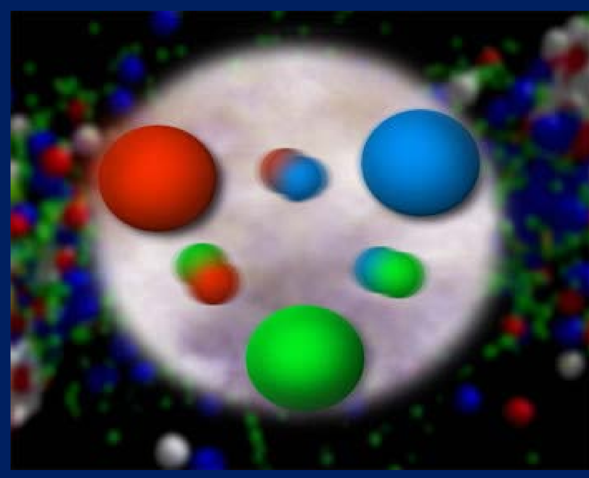
Peering Into the Proton: Proton Substructure and Internal Dynamics

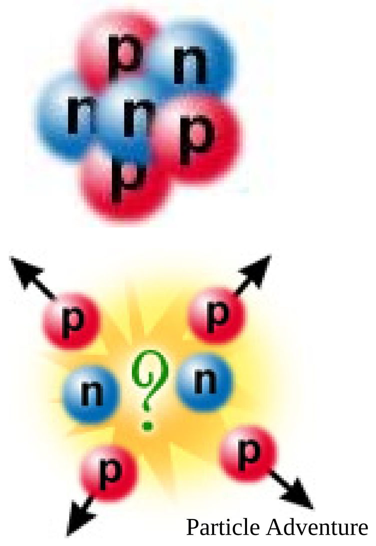
Christine A. Aidala

Department of Physics

University of Michigan



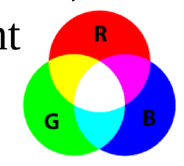
The Strong Force



Particle Adventure

Four known forces in nature
- Gravity
- Electromagnetism
- Weak force
- Strong force

Atomic nucleus stays together because **strong force** overcomes electromagnetic repulsion of protons
- Strong force "charge": *color charge*
- *Three* charges make a neutral particle, analogous to red, green, and blue light producing "neutral" white light



- Attraction of protons and neutrons actually due to analog of van der Waals interactions between electrically neutral molecules or atoms – protons and neutrons are color neutral
- Color-charged constituents of protons and neutrons: *quarks*
- Quarks also interact via the weak and electromagnetic forces – carry *fractional* electric charge

The Gluon: Mediator of the Strong Force

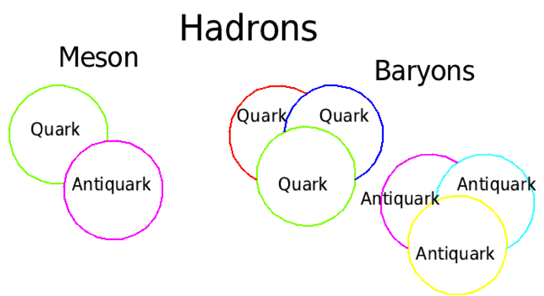
Strong force mediated by *gluon* exchange
- Analogous to role played by photon in electromagnetism
- Massless, like photon
- Carries color charge itself, unlike photon, which is electrically neutral

→ Leads to qualitatively different phenomena

Quantum field theory describing strong force interactions:
Quantum chromodynamics

Confinement

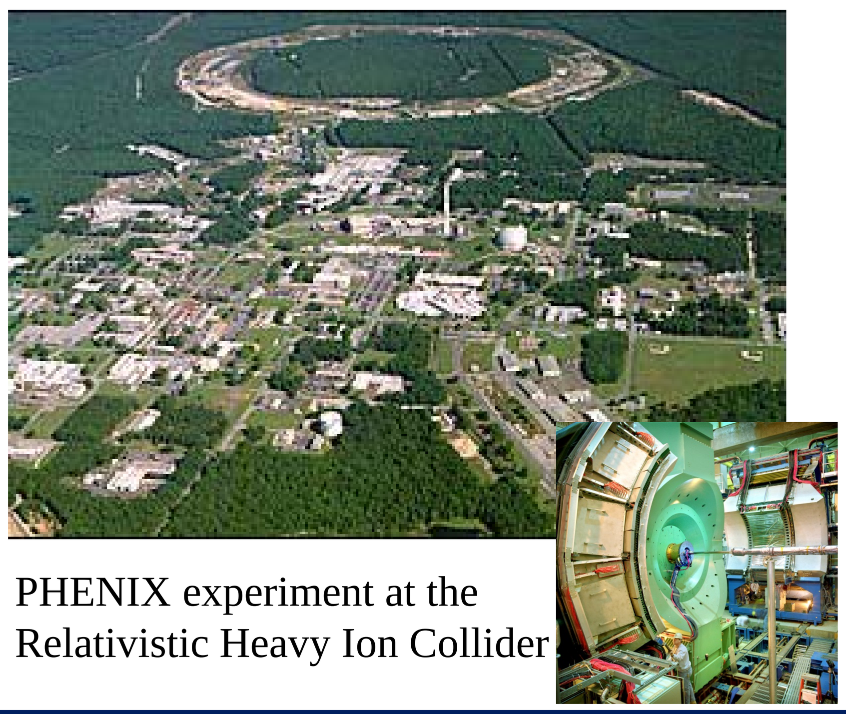
Can never isolate a quark or gluon—*confined* to color-neutral bound states called hadrons
- If you scatter a quark out of a hadron, the energy in the gluon field between the scattered quark and the hadron remnant produces quark-antiquark pairs (via $E=mc^2$), which will then bind with the scattered quark and the remnant to form new color-neutral bound states
- Can have bound states of three "valence" quarks, three valence antiquarks, or of one valence quark plus one valence antiquark
- Bound states also contain "sea" quark-antiquark pairs, due to quantum mechanical fluctuations



Large Facilities to Probe Tiny Distances

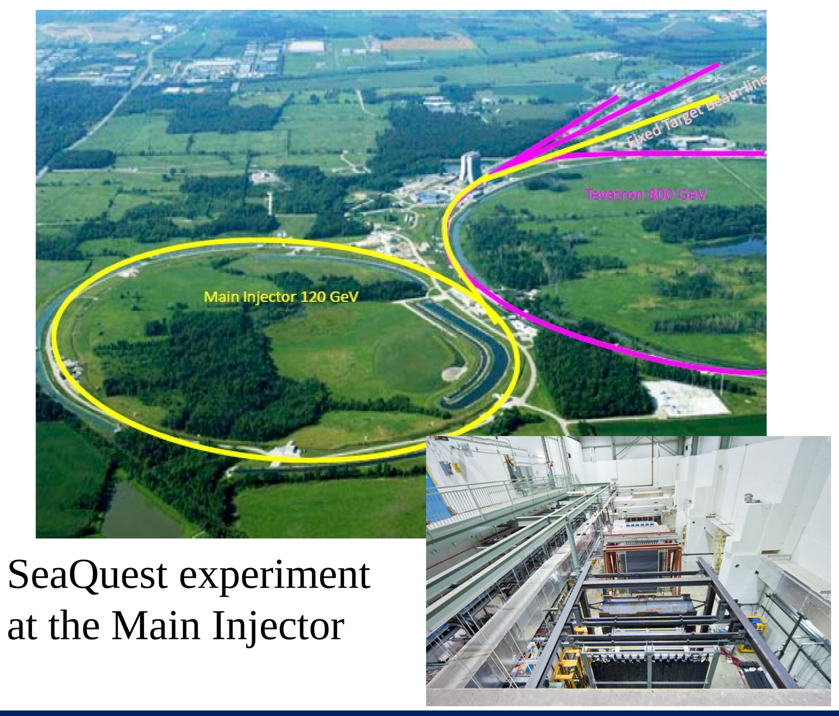
Molecular and atomic structure of matter: study using
- ultraviolet light (wavelengths 10-400 nanometers)
- x-rays (wavelengths 0.01-10 nanometers)

Nuclei and protons: 10,000× to 100,000× smaller than atoms
- need high-energy particle accelerators to probe internal structure
- de Broglie wavelength for "matter wave" of momentum p: $\lambda=h/p$



PHENIX experiment at the Relativistic Heavy Ion Collider

Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory
- Capable of colliding light and heavy nuclei from deuterium up to uranium, at center-of-mass energies ranging from 5-200 GeV per nucleon-nucleon collision
- Capable of colliding *polarized* protons up to center-of-mass energies of 0.51 TeV
- Extremely versatile facility for study of the strong force
- ~1000 scientists on two large experiments

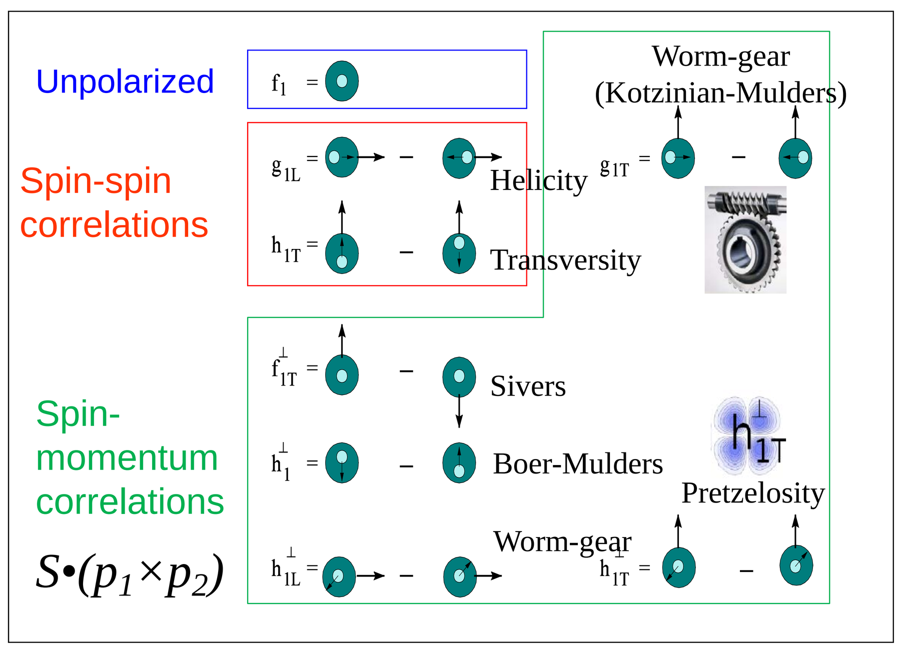


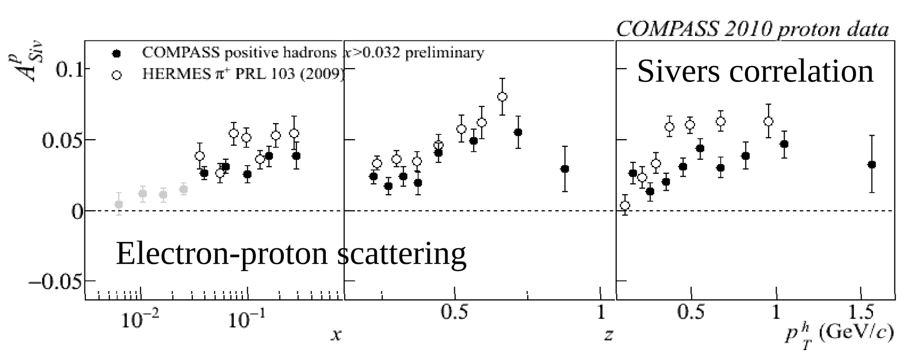
SeaQuest experiment at the Main Injector

Main Injector at Fermi National Accelerator Laboratory
- 120 GeV proton beam on stationary targets (15.4 GeV center-of-mass energy)
- One beamline for SeaQuest experiment, which uses liquid hydrogen, liquid deuterium, and solid nuclear targets
- Focused on quark-antiquark annihilation process to study antimatter in the proton and nuclei
- ~65 scientists

Spin-Spin and Spin-Momentum Correlations in the Proton

Analogous to spin-spin and spin-orbit coupling between the electron and proton in the hydrogen atom, various spin-spin and spin-orbit correlations can be defined between the proton and its constituent quarks



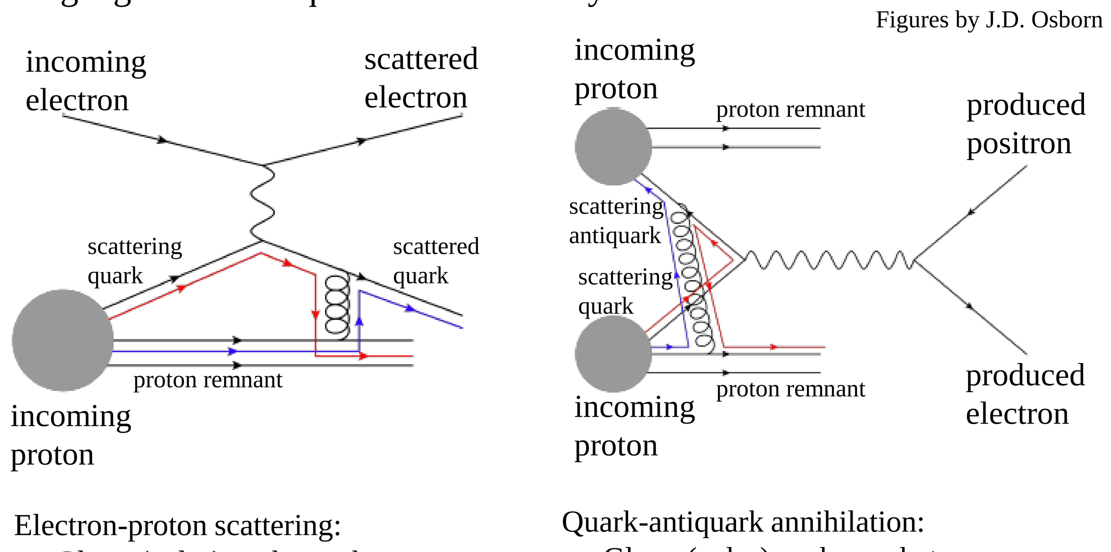


Spin-momentum correlation between spin of proton and orbital motion of quarks within proton—observed in electron-proton scattering experiments to be as large as ~5-10%.

Quark Dynamics and Color Flow

In 2002 (Collins, Phys. Lett. B536, 43), importance of color flow paths in different scattering processes came to light as means of
- probing spin-momentum correlations in proton
- studying fundamental properties of quantum chromodynamics as a gauge-invariant quantum field theory

Figures by J.D. Osborn



Electron-proton scattering:
- Gluon (color) exchange between scattered quark and remnant of its own parent proton
  - Final-state gluon exchange
- Nonzero correlation between proton spin and quark orbital angular momentum observed is only possible via this gluon exchange

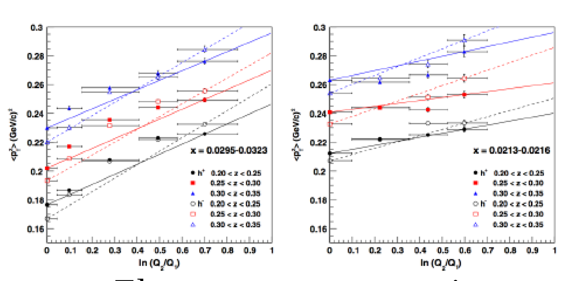
Quark-antiquark annihilation:
- Gluon (color) exchange between scattering quark or antiquark and remnant of the *other* proton
  - Initial-state gluon exchange
- Nonzero correlation only possible via this gluon exchange
- *Different color flow than in electron-proton scattering*

Fundamental prediction within quantum chromodynamics: different color flows in these two processes → relative sign difference in spin-momentum correlation observables. Conclusive spin-dependent measurement of quark-antiquark annihilation not yet performed.

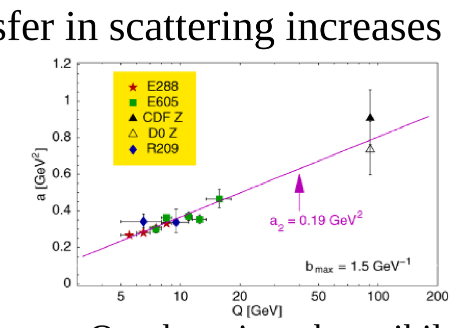
Searching for Quantum-Color-Entangled Quarks Across Colliding Protons

Processes involving two incoming protons and at least one scattered quark (no annihilation)
- Simultaneous gluon exchange in *both* initial and final state
- Qualitatively different color flow paths from those due to only initial-state or only final-state gluon exchange
- In 2010, was realized that these color flow paths could lead to color-entangled quarks *across* the colliding protons (Rogers + Mulders, Phys. Rev. D81, 094006)
- **Currently searching for experimental evidence**

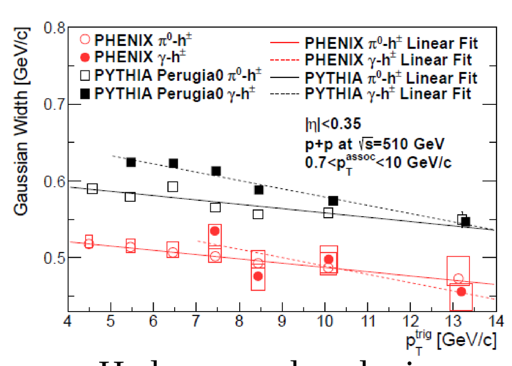
Examine trends in average nonperturbative transverse momentum as momentum transfer in scattering increases



Electron-proton scattering
Aidala et al., Phys. Rev. D89, 094002 (2014)



Quark-antiquark annihilation
Konychev + Nadolsky, Phys. Lett. B633, 710 (2006)



Hadrons produced via proton-proton collisions
Osborn, Aidala, et al. (PHENIX Collaboration) arXiv:1609.04769, submitted for publication

Qualitatively different trend observed when gluon exchange in both initial and final state possible
- *Decreasing* average nonperturbative transverse momentum
- Possible signature of color-entangled quarks
- Follow-up studies ongoing to rule out other possible causes