UNIVERSITY OF CALIFORNIA
RIVERSIDE

MEASUREMENT OF THE LONGTIDUDIANL SINGLE SPIN ASYMMETRY, A_L, FOR POLARIZED PROTON-PROTON COLLISIONS IN THE $W \to \mu$ DECAY CHANNEL

A Dissertation submitted in partial satisfaction
of the requirements for the degree of

Doctor of Philosophy

in

Physics

by

Michael J. Beaumier

August 2016

Dissertation Committee:

Professor Kenneth Barish , Chairperson
Professor Rich Seto
Professor John Ellison

The Dissertation of Michael J. Beaumier is approved:

Committee Chairperson

University of California, Riverside

Acknowledgments

Advisors and Mentors are some of the most important people any scientist will encounter in their professional career. Time and again, I have heard colleagues speak of ”that one inspirational” person that drove them to be their best, and knew how to ”grow” a researcher.

I am very greatful to my advisor, Ken Barish, whose calm, stoic and unabated support helped guide me through my research. Ken involved me in many aspects of the research group at UCR, beyond the scientific work. He insured that I was exposed to all aspects of research in particle physics, including writing grants, reviewing literature, mentoring younger students, building detectors, running a particle accelelrator detector, and of course, data analysis. Ken has always had the uncanny ability to know ”who to talk to” for nearly any problem I might have. Ken connected me with other excellent physicists, who helped me grow as a researcher, and he gave me the freedom I needed to pursue my interests, and move in the scientific directions I felt most fruitful, while helping to provide an overall direction for my academic career and research.

Beyond all this, the single most important thing Ken has done for me, is to give me a second chance in graduate school. When he accepted me into his group, I was an undoubtedly risky choice. I struggled mightily my first year in grad school. I earned poor grades, and even had to re-take a class. In fact, my performance was so poor, that my teaching responsibilities were reduced, and eventually, I lost my graduate division fellowship, which ultimately meant that I had no income, or means of supporting myself; I was effectively dismissed from graduate school. However, I was interested in the research carried out by Ken and Rich Seto’s heavy ion group, so I talked to Ken, who graciously accepted me into the group, provided me with academic and financial support, and even flew me out to Brookhaven National Lab my first summer of graduate school. I finally got to dive into ’real’ physics research. I think it was this vote of confidence from Ken, as well as the awesome physics happening at the PHENIX experiment which gave me the confidence to wholeheartedly devote myself to my studies and research. Without Ken’s vote of confidence, I fear that my graduate career would have been over in short order.

While at Brookhaven National Lab, I encountered graduate students, post docs, research staff, and other amazing physicists who taught me an incredible amount, and showed both patience, kindess, friendship and mentorship to me. Richard Hollis was one of the first people I encoutered in my research group at UCR - I have never met a more patient person. Richard helped me get my bearings, and set me straight, during my early (and later) years of graduate school. Oleg Eyser was with our group at that time as well - although I recall that he was less than thrilled to have yet another green graduate student constantly asking questions, taking time away from his work. He still made time to teach me, and introduced me to the very complicated PHENIX software system. Oleg challenged me, and expected me to find answers for myself, and was unrelenting in that regard, which I am certain made me a better researcher.

Josh Perry gave me a crash course on the PHENIX data acquisition system, boiling down this incredibly complicated system into understandable pieces, and helped me learn that ultimately, persistance pays off when tackling difficult problems. Martin Leitgab took me under his wing while I worked days and nights to learn PHENIX's fast data production systems. Martin's systematic, calm, and patient approach to problem solving has been something I have tried to emulate since my work with him - I could not have asked for a better mentor for that project. On that same project was my first introduction to Chris Pinkenburg and Martin Purschke - somewhat of the yin and yang of the PHENIX online data aquisition. I benefited enormously from conversations with both about PHENIX software, and online systems. Martin Purschke's kindness and sense of humor always spurred me on, while Chis' dogged dedication to doing things 'the right way' kept me honest. I have returned to Martin with various questions many times over the years, and he has always been cheerful, supportive and wise with his answers. Probably nobody other than Ed Desmond has been woken up so many times with emergencies at the PHENIX counting house in the middle of the night, yet even when I woke him at 3 am on many occasions, would simply state, in an execptionally dry, well practiced line: 'Martin Speaking, please state the nature of your emergency'. I don't know of many who can manage to be coy and good natured under such circumstances.

I have to acknoledge Joe Seele as well, in this regard, as he probably more than anyone else, set me on the path to learning to program well, and using a computer effectively - these skills, so often neglected in Particle Physics, have paid off for me, many, many times over.

W Analysis Crew

Ralf Seidl, Francesca Giordano, Sangwha Park, Daniel Jumper, Abraham Meles, Chong Kim,

Friends and Family

Bob Beaumier, Marian Beaumier, Joe Beaumier, David Beaumier, Emily Vance, Jackie Hubbard, Alexander Anderson-Natalie, Corey Kownacki, Chris Heidt, Pat Odenthal, Behnam Darvish Sarvestani, Oleg Martynov, Some say that it takes a village to raise a child. The same can be said of raising a graduate student up to earning a PhD. This thesis is dedicated to the multitude who have helped me become the man I am today, and to students who struggle, and their mentors who do not give up on them.

ABSTRACT OF THE DISSERTATION

MEASUREMENT OF THE LONGTIDUDIANL SINGLE SPIN ASYMMETRY, A_L, FOR POLARIZED PROTON-PROTON COLLISIONS IN THE $W \rightarrow \mu$ DECAY CHANNEL

by

Michael J. Beaumier

Doctor of Philosophy, Graduate Program in Physics
University of California, Riverside, August 2016
Professor Kenneth Barish , Chairperson

This thesis discusses the process of extracting information about the spin structure of protons, specifically, spin contributions from the sea of quarks and antiquarks, which are kinematically distinct from the 'valence quarks'. We have known since the 'proton-spin crisis' [7] of the 1990s that proton spin does not entirely reside in the valence quarks, so the thrust of experimental efforts since then have been designed to determine both how to probe the proton spin structure, and how to validate models for proton spin structure. Here, I discuss one particular approach to understanding the sea-quark spin contribution, which utilizes the production of real W-bosons, and the W coupling with polarized spin structure in the proton sea, as produced from polarized proton-proton collisions. Only one of the colliding protons is longitudinally spin polarized, in this analysis, and they are collided at an energy of $500 GeV$. The expermental observable used is referred to as "A_L" which is expressed mathematically as a ratio of sums and differences of various helicity combinations of singly polarized interactions between two protons, i.e. $p + p^{\Rightarrow} :\rightarrow W \rightarrow \mu + \nu$. Once A_L has been experimentally measured, it can then be used to determine appropriate polarizations of proton sea-quarks, within a given uncertainty, if we write the cross-sections used in the calculation of A_L in terms of polarized parton distribution functions. Finally, this thesis will also include a discussion of my work experimentally determining the absolute luminosity of collisions at RHIC, which is needed as a normalization on any cross section used in the analysis. In particular, studying the cross section of the W interaction can help to validate our models for assigning a signal-to-background ratio to the $W \rightarrow \mu$ events.

Contents

List of Figures **xiii**

List of Tables **xv**

1 Introduction **1**

1.1 A Brief History of the Proton 1

1.2 Scope and Objectives of This Work 2

2 Historic Perspective on the Structure of Matter and Spin **4**

2.1 The Phenomena of Spin 4

2.2 A Brief History of Proton Spin 6

2.2.1 Ancient Foundations 6

2.2.2 The Scientific Revolution 8

2.2.3 Atomic Theory 10

2.2.4 Early Quantum Theory 14

2.2.5 Early Particle Physics and The Eightfold Way 17

2.2.6 Deep Inelastic Scattering and The Parton Model 21

2.3 World Experiments in Deep Inelastic Scattering 25

2.3.1 CERN - European Muon Collaboration: 1979-1997 25

2.3.2 SLAC - E142: 1993-1994 26

2.3.3 SLAC - E143: 1992-1999 26

2.3.4 DESY - ZEUS: 1992-Present 26

2.3.5 CERN - Spin Muon Collaboration: 1993-1998 27

2.3.6 SLAC - E154: 1994-1997 27

2.3.7 DESY - HERMES: 1995-2007 27

2.3.8 SLAC - E155: 1997-2003 27

2.3.9 CERN - COMPASS: 2005-Present 27

2.3.10 DESY - H1: 1992-Present 27

3 Models and Associated Probes For Proton Spin Structure **28**

3.1 structure functions 28

3.2 proton spin decomposition 28

3.3 unpolarized parton distribution functions 28

3.4 polarized parton distribution functions 28

3.5 that sweet table from Delia hasch . . . 28
3.6 discussion $\bar{q}$, q, L_q, g . . . 28
3.7 DSSV . . . 28
3.8 Measurement of the Proton Spin . . . 29
3.8.1 physics probes for proton spin . . . 29
3.8.2 W cross section . . . 29
3.8.3 derivation of Asymmetry . . . 29
3.8.4 kinematic extremes of Asymmetry . . . 29
3.9 Cross Sections and Luminosity . . . 30

4 Experimental Apparatus **31**
4.1 The Relativistic Heavy Ion Collider . . . 32
4.1.1 Overview . . . 32
4.1.2 The RHIC Spin Program . . . 32
4.1.3 Production of Polarized Proton Beams . . . 32
4.2 The Pioneering High Energy Nuclear Interaction Experiment . . . 32
4.2.1 Subsystem Overview . . . 32
4.2.2 Luminosity . . . 32
4.2.3 Beam Polarization . . . 32
4.3 The Forward Upgrade . . . 32
4.3.1 The Muon Tracker + Muon Trigger Subsystems . . . 32
4.3.2 Resisitive Plate Chambers . . . 32
4.3.3 The DAQ . . . 32

5 The Data Set **33**
5.1 Overview . . . 33
5.2 Analysis Variables and the Basic Cut . . . 34
5.3 Feature Engineering . . . 36
5.3.1 Discriminating Kinematic Variables . . . 36
5.3.2 Simulations . . . 36

6 Spin Analysis **37**
6.1 Classification of Signal or Background Events . . . 37
6.1.1 Naive Bayes Classification . . . 39
6.1.2 Composition of Probability Distribution Functions . . . 41
6.1.3 Labeling Data With Likliehood Ratio: W_{ness} . . . 42
6.2 Extended Unbinned Maximum Likelihood Fits . . . 42
6.2.1 Modeling The Hadronic Background . . . 42
6.2.2 Modeling the Muon Background . . . 42
6.2.3 Modeling the W-Signal . . . 42
6.2.4 Overview . . . 42
6.2.5 Fit Performance . . . 42
6.2.6 S/BG and Muon Backgrounds . . . 42
6.2.7 W_{ness} Dependence of S/BG . . . 42
6.3 Calculation of A_L for $W \to \mu$ . . . 42

6.3.1 Overview . . . 42
6.3.2 Asymmetry Calculation . . . 42
6.3.3 Discussion of Work Done By Analysis Team . . . 42
6.4 Data Validation . . . 42
6.4.1 Simulations and The Signal to Background Ratio . . . 43
6.4.2 Gaussian Process Regression . . . 43
6.4.3 Four Way Cross Validation . . . 43
6.4.4 Asymmetry Consistency Check . . . 43
6.4.5 Beam Polarization . . . 43
6.4.6 Beam Luminosity . . . 43
6.4.7 Code Cross Validation . . . 43

7 The Vernier Analysis 44
7.1 Overview . . . 44
7.2 Analysis Note Here . . . 44
7.3 W Cross Section . . . 44

8 Discussion and Conclusion 45

Bibliography 46
.1 First Thingie . . . 50
.2 Second Thingie . . . 50

List of Figures

2.1 Two Greek philosophers, who made important philosophical contributions our understanding of matter. Empedocles (left), postulated the precursor to the elemental theory of matter **[CITATION NEEDED]** and Democritus (right), postulated the precursor to the atomic theory of matter. 7
2.2 Giants in the age of Empiricism, Newton (left) and Galileo (right) both made foundational contributions to Physics. Galileo lived in Italy, born in 1564 and dying in 1642. Newton lived in England from 1642 until his death in 1727 . 8
2.3 As we journey down further in scale, matter begins to look quite different. In fact, the models we use are scale dependent. Thomson 2.8, and Rutherford 2.5 began to see matter as collections of atoms (left) [18] (though not in terms of the orbital structure pictured), though it would not be until 20th century quantum mechanics that electron orbitals were discovered. Soon, nuclei were discovered to be divisible into protons an neutrons [27] (center), which in turn were discovered to be composed of a sea of quarks and gluons (right). (Right image drawn by the talented Astrid Morreale, PhD, [34]) . 10
2.4 Left: J.J. Thomson, who showed that cathode ray tubes were in fact producing the first observed subatomic particle: the electron. Right: A cartoon of Thomson's cathode ray tube setup. Electrons would be deflected by a magnetic field, sent from cathode to anode. 11
2.5 Ernest Rutherford, in his lab. [16] 12
2.6 Ernest Rutherford's historic experiment, showing (top right) that atoms were composed of a small dense nucleus, in contrast to Thomson's 'pudding model' of homogeneous charge (top left). The experiment, (bottom left and right) contrast the expected results (bottom left) against the observed results (bottom right) [25]. 13
2.7 The attendees of the Solvay Conference in Brussels, 1927 [8]. 14
2.8 Paul Dirac, next to his original formulation of the Dirac Equation, describing the wave function for an electron with rest-mass m, in terms of its spacetime coordinates. 15
2.9 Hideki Yukawa, the first Japanese Nobel Laureate and publisher of influential research on the theory of mesons, and other elementary particles [1]. . . . 18
2.10 An old bubble chamber, once used at Fermilab, [2] 19

2.11 An example of the photographs taken with a Bubble Chamber, in 1973. In this picture, we see a 300 GeV proton producing partices as it travels through a hydrogen-filled bubble chamber at fermilab [15]. 20
2.12 A schematic of deep inelastic scattering, where the incoming electron inelastically scatters off the proton, producing results X, via virtual photon exchange, γ^* [14] 22
2.13 "This diagram displays the structure of the standard model (in a way that displays the key relationships and patterns more completely, and less misleadingly, than in the more familiar image based on a 4x4 square of particles). In particular, this diagram depicts all of the particles in the standard model (including their letter names, masses, spins, handedness, charges, and interactions with the gauge bosons – i.e. with the strong and electroweak forces). It also depicts the role of the Higgs boson, and the structure of electroweak symmetry breaking, indicating how the Higgs vacuum expectation value breaks electroweak symmetry, and how the properties of the remaining particles change as a consequence."[10]. 24
2.14 **[FIGURE NEEDED]** **[CAPTION NEEDED]**. Results of EMC experiment showing that the structure function g1, tells us a thing about proton spin. 26

6.1 Observing the simulated production of muon as a function of p_T, we can see that in the kinematic region of W production that the dominant sources of muons come from other processes. The new PHENIX muon trigger threshold is sensitive at 10 GeV/c and above. 38
6.2 Low correlations between the signal variable distributions (from simulation), and the background variable distributions make this data set a good candidate for classfication using Naive Bayes 40

List of Tables

5.1 Summary of engineered features from the data set used in this analysis. . . 35
5.2 The Basic Cuts used in the Run 13 analysis. lastGap refers to the last gap in the MUID which saw a μ candidate event. The fourth gap is the furthest penetration possible, therefore suggesting a high energy muon. Other parameters are described in table 5.1 36

Chapter 1

Introduction

A brief note - figures used here without attribution were either: produced by me, produced in collaboration with others in my working group, or obtained by authors who labeled them for reuse without attribution. Other figures here are all fair-use.

THIS THESIS IS CURRENTLY A DRAFT. IT HAS NOT BEEN SUBMITTED AND HAS MISSING CITATIONS AND ATTRIBUTIONS.

1.1 A Brief History of the Proton

The angular momentum of the proton and neutron has been a subject of study for the last 20 years**[CITATION NEEDED]**. One of the challenges of particle physics is to create a framework which can accurately describe matter, as well as predict the behavior of matter at all energy scales. Protons and neutrons are baryons which make up the majority of the mass in the visible universe, yet fully understanding the origins of their properties - such as mass and spin, still eludes us. However, through the application of the scientific method over many generations of physicists, we have magnificently described this important particle, and understood much of its properties. However, one property which still defies our descriptions is its fundamental angular momentum, spin.

Our understanding of the proton has evolved and sharpened since the first experiments in deep inelastic scattering showed that the proton is not a fundamental particle [11]. Gell-Mann later planted the seeds of a theoretical framework which could in part describe some of the structure of baryons, a class of hadrons which we may naively describe as composed of three 'valence quarks'**[CITATION NEEDED]**. We can apply well known spin-sum rules to the individual spins of the valence quarks which compose the proton in our naive valence-model to produce a correct prediction for the protons' spin $\frac{1}{2}$. When experimenters set out to measure the contribution of these valence quarks in 1988 at the EMC experiment [7], they were flabbergasted to find that the valence quarks carry only a small fraction of the proton's spin. Although recent papers [31] suggest that this 'spin crisis' is simple due to misattribution of spin, most literature to date has focused on understanding how to model the proton with parton distribution functions. These parton distribution functions come in many varieties, and probe different degrees of freedom within the proton, in both the case of unpolarized parton distribution functions, and polarized parton distribution functions.

1.2 Scope and Objectives of This Work

This thesis will describe the research I carried out between May of 2010 through August of 2016. I will often quote work that was carried out in active collaboration with Ralf Seidel, Francesca Giordano, Daniel Jumper, Sanghwa Park, Abraham Meles and Chong Kim. Daniel, Abraham, Ralf, Francesca, and myself all worked on the 2013 polarized proton data set taken at RHIC with PHENIX. This analysis comprises the body of work devoted to calculating A_L for the $W \to \mu$ decay. Since 2013, the five of us collaborated closely on all aspects of the work, which provided invaluable cross-checks at nearly every stage. Many of the figures in this document were produced by our collective efforts, and I will do my best to cite when possible, if one analyzer played a particularly large role in generating the data or visualization, however after several years of working together, I will certainly fail to attribute, or misattribute at times.

The other portion of this thesis will discuss the Vernier Analysis, which is instrumental for every single-cross-section calculation taken with RHIC data. The thrust of the Vernier Analysis is to determine the beam luminosity at PHENIX's interaction point, so as to normalize these cross-section calculations. This is done with a series of specialized Vernier-Scans, where beams are scanned across one-another in order to measure beam geometry. The luminosity can then be calculated from first principals, and compared to the advertised machine luminosity published by RHIC's collider-accelerator department. I began working with the Vernier Analysis under the tutelage of K. Oleg Eyser, but eventually moved to work independently on the analysis, producing an entire software framework for handling data cleaning, analysis, visualization and simulation.

Chapter 2

Historic Perspective on the Structure of Matter and Spin

2.1 The Phenomena of Spin

Spin is a fundamental quantity possessed by all elementary particles. We use the word 'spin' to describe the property, because particles which possess spin, behave as though they have some kind of intrinsic, hidden rotation, as if they were 'spinning'. The dimension of spin, therefore is angular momentum. What is somewhat bizarre about spin, is that we do not observe anything physically spinning - although there are some phenomena (such as orbital angular momenta) which can be naively thought of as a 'spinning system' (but this description escapes classical analogy, due to its quantum, probabilistic nature). The role of Spin in Physics is of foundational importance, and yet, we have not successfully produced a model which can accurately predict the spin of hadrons.

The presence of spin in relativistic particles creates the phenomena of chirality, which has huge implications for how elementary particles can generate structure in matter itself **[CITATION NEEDED]**. In the case of the weak interaction, the presence of spin, which creates Chiral spinors breaks the left-right symmetry of weak coupling in matter (a fact which will be exploited in this thesis to probe the spin of the proton sea).

The phenomena of spin also changes the rules for how ensembles of particles may exist in a potential. Particles with spin are fermions, and because these particles must obey Fermi-statistics, we can observe structure in matter in the universe **[CITATION**

NEEDED]. Without spin, the world as we know would collapse on itself, making any kind of extended non-exotic structures which currently exist by virtue of the Pauli exclusion principal, impossible.

2.2 A Brief History of Proton Spin

The study of Spin is really just an outgrowth of the general study of matter. Our models for matter, and the underlying structure of matter (in the modern sense), represents over a hundred years of experimental and theoretical efforts, and thousands of years of contemplating what makes up the universe.

Although indulgent on my part, I find it interesting, and humbling, to try and map out the path that humanity and science has trodden on its way to understanding the building blocks of the universe. To find the first time that humanity had murmurings that suggested our visible world is built from invisible, fundamental building blocks, we must travel back, nearly 2,500 years into the past.

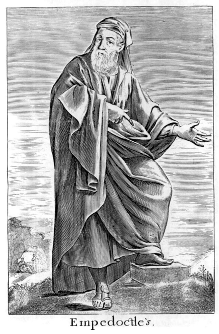
Rather than provide a complete mathematical background to my measurement from a historic perspective, I will instead focus on the experimental historic narrative surrounding our quest to understand the structure of matter. After, I will present mathematical formalism relevant to this measurement directly - if the reader desires an exhaustive mathematical context, I invite them to read the classic tomes on Field Theory by Weinberg and reference the numerous theses written by my colleagues in theoretical physics and phenomenology.

2.2.1 Ancient Foundations

Sometime around 490 - 370 BCE lived two philosophers, Empedocles (Fig 2.1a), and Democrtius (Fig 2.1b). Both men lived approximately at the same time, and made huge philosophical leaps in attempting to understand the nature of the visible world.

Democritus was part of a movement of thought which was first to make the intellectual jump that perhaps matter was not a continuum, but instead, composed of 'atomon', small, indivisible particles which when configured together, created all that is observable **[CITATION NEEDED]**. Empedocles was making equally important philosophical strides - in a manner complimentary to Democritus' opinion that matter must be made of atomon, Empedocles argued that matter is composed of elemental primitives **[CITATION NEEDED]**.

Although Empedocles' 'periodic table' was only composed of Earth, Water, Fire, and Air, the idea that some unseen transmutation of elemental forces might generate ob-



(a) Empedocles [33]

(b) Democritus [35]

Figure 2.1: Two Greek philosophers, who made important philosophical contributions our understanding of matter. Empedocles (left), postulated the precursor to the elemental theory of matter **[CITATION NEEDED]** and Democritus (right), postulated the precursor to the atomic theory of matter.

servables in nature with quite different (but perhaps reminiscent) properties then the 'pure substances' was an important step forward. Proto-scientists were beginning to generate models which derived our complicated observations, from simpler forms.

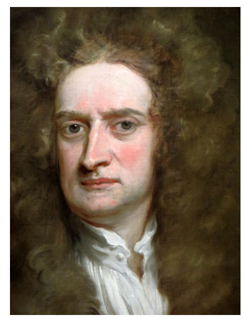
It took centuries of cultivation, leading up to the Scientific Revolution, for the next great steps to occur, for science. Thankfully, the luminaries of the Islamic Golden Age kept the fires of inquiry burning **[CITATION NEEDED]**.

2.2.2 The Scientific Revolution

Thanks to the mathematical foundations laid out, build, and maintained by the minds of the Islamic Golden Age, Europe was well poised to reignite the flames of scientific inquiry, during the post Renaissance Scientific Revolution **[CITATION NEEDED]**.

This period of growth in science was unprecedented during the Scientific Revolution, thanks to the seeds of empiricism germinated during the Islamic Golden Age, fertilized by the Italian Renaissance, and helped to flourish through British Empiricism **[CITATION NEEDED]**.

(a) Galileo [26]



(b) Newton

Figure 2.2: Giants in the age of Empiricism, Newton (left) and Galileo (right) both made foundational contributions to Physics. Galileo lived in Italy, born in 1564 and dying in 1642. Newton lived in England from 1642 until his death in 1727

2.2.2.1 Galileo Galilei

While Galileo is best known for his work in Observational Astronomy, his importance to science extends beyond this. During his years in exile for his controversial views of the heliocentric universe, he produced some of his most important scientific work in kinematics **[CITATION NEEDED]**. What made this work remarkable is the care that Galileo took in merging careful mathematical modeling with well designed experimentation. This methodical approach to inquiry laid the foundation for others to slowly begin to pull back the curtains obscuring physical law.

Galileo's formalization of the scientific method inexorably set science on a course to delving deep into the nature of matter, and the laws of nature.

2.2.2.2 Isaac Newton

Fittingly born in the same year as Galileo's death, Isaac Newton would carry on Galileo's legacy of rigorous mathematical modeling mixed with experimentation. Perhaps no other scientist has touched so many different aspects of physics, from theories of propagation of light, to celestial mechanics, to mathematics, and kinematics.

Newton's Principia is perhaps the most important scientific work ever published. It opened the doors of the universe in a way that nobody has since duplicated. Newtons' laws of motion are still taught in school today, and although they have since been shown to be inaccurate at the smallest and largest scales, they still provide startlingly accurate predictions for the regular motion of matter.

One particularly tantalizing theory of Newton's was the corpuscular theory of light. Although not his most influential theory by far, the idea that an apparently continuous medium such as a beam of light might be made of small packets of energy (corpuscles) turned out to be partially right **[CITATION NEEDED]**.

Newton's theories, and contributions to science are enormous, and have moved us deeper still into the underpinnings of matter. It would not be until roughly 200 years after his death, in the 19th century, that we finally can take the first steps into the world of the atomic, and sub-atomic: the world of the proton.

2.2.3 Atomic Theory

On the shoulders of giants such as Newton and Galileo, science finally came to know the tool which has been indispensable to modern particle physics: scattering. Rutherford and Thompson both carried out the most important scattering experiments in modern science, and provided us with the first hints of a hidden, quantum world, though it would not be until the 20th century that these important experiments would be fully contextualized with a theory of quantum scattering.

Scattering experiments offer a very powerful method where we one uses a well known initial state of matter (typically in the form of a beam), allows this beam to interact with an unknown configuration of matter, and measures the scattered beam. By carefully studying the kinematics of the scattered beam, we can create models which allow us to understand the structure of the target matter or describe the nature of the interaction between the beam and target.

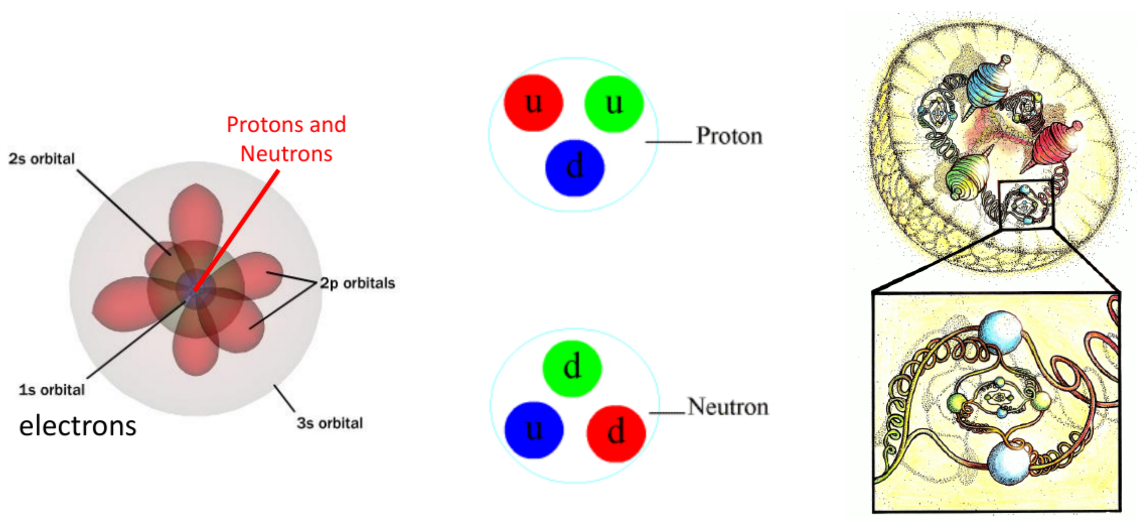


Figure 2.3: As we journey down further in scale, matter begins to look quite different. In fact, the models we use are scale dependent. Thomson 2.8, and Rutherford 2.5 began to see matter as collections of atoms (left) [18] (though not in terms of the orbital structure pictured), though it would not be until 20th century quantum mechanics that electron orbitals were discovered. Soon, nuclei were discovered to be divisible into protons an neutrons [27] (center), which in turn were discovered to be composed of a sea of quarks and gluons (right). (Right image drawn by the talented Astrid Morreale, PhD, [34])

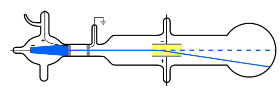
2.2.3.1 John Dalton

While many had postulated the existence of atoms, the first evidence based theory which suggested the existence of atoms was produced by John Dalton in the early 19th century. Dalton made an important conceptual leap to relate the existence of stoichiometric ratios in chemistry to the presence of small, individual functional units in his experiments with chemical reactions. Dalton's realization was only made possible due to his careful accounting of reactants in his experiments.

It was not until Einstein's 1905 theory on Brownian Motion was experimentally verified by Jean Perrin to place limits on the mass and size of atoms that Dalton's atomic theory was ultimately vindicated [30].

2.2.3.2 J.J. Thompson

(a) J.J. Thomson [36]



(b) Cathode Ray Tube [24]

Figure 2.4: Left: J.J. Thomson, who showed that cathode ray tubes were in fact producing the first observed subatomic particle: the electron. Right: A cartoon of Thomson's cathode ray tube setup. Electrons would be deflected by a magnetic field, sent from cathode to anode.

Thomson (Figure 2.4) would discover that atoms are not the smallest, indivisible piece of matter. In his landmark experiment, he used cathode ray scattering experiments to show that cathode rays were in fact subatomic particles. He showed these cathode rays were identical to particles given off by the photoelectric effect, and that these same particles were responsible for electric current. He had discovered the electron. And, if atoms were not the smallest piece of matter, then perhaps, atoms themselves might not be 'indivisible' as previously thought [28].

2.2.3.3 Ernest Rutherford

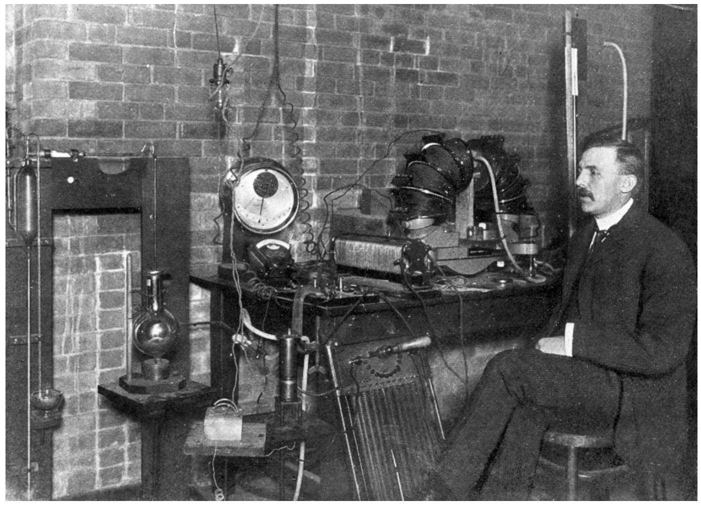


Figure 2.5: Ernest Rutherford, in his lab. [16]

Ernest Rutherford (Fig 2.5) was the first to show that atoms themselves were highly structured - and consisted of a small dense center, later called the nucleus.

Rutherford's work with radioactivity was of fundamental importance, he discovered and classified both alpha-particle radioactivity and beta-particle radioactivity. Further studies into these types of nuclear radiation would unlock the nucleus of atoms through the work of future scientists. Notably, Rutherford discovered the proton.

Rutherford's proposed planetary model for the nucleus, while technically wrong, shifted paradigms from the pudding model of atoms, to the more familiar nucleus + electron cloud model which has been spectacularly modeled and verified with the forthcoming scientists which defined the field of quantum mechanics.

Rutherford's work helped push us our of the cocoon of classical mechanics into the weird world of the quantum mechanics - scientists would soon find that the nucleus is not just a dense concentration of charge, but a probabilistic structure, with rich sub nuclear structure.

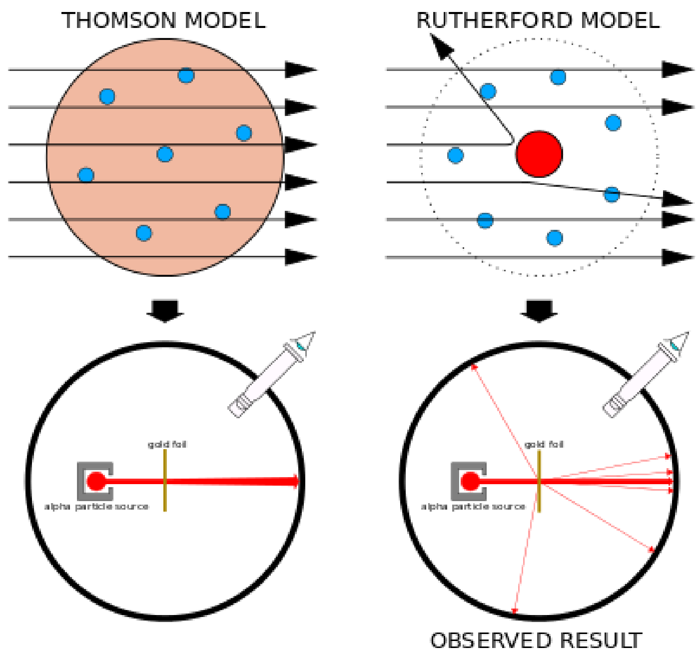


Figure 2.6: Ernest Rutherford's historic experiment, showing (top right) that atoms were composed of a small dense nucleus, in contrast to Thomson's 'pudding model' of homogeneous charge (top left). The experiment, (bottom left and right) contrast the expected results (bottom left) against the observed results (bottom right) [25].

Figure 2.7: The attendees of the Solvay Conference in Brussels, 1927 [8].

2.2.4 Early Quantum Theory

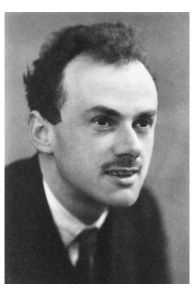
During Rutherford's time, experiments were already underway which were investigating modeling light as a wave phenomena. This was in contrast to Newton's (unverified) corpuscular theory of light. The argument whether light was wave-like or particle-like eventually lead to a classical field theory describing light, and the electromagnetic interaction, yet scientist such as Max Plank were proposing theories which required the quantization of light. **[CITATION NEEDED]**. Einstein would show that in his analysis of the photoelectric effect, that light indeed was quantized into 'corpuscles'. The nascent atomic theory of matter was also hinting at a hidden, quantized world.

At the Solvay Conference in Brussels, Figure 2.7, in 1927, we saw an unprecedented gathering of some of the most important figures in modern physics, all in one place, laying down the foundations of what would become quantum mechanics. These scientists defined the nature and rules of quantum mechanics - the weird model which accommodates a duality of matter - both wave-like, and particle like. The notion that probing the structure of matter did not yield a simple, deterministic hierarchy of structure was revolutionary, confusing, and bizarre, and still is to this day.

It was found that not only light possesses this wave-particle duality, but also the very particles that make up atoms as well. These models were formalized by Dirac, Hilbert and Von-Neumann **[CITATION NEEDED]**.

Though experiment tended to lead theory, regarding understanding the composition and rules of interactions in matter, in the mid 20th century, further refinements and additions to quantum mechanics gave birth to quantum field theory. While early quantum models were very successful at describing static particles trapped in static potentials - such as refining atomic theory to include predictions of observed atomic spectra, more work was needed to understand the relationship between electrical currents, light and magnetism. These concepts were all related by Maxwell **[CITATION NEEDED]** in the latter half of the 19th century, but did not make good predictions for systems in motion.

Dirac was first to create a model for describing the electron, its behavior in electromagnetic fields, and photon emission and absorption, under fully relativistic and quantum conditions **[CITATION NEEDED]**. Dirac's model was so successful, that it would become the basis for what we now call quantum electrodynamics. Much of the mathematical formalism has been reused to describe other field theories, which are the ultimate language which model and describe the structure of matter - including the insides of a proton.



(a) Paul Dirac, 1933 [17]

$$\left(\beta mc^2 + c\left(\sum_{n=1}^{3}\alpha_n p_n\right)\right)\psi(x,t) = i\hbar\frac{\partial\psi(x,t)}{\partial t} \quad (2.1)$$

(b) The Dirac Equation

Figure 2.8: Paul Dirac, next to his original formulation of the Dirac Equation, describing the wave function for an electron with rest-mass m, in terms of its spacetime coordinates.

Dirac's work also began to incorporate relativistic effects in his wave equations modeling the electron, as well as crucially incorporating the spin (I.e. Dirac Spinors) of these particles, which were important for making precise predictions for atomic spectra **[CITATION NEEDED]**.

By this time, the proton was already known to reside in the enigmatic nucleus of atoms, however, attempts to use Quantum Electrodynamics to describe the state of the nucleus failed - it was clear that there was a very strong force, holding together the protons of a nucleus tightly - far in excess of the electromagnetic repulsion felt by the positively charged particles. There was a completely different coupling strength between this apparent strong nuclear force, and the better known electromagnetic coupling. Further complicating an understanding of the nucleus is the fact that as the length scale of probing decreases, the energies probed increase, fundamentally making the nucleus a relativistic object. Experimental physics would once again, forge ahead, in attempting to understand the inner workings of the nucleus, in the time-honored tradition of performing scattering experiments.

2.2.5 Early Particle Physics and The Eightfold Way

The hydrogen atom, and its spectra was well modeled with quantum mechanics by the end of early 20th century, however attempts to study Helium were not as successful **[CITATION NEEDED]**. However, in 1932, when Chadwick turned a beam of helium particles (at that time only known as α particles) on a sample of Beryllium, he observed that neutral, non-ionizing, penetrating radiation was produced [29]. Photons were ruled out as possible candidates, leading to the discovery of the neutron. Protons and neutrons were hypothesized by Heisenberg to both be the same state of a new conceptual particle, the nucleon, [22]. In the same year, Anderson discovered the positron.

By 1934, Hideki Yukawa (Fig. 2.9) had created an effective field theory for interactions of 'elementary particles' (at this time, thought to be protons and neutrons). He predicted the existence of mesons, and wrote down an effective field theory which described how protons and neutrons bind together in the nucleus [37].

Though non-relativistic quantum mechanics was mostly complete by 1934, scientists were already hard at work incorporating relativistic corrections to the theory. Experiments with cosmic rays soon revealed the existence of muons and the first observation of mesons.

Three separate paths eventually lead to the development of particle accelerators, which are to date, the best mechanism we possess in physics to probe nuclear structure. These accelerators are an outgrowth of ever more intense Rutherford-style experiments, Tandem Van-Der-Graaf generators, resonant acceleration techniques, RF linacs, and betatron accelerators [12].

By the 1950's, a cornucopia of strange new particles had been discovered, both matter and antimatter. But scientists drove forward, deeper, yearning to discover what was fundamental. By the 50's, neutrinos had been proposed, as well as Kaons, Pions, and Lambdas. Physicists were doing nuclear chemistry, in a sense, attempting to work out how quickly some particles decayed, and what decays were allowed or forbidden - science entered an age of nuclear alchemy.

"Strange" particles were discovered (K and Λ), so called because in bevatron experiments, they were produced in great quantities, but were slow to decay, unlike the faster π decay. Gell-Mann proposed that this strangeness in matter was due to a new quantum number (he called it 'strangeness'). The name stuck. [19], [20], [29].

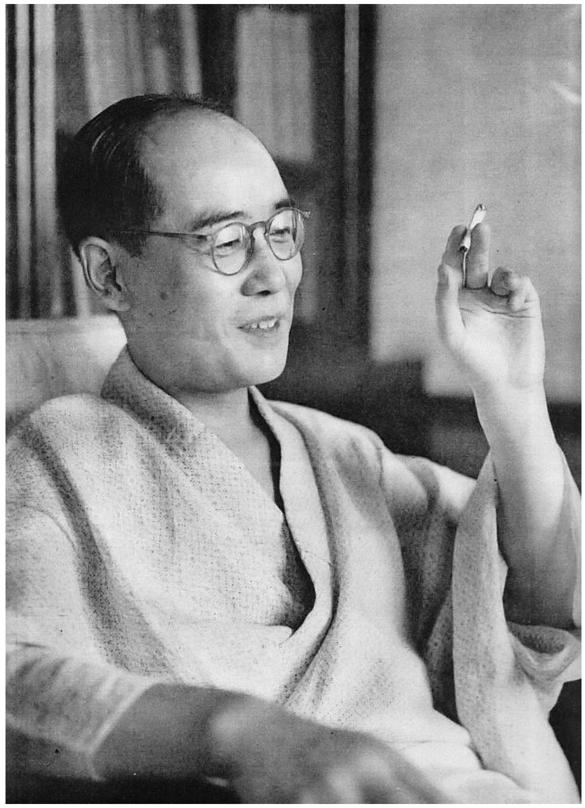


Figure 2.9: Hideki Yukawa, the first Japanese Nobel Laureate and publisher of influential research on the theory of mesons, and other elementary particles [1].

The introduction of new conserved quantities, and the vast proliferation of particles was in full swing - the subatomic world by the 1950's was confusing, and complex. In his book "The God Particle", Leon Lederman recalled his adviser, Enrico Fermi frustratedly remarking 'Young Man, if I could remember the names of these particles, I would have been a botanist'. At this time, in the mid 1950's, the number of mesons and baryons which had been discovered were at least in the dozens, if not more.

While the use of particle accelerators were speeding us along in our search for the structure of matter, one particular invention truly revolutionized the field - the bubble chamber (Figures 2.10 and 2.11.)

The bubble chamber was essentially a large vat of supercritical fluid which could easily be caused to boil with small perturbations. This feature was exploited, by positioning a bubble chamber in a magnetic field (to cause charged tracks to bend) near the interaction point between a particle beam and a fixed target. The bubble chamber itself was sometimes the target - since a popular liquid to use was hydrogen.

Figure 2.10: An old bubble chamber, once used at Fermilab, [2]

Invented by Donald Glaser in 1952, the bubble chamber was 'perfected' by Luis Alvarez when he helped to develop a version which could be used with liquid hydrogen. Hydrogen was desirable as a substance due to its extremely simple structure, which supplied much cleaner results than other fillings, unlike the original filler, Ether.

Soon after the advent of bubble chambers, physicists were able to macroscopically image these new, exotic particles interacting with normal matter as well as decaying - and develop novel computer techniques to analyze and catalog the massive influx of data.

The break-through came in 1961, when Gell-Mann and Nishijima leveraged recognized the underlying symmetry of the interactions taking place, and created what would be known as 'the eightfold way'. This theory created a scheme for organizing the observed baryons and mesons according to their properties in groupings called "octets". These octets

Figure 2.11: An example of the photographs taken with a Bubble Chamber, in 1973. In this picture, we see a 300 GeV proton producing partices as it travels through a hydrogen-filled bubble chamber at fermilab [15].

were in fact representations of the elements of members of the $SU(3)$ group. Another way of stating this, is that Gell-Mann had discovered the underlying structure of flavor-symmetry between the three lightest quarks - u, d, and s. This work directly led to the development of the quark model of matter, the foundation of what would become the foundation of the standard model of particles. To date, the standard model is the most successful theory describing particles, and their interactions.

Gell-Mann's quark model soon made important predictions which were later verified, notably the Ω^-, which was the ground-state particle of the spin-3/2 decuplet - discovered at Brookhaven National Laboratory (the same lab from which my research has been derived!).

Gell-Mann formalized his quark theory of matter in 1964, however, due to the unforeseen phenomena of color confinement, it would be several years before evidence of quarks composing baryons and mesons was directly obtained from deep inelastic scattering experiments.

2.2.6 Deep Inelastic Scattering and The Parton Model

Deep inelastic scattering experiments, Figure 2.12 were a natural outgrowth of Rutherford's experiment from the late 19th century. There are a few notable differences. Rutherford's scattering experiments could be modeled classically, by assuming some concentrated charge center to atoms, and using an impact parameter for an incoming projectile to predict where projectiles were scattered. Rutherford's experiments were considered generally 'elastic' because the target absorbed very little kinetic energy from the projectile.

However, in the late 20th century, scattering experiments became highly inelastic - targets would absorb a lot of kinetic energy - sometimes so much that targets would break apart. During the process of a high energy interaction between the projectile (often a beam) and the target (often an ionized gas, sometimes another beam), some kind of interaction occurs between the target and the projectile, in a way that changes the state of the projectile, and generates matter due to the high energies involved. One can observe the state of the projectile, and account for the matter which is created, and if there are laws which govern how the state of the projectile changes, or the kinds of matter that can be created, then we can run the clock backwards, reconstructing the kind of interactions that happened, to learn something about nuclear structure (or even partonic structure). In this way, one can also identify conserved quantities, which in turn suggest physical symmetries, which in turn help to build models.

I said the word parton, which I have been carefully avoiding, but now the cat's out of the bag. Nuclei, as we will learn, are not elementary particles, but instead, are built up from what we assume are fundamental, elementary particles. Deep inelastic scattering experiments slowly revealed that nuclei (individual protons and neutrons) were not elementary particles, but instead, composite particles. It is natural to assume then, that the properties of protons and neutrons are not fundamental either. And in fact, the vast zoo of particles that were discovered in early inelastic scattering experiments, such as π or K or Λ (discussed briefly earlier) were not fundamental either.

In Michael Riordan's excellent 1992 summary of the discovery of quarks, Riordan lays out a very succinct and thorough history of the late 20th century experimental and theoretical works which built on Rutherford and Gell-Man's work. Riordan states that surprising 'results came from a series of electron scattering experiments...from 1967 through 1973' at MIT and SLAC, which comprised the first set of evidence produced in favor of the partonic model. As described earlier, Gell-Mann created a three-quark model to produce predictions consistent with these observations [32].

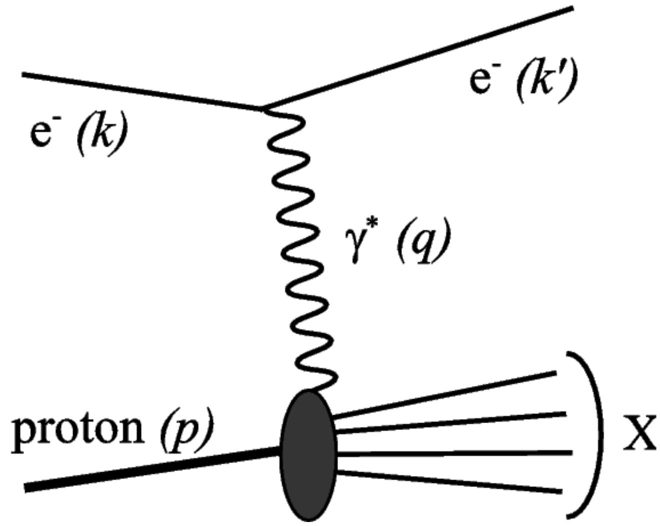


Figure 2.12: A schematic of deep inelastic scattering, where the incoming electron inelastically scatters off the proton, producing results X, via virtual photon exchange, γ^* [14]

By the 1970's, collaborations between Bjorken, Feynman, and others had produced a coherent partonic model which contained quarks, and force mediating gluons. Additionally, the concept of Structure functions had been developed. Modified from Rutherford's original scattering formula, this new formula to describe the cross section of deep inelastic scattering incorporated structure functions, which separated out the momentum exchange between target and projectile (via a virtual photon), and isolated this from W_1 and W_2, structure functions which were experimentally measured quantities representing the electron-proton interaction (the 'physics-y' part of the interaction).

The formalism of scattering theroy continued to evolve during the booming period of particle physics from 1960 to present day. Though the mechanics of scattering experiments have remained essentially unchanged, vast improvements in technology in detectors, data collection and reconstrcution, and beam production have evolved from Geiger and Marsden's humble beginnings to create scientific measurements of particles and their properties with exquisite and unprecidented precision. The kind of precision I'm talking about is exemplified in Brookhaven National Laboratory's E821 Muon (g-2) experiment - which measured the anomalous magnetic moment, g-2, of the muon to a precision of 7 parts in ten million [9].

The advent of structure functions hailed an era of non-point-like baryonic matter. The mathematics of scattering formalism had to change to accomodate the underlying physical distribution of partonic matter in baryons. Deep Inelastic Scattering continued to probe various portions of these structure functions, and the structure of the standard model began to come into focus, distilled into the relatively simple mathematical structure of group theory. Concretely, the standard model is a gauge theory, which contains the internal symmetries of $SU(3) \times SU(2) \times SU(1)$, Figure 2.13. The Standard Model is said by some to be "complete" with the discovery of the Higgs Boson, yet with emergent phenomena such as proton spin, it does not provide a straightforward prediction. The model still has not included gravitation and relativistic effects fully - and probably isn't entirely correct.

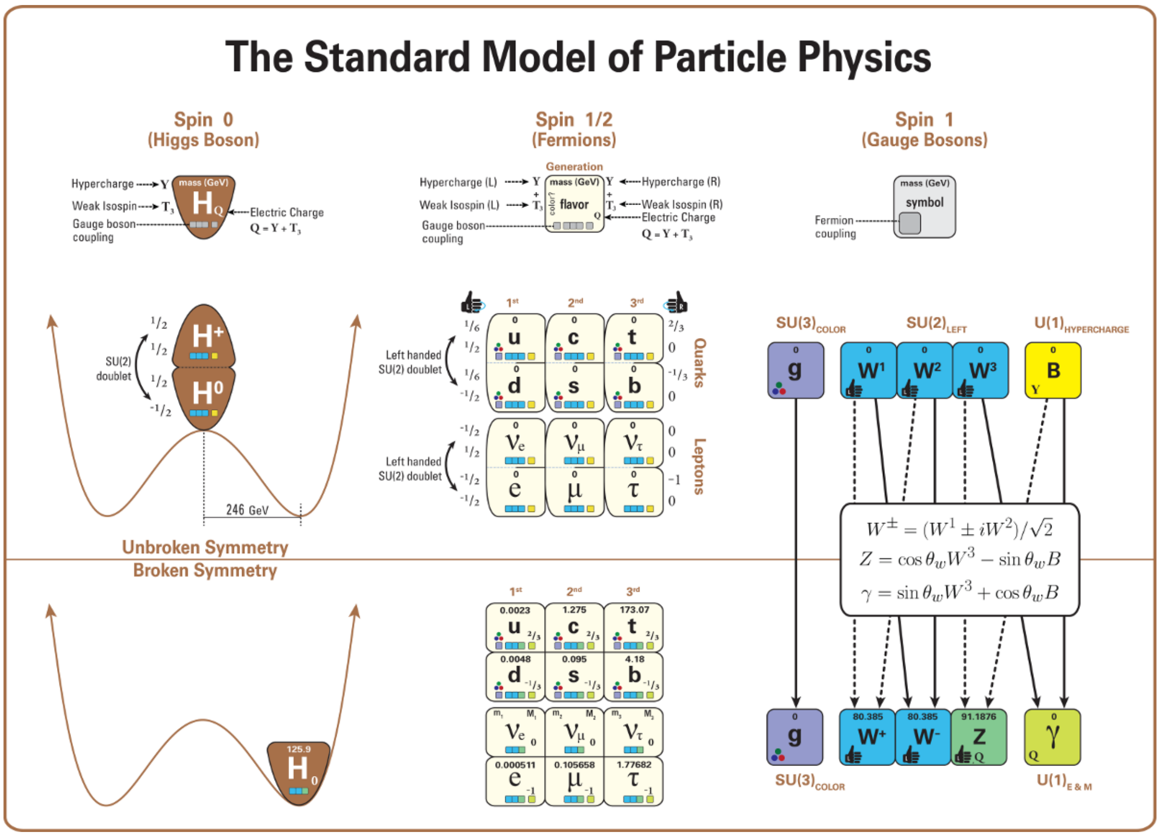


Figure 2.13: "This diagram displays the structure of the standard model (in a way that displays the key relationships and patterns more completely, and less misleadingly, than in the more familiar image based on a 4x4 square of particles). In particular, this diagram depicts all of the particles in the standard model (including their letter names, masses, spins, handedness, charges, and interactions with the gauge bosons – i.e. with the strong and electroweak forces). It also depicts the role of the Higgs boson, and the structure of electroweak symmetry breaking, indicating how the Higgs vacuum expectation value breaks electroweak symmetry, and how the properties of the remaining particles change as a consequence."[10].

2.3 World Experiments in Deep Inelastic Scattering

The following experiments highlighted here represent a period of science from approximately 1979 to present day, and focus mostly on efforts to understand the structure of baryons. Along the way, much of the Standard Model was discovered and codified, but I will try to keep the narrative focused on how experiments contributed to understanding both the structure of baryons in terms of parton distribution functions, and structure functions. Structure functions fall into two broad categories, within the scope of this work - cases which ingore the contribution of spin and cases which include the contribution of spin. Relevant maths will be presented largely only in the context of the experiments, which does not do a very good service to the progression of ideas on the theoretcial side of physics, but hey, I'm an experimentalist. Once finished, I will present a brief overview of our best models developed for understanding the proton spin, developed in parallel with these experimental efforts, before transitioning to a discussion of RHIC, and my efforts on the subject.

Many of the experiments to be discussed here took data over a long period of time - some experiments were in competition, while others complimented each-other.

Though there are other experiments which currently take data complimentary to RHIC, I will cover only the experiments which direclty lead to RHIC's spin program, with apologies to those experiments I've left out.

EIC white paper: [3]

Discuss SLAC, CERN, DESY, and RHIC. Discuss although DESY took data with HERA from 1992 - 2007, analysis and publication of the data is still ongoing.

HepData: `http://hepdata.cedar.ac.uk/review/f2/index.shtml`

2.3.1 CERN - European Muon Collaboration: 1979-1997

Overview Paper: Higlights of the European Muon Collaboration [23]

A measurement of the spin asymmetry and determination of the structure function Ag_1 in deep inelastic muon-proton scattering: [7].

An investigation of the spin structure of the proton in deep inelastic scattering: [6].

Although Gell-Mann's simple quark model of baryons [21] predicts the correct quantity for the spin of the proton, the work of Ashman et al (1988) **[CITATION NEEDED]** at the European Muon Collaboration directly measured a portion of the proton structure function g_1 and found that a rather small fraction of the proton spin comes from quarks - and most of the spin is carried by the gluons (Figure 2.14).

Figure 2.14: **[FIGURE NEEDED]** **[CAPTION NEEDED]**. Results of EMC experiment showing that the structure function g1, tells us a thing about proton spin.

inSPIRE: collaboration:'European Muon'

2.3.2 SLAC - E142: 1993-1994

inSPIRE: collaboration:'E142'

2.3.3 SLAC - E143: 1992-1999

inSPIRE: collaboration:'E143'

2.3.4 DESY - ZEUS: 1992-Present

inSPIRE: collaboration:'ZEUS' H1+ZEUS combined results: https://www.desy.de/h1zeus/combined_results/ ZEUS figures: http://www-zeus.desy.de/zeus_papers/zeus_papers.html

2.3.5 CERN - Spin Muon Collaboration: 1993-1998

Spin Asymmetry A_1 and structure functions g_1 [4] NLO QCD analysis of spin structure function g_1 [5] inSPIRE: collaboration:'Spin Muon'

2.3.6 SLAC - E154: 1994-1997

inSPIRE: collaboration:'E154'

2.3.7 DESY - HERMES: 1995-2007

inSPIRE: collaboration:HERMES HERMES website, publications, figures: http://www-hermes.desy.de/

2.3.8 SLAC - E155: 1997-2003

inSPIRE: collaboration:'E155'

2.3.9 CERN - COMPASS: 2005-Present

inSPIRE: collaboration:'COMPASS'

2.3.10 DESY - H1: 1992-Present

H1 Publications: http://h1.desy.de/e104552/e104555/ inSPIRE: collaboration:'HERA' (HERA is the accelerator) inSPIRE: collaboration:'H1' (this is the data)

Chapter 3

Models and Associated Probes For Proton Spin Structure

3.1 structure functions

3.2 proton spin decomposition

3.3 unpolarized parton distribution functions

3.4 polarized parton distribution functions

3.5 that sweet table from Delia hasch

3.6 discussion $\bar{q}$, q, L_q, g

3.7 DSSV

3.8 Measurement of the Proton Spin

3.8.1 physics probes for proton spin

3.8.2 W cross section

3.8.3 derivation of Asymmetry

3.8.4 kinematic extremes of Asymmetry

3.9 Cross Sections and Luminosity

- vernier analysis note intro, equations
- summarize the papers on Lumoninosity

Chapter 4

Experimental Apparatus

4.1 The Relativistic Heavy Ion Collider

4.1.1 Overview

4.1.2 The RHIC Spin Program

4.1.3 Production of Polarized Proton Beams

4.2 The Pioneering High Energy Nuclear Interaction Experiment

4.2.1 Subsystem Overview

4.2.2 Luminosity

4.2.3 Beam Polarization

4.3 The Forward Upgrade

4.3.1 The Muon Tracker + Muon Trigger Subsystems

4.3.2 Resisitive Plate Chambers

4.3.2.1 Design

4.3.2.2 Construction

4.3.2.3 Testing

4.3.2.4 Performance

4.3.3 The DAQ

4.3.3.1 2013 Data Set Triggers

Chapter 5

The Data Set

5.1 Overview

Now that we have discussed the various aparatuses provided by the PHENIX experiment, we can go into more depth with the process of engineering features. For this analysis, we consider only events which are identified by the Muon Arms subsystem as being muons. The raw data provided by PHENIX is quite complex, and at the hardware level is generally not too useful for physics analysis.

In this chapter, we will discuss the process of cleaning our data set, the goal of which is to get rid of background data, while keeping any event that could possibly contribute to the $W \to \mu$ signal. This cleaning is done in three stages. The first stage concerns applying a simple basic cut to our data set to remove events which are kinematically forbidden from having W boson parent particles, this is called the "Basic Cut".

After this, we label data with W_{ness}, which is an event's likelihood for coming from a W boson decay. Although this is part of data cleaning, since W_{ness} is an important parameter in the analysis, it is discussed in Section 6.1.3.

Finally, we must estimate the overall yield of μ resulting from the various proton helicity combinations, and the signal to background ratio characterizing that yield. Again, since this is also an important part of the physics, it is discussed in Section 6.2.6.

5.2 Analysis Variables and the Basic Cut

A brief summary of the kinematic variables used later in the analysis is given in Table 5.2. In addition four sets of RPC cluster variables exist which are being used as main RPC variables. These variables contain projections from either vertex, Station 1, 3 or the MuID road to the corresponding z positions of the RPCs based on the tracks in the PHMuoTracksOut node and are directly taken over from the RpcMuoTracks node in the dsts:

- newsngmuons→Branch("RpcMatchVtx",0,"Rpc3dca[_RecoTracks]/F:
Rpc3time[_RecoTracks]/F:Rpc3x[_RecoTracks]/F:Rpc3y[_RecoTracks]/F:
Rpc1dca[_RecoTracks]/F:Rpc1time[_RecoTracks]/F:Rpc1x[_RecoTracks/F:
Rpc1y[_RecoTracks]/F");

- newsngmuons→Branch("RpcMatchSt1",0,"Rpc3dca[_RecoTracks]/F:
Rpc3time[_RecoTracks]/F:Rpc3x[_RecoTracks]/F:Rpc3y[_RecoTracks]/F:
Rpc1dca[_RecoTracks]/F:Rpc1time[_RecoTracks]/F:Rpc1x[_RecoTracks]/F:
Rpc1y[_RecoTracks]/F");

- newsngmuons→Branch("RpcMatchSt3",0,"Rpc3dca[_RecoTracks]/F:
Rpc3time[_RecoTracks]/F:Rpc3x[_RecoTracks]/F:Rpc3y[_RecoTracks]/F:
Rpc1dca[_RecoTracks]/F:Rpc1time[_RecoTracks]/F:Rpc1x[_RecoTracks]/F:
Rpc1y[_RecoTracks]/F");

- newsngmuons→Branch("RpcMatchMuID",0,"Rpc3dca[_RecoTracks]/F:
Rpc3time[_RecoTracks]/F:Rpc3x[_RecoTracks]/F:Rpc3y[_RecoTracks]/F:
Rpc1dca[_RecoTracks]/F:Rpc1time[_RecoTracks]/F:Rpc1x[_RecoTracks]/F:
Rpc1y[_RecoTracks]/F");

For the moment the timing and DCA distributions we use are those matching from station 1 for RPC1 and from station3 for RPC3. In addition, in order to improve the background rejection in the FVTX acceptance, for this analysis several new variables are added in relation to the FVTX-MuTr matching which were directly taken over from the corresponding methods in the PHMuoTracksOut node. Those are fvtx_dr, fvtx_dϕ and fvtx_dθ which compare the FVTX tracklets radial position, azimuthal and polar angles with

Variable	**Definition**
η	Pseudorapidity, used in secondary likelihood cuts
χ^2_{track}	Standard chi2 of μ track Kalman fitter
$DG0$,$DDG0$	Roads generated in MUID+MuTr planes. $DG0$ is distance between first gap road and track. $DDG0$ is opening angle between road and track.
DCA_r,DCA_Z	Distance of closest approach between μ track and beam axis (DCA_r). DCA_Z is the distance between the track's intersection with PHENIX's z-axis and the event vertex.
$RpcDca_{1,3}$	Distance between extrapolated track at RPC 1 or 3, and hit cluster at RPC 1 or 3.
dw_{23}	Reduced azimuthal bending angle of track. $dw_{23} = p_T sin(\theta)(\phi_2 - \phi_3)$
$fvtx\_d\theta$	
$fvtx\_d\phi$	FVTX matched track matching residuals for ϕ, θ, dr.
$fvtx\_dr$	

Table 5.1: Summary of engineered features from the data set used in this analysis.

those of the MuTr as an extrapolated z position between the two. Another FVTX related addition is the FVTX hit multiplicity within a cone of INPUT RANGE HERE around the projected track. This varible will henceforth be called FVTX_cone.

The "Basic Cut" is defined:

In this W analysis one is interested in removing most lower momentum particles which originate predominantly from background processes while keeping most of the W decay muons. With the above cuts, we aim to reduce part of the fake muons background assuring a good muon track reconstruction ($DG0$,$DDG0$ and χ^2 cuts) and selecting tracks with momentum smaller than the maximum possible physical energy. After applying these basic cuts, the background will be further reduced via a likelihood method, described in Section 6.1.3, where background and signal features will be studied in detailed.

The correlations between the several cut variables are shown in Fig. 6.2 for data and for the W-si The only exception is the correlation between the vertex extrapolated variables DCA_z and DCA_r and the FVTX related matching variables. This is not entirely unexpected as both should be sensitive to the amount of multiple scattering in the central magnet yoke and initial shielding.

Variable	Lower Bound	Upper Bound
MuID lastGap	*	Gap 4
χ^2	0	20
$DG0$	0	20
$DDG0$	0	9
μ candidate	*	1

Table 5.2: The Basic Cuts used in the Run 13 analysis. lastGap refers to the last gap in the MUID which saw a μ candidate event. The fourth gap is the furthest penetration possible, therefore suggesting a high energy muon. Other parameters are described in table 5.1

5.3 Feature Engineering

5.3.1 Discriminating Kinematic Variables

5.3.2 Simulations

Chapter 6

Spin Analysis

6.1 Classification of Signal or Background Events

After producing our data set, engineering features which help us convert our experimental data into observables, we are then tasked with the problem of separating out signal events from background events. Many processes are capable of producing muons, many of which are dominant in the W boson kinematic regime (Figure 6.1).

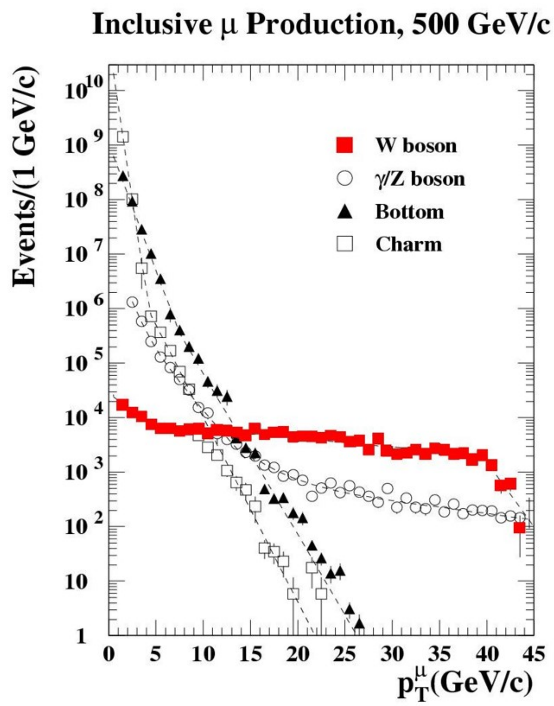


Figure 6.1: Observing the simulated production of muon as a function of p_T, we can see that in the kinematic region of W production that the dominant sources of muons come from other processes. The new PHENIX muon trigger threshold is sensitive at 10 GeV/c and above.

We can divide up the total observed muon spectrum into contributions from three sources:

- Real Muon Background
  - Z,γ^*
  - W →had
  - W →tau
  - onium
  - open charm
  - direct photon
- Fake Muons (Hadronic Background)

  - Hadrons which are reconstructed as high p_T muons due to detector resolution.

- Signal Muons
  - Real $W \to \mu$ events.

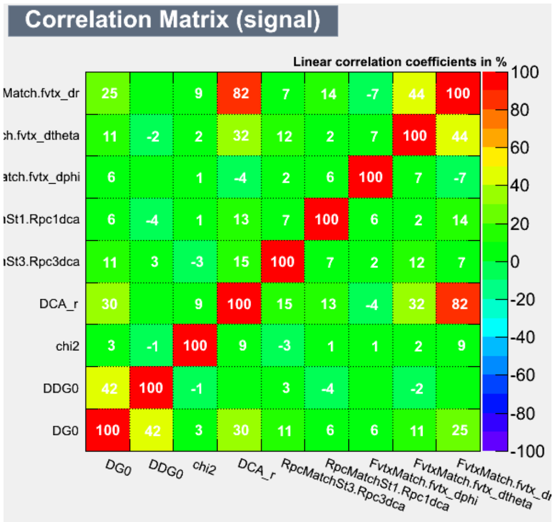
Previous analyses have attempted to separate the muon spectrum into p_T bins, to estimate the composition, however, because the $W \to \mu$ signal is so small in the forward kinematic regime, these methods are not sufficient, as there is no 'visible' cutoff in the spectrum. However, by using simulations. However, we may use other methods to split up our spectrum, with the ultimate goal of calculating A_L, and correcting for background dilution using the signal to background ratio. We must use another method to effectively describe the difference between an event which comes from a signal, vs background event.

6.1.1 Naive Bayes Classification

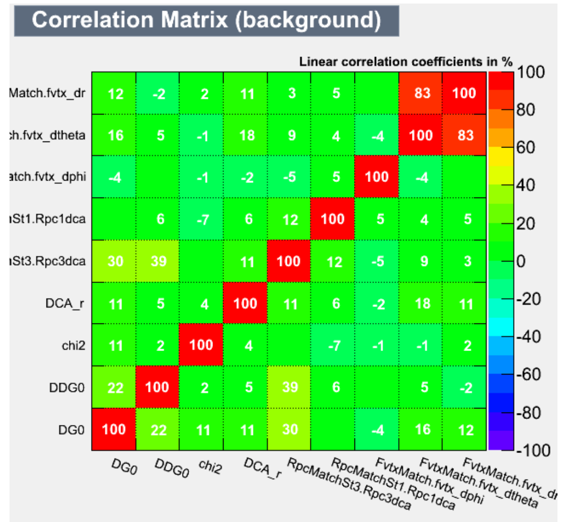
There are many techniques available for classifying a collection of variables (a feature set) into categories. Naive Bayes classification is an excellent candidate for classification, in cases where we have two classifications with distributions of featuresets which are uncorrelated. Naive Bayes even works when feature sets are slightly correlated. It is a robust, fast, scalable machine learning technique. Traditionally used for classification of text documents, Naive Bayes is also able to handle numeric features whose distributions are known [13].

In our analysis, we begin with a Naive Bayes classifer which is trained to classify two signal muons, vs background muons. We combine both Real Muon Background muons and Fake Muons (Hadronic Background Muons) in the label of "Background Muons" at this stage, though, later, we will separate out the muons further.

The descriniating variables described in 5 were chosen from the multitude of possible physical event parameters, because they were all maximally uncorrelated. Concretely, these correlations are presented in



(a) Correlations between kinematic variables, produced from simulated data.



(b) Correlations betwen kinematic variables, produced from the data, which is composed mostly of hadronic background

Figure 6.2: Low correlations between the signal variable distributions (from simulation), and the background variable distributions make this data set a good candidate for classfication using Naive Bayes

Briefly, a Naive Bayes classifier may be constructed from the core of the familiar Bayes Theorem from probability and statistics.

In our case, we understand Naive Bayes as a conditional probability. Concretely, we consider a vector of features (i.e. our discriminating kinematic variables):

$$\mathbf{x} = (x_1, \ldots, x_n) \tag{6.1}$$

and assume independence between each feature x_n. We then define the probability of a given classification, C_k given a set of features x_n:

$$p(C_k|x_1, \ldots, x_n) \tag{6.2}$$

This conditional probability is defined in terms of Bayes Theorem:

$$p(C_k|\mathbf{x}) = \frac{p(C_k)\ p(\mathbf{x}|C_k)}{p(\mathbf{x})} \tag{6.3}$$

The terms here are defined as:

- $p(C_k) \rightarrow$ prior probability
- $p(\mathbf{x}|C_k) \rightarrow$ likelihood
- $p(\mathbf{x}) \rightarrow$ evidence

In principal, the final step in a classifier is to assign a class. This is done by computing the probability of a feature-set belonging to one class, or to another class, using Bayes Theroem. The class with the larger proability is than taken as the defacto classification of that particular feature set. However, we may instead observe these probabilities directly, and label data with this probability. This is what we ultimately call our "W_{ness}" parameter. This will be discussed in section 6.1.3.

6.1.2 Composition of Probability Distribution Functions

After we have engineered appropriate features to use in the analysis, we can proceed with composing probability density functions so we can proceed with the calculation of likelihoods, which will label our data set, allowing us to reduce our data set further from the basic cuts, without removing any signal events.

6.1.3 Labeling Data With Likliehood Ratio: W_{ness}

6.2 Extended Unbinned Maximum Likelihood Fits

6.2.1 Modeling The Hadronic Background

6.2.2 Modeling the Muon Background

6.2.3 Modeling the W-Signal

6.2.4 Overview

6.2.5 Fit Performance

6.2.6 S/BG and Muon Backgrounds

6.2.7 W_{ness} Dependence of S/BG

6.3 Calculation of A_L for $W \rightarrow \mu$

6.3.1 Overview

6.3.2 Asymmetry Calculation

6.3.3 Discussion of Work Done By Analysis Team

6.4 Data Validation

Mention Daniel's GPR, Ralf's PEPSI, Abraham's FVTX work, and Francesca's cross-checks.

6.4.1 Simulations and The Signal to Background Ratio

6.4.2 Gaussian Process Regression

6.4.3 Four Way Cross Validation

6.4.4 Asymmetry Consistency Check

6.4.5 Beam Polarization

6.4.6 Beam Luminosity

6.4.7 Code Cross Validation

Chapter 7

The Vernier Analysis

7.1 Overview

7.2 Analysis Note Here

7.3 W Cross Section

Chapter 8

Discussion and Conclusion

Bibliography

[1] Hideki Yukawa. *The Mainichi Graphic*, sep 1952.

[2] Fermi National Lab Bubble Chamber, 2005.

[3] a. Accardi, J. L. Albacete, M. Anselmino, N. Armesto, E. C. Aschenauer, A. Bacchetta, D. Boer, W. K. Brooks, T. Burton, N. B. Chang, W. T. Deng, A. Deshpande, M. Diehl, A. Dumitru, R. Dupré, R. Ent, S. Fazio, H. Gao, V. Guzey, H. Hakobyan, Y. Hao, D. Hasch, R. Holt, T. Horn, M. Huang, A. Hutton, C. Hyde, J. Jalilian-Marian, S. Klein, B. Kopeliovich, Y. Kovchegov, K. Kumar, K. Kumerički, M. A. C. Lamont, T. Lappi, J. H. Lee, Y. Lee, E. M. Levin, F. L. Lin, V. Litvinenko, T. W. Ludlam, C. Marquet, Z. E. Meziani, R. McKeown, A. Metz, R. Milner, V. S. Morozov, A. H. Mueller, B. Müller, D. Müller, P. Nadel-Turonski, A. Prokudin, V. Ptitsyn, X. Qian, J. W. Qiu, M. Ramsey-Musolf, T. Roser, F. Sabatié, R. Sassot, G. Schnell, P. Schweitzer, E. Sichtermann, M. Stratmann, M. Strikman, M. Sullivan, S. Taneja, T. Toll, D. Trbojevic, T. Ullrich, R. Venugopalan, S. Vigdor, W. Vogelsang, C. Weiss, B. W. Xiao, F. Yuan, Y. H. Zhang, L. Zheng, H. Paukkunen, A. Prokudin, V. Ptitsyn, X. Qian, J. W. Qiu, M. Ramsey-Musolf, T. Roser, F. Sabatié, R. Sassot, G. Schnell, P. Schweitzer, E. Sichtermann, M. Stratmann, M. Strikman, M. Sullivan, S. Taneja, T. Toll, D. Trbojevic, T. Ullrich, R. Venugopalan, S. Vigdor, W. Vogelsang, C. Weiss, B. W. Xiao, F. Yuan, Y. H. Zhang, and L. Zheng. Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all. *arXiv preprint*, page 164, 2012.

[4] B. Adeva, T. Akdogan, E. Arik, B. Badelek, G. Bardin, G. Baum, P. Berglund, L. Betev, R. Birsa, N. de Botton, F. Bradamante, A. Bravar, A. Bressan, S. Bültmann, E. Burtin, C. Cavata, D. Crabb, J. Cranshaw, T. Çuhadai, S. Dalla Torre, R. van Dantzig, B. Derro, A. Deshpande, S. Dhawan, C. Dulya, S. Eichblatt, D. Fasching, F. Feinstein, C. Fernandez, S. Forthmann, B. Frois, A. Gallas, J. A. Garzon, H. Gilly, M. Giorgi, E. von Goeler, S. Goertz, G. Gracia, N. de Groot, M. Grosse Perdekamp, K. Haft, D. von Harrach, T. Hasegawa, P. Hautle, N. Hayashi, C. A. Heusch, N. Horikawa, V. W. Hughes, G. Igo, S. Ishimoto, T. Iwata, E. M. Kabuß, T. Kageya, A. Karev, H. J. Kessler, T. J. Ketel, J. Kiryluk, Yu. Kisselev, D. Krämer, V. Krivokhijine, W. Kröger, V. Kukhtin, K. Kurek, J. Kyynäräinen, M. Lamanna, U. Landgraf, J. M. Le Goff, F. Lehar, A. de Lesquen, J. Lichtenstadt, M. Litmaath, A. Magnon, G. K. Mallot, F. Marie, A. Martin, J. Martino, T. Matsuda, B. Mayes, J. S. McCarthy,

K. Medved, W. Meyer, G. van Middelkoop, D. Miller, Y. Miyachi, K. Mori, J. Moromisato, J. Nassalski, L. Naumann, T. O. Niinikoski, J. E. J. Oberski, A. Ogawa, C. Ozben, H. Pereira, F. Perrot-Kunne, D. Peshekhonov, R. Piegaia, L. Pinsky, S. Platchkov, M. Plo, D. Pose, H. Postma, J. Pretz, R. Puntaferro, T. Pussieux, G. Rädel, A. Rijllart, G. Reicherz, J. Roberts, M. Rodriguez, E. Rondio, I. Sabo, J. Saborido, A. Sandacz, I. Savin, P. Schiavon, A. Schiller, E. P. Sichtermann, F. Simeoni, G. I. Smirnov, A. Staude, A. Steinmetz, U. Stiegler, H. Stuhrmann, M. Szleper, F. Tessarotto, D. Thers, W. Tlaczala, A. Tripet, G. Unel, M. Velasco, J. Vogt, R. Voss, C. Whitten, R. Windmolders, R. Willumeit, W. Wislicki, A. Witzmann, J. Ylöstalo, A. M. Zanetti, K. Zaremba, and J. Zhao. Next-to-leading order QCD analysis of the spin structure function <math display=”inline”> <mrow> <msub> <mrow> <mi>g</mi> </mrow> <mrow> <mn>1</mn> </mrow> </msub> </mrow> </math>. *Physical Review D*, 58(11):112002, 1998.

[5] B. Adeva, T. Akdogan, E. Arik, B. Badelek, G. Bardin, G. Baum, P. Berglund, L. Betev, R. Birsa, N. de Botton, F. Bradamante, A. Bravar, A. Bressan, S. Bültmann, E. Burtin, C. Cavata, D. Crabb, J. Cranshaw, T. Çuhadai, S. Dalla Torre, R. van Dantzig, B. Derro, A. Deshpande, S. Dhawan, C. Dulya, S. Eichblatt, D. Fasching, F. Feinstein, C. Fernandez, S. Forthmann, B. Frois, A. Gallas, J. A. Garzon, H. Gilly, M. Giorgi, E. von Goeler, S. Goertz, G. Gracia, N. de Groot, M. Grosse Perdekamp, K. Haft, D. von Harrach, T. Hasegawa, P. Hautle, N. Hayashi, C. A. Heusch, N. Horikawa, V. W. Hughes, G. Igo, S. Ishimoto, T. Iwata, E. M. Kabuß, T. Kageya, A. Karev, H. J. Kessler, T. J. Ketel, J. Kiryluk, Yu. Kisselev, D. Krämer, V. Krivokhijine, W. Kröger, V. Kukhtin, K. Kurek, J. Kyynäräinen, M. Lamanna, U. Landgraf, J. M. Le Goff, F. Lehar, A. de Lesquen, J. Lichtenstadt, M. Litmaath, A. Magnon, G. K. Mallot, F. Marie, A. Martin, J. Martino, T. Matsuda, B. Mayes, J. S. McCarthy, K. Medved, W. Meyer, G. van Middelkoop, D. Miller, Y. Miyachi, K. Mori, J. Moromisato, J. Nassalski, L. Naumann, T. O. Niinikoski, J. E. J. Oberski, A. Ogawa, C. Ozben, H. Pereira, F. Perrot-Kunne, D. Peshekhonov, R. Piegaia, L. Pinsky, S. Platchkov, M. Plo, D. Pose, H. Postma, J. Pretz, R. Puntaferro, T. Pussieux, G. Rädel, A. Rijllart, G. Reicherz, J. Roberts, M. Rodriguez, E. Rondio, I. Sabo, J. Saborido, A. Sandacz, I. Savin, P. Schiavon, A. Schiller, E. P. Sichtermann, F. Simeoni, G. I. Smirnov, A. Staude, A. Steinmetz, U. Stiegler, H. Stuhrmann, M. Szleper, F. Tessarotto, D. Thers, W. Tlaczala, A. Tripet, G. Unel, M. Velasco, J. Vogt, R. Voss, C. Whitten, R. Windmolders, R. Willumeit, W. Wislicki, A. Witzmann, J. Ylöstalo, A. M. Zanetti, K. Zaremba, and J. Zhao. Next-to-leading order QCD analysis of the spin structure function <math display=”inline”> <mrow> <msub> <mrow> <mi>g</mi> </mrow> <mrow> <mn>1</mn> </mrow> </msub> </mrow> </math>. *Physical Review D*, 58(11):112002, 1998.

[6] J. Ashman, B. Badelek, G. Baum, J. Beaufays, C. P. Bee, C. Benchouk, I. G. Bird, S. C. Brown, M. C. Caputo, H. W K Cheung, J. S. Chima, J. Ciborowski, R. Clifft, G. Coignet, F. Combley, G. Court, G. D'Agostini, J. Drees, M. Düren, N. Dyce, A. W. Edwards, M. Edwards, T. Ernst, M. I. Ferrero, D. Francis, E. Gabathuler, R. Gamet, V. Gibson, J. Gillies, P. Grafström, K. Hamacher, D. V. Harrach, P. J. Hayman,

J. R. Holt, V. W. Hughes, A. Jacholkowska, T. Jones, E. M. Kabuss, B. Korzen, U. Krüner, S. Kullander, U. Landgraf, D. Lanske, F. Lettenström, T. Lindqvist, J. Loken, M. Matthews, Y. Mizuno, K. Mönig, F. Montanet, E. Nagy, J. Nassalski, T. Niinikoski, P. R. Norton, F. G. Oakham, R. F. Oppenheim, A. M. Osborne, V. Papavassiliou, N. Pavel, C. Peroni, H. Peschel, R. Piegaia, B. Pietrzyk, U. Pietrzyk, B. Povh, P. Renton, J. M. Rieubland, A. Rijllart, K. Rith, E. Rondio, L. Ropelewski, D. Salmon, A. Sandacz, T. Schröder, K. P. Schüler, K. Schultze, T. A. Shibata, T. Sloan, A. Staiano, H. E. Stier, J. Stock, G. N. Taylor, J. C. Thompson, T. Walcher, J. Toth, L. Urban, W. Wallucks, S. Wheeler, D. A. Williams, W. S C Williams, S. J. Wimpenny, R. Windmolders, W. J. Womersley, and K. Ziemons. An investigation of the spin structure of the proton in deep inelastic scattering of polarised muons on polarised protons. *Nuclear Physics, Section B*, 328(1):1–35, 1989.

[7] J Ashman, Others, B Badelek, G Baum, I G Bird, A W Edwards, and T Walcher. A Measurement Of The Spin Asymmetry And Determination Of The Structure Function \textit{g1} In Deep Inelastic Muon-Proton Scattering. *Phys. Lett. B*, 206(2):364–370, 1988.

[8] Bruxelles Benjamin Croupie. Participants of the 5th Solvay Congress. Technical report, 1927.

[9] GW Bennett, B Bousquet, HN Brown, G Bunce, RM Carey, P Cushman, GT Danby, PT Debevec, M Deile, H Deng, SK Dhawan, VP Druzhinin, L Duong, FJM Farley, GV Fedotovich, Fe Gray, D Grigoriev, M Grosse-Perdekamp, A Grossmann, MF Hare, DW Hertzog, X Huang, VW Hughes, M Iwasaki, K Jungmann, D Kawall, Bi Khazin, F Krienen, I Kronkvist, A Lam, R Larsen, YY Lee, I Logashenko, R McNabb, W Meng, JP Miller, WM Morse, D Nikas, CJG Onderwater, Y Orlov, CS Ozben, JM Paley, Q Peng, CC Polly, J Pretz, R Prigl, G zu Putlitz, T Qian, Si Redin, O Rind, BL Roberts, N Ryskulov, YK Semertzidis, P Shagin, YuM Shatunov, Ep Sichtermann, E Solodov, M Sossong, LR Sulak, A Trofimov, P von Walter, and A Yamamoto. Measurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm.

[10] Latham Boyle. standard_model_complete, 2014.

[11] M. Breidenbach, J. I. Friedman, H. W. Kendall, E. D. Bloom, D. H. Coward, H. Destaebler, J. Drees, L. W. Mo, and R. E. Taylor. Observed behavior of highly inelastic electron-proton scattering. *Physical Review Letters*, 23(16):935–939, 1969.

[12] Pj Bryant. A brief history and review of accelerators. *Cern European Organization for . . .*, 1994.

[13] Michael Collins. The Naive Bayes Model, Maximum-Likelihood Estimation, and the EM Algorithm. pages 1–21, 2013.

[14] Ddn2. Electron Proton Deep Inelastic Scattering, 2008.

[15] ENERGY.GOV. Bubble Chamber Tracks, 1973.

[16] Arthur Steward Eve. *Rutherford: Being the Life and Letters of the Rt. Hon. Lord Rutherford, O. M.* The University Press, 1939.

[17] Nobel Foundation. Paul Dirac, 1933.

[18] Craig Freudenrich. Combined Atomic Orbital, 2001.

[19] M. Gell-Mann. Isotopic spin and new unstable particles. *Physical Review*, 92(3):833–834, 1953.

[20] M. Gell-Mann. The interpretation of the new particles as displaced charge multiplets. *Il Nuovo Cimento Series 10*, 4(1 Supplement):848–866, 1956.

[21] M Gell-Mann. The eightfold way: A theory of strong interaction symmetry. Technical report, California Institution of Technology, Pasadina, 1961.

[22] W Heisenberg. Production of Mesons as a Shock Wave Problem Visual description of a shock wave. pages 1–17, 1952.

[23] Sven Kullander. Highlights of the European muon collaboration. *Nuclear Physics, Section A*, 518(1-2):262–296, nov 1990.

[24] Kurzon. Diagram of JJ Thomson's Experiment With Cathod Rays, 2010.

[25] Kurzon. Diagram Illustraitng Geiger-Marsden Experiment, 2014.

[26] Ottavio Leoni. Galileo Galilei, Portrait in Crayon by Leoni, 1624.

[27] Manisearth. scale_of_matter, 2010.

[28] Nobel Media. J.J. Thomson - Biographical, 2014.

[29] Strange Particles, The Standard Model, and Vector Bosons. History of Particle Physics. Technical report, Institute for Particle physics Phenomenology, University of Durham, Durham.

[30] Gary Patterson. Jean Perrin and the triumph of the atomic doctrine. *Endeavour*, 31(2):50–53, jun 2007.

[31] Bogdan Povh and Thomas Walcher. The end of the nucleon-spin crisis. 2016.

[32] Michael Riordan. The Discovery of Quarks. 1992.

[33] Thomas Stanley. The History of Philosophy, 1655.

[34] Marco Stratmann. Spin physics at rhic - a theoretical overview. Technical report, 2009.

[35] Hendrick ter Brugghen. Democritus, 1628.

[36] George Thomson. J. J. Thomson, 1956.

[37] H. Yukawa, S. Sakata, and M. Taketani. On the interaction of elementary particles. III. *Progress of Theoretical Physics Supplement*, 1(Received):24–45, 1955.

.1 First Thingie

.2 Second Thingie