The Antiups and Antidowns of Life: Studying Antiquarks in Hydrogen and Carbon

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Saturday Morning Physics

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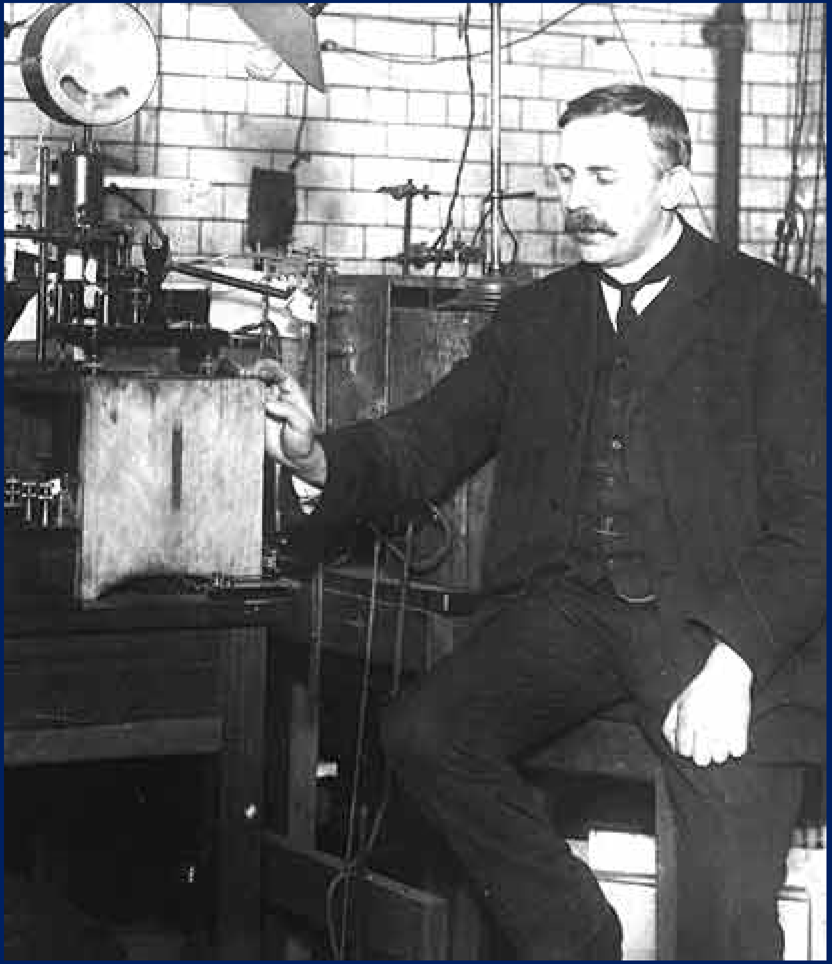
What's inside an atom? Discovery of the atomic nucleus

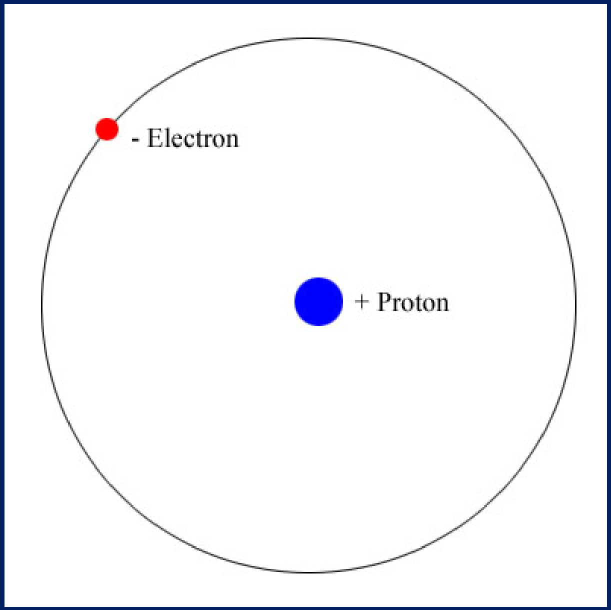
1911: Ernest Rutherford scatters alpha particles from radioactive decay off of a thin gold foil

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

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



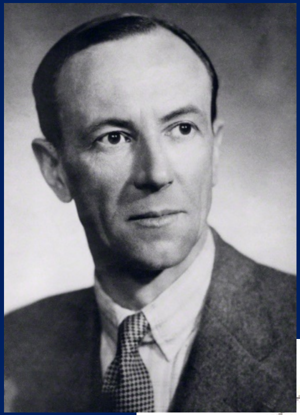
What's inside an atom? The proton

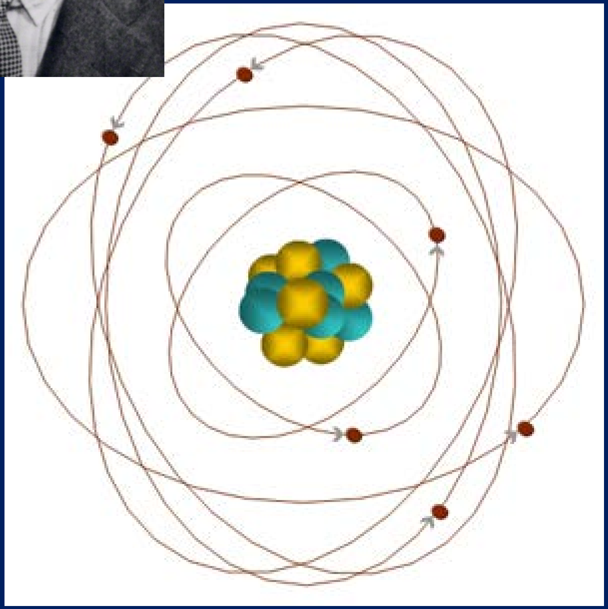


Hydrogen
- 1 proton
- 1 electron

- Rutherford named hydrogen nucleus the *proton*
- Further experiments showed that the nuclei of other elements weren't only made of protons
  - Compared to hydrogen, balance between charge and mass didn't match—other elements too heavy!
- But took another 21 years of experiments to discover what else was in the nucleus of most atoms . . .

What's inside an atom?
Discovery of the neutron



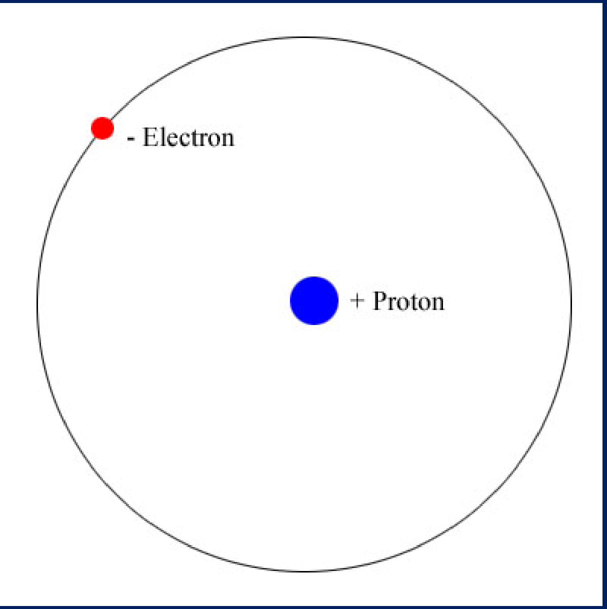


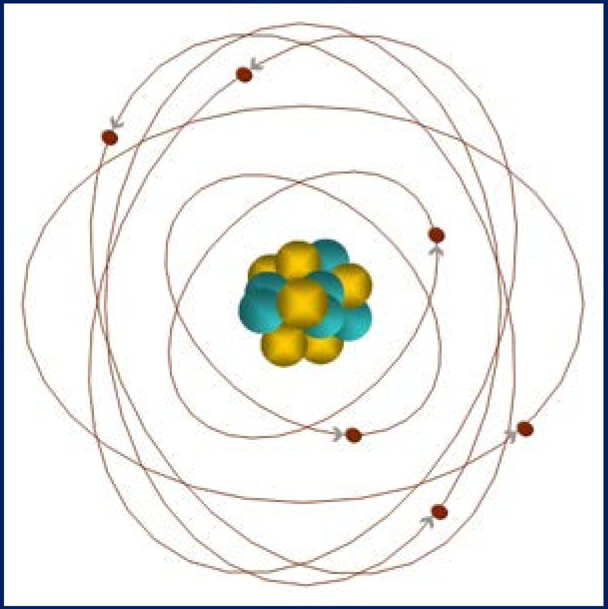
Carbon
- 6 protons
- 6 neutrons
- 6 electrons

- 1932: James Chadwick irradiated light elements with beams of alpha particles → discovered neutral particle knocked out of nucleus with nearly same mass as proton: the neutron

- Together, protons and neutrons called *nucleons*

Matter: Electrons, protons, and neutrons





Hydrogen
- 1 proton
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Carbon
- 6 protons
- 6 neutrons
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Antimatter

- 1928: Considering fast-moving electrons, Paul Dirac formulated a version of the Schrödinger equation, which describes change in time of quantum mechanical states, that was consistent with Einstein's theory of special relativity

- Realized his new equation predicted the possibility of "antielectrons"
  - Mathematically similar to finding both positive and negative values when taking a square root: $\sqrt{4} = \pm 2$

- Partner particle to the electron, same mass but opposite charge

Antimatter: Discovery!

- 1932: Carl Anderson studies cosmic rays in a cloud chamber and observes track of positively charged particle with mass similar to electron
  - Magnetic field bends charged particle paths
- “Positron” is coined by editor of the journal

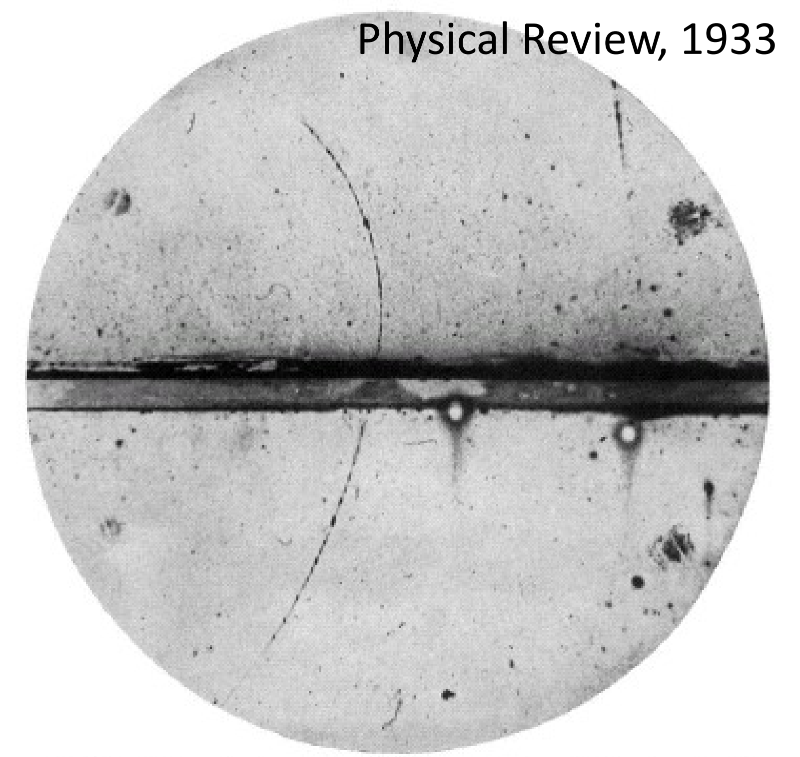
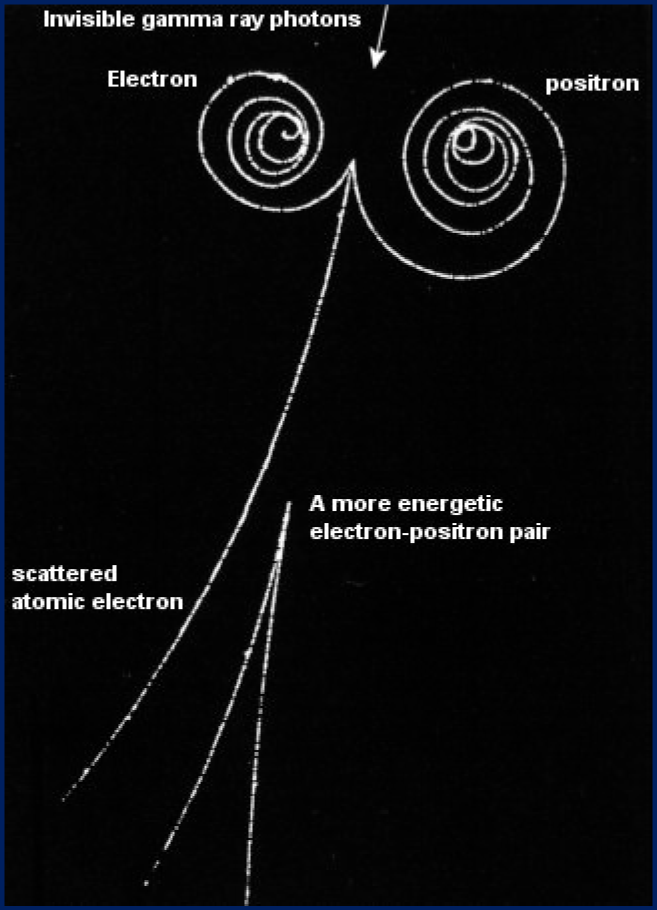


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

$E = mc^2$
Particle-antiparticle pair production

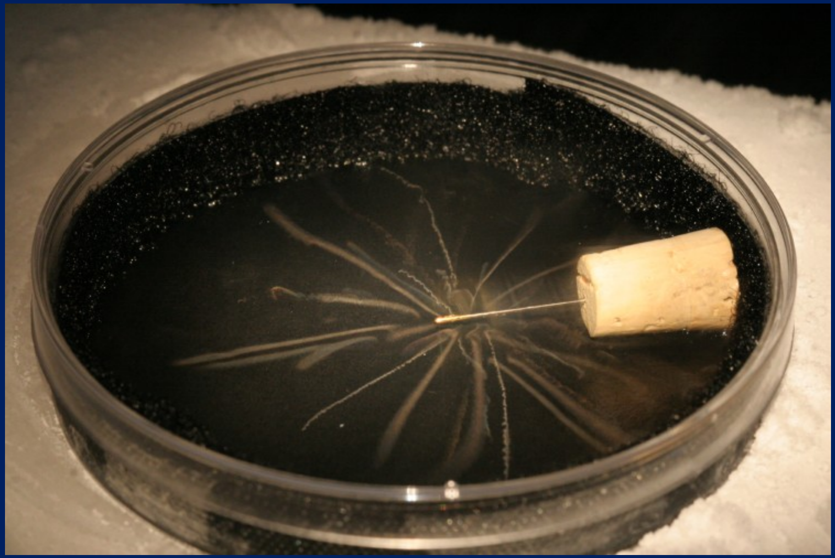


- With enough energy, can create particle-antiparticle pairs
- Conserved quantities – Can't create net electric charge out of nowhere, so if create a negative particle, also create a positive one
- Observations indicate other particle properties similarly conserved
  - *Lepton number* ("electron-ness")
  - *Baryon number* ("nucleon-ness")

Cloud chambers

- Sealed chamber filled with supersaturated water or alcohol vapor
- Passage of charged particle ionizes molecules of vapor along its path
- Ions act as "seeds" for droplets to condense, forming visible tracks

- Invented 1911 by Charles Wilson, who studied optics of the mists in the Scottish highlands



Make your own cloud chamber to observe cosmic rays! (Radioactive source shown here)

-91% isopropyl alcohol

-Dark felt

-Small container with transparent lid

-Dry ice

Antinucleons

Lawrence Berkeley National Lab
Bevatron facility

Antiproton

- Predicted by Dirac in his 1933 Nobel prize lecture
- Discovered 1955 by Emilio Segrè and Owen Chamberlain at Lawrence Berkeley National Lab, using beam of accelerated protons hitting stationary target materials
  - High enough energies to create proton-antiproton pairs!

$$E = mc^2$$

Antineutron

- Discovered 1956 by Bruce Cork, Glen Lambertson, Oreste Piccioni, and William Wenzel at Berkeley Lab, using antiprotons

$E = mc^2$
Particle-antiparticle annihilation

- Inverse process of pair production – annihilate a particle-antiparticle pair back into energy

- Energy can then produce a variety of new particles

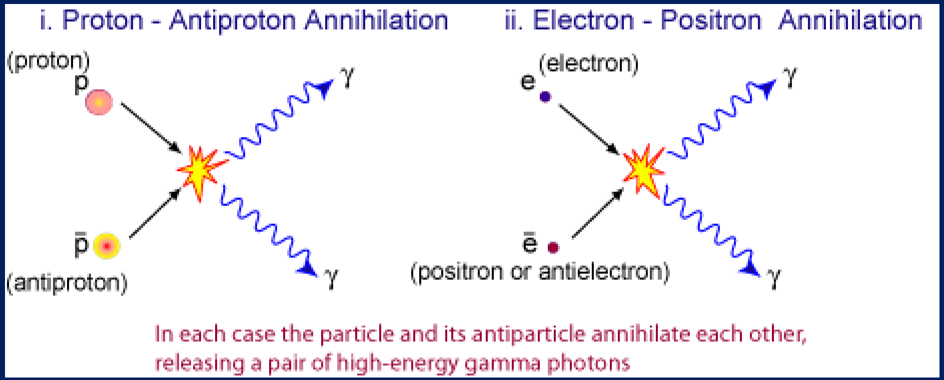
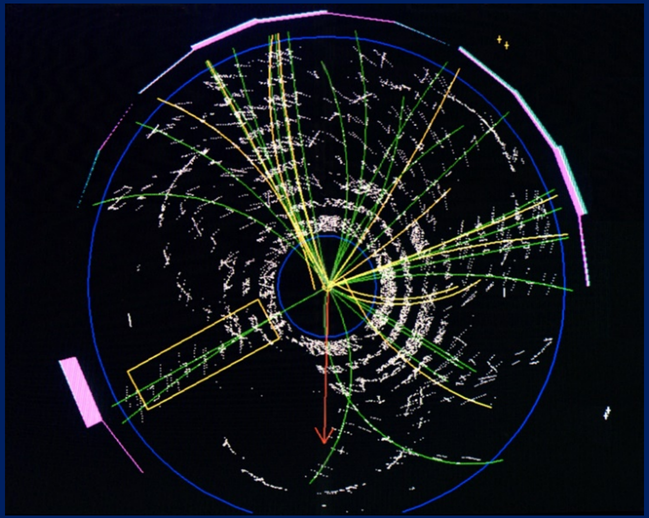


Image credit: CSIRO



Tracks from proton-antiproton annihilation at the TeVatron, Fermilab

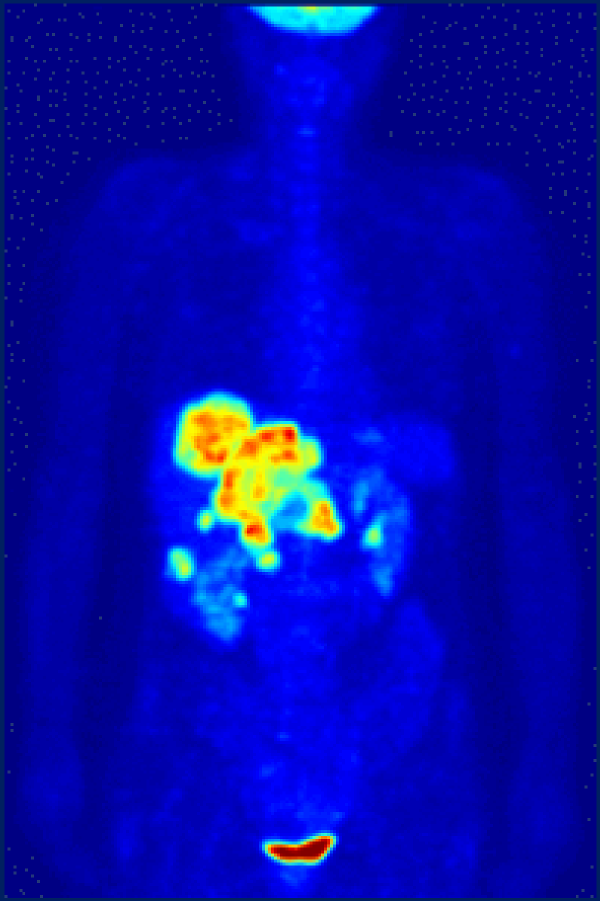
Applications of antimatter

Image credit: Jens Maus

- Medicine: Positron Emission Tomography - “PET imaging”
  - Observe metabolic processes in body
  - Take positron-emitting radioactive isotope into body
  - Positrons annihilate with body’s electrons i
  - Detect the produced photons externally

- Medicine: Antiproton radiation therapy in R&D phase—deposits more energy in tumor than protons, due to annihilation

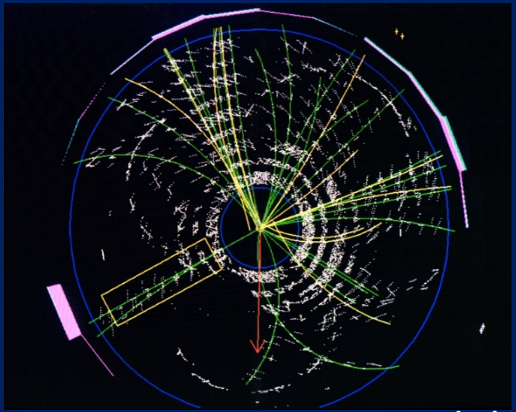
- Materials science: Positron annihilation spectroscopy
  - Use length of time delay of positron annihilation to detect defects in solids



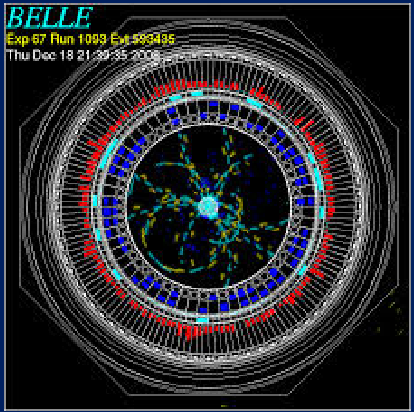
PET scan using fluorine-18

Applications of antimatter

- Nuclear and particle physics research:
  - Electron-positron and proton-antiproton colliders have been used in the U.S., Europe, and Japan
  - Produce and study different particles and their properties



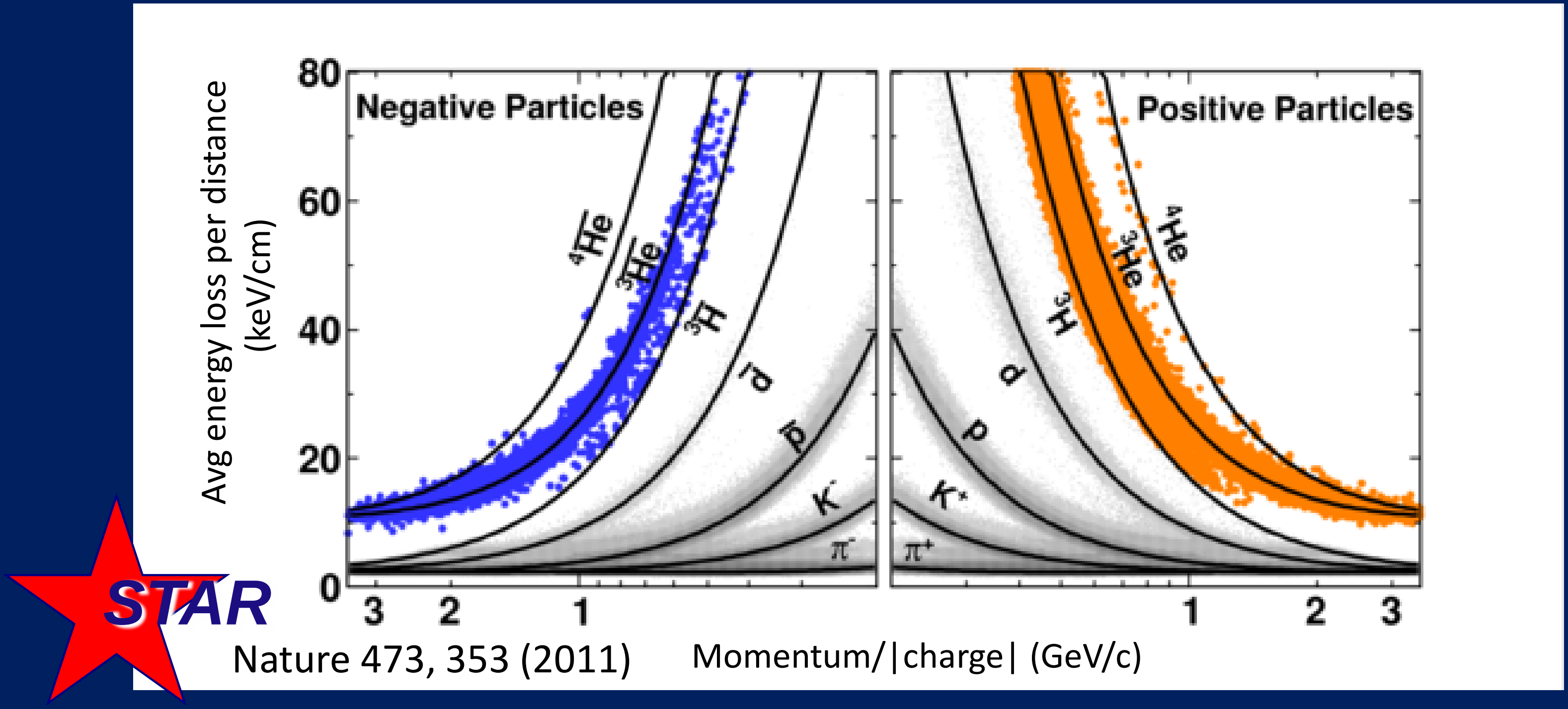
Tracks from proton-antiproton annihilation at the TeVatron, Fermilab



Tracks from electron-positron annihilation at the BELLE experiment, KEK, Japan

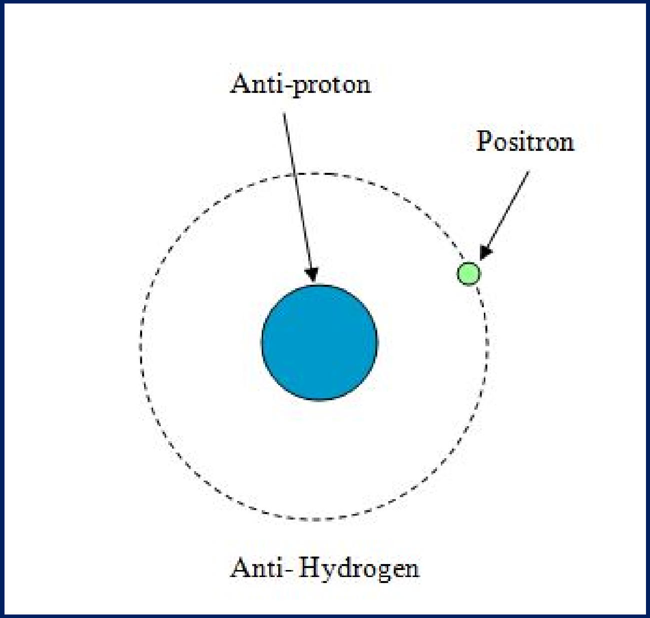
Antinuclei

In collisions of high-energy nuclei at Brookhaven National Lab and CERN, produced (anti-)particle densities are so high they sometimes bind together into (anti-)nuclei



First production of antihelium-4 announced 2011!

Antimatter atoms?



- Relatively easy now to produce positrons, antiprotons, and antineutrons in the lab, but extremely difficult to produce antimatter *atoms*
- First ground-state antihydrogen atoms produced at CERN in 2002
- Could only trap them long enough to start studying their properties in 2010
- Nothing heavier created so far

Matter within matter: Quarks

Late 1960s: scatter electrons off of protons

- Many bounced back sharply!
- But weren't bouncing off of the whole proton → subcomponents
- Constituents that make up protons and neutrons: *quarks*

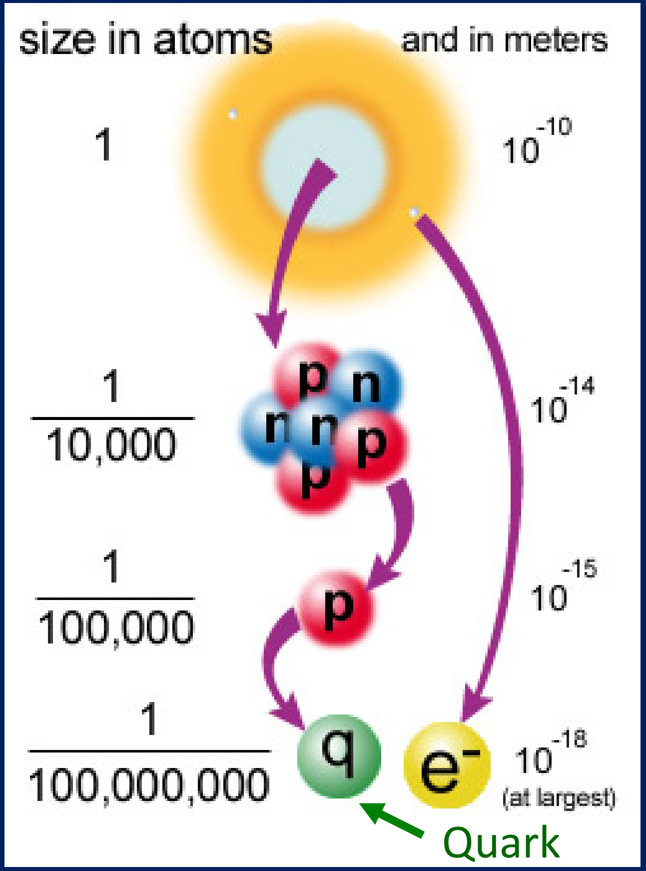
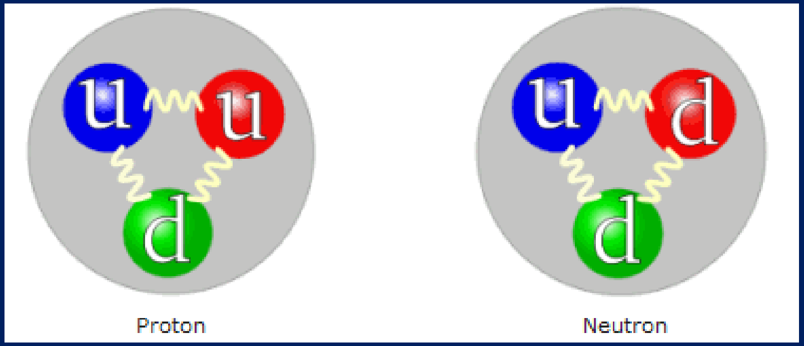


Image credit: Particle Adventure

Quarks and gluons

Simplest model of proton or neutron is three quarks

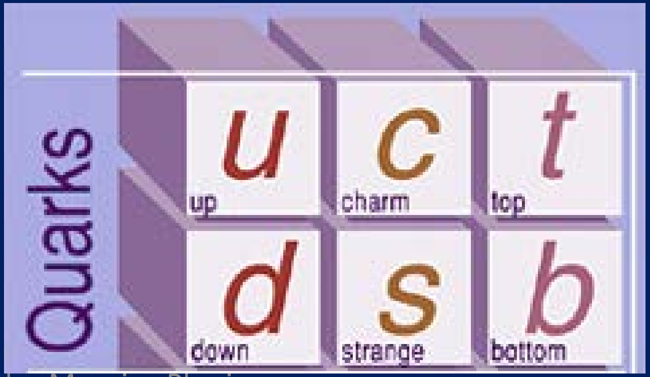
- Proton: 2 up "flavored" quarks, 1 down
- Neutron: 2 down quarks, 1 up



Quarks bound by force-carrier particles: *gluons*

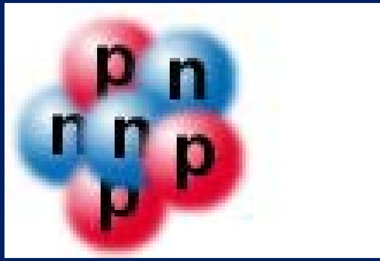
- For strong nuclear force, gluons play role analogous to photons for electromagnetism

Other flavors of quarks exist:

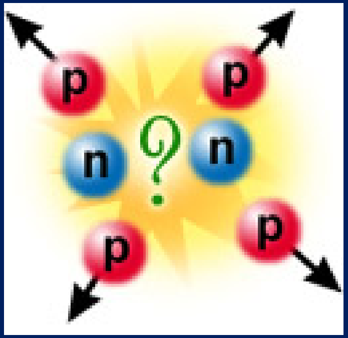


Or "truth"

and "beauty"



The strong force



- How does 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 (~10^{38}×!!) (thus the name!)
  - But—very very short range! (~10^{-15} meters)

Color charge

- 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

Quarks also carry *fractional* electric charge!!

Proton = up + up + down quarks

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

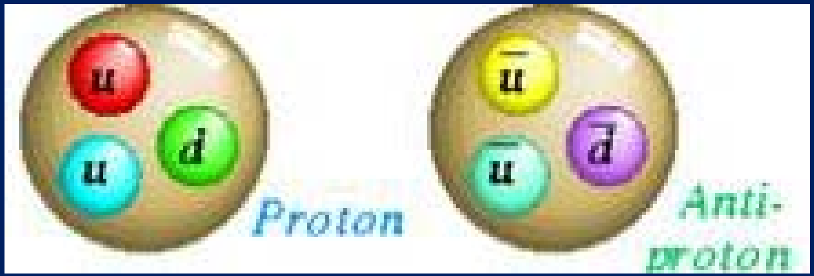
Neutron = down + down + up

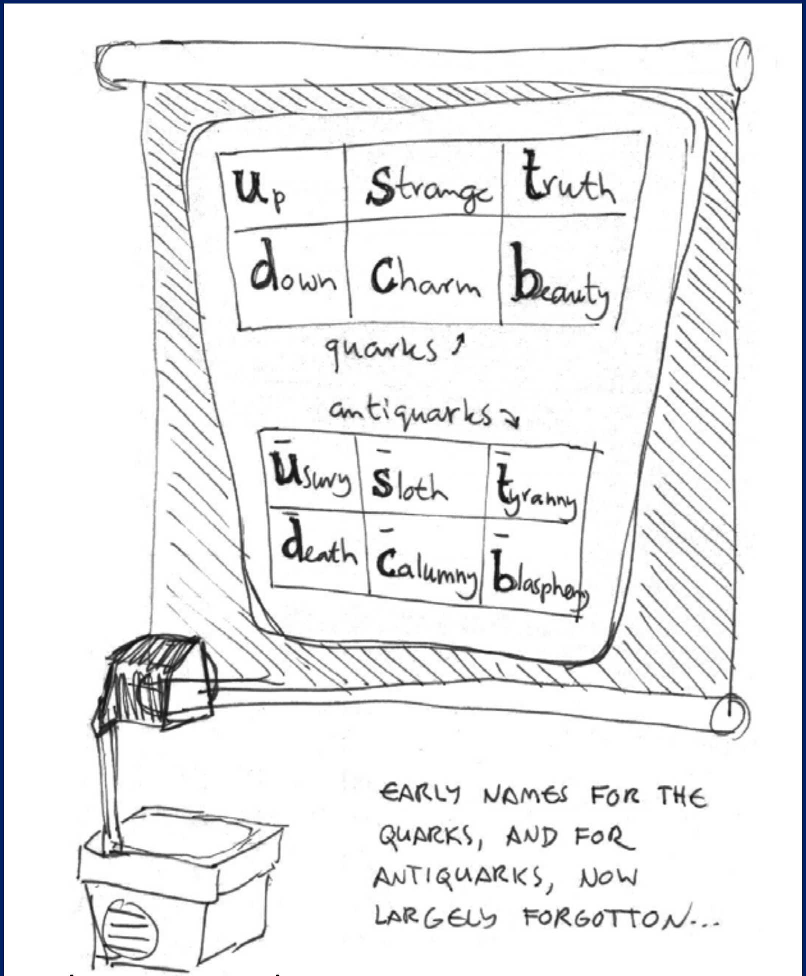
0 = (-1/3) + (-1/3) + (+2/3)

Antimatter within antimatter: Antiquarks

Antiprotons and antineutrons made of *antiquarks*

- Opposite electric charge
- Antiflavor
- Anticolor



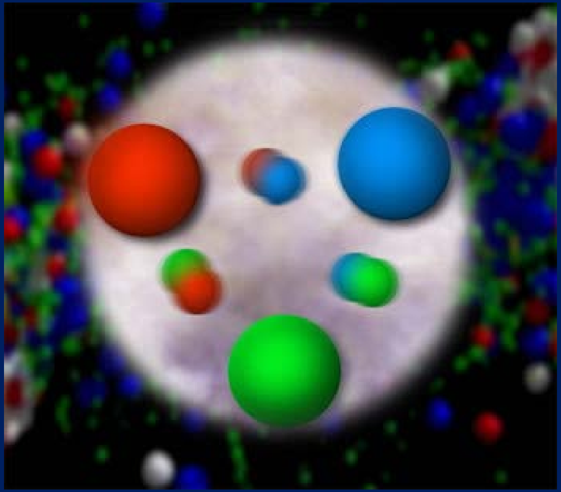


Hubert van Hecke

Antimatter within matter!

Short-lived quark-antiquark pairs from quantum mechanical fluctuations also exist in both nucleons and antinucleons:

"Sea" quarks



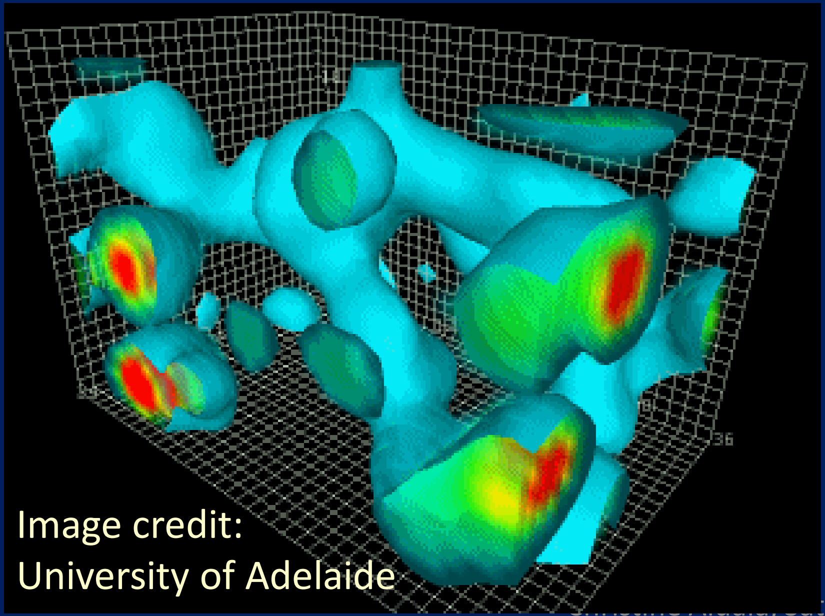


Image credit:
University of Adelaide

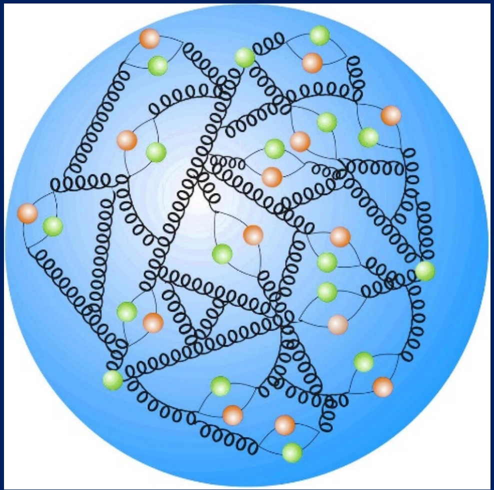


Image credit:
DESY

Studying antiquarks in protons and nuclei at the Fermilab SeaQuest experiment

U.S. DEPARTMENT OF ENERGY
Office of Science

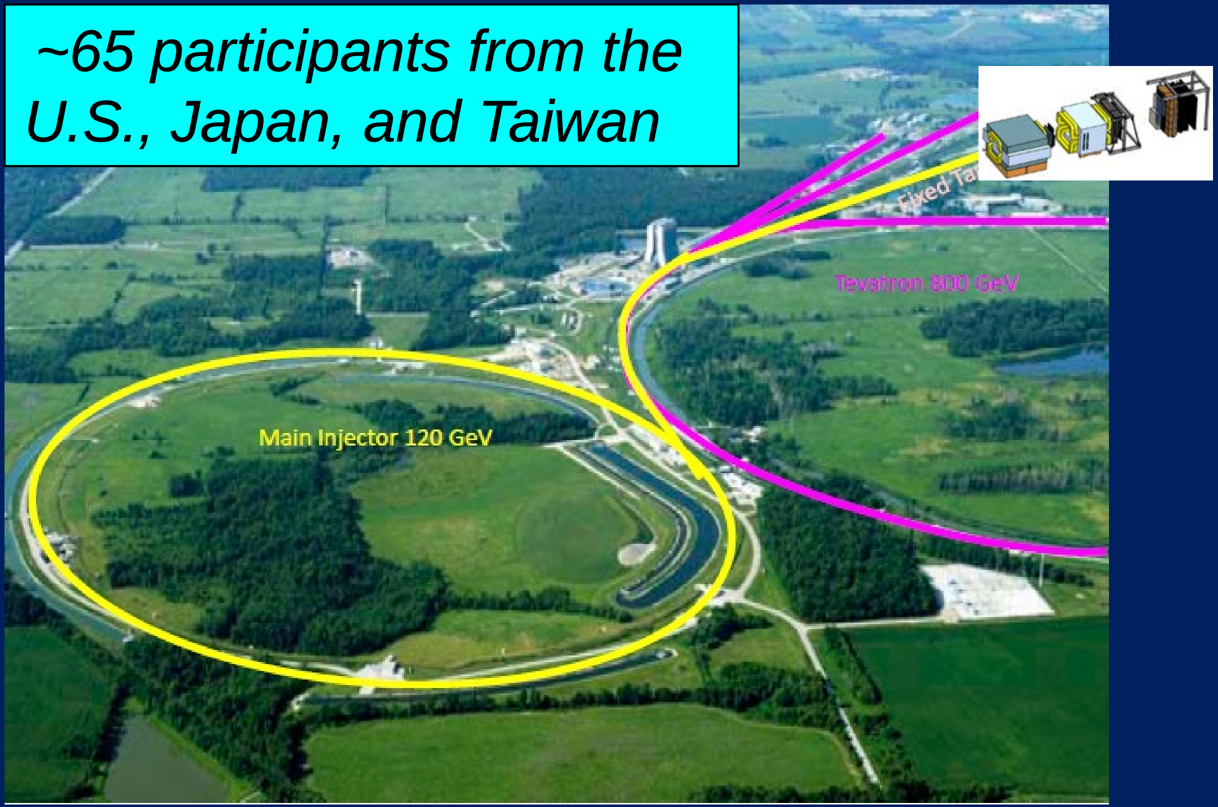
National Science Foundation

SeaQuest experiment at the Fermilab Main Injector

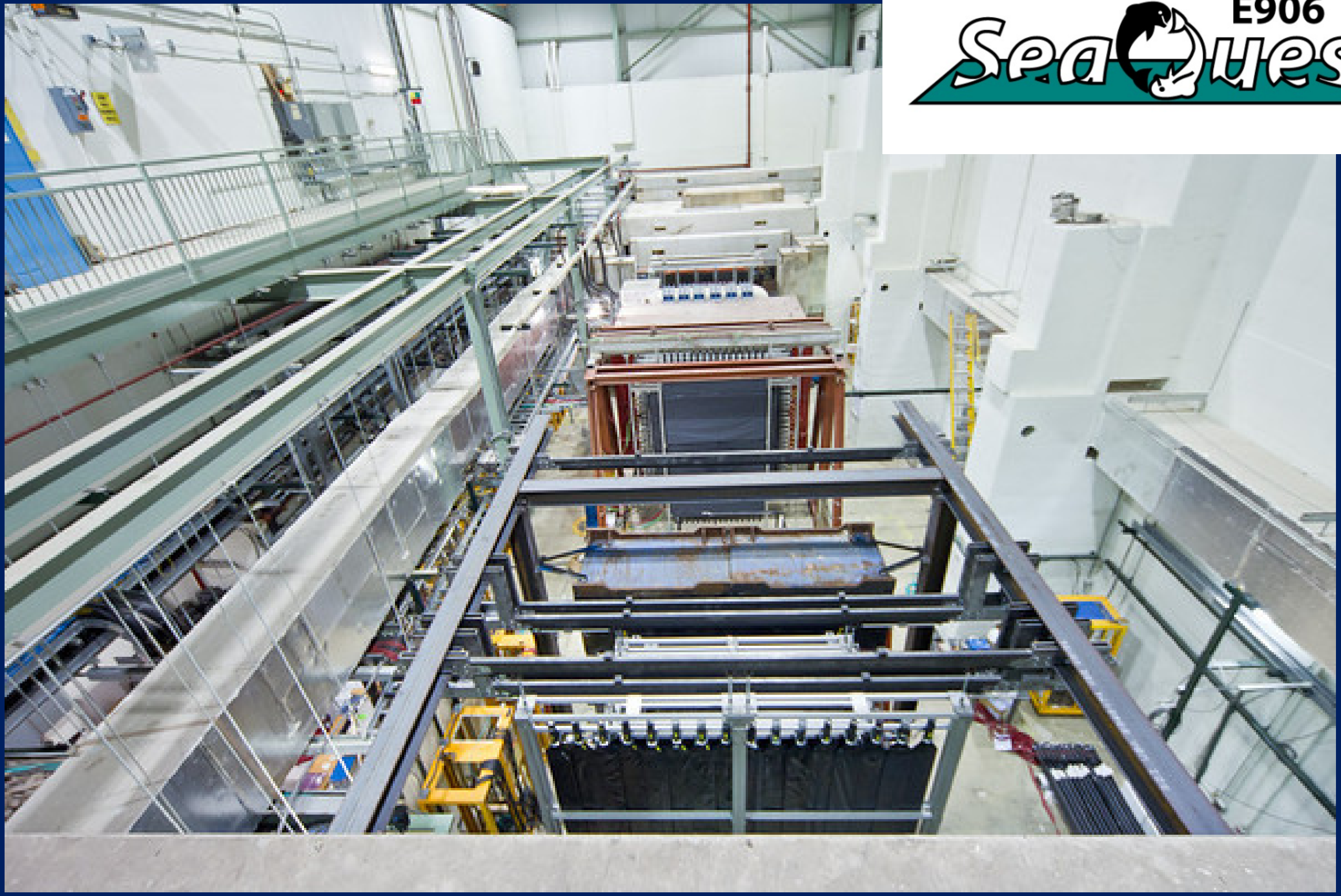
- Main Injector accelerates protons
- Hit stationary targets
  - liquid hydrogen
  - liquid deuterium (hydrogen with a neutron in the nucleus)
  - solid carbon, iron, and tungsten

- Taking data since 2014, will finish running this year

~65 participants from the U.S., Japan, and Taiwan

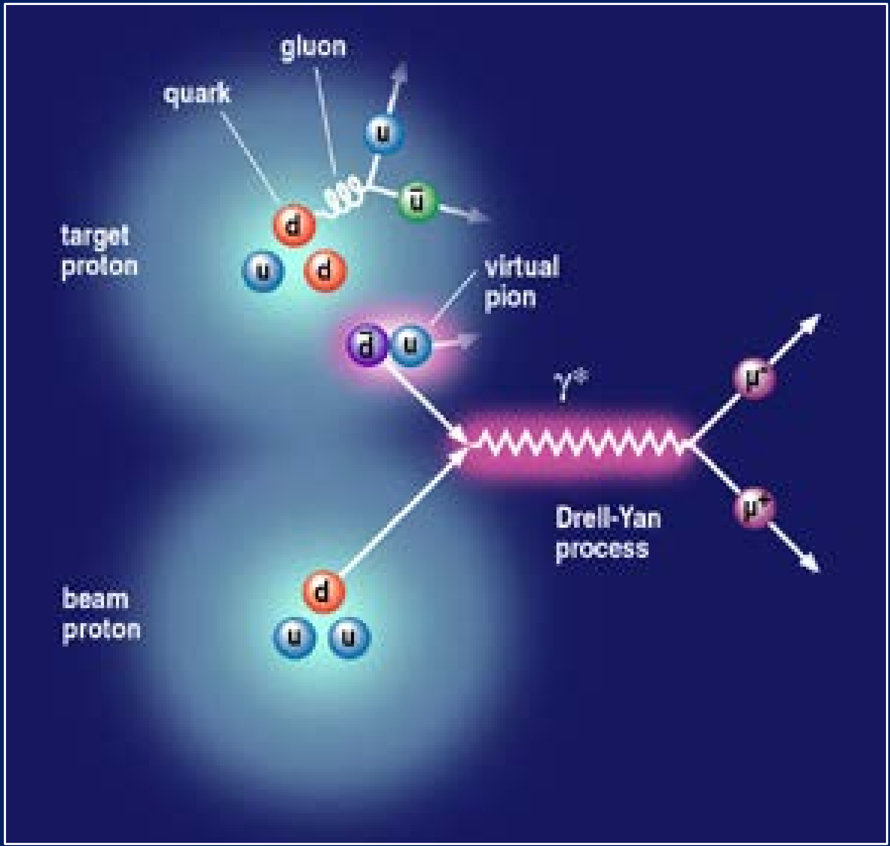


SeaQuest detector



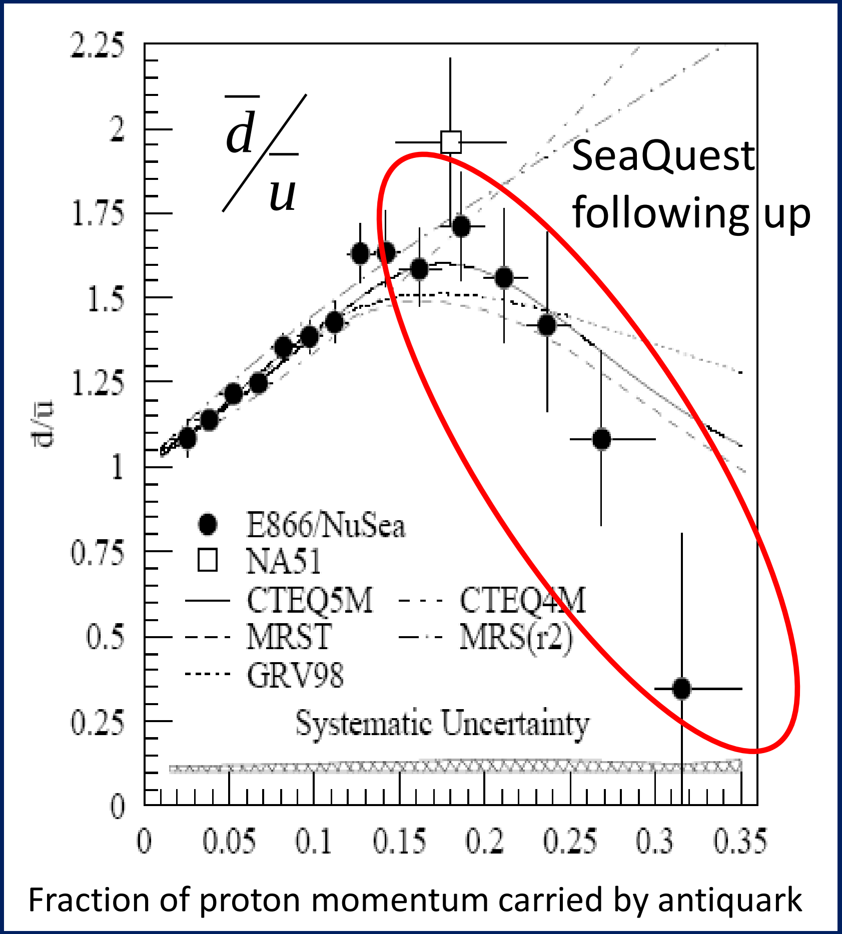
How to find an antiquark in hydrogen: Annihilate it!

- Measure quark-antiquark annihilation to electron-positron or muon-antimuon pairs
  - Muon (μ) like a heavy electron; abundant in cosmic rays
- Quark from proton in beam annihilates antiquark from proton or neutron in target



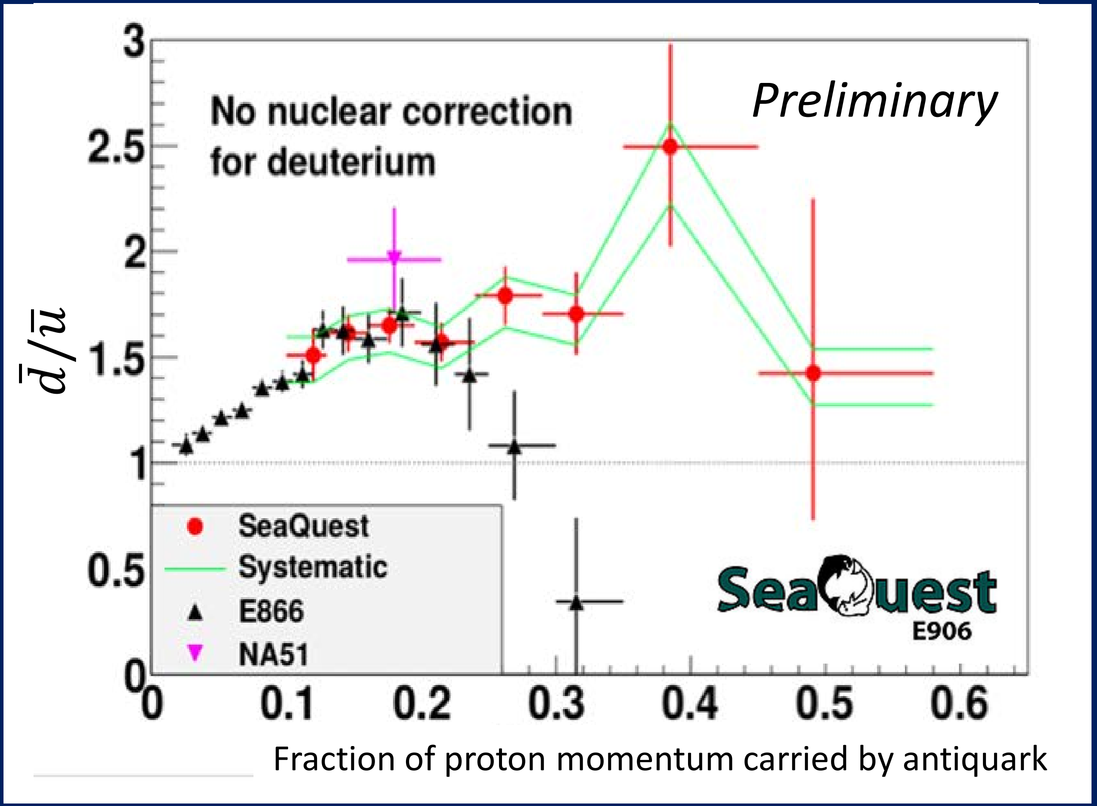
Antiups ($\bar{u}$) and antidowns ($\bar{d}$) of hydrogen

- Expect antiup = antidown if they only come from gluons fluctuating to quark-antiquark pairs
- Compare annihilation from hydrogen (proton) and deuterium (proton+neutron) → infer ratio of antidown-to-antiup in proton
- Prior experiments discovered large excess of antidown!



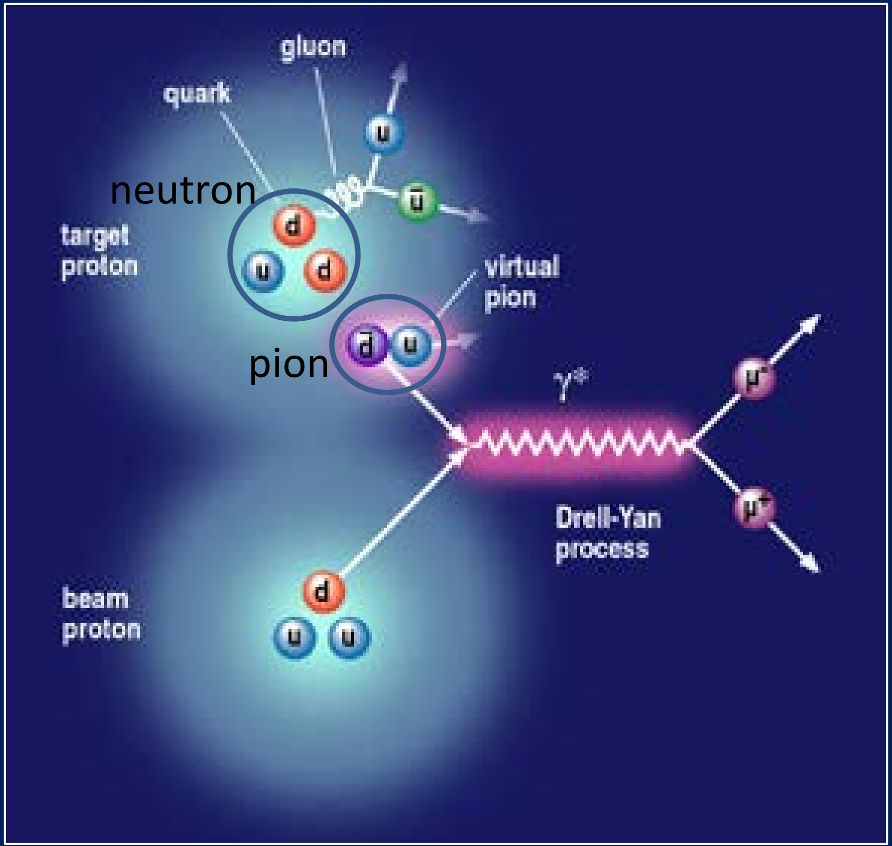
Antiups ($\bar{u}$) and antidowns ($\bar{d}$) of hydrogen

- Preliminary results: ratio may not drop quickly as suggested by prior data
- Ratio staying ≥ 1 may resolve theoretical puzzles . . .

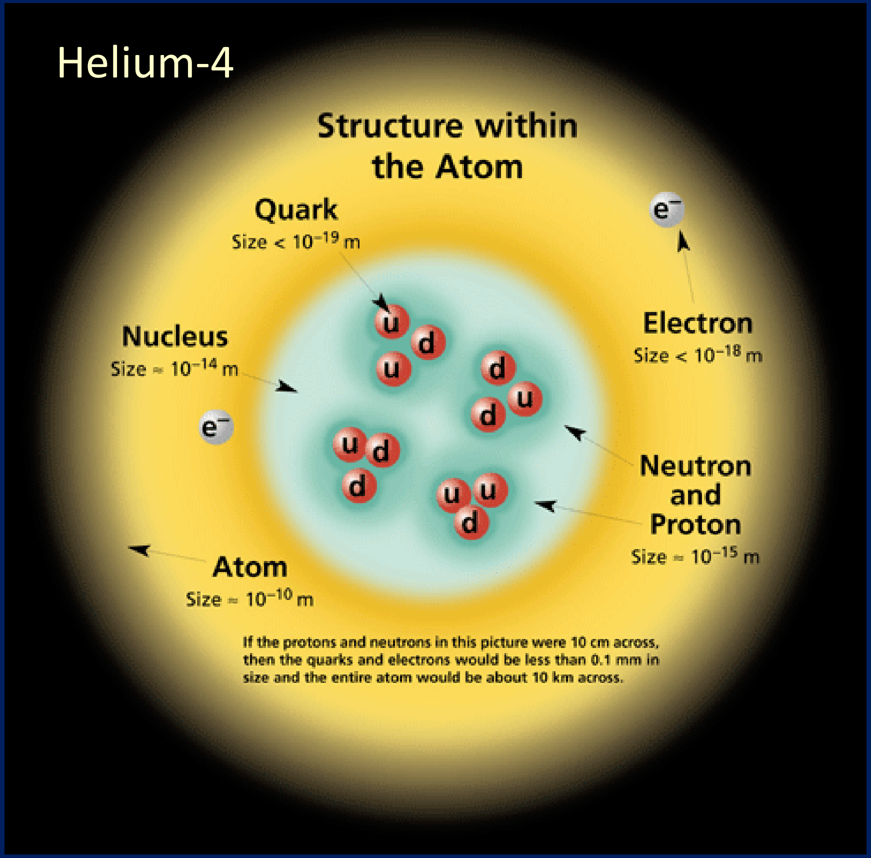


Quantum fluctuations of proton?

Proton may be fluctuating into a neutron plus a positive pion, a bound state of up-antidown

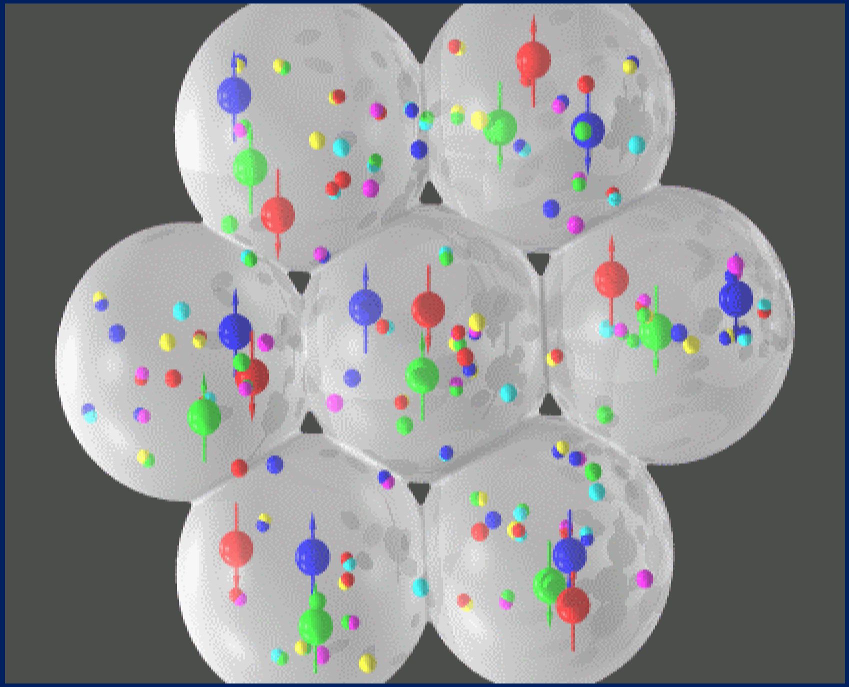


What about quarks and antiquarks in nuclei?



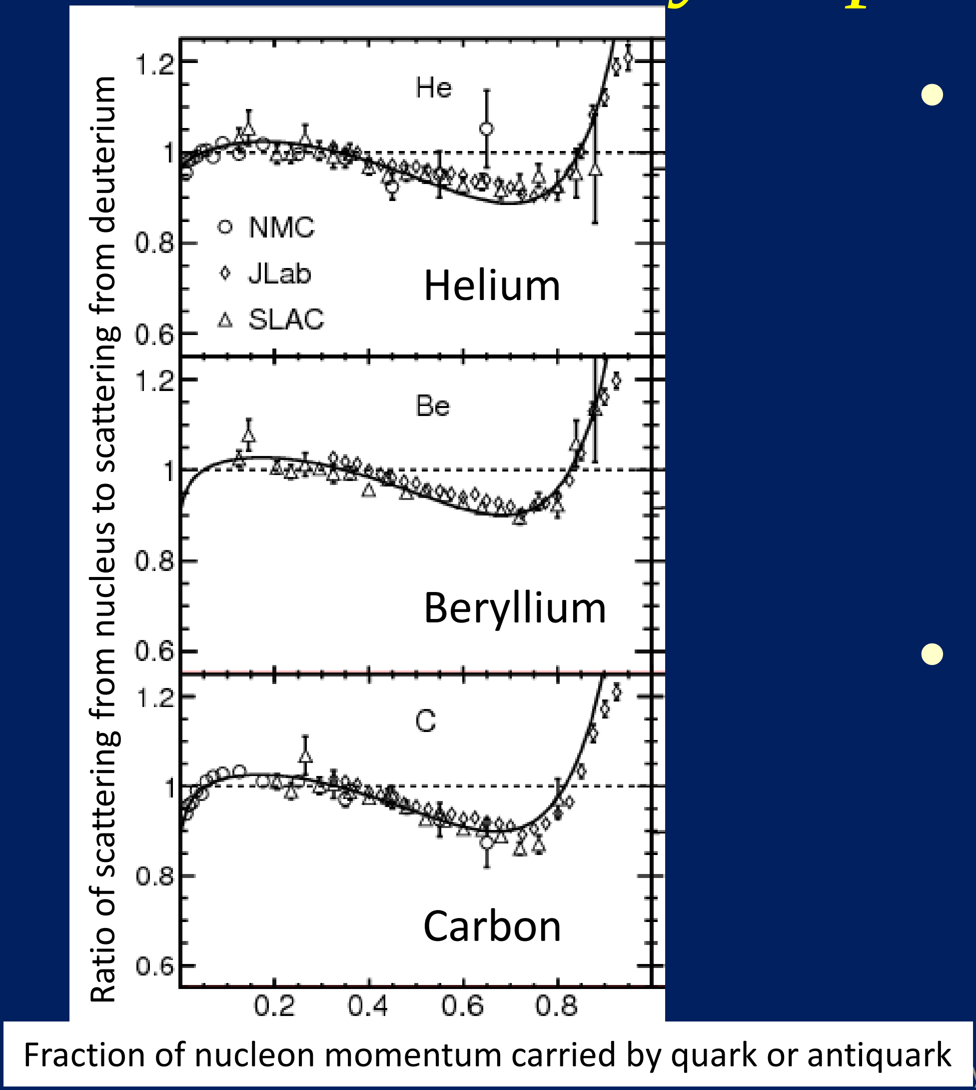
A simple picture of quarks in a nucleus

Image credit: Jens Berger



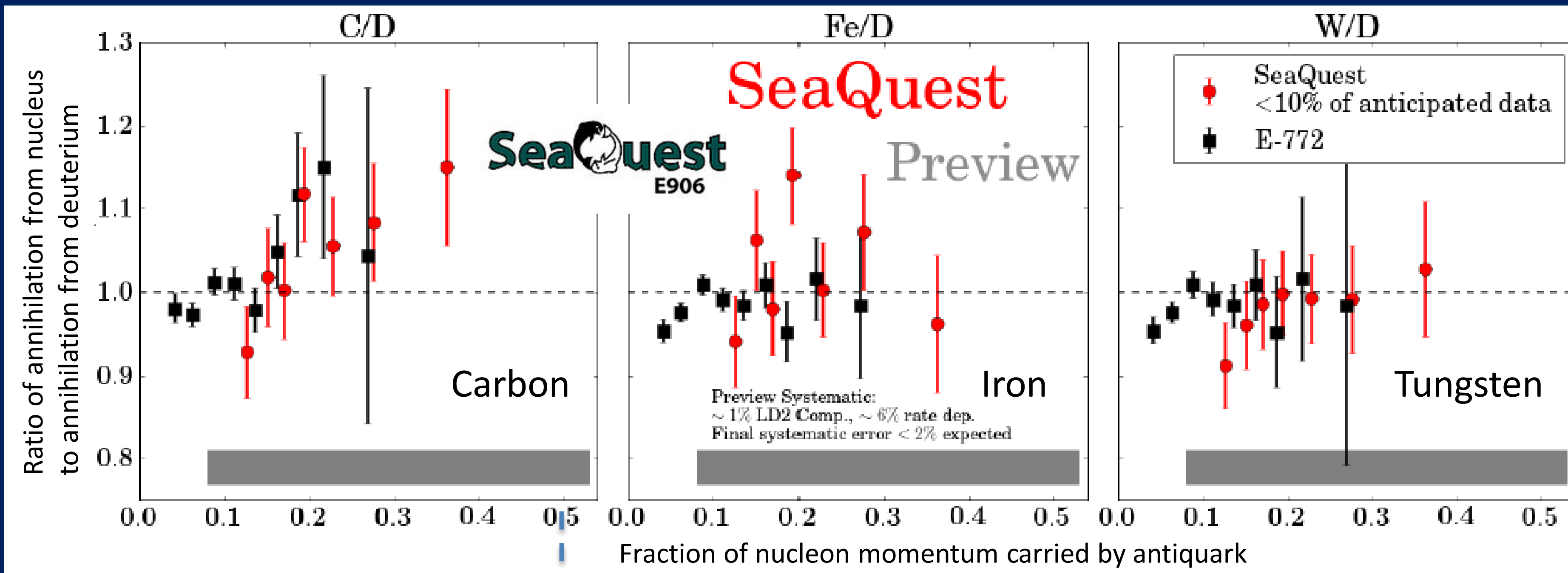
Quarks and antiquarks in a nucleus

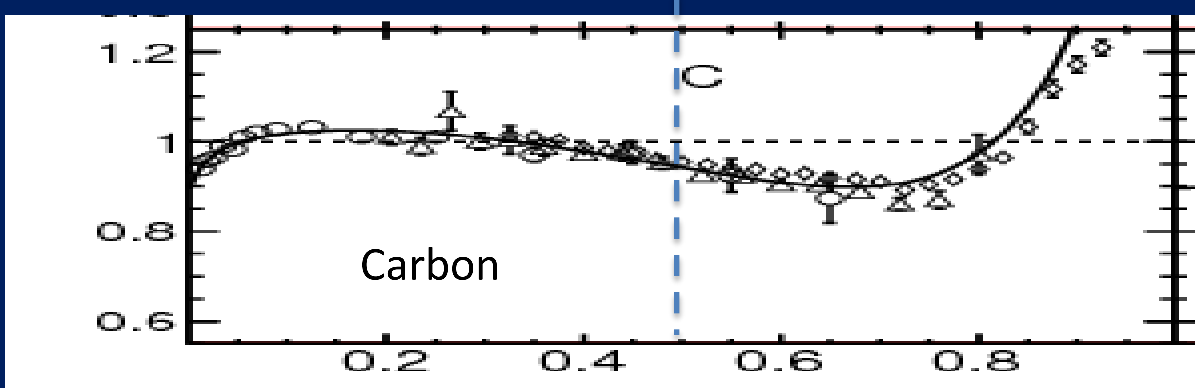
Quarks and antiquarks behave differently when they're part of a nucleus!



- Not just simple combination of quarks and antiquarks in free nucleons
  - Ratio shown would be flat at 1
- These electron-scattering data are probing quarks and antiquarks together

Probing antiquark distributions in carbon, iron, and tungsten





Isolating antiquarks may shed light the various nuclear effects.

Need more data . . .

Summary

- Scientists have been working with antiparticles for 85 years now, and there are already applications in medicine, materials science, and of course particle and nuclear physics research
- Antimatter can even be found within us!
- We still have much to learn about the quarks, antiquarks, and gluons inside the nuclei of everyday matter