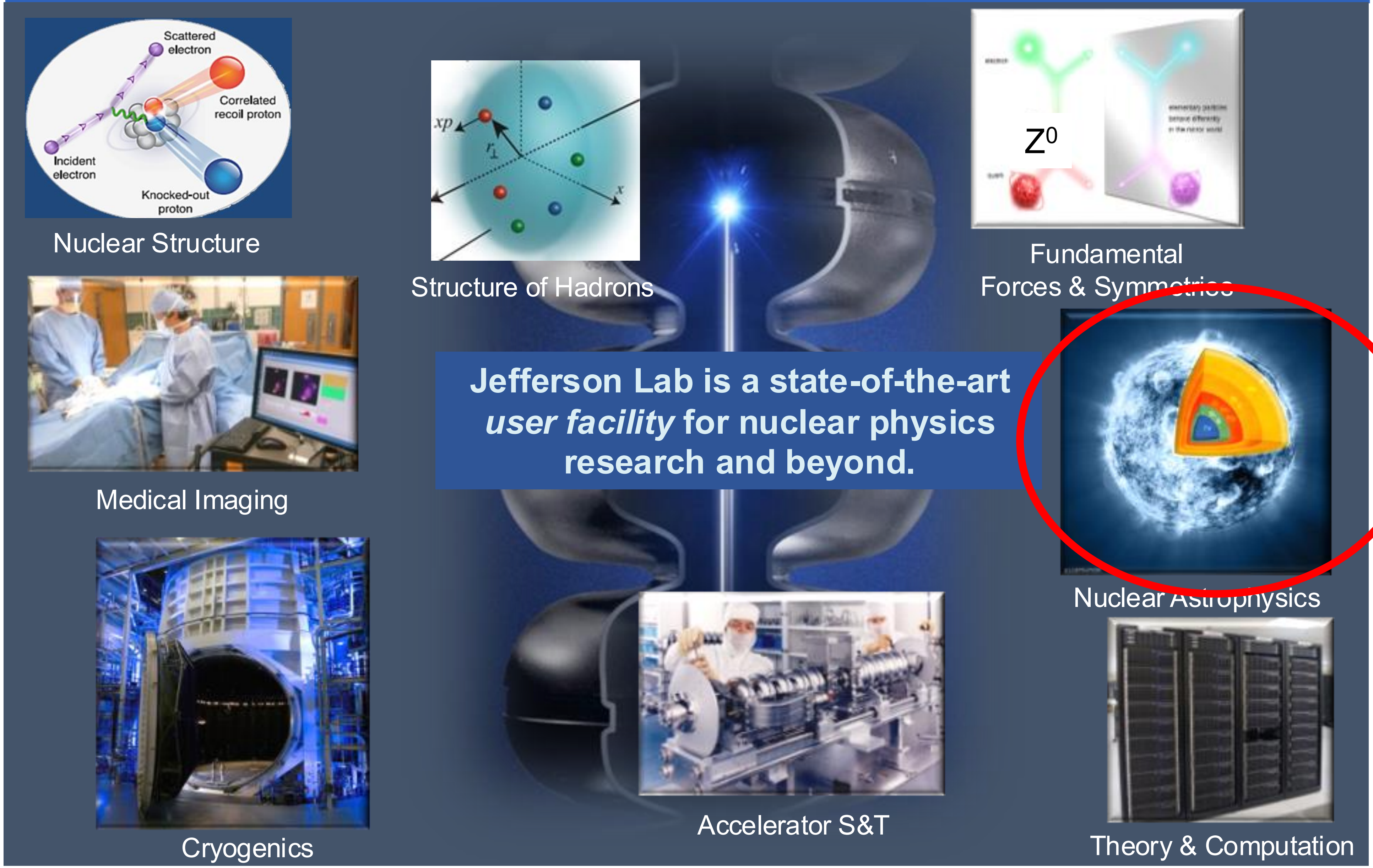
Detector package

- Depending on the needs of the experiment different detector packages can be deployed
- Common detectors are:
  - trackers (such as DC)
  - Cerenkov detectors
  - calorimeters (electromagnetic and sometime hadronic)

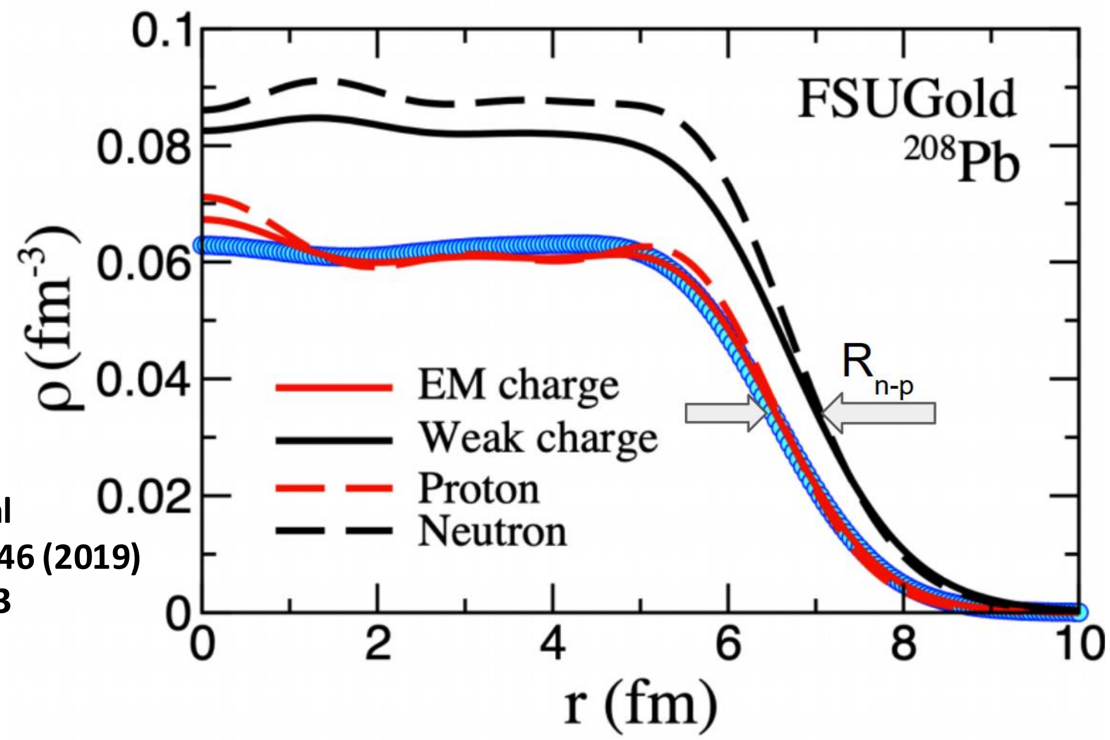
CLAS12



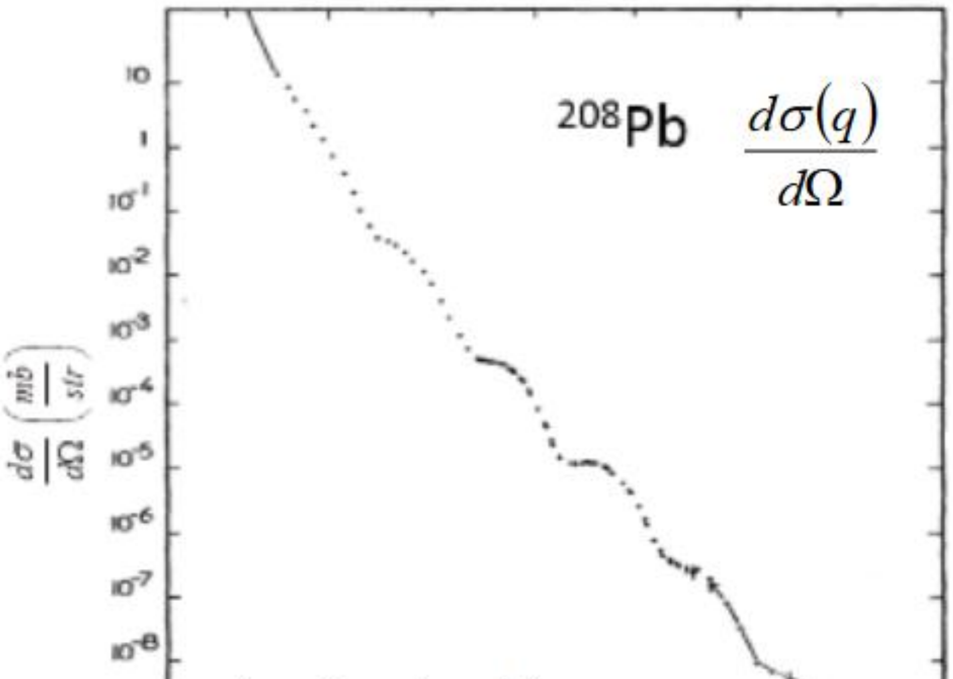
JLab: A Laboratory for Medium Energy Nuclear Science



What are we looking for?



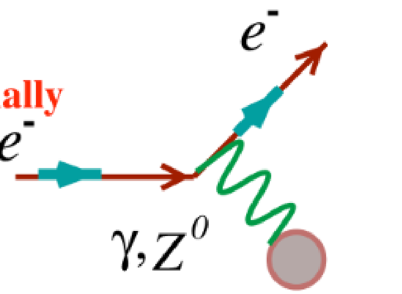
Thiel et al
J.Phys.G 46 (2019) 9, 093003



$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)^{*}_{Mott} \cdot \left|F\left(q^2\right)\right|^2$$

- The excess neutrons in ^{208}Pb are thought to form a skin on the outside of the nucleus
- Similar to how the Fourier transform of the electromagnetic form factor gives charge density so too measuring the weak form factor can give the weak distribution

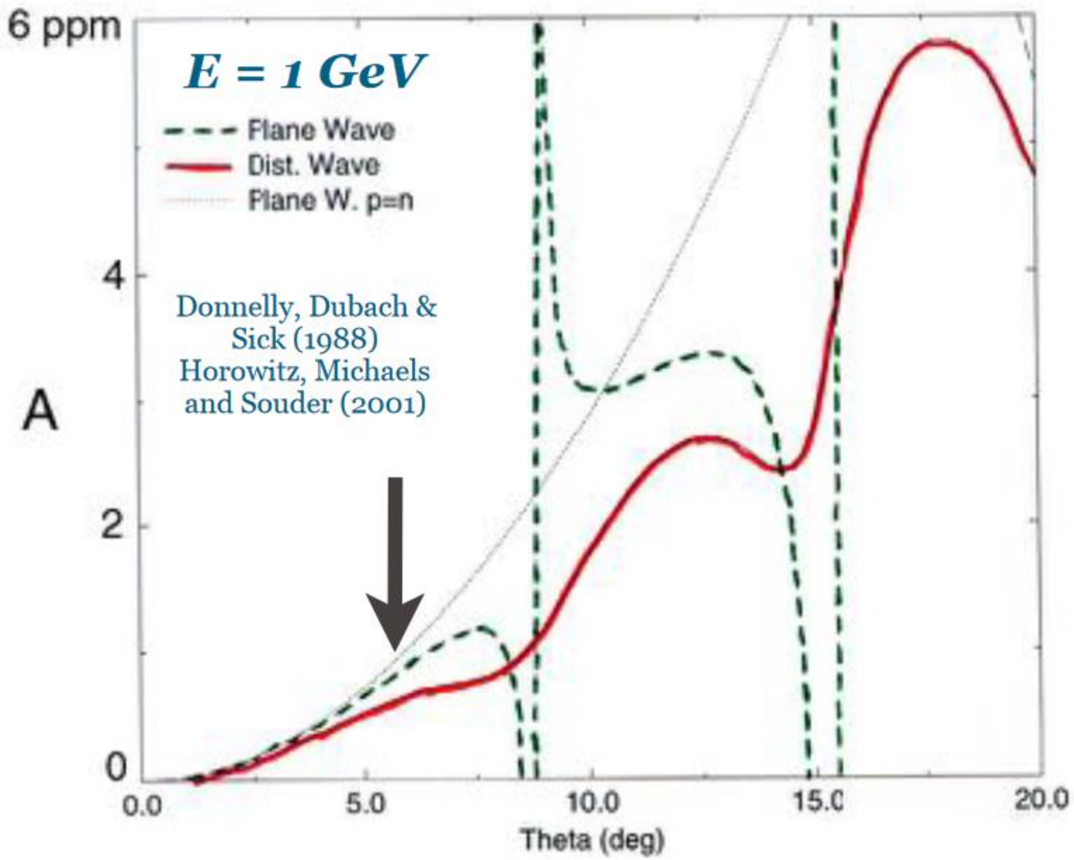
How can we find it?



$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Born approximation:

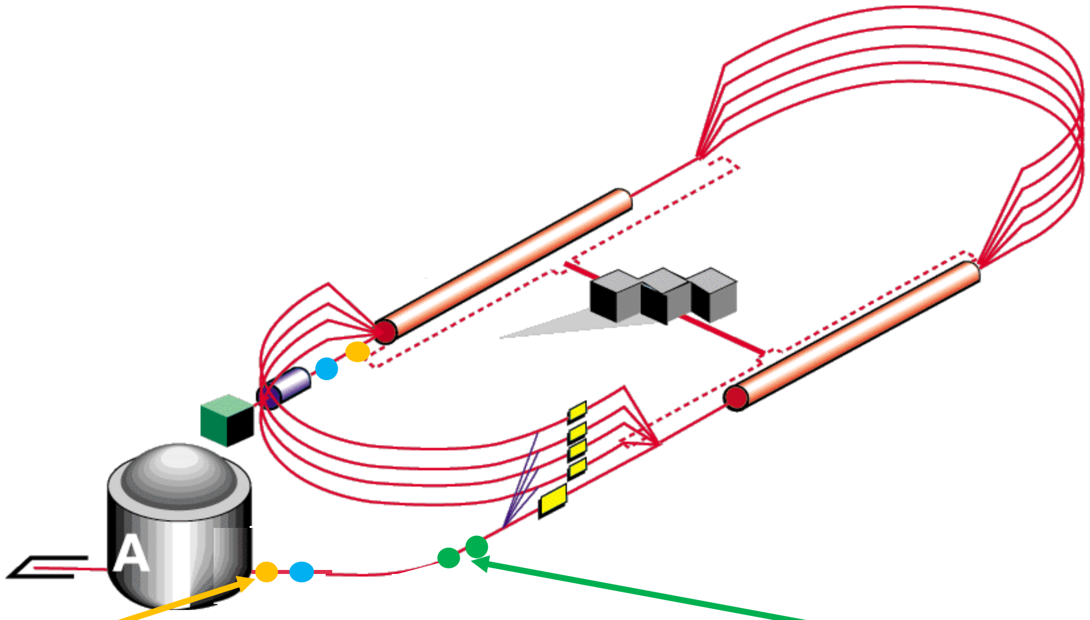
$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W \, F_W(Q^2)}{Z \, F_{ch}(Q^2)}$$



- The numerator is dominated by the gamma-Z interaction which picks up (almost exclusively) the weak charge of the neutron
- The denominator contains the parity conserving electro-magnetic interaction which is several orders of magnitude stronger than the electro-weak interference term
  - This leads to very small asymmetries that are on the level of parts-per-million

Beam modulation system

- To span the 5 dimension phase space of beam motion at the target (position, angle, energy) we made use of a set of 6 coils and an energy vernier in the extraction arc
  - The extra set of air-core dipoles (coils) can be used as a cross check to confirm our procedure doesn't introduce unwanted noise
  - This modulation is automated and was performed throughout the data taking period

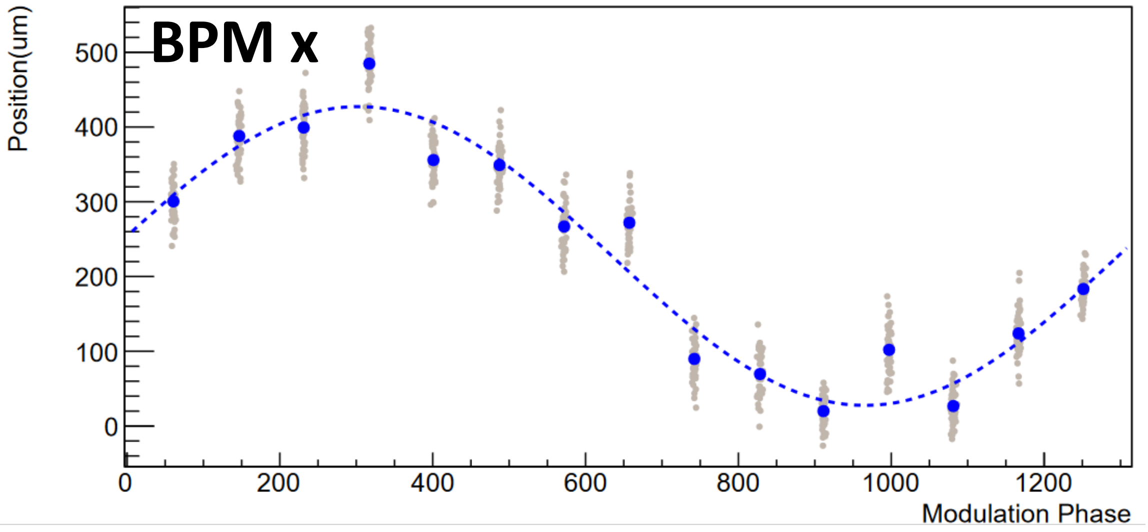


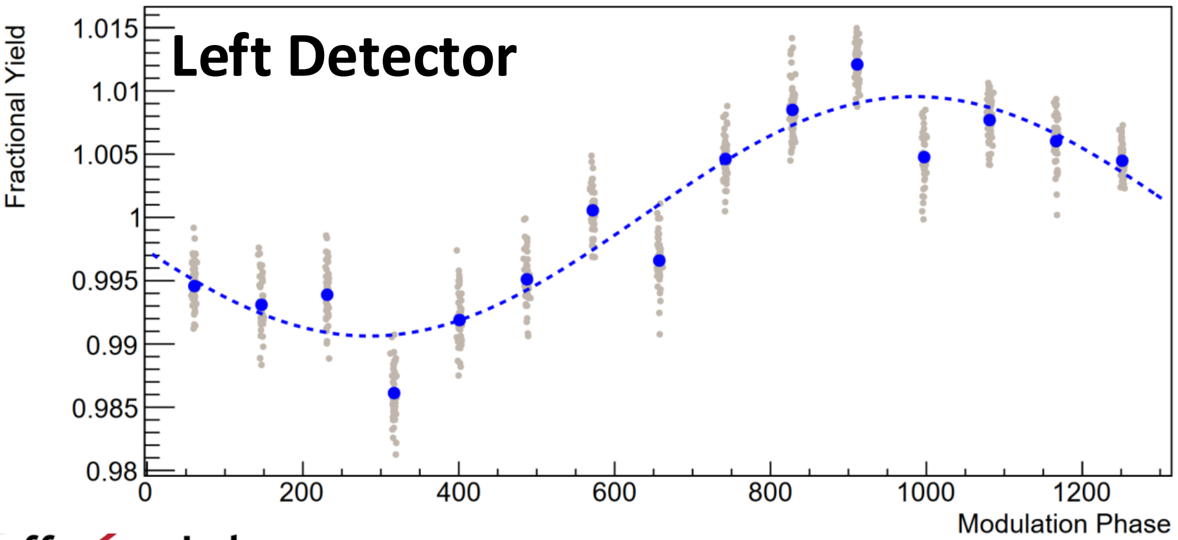
Beam monitors allow us to confirm clean transport through acceleration

Beam modulation system allows us to span the phase space of beam motion

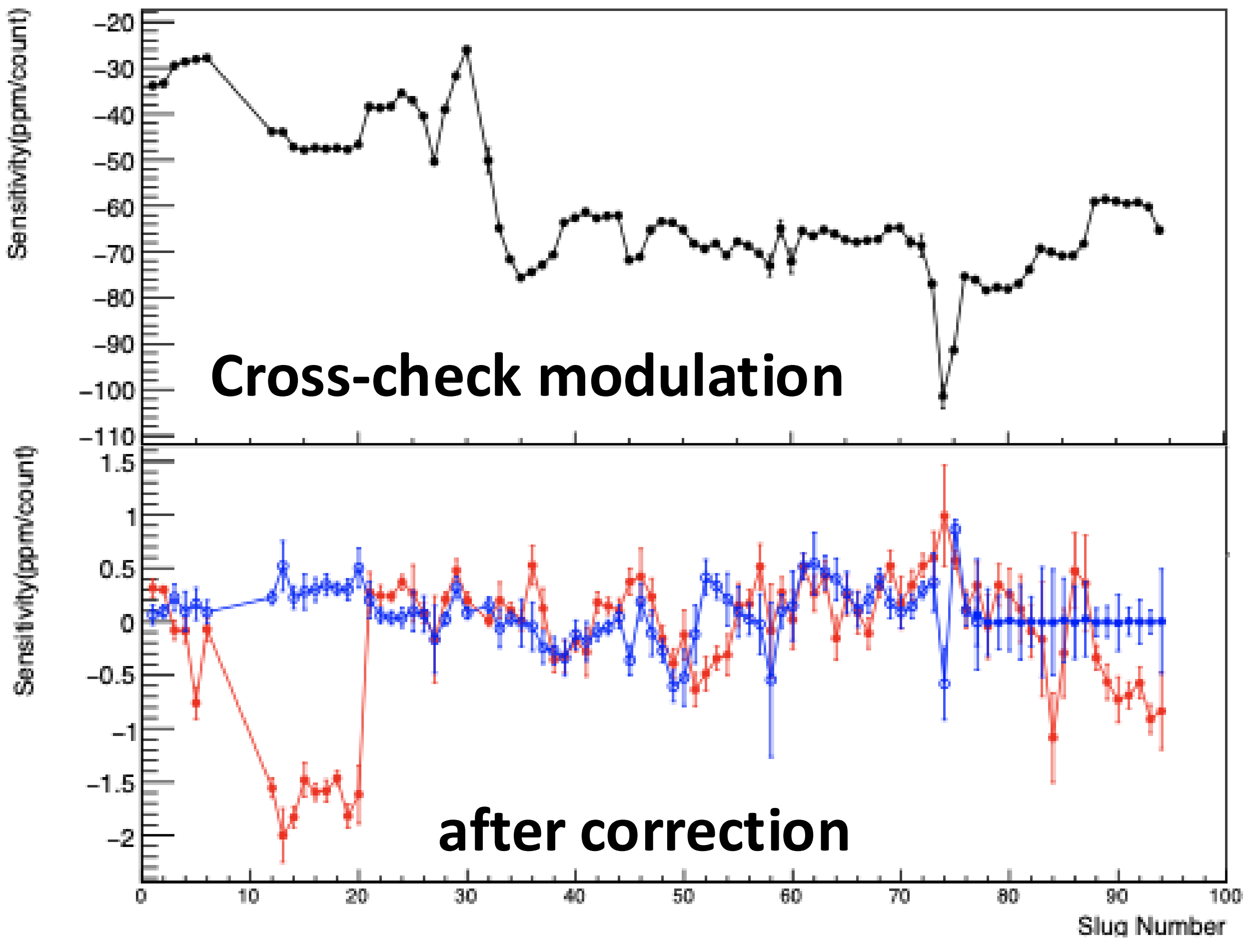
Beam Corrections

Modulation to calibrate sensitivity (α_i)

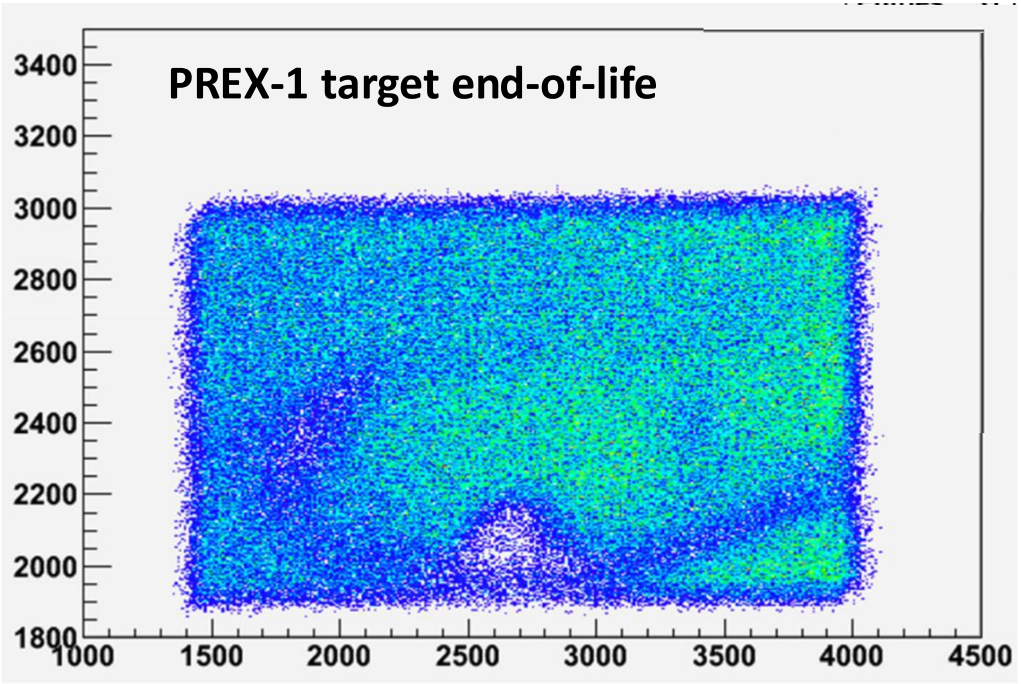


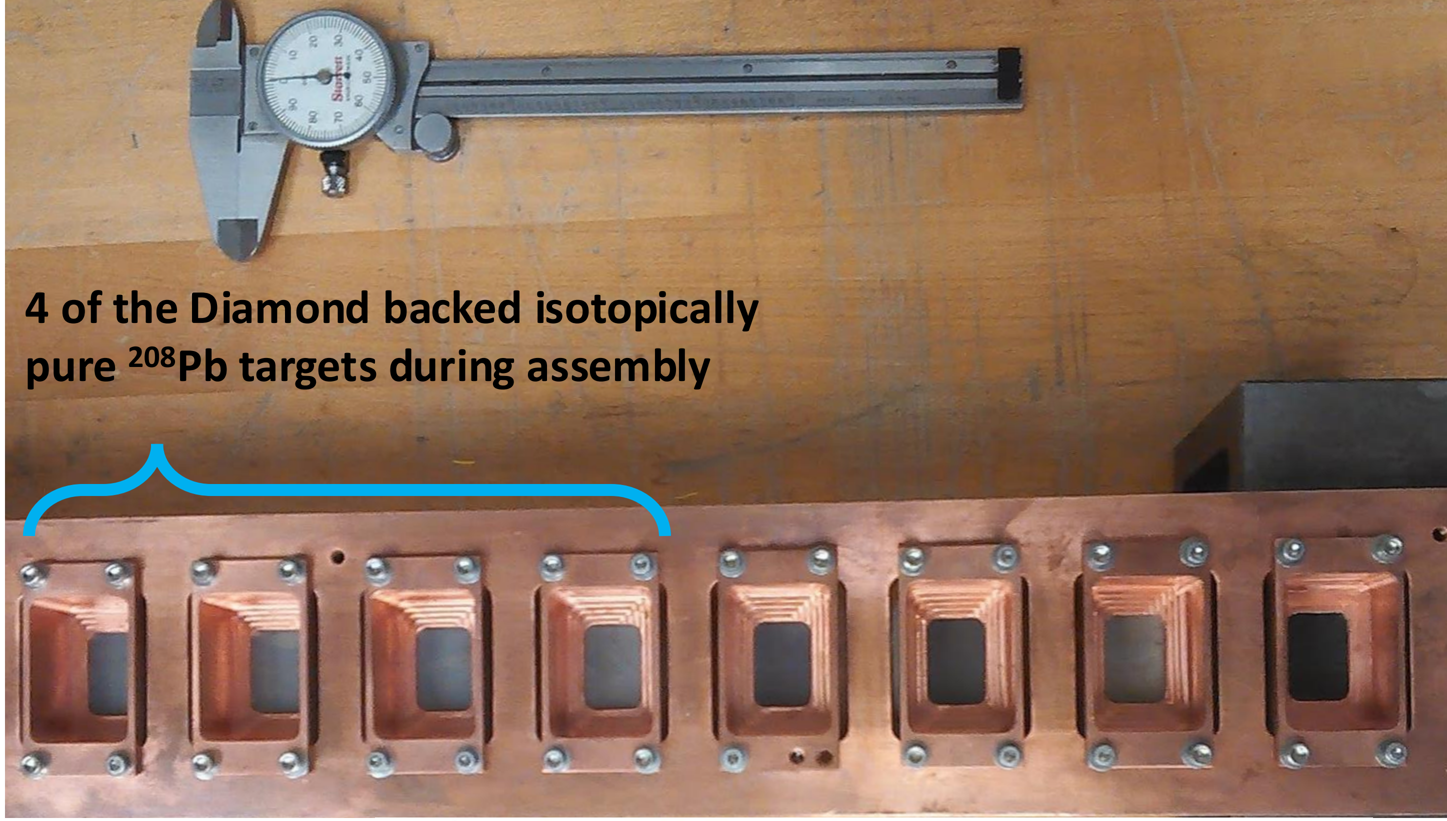


Modulation amplitude in detector

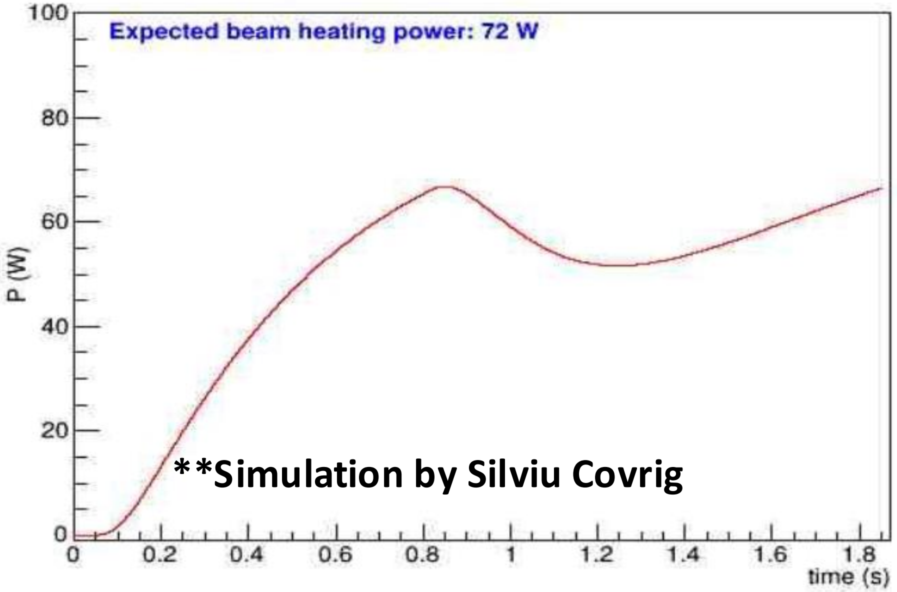


^{208}Pb Target



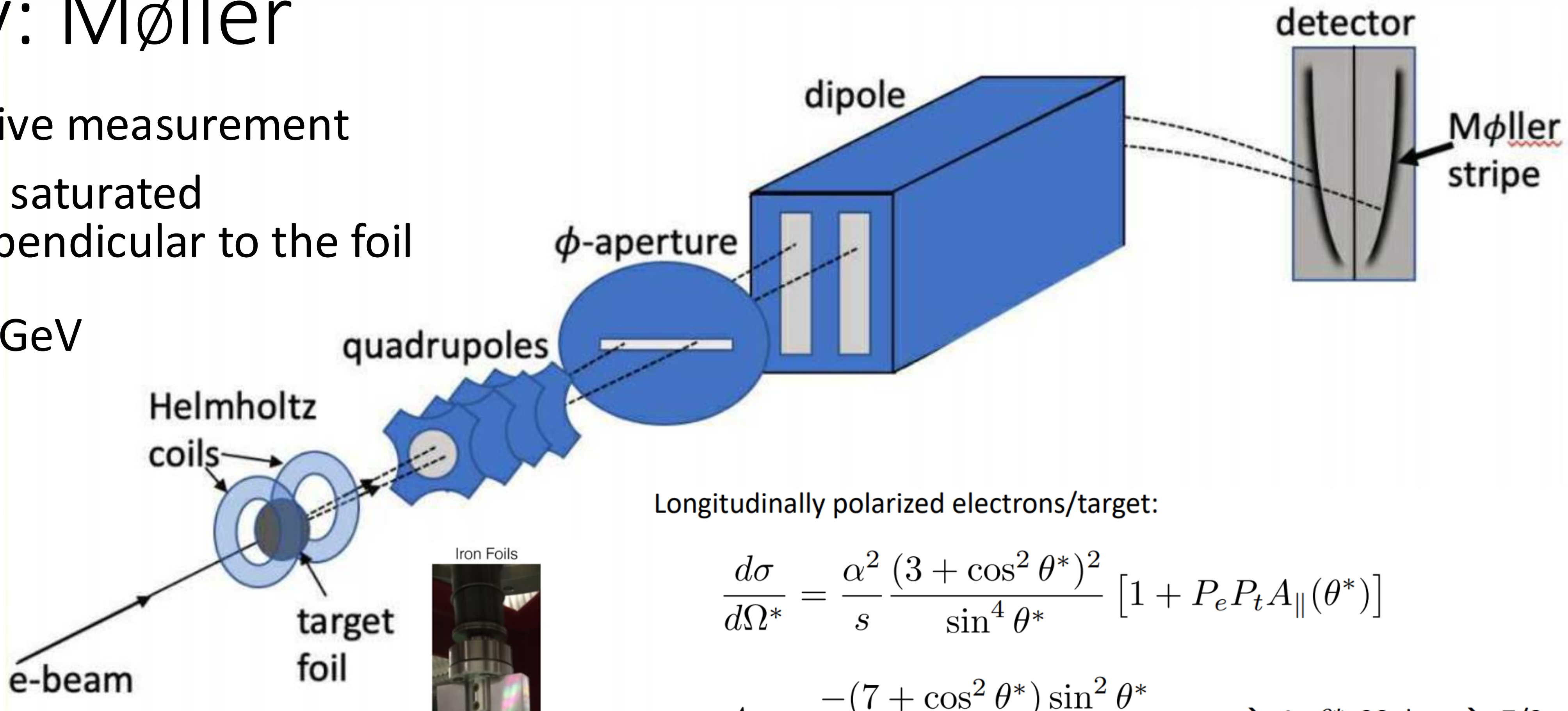


- PREX-1 confirmed that the poor thermal conductivity of Pb will eventually lead to the breakdown of the target
  - Even though we provide Carbon (Diamond) backing to increase heat flow
- For PREX-2 we prepared a complement of 10 isotopically pure targets in the expectation that we will use approximately 6
  - Simulations predicted approximately 72 W of power deposition from the 70 μA rastered beam



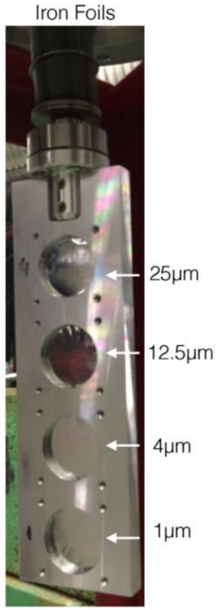
Polarimetry: Møller

- Low-current, invasive measurement
- 3-4T field provides saturated magnetization perpendicular to the foil
- Redesigned for 11 GeV running



Average polarization:
(89.7 ± 0.8)%

- One of the few sub percent polarization measurements at Jefferson Lab



Longitudinally polarized electrons/target:

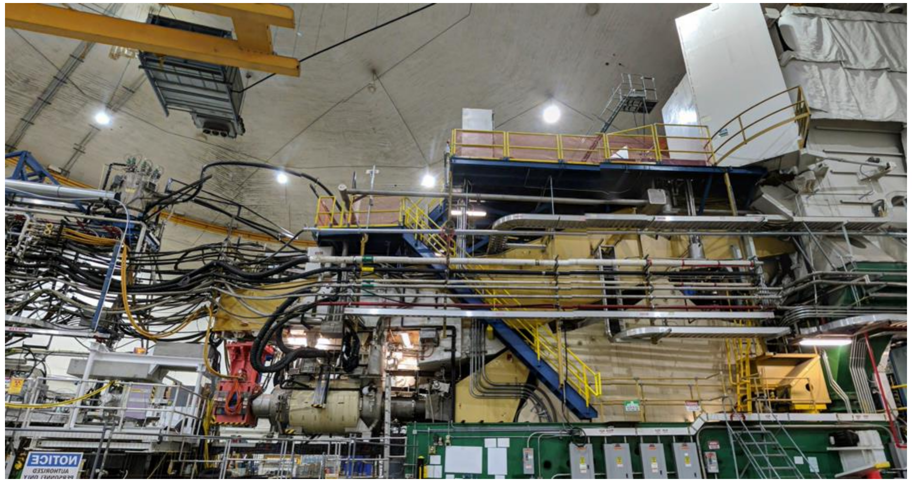
$$\frac{d\sigma}{d\Omega^*} = \frac{\alpha^2}{s}\frac{(3+\cos^2\theta^*)^2}{\sin^4\theta^*}\left[1 + P_e P_t A_{\|}(\theta^*)\right]$$

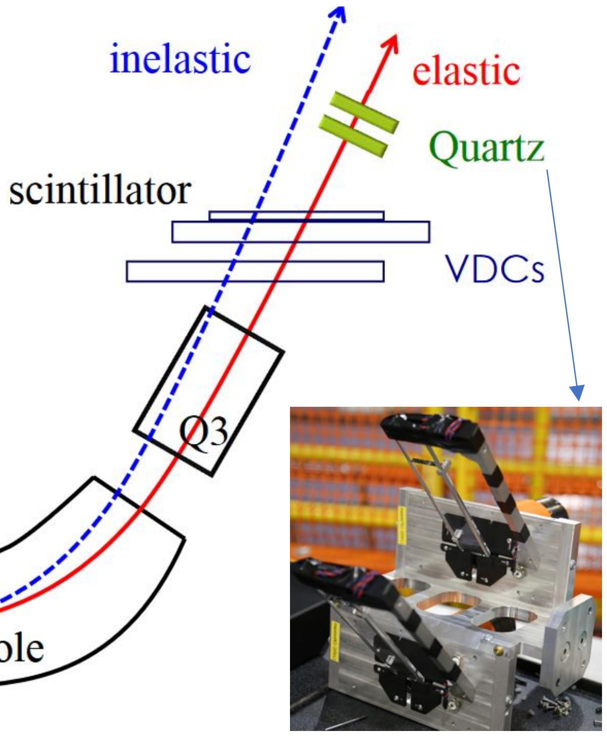
$$A_{\|} = \frac{-(7+\cos^2\theta^*)\sin^2\theta^*}{(3+\cos^2\theta^*)^2}$$

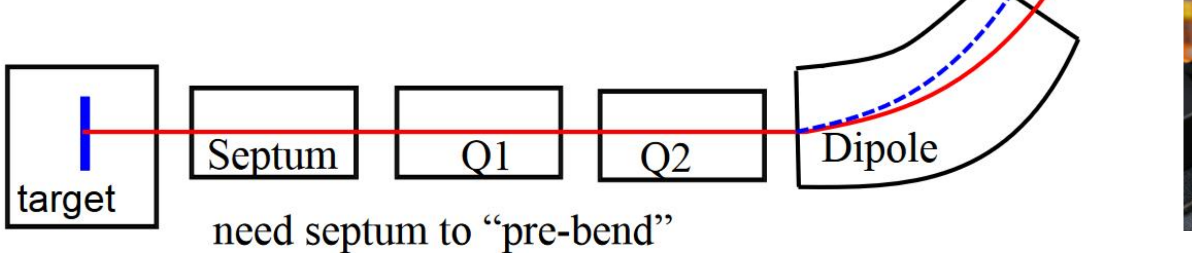
→ At θ^*=90 deg. → -7/9

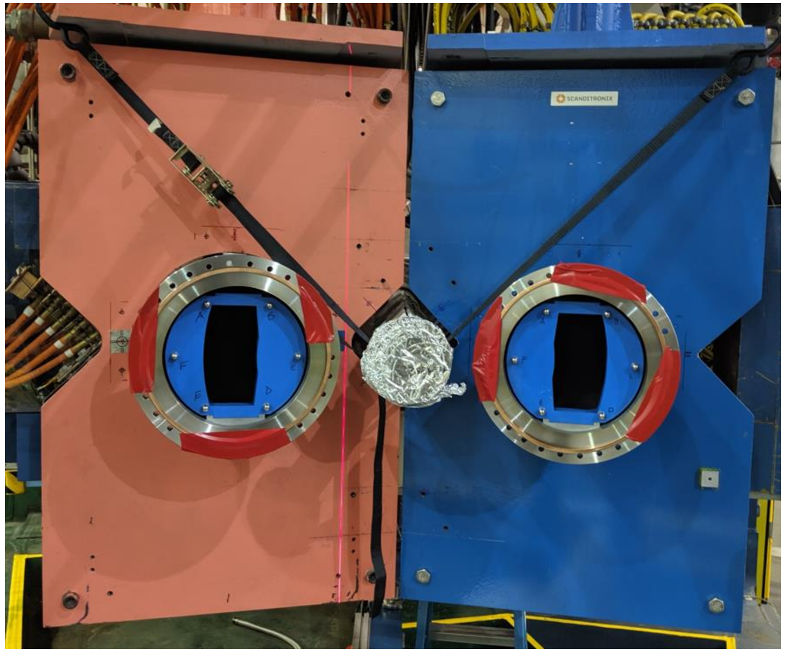
Maximum asymmetry independent of beam energy

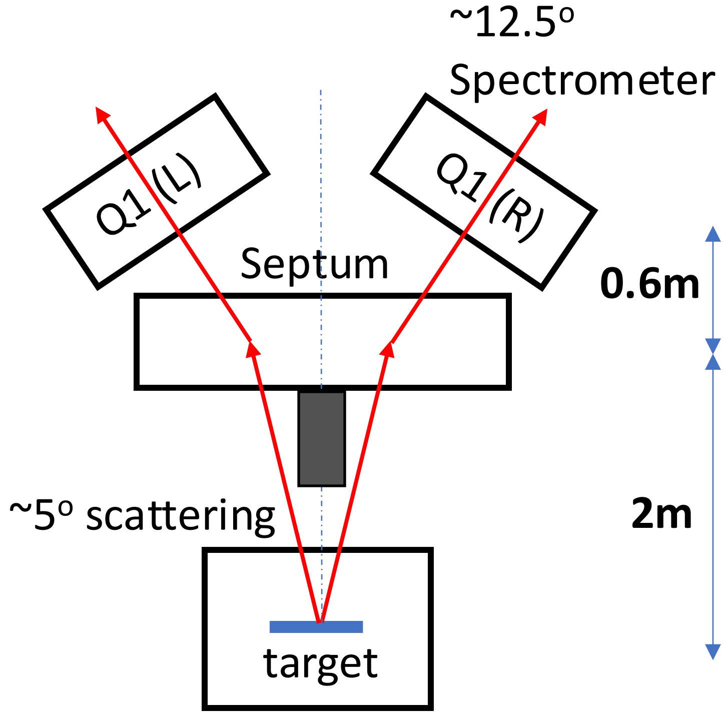
Magnet package











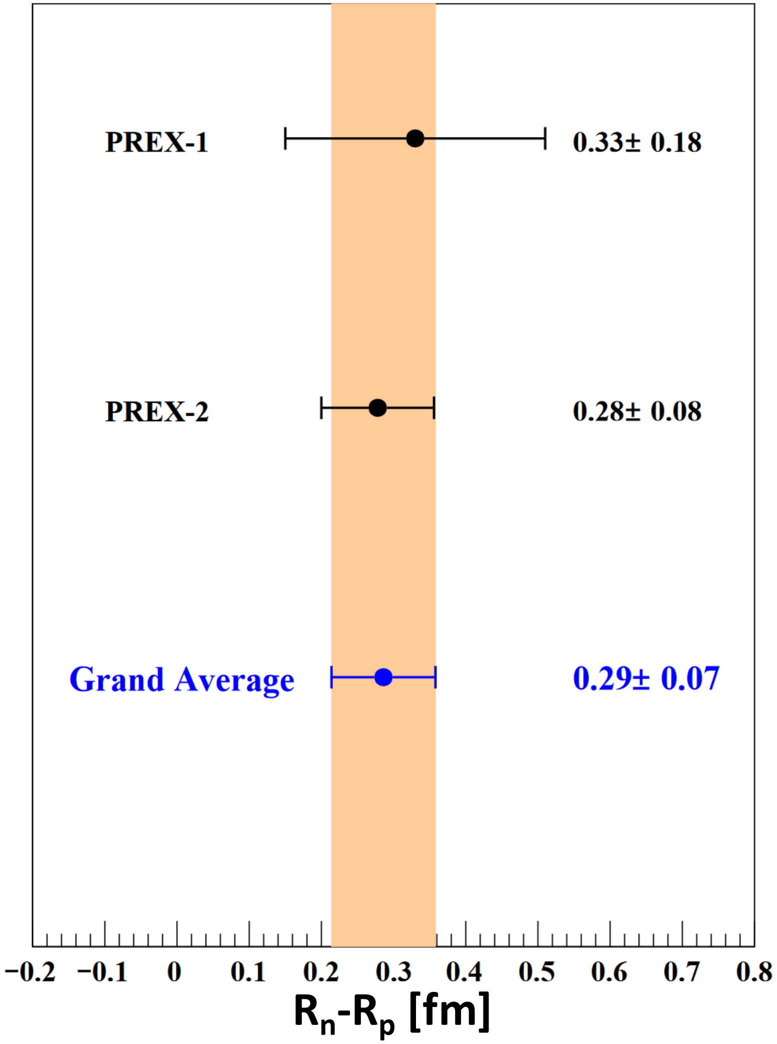
- The high resolution spectrometer (HRS) allows us to magnetically cleanly separate elastic and inelastic events
- The septum magnet provided the additional 8 degree bend into the first set of Quads
  - The acceptance defining collimators physically allow an area only as big as your palm

Implications: neutron skin

Calculations by Chuck Horowitz

$$R_W = 5.795 \pm 0.082 \text{ fm} \rightarrow 1.4\%$$
$$R_W - R_{ch} = 0.292 \pm 0.082 \text{ fm}$$
$$R_n - R_p = 0.278 \pm 0.078 \text{ fm}$$

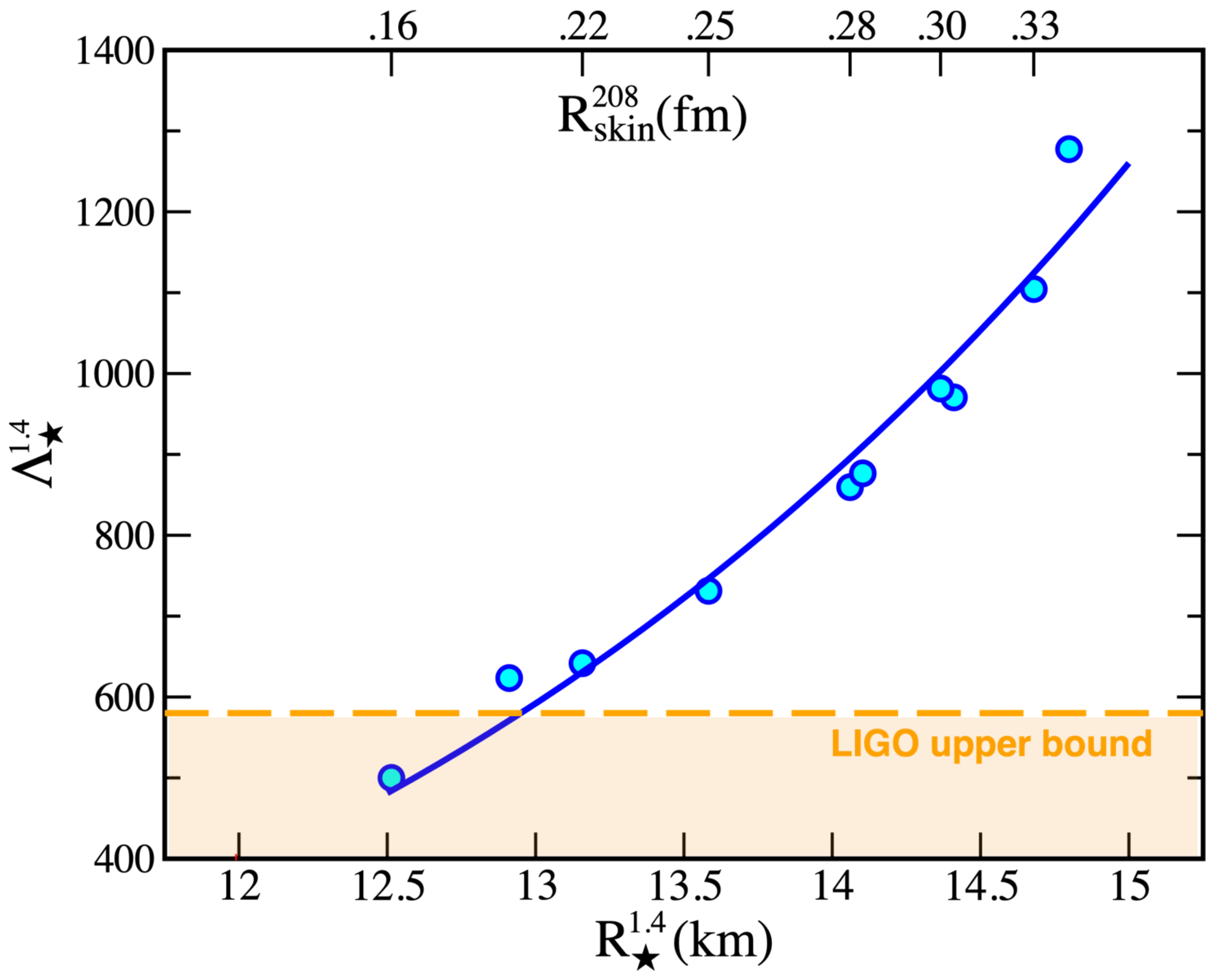
- The model uncertainty (from the surface thickness) is 0.013 fm while the γ-Z box correction error is 0.006 fm



- Thank you Jens Erler and Mikhail Gorchtein for the updated electroweak gamma-Z box corrections

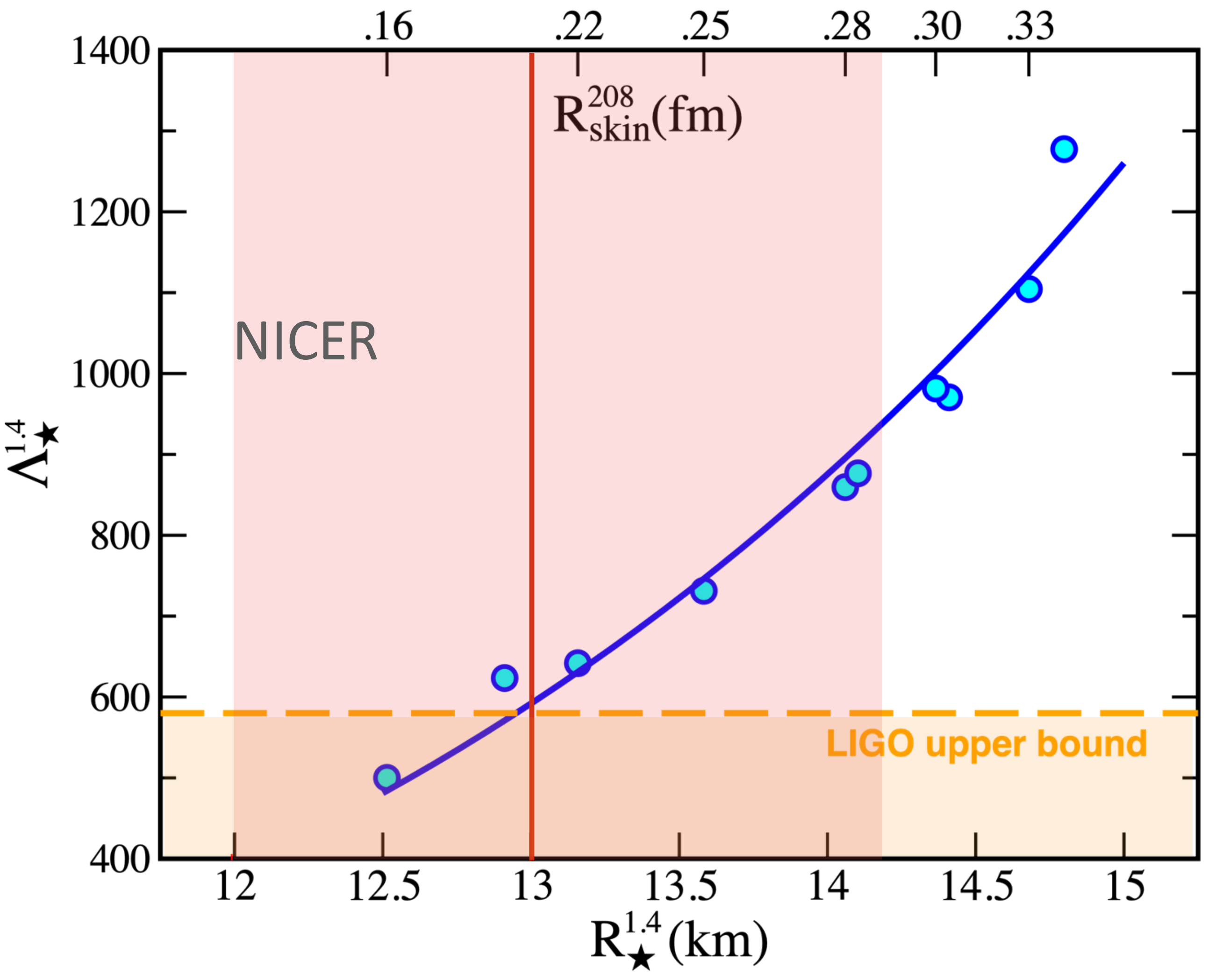
Broader Implications

- We can make use of the existing models to relate the deformability of neutron stars to both neutron skin of Pb and to the neutron star radius



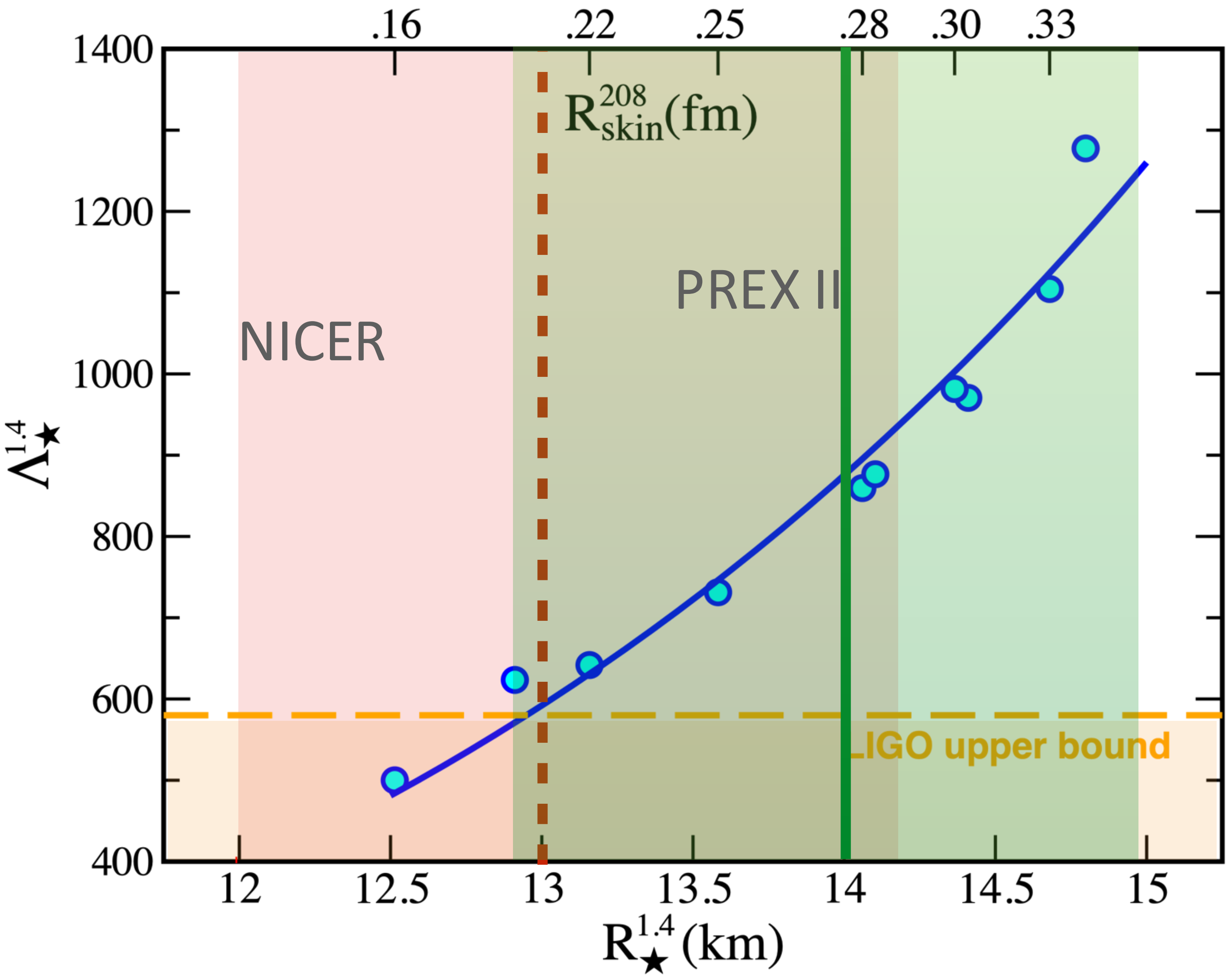
Broader Implications

- We can make use of the existing models to relate the deformability of neutron stars to both neutron skin of Pb and to the neutron star radius
- The NICER result puts a lower and upper bound on the radius of a neutron star



Broader Implications

- We can make use of the existing models to relate the deformability of neutron stars to both neutron skin of Pb and to the neutron star radius
- The PREX-2 result is in good agreement with the NICER result and in slight tension with the tidal polarizability result obtained from GW170817 neutron star merge event observed by LIGO



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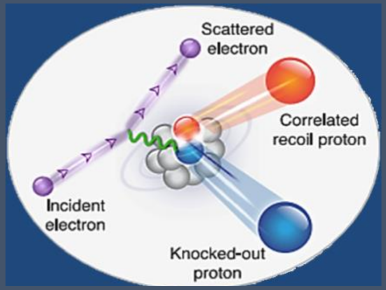
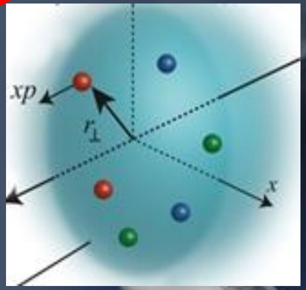
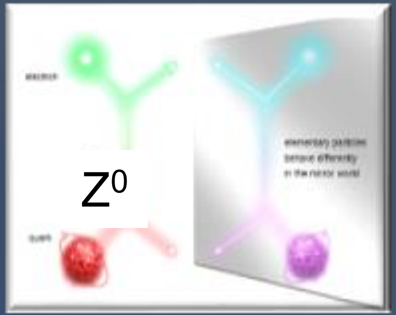


Nuclear Structure



Structure of Hadrons



Fundamental Forces & Symmetries

Medical Imaging

Jefferson Lab is a state-of-the-art *user facility* for nuclear physics research and beyond.

Nuclear Astrophysics

Cryogenics

Accelerator S&T

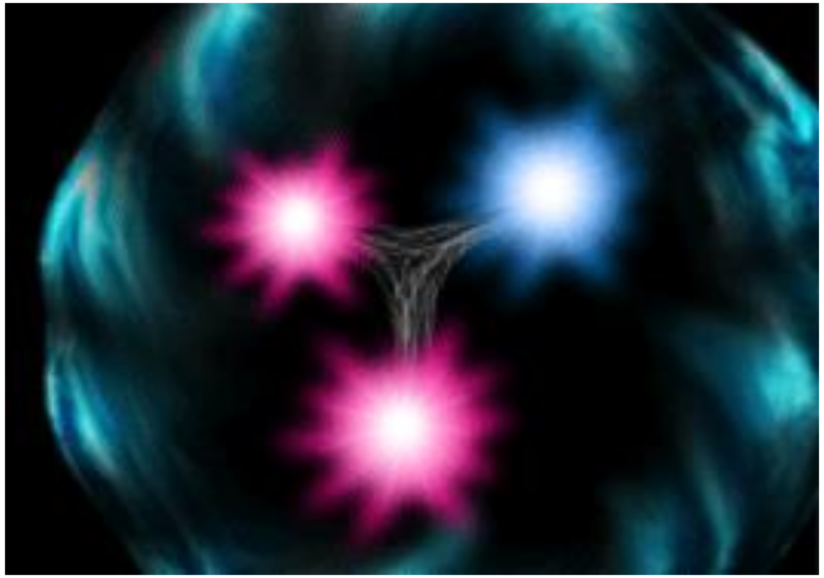
Theory & Computation

The Strange Quantum World

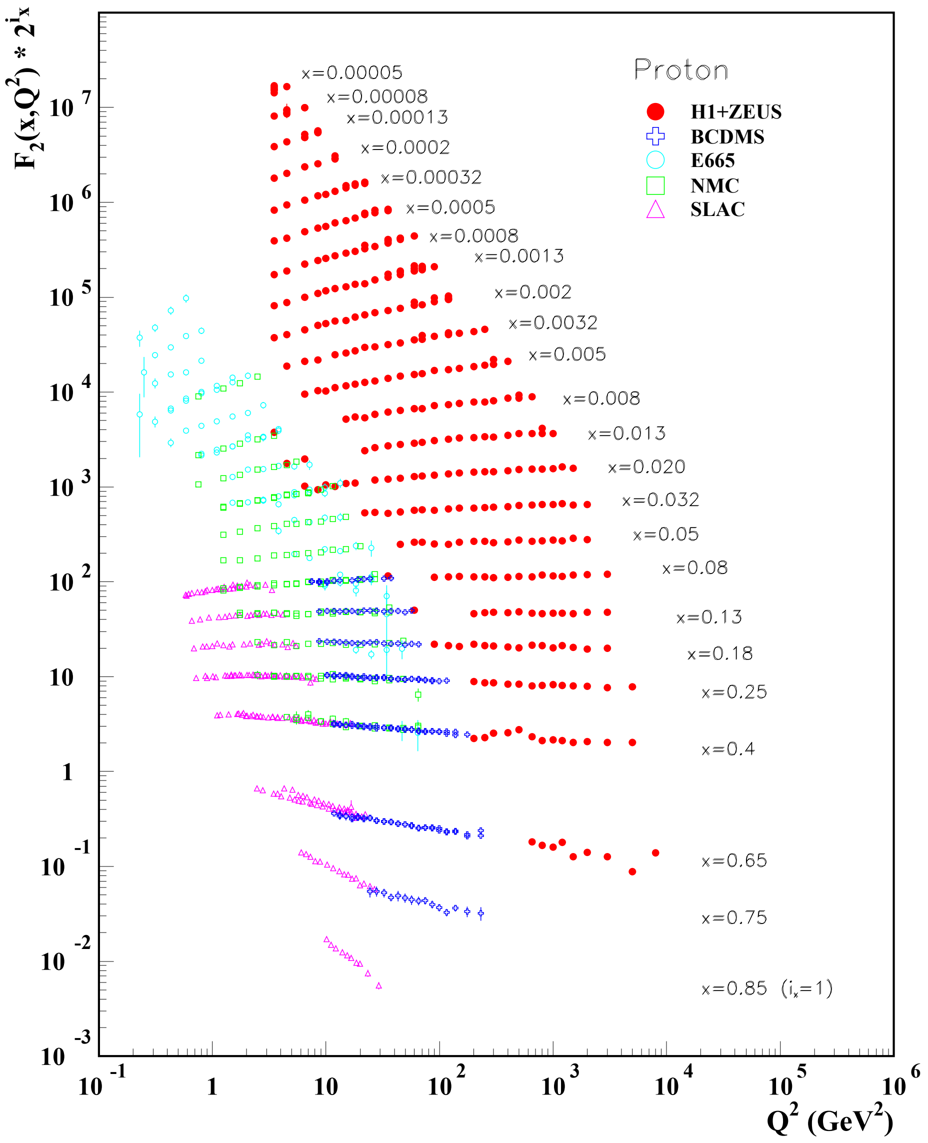
- Heisenberg's uncertainty principles say we can not measure momentum *p* and position *x* with absolute precision, or energy *E* and time *t*.

1. $\Delta p \, \Delta x \geq \frac{1}{2} \hbar$ 2. $\Delta E \, \Delta t \geq \frac{1}{2} \hbar$

- Consequences:
  1. Particles that are bound or confined to small volumes will reach near-relativistic velocities
     - ❑ Protons inside atomic nuclei move with ~1/5 the speed of light, and quarks inside protons move at relativistic speeds.
  2. Pairs of virtual matter and anti-matter are continuously created and destroyed, borrowing their mass/energy by the uncertainty principle
     - ❑ They do not exist as observable entities, but their existence is exerted on other particles as subtle pressure, like the Casimir effect in the vacuum.
     - ❑ This means that conservation of energy can be temporarily broken, and matter/anti-matter pairs with larger mass than the proton can live short times inside this proton.

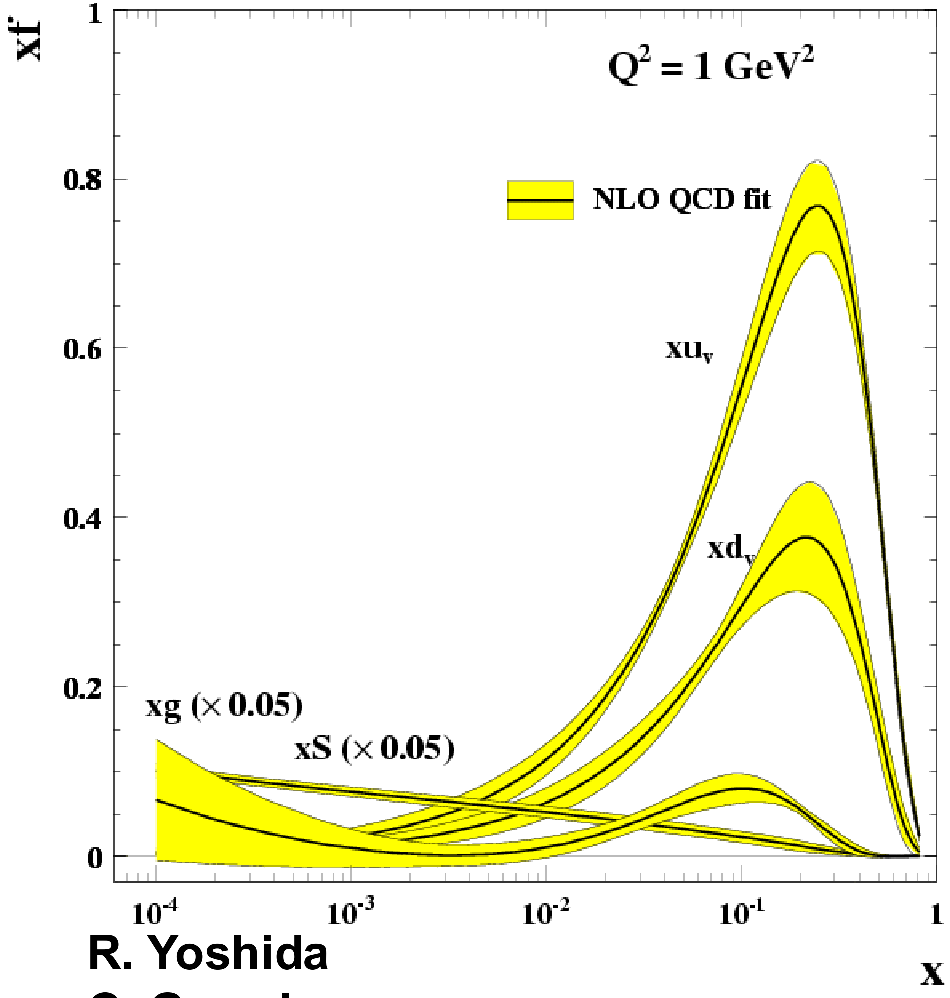


1D longitudinal momentum proton distributions



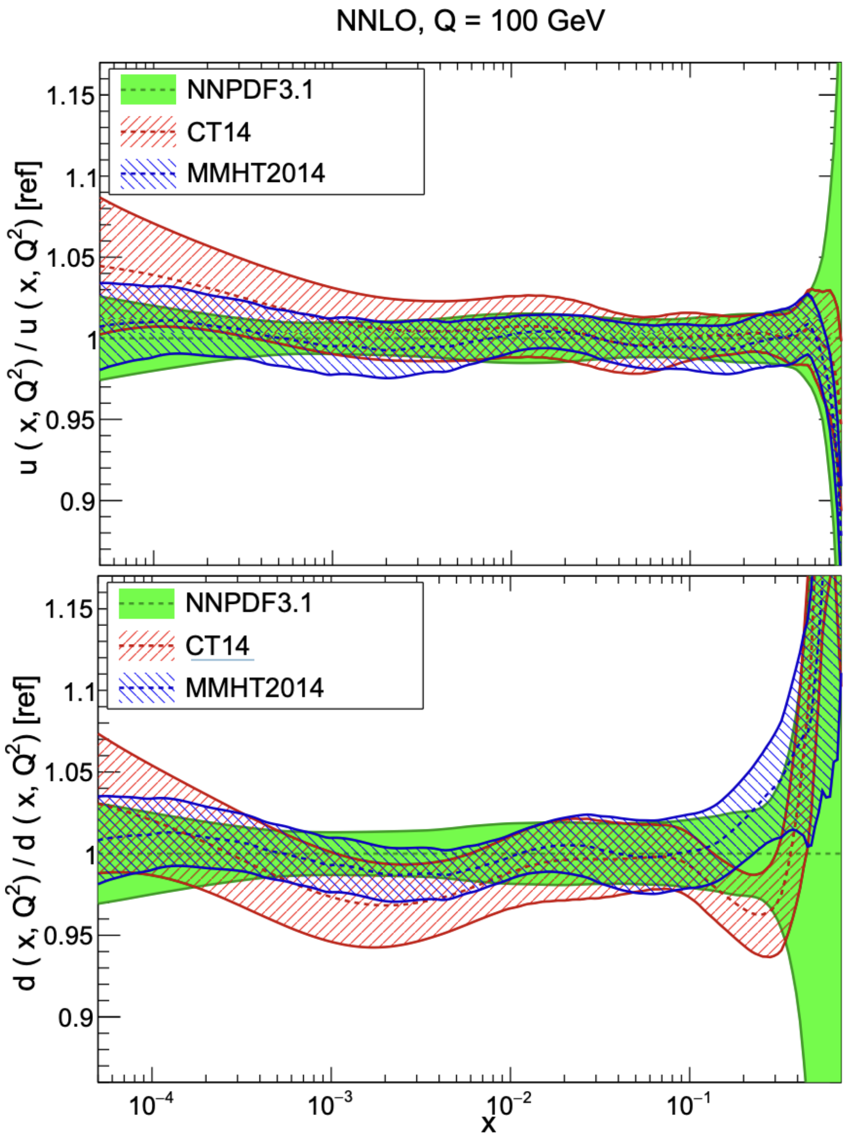
g – gluons
S – quark sea

u, d – up, down
valence quarks



R. Yoshida
C. Gwenlan

1D longitudinal momentum proton distributions



- While decades of measurements have taught us much, we still have x regions that are poorly understood especially high x
  - Less information is available for the d-quark
- The valence region defines the structure of hadrons (baryon number, charge, flavor content ..)
- High x region facilitates comparison with lattice QCD
- "Valence regime" at large x, low Q^2 evolves to low x, high Q^2
  - Intersection of nuclear and particle physics

F2n/F2p ratio

$$F_2^p = x[\frac{4}{9}(u+\bar{u}) + \frac{1}{9}(d+\bar{d}) + \frac{1}{9}(s+\bar{s})]$$

$$F_2^n = x[\frac{4}{9}(d+\bar{d}) + \frac{1}{9}(u+\bar{u}) + \frac{1}{9}(s+\bar{s})]$$

At large x,

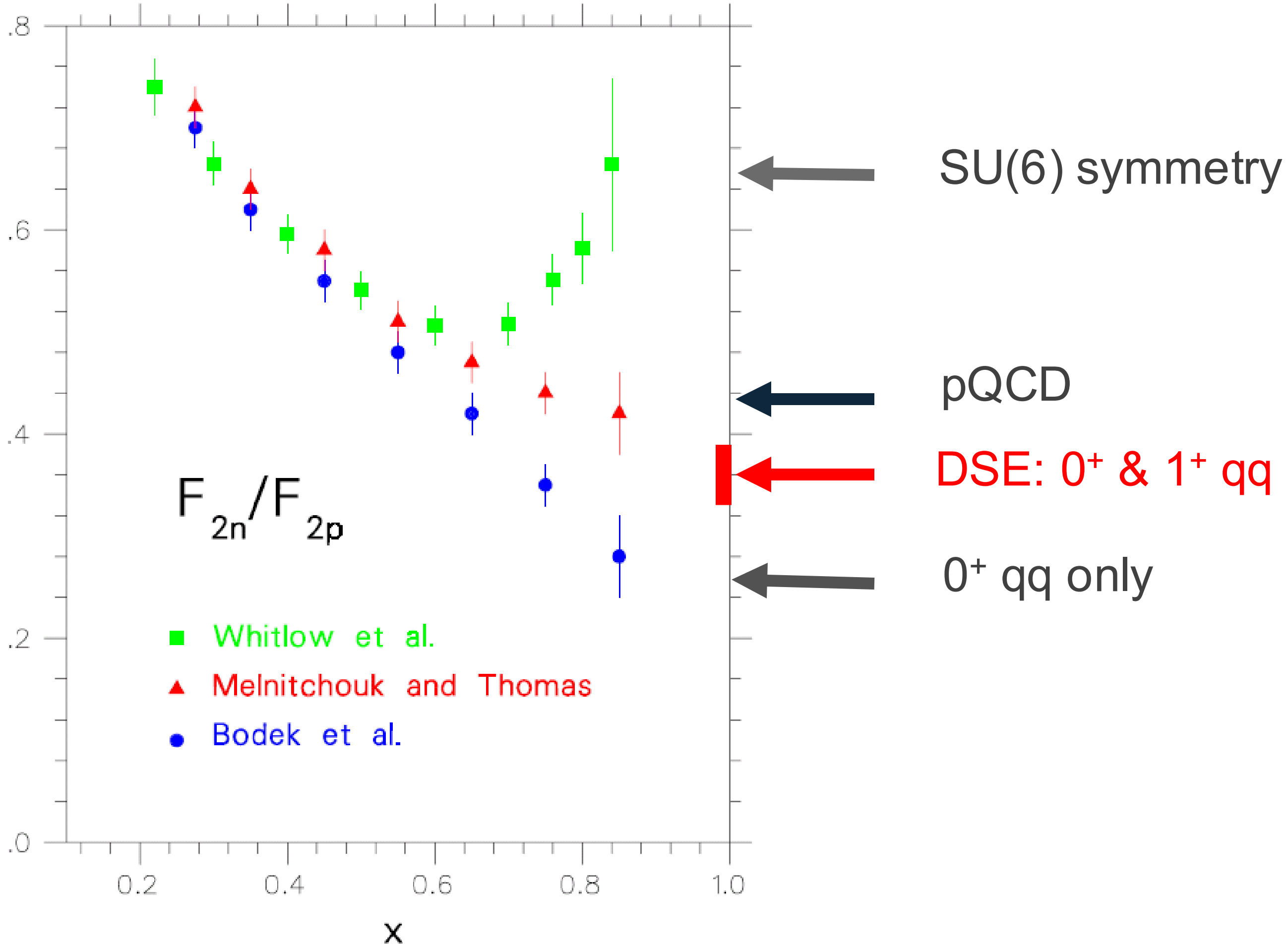
$$\frac{F_2^n}{F_2^p} \approx \frac{1+4(d/u)}{4+(d/u)}$$

Testing ground for theory models

	$F_2(n/p)$	d/u
SU(6)	2/3	1/2
Diquark model/Feynman	1/4	0
Quark model/Isgur	1/4	0
pQCD	3/7	1/5
QCD counting rules	3/7	1/5

- Unresolved issue due to lack of measurements
- The ratio is virtually unknown because we don't have access to a free neutron target
- F2d is not the sum of F2p and F2n!
  - large theory uncertainties from nuclear effects

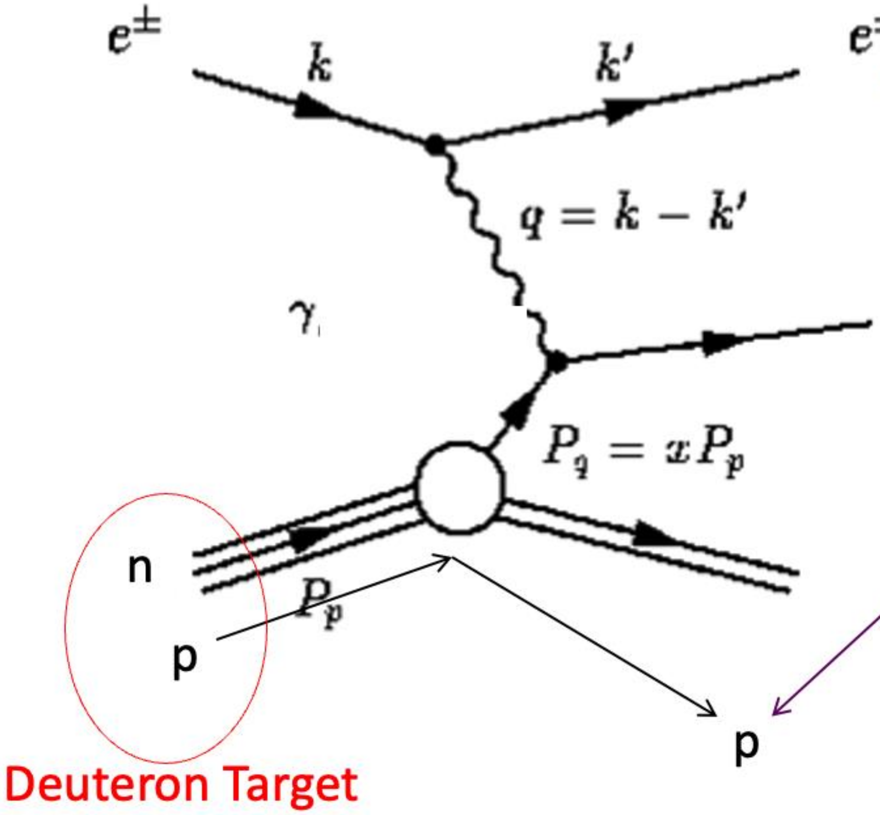
F2n/F2p ratio

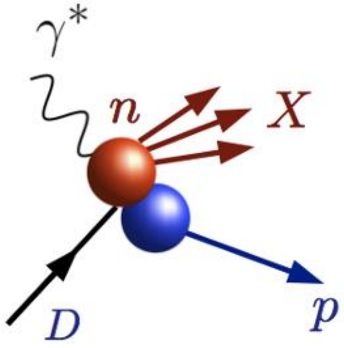


- Different approaches to extract the F2 ratio:
  - Model dependent: use deuteron high precision data
  - Reduced model dependence:
    - 3H/3He DIS data
    - Spectator tagging
  - Fully model independent:
    - parity violating DIS (SoLID)

Spectator tagging

"BONuS" Experiment at Jefferson Lab – use fixed target Tagged DIS to create an effective ***free neutron*** target



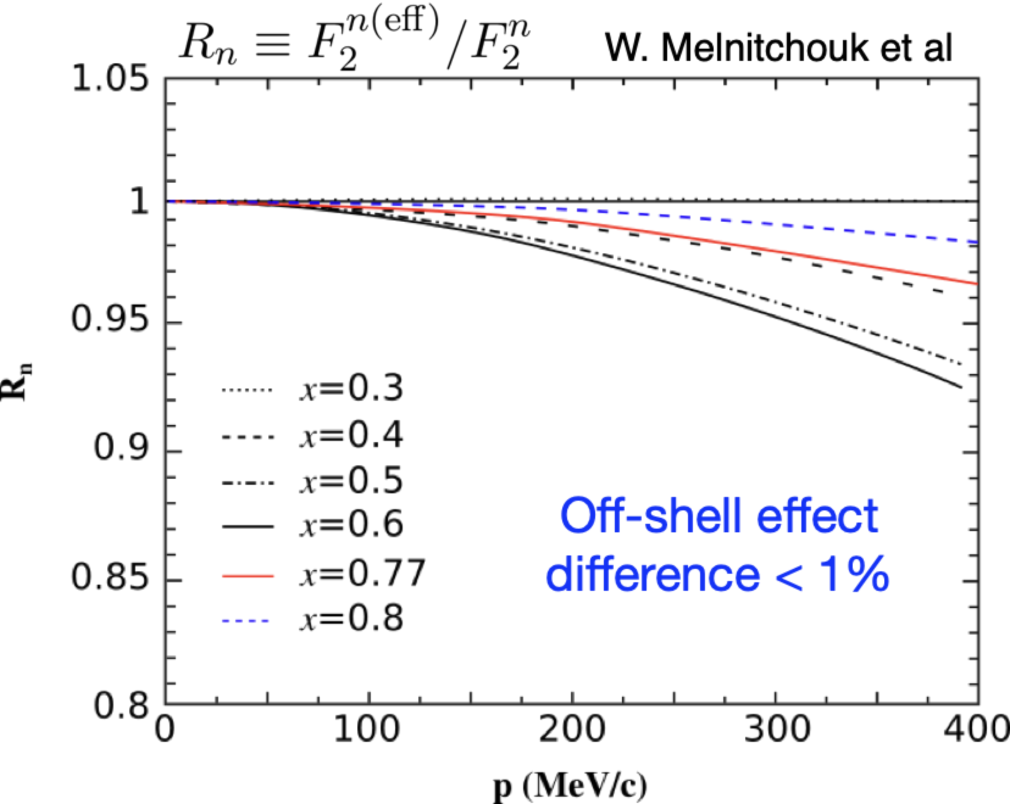


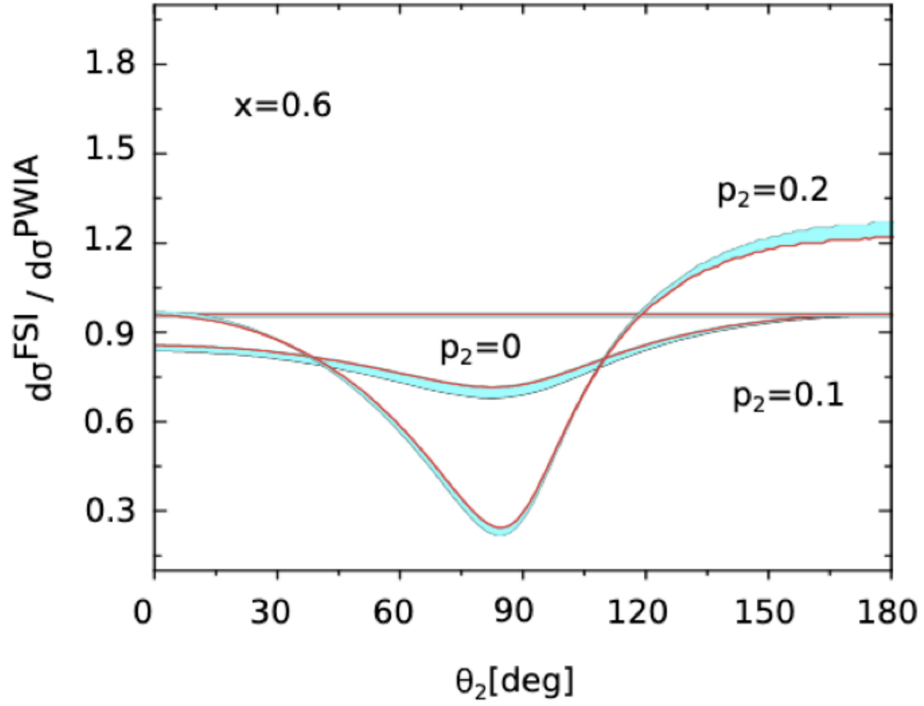
Measure DIS electron in coincidence with proton tag

- "Hard" scattering inelastic event (high Q, W)
- Proton remains intact
- Low momentum proton = nucleons barely off shell

✓ Neutron target!

Can it work?

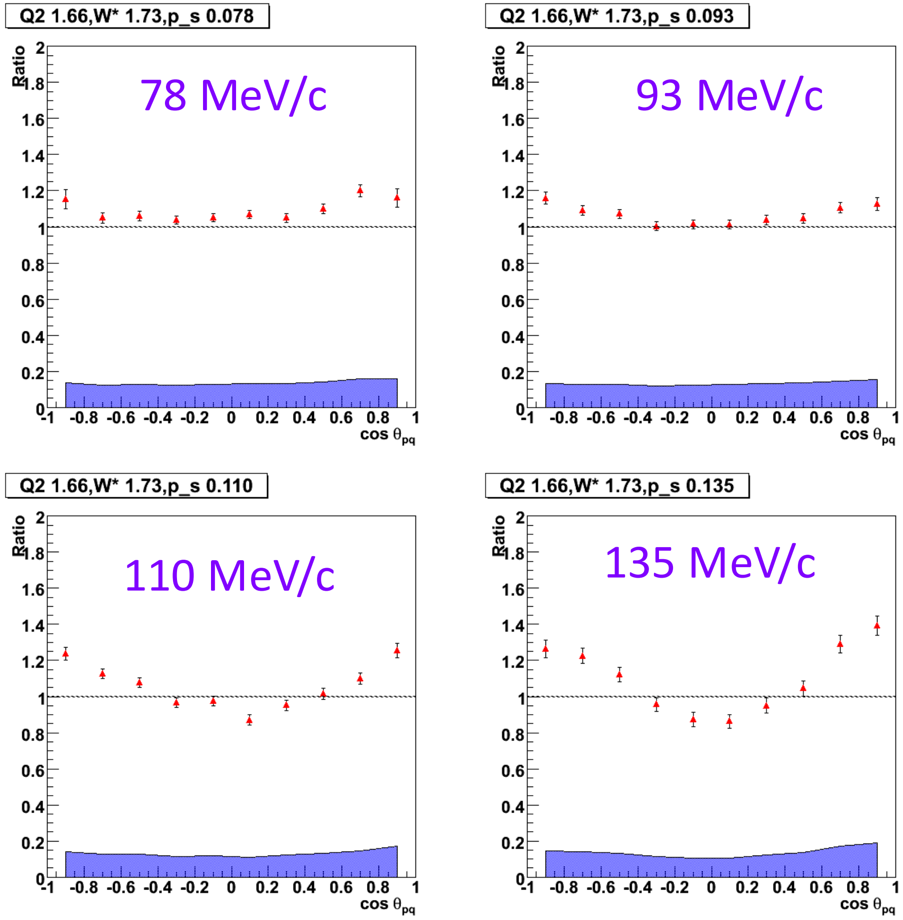




- Yes! If:
  - spectator momentum is low (<100MeV)
  - and spectator angle is very high (>100 degrees)

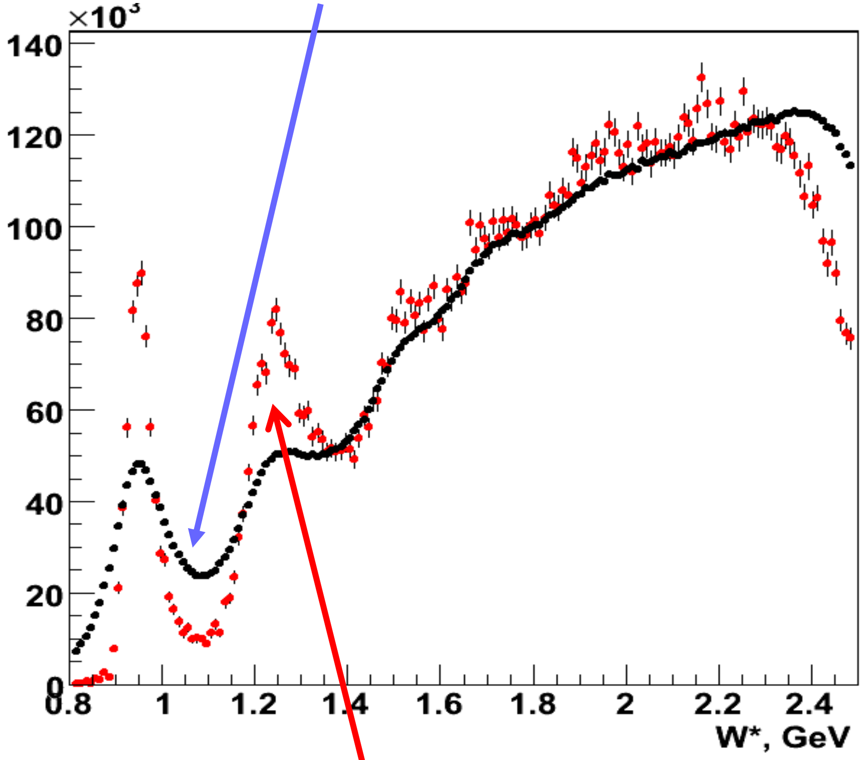
The technique works!

angle - momentum dependence



$\cos\theta_{pq}$

$$W^2 = M^2 + 2M\nu - Q^2$$

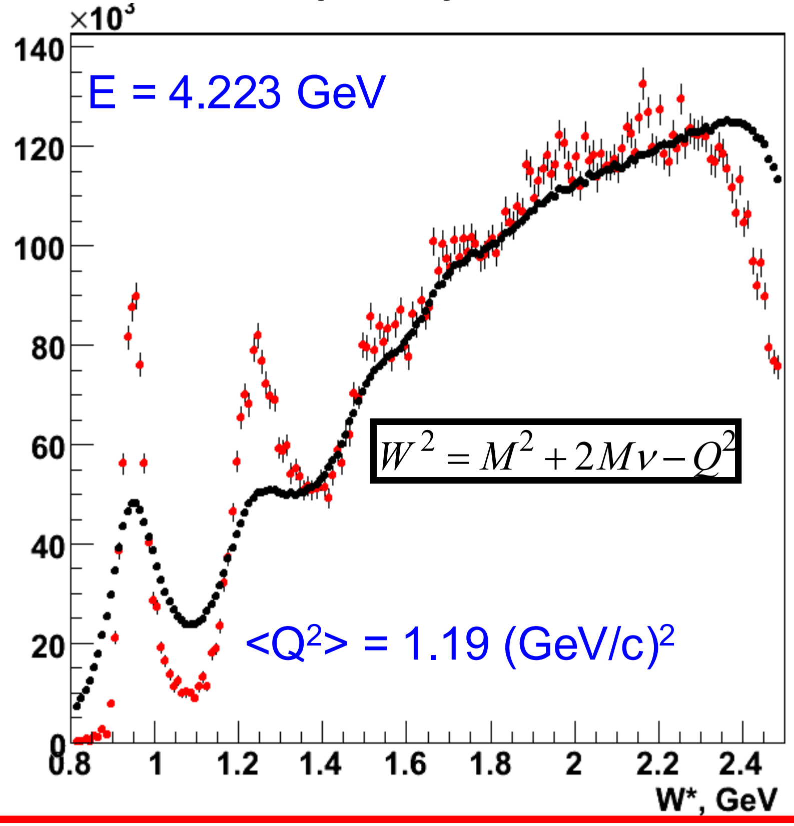


$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$

$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

$\cos\theta_{pq}$

Textbook physics



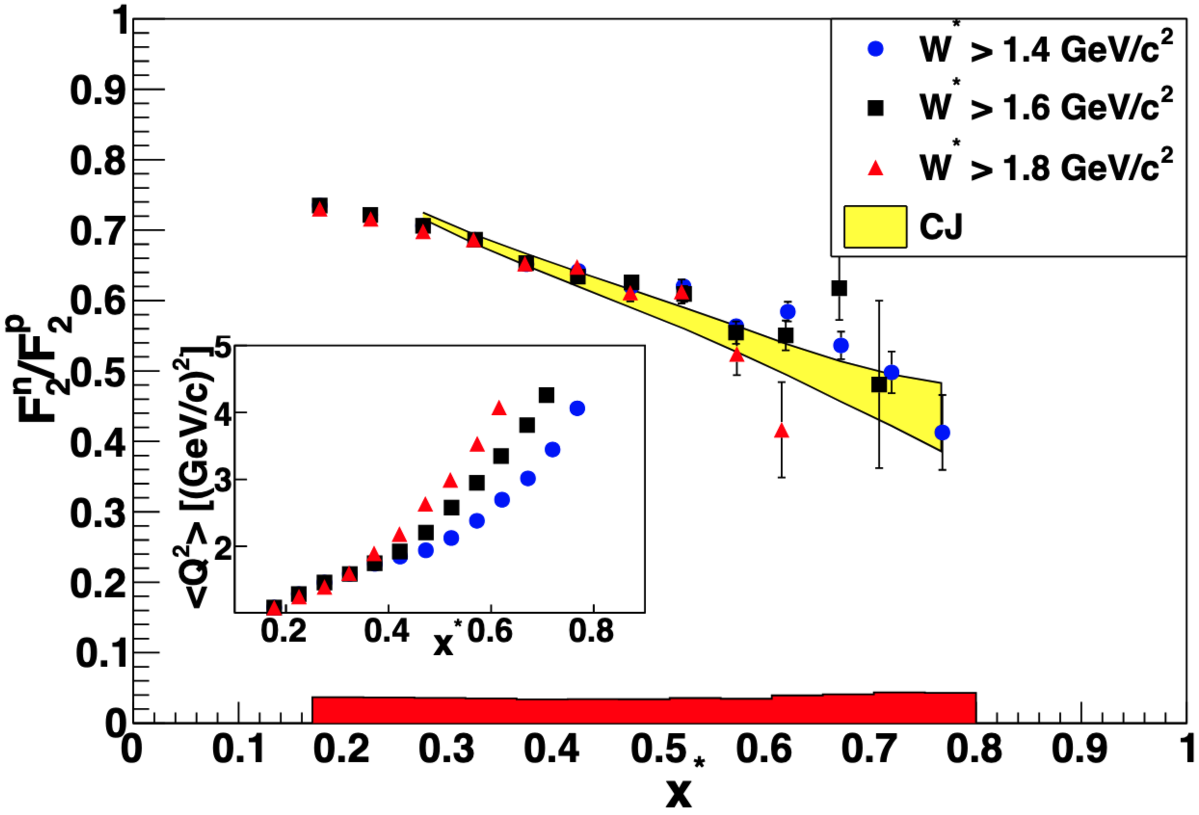
$$W^{*2} = (p_n + q)^2 = p_n^{\mu} p_{n\mu} + 2\left((M_D - E_s)\nu - \vec{p}_n \cdot \vec{q}\right) - Q^2$$
$$\approx M^{*2} + 2M\nu(2 - \alpha_S) - Q^2$$

Nucl. Instrum. Meth. A592 (2008) 273-286

Phys. Rev. Lett. 108 (2012) 199902

Phys. Rev. C92 (2015) 1, 015211

Phys. Rev. C91 (2015) 5, 055206

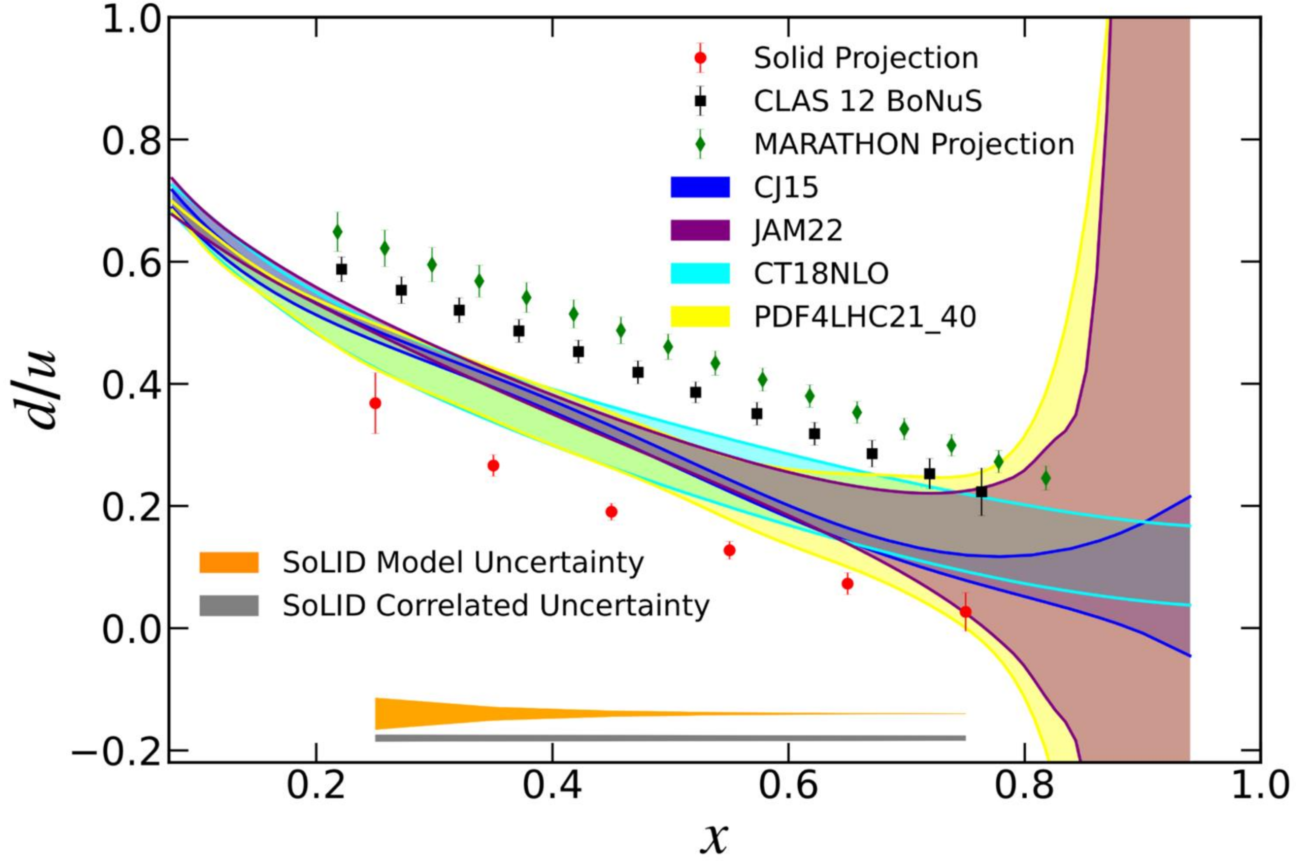


> 200 ***neutron*** data points!

- Crucial input for global PDF fits
- Measure EMC effect in deuterium
- Neutron duality studies
- Still lower W, Q^2 than desirable….

JLab 12GeV d/u constraints

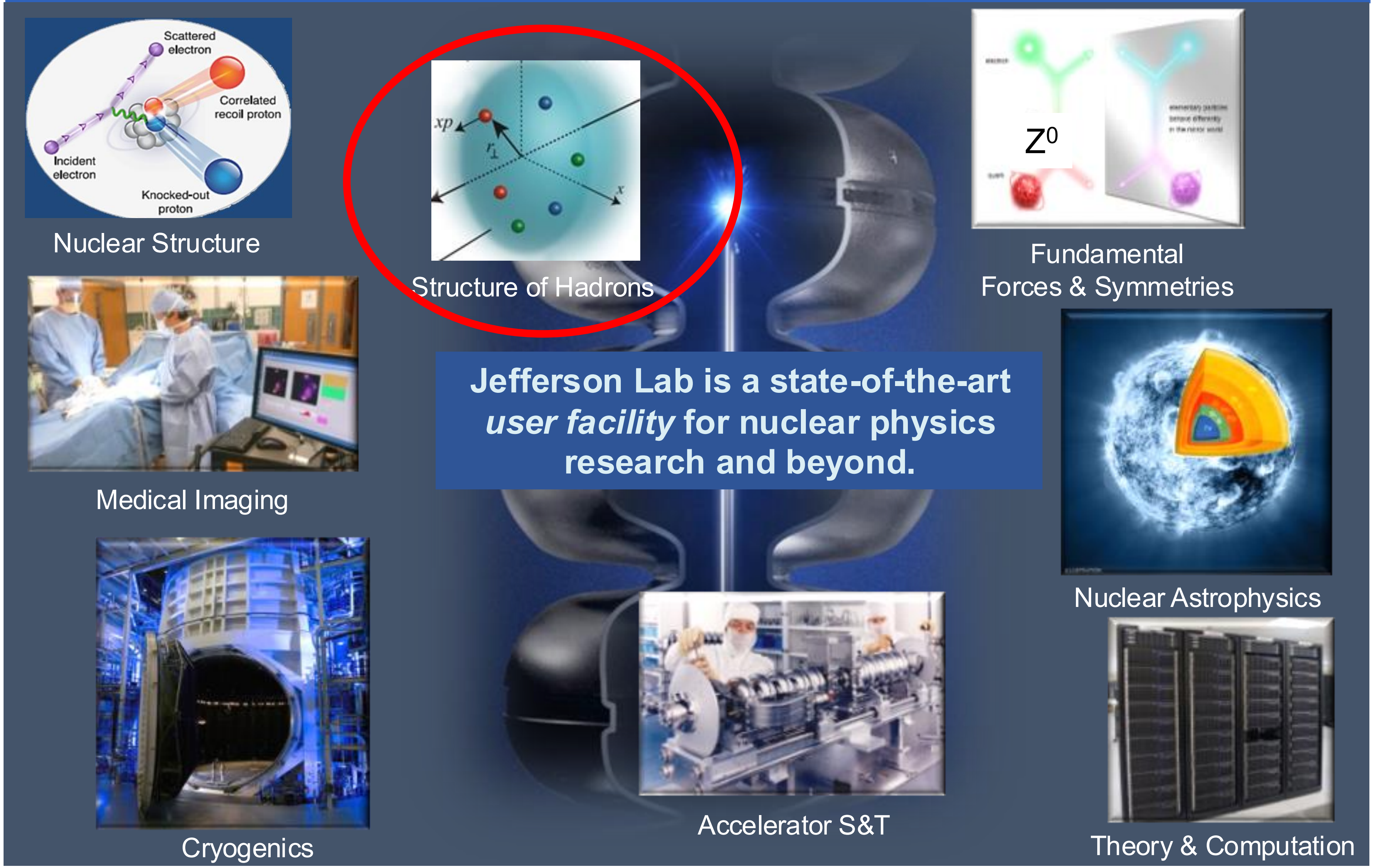
J. Phys. G: Nucl. Part. Phys., 50:110501, 2023



- Less model dependent approaches:
  3H/3He ratio (MARATHON) - results published (Phys.Rev.Lett. 128 (2022) 13, 132003)
  Spectator tagging (BoNus) - new data taken in 2020

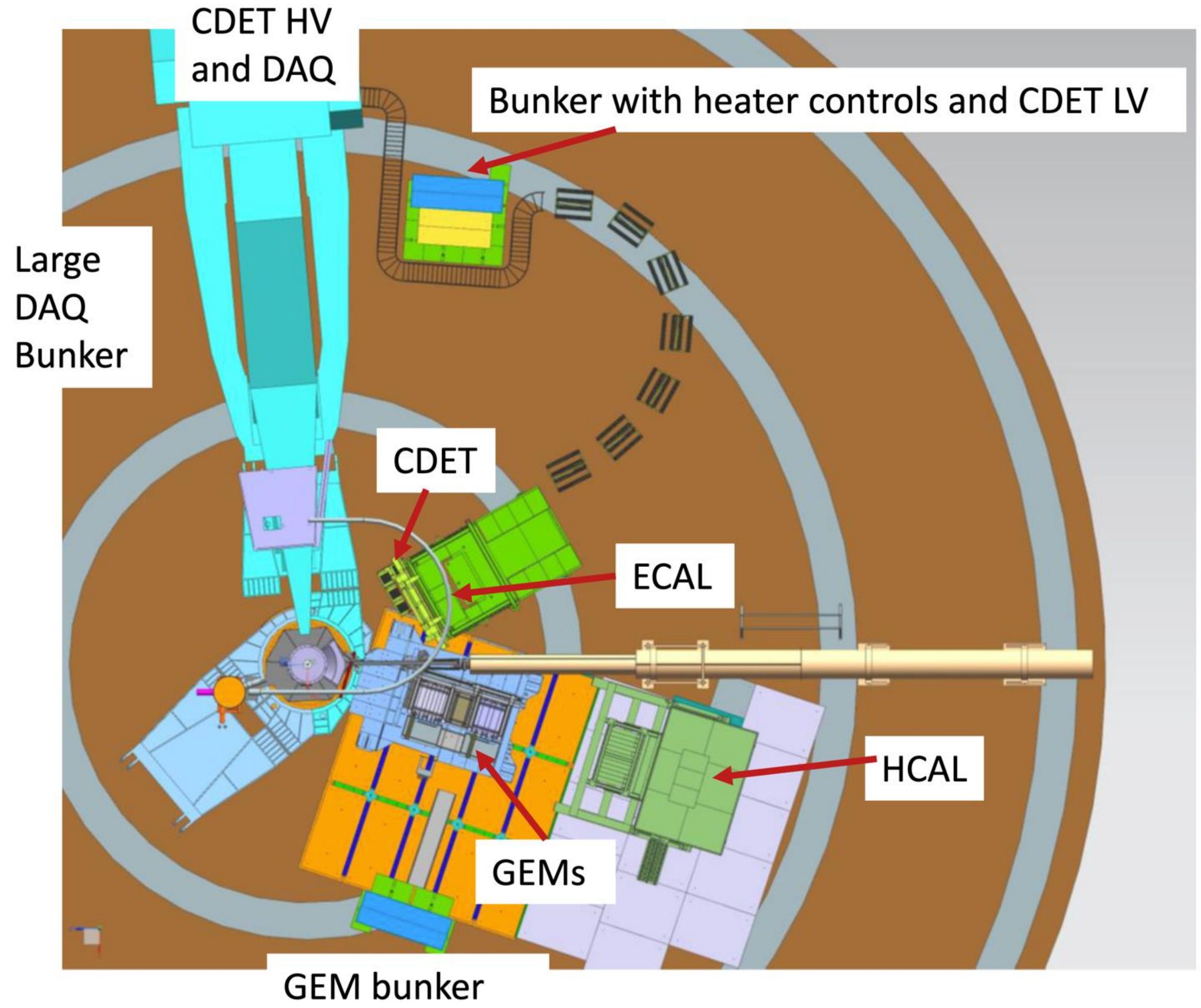
- Model independent approach:
  Future PVDIS on proton (SoLID)

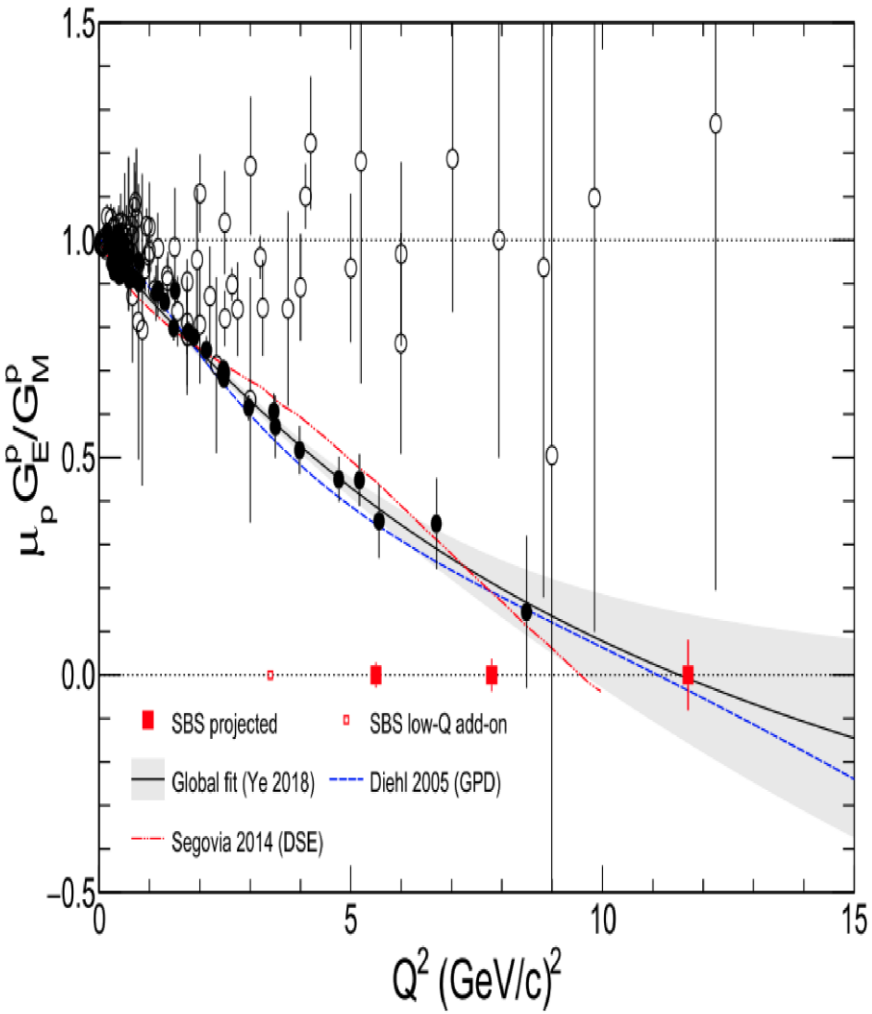
JLab: A Laboratory for Medium Energy Nuclear Science



Gep/SBS: Ratio of proton electric to magnetic form factors

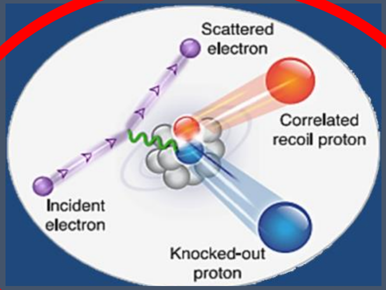
How are the charge and magnetization currents distributed in the proton?



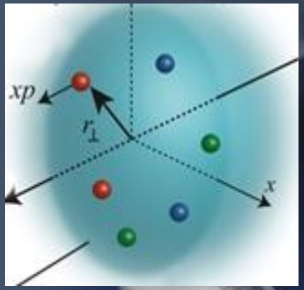


E12-24-010 proposal: A. Puckett

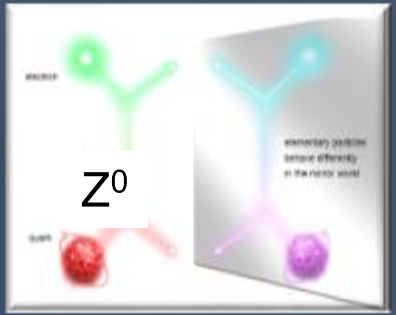
JLab: A Laboratory for Medium Energy Nuclear Science



Nuclear Structure



Structure of Hadrons



Fundamental Forces & Symmetries

Medical Imaging

Jefferson Lab is a state-of-the-art *user facility* for nuclear physics research and beyond.

Nuclear Astrophysics

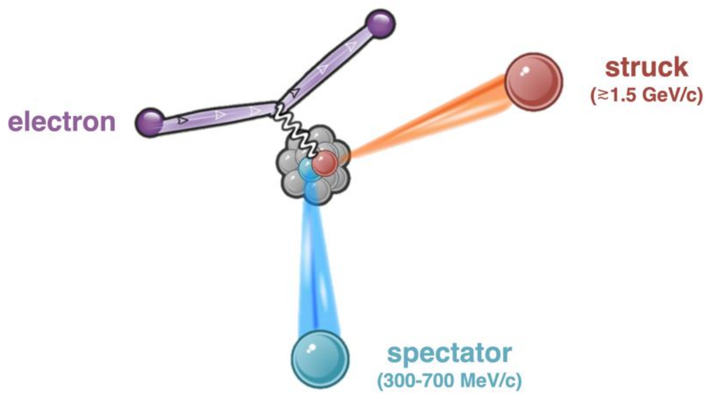
Cryogenics

Accelerator S&T

Theory & Computation

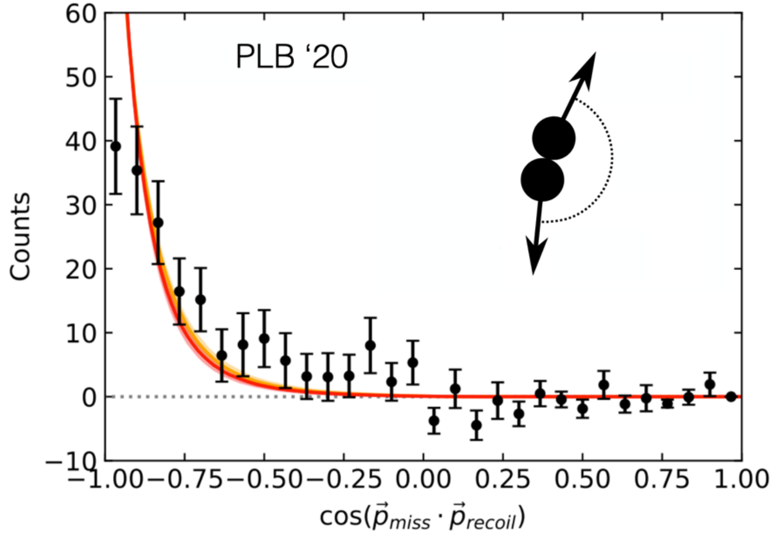
SRC measurements

PR12-23-013 proposal: O. Hen

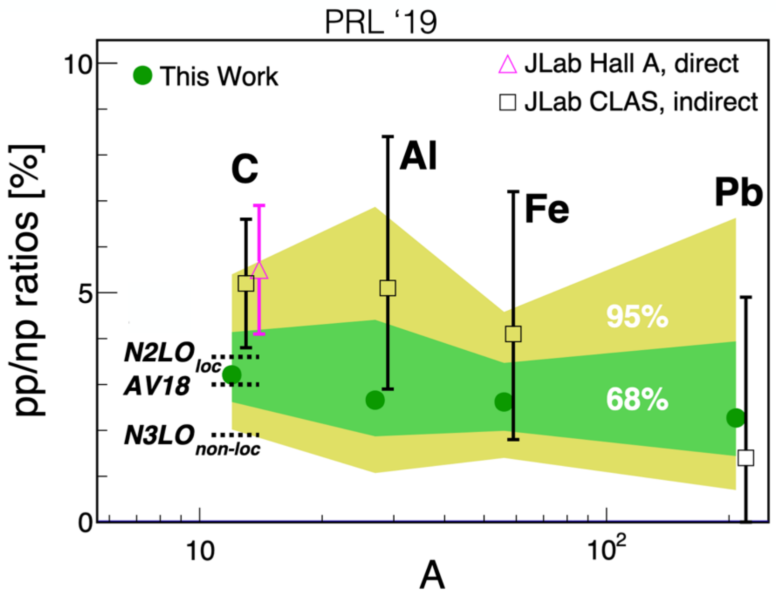


Similar to the BoNUS technique but with larger nuclei

- Breakup of SRC pairs lead to correlated nucleon emission



- Predominantly proton-neutron pairs



Quantum Numbers, Mass, Asymmetry Dependence:
Phys. Rev. C 103, L031301 (2021)
Phys. Lett. B 780, 211 (2018)
PRC 92, 024604 (2015)
PRC 92, 045205 (2015)

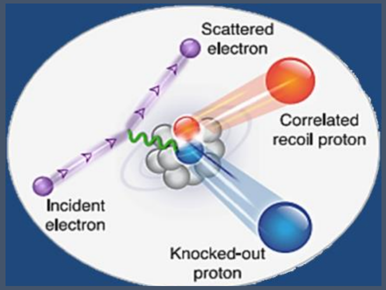
Isospin Structure:
Phys. Rev. Lett. 122, 172502 (2019)
Nature 560, 617 (2018)
Science 346, 614 (2014)
Phys. Rev. Lett. 113, 022501 (2014)

C.M. Motion:
Phys. Rev. Lett. 121, 092501 (2018)

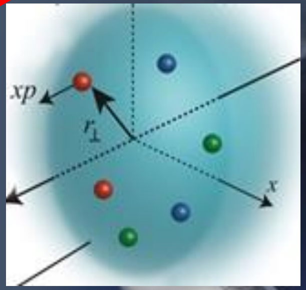
Hard-Reaction Dynamics:
Nature Physics 17, 693 (2021)
Phys. Lett. B 797, 134792 (2019)
Phys. Lett. B 722, 63 (2013)

Effective Theory:
Nature Physics 17, 306 (2021)
Phys. Lett. B 805, 135429 (2020)
Phys. Lett. B 791, 242 (2019)

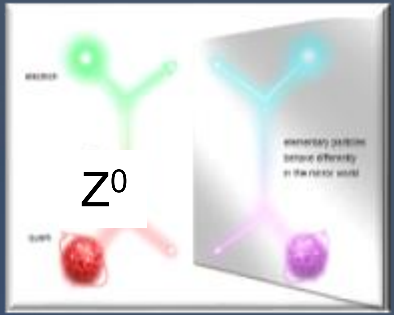
JLab: A Laboratory for Medium Energy Nuclear Science



Nuclear Structure



Structure of Hadrons



Fundamental Forces & Symmetries

Medical Imaging

Jefferson Lab is a state-of-the-art *user facility* for nuclear physics research and beyond.

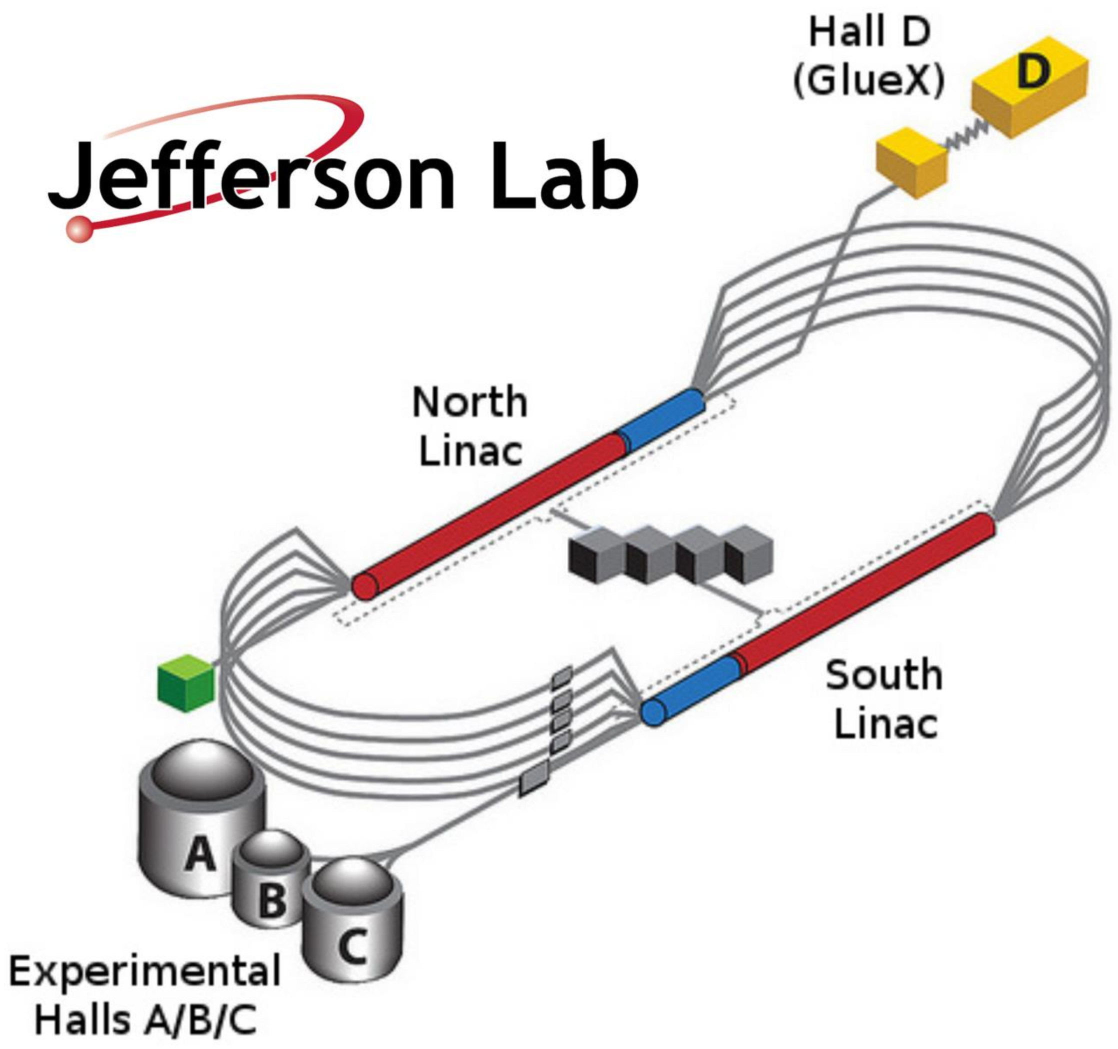
Nuclear Astrophysics

Cryogenics

Accelerator S&T

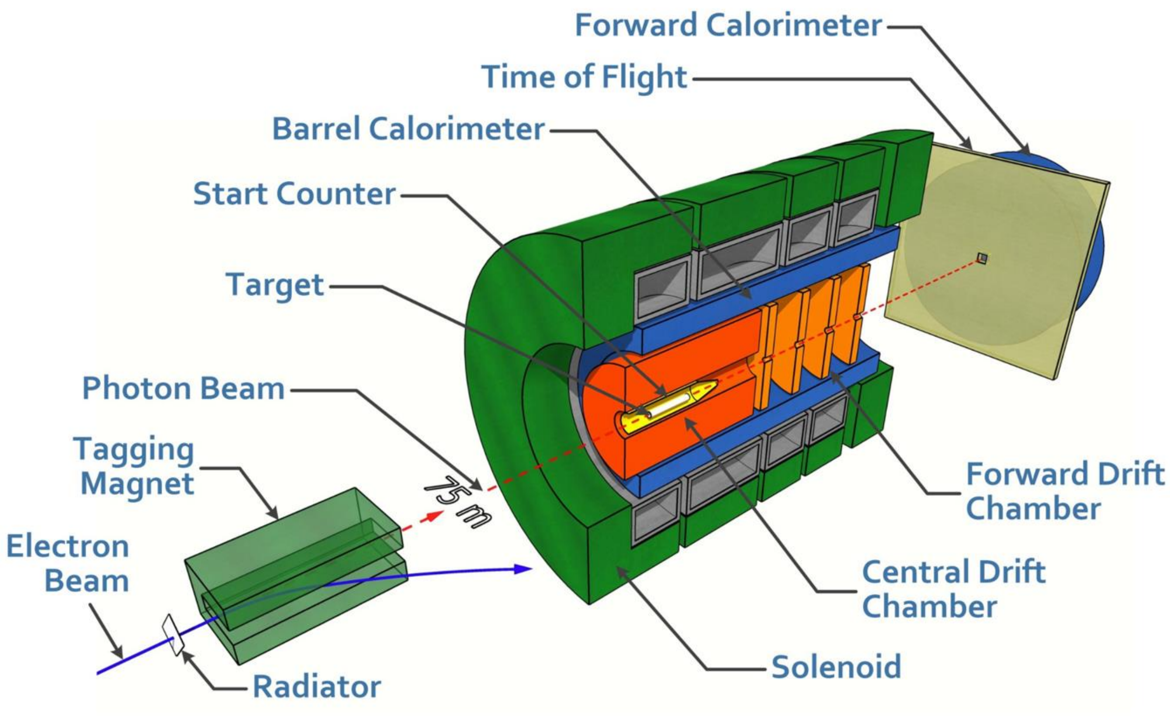
Theory & Computation

Unique capabilities in hall D

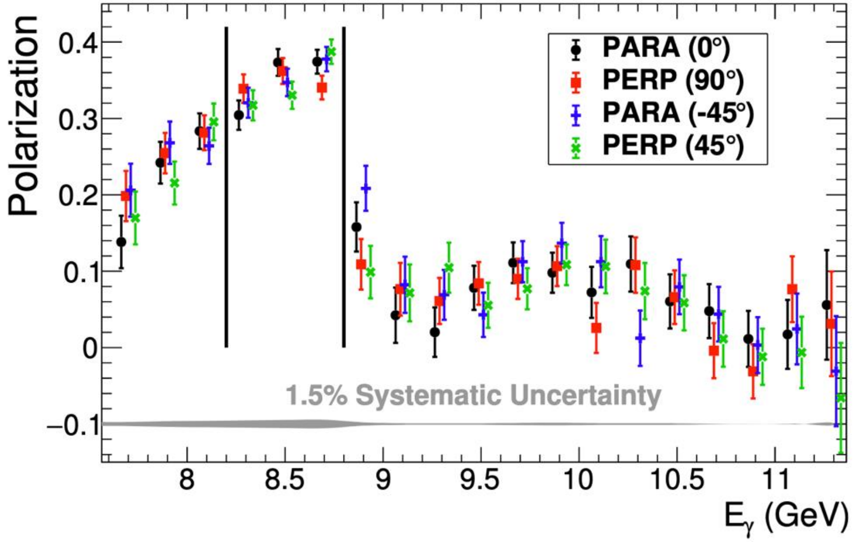


A. Austregesilo

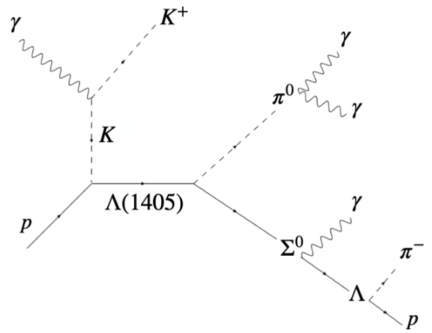
Unique capabilities in hall D



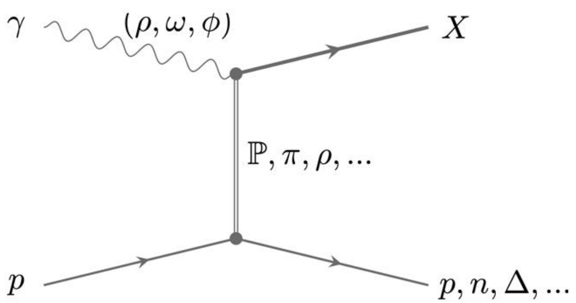
- 12 GeV electron beam from CEBAF accelerator
- Coherent Bremsstrahlung on diamond radiator
- Linear polarization in peak $P_\gamma \sim 40\%$
- Energy tagged by scattered electrons
- Beam intensity: $1 - 5 \cdot 10^7\ \gamma/\mathrm{s}$ in peak



A. Austregesilo



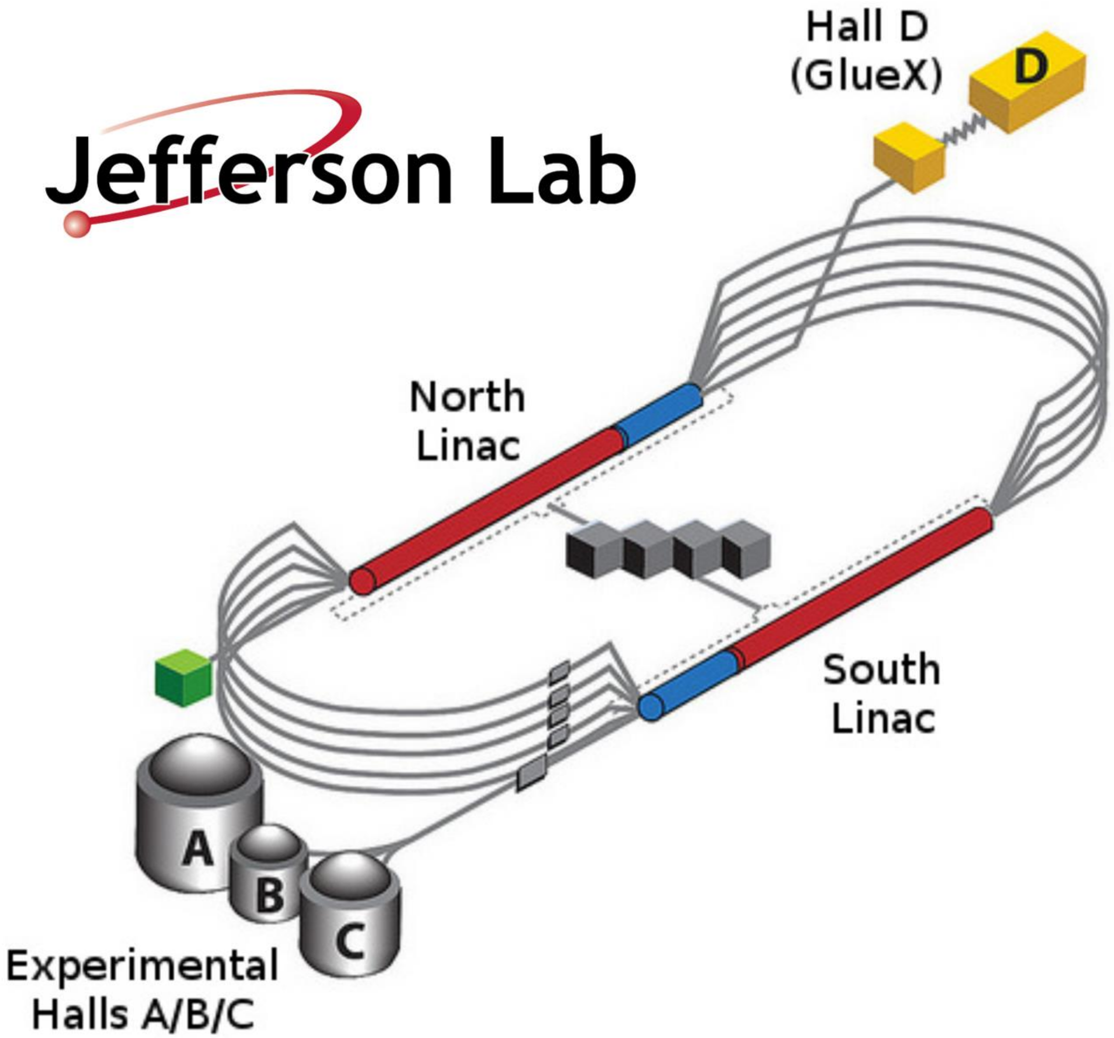
Hadron spectroscopy



Meson spectroscopy

The questions that drive us forward

- 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?



Lunch sports! – all skill levels welcome

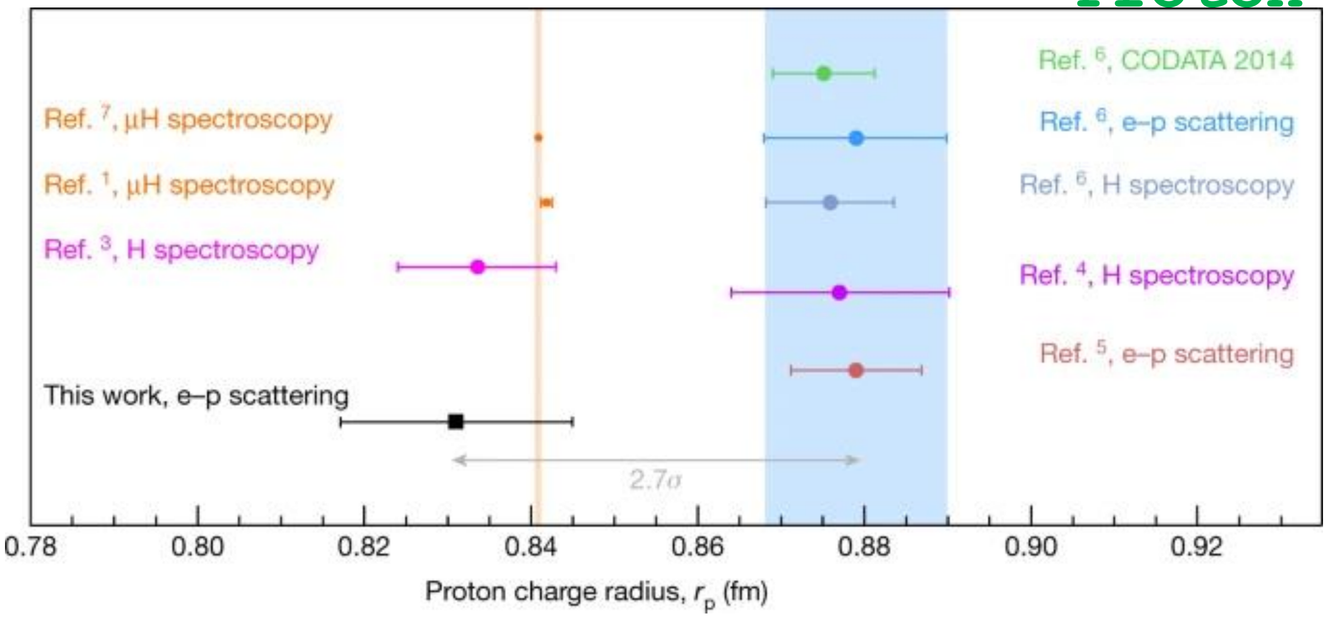
Ultimate frisbee: Th noon-1
jlabultimate@jlab.org

Soccer: Fr noon-1
jlabsoccer@jlab.org

Backups

Proton Radius

- **Novel Electron Scattering Experiment Finds a Smaller Proton Radius**

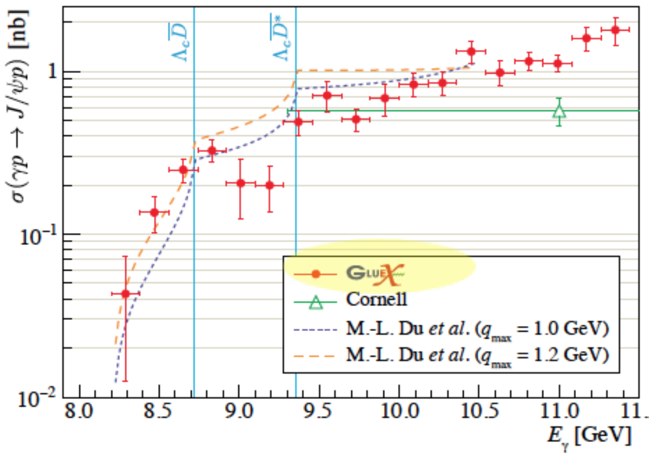


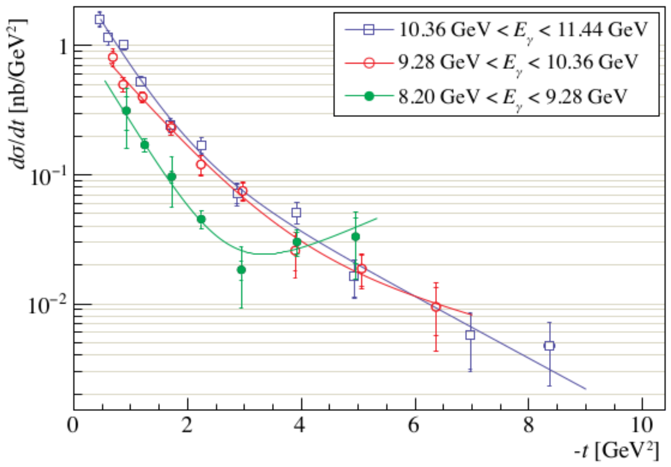
Nature 575, 147-150 (2019) – 232 citations

- **First elastic scattering at very low momentum transfers**
- **Finding agrees with the revised value for the Rydberg constant—one of the most accurately evaluated fundamental constants in physics.**

J/psi Photoproduction near Threshold

- **First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton**

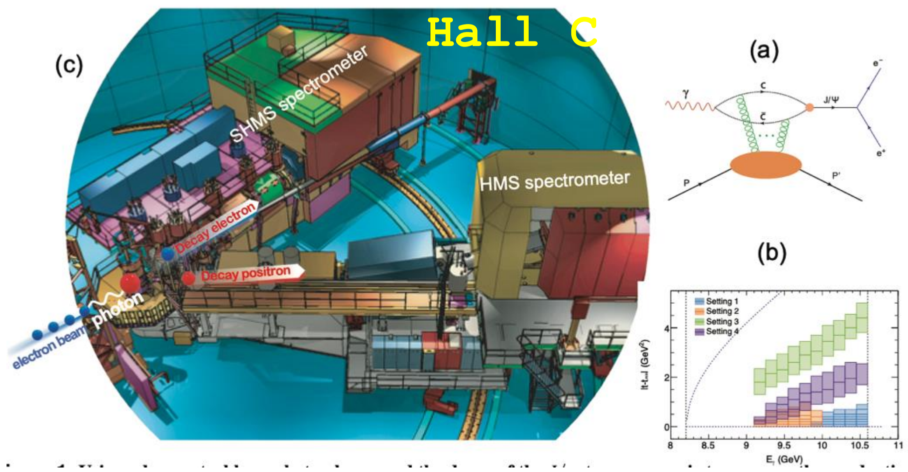


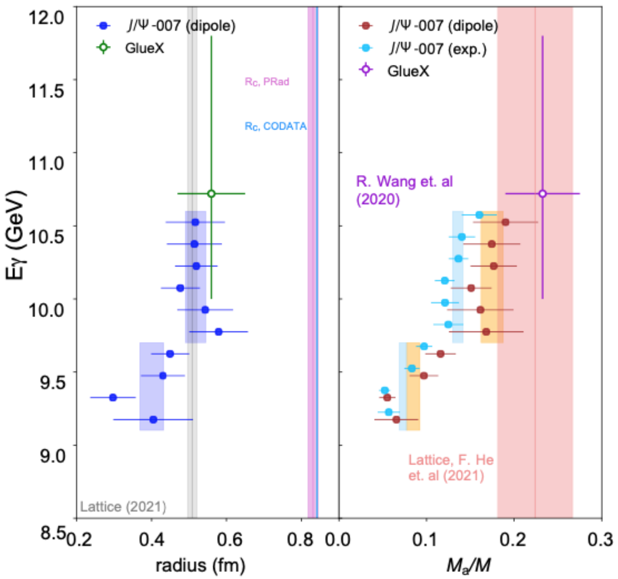


PRL 123 (2019) 177 Citations
PRC 108 (2023) 2, 025201

- **Study the gluonic component of the nucleon**

- **Determining the gluonic gravitational form factors of the proton**





- Large theoretical interest!

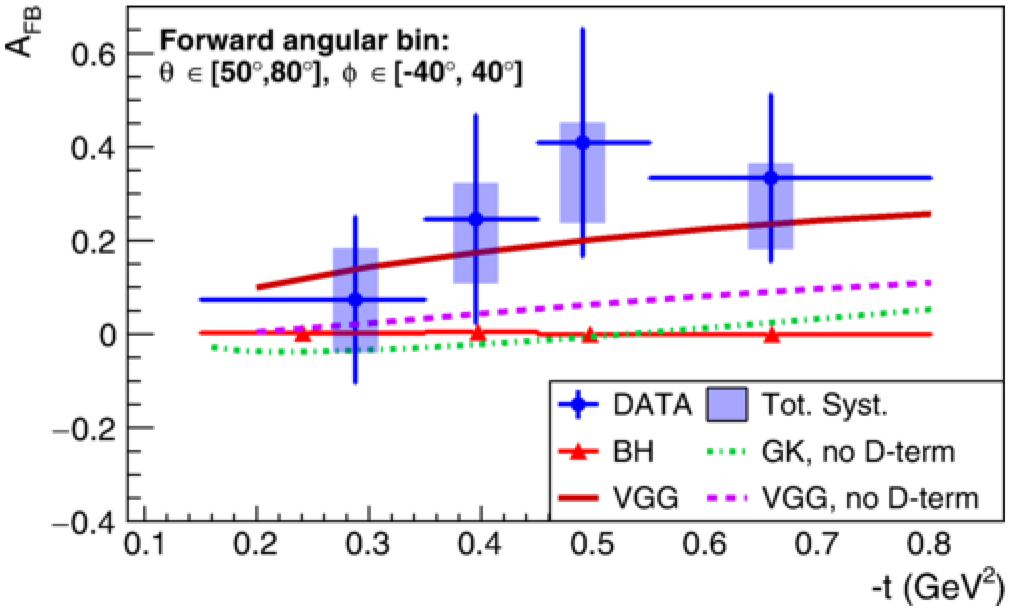
Interpretation of J/psi Photoproduction near Threshold based on the production mechanism

- 2-gluon exchange, factorization
  - Relation to gravitational formfactors,
  - EMT trace anomaly - nucleon mass
  - Relation to nucleon mass radius
- Other possible mechanisms: open charm exchange

Nature 615 (2023) 7954, 813-816 *44 Citations*

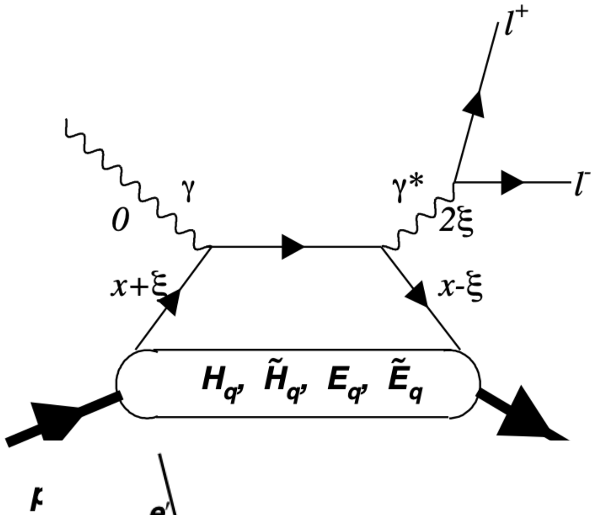
New Steps in Studying the 3D Structure of the Proton

First Measurement of Timelike Compton Scattering

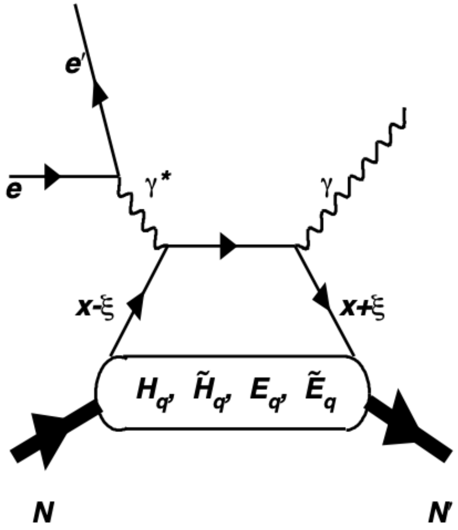


PRL 127 (2021) 26, 262501

- Test of GPDs Universality



TCS



DVCS

- **Validates the application of the GPD formalism to describe TCS data and hints at the universality of GPDs**

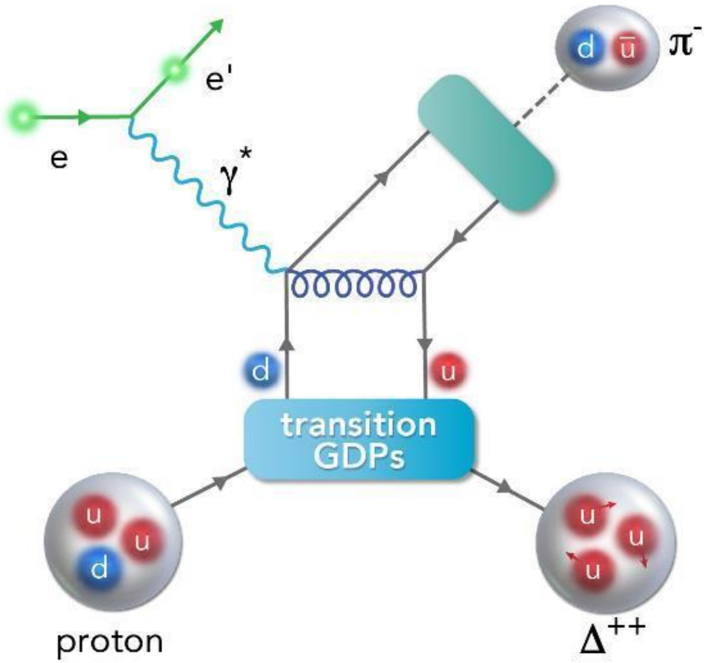
Transition GPDs

▪ Generalization of GPDs to N → Δ processes

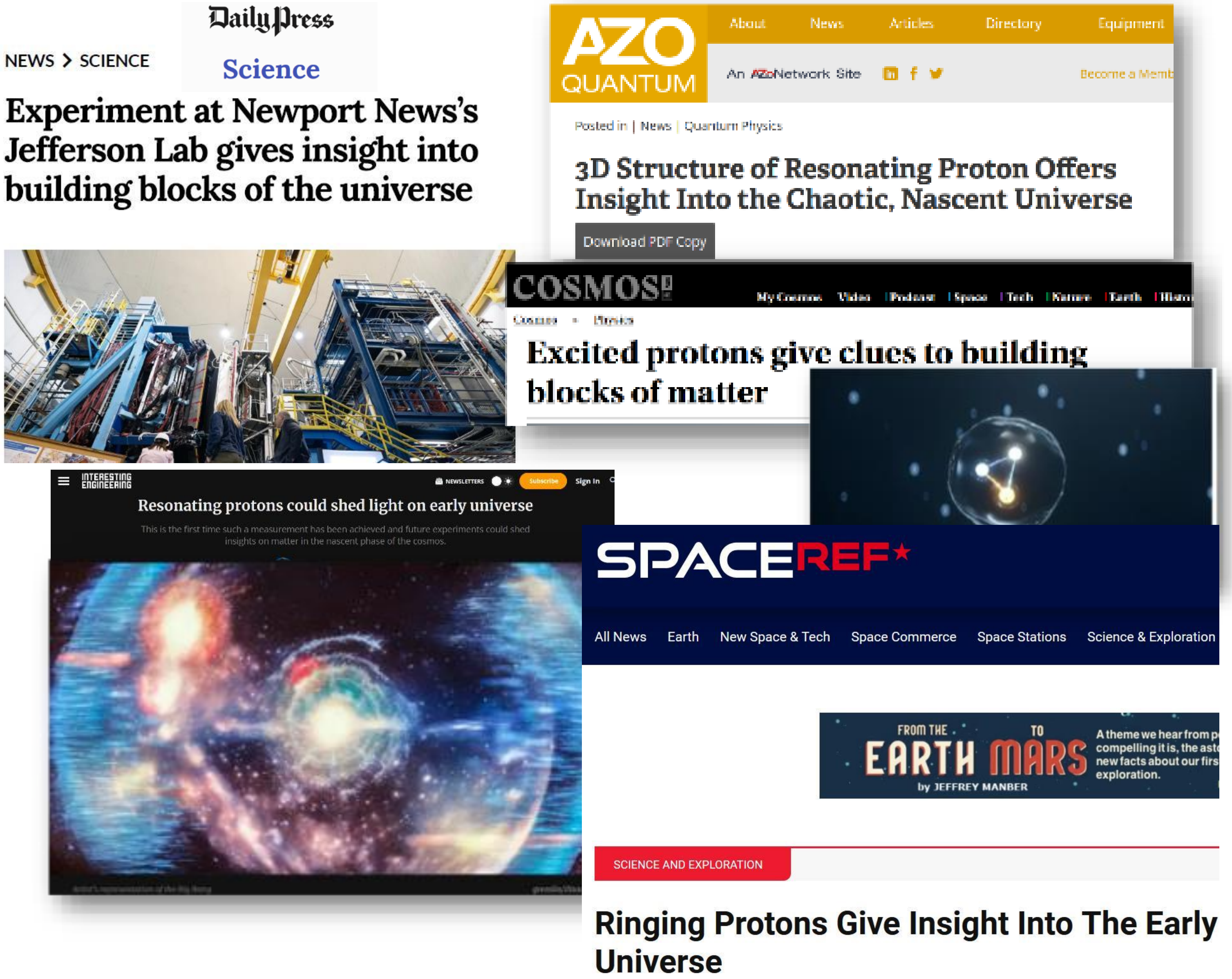
First Measurement of Hard Exclusive π-Δ++ Electroproduction Beam-Spin Asymmetries off the Proton

PRL 131, 021901,11 July 2023

$$ep \to e' p\, \pi^-(\pi^+)$$

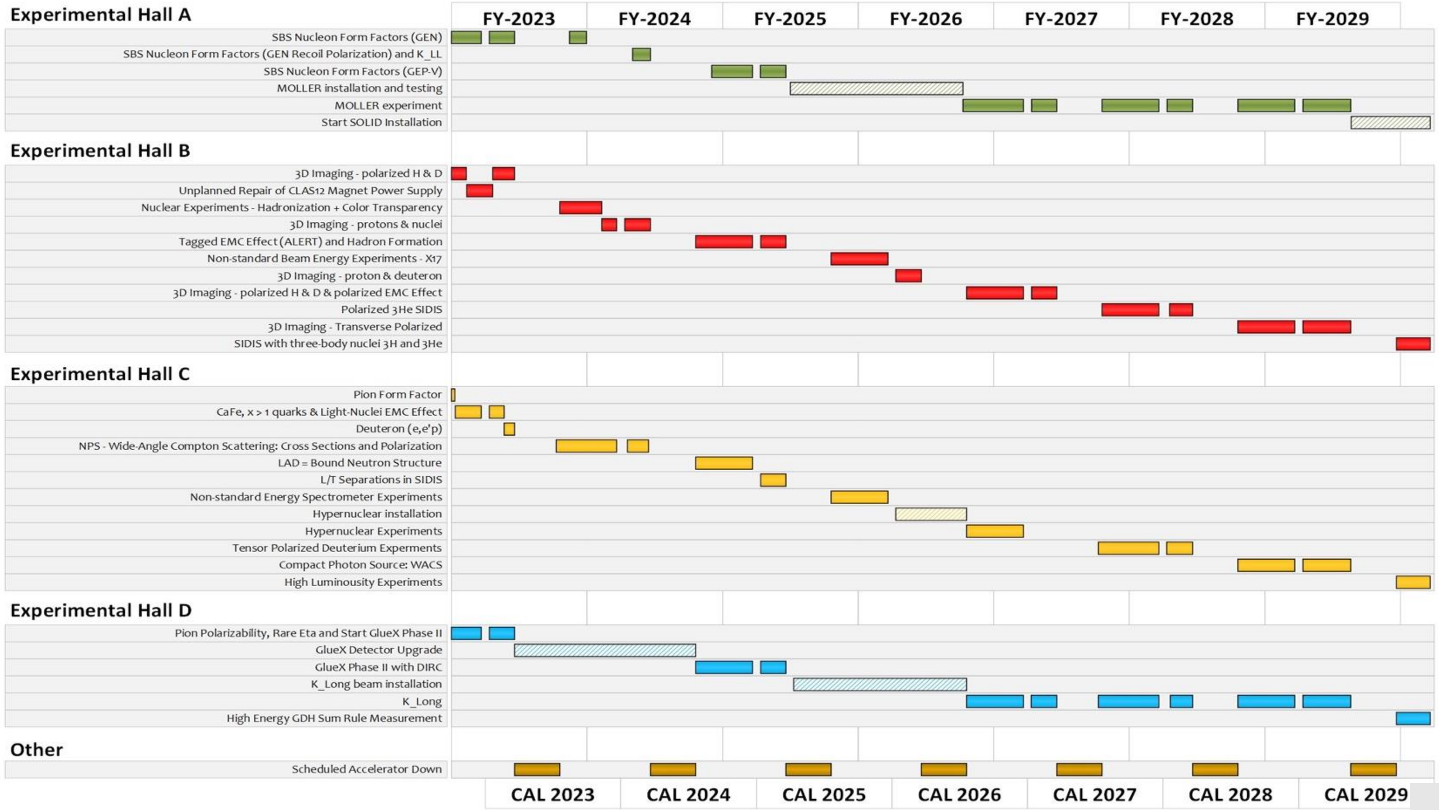


- ✦ 3D structure on resonances
- ✦ Access to *d*-quark content



The Experimental Program at a Glance

- 12 GeV scientific era is going strong
  - ~30 weeks operation in FY23 and FY24 (planned)
  - High-profile results emerging from 12 GeV program
- Scientific priority determined by the Program Advisory Committee
- Readiness determined by Division Readiness Review process
- Nuclear Physics Experimental Scheduling Committee optimizes running for scientific output

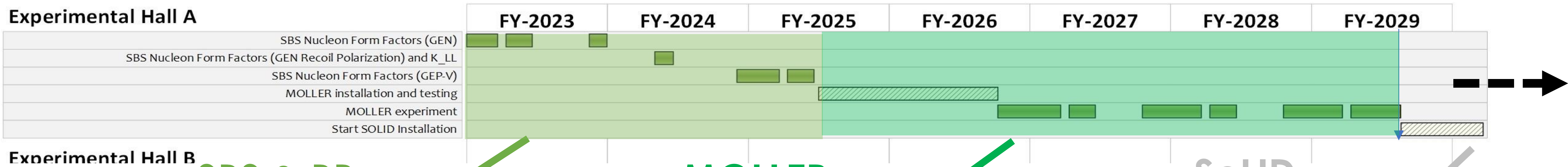


- 86% complete in FY29 without SoLID, 70% complete with SoLID (assuming optimal running operation)

...not including new proposals

- **> 2029**: we are exploring exciting scientific opportunities enabled by cost-effective and technically innovative CEBAF upgrade concept

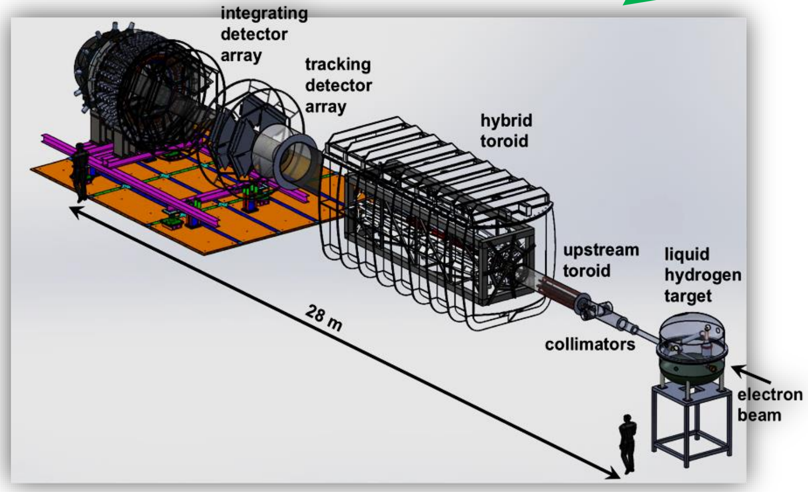
Hall A



SBS & BB

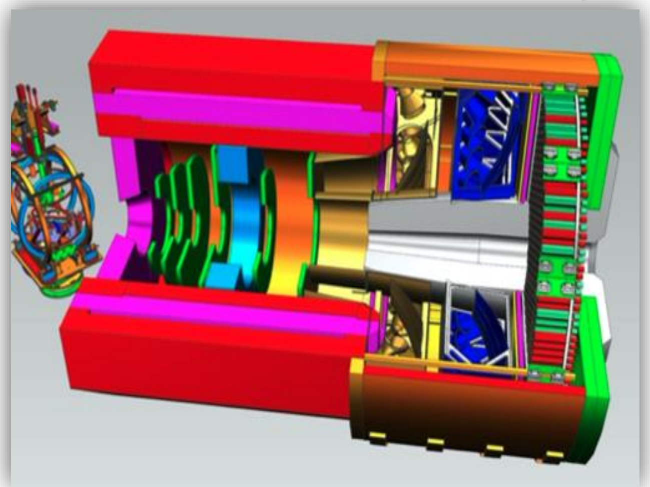
- Mapping the Nucleon Form Factors at high momentum transfer

MOLLER



- Precision measurement of the weak mixing angle off the Z-pole

SoLID



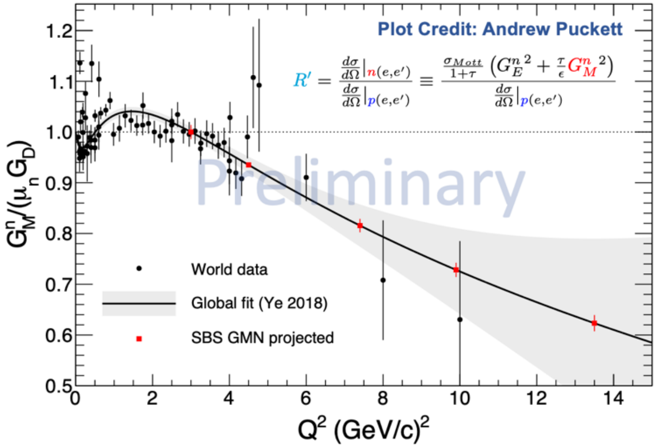
Large acceptance + high luminosity ($10^{37} – 10^{39}/cm^2/s$)

- 3D imagining of the nucleon
- PVDS Scattering to search for new interactions BSM
- J/Ψ production near threshold to study the gluonic component of QCD

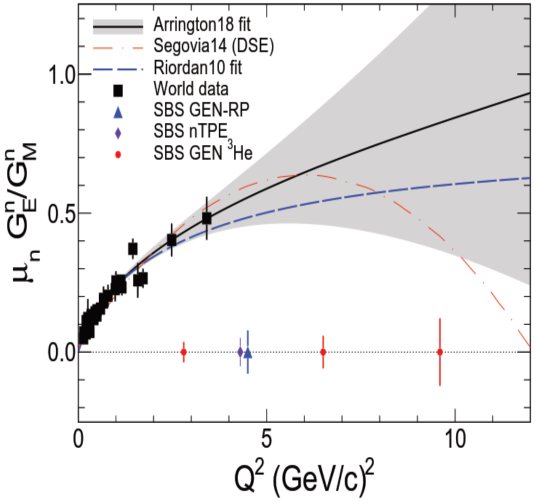
The ongoing SBS Nucleon Form Factor program

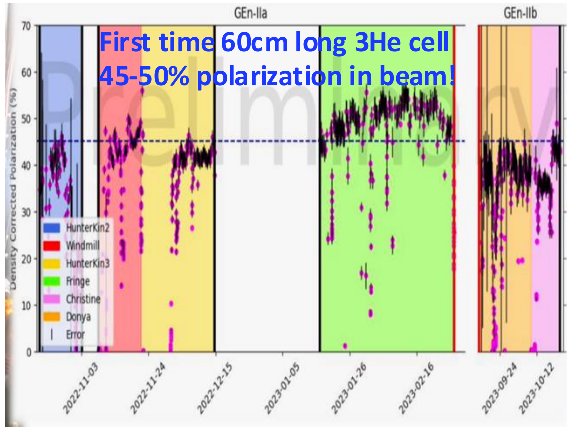
FFs: Fundamental quantities related to a two-dimensional view of the charge and magnetization distribution in the nucleon, essential in understanding the nucleon electromagnetic structure.

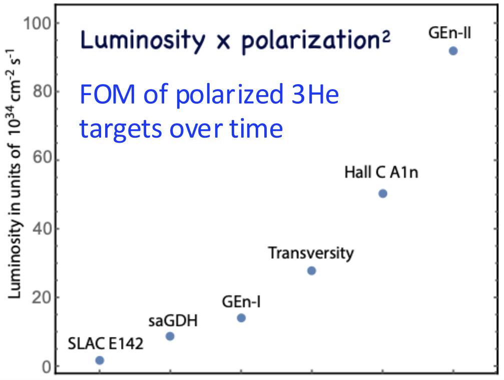
GMn/GMp (E12-09-019) - Q2 up to 13.5 GeV2.
COMPLETE!!! - **Oct. 2021 - Feb. 2022**



GEn/GMn (E12-09-016) - Q2 up to ~ 9.7 GeV2.
COMPLETE!!! - **Oct. 2022 - October 2023**

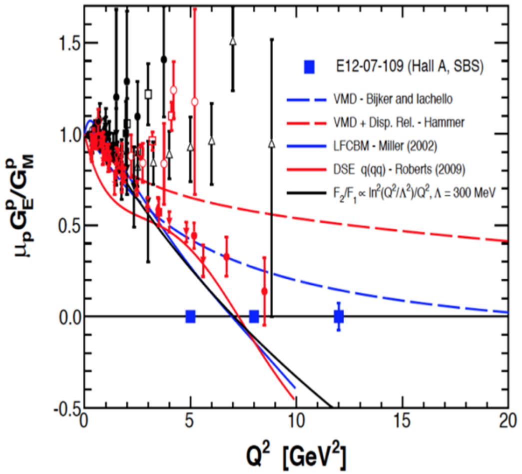




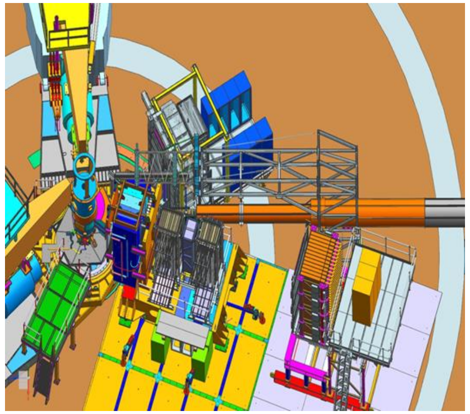


GEn-RP (E12-17-004) - Q2 ~ 4.5 GeV2 Expected start **April 2024**

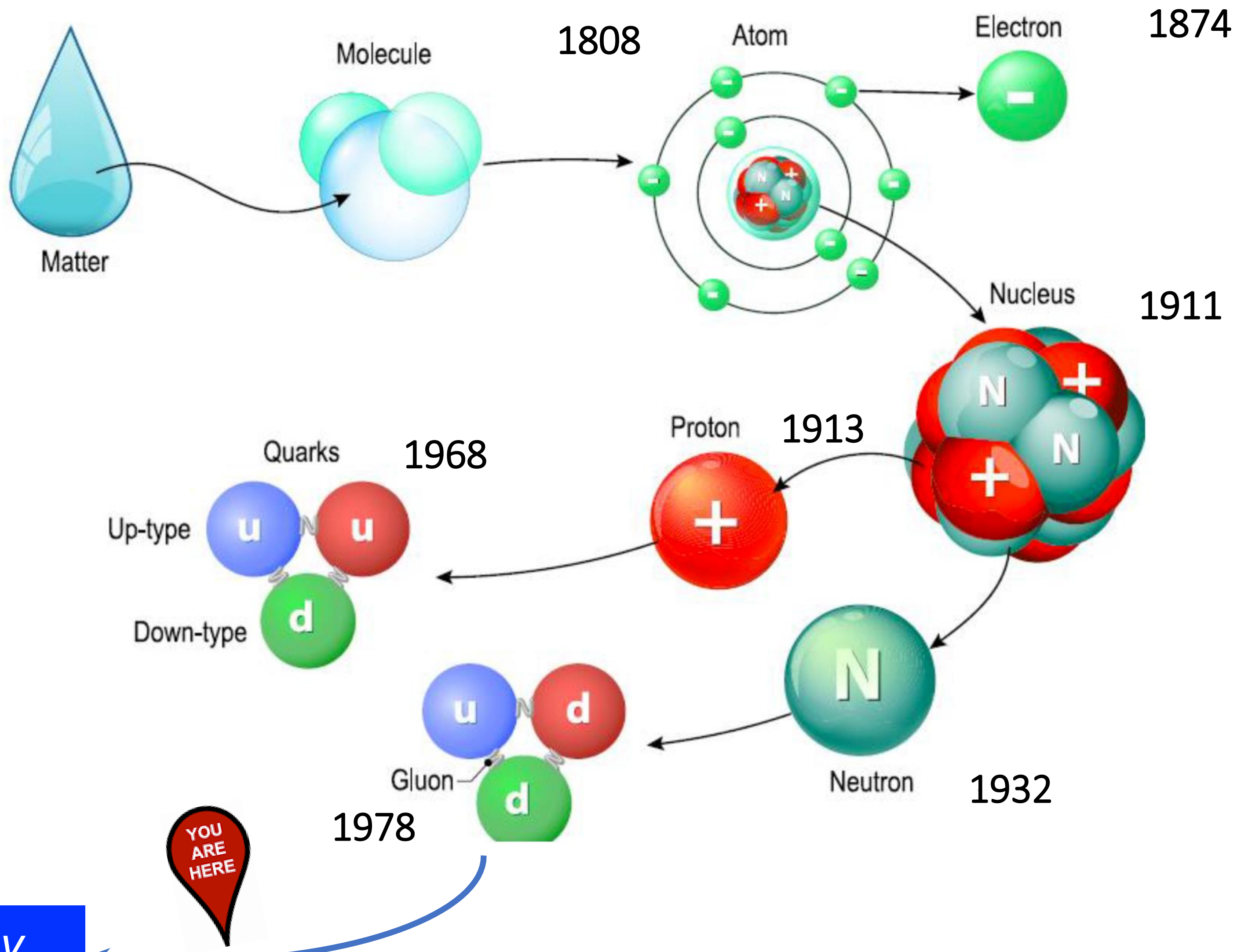
- Ratio GEn/GMn by the Double-polarized $^2\mathrm{H}(\vec{e},e'\vec{n})$tion
- Polarization Transfer in Wide-Angle Charged Pion Photoproduction (K_LL)



GEp/GMp (E12-07-109) - Q2 up to ~12 GeV2. Expected start **October 2024**

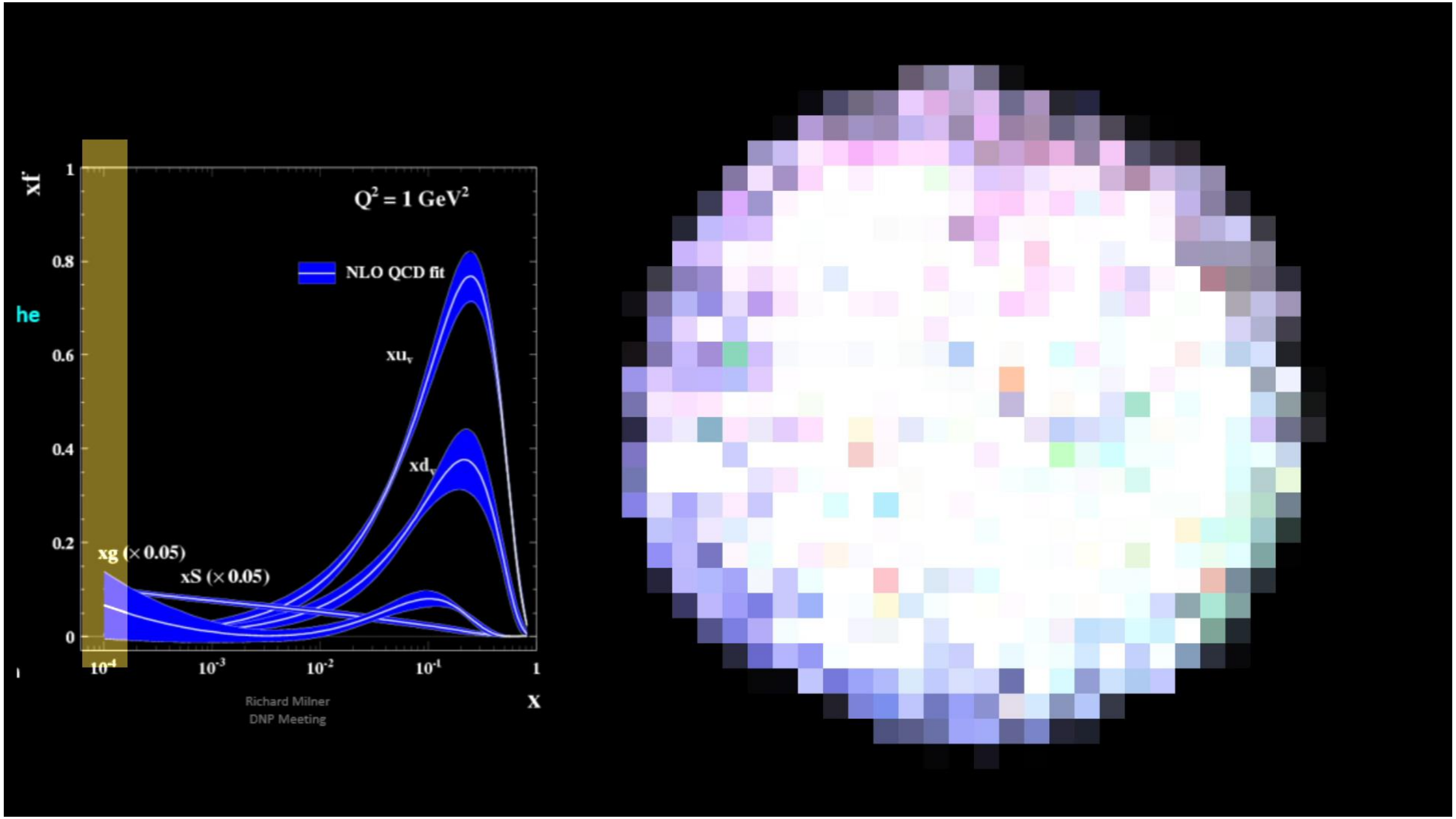


Fundamental structure of matter

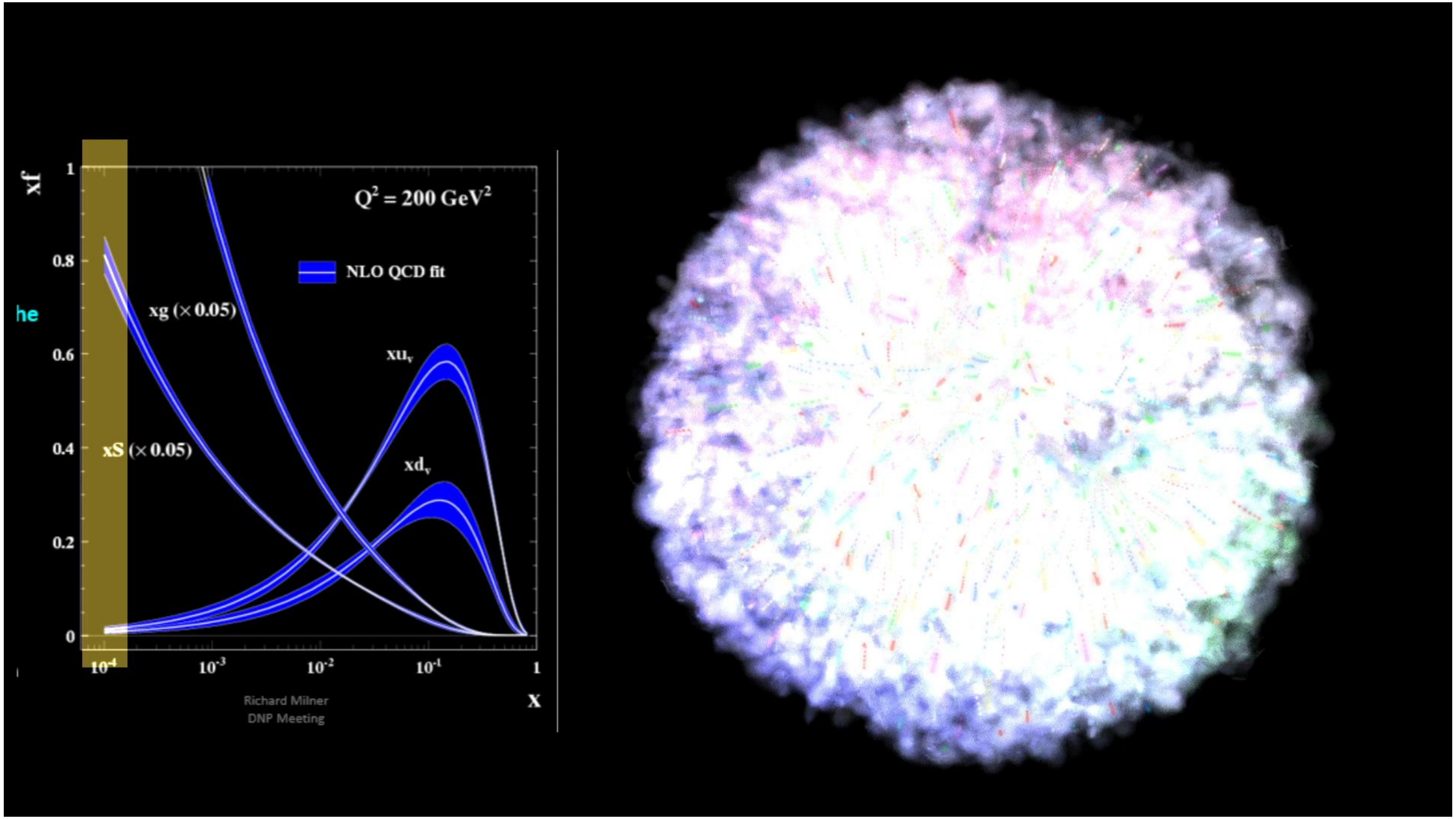


Nuclear Femtography

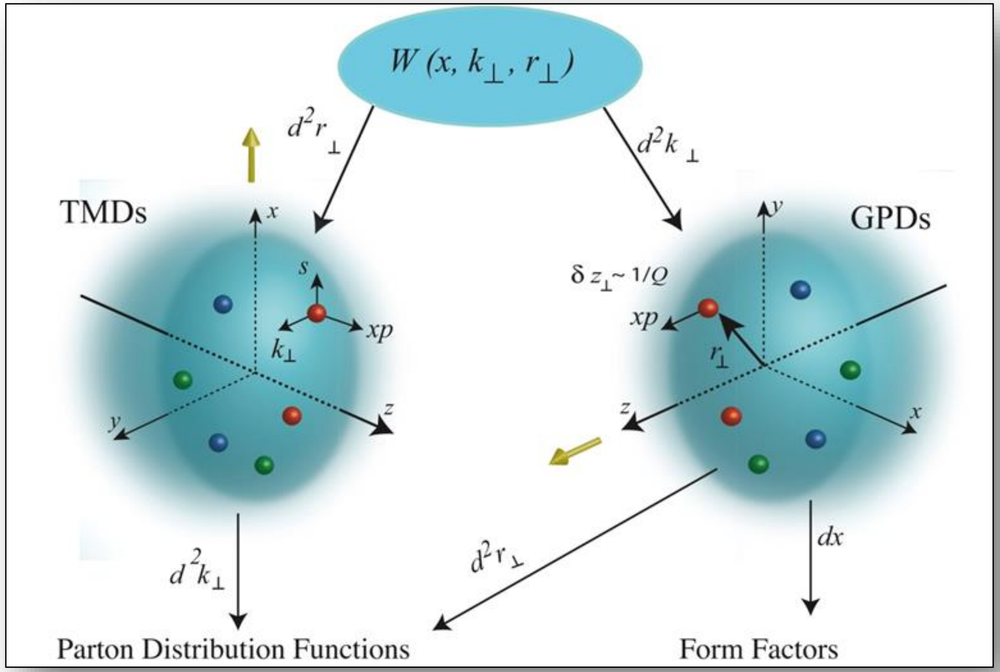
Moving past 1D longitudinal momentum

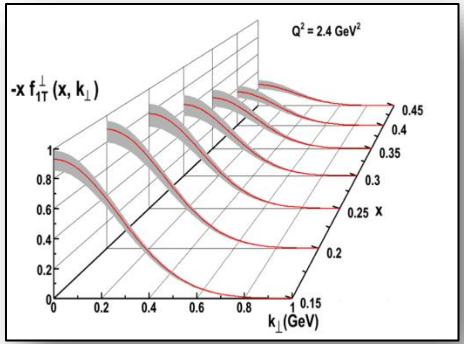


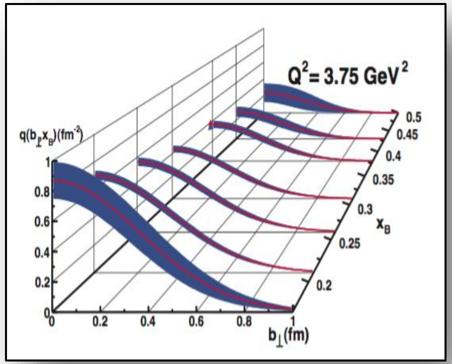
Moving past 1D longitudinal momentum



Moving past 1D longitudinal momentum

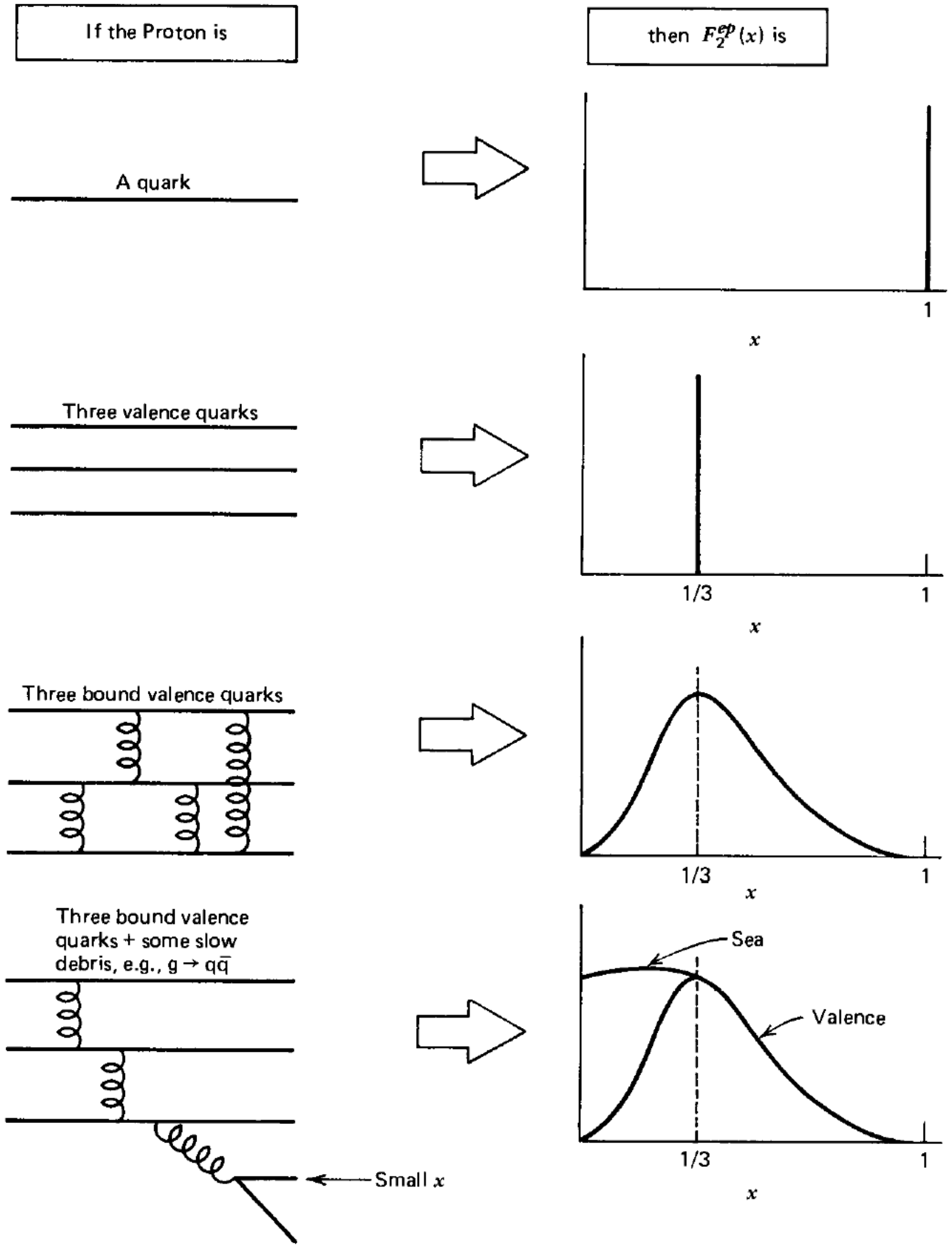




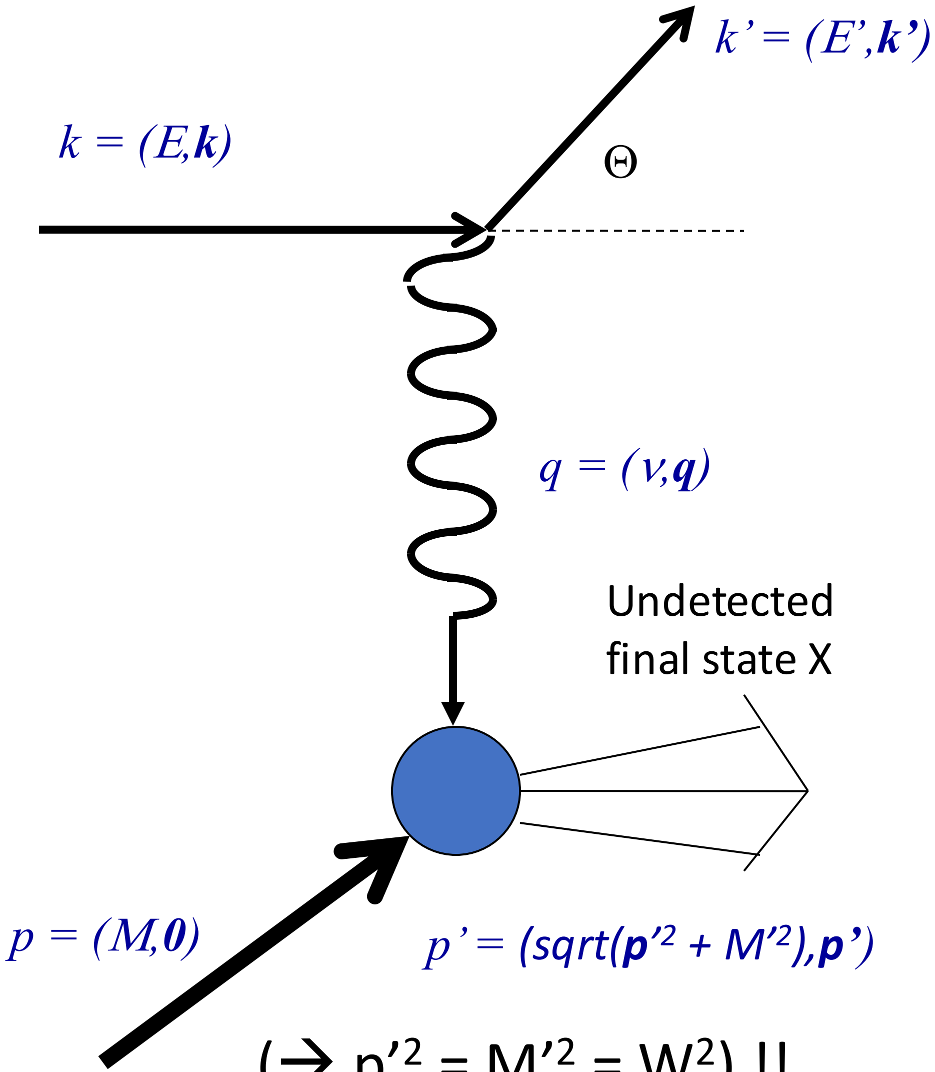


- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets
  - Sophisticated detector systems

Major new capability with JLab12 and EIC later on


If the Proton is
then $F_2^{ep}(x)$ is
A quark
1
x
Three valence quarks
1/3
1
x
Three bound valence quarks
1/3
1
x
Three bound valence quarks + some slow debris, e.g., g → q$\bar{q}$
Small x
Sea
Valence
1/3
1
x

Electron Scattering Kinematics



$(\rightarrow p'^2 = M'^2 = W^2)$!!

Virtual photon → off-mass shell

$q_\mu q^\mu = \nu^2 - \mathbf{q}^2 \neq 0$

Define **two invariants**:

1) $Q^2 = -q_\mu q^\mu \quad = -(k_\mu - k_\mu')(k^\mu - k'^\mu)$

$\quad = -2m_e^2 + 2k_\mu k'^\mu$

$(m_e \sim 0) \quad = 2k_\mu k'^\mu$

$(\text{LAB}) \quad = 2(EE' - \mathbf{k}.\mathbf{k'})$

$\quad = 2EE'(1-\cos(\Theta))$

$\quad = 4EE'\sin^2(\Theta/2)$

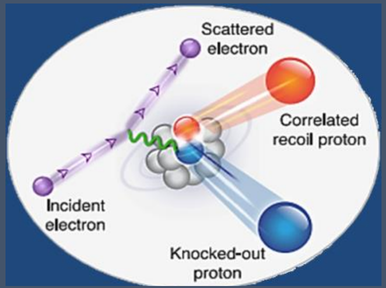
only assumption: neglecting m_e^2!!

2) $2M\nu = 2p_\mu q^\mu = Q^2 + W^2 - M^2$

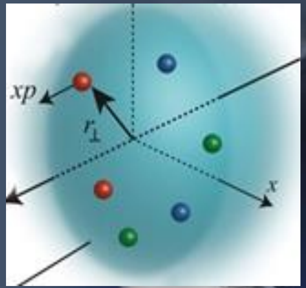
Elastic scattering

→ $W^2 = M^2$ → $Q^2 = 2M(E-E')$

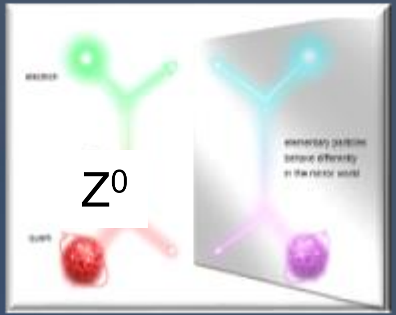
JLab: A Laboratory for Medium Energy Nuclear Science



Nuclear Structure



Structure of Hadrons



Fundamental Forces & Symmetries

Medical Imaging

Jefferson Lab is a state-of-the-art *user facility* for nuclear physics research and beyond.

Nuclear Astrophysics

Cryogenics

Accelerator S&T

Theory & Computation