INTERNAL STRUCTURE OF THE NUCLEON AND WORK AT JEFFERSON LAB

AMELIA KARLE

What I'll be covering today

WHAT IS INSIDE A NUCLEON
what we know versus what we are trying to figure out

JEFFERSON LAB
Mission and data collection

DERIVATION OF INCIDENT ELECTRON BEAM ENERGY

WHAT I WILL BE LOOKING AT FOR NEXT SEMESTER

What is inside a neutron: key discoverys

1802, **Dalton:** Matter is made up of atoms

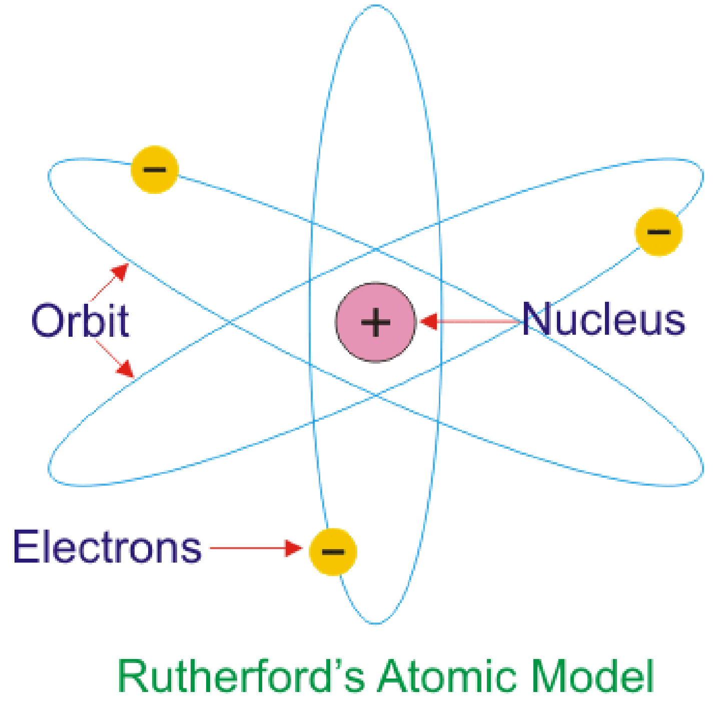
1890s, Thompson: Established the existence of electrons

1911, Rutherford: Mass is concentrated in a compact, positively charged nucleus

1950-1960s: Exploration of nuclear and particle physics led to “particle zoo” during scattering experiments

1963, Gell-Mann: proposed the quark model to classify these unknown particles.

1970s: Quantum theory for strong nuclear interaction: quantum chromodynamics



What we know

- All known matter is made of quarks and leptons (Fermions), and force carrier particles (Bosons)
- Protons and neutrons are made up of quarks, which only exist in groups
- Protons and neutrons are bound together with a strong nuclear force

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

Leptons spin = 1/2		
Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$< 7 \times 10^{-9}$	0
e electron	0.000511	−1
ν_μ muon neutrino	< 0.0003	0
μ muon	0.106	−1
ν_τ tau neutrino	< 0.03	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.005	2/3
d down	0.01	−1/3
c charm	1.5	2/3
s strange	0.2	−1/3
t top (initial evidence)	170	2/3
b bottom	4.7	−1/3

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

Unified Electroweak spin = 1		
Name	Mass GeV/c²	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/c²	Electric charge
g gluon	0	0

Higgs Boson spin = 0		
Name	Mass GeV/c²	Electric charge
H Higgs	126	0

What we are trying to figure out

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$$m_p = 2m_u + m_d = 2\left(0.005\frac{GeV}{c^2}\right) + \left(0.01\frac{GeV}{c^2}\right) = \sim 0.02\frac{GeV}{c^2}$$

$$m_n = m_u + 2m_d = \left(0.005\frac{GeV}{c^2}\right) + 2\left(0.01\frac{GeV}{c^2}\right) = \sim 0.025\frac{GeV}{c^2}$$

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Only about 1% of the total known mass of the proton/neutron

The mission at Jefferson Lab:

Test the quark nature of the atomic nucleus

1. Probe the quark structure in protons and neutrons
2. Test the Theory of Quantum color chromodynamics
   a. Describes the theory of the strong interaction
   b. Describes the nature of gluons
      i. Force carrier particles that carry the strong force between quarks

Electromagnetic form factors

$$G_M^n,\ G_E^n,\ G_M^p,\ \text{and}\ G_E^p$$

- Quantities that encode the electric and magnetic properties within the nucleus
- Provide insight into the distribution of charge and magnetization within a nucleon
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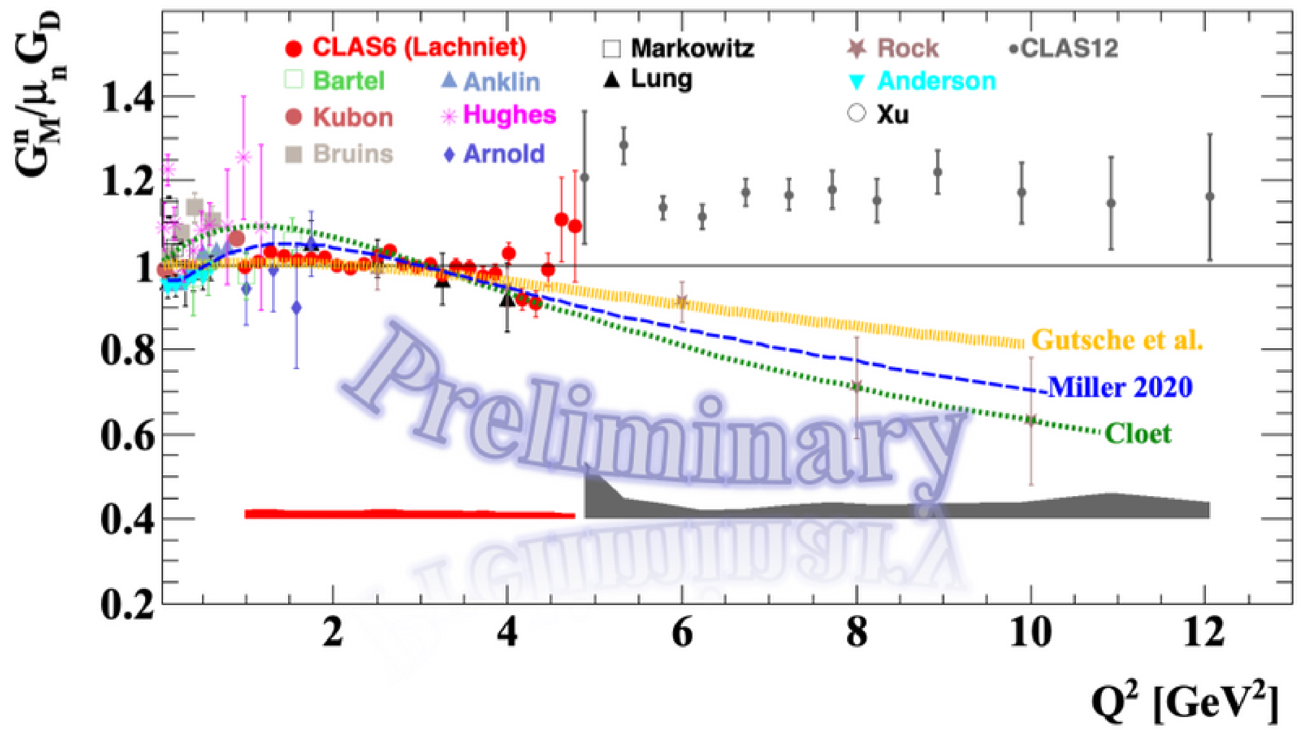
Not for distribution



Layma Baashen "Neutron Magnetic Form Factor Measured at High Q^2 with CLAS12", 7/12/23

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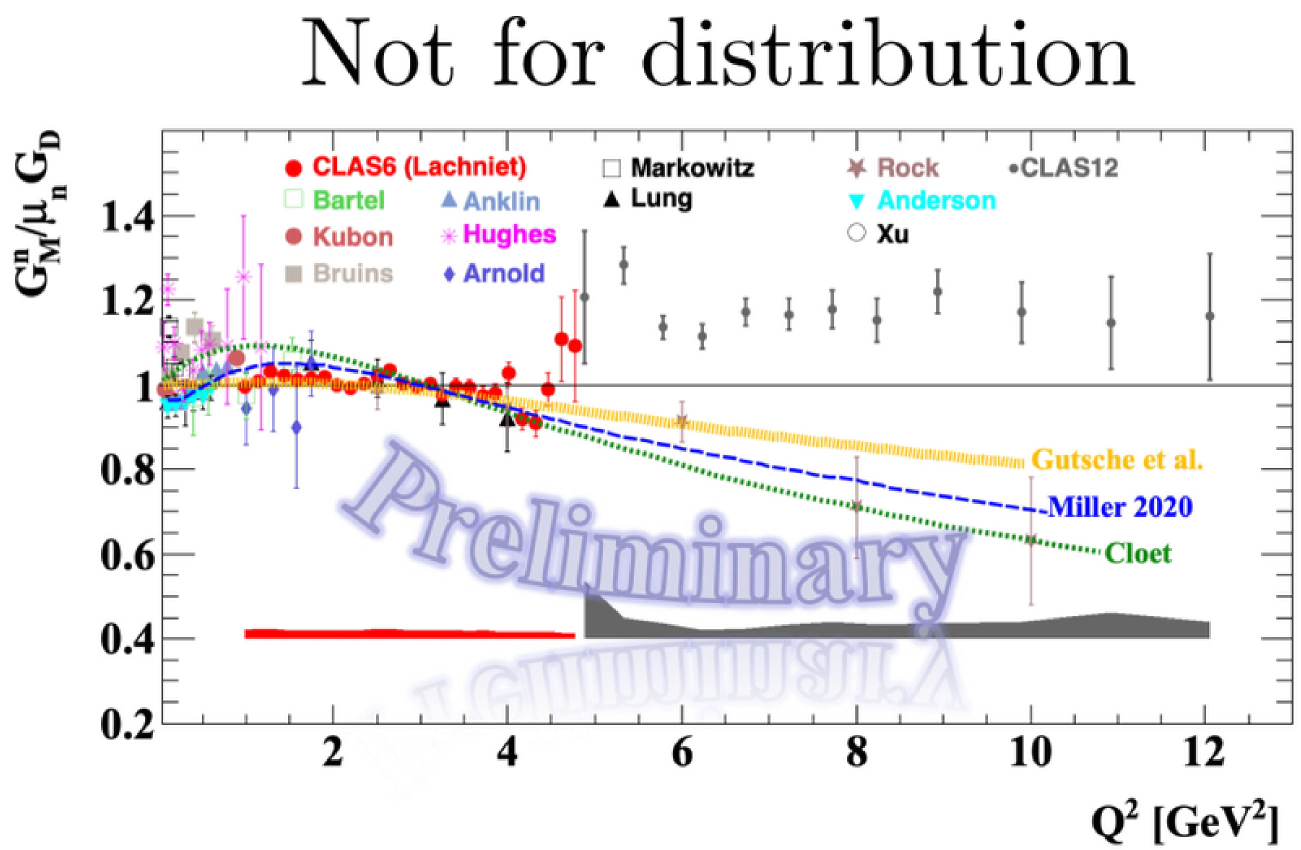

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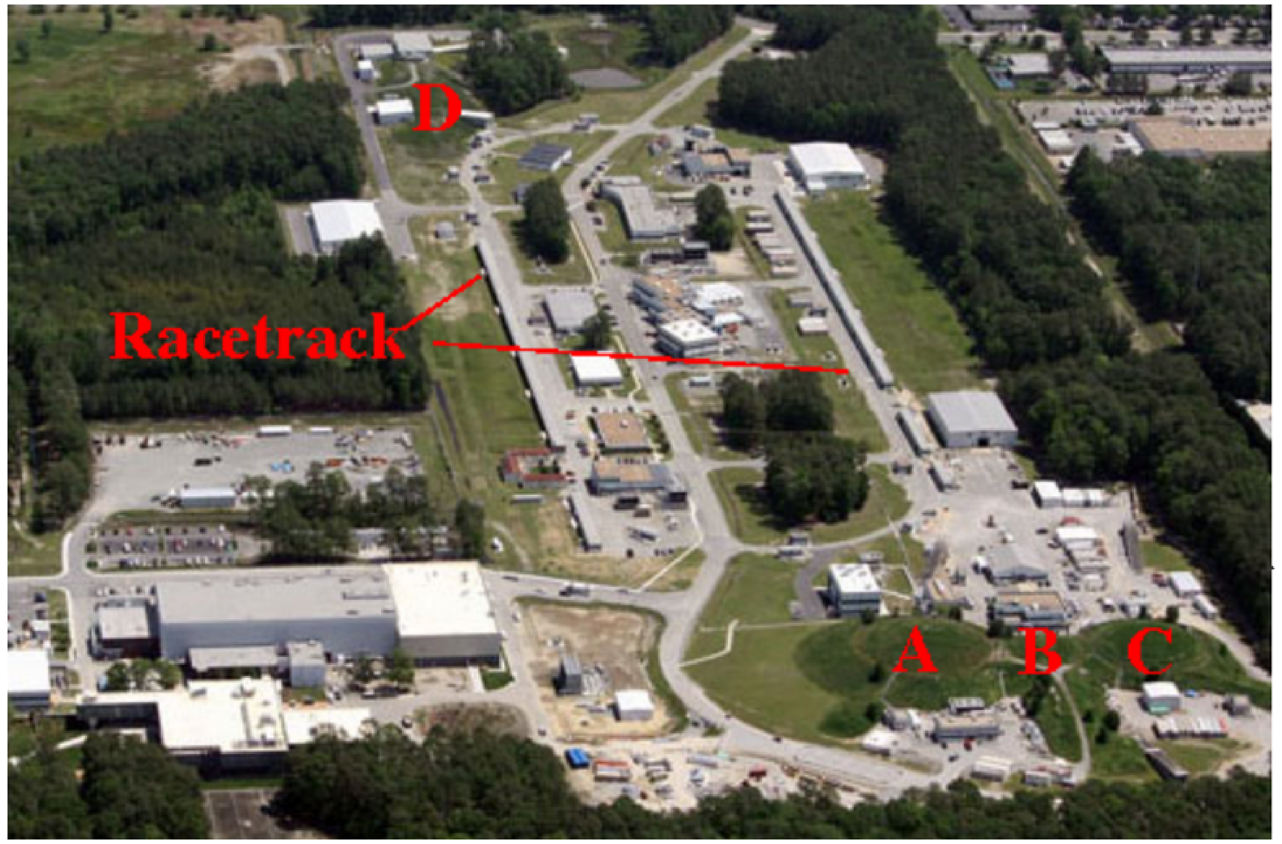
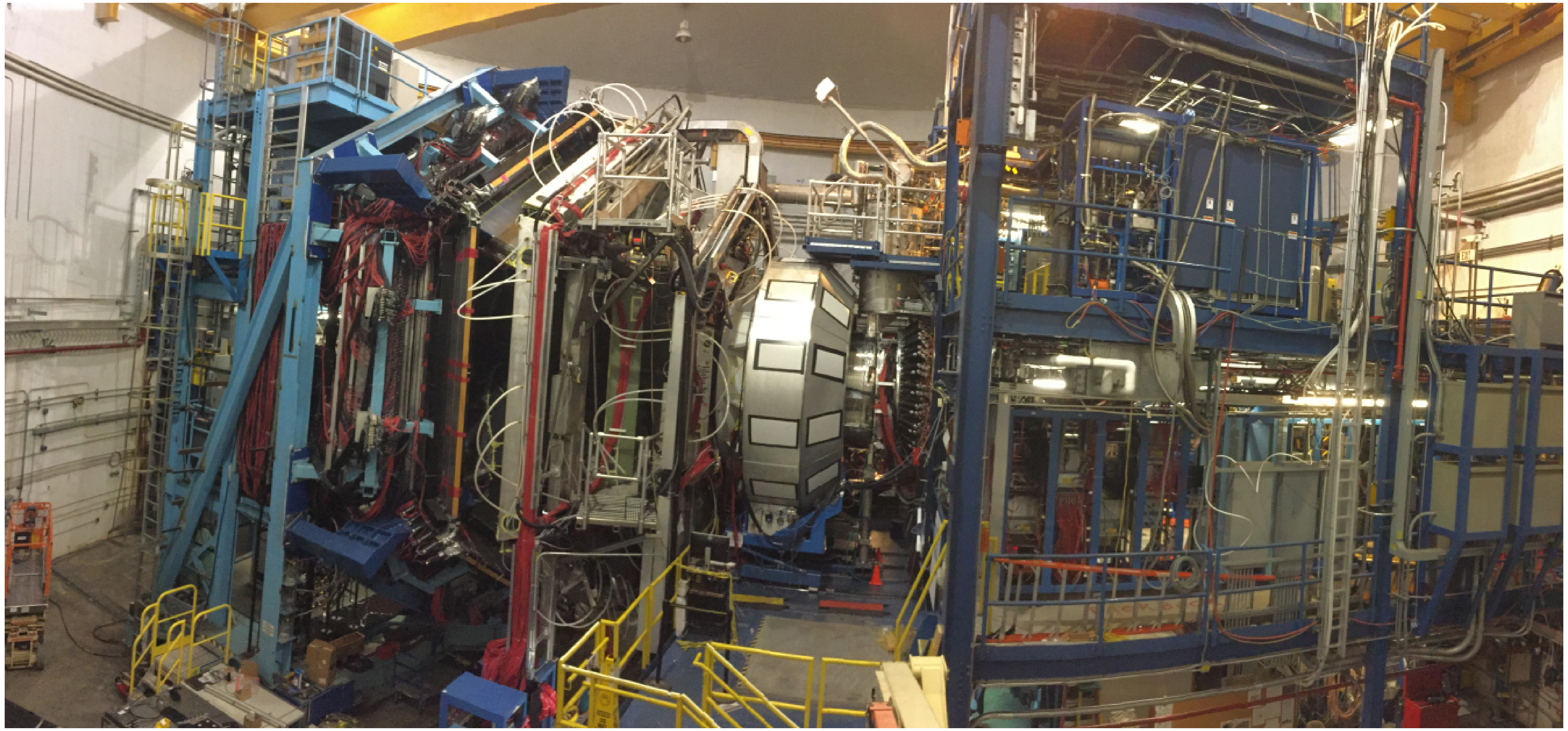
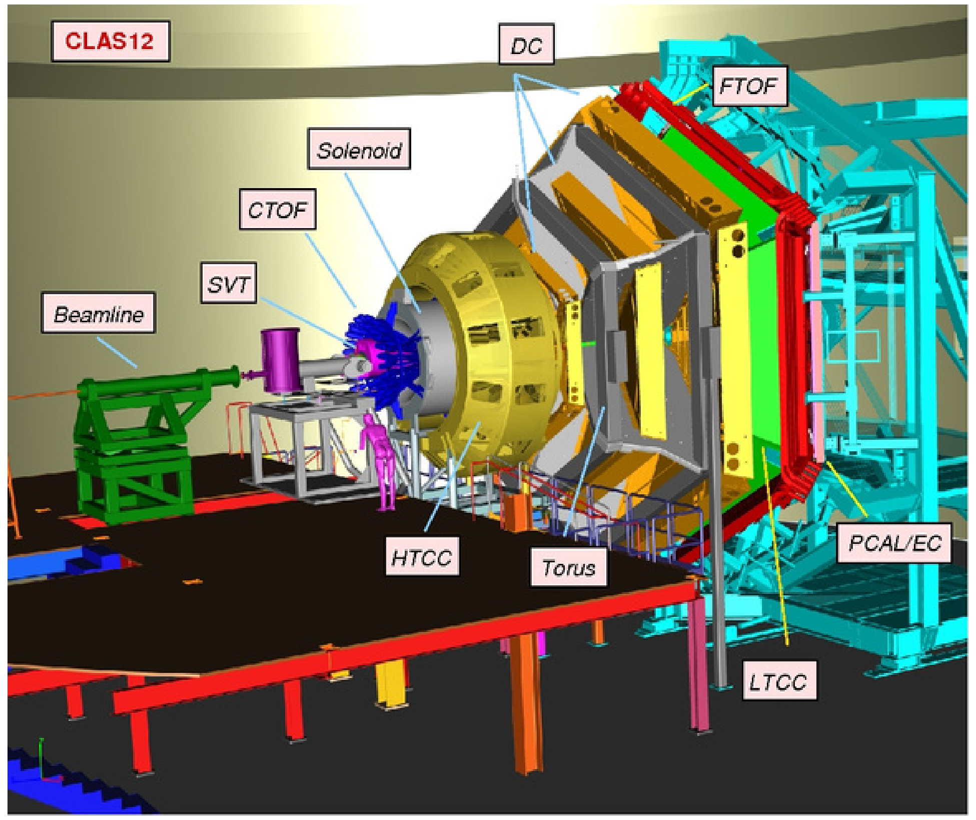
You can get these form factors using measurable quantities

Measuring these quantities

- High-energy electron scattering
- Jefferson Lab -> mile-long accelerator that accelerates electrons into a radiation detector
- Radiation detector: Large Acceptance Spectrometer
- Over 100,000 detecting elements in 40 layers
  - Trajectory
  - Particle type
  - Scattering angle
  - Particle momentum
  - Energy
  - Time of flight

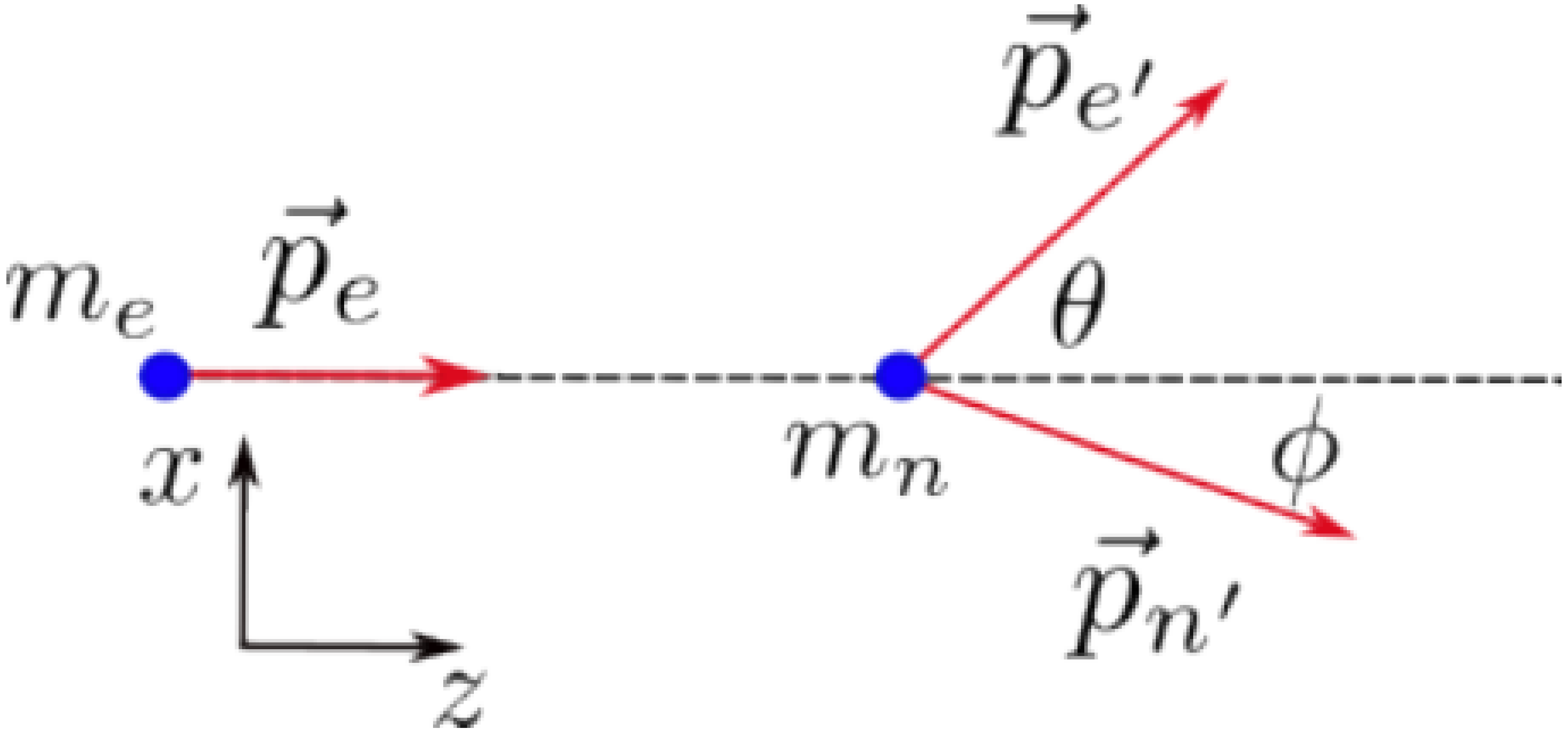






CLAS12 Spectrometer in Hall B

Momentum and Elastic Scattering
Physics 131 problem:



Relativistic effects

Impact objects traveling close to the speed of light, momentum is not conserved in the typical Newtonian three-vector.

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To account for relativistic effects, we use a four-momentum vector

$$p_\mu = \left(\frac{E}{c}, p_x, p_y, p_z \right)$$

Newtonian three-momentum vector

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Lorentz Vector

- Conserved in all reference frames
- Keep track of the momentum under Lorentz transformations

Properties of four-vector momentum

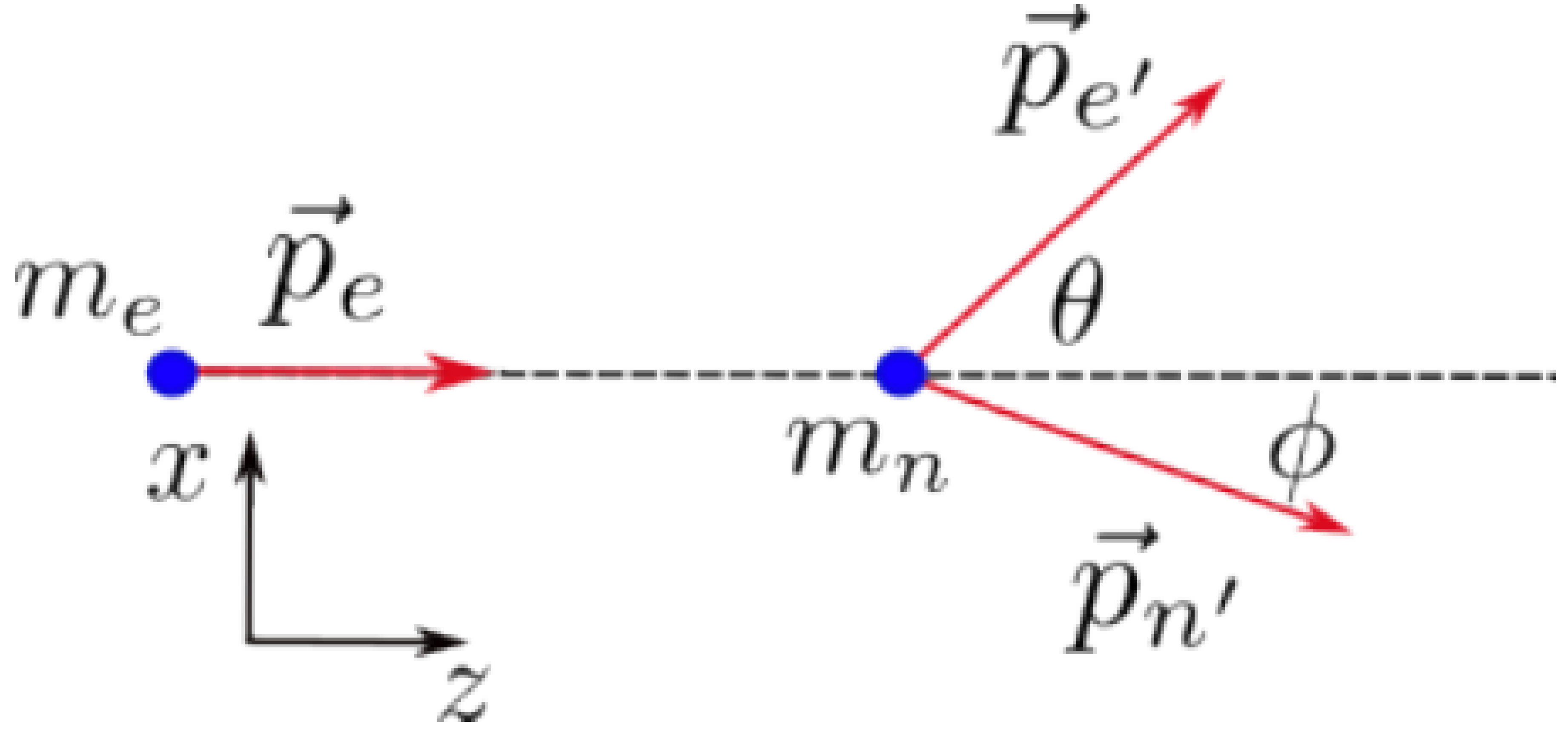
$$\underset{\sim}{P} \cdot \underset{\sim}{P} = E^2 - ({p_x}^2 + {p_y}^2 + {p_z}^2)$$

$$E^2 - p^2 = m^2$$

Now back to the problem:

Consider the electron beam and neutron target studied at JLab:

Relativistic momentum is conserved in an elastic scatting event.



We can use this to tell us information about the system

Momentum of electron beam before collision:

$$\underset{\sim}{P_e} = \left(E_e, \overrightarrow{P_e}\right) = (E_e, 0, 0, P_{e,Z})$$

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Momentum of neutron before collision:

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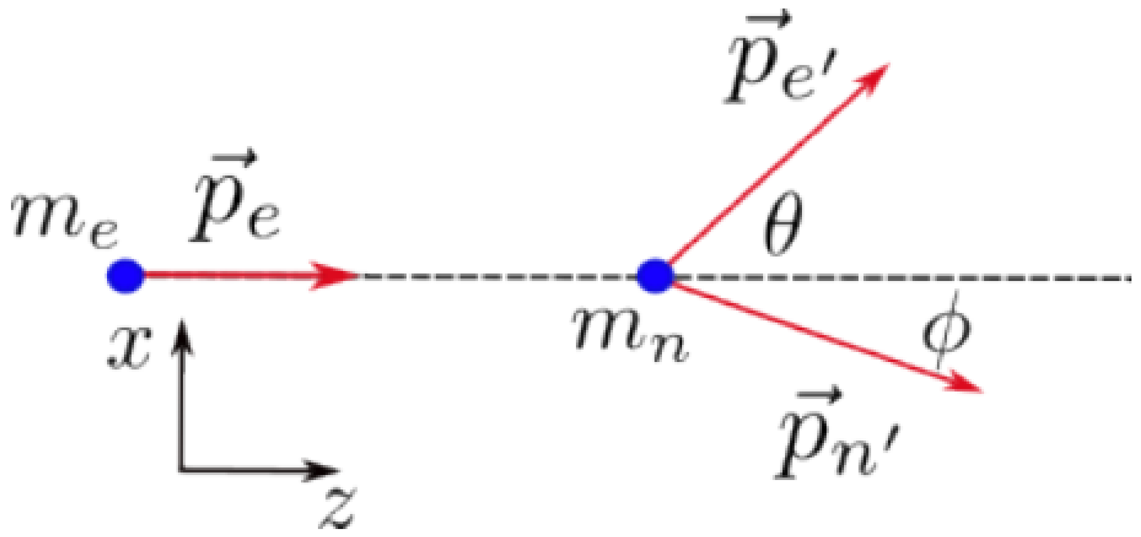

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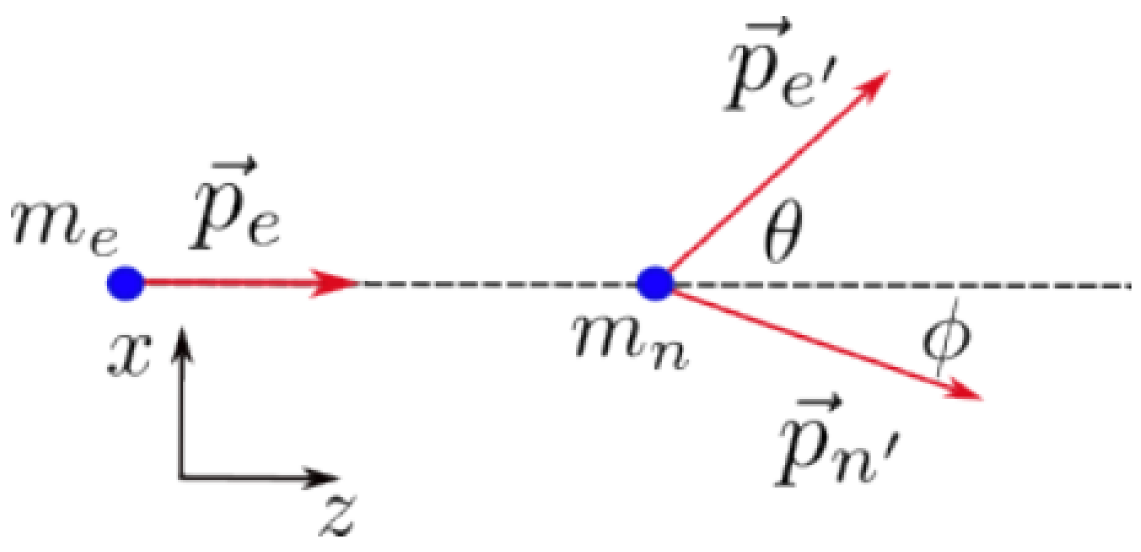

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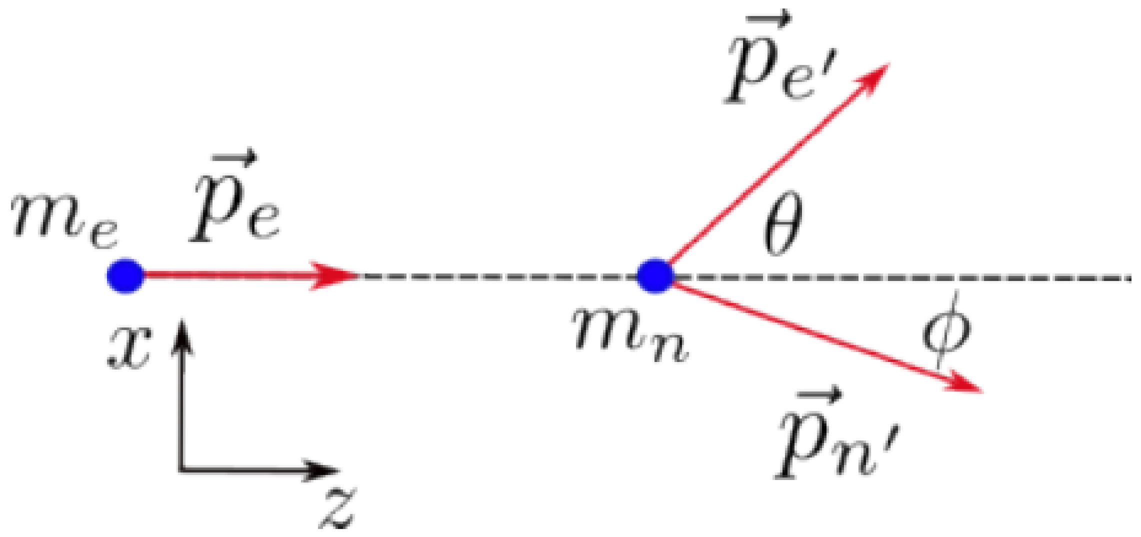

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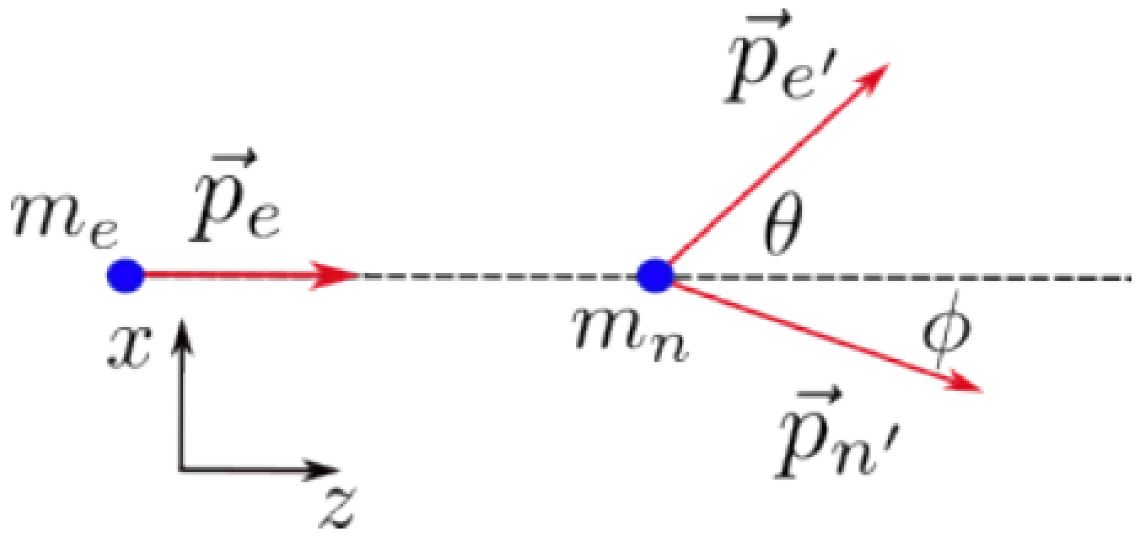

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Now using these relationships to solve for beam energy, E_e:

$$(\underset{\sim}{P_e} + \underset{\sim}{P_n})^2 = (\underset{\sim}{P_e'} + \underset{\sim}{P_n'})^2$$

$$\underset{\sim}{P_e}^2 + 2\underset{\sim}{P_e} \cdot \underset{\sim}{P_n} + \underset{\sim}{P_n}^2 = \underset{\sim}{P_e}'^2 + 2\underset{\sim}{P_e}' \cdot \underset{\sim}{P_n}' + \underset{\sim}{P_n}'^2$$

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Plugging in we get:

$$\underset{\sim}{P_e} \cdot \underset{\sim}{P_n} = \underset{\sim}{P_e'} \cdot [\underset{\sim}{P_e} + \underset{\sim}{P_n} - \underset{\sim}{P_e'}]$$

$$(\underset{\sim}{P_e} \cdot \underset{\sim}{P_n}) = (\underset{\sim}{P_e'} \cdot \underset{\sim}{P_e}) + (\underset{\sim}{P_e'} \cdot \underset{\sim}{P_n}) - (\underset{\sim}{P_e'} \cdot \underset{\sim}{P_e'})$$

(1) (2) (3) (4)

(1)

$$\underset{\sim}{P_e} \cdot \underset{\sim}{P_n} = \left(E_e, 0, 0, P_{e,Z}\right) \cdot (m_n c^2, 0, 0, 0)$$
$$= E_e m_n$$

(2)

$$\underset{\sim}{P_e'} \cdot \underset{\sim}{P_e} = (E_e', E_e' \sin(\theta), 0, E_e' \cos(\theta)) \cdot (E_e, 0, 0, E_e)$$
$$= E_e E_e' - E_e E_e' \cos(\theta)$$
$$= E_e E_e' (1 - \cos(\theta))$$

(3)

$$\underset{\sim}{P_e'} \cdot \underset{\sim}{P_n} = (E_e', E_e' \sin(\theta), 0, E_e' \cos(\theta)) \cdot (m_n c^2, 0, 0, 0)$$
$$= E_e{}' m_n$$

(4)

$$\left(\underset{\sim}{P_e'} \cdot \underset{\sim}{P_e'}\right) = m_e{}^2$$
$$= \sim 0$$

Now pulling it all together:

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Now pulling it all together:

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Energy of the scattered electron

Energy of the electron beam

$$E_e = \frac{E_e'}{1 - \frac{2E_e'}{m_n} \sin^2 \left(\frac{\theta}{2}\right)}$$

Angle of the scattered electron

Why is this result significant?

1. We can measure the angle of deflection of the electron
2. We can measure the energy of the electron after the scattering event
3. The energy of the electron beam is a known value

We can determine whether the event was “Quasi-elastic”

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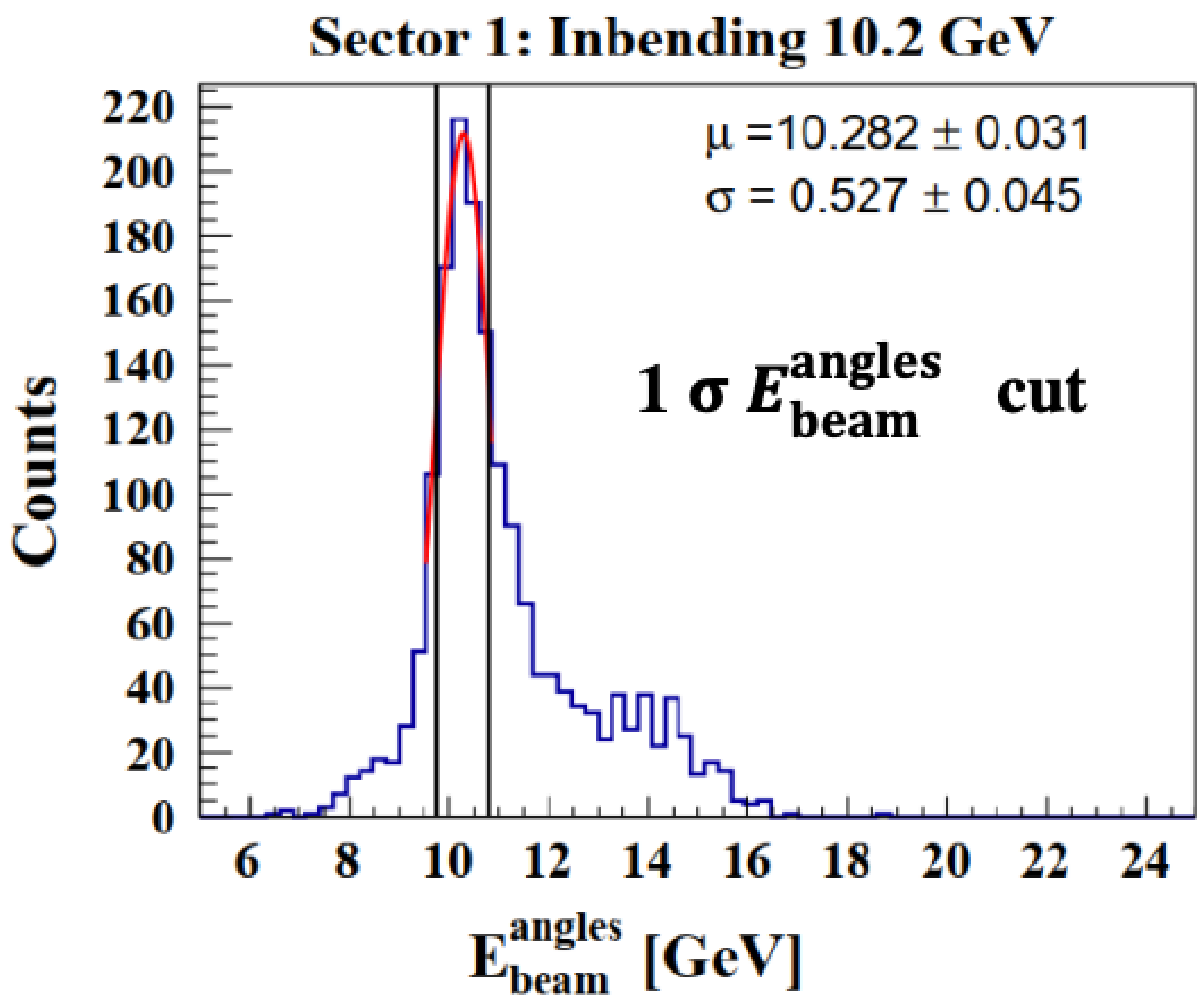
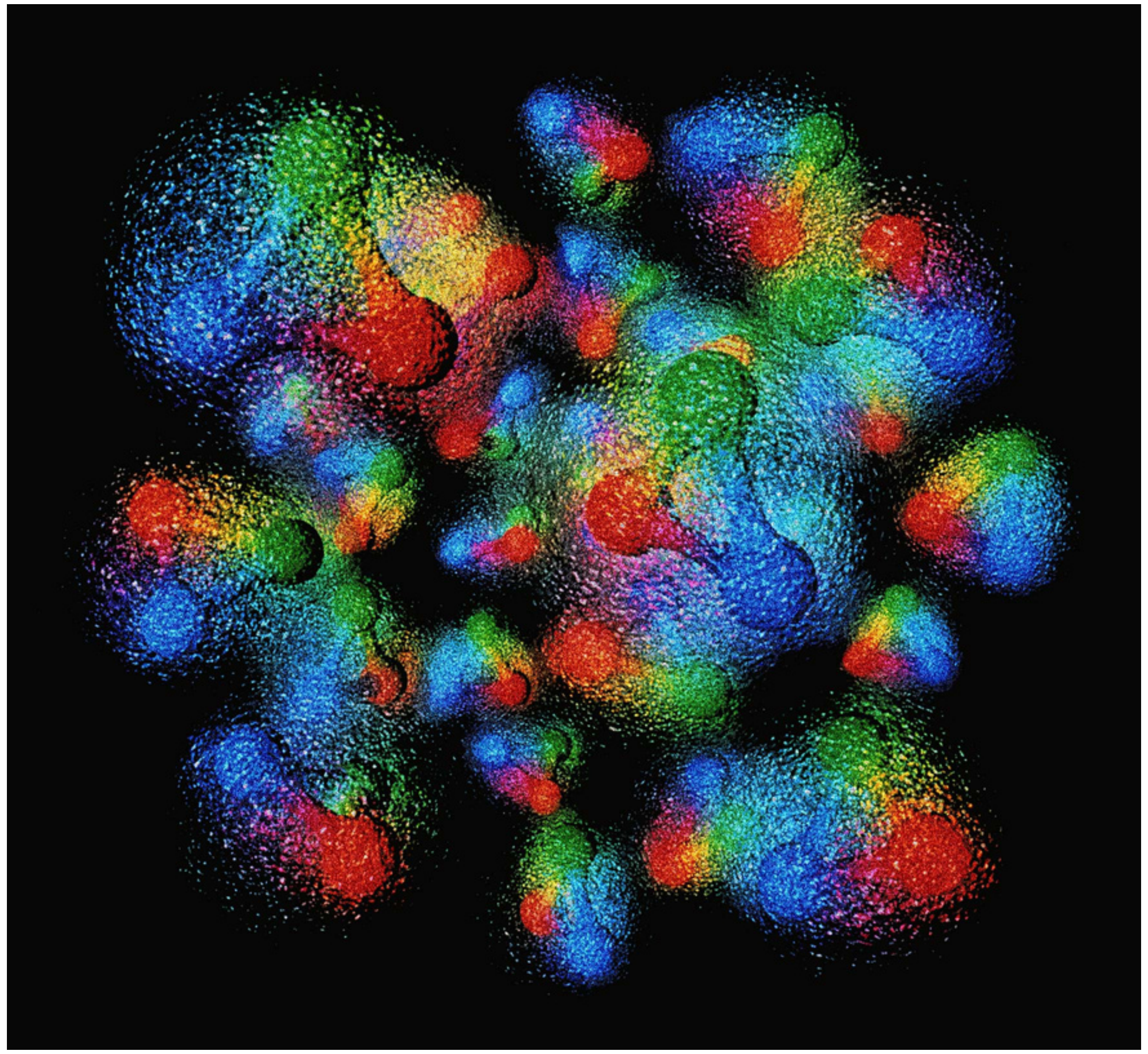
This equation allows us to select for quasi-elastic events

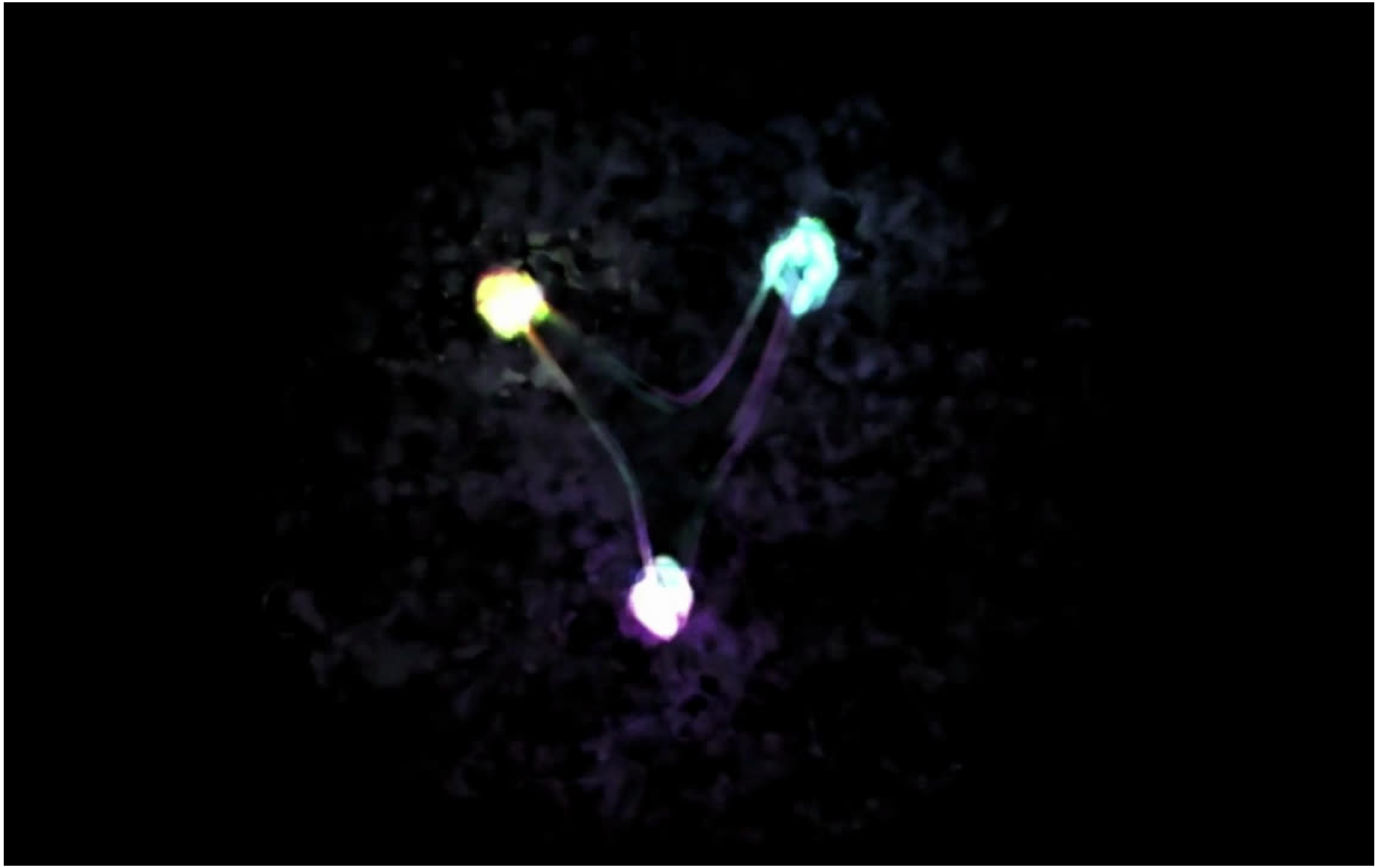


Layma Baashen "Neutron Magnetic Form Factor Measured at High Q^2 with CLAS12", 7/12/23

Goals for next semester

- Continue refining the equation used for data selection
    - Beam energy in terms of just scattering angles
- Formulate a way to automatically select data to analyze
    - Computer program
- Consider real data collected from Jefferson Lab
- Understand more about quantum chromodynamics





Collaboration between MIT Center for the Arts and Jefferson Lab to create a data-driven visualization of a proton.

Thank you for listening!

Thank you Professor Gilfoyle!

Sources:

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