JETSCAPE Summer R.E.U.

Joshua Frandsen

University of California Berkeley

Abstract

The goal of this project is to explore one method to measure the properties of a fundamental state of matter that is formed at particle colliders known as the quark gluon plasma, using data measured by the ALICE Collaboration at the CERN Large Hadron Collider. We utilize the well-understood phenomenon of jets, which are remnants of scattered quarks and gluons generated in high energy collisions and the interaction of such jets with quark gluon plasma. There are multiple methods for measuring such interactions. In this study we focus on the coincidence measurement of a high energy photon and its recoiling jet, an observable known as $\gamma + jet$. In order to determine if this channel can be measured using experimental data recorded by ALICE, simulations of collisions are carried out under conditions that match the real recorded data. However, validation of these predictions requires calibration of the simulation tools against other published measurements. This paper reports such a calibration for the PYTHIA event generator, by comparing simulated results to experimental data measured at the Large Hadron Collider.

1 Introduction

Nature has four known fundamental forces: gravitational, electromagnetic, weak, and strong. Quantum Chromodynamics (QCD) is the theory that describes the strong force, and describes how particles such as protons are constructed from elementary constituents. At the simplest level the proton can be thought of as being made of three particles called quarks that are held together by a particle known as a gluon. Quarks and gluons are referred to as partons, and bound states of partons are known as hadrons (this means a proton is a hadron). A key characteristic of the strong force is that color confinement, which means that partons cannot be observed individually, but they can only be observed in color-neutral bound states as hadrons. In order to study partons physicists must devise methods to observe hadrons, and indirectly infer properties of the partons they branched from.

In heavy-ion collisions at the Large Hadron Collider, lead ions are collided at high energies. During these collisions the temperature of the resulting fireball can reach $10^{24}K$ and at this temperature quarks and gluons can be in an unbound state (contrary to color confinement), although for a time much too short to directly observe. This unbound state of partons is a substance known as the quark gluon plasma [2]. Physicists are trying to understand the properties of this exotic plasma through high energy particle collisions, using an array of measurement tools.

In high energy collisions, such as those of protons or lead ions at the LHC, the projectiles can be thought of as beams of their constituent quarks and gluons. These constituents scatter in the collision, generating outgoing quarks and gluons that are temporarily deconfined. However, under the influence of the strong force, these scattered quarks and gluons rapidly transform to a collimated spray of stable particles. This process is known as hadronization, and the resulting collimated spray of hadrons ("jets") is what the detectors actually measure. Physicists want to understand the fate of the scattered quarks and gluons from the collision because they might interact with the QGP. The collimated cluster of observed particles that came from the original quark is the jet, and observing the jet one can infer the energy and kinematics of the quark the jet descended from. The interaction of jets with the QGP results in modification of the properties of jets in heavy ion collisions compared to those in proton-proton collisions, and such jet measurements can be used to measure the properties of the QGP.

Large Hadron Collider:

The Large Hadron Collider [3] (LHC) is the world's most energetic particle collider. LHC collisions take place in interaction regions of the four detectors at the LHC: ATLAS, ALICE, LHCb, and CMS. In this study we utilize the PYTHIA event generator to assess the feasibility of a specific jet measurement in Pb+Pb collision data recorded by the ALICE collaboration. In order to do so, we first validate the PYTHIA event generator by comparing to other LHC data measured in p+p collisions.

The writeup is structured as follows: section 2 describes the tools, sections 3 will present the results of comparisons, and section 4 will discuss future steps for coincident observables.

2 Tools

PYTHIA:

Each collision recorded by an LHC detector, which generates a spray of many particles, is called an ëvent.. Physicists utilize numerical codes, called event generators, to study the capabilities of their detectors and to assess the physics content of their datasets. PYTHIA [4] is a Monte Carlo event generator that is widely used in high energy physics, and is tuned to describe many common processes. PYTHIA generates events without detector effects. PYTHIA can generate events for pp, ee, and ep collisions. Event generators such as these allow the experimentalist to estimate the distribution of physics processes of interest in the data, including the rate those processes should occur. This allows for new methods of analysis to tested. Generators are also used to compare current theory to experimental results.

FastJet:

FastJet [5] is a software package provides multiple jet clustering algorithms. A jet clustering algorithm looks at all particles in an event and clusters them into jets if they follow certain criteria derived from QCD. The main jet reconstruction algorithm used in this research is the $anti - k_t$ algorithm [6], which has a parameter R that will represent the radius of the cone within which particles are clustered to make a single jet clustering. The clustering returns an array of objects that the algorithm has identified as jets, with each jet object in the array having kinematic properties that can then be analyzed.

ROOT:

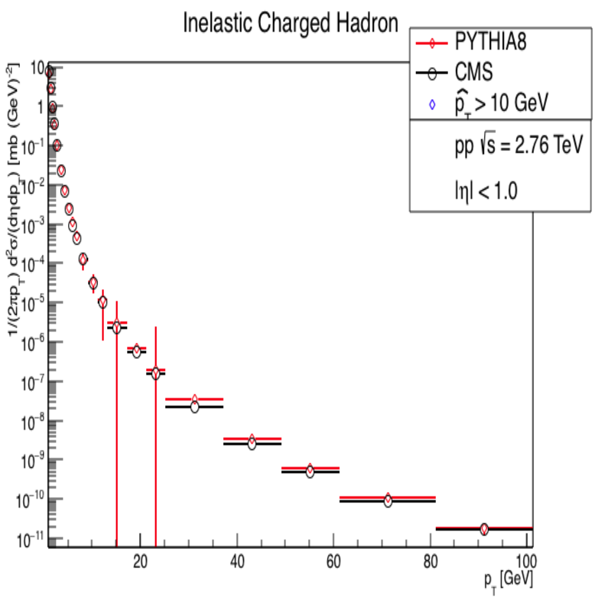
Root is a software library that allows a user to organize and analyze any type of data. Root is used to present detailed plots of desired quantities, while also allowing fits and error analysis to be done. It was developed by CERN for the purpose of analyzing large amounts of data from the LHC experiments.

In the future section different kinematic terms and definition will be used, and can be referenced in the appendix.

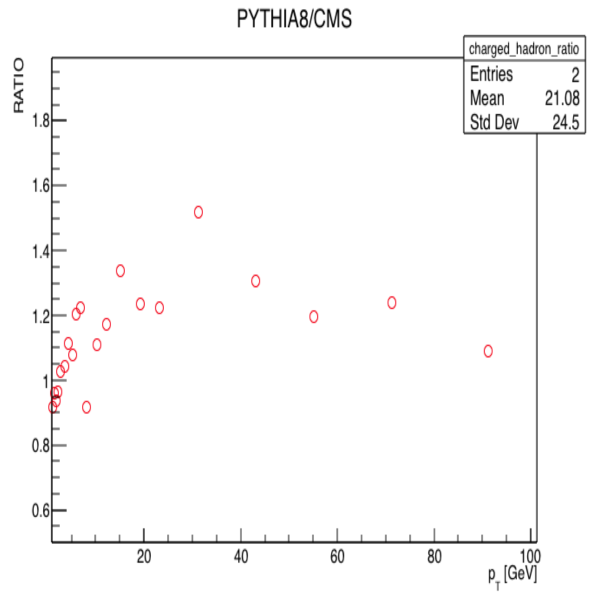
3 Comparing Data From LHC to Monte Carlo Event Generators

Differential Charged Cross Section:

The goal is to use PYTHIA to determine the rate at which coincidence process $\gamma + jet$ will occur in the experimental analysis of Pb+Pb collisions. For this purpose we require the cross section of the $\gamma + jet$ process in Pb+Pb collisions, but first one needs to be confident that the event generator is providing accurate cross sections in more elementary p+p collisions, so com-



(a) Charged Particles p_T Distribution

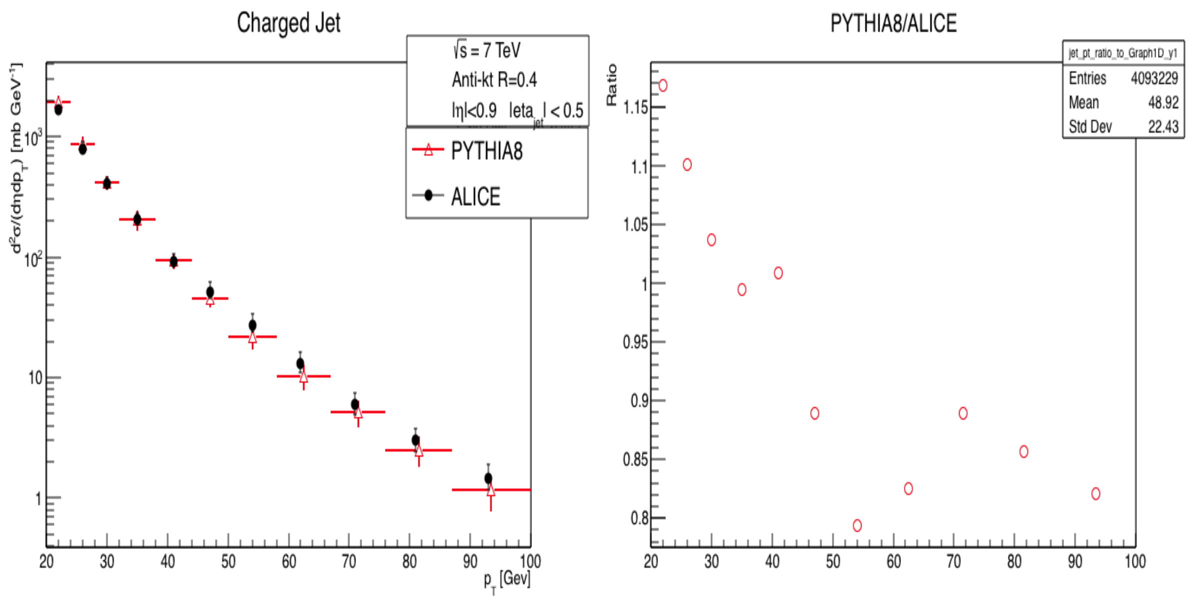


(b) Ratio of PYTHIA8 Data vs. Alice Data

Figure 1: (a) charged particle distribution comparing data generated by PYTHIA8 to the data collected from CMS. (b) ratio of the two distributions

parisons to other well known observables are done. For this calibration step, published LHC data are compared to PTYHIA results.

The first check is the differential cross section for charged particles in pp collisions. A CMS publication [7] reports the charged-particle cross section that was used for comparison to PYTHIA. The data are for pp collisions at $\sqrt{s}$ = 2.76 TeV, $|\eta| < 1.0$, where $\sqrt{s}$ refers the center of mass energy of the colliding beams. Events were generated using PYTHIA8 calibrated according to the CMS parameters. The corresponding distributions are seen in fig. 1. This agreement is within 20%, which is the expected level of agreement with data for even generators such as PYTHIA. This exercise shows that our implementation and analysis of PYTHIA is giving around the right answer, which was the initial validation task.



(a) Charged Jets

(b) Ratio of PYTHIA8 Data vs. ALICE Data

Figure 2: (a) Charged Jet cross section as measured from ALICE and generated events by PYTHIA8 (b) ratio of PYTHIA data to the ALICE data

Charged Jet Cross Section in pp Collisions:

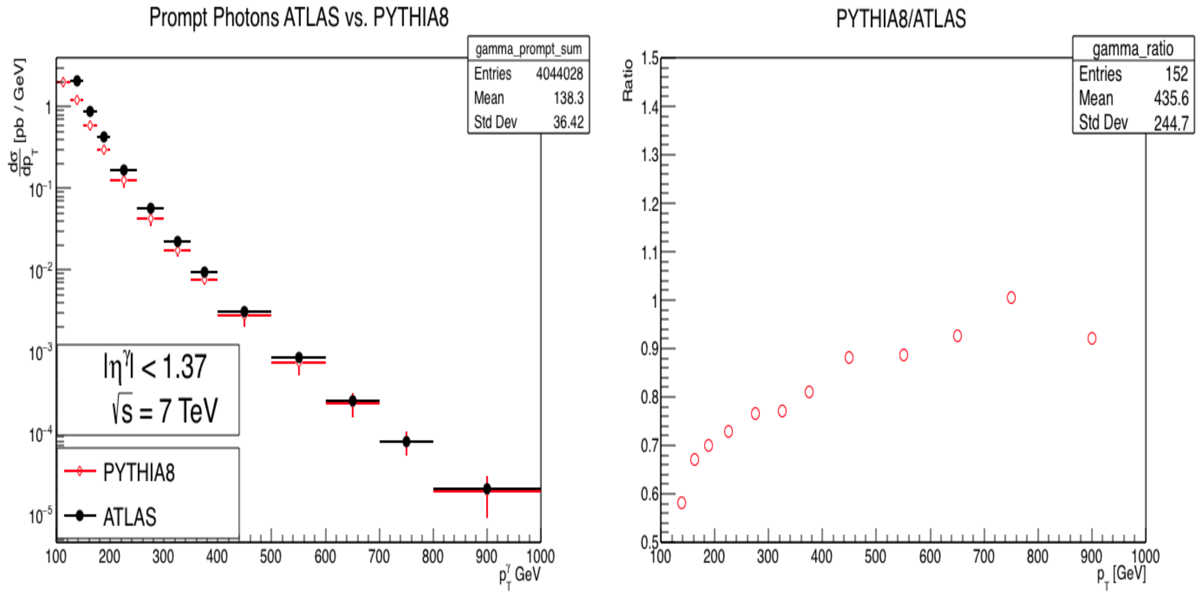
Once our PYTHIA analysis has produced appropriate results for single particles, the next step is to study jet observables. Calibration of this analysis step was carried out by comparing PYTHIA to data provided by the ALICE collaboration [8]. In the paper they report on the cross section of charged jets using the $anti - k_t$ algorithm in pp collisions at $\sqrt{s}$ = 7 TeV, and $|\eta| < 0.9$ and $|\eta_{jet}| < 0.9$ - R, R = 0.4, where η is the pseudo rapidity for the accepted particles, η_{jet} is the pseudo rapidity for the accepted jets, and R is the radius of the jet in the clustering algorithm. The results of the jet cross section produced by PYTHIA is within 20% when compared to the ALICE data, as shown in Fig 2. This level of agreement is again within the uncertainties expected from the PYTHIA generator, and this step of the analysis is likewise validated.

Prompt Photon Cross Section:

A prompt photon is defined as a photon that comes from initial collision via the leading-order processes $q + g \rightarrow \gamma + X$, where X could be a quark that then hadronizes into a jet (these are direct photons), or the fragmentation photons that result from higher-order processes. Direct photons are of interest because they do not interact with the QGP and emerged from the fireball unaltered, unlike jets. Such photons therefore provide a sort of "standard candle" for the corresponding jet measurements. The prompt photon will also be measured directly in the detectors. This allows for a reference when looking at the effects of the medium on other particles.

ATLAS data [9] were utilized for comparison to PYTHIA. The ATLAS measurement is for pp collisions at $\sqrt{s}$ = 7 TeV, $|\eta| < 1.37$. Events containing direct photons were generated in PYTHIA and compared to the ATLAS data shown in figure 3. This plot shows that PYTHIA agrees within 25%. A deviation in the data should be expected when comparing PYTHIA to real photon data because the real data cannot filter perfectly for only prompt photons, and the PYTHIA calculation has limited precision.

In particular PYTHIA only accounts for Leading Order processes which means it does not calculate the fragmentation photons, instead PYTHIA will use experimental data to gauge the number of expected fragmentation photons. To see how the cross section varies as a result, a comparison to JetPhox's prompt photon cross section generation was done. The JetPhox event generator, uses Next to Leading Order (NLO) calculations, which will account for the fragmentation photons. Fig. 4 shows the JetPhox cross section (generated by Alwina Liu) and PYTHIA8 cross section. From the plot we can see there is not a significant difference in the cross section between PYTHIA8 and an NLO generator, which means using PYTHIA is sufficient for this analysis.



(a) Prompt Photon

(b) Ratio of PYTHIA8 Data vs. ATLAS Data

Figure 3: (a) Prompt photon cross section as measured from ATLAS (in black) and generated events by PYTHIA8 (in red) (b) ratio of PYTHIA data to the Atlas data

Hadron + Jet Correlations:

Correlations between a triggered particle and a corresponding recoil jet (that is approximately aligned with the axis of that triggered particle) have been measured. The ALICE collaboration published results for their hadron+jet correlations[10] where a high p_T hadron is the trigger. The data were measured for pp collisions at $\sqrt{s}$ = 7 TeV. The ALICE publication uses an observable Δ_{recoil} which eliminates the experimental noise. Δ_{recoil} is defined as:

$$\Delta_{recoil} = \frac{1}{N_{trig}^{recoil}} \frac{d^3 N_{recoil}}{dp_T^3} - \frac{1}{N_{trig}^{ref}} \frac{d^3 N_{ref}}{dp_T^3} \quad (1)$$

Where the reference recoil jet distribution is measured using trigger hadrons with $8GeV < p_T^{hadron} < 9GeV$ T{8,9} and the recoil jet corresponds to trigger hadrons $20GeV < p_T^{hadron} <$

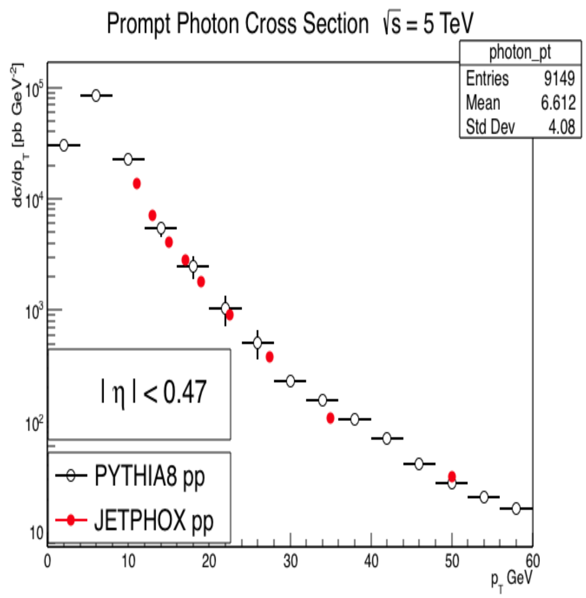
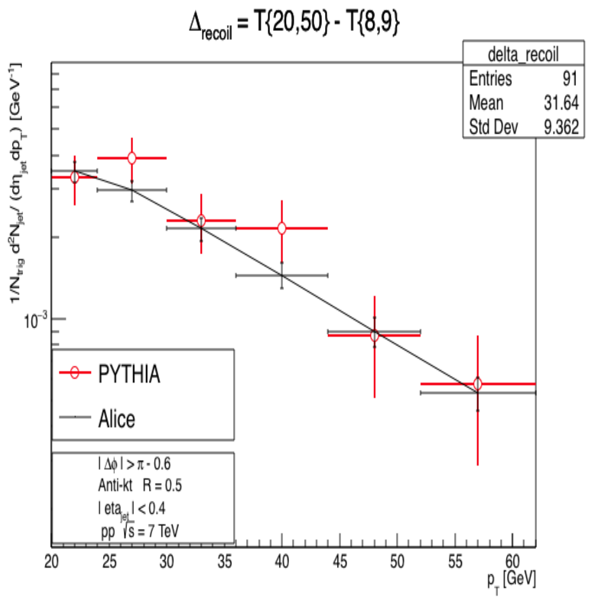


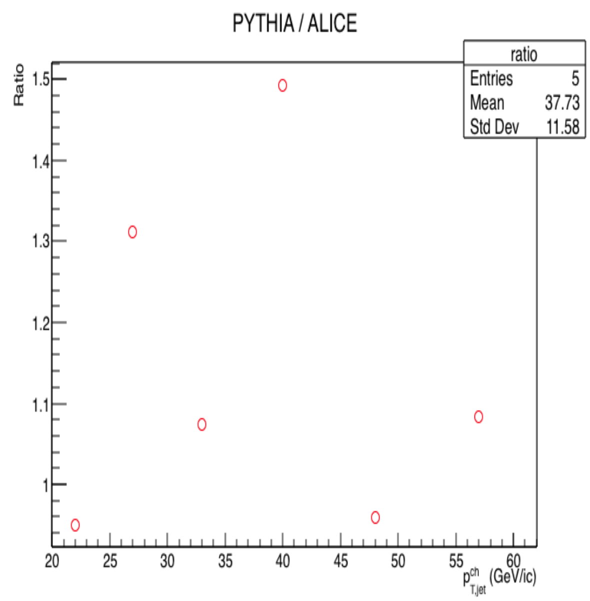
Figure 4: NLO (JetPhox) to LO (PYTHIA8) comparison on prompt photon cross section

$50GeV$ T{20,50}. Figure 5 shows the comparison of the Δ_{recoil} measured from ALICE vs. PYTHIA8.

When looking at hadron + jet correlations it is desirable to trigger on a hadron that does not traverse the QGP, but has a recoil jet that does traverse a large distance through that medium. In order to trigger on such hadrons, they need be high p_T. Hadrons with a higher p_T will be more likely to have traversed a small fraction of the medium. This does not guarantee that the corresponding recoil jet traverses a large amount of the medium, but there is a higher probability that it did. Another correlation method attempts to eliminate the need to know the location of the collision in the medium. This method triggers on prompt photons and is referred to as γ + jet which will be discussed below.



(a) Δ_{recoil}



(b) Ratio

Figure 5: (a) This is the comparison of Δ_{recoil} from PYTHIA8 and what was measured by ALICE (b) ratio of PYTHIA data to the ALICE data

4 Projections for γ + Jet Measurements:

The benefits of γ + jet correlation measurements (as was alluded to in the previous section) is that the prompt photons that are being triggered on will not be affected by the presence of a medium. The cross section for this observable is much lower than for the hadron + jet process. In order to determine whether this measurement is practical, it is necessary to gauge the number of events that would be observed in currently-recorded experimental data. This can be done by generating a prompt photon cross section with similar parameters to the ALICE pPb data set, scale the generated pp data by 208 (to emulate pPb collisions), then scale this cross section by the integrated luminosity of the recorded event set. This estimates the number of prompt photons one should expect to observe during a run with similar luminosity and triggers, and can be used to estimate the number of $\gamma + jet$ coincidences that should be present.

5 Summary

This research has shown that PYTHIA is producing accurate results when compared to cross sections of prompt photons, charged jets, charged hadrons, and hadron + jet in p+p collisions at the LCH. This will allow for a prediction measurement of new observables of interest such as γ + jet.

Appendix

Kinematics:

Transverse momentum (p_T): The transverse momentum is the momentum vector projected onto the plane defined by the x and y axis, if the beam direction is the z-axis. The p_T distribution is hadronic collisions indicates how much energy might have been transfered during the collision, because before the collision all of the momentum was in the z direction so the p_T is a result of the collision, which can give us a lot of information. The magnitude of the p_T vector is:

$$p_T = \sqrt{p_x^2 + p_y^2} \tag{2}$$

Where p_x and p_y are the momenta along the x and y components respectively.

Pseudorapidity (η): which is a standard coordinate for describing the angle of the particle relative to the beam axis. η is a Lorentz invariant quantity that is analogs to rapidity at large speeds. η defined as:

$$\eta = -\ln[\tan\frac{\theta}{2}] \tag{3}$$

Where θ is the polar angle relative to the beam axis.

Differential Cross Section (dσ): which can be thought of as the production rate of a process. The higher the cross section, the fewer collisions are needed to observe the process, where as a lower cross section is the inverse. The differential cross section is absolutely normalized and other experiments can compare results directly.

References

[1] Masud Chaichian, Kazuhiko Nishijima, ”An Essay on Color Confinement”, HIP-1999-60/TH, arXiv:hep-th/9909158

[2] Ulrich W. Heinz, ”The strongly coupled quark-gluon plasma created at RHIC”, J.Phys.A42:214003,2009, DOI: 10.1088/1751-8113/42/21/214003, arXiv:0810.5529

[3] P La Rocca, and F Riggi, ”The upgrade programme of the major experiments at the Large Hadron Collider”,Journal of Physics: Conference Series, Volume 515, conference 1, DOI: https://doi.org/10.1088/1742-6596/515/1/012012

[4] T. Sjostrand, S. Mrenna, and P. Skands, ”Pythia 6.4 Physics and Manual”, JHEP 0605:026,2006, DOI: 10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175

[5] Matteo Cacciari, Gavin P. Salam, Gregory Soyez, ”FastJet User Manual”, CERN-PH-TH/2011-297, DOI: 10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097

[6] Matteo Cacciari, Gavin P. Salam, Gregory Soyez, ”The Anti-k_t jet Clustering Algorithm”, JHEP 0804:063,2008, DOI: 10.1088/1126-6708/2008/04/063, arXiv:0802.1189

[7] The CMS Collaboration, ”Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at sqrt(s) = 7 TeV”, Phys.Rev.Lett.105:022002,2010, DOI: 10.1103/PhysRevLett.105.022002, arXiv:1005.3299

[8] ALICE Collaboration, ”Charged jet cross sections and properties in proton-proton collisions at $\sqrt{s} = 7$ TeV” , Phys. Rev. D 91 (2015) 112012, DOI: 0.1103/PhysRevD.91.112012, arXiv:1411.4969

[9] ATLAS Collaboration, ”Measurement of the inclusive isolated prompt photon cross section in pp collisions at sqrt(s) = 7 TeV with the ATLAS detector using 4.6 fb-1”, Phys. Rev. D 89, 052004 (2014), DOI: 10.1103/PhysRevD.89.052004, arXiv:1311.1440

[10] ALICE Collaboration, ”Measurement of jet quenching with semi-inclusive hadron-jet distributions in central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV”, JHEP 09 (2015) 170, DOI: 10.1007/JHEP09(2015)170, arXiv:1506.03984