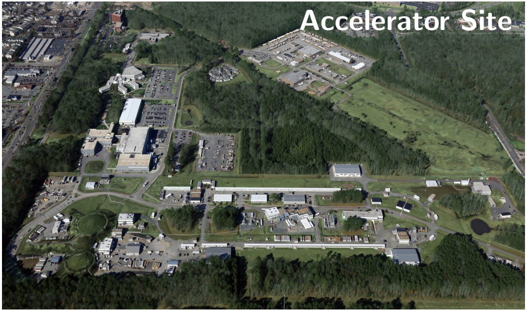
Hunting for Quarks

"The Periodic Table"

- Jefferson Lab's Mission
- What we know.
- What we don't know.
- What we measure.
- Experiments with CLAS12
- 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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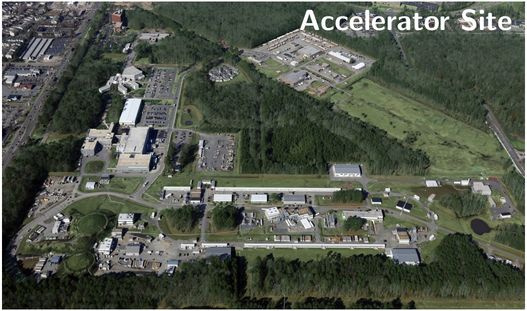


Solving QCD one of the seven Millenium Prize Problems from the Clay Mathematics Institute.

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

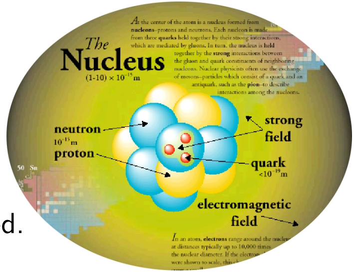
Higgs Boson spin = 0		
Name	Mass GeV/c^2	Electric charge
H Higgs	126	0

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

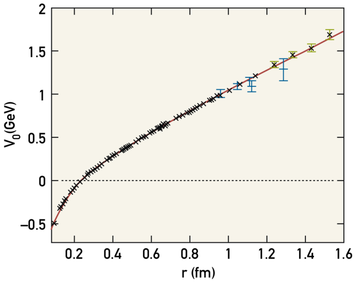
Quarks spin =1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

- 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.



What is the Force?

- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.



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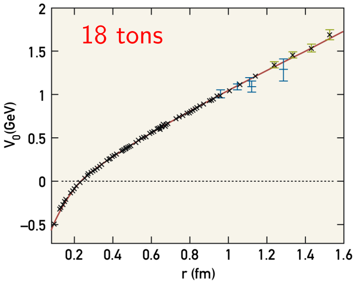

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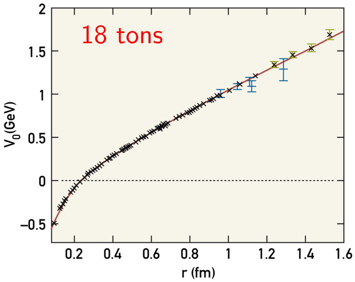
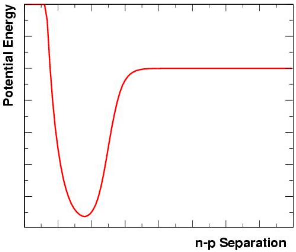
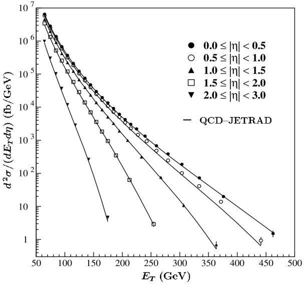


- The hadronic model uses a phenomenological force fitted to data at low energy. This 'strong' force is the residual force between quarks.

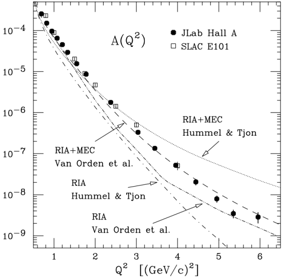


How Well Do We Know It?

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



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



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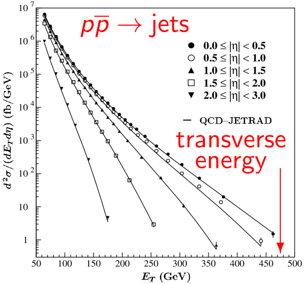

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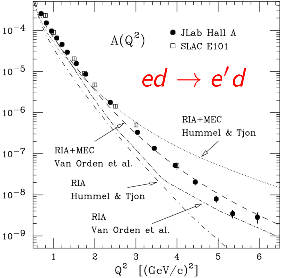

4-momentum transfer squared

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 $\rightarrow$ 2 ups + 1 down.
- Neutron $\rightarrow$ 1 up + 2 downs.

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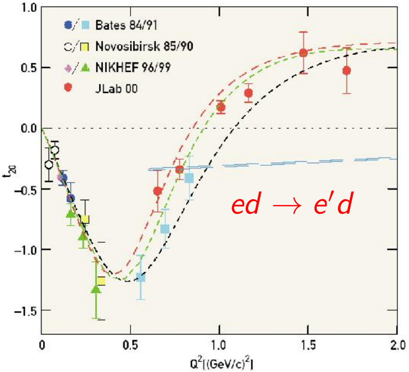
- $m_n - m_p = 1.29333205(48)\ MeV/c^2$ (exp) $= 1.51(16)(23)\ MeV/c^2$ (th)

Sz. Borsanyi et al. *Science* 347, 1452 (2015).

What Don't We Know?

1. We can't get QCD and the hadronic model to line up - D. Abbott, *et al.*, Phys. Rev Lett. **84**, 5053 (2000).

2. NEED TO FIGURE OUT QCD AT THE ENERGIES OF NUCLEI!!



What Do We Measure?

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The Magnetic Form Factor of the Neutron (G_M^n)

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- Fundamental quantity related to the distribution of magnetization/currents in the neutron.
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors (G_M^n, G_E^n, G_M^p, and G_E^p) provide key constraints on theory and the structure of hadrons.
- Part of a broad effort to understand how nucleons are 'constructed from the quarks and gluons of QCD'.*

* 'Reaching For the Horizon: The 2015 Long Range Plan for Nuclear Science', NSF/DOE Nuclear Science Advisory Committee.

How Do We Learn What's Inside the Nucleon?

- Nucleon elastic electromagnetic form factors (EEFFs) describe the distribution of charge and magnetization in the nucleon.
- They encode the deviations from point-particle behavior.
- Reveal the internal quark-gluon landscape of the nucleon and nuclei.
- We are in the region where the quarks get dressed.
- Rigorously test QCD in the non-perturbative regime.
- Jargon: G_E^p, G_M^p, G_E^n, G_M^n.

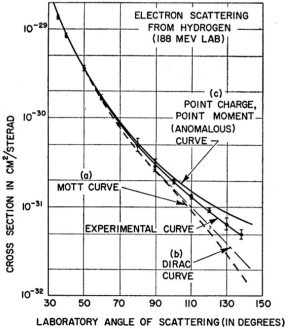

FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. 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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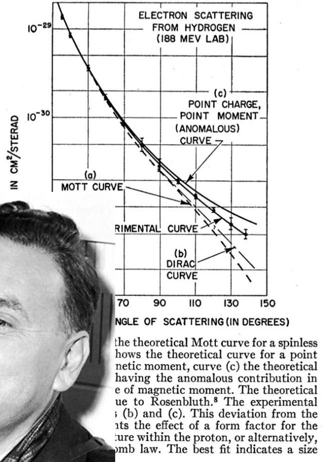

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Robert Hofstadter, Nobel Prize 1961

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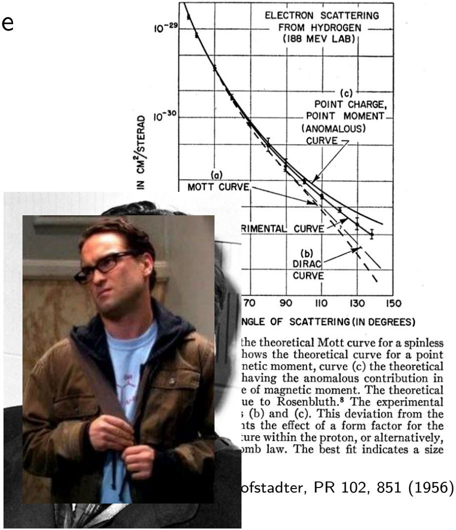

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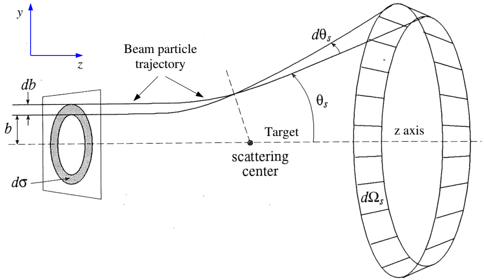
What is a Form Factor?

- Start with the cross section.

$$\frac{d\sigma}{d\Omega} = \frac{\text{scattered rate/solid angle}}{\text{incident rate/surface area}}$$

- For elastic scattering use the Rutherford cross section.

$$\frac{d\sigma}{d\Omega} = \frac{Z_{tgt}^2 Z_{beam}^2 \alpha^2 (\hbar c)^2}{16E^2 \sin^4(\theta/2)}$$



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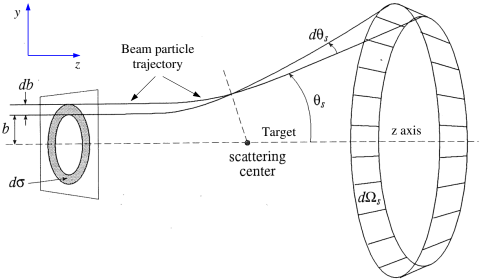

- Cross section for elastic scattering by point particles with spin.

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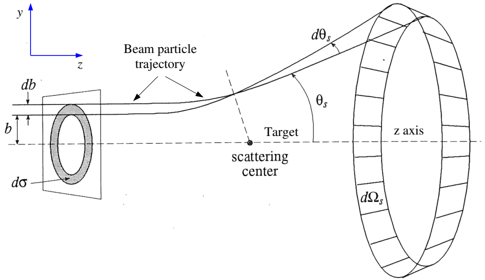

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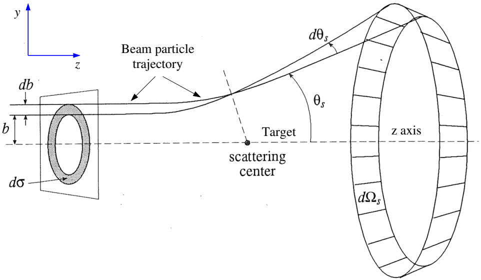

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THE FORM FACTOR!

Some Background

- EEFFs cross section described with Dirac (F_1) and Pauli (F_2) form factors

$$\frac{d\sigma}{d\Omega} = \sigma_{Mott}\left[\left(F_1^2 + \kappa^2\tau F_2^2\right) + 2\tau\left(F_1 + \kappa F_2\right)^2 \tan^2\left(\frac{\theta_e}{2}\right)\right]$$

where

$$\sigma_{Mott} = \frac{\alpha^2 E' \cos^2(\frac{\theta_e}{2})}{4E^3 \sin^4(\frac{\theta_e}{2})}$$

and κ is the anomalous magnetic moment, E (E') is the incoming (outgoing) electron energy, θ is the scattered electron angle and $\tau = Q^2/4M^2$.

- For convenience use the Sachs form factors.

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{Mott}}{\epsilon(1+\tau)}\left(\epsilon G_E^2 + \tau G_M^2\right)$$

where

$$G_E = F_1 - \tau F_2 \quad \text{and} \quad G_M = F_1 + F_2 \quad \text{and} \quad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

Why Should You Care?

- The chain of reason.

$$\frac{d\sigma}{d\Omega} \rightarrow |F(Q^2)|^2 \Leftrightarrow F(Q^2) \leftarrow \rho(\vec{r}) \leftarrow \psi(\vec{r}) \leftarrow_{\text{Constituent quarks}}^{\text{QCD,}}$$

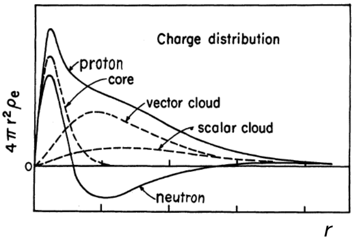
Experiment **Comparison** **Theory**

The form factors are the meeting ground between theory and experiment.

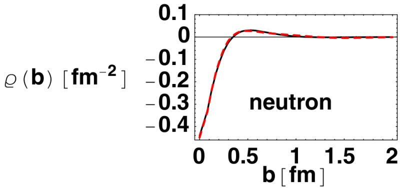
- The Fourier transform of the form factors are related to the charge and current distributions within the neutron.

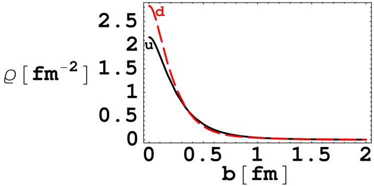
Why Should You Care Even More?

- The old picture of the neutron (and proton).



- What we know now - analysis of form factor data by G. Miller(Phys. Rev. Lett. **99**, 112001 (2007)).





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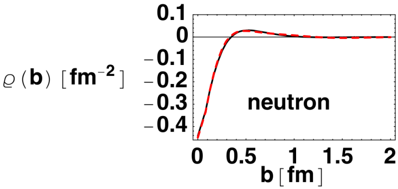
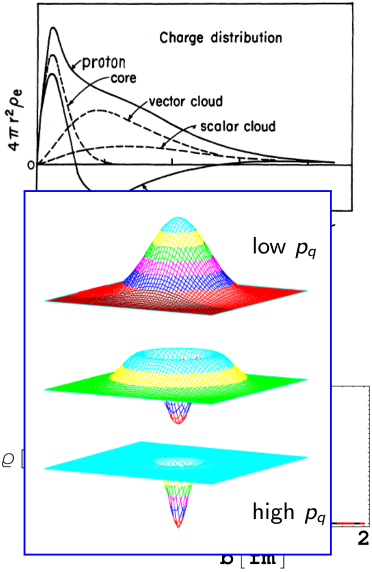


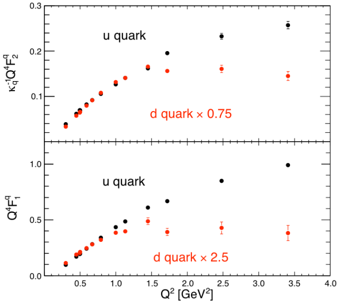


What We'll Learn - Flavor Decomposition

- With all four EEFFs we can unravel the contributions of the *u* and *d* quarks.
- Assume charge symmetry, no *s* quarks and use (Miller *et al.* Phys. Rep. **194**, 1 (1990))

$$F^u_{1(2)} = 2F^p_{1(2)} + F^n_{1(2)} \qquad F^d_{1(2)} = 2F^n_{1(2)} + F^p_{1(2)}$$

- Evidence of di-quarks? *d*-quark scattering probes the diquark.



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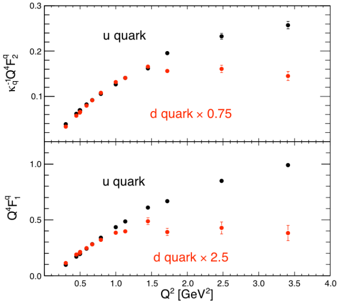

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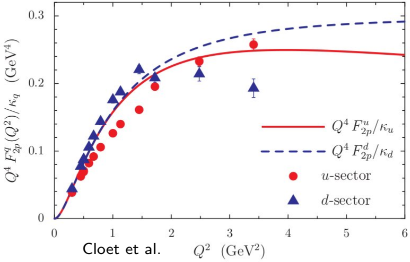

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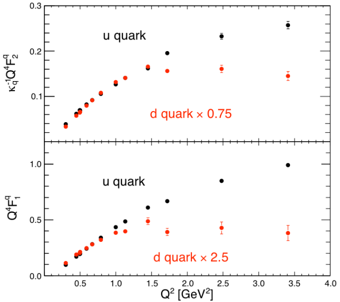

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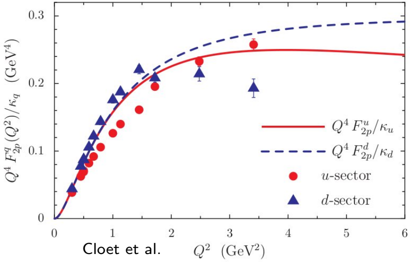

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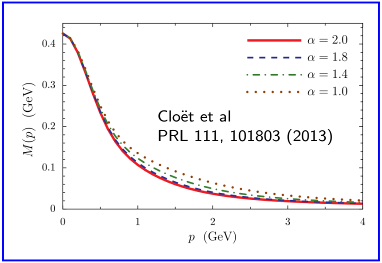
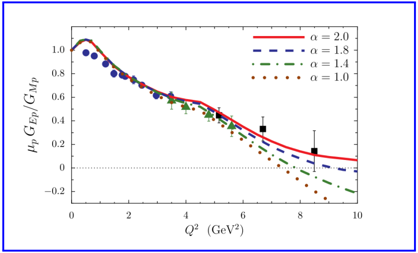
The JLab program will double our reach in Q^2 to ≈ 8 GeV^2.

What We'll Learn - Dyson-Schwinger Eqs

- Equations of motion of quantum field theory.
    - Infinite set of coupled integral equations.
    - Inherently relativistic, non-perturbative, connected to QCD.
    - Deep connection to confinement, dynamical chiral symmetry breaking.
    - Infinitely many equations, gauge dependent $\rightarrow$ Choose well!



- Results from (Cloët et al).
    - Model the nucleon dressed quark propagator as a quark-diquark.
    - Damp the shape of the mass function $M(p)$.



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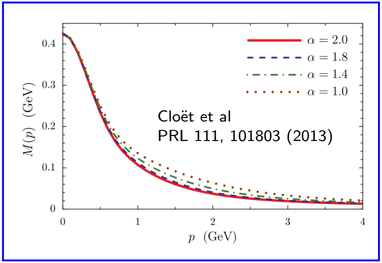

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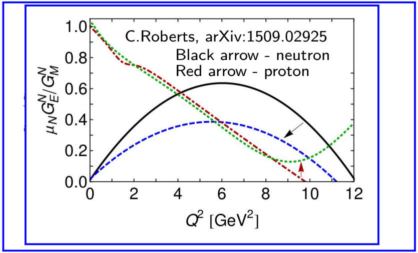

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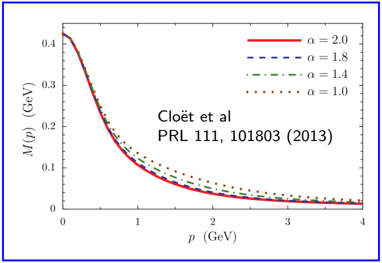

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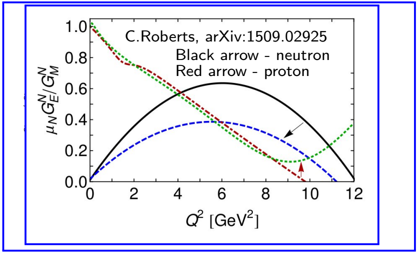
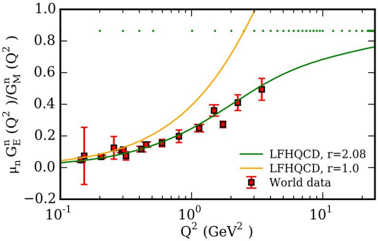
Position of zero in $\mu_p G_E^p/G_M^p$ and $\mu_n G_E^n/G_M^n$ sensitive to shape of $M(p)$!



What We'll Learn - Light Front Holographic QCD

1. Based on connections between light-front dynamics, it's holographic mapping to anti-de Sitter space, and conformal quantum mechanics.
2. Paper by Sufian *et al.* (Phys. Rev. D95, 01411 (2017)) included calculations of the electromagnetic form factors that include higher order Fock components $|qqqq\bar{q}\rangle$.
3. Obtain good agreement with all the form factor data with only three parameters, *e.g.* $\mu_n G_E^n/G_M^n$.



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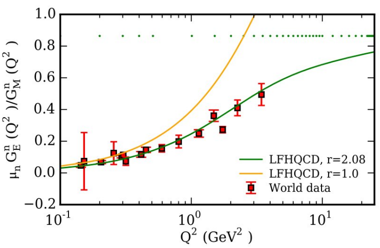
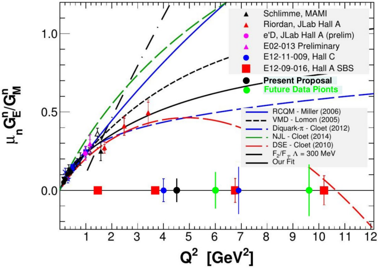
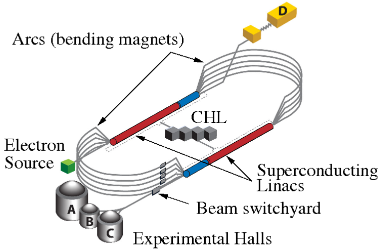




How Do We Measure G_M^n on a Neutron? (Step 1)

- 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 three experimental halls.
- All four halls can run simultaneously.



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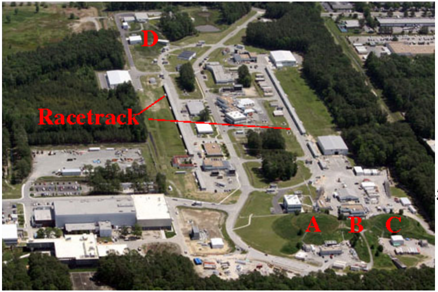

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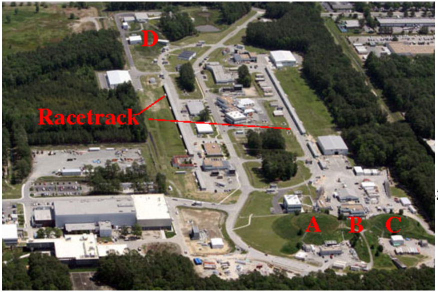

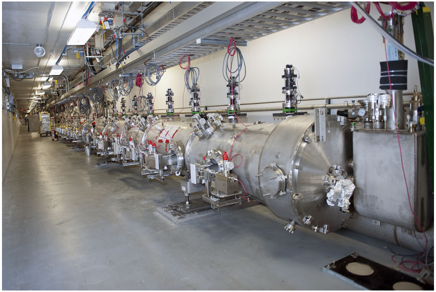

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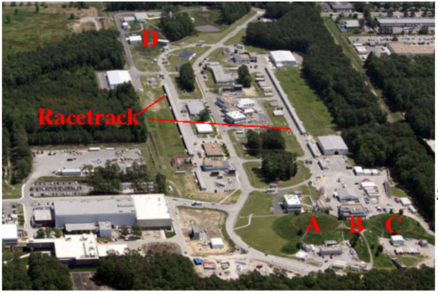
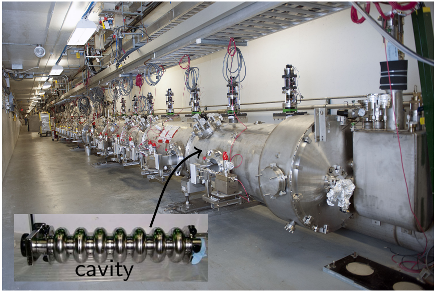
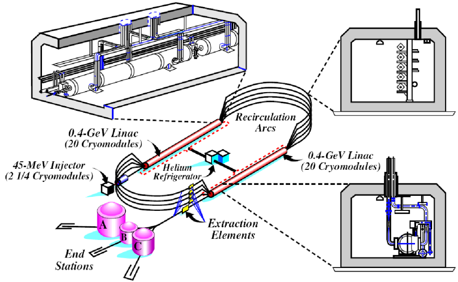
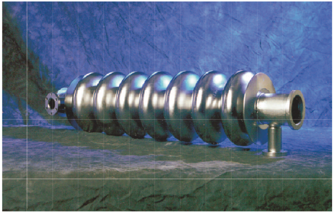




How Does CEBAF Do That?

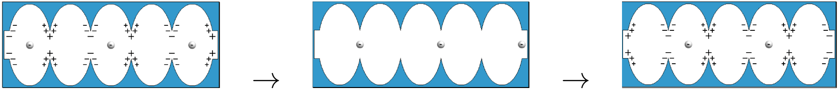
Accelerate your electrons to high energy.





Cavity

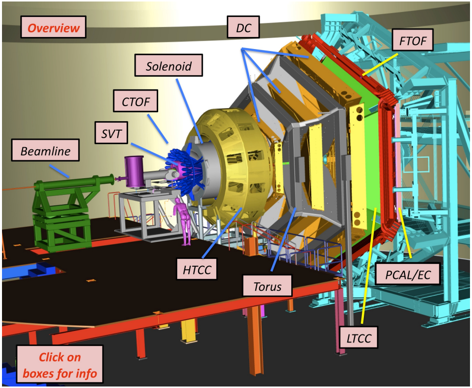
What happens inside the cavity? Feed it with oscillating, radio-frequency power at 1.5 GHz! In each hall beam buckets are about 2 picoseconds long and arrive every 2 nanoseconds.



A. → B. → C.

How Do We Measure G_M^n on a Neutron? (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 about 62,000 detecting elements in about 40 layers.



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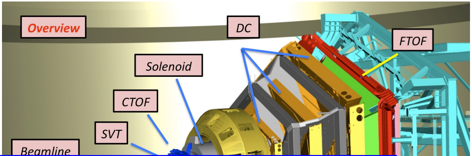

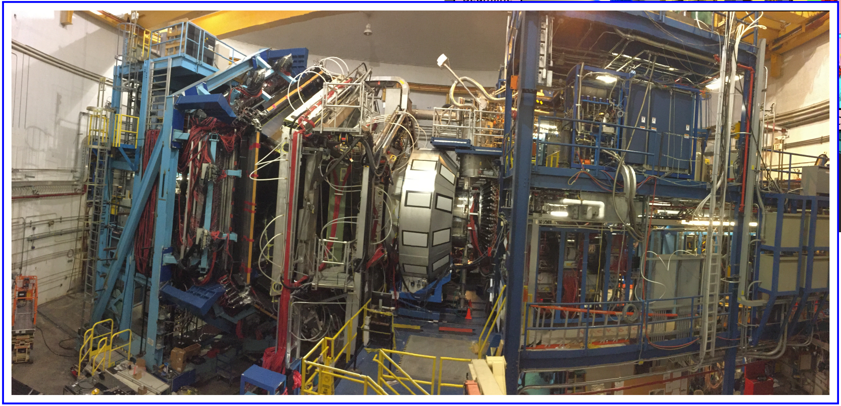

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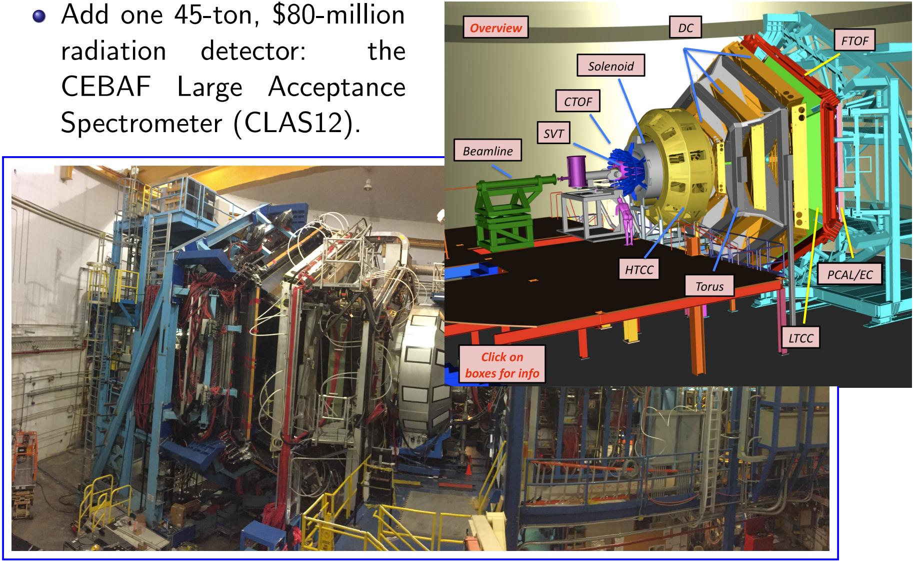
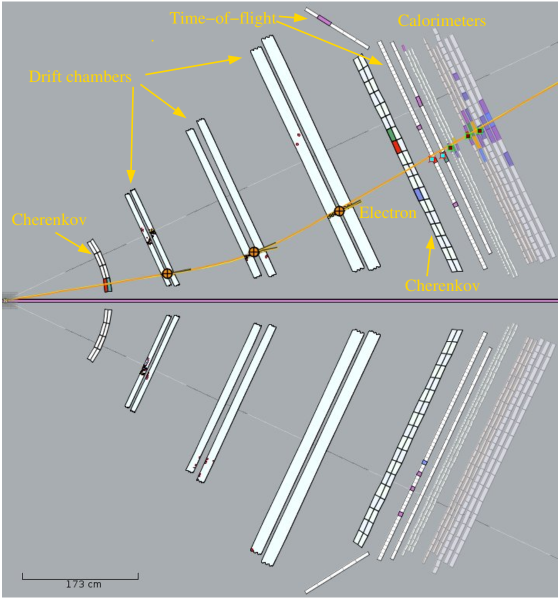
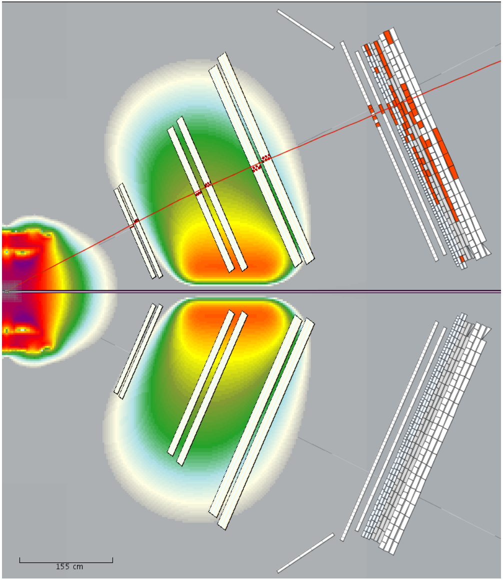


A CLAS12 Event



A Simulated CLAS12 Event - Drift Chamber close-up



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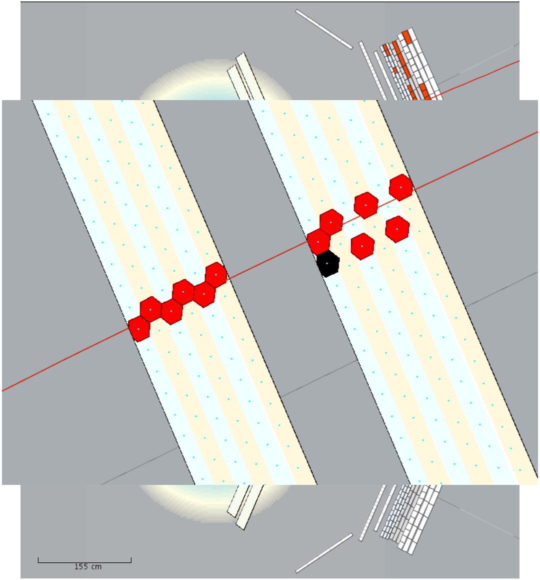

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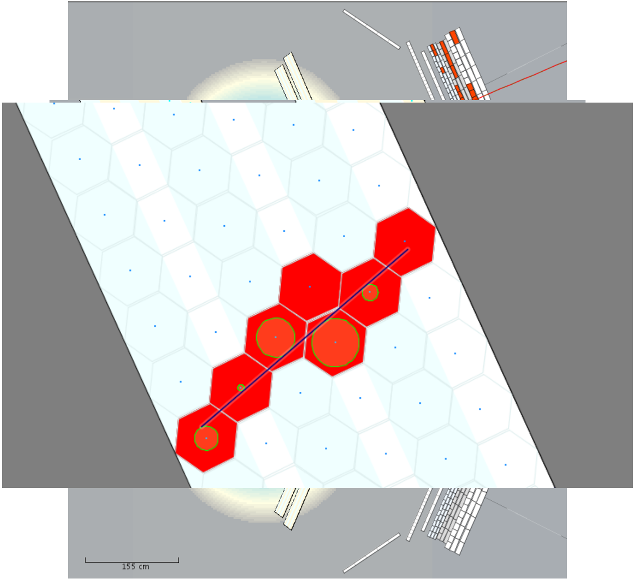
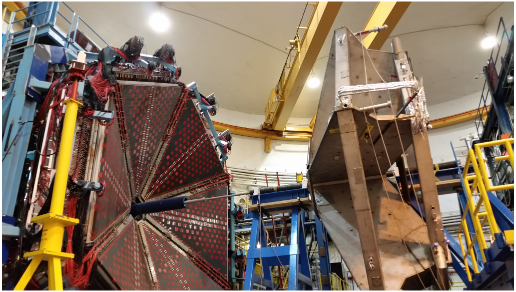


A Real CLAS12 Event - Building the Drift Chambers



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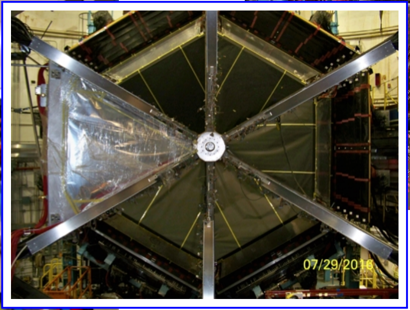

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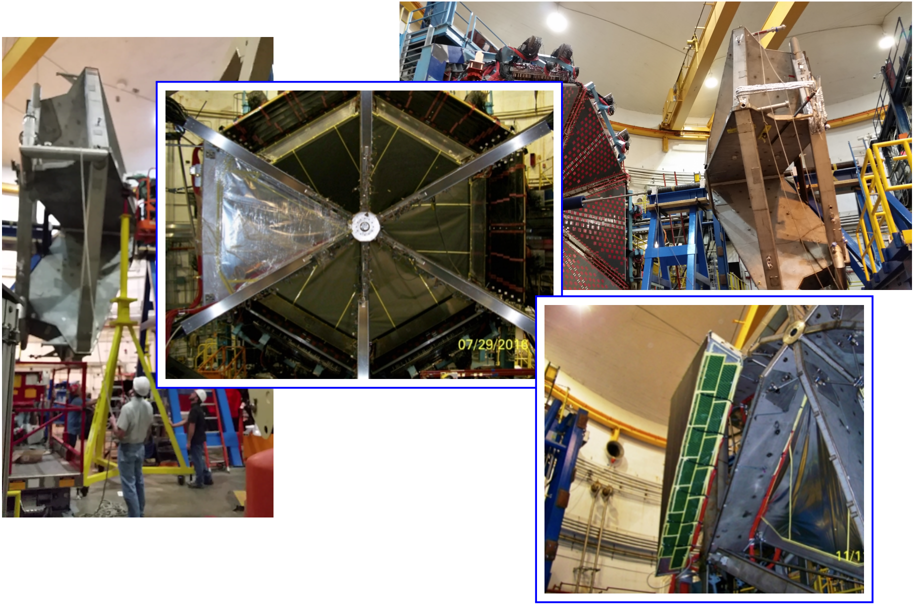
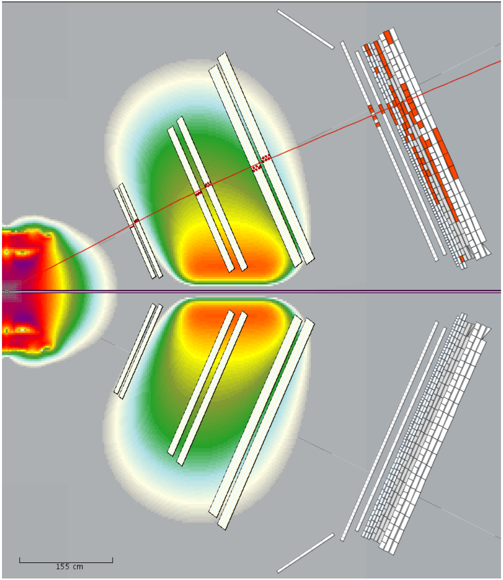


A Simulated CLAS12 Event - Calorimeter close-up



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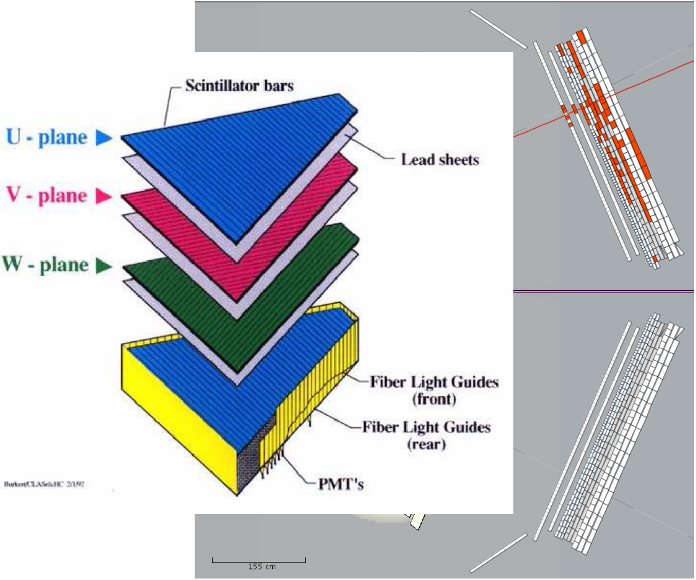

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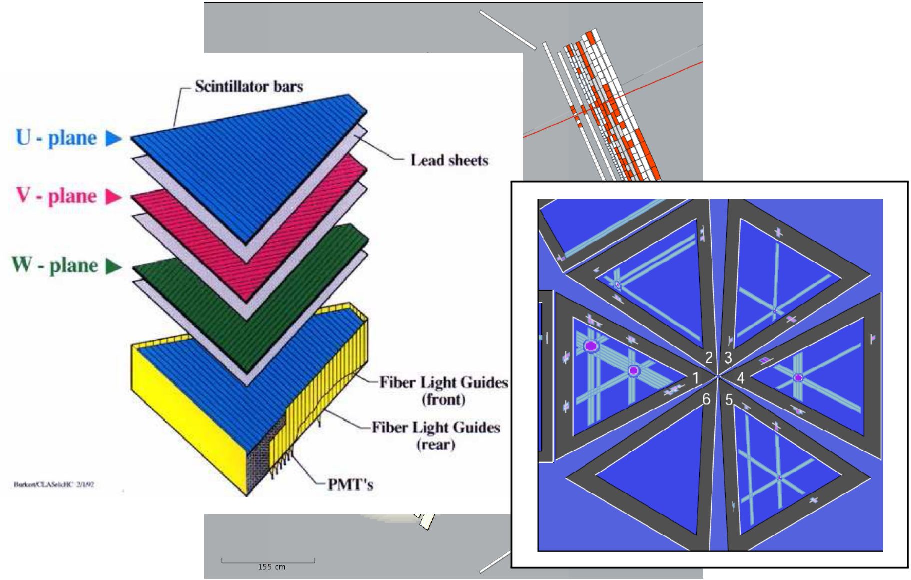

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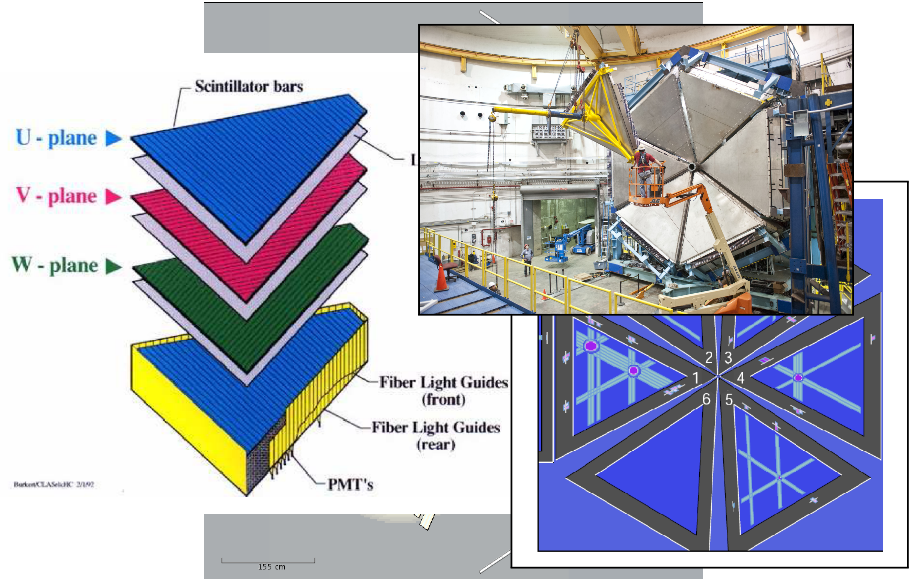
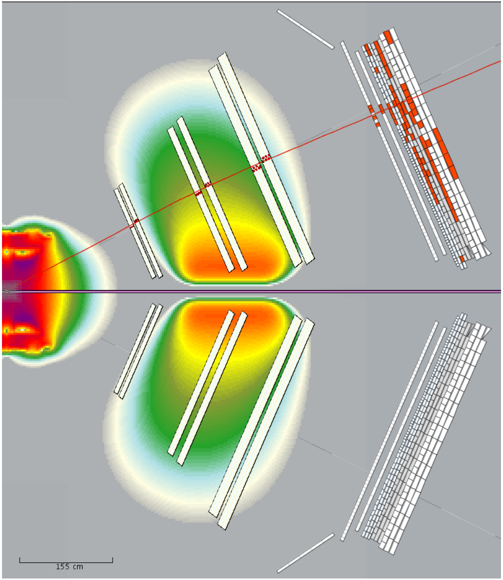


A Simulated CLAS12 Event - Time-of-Flight close-up



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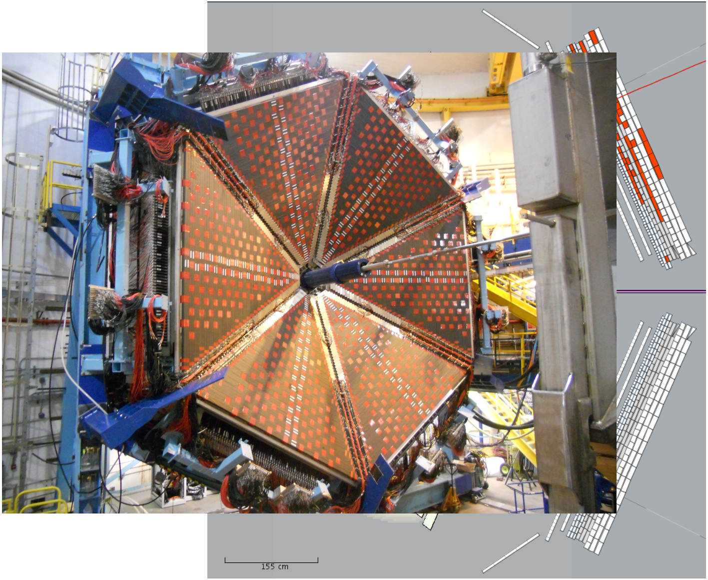

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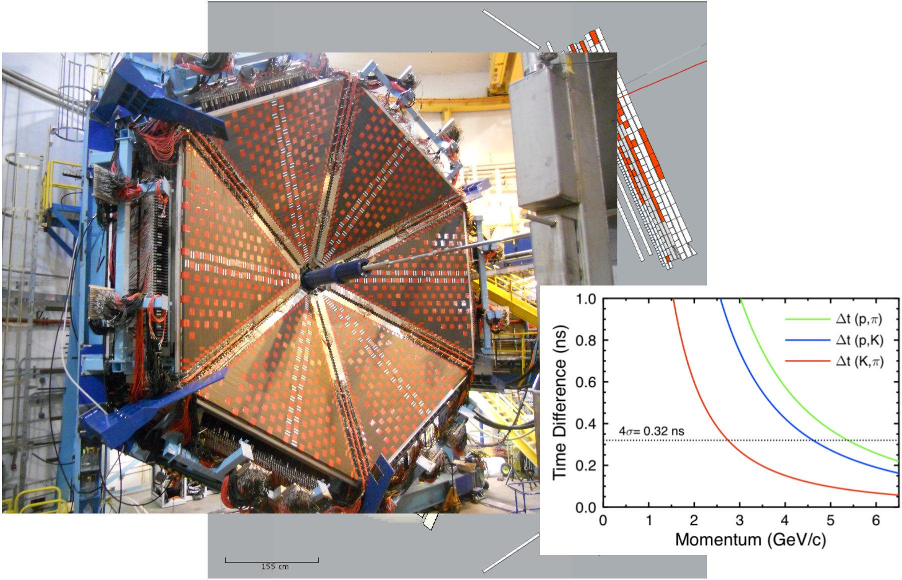

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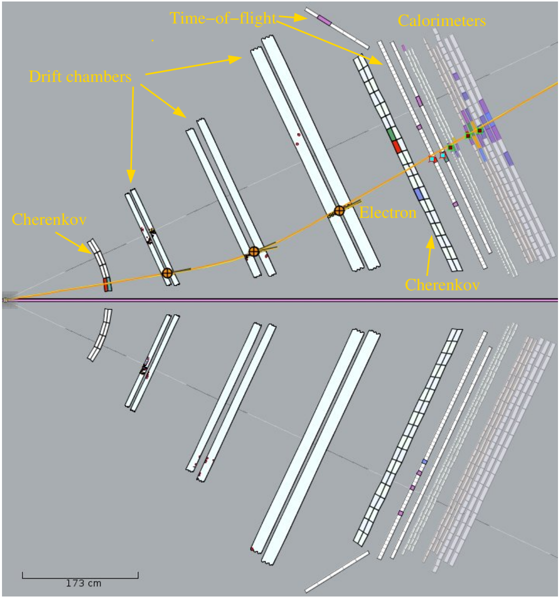
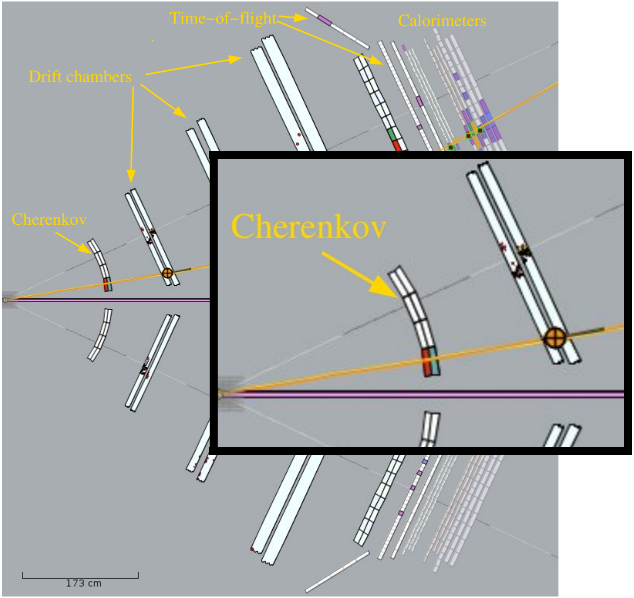


A CLAS12 Event - Cherenkov close-up



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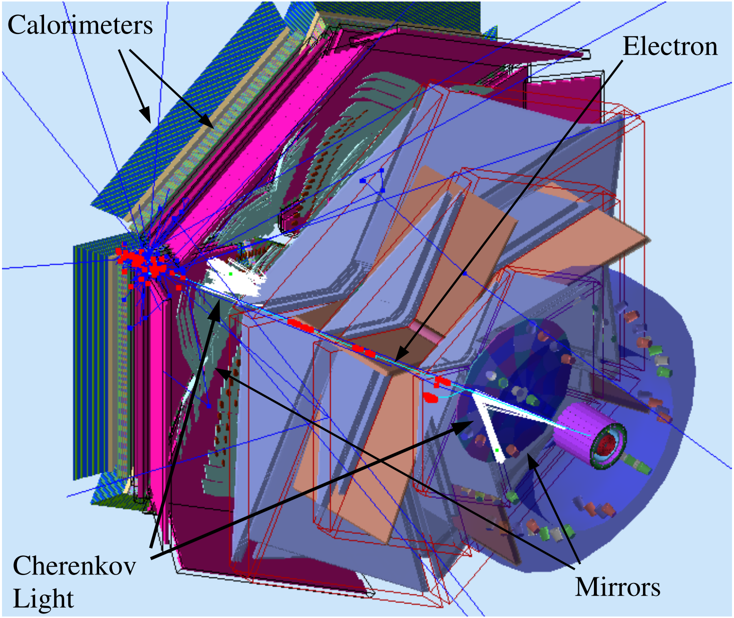

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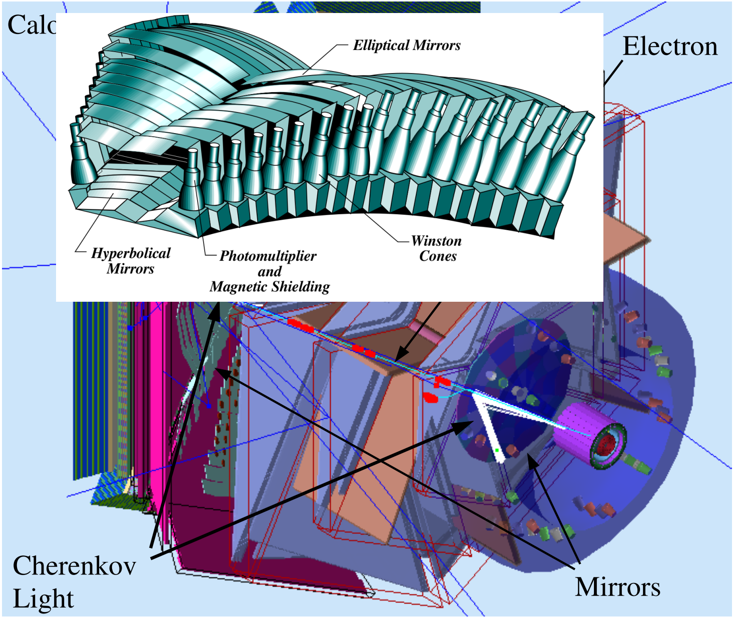

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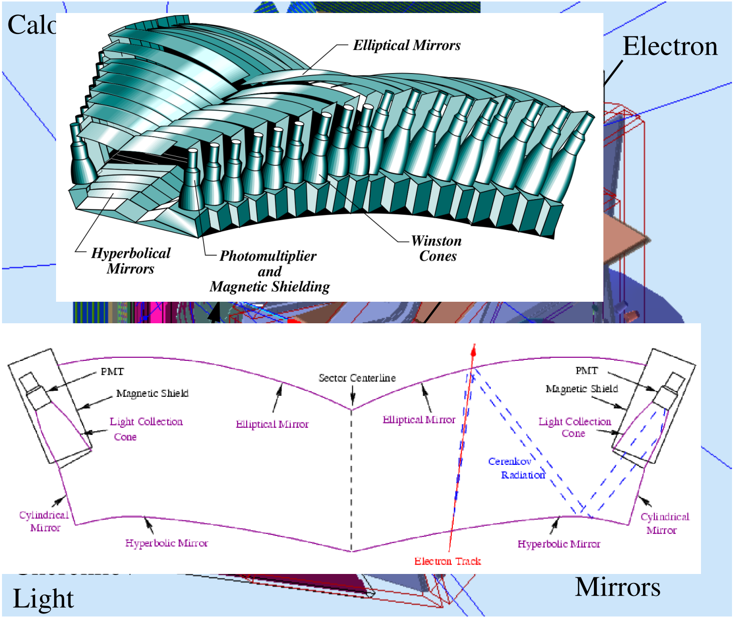
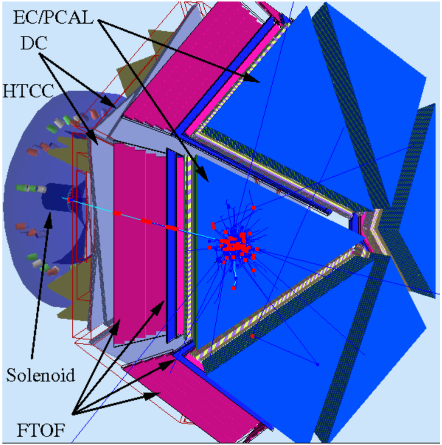


Simulated CLAS12 Events

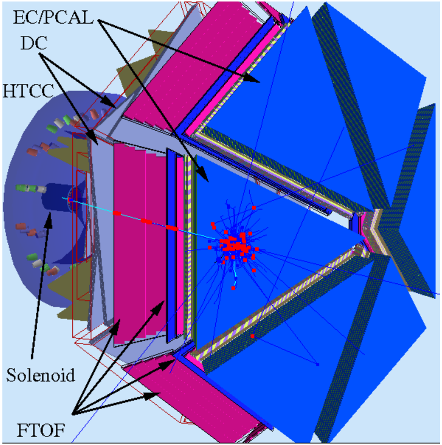
Forward Detector



Central Detector

Simulated CLAS12 Events

Forward Detector



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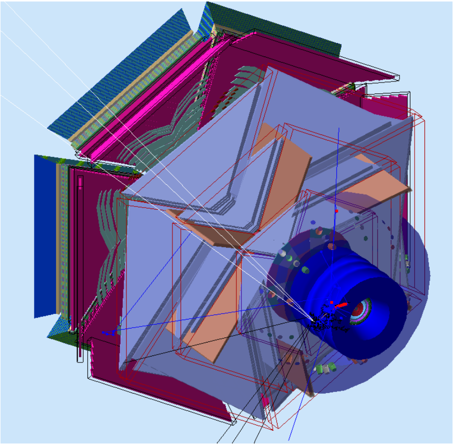
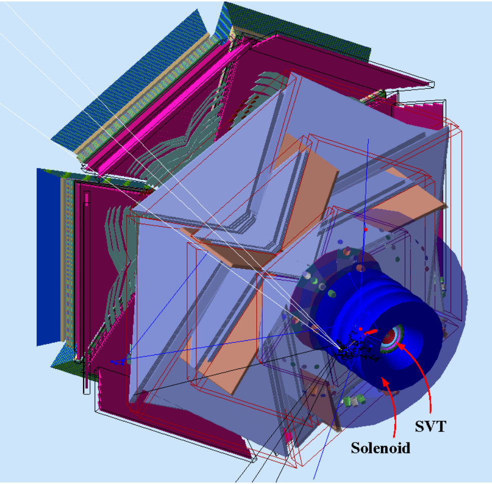


Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)



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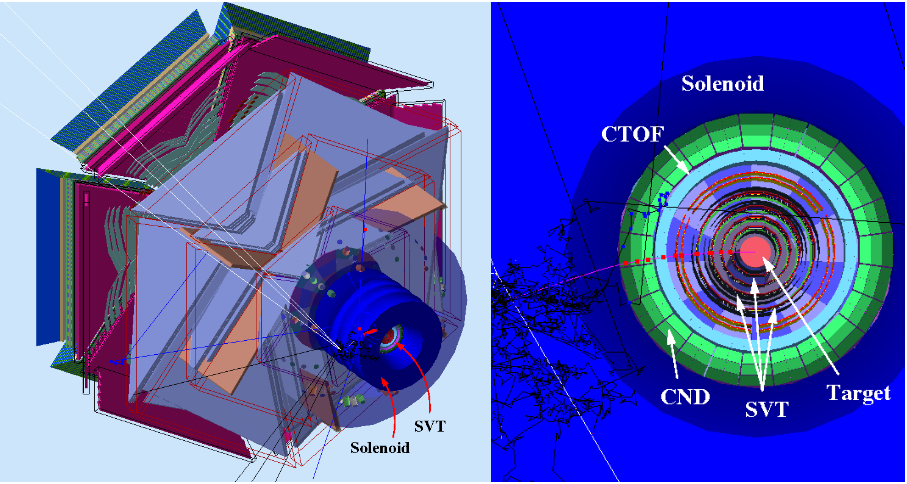

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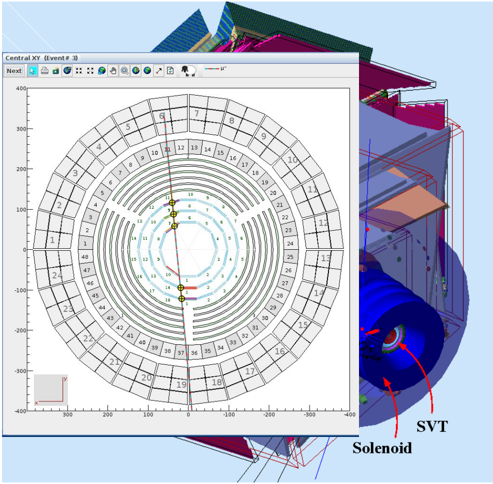
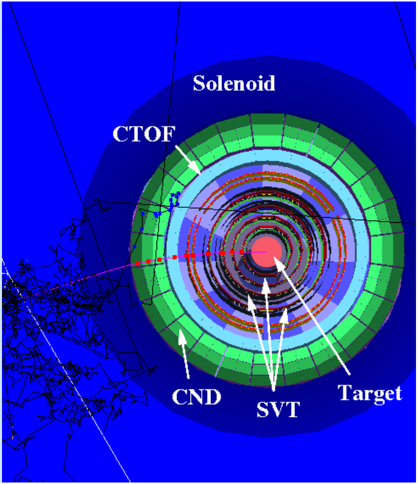
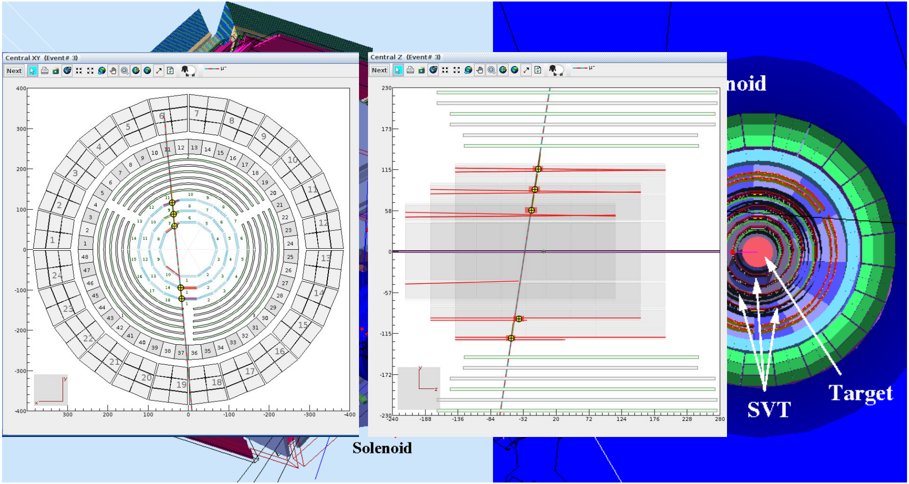
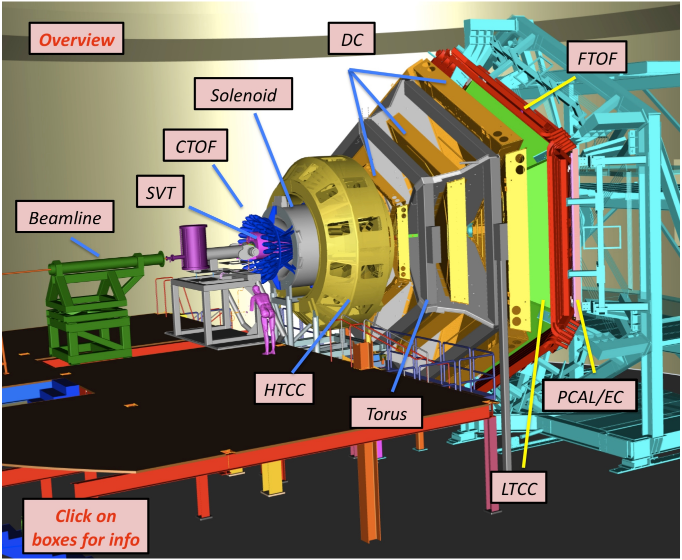




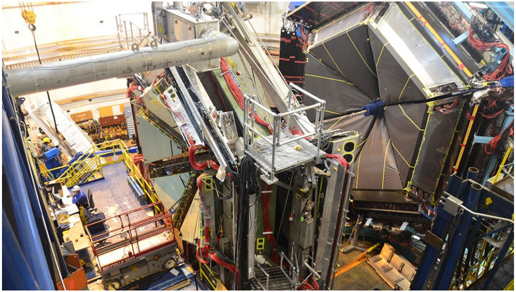
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)



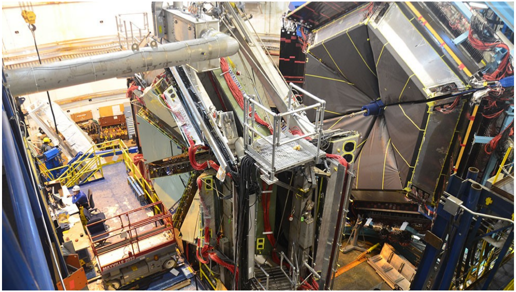
Putting It All Together - 1



Putting It All Together - 2



Putting It All Together - 2



Putting It All Together - 3

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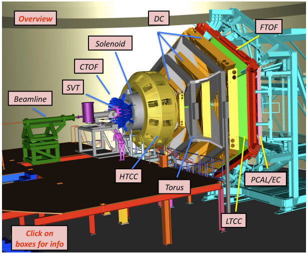
How Do We Measure G_M^n on a Neutron?

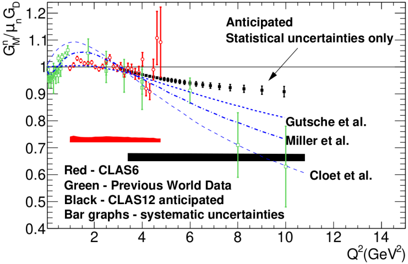
- E12-07-104 in Hall B (Gilfoyle, Hafidi, Brooks).
- Ratio Method on Deuterium:

$$R = \frac{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'n)_{QE}]}{\frac{d\sigma}{d\Omega}[^2\mathrm{H}(e,e'p)_{QE}]}$$

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

  where a is nuclear correction.
- Precise neutron detection efficiency needed to keep systematics low.
  - tagged neutrons from $^1\mathrm{H}(e,e'\pi^+n)$ (RGA).
  - LH_2 target.
- Kinematics: $\mathrm{Q}^2 = 3.5 - 10.0\ (\mathrm{GeV/c})^2$.
- Beamtime: 56 days.
- Desire systematic uncertainties $<$ 2.5% across full Q^2 range.
- Half of Run Group B done January, 2020.





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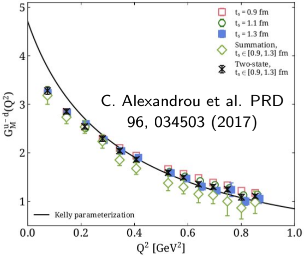
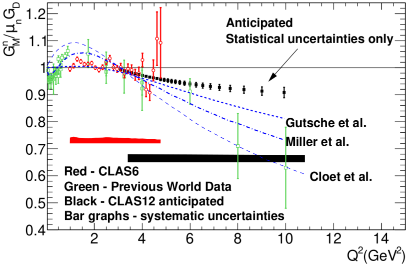
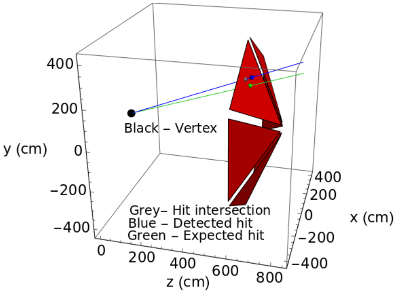




Measure the Neutron Detection Efficiency

1. Use the $^{1}\mathrm{H}(e, e'\pi^{+}n)$ reaction from a hydrogen target (RGA) as a source of tagged neutrons in the calorimeter.
2. Assume the missing neutral is a neutron. 'Swim' the neutron through CLAS12.
3. If it hits the calorimeter, this is an 'expected' event and will form the denominator of the NDE.
4. If it misses, throw the event out.
5. In the region of the expected hit look for a neutron. If one is found, this is a detected event and will for the numerator of the NDE.



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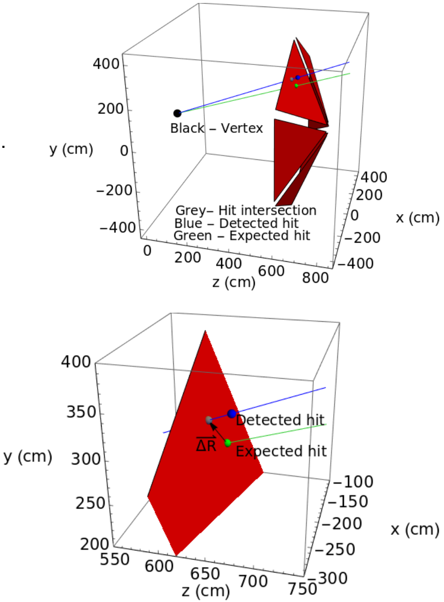
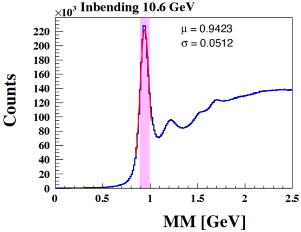
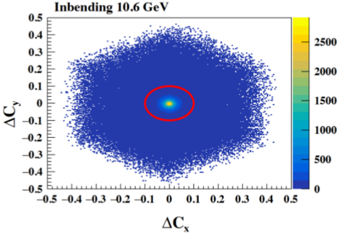


Selecting the Neutrons

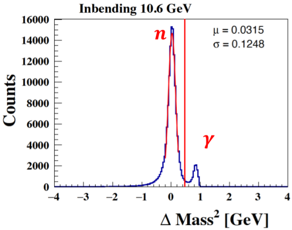
Missing mass cut.



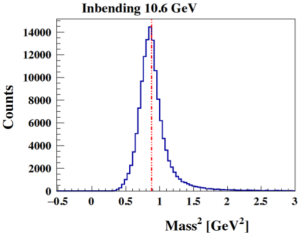
Difference between direction cosines.



ΔM^2 cut

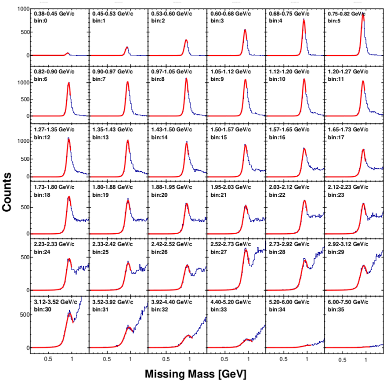


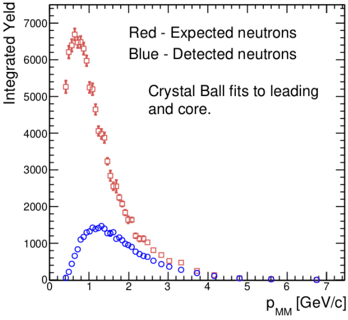
M^2 cut



Validating the NDE

- Fit the missing mass distributions as a function of P_{mm} in the region dominated by the neutron peak.
- Do the fits for the expected and detected neutrons.
- Take the ratio to get NDE.





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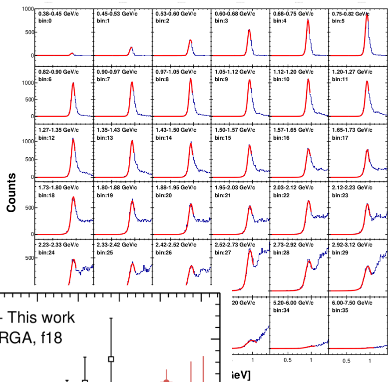
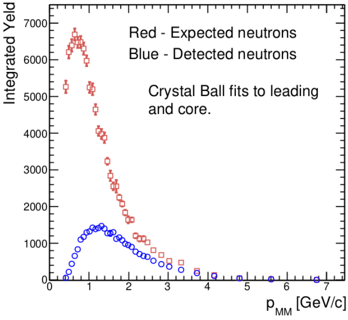
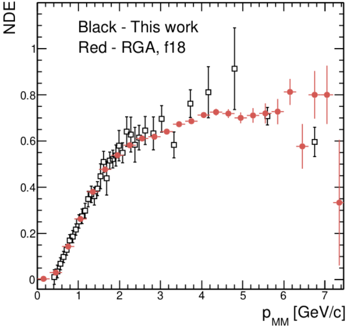
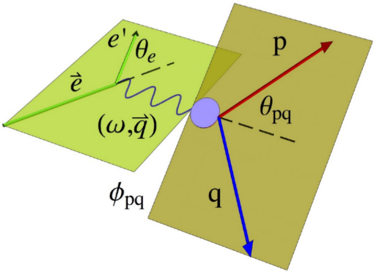


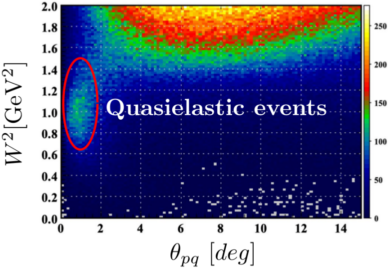




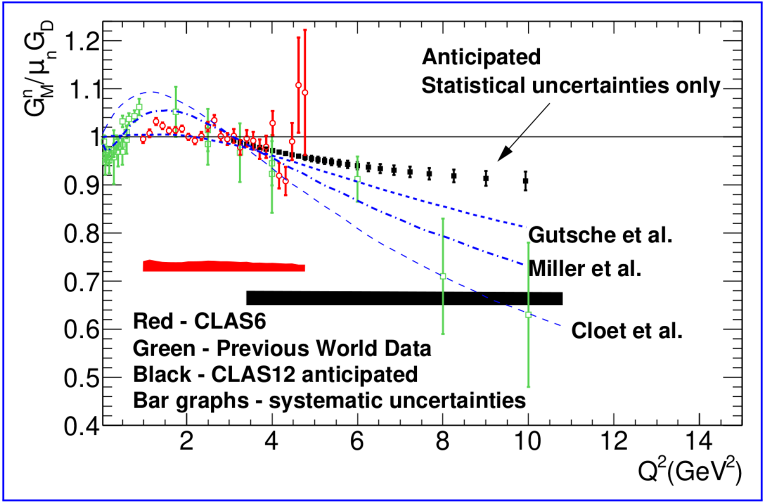
How Do We Measure G_M^n on a Neutron? (Step 4)

- Select quasi-elastic (QE) kinematics using θ_{pq} - the angle between the 3-momentum transfer and the nucleon.
- QE events are clustered at small θ_{pq}.
- Do acceptance matching to select events.
- Corrections - energy loss, Fermi motion, radiative corrections, nuclear corrections.





Anticipated 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 in the 12 GeV Era.

U. S. Department of Energy's

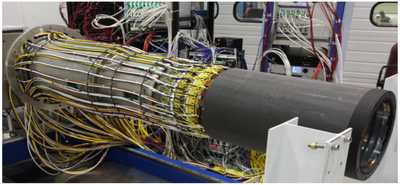
Jefferson Lab

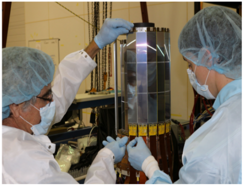
THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

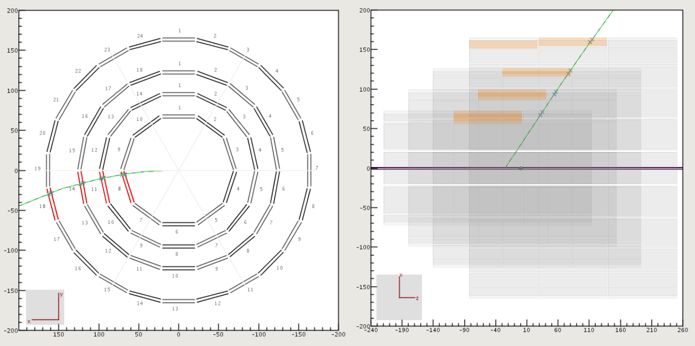
Additional Slides

What's going on now?

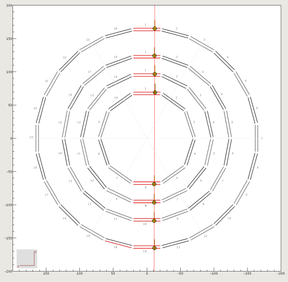
Alignment and commissioning of the silicon vertex tracker (SVT).



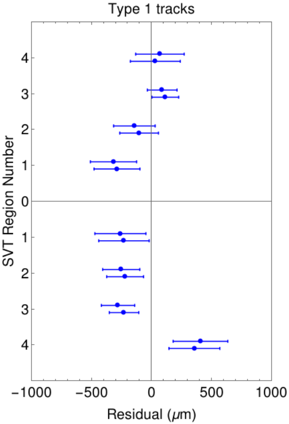




Check alignment with Type1 cosmic ray tracks



Type 1 tracks.



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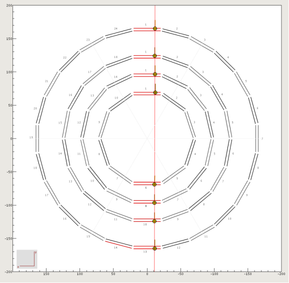

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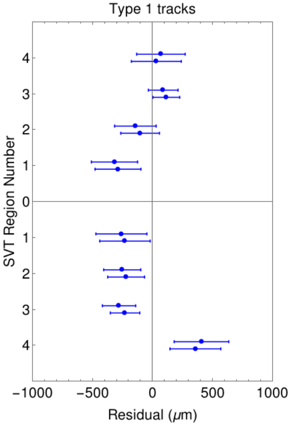
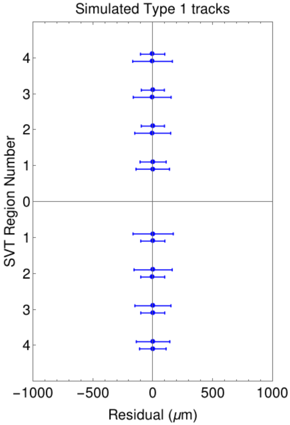
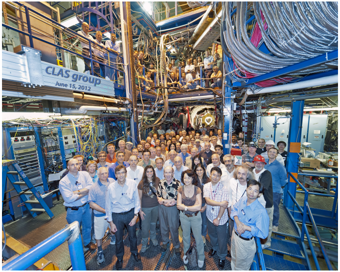


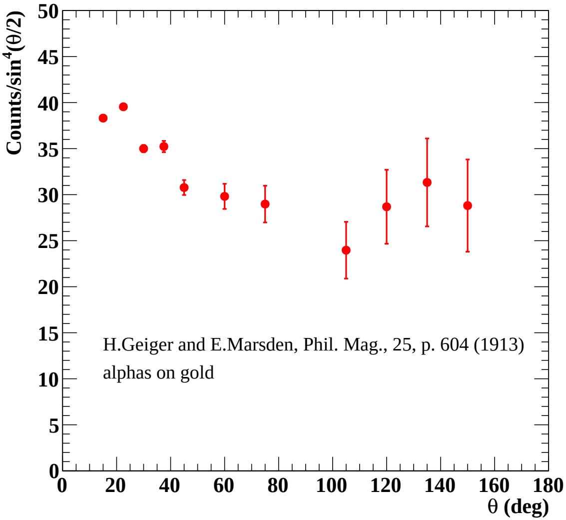


Some Facts of Life On The Frontier

- 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.
  - $\sim$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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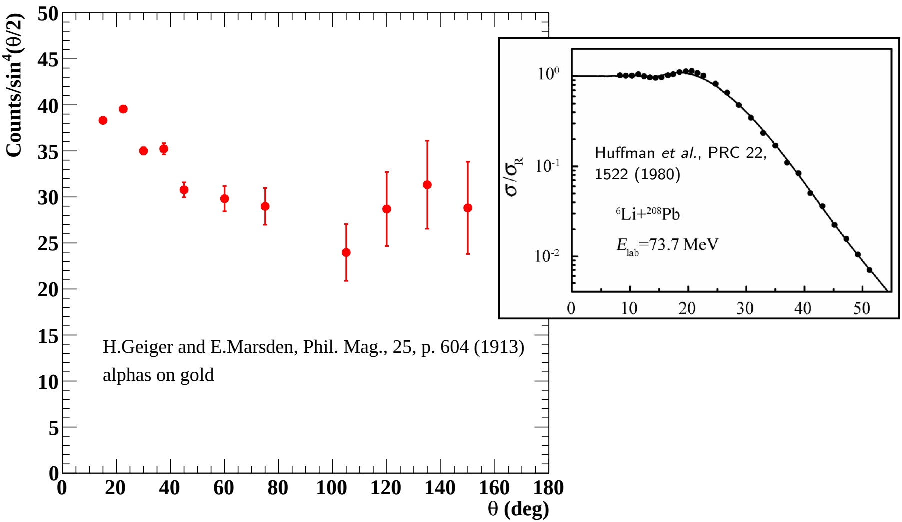

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