Beam Energy Dependence of Dielectron Production in Au+Au Collisions from STAR at RHIC

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Abstract

We present the energy-dependent study of dielectron production in 0-80% minimum-bias Au+Au collisions at \( \sqrt{s_{NN}} \) of 19.6, 27, 39, and 62.4 GeV in STAR. Invariant mass (\( M_{ee} \)) and transverse momentum (\( p_T \)) differential measurements of dielectron yields are compared to cocktail simulations of known hadronic sources and semi-leptonic charmed decays. The enhancement (excess yield) prominent in the Low-Mass Region (LMR) over the cocktail at all energies, is further compared to calculations of \( \rho \) in-medium modifications. Within statistical and systematic uncertainties, we find that the model consistently describes this enhancement from SPS up to top RHIC energies in its \( M_{ee} \)- as well as \( p_T \)-dependence. Dielectron measurements drive the statistics for the future BES Phase-II program, which promises to improve our understanding of the LMR enhancement’s trend with total baryon densities.

Keywords: Dielectron Production, Beam Energy Scan, LMR Enhancement, Vector Meson in-Medium Modifications

1. Introduction

Ultra-relativistic nucleus-nucleus collisions allow for the study of strongly interacting nuclear matter and the associated phase diagram of the underlying theory called Quantum-Chromo-Dynamics (QCD). They are currently the only means to recreate nuclear matter in the laboratory as it existed during the early universe. Under high temperatures and energy densities, nuclear matter is predicted to undergo a phase transition into the so-called Quark-Gluon-Plasma (QGP) in which quarks and gluons constitute the relevant degrees of freedom. However, amongst others the following three fundamental questions need to be raised and answered in the context of heavy-ion collisions (HICs) to prove the creation of such a hot and dense medium [1–3]. First, whether thermal equilibrium is reached through sufficient rescattering during the initial stage of the collision. Second, whether a distinctive footprint for individual partons can be identified. Conclusive measurements of QGP radiation would also help to resolve the third question for signals of chiral symmetry restoration while at the same time looking for thermal radiation from a deconfined medium, both of which are expected from QCD.

To access manifestations of these transitions, one is left with the spectroscopy of a quickly expanding and cooling fireball via short-lived resonances such as the \( \rho \)-meson as opposed to the long-lived \( \pi \)- and \( \eta \)-mesons decaying after freeze-out. Modifications of the respective spectral functions by the medium survive the fireball evolution through the mesons’ decays into e\( ^+ \)e\( ^- \) pairs (dielectrons) as they serve as electromagnetic probes with negligible final-state interactions. Note that such in-medium information would be lost in hadronic decay channels like \( \Delta \to \pi N \) and \( \rho \to \pi \pi \). In addition to hadron gas and freeze-out phases, dielectrons emanate from the initial hard scattering and from the QGP phase via electromagnetic radiation. Hence, dielectrons can be considered bulk-penetrating probes by providing dynamic and direct information about the HIC stages they originate from encoded in their invariant mass (\( M_{ee} \)) and transverse momentum (\( p_T \)).

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\(^1\)A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.
The Low-Mass Region (LMR, $M_{ee} < 1.1$ GeV/$c^2$) of dielectron spectra, on the one hand, provides information about in-medium modifications of the vector meson’s properties. The most distinct features of electromagnetic radiation from the hot hadronic phase are unfortunately hidden by the according hadronic freeze-out decays \(^1\). However, model calculations still predict about 50% reduction in the $\rho/\omega$ region and about a factor of two enhancement at 0.5 GeV/$c^2$ comparing a broadened to a vacuum-like spectral function for the dielectron spectrum from direct decays of $\rho$, $\omega$ and $\phi$ over the fireball evolution. The $\omega/\phi$ resonances appear to be less susceptible to the different scenarios. These modifications might be connected to chiral symmetry restoration but the accuracy required to test the respective differences from various scenarios in the ($\rho$) spectral function, is experimentally very challenging. The Intermediate-Mass Region (IMR, $1.1 < M_{ee} < 3$ GeV/$c^2$), on the other hand, can provide access to the initial QGP temperature as well as a possibly medium-modified correlated charm continuum.

CERES/NA45 \(^3\) first reported an enhancement in the LMR dielectron yield, and the di-muon measurements of NA60 \(^5\) established $\rho$-meson broadening driven by baryonic interactions in the hot hadronic phase as the reason for the measured excess. STAR measured dielectron spectra from Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV as well as the $p_T$- and centrality-dependent enhancement factor (ratio of LMR excess yield over cocktail) \(^{6,7}\). The latter is also found in agreement with in-medium broadened contributions to support the NA60 findings.

The completion of the Barrel Time-of-Flight detector (TOF) in 2010 has allowed STAR to play a unique role in the study of dielectron production \(^6,8\) with excellent particle identification, low material budget, full azimuthal acceptance at mid-rapidity, and a wide momentum coverage \(^9\). TOF efficiently rejects slow hadrons and provides pure electron identification together with the energy loss measured in STAR’s Time-Projection-Chamber (TPC), which makes the two detectors the primary subsystems employed in dielectron analyses at STAR. In particular, combined with the first phase of the Beam Energy Scan Program (BES Phase-I, \(^11\)), STAR presents the unprecedented opportunity to map out a significant portion of the QCD phase diagram within a homogeneous experimental environment by consistently combining various QGP and phase transition signatures. In the context of dielectrons, STAR aims to look for energy-dependent changes in the in-medium spectral function modifications and QGP radiation.

Table \(^1\) lists the datasets taken during BES Phase-I that provide sufficient number of events for the statistics-hungry dielectron analyses. Note that at 200 GeV, the statistics for the Au+Au and $p+p$ measurements has been significantly increased since QM12 \(^7\).

The objective of this conference contribution is to present the latest results of STAR’s successful endeavor extending the dielectron measurements from top RHIC energies down to the SPS energy regime, and hence, not only closing a wide gap in the phase diagram, but also providing the first comprehensive dataset of dielectron measurements with respect to energy dependence and experimental environment. After a few comments in section \(^2\) on selected analysis steps, section \(^3\) discusses the results including invariant mass spectra and new energy-dependent LMR $p_T$ spectra as well as their comparison to updated simulations and model calculations. Section \(^4\) summarizes and gives an outlook on the role of dielectron measurements in the current STAR upgrades and the future second phase of the Beam Energy Scan program (BES Phase-II).

### 2. Data Analysis

Many of the general analysis steps involved in a dielectron analysis have been reported before in detail for PHENIX \(^11\) and STAR \(^6\). We refrain from discussing them here and instead choose to only highlight two of the most important steps, namely background substraction and the simulation of hadronic cocktails.

As argued in \(^11\), $e^+/e^−$ are always created pair-wise in HICs. Thus, the unlike-sign background can be constructed as the geometric mean of the like-sign backgrounds independent of the respective primary multiplicity distribution: $\langle BG_{i−j} \rangle = \sqrt{\langle BG_{i+} \rangle \langle BG_{j−} \rangle}$. In the LMR, the like-sign same event method is used to reproduce the background contribution from correlated sources, i.e. cross pairs from $\pi$ double conversion. In this method, like-sign pairs within the same event are combined and averaged. The resulting spectrum is then corrected for the acceptance difference between like- and unlike-sign pairs. Another method is the mixed-event technique in which electrons and positrons are combined from two different events within the same event class defined by event vertex, centrality, and event plane angle. The resulting spectra are normalized to the corresponding same-event distributions and used in the mass region where combinatorial contributions account for the uncorrelated background. Particularly the IMR requires the large statistics provided by event-mixing to obtain the necessary accuracy. The $\rho/\omega$ region of dielectron
spectra measured in the BES Phase-I energy regime exhibits a signal-to-background ratio of about 1/100 - 1/250. Hence, the accurate subtraction of yield from background sources is crucial to allow for the comparison of dielectron yield from physical sources to simulations and model calculations.

For the comparison to dielectron signal spectra, cocktails of known hadronic sources from meson decays after freeze-out are simulated. Most important is the input chosen for the hadrons before decaying them according to their direct and Dalitz channels. Pseudorapidity and azimuthal distributions are simulated flat in $\eta \in [-1, 1]$ and $\phi \in [0, 2\pi]$, respectively. Transverse momentum distributions are obtained from Tsallis-Blast-Wave fits to the latest STAR BES Phase-I data using meson-to-pion ratios from SPS with the according STAR $\pi$ invariant yields $[12, 13]$. For the Dalitz decay channels of $\pi^0$, $\eta$, and $\omega$, the Kroll-Wada formalism is employed with the corresponding form factors taken from PDG $[14]$. Our cocktail simulations also include contributions from correlated charmed decays of $D$- and $\Lambda_c$-mesons simulated via PYTHIA with estimated nucleon-nucleon cross sections and scaled to Au+Au using the average number of binary collisions at the respective energy. The decay channels taken into account along with a representative cocktail at 19.6 GeV are shown in figure 1.

3. Results

Figure 1, left, depicts the invariant mass spectra of all STAR dielectron measurements enabling a systematic study of dielectron production for the wide energy range from 19.6 to 200 GeV. Cocktail simulations generally show good agreement with the data. Only in the LMR, all spectra exhibit a consistent excess over the cocktail. Note that contributions from direct $\rho$ decays after freeze-out are not included in the cocktails as they do not account for the magnitude of the enhancement $[16]$. Instead, the in-medium model calculations treat the full evolution of the $\rho$-meson and hence need to be added on top of the cocktail. The comparison of model calculations to the invariant mass dependence of dielectron LMR yields supports the conclusion that, within systematic uncertainties, in-medium modifications of the $\rho$ spectral function consistently describe the LMR enhancement from SPS to top RHIC energies $[15]$. This can especially be seen in the fact that, in the LMR, electromagnetic radiation from the hadronic gas clearly dominates
over contributions from the QGP as indicated by the model calculations. In figure 1 right, STAR’s measurements are now extended to the $p_T$ dependence of dielectron production in the LMR covering the full phase space available to dielectrons. In line with the invariant mass dependence, we observe consistency with the in-medium broadened spectral function scenario at all energies. This further supports the conclusion of it being the correct description for the LMR excess at BES Phase-I energies.

The quality of the STAR data also allows for the systematic measurement of LMR enhancement factors and excess yields with respect to their energy dependence in the BES Phase-I regime. Due to the seeming CP invariance of the strong interaction, in-medium modifications to the $\rho$ spectral function are expected to depend on total instead of net baryon density. For energies in BES Phase-I, the total baryon density is approximately constant which means that an energy-dependent enhancement might be directly related to temperature and system evolution. However, in figure 2 we do not observe a strong energy dependence in BES Phase-I.

4. Summary & Outlook

STAR’s BES program provides a unique opportunity to address long-standing questions regarding the consequences of in-medium modifications to dielectron spectra. The measurements provide the first comprehensive dataset to serve the better understanding of the LMR enhancement regarding its $M_{ee}$, $p_T$ and energy dependence. We observe that the LMR excess at all BES Phase-I energies is consistently in agreement with in-medium modifications to the $\rho$ spectral function. The corresponding yields do not show a strong energy dependence due to an approximately constant total baryon density. For the energy regime below 20 GeV, measurements of the total baryon density as well as $\rho$-meson based PHSD calculations suggest an increase of about a factor of two in LMR excess [17]. High-statistics measurements in BES Phase-II should provide enough accuracy to study these predictions and further strengthen our understanding of the LMR enhancement and its origin [18]. Besides enhanced statistics, BES Phase-II will provide improved tracking due to the proposed ITPC upgrade, and improved capabilities for the measurement of dimuons, for instance. Moreover, the recently completed upgrades of the HFT and MTD detector subsystems enable the study of a possibly medium-modified charm continuum and QGP radiation. This is especially important for the LMR since the $c\bar{c}$ contribution to the total cocktail in the 0.4 - 0.7 GeV/$c^2$ mass region increases from about 20% at 19.6 GeV up to about 60% at 200 GeV.

In conclusion, STAR’s measurements during BES Phase-I provide high-quality datasets essential to address current challenges in dieletron physics and STAR will continue along this path during BES Phase-II.

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