Neutral Pion Production in High Energy Heavy Ion Collisions at the PHENIX Experiment

abstract of PhD dissertation

Semleges pionok keletkezése nagyenergiás nehézion-ütközésekben a PHENIX kísérletnél

doktori (PhD) értekezés tézisei

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1 Introduction

What is the world made of? What holds it together? These are questions that have fascinated countless thinkers over the ages. Our knowledge about the structure of the world has undergone substantial transformations. Today, the Standard Model of particle physics describes the world as being built of “bricks” called fermions, which are held together by 4 fundamental forces: the gravitational, the electromagnetic, the weak and the strong force. Apparently different as these forces are, there are signs which give basis to the suspicion that under certain circumstances these forces can be “unified”, that is, their effects described in a common mathematical framework. This unification has already been done for the electromagnetic and the weak forces and thus we can talk about the “electroweak” force. The strong force, however, has so far resisted the unification attempts due to some of its peculiar characteristics.

One of the most fascinating aspects of the strong force is that its particles, the quarks and the gluons can never be observed in a free state, only confined in composite particles, hadrons. This impossibility does not originate from the imperfections of our experimental apparatus, it is in the very nature of the strong force. Yet according to nuclear theorists, there is a way for quarks and gluons to break free of their hadronic prison, albeit not individually. For this deconfinement to happen, we have to produce very high energy densities in a relatively large (on a particle scale) volume. Then the hadronic matter undergoes a phase transition (hadrons “melt”) and the deconfined quarks and gluons form a new state of matter. This very hot and dense medium is called the Quark-Gluon Plasma (QGP).

The existence of the QGP is a crucial question in the theory of the strong force. If it exists, we hope that by creating it in accelerators, we would eventually be able to study its properties and gain invaluable knowledge about the nature of the strong force.

Creating the QGP, however, is technologically very challenging. It requires making heavy ions collide with each other in high energy accelerators. Understanding what happens in such a collision is an even more demanding task. Whether or not the QGP is created, the collisions take but a fleeting moment – then all kinds of particles come flying away from the interaction point by the thousands. We catch these particles in huge detector systems, measure their properties and try to analyze them in such a way that would reveal if the QGP has been created. Since we don't know the properties of QGP exactly, we can only surmise what observable effects hint at the formation of the QGP. These observable hints are called the signatures of QGP, and it is the aim of heavy ion experiments to unequivocally show that as many effects as they can measure confirm or disprove the existence of QGP.

This dissertation was written based on the research at the Pioneering High Energy Nuclear Interactions eXperiment (PHENIX) at the Relativistic Heavy Ion Collider (RHIC) of the Brookhaven National Laboratory, USA. One of the design aims behind RHIC was to create a machine which can accelerate heavy ions to energies that would enable us to create the QGP. The detectors built on RHIC (including PHENIX) are built to measure and identify as many types of processes as possible, exploring several possible signatures of the QGP.

This dissertation describes the details of two analyses, both of which show one (weak) signature of the QGP, the suppression of neutral pions. Before any meaningful physics data can be extracted from the detector, however, its complicated systems need to be carefully calibrated; two such calibration efforts are also shown here.

2 New results

1. **In the second running period of RHIC I performed the physics-based timing calibration of the Electromagnetic Calorimeter, and, as the editor of the corresponding PHENIX Technical Note, I coordinated the rest of the EMCal calibration.**[1]

   It was discovered early on that the laser-based monitoring system of the calorimeter does not track the varying parameters of the phototubes accurately, thus physics-based calibration methods were needed. For the timing calibration I used samples of photons coming from the collision. The origin of the timeline was chosen to be the moment when those photons were expected to reach the calorimeter. The goal of calibration was to shift all

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[1] EMCal calibration in preparation for QM2002, PHENIX Technical Note #400, edited by P. Tarján
`https://www.phenix.bnl.gov/WWW/p/draft/ptarjan/calib_QM2002`

times of arrival in such a way that photons arrive at 0 time and all hadrons come later. To this end I used a two-tier approach:

- global (i.e. time-independent) tower-by-tower corrections compensated the differences in the response time of individual channels (9216 in the PbGl part of EMCal, 15552 in PbSc, although some towers were not instrumented) thus reducing the width of the photon timing peak;
- sector-wide, time-dependent “tracking” corrections, which move the photon peak to 0 on a per-sector basis and follow variations in time.

As a result of all these corrections, the photon peak is generally within 100 ps of 0 and in the PbSc part of the calorimeter has a standard deviation around or lower than 400 ps.

2. **In the second running period of RHIC I developed the Quality Assurance methods for the EMCal, and performed QA checks on the available data.**[2]

   The Quality Assurance effort in PHENIX served two purposes: on one hand, to make sure that the data we process is physically meaningful and is not distorted by misbehaving detector parts. On the other hand, with the results gained in assessing data quality we aimed to identify and correct any remaining detector miscalibrations.

   The QA output histograms were one of the tools that revealed an energy scale mismatch between different sectors and along three intervals of the second running period of RHIC. This mismatch manifested itself in the minimum ionizing particle energies not being aligned in the different sectors with respect to each other and also in having sudden jumps around certain times. This was clearly non-physical, so the gain tracing system was turned off, and all calibrations were done with constant (within a time-interval), time-independent gains, based on the results of the QA.

   The QA code written by me looked at both the energy and the timing performance of the Electromagnetic Calorimeter. Timing histograms were created for each sector and energy histograms were created for granules (pairs of sectors). Timing histograms were filled with a relatively clean sample of photons; energy histograms were filled with clusters from minimum ionizing particles. The QA histograms showed that sector W3 of the

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[2] An example can be found here: EMCAL QA study, 04/19-04/25/2002
`https://www.phenix.bnl.gov/WWW/p/draft/ptarjan/QAstudy`

calorimeter had serious problems due to faulty electronics boards; especially its timing performance was abysmal. Therefore it was decided to exclude W3 from every analysis where timing was an issue.

After the energy scale mismatch described above was corrected, the energy calibration of the calorimeter seemed to be in a good shape, so QA status words were assigned based on the timing performance. For the reasons mentioned above, sector W3 got a separate status value to indicate the times when it had even more problems than usual.

Based on the QA results, I also made a later round of "afterburner" corrections to the timing calibration of the calorineter.

3. **I analyzed the first data from RHIC at $\sqrt{s} = 62.4\,\mathrm{GeV}$ Au + Au collisions and determined the yields of neutral pions.**[3]

   The extraction of neutral pions from the immense number of particles created in nucleus-nucleus collisions and the subsequent analysis thereof is one of the very elegant analyses aimed to reveal the properties of matter at high densities and temperatures. The analysis done by our group relies almost entirely on the electromagnetic calorimeter.

   Neutral pions decay predominantly into two photons ($\pi^0 \to \gamma\gamma$) with a lifetime of $\approx 10^{-16}\,\mathrm{s}$. Photons travel through the tracking detectors undetected and arrive at the calorimeter, where their energy is fully absorbed. To reconstruct the properties of the parent pion from them, we have to match up the directions and energies with those of their correct partner. Since it is not known which photon belongs to which, reconstruction of individual pions is impossible.

   It is, however, possible to make statistical observations about the pions. This is done via the *combination method*, which works as follows. With some loose cuts, we select all particles that are potentially photons; then we make all possible pair combinations of those. With the assumption that the pair came from the same parent, the invariant mass and momentum of this virtual parent are calculated. The distribution of invariant masses will have a large background from the random incorrect combinations. The correct combinations, on the other hand, yield an invariant mass which is around the mass of the π^0, thus resulting in a peak on top of the background at $\approx 135\,\mathrm{GeV}/c^2$. The integral of this peak gives the number of neutral pions

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[3] Neutral Pion Spectra Measured with the EMCal in 62.4 GeV Au+Au Collisions, PHENIX Analysis Note #292, edited by P. Tarján
`https://www.phenix.bnl.gov/phenix/WWW/p/info/an/292/`

detected under the constraints of the analysis cuts; this in turn can be used to calculate the yield in the process. Spectra are produced by plotting yields versus the reconstructed pion transverse momentum p_{T}. Yields in heavy ion collisions strongly depend on the centrality of the collision. The difficulty of this kind of analysis is in the details: the event selection, cuts, yield extraction, acceptance and efficiency calculations and systematic error estimates.

A quantity called the nuclear modification factor, R_{AA} is used to characterize the effect of processes in heavy ion collisions on the particle yields. R_{AA} is defined as the ratio of the production cross sections in heavy ion collisions and $\mathrm{p}+\mathrm{p}$ collisions, respectively, scaled by the number of binary collisions, N_{coll} in the former. To put it more simply:

$$R_{\mathrm{AA}} = \frac{\text{Yield in A + A collisions}}{\text{Yield in p + p collisions}} \cdot \frac{1}{N_{\mathrm{coll}}},$$

which depends on the hadron rapidity y and transverse momentum p_{T}.

If the value of R_{AA} significantly differs from 1, that indicates that processes in heavy ion collisions have an important effect on particle production.

The R_{AA} calculated with the final spectrum and $\mathrm{p}+\mathrm{p}$ data as baseline is shown in Fig. 1 for the most central events. At the time of our analysis, PHENIX did not have any 62.4 GeV $\mathrm{p}+\mathrm{p}$ data, thus earlier ISR data were used as a baseline. Later, when PHENIX $\mathrm{p}+\mathrm{p}$ data became available, R_{AA} was recalculated with the new reference. It turned out that our reference spectrum is about 70% higher than the fit to the ISR data. The PHENIX data have a 19%, the ISR data a 25% normalization uncertainty, but the difference is higher than what these errors would explain. This difference remains unaccounted for; there is, however, a strong argument in favor of the PHENIX result: the $\mathrm{p}+\mathrm{p}$ spectrum was measured in the same experiment, by the same detector, extracted using much the same analysis as the heavy ion spectra. This means that in producing the ratio R_{AA}, many of the systematic errors cancel.

What clearly shows, regardless of the choice of the baseline is that in central events at both energies, pion yields are suppressed. Suppression sets in gradually with increasing p_{T} and then levels out. The suppression factor $1/R_{\mathrm{AA}}$ is around 4 to 5 at high transverse momenta. More central events are suppressed more.

This suppression can be explained by assuming the formation of a hot and dense medium, which slows down and/or absorbs partons flying out of it. This phenomenon is called *jet quenching.* The results shown here, however,

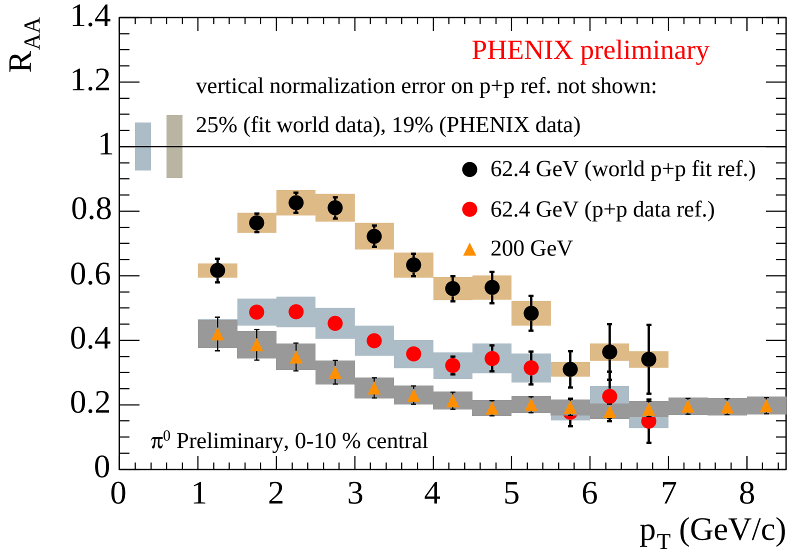

Figure 1: Nuclear modification factors for the most central events (0-10%) of neutral pions produced in 62.4 GeV (per nucleon pair) Au + Au collisions. CERN-ISR and PHENIX p + p results were used as baseline. For reference, results at 200 GeV are also shown. The error bars show point-to-point statistical errors; the shaded band shows the systematic errors which can move all the points up or down together.

are not conclusive enough to decide whether the dense medium is standard nuclear matter or it consists of deconfined quarks and gluons.

4. **I analyzed data from RHIC at $\sqrt{s} = 200\,\mathrm{GeV}$ Au + Au collisions and determined the yields of neutral pions.**[4]

   The principle of measurement is essentially the same as described above, with some changes in the details of the analysis.

   Fig. 2 shows R_{AA} as a function of p_{T} for π^0 in the most central $(0-10\%)$ and the most peripheral $(80-92\%)$ centrality classes. The nuclear modification factor in peripheral data is consistent with 1, thus peripheral events seem to be the incoherent superpositions of nucleon-nucleon collisions (no medium

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[4] Neutral Pion Measurement in the PbSc Calorimeter in Au+Au Collisions at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$, PHENIX Analysis Note #166
`https://www.phenix.bnl.gov/phenix/WWW/p/info/an/166/`

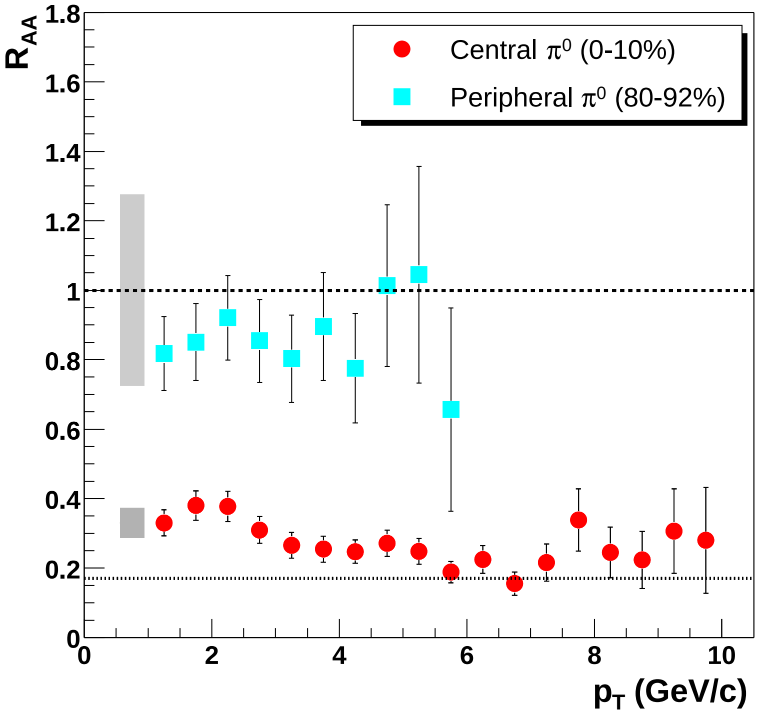

Figure 2: Nuclear modification factor for the most central and most peripheral collisions at 200 GeV (per nucleon pair) using the 200 GeV $p + p$ data from PHENIX as a reference. The error bars show all point-to-point errors, whereas the shaded bands show fractional systematic uncertainties, which can move all the points up or down together.

is formed). The R_{AA} value for central collisions is significantly less than 1, as opposed to earlier results of enhanced π^0 production at the SPS, CERN (Cronin effect). The suppression sets in gradually from peripheral to central events. This suppression of neutral pions is smallest around $2\,\mathrm{GeV}/c$ and is approximately constant at higher transverse momenta. The suppression factor $1/R_{\mathrm{AA}}$ is 4-5; the R_{AA} value is $\approx 30\%$ higher than that expected from number-of-participants (N_{part}) scaling (dotted line in Fig. 2).

Jet quenching calculations based on medium-induced energy loss can reproduce the magnitude of the π^0 suppression assuming the formation of a hot and dense partonic system. This, however does not exclude the suppression being an initial state– rather than a final state effect. To check that, in the next year RHIC also produced $\mathrm{d} + \mathrm{Au}$ collisions. In those events, due to the small size of the deuteron, a dense partonic matter (QGP) can not be formed. The yields of pions created in $\mathrm{d} + \mathrm{Au}$ collisions are not suppressed, thus the suppression must indeed be a final state effect.

3 Application of the results

Precise calibration of the EMCal was necessary not only for our analysis, but for the majority of other PHENIX analyses too; thus the calibration and QA results described here (and those of subsequent, similar calibrations) were used immediately. Later myself and others improved some of the methods mentioned above, which made it possible to measure and calibrate several parameters of the calorimete online, semi-automatically.

In addition to those already cited above, these notes show some of the further evolution of my calibration efforts:

`https://www.phenix.bnl.gov/WWW/p/draft/ptarjan/EmcTofAfterBurner/`

`https://www.phenix.bnl.gov/WWW/p/draft/ptarjan/timing/EMC_timing_calib_run3.pdf`

The results of the 200 GeV π^0-analysis was published as
“Suppressed pi^0 Production at Large Transverse Momentum in Central Au+Au Collisions at sqrt(s_NN) = 200 GeV”
the PHENIX collaboration
Phys. Rev. Lett. 91, 072301 (2003), 2003-08-13
(also available from the preprint archive as nucl-ex/0304022).

The results of the 62.4 GeV analysis show that the suppression sets in at relatively low (for RHIC) energies. This had an important impact on the interest in searches at later low energy scans.

Some of the results were shown as posters at the NPDC17 and at the 2004 IEEE-NSS conferences.
Poster: New results from the PHENIX experiment at RHIC (NPDC 17 conference)
Poster and paper: Physics analysis with the PHENIX electromagnetic calorimeter (2004 IEEE-NSS conference)

I also contributed to the following papers:

“Absence of Suppression in Particle Production at Large Transverse Momentum in sqrt(s_NN) = 200 GeV d+Au Collisions”
the PHENIX collaboration
Phys. Rev. Lett. 91, 072303 (2003) , 2003-08-15
(also available from the preprint archive as nucl-ex/0306021)

”Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX Collaboration”
Nuclear Physics A Volume 757, Issues 1-2 , 8 August 2005, Pages 184-283
(also available from the preprint archive as nucl-ex/0410003)