# Hunting for Quarks

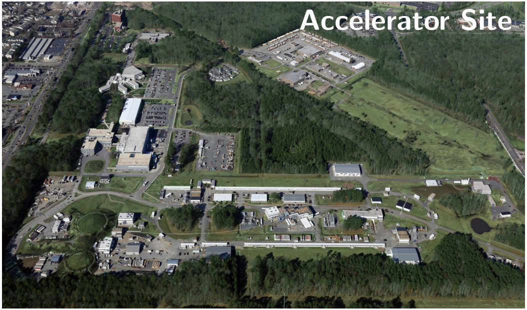
*Jerry Gilfoyle for the CLAS Collaboration*
*University of Richmond*


"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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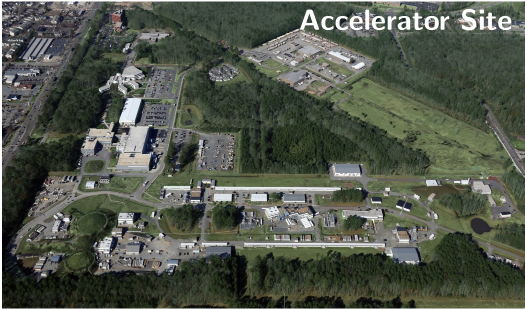


One of the seven Millenium Prize Problems from the Clay Mathematics Institute.

# 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 | | |
|---|---|---|
| Name | Mass GeV/c$^2$ | Electric charge |
| $\gamma$ photon | 0 | 0 |
| W$^-$ | 80.39 | −1 |
| W$^+$ W bosons | 80.39 | +1 |
| Z$^0$ Z boson | 91.188 | 0 |

| Strong (color) spin = 1 | | |
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| Name | Mass GeV/c$^2$ | Electric charge |
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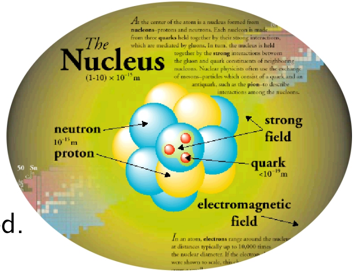
- The atomic nucleus is made of protons and neutrons bound by the strong force.
- The quarks are confined inside the protons and neutrons.
- Protons and neutrons are NOT confined.



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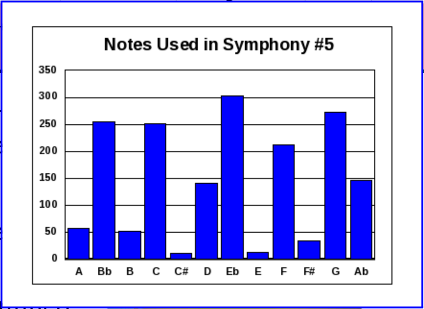


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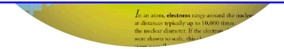

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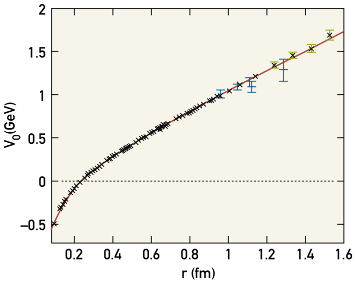
- Quantum chromodynamics (QCD) looks like the right way to get the force at high energy.



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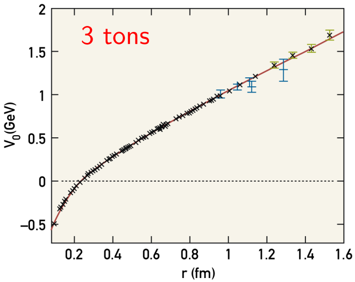

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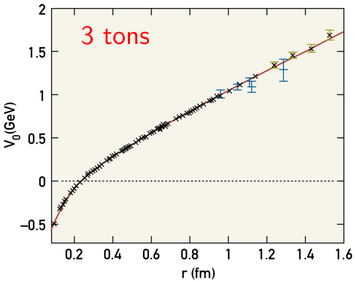
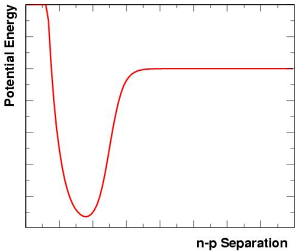
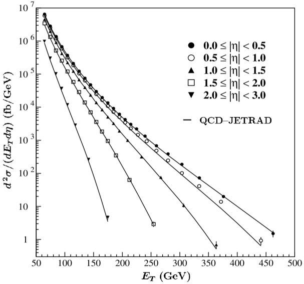



- The hadronic model uses a phenomenological force fitted to data at low energy. This 'strong' force is the residual force between quarks.



# 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)).

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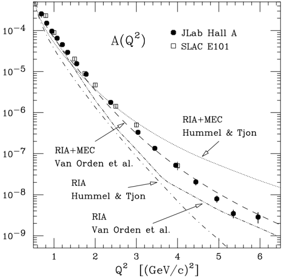

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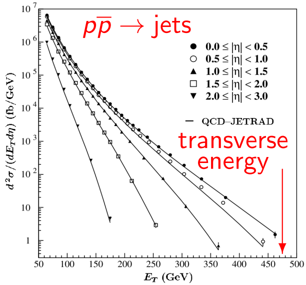


effective target area

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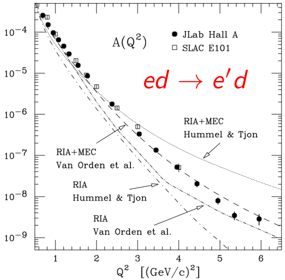


4-momentum transfer squared

# 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.
- Neutron $\rightarrow$ 1 up + 2 downs.

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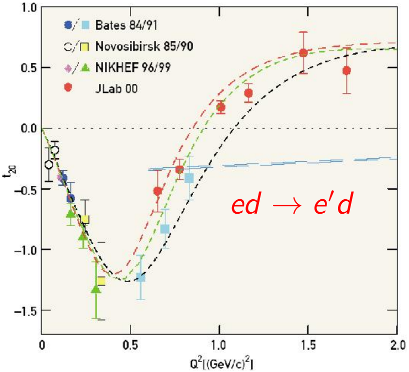
- $m_n - m_p = 1.29333205(48)\ MeV/c^2$ (exp) $= 1.51(16)(23)\ MeV/c^2$ (th)

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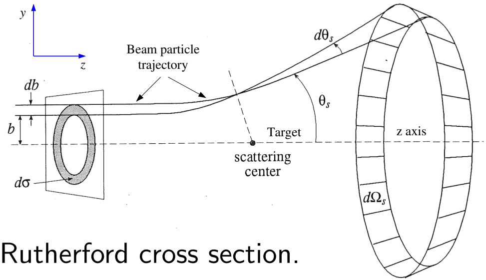
- Fundamental quantity related to the distribution of magnetization/currents in the neutron.
- Needed to extract the distribution of quarks in the neutron.
- Elastic form factors ($G_M^n$, $G_E^n$, $G_M^p$, and $G_E^p$) provide key constraints on theory and the structure of hadrons.
- Part of a broad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

* '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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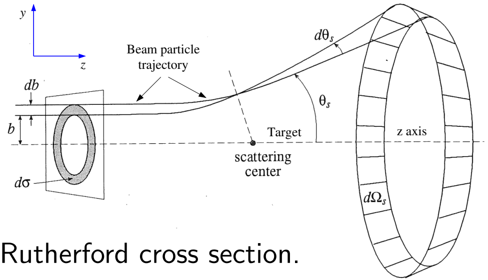


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- Cross section for elastic scattering by point particles with spin.

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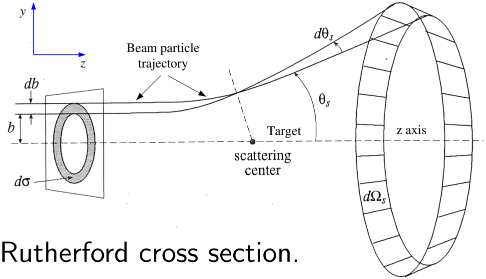


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where $Q^2$ is the 4-momentum transfer.

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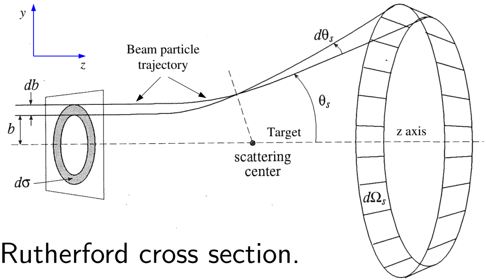


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THE FORM FACTOR!

# Why Should You Care?

- The chain of reason.

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

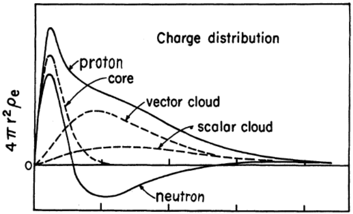
**Experiment** **Comparison** **Theory**

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

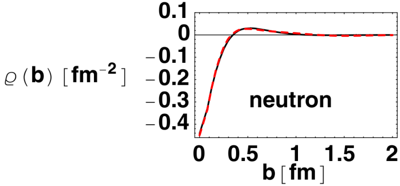
- The Fourier transform of the form factors are related to the charge and current distributions within the neutron.

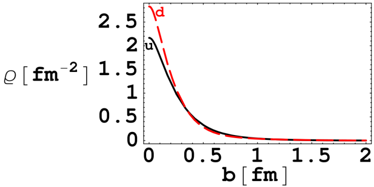
# Why Should You Care Even More?

- 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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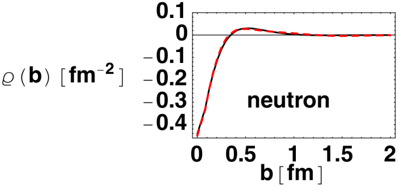
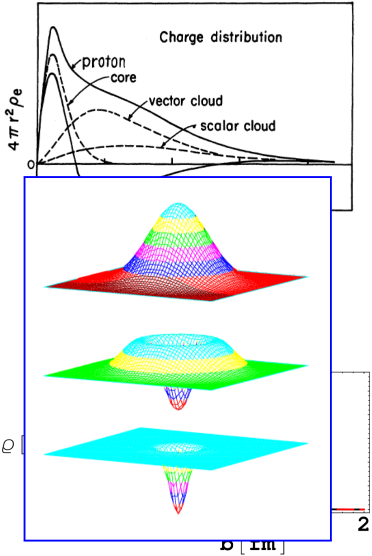


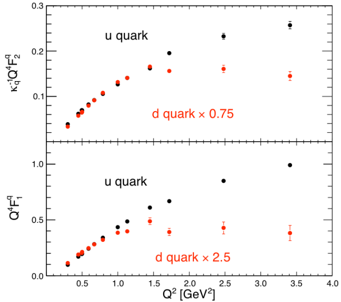



# What We'll Learn - Flavor Decomposition

- 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.




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

# What We'll Learn - Flavor Decomposition

- With all four EEFFs we can unravel the contributions of the *u* and *d* quarks.
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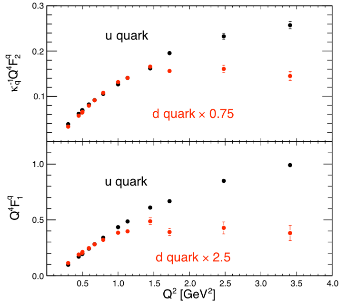

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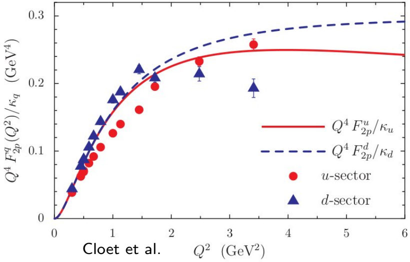

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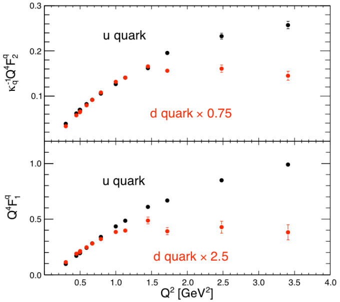


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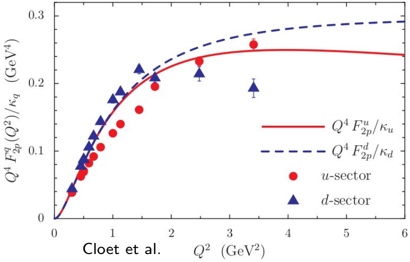


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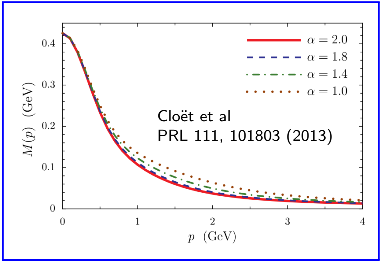
The JLab program will double our reach in $Q^2$ to $\approx 8$ $GeV^2$.

# 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 → Choose well!

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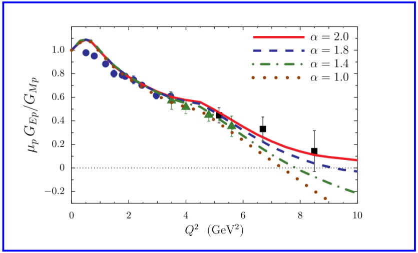

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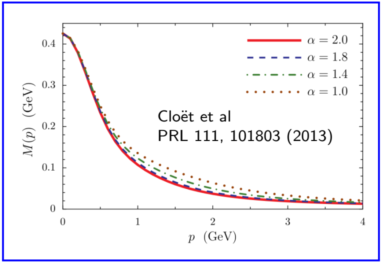


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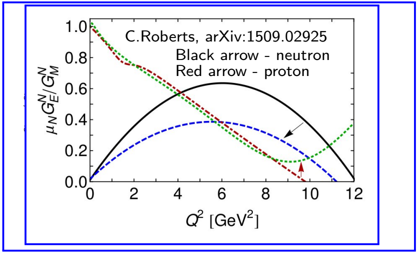

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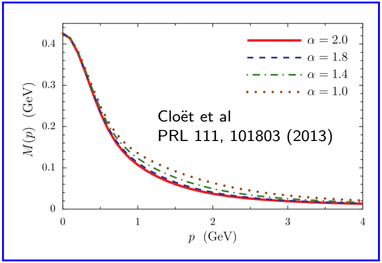


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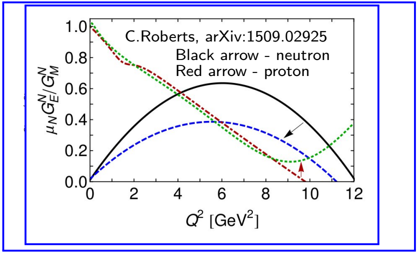
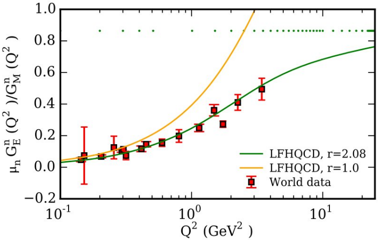



Position of zero in $\mu_p G_E^p/G_M^p$ and $\mu_n G_E^n/G_M^n$ sensitive to shape of $M(p)$!

# 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. Recent paper by Sufian *et al.* (Phys. Rev. D95, 01411 (2017)) included calculations of the electromagnetic form factors that include higher order Fock components $|qqqq\overline{q}\rangle$.
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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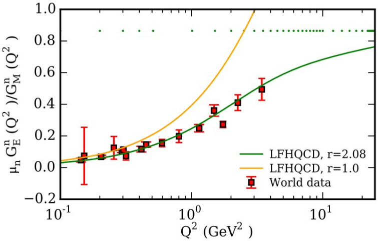
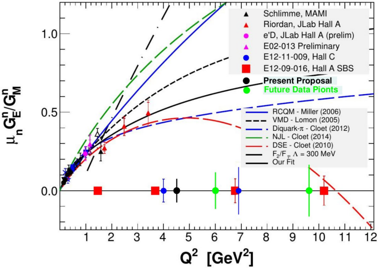


# What We'll Learn - The Campaign

**The JLab Lineup**

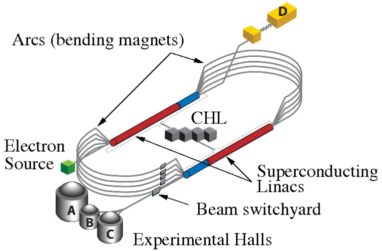
| Quantity | Method | Target | $Q^2 (GeV^2)$ | Hall | Beam Days |
|---|---|---|---|---|---|
| $G_M^p$ * | Elastic scattering | $LH_2$ | $7 - 15.5$ | A | 24 |
| $G_E^p/G_M^p$ | Polarization transfer | $LH_2$ | $5 - 12$ | A | 45 |
| $G_M^n$ | $E - p/e - n$ ratio | $LD_2, LH_2$ | $3.5 - 13.0$ | B | 30 |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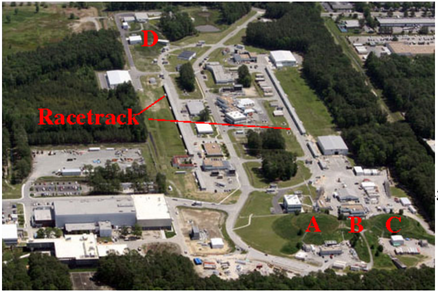

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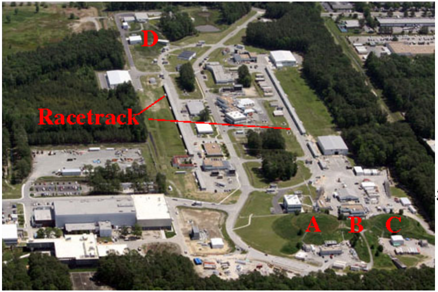
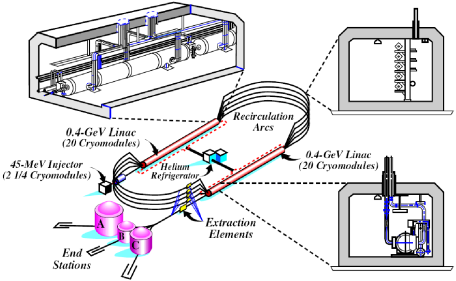
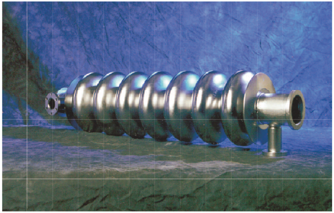



# How Does CEBAF Do That?

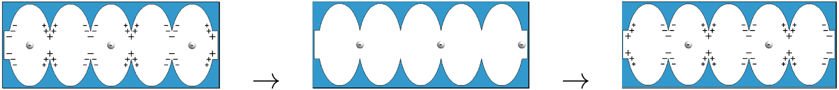
Accelerate your electrons to high energy.



*Cavity*

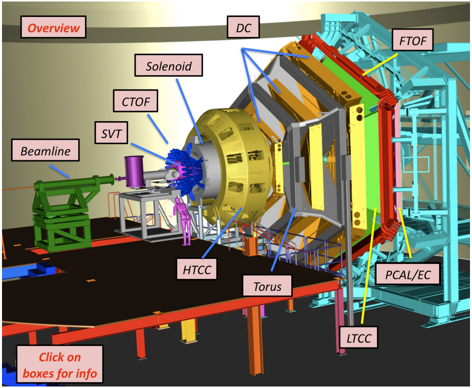
What happens inside the cavity? Feed it with oscillating, radio-frequency power at 1.5 GHz! In each hall beam buckets are about 2 picoseconds long and arrive every 2 nanoseconds.



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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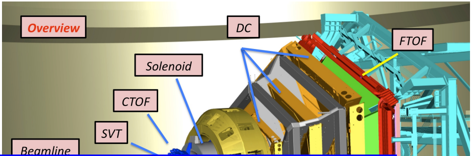


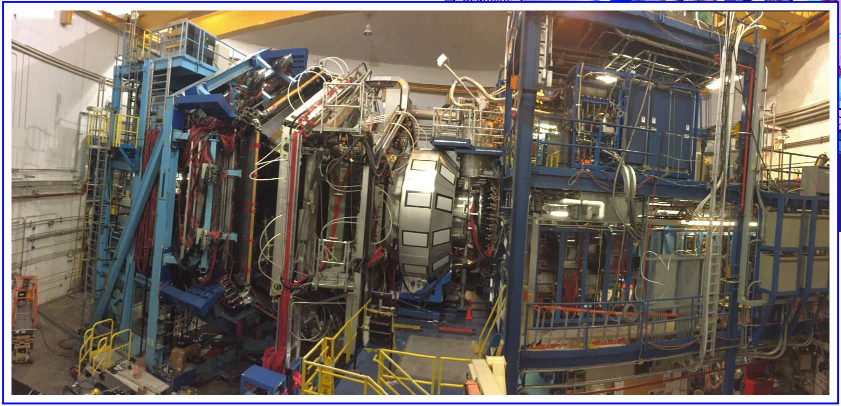

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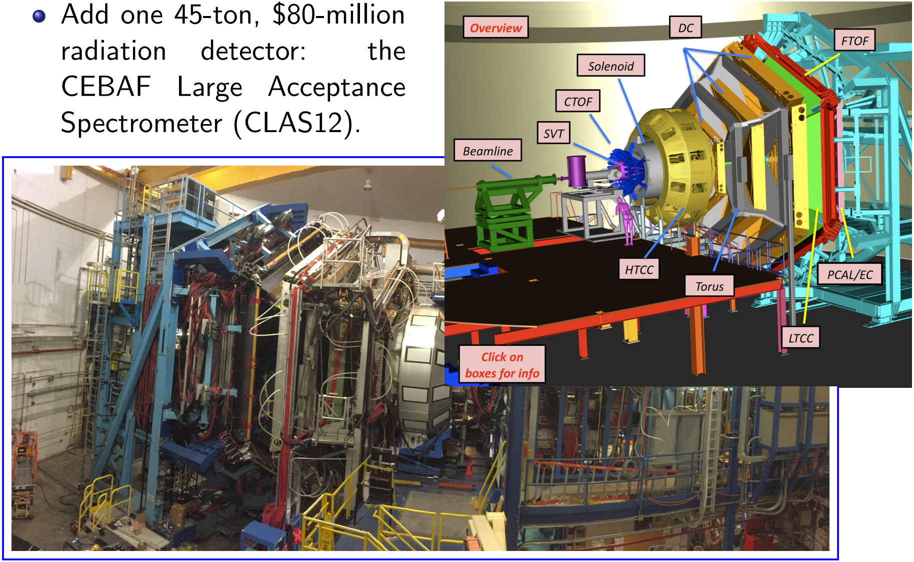
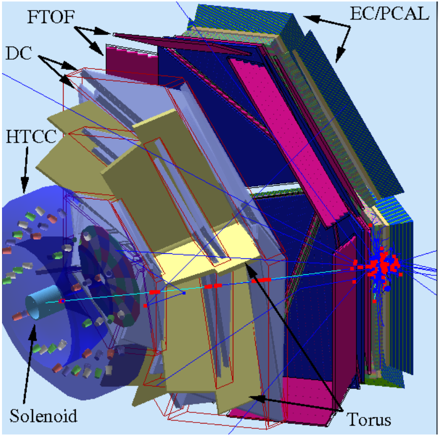
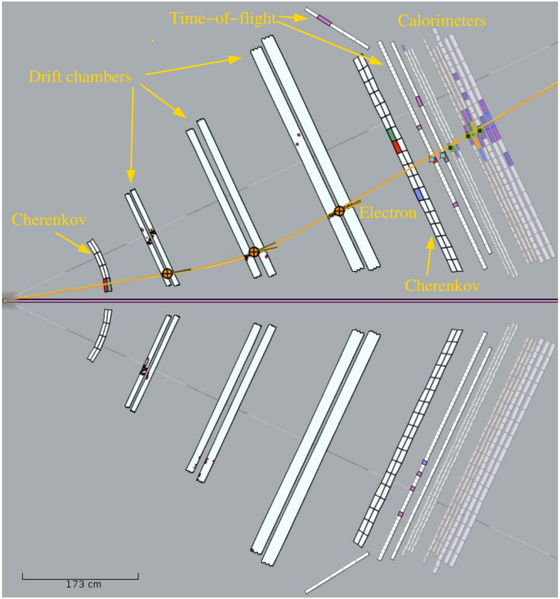


# How Do We Measure $G_M^n$ on a Neutron? (Step 2a)

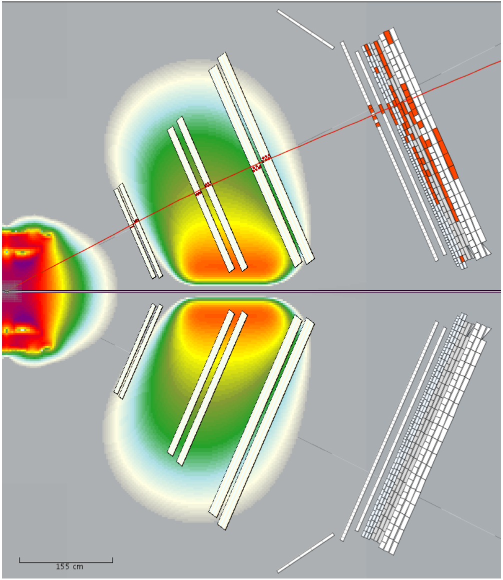
- Drift chambers map the trajectories. A toroidal magnetic field bends the particles to measure momentum.
- Other layers measure energy, time-of-flight, and particle identification.
- Each collision is reconstructed and the intensity pattern reveals the forces and structure of the colliding particles.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



# A CLAS12 Event



# A Simulated CLAS12 Event - Drift Chamber close-up



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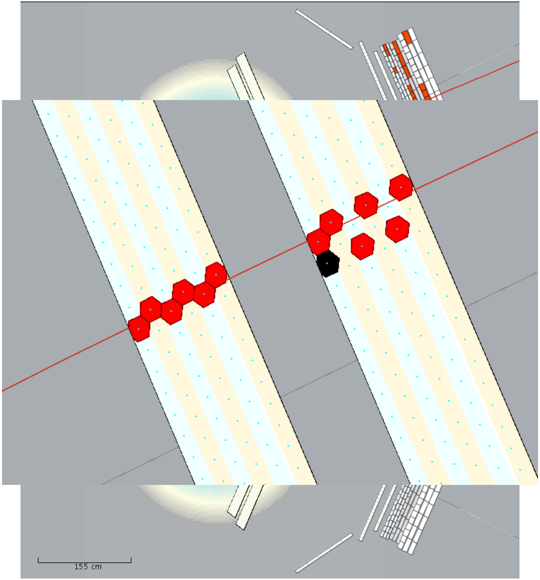

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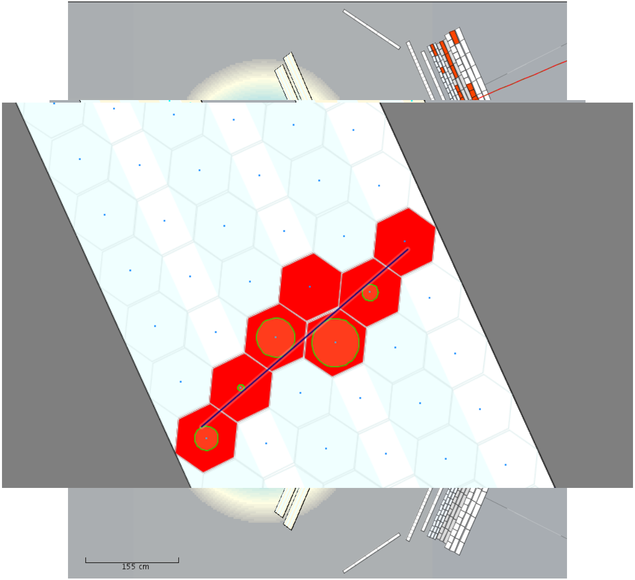
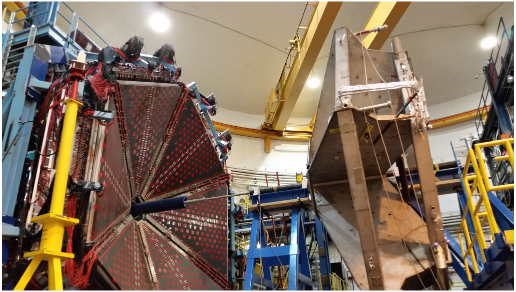


# A Real CLAS12 Event - Building the Drift Chambers



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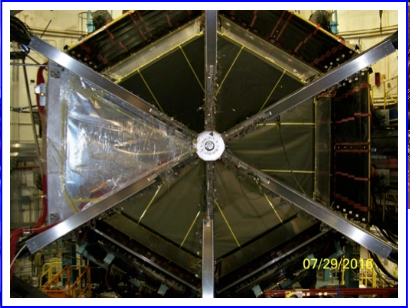


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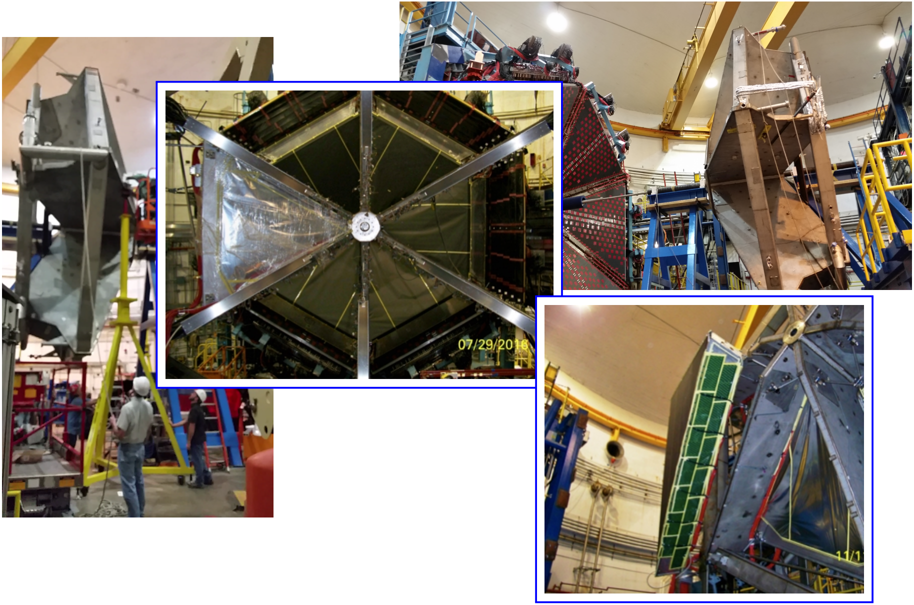

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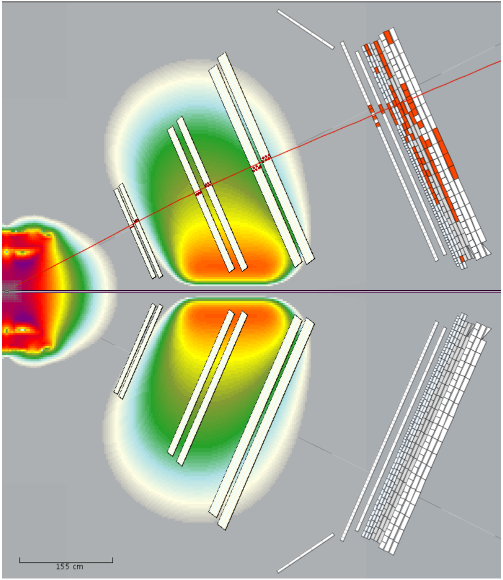

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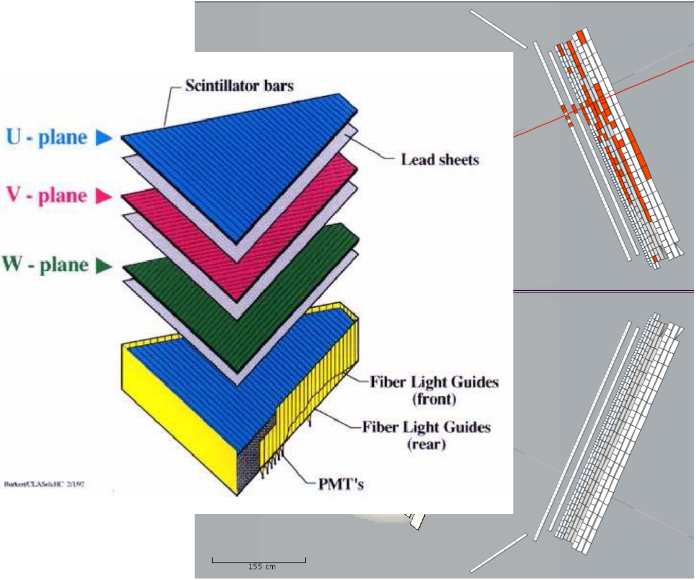

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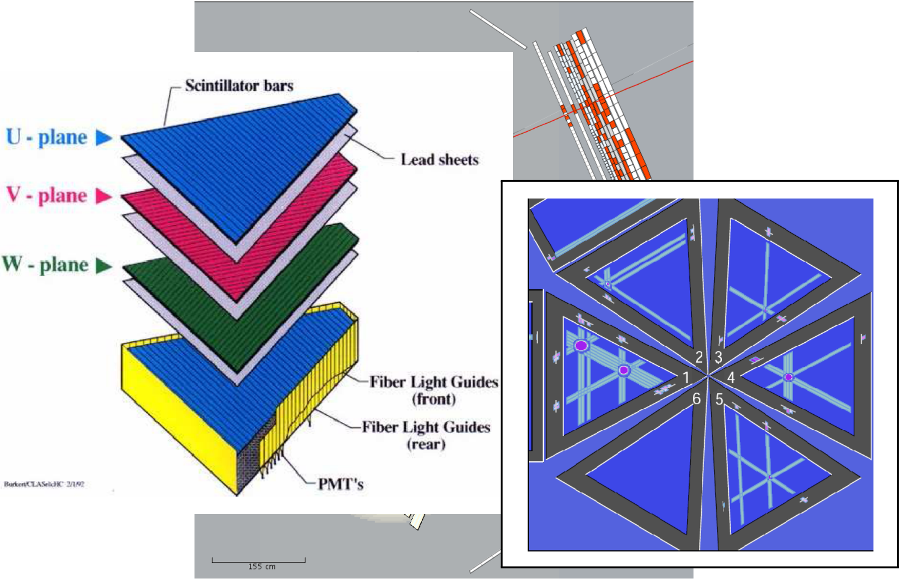

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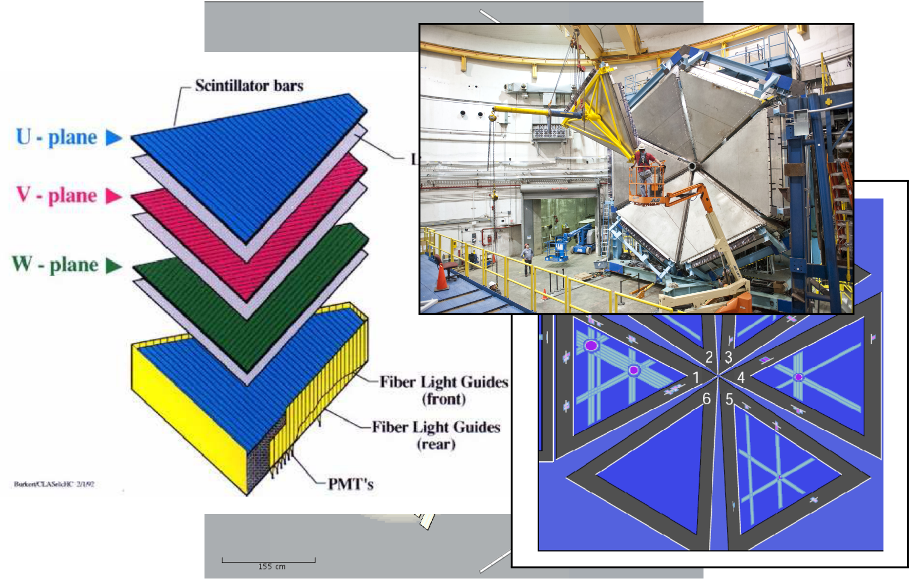
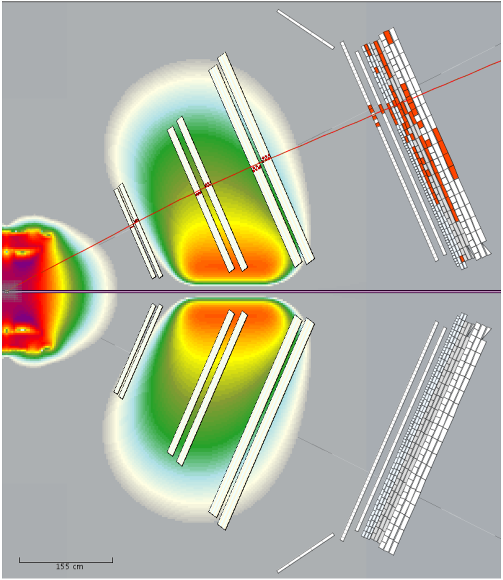


# A Simulated CLAS12 Event - Time-of-Flight close-up



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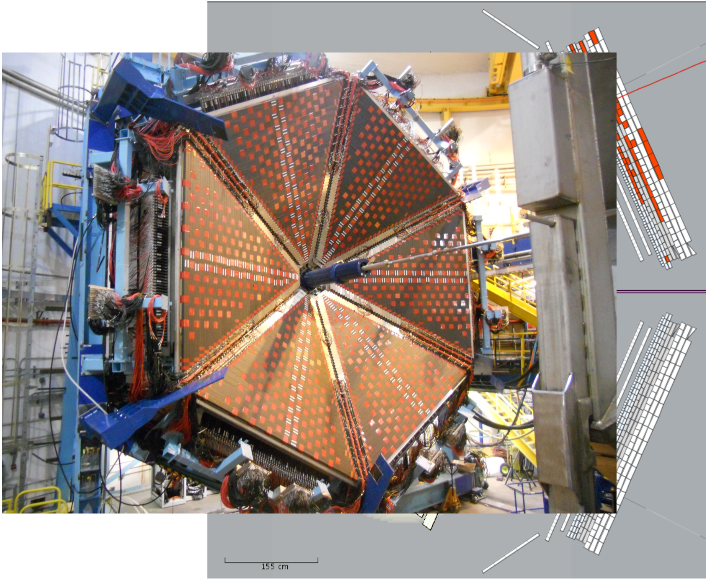

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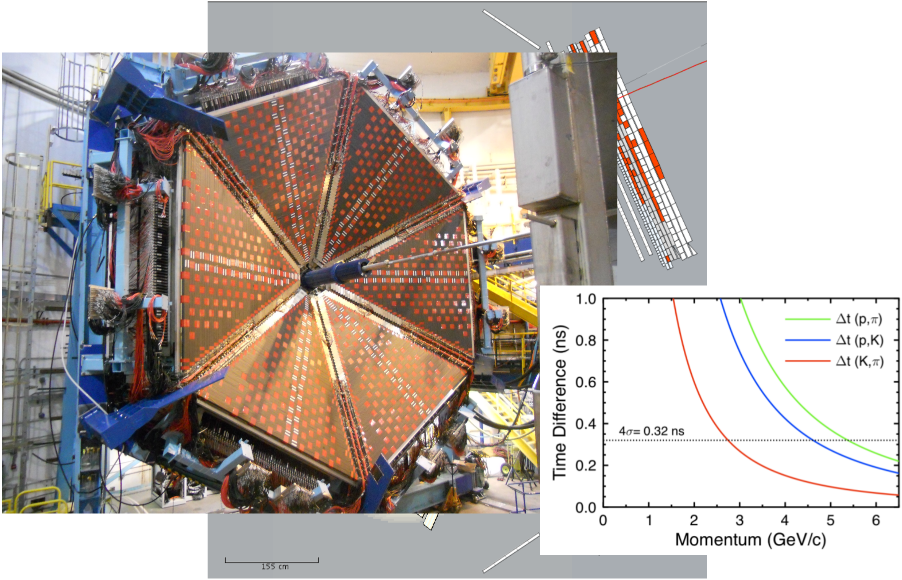
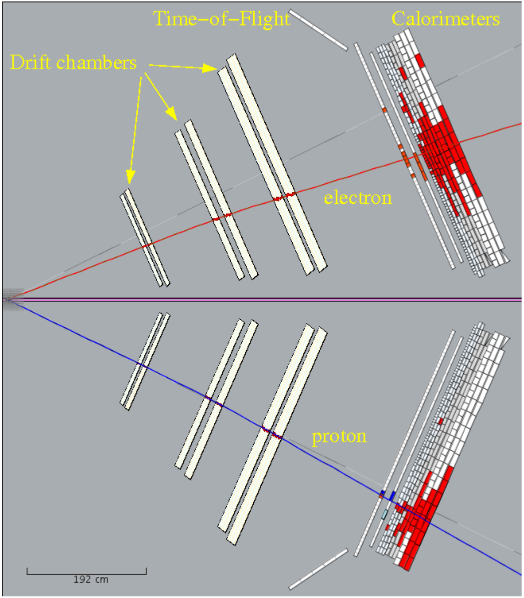
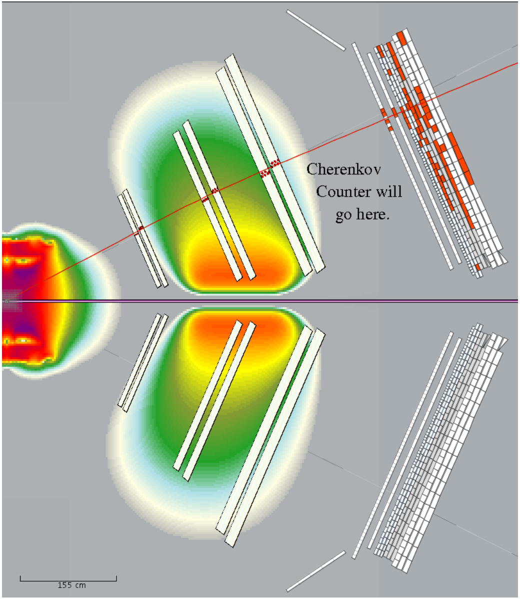


# A Simulated CLAS12 Event - Summary



# A Simulated CLAS12 Event - Cherenkov close-up



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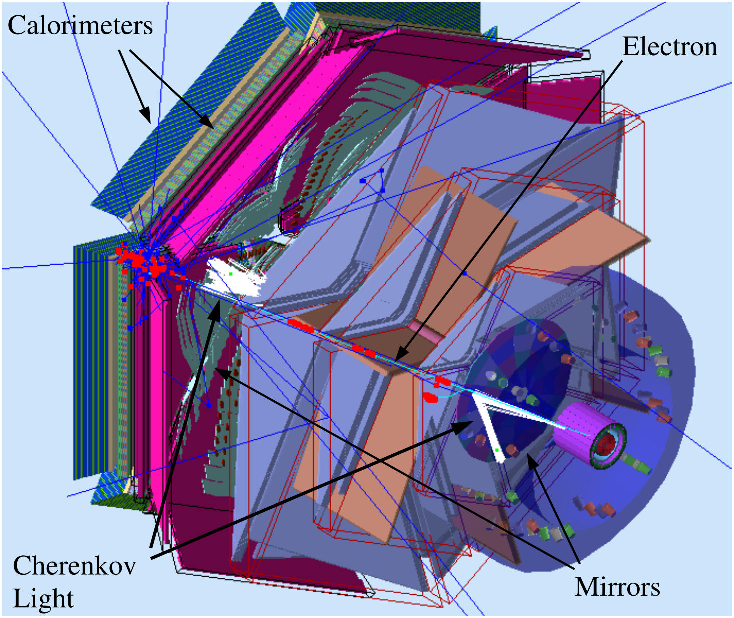

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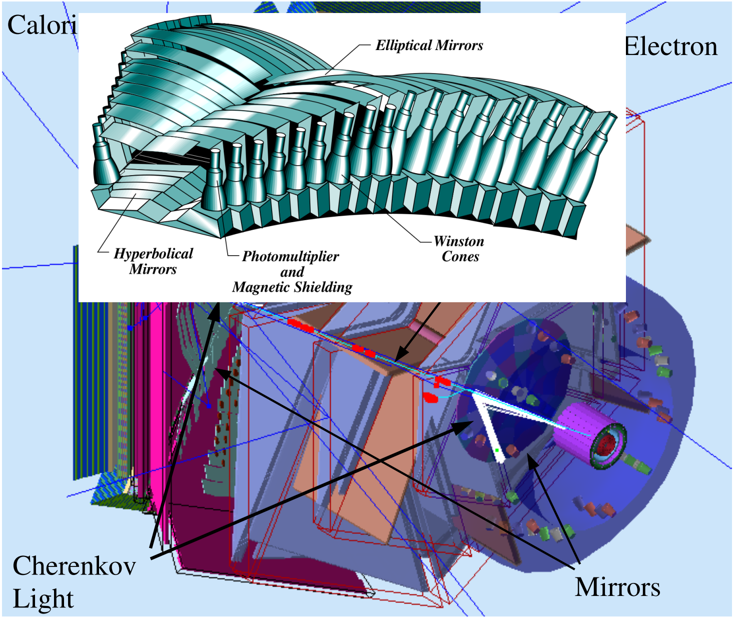

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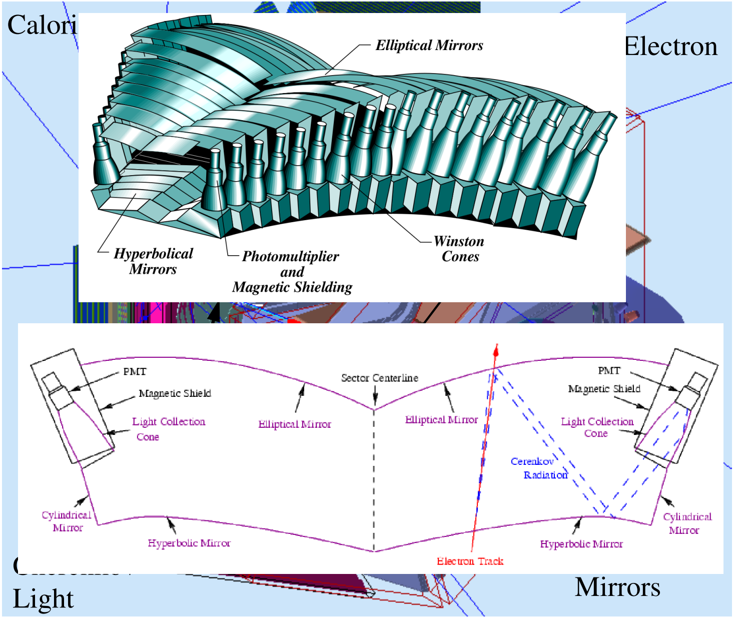
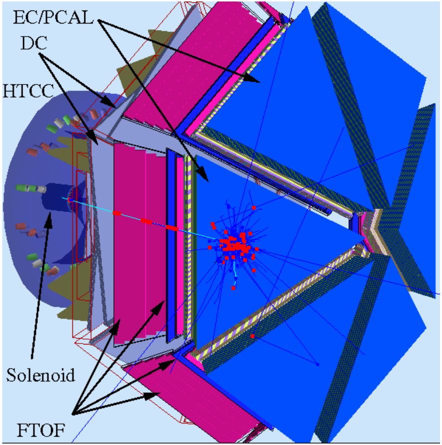


Forward Detector

Central Detector



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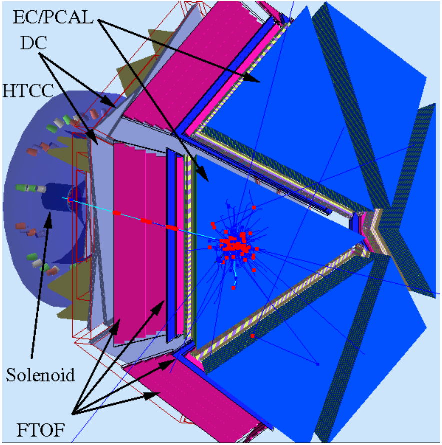


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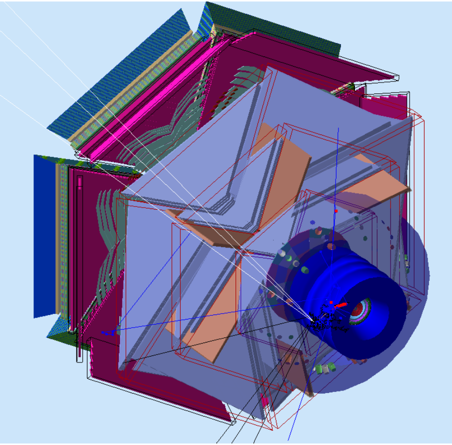
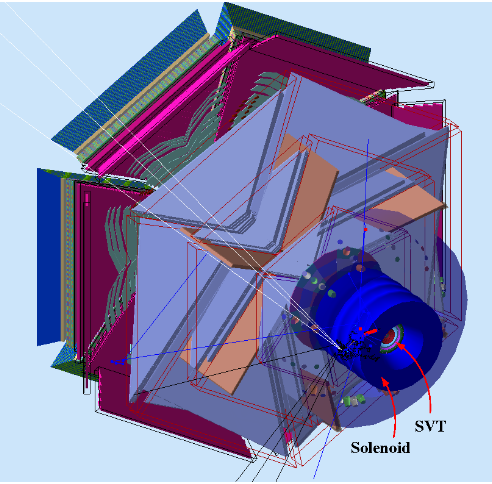


# Simulated CLAS12 Events - Silicon Vertex Tracker (SVT)



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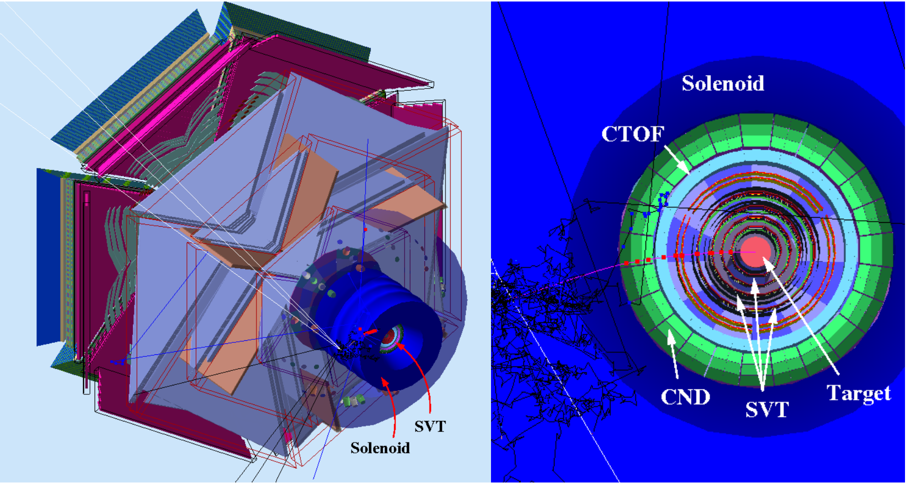

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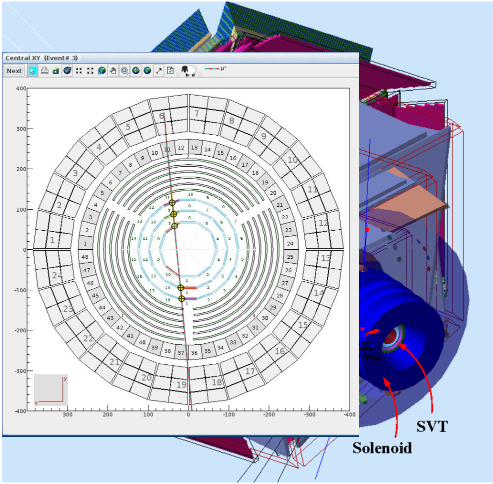


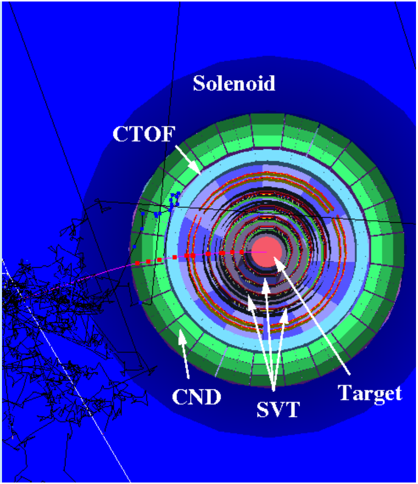

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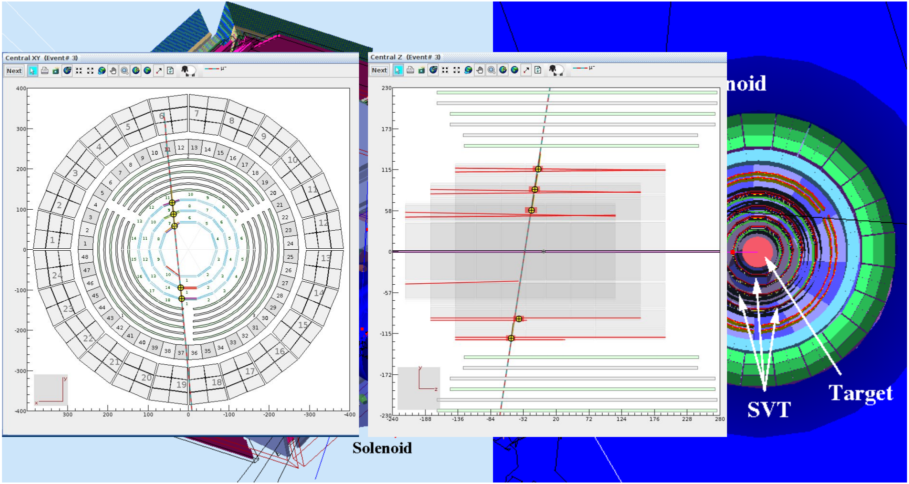
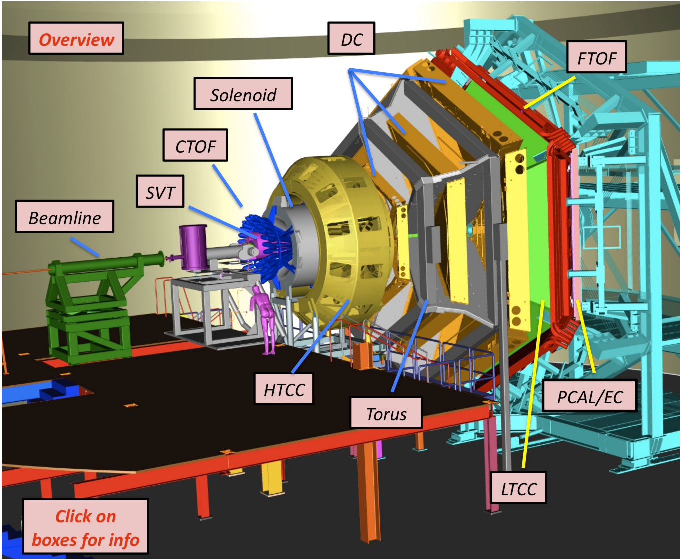
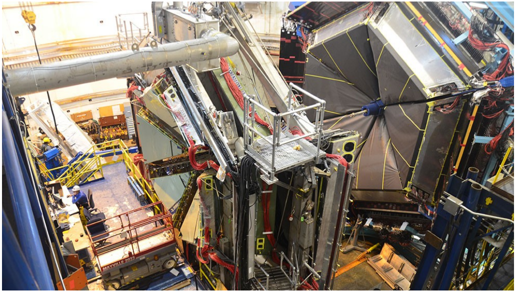


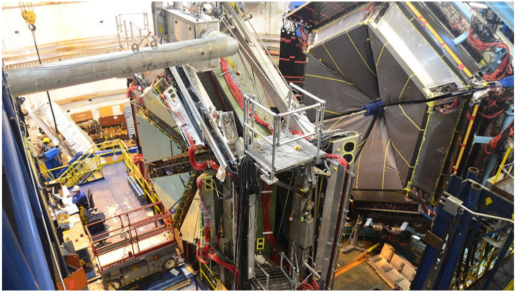
# Putting It All Together - 1



# Putting It All Together - 2



# Putting It All Together - 2



# Putting It All Together - 3

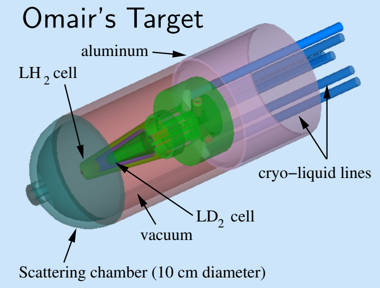
# Putting It All Together - 3


# 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!

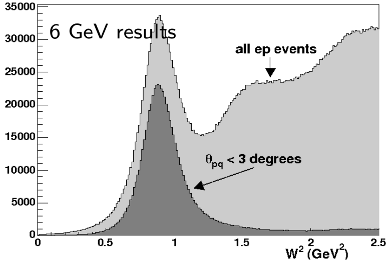



$$R = \frac{\frac{d\sigma}{d\Omega}(D(e,e'n))}{\frac{d\sigma}{d\Omega}(D(e,e'p))} = a(Q^2)\frac{\frac{G_E^{n2}+\tau G_M^{n\,2}}{1+\tau} + 2\tau G_M^{n\,2}\tan^2(\frac{\theta}{2})}{\frac{G_E^{p2}+\tau G_M^{p\,2}}{1+\tau} + 2\tau G_M^{p\,2}\tan^2(\frac{\theta}{2})}$$

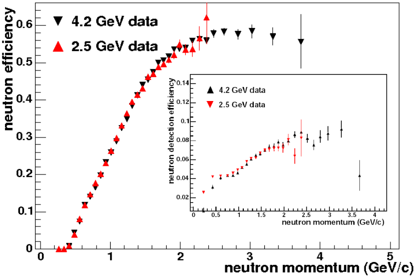
- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc*.
- Use the dual target to perform *in situ* detector calibrations.

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

- Quasi-elastic event selection: Apply a maximum $\theta_{pq}$ cut to eliminate inelastic events plus a cut on $W^2$ (J.Lachniet thesis).




- Use the $ep \to e'\pi^+ n$ 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)

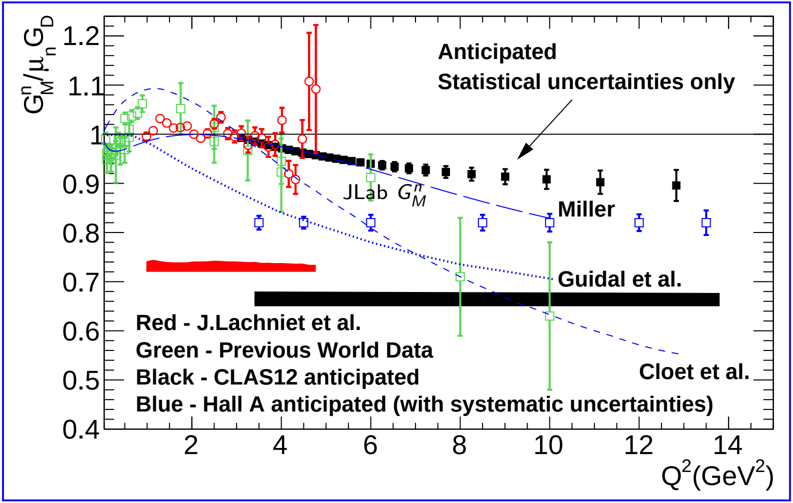
Analyzing the data - CLAS12 computing requirements.

| | 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



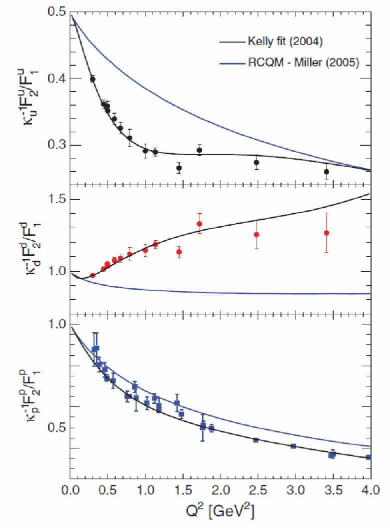
# Nuclear Structure - Flavor Decomposition

- By measuring all four EEFFs 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))

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

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

- *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

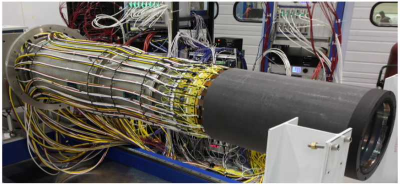
Jefferson Lab

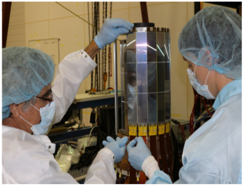
THOMAS JEFFERSON NATIONAL ACCELERATOR FACILITY

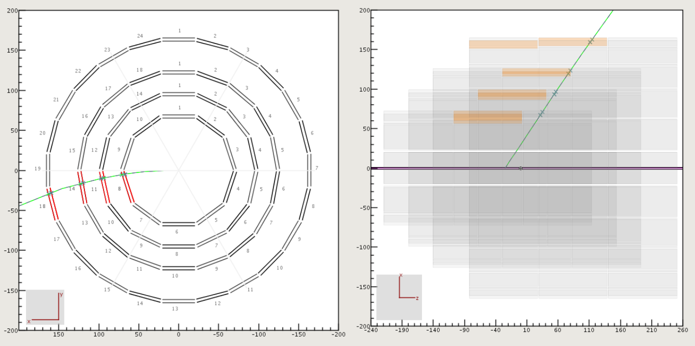
# Additional Slides

# What's going on now?

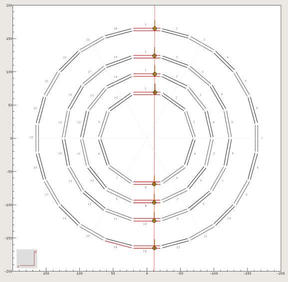
Alignment and commissioning of the silicon vertex tracker (SVT).



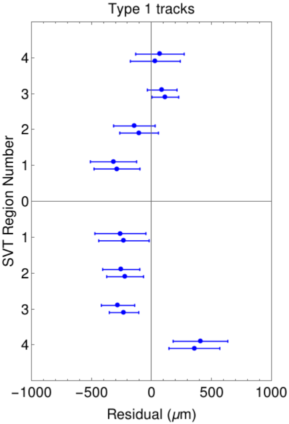




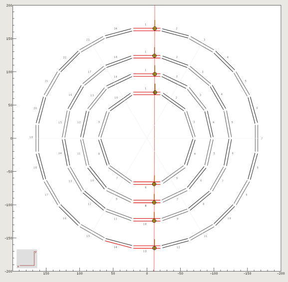
# Check alignment with Type1 cosmic ray tracks



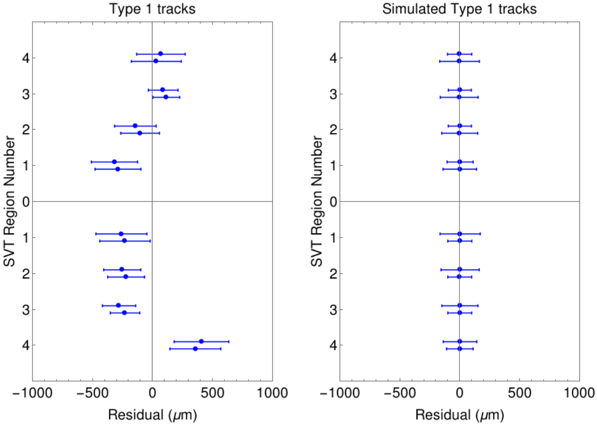
Type 1 tracks.



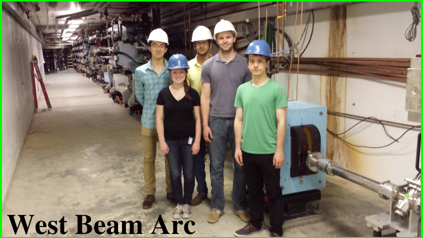
# Check alignment with Type1 cosmic ray tracks



Type 1 tracks.



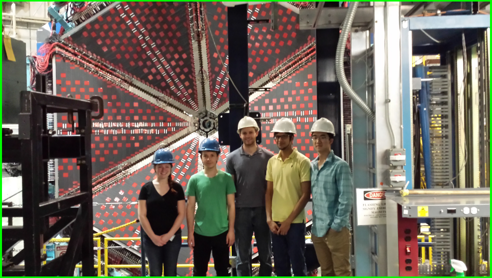
# Life on the Frontiers of Knowledge

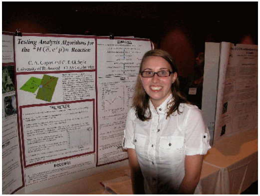


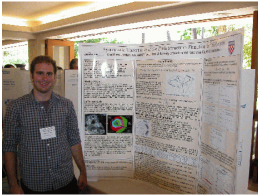
West Beam Arc

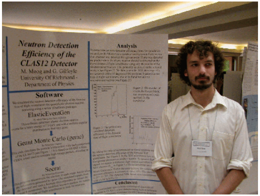
**Students from Richmond (and one from Surrey) visit JLab**

**CLAS12 detector**

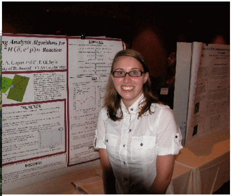


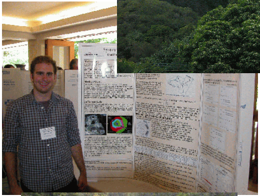

Testing Analysis Algorithms for
University of Richmond

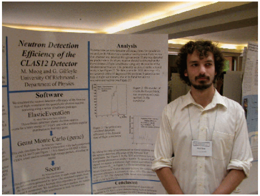


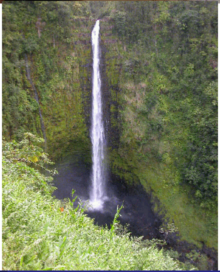

Neutron Detection
Efficiency of the
CLAS12 Detector
M. Moog and G. Gilfoyle
University Of Richmond -
Department of Physics
Analysis
Software
ElasticEventGen
Geant Monte Carlo (gemc)
Conclusion

# Life on the Frontiers of Knowledge



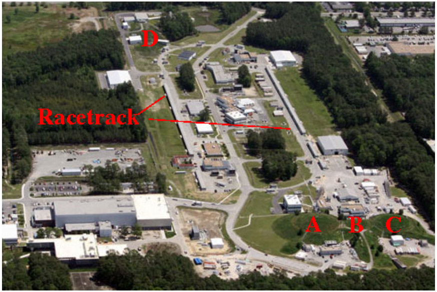




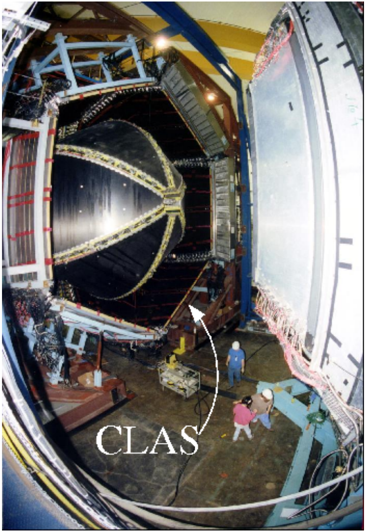
# How Do We Measure $G_M^n$ on a Neutron? (Step 1)

- 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.



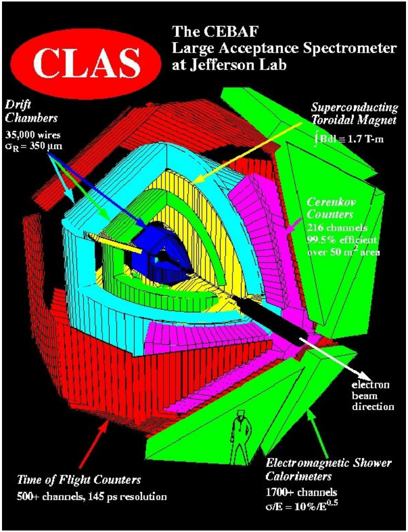

# How Do We Measure $G_M^n$ on a Neutron? (Step 2)

- 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.

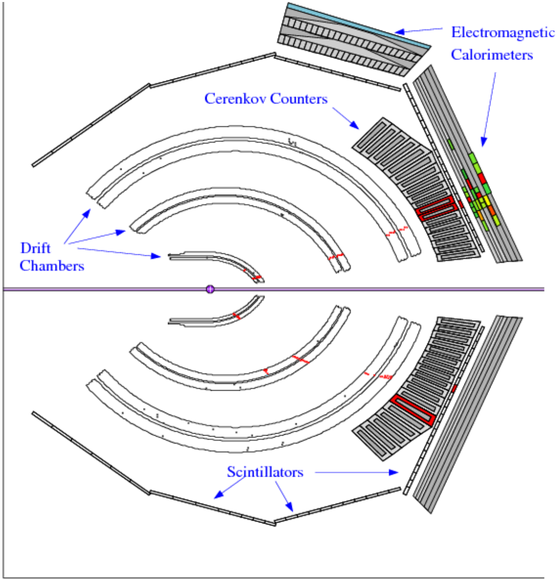


# How Do We Measure $G_M^n$ on a Neutron? (Step 2a)

- 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


Electromagnetic
Calorimeters
Cerenkov Counters
Drift
Chambers
Scintillators

# 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.

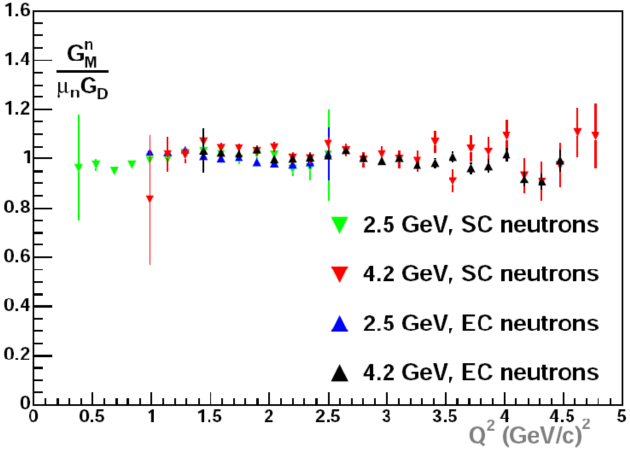

- How bad do the protons mess things up? They help!

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

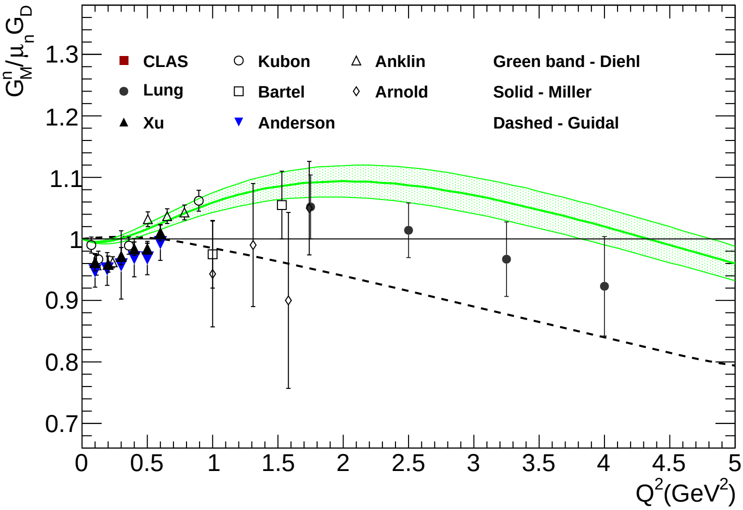
- The ratio is less vulnerable to corrections like acceptance, efficiencies, *etc*.
- Use the dual target to perform *in situ* detector calibrations.

# Results - Overlaps and Final Average

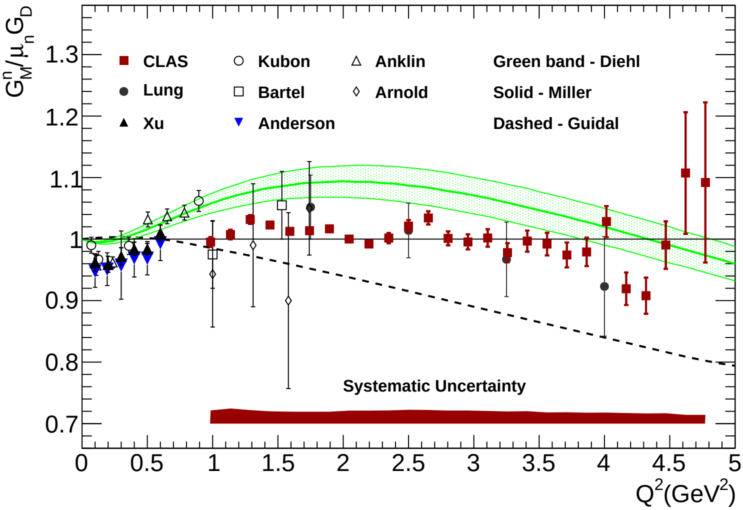
Overlapping measurements of $G_M^n$ scaled by the dipole are consistent.



# Results - Comparison with Existing Data

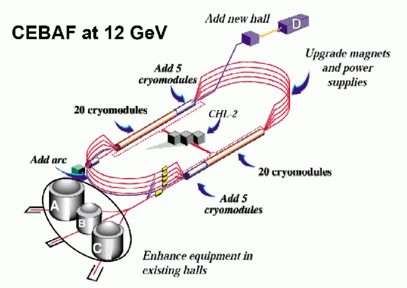


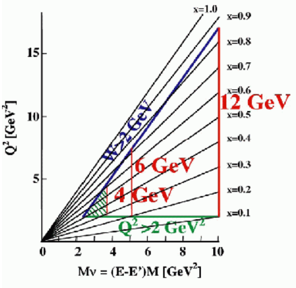
# Results - Comparison with Existing Data



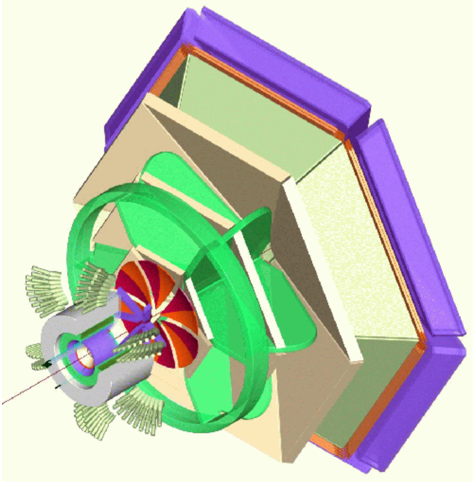
# JLab 12 GeV Upgrade - Better Accelerator

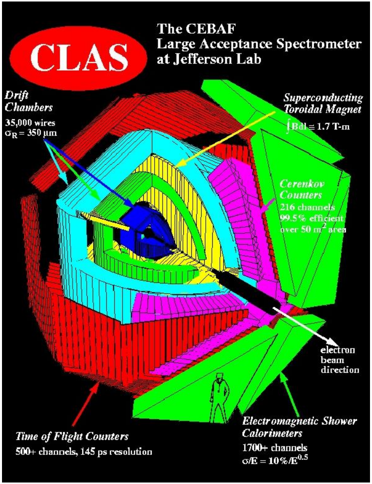
- The electron beam energy at JLab (CEBAF) has been doubled from 6 GeV to 12 GeV.
- Halls A, B and C will be upgraded to accommodate the new physics opportunities.
- A new hall (Hall D) will house a large-acceptance detector built around a solenoidal magnet for photon beam experiments.



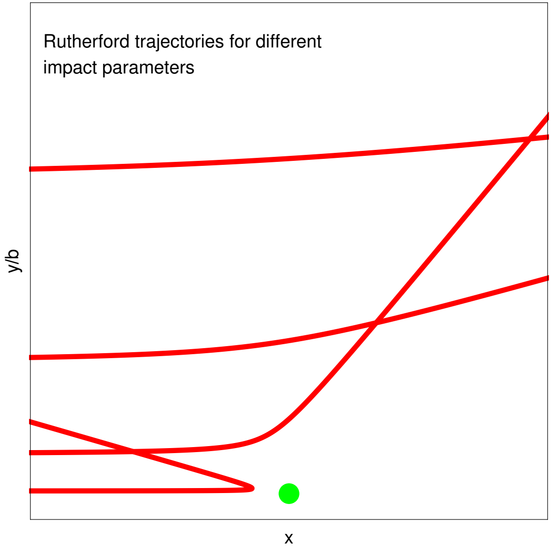



# JLab 12 GeV Upgrade - New Detectors



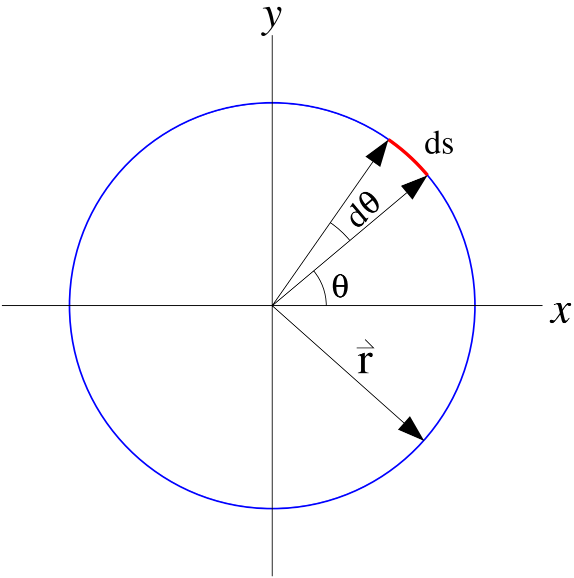


# Rutherford Trajectories



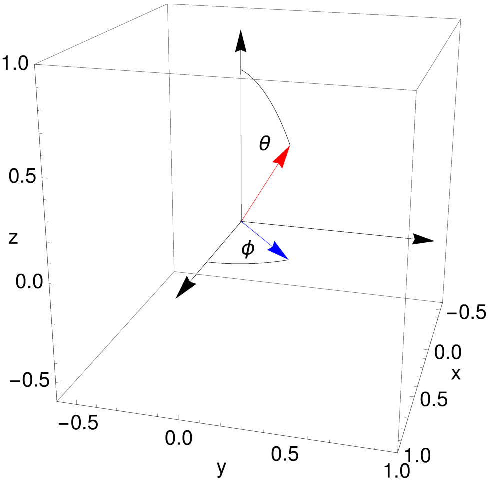
# What is an Angle?

# What is an Angle?

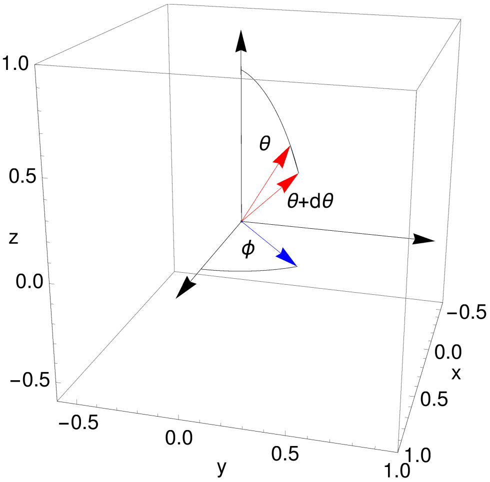



$$d\theta = \frac{ds}{|\vec{r}|}$$

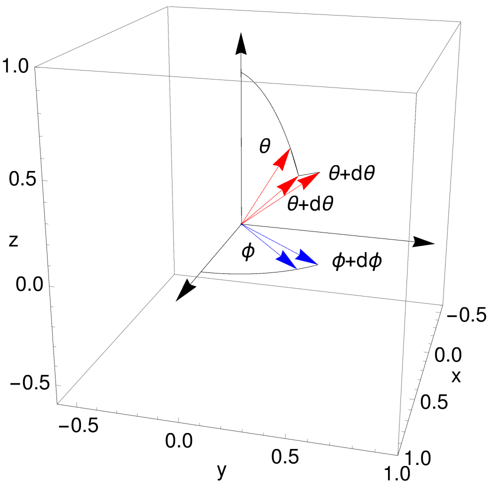
# Solid Angle



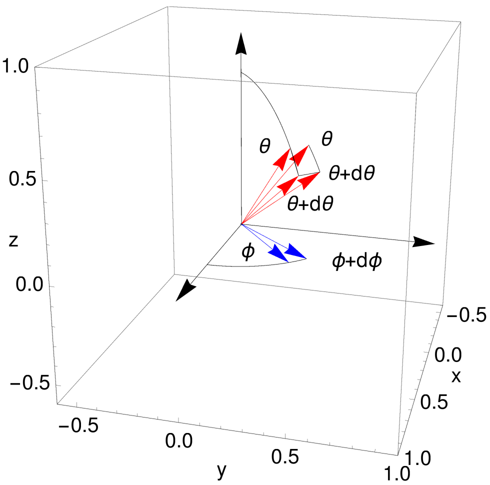
# Solid Angle



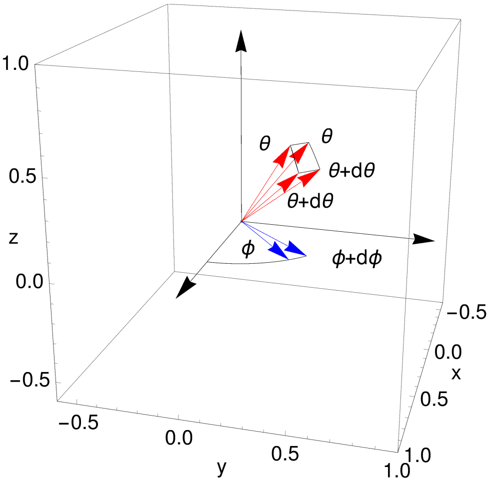
# Solid Angle



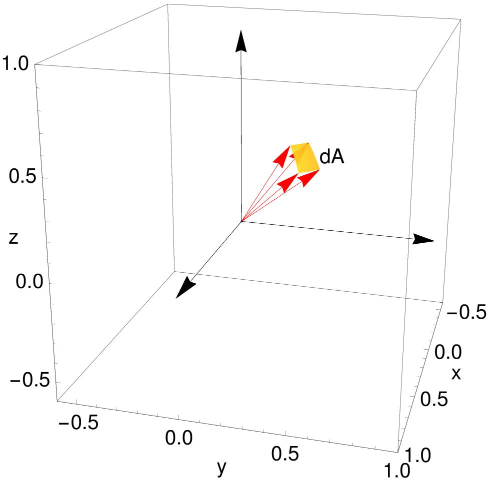
# Solid Angle



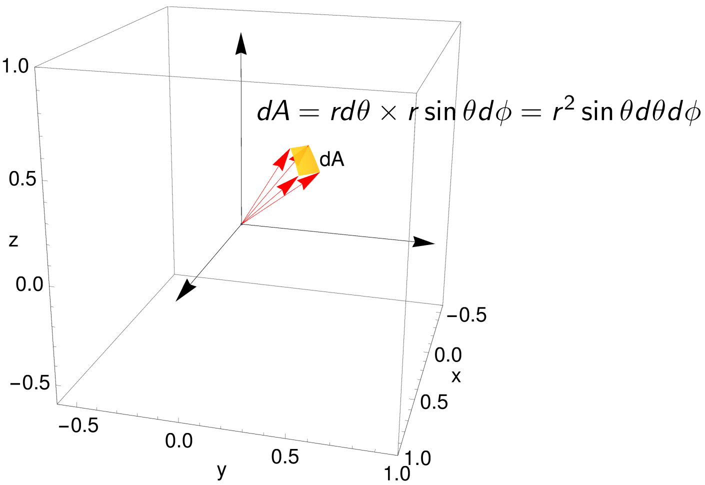
# Solid Angle



# Solid Angle

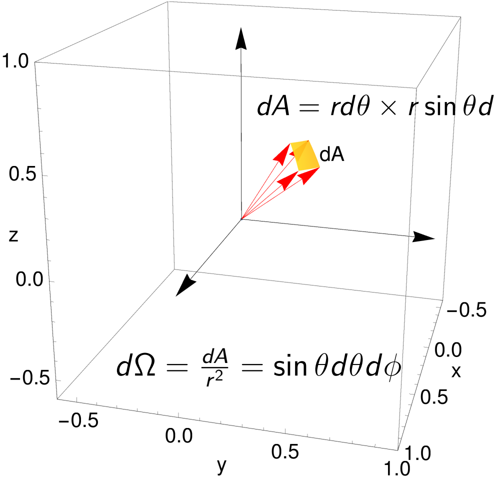


# Solid Angle



$dA = rd\theta \times r \sin\theta d\phi = r^2 \sin\theta d\theta d\phi$
dA
1.0
0.5
z
0.0
−0.5
−0.5
0.0
y
0.5
1.0
−0.5
0.0
x
0.5
1.0

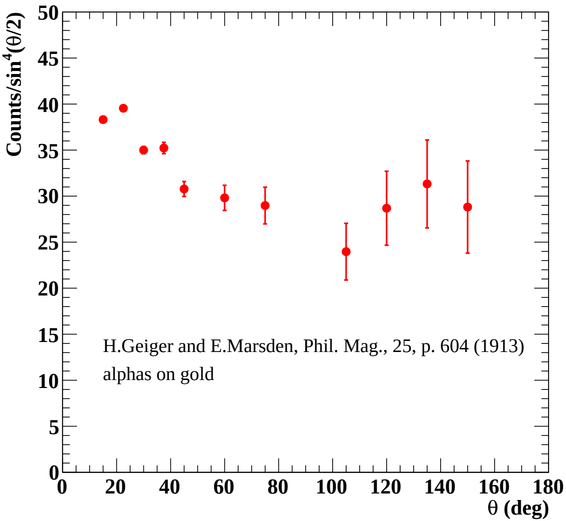
# Solid Angle




$$dA = rd\theta \times r\sin\theta d\phi = r^2 \sin\theta d\theta d\phi$$

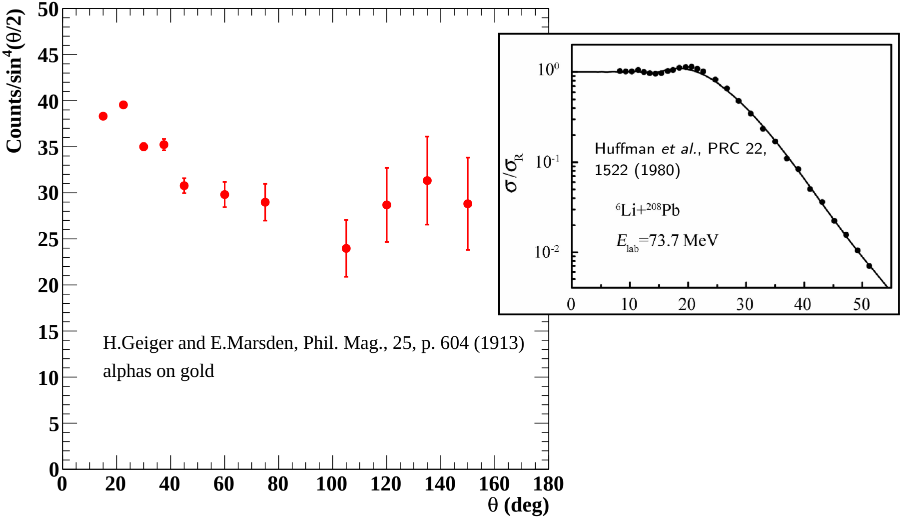
$$d\Omega = \frac{dA}{r^2} = \sin\theta d\theta d\phi$$

# Rutherford Scattering Results From Rutherford




2016-12-18 10:38:14

# Rutherford Scattering Results From Rutherford

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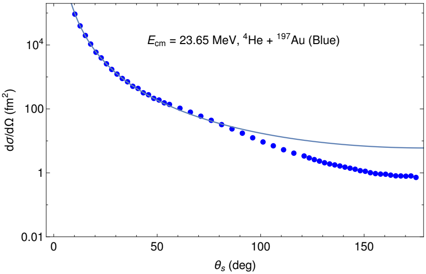
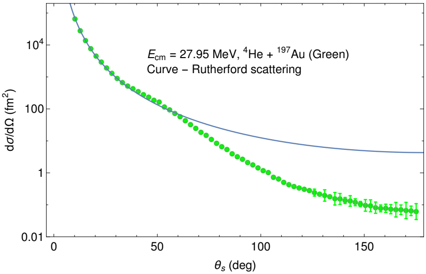
# Plotting the Homework (no. 10)



# Plotting the Homework (no. 10)