Measurement of Fragmentation Functions in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.00$ TeV Using the ALICE Detector

A Dissertation Presented for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Charles Hughes

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dedication...

Acknowledgments

I would like to thank...

Abstract

Quantum Chromodynamics (the theory of the strong interaction, responsible for the binding of positive charges in atomic nuclei) predicts that nuclear matter undergoes a phase transition at high temperature (~ 150 MeV) or high baryon chemical potential. In this phase transition, the consitutent quarks of protons and neutrons transition from their bound hadronic states to an asymptotically free "fluid" state. This "fluid" state, a new form of matter, is know as the Quark-Gluon Plasma (QGP) and is manifested in collisions of heavy atomic nuclei (such as Pb-Pb). Studying the properties of this new state of matter is a unique challenge due to the short lifetime of the QGP. Therefore, experimental physicists must use probes generated internally during these heavy ion collisions, which pass through the QGP itself, to study it. An example of an internally generated probe is a jet. Jets are collimated sprays of high energy particles produced from hard scatterings of quarks and/or gluons in the initial collision (and not the collective motion of the constituent quarks and gluons of the short-lived QGP formed just after the collision). Jets will be modified by the QGP medium and thus can reveal the medium's transport properties. One observable associated with jets is the fragmentation function. The fragmentation function is a measure of the fraction of the total jet energy a constituent particle of the jet carries. This comprehensive will present a measurement of fragmentation functions using the ALICE (A Larage Ion Collider Experiment) detector in the LHC (Large Hadron Collider) at CERN (Center for European Nuclear Research).

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Chapter 1

The Quark-Gluon Plasma

1.1 Quantum Chromo-Dynamics

Quantum Chromodynamics (QCD) is the theory of the strong interaction. The fundamental degrees of freedom of QCD are quarks and gluons. The quarks are fermionic (carry spin $\pm\ \hbar\ /2$) particles and the quarks are bosonic (carry spin $\pm$ $\hbar$). That is, quarks interact with each other via the gluon field. For example, in the case of two static quarks, one a quark (q) and one an anti-quark () shown below in Figure 1:

1.2 QCD Phase Transition

The phase transition can be understood via the QCD phase diagram shown below in Figure 1.2. The x-axis of the diagram in Figure 7 is the Baryon chemical potential. The y-axis is the Temperature of the quarks and gluons. Ordinary nuclear matter exists around 900 MeV at 0 Temperature. As one heats up ordinary nuclear matter, one creates a hadron resonance gas which would be (mostly) excited states of ordinary nuclear matter. However, at some point one crosses the white 1st-order phase transition line and the degrees of freedom become quarks and gluons instead of hadrons.

Now you are ready to fill in the proper values corresponding to your title, name, degree, etc. This can be done in the following section:

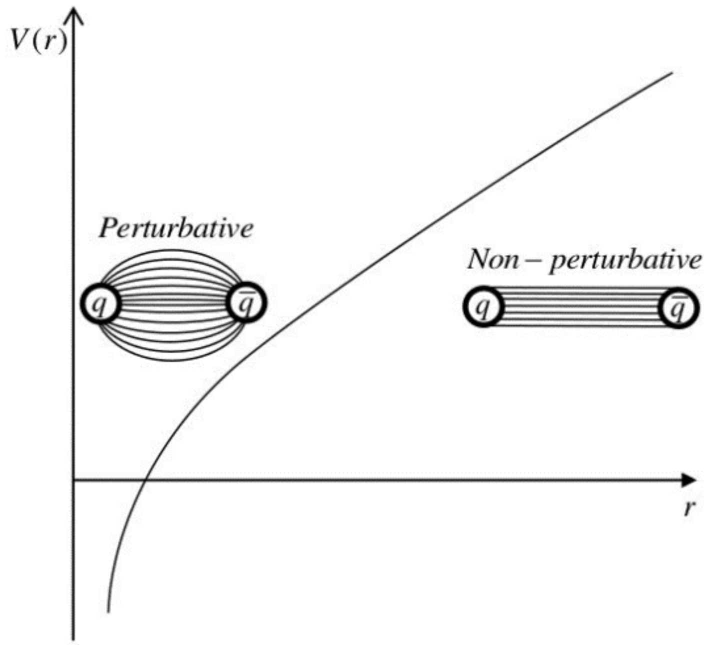

Figure 1.1: Figure 1. Static Quark Potential for a Quark, Anti-Quark Pair.

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% TO DO: FILL IN YOUR INFORMATION BELOW - READ THIS SECTION CAREFULLY
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\title{My Thesis or Dissertation Title}  % title of thesis/dissertation
\author{Smokey Volunteer}                % author's name
\copyrightYear{2017}                     % copyright year of your
                                           thesis/dissertation
\graduationMonth{May}                    % month of graduation for your
                                           thesis/dissertation
\degree{Doctor of Philosophy}   % degree: Doctor of Philosophy, Master of
                                  Science, Master of Engineering...
\university{The University  of Tennessee, Knoxville} % school name
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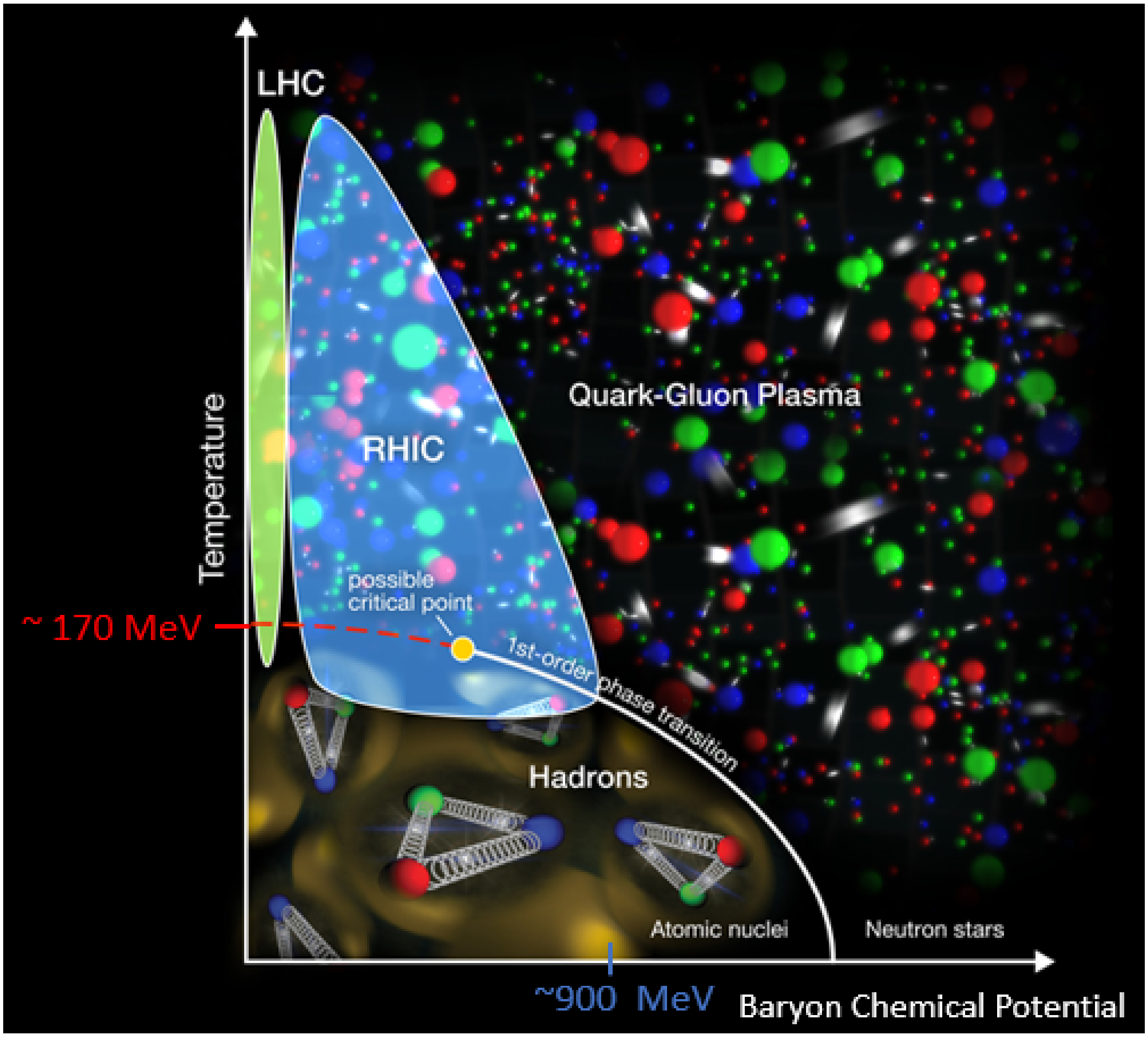

Figure 1.2: Fig 2. QCD Phase Diagram.

1.3 References

The bibliography style used in this template is "apalike". It is an author-year style based on the APA specification. Here are a few examples. T. Hungerford wrote a book on Algebra, [?]. In 1999, D. F. Anderson and P. S. Livingston wrote the defining paper on zero-divisor graphs of commutative rings in [?]. You can also point out specific theorems in papers, such as the fact that the zero-divisor graph always has diameter less than or equal to 3, [? , Theorem 2.3]. You can also list several references at once. For example, for more on zero-divisor graphs see [? ?]. However, you can change this style to any format you'd like. The code in the "my-dissertation.tex" file is

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The first entry ("#1") must remain there. It deletes the title "Bibliography" from being printed again at the top of the bibliography page. The title "Bibliography" should only appear on the title page. The second entry can be changed to any natbib style you'd like. For example, plainnat, humannat, etc. The third entry is the name of your bibliography .tex file. Remember to run BibTeX in order to compile the bibliography correctly. For more information, visit http://merkel.texture.rocks/Latex/natbib.php.

1.4 Theorem environments

This template contains predefined theorem, lemma, proposition, corollary, and definition environments. For example,

Definition 1.1. *This is your definition.*

Proposition 1.2. *This is an example of a proposition.*

Theorem 1.3 (First theorem)**.** *This is an example theorem.*

Proof for theorem. This is the proof for this theorem. □

Lemma 1.4 (First lemma)**.** *This is the first lemma.*

Proof. This is the proof for this lemma that requires Theorem 1.3. □

Corollary 1.5. *This is the first corollary.*

1.5 Figures and Tables

1.5.1 General Rules

To comply with the 2017 dissertation formatting, figure captions should be placed below the figure and table captions should be placed above the table. Also, if a table or figure takes up more than half the page, then there should be no text on that page (except for the caption of course). Lastly, you must allow tables and figures to float. DO NOT HARD CODE POSITIONS. In addition, no table or figure should go into the margins. If a table or figure does creep into the margins you can either resize it so that it properly fits within the margins, or put it on its own page and make that specific page landscape. See Figure 1.6 for an example. Note the page number location in the example. The code for this is given by:

```
\begin{landscape}
\thispagestyle{mylandscape}
\begin{figure}[h]
\centering
\includegraphics[width=9in]{32303-TheHill-byJoshQueener.jpg}
\caption{This view of The Hill is too wide for a portrait page.}
\label{fig:wide-pic}
\end{figure}
\end{landscape}
```

Be careful about where you place this landscape page, as well as all figures and tables. These objects are not considered part of the text, and thus their placement should not be assigned to a precise location. The general rule to follow is that no text page should have significant white space, with the exception being the last page of a chapter. So if you mention a figure in some paragraph but the figure will not fit on the remainder of the page, continue the text (even if it's a new section) to fill the current page with text and then place the figure on the next page. To see an example of this, consider this page you are reading now. We've mentioned Figure 1.6 in the previous paragraph. However, it requires a new page and since there is plenty of space on this page, we've filled it with text and delayed the `\begin{landscape}` section of code until the appropriate position.

1.5.2 Single figures

For more information, check out the following page:
http://en.wikibooks.org/wiki/LaTeX/Floats,_Figures_and_Captions

```
\begin{figure}[t for top, b for bottom, h for here]
    % Requires \usepackage{graphicx}
    \centering % center the figure
    \includegraphics[width=5in or 127mm etc...]{figure-name}\\
    \caption{figure caption}\label{figure label}
\end{figure}
```

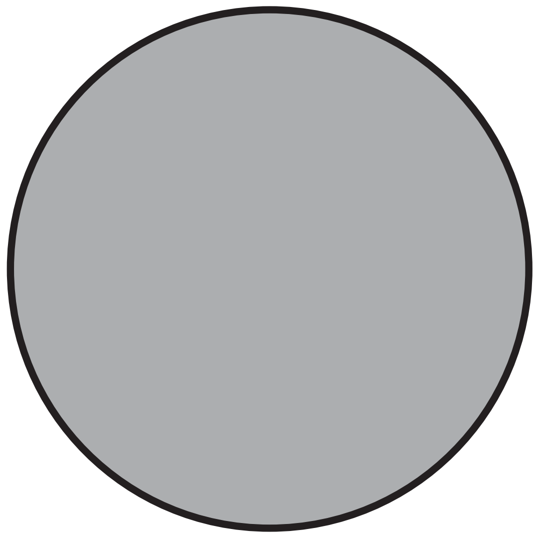


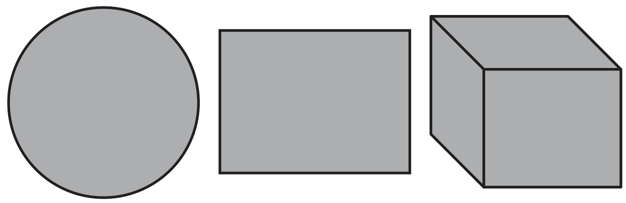
Figure 1.3: Sample caption.

1.5.3 Multipart figures

For multipart figures, you need to use the package ”subfig”. here’s an example:

```
\begin{figure}[h]
   \centering
   \subfloat[Circle]{\label{fig:figure-a}\includegraphics[width=1.1in]
     {fig02a-circle}}
   \subfloat[Rectangle]{\label{fig:figure-b}\includegraphics[width=1.1in]
     {fig02b-rectangle}}
   \subfloat[Cube]{\label{fig:figure-c}\includegraphics[width=1.1in]
     {fig02c-cube}}
```

```
   \caption{Geometric shapes.}
   \label{fig:multipart-figure}
\end{figure}
```

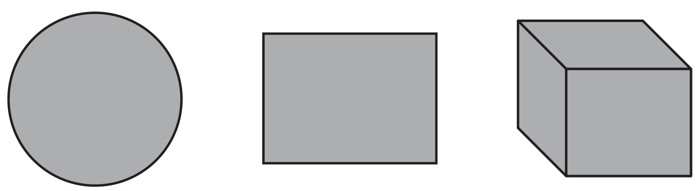


(a) Circle **(b)** Rectangle **(c)** Cube

Figure 1.4: Geometric shapes.

To add some space between the figures above, one can use the usual spacing commands such as "`\qquad`". For example,

```
\begin{figure}[h]
   \centering
   \subfloat[Circle]{\label{fig:fig-a-space}\includegraphics[width=1in]
     {fig02a-circle}} \qquad
   \subfloat[Rectangle]{\label{fig:fig-b-space}\includegraphics[width=1in]
     {fig02b-rectangle}}\qquad
   \subfloat[Cube]{\label{fig:fig-c-space}\includegraphics[width=1in]
     {fig02c-cube}}\qquad
   \caption{Geometric shapes with space between images.}
   \label{fig:multipart-figure-space}
\end{figure}
```



(a) Circle **(b)** Rectangle **(c)** Cube

Figure 1.5: Geometric shapes with space between images.

Figure 1.6: This view of The Hill is too wide for a portrait page.

1.5.4 Tables

Again, table captions should be placed above the table. See Table 1.1 for an example and to learn about Smokey's history[1]. For more information about tables, see https://en.wikibooks.org/wiki/LaTeX/Tables.

Table 1.1: Smokey's History

Dog	Years	Record	Pct.
Blue Smokey	1953-1954	10-10-1	.500
Smokey II	1955-1963	58-39-5	.597
Smokey III	1964-1977	105-39-5	.729
Smokey IV	1978-1979	12-10-1	.545
Smokey V	1980-1983	28-18-1	.608
Smokey VI	1984-1991	67-23-6	.744
Smokey VII	1992-1994	27-9	.750
Smokey VIII	1995-2003	91-22	.805
Smokey IX	2004-2012	62-53	.539
Smokey X	2013-present	21-17	.552

[1] According to Wikipedia: https://en.wikipedia.org/wiki/Smokey_(mascot)

Chapter 2

Detector Equipment and Instumentation

2.1 Large Hadron Collider

The Large Hadron Collider (LHC) is a particle accelerator designed to (currently) accelerate and collide protons up to $\sqrt{s_{pp}} = 13$ TeV and lead ions up to $\sqrt{s_{NN}} = 5.02$ TeV. The LHC straddles the borders of France and Switzerland and is part of the "Conséil Europeen pour la Recherche Nucléaire" or CERN. The CERN accelerator complex is shown below in Figure 2.1. Protons (indicated by grey arrows) originate from a proton source connected to LINAC 2 (Linear Accelerator 2,), shown with a purple line near the bottom of Figure 2.1. LINAC 2 pulses protons from a hydrogen bottle (with a pulse duration of 100 μs per pulse and about 100 billion protons expelled per pulse) and passes them into a duo-plasmatron. The duo-plasmatron applies an electric field to the neutral hydrogren to make free hydrogen ions (or protons). Next, the protons enter radiofrequency cavities that accelerate them up to a 50 MeV kinetic energy (or 31.4 % the speed of light in a vacuum). The radiofrequecy cavities are charged cylindrical conductors whose charges are alternated between positive and negative to achieve the acceleration of the positiviely charged protons. Quadrupole magnets ensure that the proton pulses remain compact. After going through LINAC 2, the proton pulses pass through a Booster Synchrotron (shown in lavender in Figure 2.1) which uses dipole magnets to direct the proton bunches in a circular motion through four

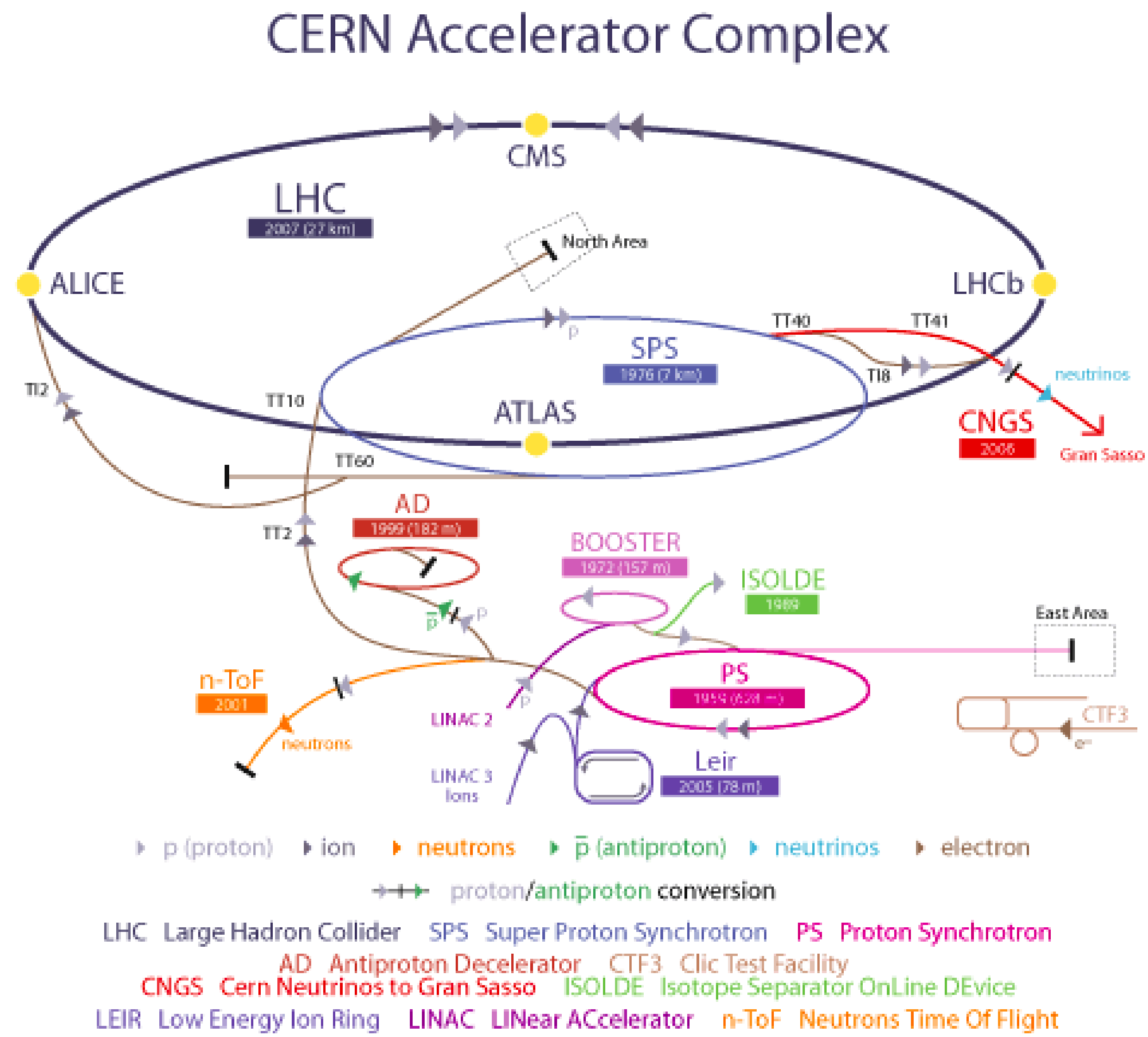


Figure 2.1: Fig 2.1 CERN Accelerator Complex.

superimposed synhcrotron rings. The magnetic field strength applied to the protons from the dipole magnet increases with time, thereby increasing the kinetic energy of the proton bunches from 50 MeV to 1.4 GeV (or 91.6 % the speed of light in a vacuum). Next, the protons enter the Proton Synchrotron (PS), which uses 100 dipole magnets to accelerate the bunches from 1.4 GeV to 25 GeV (or 99.93 % the speed of light in a vacuum).The PS is shown below in pink in Figure 2.1. The protons then transfer from the PS to the Super Proton Synchrotron (SPS) which uses 744 dipole magnets to accelerate the proton bunches from 25 GeV to 450 GeV (or 99.9998 % the speed of light in a vacuum). The Super Proton

Synchrotron is shown below in Figure 2.1 in light blue. The proton bunches exit the SPS and finally enter the Large Hadron Collider (LHC). The Large Hadron is a 27 km long ring held at 10^{-13} atm of pressure (ultra high vacuum) which utilizes 1232 superconducting Niobium Titanium electromagnets to accelerate the proton bunches from 450 GeV to 7.0 TeV (or 99.9999991 % the speed of light in a vacuum). The superconducting Nb-Ti electromagnets are held at a temperature of 1.9 K using Superfluid Helium (chose due to its extremely high thermal conductivity) and achieve peak magnetic fields of 7.74 Tesla. The LHC circulates the proton bunches in opposite directions (half the bunches going clockwise and the other half going anti-clockwise) in seperate beam lines which are designed to cross at specific points. Detector are built around these crossing points to analyze the collisions of protons that occur when the oppositely circulating beams of protons cross. There are 4 crossing points in the beam line. The 4 main detectors in the LHC beam line (CMS, ATLAS, ALICE, and LHCb) are built at these crossing points. This is shown below in Figure 2.2. The LHC also collides lead ions in addition to protons. The lead ions originate from a highly purified lead (Pb) sample heated to a temperature of around 800° Celsius[CERN brochure]. When the Pb sample is heated up, it becomes lead vapor. The Pb vapor is ionized with an electron current. Pb has an atomic number of 82. This means that neutral lead has 82 electrons. Neutral Pb has an electron configuration of [Xe] 4f14 5d10 6s2 6p2 (2 valence electrons in the 6p shell). This means that Pb^{+} will have a configuration of [Xe] 4f14 5d10 6s2 6p1, Pb^{2+} will have a configuration of [Xe] 4f14 5d10 6s2, and so on. Many charged states up to Pb^{29+} are created during the ionization process. The Pb ions are passed through a selector (to make sure only Pb ions pass into the accelerator) and then accelerated to 4.2 MeV/u (energy per nucleon) in LINAC 3 (shown in purple in Figure 2.1). The Pb ions are then passed through a carbon foil (which is fairly electronegative) which strips all the charge states of Pb to Pb^{54+}. The Pb^{54+} ions enter the Low Energy Ion Ring (LEIR) (shown in purple near the bottom of Figure 2.1) and are accelerated to 72 MeV/u. The Pb ions enter the PS (shown in pink in Figure 2.1) and are accelerated to 5.9 GeV/u. After exiting the PS, the Pb^{54+} ions are passed through a second carbon foil which strips the remaining electrons from each ion, mkaing Pb^{82+}. The Pb^{82+} ions enter the SPS (shown in light blue in Figure 2.1) and are accelerated to 177 GeV/u.The Pb^{82+} ions then enter the LHC where they are accelerated to

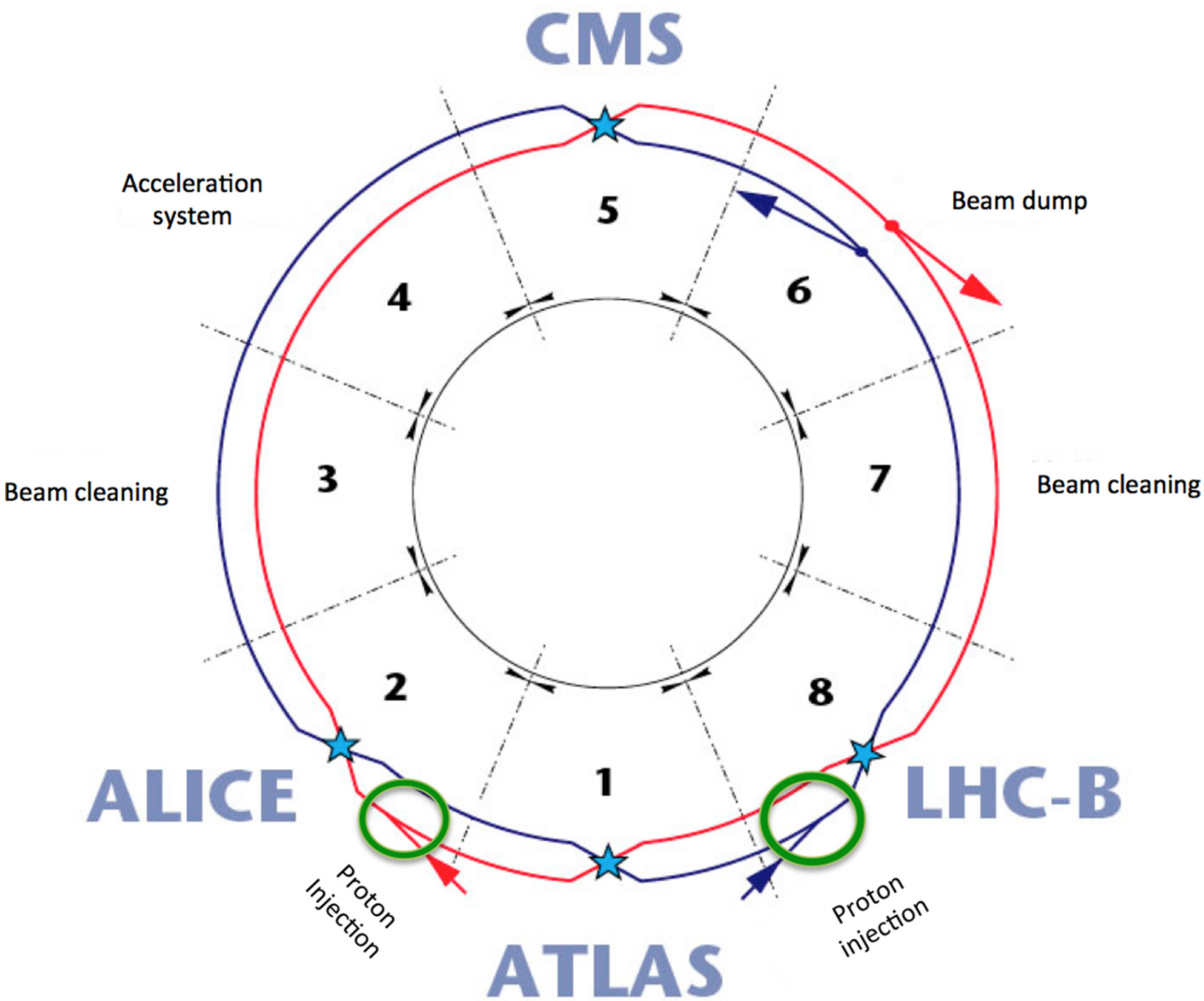


Figure 2.2: Fig 2.2 LHC Crossing Points and Detectors.

2.56 TeV/u and collide at crossing points in the LHC (see Figure 2.2). The ALICE detector is the main detector dedicated to study of Pb collisions in the LHC.

to the study of

2.2 ALICE detector

The ALICE (A Large Ion Collision Experiment) detector is specifically designed to analyze the products of heavy ion (e.g. Pb) collisions in the LHC. The ALICE detector is built by a collaboration which currently includes over 1000 physicists and engineers originating from 105 institutes in over 30 countries [IOP citation needed here]. The total volume of the detector is 16 x 16 x 26 m^3. The total weight of the ALICE detector is approixmately

10000 english tons. ALICE also has a central solenoid magnet made fromo aluminum (which serves to bend the track of the particles resulting from the collisions) which produces a field of around 0.50 T with variations ¡ $\pm$ 2 %. The ALICE detector consists of many sub-detectors which perform the following main functions: 1) trigger on collisions which produce interesting data 2) reconstruct the tracks of particles produced in the collision 3) identify the particles produced in the collision 4) measure the energies (momenta) of particles produced in the collision. The ALICE detector is shown below in Figure 2.3. Detectors that are

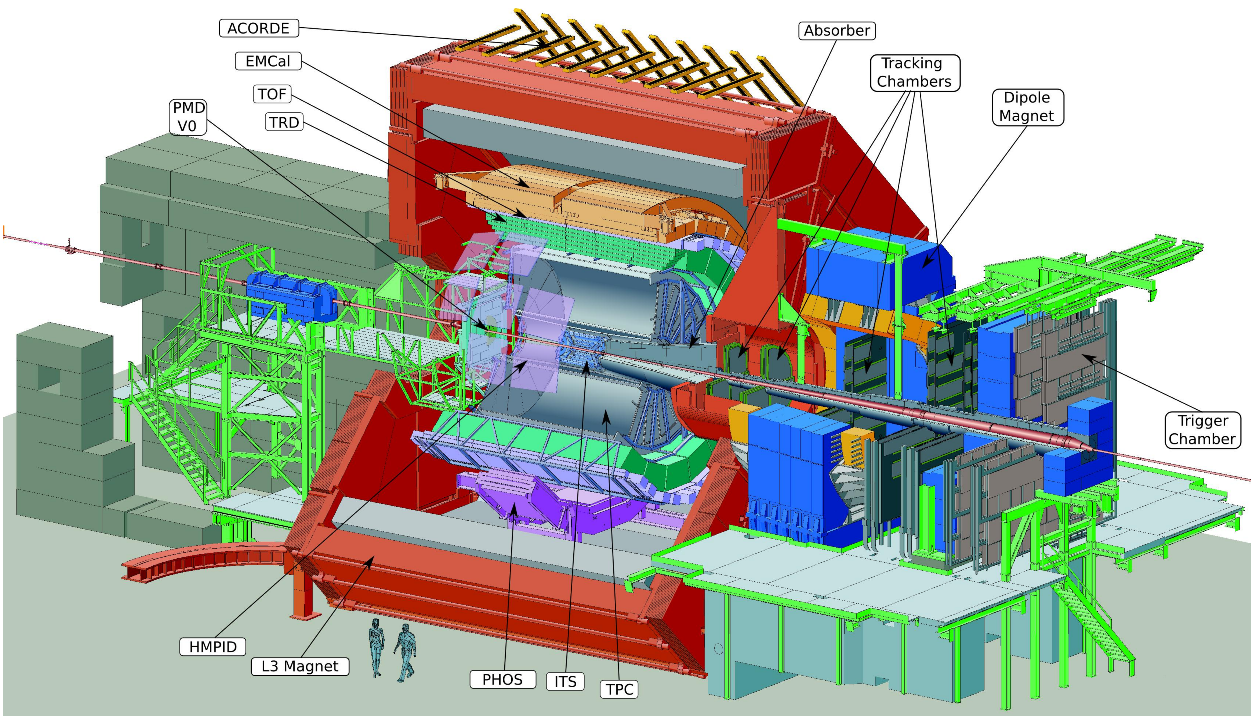


Figure 2.3: Fig 2.3 ALICE Detector Overview.

devoted to triggering include V0, T0, and Trigger Chambers. Detectors devoted to track reconstruction include the ITS, and the TPC. Detectors devoted to particle identification include the TOF, HMPID, TRD. Detectors dedicated to measured particle energies include the EMCAL, DCAL (not shown in Figure 2.3), and the PHOS. The following sections will focus on the V0, ITS, TPC, and EMCAL/DCAL as these detectors will be used in the proposed analysis.

2.2.1 V0 detector

V0 or VZERO is a sub-detector in the ALICE detector which provide minimum bias triggers for other detectors in ALICE, serves as an indicator of centrality (see Introduction Section) for collisions, measures the reaction plane for collisions, and measures the luminosity in p-p collisions to within around 10 %. The VZERO sub-detector has two main components: VZERO-A and VZERO-C. VZERO-A (A-Side) covers the pseudorapidity range 2.8 ¡ η ¡ 5.1. VZERO-C (C-Side) covers the pseduorapidity range -3.7 ¡ η ¡ -1.7. The locations of the VZERO-A and VZERO-C detectors (with respect to the TPC) are shown below in Figure 2.4 Figure 2.4 shows the location of VZERO-A (on the left side of the figure) and VZERO-C

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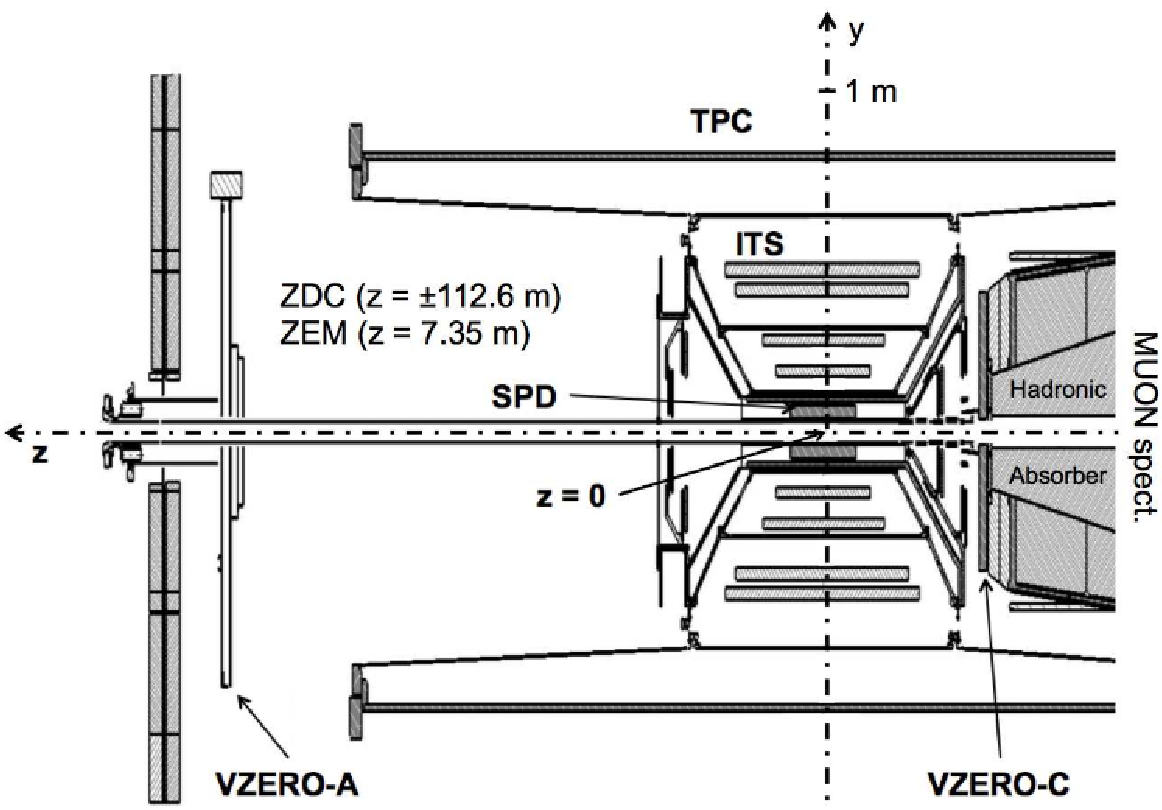

Figure 2.4: Fig 2.4 ALICE VZERO-A and VZERO-C locations.

(on the right side of the figure, but to the left of the hadronic absorber.

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The first entry ("#1") must remain there. It deletes the title "Bibliography" from being printed again at the top of the bibliography page. The title "Bibliography" should only appear on the title page. The second entry can be changed to any natbib style you'd like. For example, plainnat, humannat, etc. The third entry is the name of your bibliography .tex file. Remember to run BibTeX in order to compile the bibliography correctly. For more information, visit http://merkel.texture.rocks/Latex/natbib.php.

Chapter 3

Smokey On The Field

Chapter 4

Conclusions

Bibliography

Appendices

A Summary of Equations

some text here

A.1 Cartesian

some equations here

A.2 Cylindrical

some equations also here

B Summary of Stuff

some text here

B.1 More Things

some equations here

B.2 Other Aspects

some equations also here

Vita

Vita goes here. The vita should be a brief biography about the author written in third person and paragraph format. It should not be the author's resume or CV.