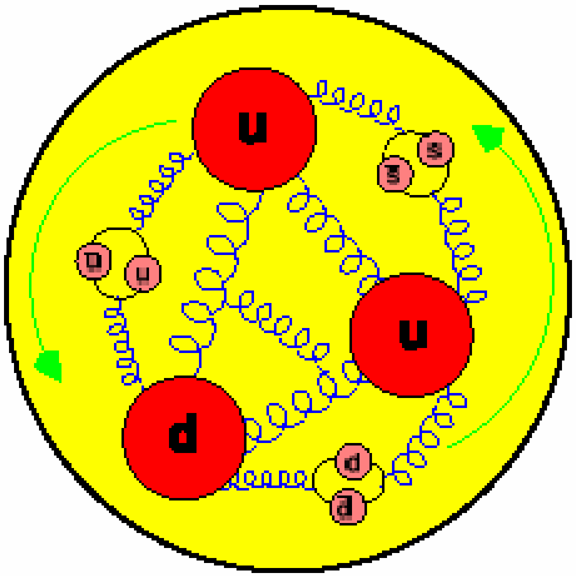
W-Bosons as a Microscope for the Observation of Quarks and Anti-Quarks Inside the Proton

M. Grosse Perdekamp
University of Illinois, Urbana Champaign



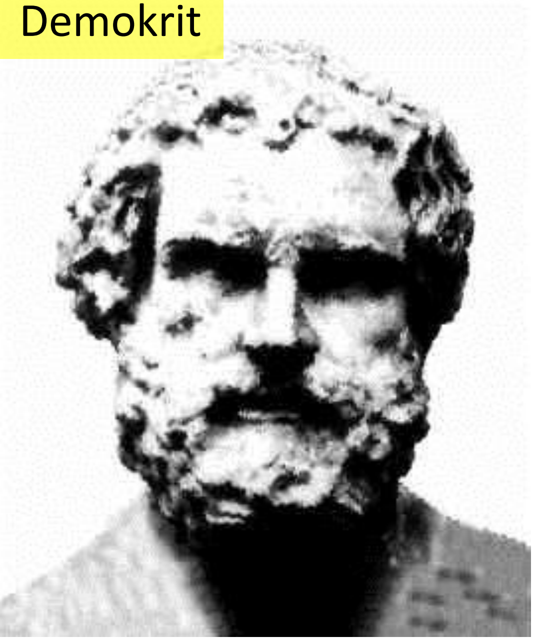
PHYS 403 – Research Talk
April 23rd, 2019

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 !

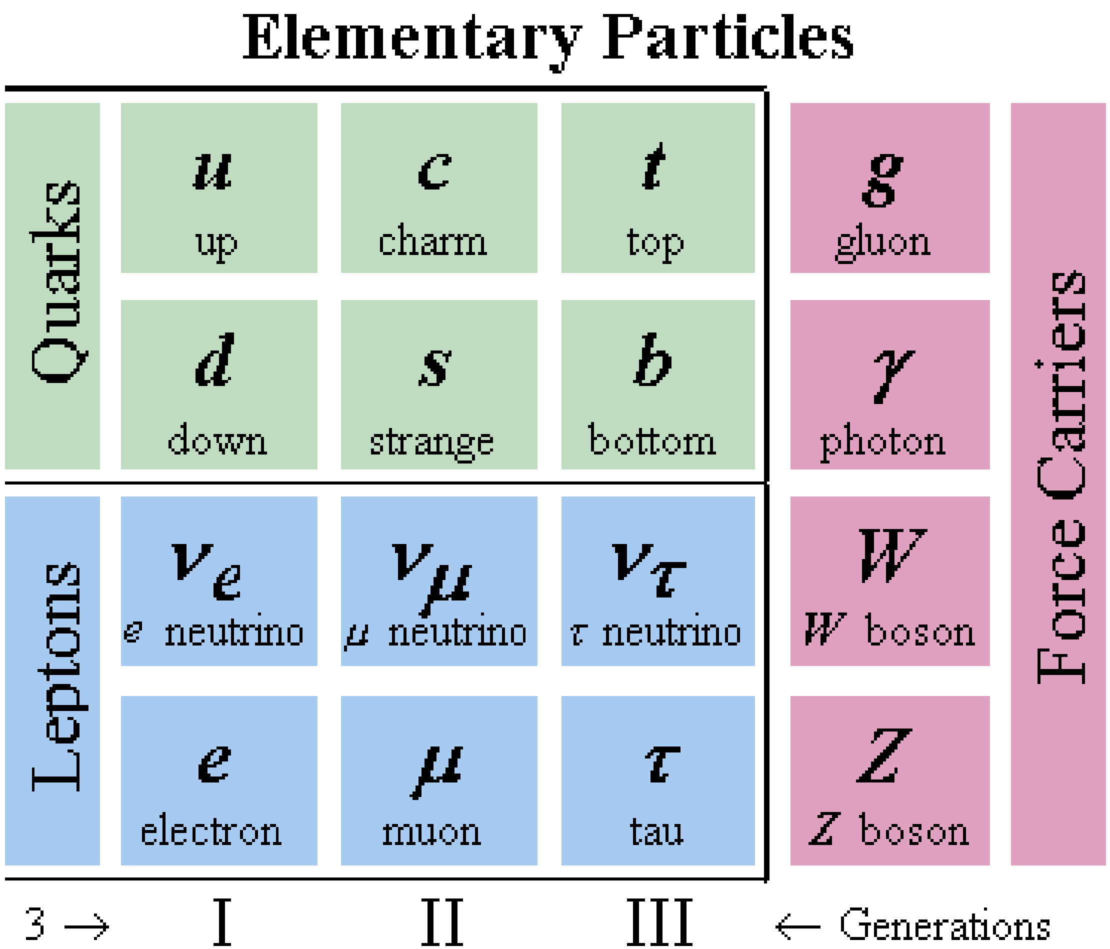
There are small particles, atoms, of which all matter is made and which cannot be divided in smaller parts.

PHENIX Experiment at Brookhaven National Lab

Some 2400 years & 80 generations later:

Modern experimental tools may provide quantitative answers in our lifetime!

The Atoms of the 20th Century: Quarks and Leptons



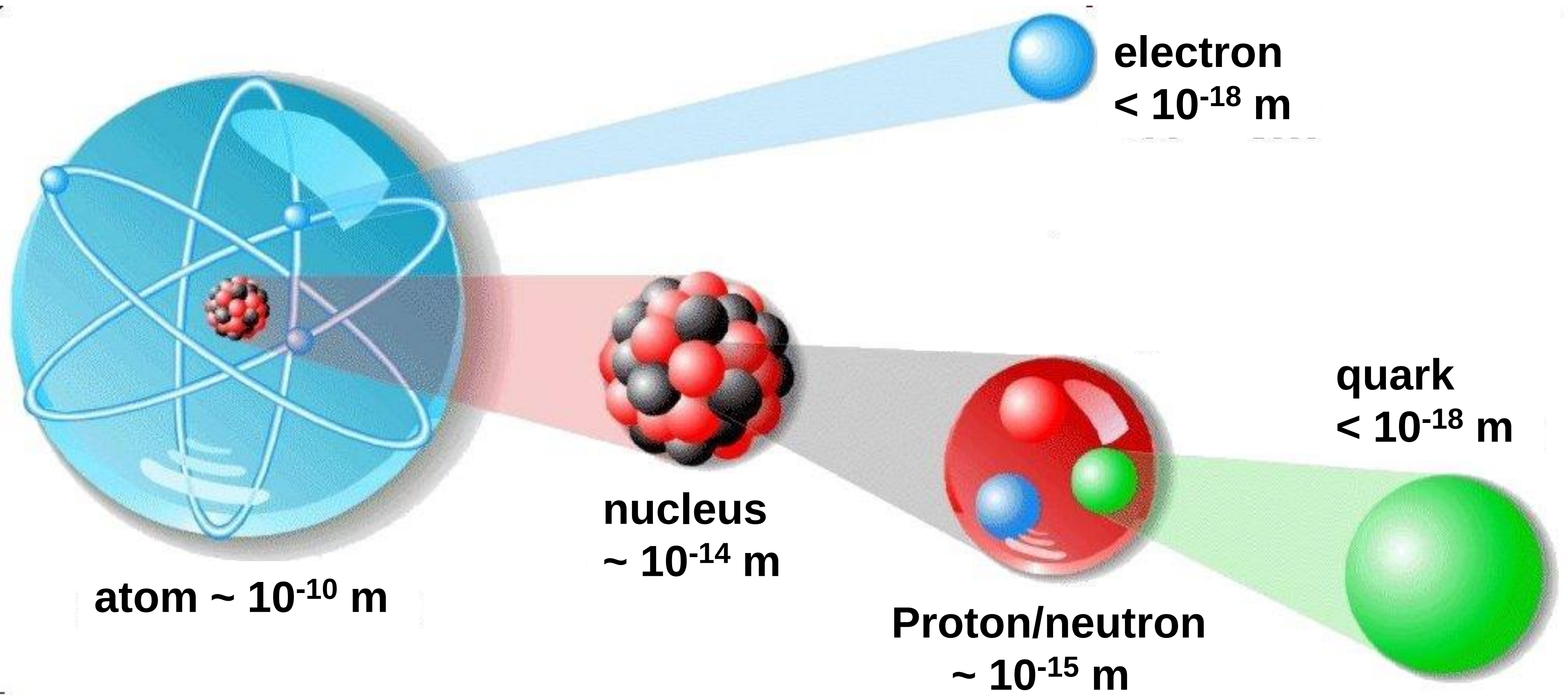
Up- and down-**quarks** are the building blocks of all **nuclear matter** in the nuclei of atoms.

Electrons make up the **shell of atoms**.

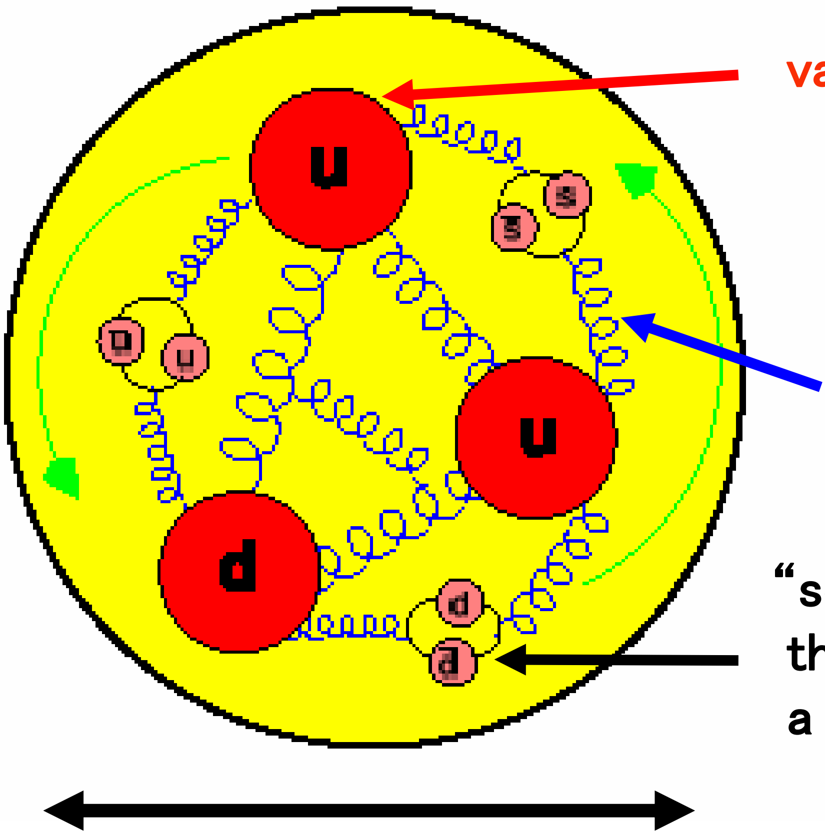
Forces:

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



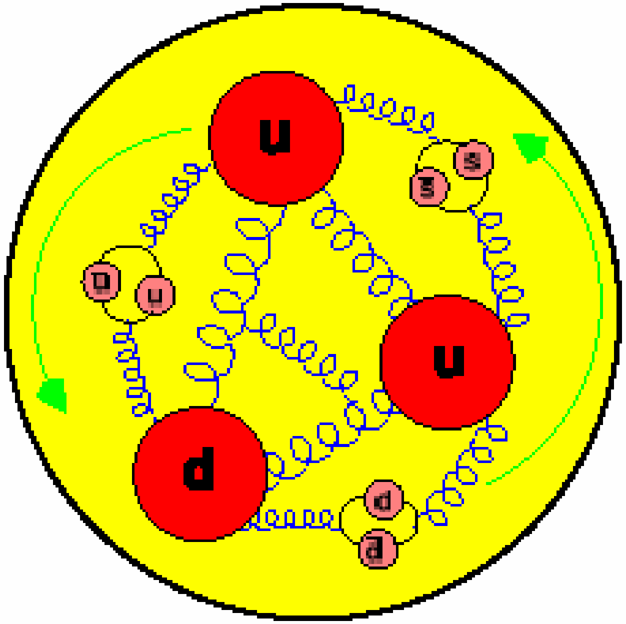
valence quarks: 2 up–, 1 down–quark

gluons, the force carriers of the strong nuclear force.

"sea–quarks" : quark–anti–quark pairs that can be formed from a gluon for a short time and annihilate again.

1 Fermi m = 1 Fm ~ 10^{-15}m

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

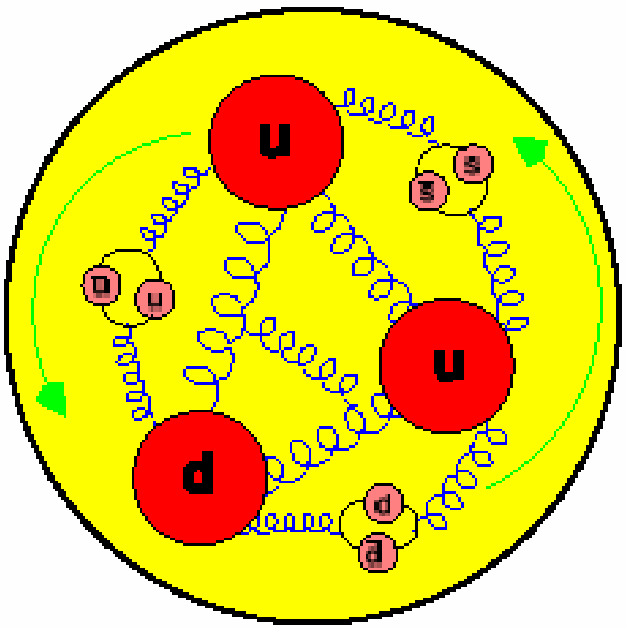
$$q(x) = \text{quark momentum distribution}$$

Probability to observe a quark q with relative momentum x.

$$G(x) = \text{gluon momentum distribution}$$

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

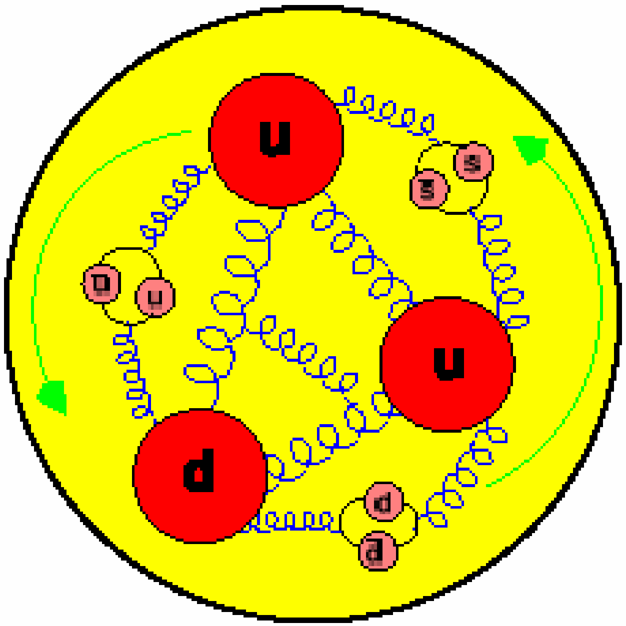
$$\Delta q(x) = \text{quark spin distribution}$$

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

$$\Delta G(x) = \text{gluon spin distribution}$$

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

Decompostion of the Proton Spin: Quark Spin + Gluon Spin + Orbital Angular Monentum



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

Origin of the Proton Spin:

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

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

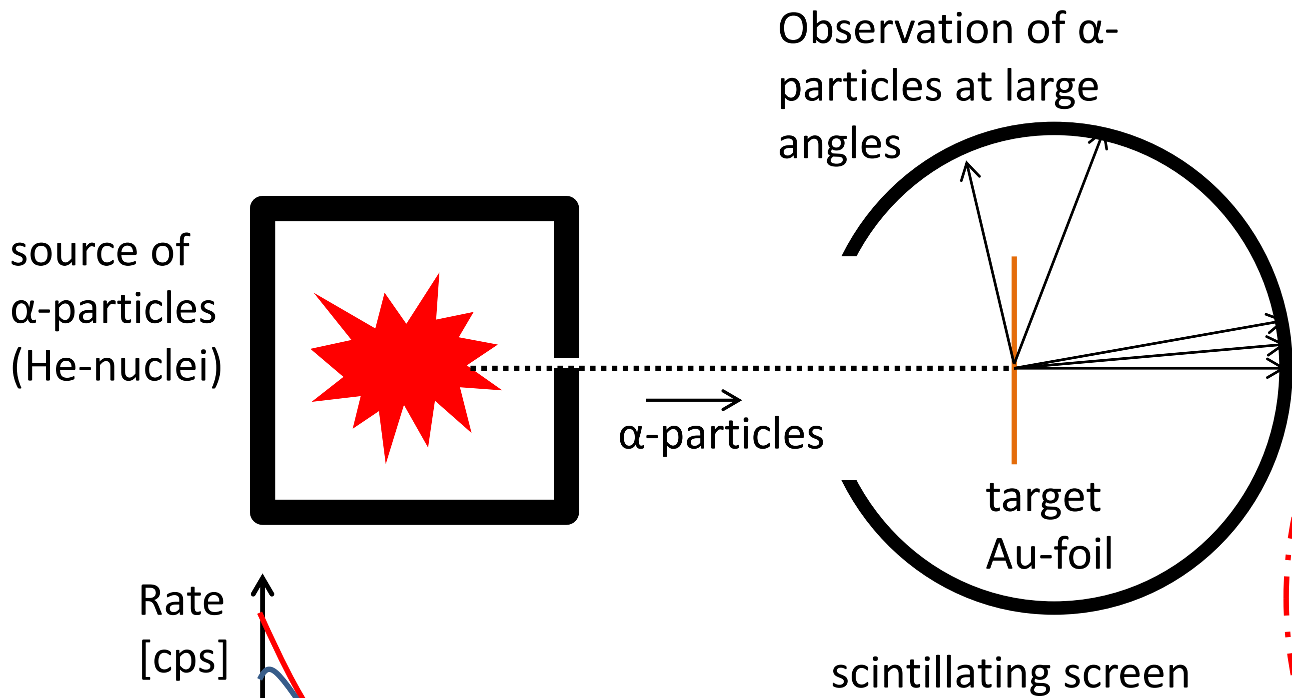
Quark Spin

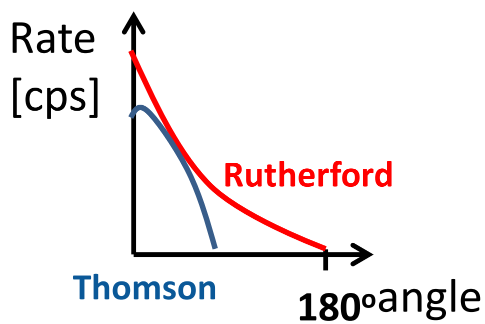
Gluon Spin

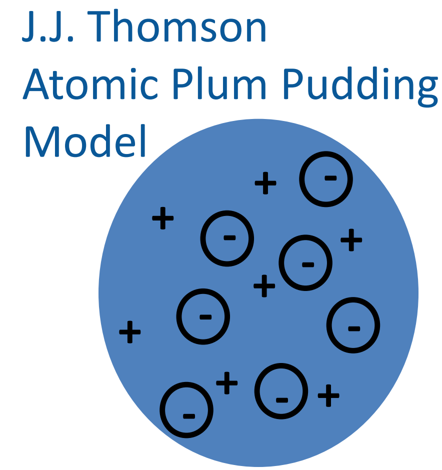
Orbital Angular momentum

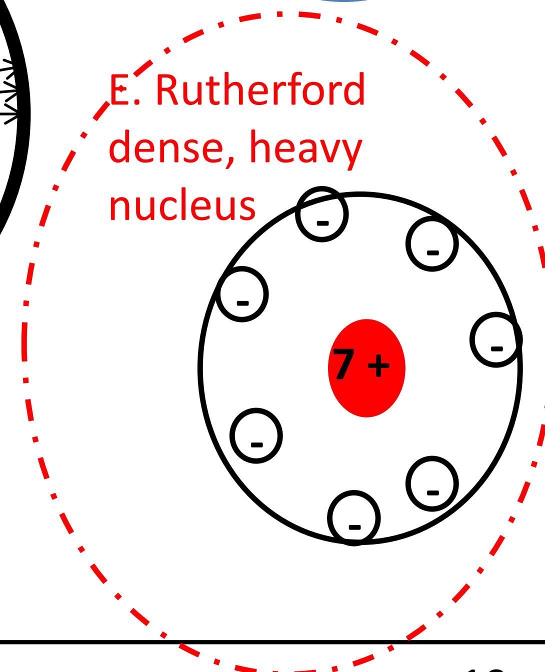
Experimental Method: Scattering of High Energy Particles on Target Material Under Study

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

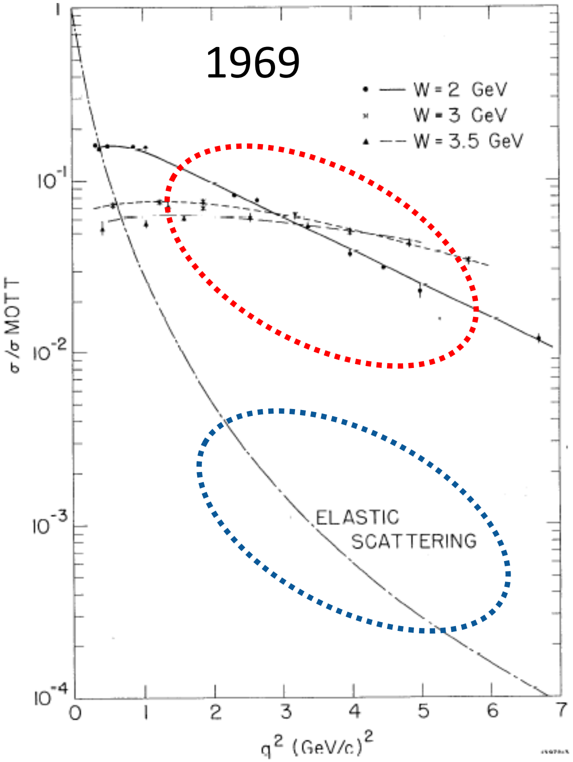








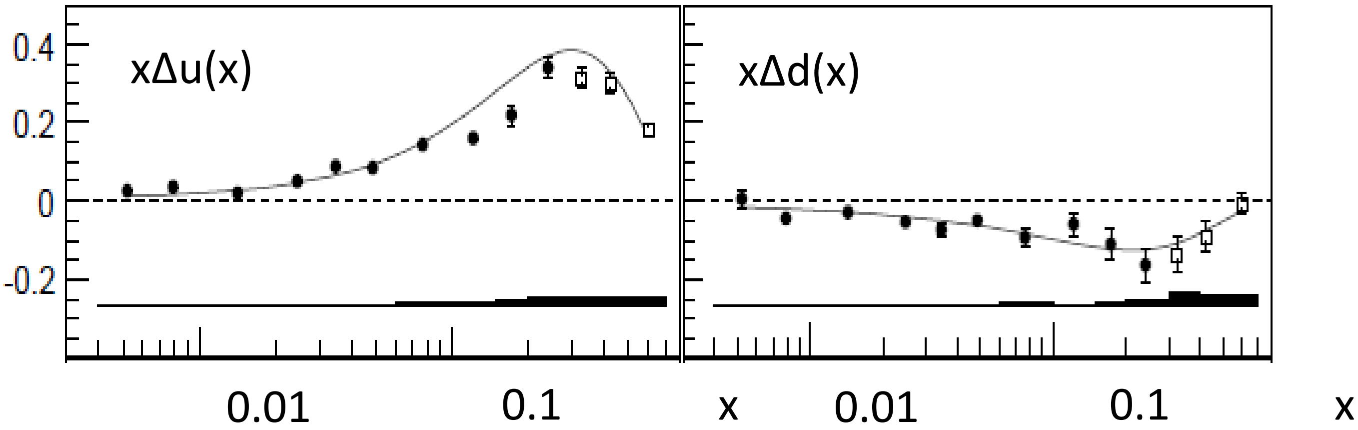
Discovery of Quark Structure in Protons Through Electron-Proton Scattering at SLAC

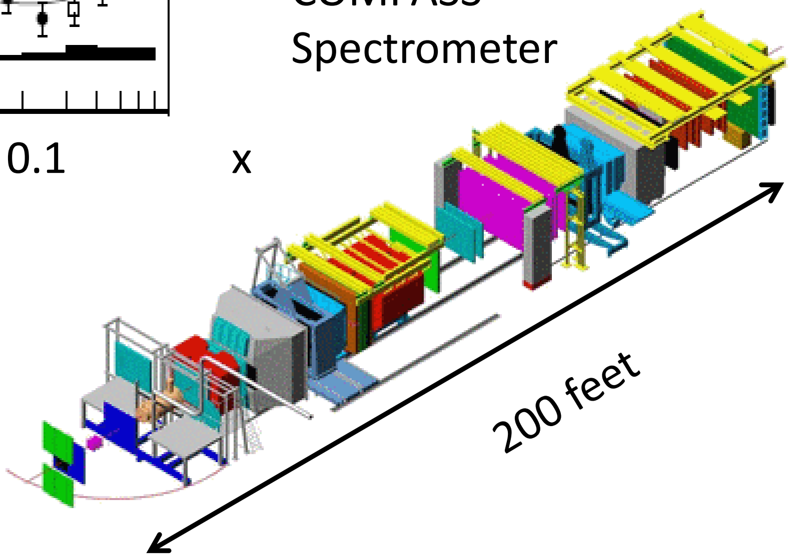


Nobel Prize 1990 for
Jerome Friedman, Henry Kendall and Richard Taylor

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 $\hbar$

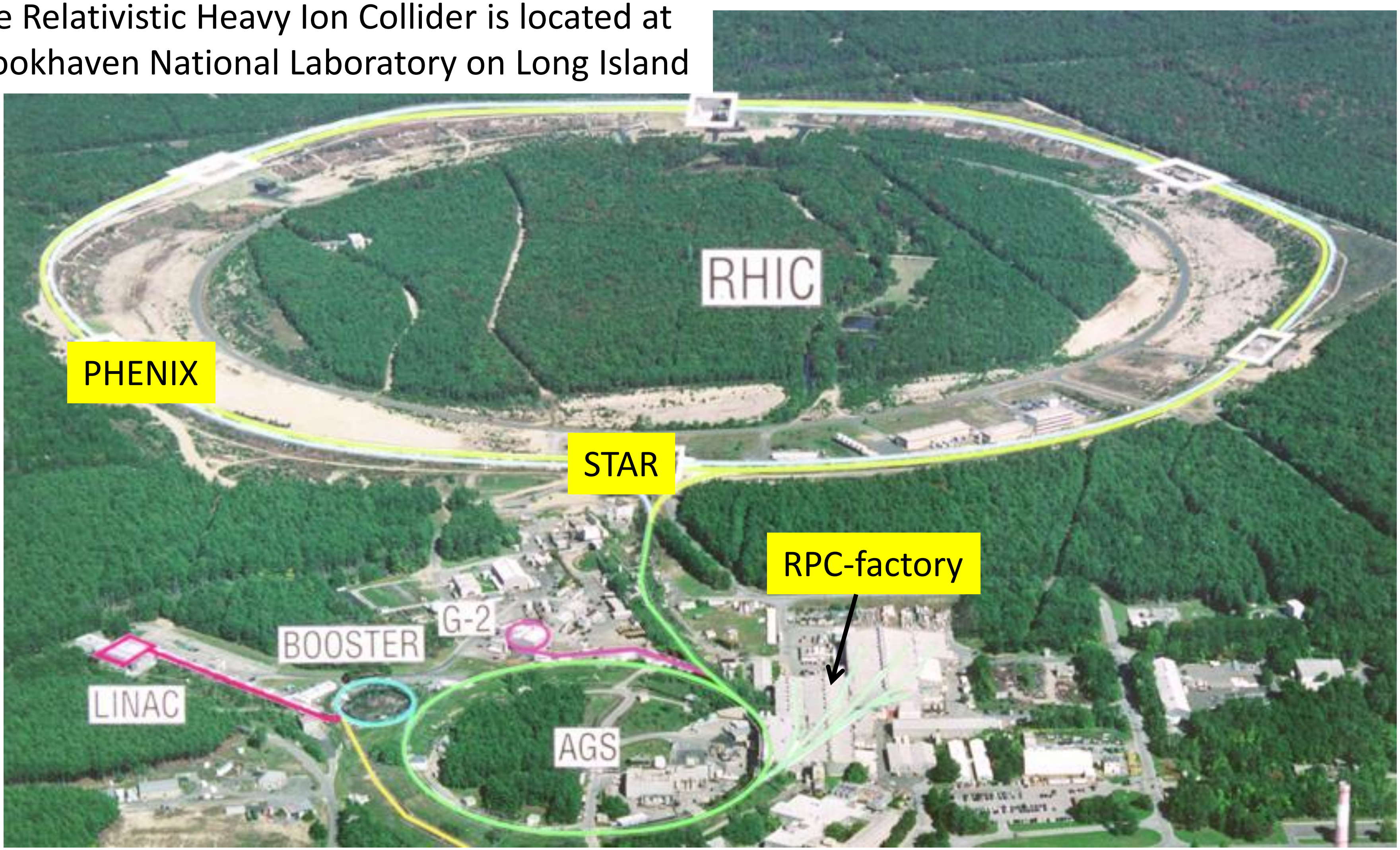
The total quark spin contribution , ΔΣ = 0.3 $\hbar$

Next steps: o measure gluon spin contribution

o probe anti-quark distributions (directly)

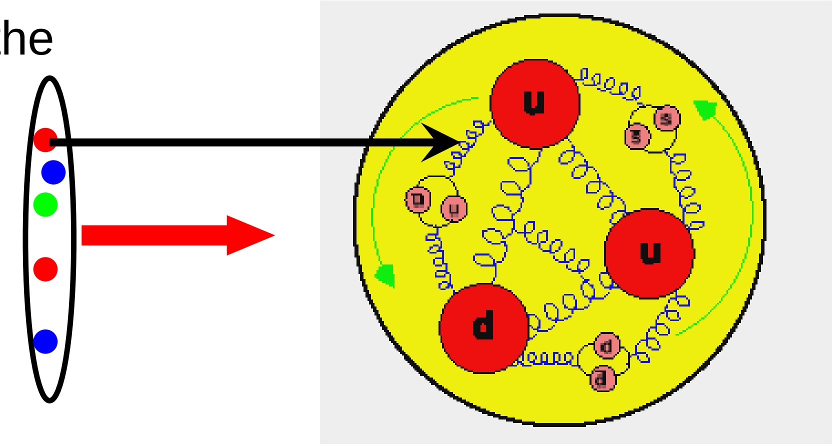
Measurement of Spin-Dependent Anti-Quark Distributions in PHENIX at RHIC

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



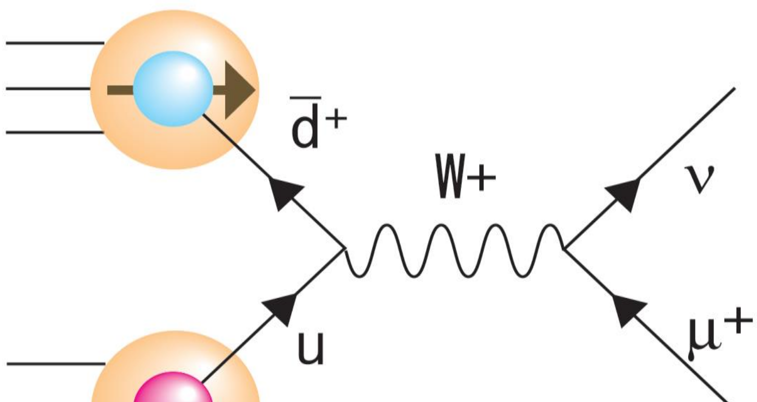
How Can we Probe Proton Spin Structure at RHIC?

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 !

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

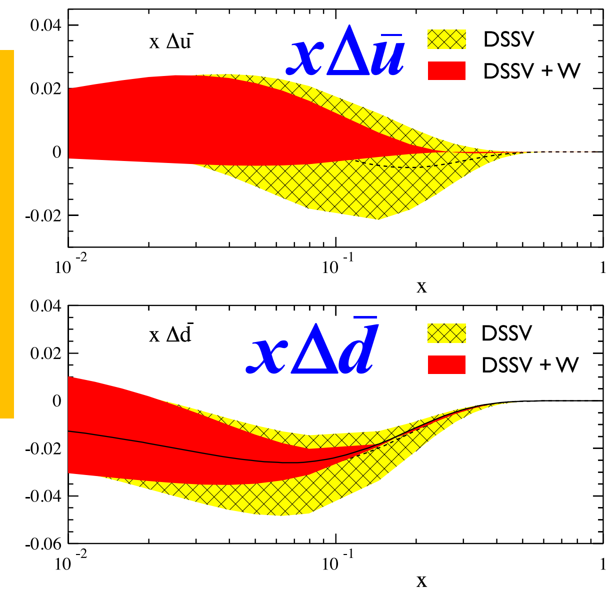


m_W=80 m_{proton}

➔ high energy muons!

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

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



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

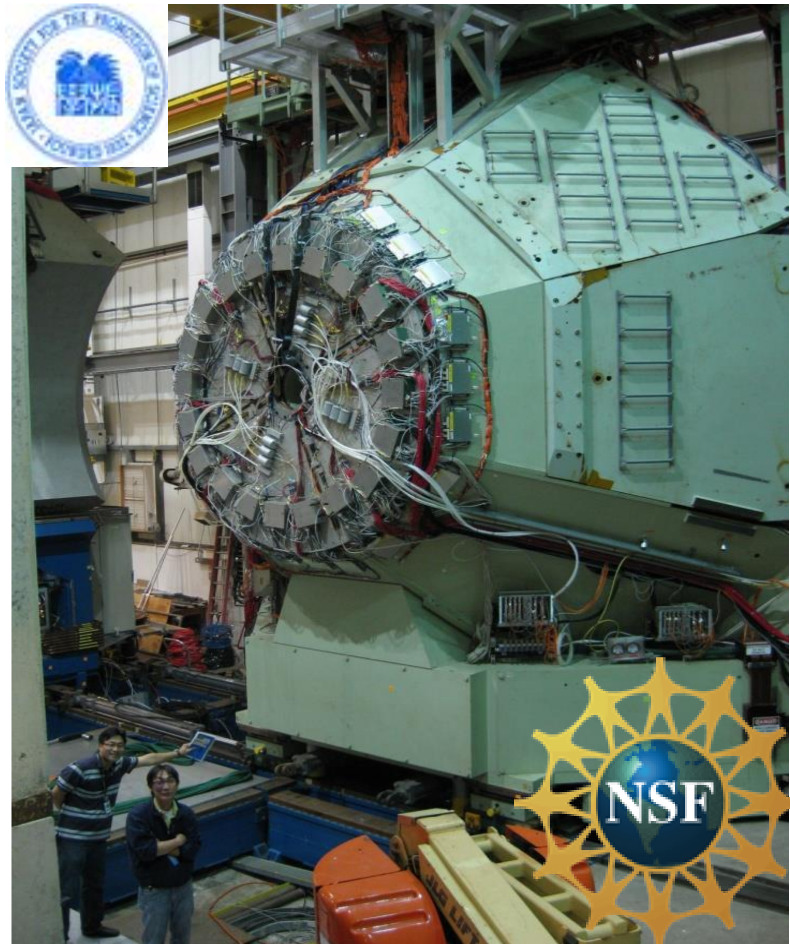
(III) Develop additional fast tracking detectors, RPCs, for timing and background rejection

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

<u>KEK,</u> Kyoto, RIKEN, Rikkyo, LANL, U. New Mexico, Seoul National University (JSPS funded)

<u>UIUC</u>, 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

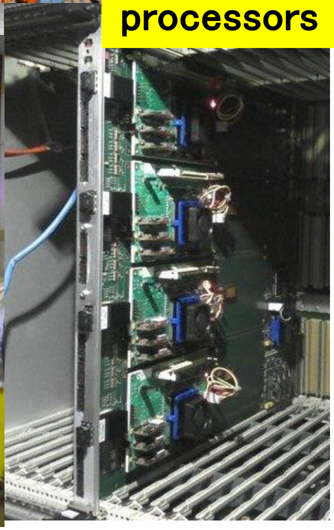


The Construction Project

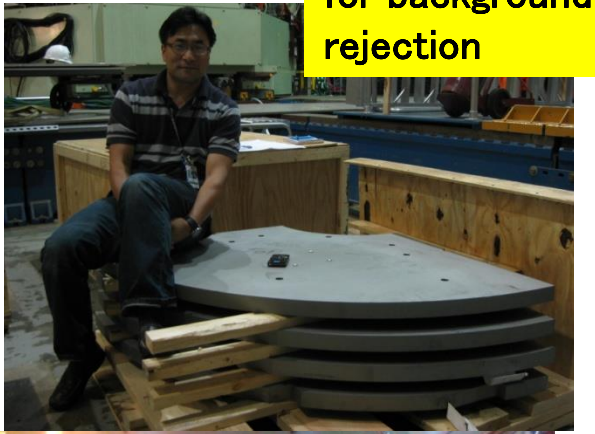
RPCs in Urbana (NSF)

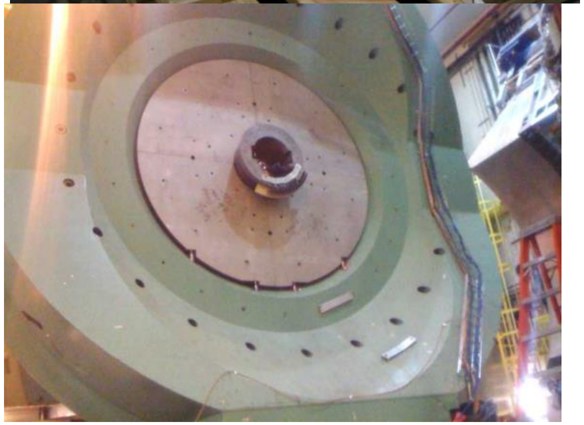
muTr trigger electronics(JSPS)

RPCs in PHENIX (NSF)



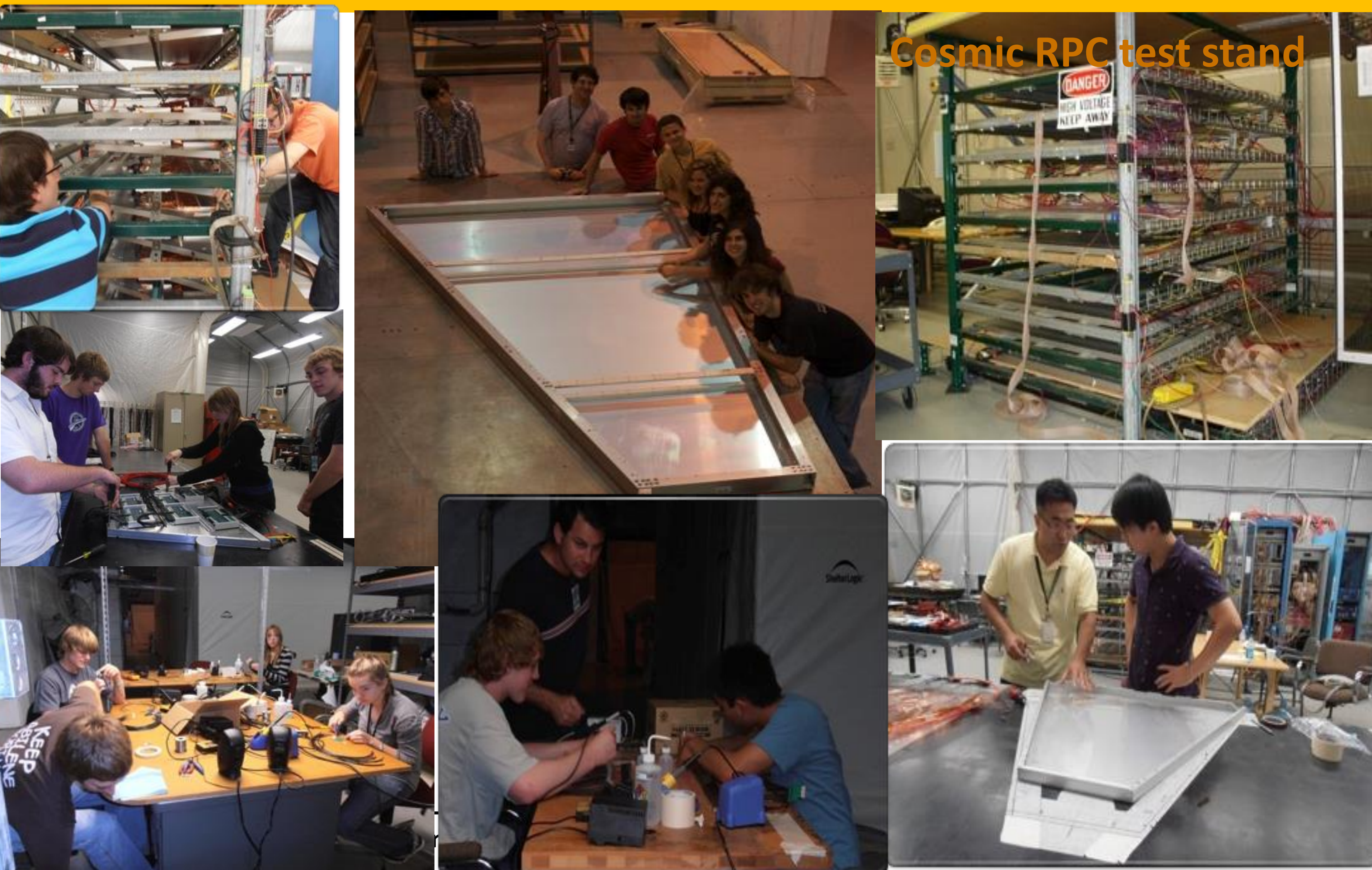
FPGA based level-1 trigger processors





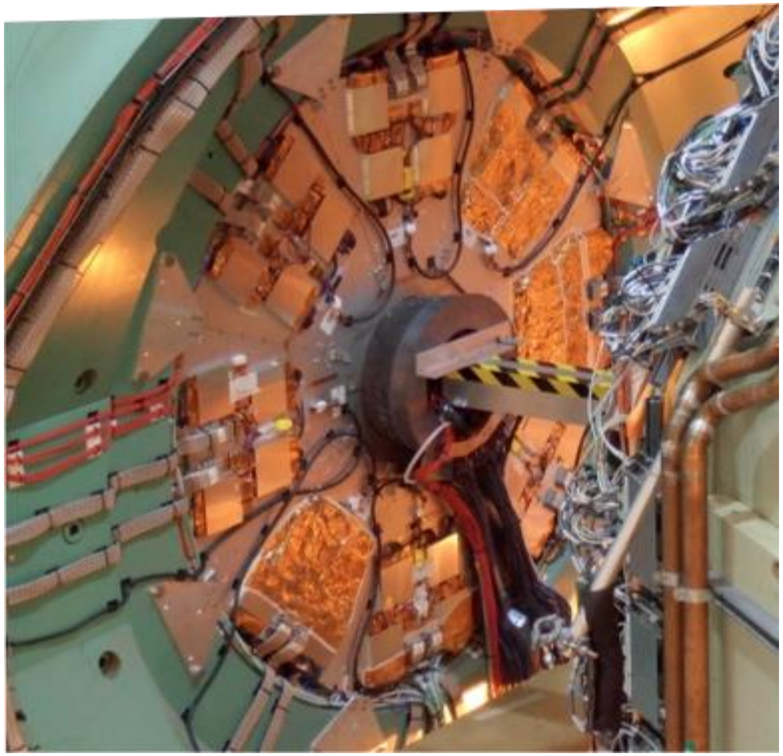
SS 310 absorbers for background rejection

Assembly in the RPC Factory at BNL



Installation in the PHENIX Spectrometer

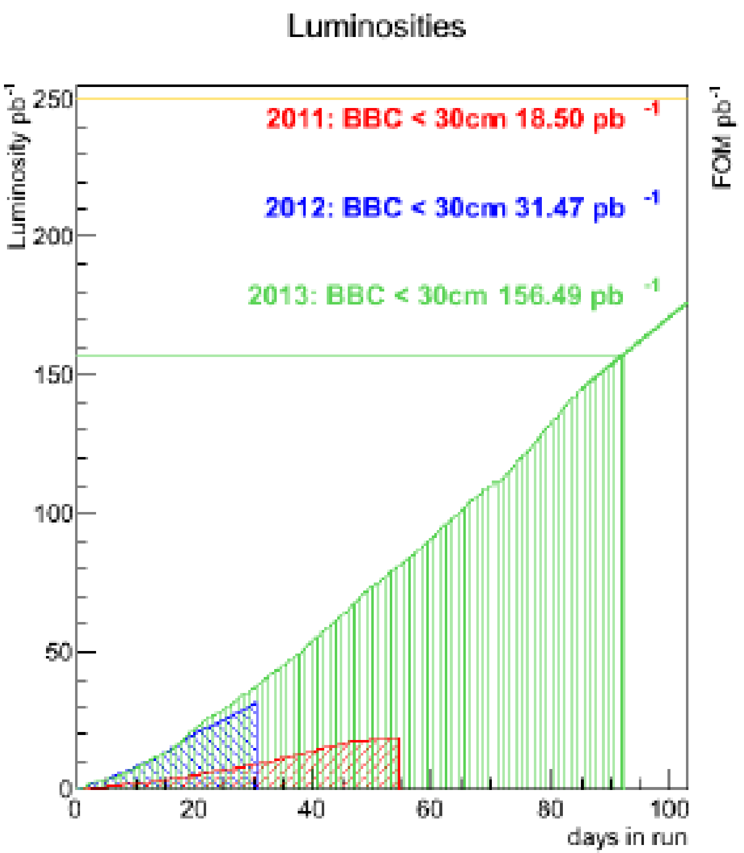
PHENIX RPC-1 north (~ 3m)



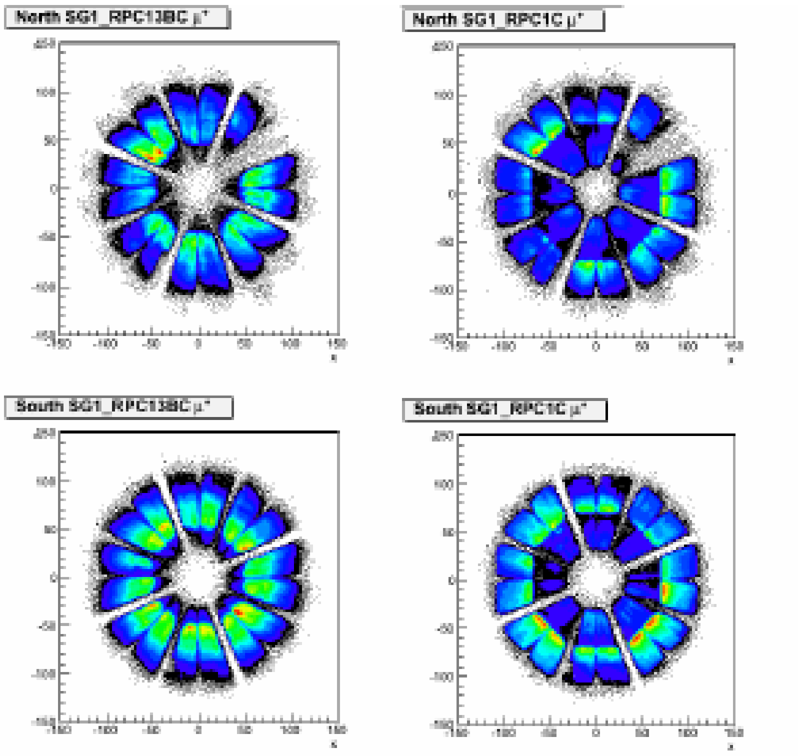
PHENIX RPC-3 north (diameter ~ 10 m)

Three Years of Data Taking

Good Accelerator Performance !

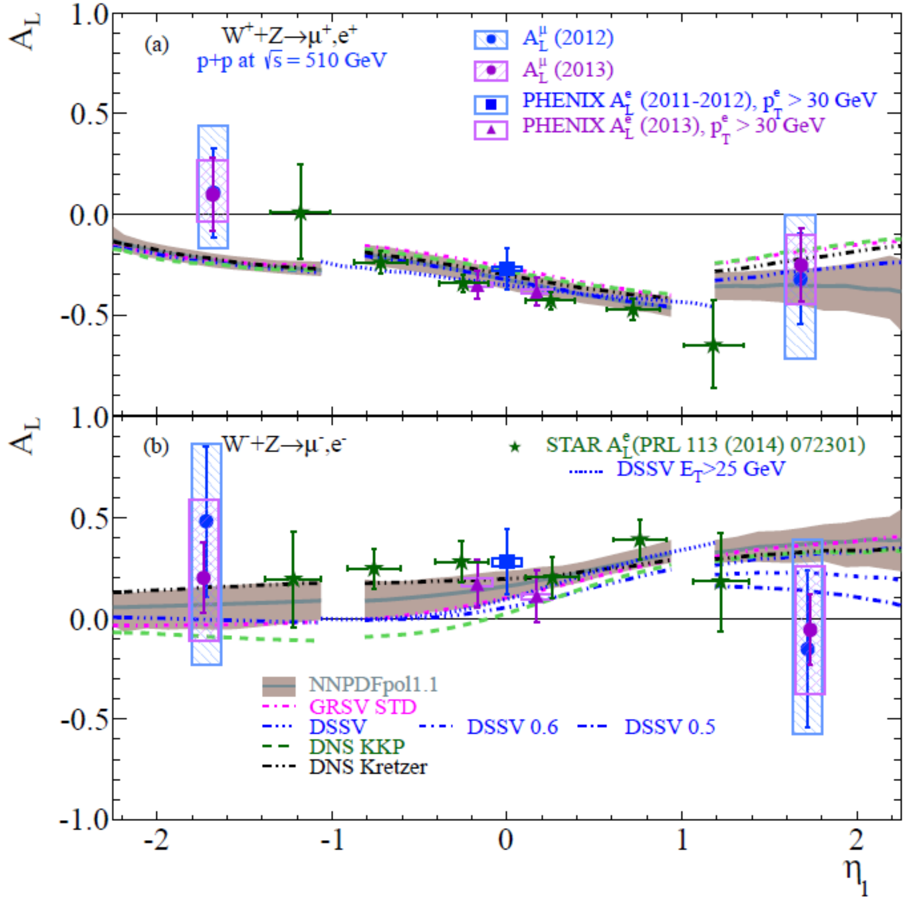


Good Detector Performance !

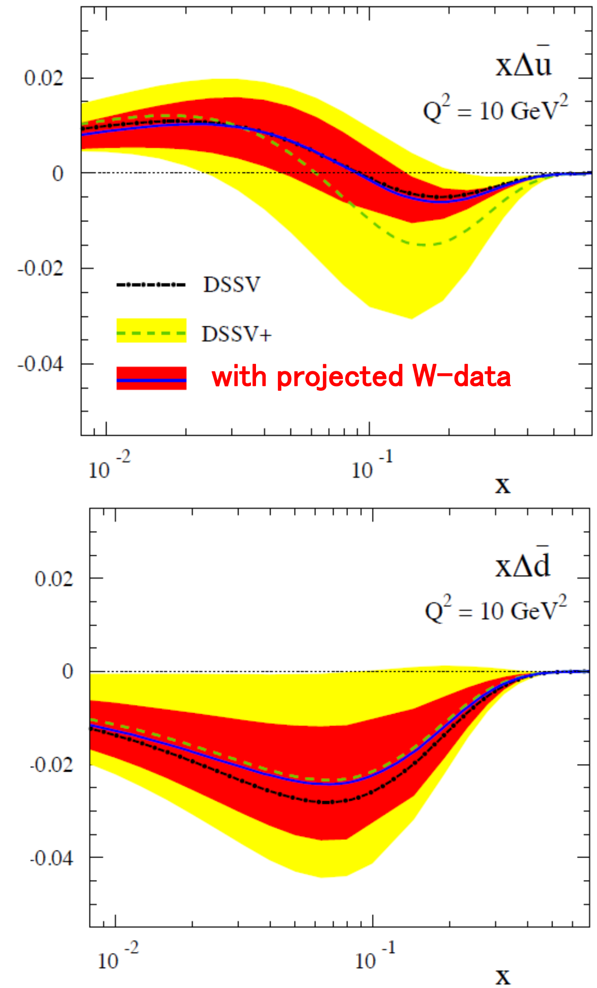


$A_L(W)$ in Runs 2012 & 2013 and Projected Impact on $\Delta\bar{q}(x)$

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. arXic: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.

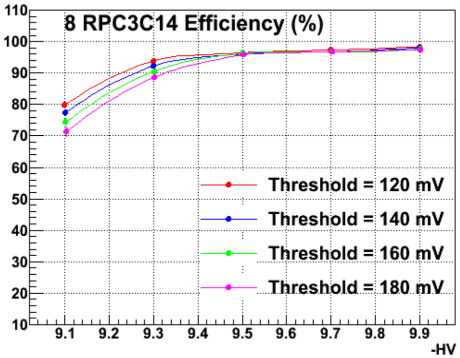
W-Production in polarized proton-proton Collisions at RHIC provide unique sensitivity to the anti-quark spin distributions in the proton.

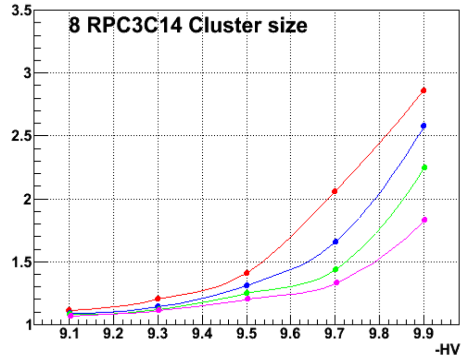
The PHENIX detector was upgraded successfully for W-physics.
Data taking has been completed successfully and
data analysis has started.

UIUC Group Working the PHENIX W-Trigger and Data Analysis

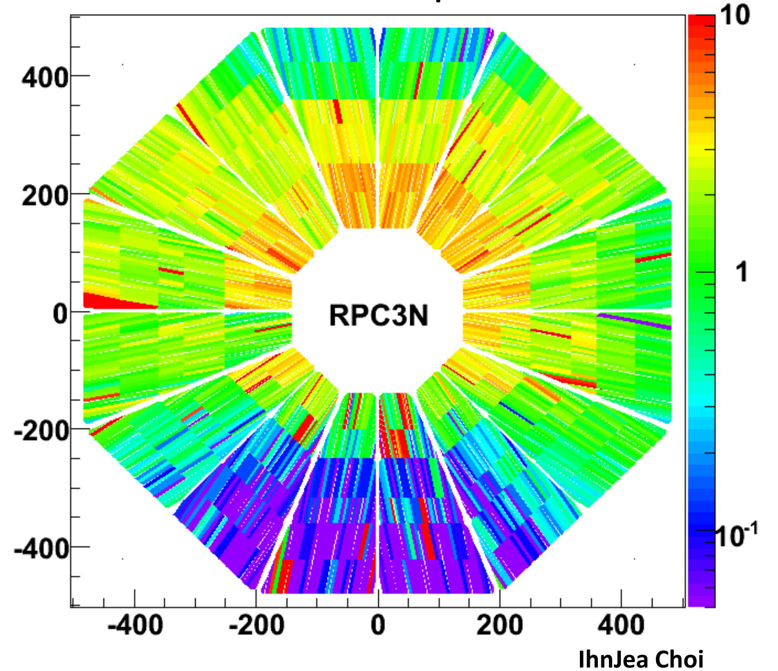
RPC Performance

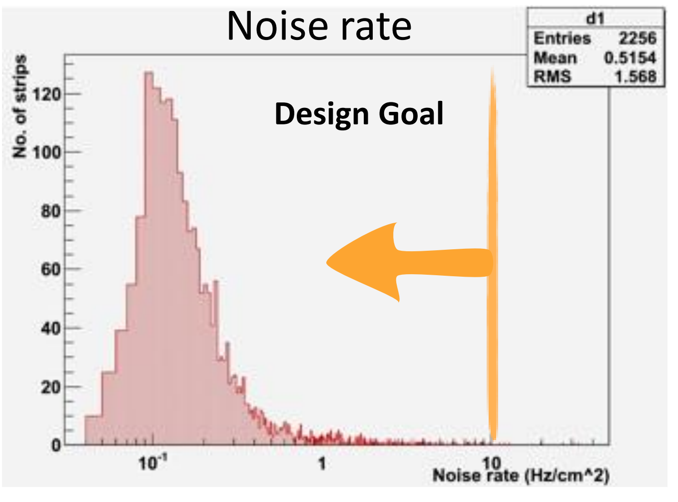
RPC Factory: efficiency & Cluster size

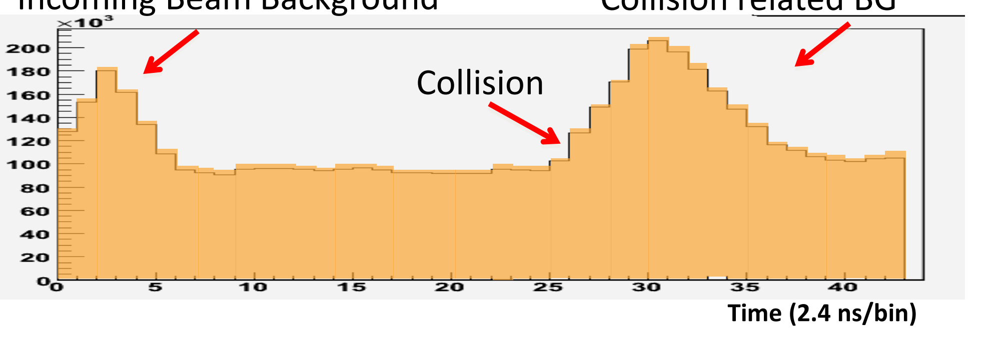




RPC3 Hit map







IhnJea Choi+ Francesca Giordano