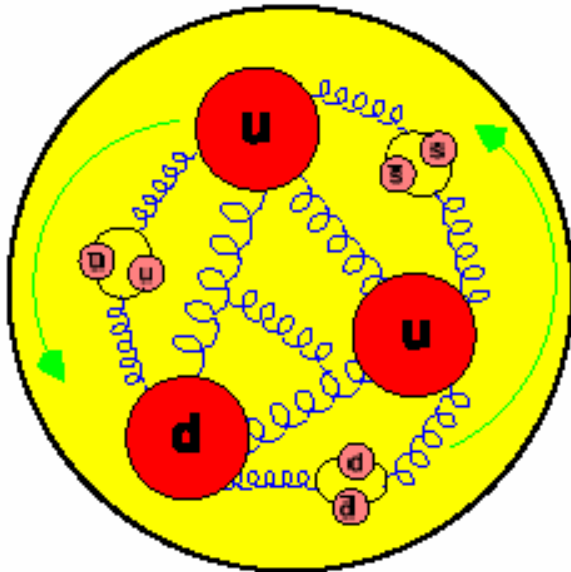


W-Bosons as a Microscope for the Observation of Quarks and Anti-Quarks Inside the Proton

M. Grosse Perdekamp
University of Illinois, Urbana Champaign

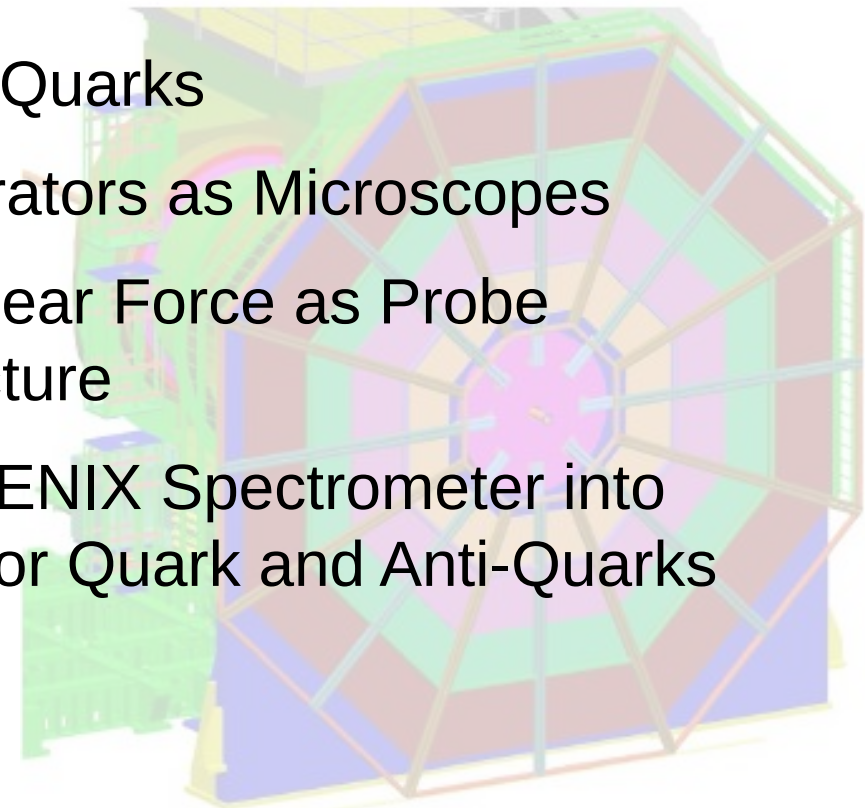


PHYS 403 – Research Talk
July 9th, 2025





W-Bosons as a Microscope for the Observation of Quarks and Anti-Quarks Inside the Proton

- ❑ From Atoms to Quarks
 - ❑ Particle Accelerators as Microscopes
 - ❑ The Weak Nuclear Force as Probe of Proton Structure
 - ❑ Turning the PHENIX Spectrometer into a Microscope for Quark and Anti-Quarks
- 

From Atoms to Quarks: What is the Substructure of Matter?

Demokrit



Asked early: Leukipp and Demokrit (~ 450-400 BC)
→ atomic hypothesis !

There are small particles, atoms, of which all matter is made and which cannot be divided in smaller parts.

Some 2400 years & 80 generations later:

Modern experimental tools may provide quantitative answers in our lifetime!



PHENIX Experiment at
Brookhaven National Lab

The Atoms of the 20th Century:

Quarks and Leptons

Elementary Particles

Quarks	u up	c charm	t top	g gluon	Force Carriers
	d down	s strange	b bottom	γ photon	
Leptons	ν_e e neutrino	ν_μ μ neutrino	ν_τ τ neutrino	W W boson	
	e electron	μ muon	τ tau	Z Z boson	
3 →	I	II	III	← Generations	

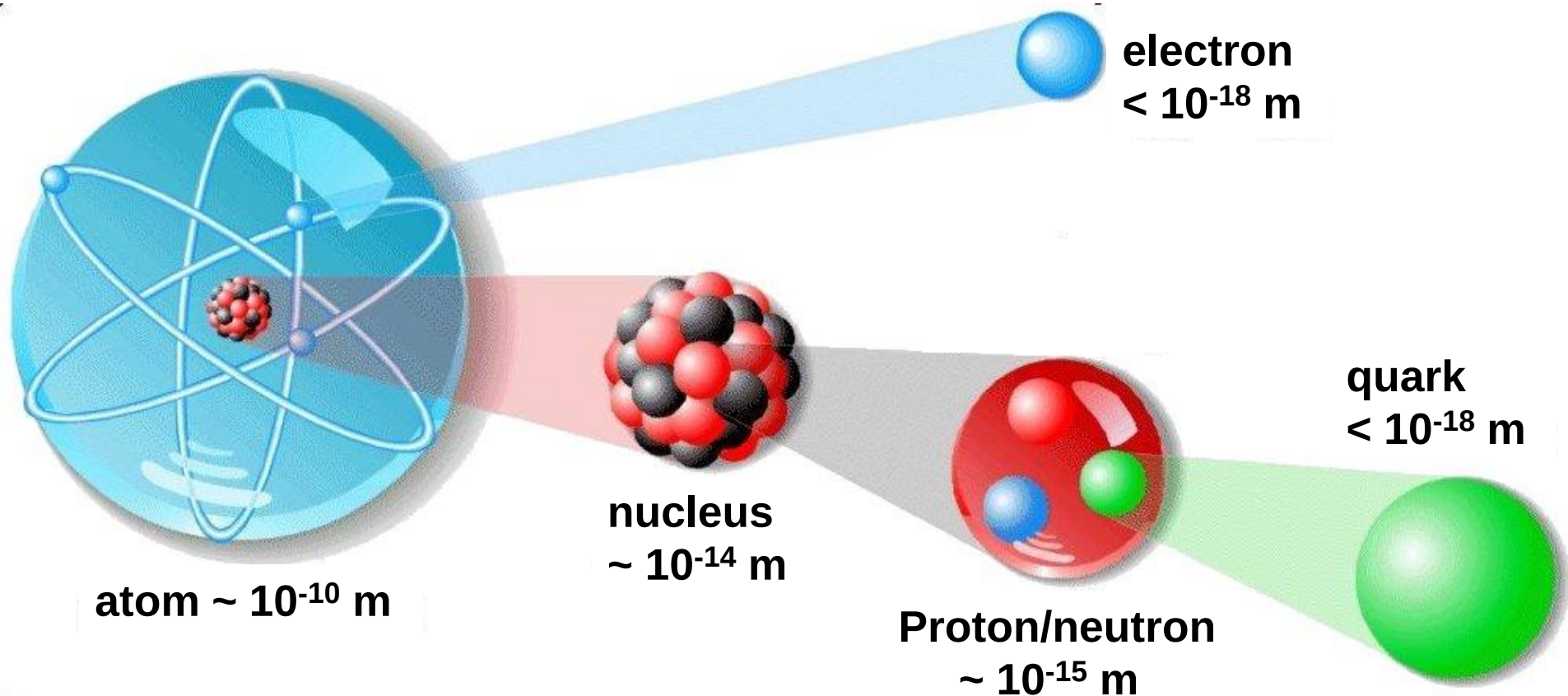
Up- and down-**quarks** are the building blocks of all **nuclear matter** in the nuclei of atoms.

Electrons make up the shell of atoms.

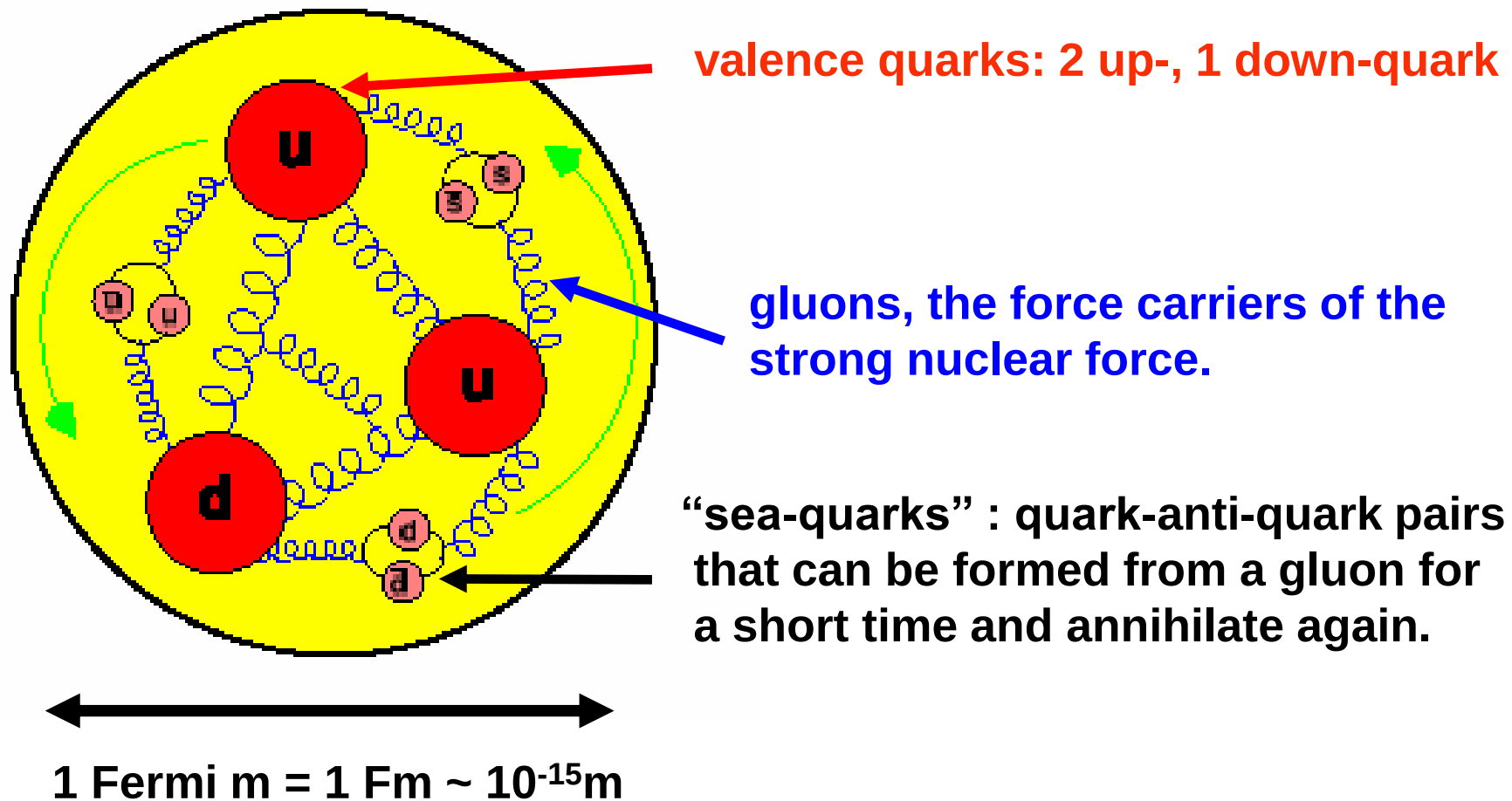
Forces:

Electromagnetic → Photon
 Strong Nuclear → Gluon
 Weak Nuclear → $Z^0, W^{+,-}$

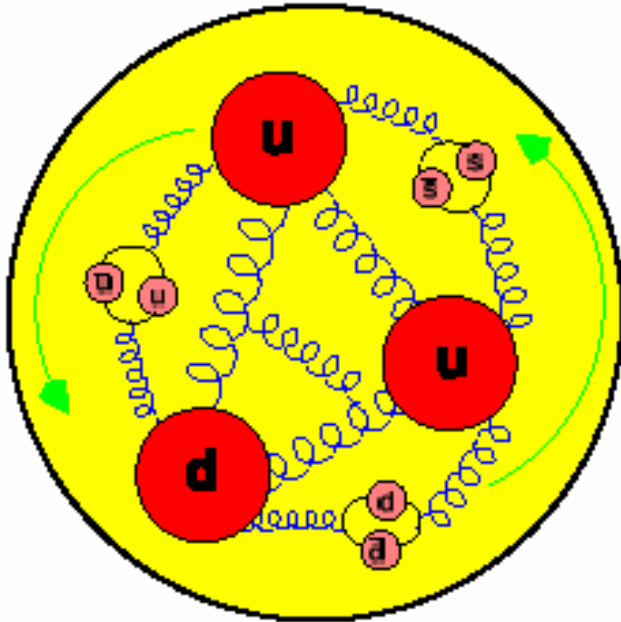
Synthesis of Atomic Matter from the 20th Century Atoms



The Proton, a Complex System of Quarks, Anti-Quarks and Gluons



Quark and Gluon Momentum Distributions



relative
quark
momentum

$$x = \frac{p_{quark}}{p_{proton}}$$

Constituents Particles of the Proton:
quarks = u, d, s and gluons

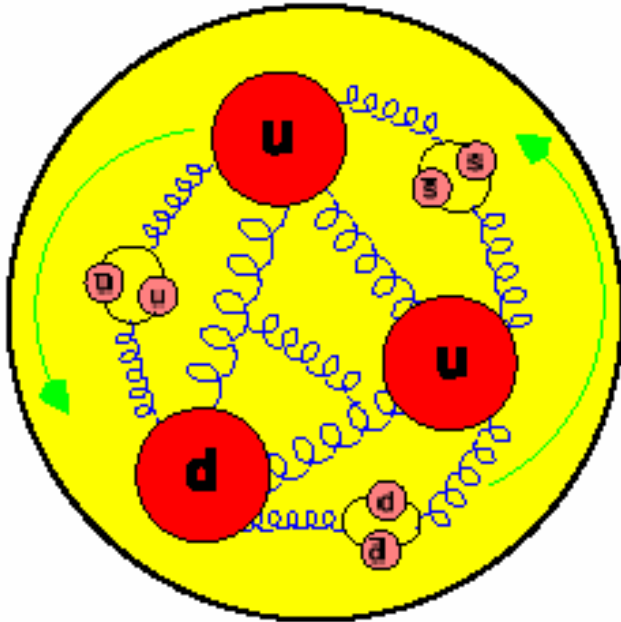
$q(x)$ = quark momentum distribution

Probability to observe a quark q with relative momentum x .

$G(x)$ = gluon momentum distribution

Probability to observe a gluon with relative momentum x .

Quark and Gluon Spin Distributions



relative
quark
momentum

$$x = \frac{p_{quark}}{p_{proton}}$$

Constituents Particles of the Proton:
quarks = u, d, s and gluons

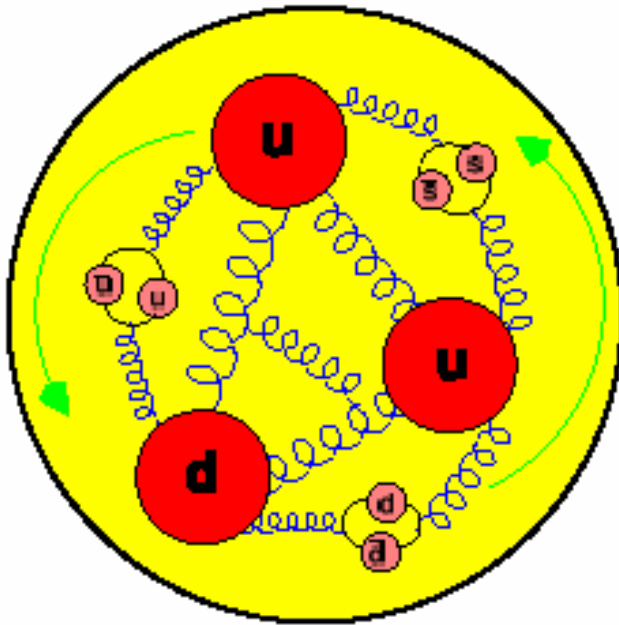
$\Delta q(x)$ = quark spin distribution

Probability to observe a quark with relative momentum x contributing to the proton spin.

$\Delta G(x)$ = gluon spin distribution

Probability to find gluon with relative momentum x contributing to the proton spin.

Decomposition of the Proton Spin: Quark Spin + Gluon Spin + Orbital Angular Momentum



$$\chi = \frac{p_{quark}}{p_{proton}}$$

Origin of the Proton Spin:

add all quark spin contributions $\Delta q(x) \rightarrow \Delta \Sigma$

add all gluon spin contributions $\Delta G(x) \rightarrow \Delta G$

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

Quark Spin

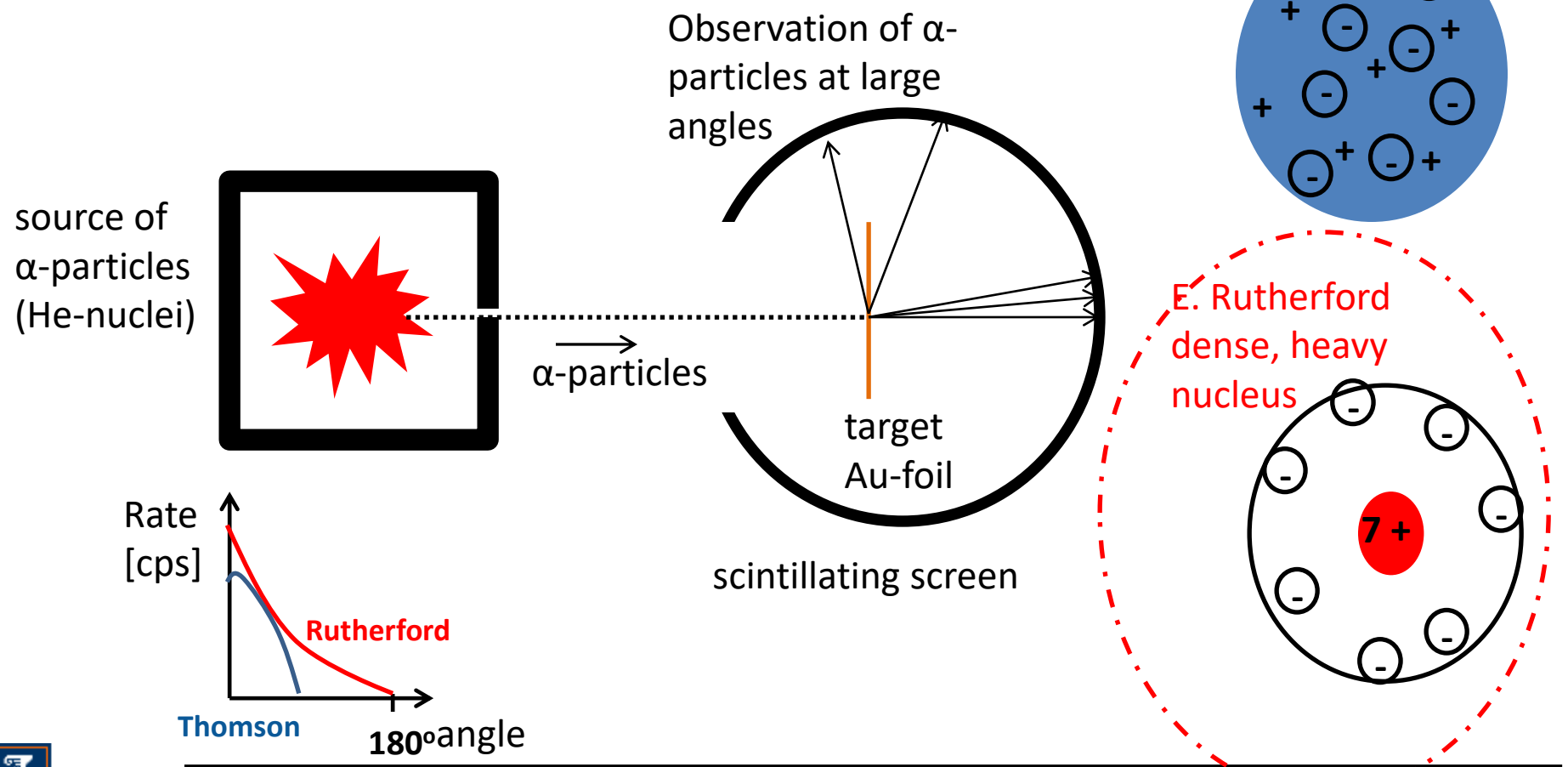
Gluon Spin

Orbital Angular momentum

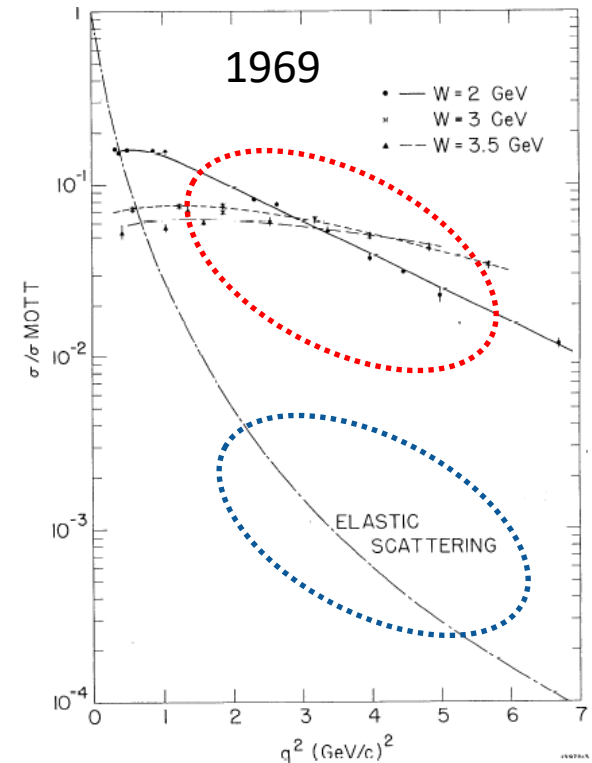
Experimental Method: Scattering of High Energy Particles on Target Material Under Study

Ernest Rutherford: Scattering experiments lead to the discovery of the atomic nucleus, 1911

J.J. Thomson
Atomic Plum Pudding
Model



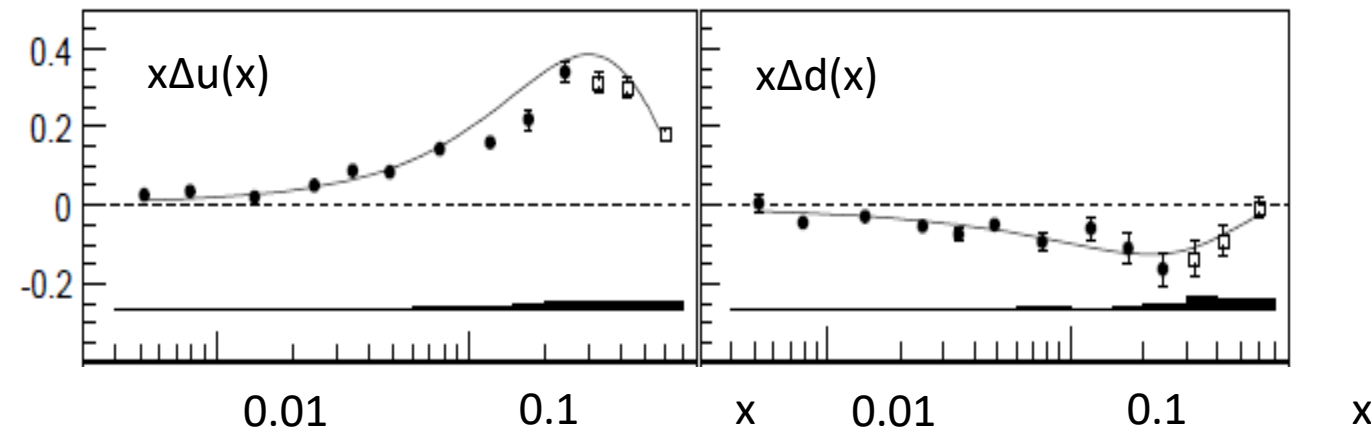
Discovery of Quark Structure in Protons Through Electron-Proton Scattering at SLAC



Nobel Prize 1990 for
Jerome Friedman, Henry Kendall and Richard Taylor

Quark Spin Distributions from the COMPASS Experiment at CERN, Switzerland

COMPASS Phys.Lett. B693 (2010) 227-235

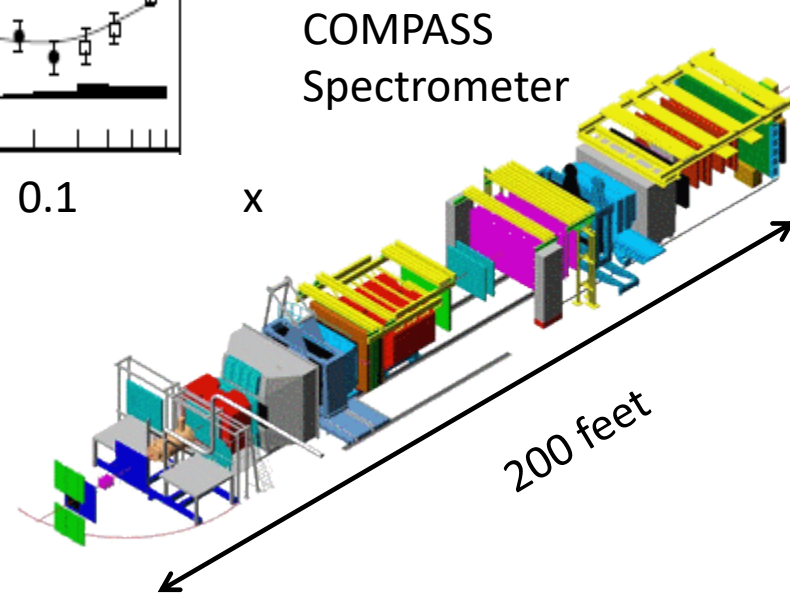


Δu is positive and contributes about $+0.69 \hbar$

Δd is negative and contributes about $-0.33 \hbar$

The total quark spin contribution, $\Delta\Sigma = 0.3 \hbar$

Next steps:
o measure gluon spin contribution
o probe anti-quark distributions (directly)



UIUC Built DC5 in COMPASS

Replacing 20 μ m
W/Au anodes



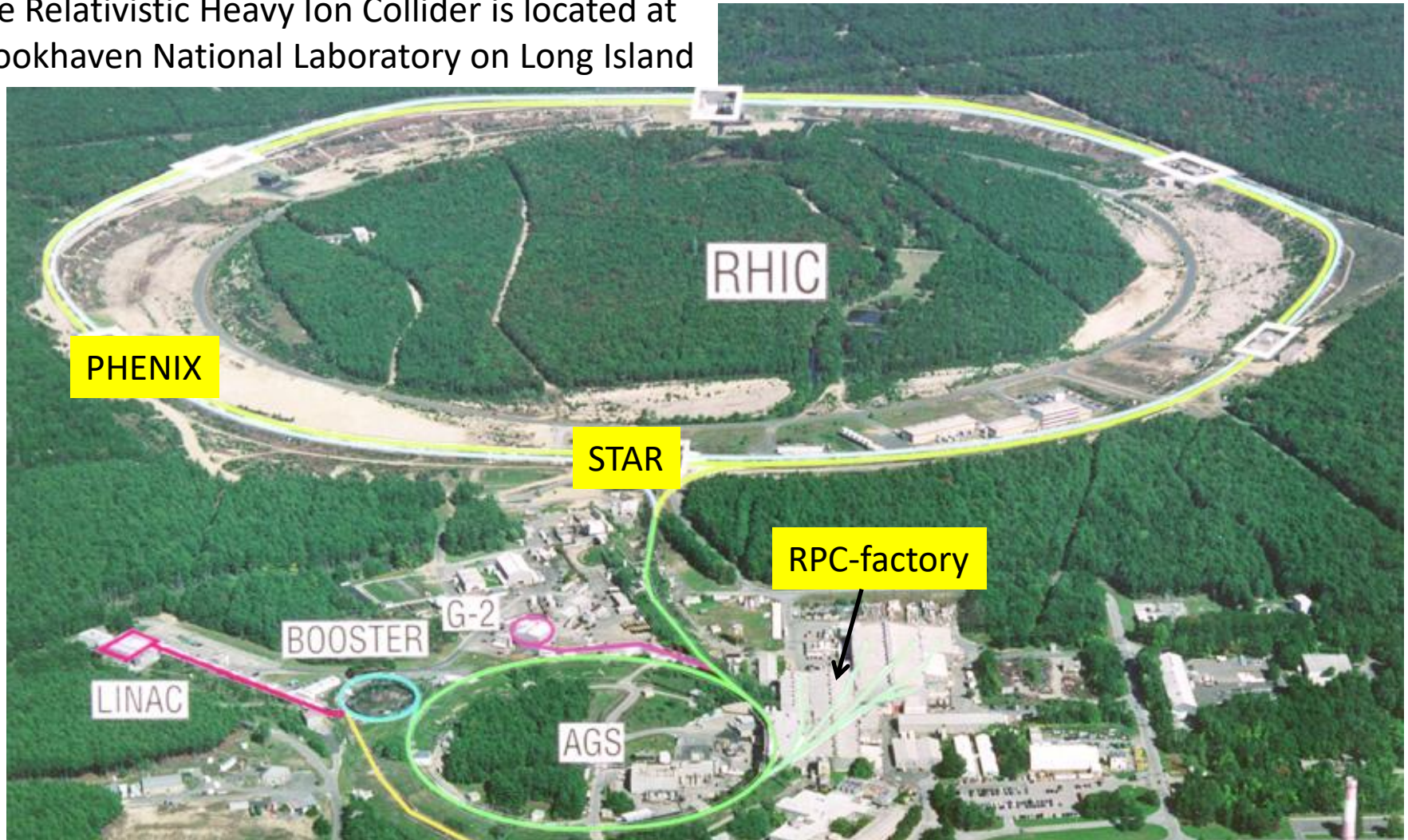
Moving out UIUC built
DC5 for repair in clean
room at CERN



UIUC research engineer Eric Thorsland and technicians Adam Wehe and Lucas Reeves

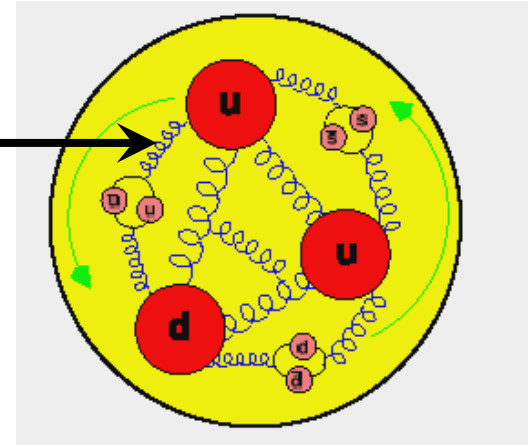
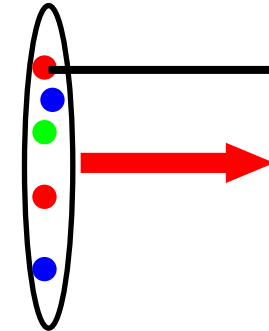
Measurement of Spin-Dependent Anti-Quark Distributions in PHENIX at RHIC

The Relativistic Heavy Ion Collider is located at Brookhaven National Laboratory on Long Island



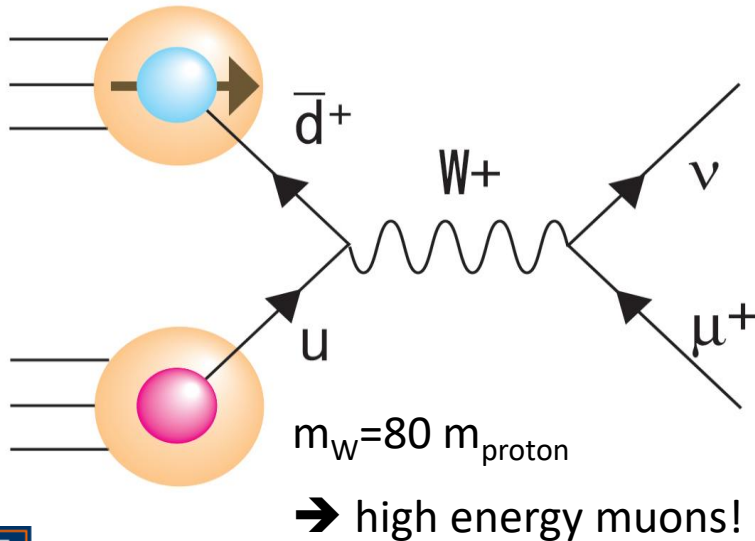
How Can we Probe Proton Spin Structure at RHIC?

At ultra-relativistic energies the proton represents a jet of quarks and gluons



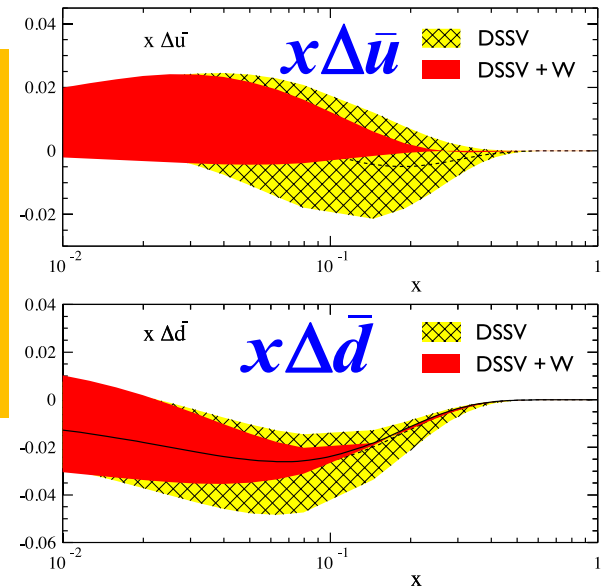
Use the weak nuclear force ($W^{+,-}$ -bosons) to directly probe anti-quarks !

$$p + p \rightarrow W^{\pm} \rightarrow \mu^{\pm} + \nu$$



Error projections from computer simulations, the future error band from Ws at RHIC is red!

$$A_L \approx \frac{\bar{u}}{u}$$



The Experimental Challenge in PHENIX

**Only 1 (useful) W-boson in
1 billion p-p collisions**

Must operate at 5-10 million p-p
collisions per second!

PHENIX has 350,000 readout channels
10 MHz corresponds to about
5 TeraByte/second detector data

All raw data are kept for 4 micro sec.
after this only selected data can be
written to tape (0.5 GigaByte/second)

**Need to develop new detectors +
fast online computers to find high
energy muons from W-boson
decay in less than 4 micro seconds!!**



The W-Trigger Upgrade in PHENIX

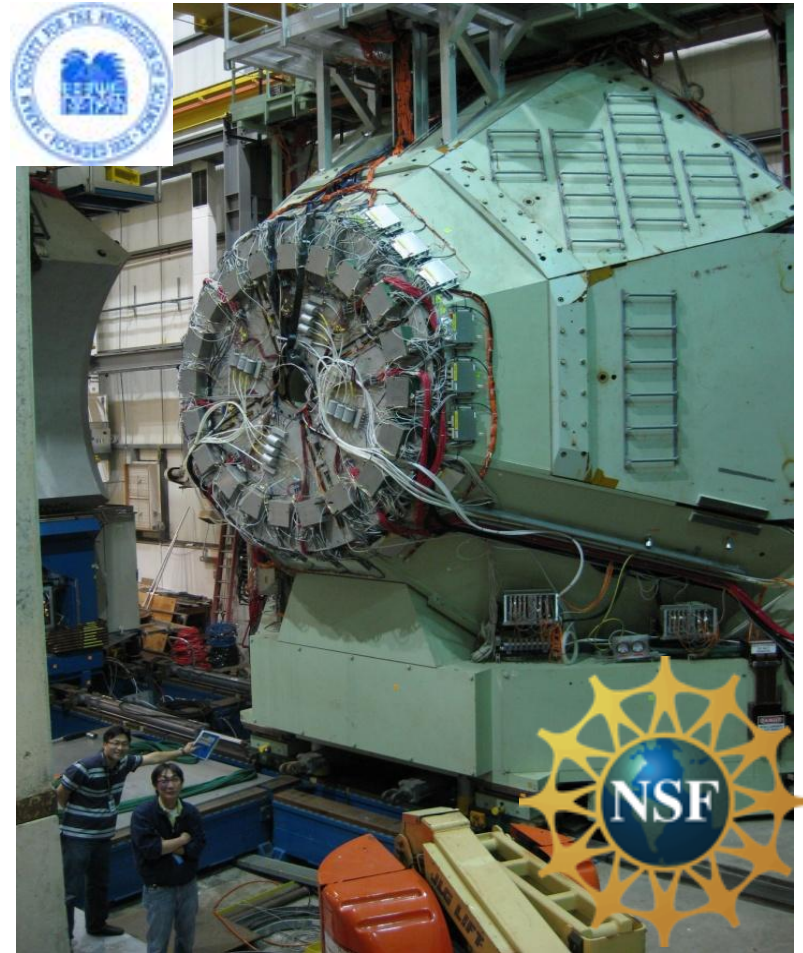
- (I) Develop fast processor boards to identify high energy muons in 4 micro seconds.
- (II) Develop fast readout electronics for existing muon tracking chambers
- (III) Develop additional fast tracking detectors, RPCs, for timing and background rejection

89 physicists from 18 institutions in the US, Japan, Korea and China:

KEK, Kyoto, RIKEN, Rikkyo, LANL, U. New Mexico, Seoul National University (**JSPS funded**)

UIUC, RBRC, UC Boulder, ISU, CIAE/PKU, Columbia University, GSU, UC Riverside, Korea University, ACU, Muhlenberg College, Hanyang University (**NSF funded**)

Construction: September 2005 to January 2012



The Construction Project

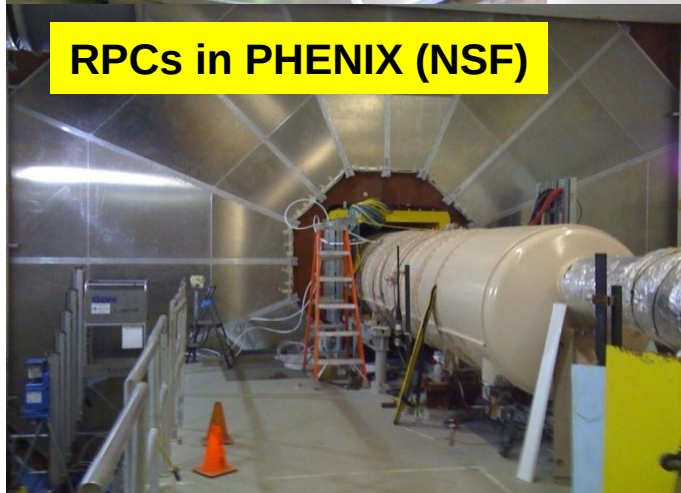


RPCs in Urbana (NSF)

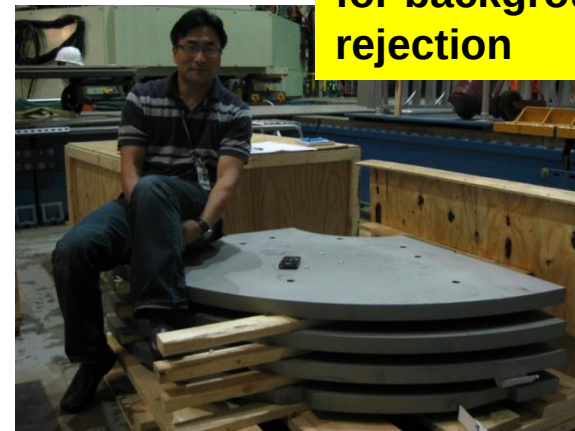
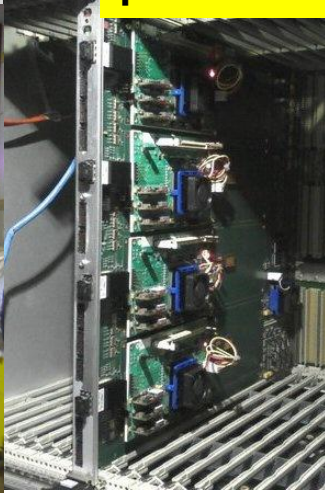


muTr trigger electronics(JSPS)

FPGA based level-1 trigger processors



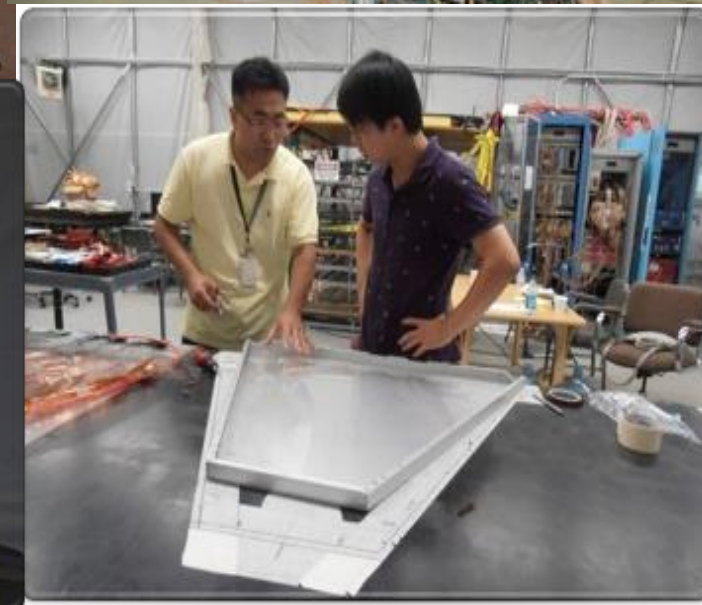
RPCs in PHENIX (NSF)



SS 310 absorbers for background rejection

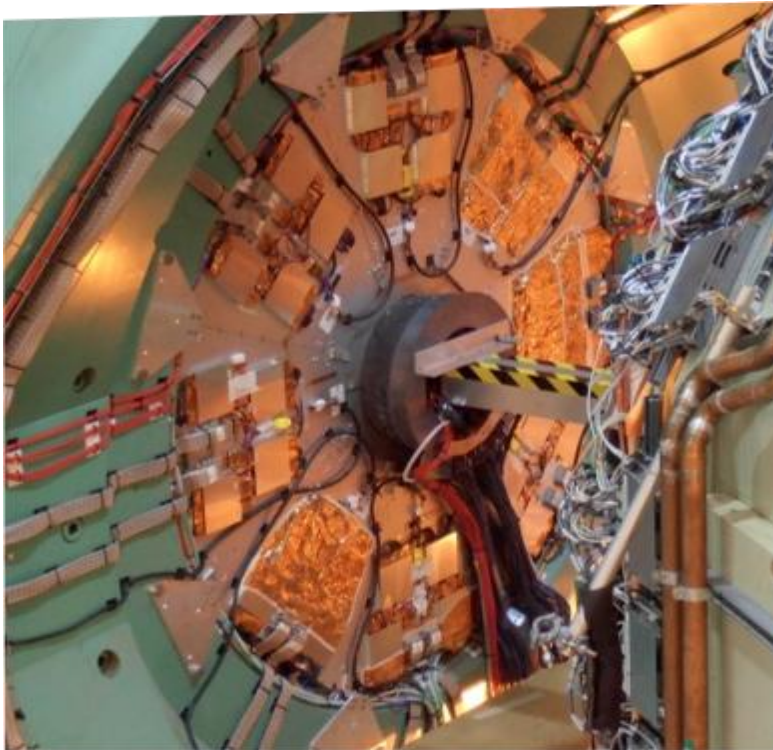


Assembly in the RPC Factory at BNL



Installation in the PHENIX Spectrometer

PHENIX RPC-1 north (~ 3m)



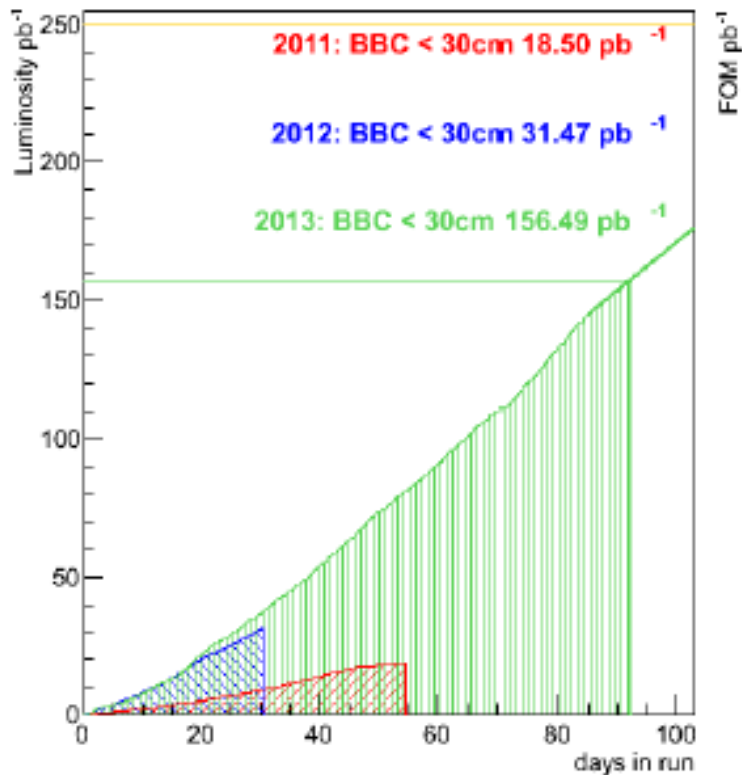
PHENIX RPC-3 north (diameter ~ 10 m)



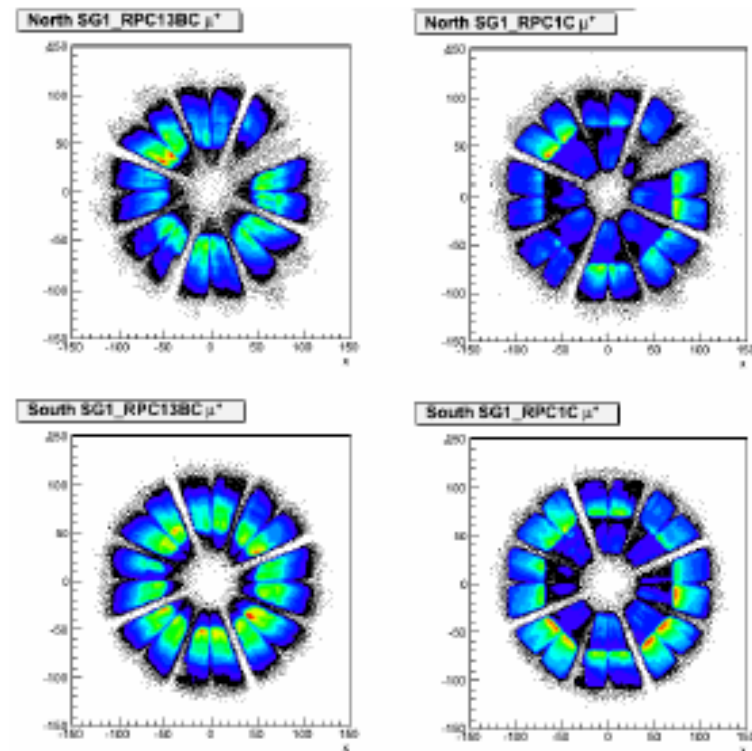
Three Years of Data Taking

Good Accelerator Performance !

Luminosities

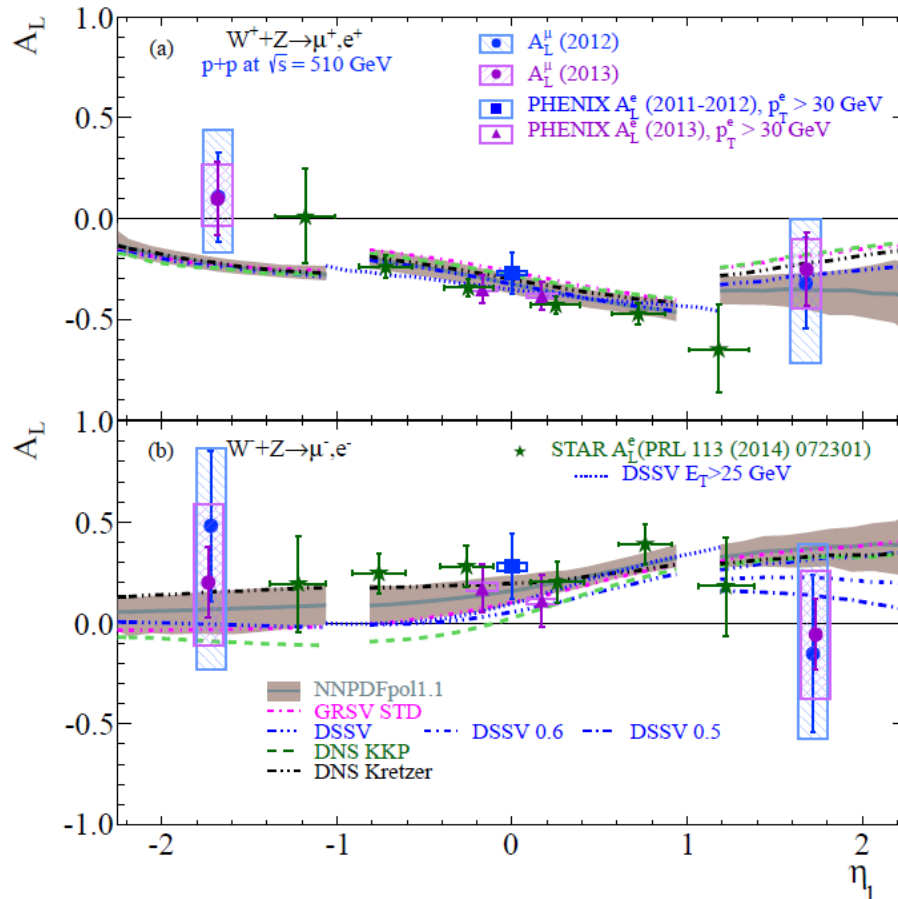


Good Detector Performance !

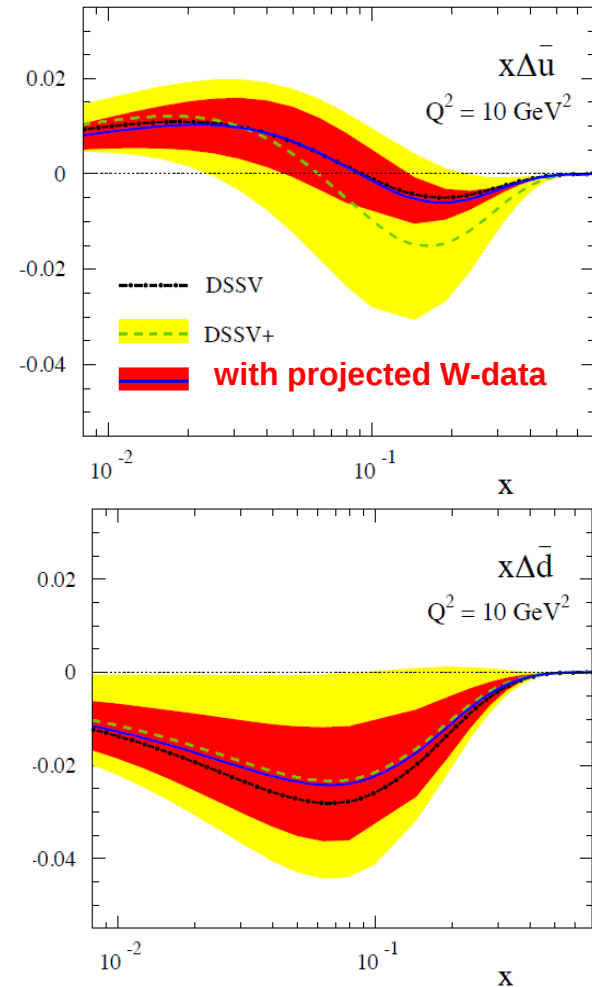


$A_L(W)$ in Runs 2012 & 2013 and Projected Impact on $\Delta\bar{q}(x)$

Final results published PRD in
summer 2018:



DSSV: projected impact of new
2013 STAR and PHENIX data



DSSV from “The RHIC Spin Program”
Aschenauer et al. arXiv:1501.01220

Summary

A large experimental effort in polarized e-p and p-p is underway to determine the spin structure of the proton.

In deep inelastic e-p scattering the quark spin contribution has been found to be $1/3$.

W-Production in polarized proton-proton Collisions at RHIC provide unique sensitivity to the anti-quark spin distributions in the proton.

The PHENIX detector was upgraded successfully for W-physics. Data taking has been completed successfully and data analysis has started.

UIUC Group Working the PHENIX W-Trigger and Data Analysis

Amazon



John Koster
New York

Korean Institute for
Fundamental Physics



Young Jin Kim
South Korea

Goldman Sachs



Ruizhe Yang
Beijing



Scott Wolin
Illinois

Northrup
Grumman



Martin Leitgab
Austria

NASA



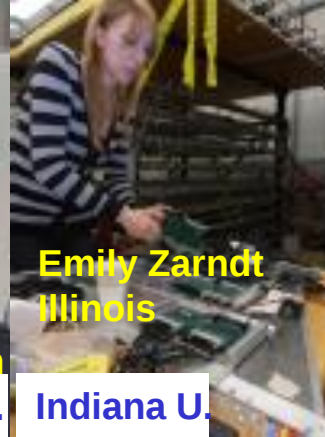
Epic.
Cameron McKinney
Indiana



Dave Northacker
Illinois



Beau Meredith
Illinois Citadel.



Emily Zarndt
Illinois



Francesca Giordano
Italy Sanger Institute
Cambridge



Pedro
Montuenga
Venezuela



John Blackburn
Illinois



JhnJea Choi
South Korea



Daniel Jumper
Texas



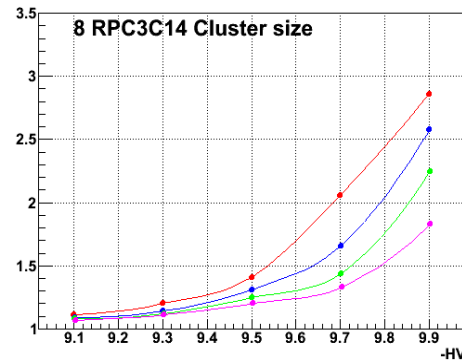
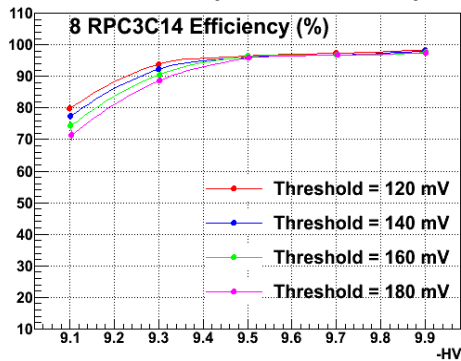
Matthias Perdekamp
Germany



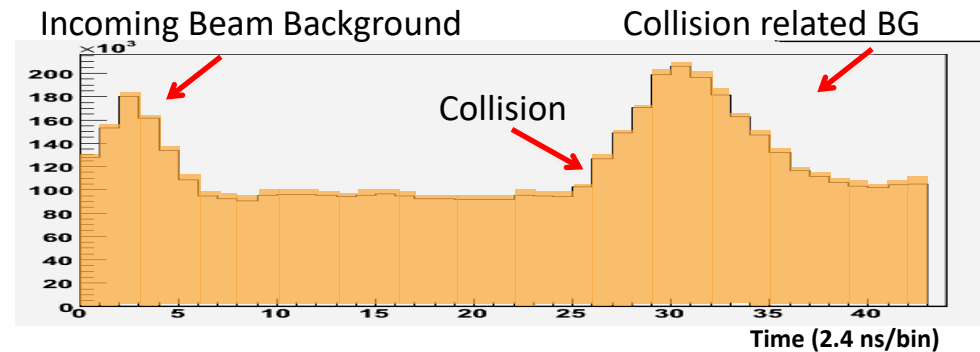
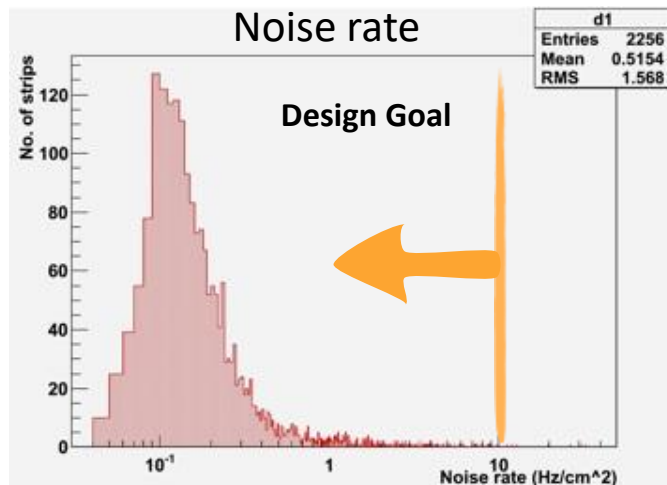
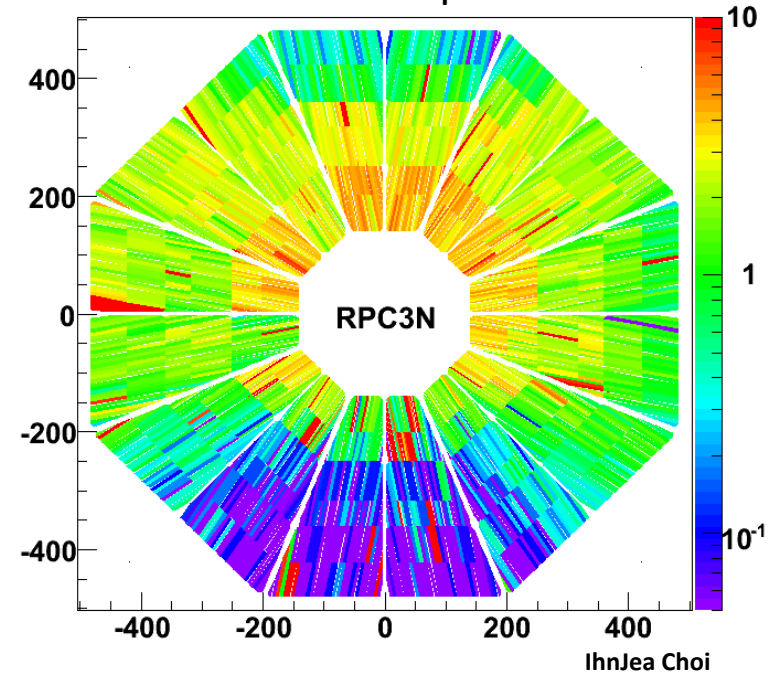
Anselm Vossen
Germany

Indiana U.

RPC Factory: efficiency & Cluster size



RPC3 Hit map



RPC Performance