Pulling Apart the Strong Force by Peering Into the Proton

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University of Michigan

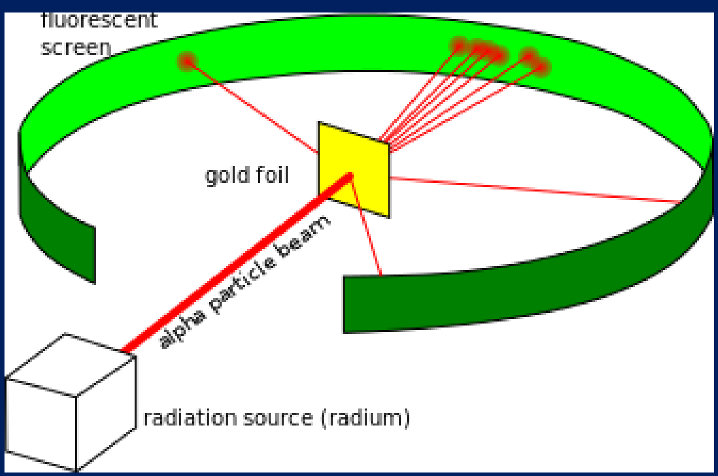
SPS Talk

September 24, 2020

Probing inside atoms: mostly empty space!

1908-1913: Ernest Rutherford, Hans Geiger, and Ernest Marsden scatter alpha particles from radioactive decay off of a thin gold foil

- Most went nearly straight through



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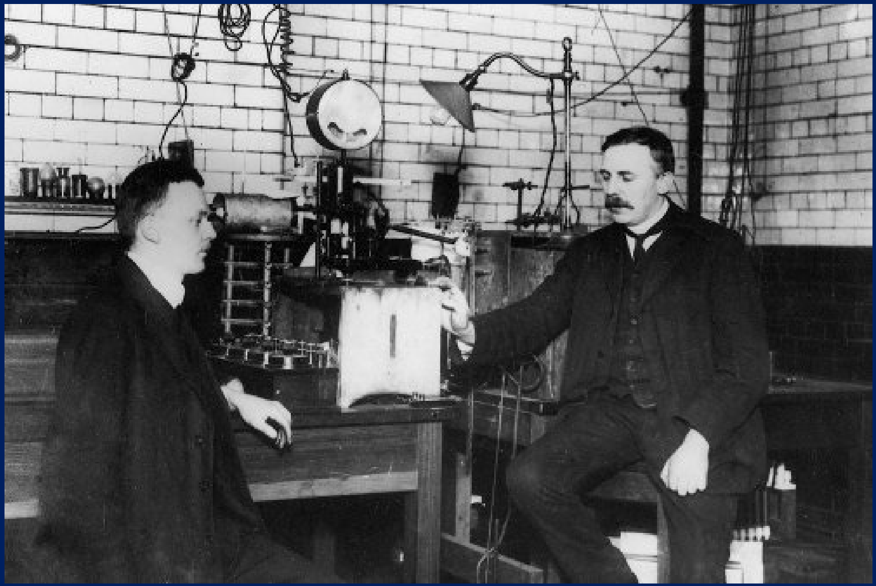

University of Manchester, UK

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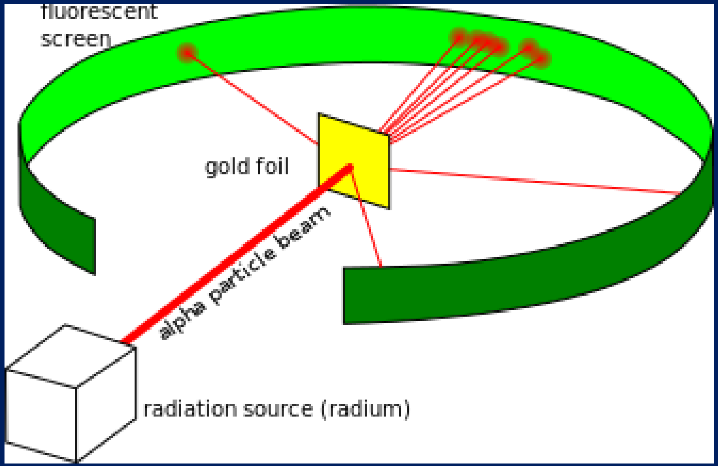

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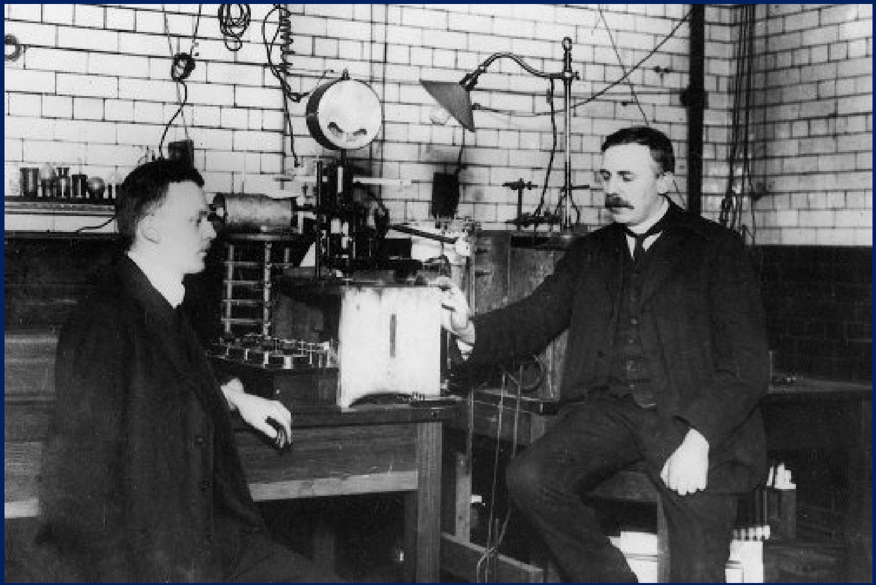
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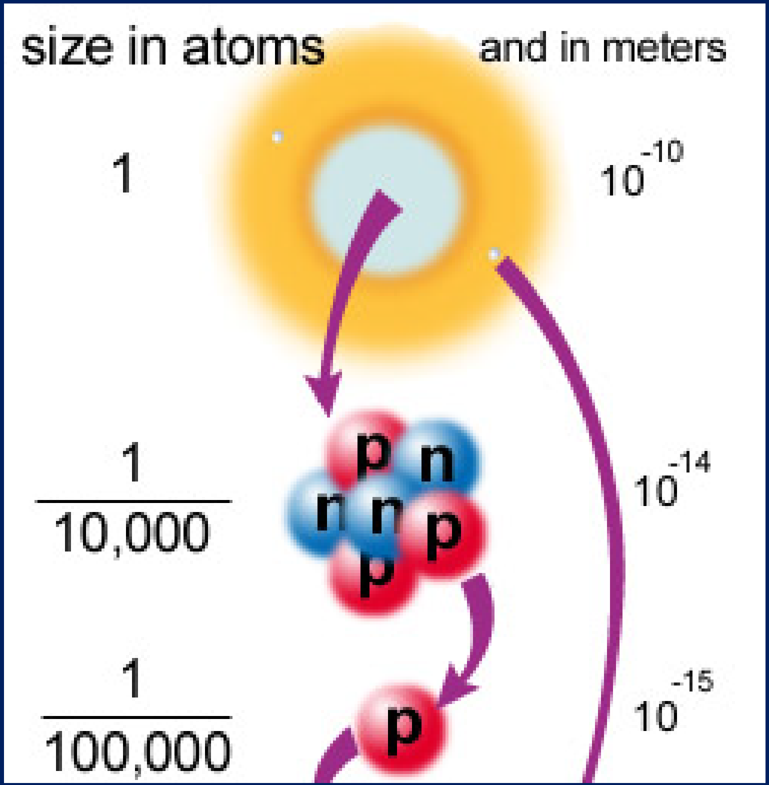
So atoms have a small, positively charged core → the nucleus



https://particleadventure.org/

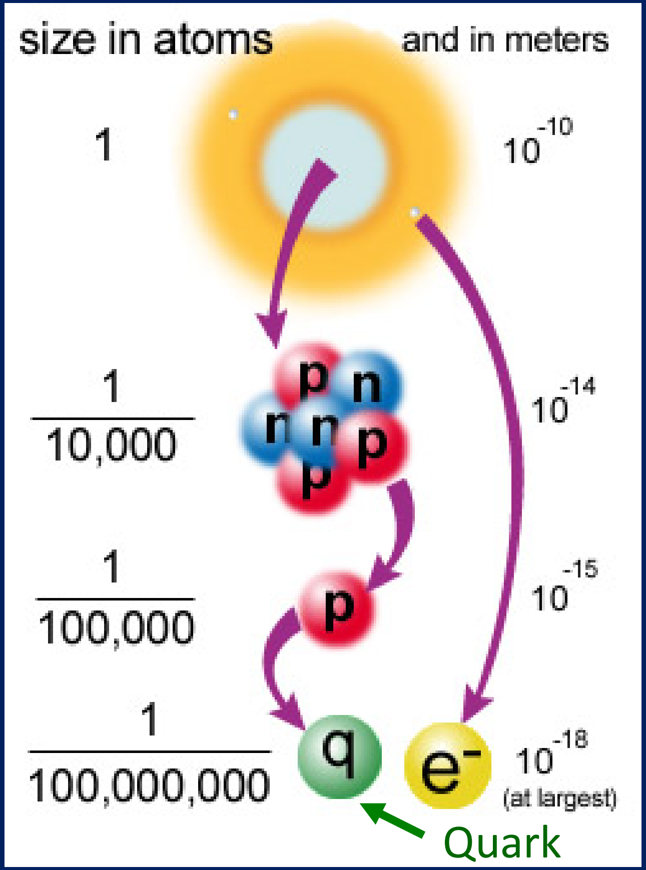
*The electrons orbit **really** far away!*

Probing inside protons . . .

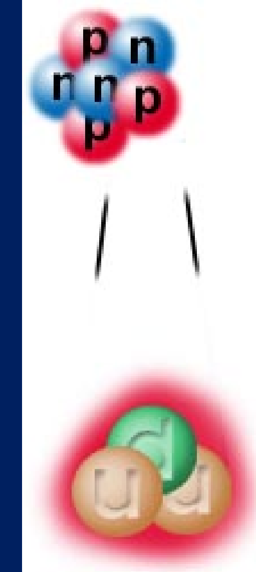
Late 1960s: scatter electrons off of protons at SLAC, Stanford

- Many bounced back sharply . . .

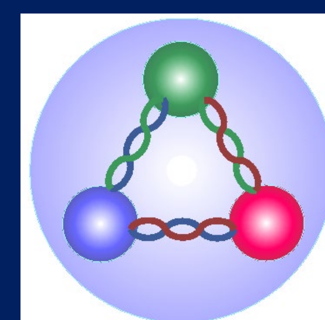
- But weren't bouncing off of the whole proton → subcomponents!
  - Protons *not* solid lumps of positive charge
  - Constituents that make up the proton now called "quarks"

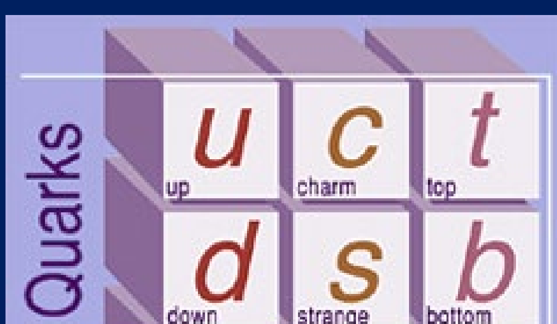


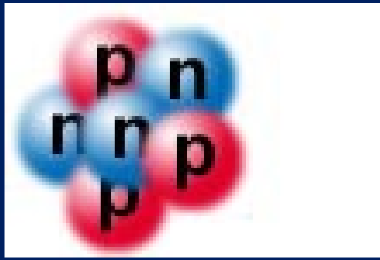
Quarks and gluons



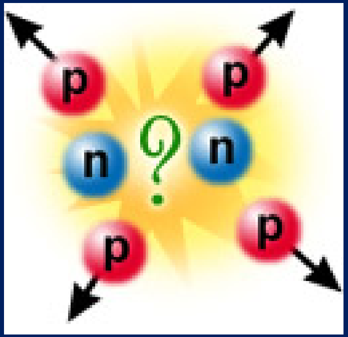
- Simplest model of the proton is three "valence" quarks: 2 up "flavored" quarks and 1 down "flavored" quark
  - Flavor is the "charge" that couples to the weak force
- But these quarks are not completely free in the proton
  - Bound by force-carrier particles called "gluons"
  - "Sea quarks" also present: short-lived quark-antiquark pairs from quantum mechanical fluctuations







The strong force



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

"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 + green + blue = 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
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  com

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

Proton = up + up + down quarks

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

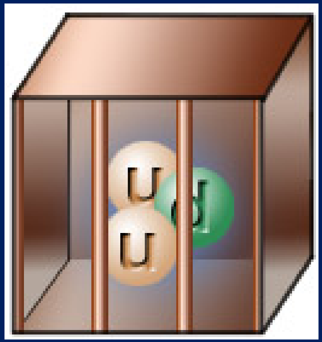
Neutron = down + down + up

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

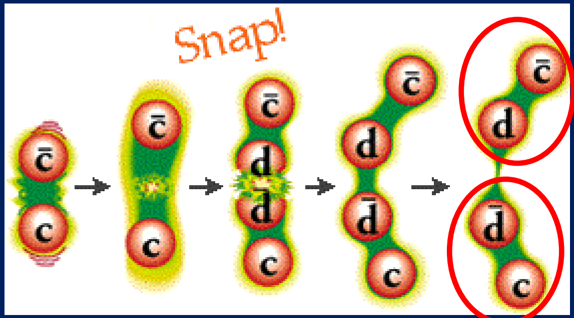
red + green + blue = white

- 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 (good old $E=mc^2$)



"D^- meson"

"D^+ meson"

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)

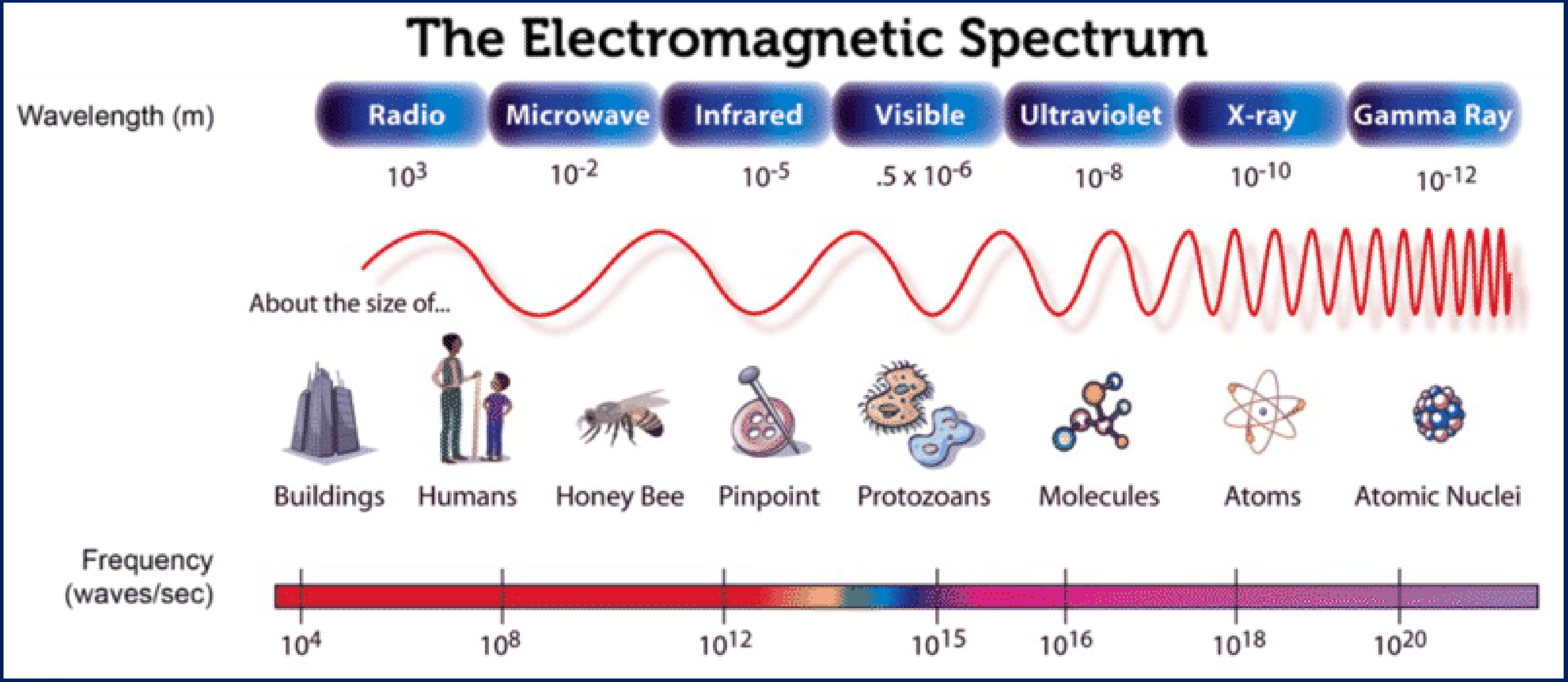
How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons described by our theory of the strong force, quantum chromodynamics?

Probes sensitive to different length scales

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

Higher energies to see smaller things

Energy



https://www.ck12.org/book/ck-12-physical-science-for-middle-school/section/21.3/

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

  https://www.bnl.gov/world/

- The LHC-beauty experiment at the Large Hadron Collider at CERN in Geneva, Switzerland

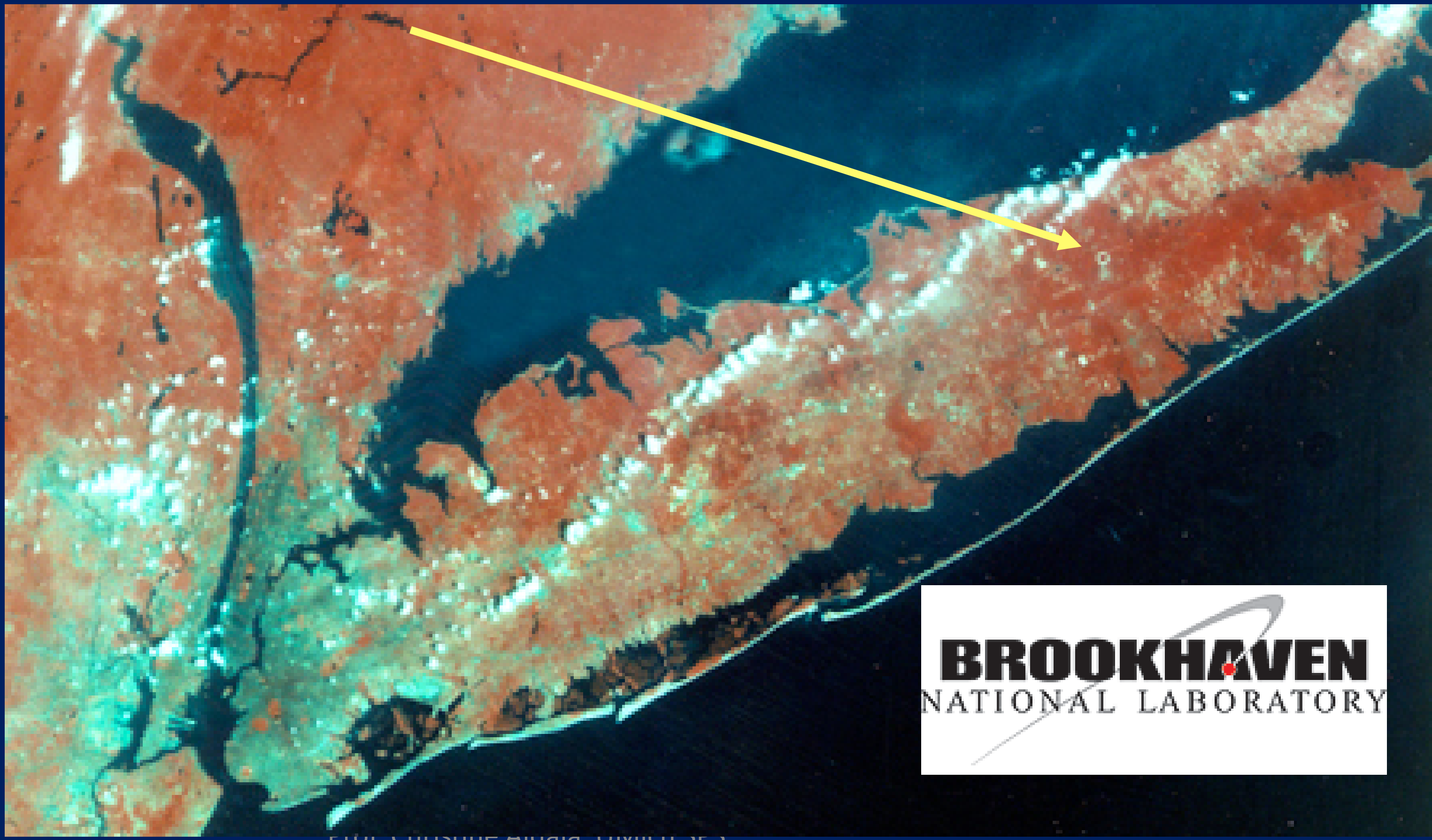
  https://home.cern/

Relativistic Heavy Ion Collider at Brookhaven National Laboratory

Only active particle collider in the U.S.!

Long Island,

New York



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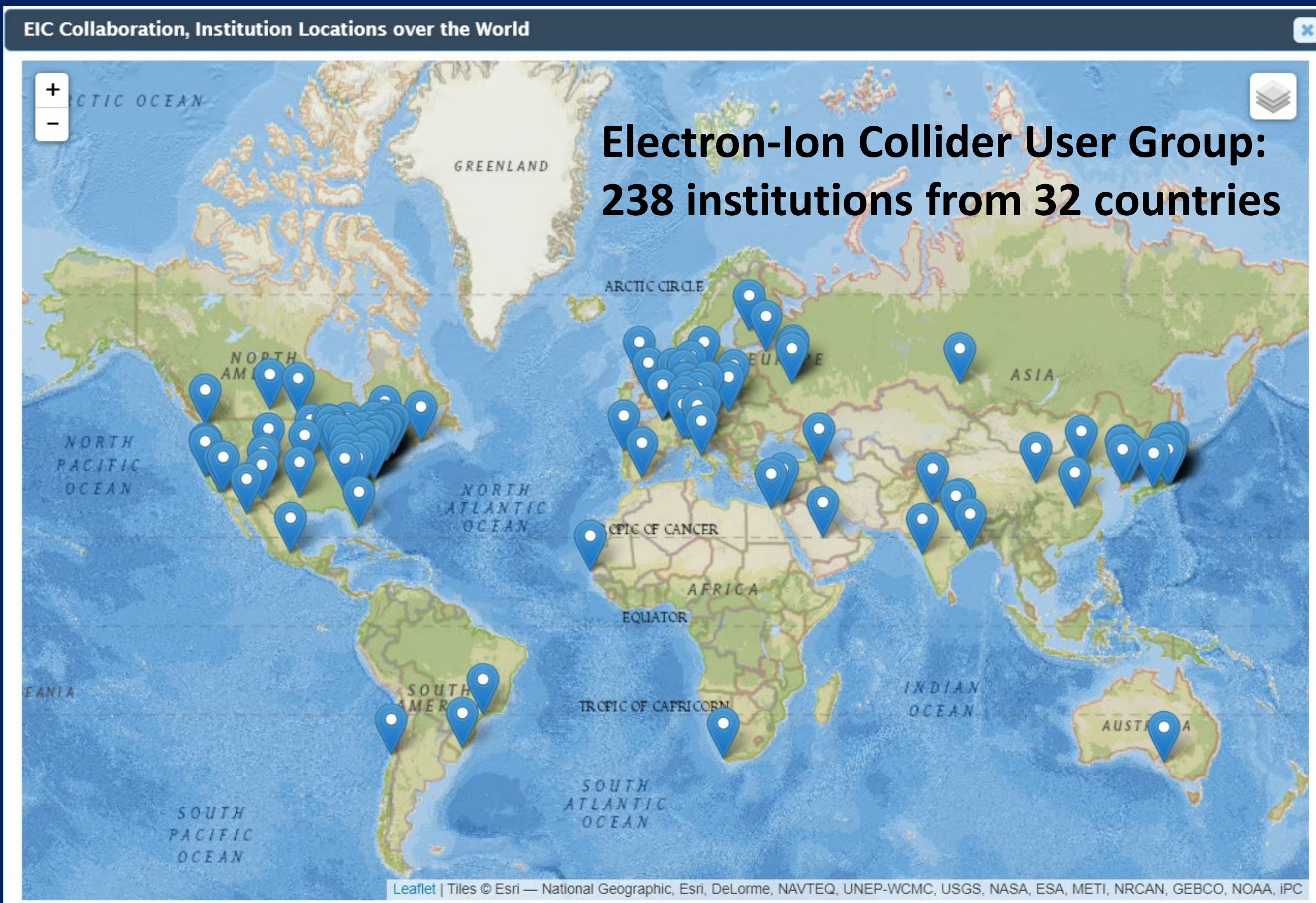
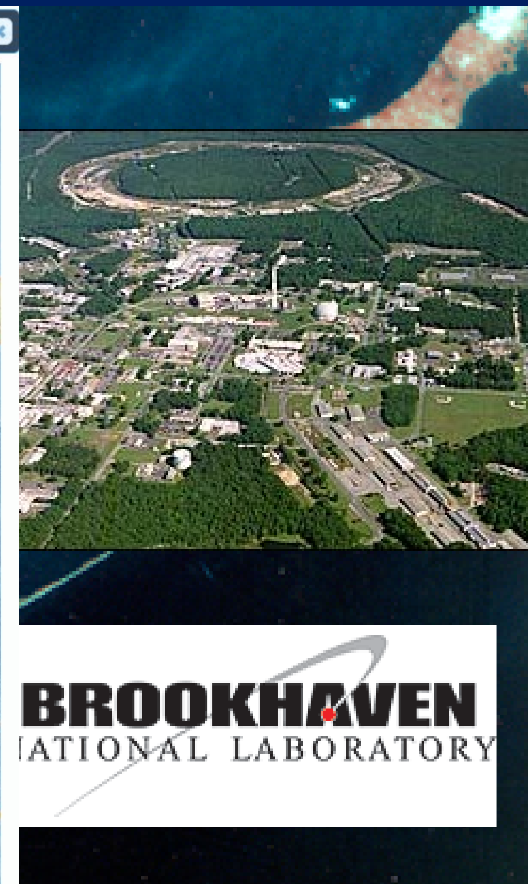
Relativistic Heavy Ion Collider at Brookhaven National Laboratory

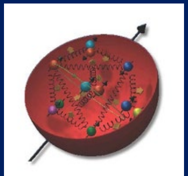
Only active particle collider in the U.S.!
By 2030 will be transformed into a new facility:
the Electron-Ion Collider

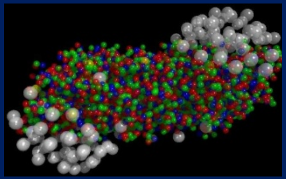




The Relativistic Heavy Ion Collider at Brookhaven National Laboratory

- A great place to study protons and the strong force!
- What systems are we studying?
  - Protons
  - Nuclei





  - Nuclear matter so hot and dense that the quarks and gluons are briefly deconfined—"quark-gluon plasma"
- Two colliding beams of ions, ranging from hydrogen (protons) through uranium nuclei
  - *All* electrons stripped off the atoms, so bare nuclei

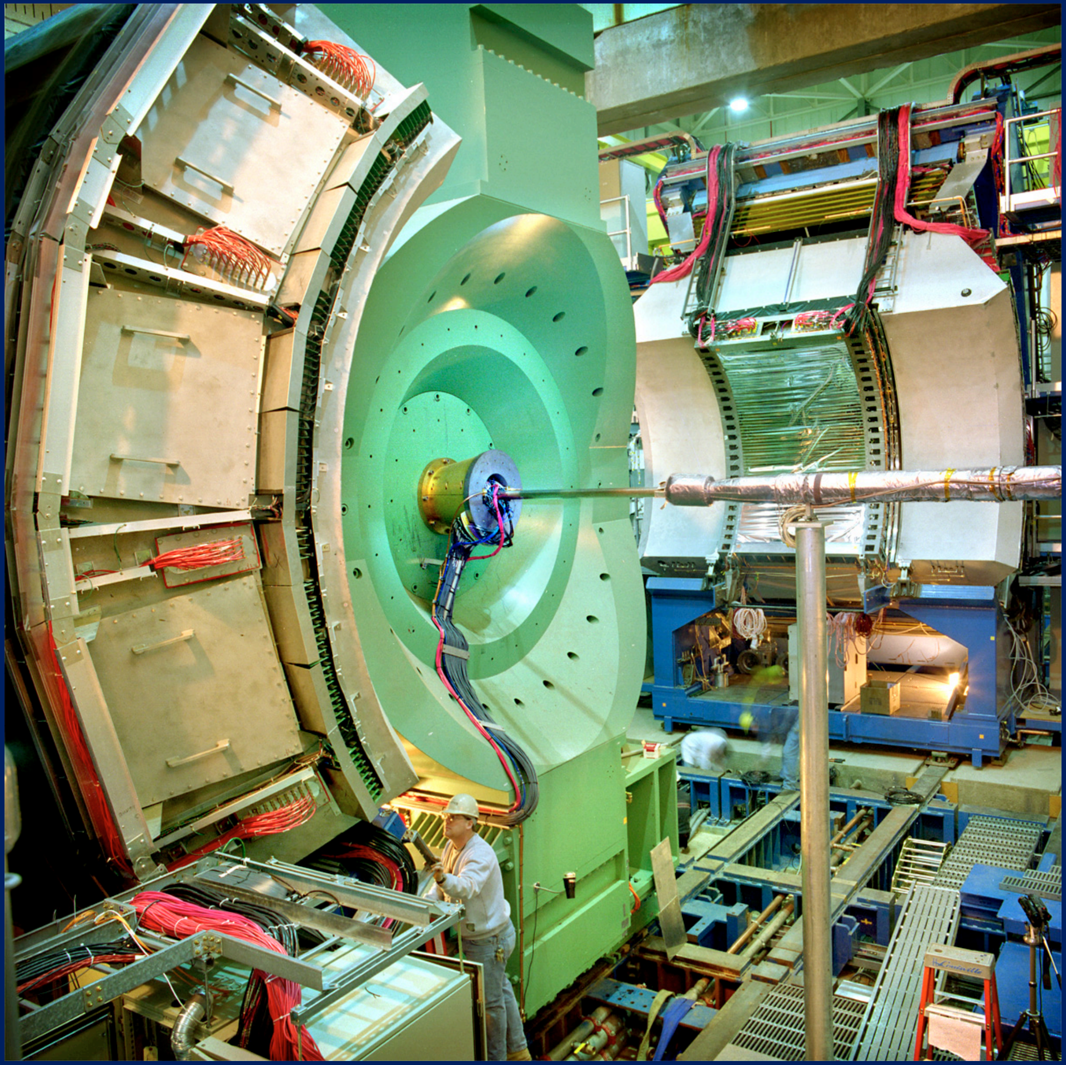
RHIC's experiments

Collider running since 2000

The PHENIX experiment

14 Countries, 73 Institutions
~500 Participants

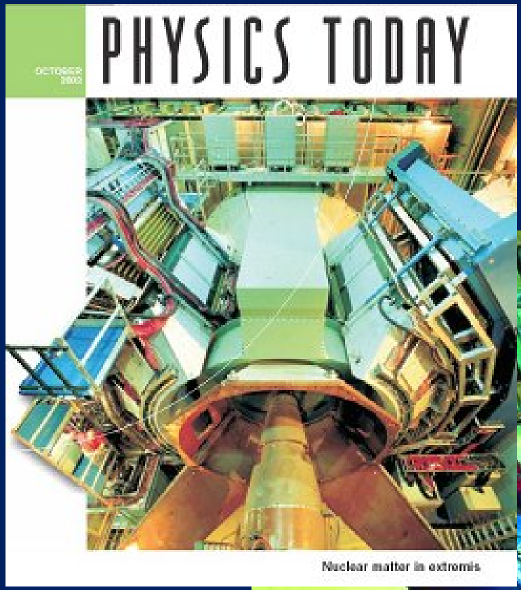
PHENIX detector



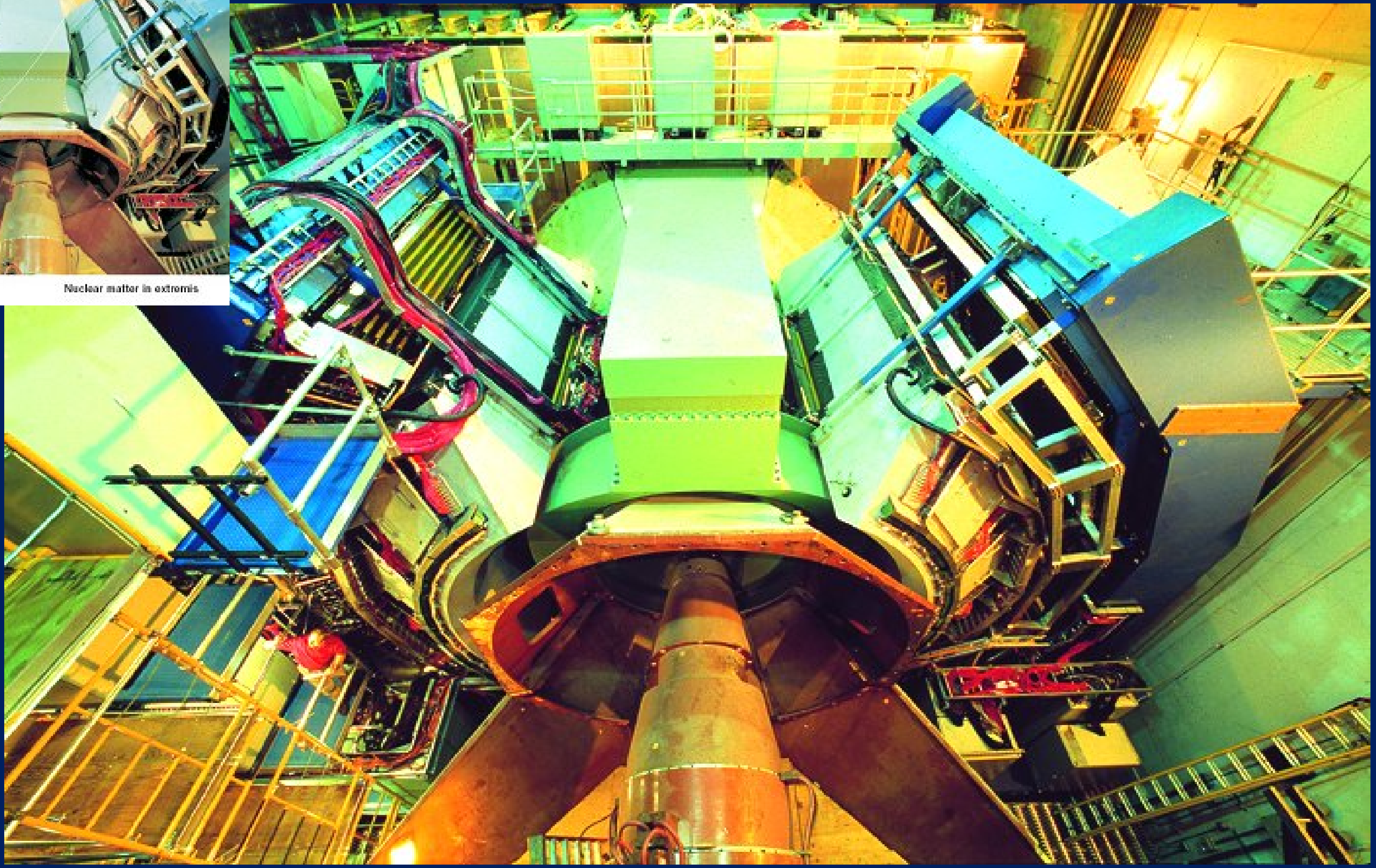
4 stories tall
40 feet long
~3000 tons

Different detector subsystems for measuring different kinds of produced particles or different information about them

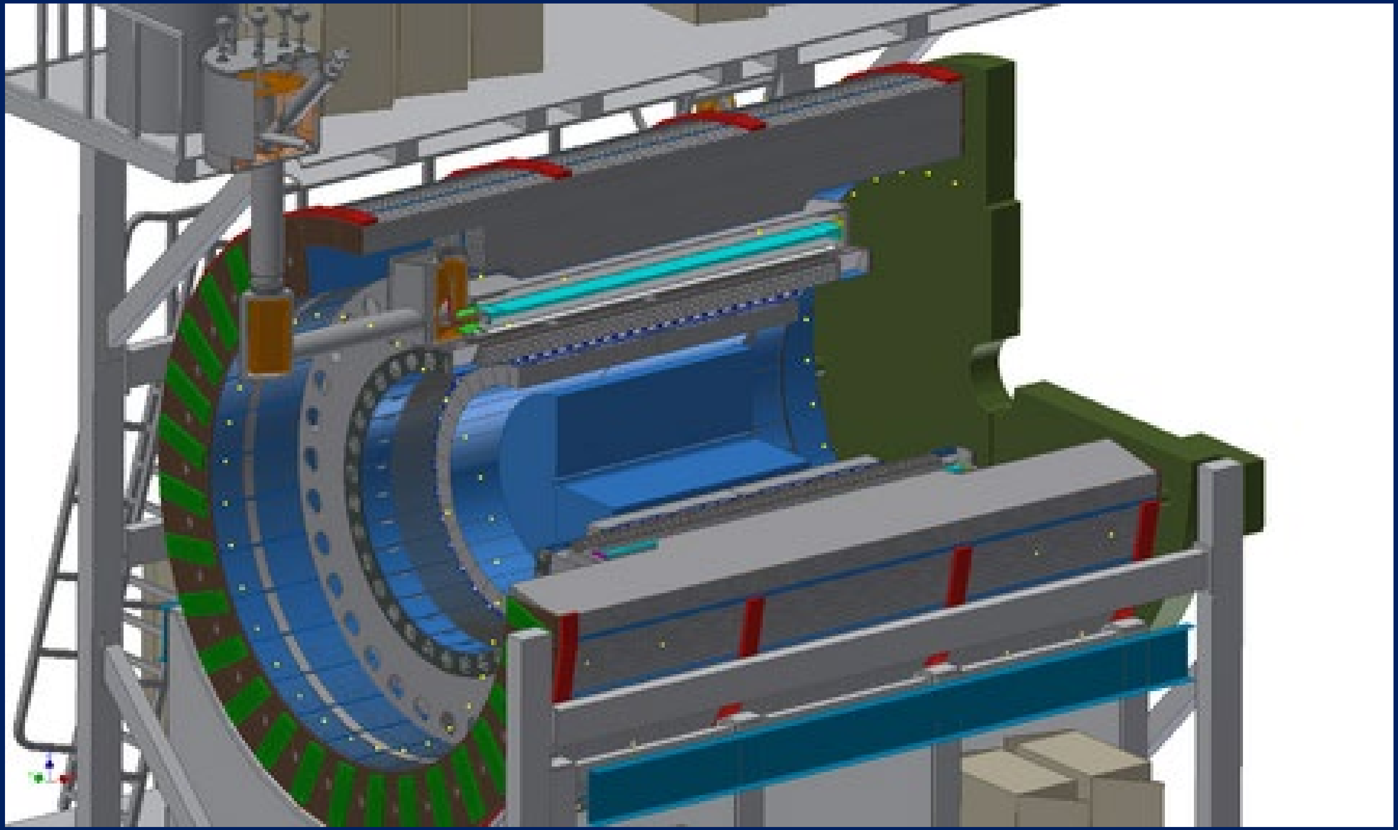
- Electric charge
- Momentum
- Energy
- Particle type



PHENIX detector



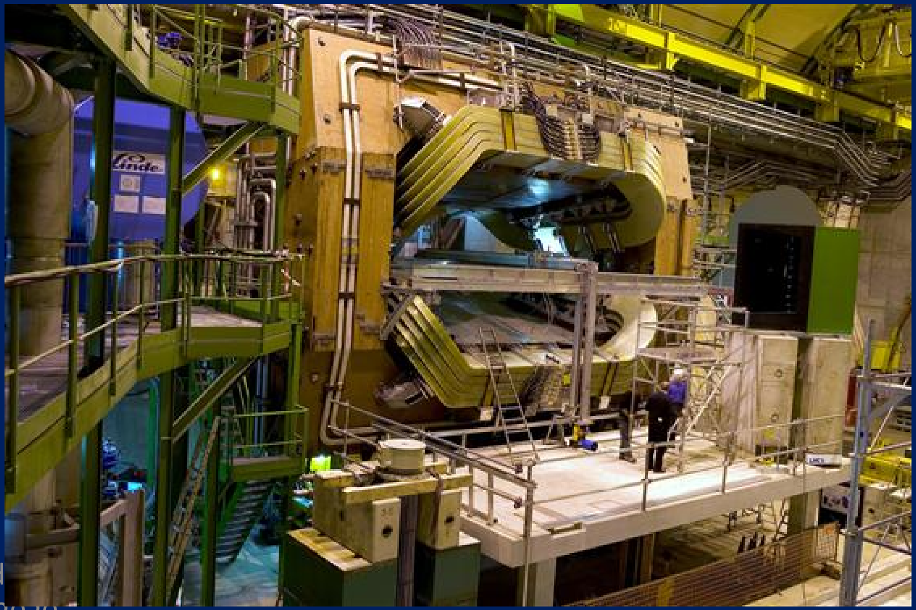
sPHENIX detector

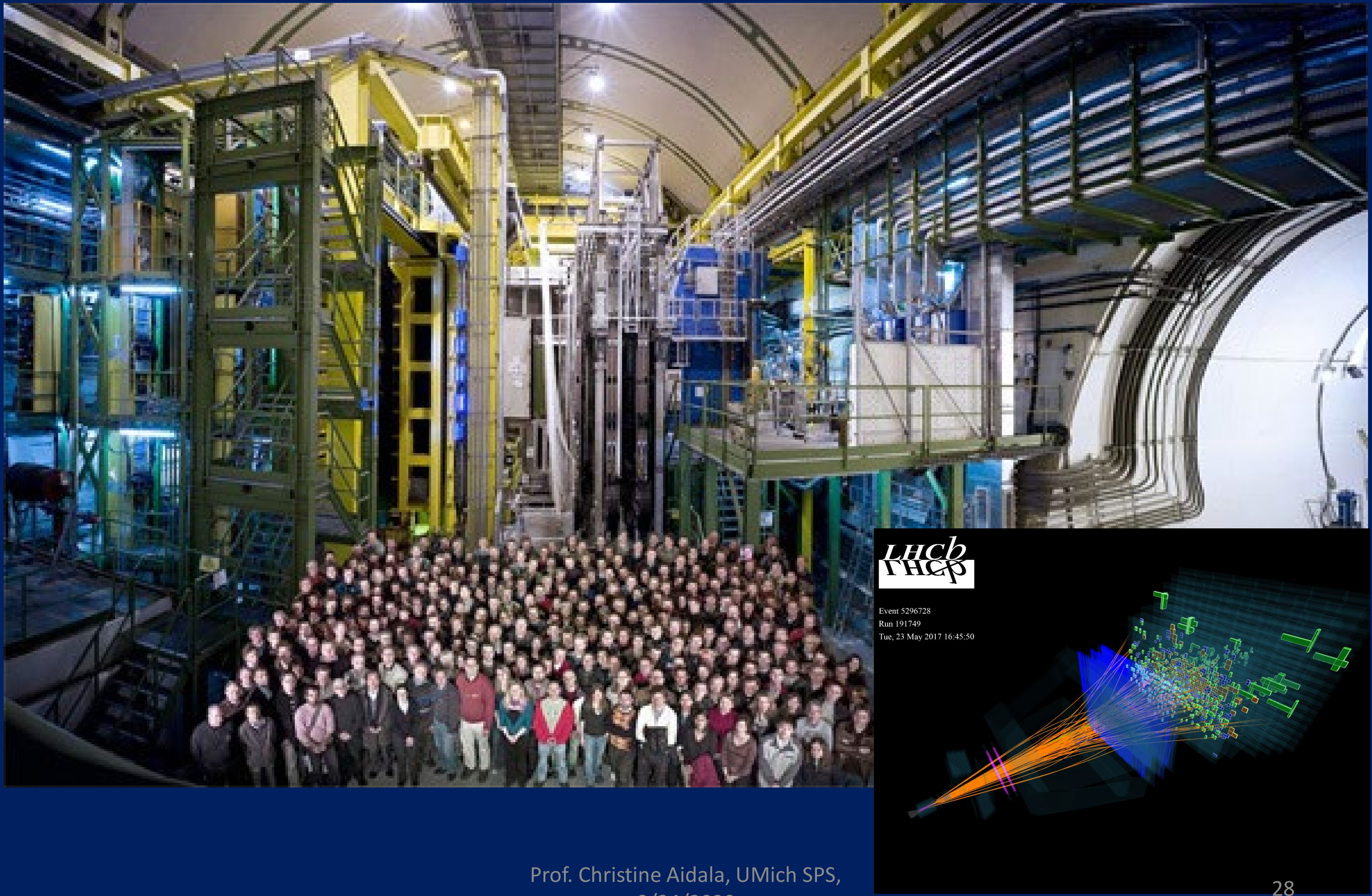


Currently under construction. Will start taking data in 2023.

LHCb experiment at CERN

- Proton-proton collisions up to center-of-mass energies of 13 TeV
  - Also proton-lead and lead-lead collisions
- Experiment design focus is studying charge-parity (CP) symmetry violation and charm and bottom quark states
- Unique at the LHC in that the detector is in the far forward region, NOT centered around the collision point




LHCb
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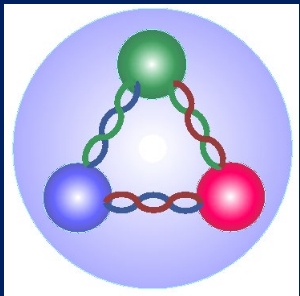
Run 191749
Tue, 23 May 2017 16:45:50



Studying proton structure

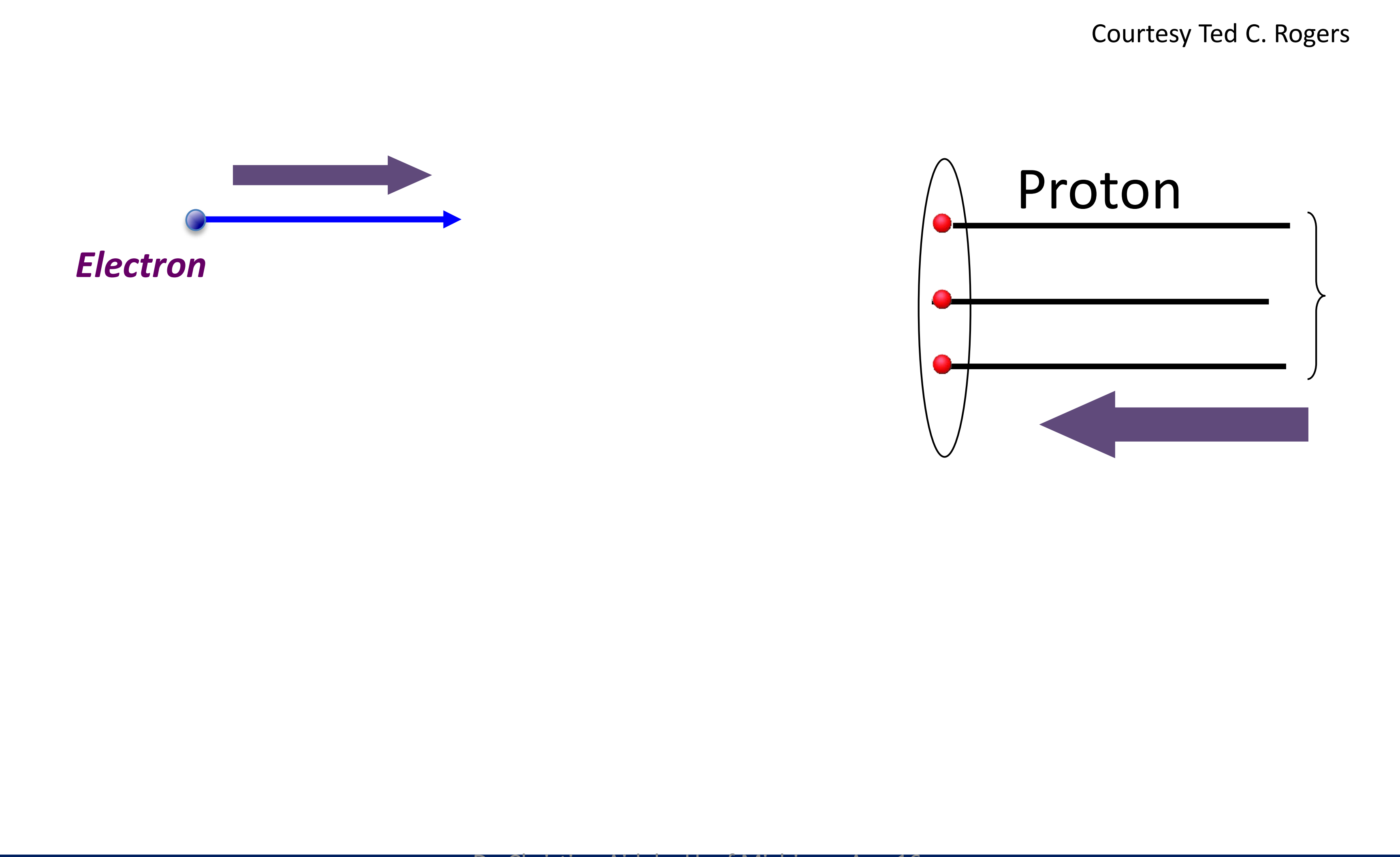
If can’t see individual quarks and gluons (“partons”), how to determine the proton’s structure?

- 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

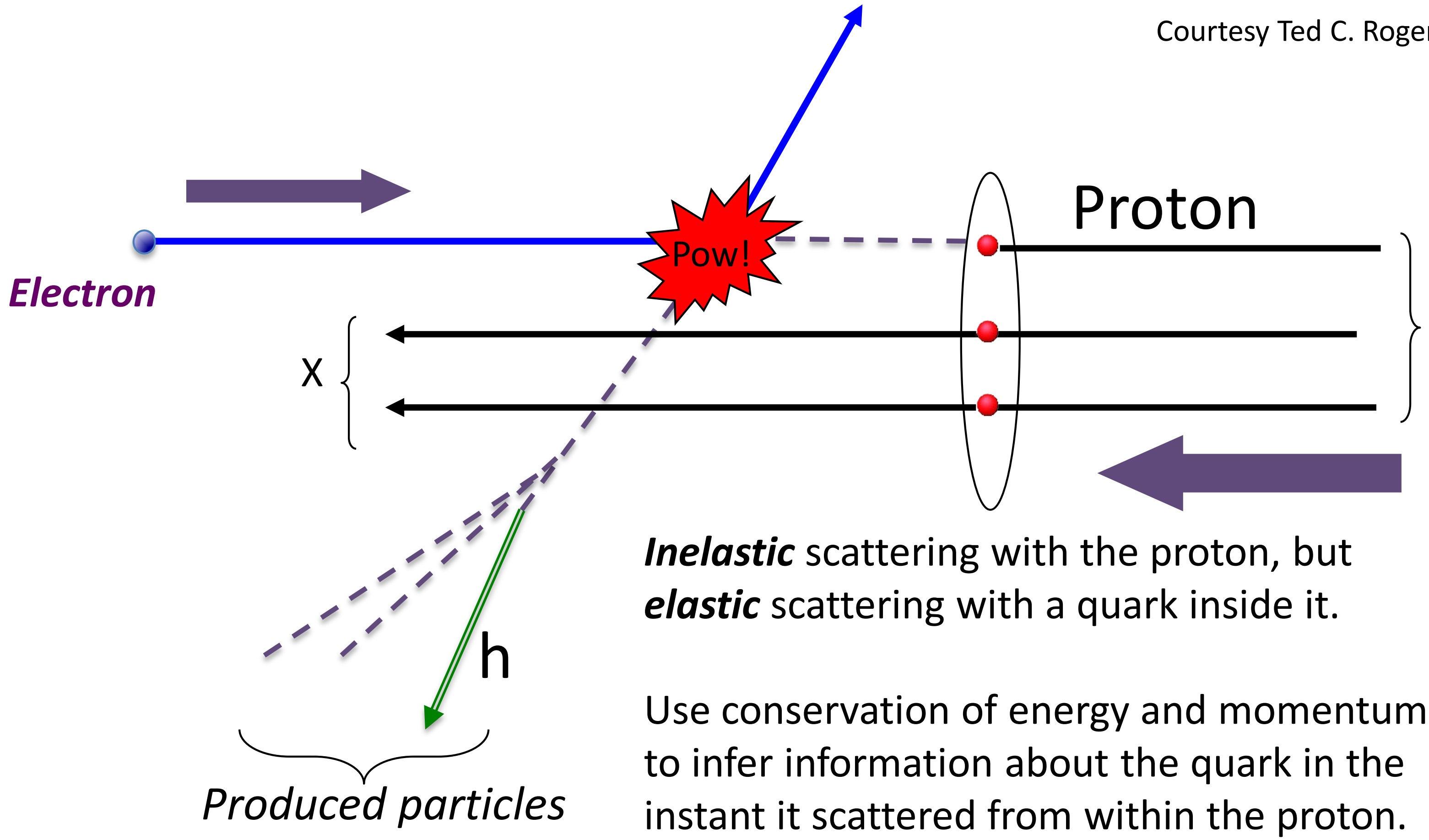
Describe proton structure in terms of *parton distribution functions* (PDFs)
 - Probability of scattering off of a parton carrying a particular fraction *x* of the proton’s momentum

(Recall that even if protons are in a stationary target, have non-zero momentum in center-of-mass frame)

Electron-proton scattering



Electron-proton scattering

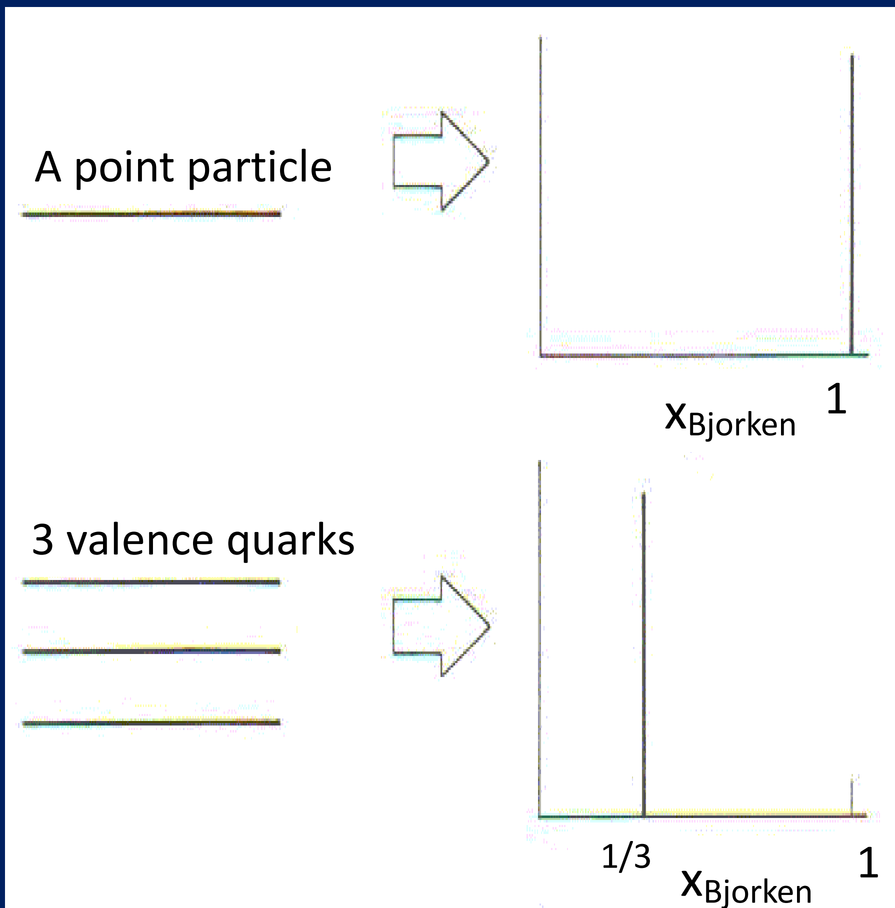


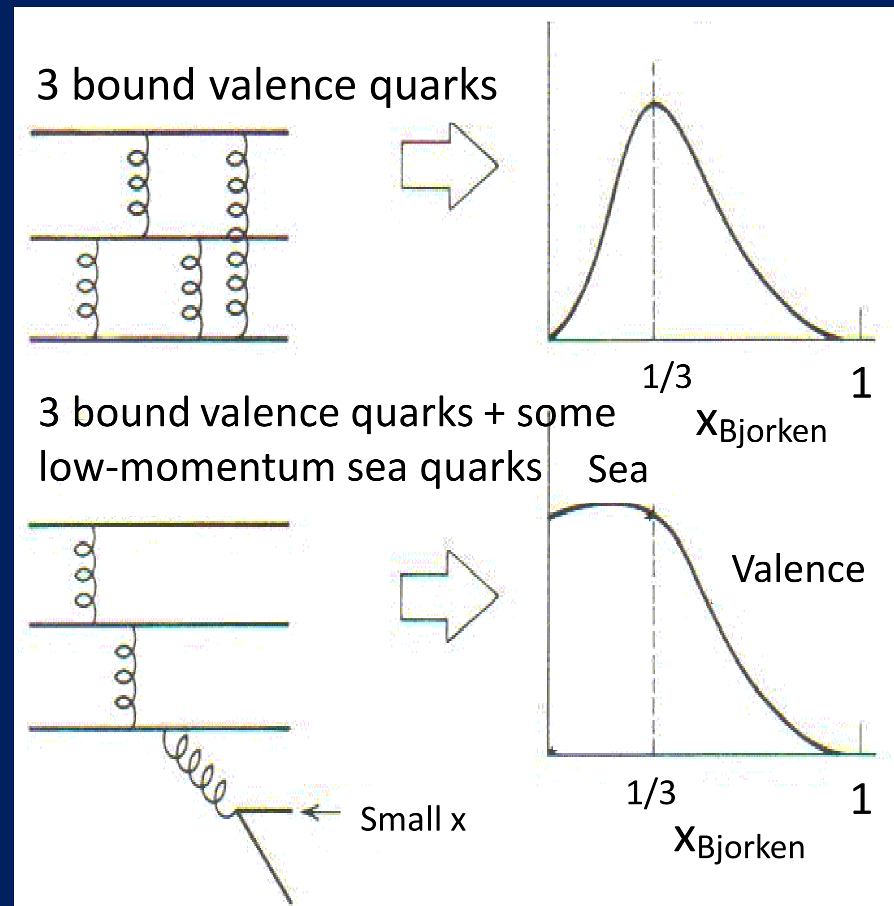
Inelastic scattering with the proton, but ***elastic*** scattering with a quark inside it.

Use conservation of energy and momentum to infer information about the quark in the instant it scattered from within the proton.

Parton distribution functions inside a nucleon: The language we've developed (so far!)

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

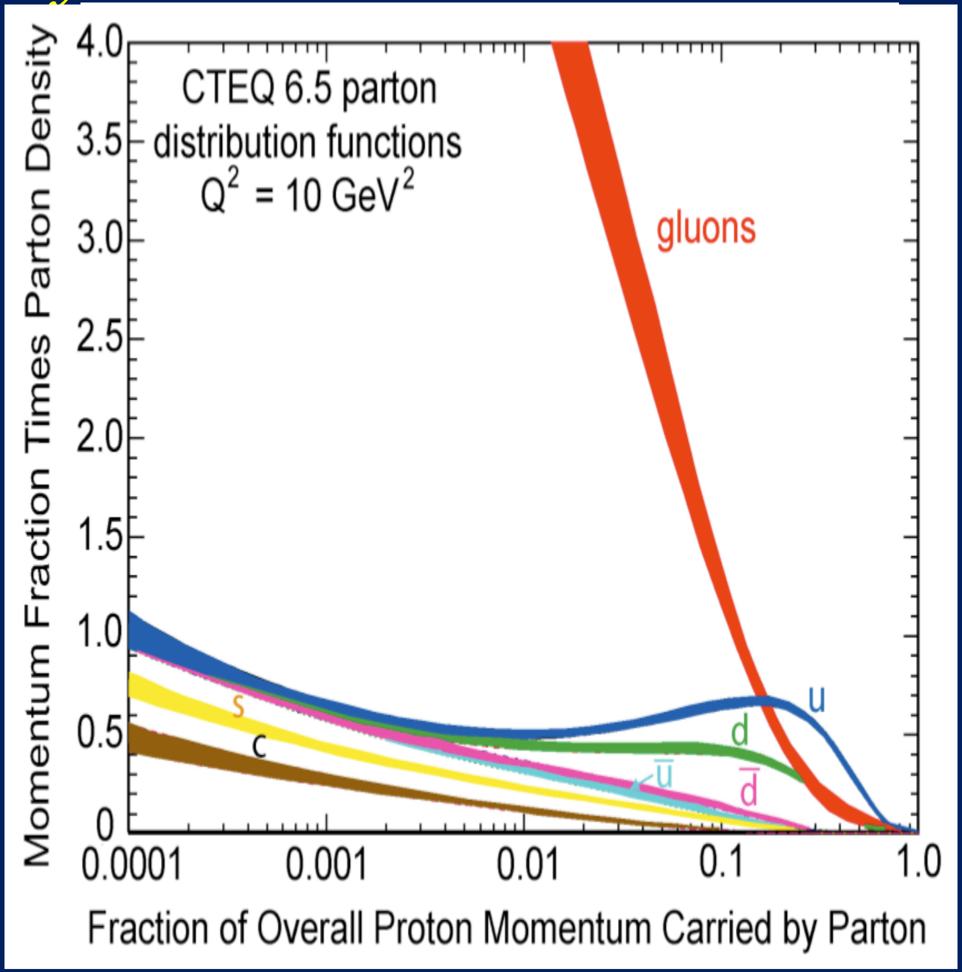




Halzen and Martin, "Quarks and Leptons", p. 201

What have we learned in terms of this picture by now?

- 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!



What have we learned in terms of this picture by now?

- 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, gluon interactions are actually responsible for more than 98% of the mass of the visible universe!!

Mapping out the quark-gluon structure of the proton

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

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

Vast majority of past five decades focused on *1-dimensional* momentum structure. Since 1990s starting to consider transverse components . . .

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

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Good measurements of flavor distributions in valence region. Flavor structure for sea quarks still yielding surprises.

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

Mapping out the quark-gluon structure of the proton

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

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

Accounted for theoretically from beginning of QCD, but more detailed, potentially observable effects of color flow have come to forefront in last decade . . .

What is spin?

Spin is a quantum mechanical property of fundamental particles or combinations of particles.

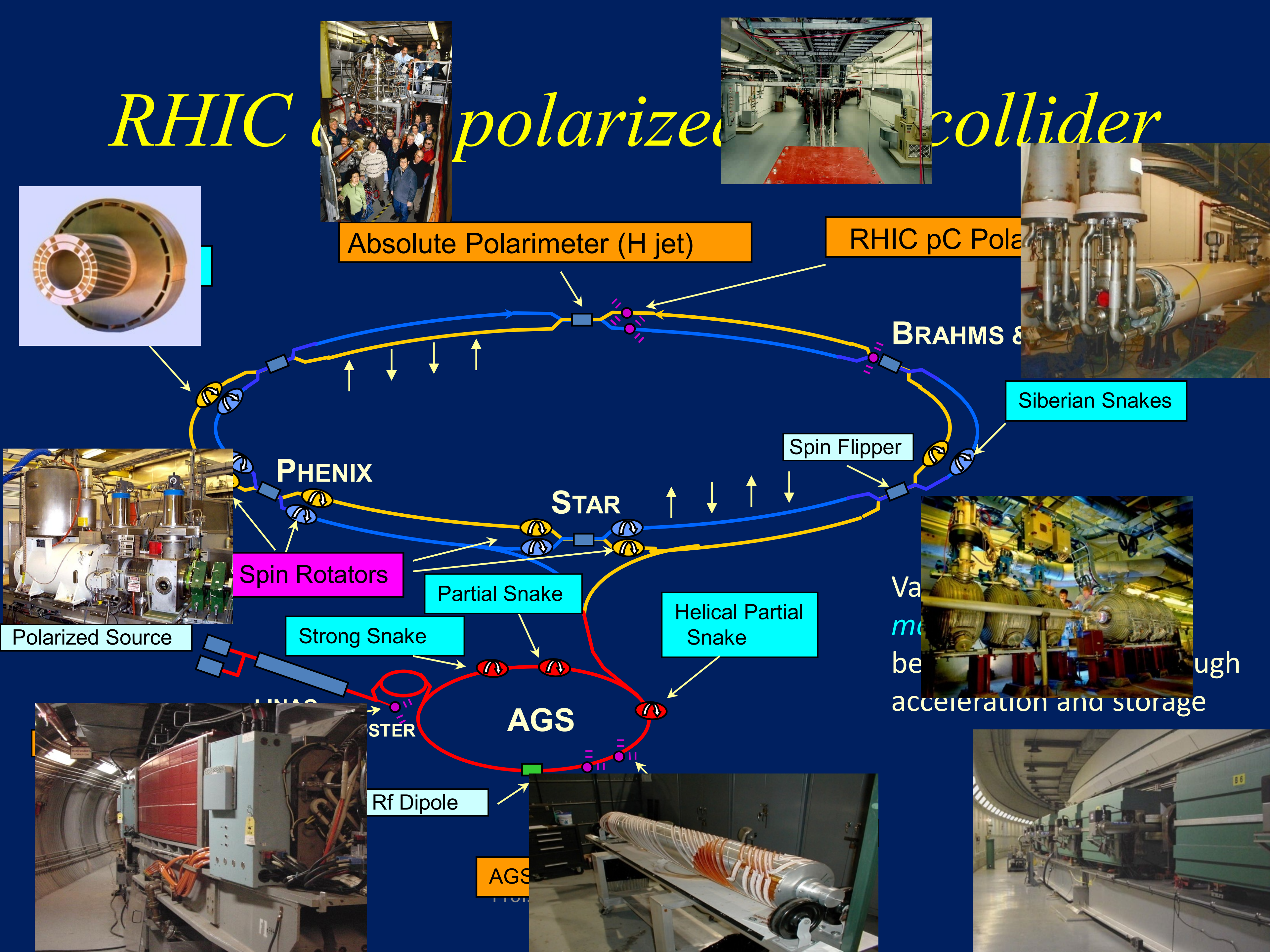
It's called "spin" because it's a type of angular momentum and is described by equations treating angular momentum.

The units of angular momentum are the same as Planck's constant, $\hbar$, and can only have values that are integer : 0, 1, 2, 3, . . .
or half-integer: 1/2, 3/2, 5/2, . . .

Quarks, like protons, have spin 1/2.

In a magnetic field, different spin states have different energies but have the same magnitude of the angular momentum.

Proton spin is what makes the medical diagnostic technique of MRI possible!



RHIC
polarize
collider
Absolute Polarimeter (H jet)
RHIC pC Pola
BRAHMS &
Siberian Snakes
Spin Flipper
PHENIX
STAR
Spin Rotators
Partial Snake
Helical Partial
Snake
Strong Snake
Polarized Source
AGS
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Rf Dipole
AGS
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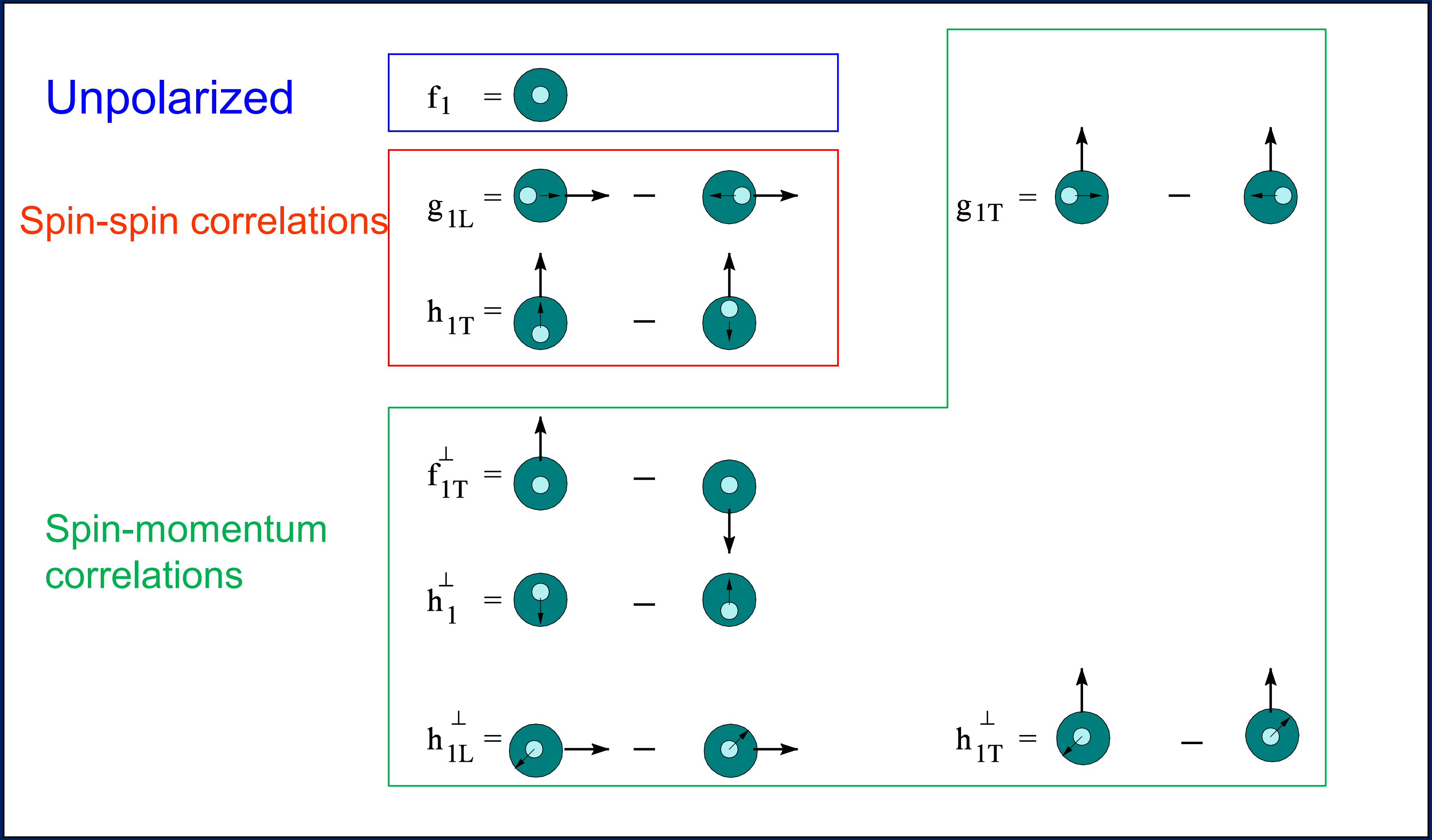
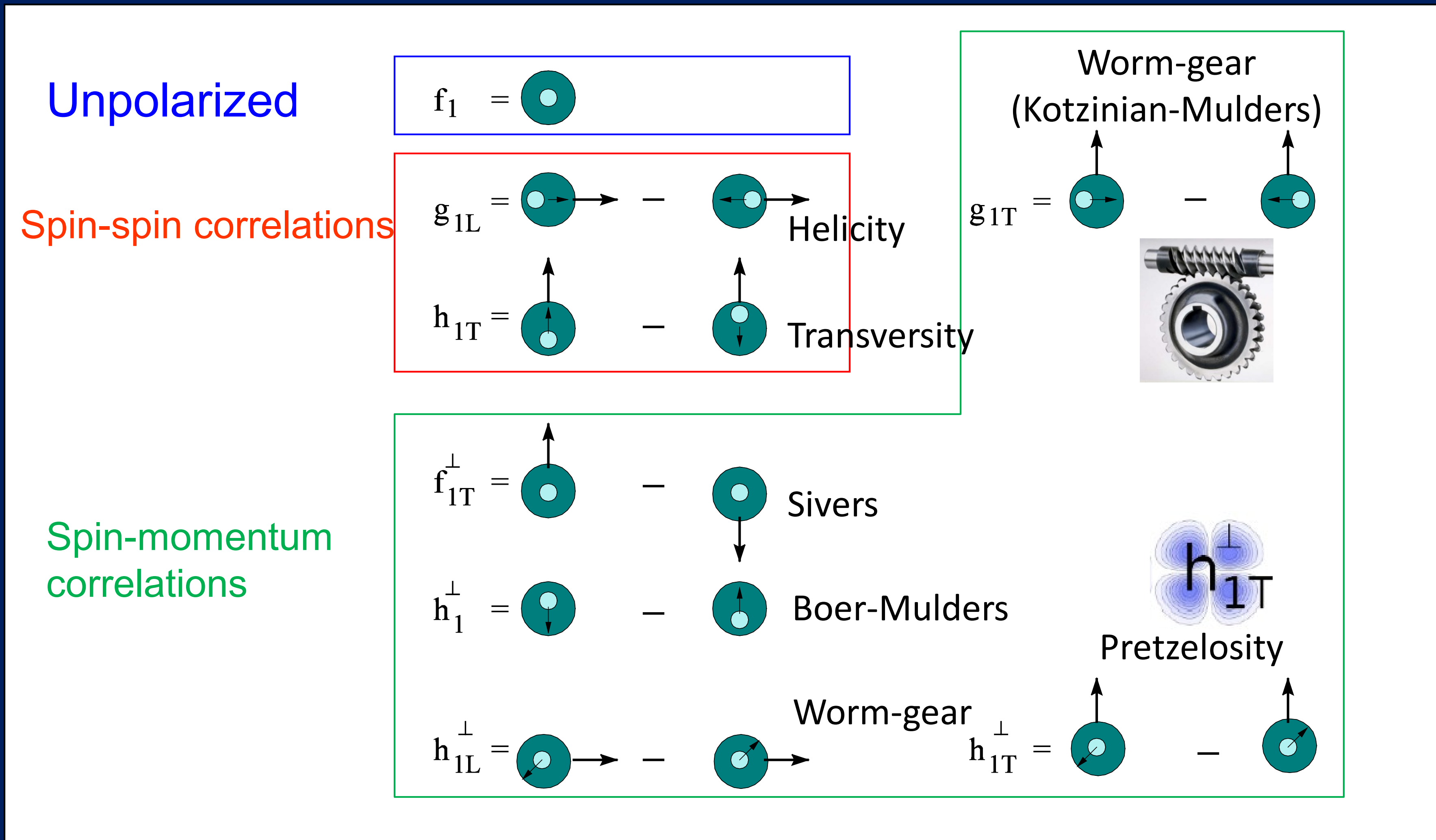
acceleration and storage

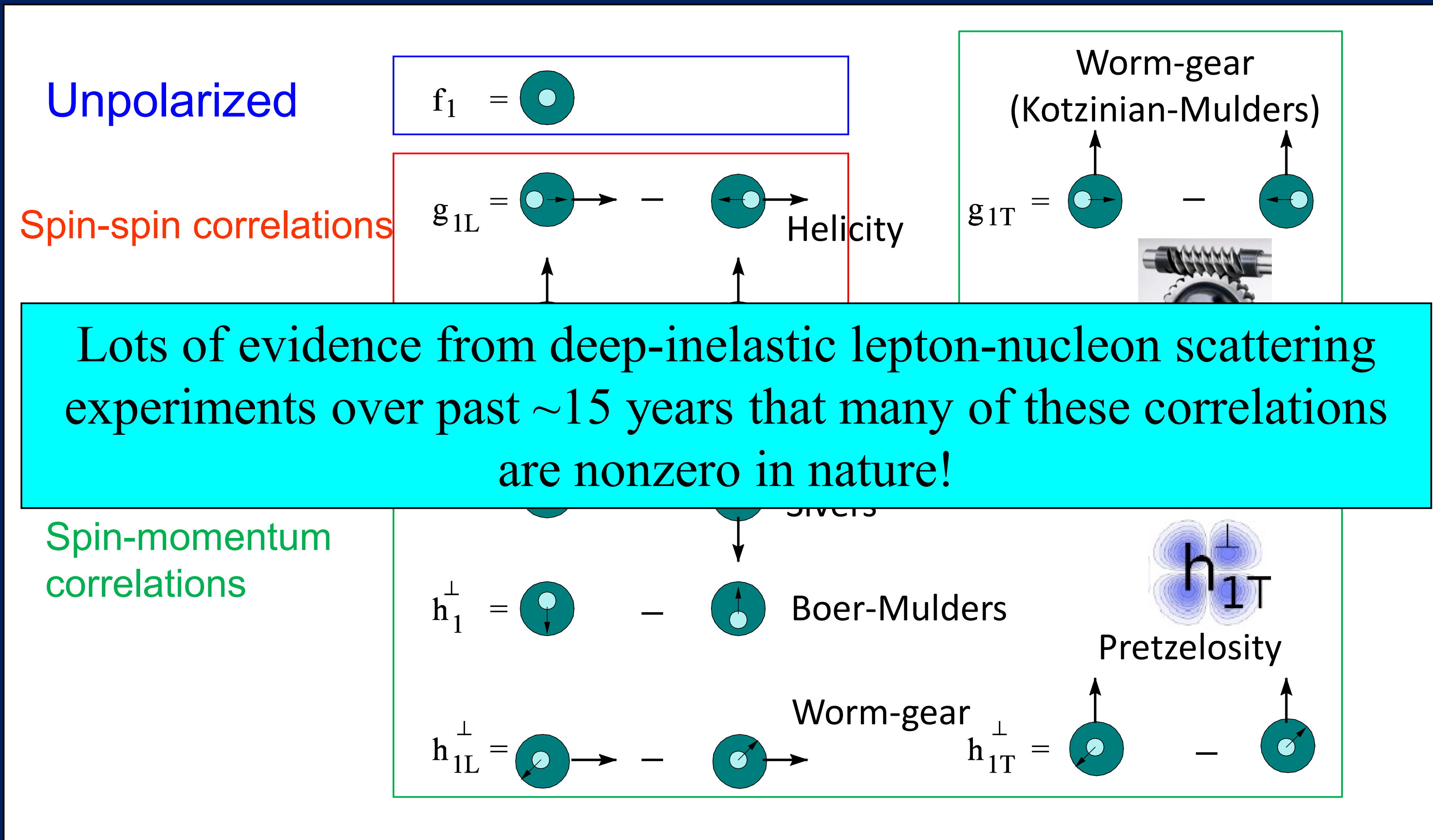
Spin-spin and spin-momentum correlations in QCD bound states



Spin-spin and spin-momentum correlations in QCD bound states



Spin-spin and spin-momentum correlations in QCD bound states



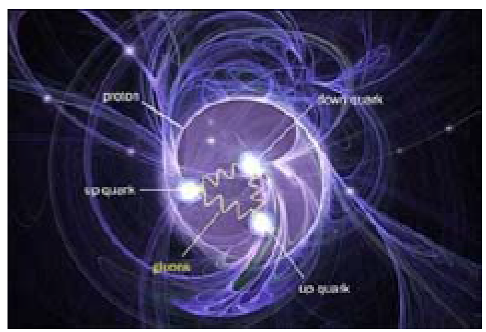
Lots of evidence from deep-inelastic lepton-nucleon scattering experiments over past ~15 years that many of these correlations are nonzero in nature!

July 2014

Proton Spin Mystery Gains a New Clue

Physicists long assumed a proton's spin came from its three constituent quarks. New measurements suggest particles called gluons make a significant contribution

By Clara Moskowitz | July 21, 2014



Brookhaven National Laboratory

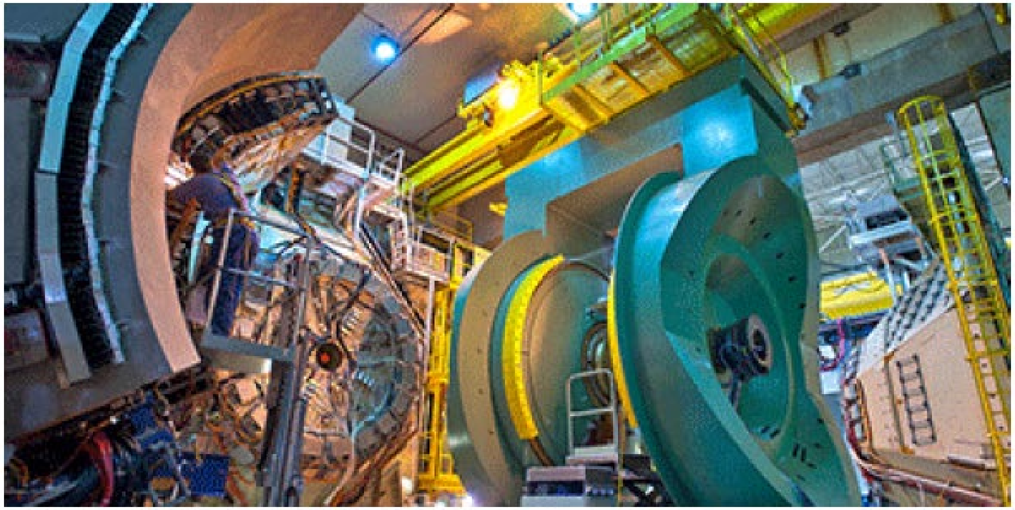
Protons have a constant spin that is an intrinsic particle property like mass or charge. Yet where this spin comes from is such a mystery it's dubbed the "proton spin crisis." Initially physicists thought a proton's spin was the sum of the spins of its three constituent quarks. But a 1987 experiment showed that quarks can account for only a small portion of a proton's spin, raising the question of where the rest arises. The quarks inside a proton are held together by gluons, so scientists suggested perhaps they contribute spin. That idea now has support from a pair of studies analyzing the results of proton collisions inside the Relativistic Heavy-Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, N.Y.

APS physics | Physics

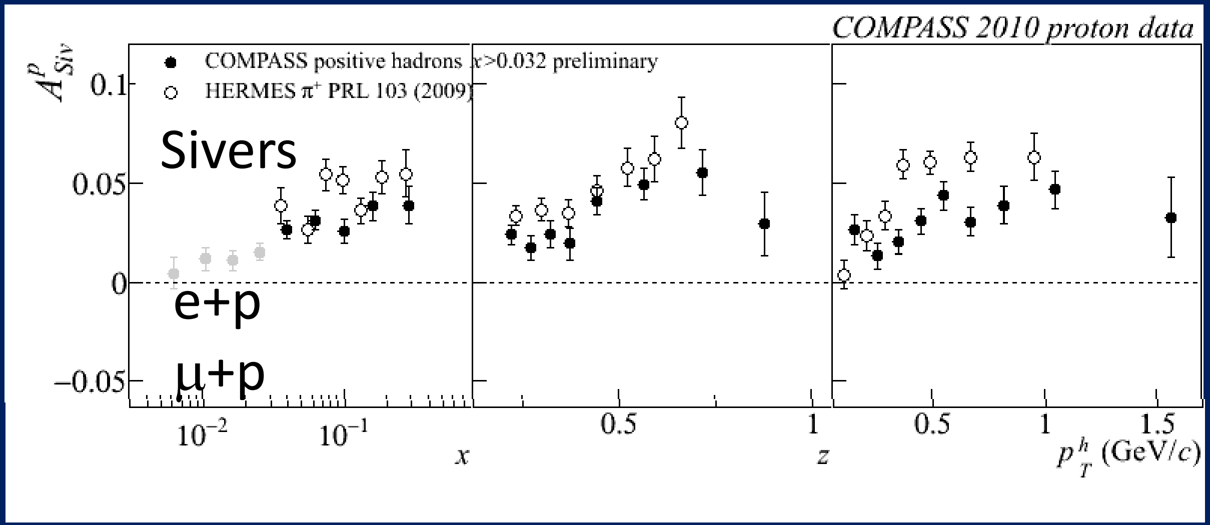
Synopsis: Gluons Chip in for Proton Spin

July 2, 2014

A new analysis of high-energy data shows that gluons may provide some of the proton's missing spin.



Brookhaven National Laboratory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COMPASS positive hadrons x>0.032 preliminary
HERMES π+ PRL 103 (2009)
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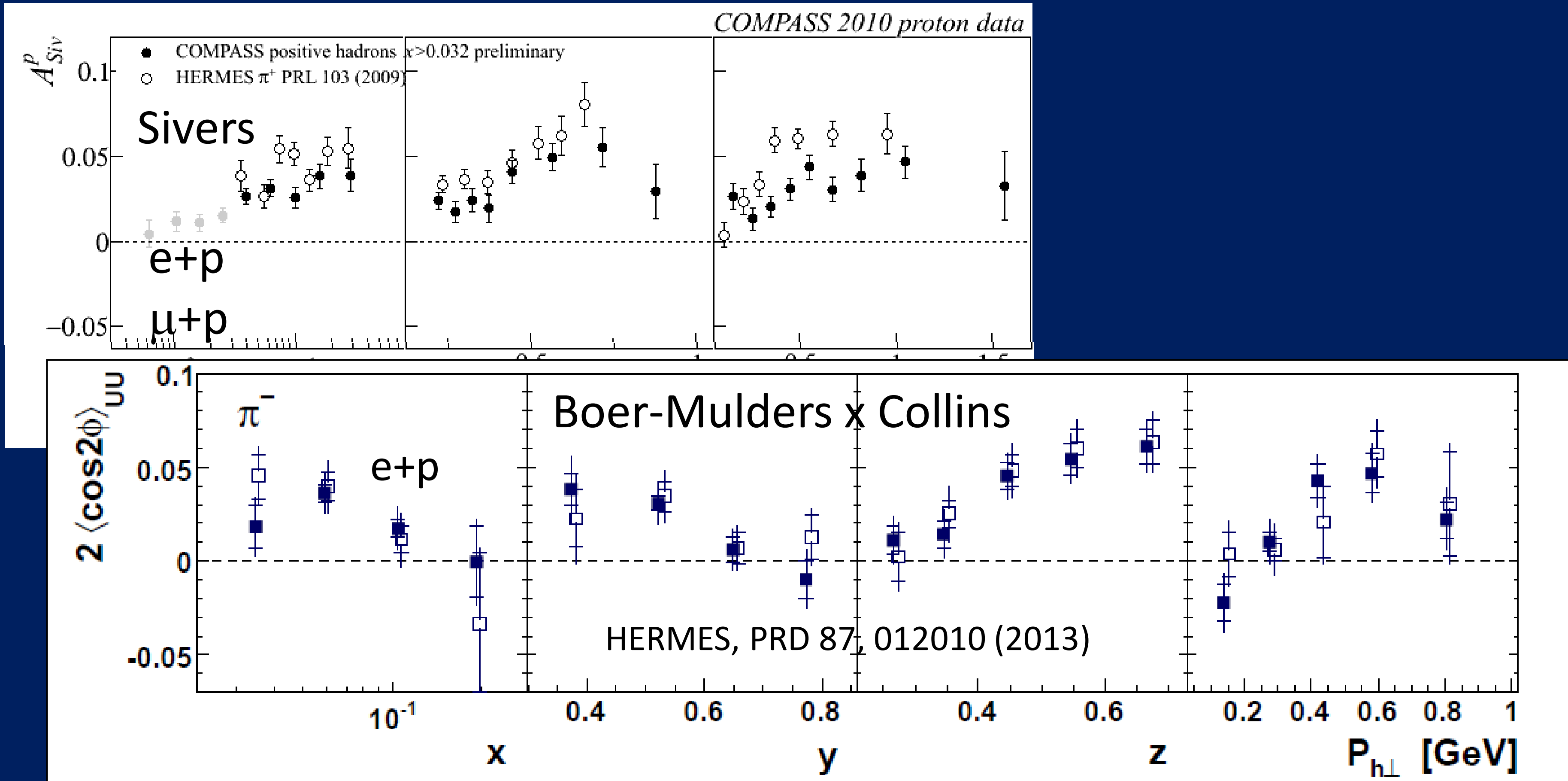
1
1.5
p^h_T (GeV/c)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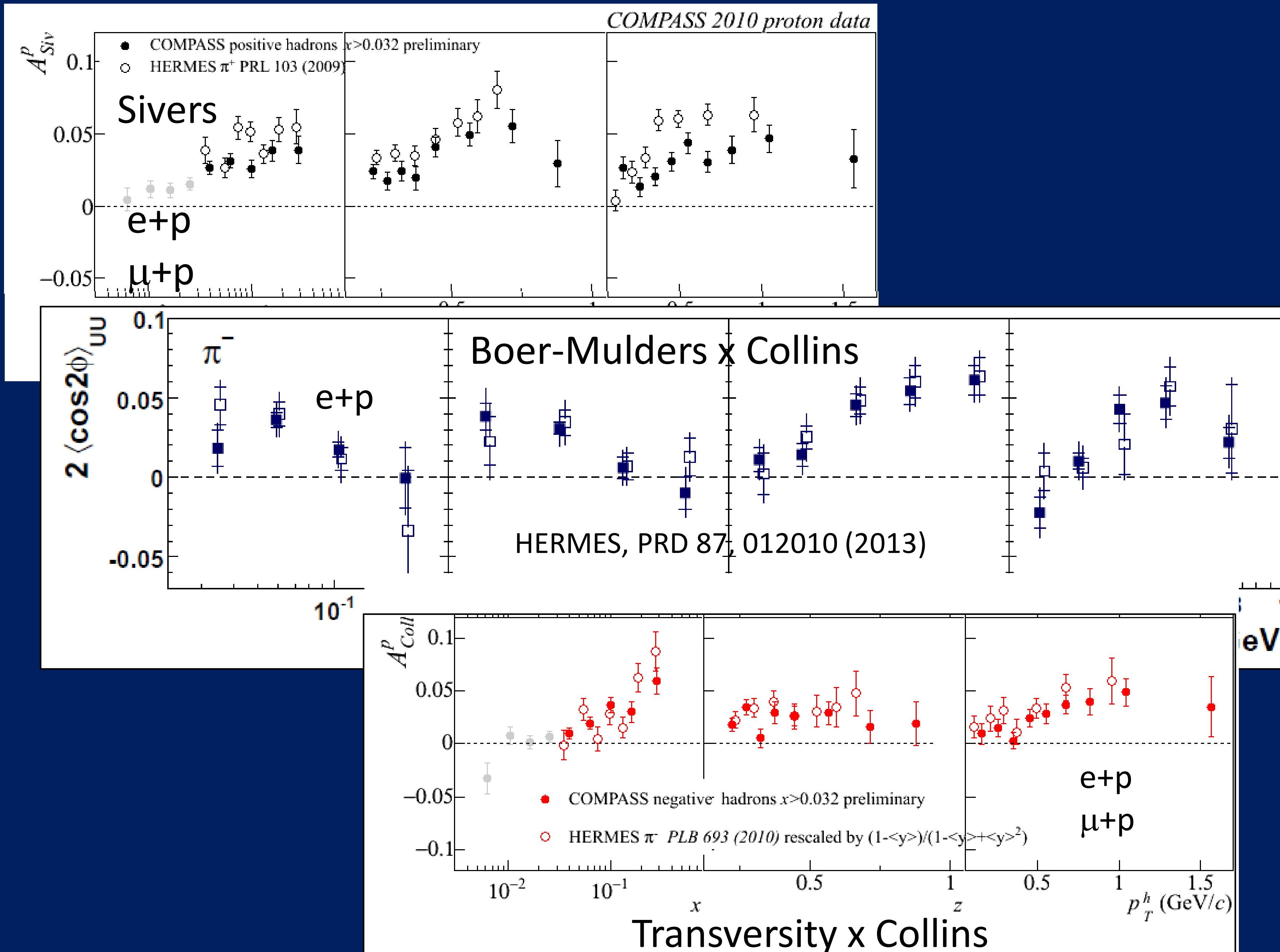
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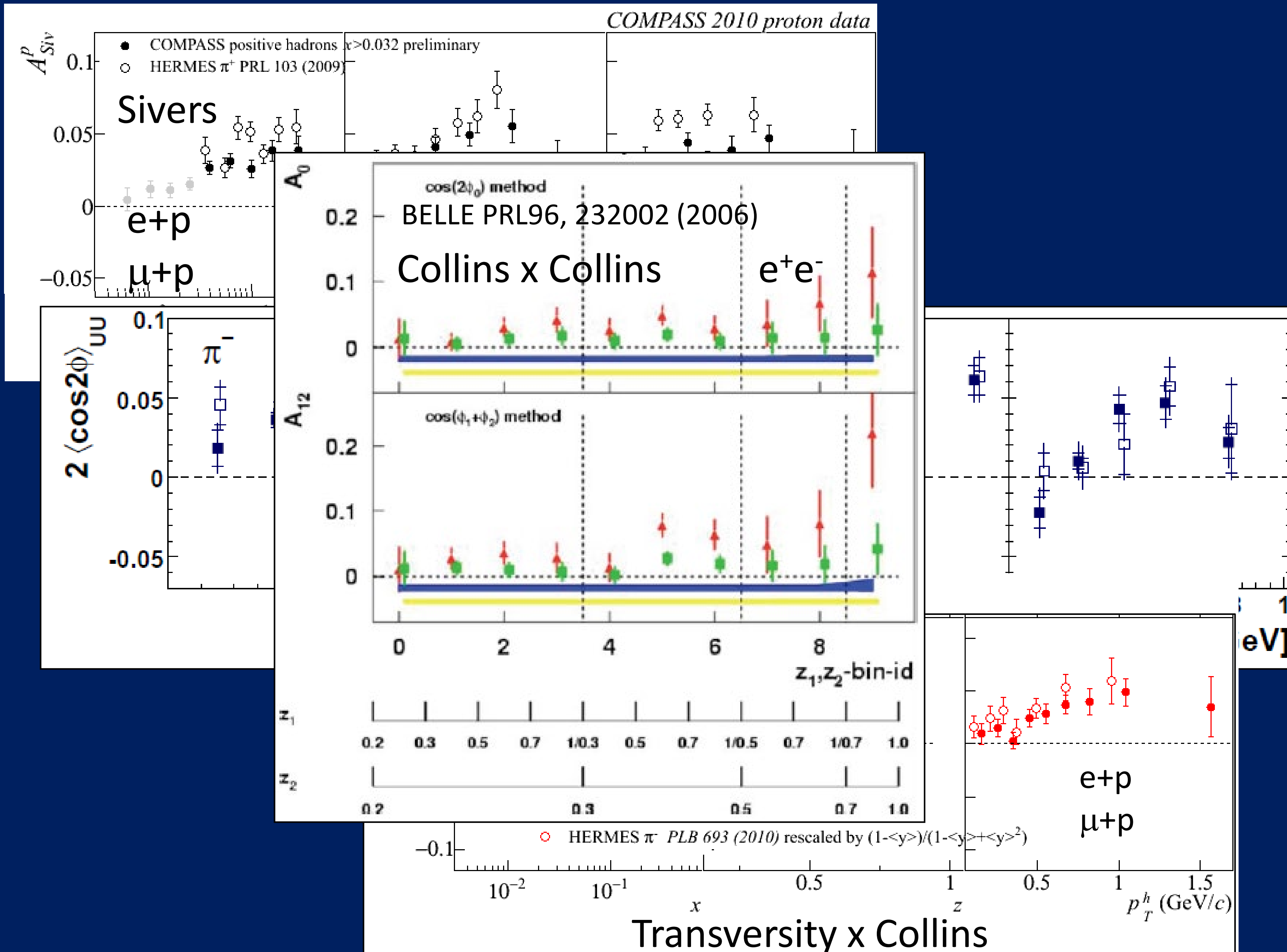
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cos(φ1+φ2) method
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μ+p
Transversity x Collins

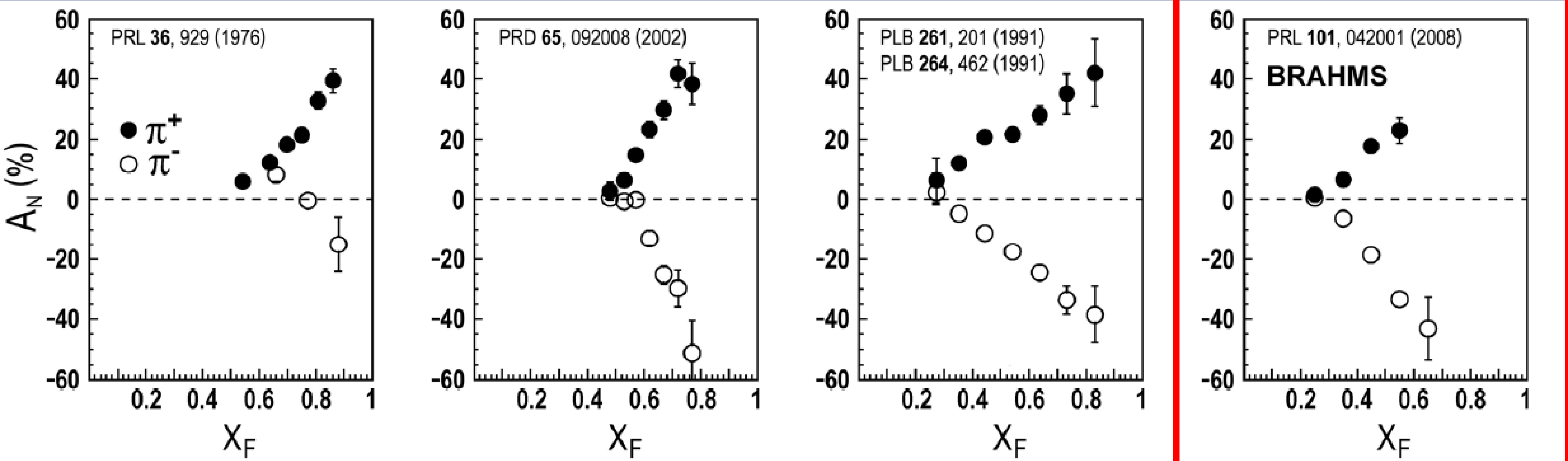
***Huge** spin-momentum correlations seen in $p^{\uparrow}+p \rightarrow$ charged pions*

ANL
$\sqrt{s}$=4.9 GeV

BNL
$\sqrt{s}$=6.6 GeV

FNAL
$\sqrt{s}$=19.4 GeV

RHIC
$\sqrt{s}$=62.4 GeV



*Proton-proton collisions—more complicated process than electron scattering off of protons! Huge correlations not yet understood and may be related to quantum color entanglement of quarks **across** the colliding protons. . .*

Group members fall 2020

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Summary

- Even though protons are a fundamental building block of everyday matter, we still have lots to learn about the complex behavior of the quarks and gluons inside them!
- In recent years things have been developing rapidly as we've discovered new questions we can ask about proton structure and have come up with ideas to perform relevant measurements
- A community of a couple thousand people around the world is working to unravel the mysteries of the proton and the strong force that holds it together . . .

Afterword:
Studying the strong force “versus” studying nucleon structure?
A personal perspective

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

Proton-Proton Scattering Vs. Electron-Proton Scattering

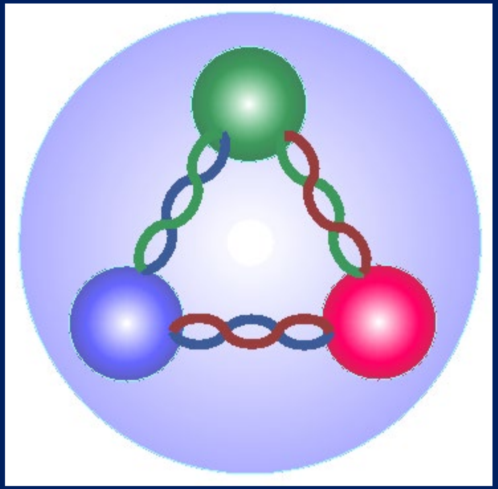
- Studying the proton by breaking it up with another proton is much more complicated than probing it with an electron beam!
  - Two composite objects colliding and breaking up
- Rely on some input from experiments performed in simpler systems
- One specific advantage: *Direct access to gluons*, which cannot be probed directly via electron beams (gluons carry no electromagnetic charge)

Fixed-Target (SeaQuest) Versus Collider (PHENIX) Experiments

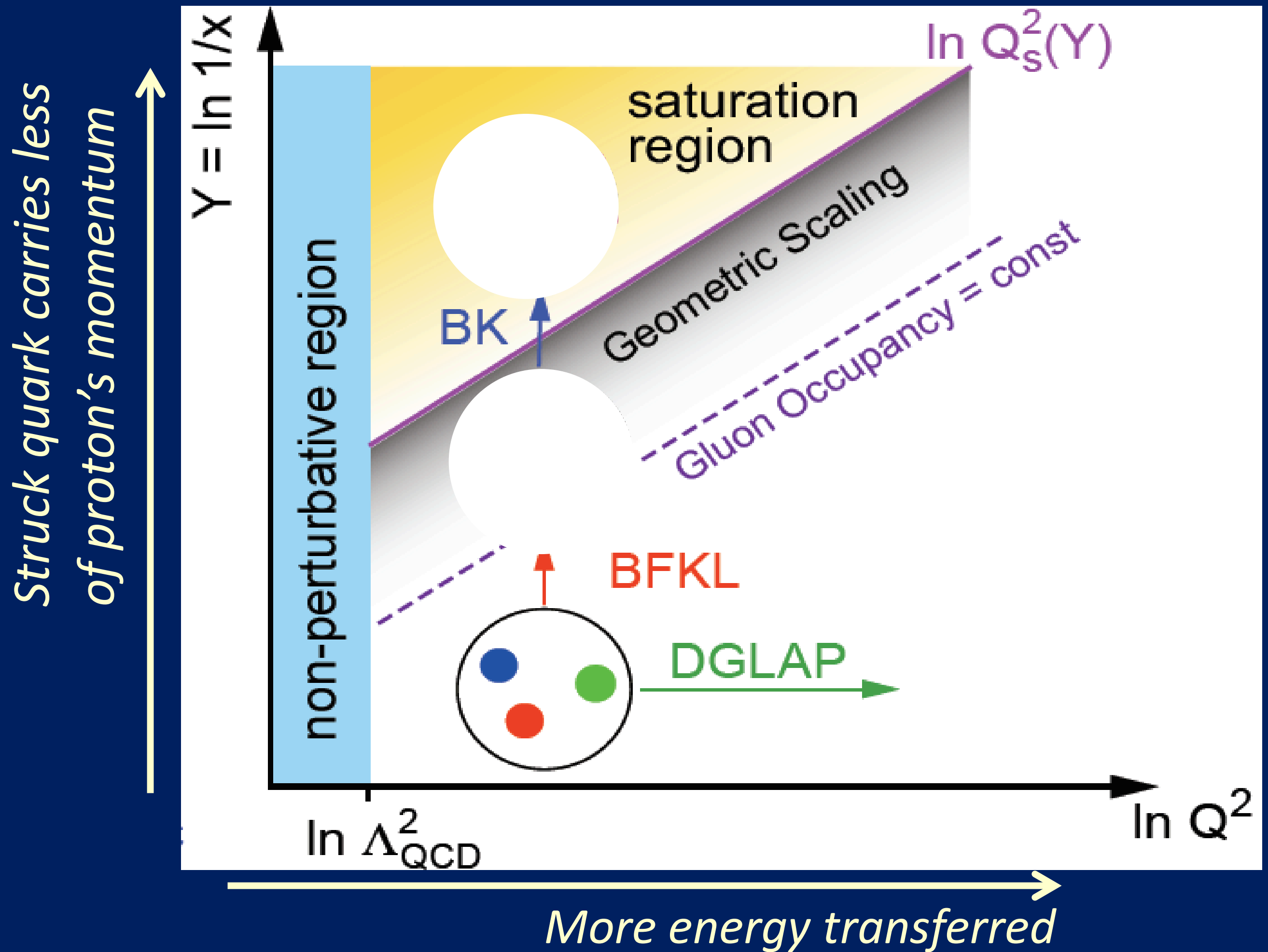
- Earliest experiments studying proton structure used electron beams to probe stationary ("fixed") proton targets (think of tube of hydrogen gas)
  - Typically easier and cheaper to perform fixed-target experiments
- Collider experiments allow you to reach higher energy
  - Can use different theoretical tools to interpret results ("perturbative QCD")
  - Can produce heavier particles ($E=mc^2$ again!)
  - Can access different kinematic region (e.g. lower momentum fraction, $x_{Bjorken}$)

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 . . .



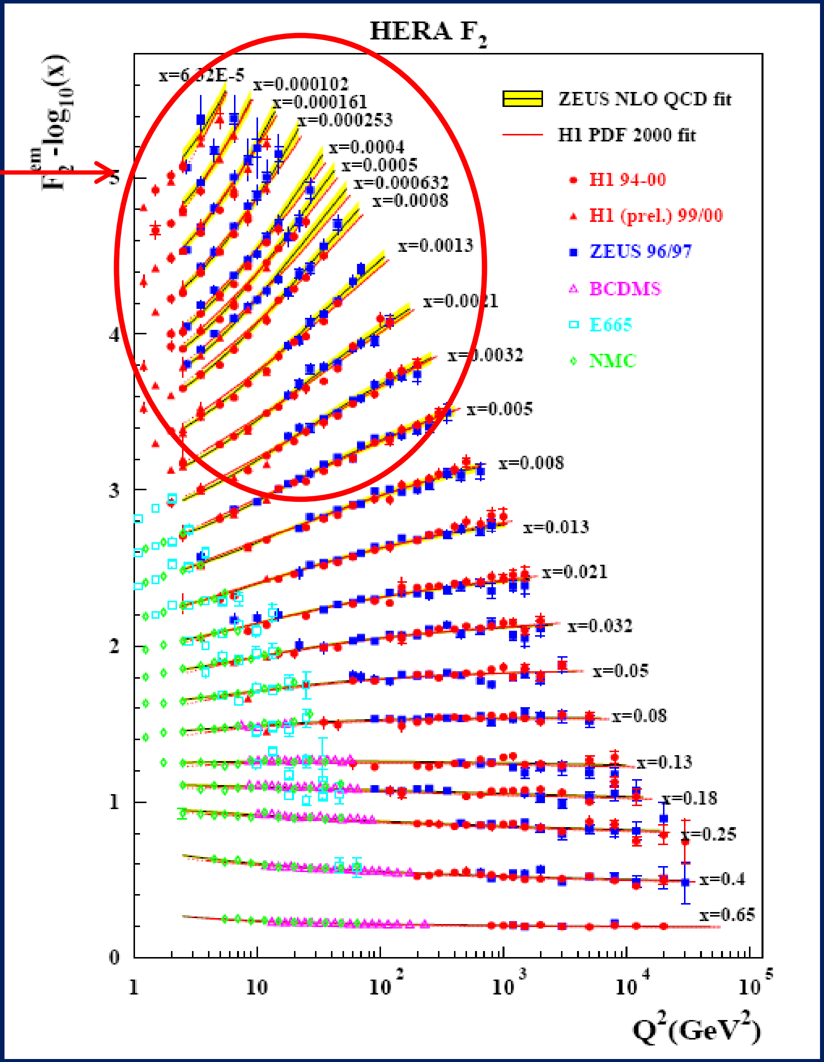
So what does it look like inside the proton? It depends . . .



Experimental data on proton structure

- Complex structure where quarks and gluons each carry only a small fraction of the proton's momentum
- ~98% of the proton's mass—and therefore the mass of everyday objects—comes from quark + gluon interactions!

Struck quark carries less of proton's momentum



More energy transferred

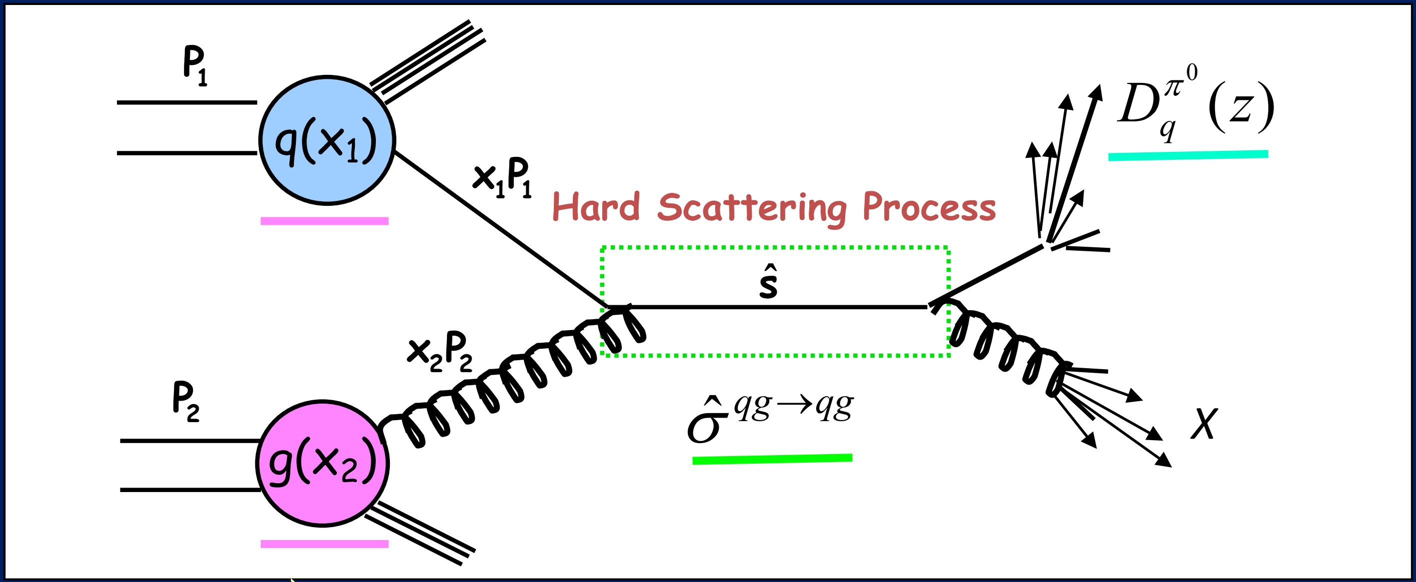
$$\frac{d^2\sigma^{ep\to eX}}{dxdQ^2} = \frac{4\pi\alpha_{e.m.}^2}{xQ^4}\left[\left(1-y+\frac{y^2}{2}\right)F_2(x,Q^2)-\frac{y^2}{2}F_L(x,Q^2)\right]$$

Factorization and universality in perturbative QCD

- Need to systematically *factorize* short- and long-distance physics—observable physical QCD processes always involve at least one long-distance scale (confinement)!
- s

Measure observables sensitive to parton distribution functions (pdfs) and fragmentation functions (FFs) in many colliding systems over a wide kinematic range→constrain by performing ***simultaneous fits to world data***

Predictive power of pQCD



$$\sigma\left(pp \to \pi^0 X\right) \propto q(x_1) \otimes g(x_2) \otimes \hat{\sigma}^{qg\to qg}(\hat{s}) \otimes D_q^{\pi^0}(z)$$

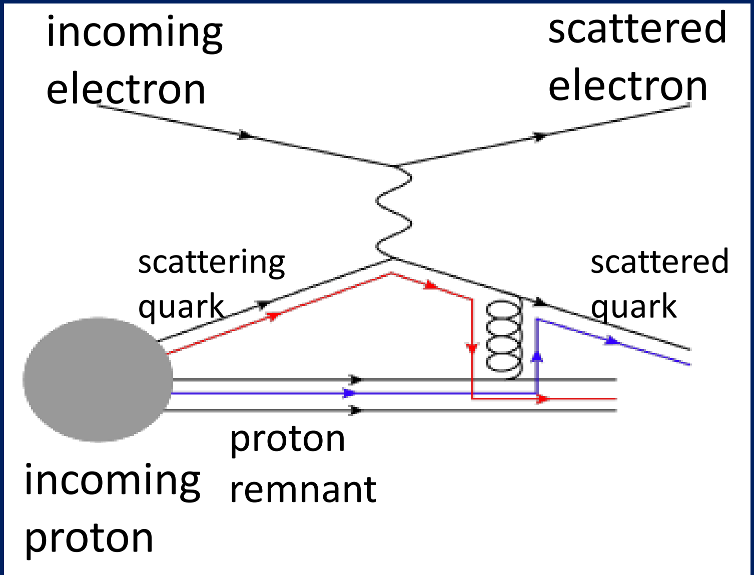
High-energy processes have predictable rates given:

- Partonic hard scattering rates (calculable in pQCD)
- Parton distribution functions (need experimental input)
- Fragmentation functions (need experimental input)

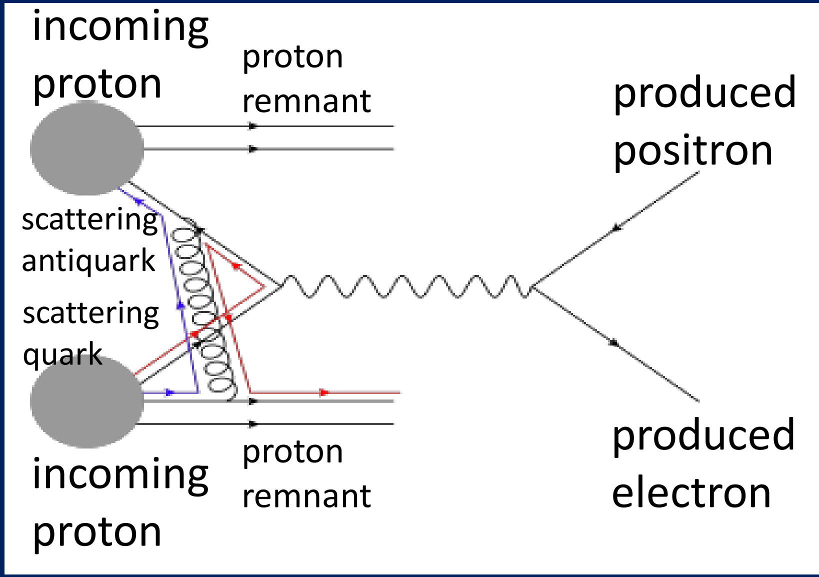
} **Universal non-perturbative factors**

Modified universality of certain spin-momentum correlations in the proton due to quantum phase interference and color exchange

Deep-inelastic electron-nucleon scattering: Final-state color exchange



Quark-antiquark annihilation to electrons: Initial-state color exchange



Get *opposite sign* for certain spin-momentum correlations in these two processes, due to phase interference effects and color exchange in the final state vs. initial state

Figures by J.D. Osborn