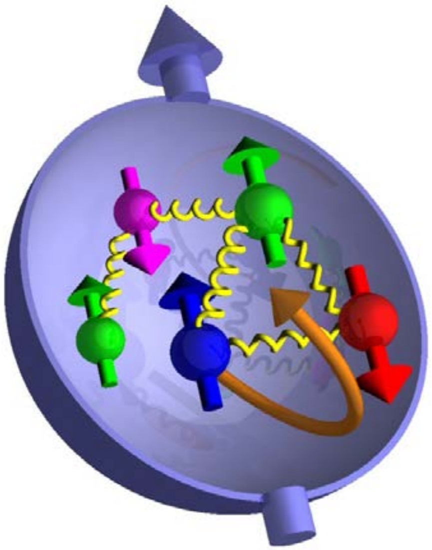
Probing the Atomic Nucleus at Jefferson Lab

(a glimpse)



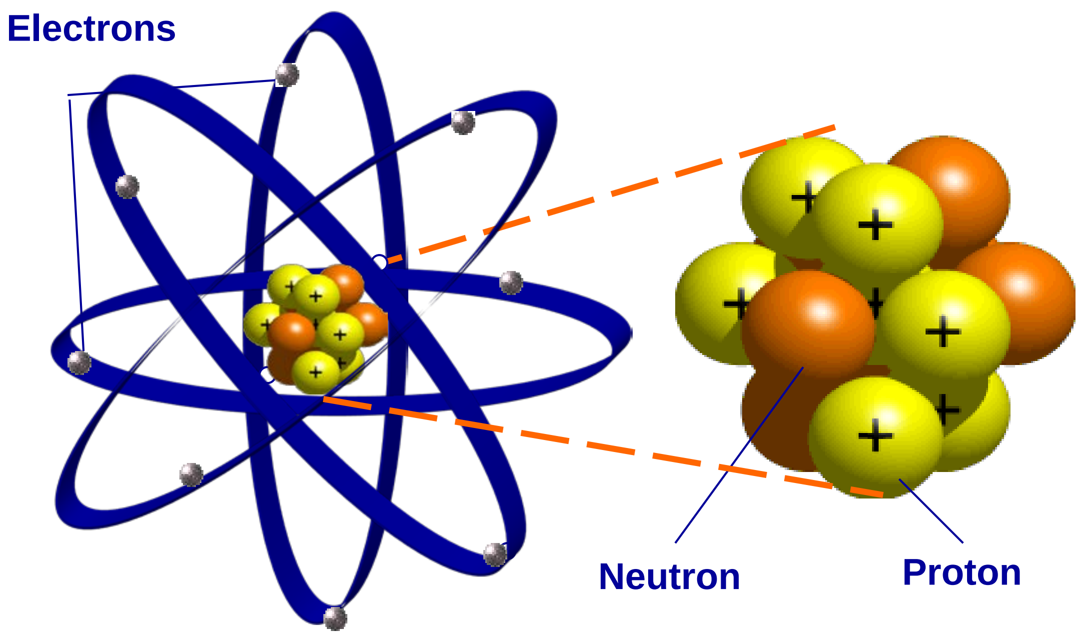
Fatiha Benmokhtar

Duquesne University.

*Thanks to R. Ent for some of the material

Building Blocks of Matter

Atom Nucleus



-**Most of the mass of an atom is carried out by the nucleus:**

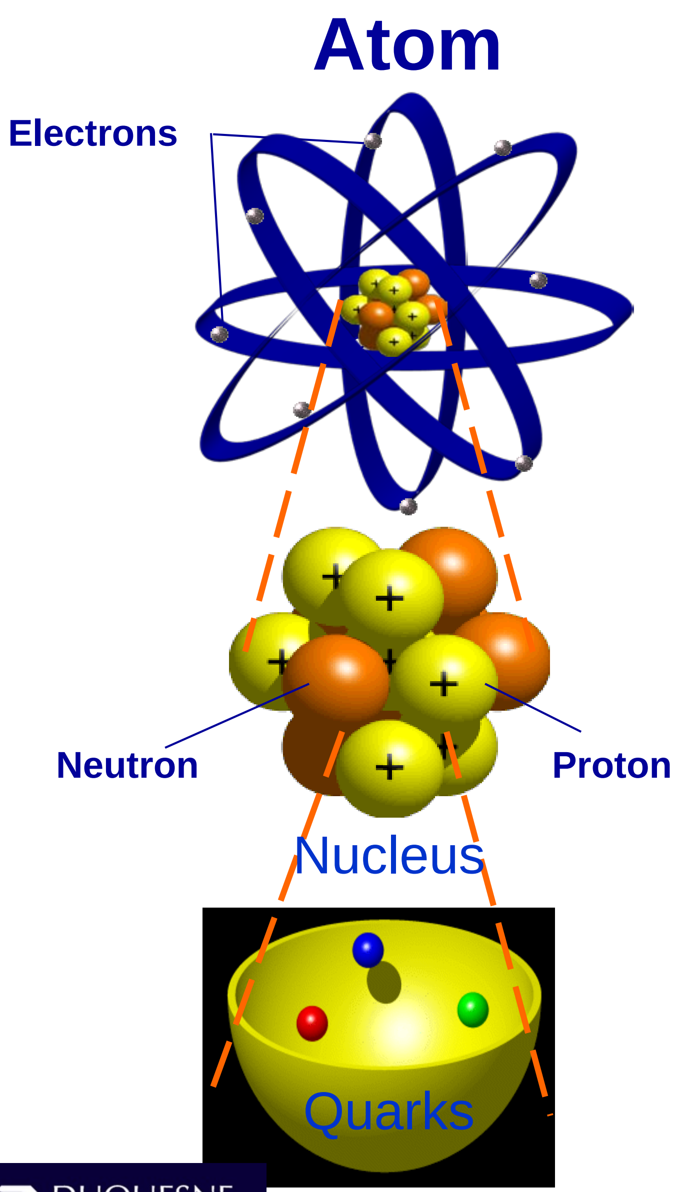
- **Mp ~938MeV, Mn 939MeV**
- **Me=0.51 MeV ~1/1836 Mp**

1 electron volt = 1.60 × 10^{-19} joules

- **Atoms are built of: Electrons, Protons and Neutrons**

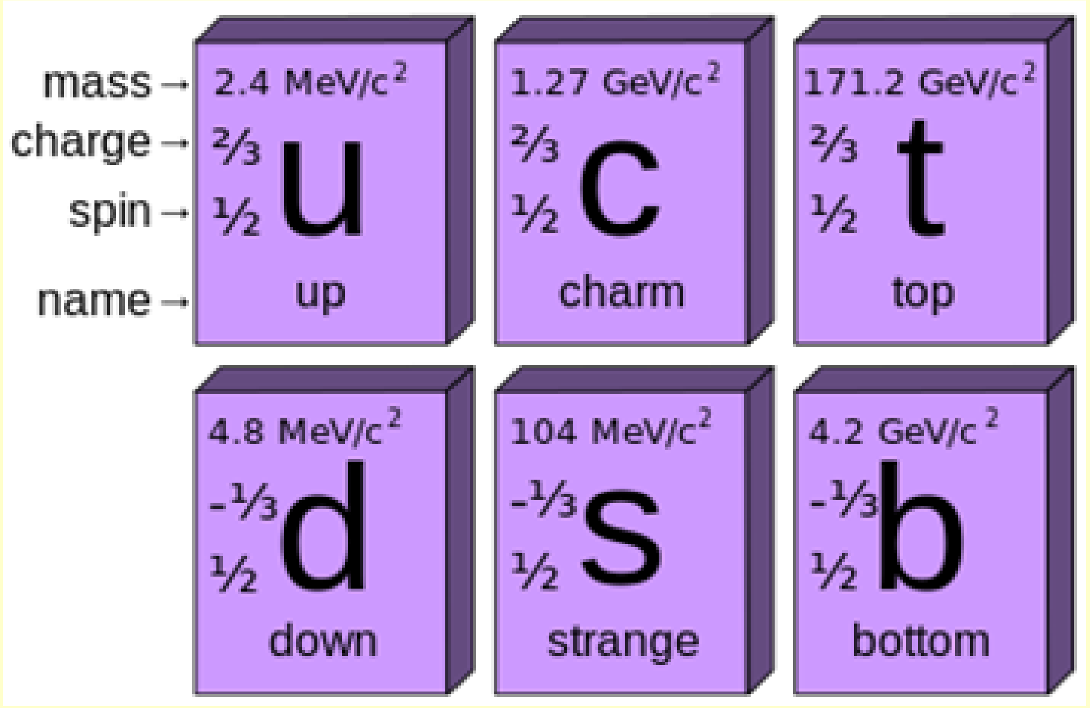
Nucleons

Matter



- **Protons and neutrons were thought of as elementary particles until Gell-Mann & Zweig proposed the Quark model 1964 (u,d,s)**

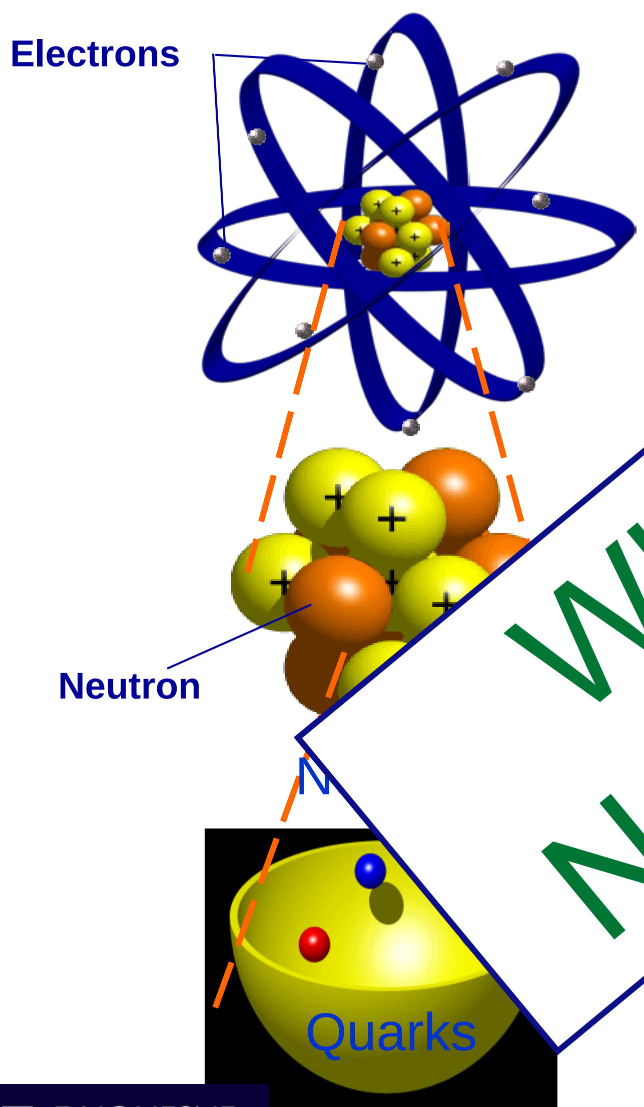
- **Experimental evidence(1968-1995):**
SLAC (u,d,s), c, b &t



.Proton: u u d $\frac{2}{3} + \frac{2}{3} + (-\frac{1}{3}) = +1$

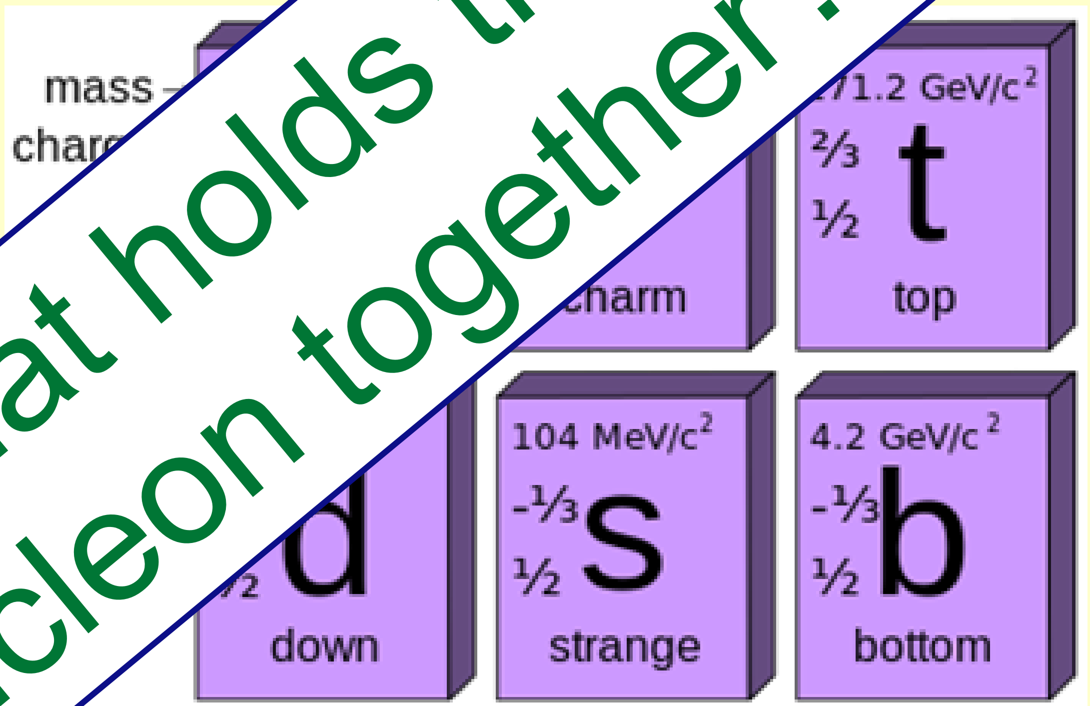
.Neutron: d d u $(-\frac{1}{3}) + (-\frac{1}{3}) + \frac{2}{3} = 0$

Matter



- **Protons and neutrons** were ... ought of as elementary particles until G... & **Zweig** proposed the Quark mo... s)

- **Experimental** e... SLAC (u,d,s), c...



What holds the Nucleon together?

.Proton: u u d $\frac{2}{3}+\frac{2}{3}+(-\frac{1}{3})=+1$

.Neutron: d d u $(-\frac{1}{3})+(-\frac{1}{3})+\frac{2}{3}=0$

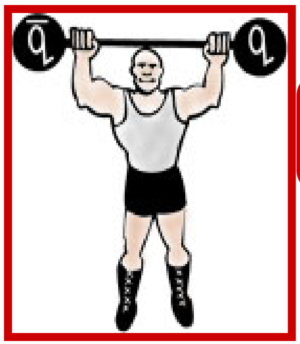
Fundamental Forces

Gravitational Force

- Attraction of masses
- Motion of planets, stars
- Infinite range
- Force Carrier: Graviton

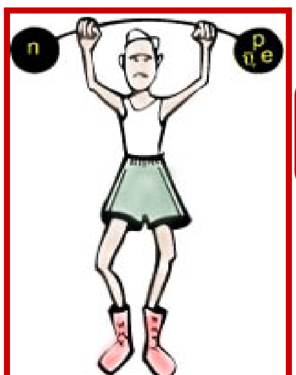
Electromagnetic Force

- Ties electrons to atoms
- Infinite range
- Force carrier: Photon



Strong Force

- Binding of atomic nuclei
- Internal structure of the proton (quarks)
- Subatomic range (< radius of proton)
- Force carrier: Gluon



Weak Force

- Radioactivity (beta decay)
- Neutrino
- Sub-nuclear range (nuclear radius/1000)
- Force carrier: Z or W bosons

Unified in the Standard Model of Particle Physics

- A model that describes all particles and particle interactions

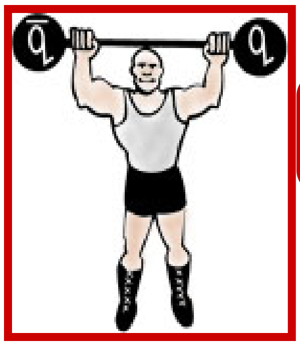
. 6 quarks and their antiparticles.
. 6 leptons (electron is an example) and their antiparticles
. Force carrier particles.
. And recently: The HIGGS BOSON!

Gravitational F

- Attraction of mass
- Motion of planets,
- Infinite range
- Force Carrier: Grav

Electromagnetic

- Ties electrons to ato
- Infinite range
- Force carrier: Photo



Strong For

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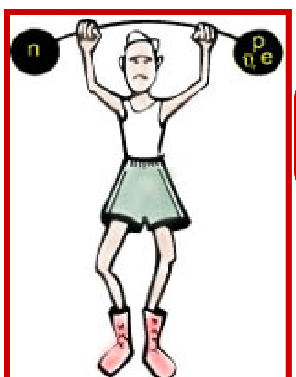

Weak Force

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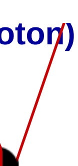
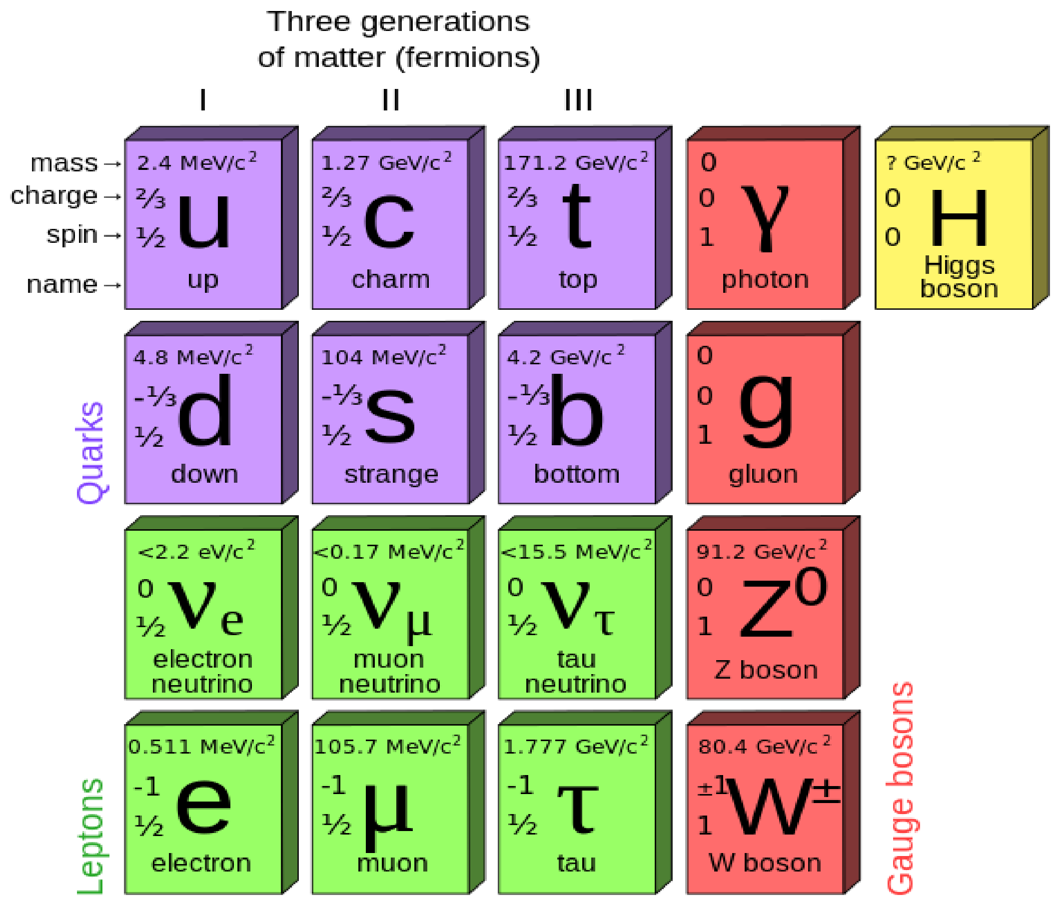




- A model that describes all particles and particle interactions

. 6 quarks and their antiparticles.
. 6 leptons (electron is an example) and their antiparticles
. Force carrier particles.
. And recently: The HIGGS BOSON!

Strong interaction and Color Charges

- Quarks have electromagnetic charge, and they also have an altogether different kind of charge called color charge. The force between color-charged particles is very strong, so this force is "creatively" called strong force.

- The strong force holds quarks together to form hadrons, its carrier particles are called gluons because they so tightly "glue" quarks together.

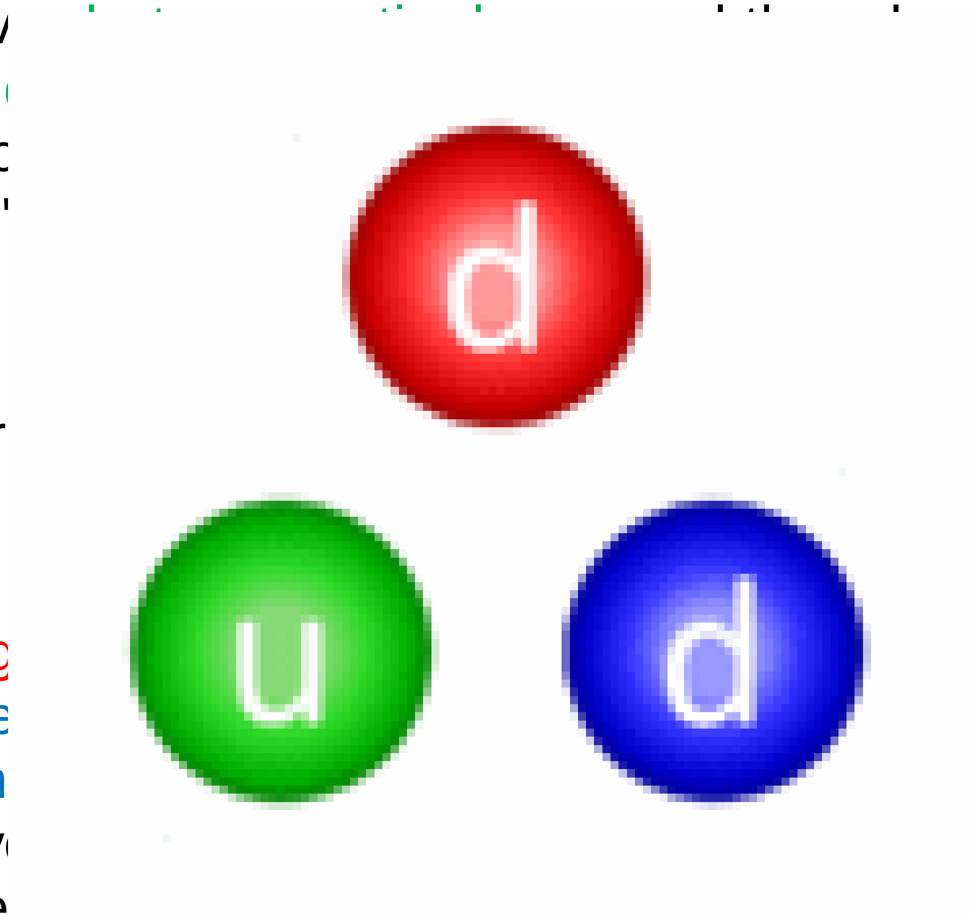
- Color charge behaves differently than electromagnetic charge. Gluons, themselves, have color charge, which is weird and not at all like photons which do not have electromagnetic charge. And while quarks have color charge, composite particles made out of quarks have no net color charge (they are color neutral). For this reason, the strong force only takes place on the really small level of quark interactions.

Strong interaction and Color Charges

- Quarks hav … have an altogether … e. The force between cc … is force is "creatively"

- The strong … ons, its carrier particles ar … glue" quarks together.

- Color charg … ic charge. Gluons, the … d and not at all like photon … ge. And while quarks hav … out of quarks have no ne … r this reason, the strong force only takes place on the really small level of quark interactions.



QCD: Quantum Chromo-Dynamics

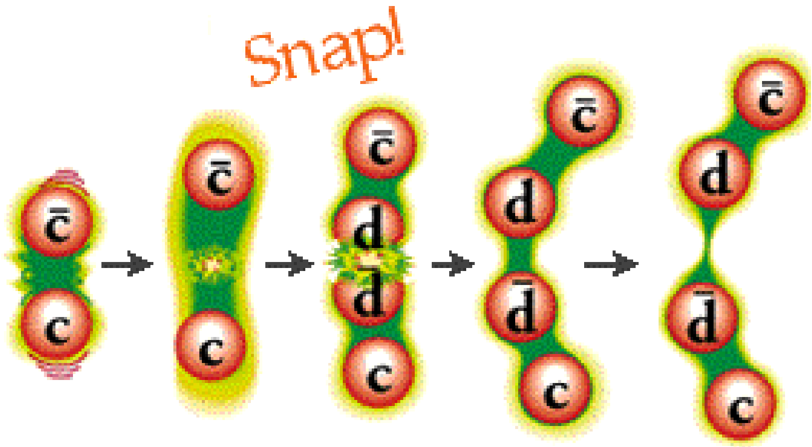
Refer to yesterday's talk, by D. Gross

- **QCD** is the theory of the strong interaction between quarks and gluons, the fundamental particles that make up protons, neutrons, pions, … It describes the formation of all form of nuclear matter!

- Experimental data on the basic properties, such as charge, mass, spin and magnetization of protons, neutrons and the very lightest nuclei, are key observables to confronting the theory.

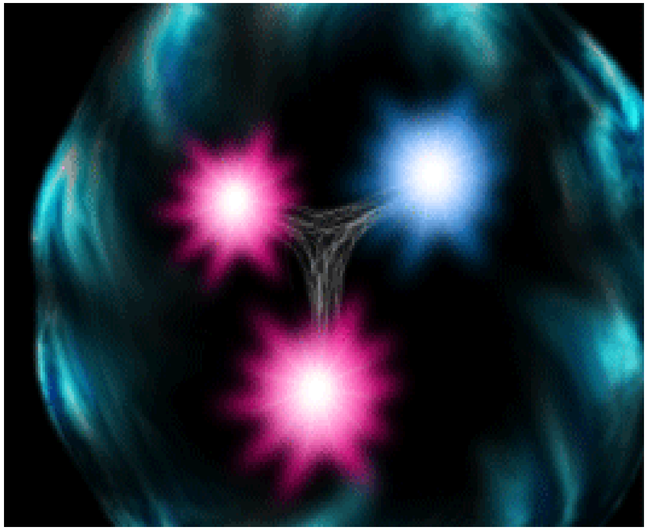
Some Cool Facts about QCD and Nuclei

- The strong force is so strong, that you can never find one quark alone (this is called "confinement").



- When pried even a little apart, quarks experience ten tons of force pulling them together again.

- Quarks and gluons jiggle around at nearly light-speed, and extra gluons and quark/anti-quark pairs pop into existence one moment to disappear the next.

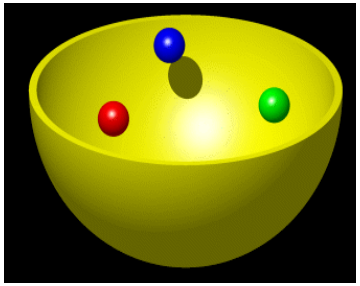


- This flurry of activity, fueled by the energy of the gluons, generates nearly all the mass of protons and neutrons, and thus ultimately of all the matter we see.

In fact…

- **If you add up the bare masses of the three quarks:**

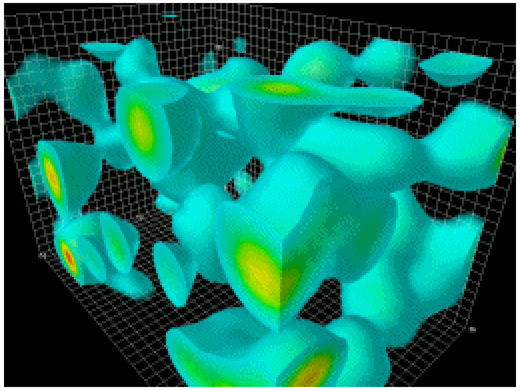
  - m_u ~2. MeV, m_d ~5. MeV
  - $2m_u + 1m_d = 9MeV$



Proton: u u d

- **BUT m_p = 938 MeV !!!**

this is less than 1% of the proton mass!



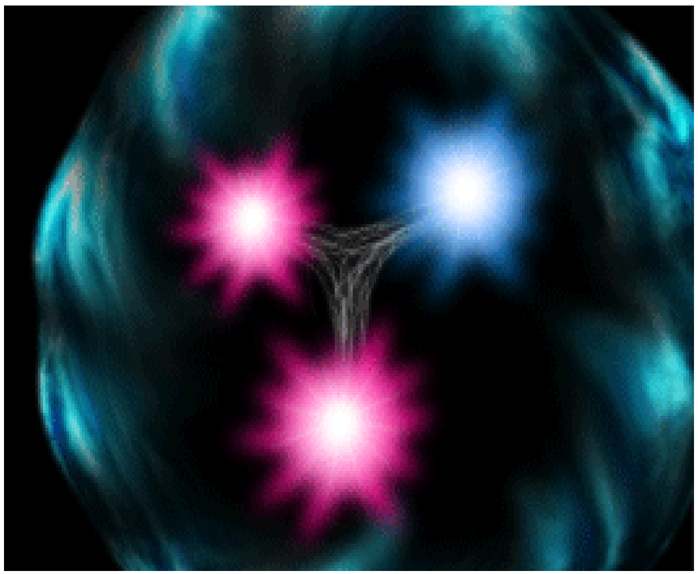
The QCD vacuum is not empty, but full of gluon fluctuations.

The Structure of the Proton

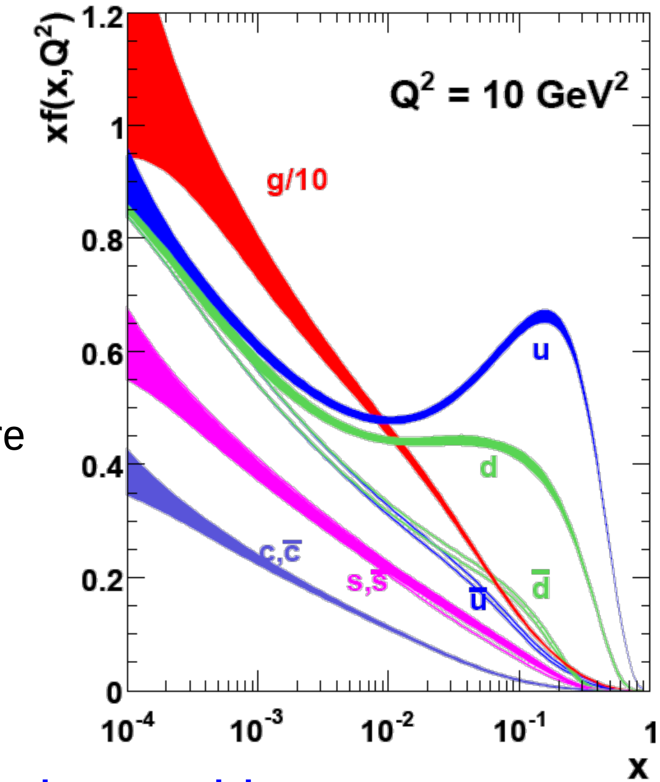
(far more than up + up +down)

$$P = uud + u\bar{u} + d\bar{d} + s\bar{s} + g + ...$$

valence « sea= virtual pairs » gluons



Non-trivial sea structure



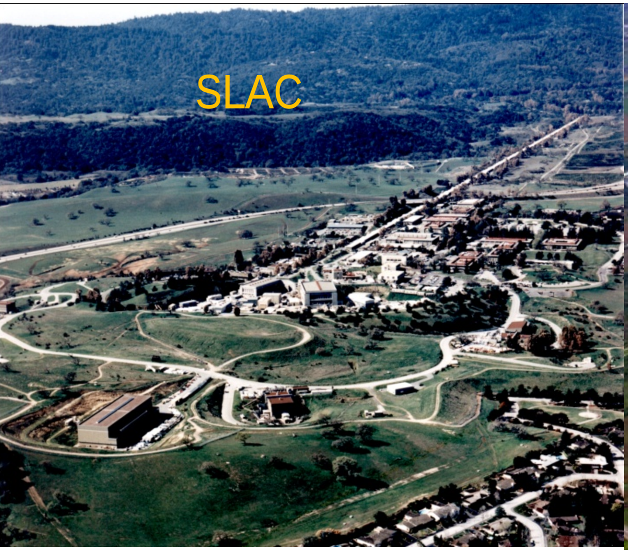
- Gluon ≠ photon: Radiates and recombines:

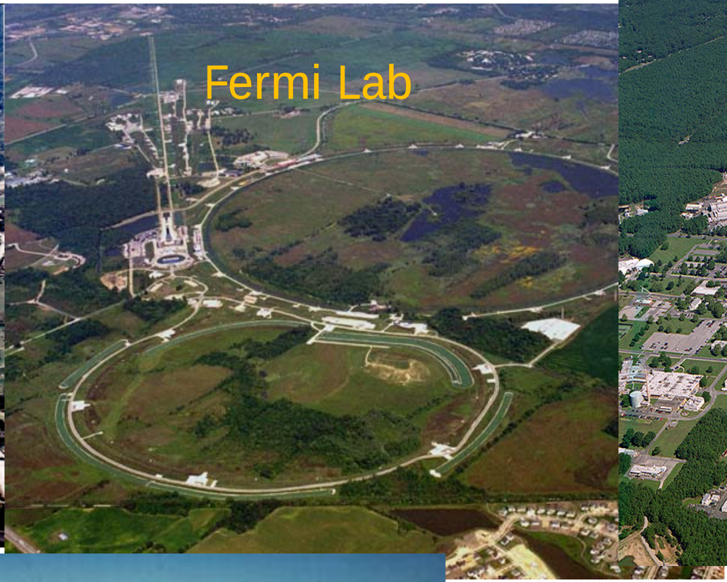
Nuclear physicists are trying to answer how basic properties like mass, shape, and spin come about from the flood of gluons, quark/anti-quark pairs, and a few ever-present quarks.

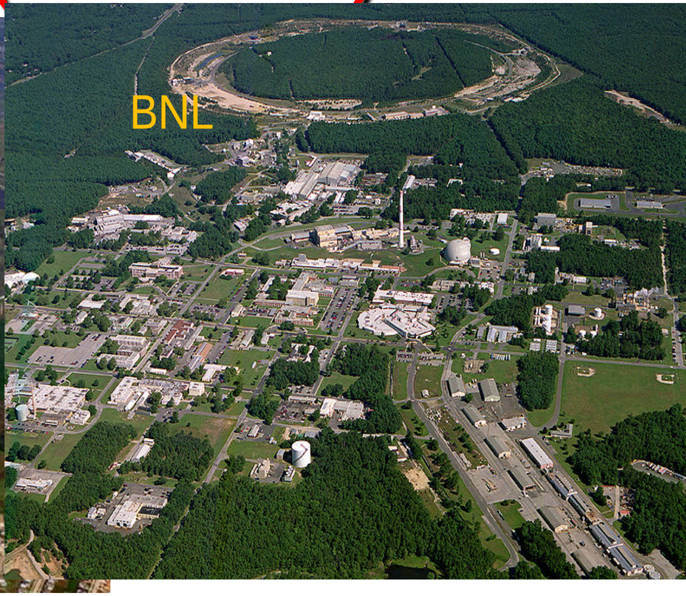
- How can we probe quarks and gluons???

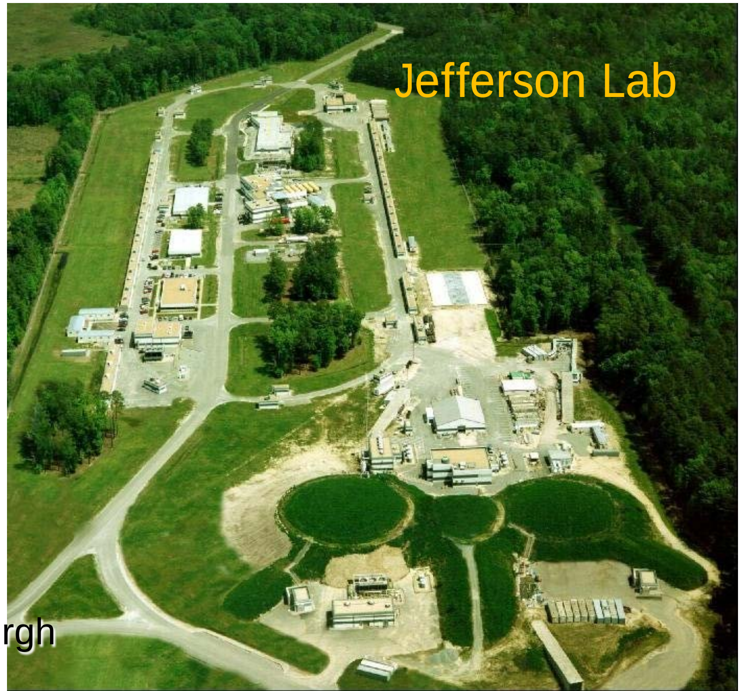
- Or even simpler question, how do we probe Protons !!!

Particle Accelerators (Some of them)

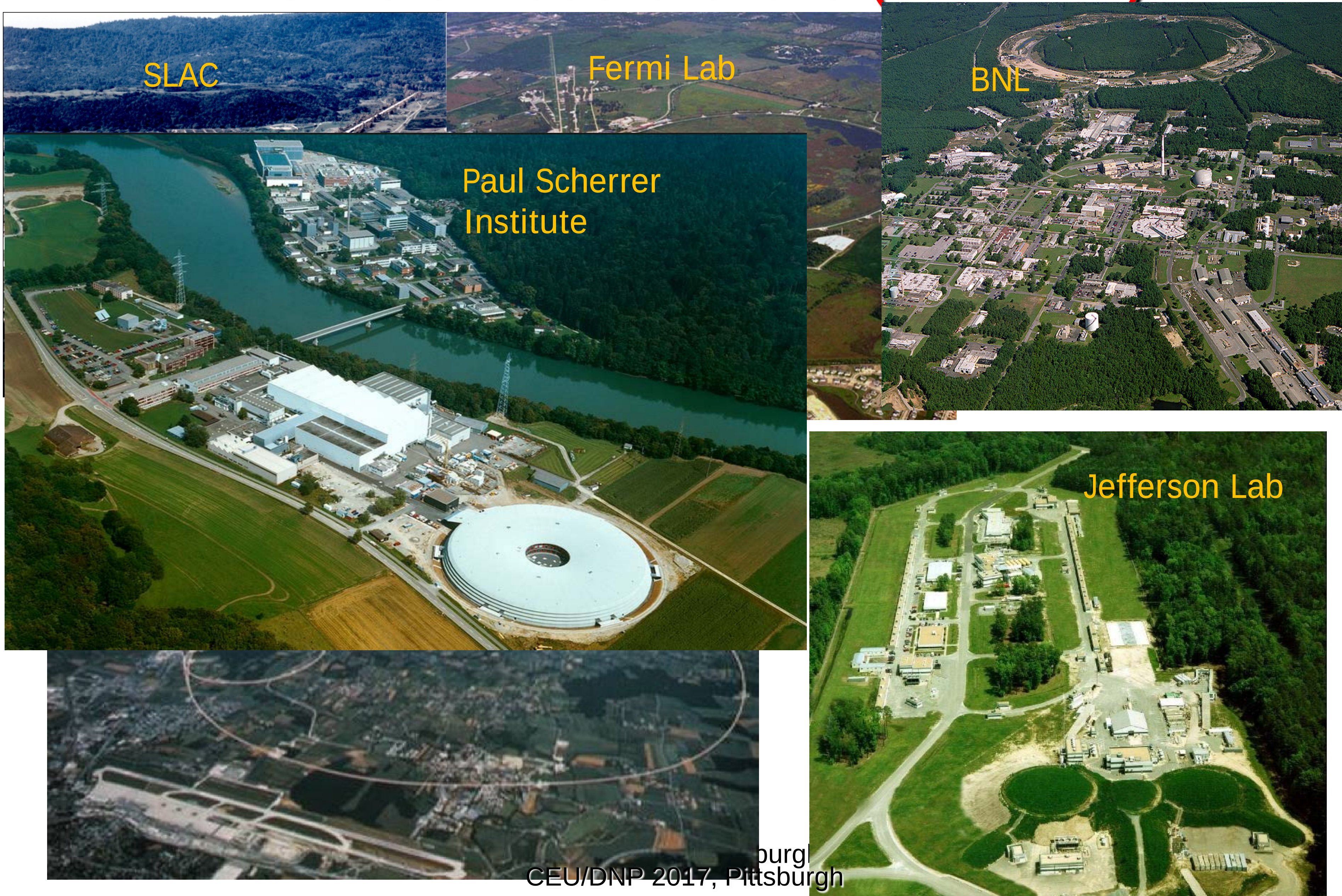


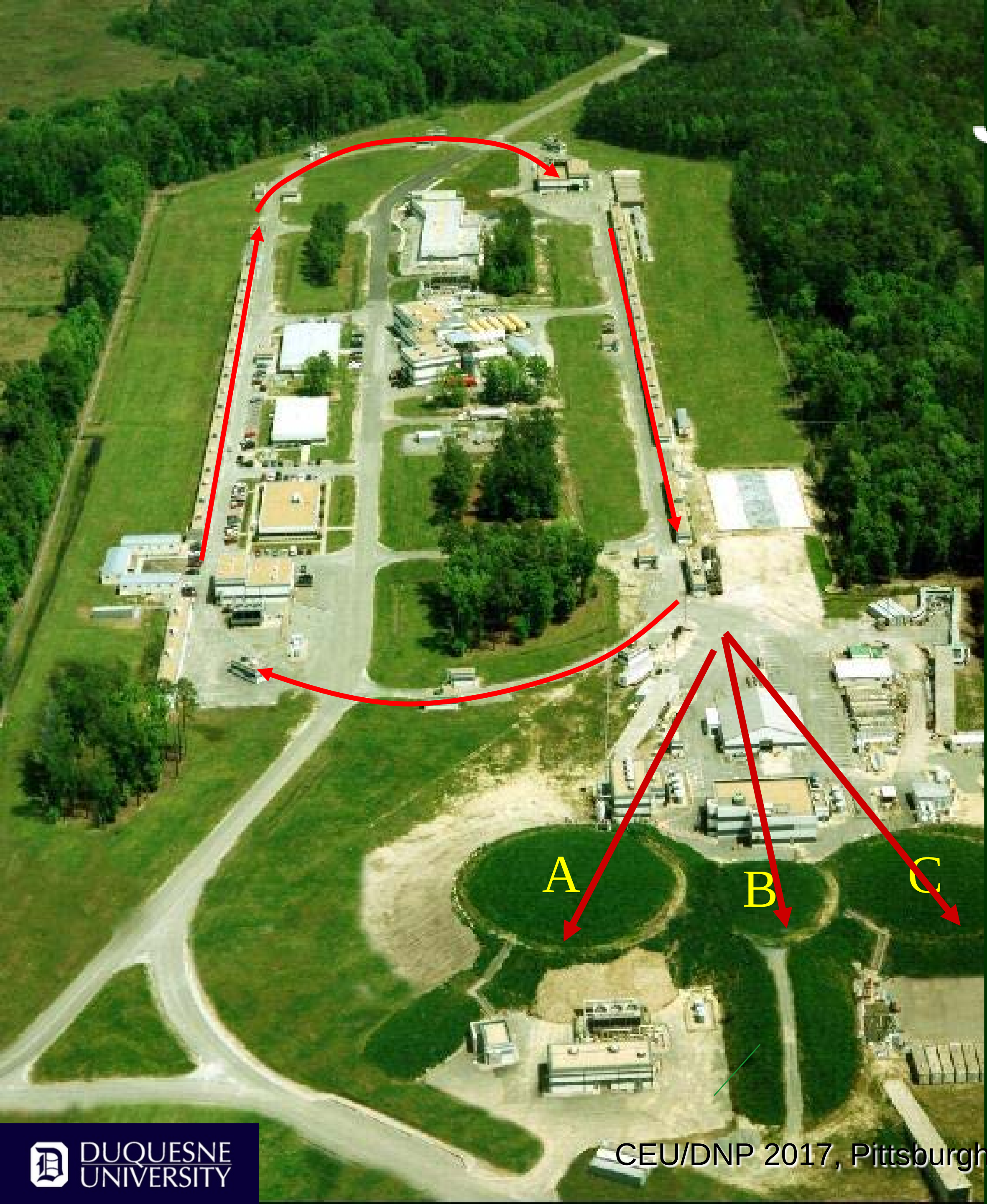






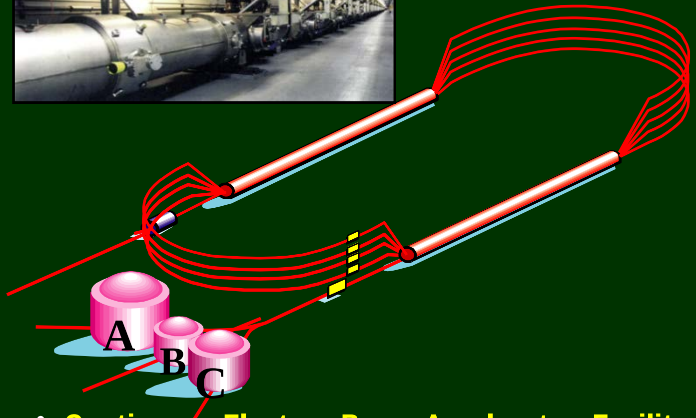
Particle Accelerators (Some of them)





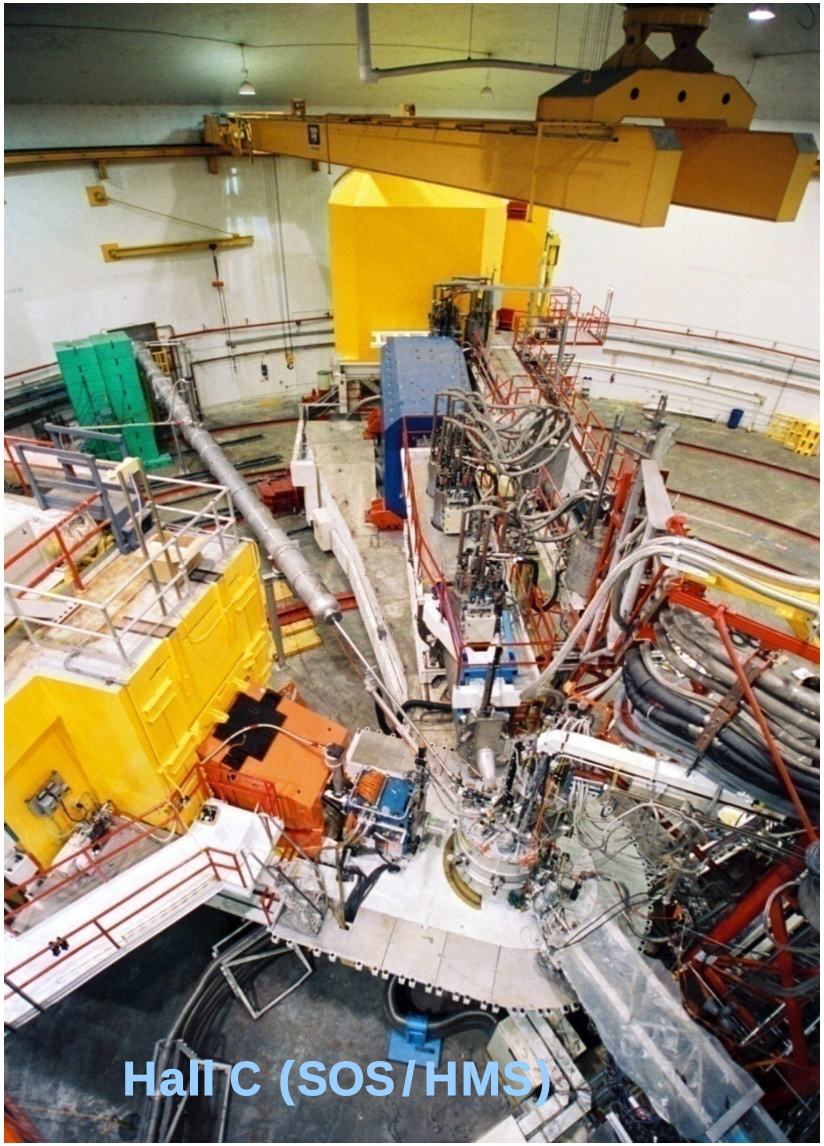
Jefferson Lab
EXPLORING THE NATURE OF MATTER

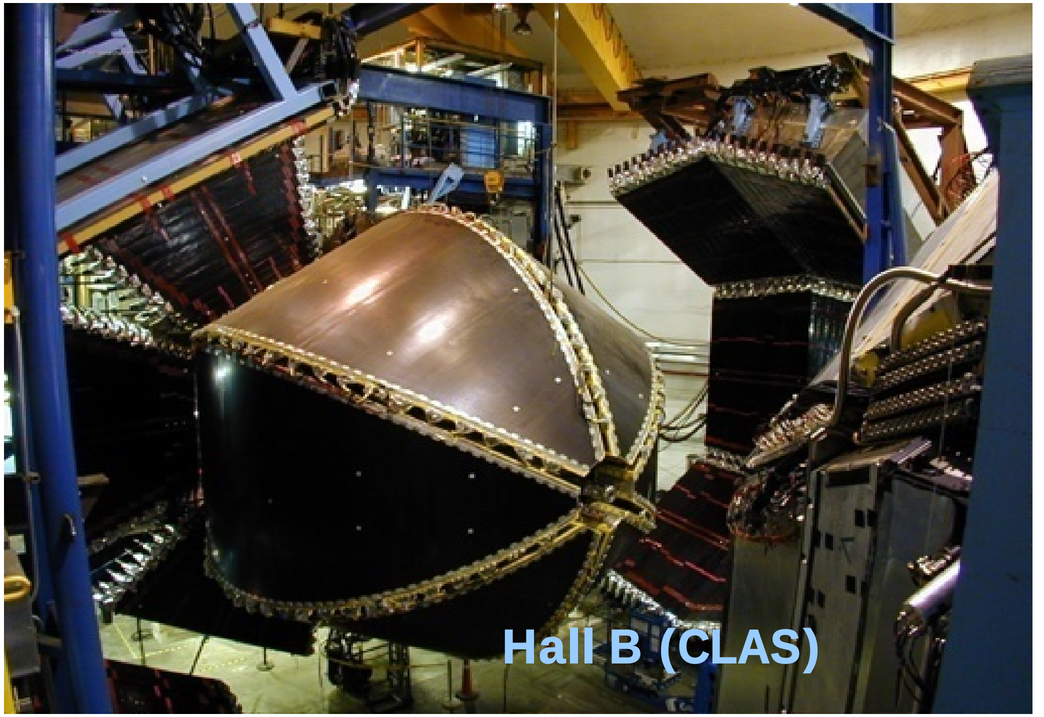
6 GeV- Up to 2012



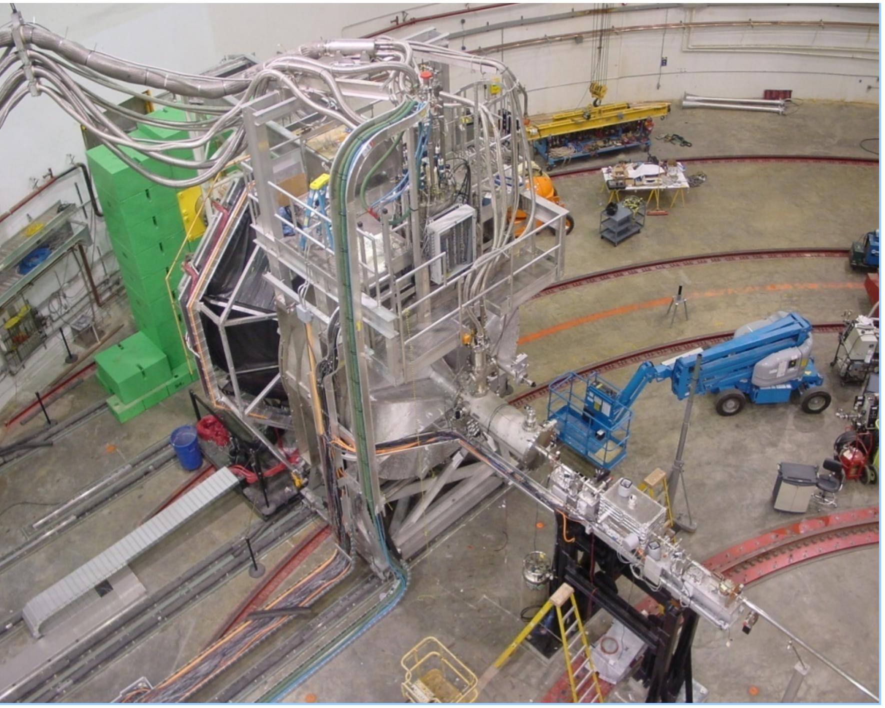
- **Continuous Electron Beam Accelerator Facility (CEBAF)**
- **2 linacs RF Cavities, 2 recirculation arcs.**
- **Almost 2000 users!**

Halls A/B/C (6-GeV) Base Equipment (1995-2012)

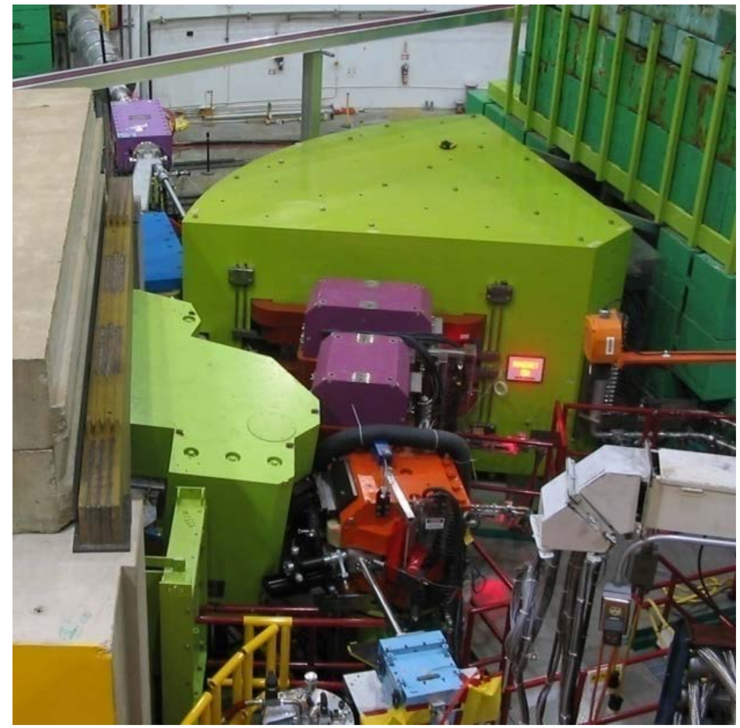




Experiment-Specific Apparatus



G0 Setup 2002-2007



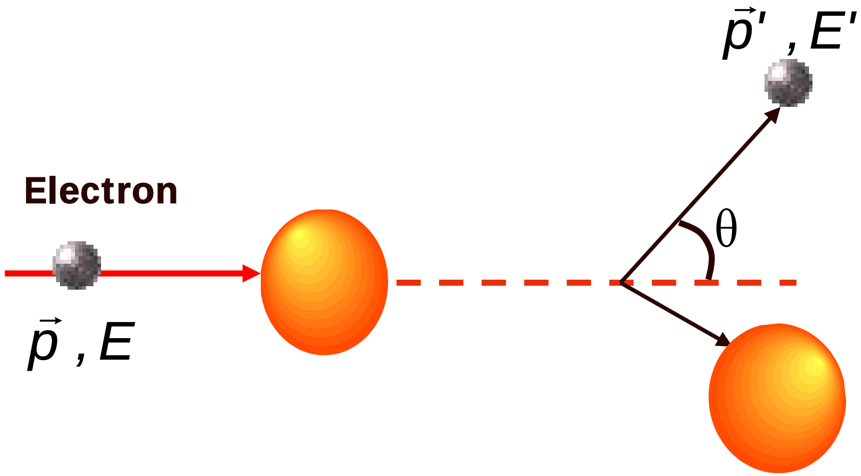
ENGE/HKS Setup 2005

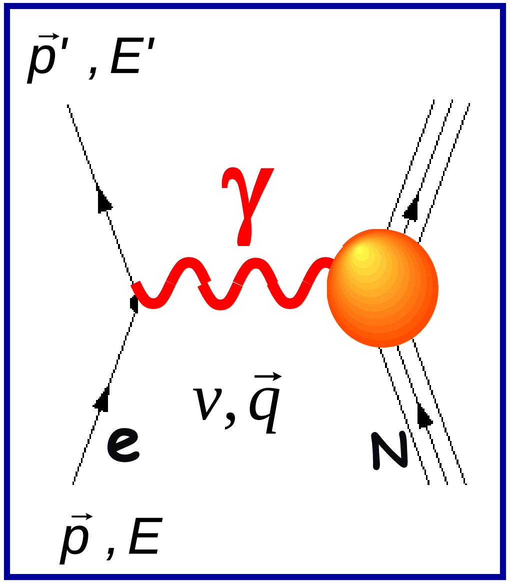
International Collaboration

~1/3 of our 1530 users (FY16) are international, from 37 countries

DUQUESNE UNIVERSITY

Elastic Electron-Nucleon Scattering





$\nu = E - E'$ **Energy transfer**

$\vec{q} = \vec{p} - \vec{p}'$ **3-Momentum transfer**

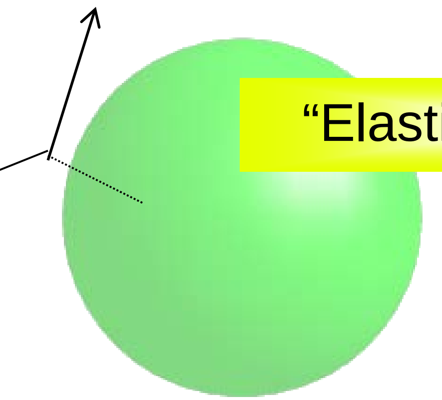
$Q^2 = \nu^2 - \vec{q}^2$ **Squared 4-Momentum transfer**

$W^2 = M^2 - 2M\nu - Q^2$ **Invariant mass**

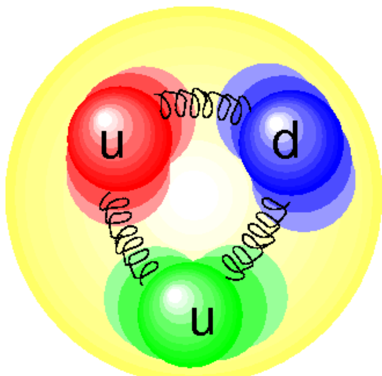
Electron - nucleon scattering: electromagnetic interaction, described as an exchange of a virtual photon.

Increasing momentum transfer
-> shorter wavelength
-> higher resolution to observe smaller structures

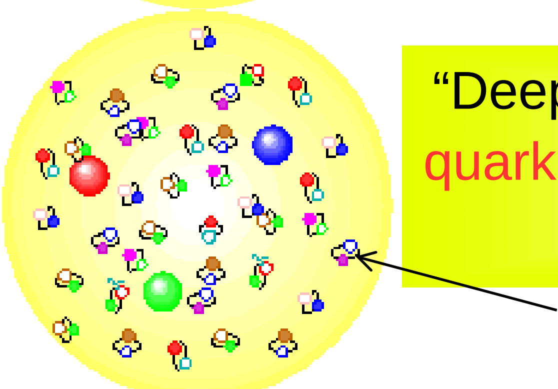
Choosing the Physics



"Elastic": $W=M_t$ or M_p

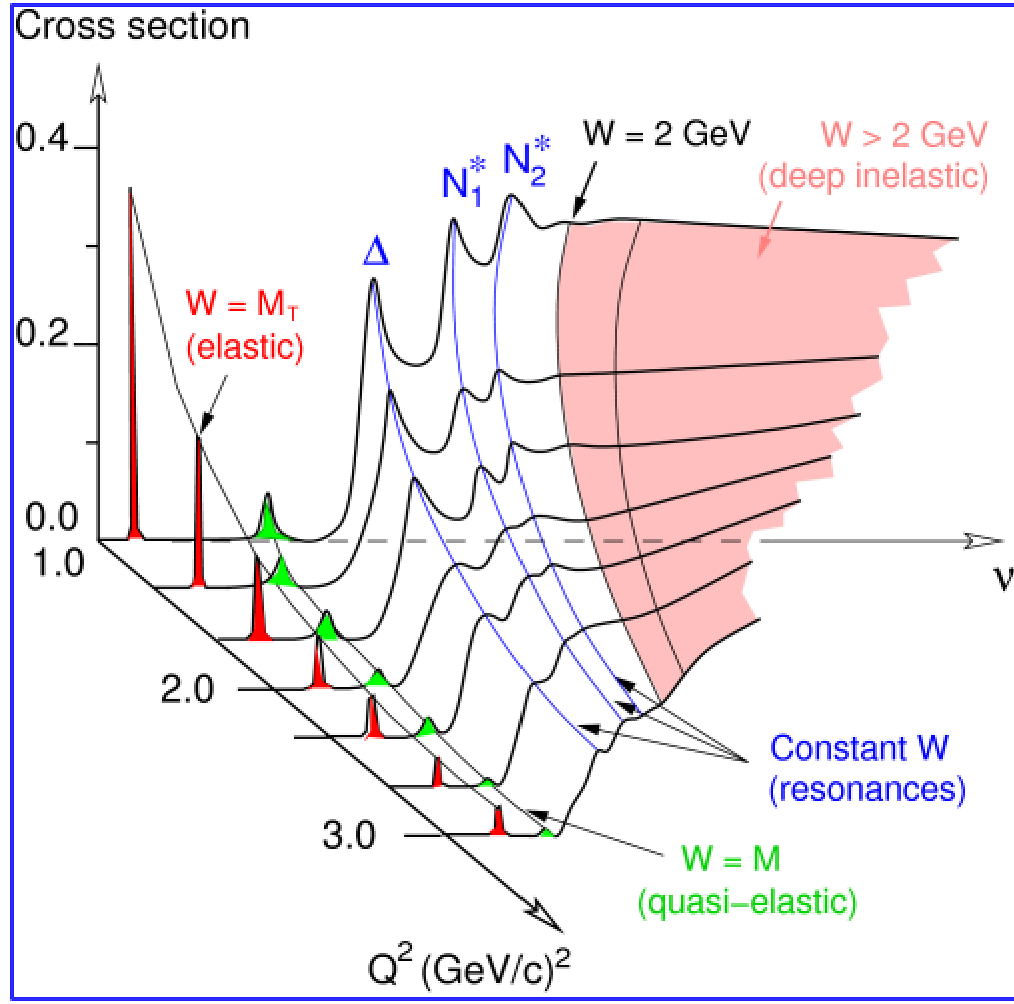


"Resonance": $1<W<2$GeV



"Deep Inelastic": W>2 GeV, first evidence of quarks; directly probes the quasi-free quarks inside the nucleon.

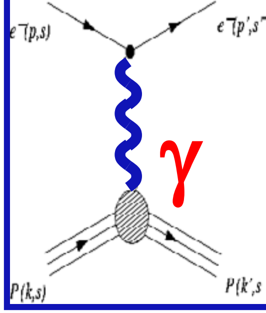
10^{-18}m or smaller



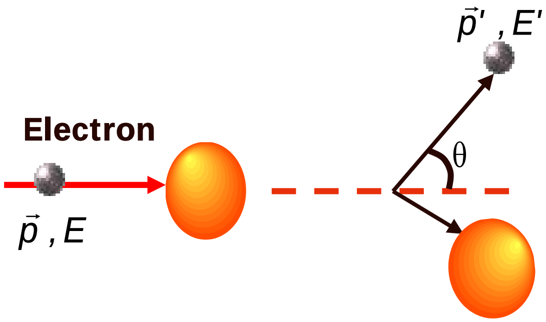
"figure credit: X. Zheng"

Few Examples!

Nucleon Charge and Magnetization?



$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} \left| F(Q^2) \right|^2$$



- **Elastic scattering by point like particles with spin**

The Form Factor!

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{Mott} \left\{ \frac{(G_E^2 + \tau G_M^2)}{1+\tau} + 2\tau G_M^2 \tan^2(\theta/2) \right\}$$

$$\tau = \frac{Q^2}{4M^2}$$

Form factors G_E and G_M are functions of Q^2

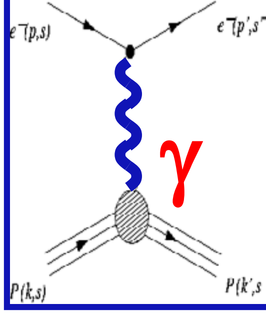
Electric *Magnetic*

At $Q^2 = 0$:	G_E	G_M
proton	1	2.79
neutron	0	−1.91

G_E: charge

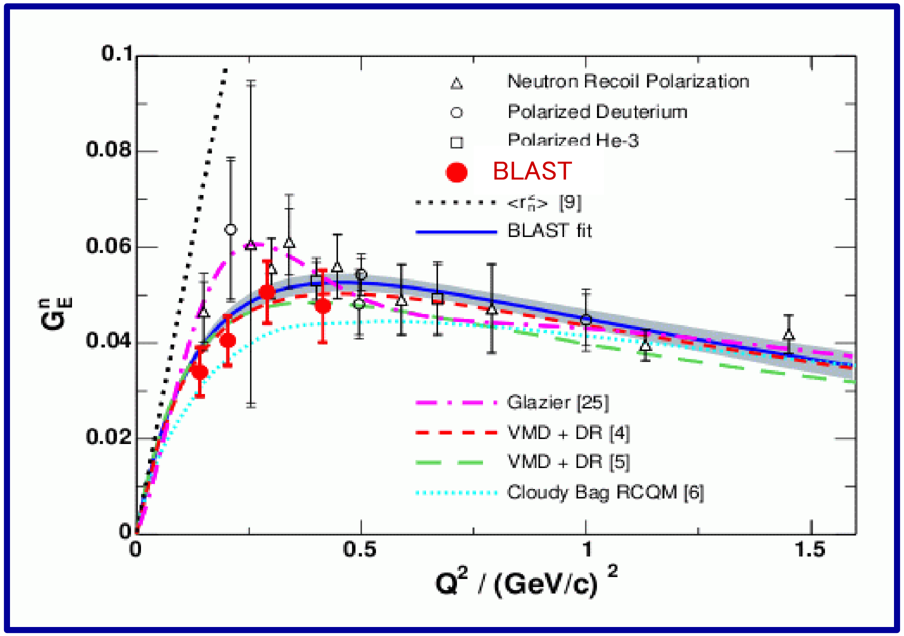
G_M: anomalous magnetic moment

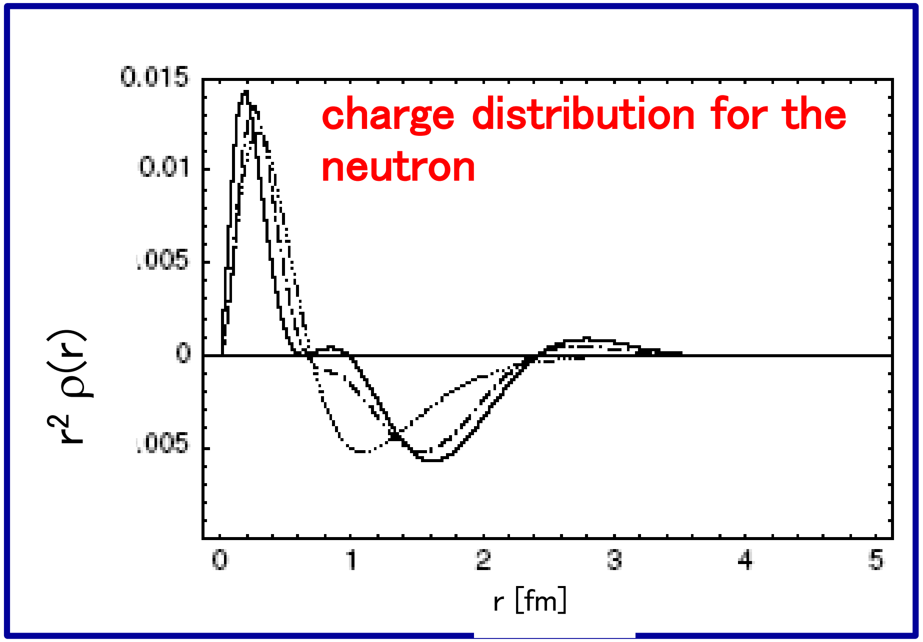
What can we learn from the FFs?



- Can be thought of as : Fourier transform of the charge and magnetic current distributions inside the nucleon

Example: Neutron Electric Form Factor:

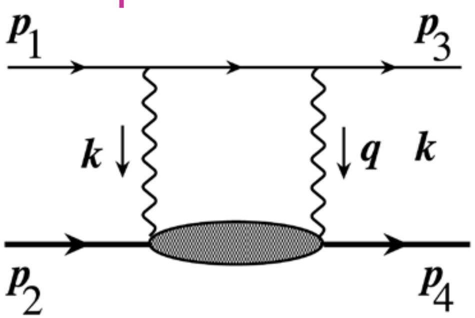




- **At $Q^2 = 0$, the form factor represents an integral over the nucleon**
- **Information on the structure of the nucleon.**
- **Compare to theoretical predictions: Quantum Chromo-Dynamics, etc…**

Proton Charge and Magnetization

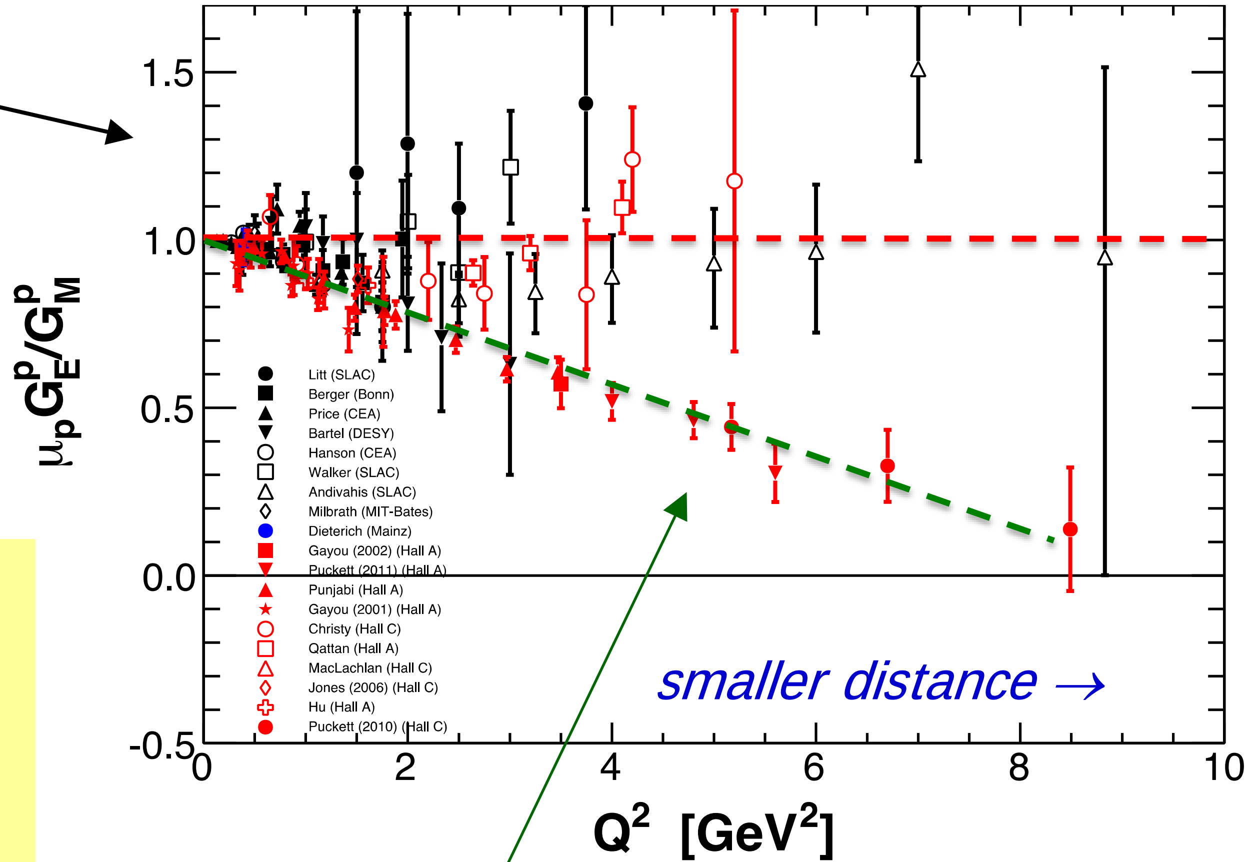
2-γ exchange important



Elastic electron-proton scattering

1) e + p → e' + p
G_E^p/G_M^p constant

2) $\vec{e}$ + p → e' + $\vec{p}$
G_E^p/G_M^p drops with Q^2

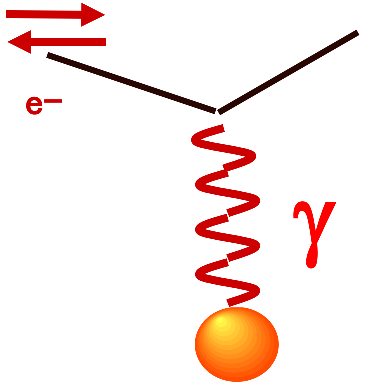


charge depletion in interior of proton

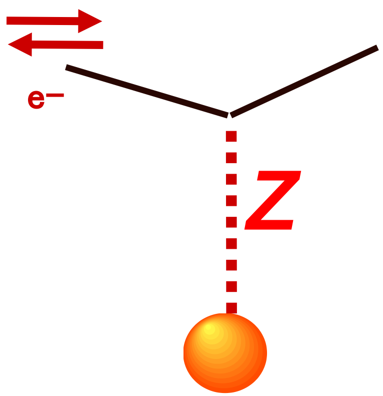
Charge & magnetization distributions in the proton **are different**

Electron Parity Violation Experiments

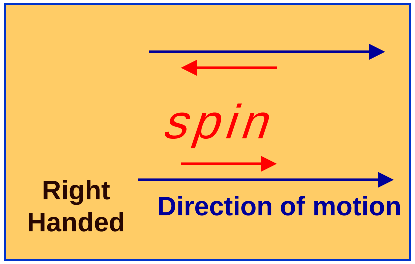
.Scatter longitudinally polarized electron beam off an unpolarized target and count the scattered electrons:



Electromagnetic force
Parity Conserving



Weak force
Parity Violating



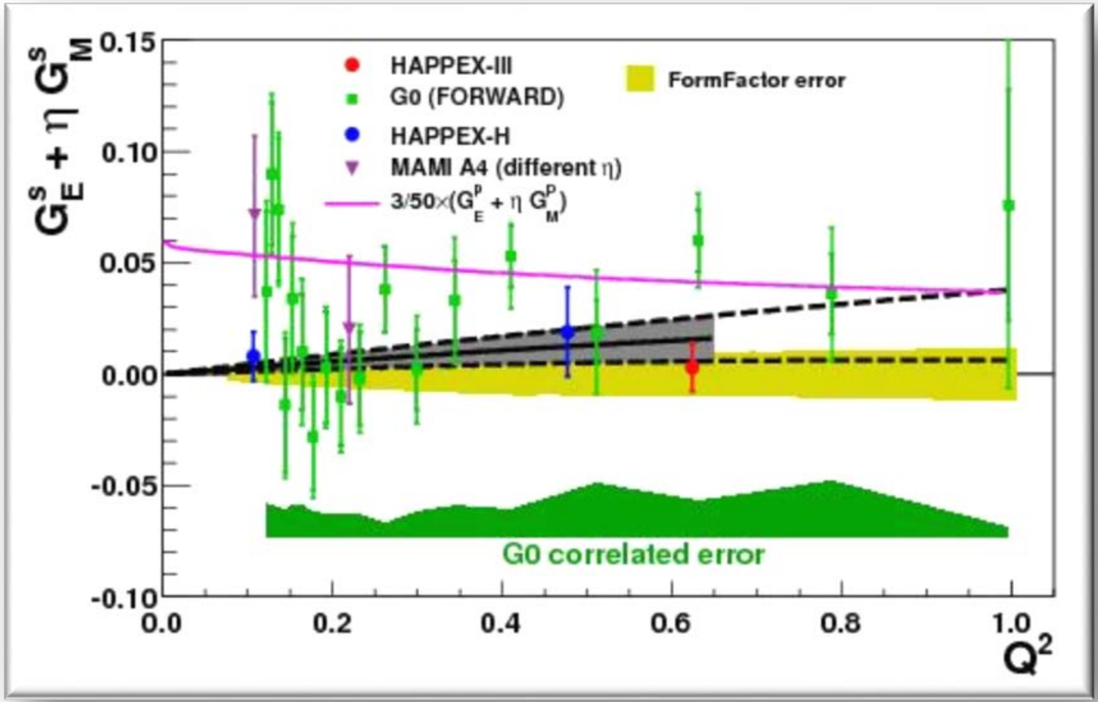
. Parity Violating: detected number of RH e- is different from the detected number of LH e- !!!

$$A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \propto \frac{2M_\gamma^* M_Z}{\left|M_\gamma\right|^2}$$

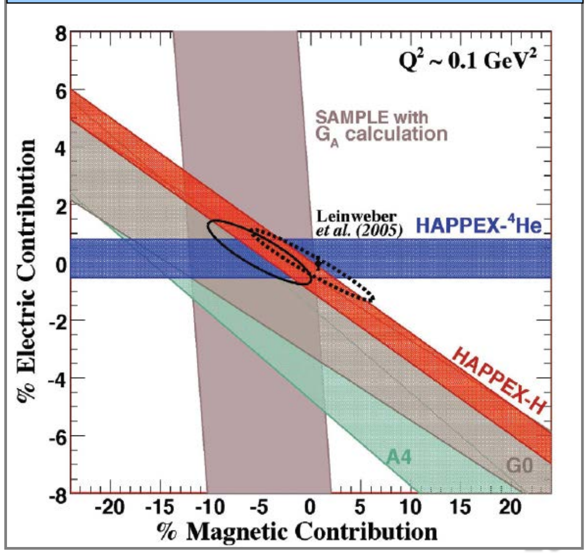
The spatial distribution of quarks and the proton's magnetism

Hall A

strange quarks **do not play a substantial role** in the long-range electromagnetic structure of nucleons



1[st] Separation using G0, HAPPEx-II & HAPPEx-He, and A4 & SAMPLE data

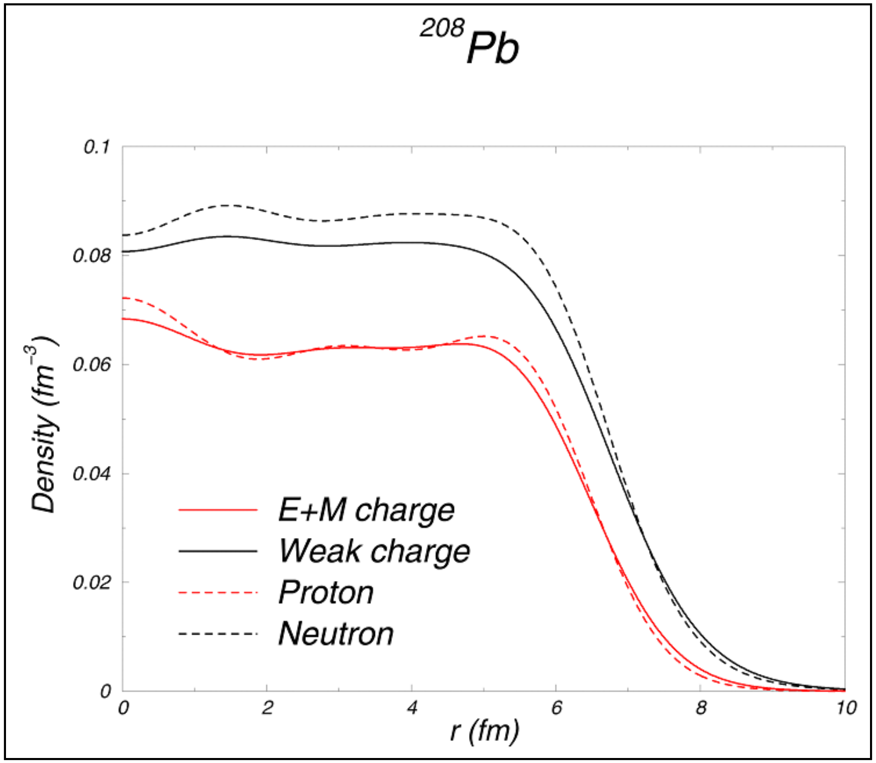


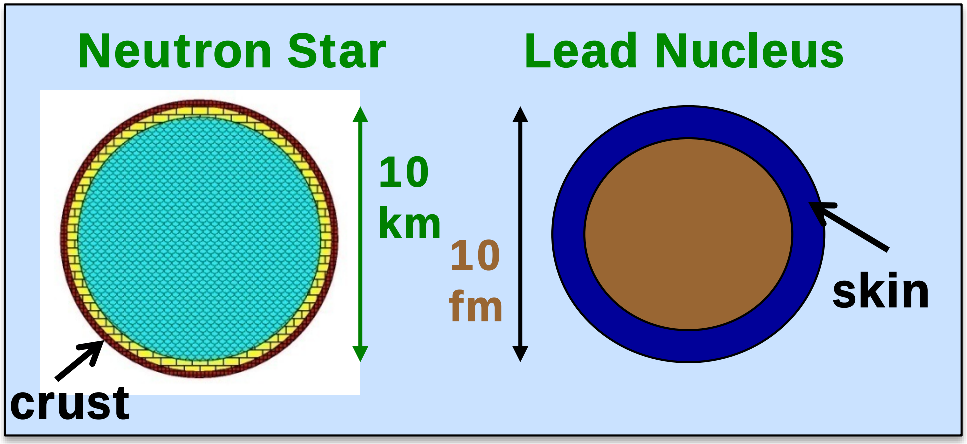
Measuring the Neutron "Skin" in the Pb Nucleus

$Q_w^p = (1 - 4 \sin^2 \theta_W)$
$Q_W^n = -1$

Weak interaction selects neutrons

- Parity violating electron scattering
- Sensitive to neutron distribution





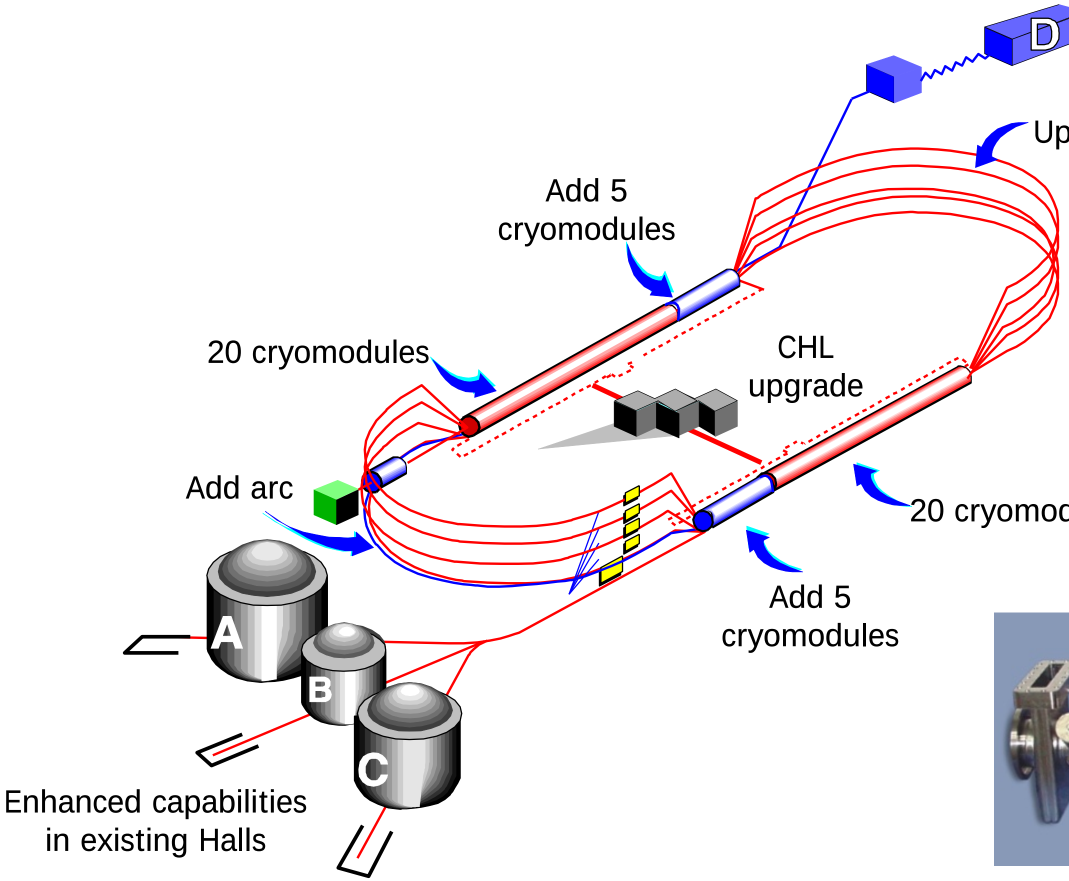
Applications: Nuclear Physics, Neutron Stars, Atomic Parity, Heavy Ion Collisions

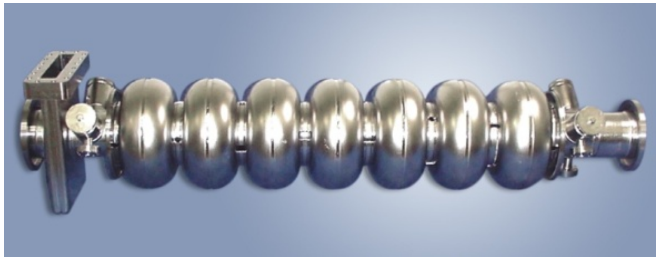
And many more…

JLab – a 12 GeV Electron Accelerator

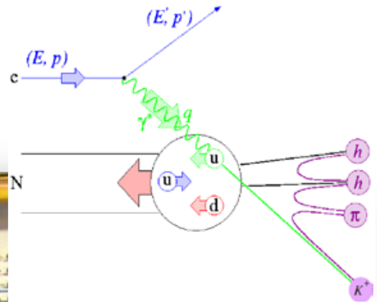
Just recently upgraded!

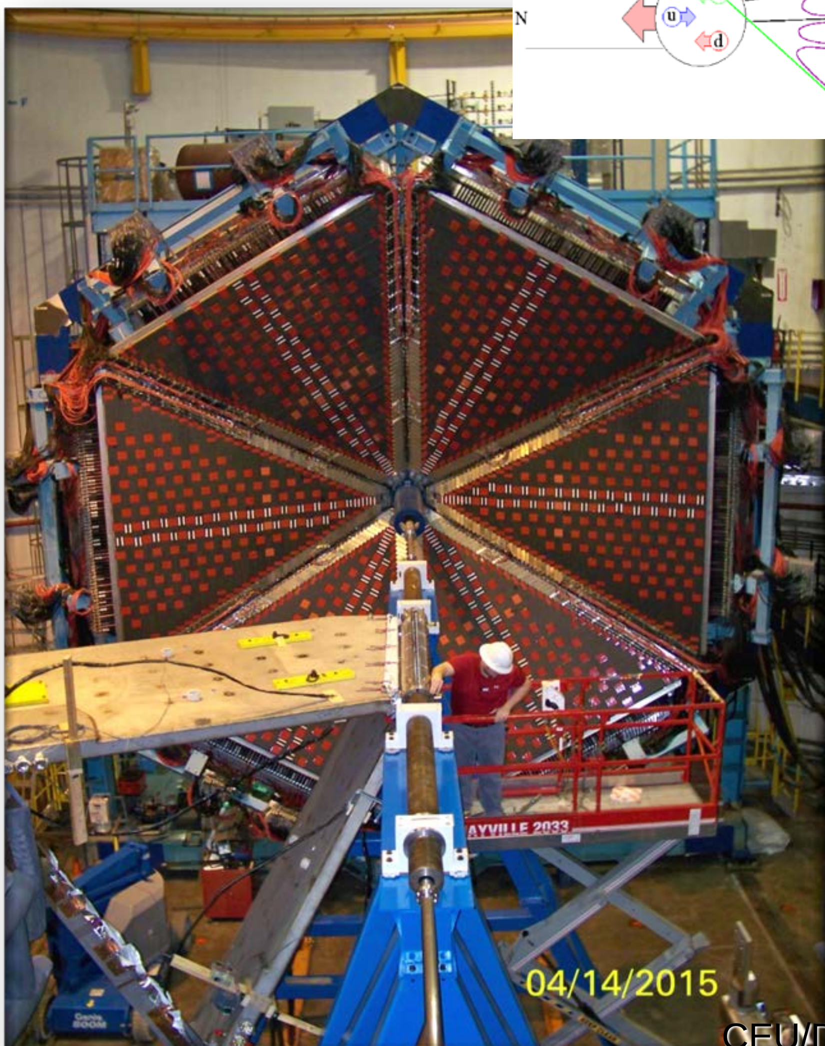
JLab @ 12 GeV

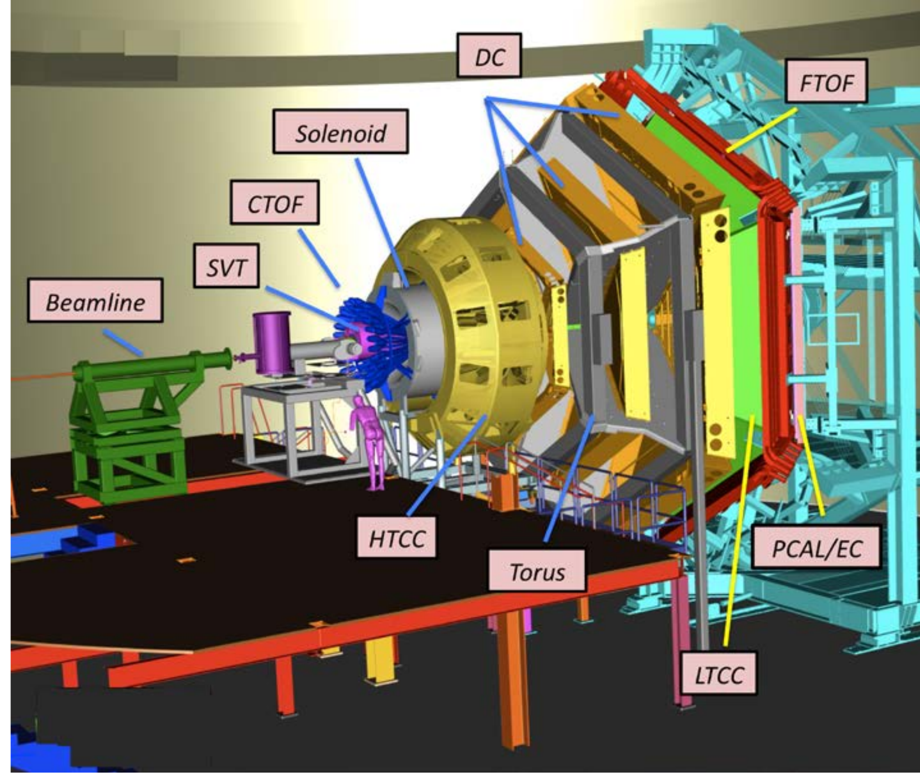

D
New Hall
Upgrade arc magnets and supplies
Add 5 cryomodules
20 cryomodules
CHL upgrade
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C
Enhanced capabilities in existing Halls

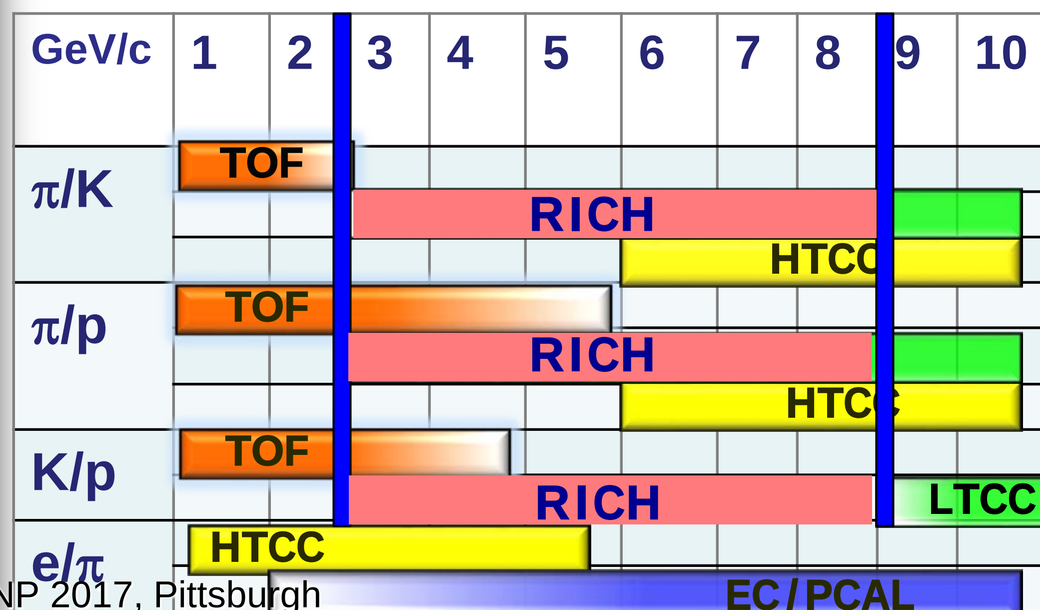


Hall B – Addition of some detectors. Example: RICH detector

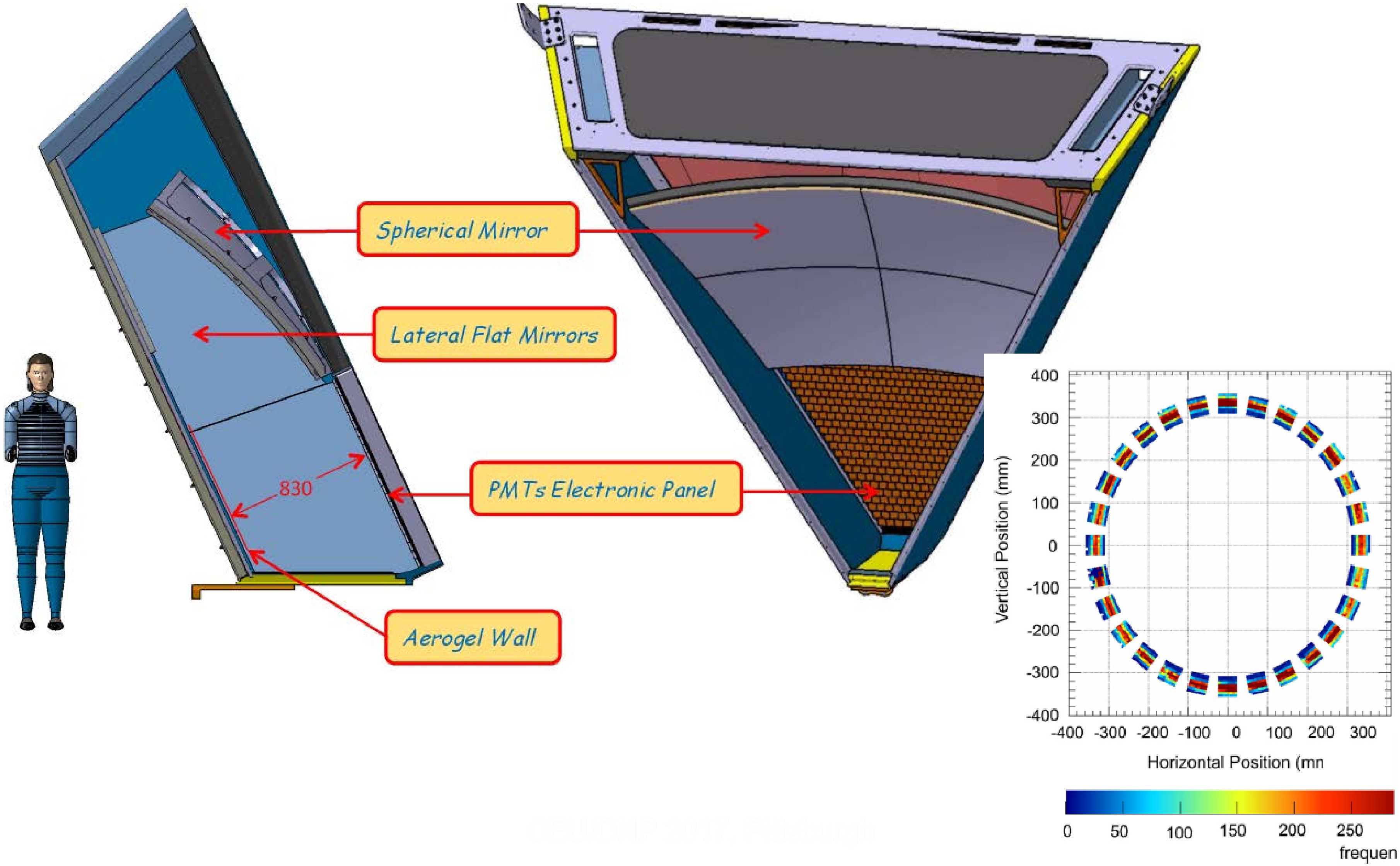




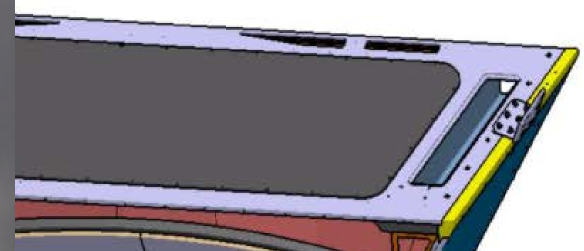


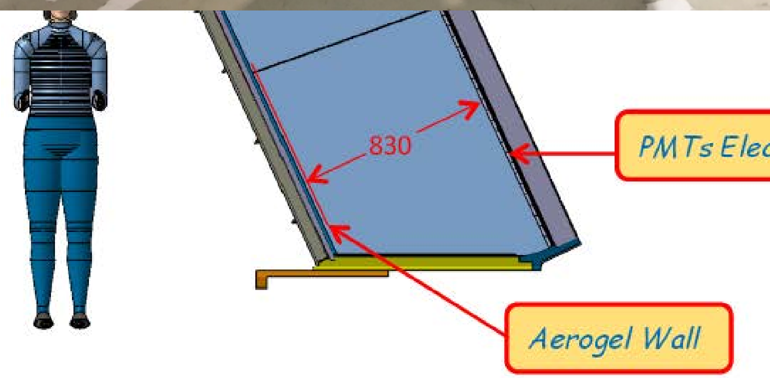


CLAS12 RICH detector, Jlab



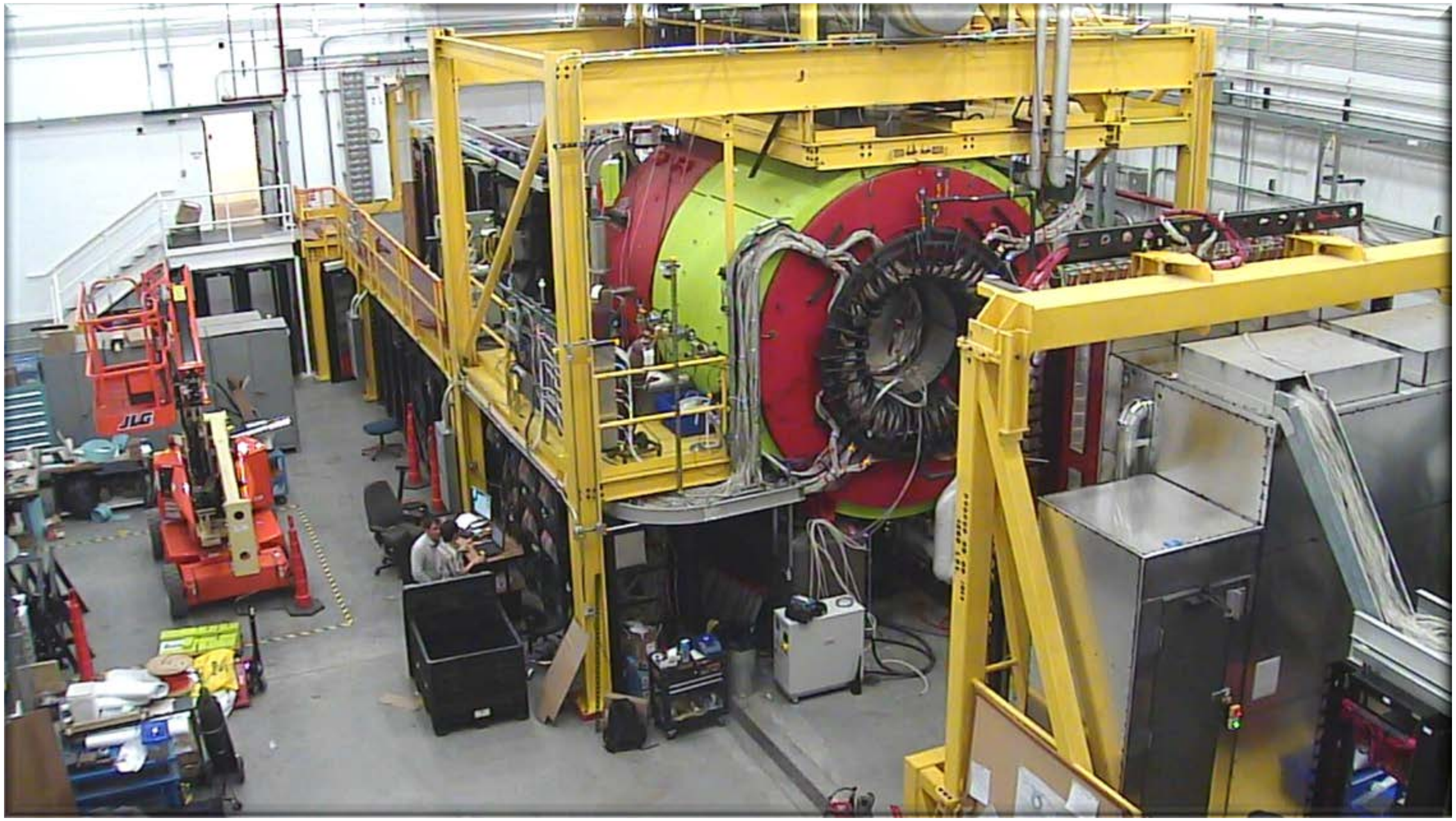
etector, Jlab





0 50 100 150 200 250
frequen

Hall D – exploring origin of confinement by studying exotic mesons

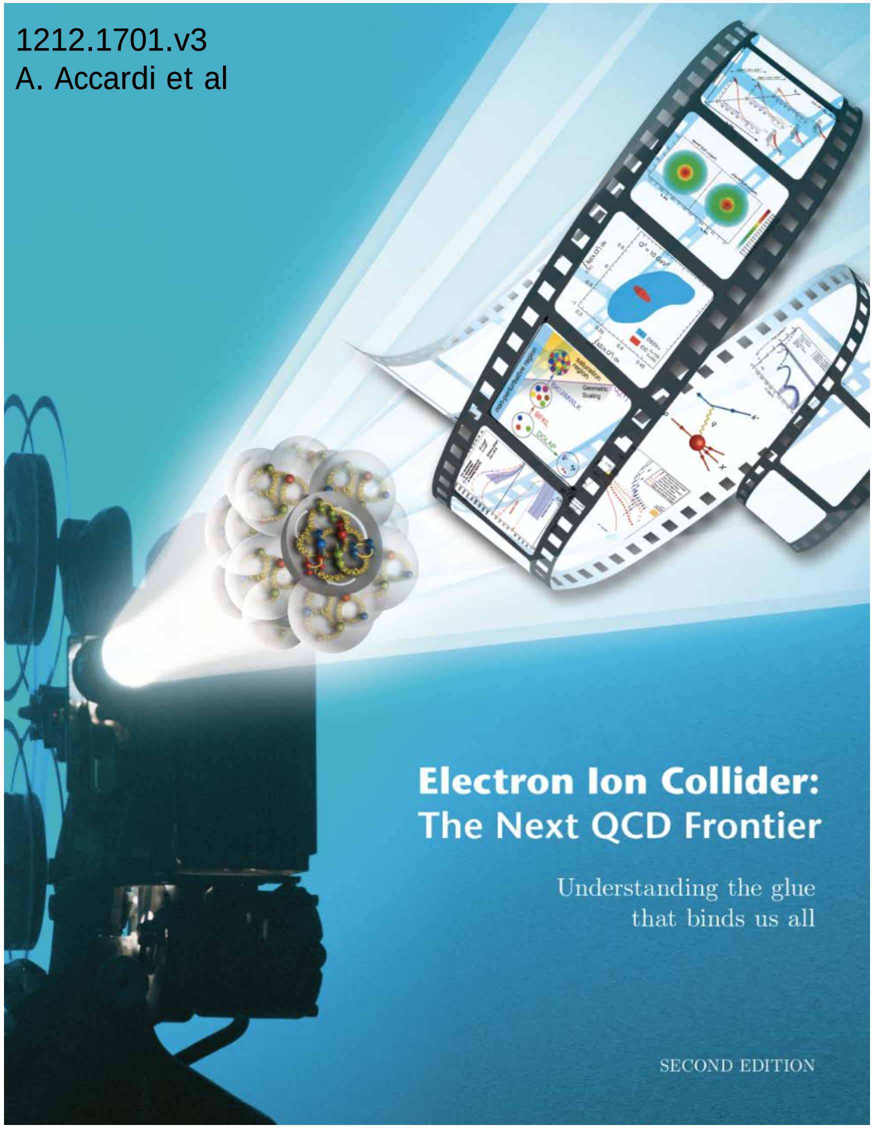


The Electron Ion Collider

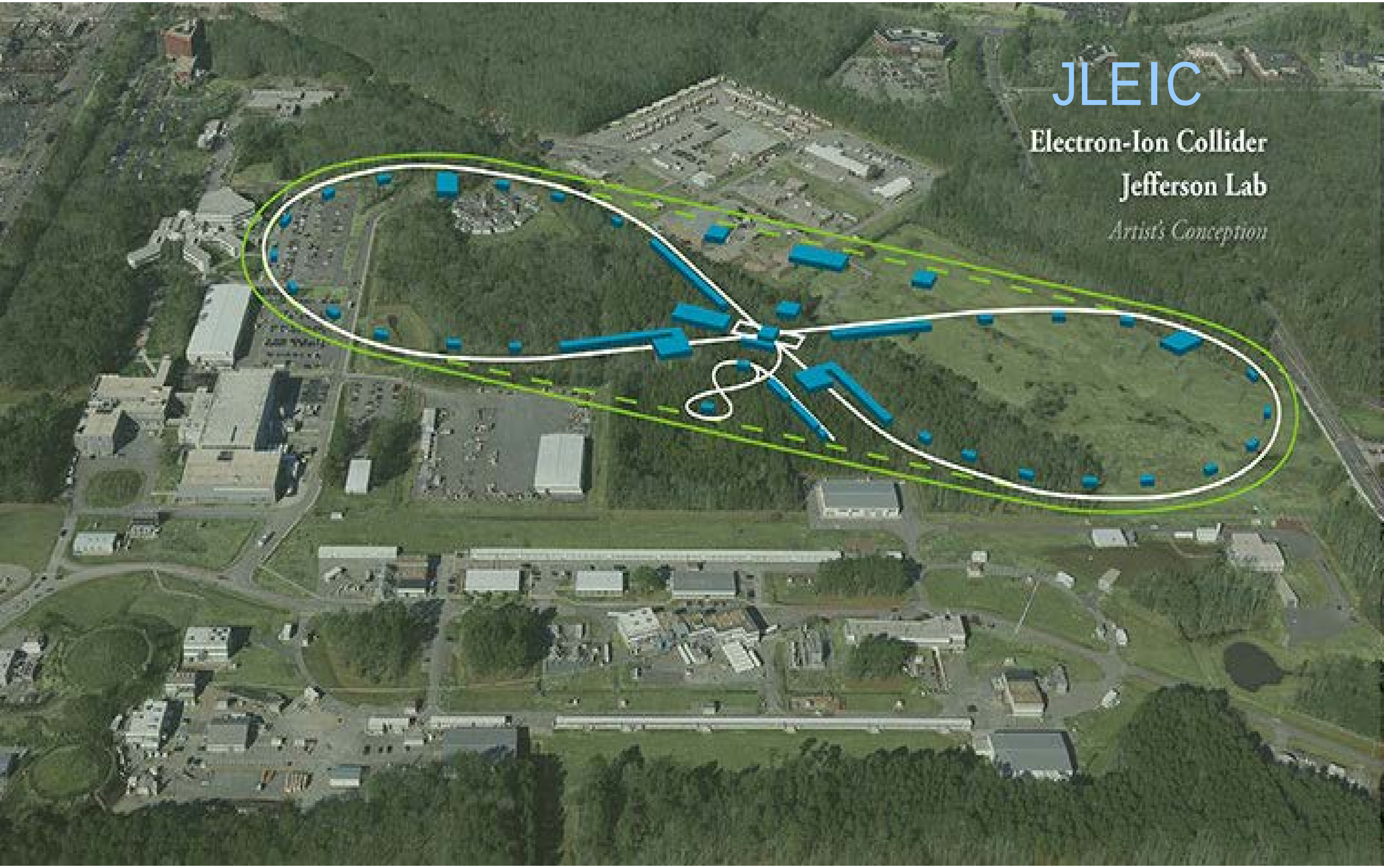
For e-N collisions at the EIC:
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 3-10(20) GeV
- ✓ Luminosity L_{ep} ~ $10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-~100 (140) GeV Variable CM Energy

For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

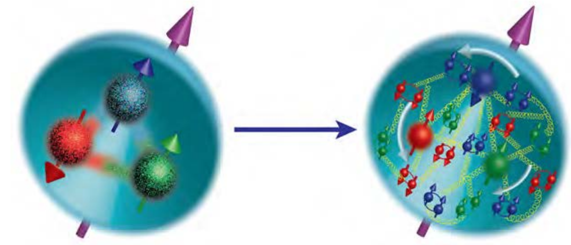
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider



An Electron-Ion Collider @ Jefferson Lab

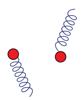


EIC Science Questions



How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

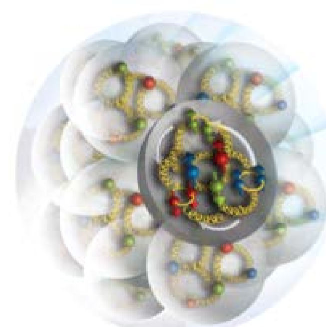
How do the nucleon properties emerge from them and their interactions?



How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?



How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

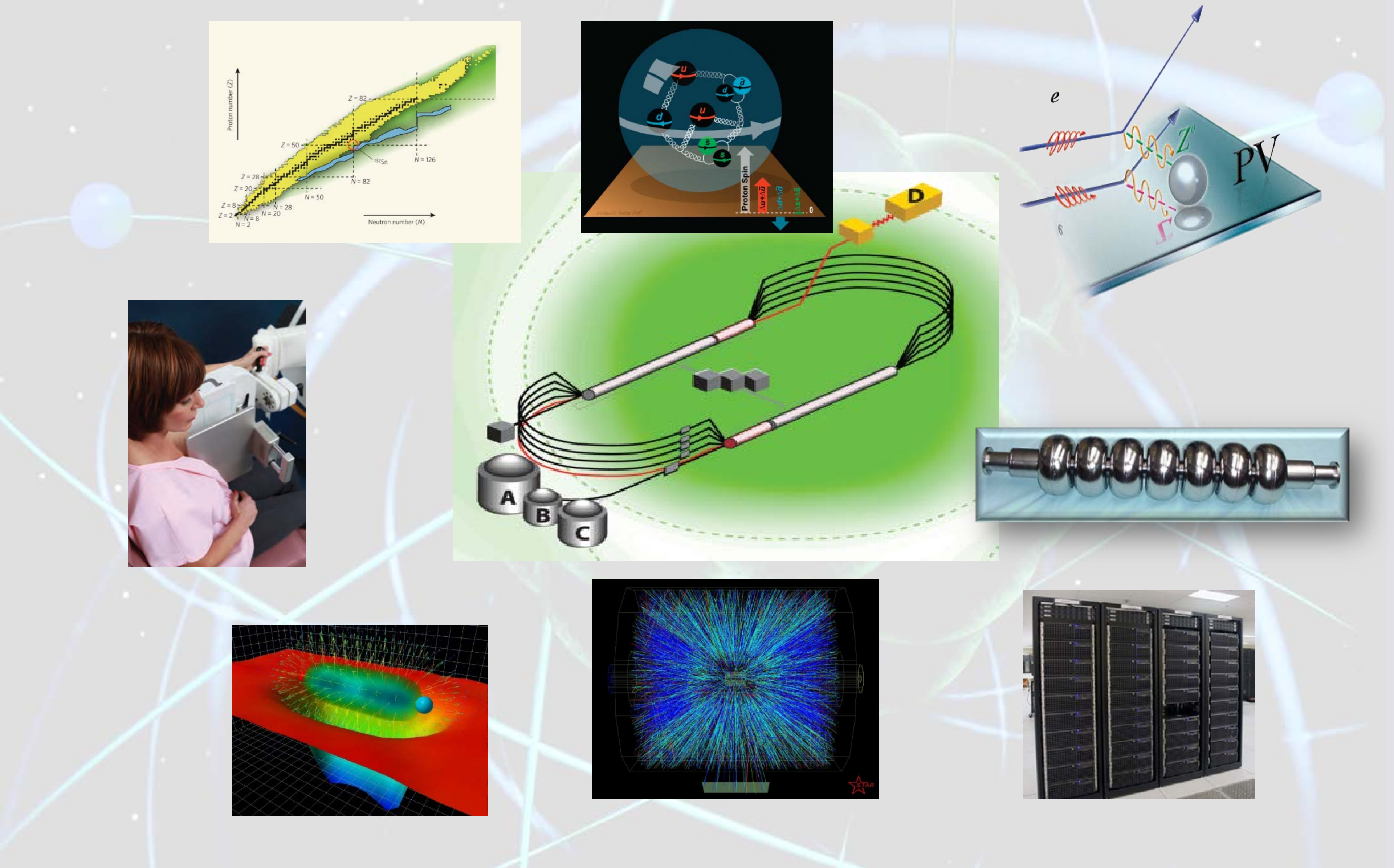
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

gluon recombination

?=?

A Laboratory for Nuclear Science



A Laboratory for Nuclear Science

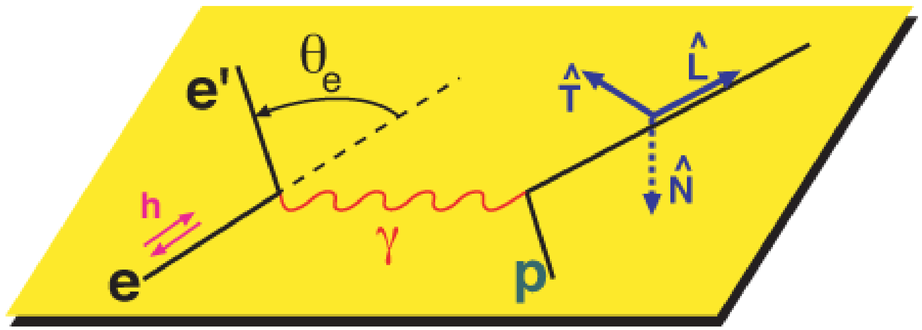
- The Jefferson Lab electron accelerator is a unique world leading facility for nuclear physics research, with a strong and engaged international user community
- These are exciting times at Jefferson Lab
  - Upgraded accelerator operational, Halls commissioned
  - Have begun 12-GeV physics program
  - Construction of Hall B continues through FY17
- 12 GeV program ensures at least a decade of excellent opportunities for discovery
  - New vistas in QCD
  - Growing program Beyond the Standard Model
  - Additional equipment: MOLLER, SoLID
- EIC moving forward:
  - JLab design well developed and low risk, with modest R&D
  -

Backup Slides

JLab Revolutionized Polarization Experiments!

Precise access to (small) charge form factor of proton utilizing polarization transfer technique: $\vec{e} + p \rightarrow e' + \vec{p}$

$$\frac{G_E}{G_M} = -\frac{P'_x}{P'_z}\frac{(E_i + E_f)}{2m}\tan\frac{\Theta_e}{2}$$



Focal Plane Polarimeter