Pulling Apart the Strong Force by Peering Into the Proton

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REU Seminar

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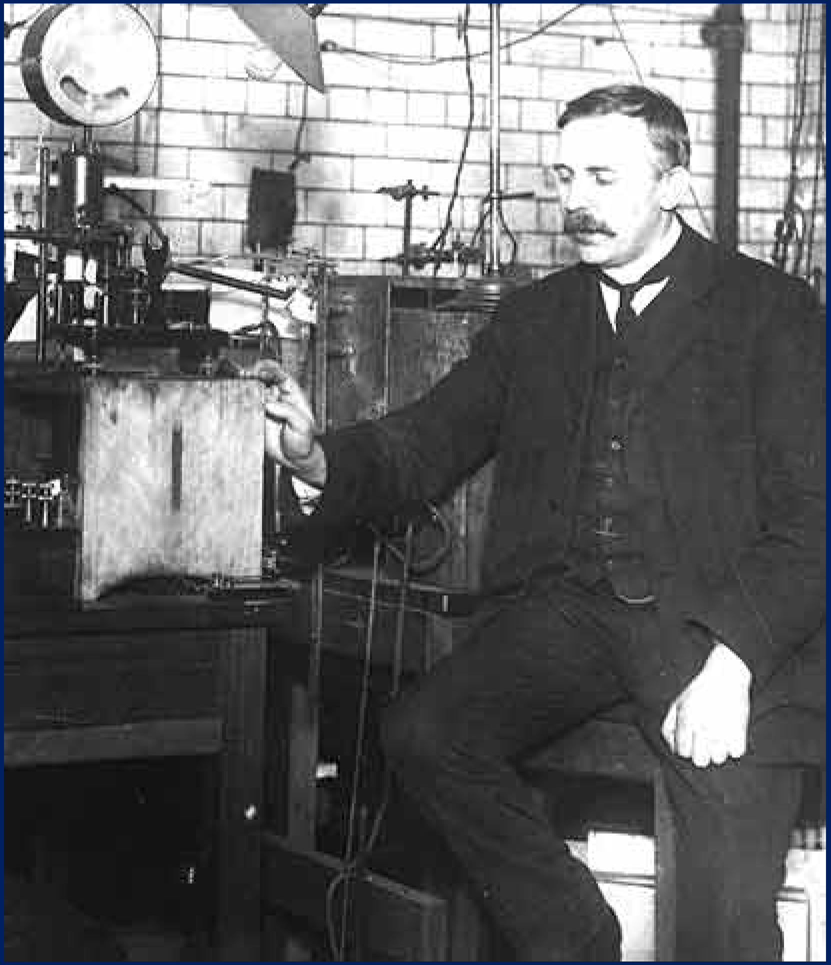
Probing inside atoms: mostly empty space!

1911: Ernest Rutherford, Hans Geiger, Ernest Marsden scatter alpha particles from radioactive decay off of a thin gold foil

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

"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you." - Rutherford

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

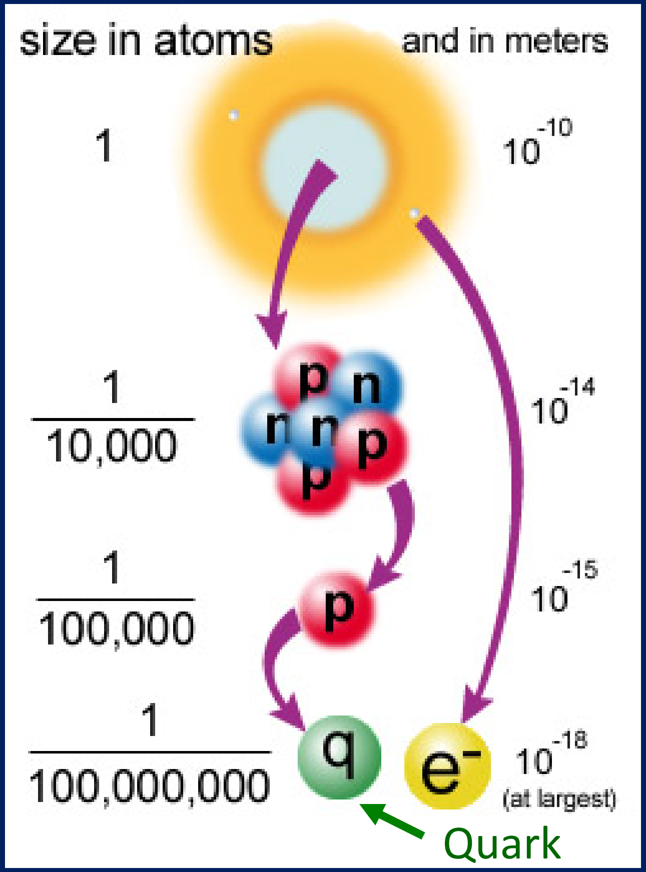


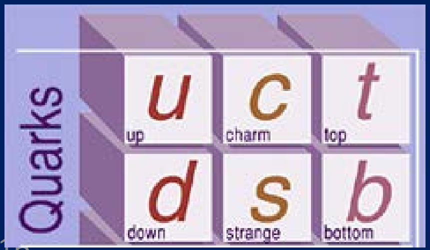
Probing inside protons . . .

Late 1960s, Stanford Linear Accelerator Center: scatter electrons off of protons

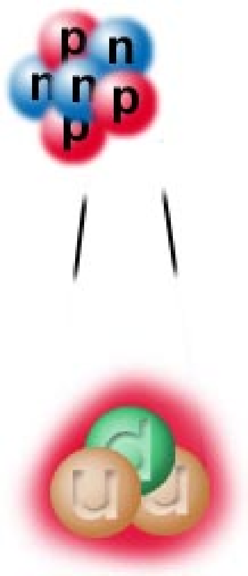
- Many bounced back sharply . . .

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

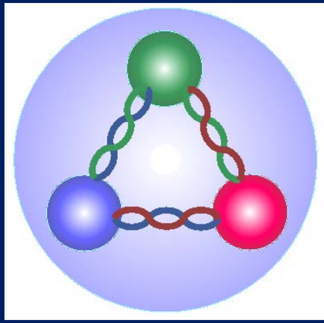


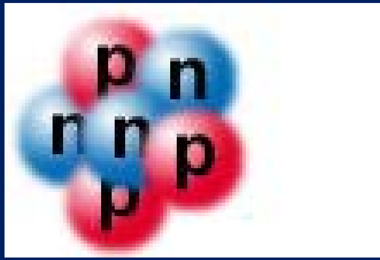


Quark-Parton Model

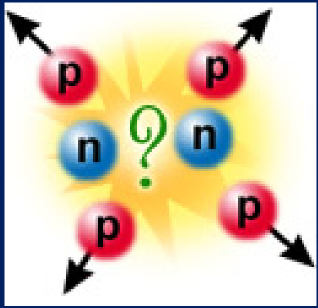


- Simplest model - proton made of three "valence" quarks: 2 up "flavored" quarks and 1 down "flavored" quark
  - "Flavor" – charge that couples to the weak force
- But these quarks not completely free in nucleon
  - Bound by force-carrier particles called "gluons"
  - "Sea quarks" also present: short-lived quark-antiquark pairs from quantum mechanical fluctuations
- Hit proton with more energy → resolve shorter-lived fluctuations: gluons and sea quarks





Strong force



- How does nucleus stay together? Electromagnetic force should cause protons to repel one another
- Protons and neutrons interact via *strong force*, carried by gluons
  - Much stronger than 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:

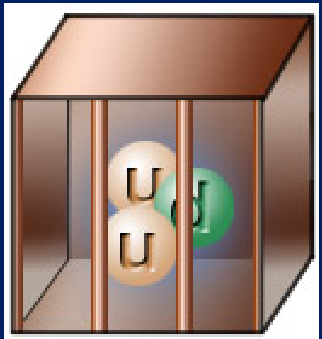
red + blue + green = white

- Quantum $\boxed{\textit{Chromo}}$dynamics (QCD)—theory describing strong force

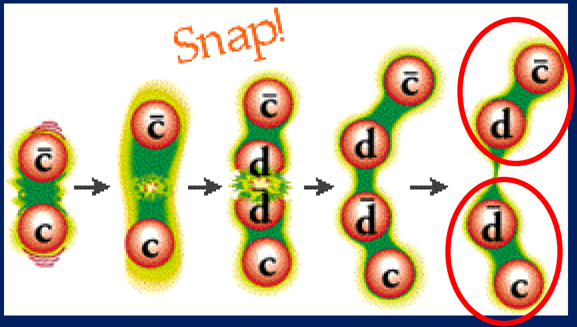
Quarks also carry *fractional* electric charge!!

Proton = up + up + down quarks	Neutron = down + down + up
+1 = (+2/3) + (+2/3) + (-1/3)	0 = (-1/3) + (-1/3) + (+2/3)

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

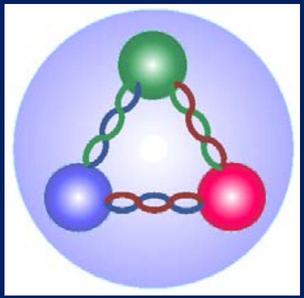
- For more info on quarks, gluons, and the strong force, see

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 quarks and gluons described by our theory of the strong force, quantum chromodynamics?

How can studying QCD systems teach us more about fundamental aspects of QCD as a theory?



Studying proton structure

- If can't see individual quarks and gluons, how to determine proton structure?

- Inelastic scattering—shoot high-energy beam (e.g. of electrons) at proton to break it up, and try to understand what happens
  - Electron exchanges 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

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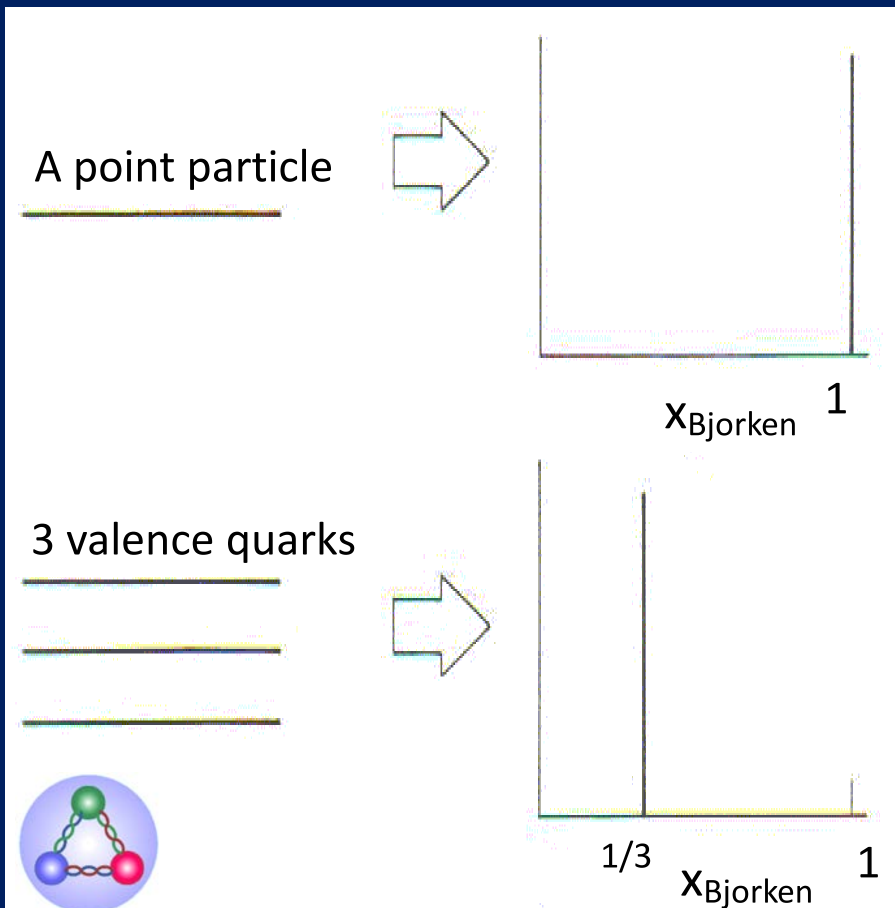
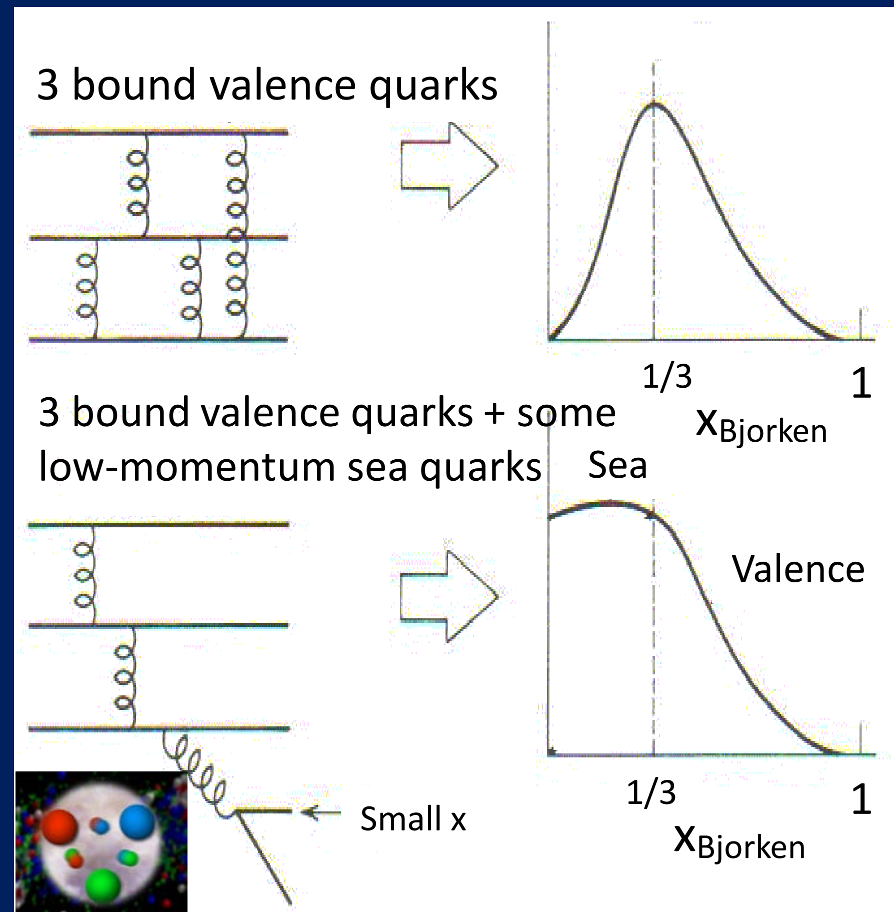
High-energy particle accelerators

- *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

Proton structure, momentum fraction, and "parton distribution functions"

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

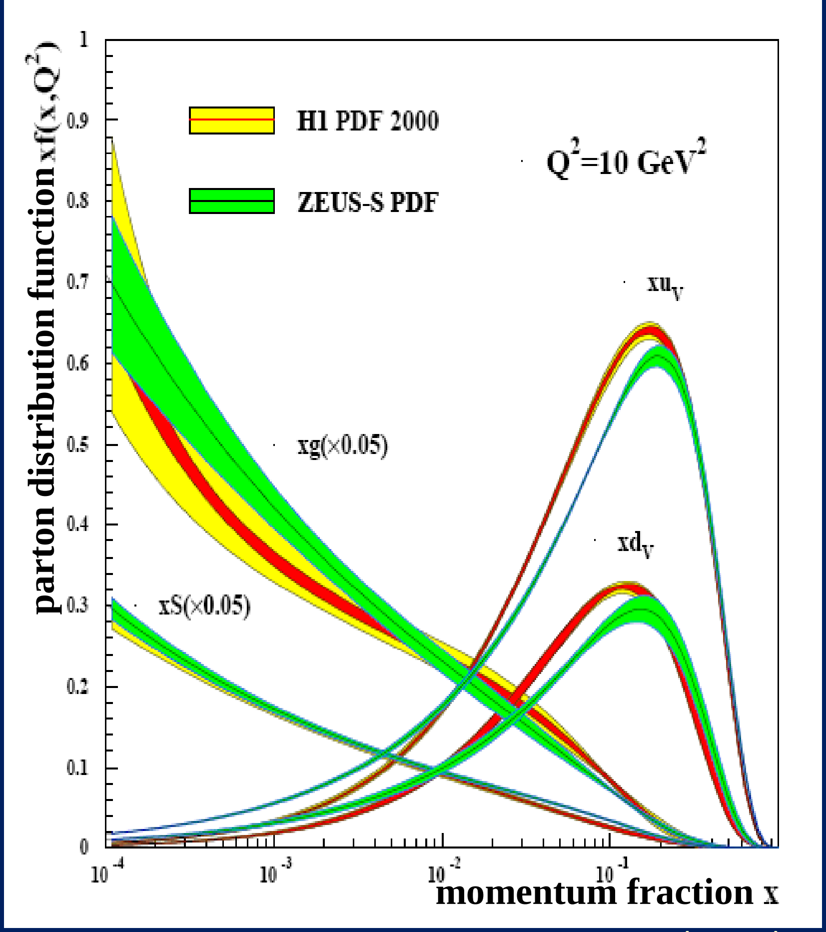




Halzen and Martin, "Quarks and Leptons", p. 201

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 20× in figure!)



PRD67, 012007 (2003)

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, gluon interactions 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*

Vast majority of past four decades focused on *1-dimensional* momentum structure! Since 1990s starting to consider other directions . . .

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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 at lower momentum fractions 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 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*

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

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.

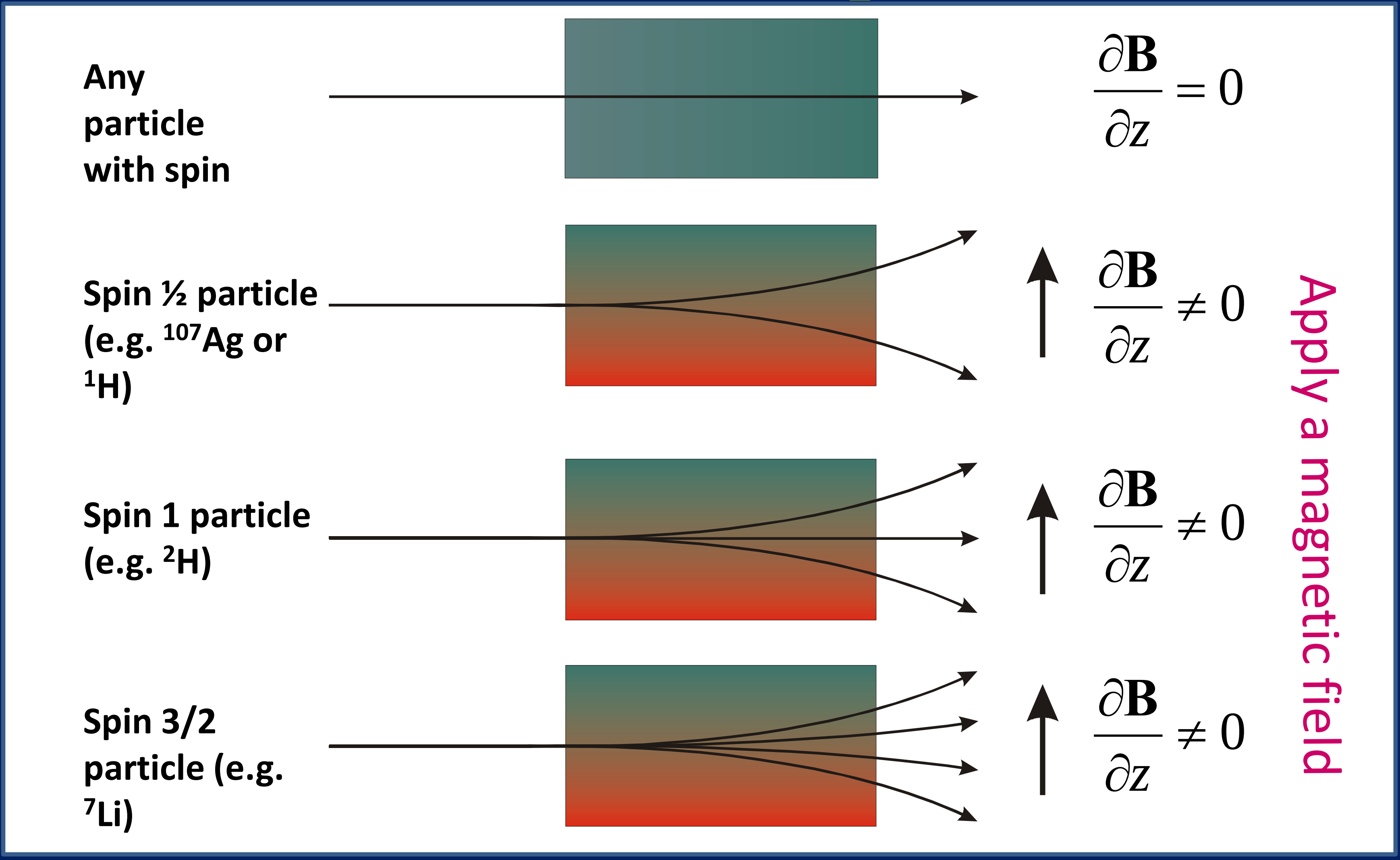
The units of angular momentum are the same as Planck's constant, $\hbar$, and can only have values that are integer : 0, 1, 2, 3, . . .
or half-integer: 1/2, 3/2, 5/2, . . .

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!

Stern-Gerlach experiment



$2s+1$ Energy Levels

My current research efforts

- 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

- Studies for light sensing and electronics for calorimeters of proposed large new experiment

- R&D for a novel neutron detector

U.S. DEPARTMENT OF ENERGY Office of Science

National Science Foundation

THE PHOENIX PROJECT · UNIVERSITY OF MICHIGAN

My experiments

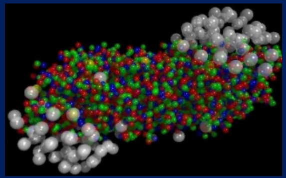
- Polarized proton-proton collisions to a variety of final states at the PHENIX experiment at Brookhaven National Lab (BNL) on Long Island, NY
  – Very flexible, multi-purpose experiment
  – "sPHENIX" is proposed follow-up experiment

- Quark-antiquark annihilation to muon pairs at the SeaQuest experiment at Fermilab outside Chicago
  – Dedicated measurement of simple final state—doesn't carry color! (Muons are like heavy electrons)

- POLARIS neutron detector R&D experiment

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!)



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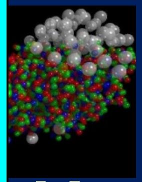
  – able

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



  – Collections of QCD bound states (nuclei, also available out of the box!)
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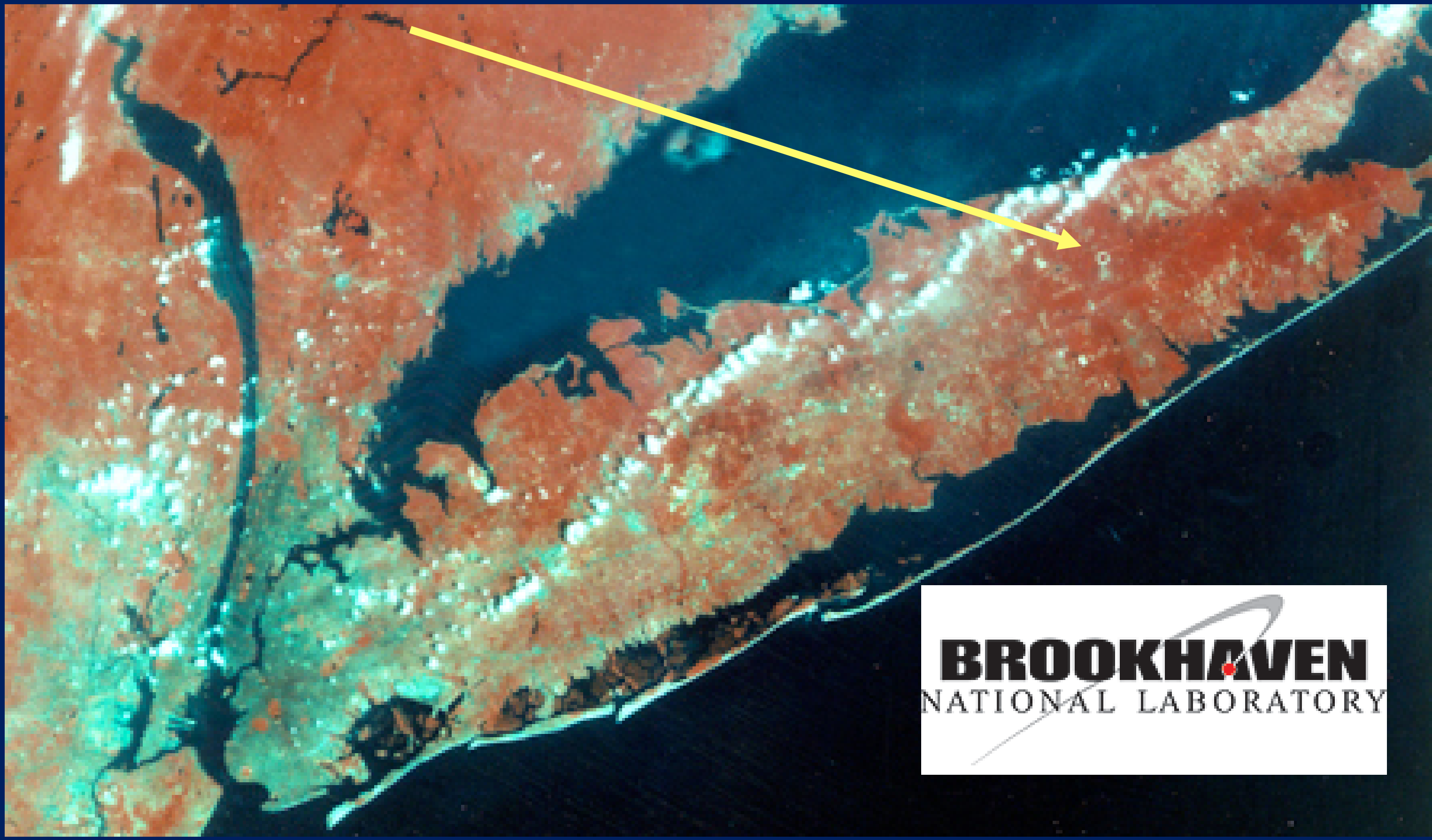
RHIC at Brookhaven National Laboratory

Long Island,

New York



RHIC at Brookhaven National Laboratory

Long Island,

New York

RHIC's experiments

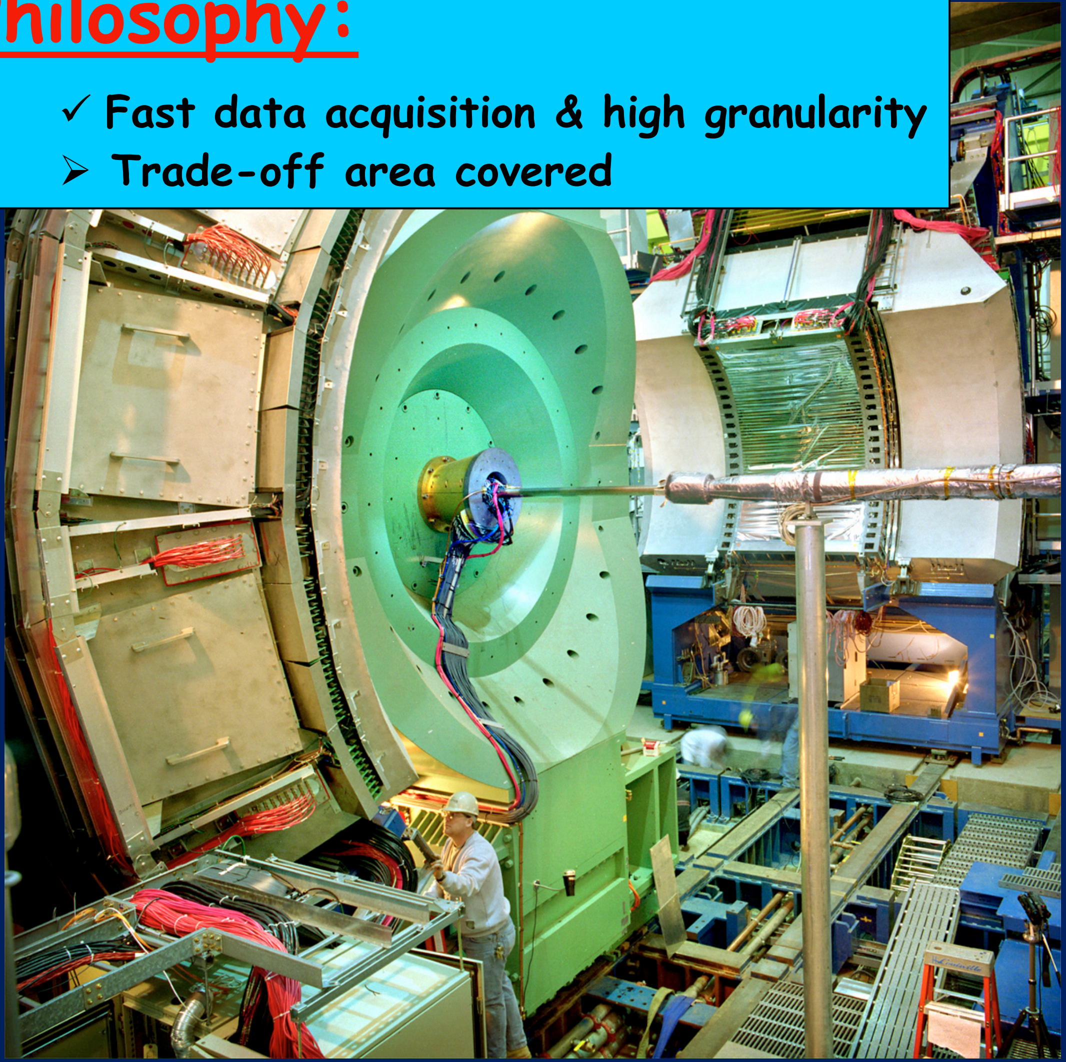
PHENIX

14 Countries; 74 Institutions; ~500 Participants

PHENIX Detector

Philosophy:

- ✓ Fast data acquisition & high granularity
- ➢ Trade-off area covered

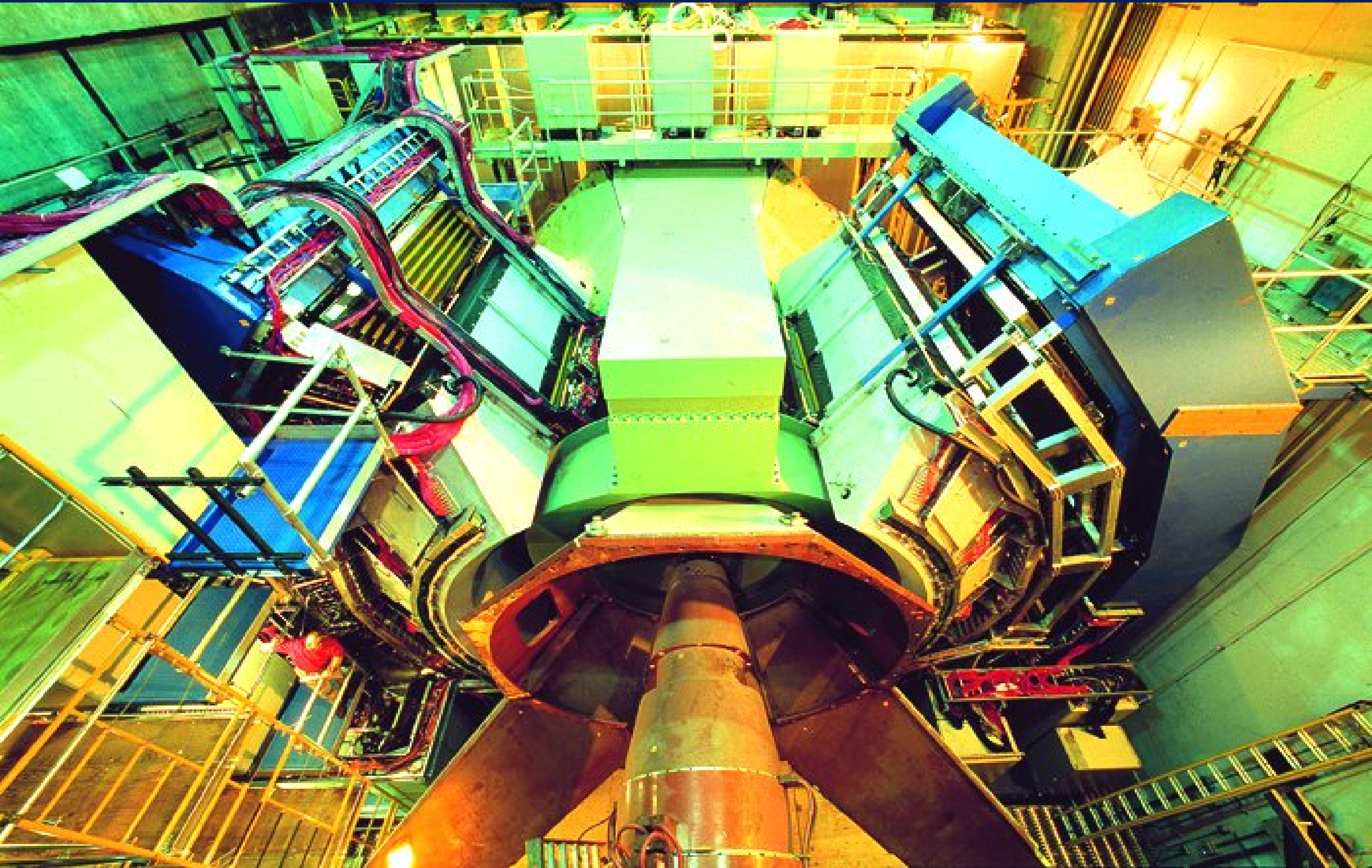


2 central arms
- Track charged particles and detect electromagnetic processes

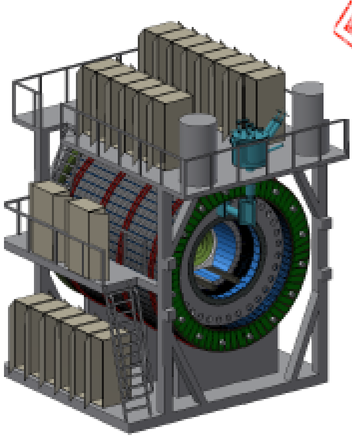
2 forward muon arms
- **Identify and track muons**

2 forward electromagnetic calorimeters

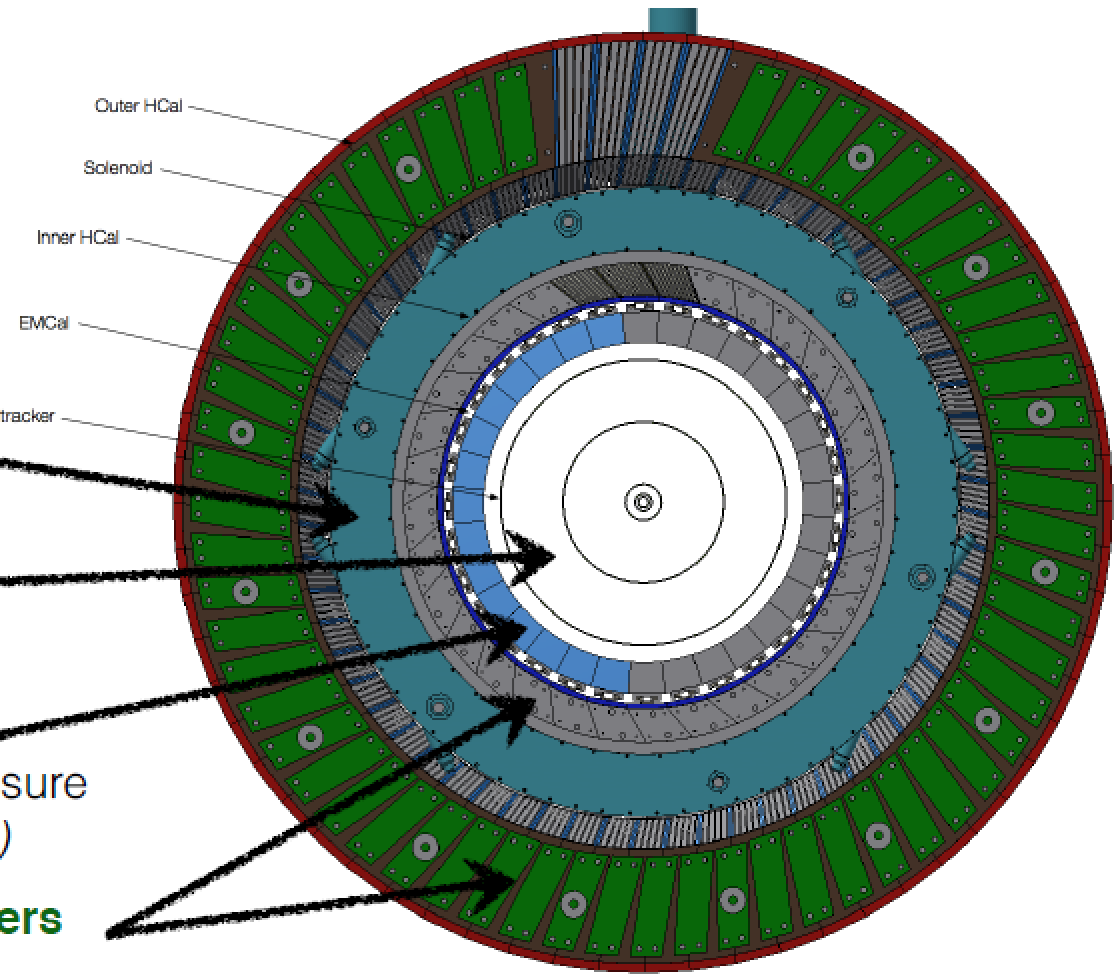
PHENIX Detector



Proposed sPHENIX detector

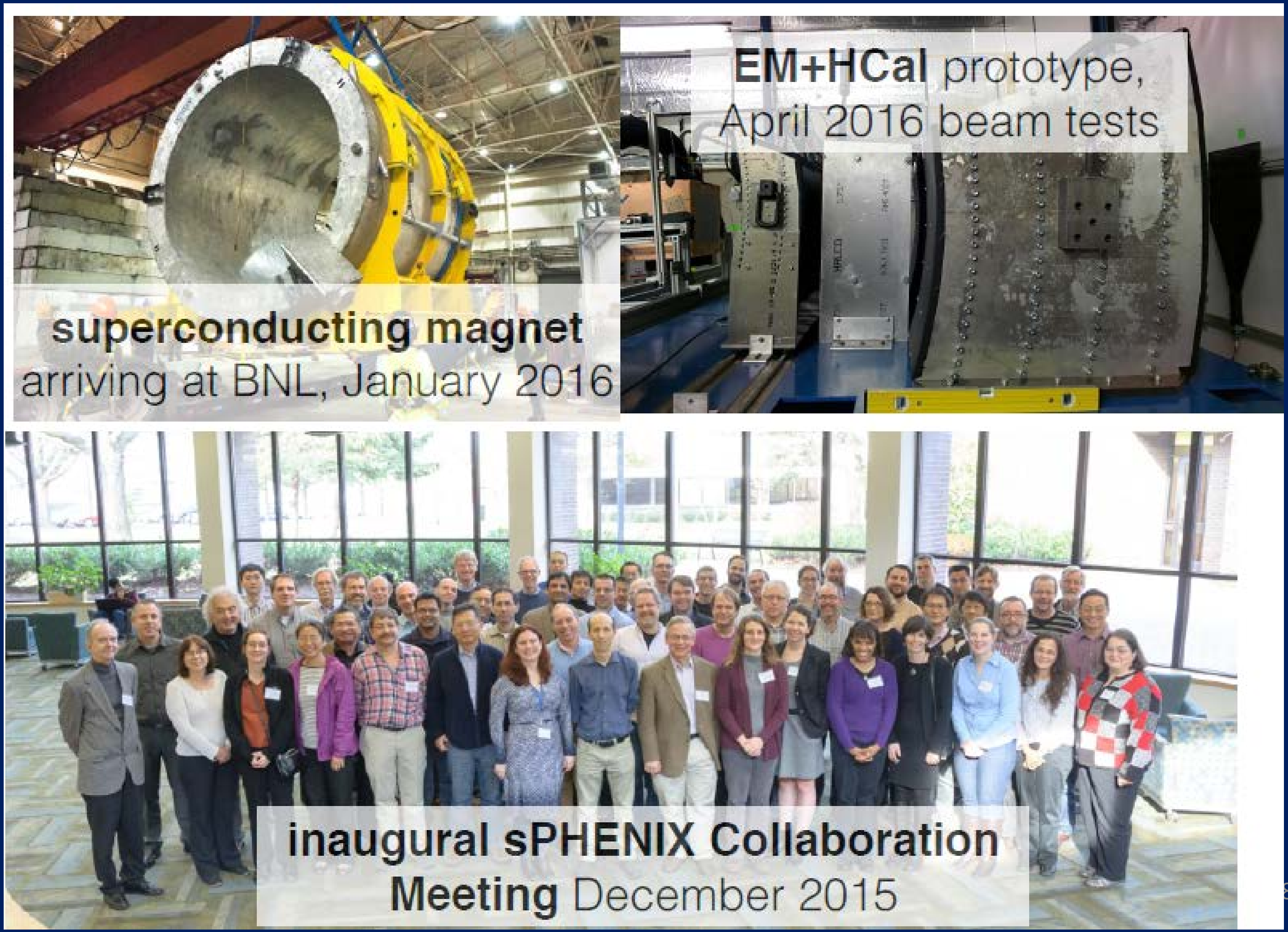


sPHENIX Detector design

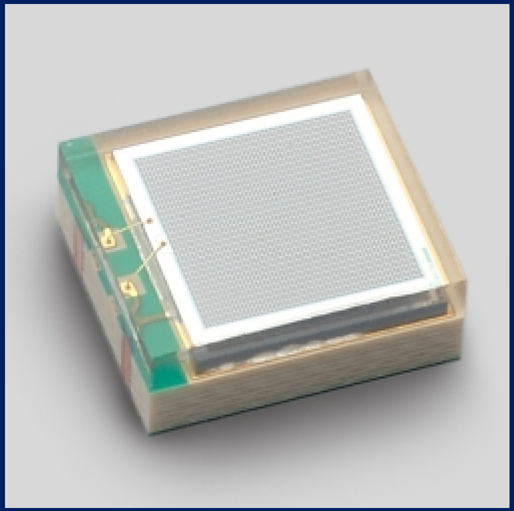


- 1.5 Tesla **magnet** from BaBar epxt.
- **vertex / tracker** (to measure *charged particles*)
- **electromagnetic calorimeter** (to measure *photons & electrons*)
- **hadronic calorimeters** (to measure *jets*)

Officially became new RHIC collaboration in 2015 – Efforts ramping up!



Silicon photomultipliers for sPHENIX



Silicon photomultipliers (SiPMs) are new single-photon sensor technology

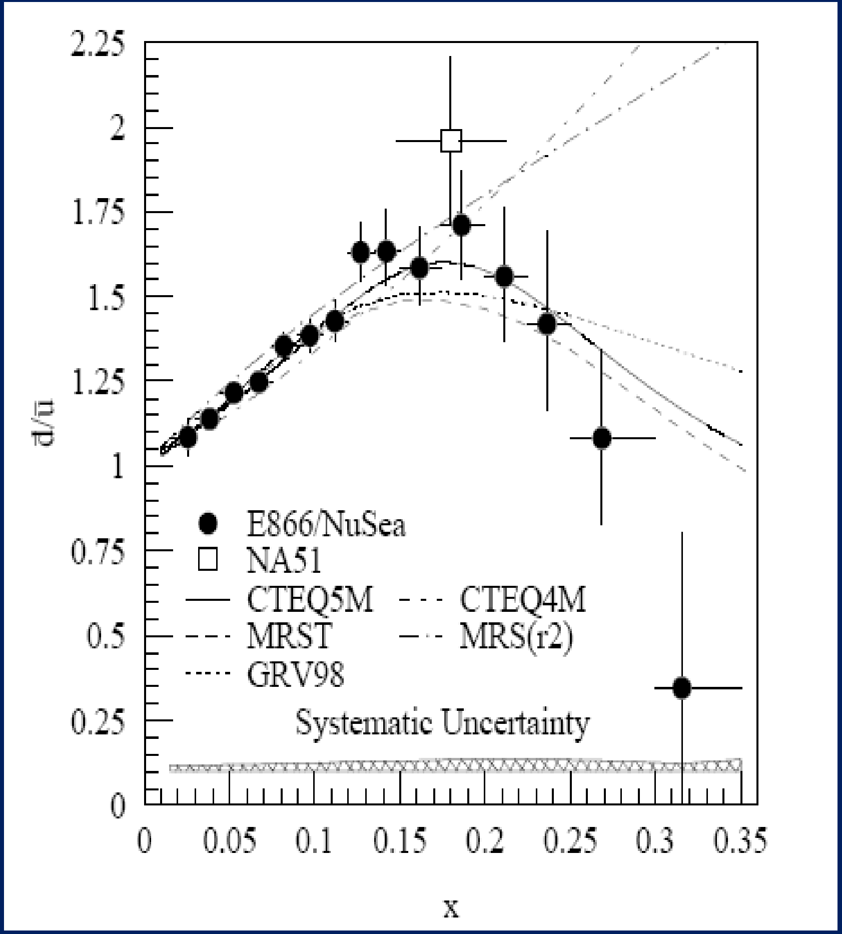
- Advantages compared to photomuliplier tubes (PMTs):
  - Insensitive to magnetic fields
  - Smaller → more flexible geometry
  - Lower operating voltage: <100 V instead of >1000 V
- Disadvantages:
  - Damaged in high-radiation environments
  - Temperature-dependent
- Will use SiPMs to collect light generated by electromagnetic and hadronic showers in the sPHENIX calorimeters

2001: A surprising discovery in the proton flavor structure

- Fermilab Experiment NuSea used proton-hydrogen and proton-deuterium collisions to probe nucleon structure via the Drell-Yan process

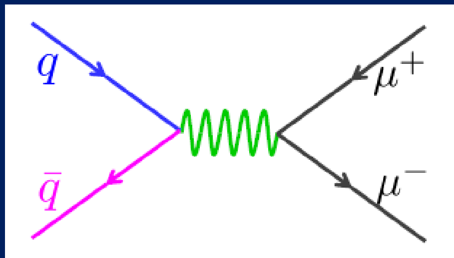
$$q + \overline{q} \rightarrow \mu^{+} + \mu^{-}$$

- Anti-up/anti-down asymmetry in the quark sea!
  - Previously expected to be ~constant at 1
  - Implies antiquarks not just generated by “perturbative” gluon splitting to quark-antiquark pairs

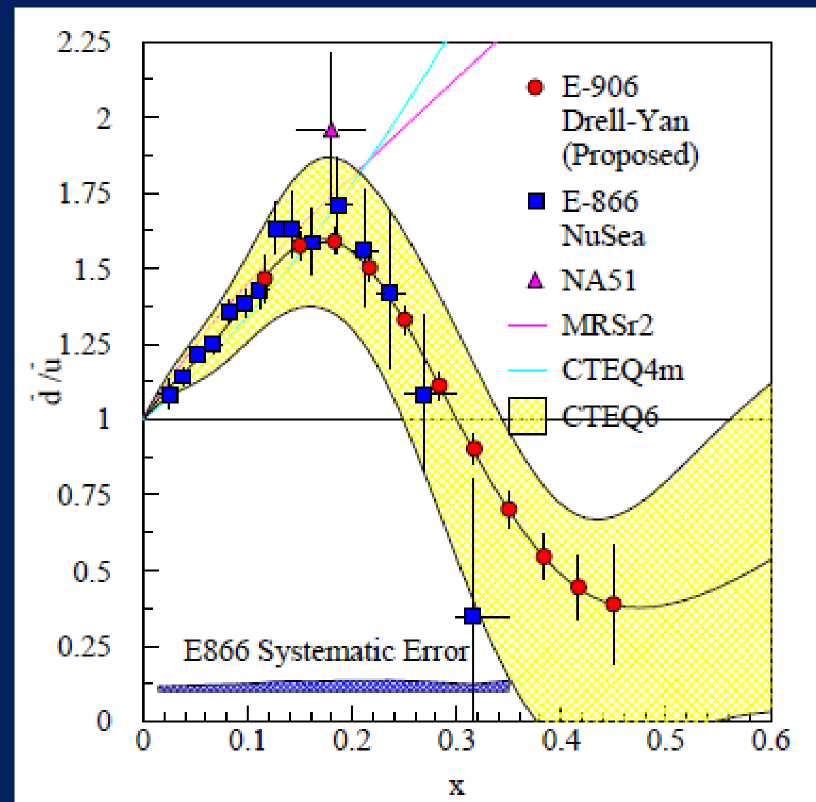


PRD64, 052002 (2001)

Fermilab SeaQuest: To understand this flavor structure better



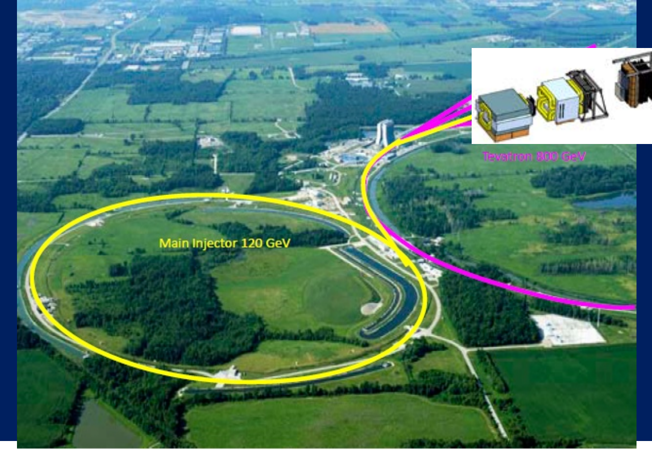
- Follow-up experiment to Fermilab NuSea with main goal of extending measurements to higher momentum fraction *x*
- 120 GeV proton beam from Fermilab Main Injector + proton, deuteron (proton+neutron), and nuclear targets (C, Fe, W)



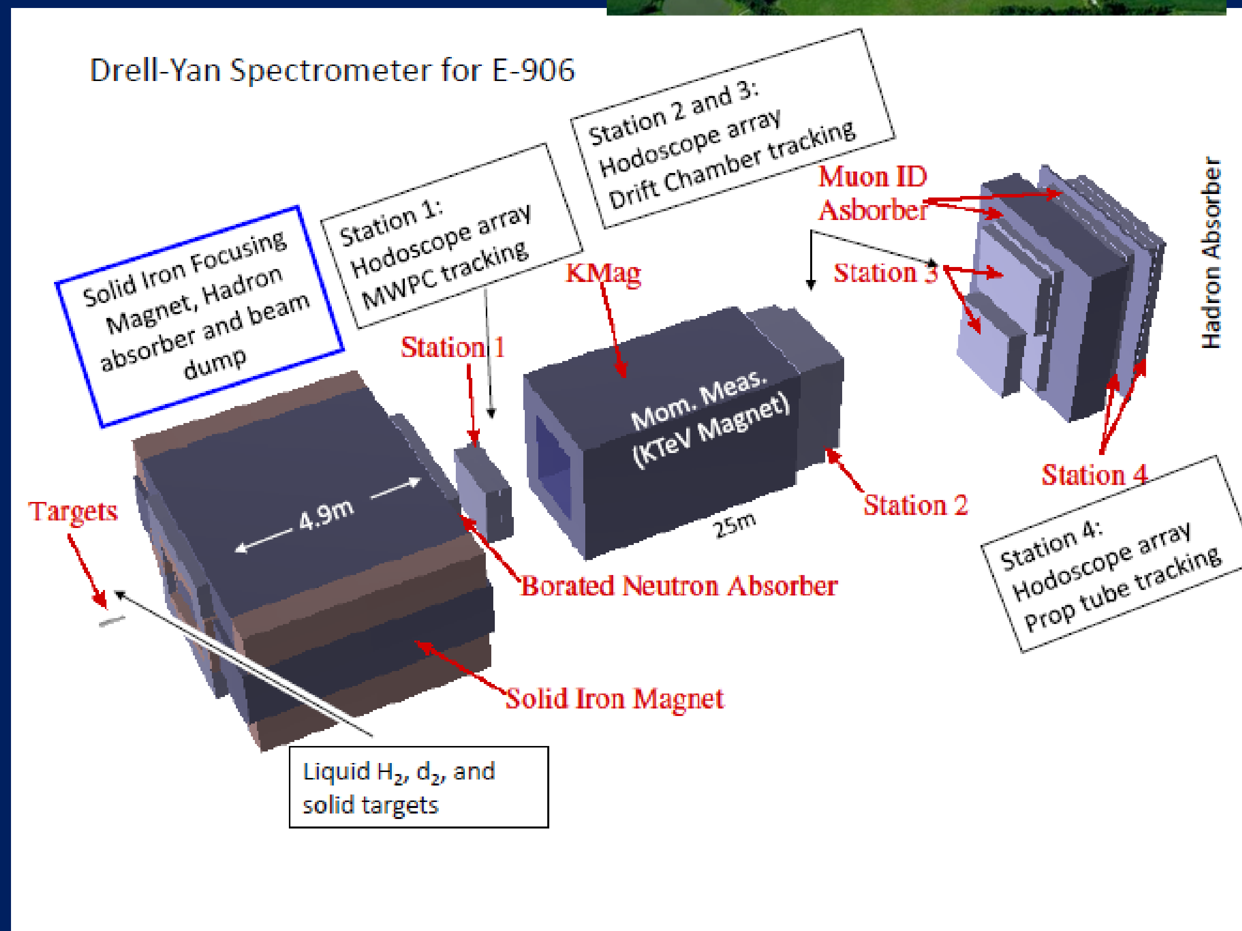
Fixed-target (SeaQuest) vs. collider (PHENIX/sPHENIX) experiments

- 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, $x_{Bjorken}$)

Fermilab SeaQuest



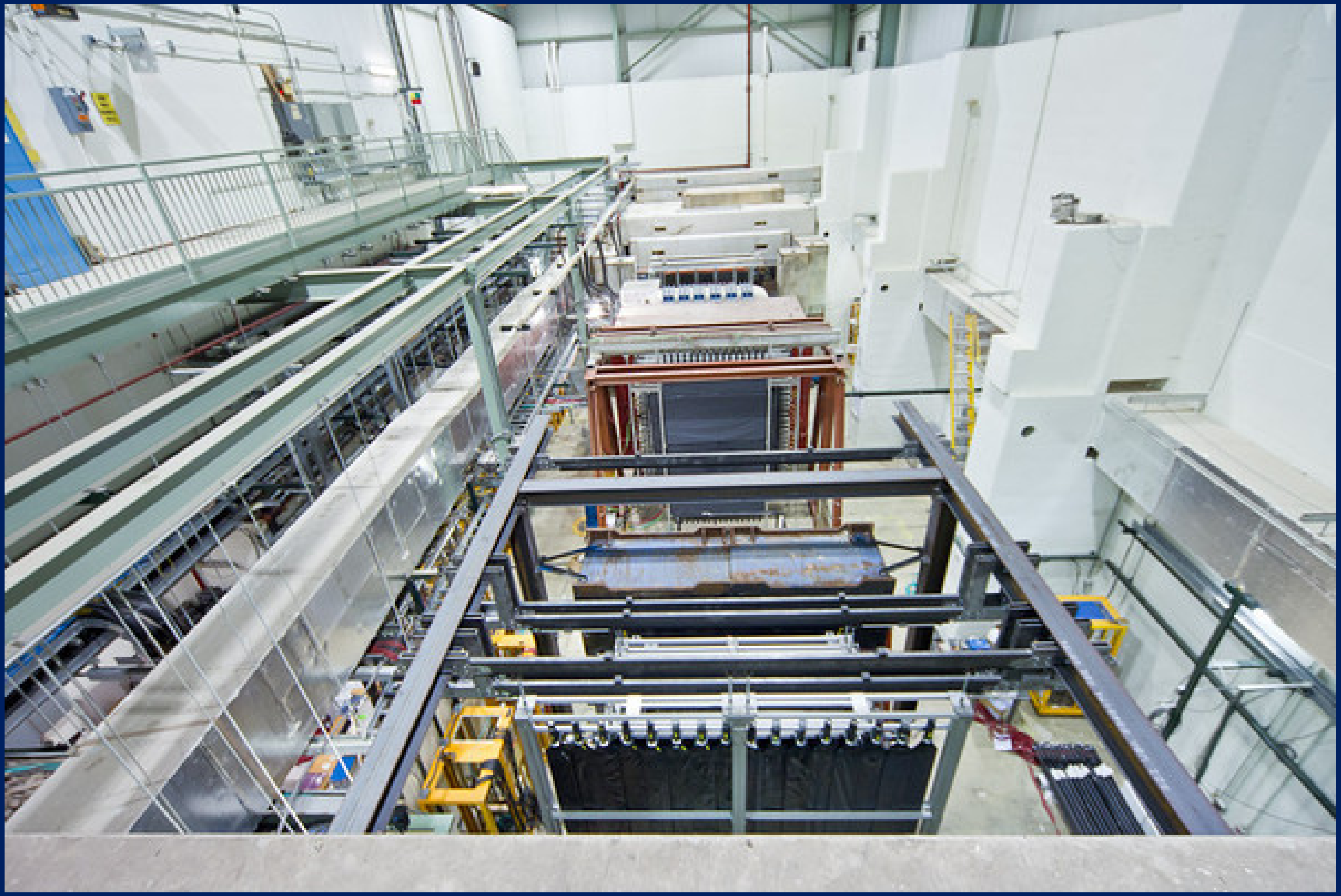
- Targets: Liquid hydrogen and deuterium (U-M responsibility!), and C, Fe, W nuclei
- Commissioned 2012, physics data-taking 2014-17
- ~65 participants from 14 institutions



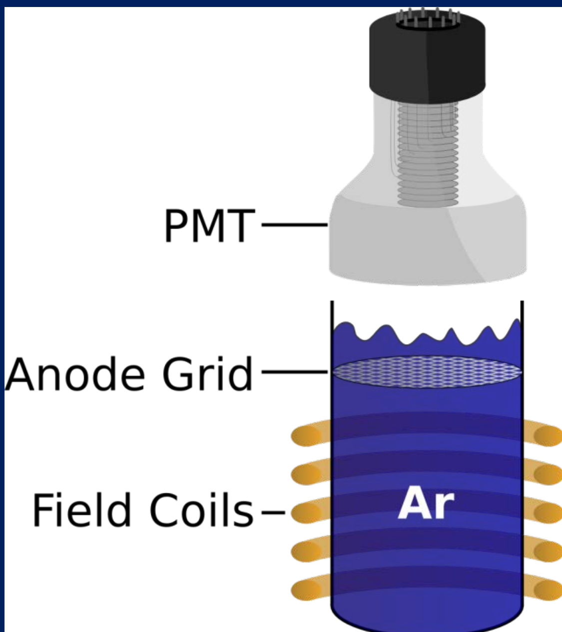
SeaQuest model: Reuse, recycle!

Station 4 tracking plane assembled from old proportional tubes scavenged from LANL "threat reduction" experiments!

View of SeaQuest experimental hall from downstream platform



POLARIS: A scintillating liquid argon time projection chamber for neutron detection

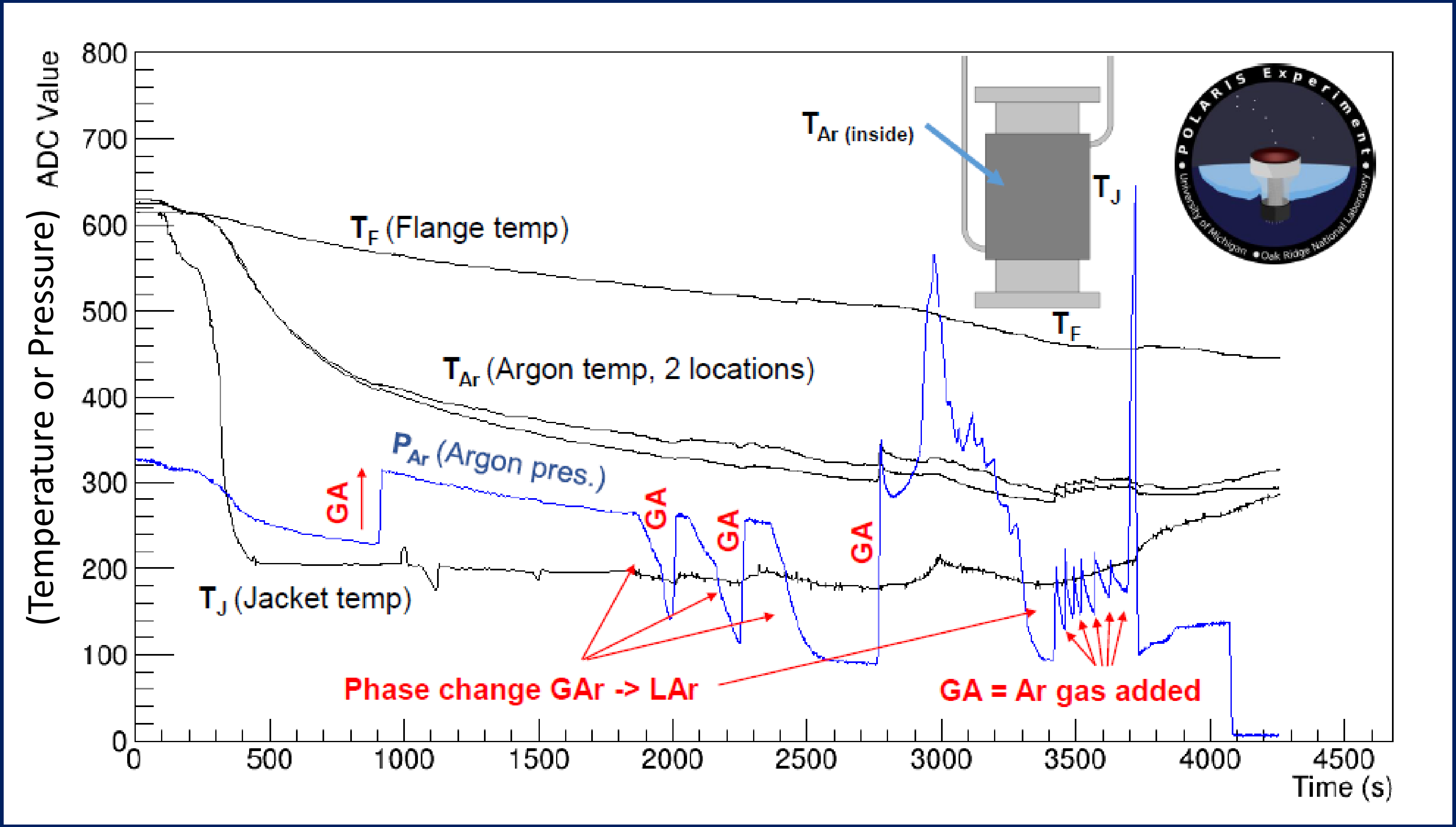


Liquid argon, boiling

- Adapting existing technology used by neutrino and dark matter communities to optimize for neutron detection
- Neutron strikes Ar nucleus, knocking off some electrons and exciting others
  - Recoil Ar creates additional ionization and excitation
- Excited electrons return to ground state, emitting scintillation light, collected by a photomultiplier tube
- Ionization electrons are drifted by an external electric field to an anode charge collection grid
- Amount of light plus charge collected gives neutron energy
- Time difference between light and charge collection in combination with known electric field gives position of neutron-Ar collision along field direction

- In collaboration with nuclear astrophysics group at Oak Ridge National Lab

Temperature and pressure as argon is liquefied



Undergraduate group members

- Meghan Tanner – sPHENIX silicon photomultiplier test stand setup, sPHENIX simulations
- Puyang Ma – SeaQuest statistical uncertainty checks, background simulations
- Emily Camras – reconstruction of simulated jets in PHENIX; POLARIS neutron detector
- Nick Kamp – POLARIS neutron detector
- Ezra Lesser – POLARIS neutron detector

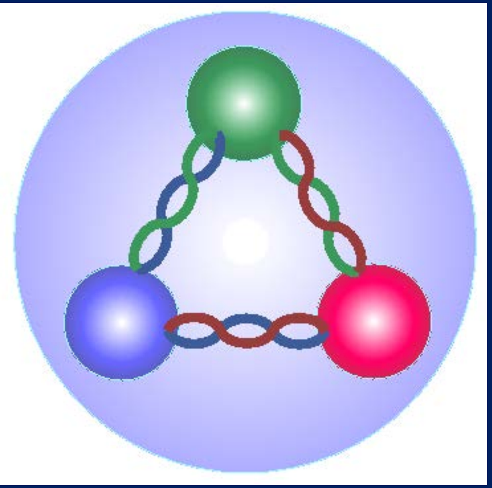
Summary

- We still have a ways to go from the quarks and gluons of the theory of the strong force to full descriptions of the protons and nuclei of the world around us!
- Since the late 1990s 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
- Different experiments at BNL, Fermilab, and other world facilities are working to unravel the mysteries of the proton . . .
  – And with new detectors, we'll be able to learn even more!

Extra

Nucleon structure: The early years

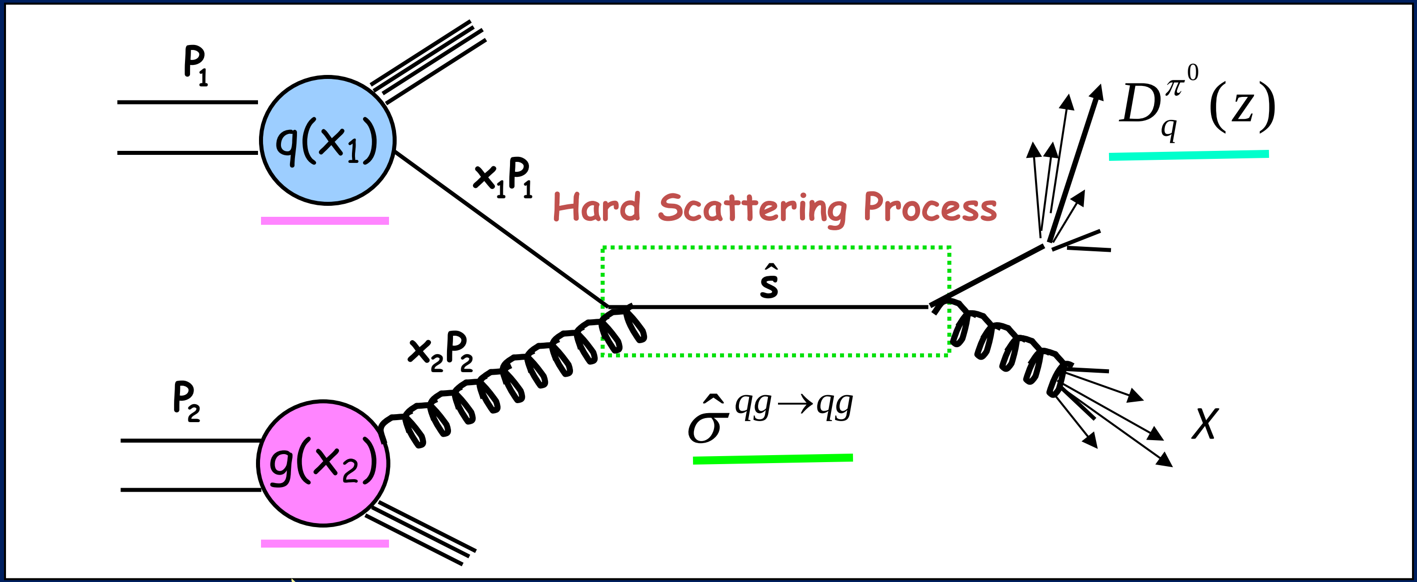
- 1932: Estermann and Stern measure proton anomalous magnetic moment → proton not a pointlike particle!
- 1960s: Quark structure of the nucleon
  - SLAC inelastic electron-nucleon scattering experiments by Friedman, Kendall, Taylor → Nobel Prize
  - Theoretical development by Gell-Mann → Nobel Prize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



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 (no electromagnetic charge)

Predictive power of perturbative QCD



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

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)

$\Big\}$ **Universal non-perturbative factors**

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)!
- Long-distance (i.e. non-perturbative) functions need to be *universal* in order to be portable across calculations for many processes (and to be meaningful in describing hadron structure!)

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)!
-

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***

PHENIX detector

Philosophy:

High rate capability to measure rare probes, limited acceptance.

- 2 central spectrometers
  - Track charged particles and detect electromagnetic processes

$|\eta| < 0.35$

$90^\circ + 90^\circ$ azimuth

- 2 forward muon spectrometers
  - Identify and track muons

$1.2 < |\eta| < 2.4$

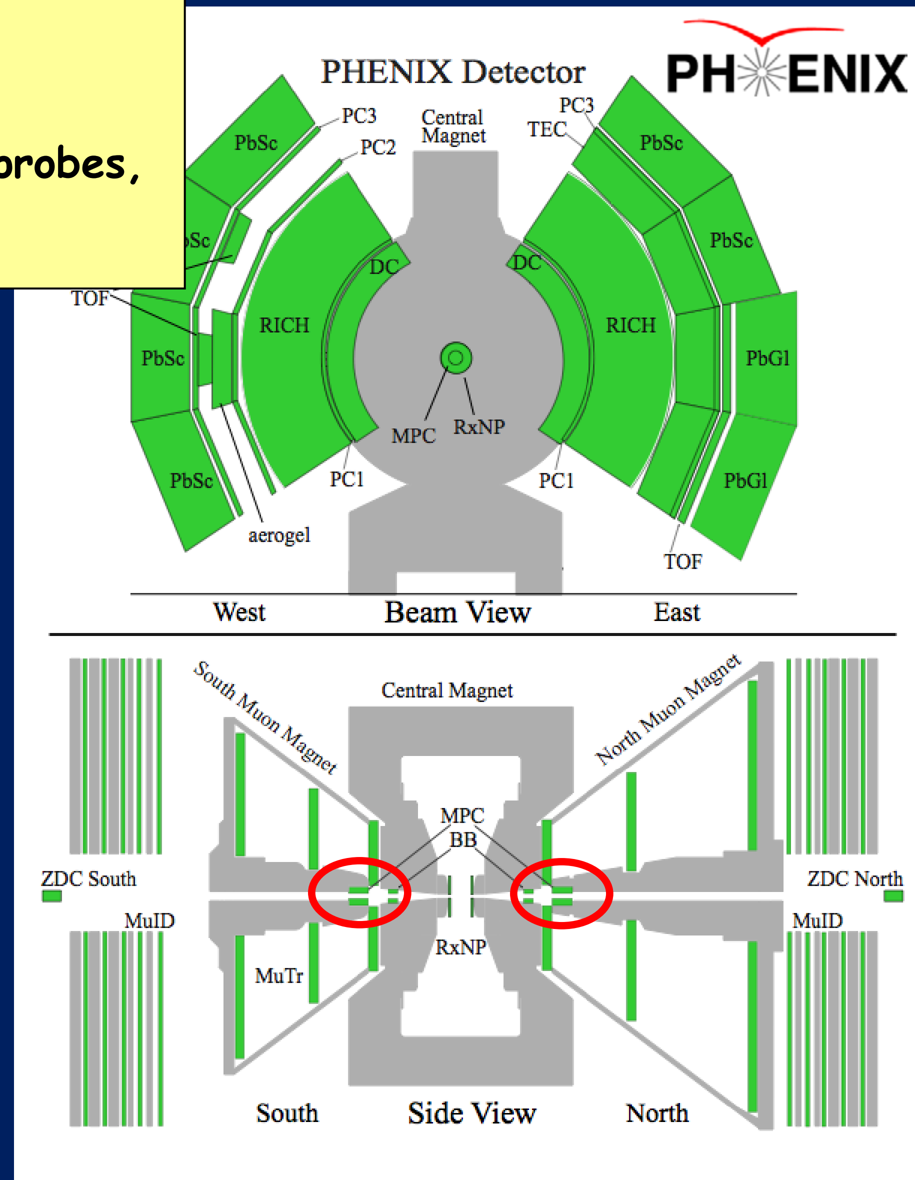
2π azimuth

- 2 forward calorimeters (as of 2007)
  - Measure forward pions, etas

$3.1 < |\eta| < 3.7$

2π azimuth

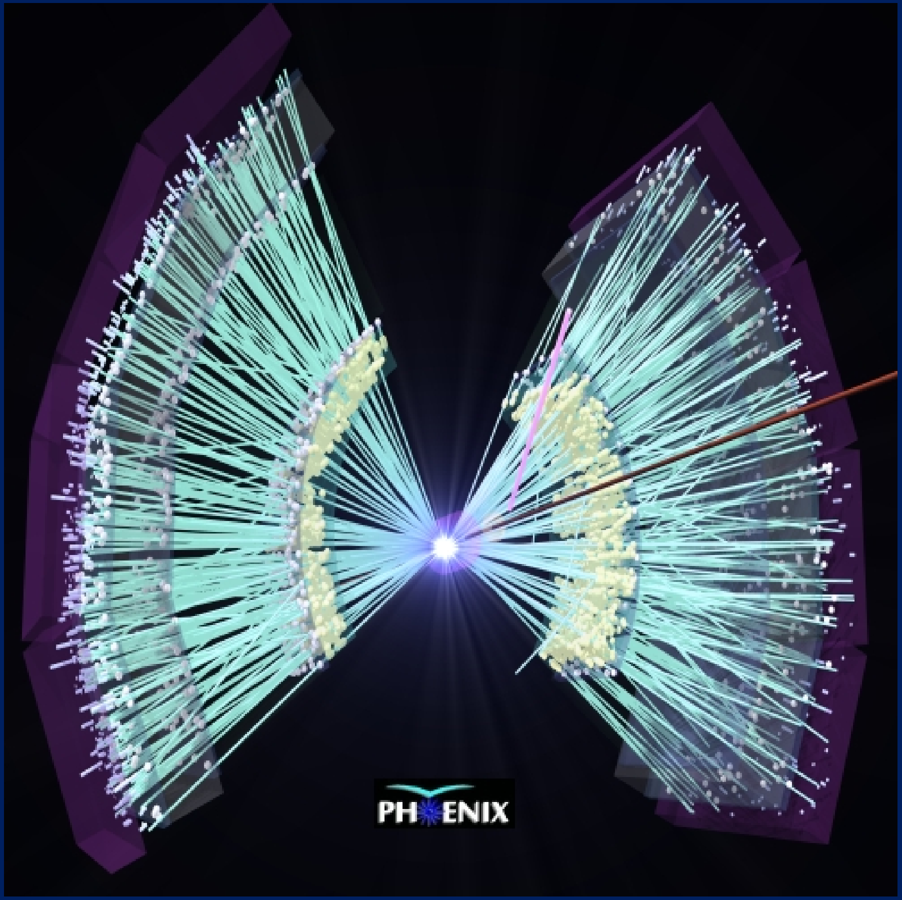
- Relative Luminosity
  - Beam-Beam Counter (BBC)
  - Zero-Degree Calorimeter (ZDC)



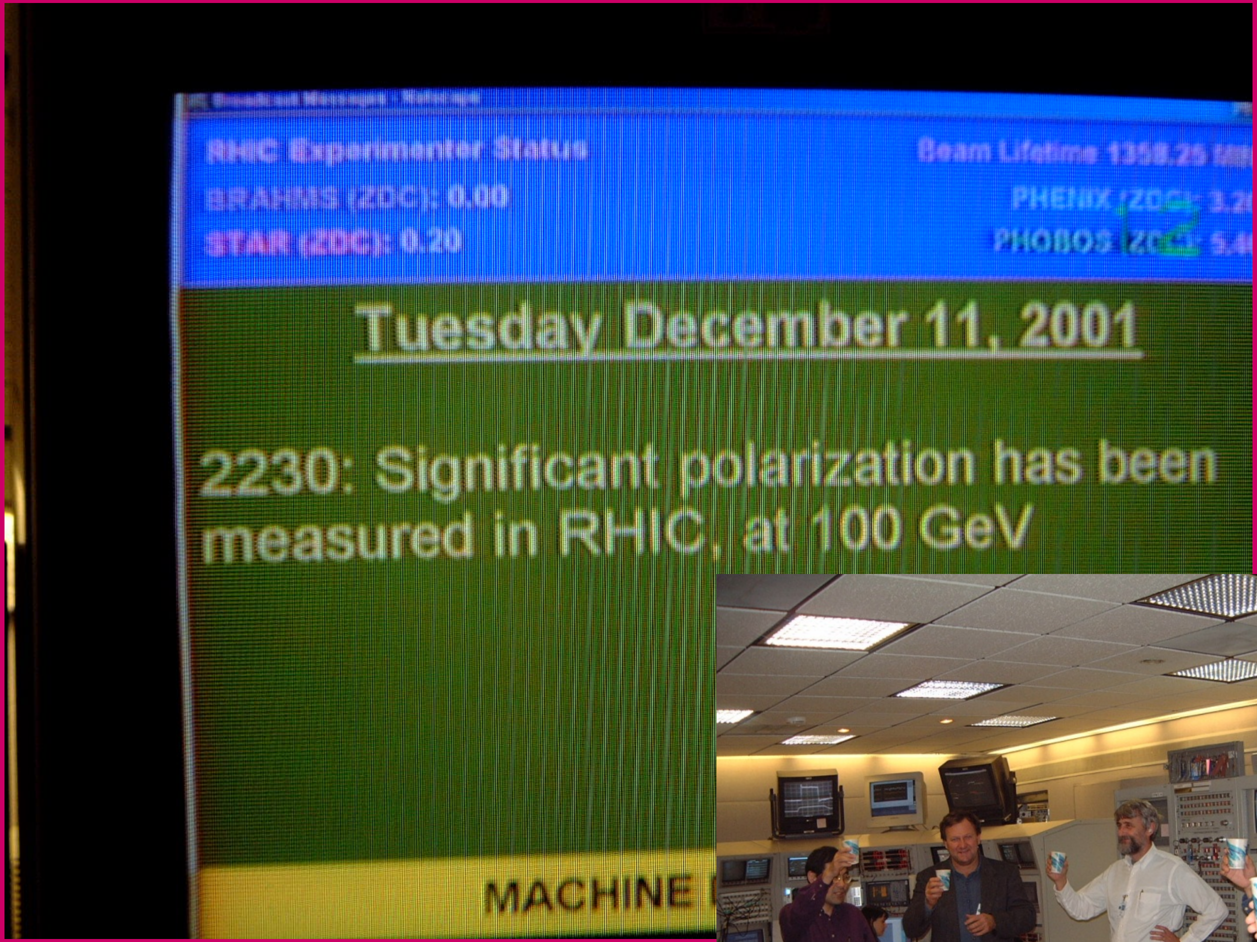
Gold-Gold Collision in PHENIX Central Arms

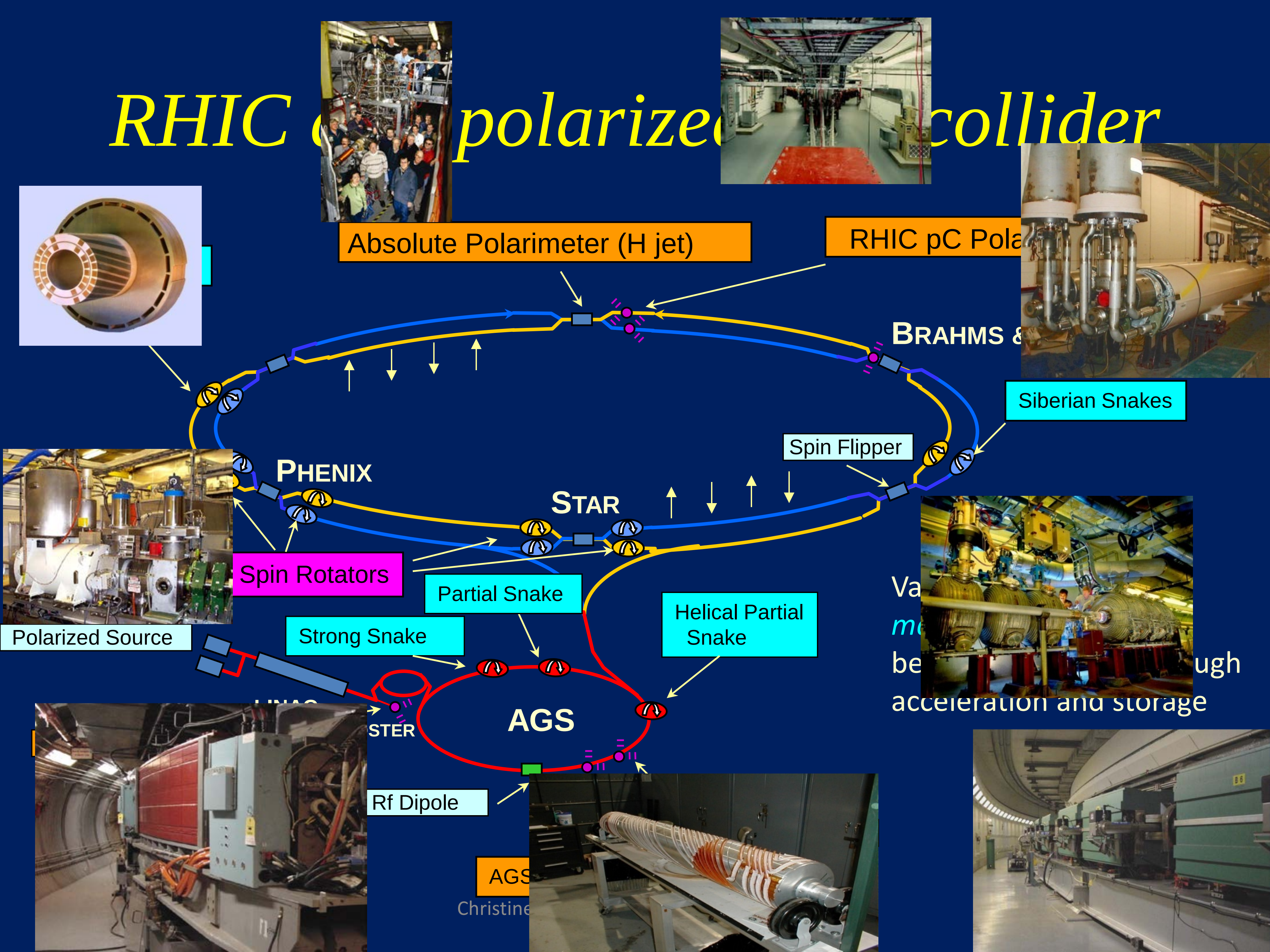
Thousands of tracks!

Proton-proton collisions only produce ~5-10 tracks at the energies I study



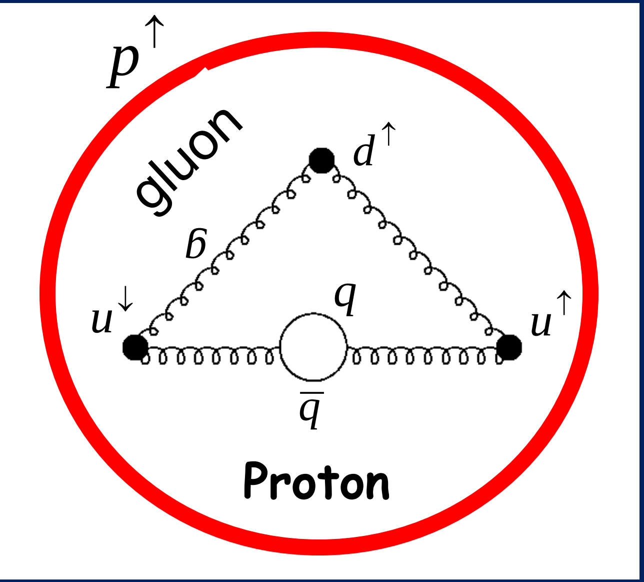
*First and only **polarized** proton collider*





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
STER
AGS
Rf Dipole
AGS
Christine

The Proton Spin Crisis



Say you have a proton with total spin +1/2 along some axis. You'd expect it to contain two quarks with spin +1/2 and one with spin -1/2.
1/2 + 1/2 - 1/2 = +1/2

Surprising data from late 1980s!

1987: Only 12% +- 16% of proton's spin carried by quarks' spins!

The Proton Spin Crisis begins!!

Quark Spin

Gluon Spin

Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Orbital Angular Momentum

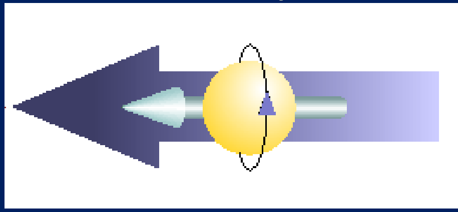
The rest now expected to be from gluon spin and orbital angular momentum of quarks and gluons, but this hasn't been easy to measure!

Polarized Parton Distribution Functions

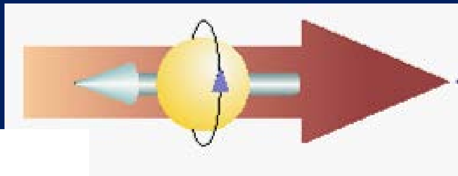
- Describe spin structure in terms of *polarized* parton distribution functions
- Helicity distributions—*difference* in probability of scattering off of a quark or gluon with *same vs. opposite helicity* of proton

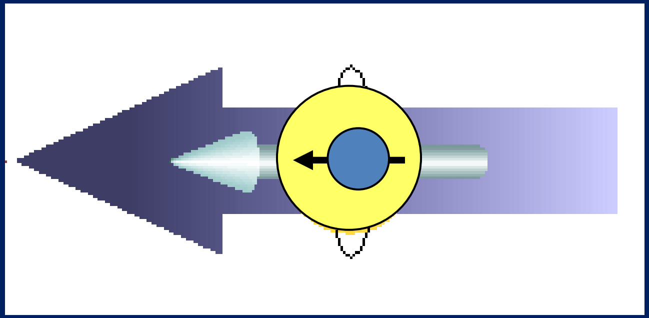
Helicity: Projection of spin vector onto momentum vector for particles polarized longitudinally, i.e. parallel to direction of motion.
Either positive or negative.

Positive helicity

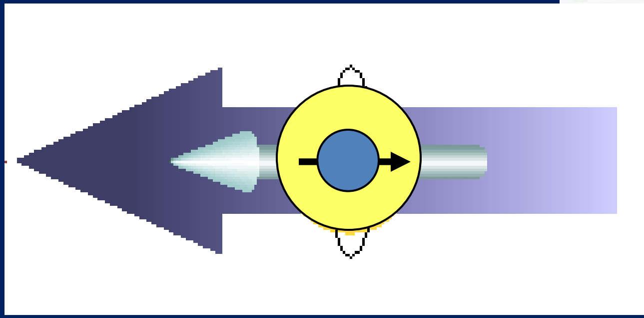


Negative helicity





vs.

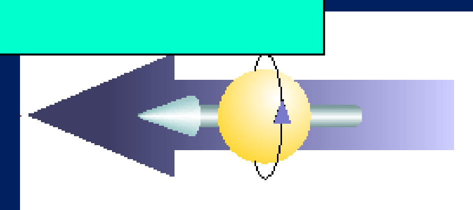


Polarized Parton Distribution Functions

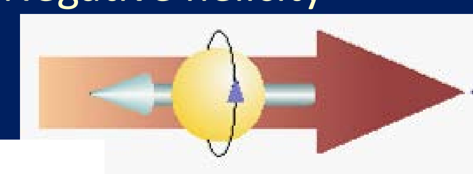
- Describe spin structure in terms of *polarized* parton distribution functions

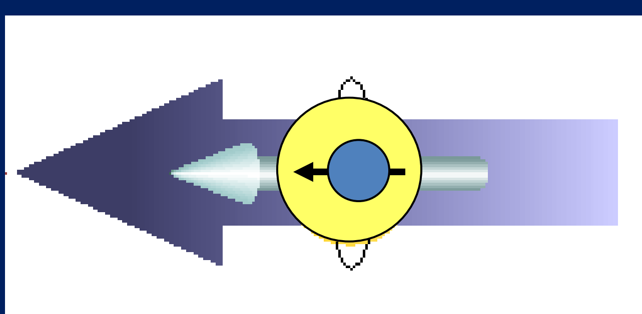
To study the *spin* structure of the proton:
Do inelastic scattering with *polarized* protons!
(spin directions all aligned)

Helicity: Projection of spin vector onto momentum vector for particles polarized longitudinally, i.e. parallel to direction of motion.
Either positive or negative.

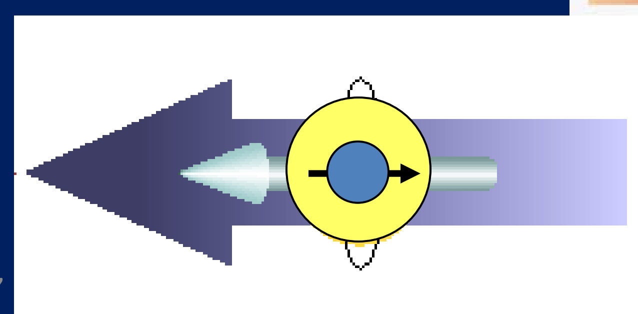


Negative helicity



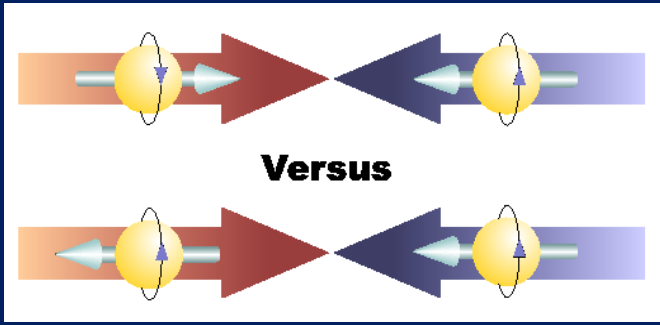


vs.



How Can We Investigate the Proton's Spin at RHIC?

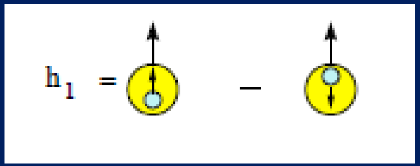
$$Asymmetry \propto \frac{B-C}{B+C}$$



- Collide polarized protons in different configurations and see what we observe in our detector
- Most often examining *asymmetries*
  - *e.g*. difference in the number of a certain particle produced when the beams have the same vs. opposite polarization
  - Same number produced gives asymmetry = 0.
  - All from one configuration and none from the other gives +1 or -1.
- Knowing what processes involving quarks and gluons led to production of the observed particle gives us a handle on the quarks' and gluons' contribution to the spin.

Spin-momentum correlations and the proton as a QCD "laboratory"

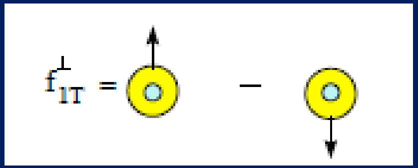
"Transversity" pdf:



Correlates *proton transverse spin* and *quark transverse spin*

S_p-S_q coupling

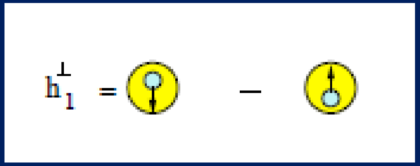
"Sivers" pdf:



Correlates *proton transverse spin* and *quark transverse momentum*

S_p-L_q coupling

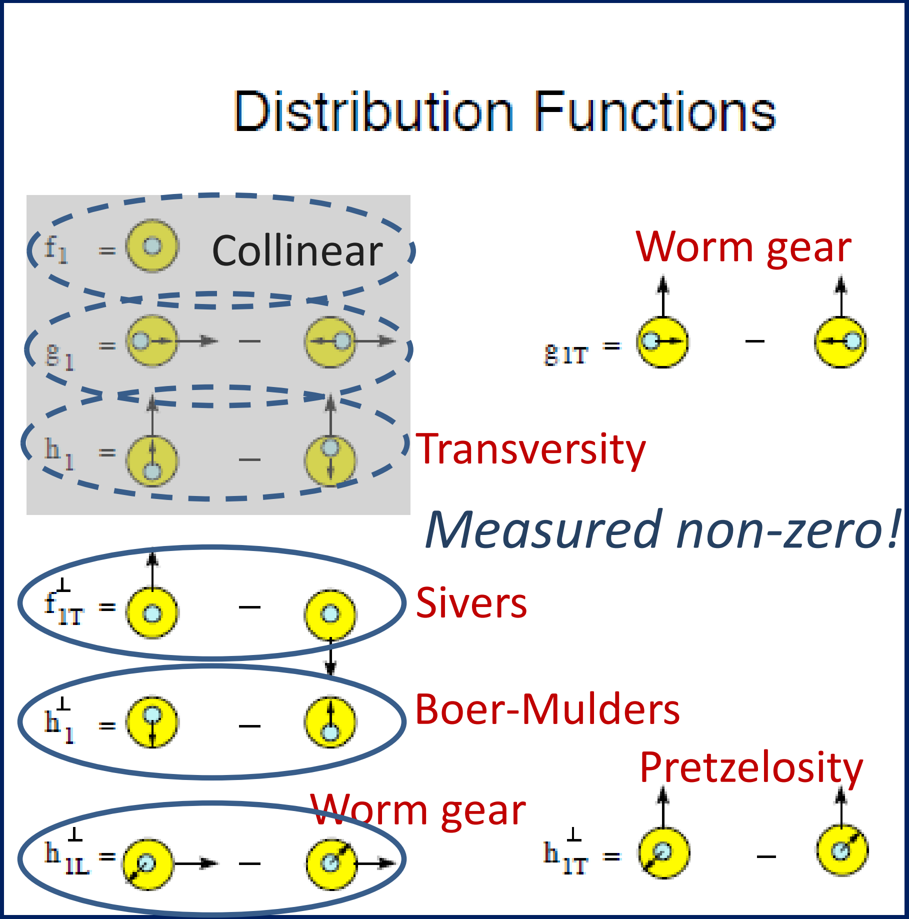
"Boer-Mulders" pdf:



Correlates *quark transverse spin* and *quark transverse momentum*

S_q-L_q coupling

Spin-momentum correlations in proton! A recent and rapidly developing area of QCD research



$S \cdot (p_1 \times p_2)$

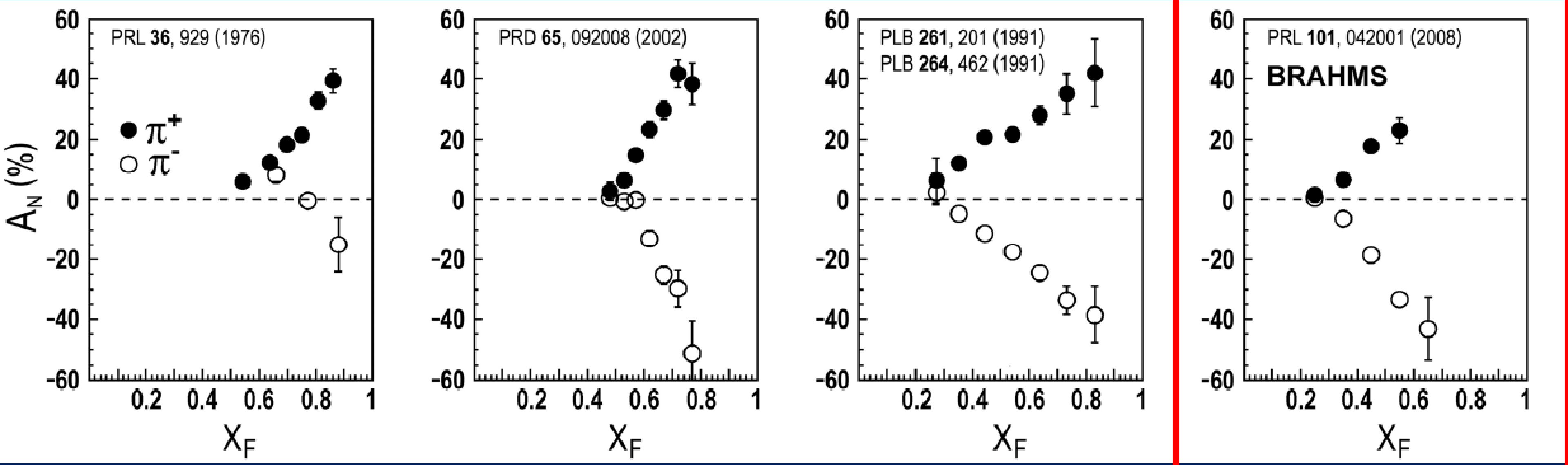
Transverse single-spin asymmetries in p+p collisions: From low to high energies!

ANL
√s=4.9 GeV

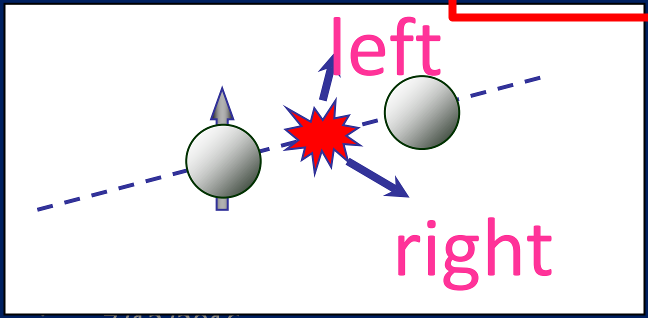
BNL
√s=6.6 GeV

FNAL
√s=19.4 GeV

RHIC
√s=62.4 GeV



$$x_F = 2\,p_{long} / \sqrt{s}$$
$$= x_1 - x_2$$



Transverse single-spin asymmetries in p+p collisions: From low to high energies!

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$\sqrt{s}$=4.9 GeV

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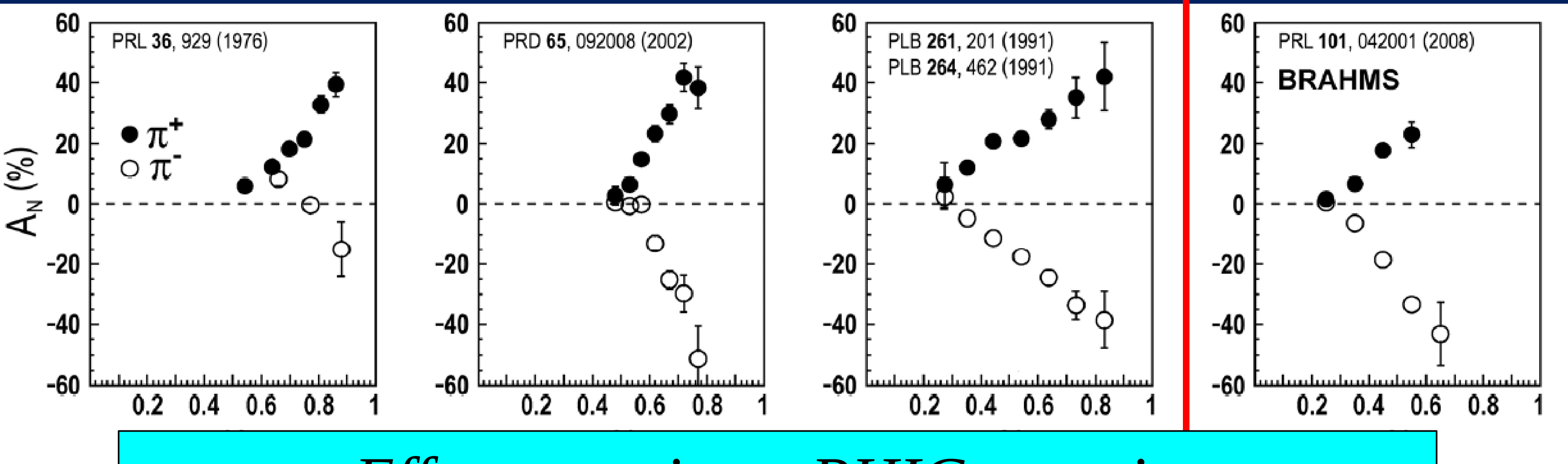
$\sqrt{s}$=6.6 GeV

FNAL
$\sqrt{s}$=19.4 GeV

RHIC
$\sqrt{s}$=62.4 GeV

BRAHMS

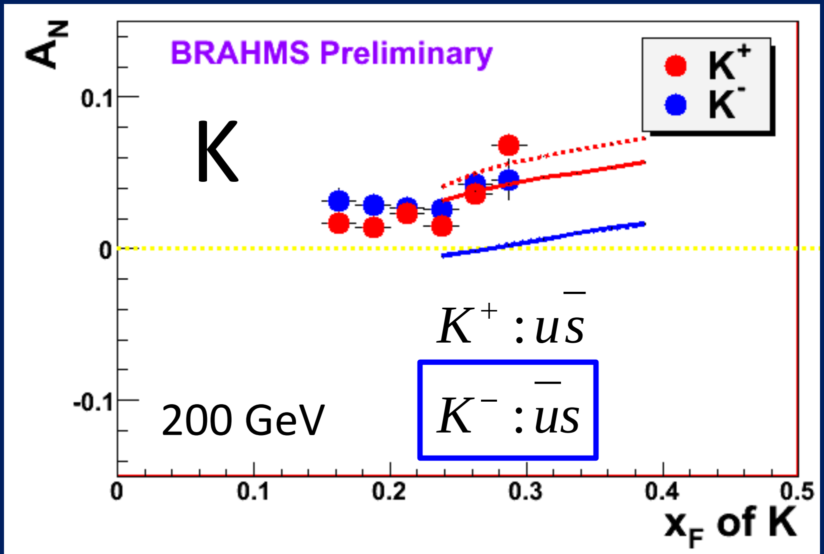


x_F

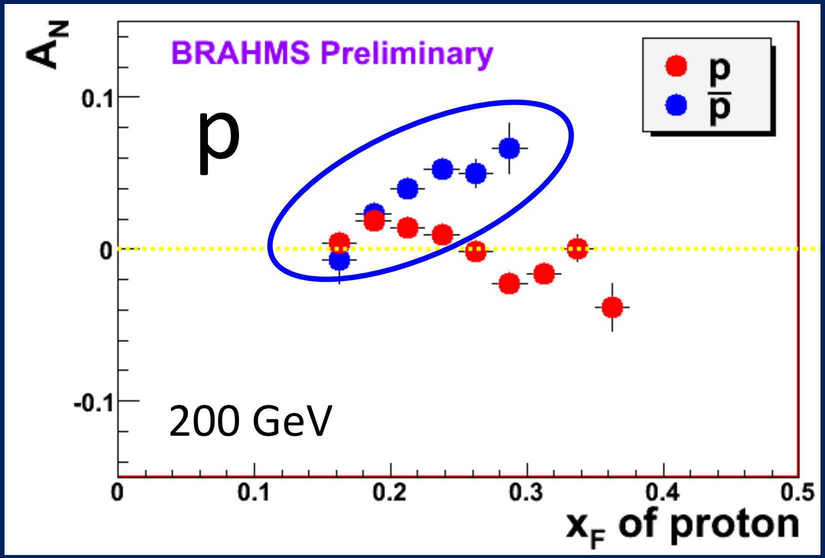
Effects persist to RHIC energies
*→ Can probe this striking spin-momentum correlation in a **calculable regime** and extract physics by comparing experiment to theory!*

High-x_F asymmetries, but not valence quarks??

$$x_F = 2p_{long}/\sqrt{s} = x_1 - x_2$$



Negative kaons same as positive??

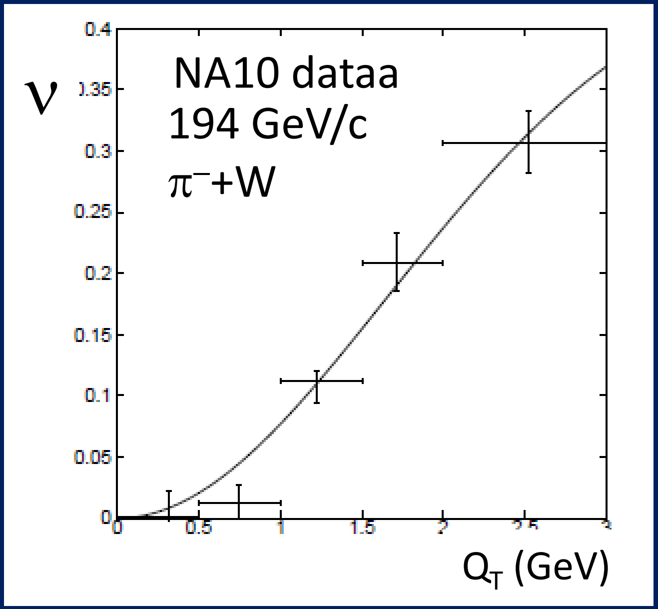


Large antiproton asymmetry?!

Pattern of pion species asymmetries in the forward direction
→ valence quark effect.
But this conclusion confounded by kaon and antiproton asymmetries from RHIC!
Lots of interesting effects to be explored!

My own physics focus on SeaQuest: Azimuthal dependence of unpolarized Drell-Yan cross section

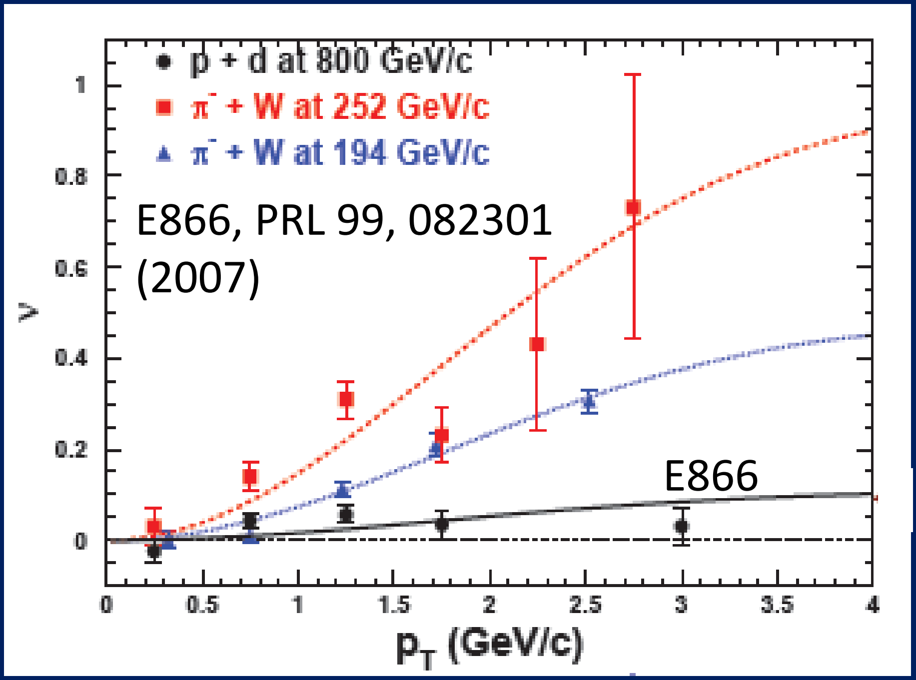
$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta + \frac{\nu}{2} \sin^2\theta \cos 2\phi$$



D. Boer, PRD60, 014012 (1999)

- $\cos 2\phi$ term sensitive to *correlations between quark transverse spin and quark transverse momentum*!
- Large $\cos 2\phi$ dependence seen in pion-induced Drell-Yan

What about proton-induced Drell-Yan?



Boer - Mulders function $h_1^{\perp}$

$\nu(\pi^- W \rightarrow \mu^+ \mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \rightarrow \mu^+ \mu^- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

- Significantly reduced cos2ϕ dependence in proton-induced Drell-Yan observed by E866
- Suggests sea quark transverse spin-momentum correlations small?
- Will be interesting to measure for higher-*x* sea quarks in SeaQuest!