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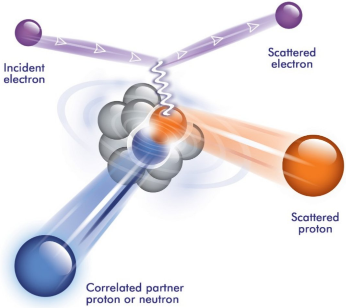
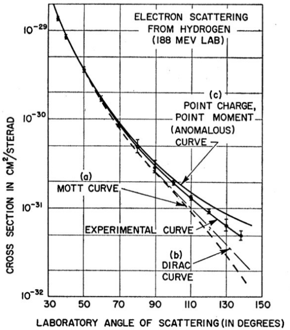



What is the energy of the scattered electron in terms of the incident/beam energy of the electron and angle $\theta$ with respect to the beam direction? How would you select these particles?

# What's Inside a Proton or Neutron? 2

# What's Inside a Proton or Neutron? 3

- QUARKS!!

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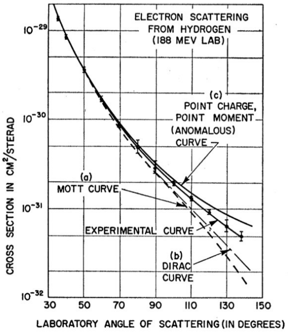
McAllister and Hofstadter, PR 102, 851 (1956)

- QUARKS!!
- MESONS!!

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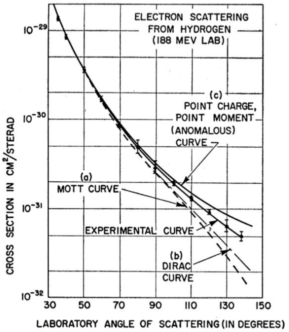
McAllister and Hofstadter, PR 102, 851 (1956)

# What's Inside a Proton or Neutron? 5

- QUARKS!!
- MESONS!!
- GLUONS!!

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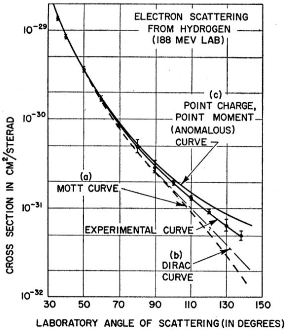
McAllister and Hofstadter, PR 102, 851 (1956)

- QUARKS!!
- MESONS!!
- GLUONS!!

Robert Hofstadter, Nobel Prize 1961

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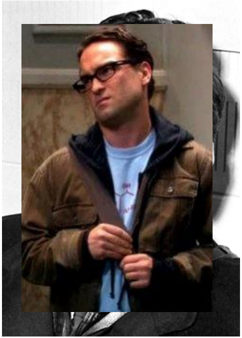
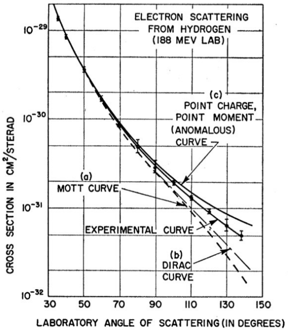
McAllister and Hofstadter, PR 102, 851 (1956)

# What's Inside a Proton or Neutron? 7

- QUARKS!!
- MESONS!!
- GLUONS!!



Robert Hofstadter, Nobel Prize 1961

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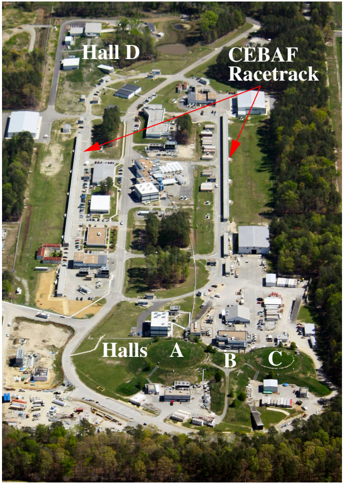
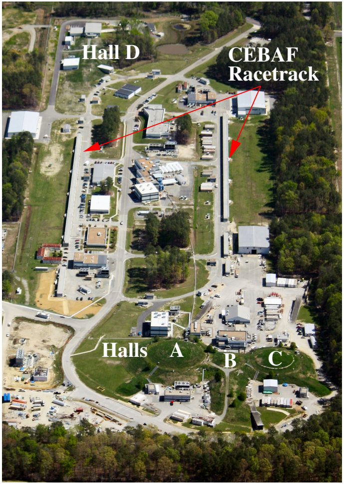
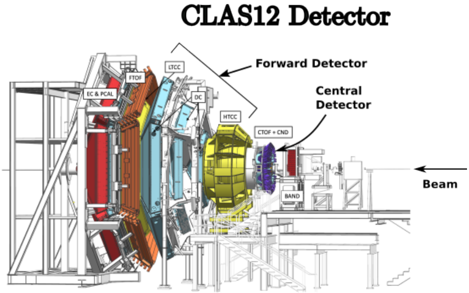
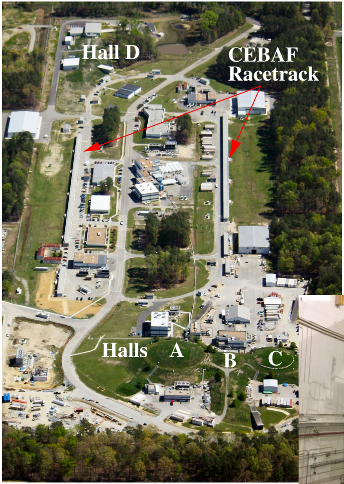
McAllister and Hofstadter, PR 102, 851 (1956)

# Scattering Experiments 8

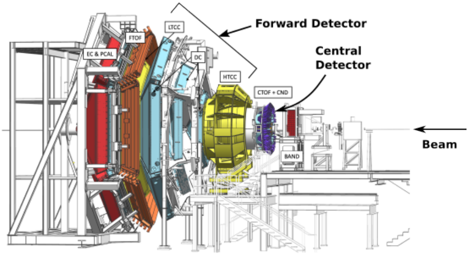


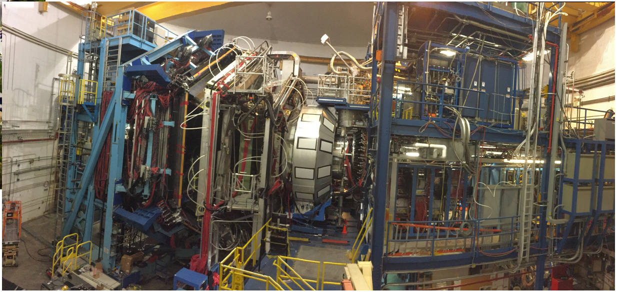

Hall D
CEBAF
Racetrack
Halls A
B
C

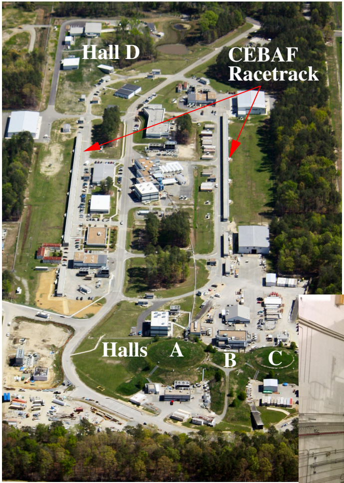

CLAS12 Detector
Forward Detector
Central
Detector
Beam
LTCC
FTOF
EC & PCAL
DC
HTCC
CTOF + CND
BAND



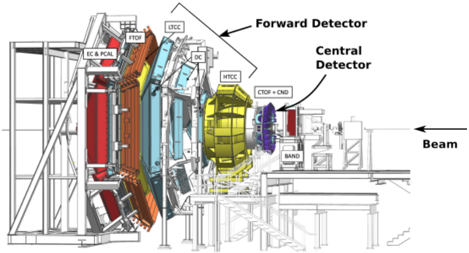

## CLAS12 Detector

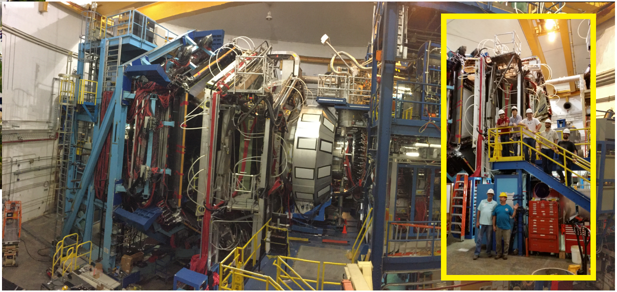





## CLAS12 Detector



# Newtonian 3-Momentum Is Not Conserved! 12

Two particles of identical mass $m$ collide perfectly inelastically in one dimension. The initial momentum of one particle is $v_i = 0.5c$. The other is stationary. What is the final velocity in the Home frame in terms of $v_i$?

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If the Other frame is moving with the projectile is the 3-momentum still conserved?

primes refer to the frame moving with velocity $v$.

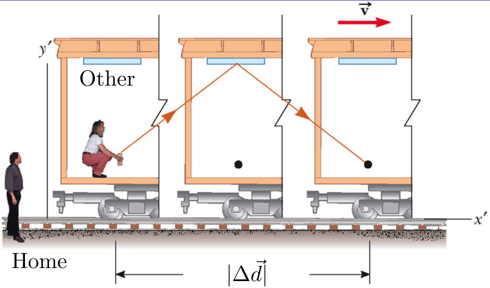
$v$ - velocity of moving frame.

$u_i$ - $i^{th}$ component of the velocity of an object in the stationary frame.

$u_i'$ - $i^{th}$ component of the velocity of an object in the moving frame.

$\gamma = \frac{1}{\sqrt{1-v^2/c^2}}$ where $c$ is the speed of light.

| Galilean | Lorentz |
|---|---|
| $x' = x - vt$ | $x' = \gamma(x - vt)$ |
| $y' = y$ | $y' = y$ |
| $z' = z$ | $z' = z$ |
| $t' = t$ | $t' = \gamma(t - vx/c^2)$ |
| $u_x' = u_x - v$ | $u_x' = \frac{u_x - v}{1 - u_x v/c^2}$ |
| $u_y' = u_y$ | $u_y' = u_y$ |
| $u_z' = u_z$ | $u_z' = u_z$ |

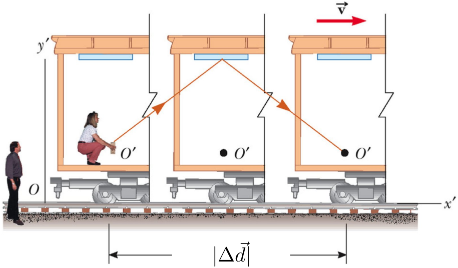



unprimed - Home
primed - Other

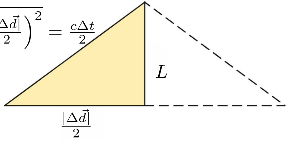
Metric Equation: $\Delta s^2 = c^2 \Delta t^2 - \Delta d^2 = \Delta s'^2 = c^2 \Delta t'^2$ (SI units)

| Coordinate Time | Proper Time | Spacetime Interval |
|---|---|---|
| Time between two events in an inertial frame measured with synchronized clocks at each event | Time between two events measured by the same clock at both events. | Time between two events measured by the same, inertial clock at both events. |
| $\Delta t$ | $\Delta \tau_{SI} = \int_{t_A}^{t_B} \sqrt{1 - v^2/c^2}\ dt$ | $\Delta s_{SI}^2 = c^2 \Delta t^2 - \lvert\Delta \vec{d}\rvert^2$ |
| Frame dependent | Frame independent | Frame independent |

# Recall the Spacetime Interval 




$$L_{Home} = \sqrt{L^2 + \left(\frac{|\Delta \vec{d}|}{2}\right)^2} = \frac{c\Delta t}{2}$$

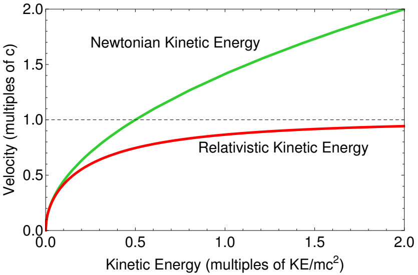


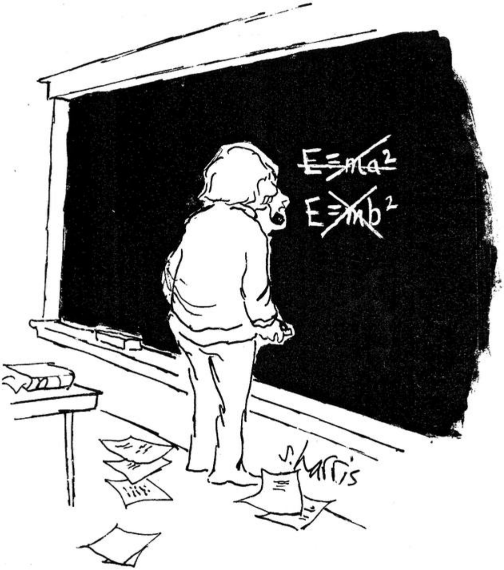

Spacetime interval in clock frame (#1): $\Delta t_1 = \Delta s_1 = \dfrac{2L}{c}$ ($v$ constant)

Spacetime interval in Home frame (#2): $\Delta t_2^2 = \Delta t_1^2 + \dfrac{\Delta d^2}{c^2}$

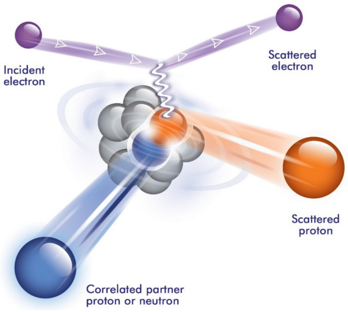
Metric Equation: $\Delta t_1^2 = \Delta s_1^2 = \Delta t_2^2 - \dfrac{\Delta d^2}{c^2}$ ($v$ constant)

An electron is accelerated to an energy $E = 6 \text{ GeV}$ where $1 \text{ GeV} = 10^9 \text{ GeV}$ at the Thomas Jefferson National Accelerator Facility in Newport News. What is the electron's speed and kinetic energy?





E=ma²
E=mb²
S. Harris

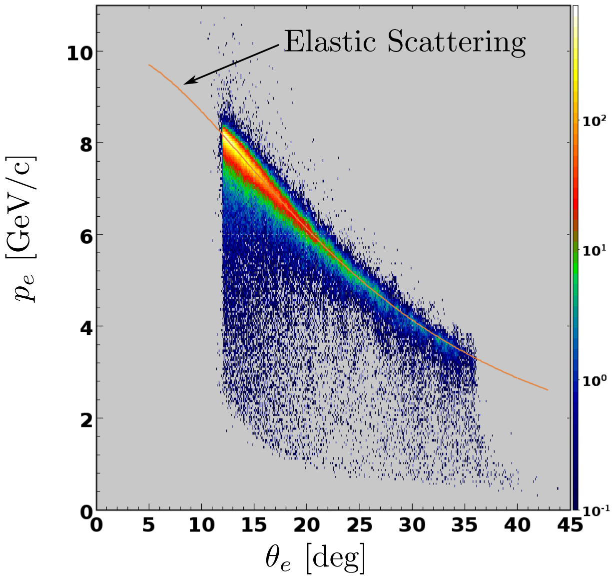
One of the essential tools for probing the structure of matter is scattering. Two sub-atomic particles collide and the properties of the debris tell us about the forces. In the figure an incident electron knocks a proton out of an atomic nucleus along with some other particles. If we can select events that are elastic (no kinetic energy lost in the collision), then we can 'see' the internal structure of the nucleon.



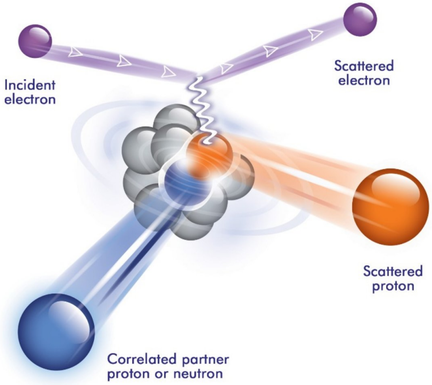

What is the energy of the scattered electron in terms of the incident/beam energy of the electron and angle $\theta$ with respect to the beam direction? What is the energy of a scattered electron at $\theta = 10^\circ$? How would you select these particles?

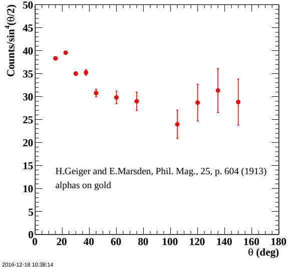
# Does it work?

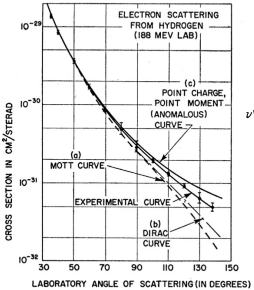



Elastic Scattering
$p_e$ [GeV/c]
$\theta_e$ [deg]
0
2
4
6
8
10
0
5
10
15
20
25
30
35
40
45
$10^{-1}$
$10^{0}$
$10^{1}$
$10^{2}$

What is the energy and angle of the scattered proton?



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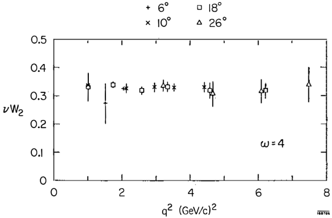


FIGURE 17. $\nu W_2$ for the proton as a function of $q^2$ for $W>2$ GeV, at $\omega=4$. Results from (7, 8, and 49).

McAllister and Hofstadter, PR 102, 851 (1956)

$$E_{e'} = \frac{E_e}{1 + \frac{2E_e}{m_n}\sin^2\left(\frac{\theta_e}{2}\right)} \qquad p_{n'} = \frac{2m_n\cos\phi(1 + m_n/E_e)}{1 + \frac{m_n^2}{E_e^2} + \frac{2m_n}{E_e} - \cos^2\phi}$$