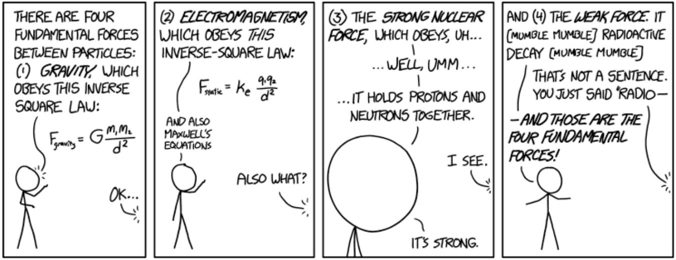
Hunting for Quarks

Jerry Gilfoyle for the CLAS Collaboration

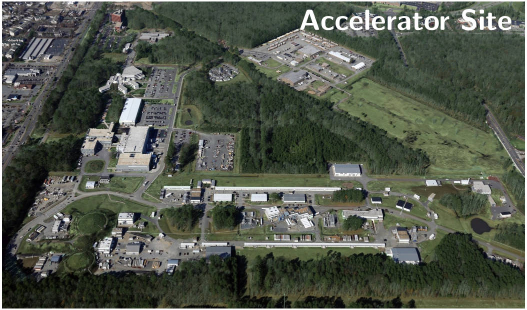
University of Richmond

1. Jefferson Lab's mission
2. What we know.
3. What we don't know.
4. What we measure.
5. What we'll learn.
6. How we do it.
7. Concluding remarks



What is the Mission of Jefferson Lab?

- Basic research into the quark nature of the atomic nucleus.
- Probe the quark-gluon structure of hadronic matter and how it evolves within nuclei.
- Test the theory of the color force Quantum Chromodynamics (QCD) and the nature of quark confinement.
- Completed doubling of beam energy and upgraded detectors in 2016.



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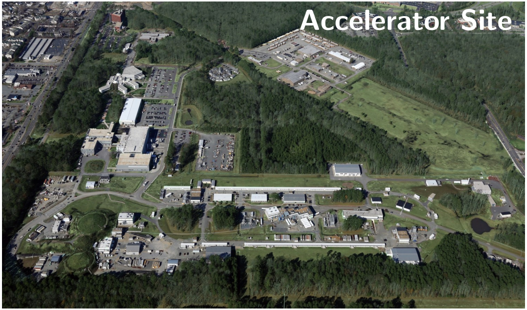


Solving QCD one of the six Millenium Prize Problems from the Clay Mathematics Institute.

What Do We Know?

- The Universe is made of quarks and leptons and the force carriers.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.39	−1
W$^+$ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

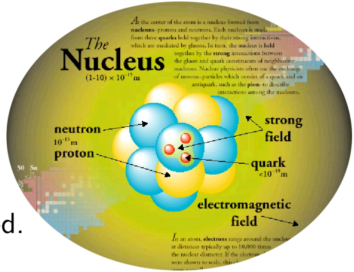
Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-2)\times10^{-9}$	0
e electron	0.000511	−1
ν_M middle neutrino*	$(0.009-2)\times10^{-9}$	0
μ muon	0.106	−1
ν_H heaviest neutrino*	$(0.05-2)\times10^{-9}$	0
τ tau	1.777	−1

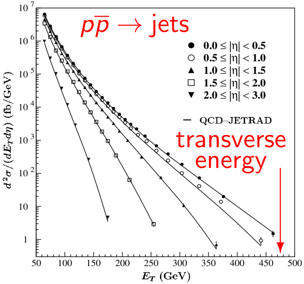
Quarks spin =1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	173	2/3
b bottom	4.2	−1/3

- The atomic nucleus is made of protons and neutrons bound by the strong force.
- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.



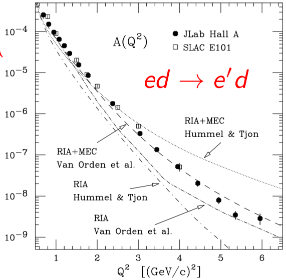
How Well Do We Know It?

- We have a working theory of strong interactions: quantum chromodynamics or QCD (B.Abbott, *et al.*, Phys. Rev. Lett., **86**, 1707 (2001)).



effective area

- The coherent hadronic model (the standard model of nuclear physics) works too (L.C.Alexa, *et al.*, Phys. Rev. Lett., **82**, 1374 (1999)).



4-momentum transfer squared

What Don't We Know?

- Matter comes in pairs of quarks or triplets.
- We are mostly triplets (protons and neutrons).
- More than 99% of our mass is in nucleons.
- Proton → 2 ups + 1 down.
- Neutron → 1 up + 2 downs.

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$$= 939\ MeV/c^2 \quad \text{OOOPS!!!????}$$

What We Measure

- High-energy electron beams are scattered off protons and/or nuclear targets - analogous to a ginormous electron microscope.
- The debris from the collisions is collected and analyzed to measure energy, momentum, *etc*.
- The pattern of the debris (angles, counts, energies) reveal the forces in action during the collision.
- At CEBAF energies the electrons are quantum mechanical waves probing deep inside the nuclei.
- Rigorously test QCD in the non-perturbative regime.

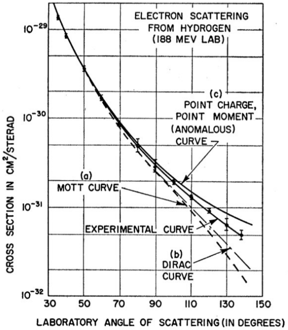

FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. The theoretical curves (b) and (c) are due to Rosenbluth.[8] The experimental curve falls between curves (b) and (c). This deviation from the theoretical curves represents the effect of a form factor for the proton and indicates structure within the proton, or alternatively, a breakdown of the Coulomb law. The best fit indicates a size of 0.70×10^{-13} cm.

McAllister and Hofstadter, PR 102, 851 (1956)

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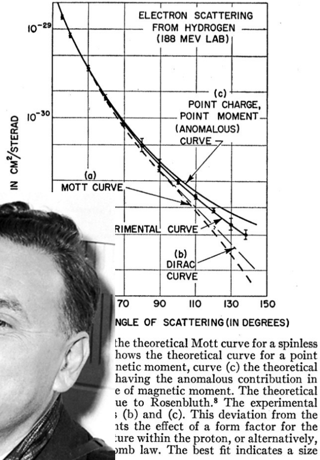

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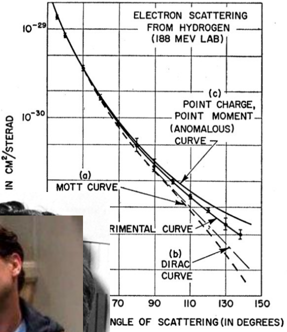

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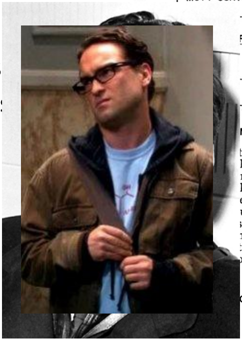

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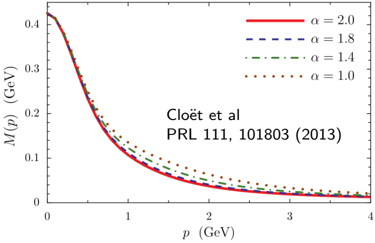
What We'll Learn

1. A wee bit of quantum mechanics.
   - Matter with momentum magnitude p can act like a wave with a wavelength λ defined by the deBroglie equation.

$$p = \frac{h}{\lambda} \quad \text{so} \quad \lambda = \frac{h}{p}$$

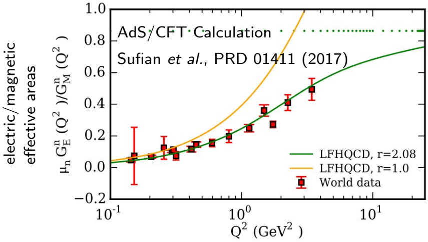
   - Lower momentum implies a larger wavelength. High momentum particles probe smaller regions of space.

2. Dyson-Schwinger Equations (DSE)
   - Equations of motion of quantum field theory.
   - Deep connection to confinement, dynamical chiral symmetry breaking.
   - Infinitely many equations, gauge dependent $\rightarrow$ Choose well!
   - DSE are a potential solution to QCD.



What We'll Learn

1. Anti-de Sitter space (AdS) describes spacetime with a negative curvature in Einstein's theory of General Relativity and can be formed from string theory.
2. Conformal field theory (CFT) is a quantum field theory (like QCD) invariant under conformal transformations. A conformal map is a function that locally preserves angles, but not necessarily lengths.
3. The CFT fields are strongly interacting - hard to solve.
4. The gravitational fields (AdS) are weakly interacting - more tractable.
5. AdS/CFT approach gives good agreement with existing form factor data.



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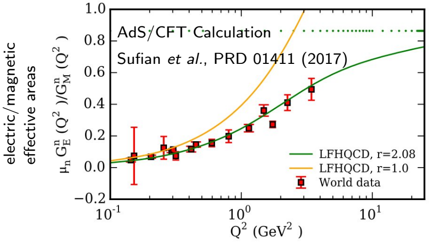

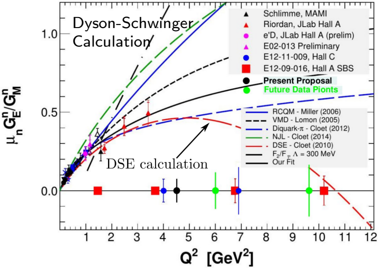

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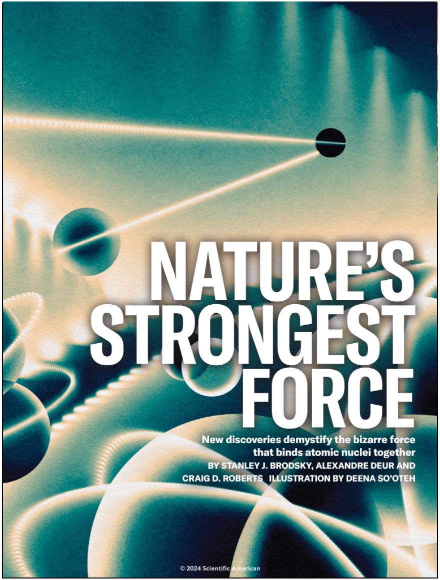
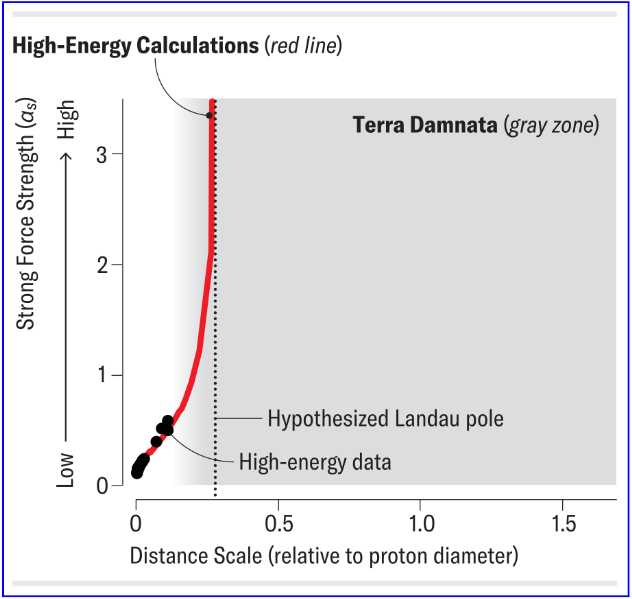


Coupling Constants of Fundamental Forces

Couplings		
Strong	α_S	1
Weak	α_W	10^{-6}
EM	α	$1/137$
Gravity	α_g	10^{-39}

- Coupling constants tell us the strength of a force compared with other forces.
- For example, The electromagnetic constant is $2\pi k_e e^2/(E_\gamma \lambda)$.
- The strong coupling constant α_S between quarks varies with distance - gets stronger with separation $\rightarrow$ confinement.
- At high energies QCD can be solved analytically using perturbation theory (Nobel Prize 2004).
- At moderate energies (≈ 1 GeV) that method fails - α_S goes to infinity.
- The AdS-CFT and DSE approaches have been brought into agreement.

What We'll Learn - Measured Couplings



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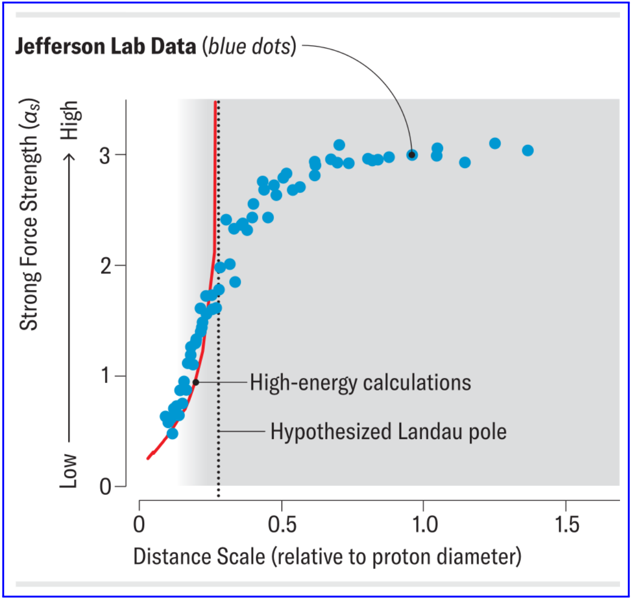

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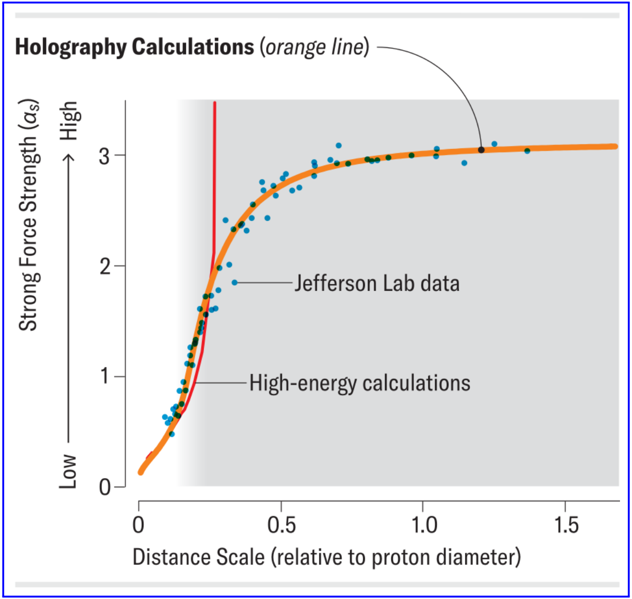

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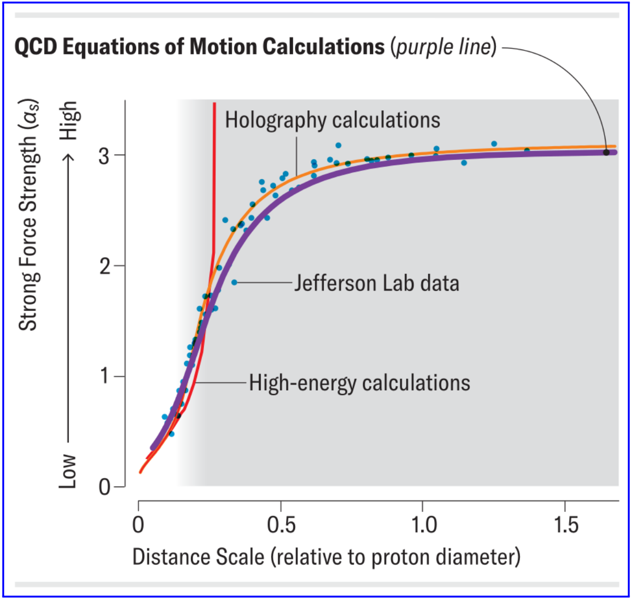
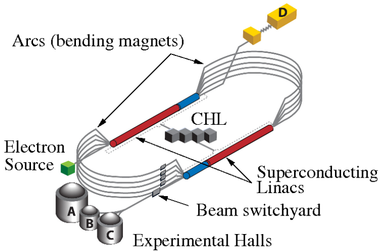


How Do We Do All This? (Step 1)

- Start at your local mile-long, high-precision, 12-GeV electron accelerator.
- The Continuous Electron Beam Accelerator Facility (CEBAF) produces beams of unrivaled quality.
- Electrons do up to five laps, are extracted, and sent to one of four experimental halls.
- Four halls can run simultaneously.



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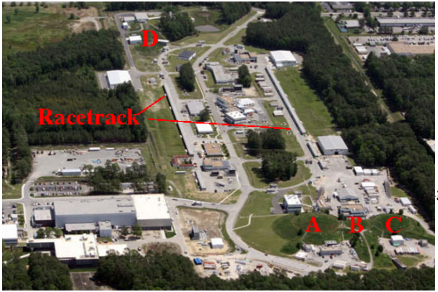

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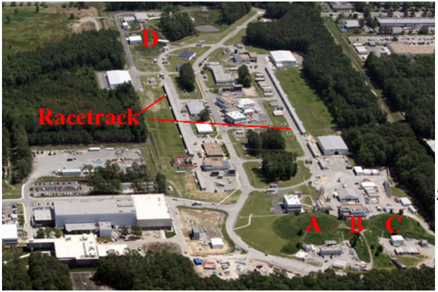

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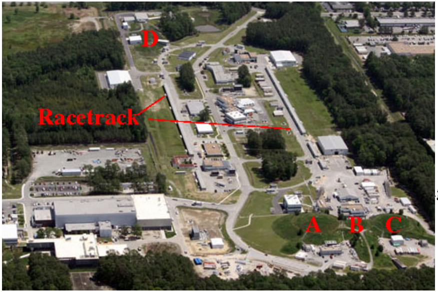
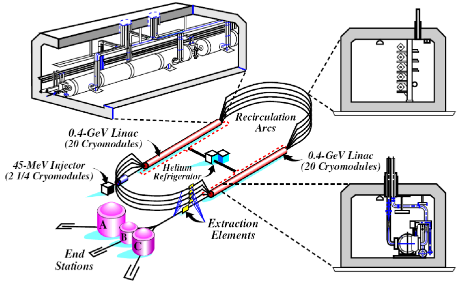
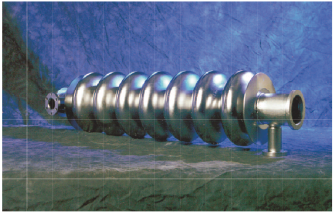


How Does CEBAF Do That?

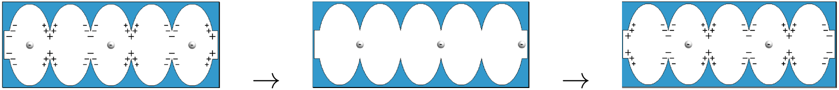
Accelerate your electrons to high energy.





Cavity

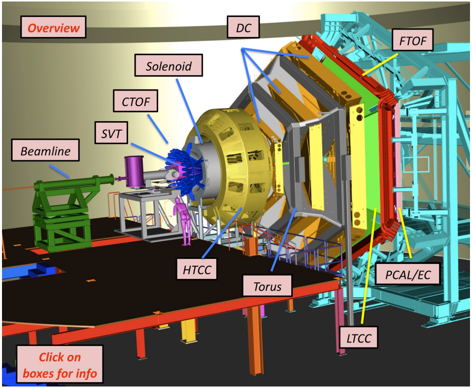
What happens inside the cavity? Feed it with oscillating, radio-frequency power at 1.5 GHz! In each hall beam buckets are about 200 picoseconds long and arrive every 2 nanoseconds.



A. → B. → C.

How Do We Measure the Nucleus? (Step 2)

- Add one 45-ton, $80-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS12).
- CLAS covers a large fraction of the total solid angle at forward angles.
- Has over 100,000 detecting elements in about 40 layers.



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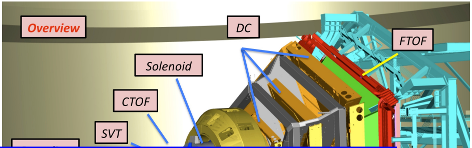

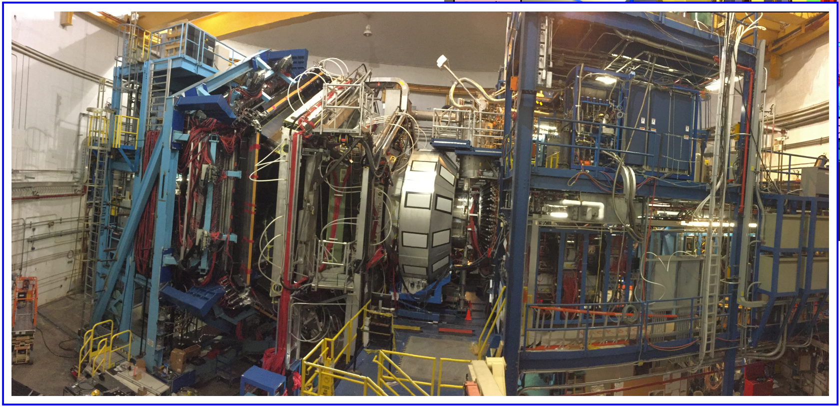

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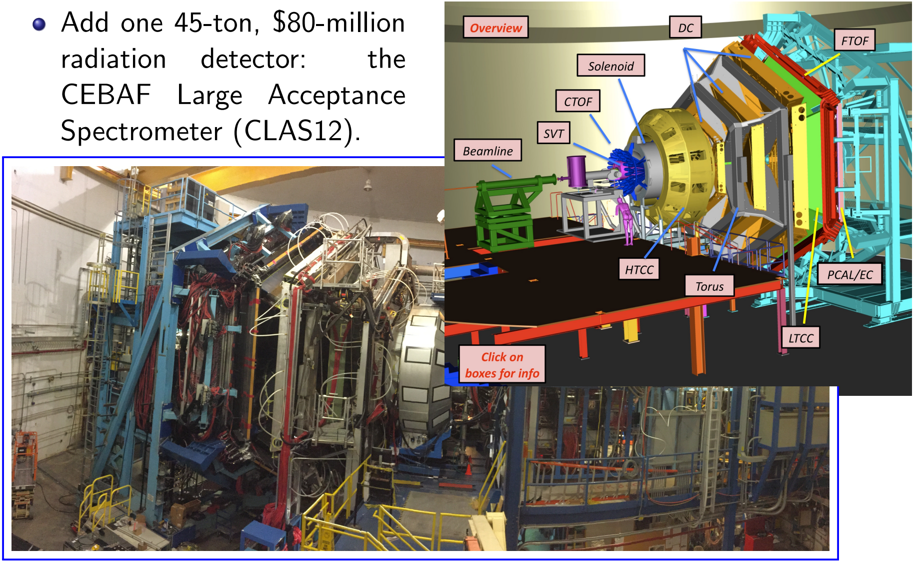
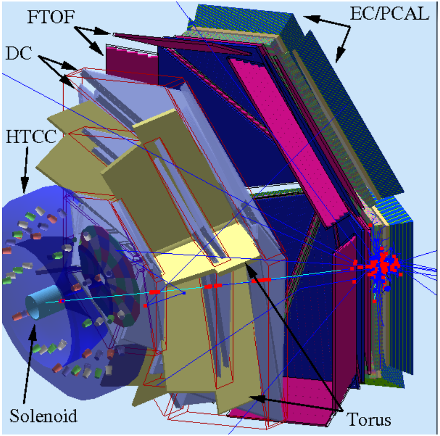
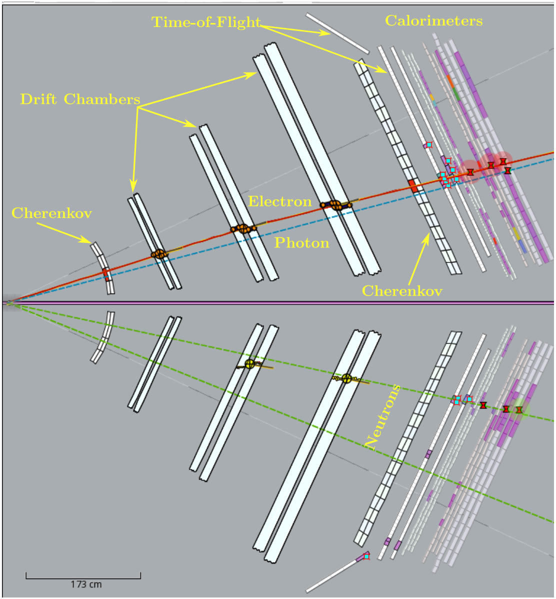


Particles leave 'bread crumbs' behind (Step 3)

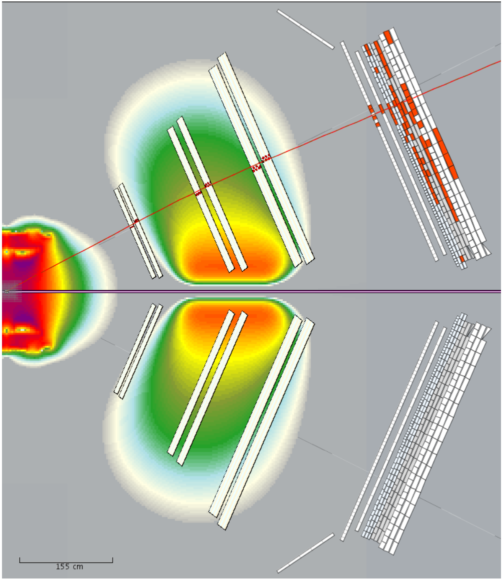
- Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.
- Scatter electrons off protons and deuterons (proton+neutron).



A CLAS12 Event



A CLAS12 Event - Drift Chamber close-up



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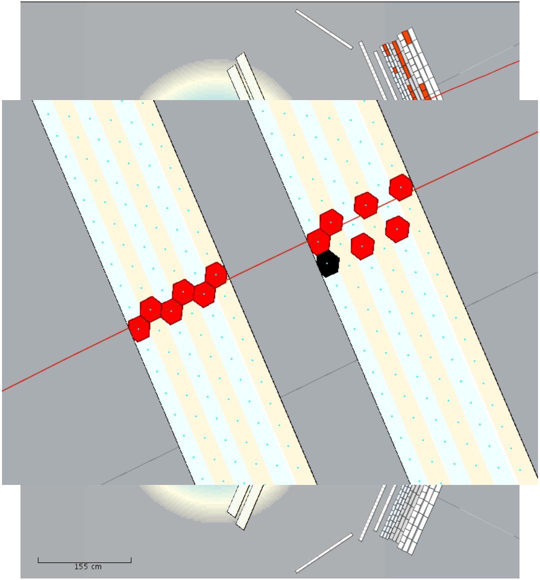
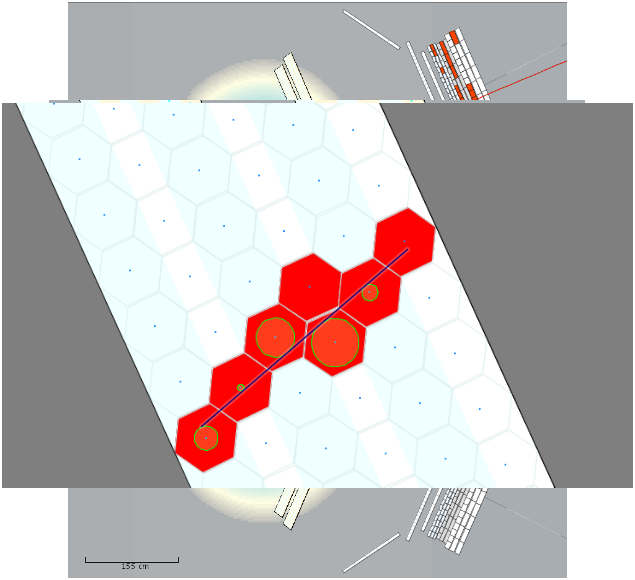
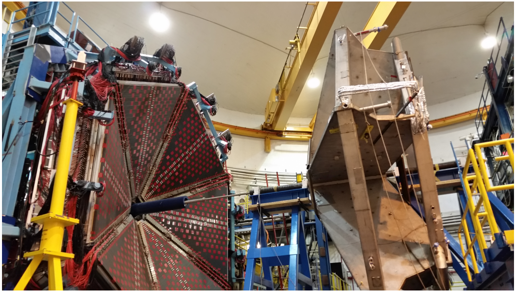


A CLAS12 Event - Drift Chamber close-up



A Real CLAS12 Event - Building the Drift Chambers



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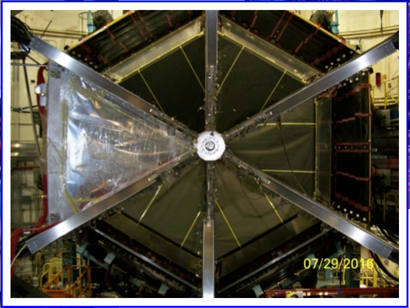
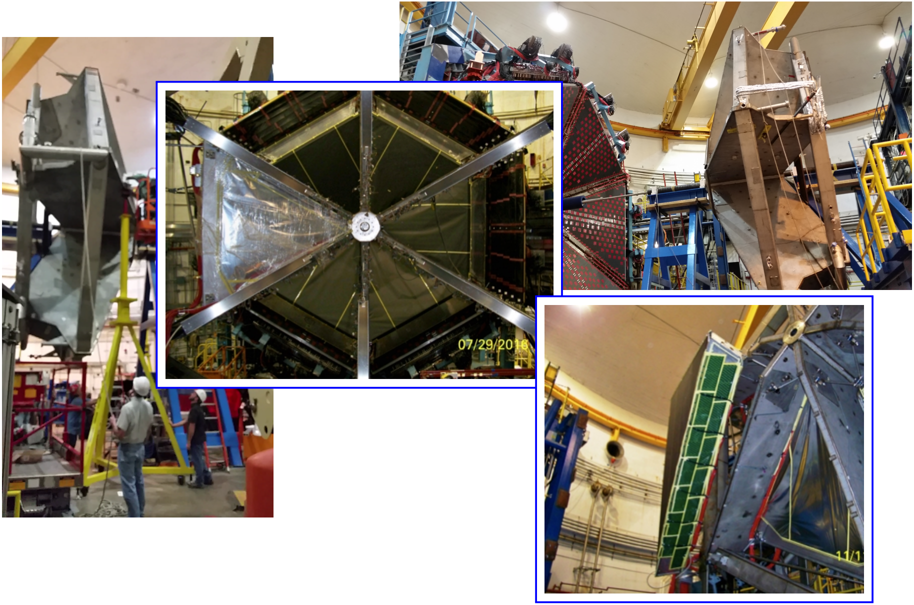
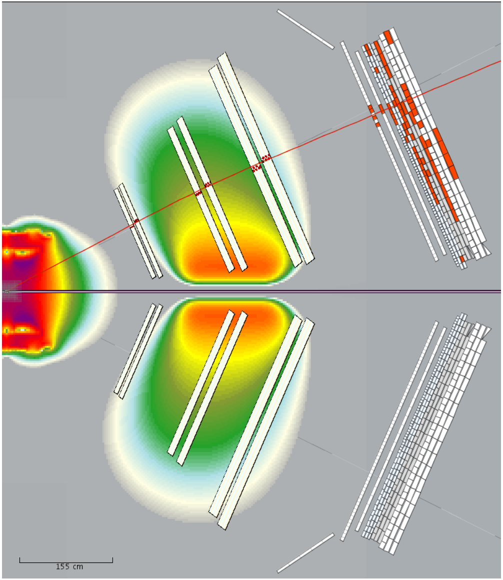


A Real CLAS12 Event - Building the Drift Chambers



A CLAS12 Event - Calorimeter close-up



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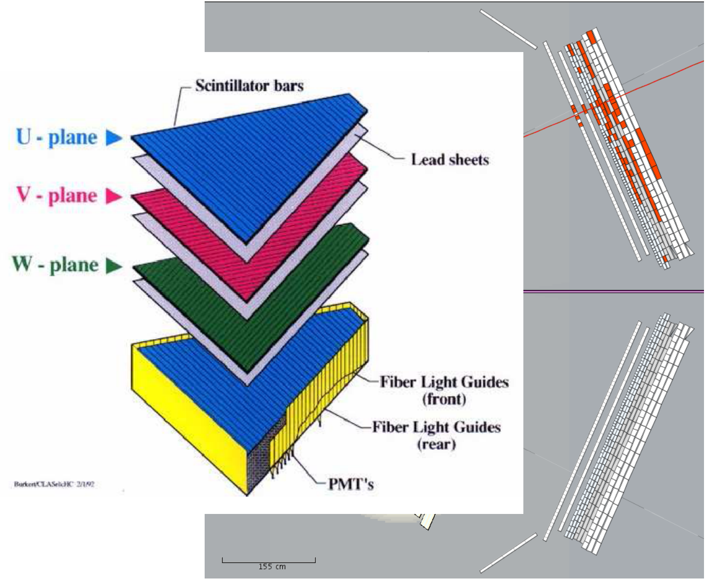
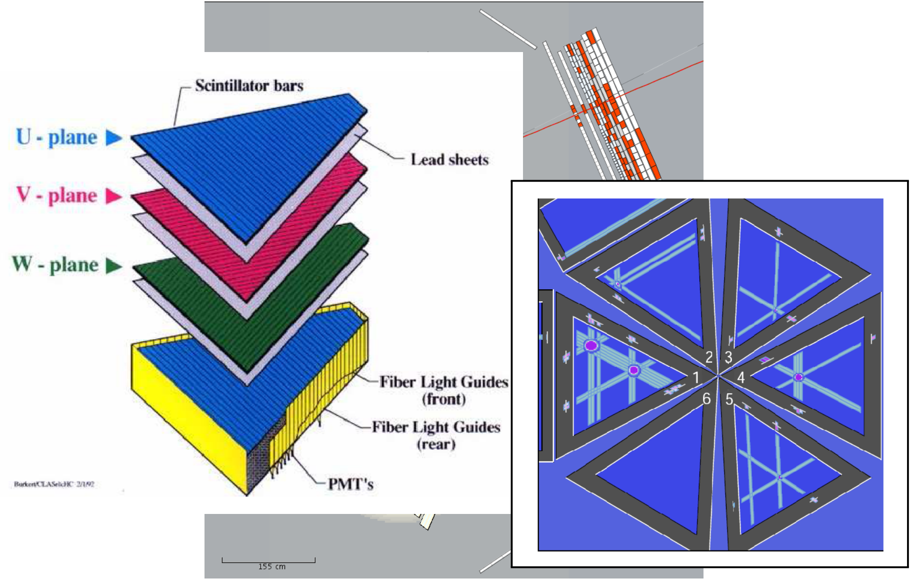
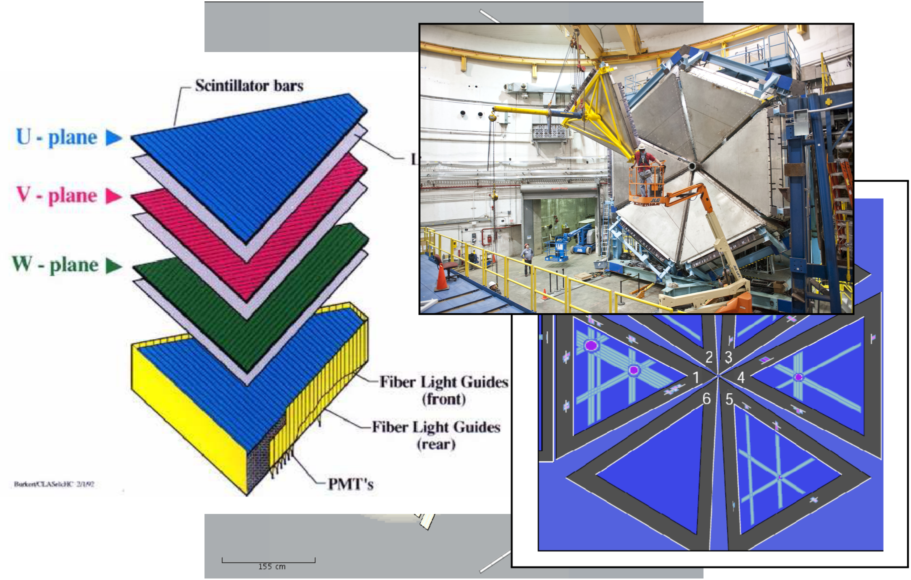


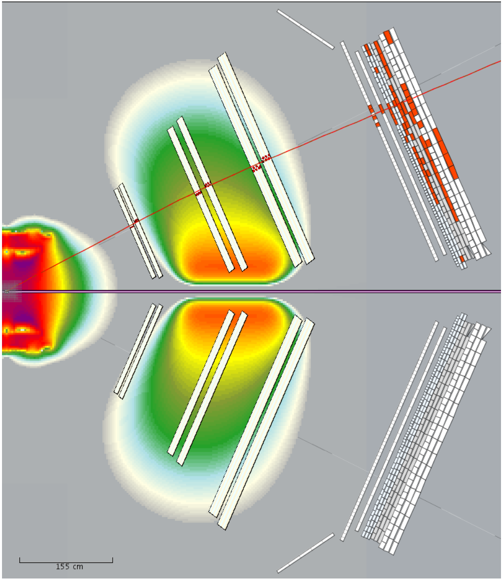
A CLAS12 Event - Calorimeter close-up



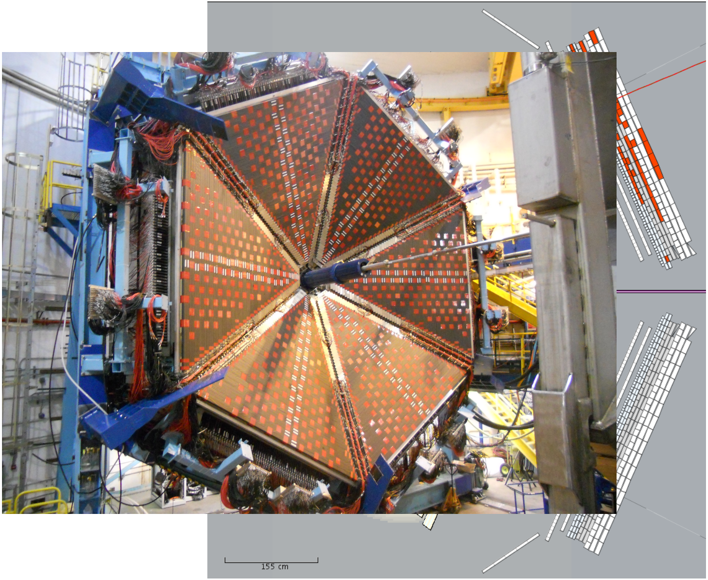
A CLAS12 Event - Calorimeter close-up



A CLAS12 Event - Time-of-Flight close-up



A CLAS12 Event - Time-of-Flight close-up



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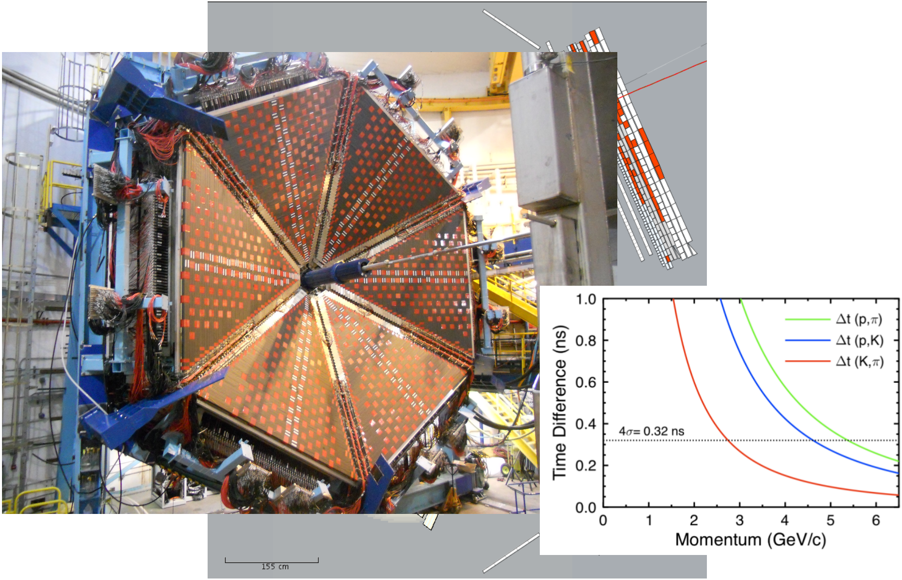
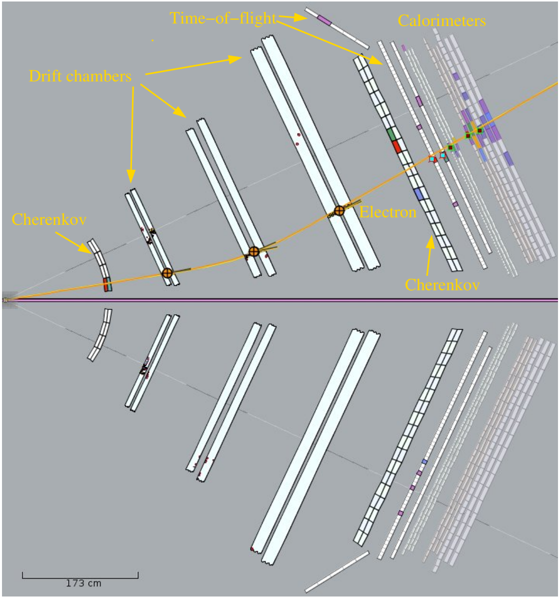
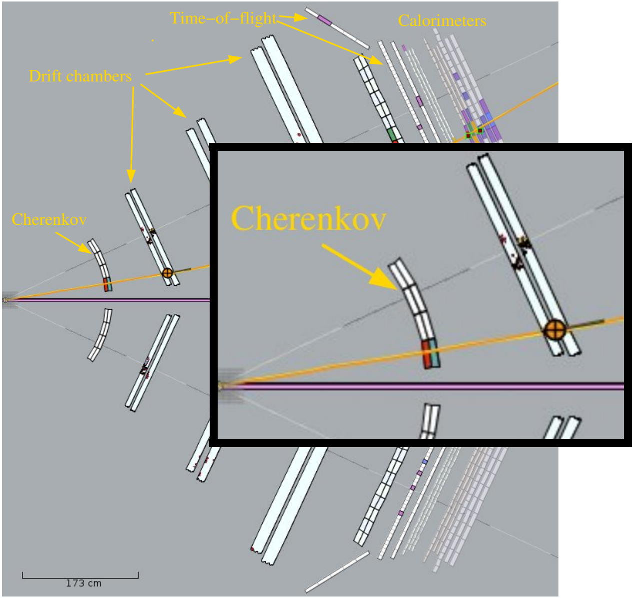


A CLAS12 Event



A CLAS12 Event - Cherenkov close-up



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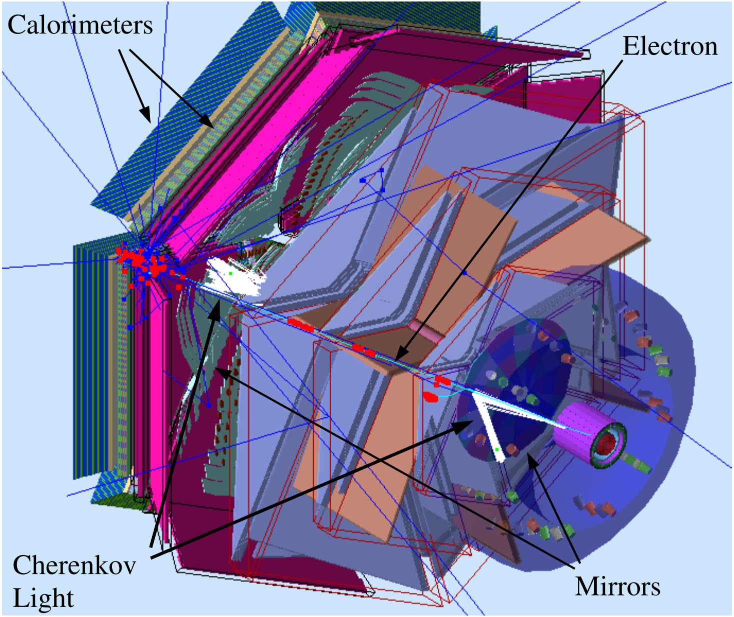

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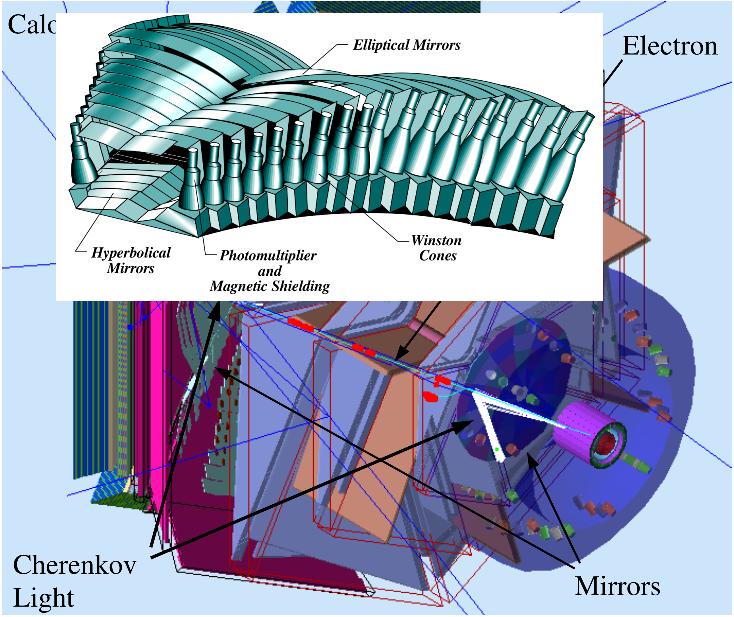

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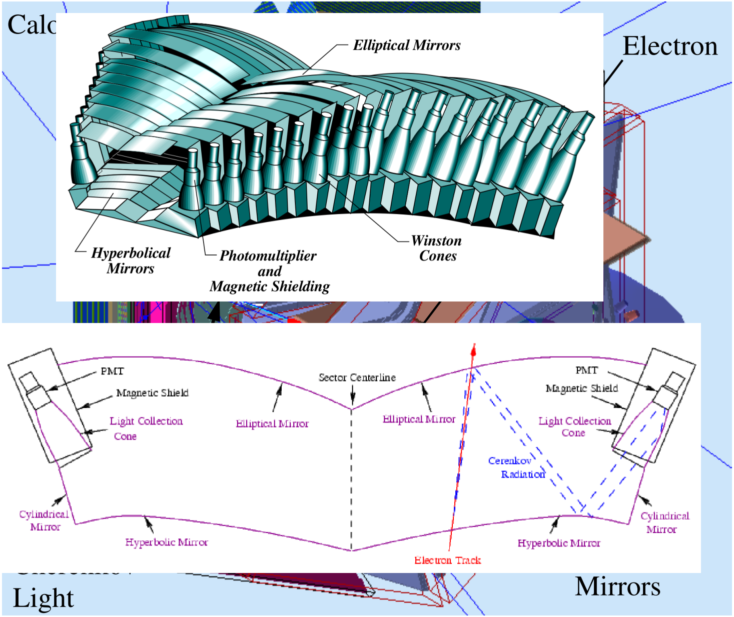
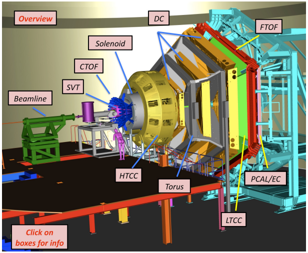


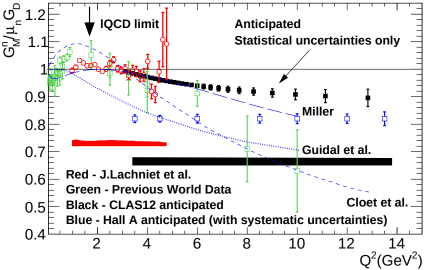
Bring the bread crumbs together (Step 4)

- E12-07-104 in Hall B (Gilfoyle, Hafidi, Brooks).
- Ratio Method on Deuterium:

$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]}$$
$$= a \times \frac{\sigma_{Mott}\left(\frac{(G_E^n)^2+\tau(G_M^n)^2}{1+\tau}+2\tau\tan^2\frac{\theta_e}{2}(G_M^n)^2\right)}{\frac{d\sigma}{d\Omega}[^1\mathrm{H}(e,e')p]}$$

  where a is nuclear correction.
- Precise neutron detection efficiency needed to keep systematics low.
  - tagged neutrons from $^2\mathrm{H}(e,e'pn)$.
  - LH_2 target.
- Kinematics: $\mathrm{Q}^2 = 3.5 - 13.0\ (\mathrm{GeV/c})^2$.
- Beamtime: 40 days.
- Systematic uncertainties $<$ 2.5% across full Q^2 range.
- Half of Run Group B done January, 2020.

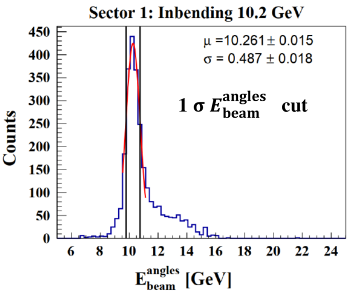


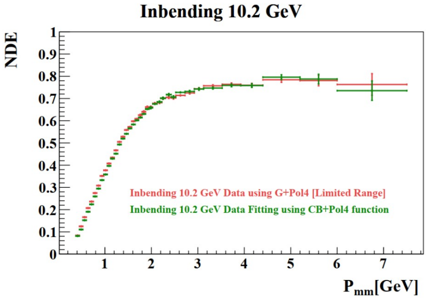


Do the hard work (Step 5)

- Quasi-elastic event selection: Apply a cut on the beam energy calculated from the $e-p$ angles. Apply a second cut on θ_{pq} cut to eliminate inelastic events.

- Use the $ep \to e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.





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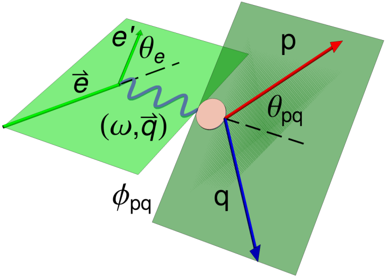
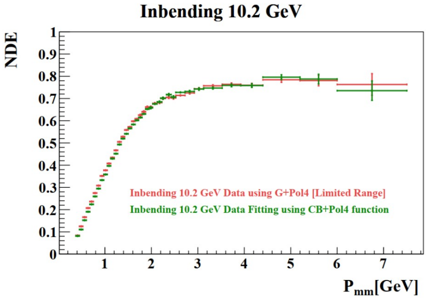


- Use the $ep \to e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.



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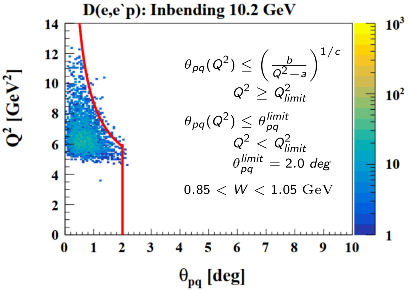
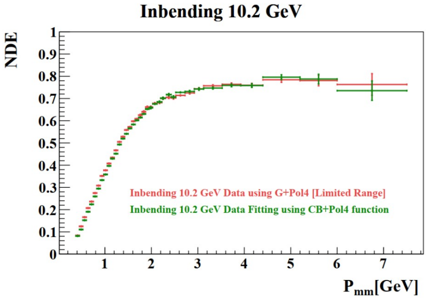


- Use the $ep \rightarrow e'\pi^+ n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.



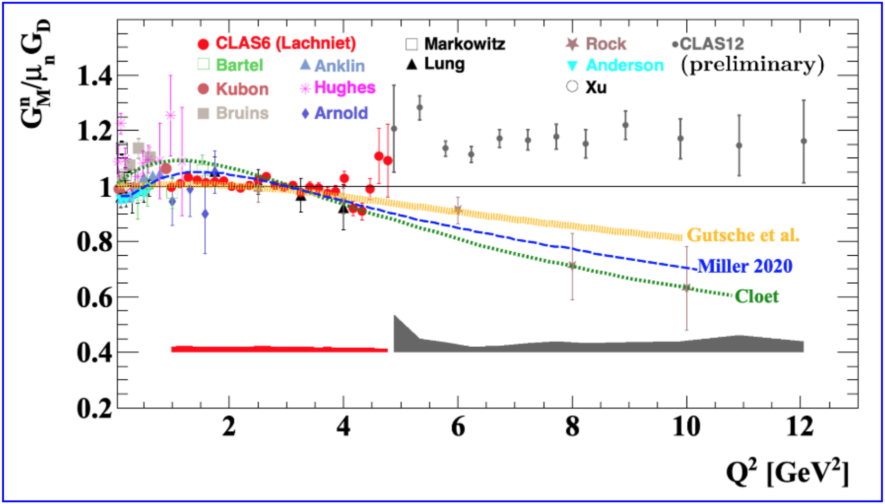
Use the machines (Step 6)

Analyzing the data - Scientific computing at Jefferson Lab is large. The Computer Center must keep up with calibration and reconstruction of a data flow that can reach over 30 terabytes per day (that's 30,000 gigabytes). To do that requires extensive computing facilities.

That experience has lead JLab to the leadership of a US Department of Energy project to build a new High Performance Data Facility Hub (HPDF). It will provide transformational capabilities for data analysis, networking and storage for the nation's research enterprise. The HPDF will cost $300-500 million.

The 10g cluster - one of an array of high performance computing systems.

Preliminary Results



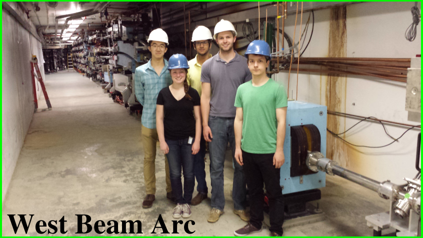
Concluding Remarks

- JLab is a laboratory to test and expand our understanding of quark and nuclear matter, QCD, and the Standard Model.
- We continue the quest to unravel the nature of matter at greater and greater depths.
- Lots of new and exciting results are coming out.
- A bright future lies ahead.

U. S. Department of Energy's

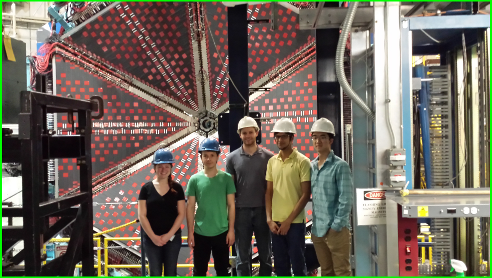
Jefferson Lab

THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

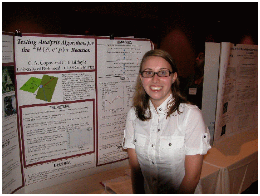


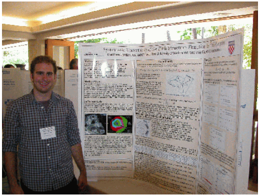
Students from Richmond (and one from Surrey) visit JLab

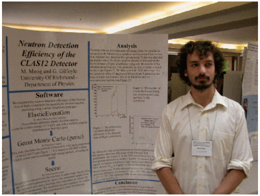
CLAS12 detector



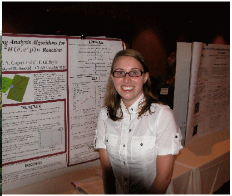
Life on the Frontiers of Knowledge

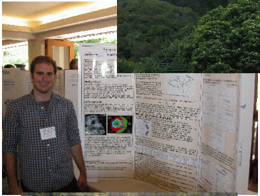


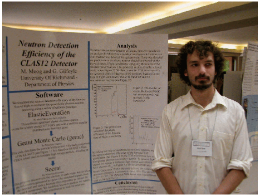


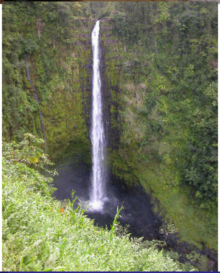


Life on the Frontiers of Knowledge



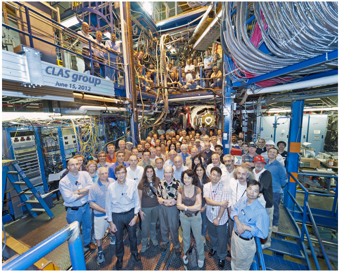




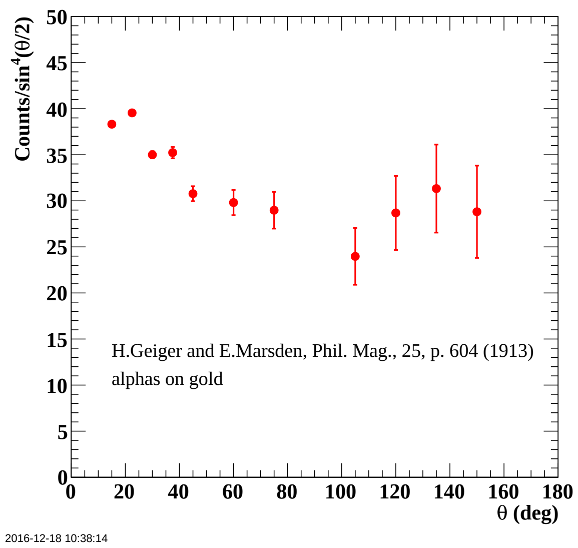


Some Facts of Life On The Frontier

- Work at Jefferson Lab in Newport News.
  - 700 physicists, engineers, technicians, and staff.
  - Vibrant intellectual environment - talks, visitors, educational programs...
  - Lots going on.
- Richmond group part of CLAS Collaboration.
  - operates CLAS12.
  - ∼190 physicists, 40 institutions, 13 countries.
  - Part of Software Group - emphasis on software development.
  - Past Surrey masters students (and Richmond undergrads) have presented posters at meetings, appeared on JLab publications,....
- Run-Group B consists of seven experiments (including G_M^n) and ran in spring 2019.



Rutherford Scattering Results From Rutherford



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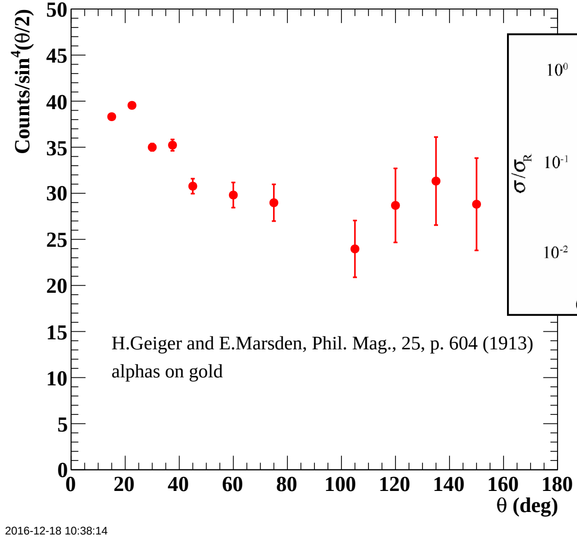

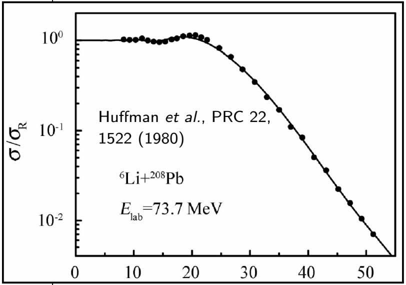

Standard Model