# Transverse energy analysis of relativistic heavy ion collisions through the use of identified particles spectra

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Biswas Sharma

May 2018

# Table of Contents

# List of Tables

# List of Figures

# Chapter 1

# Introduction

The Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory have the ability to collide heavy nuclei, such as those of gold and uranium, at nearly the speed of light, reaching temperatures of trillions of degrees Celcius. These laboratories have provided evidence of the formation of an exotic state of matter, called the quark-gluon plasma (QGP). It only exists for a brief amount of time after such collisions and instantly freezes out into a plethora of new particles, which carry the signatures we can use to deduct QGP properties. It reportedly behaves like an almost perfect quantum fluid with no resistance and exhibits other interesting properties.

One of the methods to probe the properties of this matter is by analyzing the conversion of the beam-direction energy at the time of collision into transverse energy after the collision. This analysis is generally done by using data from the calorimeters placed around the collision site. In this thesis, I use the data collected by the tracking detectors, instead of the conventional calorimeters, to perform the transverse energy analysis.

The organization of the thesis is as follows. In Chapter 2, I attempt to summarize the physical concepts pertaining to nuclear matter, heavy-ion collisions, and the production and detection of QGP. Chapter 3 consists of the formalism of the measurement of transverse energy using calorimeters as well as tracking detectors. It also gives an example of what has been done using calorimeters. Chapter 4 describes the data used to perform the analysis in this thesis and notes down the details of the analysis. In Chapter 5, I present the results

<sub>98</sub> and compare them to the ones in literature obtained using a different method. Chapter 6
<sub>99</sub> concludes the thesis by summarizing it and shedding light on some of its implications.

# Chapter 2

# Theoretical Background

## 2.1 Quantum Chromodynamics

The strong force is one of the four fundamental interactions in physics. At large scale, it is responsible for binding the nucleons together to give the nucleus its structure. At the smaller scale, it binds the fundamental units of subnuclear matter, the quarks, together to form the nucleons. The electrodynamic interaction between charged particles such as protons and electrons is described by quantum electrodynamics (QED) as mediated by photons; the strong interaction, albeit more complicated, is explained under the framework of quantum chromodynamics (QCD) as mediated by gluons. [18, 29] ???? The quarks and gluons of QCD are collectively known as partons. The gluons are the gauge bosons of the Yang-Mills theory.

The Yang-Mills theory is a non-Abelian gauge theory. It has a Lagrangian that is described by several parameters, some of which are redundant and need to be gauged. This is done by a mathematical treatment as prescribed under a gauge theory. The gauge theory associated with the Yang-Mills theory is based on the SU(N) group. It is non-Abelian as represented by the transformations being non-commutative. QCD is a gauge theory that describes the application of the SU(3) symmetry transformations on the triplet of quarks. The Electroweak interaction, on the other hand, can be formalized under the gauge group SU(2) × U(1). Together, they form the SU(3)×SU(2)×(U1) gauge theory called the standard model. One of the phenomenological aspects in which QCD is different from QED is the

confinement of partons. In QED, the fundamental particles are bound together by the Coulomb potential, which diminishes with distance between the charge-carrying particles, as demonstrated by the relation 2.1:

$$V_C \propto \frac{1}{r} \tag{2.1}$$

where $V_C$ is the Coulomb potential, and $r$ is the spatial separation between the particles. This means that bound QED particles can be isolated by increasing their spatial separation. The QCD potential, on the other hand, has an extra linear term in it:

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_S}{r} + kr \tag{2.2}$$

where $\alpha_S$ is the QCD fine-structure constant and $k$ is is the strengh of the color interaction ( 1 GeV/fm). This means that the potential increases linearly with distance at large distances, and so an infinite amount of energy is required to separate quarks. Hence, we never observe isolated quarks and they are said to be confined, not just bound, to form composite structures called hadrons.[27] Composition of a quark and an anti-quark forms a meson and that of three quarks forms a baryon.

QCD is a gauge theory. Its Lagrangian remains unchanged under certain transformations. The Lagrangian has a number of degrees of freedom, some of which are redundant and need to be gauged, meaning regulated by a particular mathematical treatment. That mathematical treatment, in which the transformations of the gauge group are non-commutative, is described by a non-Abelian gauge theory. The Yang-Mills theory is an example of it. In this theory, the gauge boson is the gluon.

## 2.2  Phase Transitions

In everyday life, we observe matter existing in four distinct phases: solid, liquid, gas, and plasma. Changes in physical conditions can lead to a transition from one of these phases to another, exemplified by the commonly observed coversion of ice to water. Distinctions among the various phases can be represented in a chart called the phase diagram.

The phase diagram consists of thermodynamic observables such as temperature and density on its axes. Curves in the phase diagram represent boundries of physical conditions at which two or more phases of matter can coexist in equilibrium. Crossing a boundary represents an abrupt transition from one phase to another; this abruptness is mathematically characterized by the discontinuity in the change of the derivative of the free energy – a thermodynamic varible – with respect to the physical quantities in the axes. There can also be regions in the diagram representing the ranges of physical conditions in which a smooth phase transition can take place.

One of the main focuses of current experimental and theoretical nuclear physics research is the study of the phase diagram of strongly interacting matter at a range of temperatures and baryon chemical potentials. In experiments involving the collisions of heavy ions at high and low energies, different regions of the phase diagram can be probed by varying the collision energy [3]. For instance, the high-baryon chemical potential regime corresponds to lower beam energies and higher temperatures correspond to higher beam energies. The results of these experiments and model calculations can be used to study the nature of transitions in the QCD phase diagram.

A schematic representing the QCD phase diagram on the temperature (T) and quark chemical potential ($\mu$) plane is shown in Figure 2.1 [7]. A second-order transition is predicted at low baryon chemical potentials (close to baryon-antibaryon symmetry) and high temperatures reminiscent of the early universe. Methods to study this region of the phase space will be explored in this thesis. At low temperatures and high chemical potentials, loose predictions have been made regarding the existence of exotic phases of high density matter, and programs, such as the Compressed Baryonic Matter experiment at the Facility for Antiproton and Ion Research in Germany, are being designed to study this region of the phase diagram.

## 2.3   Quark-Gluon Plasma

The confinement of quarks into the hardonic phase of QCD matter, as described in section 2.1, has its limitations. At very high densities, when the wave function of a single hadron
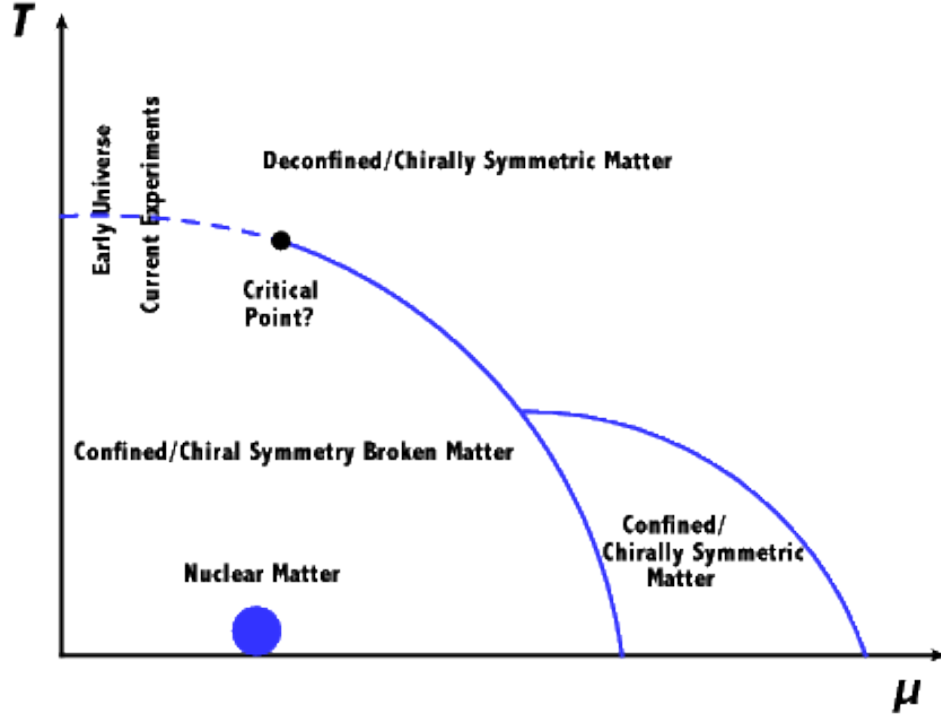
**Figure 2.1:** Schematic of the QCD phase diagram [7].

encompasses the spatial regions covered by multiple such hadrons, it is impossible to classify which pair or triplet of quarks belongs to which meson or baryon. As long as a particular quark is close enough to the other quarks in the volume, it is deconfined in such a way that it can freely move anywhere in the volume. [27] QCD predicts such phase transition, at energy densities above 0.2-1 GeV/fm$^3$ [1] and around a critical temperature of about 200 MeV [20], of strongly interacting matter to a phase with quarks and gluons in thermal and chemical equilibrium representing the relevant degrees of freedom and behaving like an almost perfect quantum fluid [9]. This deconfined state of quarks and gluons is termed the quark-gluon plasma (QGP) in analogy to the quantum electrodynamical plasma phase of matter.

# Chapter 3

# Relativistic Heavy Ion Collisions

The experimental evidences of the theoretically appealing existence of QGP come from the collisions of large nuclei. The signatures of such evidence are described in section 3.6. Physicists started noting down such evidences since as far back as 1984, when nuclei were accelerated and collided with stationary targets.[15] They were able to agree on a conclusive discovery of this matter during the 2000s, after colliding accelerated nuclei with other such nuclei or smaller species (protons, deuterons) at unprecedented energies and with improved detection schemes.[30] With further increase in collision energies and enhancement in detector technololgy, modern accelerator facilities have not only added such evidences but also provided estimates of some of the properties as well as the dynamics of the evolution of the QGP. The following sections describe two such facilities, the physics of the collisions and what happens after the collisions.

## 3.1  RHIC and LHC

The Relativistic Heavy Ion Collider (RHIC) is located in Upton, New York in the premises of the Brookhaven National Laboratory (BNL). Its construction started in 1991 and was completed in 1999. Figure 3.1 shows the layout, at the time of construction, of the collider along with the Alternating Gradient Synchrotron (AGS) complex and the locations of the original four detectors: Solenoidal Tracker At RHIC (STAR), Pioneering High Energy Nuclear Interaction eXperiment (PHENIX), PHOBOS and BRAHMS (Broad RAnge

Hadron Magnetic Spectrometers). PHOBOS and BRAHMS were decommissioned after the completion of their science objectives, but STAR and PHENIX are still functional. The AGS was part of BNL before the construction of the RHIC, and its capabilities were augmented with the construction of the AGS Booster in 1991.
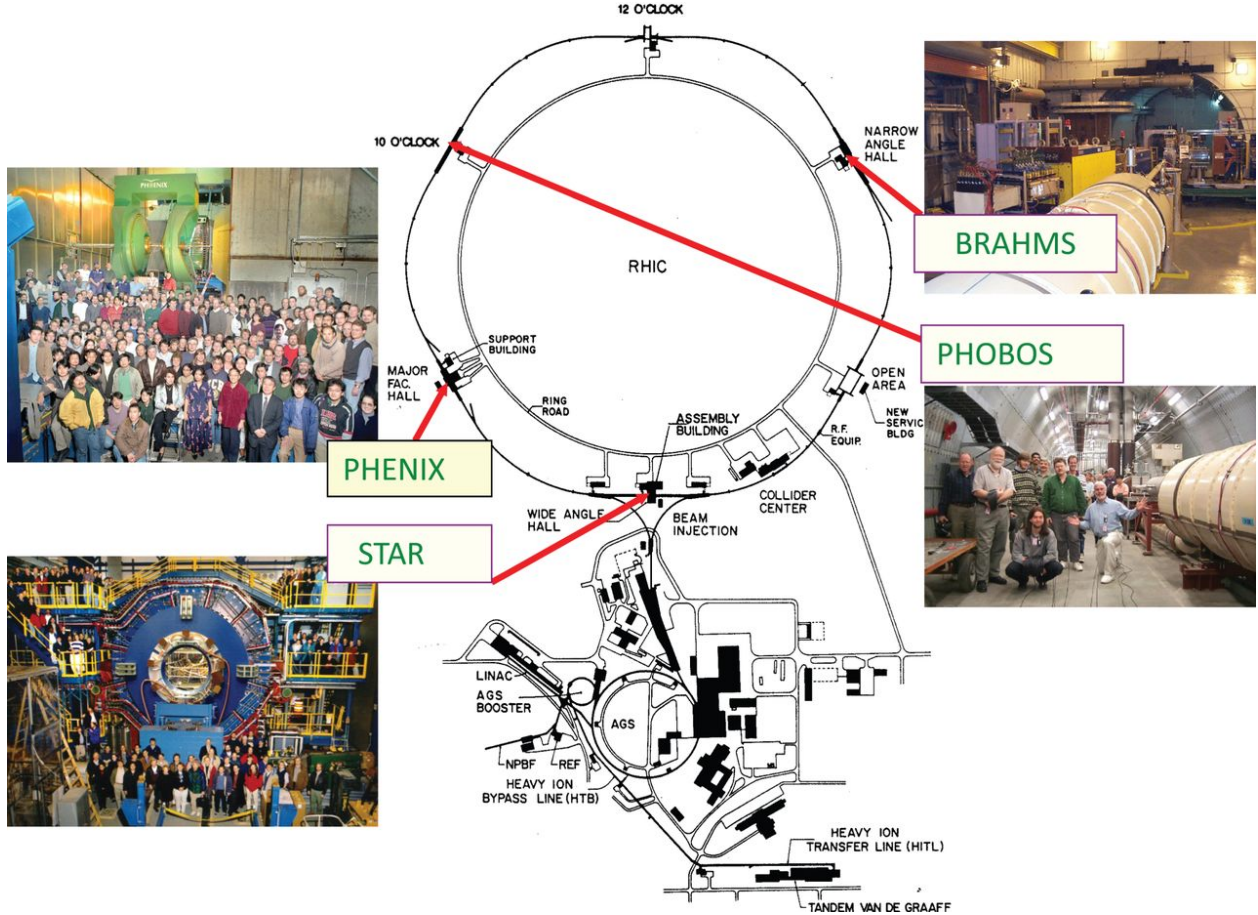


**Figure 3.1:** Initial layout of the RHIC.[25].

Heavy ion beams in the RHIC are created in a series of steps before collision. In case of gold ions, a pulsed sputter source produces negatively charged ions, which are stripped of some of their electrons with a foil on the positive end of the high-voltage Tandem Van de Graff. The ions are now positively charged and are accelerated to 1MeV/u toward the negative terminal of the Tandem, upon exiting which some more stripping takes place. The bending magnets then selectively deliver +32 charge states of the ions to the Booster Synchrotron, which accelerates them to 95MeV/u and strips them to +77 charge state before injecting them to the AGS. The AGS accelerates them to 10.8 GeV/u and strips them of

the remaining two electrons at the exit. The gold ions are then injected through the AGS-to-RHIC Beam Transfer Line to the two RHIC rings. These rings carry beams moving in opposite directions and intersect at six symmetric locations in the 3.8 km circumference. The original four detectors are located in four of these six locations where the beams undergo head-on collisions.

The Large Hadron Collider (LHC) is located underground (between 45m and 170m) beneath the France-Switzerland border near the city of Geneva. The two rings of the collider were constructed between 1998 and 2008 by the European Organization for Nuclear Research (CERN) in the 26.7 km circular tunnel originally housing CERN's Large Electron-Positron collider. Analogous to the RHIC, the LHC gets its beams prepared by a series of machines in the CERN accelerator complex. The collisions occur at the locations of the four big LHC experiments: Compact Muon Solenoid (CMS), A Toroidal LHC ApparatuS (ATLAS), Large Hadron Collider beauty (LHCb) experiment, and A Large Ion Collider Experiment (ALICE). ALICE is dedicated to the study of heavy-ion collisions. [13]

## 3.2 Collision Energy and Geometry

What happens in the aftermath of a collision depends on how much energy is available at the time of the collision as well as the geometry of the collision. The experimenter controls the collision energy, so it's known before the collision. The geometry of the collision is deducted from the constraints imposed by the static (eg. rest mass) and dynamic (eg. trajectory) properties of the detected products.

In collision experiments, it is convenient to use a reference frame in which the net momentum of the pair of colliding species is zero. This frame is called the center-of-mass frame. In this frame, the total energy of the species in the two beams is a function of the number of nucleons and the center-of-mass energy per nucleon. In case of symmetric collisions, i.e, collisions involving identical species in the two beams, the collision energy is reported as the center-of-mass energy per nucleon pair, $\sqrt{s_{NN}}$. The magnitude of this quantity constrains the species that can be produced from any collision.

The RHIC has the unique capability of colliding species at a range of energies spanning almost two orders of magnitude. Table 3.1 lists the collision energies produced so far at RHIC for various collision systems. The LHC, on the other hand, boasts the highest amount of collision energy for any collider on earth. It collided species (p+p, p+A, Pb+Pb) at a center of mass energy upto 2.76 TeV per nucleon pair at the end of 2010. At the end of 2015, 5.02 TeV Pb-Pb collisions were successfully completed. [14]

| Collision system | $\sqrt{s_{NN}}(GeV)$ |
|---|---|
| p+p | 200, 500 |
| d+Au | 200 |
| Cu+Cu | 62, 200 |
| Au+Au | 9, 20, 62, 130, 200 |

**Table 3.1:** Colliding species and associated collision energies at RHIC [23]

In general, any collision between two nuclei is not perfectly head-on. Some collisions are close to being head-on and are called central collisions. Some are far from being head-on and are called peripheral collisions. The amount by which a collision is central is quantitatively represented by a variable called centrality. By convention, 0% is the centrality of a perfectly head-on collision and 100% is that of the least head-on, i.e., the most peripheral collision. In practice, each collision event is deducted to belong to a specific centrality bin, for instance, 0-5%. Figure 3.2 illustrates the aftermath of a mid-central collision, i.e, a collision in which about half of the volume of each of the nuclei intersects the other.

The collision of two nuclei can be modeled as a set of collisions of the constituents that make up the nuclei. The constituents that take part in the collisions and are called participants. The rest of the constituents are known as spectators. Figure 3.3 illustrates the distribution of participants and spectators in two colliding nuclei. Expectedly, the number of participants is more in more central collisions.

10
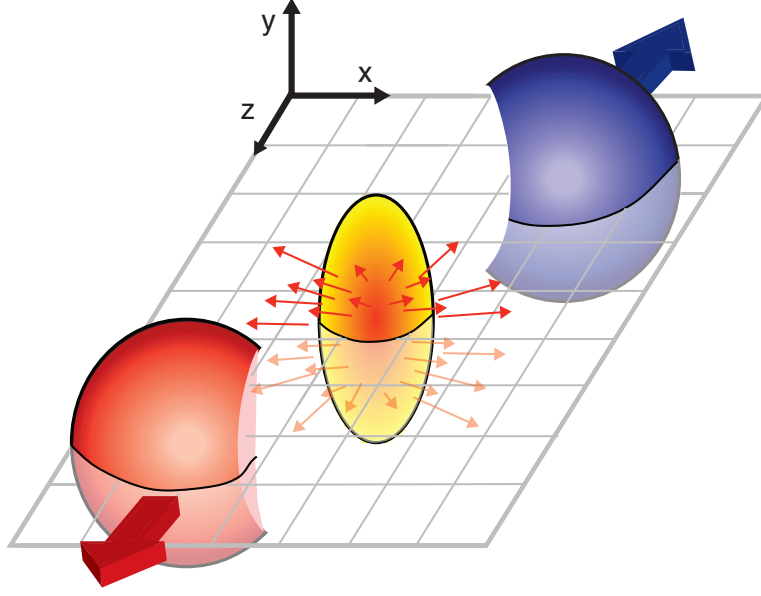
**Figure 3.2:** An illustration of a mid-central collision of two nuclei traveling in the z direction. The X-axis is parallel to the line joining the centers of the two nuclei at the time of collision. [11].

## 3.3   Kinematic Variables

The description of the collision physics and the interpretation of its results are aided by the construction of variables that undergo simple transformations under a change of reference frame. Two such variables, rapidity and pseudorapidity, are described in this section.

The rapidity, $y$, of a particle is defined as:

$$y \equiv \frac{1}{2} \ln \frac{p_0 + p_z}{p_0 - p_z} \tag{3.1}$$

$$= \frac{1}{2} \ln \frac{E + p_z}{E - p_z}, \tag{3.2}$$

where $p_0$ and $p_z$ are the components of its contravariant four-momentum $p = (p_0, p_x, p_y p_z)$ with $p_0 = \frac{E}{c}$, $E$ being the relativistic energy of the particle and $c$, the speed of light, being equal to 1 in natural units.

The rapidity of a particle is used as a relativistic description of its velocity. Unlike the canonical velocity of a particle, its rapidity transforms simply additively under a Lorentz

11
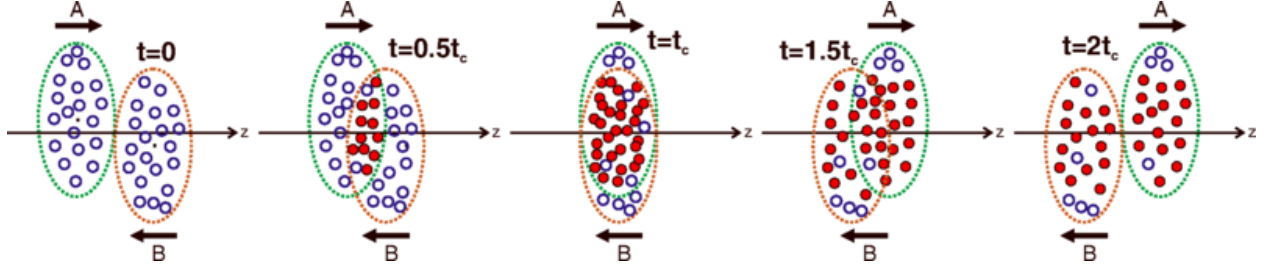
**Figure 3.3:** An illustration of a collision consisting of participants (solid red) and spectators (open blue) within the colliding nuclei labeled A and B. $t_c$ denotes the time of maximum overlap of the two nuclei. The apparent narrowing of the volumes of the nuclei in the z-direction is due to Lorentz contraction. [31]

boost of the frame of reference. For example, suppose a particle has a rapidity $y$ in a laboratory frame. Let $y'$ denote its rapidity as measured in a frame that is Lorentz boosted with a velocity $\beta$ in the $z$-direction with respect to the laboratory frame. Then the relationship between the rapidities in the two different frames is simply

$$y' = y - y_\beta \tag{3.3}$$

Here,

$$y_\beta = \frac{1}{2} \ln \frac{1+\beta}{1-\beta} \tag{3.4}$$

is the rapidity the particle would have in the laboratory frame if it were moving with a velocity $\beta$ in the $z$-direction with respect to the laboratory frame, as can be verified from equation 3.1 with $p_0 = \gamma m$ and $p_z = \gamma \beta m$, $\gamma$ being the Lorentz factor $\frac{1}{\sqrt{1-\beta^2}}$.[33]

The convenience provided by this construct comes with a cost. As evident from equation 3.1, the calculation of the rapidity of a particle requires the measurement of two different observables associated with it, such as the energy and the $z$-direction momentum. However, experimental constraints may sometimes only facilitate the measurement of the direction of the detected particle with respect to the beam axis. What's more convenient in such a case is the use of another variable construct called pseudorapidity, $\eta$, defined as:

$$\eta \equiv -\ln \tan \frac{\theta}{2}, \tag{3.5}$$

12

where $\theta$ is the angle the particle's momentum vector, $\boldsymbol{p}$, makes with the $z$-direction. The above equation can also be written in terms of the momentum as:

$$\eta = \frac{1}{2} \ln \frac{|\boldsymbol{p}| + p_z}{|\boldsymbol{p}| - p_z} \tag{3.6}$$

From equations 3.1 and 3.6, it is evident that $\eta \approx y$ when $|\boldsymbol{p}| \approx p_0$, i.e., when the momentum is large. The transformation of the particle distribution from the $y$-space to the $\eta$-space is discussed in section 4.3.1.

.................................................. .................................................. ..................................................

## 3.4   QGP Evolution

The evolution of the QGP is shown in a lightcone diagram in figure 3.4. The initial state of the colliding nuclei is not well known and is the topic of research for upcoming experiments. During the collision, the participants scatter off of each other while the spectators don't and keep traveling almost unperturbed in their original direction. The immediate aftermath of a central collision of heavy ions at RHIC and LHC energies is the formation of a hot fireball. This fireball evolves in time to form a liquid-like medium of quarks and gluons. This medium attains a local equilibrium and remains in such a state, depending on the collision energy, for about 1-10 fm/c. This equilibrium is broken as the liquid QGP evolves by expanding and cooling to attain a density and temperature at which the deconfinement of quarks and gluons is lost and they undergo a chemical freeze-out to form a hadron gas. Collisions between the constituents of this gas become scant as it evolves with further expansion and cooling, and the hadrons undergo a thermal freeze-out to attain their final energies and momenta.

## 3.5   Detection of Collision Products

Detectors are placed around the collision site to perform measurements on the final state particles emitting from the thermal freeze-out of the medium. These measurements typically include the estimation of the location and time of production of the final states, the type of particle, and the momentum and energy it carries.
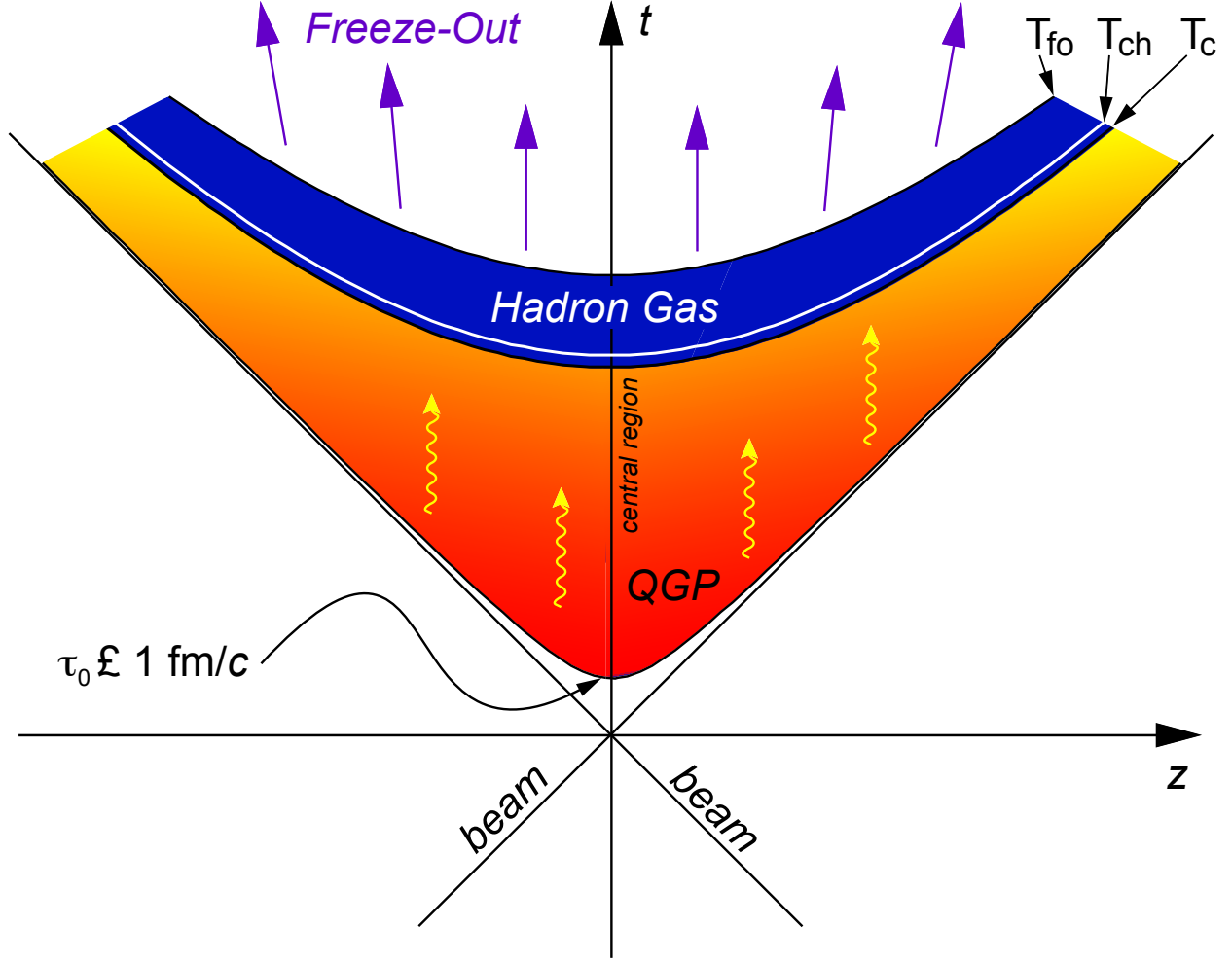
**Figure 3.4:** Evolution of the QGP represented in a lightcone diagram. $\tau_0$ denotes the formation time of the QGP. $T_c$ is the critical temperature of the transition from the QGP to the hadron gas phase. $T_{ch}$ and $T_{fo}$ stand for the temperatures at, respectively, chemical freeze-out and thermal freeze-out. [11]

Generally, a tracking detector surrounds the collision site, and there are calorimeters followed by particle identifiers around it. A magnetic field is applied parallel to the beam direction around the collision site. Due to this orientation of the magnetic field, the spectators traveling parallel to it move undeflected and the final state charged particles with components of velocity transverse to the beam axis get deflected around the beam axis with angular frequency given by

$$\omega = \frac{qB}{m}, \tag{3.7}$$

where $q$ is the electric charge of the particle, $m$ is its mass and $B$ is the applied magnetic field. Two kinds of detectors most relevant to this thesis, tracking detectors and calorimeters, are described in chapter 4.

## 3.6   Detection of QGP Signatures

http://iopscience.iop.org/article/10.1088/0954-3899/25/3/013/meta, and:

The existence and properties of the QGP in the aftermath of high-energy heavy-ion collisions can be probed using different techniques relevant to several theoretical characteristics of the phase. Some of these probes are described below.

For instance, the interacting nuclei carry no net strangeness before colliding, and so a post-collision observation of strange and multi-strange particles can be a signal for an antecedent existence of deconfined quarks and gluons [12]. This signal, when complemented with an observation of the enhancement of strange particles production, provides a strong hint of the formation of QGP. This can be further complemented with the estimate of the energy density and the temperature attained after the collision.

Analyses of experimental results have thus far provided signatures of the formation of matter with partonic degrees of freedom at the early stages of the collisions. Such signatures include suppression of high monentum hadrons, known as jet quenching, because the QGP is nearly opaque to colored probes, and large azimuthal anisotropies, indicating that the medium is a liquid of quarks and gluons [2]?????. Experiments also reveal the initial energy density of this matter to be about two orders of magnitude larger than that of low energy nuclear matter – comfortably more than the deconfinement phase transition critical density predicted by lattice QCD [17].

The state of the colliding nuclei before the collision at LHC and top RHIC energies has indications of being a Color Glass Condensate – strongly interacting, weakly coupled highly coherent gluonic matter [21]. The characteristics of the initial states of these nuclei affect the partonic distributions within the nuclei and ultimately the products of the collision. The collision products are also affected by variables such as the initial energy and entropy densities of the partonic matter [17].

Different observables can be used to study different aspects of heavy ion collisions. The charged particle multiplicity, $\langle N_{ch} \rangle$, is a global variable that relates to the entropy production during the collision (analysis note). The transverse energy, $E_T$, a global variable related to $\langle N_{ch} \rangle$, provides information about the conversion of the initial beam-direction kinetic energy into energy flowing in the transverse direction after the collision. Together, the studies of the fluctuation of the $\langle N_{ch} \rangle$ and the $E_T$ pseudorapidity [footnote] density with respect to the beam energy and the collision centrality [footnote] help probe the characteristics of the initial conditions at the time of the collision. One can study, for instance, the distinctions between models based on quark participants against those based on nucleon participants [analysis note]. These quantities can also lead to the rough estimate of the initial energy density through the use of the Bjorken formula [22]:

$$\epsilon \geq \frac{\frac{dE_T}{d\eta}}{\tau_0 \pi R^2} = \frac{3}{2} \langle \frac{E_T}{N} \rangle \frac{\frac{dN_{ch}}{d\eta}}{\tau_0 \pi R^2} \tag{3.8}$$

The transverse energy and the charged particle pseudorapidity densities have conventionally been calculated by using the transverse energy measurements obtained from calorimeters. This thesis details the use of particle spectra, reported as $\frac{d^2 N}{dy dp_T}$, from Au+Au collisions at RHIC to calculate the same global variables and serve as a method to cross check the ones involving calorimeters.

## 3.6.1 Dilepton Production

When the color degree of freedom is liberated, a quark can interact with an antiquark to produce a virtual photon which decays into a lepton and an antilepton. This pair of leptons is devoid of a color charge and can interact with the particles in the fireball only electromagnetically. This leads to them having a significantly larger mean-free path as compared to colored probes, and the number of collision they undergo before reaching a decector is negligible. However, the thermodynamic state of the fireball affects the momenta of the quarks and the antiquarks, which in turn affect the momenta and the production rates of the lepton pairs. Specifically, the temperature of the QGP can be estimated using the dilepton spectra. The caveat of doing so is that the QGP is not the only possible source of
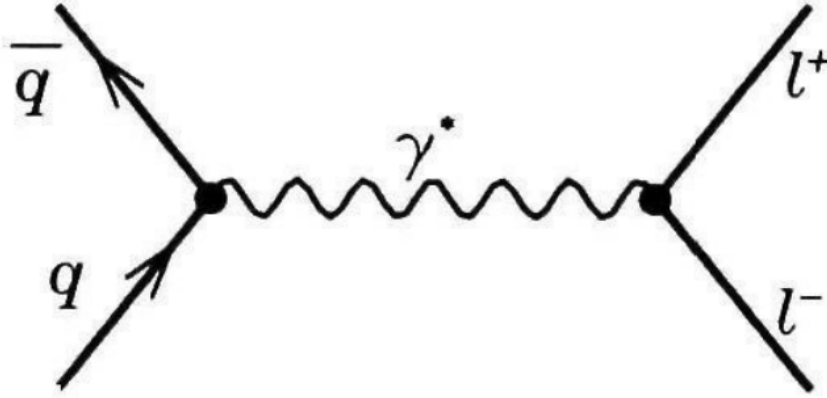
**Figure 3.5:** Feynman diagram representing the production of a lepton pair from a quark and an antiquark. [33]

367  dileptons. Hence, the contributions from other sources, mainly the Drell-Yan process, must

368  be figured out before using the dilepton spectra as a QGP diagnostic. [33]

369  ## 3.6.2   Direct photons
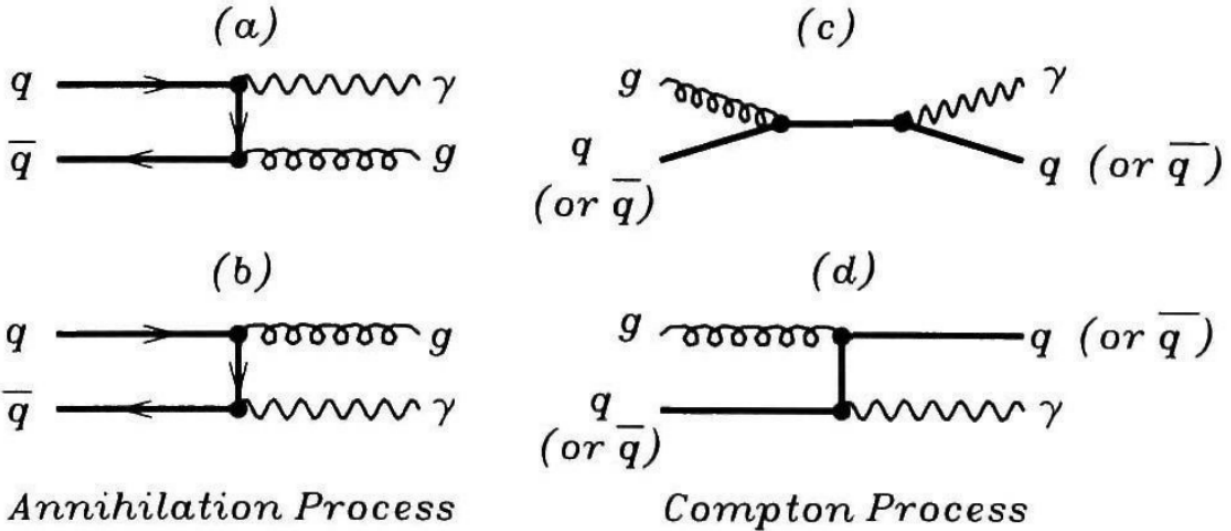


**Figure 3.6:** Feynman diagram representing the production of photons from quarks and gluons. (*a*) and (*b*) represent annihilation processes, whereas (*c*) and (*d*) represent Compton processes.[33]

370      In the QGP, a quark and an antiquark can annihilate to produce a photon and a gluon.

371  It is also possible for the pair to annihilate and produce two photons, but the probability

372  of this process is smaller than the former by about two orders of magnitude. Furthermore,

a quark (or an antiquark) can interact with a gluon to produce an antiquark (or a quark) and a photon, a process analogous to Compton scattering in QED. Just like the leptons described in the previous section, the photons produced in the QGP can only interact with the medium electromagnetically. Therefore, they undergo minimal scattering before being detected, and hence can be used to probe the thermodynamical state of the medium at the time of their creation.[33] Photons can also be produced after hadronization as a result of the scattering of the hadrons within the evolved medium. However, the nature of the $p_T$ distribution is different in this case, and this difference helps distinguish these photons from the direct photons produced by partonic interactions.[32]

### 3.6.3 Bjorken Energy Density

mostly pg 271 to 275 in [32]

### 3.6.4 Collective Flow

### 3.6.5 Strangeness Enhancement

### 3.6.6 Jet Quenching

A scattering event in which the participants transfer a large amount of their original momenta is called hard scattering, and it mostly results in partons traveling ...

## 3.7 Transverse Energy

## 3.8 RHIC Beam Energy Scan Program

# Chapter 4

# Measurement of Transverse Energy

This chapter indroduces the definitions of transverse energy, ways to measure it using different detectors, and particular examples from the STAR detector.

## 4.1   Definition of Transverse Energy

In theory, $E_T$ from a collision can be defined as the sum of the transverse masses, $m_T$, of all the particles produced in the collision, i.e.,

$$E_T \equiv \sum_i m_{T,i} \tag{4.1}$$

with

$$m_T \equiv \sqrt{p_T^2 + m^2} \tag{4.2}$$

where $m$ is the rest mass of the particle and $p_T$ is its transverse momentum. Using this definition to calculate the $E_T$ requires perfect identification of all the particles. It has not been possible to do so in experiments, and so a more feasible, operational definition of $E_T$ is fabricated. A commonly accepted definition in case of the feasibility of calorimetric measurements is [4, 9]:

$$E_T = \sum_i E_i \sin \theta_i, \tag{4.3}$$

$$\frac{dE_T}{d\eta} = \sin\theta \frac{dE}{d\eta}, \tag{4.4}$$

where the index $i$ runs over all the particles going into a fixed solid angle for each event, $\theta$ is the polar angle, i.e, the angle with respect to the beam axis, $\eta$ is the pseudorapidity defined as

$$\eta \equiv -\ln\tan\frac{\theta}{2}, \tag{4.5}$$

and $E_i$ is the energy deposited in the calorimeter by the $i^{th}$ particle. $E_i$ is considered to be, by convention [5], the following

$$E_i = \begin{cases} E_i^{tot} - m_0 & \text{for baryons} \\ E_i^{tot} + m_0 & \text{for anti-baryons} \\ E_i^{tot} & \text{otherwise} \end{cases} \tag{4.6}$$

where $E_i^{tot}$ is the total energy of the $i^{th}$ particle defined canonically as

$$E^{tot} \equiv \sqrt{p^2 + m_0^2} \tag{4.7}$$

and $m_0$ is the particle's rest mass. In order to account for the portion of the emitted transverse energy not detected or overestimated by the calorimeters, corrections are made based on GEANT simulations.

## 4.2    $E_T$ Measurement with Calorimeters

## 4.3    $E_T$ Measurement with Tracking Detectors

Transverse energy analysis can be done using tracking detectors as well if they are able to produce measurements of other physical quantities that implicitly contain information about the transverse energy. Specifically, the charged particle multiplicity distributions with respect to the transverse momenta can be used to calculate the particle's transverse energy pseudorapidity density. In fact, since the corrections related to the tracking detectors are

very different from those related to the calorimeters, results from the two different methods can be used to test the assumptions involved in each.

The tracking detectors in experiments such as the STAR (Solenoidal Tracker At RHIC) experiment and ALICE (A Large Ion Collider Experiment) at CERN include Time Projection Chambers (TPCs) and Time-of-Flight (TOF) detectors that can give us the $p_T$ spectra, yields and particle ratios of the identified charged hadrons [26, 2]. The TPCs provide measurements of particle trajectories – that can be used to determine the momenta for low-momentum particles – and of their specific energy loss,

$$\frac{dE}{dx},\qquad(4.8)$$

which can be used with the trajectories to make particle identifications (PID) using the Bethe-Bloch formula [8]. TOF detectors, on the other hand, cover the high-momentum part of the measurements. In ALICE, the combination of the measurements of the TPC with those of the Inner Tracking System (ITS) effectively adds the tracking length, thereby improving the resolution of the measured $p_T$ spectrum. Details about the PID and momentum determination capabilities of the detectors in ALICE can be found in [10].

The $p_T$ spectra, available as the counts $\frac{d^2N}{dy\,dp_T}$ with respect to $p_T$, can be used to calculate $\frac{dE_T}{d\eta}$ as formulated in the following section.

## 4.3.1 Calculation of $\frac{dE_T}{d\eta}$ from $p_T$ spectra

In relativistic heavy ion collisions, rapidity ($y$) is defined as follows:

$$y \equiv \frac{1}{2}\ln\frac{E+p_z}{E-p_z},\qquad(4.9)$$

where $E$ is given by equation 4.7 and $p_z$ is the component of the momentum parallel to the beam axis. Pseudorapidity, $\eta$, is just $y$ with $m_0 = 0$:

$$\begin{aligned}
\eta &= \frac{1}{2} \ln \frac{p + p_z}{p - p_z} \\
&= \frac{1}{2} \ln \frac{1 + \cos\theta}{1 - \cos\theta} \\
&= \frac{1}{2} \ln \frac{2\cos^2 \frac{\theta}{2}}{2\sin^2 \frac{\theta}{2}}
\end{aligned}$$

$$\therefore \eta = -\ln \left| \tan \frac{\theta}{2} \right| \tag{4.10}$$

Note that the absolute value is not necessary for $0 \leq \theta \leq \pi$. Then, taking the exponential of both sides of the above equation and using Euler's formula, we get:

$$\sin\theta = \frac{1}{\cosh\eta}. \tag{4.11}$$

Hence,

$$\begin{aligned}
p &= \frac{p_T}{\sin\theta} \\
&= p_T \cosh\eta,
\end{aligned}$$

and so we have

$$E_T = E\sin\theta = \frac{\sqrt{p_T^2 \cosh^2\eta + m_0^2}}{\cosh\eta} \tag{4.12}$$

The Jacobian for the transformation from $y$-space to $\eta$-space is derived, by differentiating $y$ with respect to $\eta$ (obtained form equations 4.9 and 4.10), to be:

$$\frac{\partial y}{\partial\eta} = \frac{p_T \cosh\eta}{\sqrt{m_0^2 + p_T^2 \cosh^2\eta}} \tag{4.13}$$

22

From equations 4.12 and 4.13, we can see that the product of $E_T$ with the Jacobian is equal to $p_T$. That leads to a formulation of $\frac{dE_T}{d\eta}$ as a function of only $\eta$ and $p_T$:

$$\frac{dE_T}{d\eta} = \frac{1}{2a} \int_0^{10GeV/c} \int_{-a}^a p_T \frac{d^2N}{dy dp_T} \, d\eta \, dp_T \qquad (4.14)$$

where $a$ and $-a$ are the bounds for $\eta$.

## 4.3.2   Tracking Detectors in STAR

In the STAR experiment, the TPC is the primary tracking detector. It is 4.2 m long and it cylindrically enshrouds the accelerator beam pipe from its outside, with an inner diameter of 1 m and an outer diameter of 4 m [23]. It covers a pseudorapidity range of $|y| < 1.8$ in all of azimuth in terms of acceptance of charged particles. It can identify particles with momenta over 100 MeV/c up to about 1 GeV/c as well as measure their momenta from 100 MeV/c to 30 GeV/c [6]. Figure 4.1 shows the PID capability of the STAR TPC for very high-multiplicity events [16]. Separation of pions from protons is demonstrated up to a little more than 1 GeV/c. At higher momenta, separating particles is more difficult because their energy loss has lower dependence on the rest mass [6]. The TOF system in STAR, with a time resolution of $\lessapprox$ 100 ps, aids PID at higher momenta. However, at intermediate $p_T$, between $\approx$ 2.0 and 4.0 GeV/c, the TPC by itself cannot distinguish between pions and protons and the TOF by itself cannot separate pions from kaons. This problem is resolved by utilizing the fact that the dependence of the particle velocity on $p_T$ – in case of the TPC – is different from that of the energy loss on $p_T$ in case of the TPC; combining the results from the two, hence, makes PID feasible in this $p_T$ range. [28]

## 4.4   The Beam Energy Scan Program

The RHIC, in 2010, started a multi-phase Beam Energy Scan (BES) program to study the QCD phase diagram. The collider has the unique facility to collide nulclei at a range of center-of-mass energies per nucleon, $\sqrt{s_{NN}}$. It also has two different detectors that are currently operational, STAR and PHENIX (Pioneering High Energy Nuclear Interactions
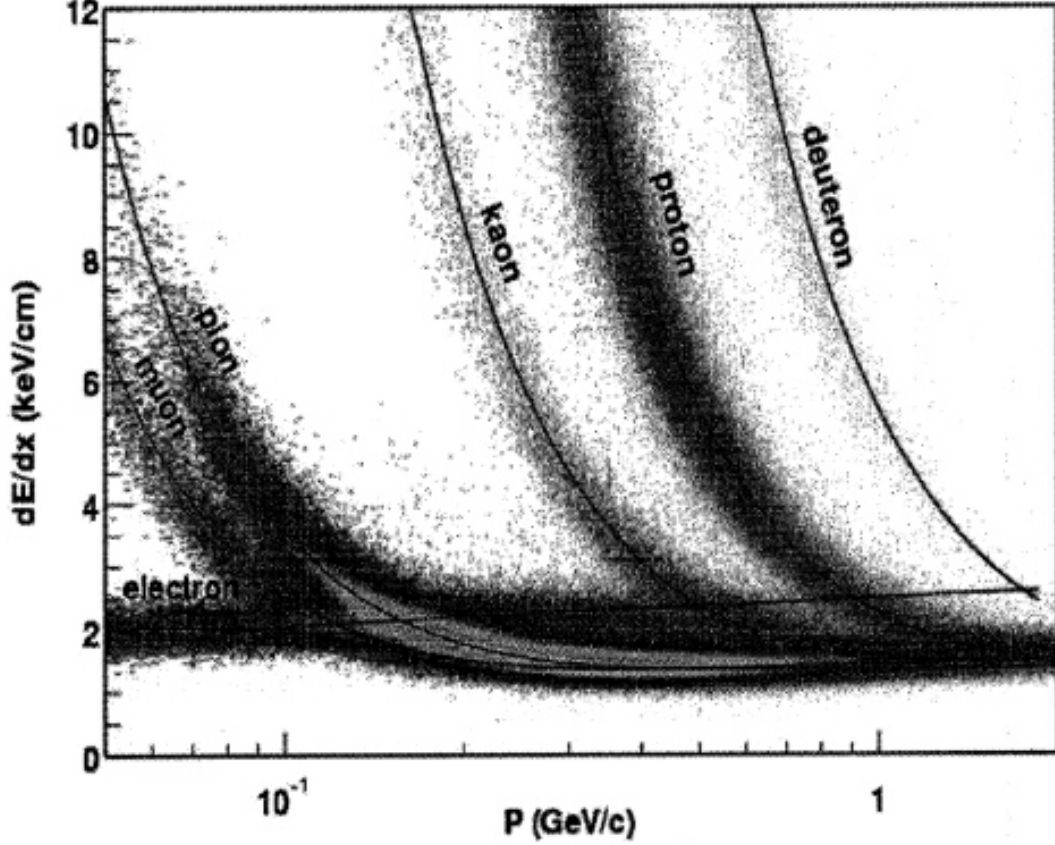
**Figure 4.1:** Energy loss distribution in the STAR TPC for primary and secondary particles. [16].

eXperiment), which facilitate the cross-checking of results. Between 2010 and 2011, under the exploratory phase I of the BES program, 7.7, 11.5 (not completed in PHENIX), 19.6, 27, and 39 GeV collisions were completed using pairs of Au nuclei. Together with the data formerly collected by the RHIC at higher collision energies, BES phase I data can scan the interval from 450 MeV to 20 MeV in $\mu_B$ space [24, 19]. One of the things that can be studied with the data associated with this region of the phase space is statedly the possibility of a "turn-off of new phenomena already established at higher RHIC energies" (https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493). Results corresponding to the high-$\mu_B$ region might provide evidence of a first order phase transition, and possibly the critical point [19].

The manifestation of such phenomena would be in terms of the fluctuations in the properties of the post-collision system. One can, for instance, study the scaling of the

24

480 transverse energy after the collision with the longidutional energy at the time of the collision,
481 $\sqrt{s_{NN}}$. This can be done in multiple ways for a detector like STAR or PHENIX that is made
482 up of sub-systems such as the TOF detectors, TPCs/Time Expansion Chambers, as well as
483 calorimeters.

## 4.4.1  BES Calorimetry

485 Adare et al. [3] use calorimetry in PHENIX to analyze the transverse energy corresponding
486 to several different pairs of species colliding at a range of energies. They use the raw
487 transverse energy measured by the EMCal, $E_{TEMC}$, to obtain the total hadronic $E_T$ by
488 making corrections in three different steps. They first scale the data by a constant factor
489 calculated to account for the fiducial acceptance in azimuth and pseudorapidity. The second
490 factor is calculated to adjust for the effects of the calorimeter towers that are disabled. The
491 third factor, $k$, is computed as follows

$$k = k_{response} \times k_{inflow} \times k_{losses} \tag{4.15}$$

492 where $k_{response}$ corresponds to hadronic particles only depositing a fraction of their total
493 energy while passing through the EMCal, $k_{inflow}$ is attributable to the energy deposited
494 by particles coming from outside the EMCal's fiducial aperture, and $k_{losses}$ accounts for
495 the energy not registered in the EMCal due to energy thresholds, edge effects, and more
496 importantly due to the particles that make it into the fiducial aperture but decay into
497 products outside the aperture.

## 4.4.2  BES $p_T$ spectra

499 This thesis details the method of transverse energy analysis through the use of $p_T$ spectra
500 from the STAR BES data. As described in section 4.3.2, the TPCs and TOF detectors in
501 STAR can identify particles as well as their trajectories and ultimately their multiplicity
502 distributions with respect to the momenta. Adamczyk et al. [2] report the results for the
503 $p_T$ spectra for six different identified hadrons, $\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$, and $\bar{p}$, from the STAR
504 experiment. The spectra come from Au+Au collisions – at $\sqrt{s_{NN}} = 7.7$, 11.5, and 39 GeV

25

in the year 2010 and at $\sqrt{s_{NN}} = 19.6$ and 27 GeV in 2011 – under the BES Program. Figure 4.2 [2] shows the spectra corresponding to 39 GeV collisions categorized into seven different collision centralitiy classes. These spectra, and their counterparts for the rest of the energies, were used to calculate an estimate of the total transverse energy per event per particle species. This result was then used to estimate the total transverse energy due to all the collision products.
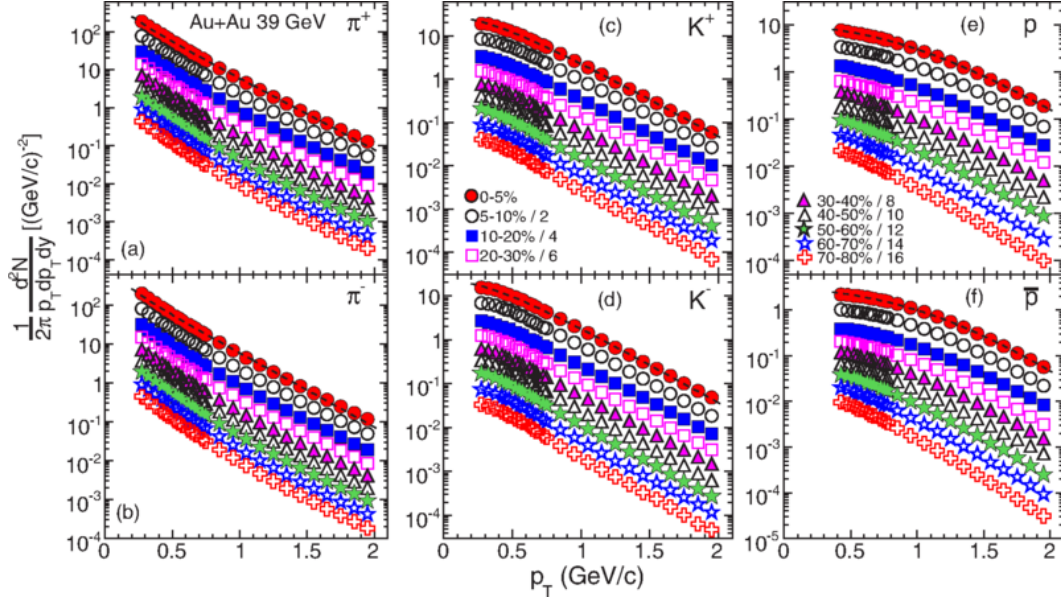


**Figure 4.2:** Transverse momentum spectra for $\pi^+$, $\pi^-$, $K^+$, $K^-$, $p$, and $\bar{p}$ at midrapidity ($|y| < 0.1$) from 39 GeV Au+Au collisions at RHIC. The fitting curves on the 0-5% central collision spectra for pions, kaons, and protons/anti-protons represent, respectively, the Bose-Einstein, $m_T$-exponential, and double-exponential functions. [2].

The corrections applied by Adamczyk et al. [2] to the raw data to obtain the spectra and the reported systematic uncertainties in their results are discussed below (under construction)

// Next section will contain the method of extrapolation and the section after that will explain the analysis using the root framework. Then comes the results section, which I will add after I finish analyzing all the data and get all the results including for lambdas.

# Chapter 5

# Data Analysis

## 5.1   Extrapolation of Spectra

### 5.1.1   Boltzmann-Gibbs Blast Wave

# Chapter 6

# Results

Present results and comparisons to Adare et al.

# Bibliography

[1] Adam, J., Adamova, D., Aggarwal, M. M., Aglieri Rinella, G., Agnello, M., Agrawal, N., Ahammed, Z., Ahmad, S., Ahn, S. U., Aiola, S., Akindinov, A., Alam, S. N., Silva De Albuquerque, D., Aleksandrov, D., Alessandro, B., Alexandre, D., Alfaro Molina, J. R., Alici, A., Alkin, A., Millan Almaraz, J. R., Alme, J., Alt, T., Altinpinar, S., Altsybeev, I., Alves Garcia Prado, C., Andrei, C., Andronic, A., Anguelov, V., Anticic, T., Antinori, F., Antonioli, P., Aphecetche, L. B., Appelshaeuser, H., Arcelli, S., Arnaldi, R., Arnold, O. W., Arsene, I. C., Arslandok, M., Audurier, B., Augustinus, A., Averbeck, R. P., Azmi, M. D., Badala, A., Baek, Y. W., Bagnasco, S., Bailhache, R. M., Bala, R., Balasubramanian, S., Baldisseri, A., Baral, R. C., Barbano, A. M., Barbera, R., Barile, F., Barnafoldi, G. G., Barnby, L. S., Ramillien Barret, V., Bartalini, P., Barth, K., Bartke, J. G., Bartsch, E., Basile, M., Bastid, N., Basu, S., Bathen, B., Batigne, G., Batista Camejo, A., Batyunya, B., Batzing, P. C., Bearden, I. G., Beck, H., Bedda, C., Behera, N. K., Belikov, I., Bellini, F., Bello Martinez, H., Bellwied, R., Belmont Iii, R. J., Belmont Moreno, E., Belyaev, V., Bencedi, G., Beole, S., Berceanu, I., Bercuci, A., Berdnikov, Y., Berenyi, D., Bertens, R. A., Berzano, D., Betev, L., Bhasin, A., Bhat, I. R., Bhati, A. K., Bhattacharjee, B., Bhom, J., Bianchi, L., Bianchi, N., Bianchin, C., Bielcik, J., Bielcikova, J., Bilandzic, A., Biro, G., Biswas, R., Biswas, S., Bjelogrlic, S., Blair, J. T., Blau, D., Blume, C., Bock, F., Bogdanov, A., Boggild, H., Boldizsar, L., Bombara, M., Book, J. H., Borel, H., Borissov, A., Borri, M., Bossu, F., Botta, E., Bourjau, C., Braun-Munzinger, P., Bregant, M., Breitner, T. G., Broker, T. A., Browning, T. A., Broz, M., Brucken, E. J., Bruna, E., Bruno, G. E., Budnikov, D., Buesching, H., Bufalino, S., Buncic, P., Busch, O., Buthelezi, E. Z., Bashir Butt, J., Buxton, J. T., Cabala, J., Caffarri, D., Cai, X., Caines, H. L., Calero Diaz, L., Caliva, A., Calvo Villar, E., Camerini, P., Carena, F., Carena, W., Carnesecchi, F., Castillo Castellanos, J. E., Castro, A. J., Casula, E. A. R., Ceballos Sanchez, C., Cepila, J., Cerello, P., Cerkala, J., Chang, B., Chapeland, S., Chartier, M., Charvet, J.-L. F., Chattopadhyay, S., Chattopadhyay, S., Chauvin, A., Chelnokov, V., Cherney, M. G., Cheshkov, C. V., Cheynis, B., Chibante Barroso, V. M., Dobrigkeit Chinellato, D., Cho, S., Chochula, P., Choi, K., Chojnacki, M., Choudhury, S., Christakoglou, P., Christensen, C. H., Christiansen, P., Chujo, T., Chung, S.-U., Cicalo, C., Cifarelli, L., Cindolo, F., Cleymans, J. W. A., Colamaria, F. F., Colella, D., Collu, A.,

Colocci, M., Conesa Balbastre, G., Conesa Del Valle, Z., Connors, M. E., Contreras Nuno, J. G., Cormier, T. M., Corrales Morales, Y., Cortes Maldonado, I., Cortese, P., Cosentino, M. R., Costa, F., Crochet, P., Cruz Albino, R., Cuautle Flores, E., Cunqueiro Mendez, L., Dahms, T., Dainese, A., Danisch, M. C., Danu, A., Das, D., Das, I., Das, S., Dash, A. K., Dash, S., De, S., De Caro, A., De Cataldo, G., De Conti, C., De Cuveland, J., De Falco, A., De Gruttola, D., De Marco, N., De Pasquale, S., Deisting, A., Deloff, A., Denes, E. S., Deplano, C., Dhankher, P., Di Bari, D., Di Mauro, A., Di Nezza, P., Diaz Corchero, M. A., Dietel, T., Dillenseger, P., Divia, R., Djuvsland, O., Dobrin, A. F., Domenicis Gimenez, D., Donigus, B., Dordic, O., Drozhzhova, T., Dubey, A. K., Dubla, A., Ducroux, L., Dupieux, P., Ehlers Iii, R. J., Elia, D., Endress, E., Engel, H., Epple, E., Erazmus, B. E., Erdemir, I., Erhardt, F., Espagnon, B., Estienne, M. D., Esumi, S., Eum, J., Evans, D., Evdokimov, S., Eyyubova, G., Fabbietti, L., Fabris, D., Faivre, J., Fantoni, A., Fasel, M., Feldkamp, L., Feliciello, A., Feofilov, G., Ferencei, J., Fernandez Tellez, A., Gonzalez Ferreiro, E., Ferretti, A., Festanti, A., Feuillard, V. J. G., Figiel, J., Araujo Silva Figueredo, M., Filchagin, S., Finogeev, D., Fionda, F., Fiore, E. M., Fleck, M. G., Floris, M., Foertsch, S. V., Foka, P., Fokin, S., Fragiacomo, E., Francescon, A., Frankenfeld, U. M., Fronze, G. G., Fuchs, U., Furget, C., Furs, A., Fusco Girard, M., Gaardhoeje, J. J., Gagliardi, M., Gago Medina, A. M., Gallio, M., Gangadharan, D. R., Ganoti, P., Gao, C., Garabatos Cuadrado, J., Garcia-Solis, E. J., Gargiulo, C., Gasik, P. J., Gauger, E. F., Germain, M., Gheata, M., Ghosh, P., Ghosh, S. K., Gianotti, P., Giubellino, P., Giubilato, P., Gladysz-Dziadus, E., Glassel, P., Gomez Coral, D. M., Gomez Ramirez, A., Sanchez Gonzalez, A., Gonzalez, V., Gonzalez Zamora, P., Gorbunov, S., Gorlich, L. M., Gotovac, S., Grabski, V., Grachov, O. A., Graczykowski, L. K., Graham, K. L., Grelli, A., Grigoras, A. G., Grigoras, C., Grigoryev, V., Grigoryan, A., Grigoryan, S., Grynyov, B., Grion, N., Gronefeld, J. M., Grosse-Oetringhaus, J. F., Grosso, R., Guber, F., Guernane, R., Guerzoni, B., Gulbrandsen, K. H., Gunji, T., Gupta, A., Gupta, R., Haake, R., Haaland, O. S., Hadjidakis, C. M., Haiduc, M., Hamagaki, H., Hamar, G., Hamon, J. C., Harris, J. W., Harton, A. V., Hatzifotiadou, D., Hayashi, S., Heckel, S. T., Hellbar, E., Helstrup, H., Herghelegiu, A. I., Herrera Corral, G. A., Hess, B. A., Hetland, K. F., Hillemanns, H., Hippolyte, B., Horak, D., Hosokawa, R., Hristov, P. Z., Humanic,

31

T., Hussain, N., Hussain, T., Hutter, D., Hwang, D. S., Ilkaev, R., Inaba, M., Incani, E., Ippolitov, M., Irfan, M., Ivanov, M., Ivanov, V., Izucheev, V., Jacazio, N., Jacobs, P. M., Jadhav, M. B., Jadlovska, S., Jadlovsky, J., Jahnke, C., Jakubowska, M. J., Jang, H. J., Janik, M. A., Pahula Hewage, S., Jena, C., Jena, S., Jimenez Bustamante, R. T., Jones, P. G., Jusko, A., Kalinak, P., Kalweit, A. P., Kamin, J. A., Kang, J. H., Kaplin, V., Kar, S., Karasu Uysal, A., Karavichev, O., Karavicheva, T., Karayan, L., Karpechev, E., Kebschull, U. W., Keidel, R., Keijdener, D. L., Keil, M., Khan, M. M., Khan, P., Khan, S. A., Khanzadeev, A., Kharlov, Y., Kileng, B., Kim, D. W., Kim, D. J., Kim, D., Kim, H., Kim, J., Kim, M., Kim, S. Y., Kim, T., Kirsch, S., Kisel, I., Kiselev, S., Kisiel, A. R., Kiss, G., Klay, J. L., Klein, C., Klein, J., Klein-Boesing, C., Klewin, S., Kluge, A., Knichel, M. L., Knospe, A. G., Kobdaj, C., Kofarago, M., Kollegger, T., Kolozhvari, A., Kondratev, V., Kondratyeva, N., Kondratyuk, E., Konevskikh, A., Kopcik, M., Kostarakis, P., Kour, M., Kouzinopoulos, C., Kovalenko, O., Kovalenko, V., Kowalski, M., Koyithatta Meethaleveedu, G., Kralik, I., Kravcakova, A., Krivda, M., Krizek, F., Kryshen, E., Krzewicki, M., Kubera, A. M., Kucera, V., Kuhn, C. C., Kuijer, P. G., Kumar, A., Kumar, J., Kumar, L., Kumar, S., Kurashvili, P., Kurepin, A., Kurepin, A., Kuryakin, A., Kweon, M. J., Kwon, Y., La Pointe, S. L., La Rocca, P., Ladron De Guevara, P., Lagana Fernandes, C., Lakomov, I., Langoy, R., Lapidus, K., Lara Martinez, C. E., Lardeux, A. X., Lattuca, A., Laudi, E., Lea, R., Leardini, L., Lee, G. R., Lee, S., Lehas, F., Lemmon, R. C., Lenti, V., Leogrande, E., Leon Monzon, I., Leon Vargas, H., Leoncino, M., Levai, P., Li, S., Li, X., Lien, J. A., Lietava, R., Lindal, S., Lindenstruth, V., Lippmann, C., Lisa, M. A., Ljunggren, H. M., Lodato, D. F., Lonne, P.-I., Loginov, V., Loizides, C., Lopez, X. B., Lopez Torres, E., Lowe, A. J., Luettig, P. J., Lunardon, M., Luparello, G., Lutz, T. H., Maevskaya, A., Mager, M., Mahajan, S., Mahmood, S. M., Maire, A., Majka, R. D., Malaev, M., Maldonado Cervantes, I. A., Malinina, L., Mal'Kevich, D., Malzacher, P., Mamonov, A., Manko, V., Manso, F., Manzari, V., Marchisone, M., Mares, J., Margagliotti, G. V., Margotti, A., Margutti, J., Marin, A. M., Markert, C., Marquard, M., Martin, N. A., Martin Blanco, J., Martinengo, P., Martinez Hernandez, M. I., Martinez-Garcia, G., Martinez Pedreira, M., Mas, A. J.-M., Masciocchi, S., Masera, M., Masoni, A., Mastroserio, A., Matyja, A. T., Mayer, C., Mazer, J. A., Mazzoni,

A. M., Mcdonald, D., Meddi, F., Melikyan, Y., Menchaca-Rocha, A. A., Meninno, E., Mercado-Perez, J., Meres, M., Miake, Y., Mieskolainen, M. M., Mikhaylov, K., Milano, L., Milosevic, J., Mischke, A., Mishra, A. N., Miskowiec, D. C., Mitra, J., Mitu, C. M., Mohammadi, N., Mohanty, B., Molnar, L., Montano Zetina, L. M., Montes Prado, E., Moreira De Godoy, D. A., Perez Moreno, L. A., Moretto, S., Morreale, A., Morsch, A., Muccifora, V., Mudnic, E., Muhlheim, D. M., Muhuri, S., Mukherjee, M., Mulligan, J. D., Gameiro Munhoz, M., Munzer, R. H., Murakami, H., Murray, S., Musa, L., Musinsky, J., Naik, B., Nair, R., Nandi, B. K., Nania, R., Nappi, E., Naru, M. U., Ferreira Natal Da Luz, P. H., Nattrass, C., Rosado Navarro, S., Nayak, K., Nayak, R., Nayak, T. K., Nazarenko, S., Nedosekin, A., Nellen, L., Ng, F., Nicassio, M., Niculescu, M., Niedziela, J., Nielsen, B. S., Nikolaev, S., Nikulin, S., Nikulin, V., Noferini, F., Nomokonov, P., Nooren, G., Cabanillas Noris, J. C., Norman, J., Nyanin, A., Nystrand, J. I., Oeschler, H. O., Oh, S., Oh, S. K., Ohlson, A. E., Okatan, A., Okubo, T., Olah, L., Oleniacz, J., Oliveira Da Silva, A. C., Oliver, M. H., Onderwaater, J., Oppedisano, C., Orava, R., Oravec, M., Ortiz Velasquez, A., Oskarsson, A. N. E., Otwinowski, J. T., Oyama, K., Ozdemir, M., Pachmayer, Y. C., Pagano, D., Pagano, P., Paic, G., Pal, S. K., Pan, J., Pandey, A. K., Papikyan, V., Pappalardo, G., Pareek, P., Park, W., Parmar, S., Passfeld, A., Paticchio, V., Patra, R. N., Paul, B., Pei, H., Peitzmann, T., Pereira Da Costa, H. D. A., Peresunko, D. Y., Perez Lara, C. E., Perez Lezama, E., Peskov, V., Pestov, Y., Petracek, V., Petrov, V., Petrovici, M., Petta, C., Piano, S., Pikna, M., Pillot, P., Ozelin De Lima Pimentel, L., Pinazza, O., Pinsky, L., Piyarathna, D., Ploskon, M. A., Planinic, M., Pluta, J. M., Pochybova, S., Podesta Lerma, P. L. M., Poghosyan, M., Polishchuk, B., Poljak, N., Poonsawat, W., Pop, A., Porteboeuf, S. J., Porter, R. J., Pospisil, J., Prasad, S. K., Preghenella, R., Prino, F., Pruneau, C. A., Pshenichnov, I., Puccio, M., Puddu, G., Pujahari, P. R., Punin, V., Putschke, J. H., Qvigstad, H., Rachevski, A., Raha, S., Rajput, S., Rak, J., Rakotozafindrabe, A. M., Ramello, L., Rami, F., Raniwala, R., Raniwala, S., Rasanen, S. S., Rascanu, B. T., Rathee, D., Read, K. F., Redlich, K., Reed, R. J., Rehman, A. U., Reichelt, P. S., Reidt, F., Ren, X., Renfordt, R. A. E., Reolon, A. R., Reshetin, A., Reygers, K. J., Riabov, V., Ricci, R. A., Richert, T. O. H., Richter, M. R., Riedler, P., Riegler, W., Riggi, F., Ristea, C.-L., Rocco, E., Rodriguez Cahuantzi, M.,

Rodriguez Manso, A., Roeed, K., Rogochaya, E., Rohr, D. M., Roehrich, D., Ronchetti, F., Ronflette, L., Rosnet, P., Rossi, A., Roukoutakis, F., Roy, A., Roy, C. S., Roy, P. K., Rubio Montero, A. J., Rui, R., Russo, R., Di Ruzza, B., Ryabinkin, E., Ryabov, Y., Rybicki, A., Saarinen, S., Sadhu, S., Sadovskiy, S., Safarik, K., Sahlmuller, B., Sahoo, P., Sahoo, R., Sahoo, S., Sahu, P. K., Saini, J., Sakai, S., Saleh, M. A., Salzwedel, J. S. N., Sambyal, S. S., Samsonov, V., Sandor, L., Sandoval, A., Sano, M., Sarkar, D., Sarkar, N., Sarma, P., Scapparone, E., Scarlassara, F., Schiaua, C. C., Schicker, R. M., Schmidt, C. J., Schmidt, H. R., Schuchmann, S., Schukraft, J., Schulc, M., Schutz, Y. R., Schwarz, K. E., Schweda, K. O., Scioli, G., Scomparin, E., Scott, R. M., Sefcik, M., Seger, J. E., Sekiguchi, Y., Sekihata, D., Selyuzhenkov, I., Senosi, K., Senyukov, S., Serradilla Rodriguez, E., Sevcenco, A., Shabanov, A., Shabetai, A., Shadura, O., Shahoyan, R., Shahzad, M. I., Shangaraev, A., Sharma, A., Sharma, M., Sharma, M., Sharma, N., Sheikh, A. I., Shigaki, K., Shou, Q., Shtejer Diaz, K., Sibiryak, Y., Siddhanta, S., Sielewicz, K. M., Siemiarczuk, T., Silvermyr, D. O. R., Silvestre, C. M., Simatovic, G., Simonetti, G., Singaraju, R. N., Singh, R., Singha, S., Singhal, V., Sinha, B., Sarkar Sinha, T., Sitar, B., Sitta, M., Skaali, B., Slupecki, M., Smirnov, N., Snellings, R., Snellman, T. W., Song, J., Song, M., Song, Z., Soramel, F., Sorensen, S. P., Derradi De Souza, R., Sozzi, F., Spacek, M., Spiriti, E., Sputowska, I. A., Spyropoulou-Stassinaki, M., Stachel, J., Stan, I., Stankus, P., Stenlund, E. A., Steyn, G. F., Stiller, J. H., Stocco, D., Strmen, P., Alarcon Do Passo Suaide, A., Sugitate, T., Suire, C. P., Suleymanov, M. K. O., Suljic, M., Sultanov, R., Sumbera, M., Sumowidagdo, S., Szabo, A., Szanto De Toledo, A., Szarka, I., Szczepankiewicz, A., Szymanski, M. P., Tabassam, U., Takahashi, J., Tambave, G. J., Tanaka, N., Tarhini, M., Tariq, M., Tarzila, M.-G., Tauro, A., Tejeda Munoz, G., Telesca, A., Terasaki, K., Terrevoli, C., Teyssier, B., Thaeder, J. M., Thakur, D., Thomas, D., Tieulent, R. N., Tikhonov, A., Timmins, A. R., Toia, A., Trogolo, S., Trombetta, G., Trubnikov, V., Trzaska, W. H., Tsuji, T., Tumkin, A., Turrisi, R., Tveter, T. S., Ullaland, K., Uras, A., Usai, G., Utrobicic, A., Vala, M., Valencia Palomo, L., Vallero, S., Van Der Maarel, J., Van Hoorne, J. W., Van Leeuwen, M., Vanat, T., Vande Vyvre, P., Varga, D., Diozcora Vargas Trevino, A., Vargyas, M., Varma, R., Vasileiou, M., Vasiliev, A., Vauthier, A., Vazquez Doce, O., Vechernin, V., Veen, A. M., Veldhoen, M., Velure, A., Vercellin, E.,

34

Vergara Limon, S., Vernet, R., Verweij, M., Vickovic, L., Viinikainen, J. S., Vilakazi, Z., Villalobos Baillie, O., Villatoro Tello, A., Vinogradov, A., Vinogradov, L., Vinogradov, Y., Virgili, T., Vislavicius, V., Viyogi, Y., Vodopyanov, A., Volkl, M. A., Voloshin, K., Voloshin, S., Volpe, G., Von Haller, B., Vorobyev, I., Vranic, D., Vrlakova, J., Vulpescu, B., Wagner, B., Wagner, J., Wang, H., Wang, M., Watanabe, D., Watanabe, Y., Weber, M., Weber, S. G., Weiser, D. F., Wessels, J. P., Westerhoff, U., Whitehead, A. M., Wiechula, J., Wikne, J., Wilk, G. A., Wilkinson, J. J., Williams, C., Windelband, B. S., Winn, M. A., Yang, P., Yano, S., Yasin, Z., Yin, Z., Yokoyama, H., Yoo, I.-K., Yoon, J. H., Yurchenko, V., Yushmanov, I., Zaborowska, A., Zaccolo, V., Zaman, A., Zampolli, C., Correia Zanoli, H. J., Zaporozhets, S., Zardoshti, N., Zarochentsev, A., Zavada, P., Zavyalov, N., Zbroszczyk, H. P., Zgura, S. I., Zhalov, M., Zhang, H., Zhang, X., Zhang, Y., Chunhui, Z., Zhang, Z., Zhao, C., Zhigareva, N., Zhou, D., Zhou, Y., Zhou, Z., Zhu, H., Zhu, J., Zichichi, A., Zimmermann, A., Zimmermann, M. B., Zinovjev, G., and Zyzak, M. (2016). Measurement of transverse energy at midrapidity in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV. *Phys. Rev. C*, 94(CERN-EP-2016-071. CERN-EP-2016-071):034903. 30 p. 30 pages, 14 captioned figures, 2 tables, authors from page 25, published version, figures at http://aliceinfo.cern.ch/ArtSubmission/node/2400. 6

[2] Adamczyk, L., Adkins, J. K., Agakishiev, G., Aggarwal, M. M., Ahammed, Z., Ajitanand, N. N., Alekseev, I., Anderson, D. M., Aoyama, R., Aparin, A., Arkhipkin, D., Aschenauer, E. C., Ashraf, M. U., Attri, A., Averichev, G. S., Bai, X., Bairathi, V., Behera, A., Bellwied, R., Bhasin, A., Bhati, A. K., Bhattarai, P., Bielcik, J., Bielcikova, J., Bland, L. C., Bordyuzhin, I. G., Bouchet, J., Brandenburg, J. D., Brandin, A. V., Brown, D., Bunzarov, I., Butterworth, J., Caines, H., Calderón de la Barca Sánchez, M., Campbell, J. M., Cebra, D., Chakaberia, I., Chaloupka, P., Chang, Z., Chankova-Bunzarova, N., Chatterjee, A., Chattopadhyay, S., Chen, X., Chen, J. H., Chen, X., Cheng, J., Cherney, M., Christie, W., Contin, G., Crawford, H. J., Das, S., De Silva, L. C., Debbe, R. R., Dedovich, T. G., Deng, J., Derevschikov, A. A., Didenko, L., Dilks, C., Dong, X., Drachenberg, J. L., Draper, J. E., Dunkelberger, L. E., Dunlop, J. C., Efimov, L. G., Elsey, N., Engelage, J., Eppley, G., Esha, R., Esumi, S., Evdokimov, O., Ewigleben,

35

J., Eyser, O., Fatemi, R., Fazio, S., Federic, P., Federicova, P., Fedorisin, J., Feng, Z., Filip, P., Finch, E., Fisyak, Y., Flores, C. E., Fulek, L., Gagliardi, C. A., Garand, D., Geurts, F., Gibson, A., Girard, M., Grosnick, D., Gunarathne, D. S., Guo, Y., Gupta, A., Gupta, S., Guryn, W., Hamad, A. I., Hamed, A., Harlenderova, A., Harris, J. W., He, L., Heppelmann, S., Heppelmann, S., Hirsch, A., Hoffmann, G. W., Horvat, S., Huang, T., Huang, B., Huang, X., Huang, H. Z., Humanic, T. J., Huo, P., Igo, G., Jacobs, W. W., Jentsch, A., Jia, J., Jiang, K., Jowzaee, S., Judd, E. G., Kabana, S., Kalinkin, D., Kang, K., Kauder, K., Ke, H. W., Keane, D., Kechechyan, A., Khan, Z., Kikoła, D. P., Kisel, I., Kisiel, A., Kochenda, L., Kocmanek, M., Kollegger, T., Kosarzewski, L. K., Kraishan, A. F., Kravtsov, P., Krueger, K., Kulathunga, N., Kumar, L., Kvapil, J., Kwasizur, J. H., Lacey, R., Landgraf, J. M., Landry, K. D., Lauret, J., Lebedev, A., Lednicky, R., Lee, J. H., Li, X., Li, C., Li, W., Li, Y., Lidrych, J., Lin, T., Lisa, M. A., Liu, H., Liu, P., Liu, Y., Liu, F., Ljubicic, T., Llope, W. J., Lomnitz, M., Longacre, R. S., Luo, S., Luo, X., Ma, G. L., Ma, L., Ma, Y. G., Ma, R., Magdy, N., Majka, R., Mallick, D., Margetis, S., Markert, C., Matis, H. S., Meehan, K., Mei, J. C., Miller, Z. W., Minaev, N. G., Mioduszewski, S., Mishra, D., Mizuno, S., Mohanty, B., Mondal, M. M., Morozov, D. A., Mustafa, M. K., Nasim, M., Nayak, T. K., Nelson, J. M., Nie, M., Nigmatkulov, G., Niida, T., Nogach, L. V., Nonaka, T., Nurushev, S. B., Odyniec, G., Ogawa, A., Oh, K., Okorokov, V. A., Olvitt, D., Page, B. S., Pak, R., Pandit, Y., Panebratsev, Y., Pawlik, B., Pei, H., Perkins, C., Pile, P., Pluta, J., Poniatowska, K., Porter, J., Posik, M., Poskanzer, A. M., Pruthi, N. K., Przybycien, M., Putschke, J., Qiu, H., Quintero, A., Ramachandran, S., Ray, R. L., Reed, R., Rehbein, M. J., Ritter, H. G., Roberts, J. B., Rogachevskiy, O. V., Romero, J. L., Roth, J. D., Ruan, L., Rusnak, J., Rusnakova, O., Sahoo, N. R., Sahu, P. K., Salur, S., Sandweiss, J., Saur, M., Schambach, J., Schmah, A. M., Schmidke, W. B., Schmitz, N., Schweid, B. R., Seger, J., Sergeeva, M., Seyboth, P., Shah, N., Shahaliev, E., Shanmuganathan, P. V., Shao, M., Sharma, A., Sharma, M. K., Shen, W. Q., Shi, Z., Shi, S. S., Shou, Q. Y., Sichtermann, E. P., Sikora, R., Simko, M., Singha, S., Skoby, M. J., Smirnov, N., Smirnov, D., Solyst, W., Song, L., Sorensen, P., Spinka, H. M., Srivastava, B., Stanislaus, T. D. S., Strikhanov, M., Stringfellow, B., Sugiura, T., Sumbera, M., Summa, B., Sun, Y., Sun, X. M., Sun, X., Surrow, B., Svirida,

D. N., Tang, A. H., Tang, Z., Taranenko, A., Tarnowsky, T., Tawfik, A., Thäder, J., Thomas, J. H., Timmins, A. R., Tlusty, D., Todoroki, T., Tokarev, M., Trentalange, S., Tribble, R. E., Tribedy, P., Tripathy, S. K., Trzeciak, B. A., Tsai, O. D., Ullrich, T., Underwood, D. G., Upsal, I., Van Buren, G., van Nieuwenhuizen, G., Vasiliev, A. N., Videbæk, F., Vokal, S., Voloshin, S. A., Vossen, A., Wang, G., Wang, Y., Wang, F., Wang, Y., Webb, J. C., Webb, G., Wen, L., Westfall, G. D., Wieman, H., Wissink, S. W., Witt, R., Wu, Y., Xiao, Z. G., Xie, W., Xie, G., Xu, J., Xu, N., Xu, Q. H., Xu, Y. F., Xu, Z., Yang, Y., Yang, Q., Yang, C., Yang, S., Ye, Z., Ye, Z., Yi, L., Yip, K., Yoo, I.-K., Yu, N., Zbroszczyk, H., Zha, W., Zhang, Z., Zhang, X. P., Zhang, J. B., Zhang, S., Zhang, J., Zhang, Y., Zhang, J., Zhang, S., Zhao, J., Zhong, C., Zhou, L., Zhou, C., Zhu, X., Zhu, Z., and Zyzak, M. (2017). Bulk properties of the medium produced in relativistic heavy-ion collisions from the beam energy scan program. *Phys. Rev. C*, 96:044904. vii, 15, 21, 25, 26

[3] Adare, A., Afanasiev, S., Aidala, C., Ajitanand, N. N., Akiba, Y., Akimoto, R., Al-Bataineh, H., Alexander, J., Alfred, M., Al-Jamel, A., Al-Ta'ani, H., Angerami, A., Aoki, K., Apadula, N., Aphecetche, L., Aramaki, Y., Armendariz, R., Aronson, S. H., Asai, J., Asano, H., Aschenauer, E. C., Atomssa, E. T., Averbeck, R., Awes, T. C., Azmoun, B., Babintsev, V., Bai, M., Bai, X., Baksay, G., Baksay, L., Baldisseri, A., Bandara, N. S., Bannier, B., Barish, K. N., Barnes, P. D., Bassalleck, B., Basye, A. T., Bathe, S., Batsouli, S., Baublis, V., Bauer, F., Baumann, C., Baumgart, S., Bazilevsky, A., Beaumier, M., Beckman, S., Belikov, S., Belmont, R., Bennett, R., Berdnikov, A., Berdnikov, Y., Bhom, J. H., Bickley, A. A., Bjorndal, M. T., Black, D., Blau, D. S., Boissevain, J. G., Bok, J. S., Borel, H., Boyle, K., Brooks, M. L., Brown, D. S., Bryslawskyj, J., Bucher, D., Buesching, H., Bumazhnov, V., Bunce, G., Burward-Hoy, J. M., Butsyk, S., Campbell, S., Caringi, A., Castera, P., Chai, J.-S., Chang, B. S., Charvet, J.-L., Chen, C.-H., Chernichenko, S., Chi, C. Y., Chiba, J., Chiu, M., Choi, I. J., Choi, J. B., Choi, S., Choudhury, R. K., Christiansen, P., Chujo, T., Chung, P., Churyn, A., Chvala, O., Cianciolo, V., Citron, Z., Cleven, C. R., Cobigo, Y., Cole, B. A., Comets, M. P., Conesa del Valle, Z., Connors, M., Constantin, P., Cronin, N., Crossette, N., Csanád, M., Csörgő, T., Dahms,

T., Dairaku, S., Danchev, I., Danley, T. W., Das, K., Datta, A., Daugherity, M. S., David, G., Dayananda, M. K., Deaton, M. B., DeBlasio, K., Dehmelt, K., Delagrange, H., Denisov, A., d'Enterria, D., Deshpande, A., Desmond, E. J., Dharmawardane, K. V., Dietzsch, O., Ding, L., Dion, A., Diss, P. B., Do, J. H., Donadelli, M., D'Orazio, L., Drachenberg, J. L., Drapier, O., Drees, A., Drees, K. A., Dubey, A. K., Durham, J. M., Durum, A., Dutta, D., Dzhordzhadze, V., Edwards, S., Efremenko, Y. V., Egdemir, J., Ellinghaus, F., Emam, W. S., Engelmore, T., Enokizono, A., En'yo, H., Espagnon, B., Esumi, S., Eyser, K. O., Fadem, B., Feege, N., Fields, D. E., Finger, M., Finger, M., Fleuret, F., Fokin, S. L., Forestier, B., Fraenkel, Z., Frantz, J. E., Franz, A., Frawley, A. D., Fujiwara, K., Fukao, Y., Fung, S.-Y., Fusayasu, T., Gadrat, S., Gainey, K., Gal, C., Gallus, P., Garg, P., Garishvili, A., Garishvili, I., Gastineau, F., Ge, H., Germain, M., Giordano, F., Glenn, A., Gong, H., Gong, X., Gonin, M., Gosset, J., Goto, Y., Granier de Cassagnac, R., Grau, N., Greene, S. V., Grim, G., Grosse Perdekamp, M., Gu, Y., Gunji, T., Guo, L., Guragain, H., Gustafsson, H.-A., Hachiya, T., Hadj Henni, A., Haegemann, C., Haggerty, J. S., Hagiwara, M. N., Hahn, K. I., Hamagaki, H., Hamblen, J., Hamilton, H. F., Han, R., Han, S. Y., Hanks, J., Harada, H., Hartouni, E. P., Haruna, K., Harvey, M., Hasegawa, S., Haseler, T. O. S., Hashimoto, K., Haslum, E., Hasuko, K., Hayano, R., Hayashi, S., He, X., Heffner, M., Hemmick, T. K., Hester, T., Heuser, J. M., Hiejima, H., Hill, J. C., Hobbs, R., Hohlmann, M., Hollis, R. S., Holmes, M., Holzmann, W., Homma, K., Hong, B., Horaguchi, T., Hori, Y., Hornback, D., Hoshino, T., Hotvedt, N., Huang, J., Huang, S., Hur, M. G., Ichihara, T., Ichimiya, R., Iinuma, H., Ikeda, Y., Imai, K., Imazu, Y., Imrek, J., Inaba, M., Inoue, Y., Iordanova, A., Isenhower, D., Isenhower, L., Ishihara, M., Isinhue, A., Isobe, T., Issah, M., Isupov, A., Ivanishchev, D., Iwanaga, Y., Jacak, B. V., Javani, M., Jeon, S. J., Jezghani, M., Jia, J., Jiang, X., Jin, J., Jinnouchi, O., Johnson, B. M., Jones, T., Joo, K. S., Jouan, D., Jumper, D. S., Kajihara, F., Kametani, S., Kamihara, N., Kamin, J., Kanda, S., Kaneta, M., Kaneti, S., Kang, B. H., Kang, J. H., Kang, J. S., Kanou, H., Kapustinsky, J., Karatsu, K., Kasai, M., Kawagishi, T., Kawall, D., Kawashima, M., Kazantsev, A. V., Kelly, S., Kempel, T., Key, J. A., Khachatryan, V., Khandai, P. K., Khanzadeev, A., Kijima, K. M., Kikuchi, J., Kim, A., Kim, B. I., Kim, C., Kim, D. H., Kim, D. J., Kim, E., Kim, E.-J., Kim, G. W., Kim, H. J., Kim, K.-B., Kim,

M., Kim, Y.-J., Kim, Y. K., Kim, Y.-S., Kimelman, B., Kinney, E., Kiss, A., Kistenev, E.,
Kitamura, R., Kiyomichi, A., Klatsky, J., Klay, J., Klein-Boesing, C., Kleinjan, D., Kline,
P., Koblesky, T., Kochenda, L., Kochetkov, V., Kofarago, M., Komatsu, Y., Komkov,
B., Konno, M., Koster, J., Kotchetkov, D., Kotov, D., Kozlov, A., Král, A., Kravitz, A.,
Krizek, F., Kroon, P. J., Kubart, J., Kunde, G. J., Kurihara, N., Kurita, K., Kurosawa,
M., Kweon, M. J., Kwon, Y., Kyle, G. S., Lacey, R., Lai, Y. S., Lajoie, J. G., Lebedev,
A., Le Bornec, Y., Leckey, S., Lee, B., Lee, D. M., Lee, G. H., Lee, J., Lee, K. B.,
Lee, K. S., Lee, M. K., Lee, S., Lee, S. H., Lee, S. R., Lee, T., Leitch, M. J., Leite, M.
A. L., Leitgab, M., Lenzi, B., Lewis, B., Li, X., Li, X. H., Lichtenwalner, P., Liebing, P.,
Lim, H., Lim, S. H., Linden Levy, L. A., Liška, T., Litvinenko, A., Liu, H., Liu, M. X.,
Love, B., Lynch, D., Maguire, C. F., Makdisi, Y. I., Makek, M., Malakhov, A., Malik,
M. D., Manion, A., Manko, V. I., Mannel, E., Mao, Y., Maruyama, T., Mašek, L., Masui,
H., Masumoto, S., Matathias, F., McCain, M. C., McCumber, M., McGaughey, P. L.,
McGlinchey, D., McKinney, C., Means, N., Meles, A., Mendoza, M., Meredith, B., Miake,
Y., Mibe, T., Midori, J., Mignerey, A. C., Mikeš, P., Miki, K., Miller, T. E., Milov, A.,
Mioduszewski, S., Mishra, D. K., Mishra, G. C., Mishra, M., Mitchell, J. T., Mitrovski,
M., Miyachi, Y., Miyasaka, S., Mizuno, S., Mohanty, A. K., Mohapatra, S., Montuenga,
P., Moon, H. J., Moon, T., Morino, Y., Morreale, A., Morrison, D. P., Moskowitz, M.,
Moss, J. M., Motschwiller, S., Moukhanova, T. V., Mukhopadhyay, D., Murakami, T.,
Murata, J., Mwai, A., Nagae, T., Nagamiya, S., Nagashima, K., Nagata, Y., Nagle, J. L.,
Naglis, M., Nagy, M. I., Nakagawa, I., Nakagomi, H., Nakamiya, Y., Nakamura, K. R.,
Nakamura, T., Nakano, K., Nam, S., Nattrass, C., Nederlof, A., Netrakanti, P. K., Newby,
J., Nguyen, M., Nihashi, M., Niida, T., Nishimura, S., Norman, B. E., Nouicer, R., Novák,
T., Novitzky, N., Nukariya, A., Nyanin, A. S., Nystrand, J., Oakley, C., Obayashi, H.,
O'Brien, E., Oda, S. X., Ogilvie, C. A., Ohnishi, H., Oide, H., Ojha, I. D., Oka, M.,
Okada, K., Omiwade, O. O., Onuki, Y., Orjuela Koop, J. D., Osborn, J. D., Oskarsson,
A., Otterlund, I., Ouchida, M., Ozawa, K., Pak, R., Pal, D., Palounek, A. P. T., Pantuev,
V., Papavassiliou, V., Park, B. H., Park, I. H., Park, J., Park, J. S., Park, S., Park, S. K.,
Park, W. J., Pate, S. F., Patel, L., Patel, M., Pei, H., Peng, J.-C., Pereira, H., Perepelitsa,
D. V., Perera, G. D. N., Peresedov, V., Peressounko, D., Perry, J., Petti, R., Pinkenburg,

C., Pinson, R., Pisani, R. P., Proissl, M., Purschke, M. L., Purwar, A. K., Qu, H., Rak, J., Rakotozafindrabe, A., Ramson, B. J., Ravinovich, I., Read, K. F., Rembeczki, S., Reuter, M., Reygers, K., Reynolds, D., Riabov, V., Riabov, Y., Richardson, E., Rinn, T., Riveli, N., Roach, D., Roche, G., Rolnick, S. D., Romana, A., Rosati, M., Rosen, C. A., Rosendahl, S. S. E., Rosnet, P., Rowan, Z., Rubin, J. G., Rukoyatkin, P., Ružička, P., Rykov, V. L., Ryu, M. S., Ryu, S. S., Sahlmueller, B., Saito, N., Sakaguchi, T., Sakai, S., Sakashita, K., Sakata, H., Sako, H., Samsonov, V., Sano, M., Sano, S., Sarsour, M., Sato, H. D., Sato, S., Sato, T., Sawada, S., Schaefer, B., Schmoll, B. K., Sedgwick, K., Seele, J., Seidl, R., Sekiguchi, Y., Semenov, V., Sen, A., Seto, R., Sett, P., Sexton, A., Sharma, D., Shaver, A., Shea, T. K., Shein, I., Shevel, A., Shibata, T.-A., Shigaki, K., Shimomura, M., Shohjoh, T., Shoji, K., Shukla, P., Sickles, A., Silva, C. L., Silvermyr, D., Silvestre, C., Sim, K. S., Singh, B. K., Singh, C. P., Singh, V., Skolnik, M., Skutnik, S., Slunečka, M., Smith, W. C., Snowball, M., Solano, S., Soldatov, A., Soltz, R. A., Sondheim, W. E., Sorensen, S. P., Sourikova, I. V., Staley, F., Stankus, P. W., Steinberg, P., Stenlund, E., Stepanov, M., Ster, A., Stoll, S. P., Stone, M. R., Sugitate, T., Suire, C., Sukhanov, A., Sullivan, J. P., Sumita, T., Sun, J., Sziklai, J., Tabaru, T., Takagi, S., Takagui, E. M., Takahara, A., Taketani, A., Tanabe, R., Tanaka, K. H., Tanaka, Y., Taneja, S., Tanida, K., Tannenbaum, M. J., Tarafdar, S., Taranenko, A., Tarján, P., Tennant, E., Themann, H., Thomas, D., Thomas, T. L., Tieulent, R., Timilsina, A., Todoroki, T., Togawa, M., Toia, A., Tojo, J., Tomášek, L., Tomášek, M., Torii, H., Towell, C. L., Towell, R., Towell, R. S., Tram, V.-N., Tserruya, I., Tsuchimoto, Y., Tsuji, T., Tuli, S. K., Tydesjö, H., Tyurin, N., Vale, C., Valle, H., van Hecke, H. W., Vargyas, M., Vazquez-Zambrano, E., Veicht, A., Velkovska, J., Vértesi, R., Vinogradov, A. A., Virius, M., Voas, B., Vossen, A., Vrba, V., Vznuzdaev, E., Wagner, M., Walker, D., Wang, X. R., Watanabe, D., Watanabe, K., Watanabe, Y., Watanabe, Y. S., Wei, F., Wei, R., Wessels, J., Whitaker, S., White, A. S., White, S. N., Willis, N., Winter, D., Wolin, S., Woody, C. L., Wright, R. M., Wysocki, M., Xia, B., Xie, W., Xue, L., Yalcin, S., Yamaguchi, Y. L., Yamaura, K., Yang, R., Yanovich, A., Yasin, Z., Ying, J., Yokkaichi, S., Yoo, J. H., Yoon, I., You, Z., Young, G. R., Younus, I., Yu, H., Yushmanov, I. E., Zajc, W. A., Zaudtke, O., Zelenski, A., Zhang, C., Zhou, S.,

Zimamyi, J., Zolin, L., and Zou, L. (2016). Transverse energy production and charged-particle multiplicity at midrapidity in various systems from $\sqrt{s_{NN}} = 7.7$ to 200 gev. *Phys. Rev. C*, 93:024901. 5, 25

[4] Adler, S. S., Afanasiev, S., Aidala, C., Ajitanand, N. N., Akiba, Y., Al-Jamel, A., Alexander, J., Aoki, K., Aphecetche, L., Armendariz, R., Aronson, S. H., Averbeck, R., Awes, T. C., Azmoun, B., Babintsev, V., Baldisseri, A., Barish, K. N., Barnes, P. D., Bassalleck, B., Bathe, S., Batsouli, S., Baublis, V., Bauer, F., Bazilevsky, A., Belikov, S., Bennett, R., Berdnikov, Y., Bjorndal, M. T., Boissevain, J. G., Borel, H., Boyle, K., Brooks, M. L., Brown, D. S., Bruner, N., Bucher, D., Buesching, H., Bumazhnov, V., Bunce, G., Burward-Hoy, J. M., Butsyk, S., Camard, X., Campbell, S., Chai, J.-S., Chand, P., Chang, W. C., Chernichenko, S., Chi, C. Y., Chiba, J., Chiu, M., Choi, I. J., Choudhury, R. K., Chujo, T., Cianciolo, V., Cleven, C. R., Cobigo, Y., Cole, B. A., Comets, M. P., Constantin, P., Csanád, M., Csörgő, T., Cussonneau, J. P., Dahms, T., Das, K., David, G., Deák, F., Delagrange, H., Denisov, A., d'Enterria, D., Deshpande, A., Desmond, E. J., Devismes, A., Dietzsch, O., Dion, A., Drachenberg, J. L., Drapier, O., Drees, A., Dubey, A. K., Durum, A., Dutta, D., Dzhordzhadze, V., Efremenko, Y. V., Egdemir, J., Enokizono, A., En'yo, H., Espagnon, B., Esumi, S., Fields, D. E., Finck, C., Fleuret, F., Fokin, S. L., Forestier, B., Fox, B. D., Fraenkel, Z., Frantz, J. E., Franz, A., Frawley, A. D., Fukao, Y., Fung, S.-Y., Gadrat, S., Gastineau, F., Germain, M., Glenn, A., Gonin, M., Gosset, J., Goto, Y., Granier de Cassagnac, R., Grau, N., Greene, S. V., Grosse Perdekamp, M., Gunji, T., Gustafsson, H.-A., Hachiya, T., Hadj Henni, A., Haggerty, J. S., Hagiwara, M. N., Hamagaki, H., Hansen, A. G., Harada, H., Hartouni, E. P., Haruna, K., Harvey, M., Haslum, E., Hasuko, K., Hayano, R., He, X., Heffner, M., Hemmick, T. K., Heuser, J. M., Hidas, P., Hiejima, H., Hill, J. C., Hobbs, R., Holmes, M., Holzmann, W., Homma, K., Hong, B., Hoover, A., Horaguchi, T., Hur, M. G., Ichihara, T., Iinuma, H., Ikonnikov, V. V., Imai, K., Inaba, M., Inuzuka, M., Isenhower, D., Isenhower, L., Ishihara, M., Isobe, T., Issah, M., Isupov, A., Jacak, B. V., Jia, J., Jin, J., Jinnouchi, O., Johnson, B. M., Johnson, S. C., Joo, K. S., Jouan, D., Kajihara, F., Kametani, S., Kamihara, N., Kaneta, M., Kang, J. H., Katou, K., Kawabata, T., Kawagishi, T.,

Kazantsev, A. V., Kelly, S., Khachaturov, B., Khanzadeev, A., Kikuchi, J., Kim, D. J., Kim, E., Kim, E. J., Kim, G.-B., Kim, H. J., Kim, Y.-S., Kinney, E., Kiss, A., Kistenev, E., Kiyomichi, A., Klein-Boesing, C., Kobayashi, H., Kochenda, L., Kochetkov, V., Kohara, R., Komkov, B., Konno, M., Kotchetkov, D., Kozlov, A., Kroon, P. J., Kuberg, C. H., Kunde, G. J., Kurihara, N., Kurita, K., Kweon, M. J., Kwon, Y., Kyle, G. S., Lacey, R., Lajoie, J. G., Lebedev, A., Le Bornec, Y., Leckey, S., Lee, D. M., Lee, M. K., Leitch, M. J., Leite, M. A. L., Li, X. H., Lim, H., Litvinenko, A., Liu, M. X., Maguire, C. F., Makdisi, Y. I., Malakhov, A., Malik, M. D., Manko, V. I., Mao, Y., Martinez, G., Masui, H., Matathias, F., Matsumoto, T., McCain, M. C., McGaughey, P. L., Miake, Y., Miller, T. E., Milov, A., Mioduszewski, S., Mishra, G. C., Mitchell, J. T., Mohanty, A. K., Morrison, D. P., Moss, J. M., Moukhanova, T. V., Mukhopadhyay, D., Muniruzzaman, M., Murata, J., Nagamiya, S., Nagata, Y., Nagle, J. L., Naglis, M., Nakamura, T., Newby, J., Nguyen, M., Norman, B. E., Nyanin, A. S., Nystrand, J., O'Brien, E., Ogilvie, C. A., Ohnishi, H., Ojha, I. D., Okada, K., Omiwade, O. O., Oskarsson, A., Otterlund, I., Oyama, K., Ozawa, K., Pal, D., Palounek, A. P. T., Pantuev, V., Papavassiliou, V., Park, J., Park, W. J., Pate, S. F., Pei, H., Penev, V., Peng, J.-C., Pereira, H., Peresedov, V., Peressounko, D., Pierson, A., Pinkenburg, C., Pisani, R. P., Purschke, M. L., Purwar, A. K., Qu, H., Qualls, J. M., Rak, J., Ravinovich, I., Read, K. F., Reuter, M., Reygers, K., Riabov, V., Riabov, Y., Roche, G., Romana, A., Rosati, M., Rosendahl, S. S. E., Rosnet, P., Rukoyatkin, P., Rykov, V. L., Ryu, S. S., Sahlmueller, B., Saito, N., Sakaguchi, T., Sakai, S., Samsonov, V., Sanfratello, L., Santo, R., Sarsour, M., Sato, H. D., Sato, S., Sawada, S., Schutz, Y., Semenov, V., Seto, R., Sharma, D., Shea, T. K., Shein, I., Shibata, T.-A., Shigaki, K., Shimomura, M., Shohjoh, T., Shoji, K., Sickles, A., Silva, C. L., Silvermyr, D., Sim, K. S., Singh, C. P., Singh, V., Skutnik, S., Smith, W. C., Soldatov, A., Soltz, R. A., Sondheim, W. E., Sorensen, S. P., Sourikova, I. V., Staley, F., Stankus, P. W., Stenlund, E., Stepanov, M., Ster, A., Stoll, S. P., Sugitate, T., Suire, C., Sullivan, J. P., Sziklai, J., Tabaru, T., Takagi, S., Takagui, E. M., Taketani, A., Tanaka, K. H., Tanaka, Y., Tanida, K., Tannenbaum, M. J., Taranenko, A., Tarján, P., Thomas, T. L., Togawa, M., Tojo, J., Torii, H., Towell, R. S., Tram, V.-N., Tserruya, I., Tsuchimoto, Y., Tuli, S. K., Tydesjö, H., Tyurin, N., Uam, T. J., Vale, C., Valle, H., van Hecke, H. W., Velkovska, J., Velkovsky,

42

M., Vértesi, R., Veszprémi, V., Vinogradov, A. A., Volkov, M. A., Vznuzdaev, E., Wagner, M., Wang, X. R., Watanabe, Y., Wessels, J., White, S. N., Willis, N., Winter, D., Wohn, F. K., Woody, C. L., Wysocki, M., Xie, W., Yanovich, A., Yokkaichi, S., Young, G. R., Younus, I., Yushmanov, I. E., Zajc, W. A., Zaudtke, O., Zhang, C., Zhou, S., Zimányi, J., Zolin, L., and Zong, X. (2014). Transverse-energy distributions at midrapidity in $p + p$, $d + $ Au, and Au $+$ Au collisions at $\sqrt{s_{\mathrm{NN}}} = 62.4\check{}200$ gev and implications for particle-production models. *Phys. Rev. C*, 89:044905. 19

[5] Adler, S. S., Afanasiev, S., Aidala, C., Ajitanand, N. N., Akiba, Y., Alexander, J., Amirikas, R., Aphecetche, L., Aronson, S. H., Averbeck, R., Awes, T. C., Azmoun, R., Babintsev, V., Baldisseri, A., Barish, K. N., Barnes, P. D., Bassalleck, B., Bathe, S., Batsouli, S., Baublis, V., Bazilevsky, A., Belikov, S., Berdnikov, Y., Bhagavatula, S., Boissevain, J. G., Borel, H., Borenstein, S., Brooks, M. L., Brown, D. S., Bruner, N., Bucher, D., Buesching, H., Bumazhnov, V., Bunce, G., Burward-Hoy, J. M., Butsyk, S., Camard, X., Chai, J.-S., Chand, P., Chang, W. C., Chernichenko, S., Chi, C. Y., Chiba, J., Chiu, M., Choi, I. J., Choi, J., Choudhury, R. K., Chujo, T., Cianciolo, V., Cobigo, Y., Cole, B. A., Constantin, P., d'Enterria, D. G., David, G., Delagrange, H., Denisov, A., Deshpande, A., Desmond, E. J., Dietzsch, O., Drapier, O., Drees, A., Rietz, R. d., Durum, A., Dutta, D., Efremenko, Y. V., Chenawi, K. E., Enokizono, A., En'yo, H., Esumi, S., Ewell, L., Fields, D. E., Fleuret, F., Fokin, S. L., Fox, B. D., Fraenkel, Z., Frantz, J. E., Franz, A., Frawley, A. D., Fung, S.-Y., Garpman, S., Ghosh, T. K., Glenn, A., Gogiberidze, G., Gonin, M., Gosset, J., Goto, Y., Cassagnac, R. G. d., Grau, N., Greene, S. V., Perdekamp, M. G., Guryn, W., Gustafsson, H.-A., Hachiya, T., Haggerty, J. S., Hamagaki, H., Hansen, A. G., Hartouni, E. P., Harvey, M., Hayano, R., He, X., Heffner, M., Hemmick, T. K., Heuser, J. M., Hibino, M., Hill, J. C., Holzmann, W., Homma, K., Hong, B., Hoover, A., Ichihara, T., Ikonnikov, V. V., Imai, K., Isenhower, D., Ishihara, M., Issah, M., Isupov, A., Jacak, B. V., Jang, W. Y., Jeong, Y., Jia, J., Jinnouchi, O., Johnson, B. M., Johnson, S. C., Joo, K. S., Jouan, D., Kametani, S., Kamihara, N., Kang, J. H., Kapoor, S. S., Katou, K., Kelly, S., Khachaturov, B., Khanzadeev, A., Kikuchi, J., Kim, D. H., Kim, D. J., Kim, D. W., Kim, E., Kim, G.-B., Kim, H. J.,

Kistenev, E., Kiyomichi, A., Kiyoyama, K., Klein-Boesing, C., Kobayashi, H., Kochenda, L., Kochetkov, V., Koehler, D., Kohama, T., Kopytine, M., Kotchetkov, D., Kozlov, A., Kroon, P. J., Kuberg, C. H., Kurita, K., Kuroki, Y., Kweon, M. J., Kwon, Y., Kyle, G. S., Lacey, R., Ladygin, V., Lajoie, J. G., Lebedev, A., Leckey, S., Lee, D. M., Lee, S., Leitch, M. J., Li, X. H., Lim, H., Litvinenko, A., Liu, M. X., Liu, Y., Maguire, C. F., Makdisi, Y. I., Malakhov, A., Manko, V. I., Mao, Y., Martinez, G., Marx, M. D., Masui, H., Matathias, F., Matsumoto, T., McGaughey, P. L., Melnikov, E., Mendenhall, M., Messer, F., Miake, Y., Milan, J., Miller, T. E., Milov, A., Mioduszewski, S., Mischke, R. E., Mishra, G. C., Mitchell, J. T., Mohanty, A. K., Morrison, D. P., Moss, J. M., Mühlbacher, F., Mukhopadhyay, D., Muniruzzaman, M., Murata, J., Nagamiya, S., Nagle, J. L., Nakamura, T., Nandi, B. K., Nara, M., Newby, J., Nilsson, P., Nyanin, A. S., Nystrand, J., O'Brien, E., Ogilvie, C. A., Ohnishi, H., Ojha, I. D., Okada, K., Ono, M., Onuchin, V., Oskarsson, A., Otterlund, I., Oyama, K., Ozawa, K., Pal, D., Palounek, A. P. T., Pantuev, V. S., Papavassiliou, V., Park, J., Parmar, A., Pate, S. F., Peitzmann, T., Peng, J.-C., Peresedov, V., Pinkenburg, C., Pisani, R. P., Plasil, F., Purschke, M. L., Purwar, A. K., Rak, J., Ravinovich, I., Read, K. F., Reuter, M., Reygers, K., Riabov, V., Riabov, Y., Roche, G., Romana, A., Rosati, M., Rosnet, P., Ryu, S. S., Sadler, M. E., Saito, N., Sakaguchi, T., Sakai, M., Sakai, S., Samsonov, V., Sanfratello, L., Santo, R., Sato, H. D., Sato, S., Sawada, S., Schutz, Y., Semenov, V., Seto, R., Shaw, M. R., Shea, T. K., Shibata, T.-A., Shigaki, K., Shiina, T., Silva, C. L., Silvermyr, D., Sim, K. S., Singh, C. P., Singh, V., Sivertz, M., Soldatov, A., Soltz, R. A., Sondheim, W. E., Sorensen, S. P., Sourikova, I. V., Staley, F., Stankus, P. W., Stenlund, E., Stepanov, M., Ster, A., Stoll, S. P., Sugitate, T., Sullivan, J. P., Takagui, E. M., Taketani, A., Tamai, M., Tanaka, K. H., Tanaka, Y., Tanida, K., Tannenbaum, M. J., Tarján, P., Tepe, J. D., Thomas, T. L., Tojo, J., Torii, H., Towell, R. S., Tserruya, I., Tsuruoka, H., Tuli, S. K., Tydesjö, H., Tyurin, N., Hecke, H. W. v., Velkovska, J., Velkovsky, M., Villatte, L., Vinogradov, A. A., Volkov, M. A., Vznuzdaev, E., Wang, X. R., Watanabe, Y., White, S. N., Wohn, F. K., Woody, C. L., Xie, W., Yang, Y., Yanovich, A., Yokkaichi, S., Young, G. R., Yushmanov, I. E., Zajc, W. A., Zhang, C., Zhou, S., Zhou, S. J., and Zolin, L. (2005). Systematic studies of the centrality and $\sqrt{s_{NN}}$ dependence of the $de_T/d\eta$ and $dn_{ch}/d\eta$ in heavy ion collisions at

969  midrapidity. *Phys. Rev. C*, 71:034908. 20

970  [6] Anderson, M. et al. (2003). The Star time projection chamber: A Unique tool for studying

971  high multiplicity events at RHIC. *Nucl. Instrum. Meth.*, A499:659–678. 23

972  [7] Ayala, A. (2016). Hadronic matter at the edge: A survey of some theoretical approaches

973  to the physics of the qcd phase diagram. *Journal of Physics: Conference Series*,

974  761(1):012066. vi, 5, 6

975  [8] Bethe, H. A. and Ashkin, J. (1953). Passage of radiations through matter experimental

976  nuclear physics vol 1 ed e segre. 21

977  [9] Chatrchyan, S., Khachatryan, V., Sirunyan, A. M., Tumasyan, A., Adam, W., Bergauer,

978  T., Dragicevic, M., Erö, J., Fabjan, C., Friedl, M., Frühwirth, R., Ghete, V. M., Hammer,

979  J., Hörmann, N., Hrubec, J., Jeitler, M., Kiesenhofer, W., Knünz, V., Krammer, M., Liko,

980  D., Mikulec, I., Pernicka, M., Rahbaran, B., Rohringer, C., Rohringer, H., Schöfbeck, R.,

981  Strauss, J., Taurok, A., Wagner, P., Waltenberger, W., Walzel, G., Widl, E., Wulz, C.-E.,

982  Mossolov, V., Shumeiko, N., Suarez Gonzalez, J., Bansal, S., Cornelis, T., De Wolf, E. A.,

983  Janssen, X., Luyckx, S., Maes, T., Mucibello, L., Ochesanu, S., Roland, B., Rougny,

984  R., Selvaggi, M., Staykova, Z., Van Haevermaet, H., Van Mechelen, P., Van Remortel,

985  N., Van Spilbeeck, A., Blekman, F., Blyweert, S., D'Hondt, J., Gonzalez Suarez, R.,

986  Kalogeropoulos, A., Maes, M., Olbrechts, A., Van Doninck, W., Van Mulders, P.,

987  Van Onsem, G. P., Villella, I., Clerbaux, B., De Lentdecker, G., Dero, V., Gay, A. P. R.,

988  Hreus, T., Léonard, A., Marage, P. E., Reis, T., Thomas, L., Vander Velde, C., Vanlaer, P.,

989  Wang, J., Adler, V., Beernaert, K., Cimmino, A., Costantini, S., Garcia, G., Grunewald,

990  M., Klein, B., Lellouch, J., Marinov, A., Mccartin, J., Ocampo Rios, A. A., Ryckbosch, D.,

991  Strobbe, N., Thyssen, F., Tytgat, M., Verwilligen, P., Walsh, S., Yazgan, E., Zaganidis,

992  N., Basegmez, S., Bruno, G., Castello, R., Ceard, L., Delaere, C., du Pree, T., Favart, D.,

993  Forthomme, L., Giammanco, A., Hollar, J., Lemaitre, V., Liao, J., Militaru, O., Nuttens,

994  C., Pagano, D., Pin, A., Piotrzkowski, K., Schul, N., Vizan Garcia, J. M., Beliy, N.,

995  Caebergs, T., Daubie, E., Hammad, G. H., Alves, G. A., Correa Martins Junior, M.,

996  De Jesus Damiao, D., Martins, T., Pol, M. E., Souza, M. H. G., Aldá Júnior, W. L.,

45

Carvalho, W., Custódio, A., Da Costa, E. M., De Oliveira Martins, C., Fonseca De Souza, S., Matos Figueiredo, D., Mundim, L., Nogima, H., Oguri, V., Prado Da Silva, W. L., Santoro, A., Soares Jorge, L., Sznajder, A., Bernardes, C. A., Dias, F. A., Fernandez Perez Tomei, T. R., Gregores, E. M., Lagana, C., Marinho, F., Mercadante, P. G., Novaes, S. F., Padula, S. S., Genchev, V., Iaydjiev, P., Piperov, S., Rodozov, M., Stoykova, S., Sultanov, G., Tcholakov, V., Trayanov, R., Vutova, M., Dimitrov, A., Hadjiiska, R., Kozhuharov, V., Litov, L., Pavlov, B., Petkov, P., Bian, J. G., Chen, G. M., Chen, H. S., Jiang, C. H., Liang, D., Liang, S., Meng, X., Tao, J., Wang, J., Wang, X., Wang, Z., Xiao, H., Xu, M., Zang, J., Zhang, Z., Asawatangtrakuldee, C., Ban, Y., Guo, S., Guo, Y., Li, W., Liu, S., Mao, Y., Qian, S. J., Teng, H., Wang, S., Zhu, B., Zou, W., Avila, C., Gomez, J. P., Gomez Moreno, B., Osorio Oliveros, A. F., Sanabria, J. C., Godinovic, N., Lelas, D., Plestina, R., Polic, D., Puljak, I., Antunovic, Z., Kovac, M., Brigljevic, V., Duric, S., Kadija, K., Luetic, J., Morovic, S., Attikis, A., Galanti, M., Mavromanolakis, G., Mousa, J., Nicolaou, C., Ptochos, F., Razis, P. A., Finger, M., Finger, M., Assran, Y., Elgammal, S., Ellithi Kamel, A., Khalil, S., Mahmoud, M. A., Radi, A., Kadastik, M., Müntel, M., Raidal, M., Rebane, L., Tiko, A., Azzolini, V., Eerola, P., Fedi, G., Voutilainen, M., Härkönen, J., Heikkinen, A., Karimäki, V., Kinnunen, R., Kortelainen, M. J., Lampén, T., Lassila-Perini, K., Lehti, S., Lindén, T., Luukka, P., Mäenpää, T., Peltola, T., Tuominen, E., Tuominiemi, J., Tuovinen, E., Ungaro, D., Wendland, L., Banzuzi, K., Karjalainen, A., Korpela, A., Tuuva, T., Besancon, M., Choudhury, S., Dejardin, M., Denegri, D., Fabbro, B., Faure, J. L., Ferri, F., Ganjour, S., Givernaud, A., Gras, P., Hamel de Monchenault, G., Jarry, P., Locci, E., Malcles, J., Millischer, L., Nayak, A., Rander, J., Rosowsky, A., Shreyber, I., Titov, M., Baffioni, S., Beaudette, F., Benhabib, L., Bianchini, L., Bluj, M., Broutin, C., Busson, P., Charlot, C., Daci, N., Dahms, T., Dobrzynski, L., Granier de Cassagnac, R., Haguenauer, M., Miné, P., Mironov, C., Nguyen, M., Ochando, C., Paganini, P., Sabes, D., Salerno, R., Sirois, Y., Veelken, C., Zabi, A., Agram, J.-L., Andrea, J., Bloch, D., Bodin, D., Brom, J.-M., Cardaci, M., Chabert, E. C., Collard, C., Conte, E., Drouhin, F., Ferro, C., Fontaine, J.-C., Gelé, D., Goerlach, U., Juillot, P., Le Bihan, A.-C., Van Hove, P., Fassi, F., Mercier, D., Beauceron, S., Beaupere, N., Bondu, O., Boudoul, G., Chasserat, J., Chierici, R.,

Contardo, D., Depasse, P., El Mamouni, H., Fay, J., Gascon, S., Gouzevitch, M., Ille, B., Kurca, T., Lethuillier, M., Mirabito, L., Perries, S., Sordini, V., Tosi, S., Tschudi, Y., Verdier, P., Viret, S., Tsamalaidze, Z., Anagnostou, G., Beranek, S., Edelhoff, M., Feld, L., Heracleous, N., Hindrichs, O., Jussen, R., Klein, K., Merz, J., Ostapchuk, A., Perieanu, A., Raupach, F., Sammet, J., Schael, S., Sprenger, D., Weber, H., Wittmer, B., Zhukov, V., Ata, M., Caudron, J., Dietz-Laursonn, E., Erdmann, M., Güth, A., Hebbeker, T., Heidemann, C., Hoepfner, K., Klingebiel, D., Kreuzer, P., Lingemann, J., Magass, C., Merschmeyer, M., Meyer, A., Olschewski, M., Papacz, P., Pieta, H., Reithler, H., Schmitz, S. A., Sonnenschein, L., Steggemann, J., Teyssier, D., Weber, M., Bontenackels, M., Cherepanov, V., Flügge, G., Geenen, H., Geisler, M., Haj Ahmad, W., Hoehle, F., Kargoll, B., Kress, T., Kuessel, Y., Nowack, A., Perchalla, L., Pooth, O., Rennefeld, J., Sauerland, P., Stahl, A., Aldaya Martin, M., Behr, J., Behrenhoff, W., Behrens, U., Bergholz, M., Bethani, A., Borras, K., Burgmeier, A., Cakir, A., Calligaris, L., Campbell, A., Castro, E., Costanza, F., Dammann, D., Diez Pardos, C., Eckerlin, G., Eckstein, D., Flucke, G., Geiser, A., Glushkov, I., Gunnellini, P., Habib, S., Hauk, J., Jung, H., Kasemann, M., Katsas, P., Kleinwort, C., Kluge, H., Knutsson, A., Krämer, M., Krücker, D., Kuznetsova, E., Lange, W., Lohmann, W., Lutz, B., Mankel, R., Marfin, I., Marienfeld, M., Melzer-Pellmann, I.-A., Meyer, A. B., Mnich, J., Mussgiller, A., Naumann-Emme, S., Olzem, J., Perrey, H., Petrukhin, A., Pitzl, D., Raspereza, A., Ribeiro Cipriano, P. M., Riedl, C., Ron, E., Rosin, M., Salfeld-Nebgen, J., Schmidt, R., Schoerner-Sadenius, T., Sen, N., Spiridonov, A., Stein, M., Walsh, R., Wissing, C., Autermann, C., Blobel, V., Draeger, J., Enderle, H., Erfle, J., Gebbert, U., Görner, M., Hermanns, T., Höing, R. S., Kaschube, K., Kaussen, G., Kirschenmann, H., Klanner, R., Lange, J., Mura, B., Nowak, F., Peiffer, T., Pietsch, N., Sander, C., Schettler, H., Schleper, P., Schlieckau, E., Schmidt, A., Schröder, M., Schum, T., Sola, V., Stadie, H., Steinbrück, G., Thomsen, J., Vanelderen, L., Barth, C., Berger, J., Chwalek, T., De Boer, W., Dierlamm, A., Feindt, M., Guthoff, M., Hackstein, C., Hartmann, F., Heinrich, M., Held, H., Hoffmann, K. H., Honc, S., Katkov, I., Komaragiri, J. R., Lobelle Pardo, P., Martschei, D., Mueller, S., Müller, T., Niegel, M., Nürnberg, A., Oberst, O., Oehler, A., Ott, J., Quast, G., Rabbertz, K., Ratnikov, F., Ratnikova, N., Röcker, S., Scheurer, A., Schilling, F.-P.,

Schott, G., Simonis, H. J., Stober, F. M., Troendle, D., Ulrich, R., Wagner-Kuhr, J., Weiler, T., Zeise, M., Daskalakis, G., Geralis, T., Kesisoglou, S., Kyriakis, A., Loukas, D., Manolakos, I., Markou, A., Markou, C., Mavrommatis, C., Ntomari, E., Gouskos, L., Mertzimekis, T. J., Panagiotou, A., Saoulidou, N., Evangelou, I., Foudas, C., Kokkas, P., Manthos, N., Papadopoulos, I., Patras, V., Bencze, G., Hajdu, C., Hidas, P., Horvath, D., Sikler, F., Veszpremi, V., Vesztergombi, G., Beni, N., Czellar, S., Molnar, J., Palinkas, J., Szillasi, Z., Karancsi, J., Raics, P., Trocsanyi, Z. L., Ujvari, B., Beri, S. B., Bhatnagar, V., Dhingra, N., Gupta, R., Jindal, M., Kaur, M., Mehta, M. Z., Nishu, N., Saini, L. K., Sharma, A., Singh, J., Ahuja, S., Bhardwaj, A., Choudhary, B. C., Kumar, A., Kumar, A., Malhotra, S., Naimuddin, M., Ranjan, K., Sharma, V., Shivpuri, R. K., Banerjee, S., Bhattacharya, S., Dutta, S., Gomber, B., Jain, S., Jain, S., Khurana, R., Sarkar, S., Sharan, M., Abdulsalam, A., Choudhury, R. K., Dutta, D., Kailas, S., Kumar, V., Mehta, P., Mohanty, A. K., Pant, L. M., Shukla, P., Aziz, T., Ganguly, S., Guchait, M., Maity, M., Majumder, G., Mazumdar, K., Mohanty, G. B., Parida, B., Sudhakar, K., Wickramage, N., Banerjee, S., Dugad, S., Arfaei, H., Bakhshiansohi, H., Etesami, S. M., Fahim, A., Hashemi, M., Hesari, H., Jafari, A., Khakzad, M., Mohammadi Najafabadi, M., Paktinat Mehdiabadi, S., Safarzadeh, B., Zeinali, M., Abbrescia, M., Barbone, L., Calabria, C., Chhibra, S. S., Colaleo, A., Creanza, D., De Filippis, N., De Palma, M., Fiore, L., Iaselli, G., Lusito, L., Maggi, G., Maggi, M., Marangelli, B., My, S., Nuzzo, S., Pacifico, N., Pompili, A., Pugliese, G., Selvaggi, G., Silvestris, L., Singh, G., Zito, G., Abbiendi, G., Benvenuti, A. C., Bonacorsi, D., Braibant-Giacomelli, S., Brigliadori, L., Capiluppi, P., Castro, A., Cavallo, F. R., Cuffiani, M., Dallavalle, G. M., Fabbri, F., Fanfani, A., Fasanella, D., Giacomelli, P., Grandi, C., Guiducci, L., Marcellini, S., Masetti, G., Meneghelli, M., Montanari, A., Navarria, F. L., Odorici, F., Perrotta, A., Primavera, F., Rossi, A. M., Rovelli, T., Siroli, G., Travaglini, R., Albergo, S., Cappello, G., Chiorboli, M., Costa, S., Potenza, R., Tricomi, A., Tuve, C., Barbagli, G., Ciulli, V., Civinini, C., D'Alessandro, R., Focardi, E., Frosali, S., Gallo, E., Gonzi, S., Meschini, M., Paoletti, S., Sguazzoni, G., Tropiano, A., Benussi, L., Bianco, S., Colafranceschi, S., Fabbri, F., Piccolo, D., Fabbricatore, P., Musenich, R., Benaglia, A., De Guio, F., Di Matteo, L., Fiorendi, S., Gennai, S., Ghezzi, A., Malvezzi, S., Manzoni, R. A., Martelli, A., Massironi,

48

A., Menasce, D., Moroni, L., Paganoni, M., Pedrini, D., Ragazzi, S., Redaelli, N., Sala, S., Tabarelli de Fatis, T., Buontempo, S., Carrillo Montoya, C. A., Cavallo, N., De Cosa, A., Dogangun, O., Fabozzi, F., Iorio, A. O. M., Lista, L., Meola, S., Merola, M., Paolucci, P., Azzi, P., Bacchetta, N., Bellan, P., Bisello, D., Branca, A., Carlin, R., Checchia, P., Dorigo, T., Dosselli, U., Gasparini, F., Gasparini, U., Gozzelino, A., Kanishchev, K., Lacaprara, S., Lazzizzera, I., Margoni, M., Meneguzzo, A. T., Nespolo, M., Ronchese, P., Simonetto, F., Torassa, E., Vanini, S., Zotto, P., Zumerle, G., Gabusi, M., Ratti, S. P., Riccardi, C., Torre, P., Vitulo, P., Biasini, M., Bilei, G. M., Fanò, L., Lariccia, P., Lucaroni, A., Mantovani, G., Menichelli, M., Nappi, A., Romeo, F., Saha, A., Santocchia, A., Taroni, S., Azzurri, P., Bagliesi, G., Boccali, T., Broccolo, G., Castaldi, R., D'Agnolo, R. T., Dell'Orso, R., Fiori, F., Foà, L., Giassi, A., Kraan, A., Ligabue, F., Lomtadze, T., Martini, L., Messineo, A., Palla, F., Rizzi, A., Serban, A. T., Spagnolo, P., Squillacioti, P., Tenchini, R., Tonelli, G., Venturi, A., Verdini, P. G., Barone, L., Cavallari, F., Del Re, D., Diemoz, M., Grassi, M., Longo, E., Meridiani, P., Micheli, F., Nourbakhsh, S., Organtini, G., Paramatti, R., Rahatlou, S., Sigamani, M., Soffi, L., Amapane, N., Arcidiacono, R., Argiro, S., Arneodo, M., Biino, C., Cartiglia, N., Costa, M., Demaria, N., Graziano, A., Mariotti, C., Maselli, S., Migliore, E., Monaco, V., Musich, M., Obertino, M. M., Pastrone, N., Pelliccioni, M., Potenza, A., Romero, A., Ruspa, M., Sacchi, R., Solano, A., Staiano, A., Vilela Pereira, A., Belforte, S., Candelise, V., Cossutti, F., Della Ricca, G., Gobbo, B., Marone, M., Montanino, D., Penzo, A., Schizzi, A., Heo, S. G., Kim, T. Y., Nam, S. K., Chang, S., Kim, D. H., Kim, G. N., Kong, D. J., Park, H., Ro, S. R., Son, D. C., Son, T., Kim, J. Y., Kim, Z. J., Song, S., Choi, S., Gyun, D., Hong, B., Jo, M., Kim, H., Kim, T. J., Lee, K. S., Moon, D. H., Park, S. K., Choi, M., Kim, J. H., Park, C., Park, I. C., Park, S., Ryu, G., Cho, Y., Choi, Y., Choi, Y. K., Goh, J., Kim, M. S., Kwon, E., Lee, B., Lee, J., Lee, S., Seo, H., Yu, I., Bilinskas, M. J., Grigelionis, I., Janulis, M., Juodagalvis, A., Castilla-Valdez, H., De La Cruz-Burelo, E., Heredia-de La Cruz, I., Lopez-Fernandez, R., Magaña Villalba, R., Martínez-Ortega, J., Sánchez-Hernández, A., Villasenor-Cendejas, L. M., Carrillo Moreno, S., Vazquez Valencia, F., Salazar Ibarguen, H. A., Casimiro Linares, E., Morelos Pineda, A., Reyes-Santos, M. A., Krofcheck, D., Bell, A. J., Butler, P. H., Doesburg, R., Reucroft, S., Silverwood, H., Ahmad, M.,

49

Asghar, M. I., Hoorani, H. R., Khalid, S., Khan, W. A., Khurshid, T., Qazi, S., Shah, M. A., Shoaib, M., Bialkowska, H., Boimska, B., Frueboes, T., Gokieli, R., Górski, M., Kazana, M., Nawrocki, K., Romanowska-Rybinska, K., Szleper, M., Wrochna, G., Zalewski, P., Brona, G., Bunkowski, K., Cwiok, M., Dominik, W., Doroba, K., Kalinowski, A., Konecki, M., Krolikowski, J., Almeida, N., Bargassa, P., David, A., Faccioli, P., Ferreira Parracho, P. G., Gallinaro, M., Seixas, J., Varela, J., Vischia, P., Belotelov, I., Bunin, P., Gavrilenko, M., Golutvin, I., Gorbunov, I., Kamenev, A., Karjavin, V., Kozlov, G., Lanev, A., Malakhov, A., Moisenz, P., Palichik, V., Perelygin, V., Shmatov, S., Smirnov, V., Volodko, A., Zarubin, A., Evstyukhin, S., Golovtsov, V., Ivanov, Y., Kim, V., Levchenko, P., Murzin, V., Oreshkin, V., Smirnov, I., Sulimov, V., Uvarov, L., Vavilov, S., Vorobyev, A., Vorobyev, A., Andreev, Y., Dermenev, A., Gninenko, S., Golubev, N., Kirsanov, M., Krasnikov, N., Matveev, V., Pashenkov, A., Tlisov, D., Toropin, A., Epshteyn, V., Erofeeva, M., Gavrilov, V., Kossov, M., Lychkovskaya, N., Popov, V., Safronov, G., Semenov, S., Stolin, V., Vlasov, E., Zhokin, A., Belyaev, A., Boos, E., Ershov, A., Gribushin, A., Klyukhin, V., Kodolova, O., Korotkikh, V., Lokhtin, I., Markina, A., Obraztsov, S., Perfilov, M., Petrushanko, S., Popov, A., Sarycheva, L., Savrin, V., Snigirev, A., Vardanyan, I., Andreev, V., Azarkin, M., Dremin, I., Kirakosyan, M., Leonidov, A., Mesyats, G., Rusakov, S. V., Vinogradov, A., Azhgirey, I., Bayshev, I., Bitioukov, S., Grishin, V., Kachanov, V., Konstantinov, D., Korablev, A., Krychkine, V., Petrov, V., Ryutin, R., Sobol, A., Tourtchanovitch, L., Troshin, S., Tyurin, N., Uzunian, A., Volkov, A., Adzic, P., Djordjevic, M., Ekmedzic, M., Krpic, D., Milosevic, J., Aguilar-Benitez, M., Alcaraz Maestre, J., Arce, P., Battilana, C., Calvo, E., Cerrada, M., Chamizo Llatas, M., Colino, N., De La Cruz, B., Delgado Peris, A., Domínguez Vázquez, D., Fernandez Bedoya, C., Fernández Ramos, J. P., Ferrando, A., Flix, J., Fouz, M. C., Garcia-Abia, P., Gonzalez Lopez, O., Goy Lopez, S., Hernandez, J. M., Josa, M. I., Merino, G., Puerta Pelayo, J., Quintario Olmeda, A., Redondo, I., Romero, L., Santaolalla, J., Soares, M. S., Willmott, C., Albajar, C., Codispoti, G., de Trocóniz, J. F., Brun, H., Cuevas, J., Fernandez Menendez, J., Folgueras, S., Gonzalez Caballero, I., Lloret Iglesias, L., Piedra Gomez, J., Brochero Cifuentes, J. A., Cabrillo, I. J., Calderon, A., Chuang, S. H., Duarte Campderros, J., Felcini, M., Fernandez, M., Gomez, G., Gonzalez Sanchez,

J., Jorda, C., Lopez Virto, A., Marco, J., Marco, R., Martinez Rivero, C., Matorras, F., Munoz Sanchez, F. J., Rodrigo, T., Rodríguez-Marrero, A. Y., Ruiz-Jimeno, A., Scodellaro, L., Sobron Sanudo, M., Vila, I., Vilar Cortabitarte, R., Abbaneo, D., Auffray, E., Auzinger, G., Baillon, P., Ball, A. H., Barney, D., Benitez, J. F., Bernet, C., Bianchi, G., Bloch, P., Bocci, A., Bonato, A., Botta, C., Breuker, H., Camporesi, T., Cerminara, G., Christiansen, T., Coarasa Perez, J. A., D'Enterria, D., Dabrowski, A., De Roeck, A., Di Guida, S., Dobson, M., Dupont-Sagorin, N., Elliott-Peisert, A., Frisch, B., Funk, W., Georgiou, G., Giffels, M., Gigi, D., Gill, K., Giordano, D., Giunta, M., Glege, F., Gomez-Reino Garrido, R., Govoni, P., Gowdy, S., Guida, R., Hansen, M., Harris, P., Hartl, C., Harvey, J., Hegner, B., Hinzmann, A., Innocente, V., Janot, P., Kaadze, K., Karavakis, E., Kousouris, K., Lecoq, P., Lee, Y.-J., Lenzi, P., Lourenço, C., Mäki, T., Malberti, M., Malgeri, L., Mannelli, M., Masetti, L., Meijers, F., Mersi, S., Meschi, E., Moser, R., Mozer, M. U., Mulders, M., Musella, P., Nesvold, E., Orimoto, T., Orsini, L., Palencia Cortezon, E., Perez, E., Perrozzi, L., Petrilli, A., Pfeiffer, A., Pierini, M., Pimiä, M., Piparo, D., Polese, G., Quertenmont, L., Racz, A., Reece, W., Rodrigues Antunes, J., Rolandi, G., Rommerskirchen, T., Rovelli, C., Rovere, M., Sakulin, H., Santanastasio, F., Schäfer, C., Schwick, C., Segoni, I., Sekmen, S., Sharma, A., Siegrist, P., Silva, P., Simon, M., Sphicas, P., Spiga, D., Spiropulu, M., Tsirou, A., Veres, G. I., Vlimant, J. R., Wöhri, H. K., Worm, S. D., Zeuner, W. D., Bertl, W., Deiters, K., Erdmann, W., Gabathuler, K., Horisberger, R., Ingram, Q., Kaestli, H. C., König, S., Kotlinski, D., Langenegger, U., Meier, F., Renker, D., Rohe, T., Sibille, J., Bäni, L., Bortignon, P., Buchmann, M. A., Casal, B., Chanon, N., Deisher, A., Dissertori, G., Dittmar, M., Dünser, M., Eugster, J., Freudenreich, K., Grab, C., Hits, D., Lecomte, P., Lustermann, W., Martinez Ruiz del Arbol, P., Mohr, N., Moortgat, F., Nägeli, C., Nef, P., Nessi-Tedaldi, F., Pandolfi, F., Pape, L., Pauss, F., Peruzzi, M., Ronga, F. J., Rossini, M., Sala, L., Sanchez, A. K., Starodumov, A., Stieger, B., Takahashi, M., Tauscher, L., Thea, A., Theofilatos, K., Treille, D., Urscheler, C., Wallny, R., Weber, H. A., Wehrli, L., Aguilo, E., Amsler, C., Chiochia, V., De Visscher, S., Favaro, C., Ivova Rikova, M., Millan Mejias, B., Otiougova, P., Robmann, P., Snoek, H., Tupputi, S., Verzetti, M., Chang, Y. H., Chen, K. H., Kuo, C. M., Li, S. W., Lin, W., Liu, Z. K., Lu, Y. J., Mekterovic, D., Singh, A. P., Volpe, R., Yu,

S. S., Bartalini, P., Chang, P., Chang, Y. H., Chang, Y. W., Chao, Y., Chen, K. F., Dietz, C., Grundler, U., Hou, W.-S., Hsiung, Y., Kao, K. Y., Lei, Y. J., Lu, R.-S., Majumder, D., Petrakou, E., Shi, X., Shiu, J. G., Tzeng, Y. M., Wan, X., Wang, M., Adiguzel, A., Bakirci, M. N., Cerci, S., Dozen, C., Dumanoglu, I., Eskut, E., Girgis, S., Gokbulut, G., Gurpinar, E., Hos, I., Kangal, E. E., Karapinar, G., Kayis Topaksu, A., Onengut, G., Ozdemir, K., Ozturk, S., Polatoz, A., Sogut, K., Sunar Cerci, D., Tali, B., Topakli, H., Vergili, L. N., Vergili, M., Akin, I. V., Aliev, T., Bilin, B., Bilmis, S., Deniz, M., Gamsizkan, H., Guler, A. M., Ocalan, K., Ozpineci, A., Serin, M., Sever, R., Surat, U. E., Yalvac, M., Yildirim, E., Zeyrek, M., Gülmez, E., Isildak, B., Kaya, M., Kaya, O., Ozkorucuklu, S., Sonmez, N., Cankocak, K., Levchuk, L., Bostock, F., Brooke, J. J., Clement, E., Cussans, D., Flacher, H., Frazier, R., Goldstein, J., Grimes, M., Heath, G. P., Heath, H. F., Kreczko, L., Metson, S., Newbold, D. M., Nirunpong, K., Poll, A., Senkin, S., Smith, V. J., Williams, T., Basso, L., Bell, K. W., Belyaev, A., Brew, C., Brown, R. M., Cockerill, D. J. A., Coughlan, J. A., Harder, K., Harper, S., Jackson, J., Kennedy, B. W., Olaiya, E., Petyt, D., Radburn-Smith, B. C., Shepherd-Themistocleous, C. H., Tomalin, I. R., Womersley, W. J., Bainbridge, R., Ball, G., Beuselinck, R., Buchmuller, O., Colling, D., Cripps, N., Cutajar, M., Dauncey, P., Davies, G., Della Negra, M., Ferguson, W., Fulcher, J., Futyan, D., Gilbert, A., Guneratne Bryer, A., Hall, G., Hatherell, Z., Hays, J., Iles, G., Jarvis, M., Karapostoli, G., Lyons, L., Magnan, A.-M., Marrouche, J., Mathias, B., Nandi, R., Nash, J., Nikitenko, A., Papageorgiou, A., Pela, J., Pesaresi, M., Petridis, K., Pioppi, M., Raymond, D. M., Rogerson, S., Rose, A., Ryan, M. J., Seez, C., Sharp, P., Sparrow, A., Stoye, M., Tapper, A., Vazquez Acosta, M., Virdee, T., Wakefield, S., Wardle, N., Whyntie, T., Chadwick, M., Cole, J. E., Hobson, P. R., Khan, A., Kyberd, P., Leslie, D., Martin, W., Reid, I. D., Symonds, P., Teodorescu, L., Turner, M., Hatakeyama, K., Liu, H., Scarborough, T., Charaf, O., Henderson, C., Rumerio, P., Avetisyan, A., Bose, T., Fantasia, C., Heiste (2012). Measurement of the pseudorapidity and centrality dependence of the transverse energy density in pb-pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV. *Phys. Rev. Lett.*, 109:152303. 6, 19

[10] Collaboration, T. A., Aamodt, K., Quintana, A. A., Achenbach, R., Acounis, S., Adamov, D., Adler, C., Aggarwal, M., Agnese, F., Rinella, G. A., Ahammed, Z., Ahmad, A., Ahmad, N., Ahmad, S., Akindinov, A., Akishin, P., Aleksandrov, D., Alessandro, B., Alfaro, R., Alfarone, G., Alici, A., Alme, J., Alt, T., Altinpinar, S., Amend, W., Andrei, C., Andres, Y., Andronic, A., Anelli, G., Anfreville, M., Angelov, V., Anzo, A., Anson, C., Antici, T., Antonenko, V., Antonczyk, D., Antinori, F., Antinori, S., Antonioli, P., Aphecetche, L., Appelshuser, H., Aprodu, V., Arba, M., Arcelli, S., Argentieri, A., Armesto, N., Arnaldi, R., Arefiev, A., Arsene, I., Asryan, A., Augustinus, A., Awes, T. C., ysto, J., Azmi, M. D., Bablock, S., Badal, A., Badyal, S. K., Baechler, J., Bagnasco, S., Bailhache, R., Bala, R., Baldisseri, A., Baldit, A., Bn, J., Barbera, R., Barberis, P.-L., Barbet, J. M., Barnfoldi, G., Barret, V., Bartke, J., Bartos, D., Basile, M., Basmanov, V., Bastid, N., Batigne, G., Batyunya, B., Baudot, J., Baumann, C., Bearden, I., Becker, B., Belikov, J., Bellwied, R., Belmont-Moreno, E., Belogianni, A., Belyaev, S., Benato, A., Beney, J. L., Benhabib, L., Benotto, F., Beol, S., Berceanu, I., Bercuci, A., Berdermann, E., Berdnikov, Y., Bernard, C., Berny, R., Berst, J. D., Bertelsen, H., Betev, L., Bhasin, A., Baskar, P., Bhati, A., Bianchi, N., Bielik, J., Bielikov, J., Bimbot, L., Blanchard, G., Blanco, F., Blanco, F., Blau, D., Blume, C., Blyth, S., Boccioli, M., Bogdanov, A., Bggild, H., Bogolyubsky, M., Boldizsr, L., Bombara, M., Bombonati, C., Bondila, M., Bonnet, D., Bonvicini, V., Borel, H., Borotto, F., Borshchov, V., Bortoli, Y., Borysov, O., Bose, S., Bosisio, L., Botje, M., Bttger, S., Bourdaud, G., Bourrion, O., Bouvier, S., Braem, A., Braun, M., Braun-Munzinger, P., Bravina, L., Bregant, M., Bruckner, G., Brun, R., Bruna, E., Brunasso, O., Bruno, G. E., Bucher, D., Budilov, V., Budnikov, D., Buesching, H., Buncic, P., Burns, M., Burachas, S., Busch, O., Bushop, J., Cai, X., Caines, H., Calaon, F., Caldogno, M., Cali, I., Camerini, P., Campagnolo, R., Campbell, M., Cao, X., Capitani, G. P., Romeo, G. C., Cardenas-Montes, M., Carduner, H., Carena, F., Carena, W., Cariola, P., Carminati, F., Casado, J., Diaz, A. C., Caselle, M., Castellanos, J. C., Castor, J., Catanescu, V., Cattaruzza, E., Cavazza, D., Cerello, P., Ceresa, S., ern, V., Chambert, V., Chapeland, S., Charpy, A., Charrier, D., Chartoire, M., Charvet, J. L., Chattopadhyay, S., Chattopadhyay, S., Chepurnov, V., Chernenko, S., Cherney, M., Cheshkov, C., Cheynis, B., Chochula, P., Chiavassa, E., Barroso, V. C., Choi, J.,

53

Christakoglou, P., Christiansen, P., Christensen, C., Chykalov, O. A., Cicalo, C., Cifarelli-Strolin, L., Ciobanu, M., Cindolo, F., Cirstoiu, C., Clausse, O., Cleymans, J., Cobanoglu, O., Coffin, J.-P., Coli, S., Colla, A., Colledani, C., Combaret, C., Combet, M., Comets, M., Balbastre, G. C., del Valle, Z. C., Contin, G., Contreras, J., Cormier, T., Corsi, F., Cortese, P., Costa, F., Crescio, E., Crochet, P., Cuautle, E., Cussonneau, J., Dahlinger, M., Dainese, A., Dalsgaard, H. H., Daniel, L., Das, I., Das, T., Dash, A., Silva, R. D., Davenport, M., Daues, H., Caro, A. D., de Cataldo, G., Cuveland, J. D., Falco, A. D., de Gaspari, M., de Girolamo, P., de Groot, J., Gruttola, D. D., Haas, A. D., Marco, N. D., Pasquale, S. D., Remigis, P. D., de Vaux, D., Decock, G., Delagrange, H., Franco, M. D., Dellacasa, G., Dell'Olio, C., Dell'Olio, D., Deloff, A., Demanov, V., Dnes, E., D'Erasmo, G., Derkach, D., Devaux, A., Bari, D. D., Bartolomeo, A. D., Giglio, C. D., Liberto, S. D., Mauro, A. D., Nezza, P. D., Dialinas, M., Diaz, L., Valdes, R. D., Dietel, T., Dima, R., Ding, H., Dinca, C., Divi, R., Dobretsov, V., Dobrin, A., Doenigus, B., Dobrowolski, T., Domnguez, I., Dorn, M., Drouet, S., Dubey, A. E., Ducroux, L., Dumitrache, F., Dumonteil, E., Dupieux, P., Duta, V., Majumdar, A. D., Majumdar, M. D., Dyhre, T., Efimov, L., Efremov, A., Elia, D., Emschermann, D., Engster, C., Enokizono, A., Espagnon, B., Estienne, M., Evangelista, A., Evans, D., Evrard, S., Fabjan, C. W., Fabris, D., Faivre, J., Falchieri, D., Fantoni, A., Farano, R., Fearick, R., Fedorov, O., Fekete, V., Felea, D., Feofilov, G., Tllez, A. F., Ferretti, A., Fichera, F., Filchagin, S., Filoni, E., Finck, C., Fini, R., Fiore, E. M., Flierl, D., Floris, M., Fodor, Z., Foka, Y., Fokin, S., Force, P., Formenti, F., Fragiacomo, E., Fragkiadakis, M., Fraissard, D., Franco, A., Franco, M., Frankenfeld, U., Fratino, U., Fresneau, S., Frolov, A., Fuchs, U., Fujita, J., Furget, C., Furini, M., Girard, M. F., Gaardhje, J.-J., Gabrielli, A., Gadrat, S., Gagliardi, M., Gago, A., Gaido, L., Torreira, A. G., Gallio, M., Gandolfi, E., Ganoti, P., Ganti, M., Garabatos, J., Lopez, A. G., Garizzo, L., Gaudichet, L., Gemme, R., Germain, M., Gheata, A., Gheata, M., Ghidini, B., Ghosh, P., Giolu, G., Giraudo, G., Giubellino, P., Glasow, R., Glssel, P., Ferreiro, E. G., Gutierrez, C. G., Gonzales-Trueba, L. H., Gorbunov, S., Gorbunov, Y., Gos, H., Gosset, J., Gotovac, S., Gottschlag, H., Gottschalk, D., Grabski, V., Grassi, T., Gray, H., Grebenyuk, O., Grebieszkow, K., Gregory, C., Grigoras, C., Grion, N., Grigoriev, V., Grigoryan, A., Grigoryan, C., Grigoryan, S., Grishuk, Y., Gros,

P., Grosse-Oetringhaus, J., Grossiord, J.-Y., Grosso, R., Grynyov, B., Guarnaccia, C., Guber, F., Guerin, F., Guernane, R., Guerzoni, M., Guichard, A., Guida, M., Guilloux, G., Gulkanyan, H., Gulbrandsen, K., Gunji, T., Gupta, A., Gupta, V., Gustafsson, H.-A., Gutbrod, H., Hadjidakis, C., Haiduc, M., Hamar, G., Hamagaki, H., Hamblen, J., Hansen, J. C., Hardy, P., Hatzifotiadou, D., Harris, J. W., Hartig, M., Harutyunyan, A., Hayrapetyan, A., Hasch, D., Hasegan, D., Hehner, J., Heine, N., Heinz, M., Helstrup, H., Herghelegiu, A., Herlant, S., Corral, G. H., Herrmann, N., Hetland, K., Hille, P., Hinke, H., Hippolyte, B., Hoch, M., Hoebbel, H., Hoedlmoser, H., Horaguchi, T., Horner, M., Hristov, P., Hivnov, I., Hu, S., Guo, C. H., Humanic, T., Hurtado, A., Hwang, D. S., Ianigro, J. C., Idzik, M., Igolkin, S., Ilkaev, R., Ilkiv, I., Imhoff, M., Innocenti, P. G., Ionescu, E., Ippolitov, M., Irfan, M., Insa, C., Inuzuka, M., Ivan, C., Ivanov, A., Ivanov, M., Ivanov, V., Jacobs, P., Jacholkowski, A., Janurov, L., Janik, R., Jasper, M., Jena, C., Jirden, L., Johnson, D. P., Jones, G. T., Jorgensen, C., Jouve, F., Jovanovi, P., Junique, A., Jusko, A., Jung, H., Jung, W., Kadija, K., Kamal, A., Kamermans, R., Kapusta, S., Kaidalov, A., Kakoyan, V., Kalcher, S., Kang, E., Kapitan, J., Kaplin, V., Karadzhev, K., Karavichev, O., Karavicheva, T., Karpechev, E., Karpio, K., Kazantsev, A., Kebschull, U., Keidel, R., Khan, M. M., Khanzadeev, A., Kharlov, Y., Kikola, D., Kileng, B., Kim, D., Kim, D. S., Kim, D. W., Kim, H. N., Kim, J. S., Kim, S., Kinson, J. B., Kiprich, S. K., Kisel, I., Kiselev, S., Kisiel, A., Kiss, T., Kiworra, V., Klay, J., Bsing, C. K., Kliemant, M., Klimov, A., Klovning, A., Kluge, A., Kluit, R., Kniege, S., Kolevatov, R., Kollegger, T., Kolojvari, A., Kondratiev, V., Kornas, E., Koshurnikov, E., Kotov, I., Kour, R., Kowalski, M., Kox, S., Kozlov, K., Krlik, I., Kramer, F., Kraus, I., Kravkov, A., Krawutschke, T., Krivda, M., Kryshen, E., Kucheriaev, Y., Kugler, A., Kuhn, C., Kuijer, P., Kumar, L., Kumar, N., Kumpumaeki, P., Kurepin, A., Kurepin, A. N., Kushpil, S., Kushpil, V., Kutovsky, M., Kvaerno, H., Kweon, M., Labb, J.-C., Lackner, F., de Guevara, P. L., Lafage, V., Rocca, P. L., Lamont, M., Lara, C., Larsen, D. T., Laurenti, G., Lazzeroni, C., Bornec, Y. L., Bris, N. L., Gailliard, C. L., Lebedev, V., Lecoq, J., Lee, K. S., Lee, S. C., Lefvre, F., Legrand, I., Lehmann, T., Leistam, L., Lenoir, P., Lenti, V., Leon, H., Monzon, I. L., Lvai, P., Li, Q., Li, X., Librizzi, F., Lietava, R., Lindegaard, N., Lindenstruth, V., Lippmann, C., Lisa, M., Listratenko, O. M., Littel, F., Liu, Y., Lo, J., Lobanov, V.,

Loginov, V., Noriega, M. L., Lpez-Ramrez, R., Torres, E. L., Lorenzo, P. M., Lvhiden, G., Lu, S., Ludolphs, W., Lunardon, M., Luquin, L., Lusso, S., Lutz, J.-R., Luvisetto, M., Lyapin, V., Maevskaya, A., Magureanu, C., Mahajan, A., Majahan, S., Mahmoud, T., Mairani, A., Mahapatra, D., Makarov, A., Makhlyueva, I., Malek, M., Malkiewicz, T., Mal'Kevich, D., Malzacher, P., Mamonov, A., Manea, C., Mangotra, L. K., Maniero, D., Manko, V., Manso, F., Manzari, V., Mao, Y., Marcel, A., Marchini, S., Mare, J., Margagliotti, G. V., Margotti, A., Marin, A., Marin, J.-C., Marras, D., Martinengo, P., Martnez, M. I., Martinez-Davalos, A., Garcia, G. M., Martini, S., Chiesa, A. M., Marzocca, C., Masciocchi, S., Masera, M., Masetti, M., Maslov, N. I., Masoni, A., Massera, F., Mast, M., Mastroserio, A., Matthews, Z. L., Mayer, B., Mazza, G., Mazzaro, M. D., Mazzoni, A., Meddi, F., Meleshko, E., Menchaca-Rocha, A., Meneghini, S., Meoni, M., Perez, J. M., Mereu, P., Meunier, O., Miake, Y., Michalon, A., Michinelli, R., Miftakhov, N., Mignone, M., Mikhailov, K., Milosevic, J., Minaev, Y., Minafra, F., Mischke, A., Mikowiec, D., Mitsyn, V., Mitu, C., Mohanty, B., Moisa, D., Molnar, L., Mondal, M., Mondal, N., Zetina, L. M., Monteno, M., Morando, M., Morel, M., Moretto, S., Morhardt, T., Morsch, A., Moukhanova, T., Mucchi, M., Muccifora, V., Mudnic, E., Mller, H., Mller, W., Munoz, J., Mura, D., Musa, L., Muraz, J. F., Musso, A., Nania, R., Nandi, B., Nappi, E., Navach, F., Navin, S., Nayak, T., Nazarenko, S., Nazarov, G., Nellen, L., Nendaz, F., Nianine, A., Nicassio, M., Nielsen, B. S., Nikolaev, S., Nikolic, V., Nikulin, S., Nikulin, V., Nilsen, B., Nitti, M., Noferini, F., Nomokonov, P., Nooren, G., Noto, F., Nouais, D., Nyiri, A., Nystrand, J., Odyniec, G., Oeschler, H., Oinonen, M., Oldenburg, M., Oleks, I., Olsen, E. K., Onuchin, V., Oppedisano, C., Orsini, F., Ortiz-Velzquez, A., Oskamp, C., Oskarsson, A., Osmic, F., sterman, L., Otterlund, I., Ovrebekk, G., Oyama, K., Pachr, M., Pagano, P., Pai, G., Pajares, C., Pal, S., Pal, S., Plla, G., Palmeri, A., Pancaldi, G., Panse, R., Pantaleo, A., Pappalardo, G. S., Pastirk, B., Pastore, C., Patarakin, O., Paticchio, V., Patimo, G., Pavlinov, A., Pawlak, T., Peitzmann, T., Pnichot, Y., Pepato, A., Pereira, H., Peresunko, D., Perez, C., Griffo, J. P., Perini, D., Perrino, D., Peryt, W., Pesci, A., Peskov, V., Pestov, Y., Peters, A. J., Petrek, V., Petridis, A., Petris, M., Petrov, V., Petrov, V., Petrovici, M., Peyr, J., Piano, S., Piccotti, A., Pichot, P., Piemonte, C., Pikna, M., Pilastrini, R., Pillot, P., Pinazza, O., Pini, B., Pinsky, L., Morais, V. P.,

Pismennaya, V., Piuz, F., Platt, R., Ploskon, M., Plumeri, S., Pluta, J., Pocheptsov, T., Podesta, P., Poggio, F., Poghosyan, M., Poghosyan, T., Polk, K., Polichtchouk, B., Polozov, P., Polyakov, V., Pommeresch, B., Pompei, F., Pop, A., Popescu, S., Posa, F., Pospil, V., Potukuchi, B., Pouthas, J., Prasad, S., Preghenella, R., Prino, F., Prodan, L., Prono, G., Protsenko, M. A., Pruneau, C. A., Przybyla, A., Pshenichnov, I., Puddu, G., Pujahari, P., Pulvirenti, A., Punin, A., Punin, V., Putschke, J., Quartieri, J., Quercigh, E., Rachevskaya, I., Rachevski, A., Rademakers, A., Radomski, S., Radu, A., Rak, J., Ramello, L., Raniwala, R., Raniwala, S., Rasmussen, O. B., Rasson, J., Razin, V., Read, K., Real, J., Redlich, K., Reichling, C., Renard, C., Renault, G., Renfordt, R., Reolon, A. R., Reshetin, A., Revol, J.-P., Reygers, K., Ricaud, H., Riccati, L., Ricci, R. A., Richter, M., Riedler, P., Rigalleau, L. M., Riggi, F., Riegler, W., Rindel, E., Riso, J., Rivetti, A., Rizzi, M., Rizzi, V., Cahuantzi, M. R., Red, K., Rhrich, D., Romn-Lpez, S., Romanato, M., Romita, R., Ronchetti, F., Rosinsky, P., Rosnet, P., Rossegger, S., Rossi, A., Rostchin, V., Rotondo, F., Roukoutakis, F., Rousseau, S., Roy, C., Roy, D., Roy, P., Royer, L., Rubin, G., Rubio, A., Rui, R., Rusanov, I., Russo, G., Ruuskanen, V., Ryabinkin, E., Rybicki, A., Sadovsky, S., afak, K., Sahoo, R., Saini, J., Saiz, P., Salur, S., Sambyal, S., Samsonov, V., ndor, L., Sandoval, A., Sann, H., Santiard, J.-C., Santo, R., Santoro, R., Sargsyan, G., Saturnini, P., Scapparone, E., Scarlassara, F., Schackert, B., Schiaua, C., Schicker, R., Schioler, T., Schippers, J. D., Schmidt, C., Schmidt, H., Schneider, R., Schossmaier, K., Schukraft, J., Schutz, Y., Schwarz, K., Schweda, K., Schyns, E., Scioli, G., Scomparin, E., Snow, H., Sedykh, S., Segato, G., Sellitto, S., Semeria, F., Senyukov, S., Seppnen, H., Serci, S., Serkin, L., Serra, S., Sesselmann, T., Sevcenco, A., Sgura, I., Shabratova, G., Shahoyan, R., Sharkov, E., Sharma, S., Shigaki, K., Shileev, K., Shukla, P., Shurygin, A., Shurygina, M., Sibiriak, Y., Siddi, E., Siemiarczuk, T., Sigward, M. H., Silenzi, A., Silvermyr, D., Silvestri, R., Simili, E., Simion, V., Simon, R., Simonetti, L., Singaraju, R., Singhal, V., Sinha, B., Sinha, T., Siska, M., Sitr, B., Sitta, M., Skaali, B., Skowronski, P., Slodkowski, M., Smirnov, N., Smykov, L., Snellings, R., Snoeys, W., Soegaard, C., Soerensen, J., Sokolov, O., Soldatov, A., Soloviev, A., Soltveit, H., Soltz, R., Sommer, W., Soos, C., Soramel, F., Sorensen, S., Soyk, D., Spyropoulou-Stassinaki, M., Stachel, J., Staley, F., Stan, I., Stavinskiy, A., Steckert, J., Stefanini, G., Stefanek,

G., Steinbeck, T., Stelzer, H., Stenlund, E., Stocco, D., Stockmeier, M., Stoicea, G., Stolpovsky, P., Strme, P., Stutzmann, J. S., Su, G., Sugitate, T., umbera, M., Suire, C., Susa, T., Kumar, K. S., Swoboda, D., Symons, J., Szarka, I., Szostak, A., Szuba, M., Szymanski, P., Tadel, M., Tagridis, C., Tan, L., Takaki, D. T., Taureg, H., Tauro, A., Tavlet, M., Munoz, G. T., Thder, J., Tieulent, R., Timmer, P., Tolyhy, T., Topilskaya, N., de Matos, C. T., Torii, H., Toscano, L., Tosello, F., Tournaire, A., Traczyk, T., Trger, G., Tromeur, W., Truesdale, D., Trzaska, W., Tsiledakis, G., Tsilis, E., Tsvetkov, A., Turcato, M., Turrisi, R., Tuveri, M., Tveter, T., Tydesjo, H., Tykarski, L., Tywoniuk, K., Ugolini, E., Ullaland, K., Urbn, J., Urciuoli, G. M., Usai, G. L., Usseglio, M., Vacchi, A., Vala, M., Valiev, F., Vyvre, P. V., Brink, A. V. D., Eijndhoven, N. V., Kolk, N. V. D., van Leeuwen, M., Vannucci, L., Vanzetto, S., Vanuxem, J.-P., Vargas, M. A., Varma, R., Vascotto, A., Vasiliev, A., Vassiliou, M., Vasta, P., Vechernin, V., Venaruzzo, M., Vercellin, E., Vergara, S., Verhoeven, W., Veronese, F., Vetlitskiy, I., Vernet, R., Victorov, V., Vidak, L., Viesti, G., Vikhlyantsev, O., Vilakazi, Z., Baillie, O. V., Vinogradov, A., Vinogradov, L., Vinogradov, Y., Virgili, T., Viyogi, Y., Vodopianov, A., Volpe, G., Vranic, D., Vrlkov, J., Vulpescu, B., Wabnitz, C., Wagner, V., Wallet, L., Wan, R., Wang, Y., Wang, Y., Wheadon, R., Weis, R., Wen, Q., Wessels, J., Westergaard, J., Wiechula, J., Wiesenaecker, A., Wikne, J., Wilk, A., Wilk, G., Williams, C., Willis, N., Windelband, B., Witt, R., Woehri, H., Wyllie, K., Xu, C., Yang, C., Yang, H., Yermia, F., Yin, Z., Yin, Z., Ky, B. Y., Yushmanov, I., Yuting, B., Zabrodin, E., Zagato, S., Zagreev, B., Zaharia, P., Zalite, A., Zampa, G., Zampolli, C., Zanevskiy, Y., Zarochentsev, A., Zaudtke, O., Zvada, P., Zbroszczyk, H., Zepeda, A., Zeter, V., Zgura, I., Zhalov, M., Zhou, D., Zhou, S., Zhu, G., Zichichi, A., Zinchenko, A., Zinovjev, G., Zoccarato, Y., Zubarev, A., Zucchini, A., and Zuffa, M. (2008). The alice experiment at the cern lhc. *Journal of Instrumentation*, 3(08):S08002. 21

[11] Connors, M., Nattrass, C., Reed, R., and Salur, S. (2017). Review of Jet Measurements in Heavy Ion Collisions. vi, 11, 14

[12] Elia, D. and the ALICE Collaboration (2013). Strangeness production in alice. *Journal of Physics: Conference Series*, 455(1):012005. 15

[13] Evans, L. and Bryant, P. (2008). Lhc machine. *Journal of Instrumentation*, 3(08):S08001. 9

[14] Foka, P. and Janik, M. A. (2016). An overview of experimental results from ultra-relativistic heavy-ion collisions at the cern lhc: Bulk properties and dynamical evolution. *Reviews in Physics*, 1:154 – 171. 10

[15] Gyulassy, M. (2004). The QGP discovered at RHIC. In *Structure and dynamics of elementary matter. Proceedings, NATO Advanced Study Institute, Camyuva-Kemer, Turkey, September 22-October 2, 2003*, pages 159–182. 7

[16] Hilke, H. J. (2010). Time projection chambers. *Reports on Progress in Physics*, 73(11):116201. vi, 23, 24

[17] Jacobs, P. and Wang, X.-N. (2005). Matter in extremis: ultrarelativistic nuclear collisions at RHIC. *Progress in Particle and Nuclear Physics*, 54:443–534. 15

[18] Kapusta, J. I. (1979). Quantum chromodynamics at high temperature. *Nuclear Physics B*, 148(3):461 – 498. 3

[19] Luo, X. (2016). Exploring the qcd phase structure with beam energy scan in heavy-ion collisions. *Nuclear Physics A*, 956:75 – 82. The XXV International Conference on Ultrarelativistic Nucleus-Nucleus Collisions: Quark Matter 2015. 24

[20] Martinez, G. (2013). Advances in Quark Gluon Plasma. *ArXiv e-prints*. 6

[21] McLerran, L. (2013). The color glass condensate, glasma and the quark gluon plasma in the context of recent ppb results from lhc. *Journal of Physics: Conference Series*, 458(1):012024. 15

[22] Müller, B., Schukraft, J., and Wysłouch, B. (2012). First Results from Pb+Pb Collisions at the LHC. *Annual Review of Nuclear and Particle Science*, 62:361–386. 16

[23] Nattrass, C. (2009). System, energy, and flavor dependence of jets through di-hadron correlations in heavy ion collisions. v, 10, 23

[24] Odyniec, G. (2013). The rhic beam energy scan program in star and what's next ... *Journal of Physics: Conference Series*, 455(1):012037. 24

[25] Ozaki, S. and Roser, T. (2015). Relativistic heavy ion collider, its construction and upgrade. *Progress of Theoretical and Experimental Physics*, 2015(3):03A102. vi, 8

[26] Preghenella, R. (2011). Transverse momentum spectra of identified charged hadrons with the ALICE detector in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV. *PoS*, EPS-HEP2011:118. 21

[27] Satz, H. (2006). Colour deconfinement and quarkonium binding. *Journal of Physics G: Nuclear and Particle Physics*, 32(3):R25. 4, 6

[28] Shao, M., Barannikova, O. Yu., Dong, X., Fisyak, Y., Ruan, L., Sorensen, P., and Xu, Z. (2006). Extensive particle identification with TPC and TOF at the STAR experiment. *Nucl. Instrum. Meth.*, A558:419–429. 23

[29] Shuryak, E. V. (1988). The qcd vacuum and quark-gluon plasma. *Zeitschrift für Physik C Particles and Fields*, 38(1):141–145. 3

[30] Stock, R. (2004). Ultra-relativistic nucleus-nucleus collisions. Proceedings, 17th International Conference, Quark Matter 2004, Oakland, USA, January 11-17, 2004. *J. Phys.*, G30:S633–S648. 7

[31] Vovchenko, V., Anchishkin, D., and Csernai, L. P. (2014). Time dependence of partition into spectators and participants in relativistic heavy-ion collisions. *Phys. Rev. C*, 90:044907. vi, 12

[32] Wilde, M. (2013). Measurement of Direct Photons in pp and Pb-Pb Collisions with ALICE. *Nucl. Phys.*, A904-905:573c–576c. 18

[33] Wong, C.-Y. (1994). *Introduction to high-energy heavy-ion collisions.* World scientific. vi, 12, 17, 18

# Appendices