

Hunting for Quarks

*Jerry Gilfoyle for the CLAS Collaboration
University of Richmond*

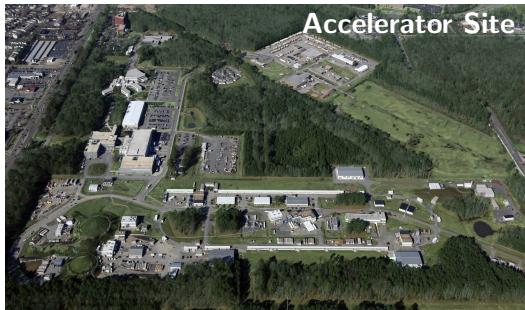


"The Periodic Table"

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

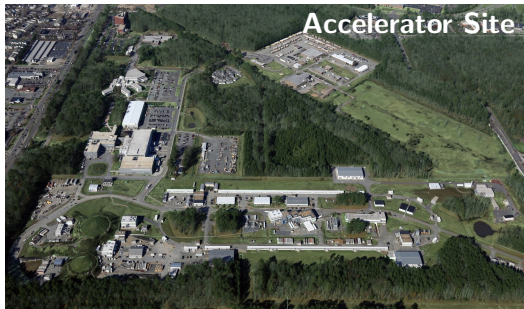
What is the Mission of Jefferson Lab?

- Basic research into the quark nature of the atomic nucleus.
- Map the geography of the transition from proton-neutron picture of nuclei to one based on quarks and gluons.
- 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.



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One of the seven Millenium Prize Problems from the Clay Mathematics Institute.

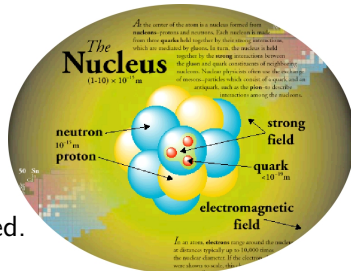
What Do We Know?

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

BOSONS			force carriers spin = 0, 1, 2, ...		
Unified Electroweak spin = 1			Strong (color) spin = 1		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W⁻	80.39	-1	Higgs Boson spin = 0		
W⁺ W bosons	80.39	+1	Name	Mass GeV/c ²	Electric charge
Z⁰ Z boson	91.188	0	H Higgs	126	0

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



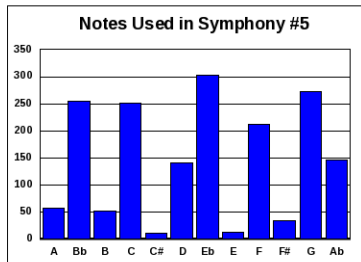
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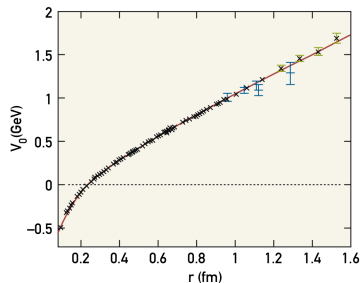
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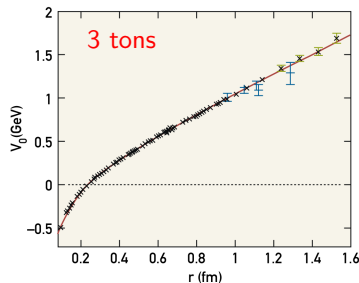
What is the Force?

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



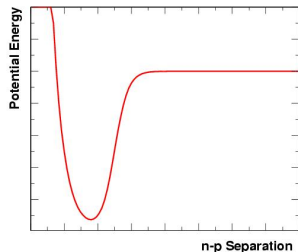
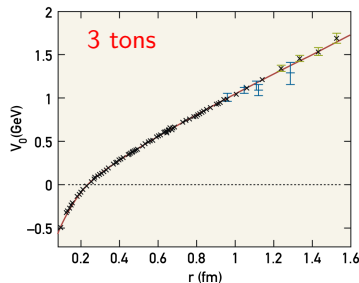
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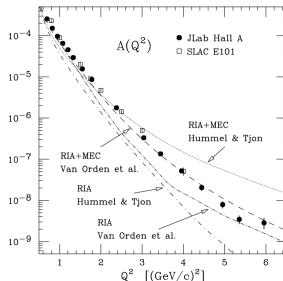
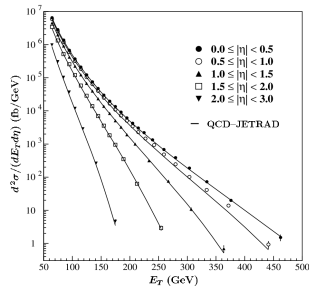
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- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.
- The hadronic model uses a phenomenological force fitted to data at low energy. This 'strong' force is the residual force between quarks.



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)).



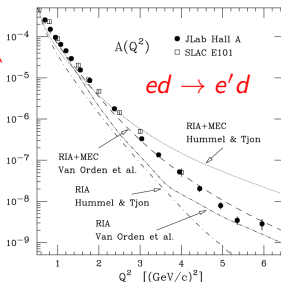
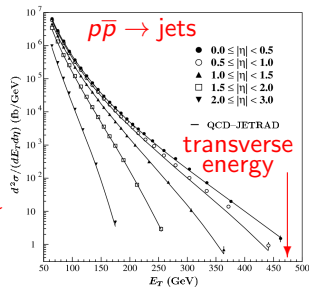
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effective target area

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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.
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$$\begin{aligned}
 m_p &= 2m_{up} + m_{down} = 2(2 \text{ MeV}/c^2) + 5 \text{ MeV}/c^2 \\
 &= 939 \text{ MeV}/c^2 \quad \text{OOOPS!!!!????}
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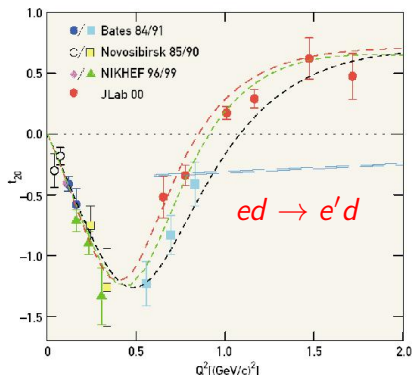
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- $m_n - m_p = 1.29333205(48) \text{ MeV}/c^2$ (exp) Sz. Borsanyi et al. *Science* 347, 1452 (2015).
- $= 1.51(16)(23) \text{ MeV}/c^2$ (th)

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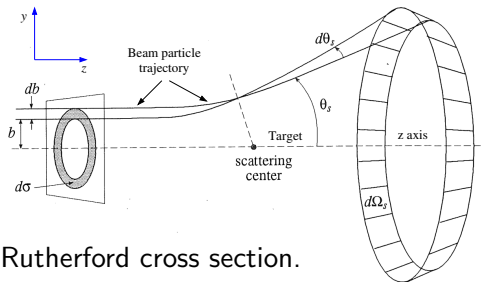
- Fundamental quantity related to the distribution of magnetization/currents in the neutron.
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors (G_M^n , G_E^n , G_M^p , and G_E^p) provide key constraints on theory and the structure of hadrons.
- Part of a broad effort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

* 'The Frontiers of Nuclear Science: A Long-Range Plan', NSF/DOE Nuclear Science Advisory Committee, April, 2007.

What is a Form Factor?

- Start with the cross section.

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

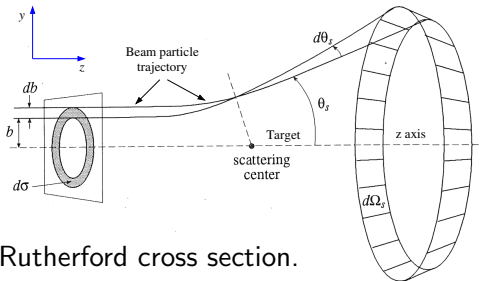


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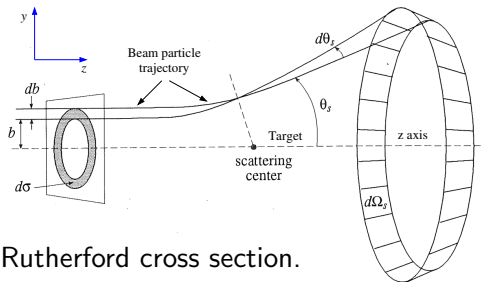
- Cross section for elastic scattering by point particles with spin.

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- What happens when the beam is electrons and the target is not a point?

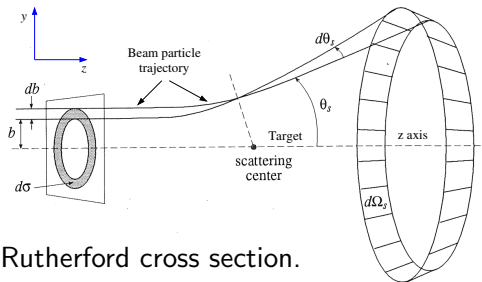
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where Q^2 is the 4-momentum transfer.

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THE FORM FACTOR!

Why Should You Care?

- The chain of reason.

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

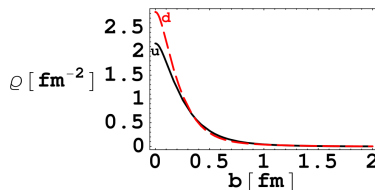
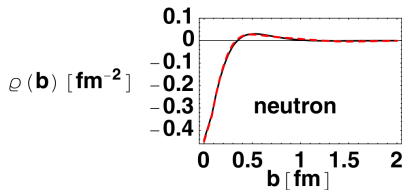
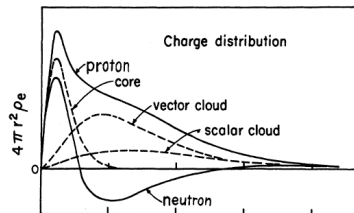
Experiment **Comparison** **Theory**

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.

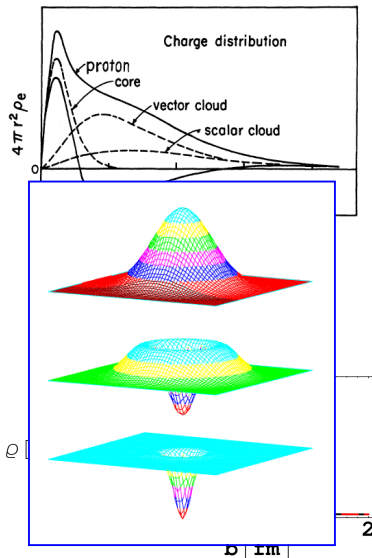
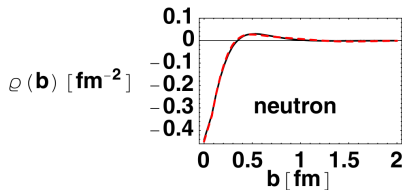
Why Should You Care Even More?

- 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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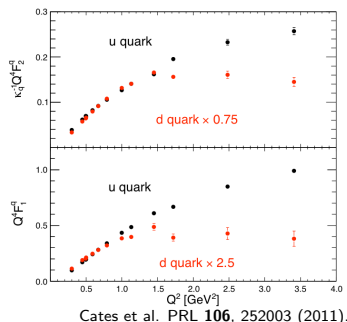


What We'll Learn - Flavor Decomposition

- 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))

$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n \quad F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p$$

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

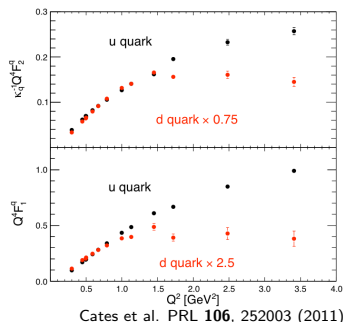
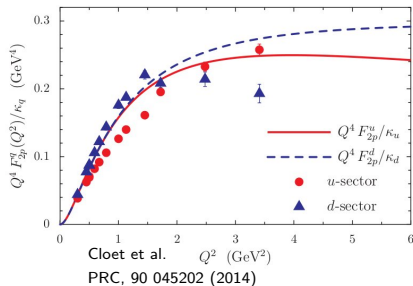


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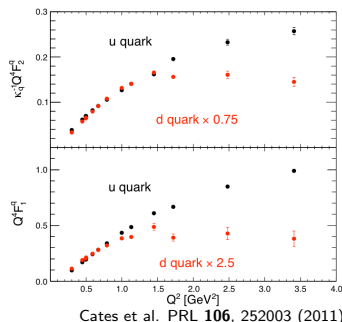
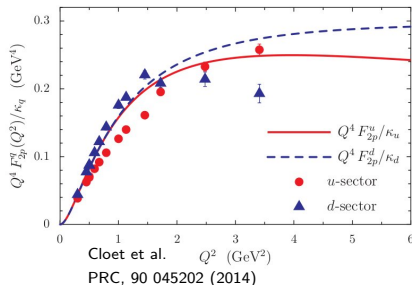
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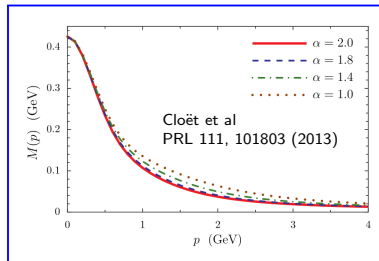
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The JLab program will double our reach in Q^2 to $\approx 8 \text{ GeV}^2$.

What We'll Learn - Dyson-Schwinger Eqs

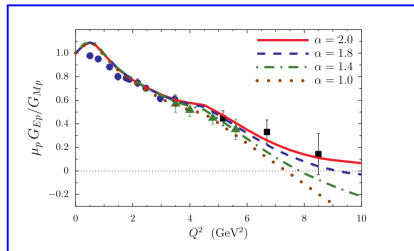
- Equations of motion of quantum field theory.

- 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!



- Recent results (Cloët et al).

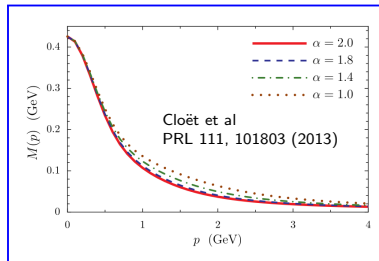
- Model the nucleon dressed quark propagator as a quark-diquark.
- Damp the shape of the mass function $M(p)$.



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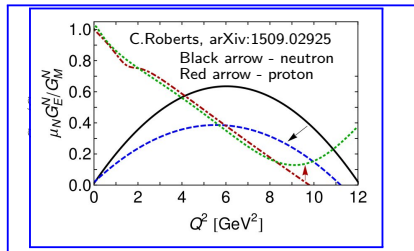
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- Infinite set of coupled integral equations.
- Inherently relativistic, non-perturbative, connected to QCD.
- Deep connection to confinement, dynamical chiral symmetry breaking.
- Infinitely many equations, gauge dependent $\rightarrow$ Choose well!



- Recent results (Cloët et al).

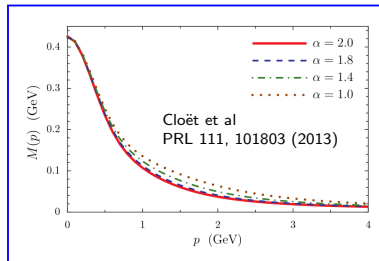
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What We'll Learn - Dyson-Schwinger Eqs

- Equations of motion of quantum field theory.

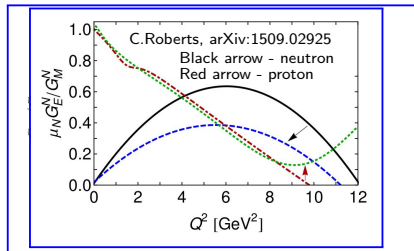
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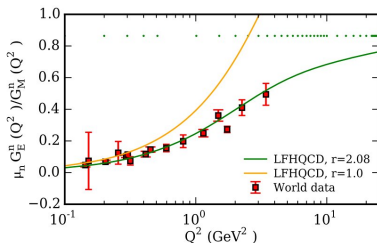
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- Damp the shape of the mass function $M(p)$.

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 $M(p)$!



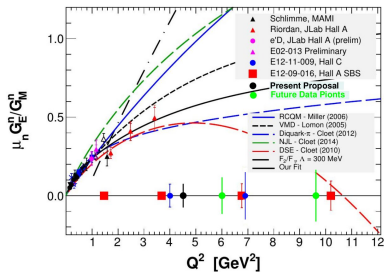
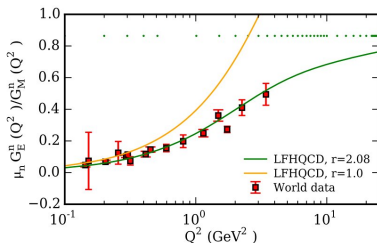
What We'll Learn - Light Front Holographic QCD

- 1 Based on connections between light-front dynamics, it's holographic mapping to anti-de Sitter space, and conformal quantum mechanics.
- 2 Recent 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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What We'll Learn - The Campaign

The JLab Lineup

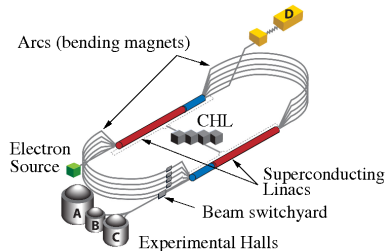
Quantity	Method	Target	$Q^2(\text{GeV}^2)$	Hall	Beam Days
G_M^p *	Elastic scattering	LH_2	7 – 15.5	A	24
G_E^p/G_M^p	Polarization transfer	LH_2	5 – 12	A	45
G_M^n	$E - p/e - n$ ratio	LD_2, LH_2	3.5 – 13.0	B	30
G_M^n	$E - p/e - n$ ratio	LD_2, LH_2	3.5 – 13.5	A	25
G_E^n/G_M^n	Double polarization asymmetry	polarized ^3He	5 – 8	A	50
G_E^n/G_M^n	Polarization transfer	LD_2	4 – 7	C	50
G_E^n/G_M^n	Polarization transfer	LD_2	4.5	A	5

* Data collection is complete.

PAC approval for 229 days of running in the first five years.

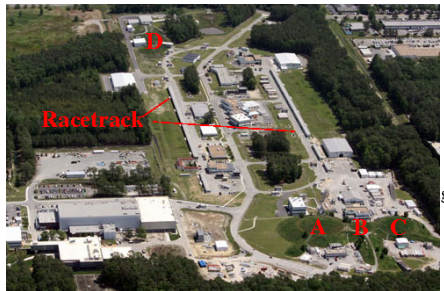
How Do We Measure G_M^n on a Neutron? (Step 1)

- 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.
- Three of four halls can run simultaneously.



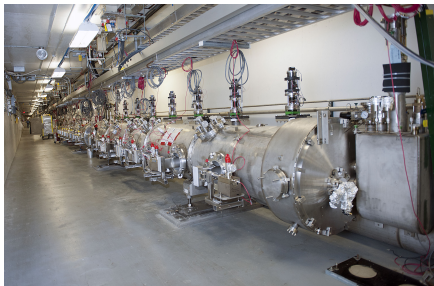
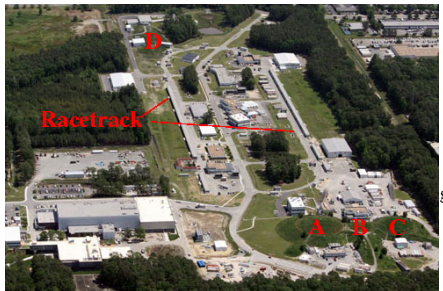
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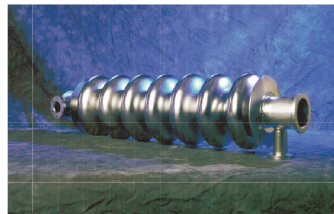
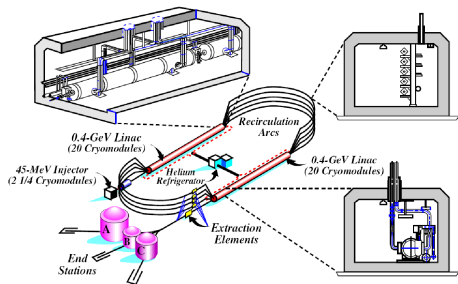
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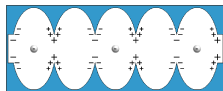
How Does CEBAF Do That?

Accelerate your electrons to high energy.



Cavity

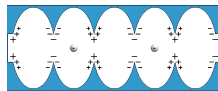
What happens inside the cavity? Feed it with oscillating, radio-frequency power at 1.5 GHz! In each half beam buckets are about 2 picoseconds long and arrive every 2 nanoseconds.



A.



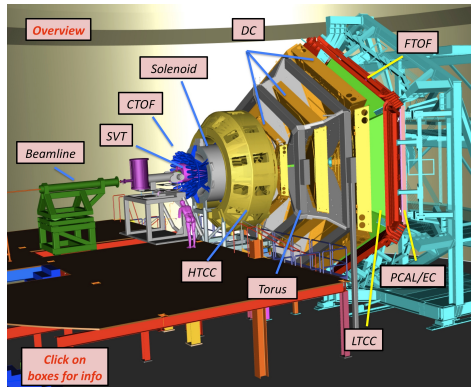
B.



C.

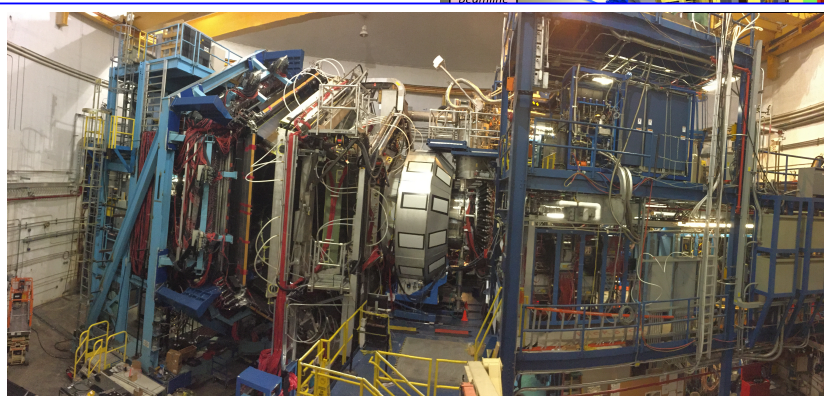
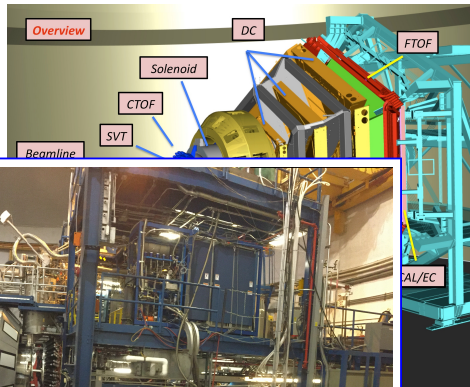
How Do We Measure G_M^n on a Neutron? (Step 2)

- 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.



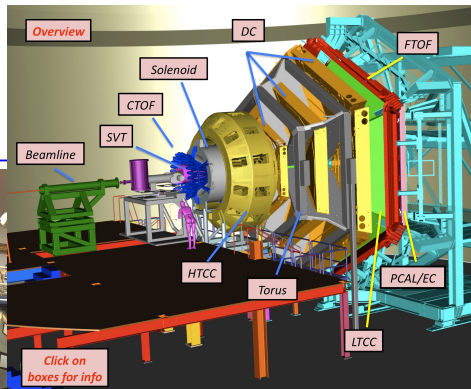
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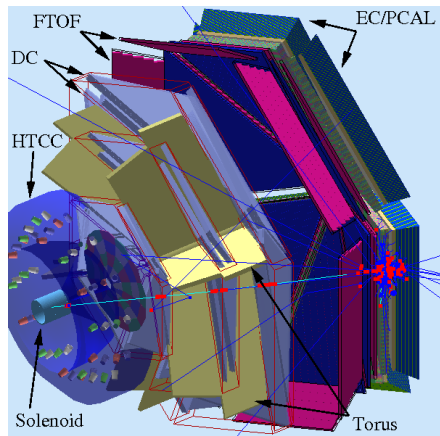
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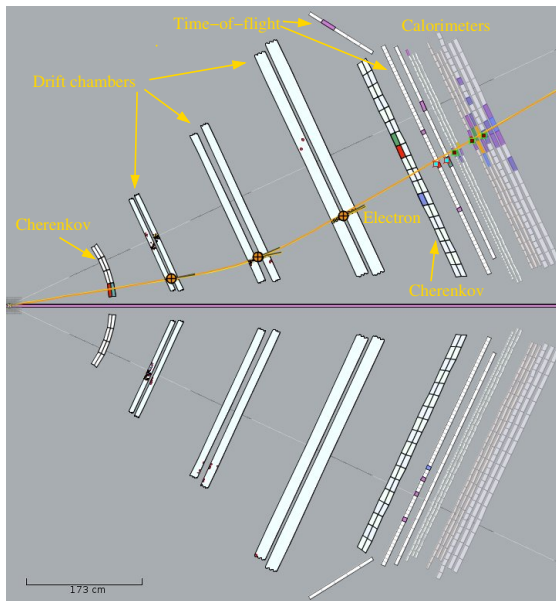


How Do We Measure G_M^n on a Neutron? (Step 2a)

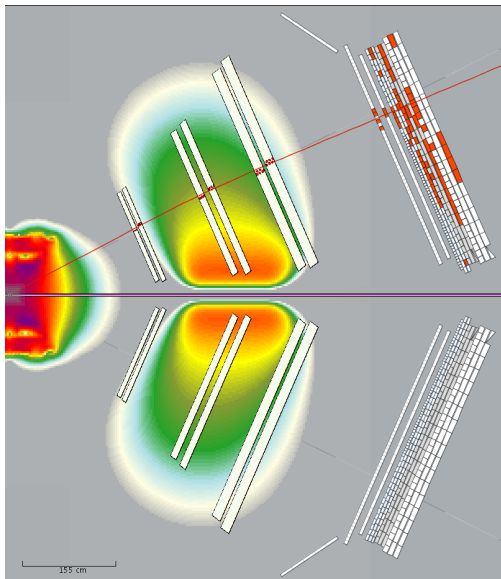
- Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.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



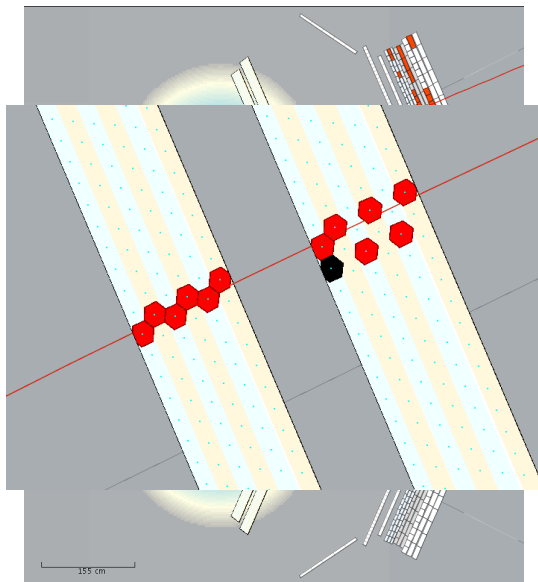
A CLAS12 Event



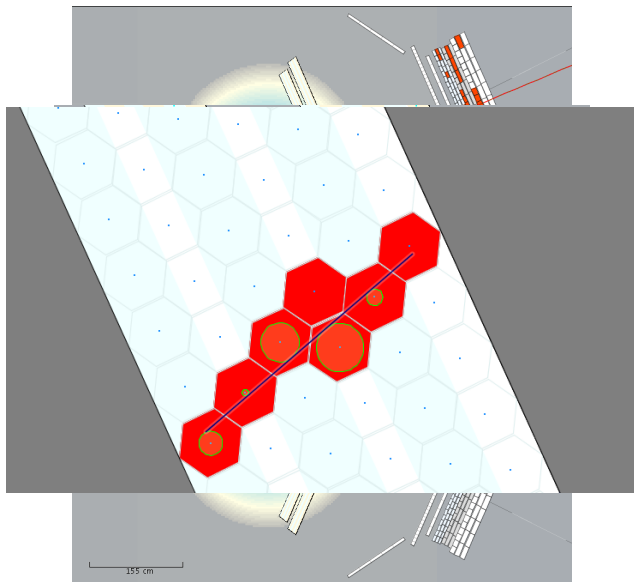
A Simulated CLAS12 Event - Drift Chamber close-up



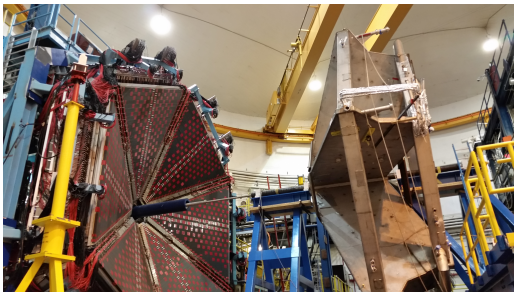
A Simulated CLAS12 Event - Drift Chamber close-up



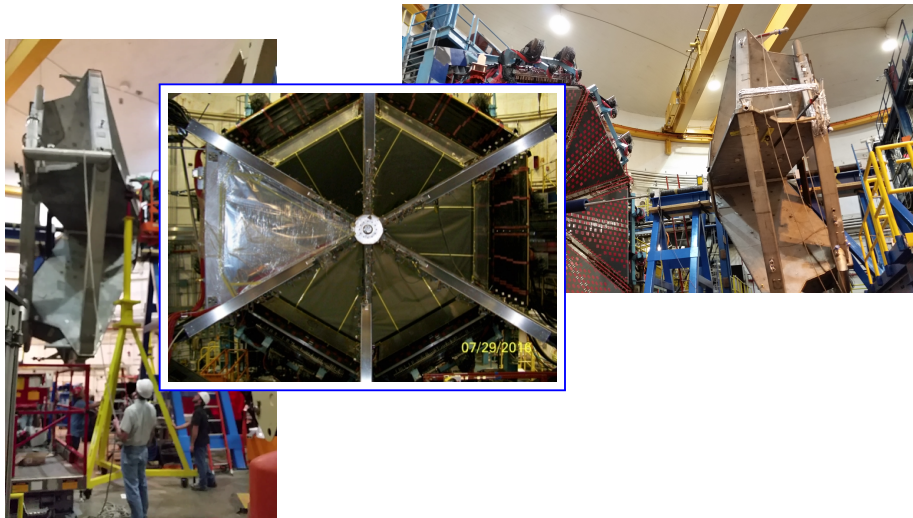
A Simulated CLAS12 Event - Drift Chamber close-up



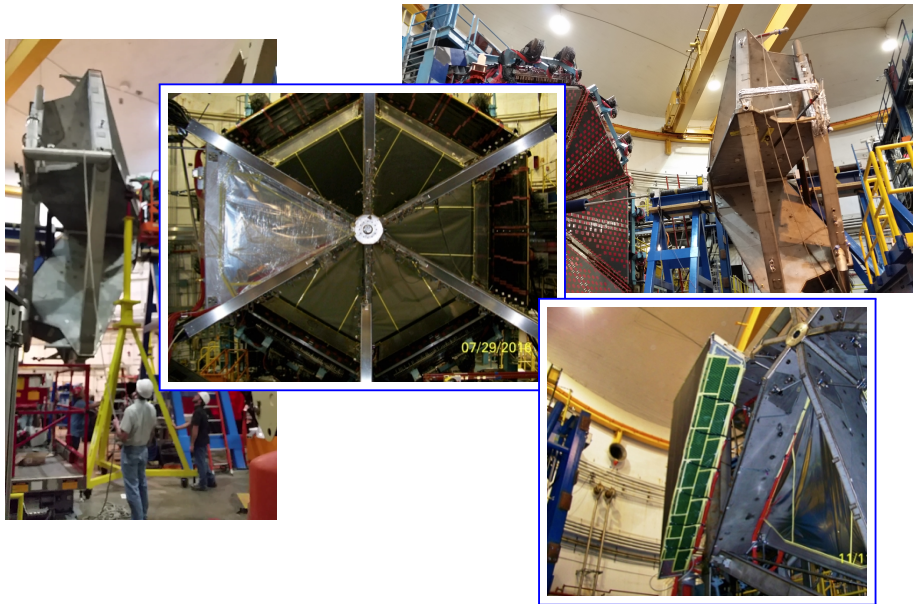
A Real CLAS12 Event - Building the Drift Chambers



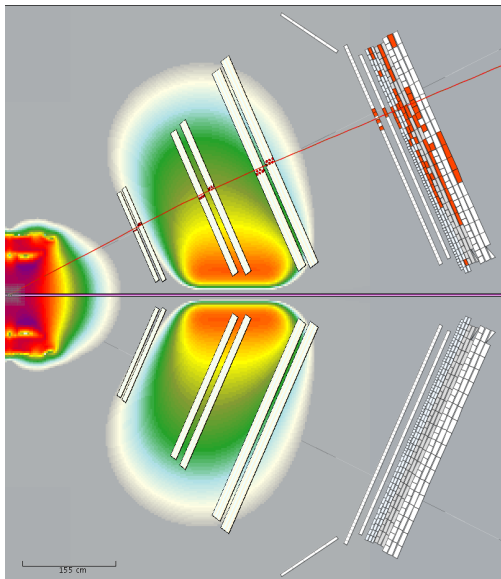
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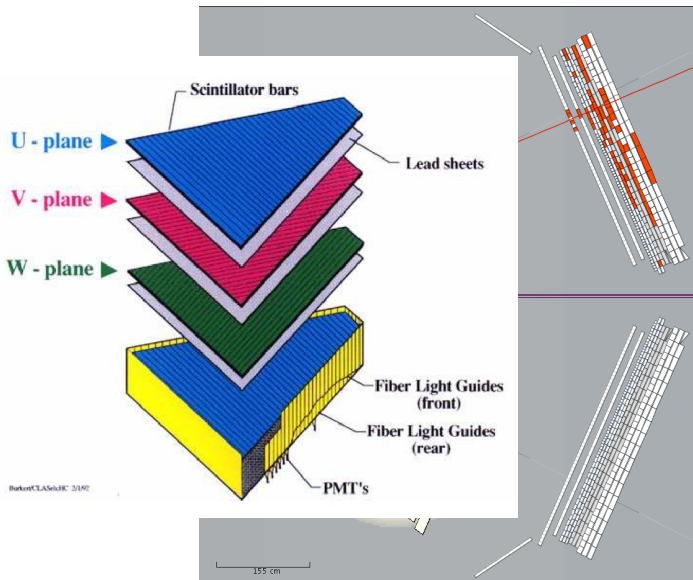
A Real CLAS12 Event - Building the Drift Chambers



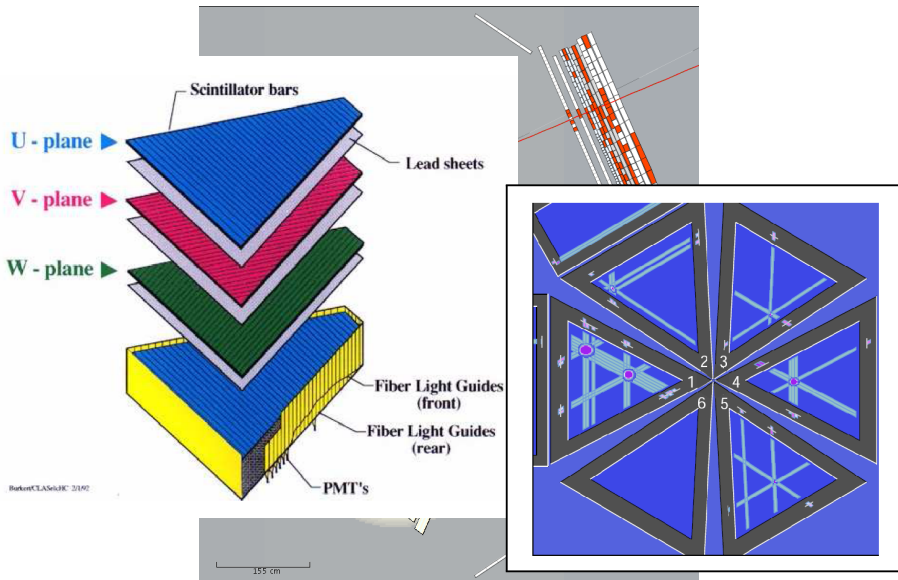
A Simulated CLAS12 Event - Calorimeter close-up



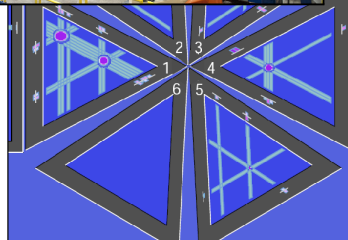
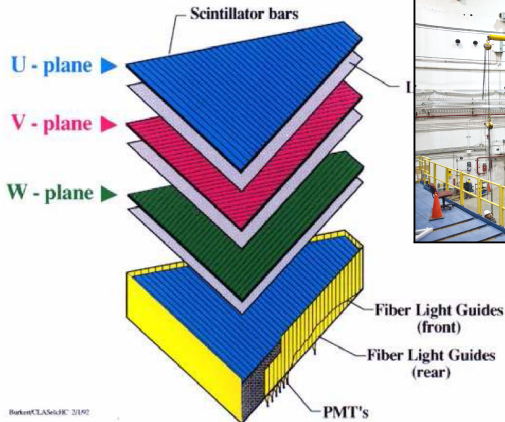
A Simulated CLAS12 Event - Calorimeter close-up



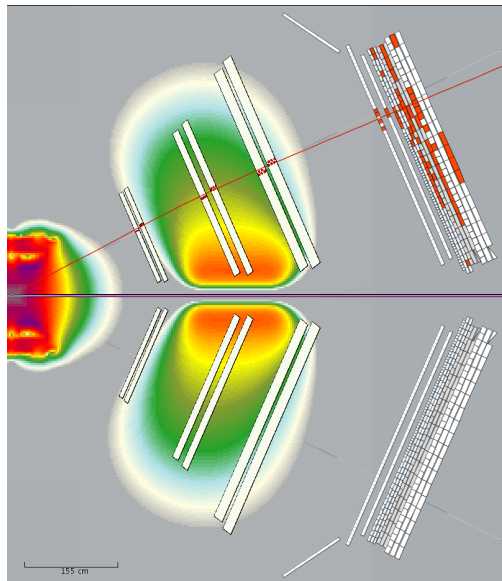
A Simulated CLAS12 Event - Calorimeter close-up



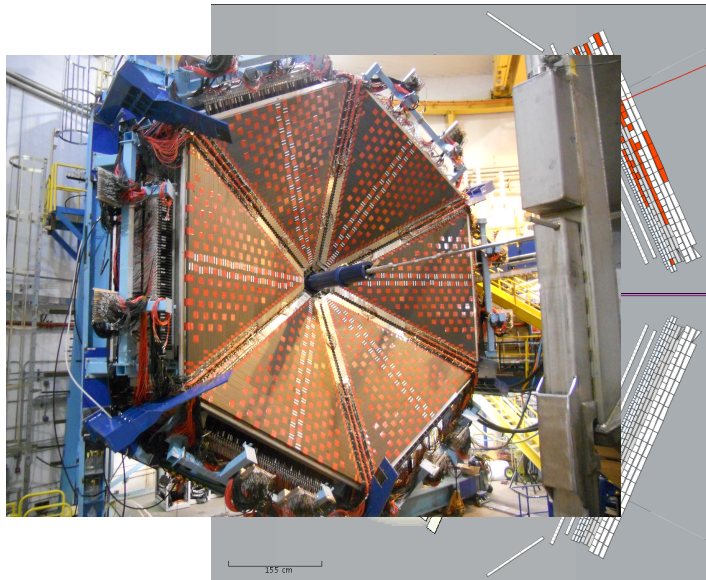
A Simulated CLAS12 Event - Calorimeter close-up



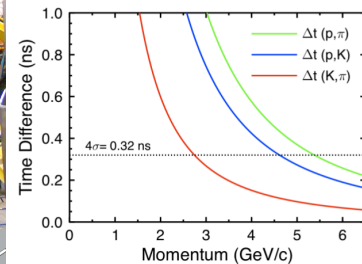
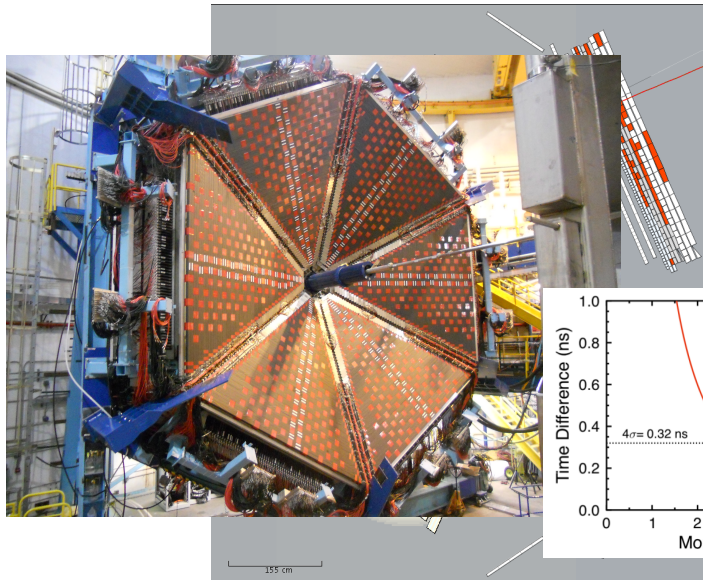
A Simulated CLAS12 Event - Time-of-Flight close-up



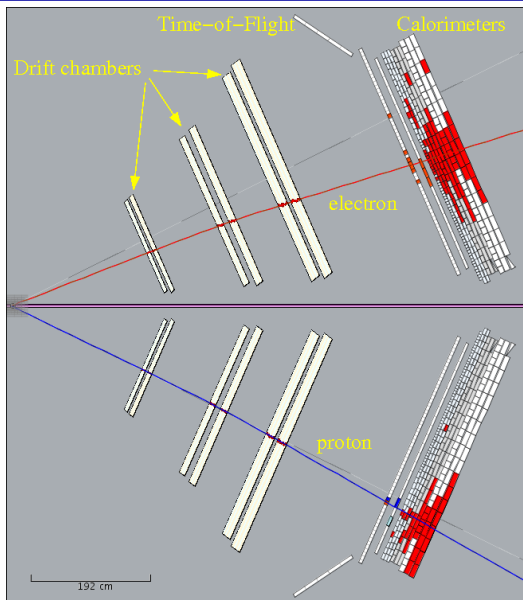
A Simulated CLAS12 Event - Time-of-Flight close-up



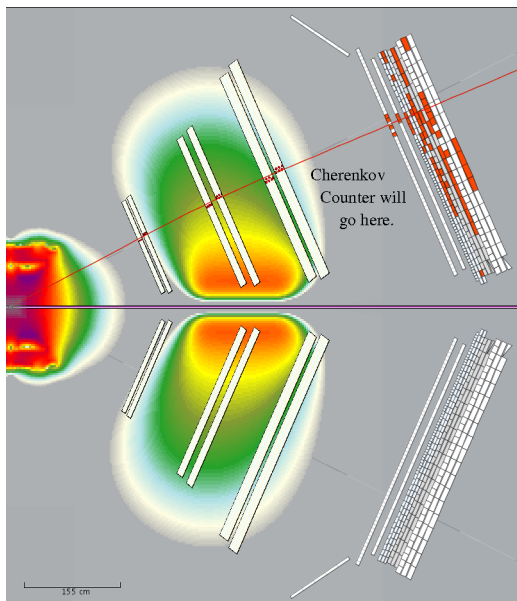
A Simulated CLAS12 Event - Time-of-Flight close-up



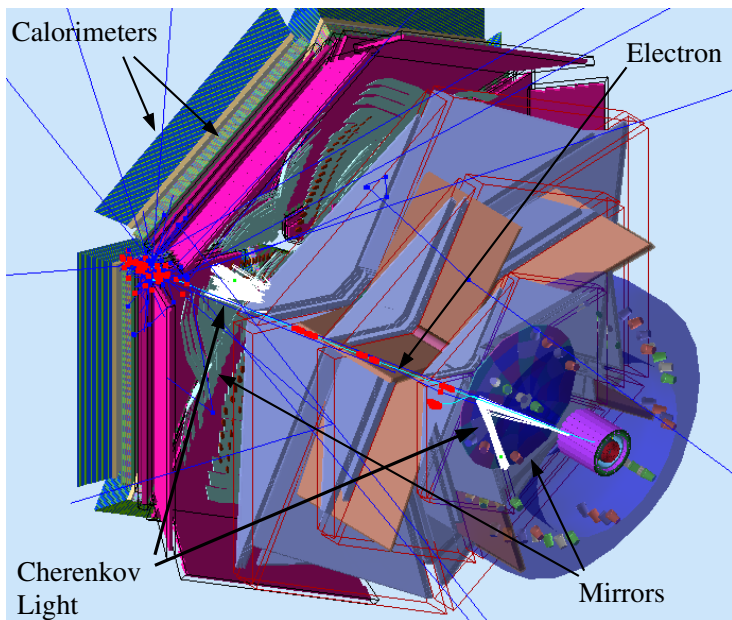
A Simulated CLAS12 Event - Summary



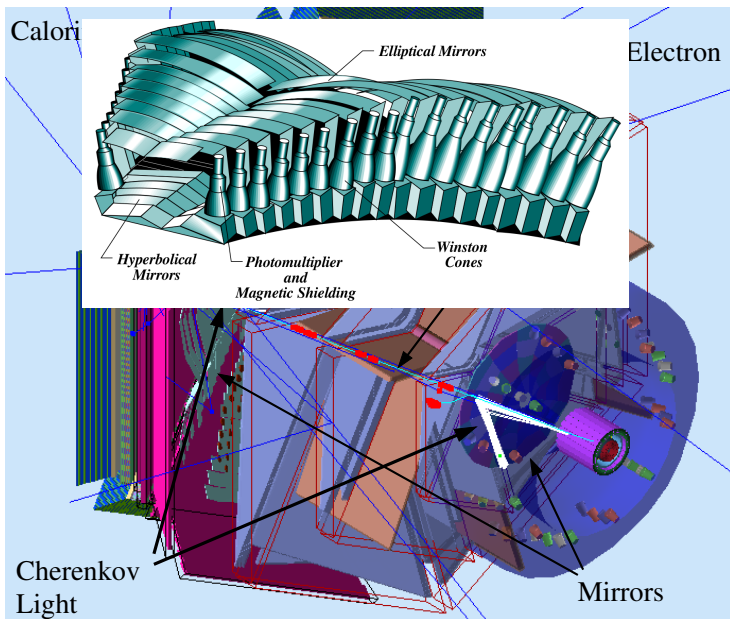
A Simulated CLAS12 Event - Cherenkov close-up



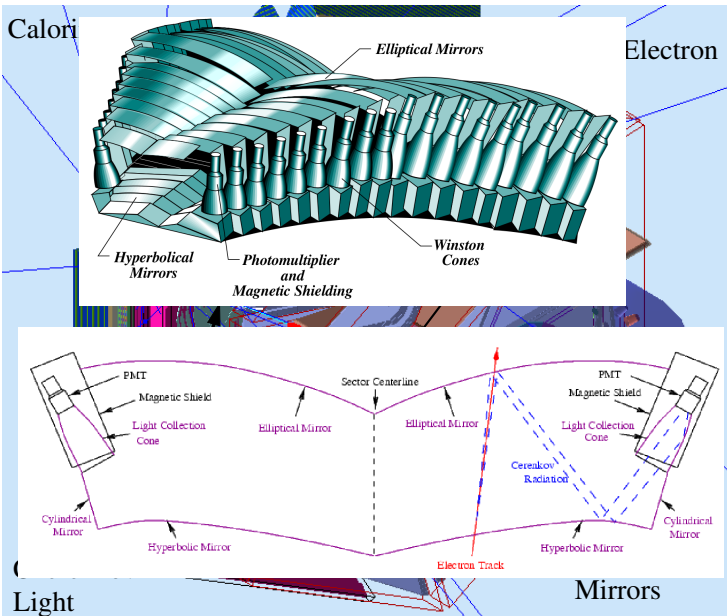
A Simulated CLAS12 Event - Cherenkov close-up



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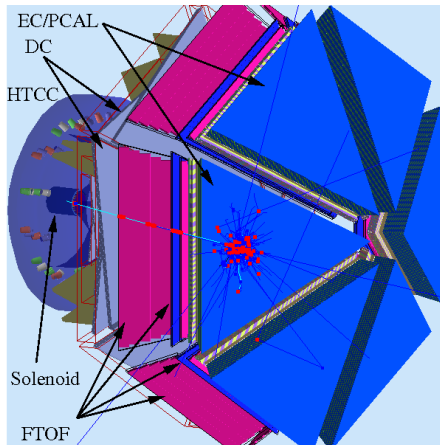


A Simulated CLAS12 Event - Cherenkov close-up



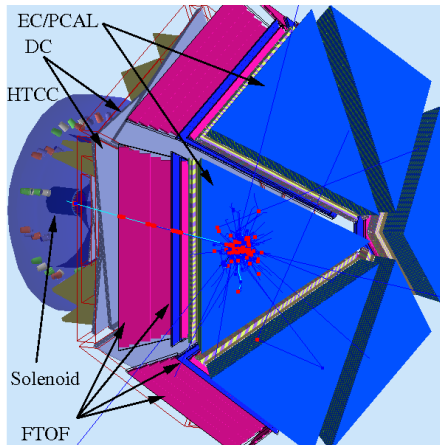
Forward Detector

Central Detector

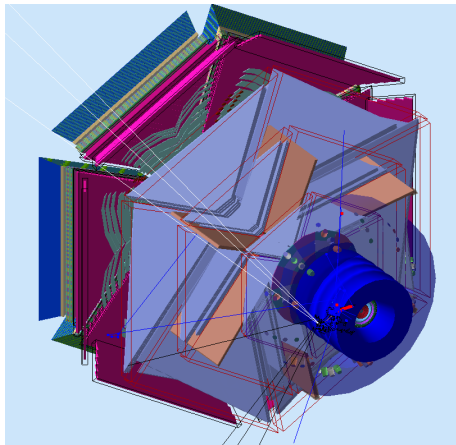


Simulated CLAS12 Events

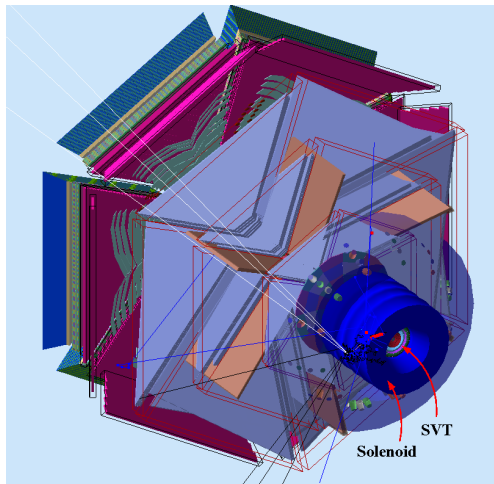
Forward Detector



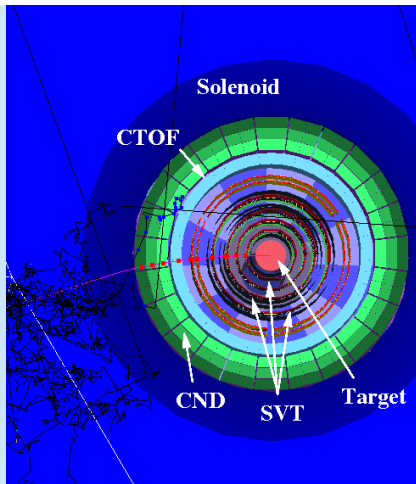
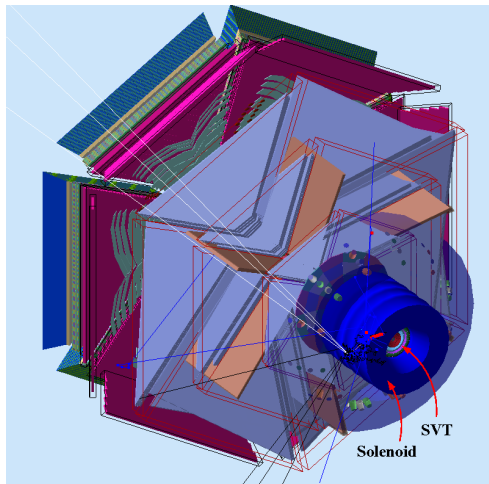
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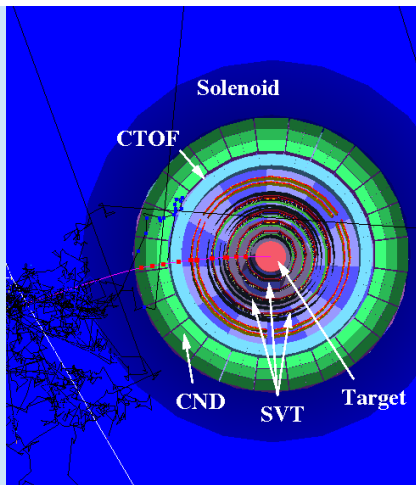
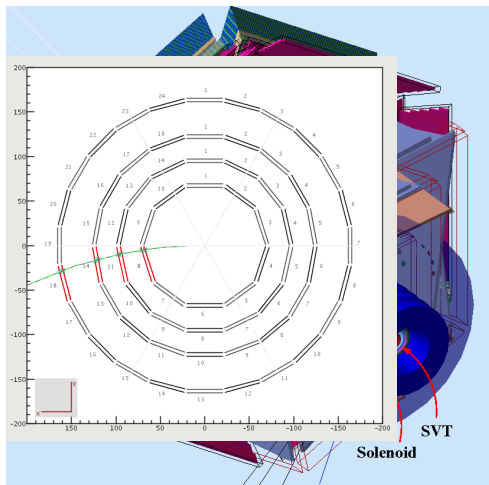
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)



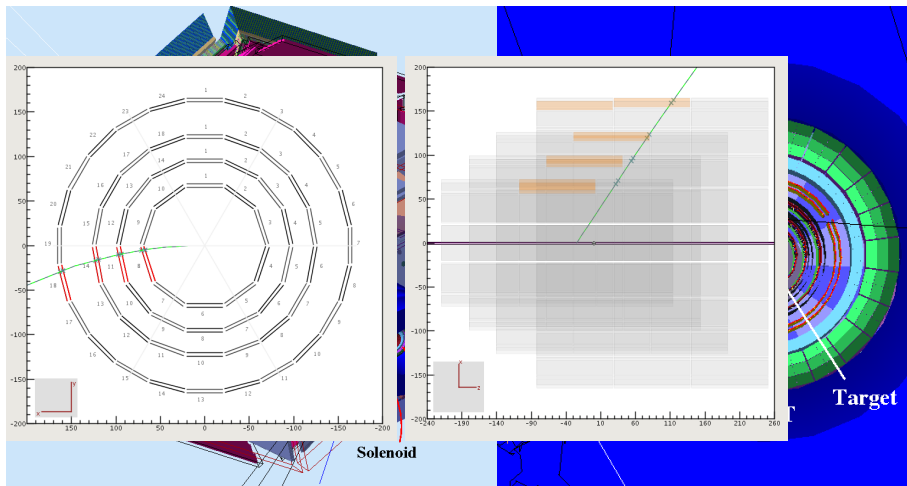
Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)



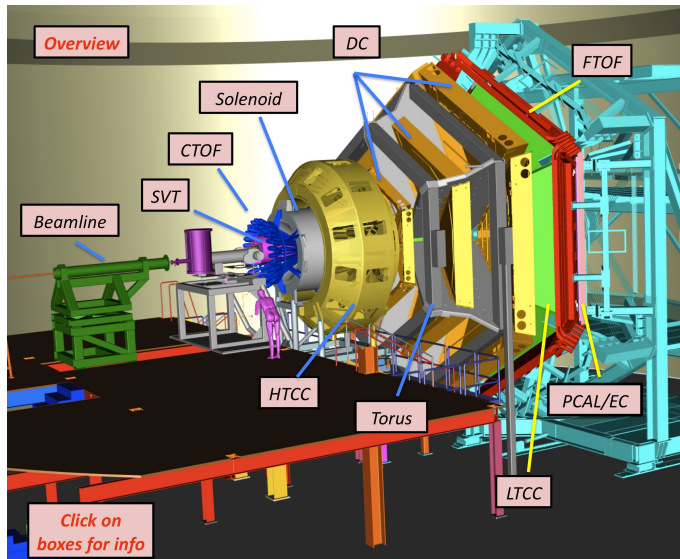
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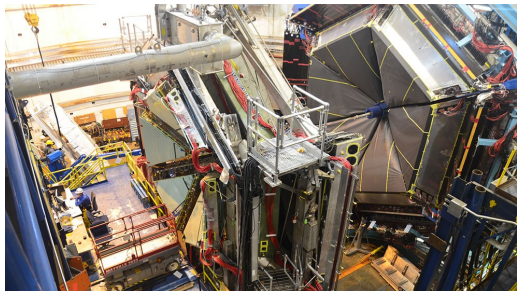
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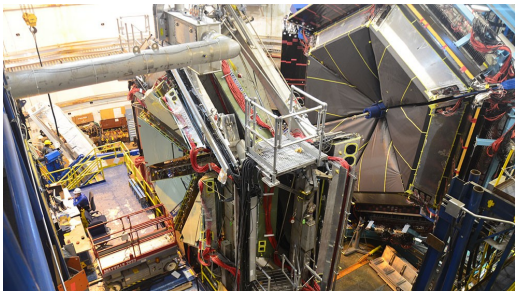
Putting It All Together - 1



Putting It All Together - 2



Putting It All Together - 2



Putting It All Together - 3



Putting It All Together - 3

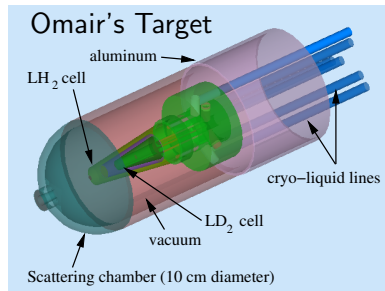


How Do We Measure G_M^n on a Neutron? (Step 3)

- Where's my target?

Use a dual target cell with liquid hydrogen and deuterium.

- How bad do the protons mess things up? They help!

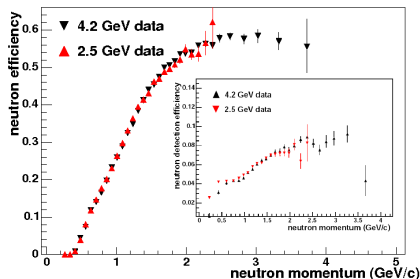
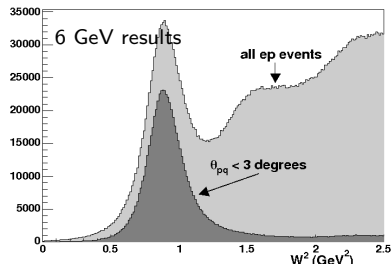


$$R = \frac{\frac{d\sigma}{d\Omega}(D(e, e'n))}{\frac{d\sigma}{d\Omega}(D(e, e'p))} = a(Q^2) \frac{\frac{G_E^{n^2} + \tau G_M^{n^2}}{1 + \tau} + 2\tau G_M^{n^2} \tan^2(\frac{\theta}{2})}{\frac{G_E^{p^2} + \tau G_M^{p^2}}{1 + \tau} + 2\tau G_M^{p^2} \tan^2(\frac{\theta}{2})}$$

- The ratio is less vulnerable to corrections like acceptance, efficiencies, etc.
- Use the dual target to perform *in situ* detector calibrations.

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

- Quasi-elastic event selection: Apply a maximum θ_{pq} cut to eliminate inelastic events plus a cut on W^2 (J.Lachniet thesis).
- Use the $ep \rightarrow e'\pi^+n$ reaction from the hydrogen target as a source of tagged neutrons in the TOF and calorimeter.



How Do We Measure G_M^n on a Neutron? (Step 5)

Analyzing the data - CLAS12 computing requirements.

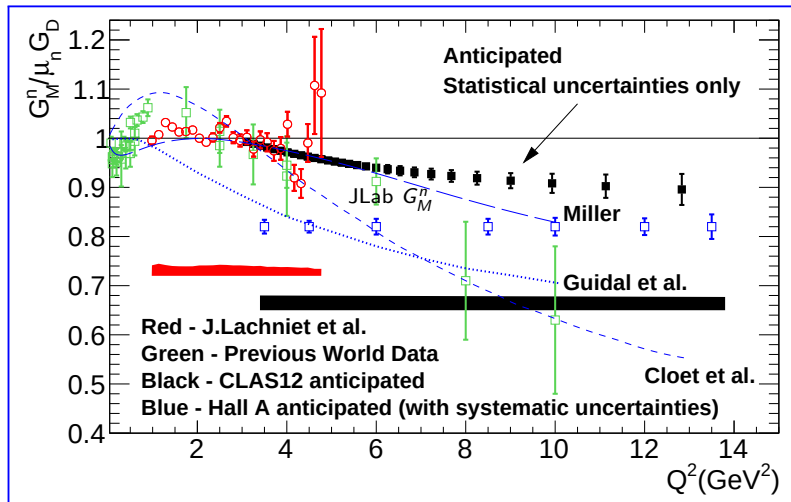
	Cores	Disk(TBytes)	Tape (TByte/year)
DAQ			1,270
Calibration	173		
Reconstruction	1,387	508	5,080
Simulation	8,139	318	1,558
Reconstruction Studies	1,214	508	
Physics Analysis	607	889	
Sum	11,520	2,223	7,938

We'll collect 5-10 TByte/day!

Intel Many-Integrated
CoProcessor computer



Anticipated Results



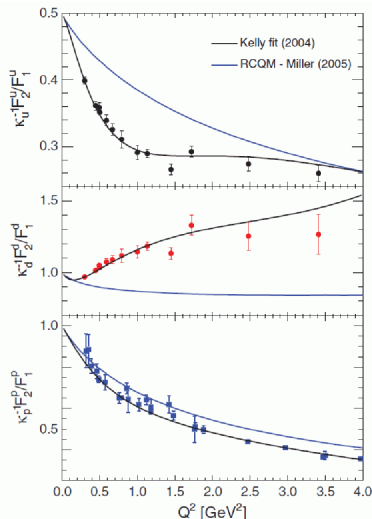
Nuclear Structure - Flavor Decomposition

- By measuring all four EEEFs we have an opportunity to 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))

$$F_{1(2)}^u = 2F_{1(2)}^p + F_{1(2)}^n$$

$$F_{1(2)}^d = 2F_{1(2)}^n + F_{1(2)}^p$$

- u and d are different.
- AND different from the proton and neutron form factors.
- Evidence of di-quarks, s quark influence, ...?



Gordon Cates, Sean Riordan *et al.*, PRL **106**, 252003 (2011).

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

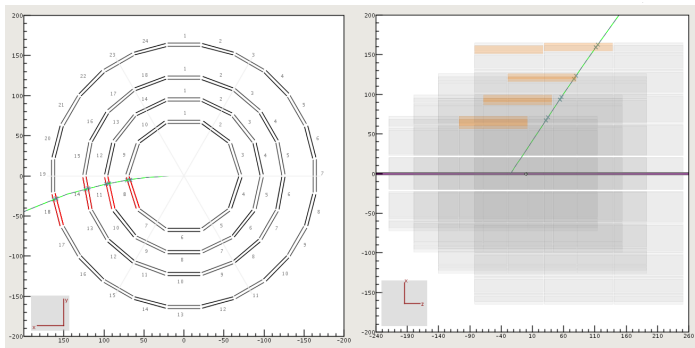
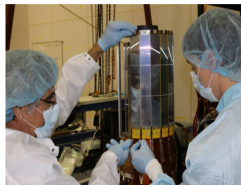
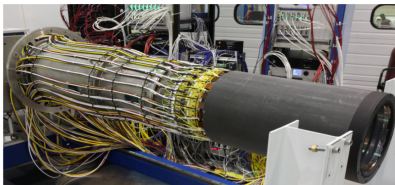


THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

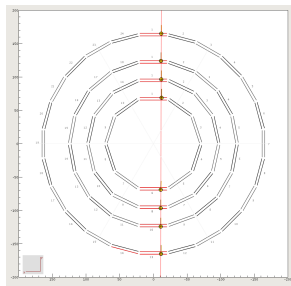
Additional Slides

What's going on now?

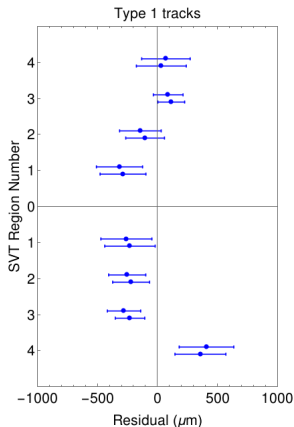
Alignment and commissioning of the silicon vertex tracker (SVT).



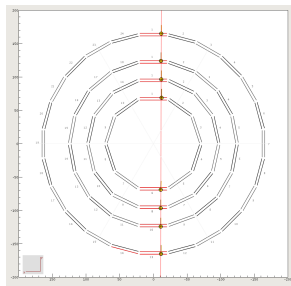
Check alignment with Type1 cosmic ray tracks



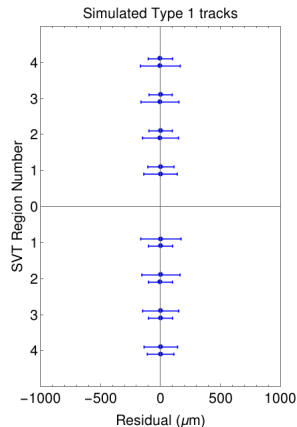
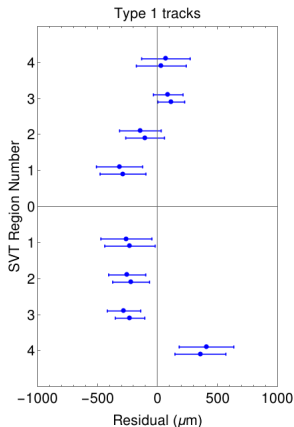
Type 1 tracks.



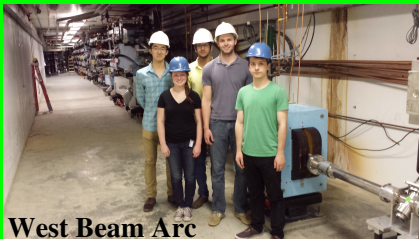
Check alignment with Type1 cosmic ray tracks



Type 1 tracks.



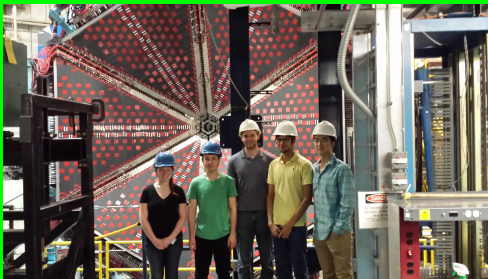
Life on the Frontiers of Knowledge



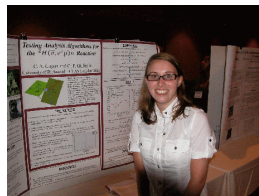
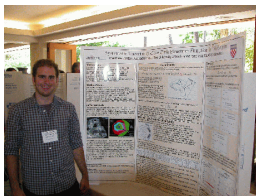
West Beam Arc

**Students from
Richmond (and one
from Surrey) visit
JLab**

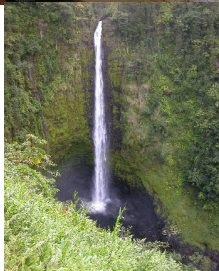
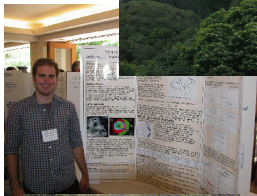
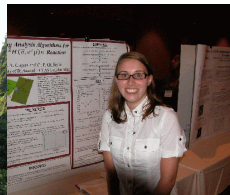
CLAS12 detector



Life on the Frontiers of Knowledge

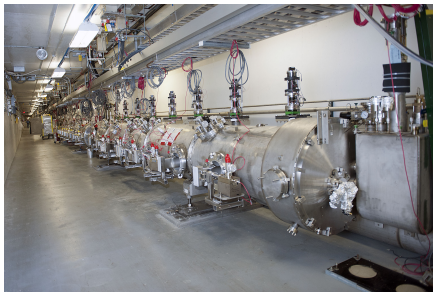
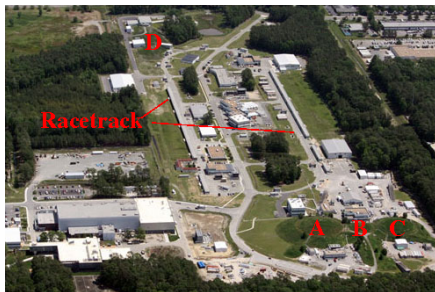


Life on the Frontiers of Knowledge



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 three halls can run simultaneously.



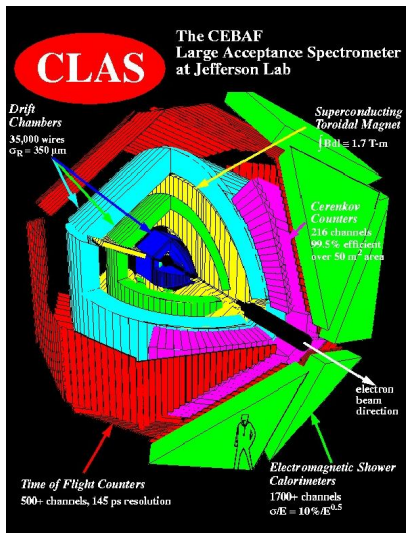
How Do We Measure G_M^n on a Neutron? (Step 2)

- Add one 45-ton, \$50-million radiation detector: the CEBAF Large Acceptance Spectrometer (CLAS).
- CLAS covers a large fraction of the total solid angle.
- Has about 35,000 detecting elements in about 40 layers.

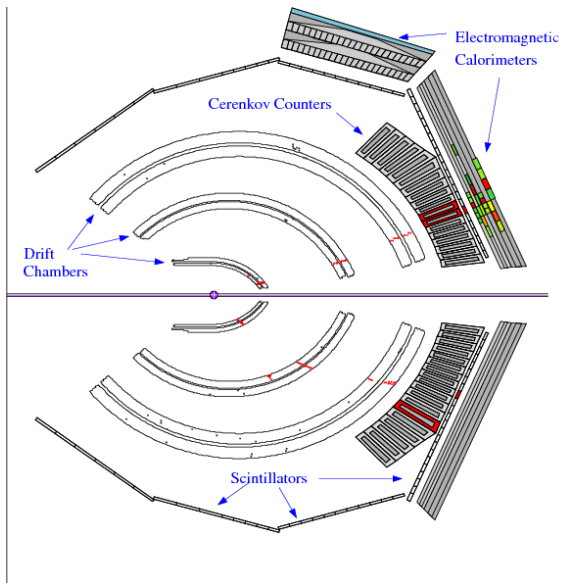


How Do We Measure G_M^n on a Neutron? (Step 2a)

- 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.



A CLAS Event



How Do We Measure G_M^n on a Neutron? (Step 3)

- Where's my target?

Use a dual target cell with liquid hydrogen and deuterium.

- How bad do the protons mess things up? They help!

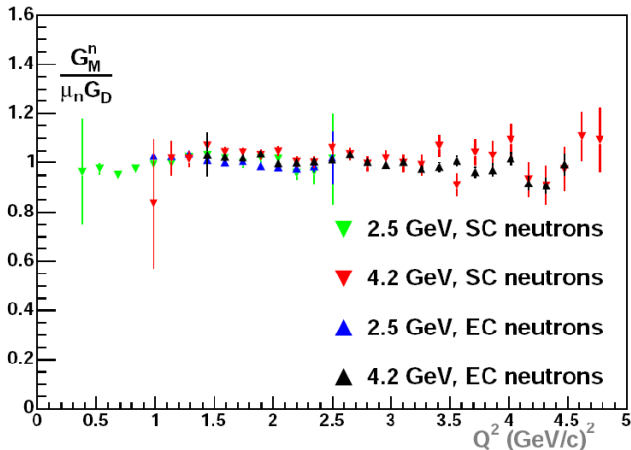


$$R = \frac{\frac{d\sigma}{d\Omega}(D(e, e'n))}{\frac{d\sigma}{d\Omega}(D(e, e'p))} = a(Q^2) \frac{\frac{G_E^{n2} + \tau G_M^{n2}}{1 + \tau} + 2\tau G_M^{n2} \tan^2(\frac{\theta}{2})}{\frac{G_E^{p2} + \tau G_M^{p2}}{1 + \tau} + 2\tau G_M^{p2} \tan^2(\frac{\theta}{2})}$$

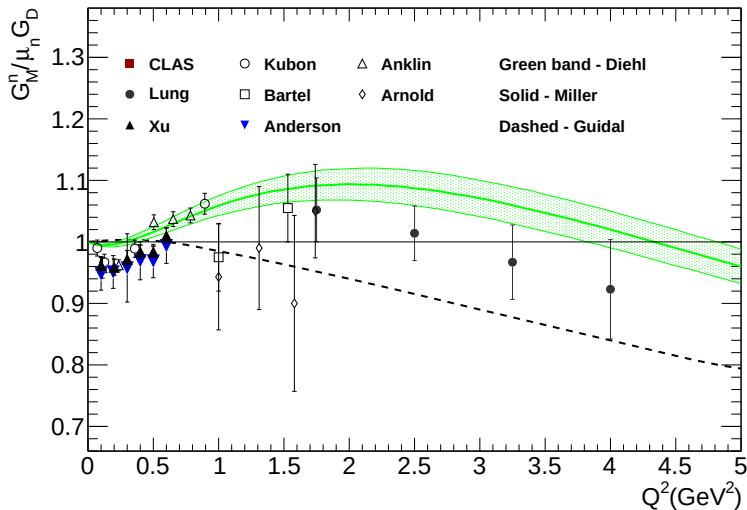
- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc.*
- Use the dual target to perform *in situ* detector calibrations.

Results - Overlaps and Final Average

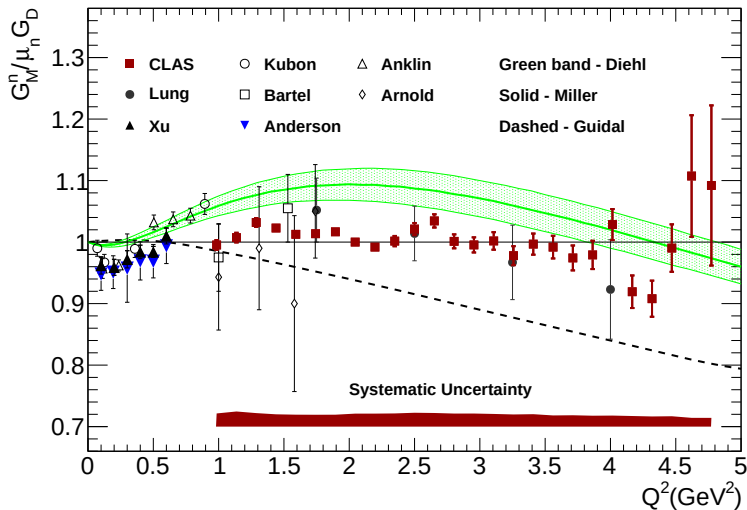
Overlapping measurements of G_M^n scaled by the dipole are consistent.



Results - Comparison with Existing Data

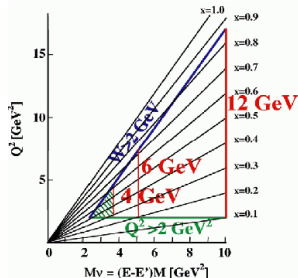
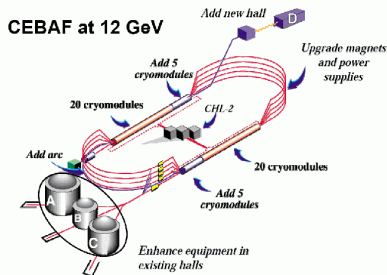


Results - Comparison with Existing Data

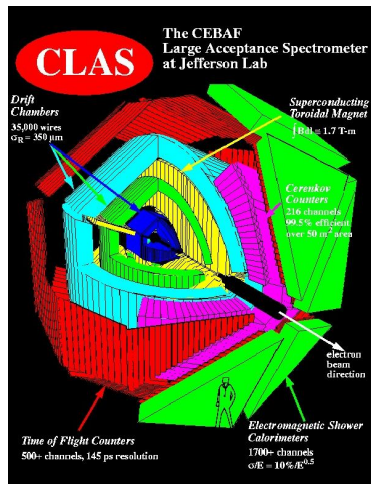
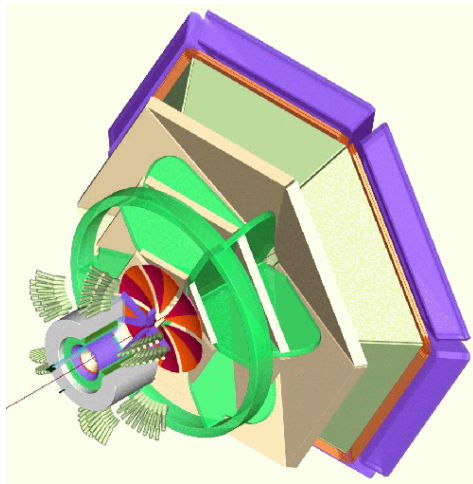


JLab 12 GeV Upgrade - Better Accelerator

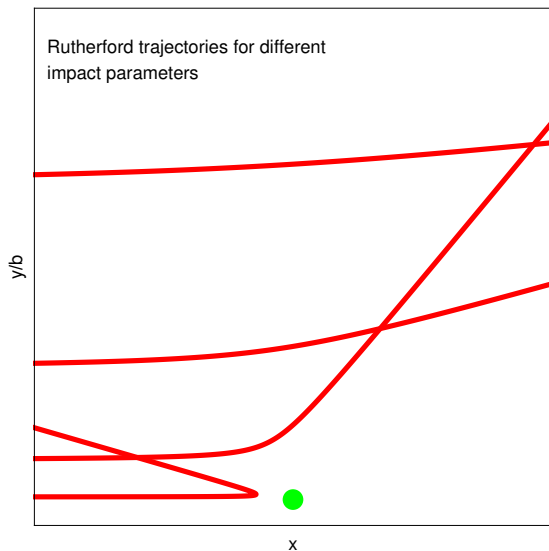
- The electron beam energy at JLab (CEBAF) has been doubled from 6 GeV to 12 GeV.
- Halls A, B and C will be upgraded to accommodate the new physics opportunities.
- A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.



JLab 12 GeV Upgrade - New Detectors

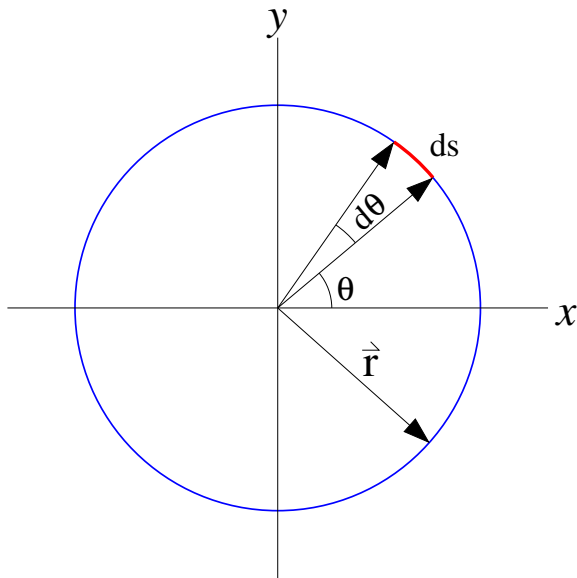


Rutherford Trajectories



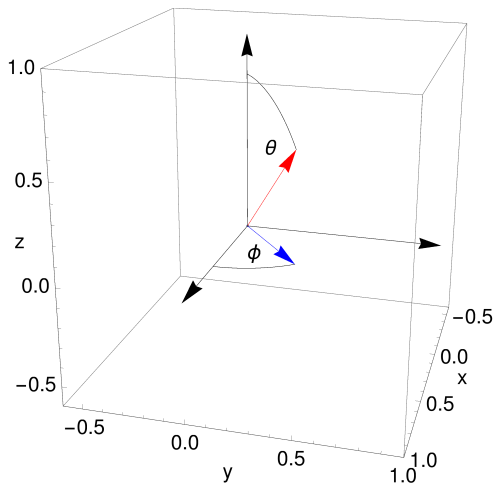
What is an Angle?

What is an Angle?

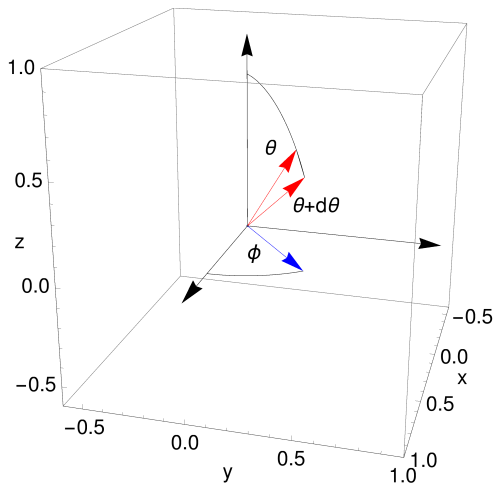


$$d\theta = \frac{ds}{|\vec{r}|}$$

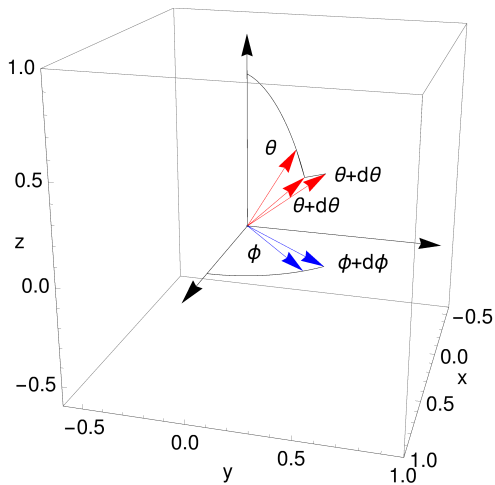
Solid Angle



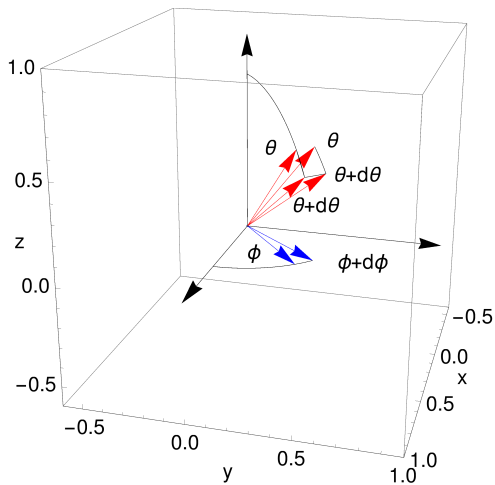
Solid Angle



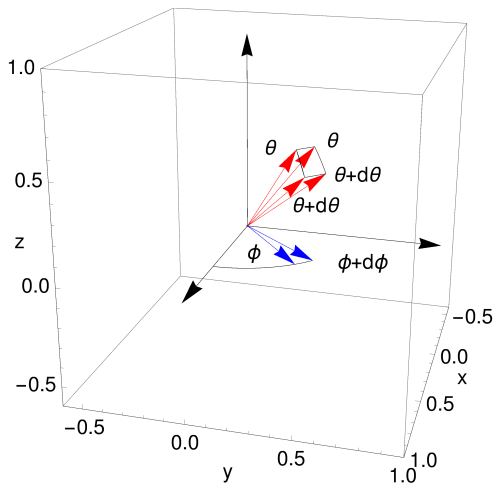
Solid Angle



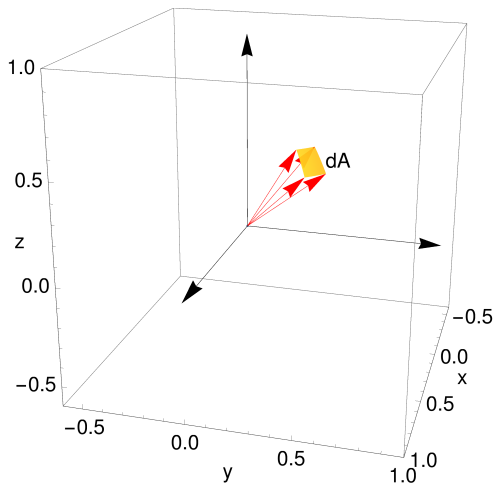
Solid Angle



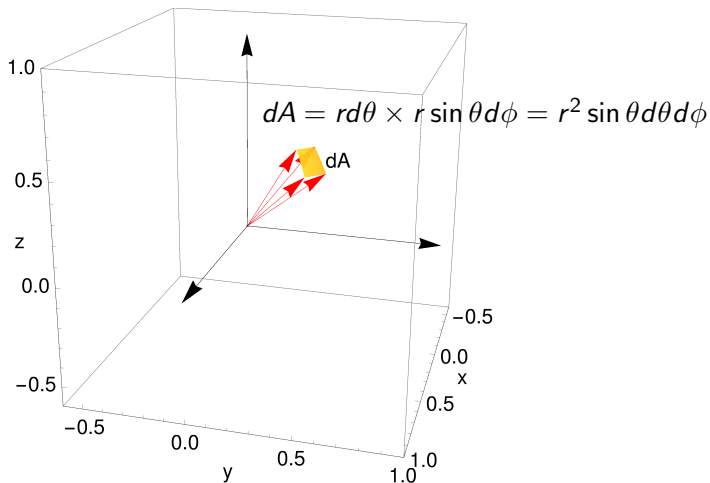
Solid Angle



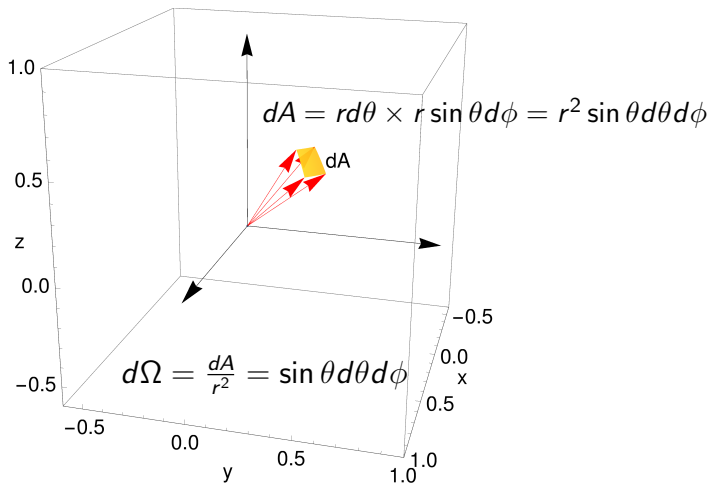
Solid Angle



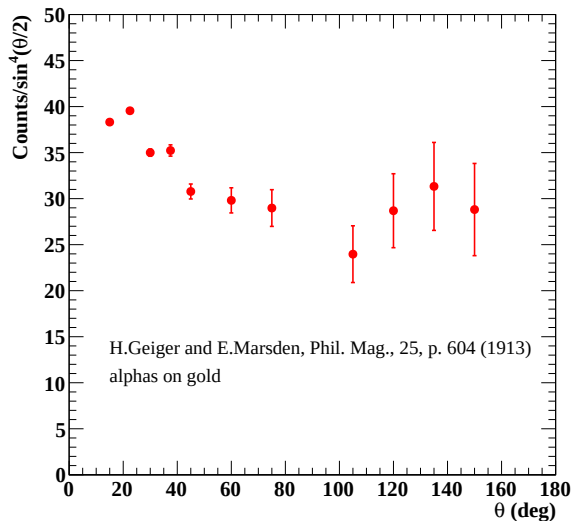
Solid Angle



Solid Angle

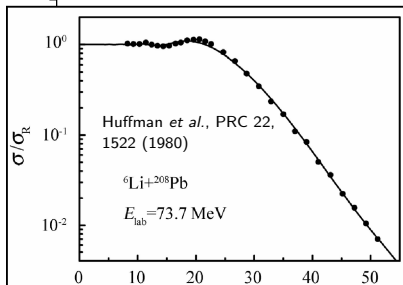
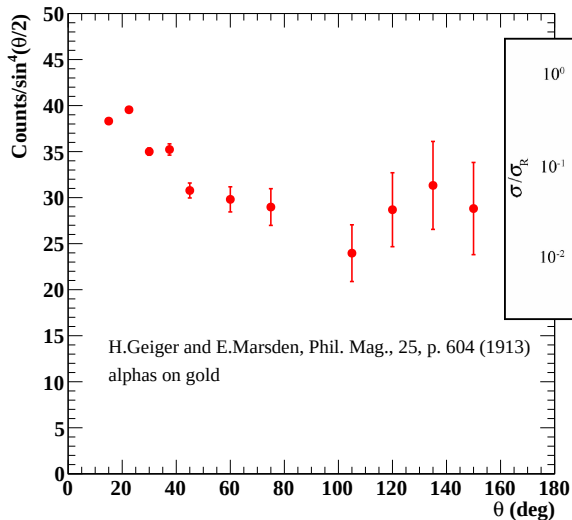


Rutherford Scattering Results From Rutherford



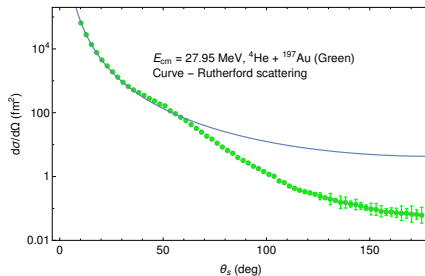
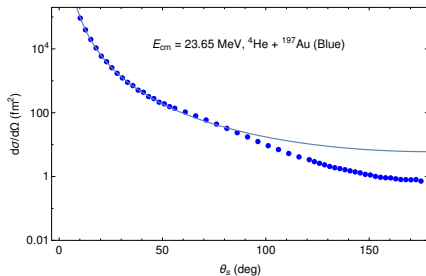
2016-12-18 10:38:14

Rutherford Scattering Results From Rutherford



2016-12-18 10:38:14

Plotting the Homework (no. 10)



Plotting the Homework (no. 10)

