Probing the Proton: Entangled Personal and Particle Paths

Christine A. Aidala

University of Michigan

ODU/JLab CUWiP

January 16, 2016

My own experiences

Since the summer after my freshman year, have woven my way through various energies and collision systems in nuclear and particle physics

My own experiences

Since the summer after my freshman year, have woven my way through various energies and collision systems in nuclear and particle physics

- Low-energy nuclear structure at Wright Nuclear Structure Lab, Yale University (nuclear fusion-evaporation cross section studies, 100 MeV beam on fixed target) Summer, through my university

My own experiences

Since the summer after my freshman year, have woven my way through various energies and collision systems in nuclear and particle physics

- Low-energy nuclear structure at Wright Nuclear Structure Lab, Yale University (nuclear fusion-evaporation cross section studies, 100 MeV beam on fixed target) Summer, through my university
- Relativistic heavy ion physics at Brookhaven National Lab (detector simulation, 200 GeV per nucleon center-of-mass) Summer REU

My own experiences

Since the summer after my freshman year, have woven my way through various energies and collision systems in nuclear and particle physics

- Low-energy nuclear structure at Wright Nuclear Structure Lab, Yale University (nuclear fusion-evaporation cross section studies, 100 MeV beam on fixed target) Summer, through my university
- Relativistic heavy ion physics at Brookhaven National Lab (detector simulation, 200 GeV per nucleon center-of-mass) Summer REU
- Proton-proton particle physics at CERN (detector hardware and data acquisition, 14 TeV c.m.) Summer REU

My own experiences

- Polarized proton structure at DESY (simulations for proposed polarized proton-electron collider, 300 GeV c.m.)

Senior project, two semesters

My own experiences

- Polarized proton structure at DESY (simulations for proposed polarized proton-electron collider, 300 GeV c.m.) Senior project, two semesters

- e+e- particle physics at CERN (exotic physics searches, 200 GeV c.m.) Summer before grad school

My own experiences

- Polarized proton structure at DESY (simulations for proposed polarized proton-electron collider, 300 GeV c.m.)

Senior project, two semesters

- e+e- particle physics at CERN (exotic physics searches, 200 GeV c.m.)

Summer before grad school

- More relativistic heavy ion physics and more proton structure at Brookhaven National Lab (200 GeV c.m.)

Temporary employment,
back to grad school, and postdoc . . .

My own experiences

- Polarized proton structure at DESY (simulations for proposed polarized proton-electron collider, 300 GeV c.m.)

Senior project, two semesters

- e+e- particle physics at CERN (exotic physics searches, 200 GeV c.m.)

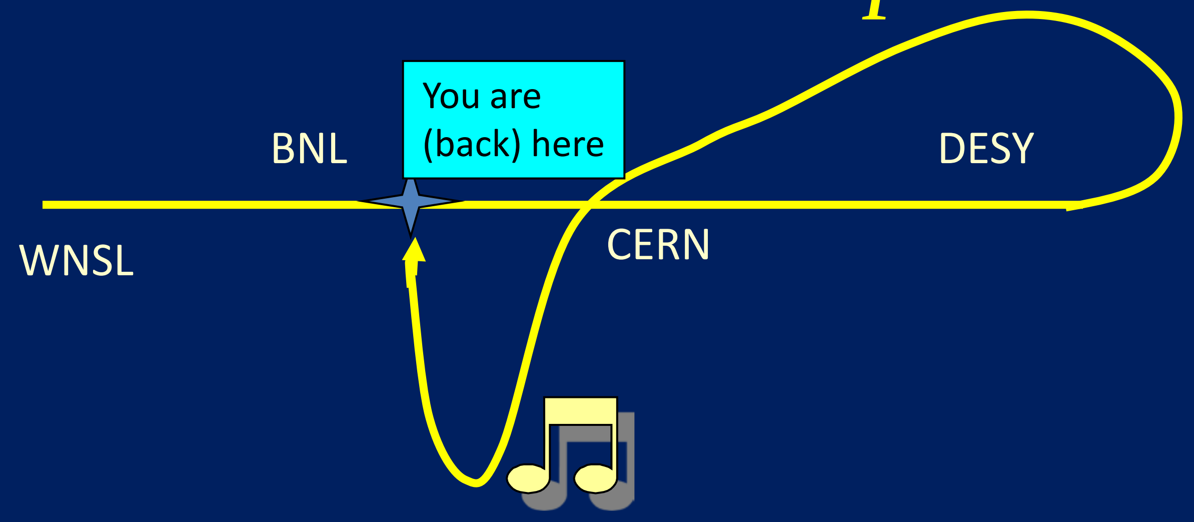
Summer before grad school

Interlude teaching English and music in Italy for 1 ½ years . . .

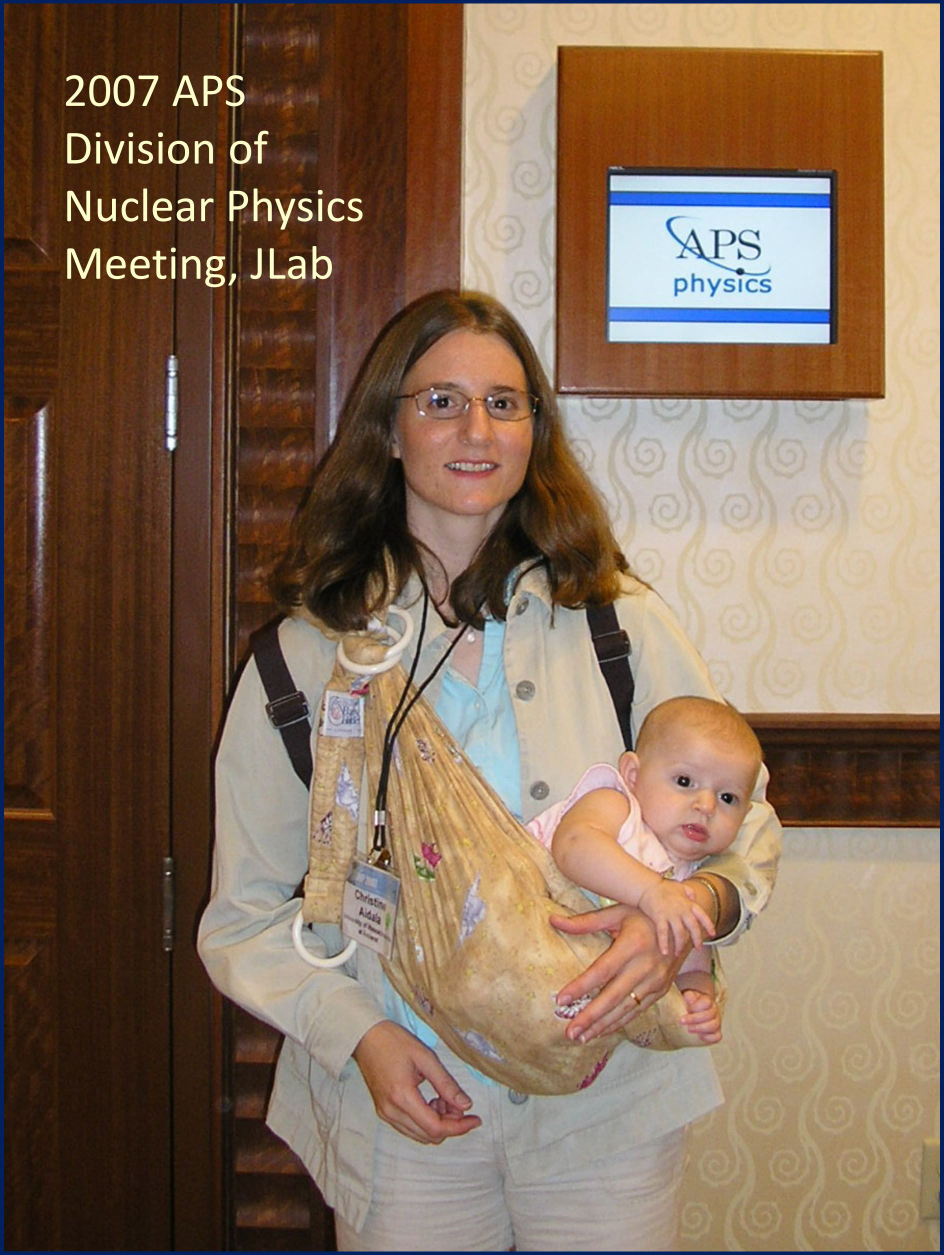
- More relativistic heavy ion physics and more proton structure at Brookhaven National Lab (200 GeV c.m.)

Temporary employment,
back to grad school, and postdoc . . .

My career 1996-2012 in pictures . . .



- A 12-month temporary contract at BNL generated the initial conditions that set much of my course for the next 11 years
- Sat in same hallway in BNL Physics Dept. for that time, supported in turn by 4 different institutions!
  - Turned down multiple career opportunities to maintain geographical stability


2007 APS
Division of
Nuclear Physics
Meeting, JLab
APS
physics

PHENIX experiment at the Relativistic Heavy Ion Collider

15 Countries, 76 Institutions
~500 Participants

PHENIX experiment at the Relativistic Heavy Ion Collider

15 Countries, 76 Institutions
~500 Participants

Finding a passion . . .

- Maybe I actually missed my "true" calling as a condensed matter theorist (you can never try everything!), or even as a park ranger (got a summer job offer from the National Park Service a couple weeks after I'd agreed to take my first research job!)
- But among the areas I have explored, I've found a passion in one of them . . .

And finding a niche

- I've also found a community of people that I respect and enjoy
  - With comfortable room for me to make meaningful scientific contributions

And finding a niche

- I’ve also found a community of people that I respect and enjoy
  - With comfortable room for me to make meaningful scientific contributions

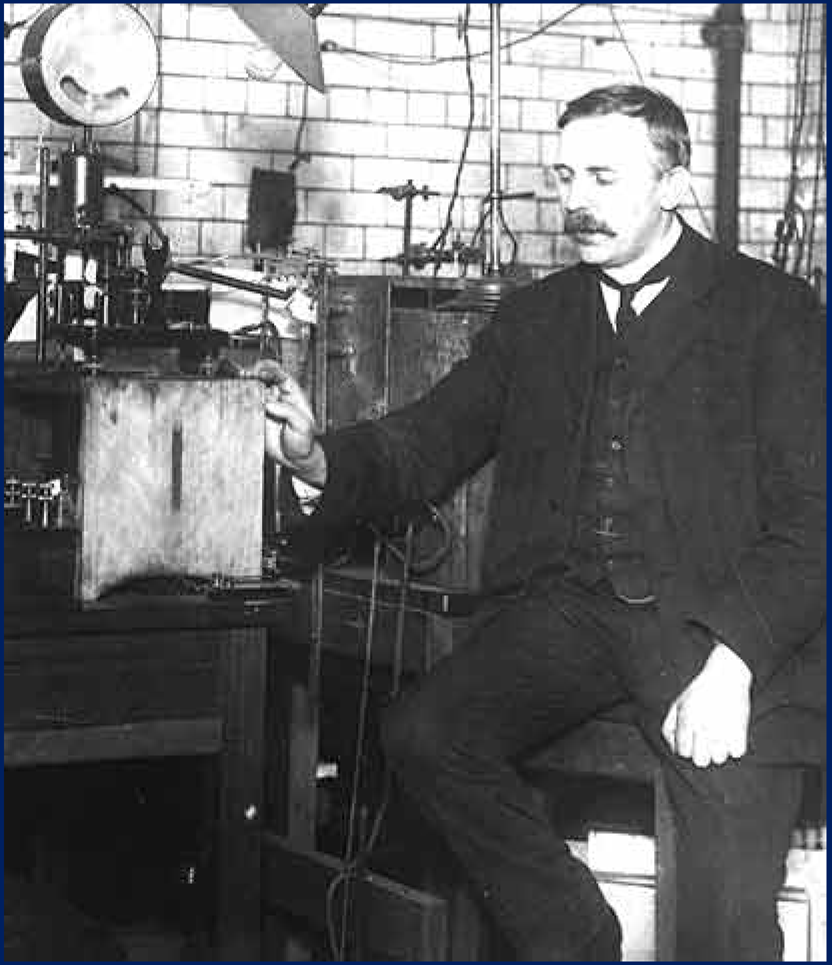
I’ve come to feel at home within the community of people studying the strong force and structure of the proton

Probing inside atoms: mostly empty space!

1911: Ernest Rutherford scatters alpha particles from radioactive decay off of a thin gold foil

- Most went right through!
- *But*—about 1/8000 bounced back!

So atoms have a small, positively charged core → the nucleus

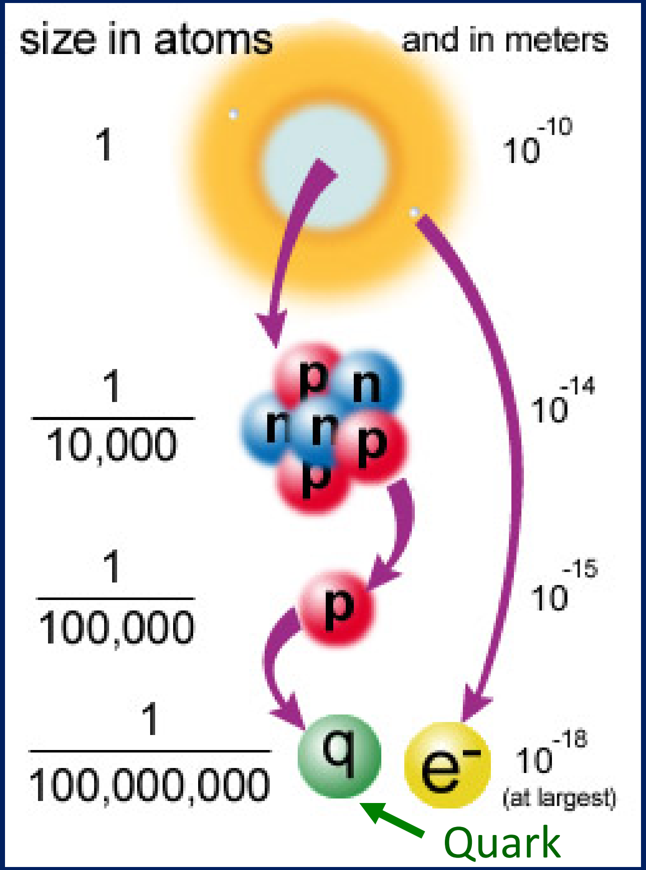


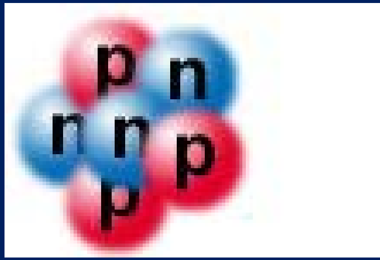
Probing inside protons . . .

Late 1960s: scatter electrons off of protons

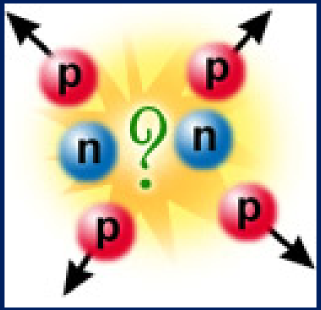
- Many bounced back sharply . . .

- But weren't bouncing off of the whole proton → subcomponents!
  - Protons *not* solid lumps of positive charge
  - Constituents that make up the proton now called "quarks"





Strong force



- How does the nucleus stay together? The electromagnetic force should cause the protons to repel one another
- Protons and neutrons interact via the *strong force*, carried by gluons
  - Much stronger than the electromagnetic force (~100x) and waaayyy stronger than gravity (~10^{38}x!!) (thus the name!)
  - But—very very short range! (~10^{-15} m)

"Color" charge and Quantum Chromodynamics

- Strong force acts on particles with *color* charge
  - Quarks, plus gluons themselves! (Contrast with photons, which are electrically neutral)
- "Color" because three different "charges" combine to make a neutral particle:

red + blue + green = white

- Quantum *Chromo*dynamics (QCD)—theory describing the strong force

"Color" charge and Quantum Chromodynamics

- Strong force acts on particles with *color* charge
  - Q… ith
    p…
- "Co…
  com…

Note that quarks also carry *fractional* electric charge!!

Proton = up + up + down quarks

+1 = (+2/3) + (+2/3) + (-1/3)

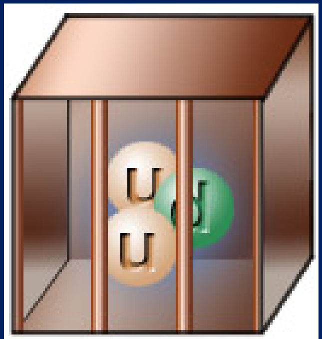
Neutron = down + down + up

0 = (-1/3) + (-1/3) + (+2/3)

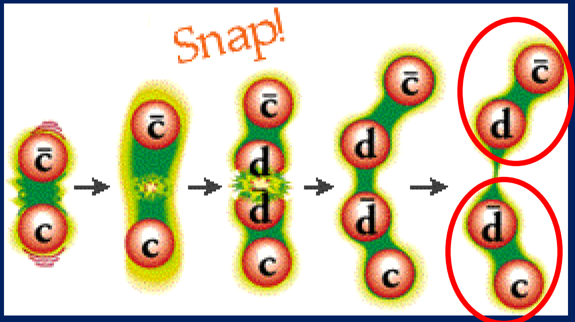
red + blue + green = white

- Quantum *Chromo*dynamics (QCD)—theory describing the strong force

Quark confinement

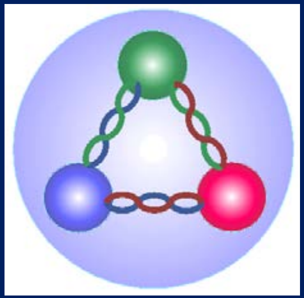


- Never see quarks or gluons directly!
  - *Confined* to composite, color-neutral particles
  - Groups of three quarks (rgb), called *baryons*, or quark-antiquark pairs (red-antired, . . .), called *mesons*
- If you try to pull two quarks apart, energy between them increases until you produce a new quark-antiquark pair (recall good old $E=mc^2$)



"D^- meson"

"D^+ meson"



Studying proton structure

- If can’t see individual quarks and gluons, how to determine the proton’s structure?
- Inelastic scattering—shoot a high-energy beam (e.g. of electrons) at the proton to break it up, and try to understand what happens
  - Electron exchanges a photon with quarks, because quarks carry electromagnetic charge as well as color

Probes sensitive to different length scales

What size potholes will bother you if you're driving/riding a . . .

Probes sensitive to different length scales

What size potholes will bother you if you're driving/riding a . . .

Probes sensitive to different length scales

What size potholes will bother you if you're driving/riding a . . .

Probes sensitive to different length scales

What size potholes will bother you if you're driving/riding a . . .

Probes sensitive to different length scales

What size potholes will bother you if you're driving/riding a . . .

High-energy particle accelerators

- *Molecular and atomic* structure of matter: study using
  - ultraviolet light (wavelengths 10-400 nanometers)
  - x-rays (wavelengths 0.01-10 nanometers)

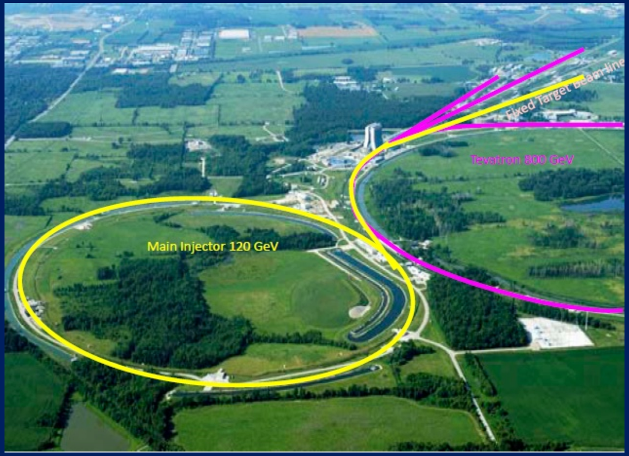
High-energy particle accelerators

- *Molecular and atomic* structure of matter: study using
  - ultraviolet light (wavelengths 10-400 nanometers)
  - x-rays (wavelengths 0.01-10 nanometers)
- Nuclei and protons: 10,000× to 100,000× smaller than atoms → Need high-energy particle accelerators to see inside them

My experiments

- The PHENIX experiment at the Relativistic Heavy Ion Collider at Brookhaven National Lab (BNL) on Long Island, NY

- The SeaQuest experiment at Fermi National Accelerator Laboratory outside Chicago



Focus of my current research

- Spin-momentum correlations within the proton
  - Can think of as quantum mechanical spin-orbit couplings

- Searching for experimental evidence of an exciting recent prediction of *quantum color entanglement* of quarks across two colliding protons!

2012: "Landing" at the University of Michigan

- Didn't see working remotely from my employing institution as a permanent option, and by 2012, felt it was time to move on in one way or another

- Happy to have landed where I am now . . .

Concluding remarks

- Actively think about where you'd like your path to take you, but don't be afraid to change directions (or have them changed by external forces) en route
  - You usually have more options than are immediately obvious!

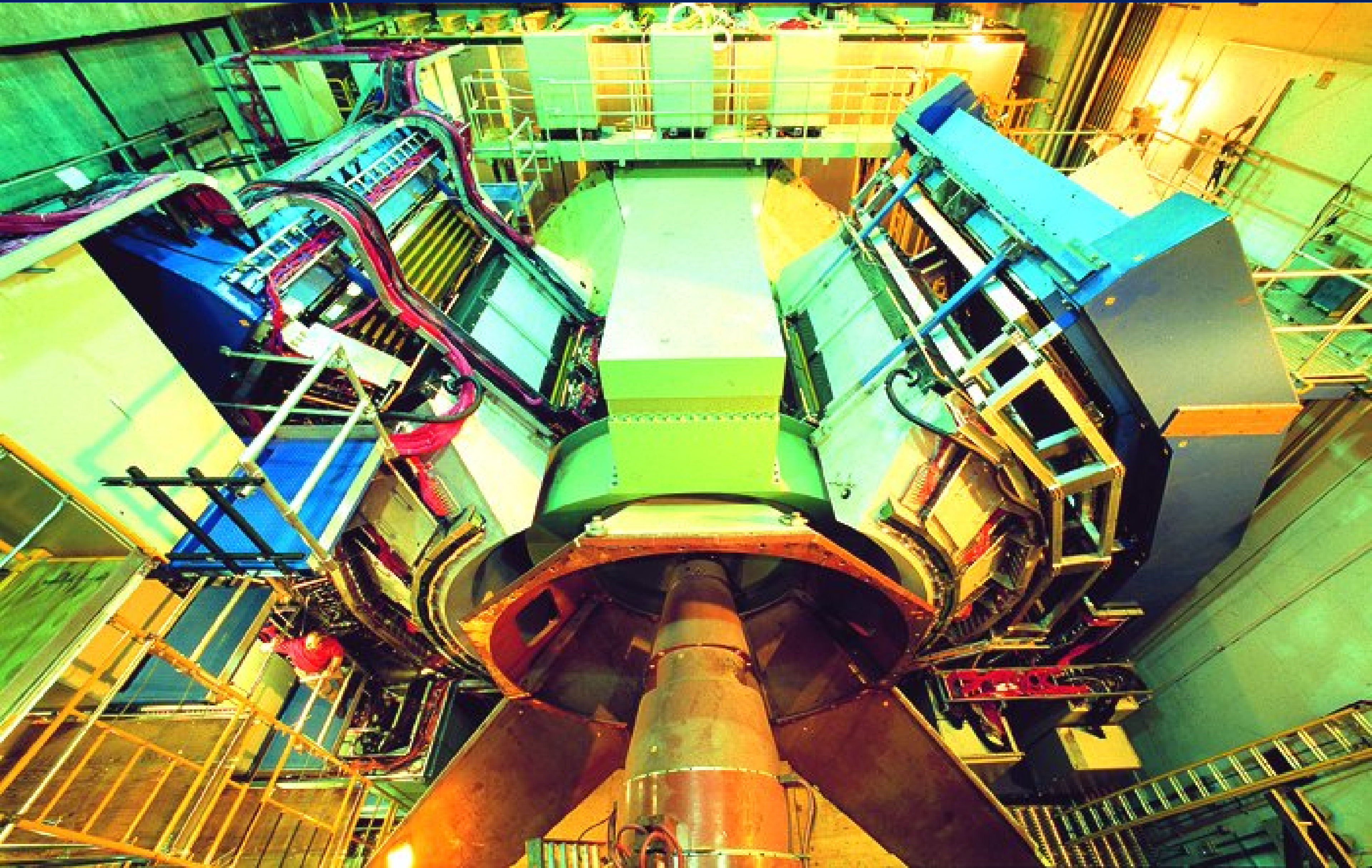
- There are many paths—some more linear than others—to success (= happiness)!

We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time.

T.S. Eliot

Extra

PHENIX Detector



SeaQuest model: Reuse, recycle!

Station 4 tracking plane assembled from old proportional tubes scavenged from Los Alamos National Lab “threat reduction” experiments!

What have we learned?

- Conclusions from decades of inelastic scattering data investigating proton momentum structure:
  - 3 “valence” quarks carry (on average) the largest single momentum fractions of the proton
  - But lots of gluons and “sea” quark-antiquark pairs in the proton as well! Gluons carry ~50% of total momentum of proton.

What have we learned?

- Conclusions from decades of inelastic scattering data investigating proton momentum structure:
  - 3 "valence" quarks carry (on average) the largest single momentum fractions of the proton
  - But lots of gluons and "sea" quark-antiquark pairs in the proton as well! Gluons carry ~50% of total momentum of proton.

Despite all the recent excitement about the Higgs boson, gluons are actually responsible for more than 98% of the mass of the visible universe!!

Mapping out the proton: Other questions to ask!

What does the proton look like in terms of the quarks and gluons inside it?

- *Position*
- *Momentum*
- *Spin*
- *Flavor*
- *Color*

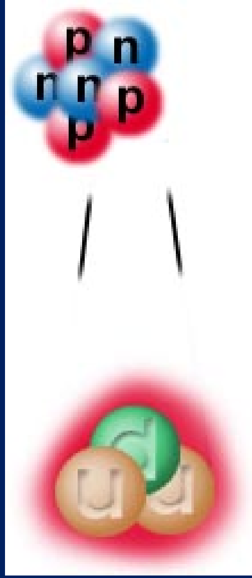
Theoretical and experimental concepts to describe and access position only born in mid-1990s. Pioneering measurements over past decade.

Polarized protons first studied in 1980s. How angular momentum of quarks and gluons add up still not well

Good measurements of flavor distributions in valence region. Flavor structure at lower momentum fractions

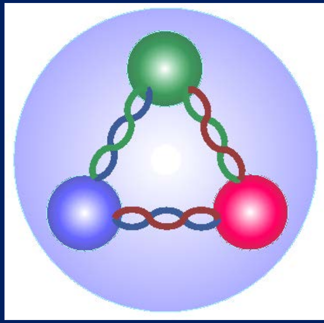
Accounted for by theorists from beginning of QCD, but more detailed, potentially observable effects of color have come to forefront since 2010.

Quark-Parton Model



The simplest model says a proton's made of three "valence" quarks: 2 up "flavored" quarks and 1 down "flavored" quark.

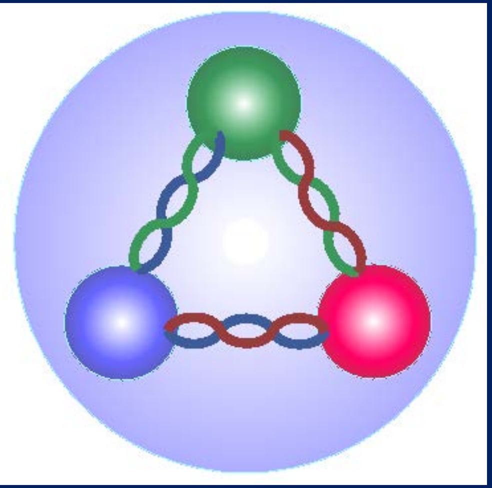
- But these quarks are not completely free in the nucleon!
  - Bound by force-carrier particles called "gluons."
  - "Sea quarks" are also present: short-lived quark-antiquark pairs from quantum mechanical fluctuations.



- As you hit the proton with more energy, you resolve shorter-lived fluctuations: gluons and sea quarks.

Nucleon structure: The early years

- 1932: Estermann and Stern measure proton anomalous magnetic moment → proton not a pointlike particle!
- 1960s: Quark structure of the nucleon
  - SLAC inelastic electron-nucleon scattering experiments by Friedman, Kendall, Taylor → Nobel Prize
  - Theoretical development by Gell-Mann → Nobel Prize
- 1970s: Formulation of QCD . . .



For More Information

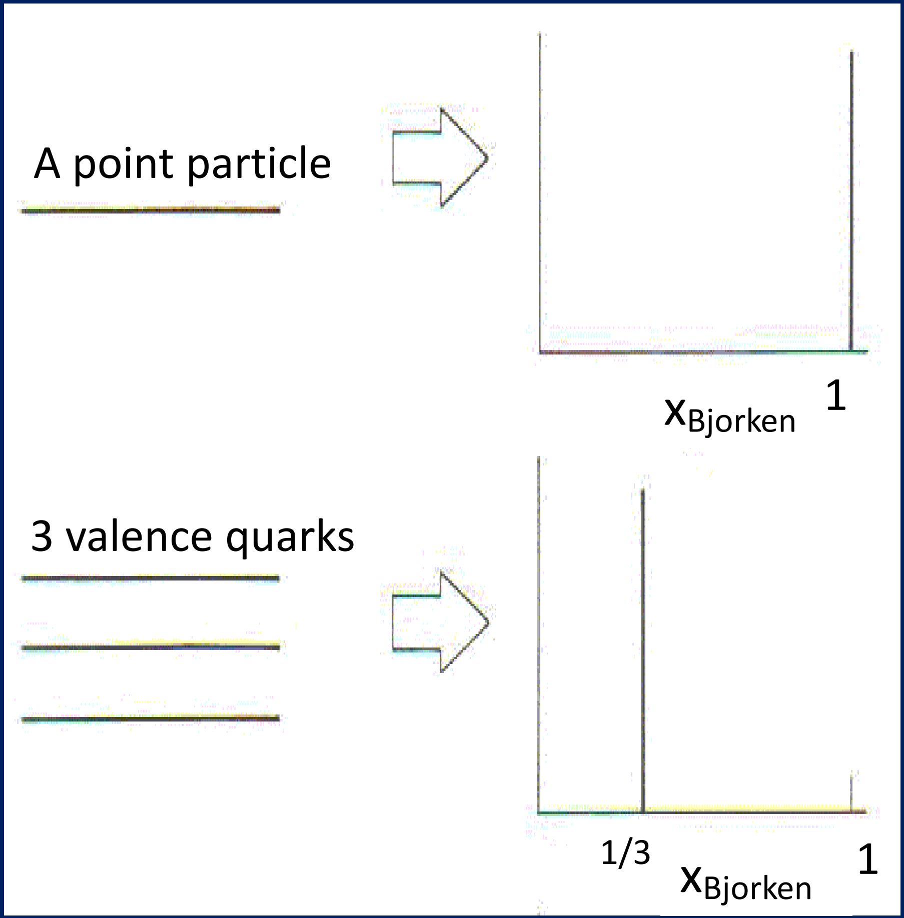
- For more info on quarks, gluons, and the strong force, see

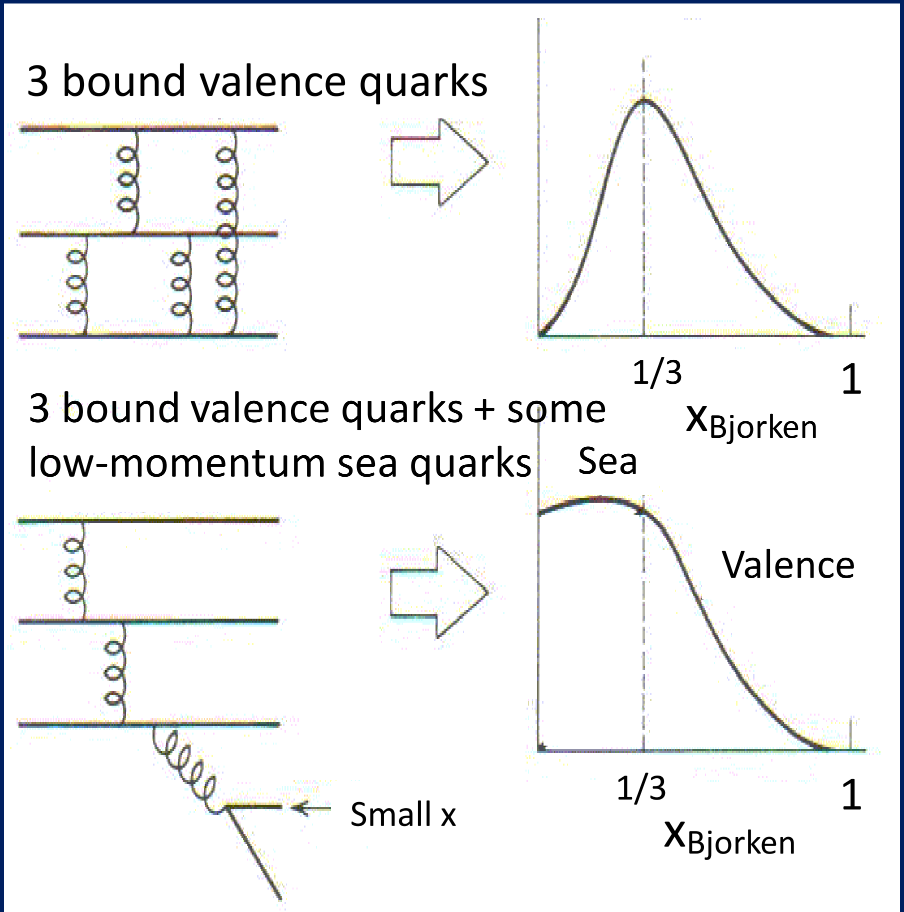
http://www.particleadventure.org/

(Many pictures on previous pages borrowed from this site)

Proton structure and momentum fraction

What momentum fraction would the scattering particle carry if the proton were made of …

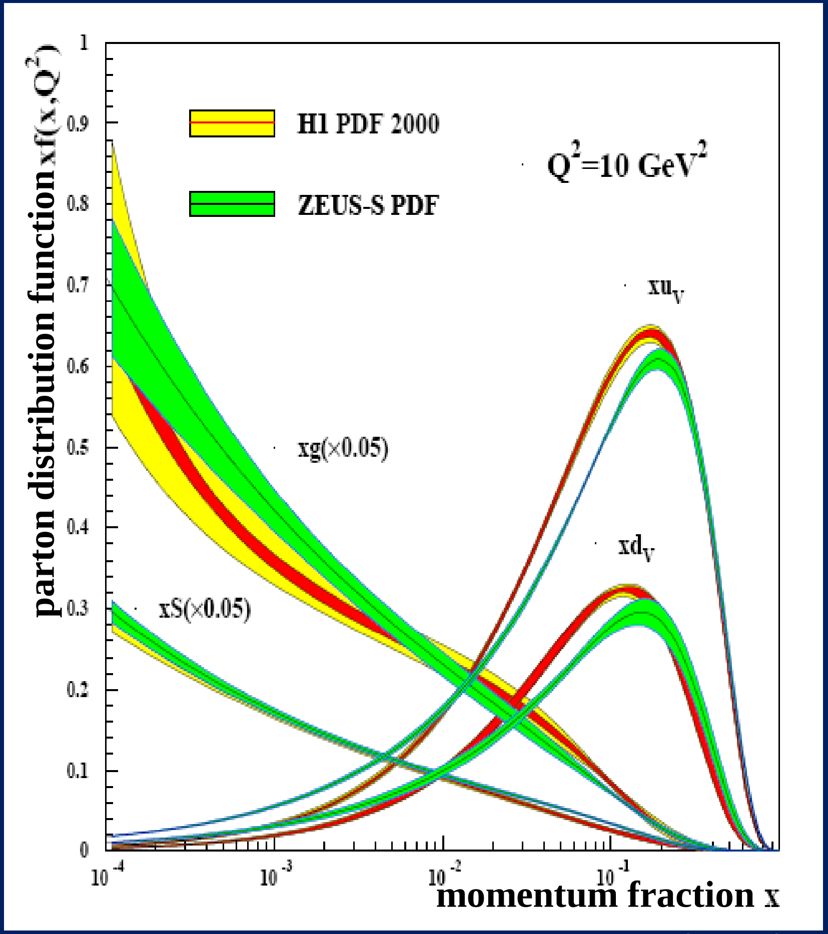




Halzen and Martin, "Quarks and Leptons", p. 201

So what do the parton distribution functions look like?

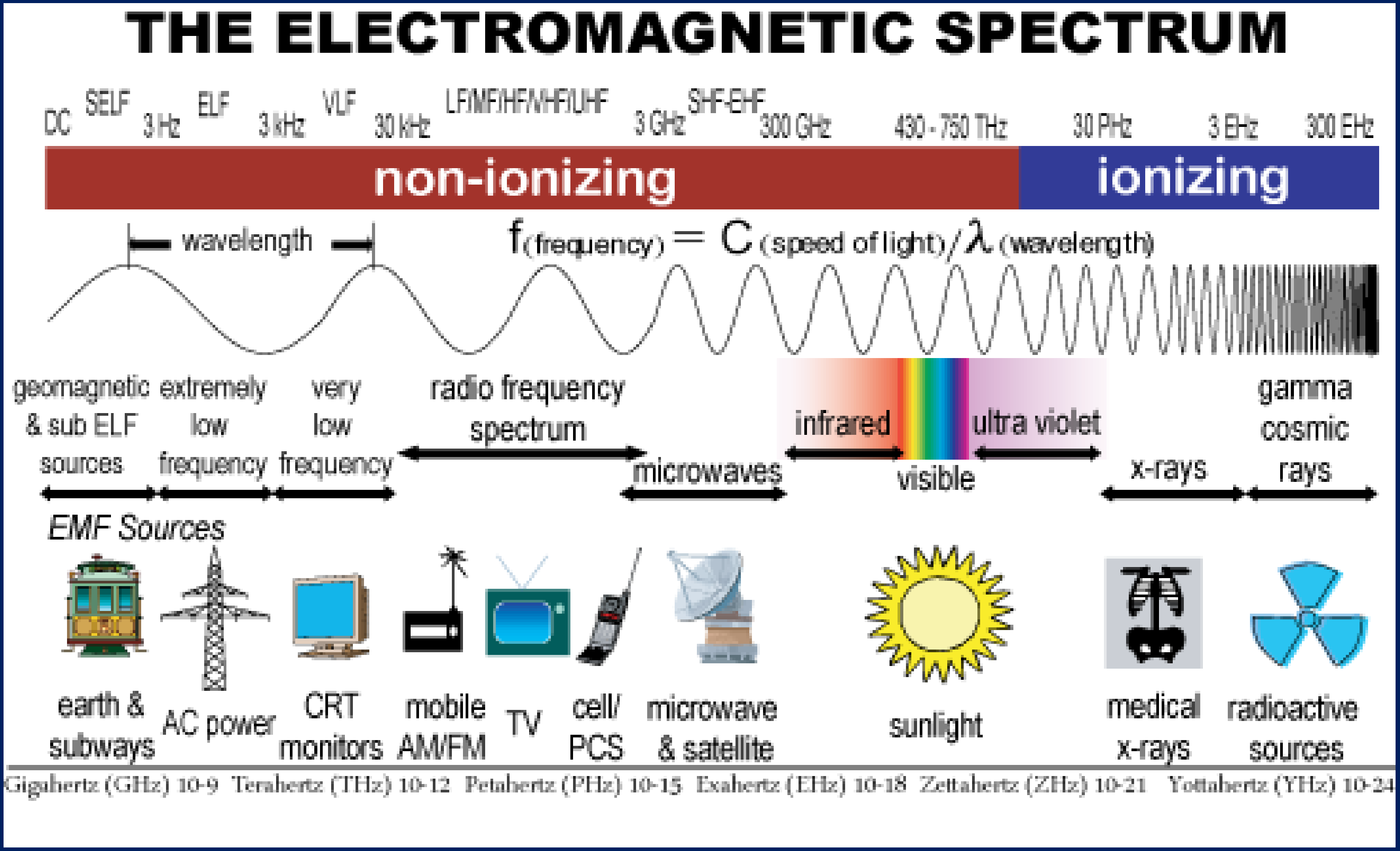
- Wealth of data largely thanks to proton-electron collider, HERA, in Hamburg, Germany (1992-2007)
- Up and down valence quark distributions peaked at a little less than 1/3
- Lots of sea quark-antiquark pairs and even more gluons (scaled down by 20x in figure!)



PRD67, 012007 (2003)

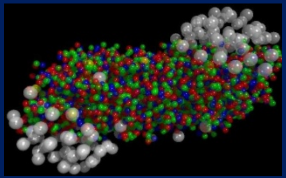
Higher energies to see smaller things

Energy



The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

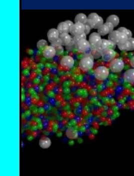
- A great place to be to study QCD!
- An accelerator-based program, but not designed to be at the energy (or intensity) frontier. More closely analogous to many areas of condensed matter research—create a system and study its properties!



- What systems are we studying?
  - "Simple" QCD bound states—the proton is the simplest stable bound state in QCD (and conveniently, nature has already created it for us!)
  - Collections of QCD bound states (nuclei, also available out of the box!)
  - QCD deconfined! ("quark-gluon plasma", some assembly required!)

The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

- A great place to be to study QCD!
- An accelerator-based program, but not designed to be at the energy (or intensity) frontier. More closely analogous to many areas of condensed matter research – create a sy
- W
  - able
  - Collections of QCD bound states (nuclei, also available out of the box!)
  - QCD deconfined! ("quark-gluon plasma", some assembly required!)



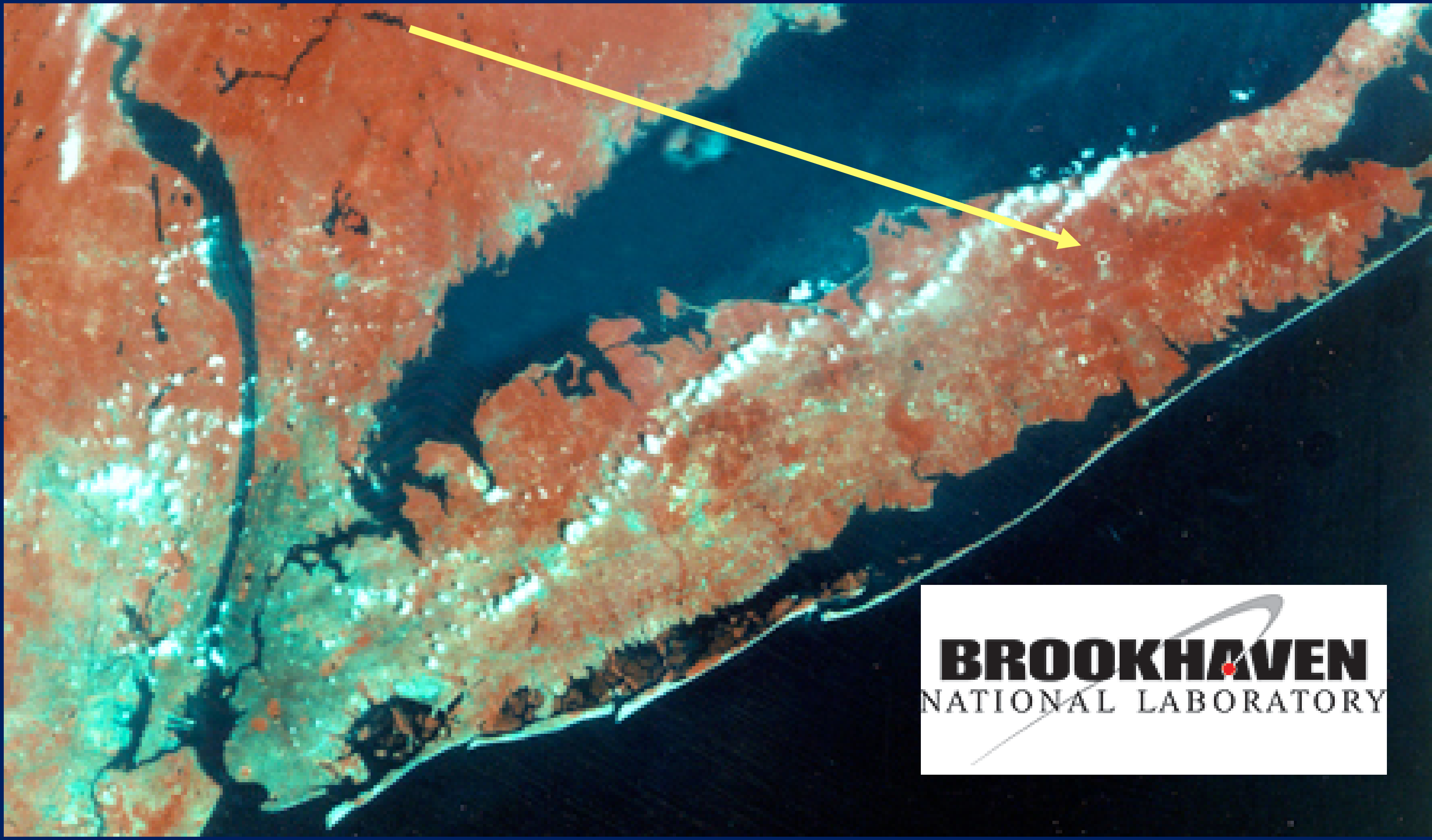
Understand more complex QCD systems within the context of simpler ones

→RHIC was designed from the start as a *single* facility capable of nucleus-nucleus, proton-nucleus, and proton-proton collisions

RHIC at Brookhaven National Laboratory

Long Island,

New York



RHIC at Brookhaven National Laboratory

Long Island,

New York

*First and only **polarized** proton collider*

*First and only **polarized** proton collider*