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

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PHYS 403 – Research Talk
July 17th, 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?

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

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 ➔ $Z^0$, $W^+$, $W^-$
Synthesis of Atomic Matter from the 20th Century Atoms

atom $\sim 10^{-10}$ m

electron $< 10^{-18}$ m

nucleus $\sim 10^{-14}$ m

quark $< 10^{-18}$ m

Proton/neutron $\sim 10^{-15}$ m
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 \(\sim 10^{-15}m\)
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 \( x \).

\[ x = \frac{P_{\text{quark}}}{P_{\text{proton}}} \]
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 a gluon with relative momentum \( x \) contributing to the proton spin.

\[ x = \frac{p_{\text{quark}}}{p_{\text{proton}}} \]
Decomposition of the Proton Spin: Quark Spin + Gluon Spin + Orbital Angular Momentum

Origin of the Proton Spin:
- Add all quark spin contributions $\Delta q(x) \to \Delta \Sigma$
- Add all gluon spin contributions $\Delta G(x) \to \Delta G$

\[
\frac{1}{2} \frac{\hbar}{\Delta} = \frac{1}{2} \frac{\hbar}{\Delta} \sum + \frac{\hbar}{\Delta} G + \frac{\hbar}{L_z}.
\]

Quark Spin

Orbital Angular momentum

Gluon Spin

\[\chi = \frac{P_{\text{quark}}}{P_{\text{proton}}}\]
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

source of α-particles (He-nuclei)

Observation of α-particles at large angles

target Au-foil

scintillating screen

E. Rutherford dense, heavy nucleus

J.J. Thomson Atomic Plum Pudding Model

Rate [cps]

Observing Quarks and Anti-Quarks Inside the Proton
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


\[ x \Delta u(x) \]
\[ x \Delta d(x) \]

\( \Delta u \) is positive and contributes about + 0.69 \( \hbar \)

\( \Delta d \) is negative and contributes about - 0.33 \( \hbar \)

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

Next steps:
- Measure gluon spin contribution
- 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!

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

$m_W = 80$ $m_{\text{proton}}$

$\Rightarrow$ high energy muons!

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

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

$A_L \approx \frac{x \Delta \bar{d}}{d}$
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)
- RPCs in PHENIX (NSF)
- muTr trigger electronics (JSPS)
- FPGA based level-1 trigger processors
- SS 310 absorbers for background rejection
Assembly in the RPC Factory at BNL

Cosmic RPC test stand
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!

Luminosities

2011: BBC < 30cm 18.50 pb$^{-1}$

2012: BBC < 30cm 31.47 pb$^{-1}$

2013: BBC < 30cm 156.49 pb$^{-1}$
Final results published PRD in summer 2018:

DSSV: projected impact of new 2013 STAR and PHENIX data

Aschenauer et al. arXiv:1501.01220

DSSV from “The RHIC Spin Program”
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

- Ruizhe Yang
  - Beijing, China
  - China

- Scott Wolin
  - Illinois, USA
  - USA

- Matthias Perdekamp
  - Germany
  - Germany

- Cameron McKinney
  - Indiana, USA
  - USA

- Young Jin Kim
  - South Korea
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- Dave Northacker
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- Beau Meredith
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- Emily Zarndt
  - Indiana U., USA
  - USA

- Francesca Giordano
  - Italy
  - Italy

- Pedro Montuenga
  - Venezuela
  - Venezuela

- John Blackburn
  - Illinois, USA
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- Daniel Jumper
  - Texas, USA
  - USA

- Matthijs Vossen
  - Northrup Grumman, USA
  - USA

- Martin Leitgab
  - Austria
  - Austria

- Amazon
  - USA
  - USA

- Goldman Sachs
  - USA
  - USA

- South Korea
  - South Korea

- Sanger Institute
  - Cambridge, UK
  - UK

- Cameron McKinney
  - Indiana, USA
  - USA

- Anselm Vossen
  - Germany
  - Germany

- Indiana University
  - USA
RPC Factory: efficiency & Cluster size

8 RPC3C14 Efficiency (%)

8 RPC3C14 Cluster size

Noise rate

Design Goal

RPC3 Hit map

RPC3N

Incoming Beam Background

Collision related BG

Collision

Time (2.4 ns/bin)

RPC Performance

IhnJea Choi + Francesca Giordano