EPJ Web of Conferences **291**, 04002 (2024) https://doi.org/10.1051/epjconf/202429104002
MESON 2023

Photon-photon correlations in Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV

Mateusz Grunwald[1,*] for the HADES collaboration

[1]Warsaw University of Technology, 00-662 Warsaw, Poland

Abstract. Photons, as penetrative probes, can deliver information about early stages of heavy-ion collisions, in contrast to hadrons, whose kinematics are determined after the freeze-out era. Given that, they provide access to quantities inaccessible for many other particle species. However, due to technical challenges of photon detection and dominance of photons from particle decays, exploiting their properties requires significant effort. Femtoscopy, a technique used to investigate the space-time characteristics of the source area, is sensitive to the emission sequence of studied particles. Hence, it can be utilized as a tool to separate photons originating from different sources. Studying femtoscopic correlations of photons can offer a new and unique perspective on source parameters before kinematic freeze-out. Using data from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV, collected by the HADES spectrometer, a preliminary study of photon-photon correlations was performed.

1 Introduction

Photons are a versatile tool for studying the properties of heavy-ion collisions. Unlike charged particles, photons are not subject to strong, nor electromagnetic interactions with each other, having relatively long mean free path. That imply little to no distortion of their kinematics from surrounding particles, preserving the information at the time of their emission. Consequently, it is possible to access not only information available after thermal freeze-out, but also to include previous stages of expansion.

Femtoscopy [1] is a method exploring space-time properties of a source area (not investigable directly, due to size of $\sim 10^{-15}$ m and life-time $\sim 10^{-23}$ s). The correlations between particle momenta are utilized, in order to extract its characteristics. The correlation function is defined as:

$$CF(q) = \int S(q, \boldsymbol{r})\, |\Psi(q, \boldsymbol{r})|^2\, d\boldsymbol{r}^3 = \frac{\text{Same}(q)}{\text{Mixed}(q)} \tag{1}$$

where: $q = |\boldsymbol{p_1} - \boldsymbol{p_2}|$ is the momentum difference, $S(q, \boldsymbol{r})$ is the source function, $\Psi(q, \boldsymbol{r})$ is the 2-particle wave function, Same(q)/Mixed(q) are the q distributions from same/mixed events respectively. The same/mixed event approach is used experimentally, since $S(q, \boldsymbol{r})$ is inaccessible directly and $\Psi(q, \boldsymbol{r})$ is not always known (i.e. due to unknown interaction parameters). One can define one-dimentional, boost-invariant momentum difference as:

$$q_{INV} = \sqrt{|\boldsymbol{p_1} - \boldsymbol{p_2}|^2 - (E_1 - E_2)^2} \tag{2}$$

---

[*] e-mail: mateusz.grunwald.dokt@pw.edu.pl

where $\boldsymbol{p}$ is the particle's momentum, E is the particle's energy.

The study of femtoscopic correlations of photons can serve as an unique probe of the source's space-time evolution. Complementing the study of hadron femtoscopy, it provides an insight on early stages of evolution. Moreover, since photons can be produced via various different mechanisms (i.e. hard scattering, thermal emission from QGP/hadron gas, particle decays etc.), femtoscopy, being sensitive to the particle's emission time, can be used to identify contributions from different sources. Besides, due to their massless nature, photon pairs follow a relation of:

$$M_{\gamma\gamma} = \sqrt{2E_1E_2(1 - cos\alpha_{\gamma\gamma})} = q_{INV} \tag{3}$$

where $\alpha_{\gamma\gamma}$ is the opening angle between photons. Photon detection is not a trivial problem, as it requires detectors sensitive to neutral particles or an efficient way of reconstructing conversion channels. Additionally, the photon yield is mainly dominated by π^0 meson decays, which occur long after freeze-out ($\tau_{\pi^0} \sim 10^{-17}$ s). Therefore direct photons, emitted at times t < 10^{-22} s and carrying information about the early stages, are often overshadowed.

As a part of FAIR/GSI [2, 3] scientific complex, the HADES [4] experiment specializes in detecting light vector mesons, decaying into dielectron ($e^{\pm}$) channels, created in heavy-ion collisions at energies of several (1-2) A GeV. The HADES spectrometer [5], designed for fixed-target reactions, provides wide angular acceptance, great dielectron reconstruction efficiency and $\pi^{\pm}$ - p separation. Since 2019, detector setup contains electromagnetic calorimeter modules (ECAL [6]), capable of detecting neutral particles. With use of data from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV, the photon sample was reconstructed, allowing for exploring the possibilities of photon femtoscopy.

2 Photon identification with HADES spectrometer

Photon reconstruction differs from the detection of charged particles, since most commonly used detectors are insensitive to neutral particles. Therefore, one needs to rely on the photon conversion method (PCM) [7] or detection with calorimeters.

The photon conversion method, thanks to HADES's specialization in dielectron detection, provides high angular and momentum reconstruction resolution, along with low contamination from mismatched particles or random e^-e^+ pairs with an invariant mass < 15 MeV/c^2 (see Figure 1). However, due to low material budget (thus low conversion probability), multi-step reconstruction (single leptons →photons) and need for both leptons being reconstructed, the efficiency of such approach is low. Moreover, since most of the photon conversion happens in the mirror of the RICH detector [5], only a fraction of leptons can be efficiently identified using RICH information.

Electromagnetic calorimeters (ECAL) allow for the direct detection of neutral particles, thus providing significantly greater efficiency compared to PCM, along with wider energy coverage. Unfortunately, the angular resolution of such detectors is relatively poor due to limited granularity, and the energy resolution at the lower end of the spectrum is worse than PCM, since calorimeter resolution behaves like $\sigma_E \sim \frac{1}{\sqrt{E}}$.

For the photon conversion method, a set of criteria for lepton reconstruction were applied, including $dE/dx, \beta$ and $E_{ECAL} - p$ distribution (where $\beta = \frac{v}{c}$, E_{ECAL} is the energy deposited in calorimeter, p is the particle's momentum) with respect to p, alongside with RICH "track-ring matching" indicator and dependent on whatever RICH and ECAL information is available, as well as for both time of flight detectors (RPC/TOF) separately. Additionally, dilepton pairs need to satisfy specific thresholds for conversion vertex, opening angle, and the minimum distance between both daughter tracks. Photons from ECAL are chosen by rejecting all hits correlated with charged tracks, along with β and energy requirements.

Figures 1 and 2 present results from UrQMD [8] simulations with implemented detector response in GEANT [9], showing reference distributions, obtained with both reconstruction methods.

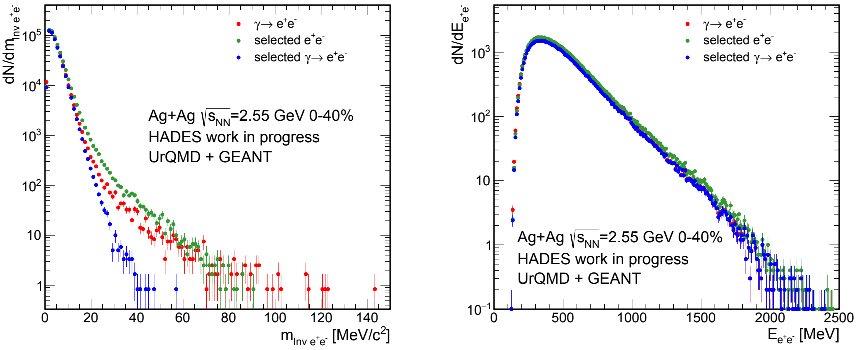

Figure 1: Invariant mass of e^+e^- pair from γ conversion (left), energy distribution (right). Red circles represent all γ simulated with UrQMD+GEANT that could be reconstructed within obtained lepton sample. Green circles show γ candidates reconstructed via selection criteria. Blue circles, being subset of green, represent properly selected γ among selected candidates.

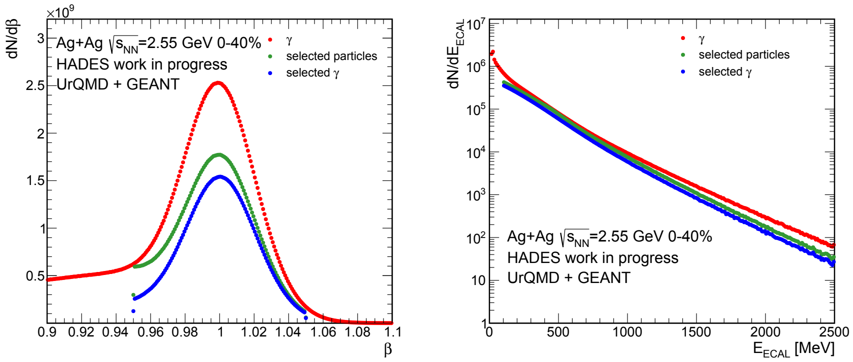

Figure 2: ECAL photons β distribution (left), energy distribution (right). Same categories pattern as for Figure 1, but for direct photon detection with calorimeters.

3 Photon-photon correlation functions

Once photons are identified, one can create photon pairs for the correlation function using either previously introduced method. Figure 3 displays photon correlation functions for PCM and ECAL photon pairs, obtained from simulations and real data. It is important to note that in simulations, no interactions or quantum statistics are implemented; therefore, in case of simulations, any deviation from unity represents non-femtoscopic correlation (typically for large q_{INV}, e.g. a peak at $q_{INV} \sim 135$ MeV/c^2, being a product of $\pi^0 \rightarrow \gamma\gamma$ decay), or a detector effect (typically for small q_{INV}).

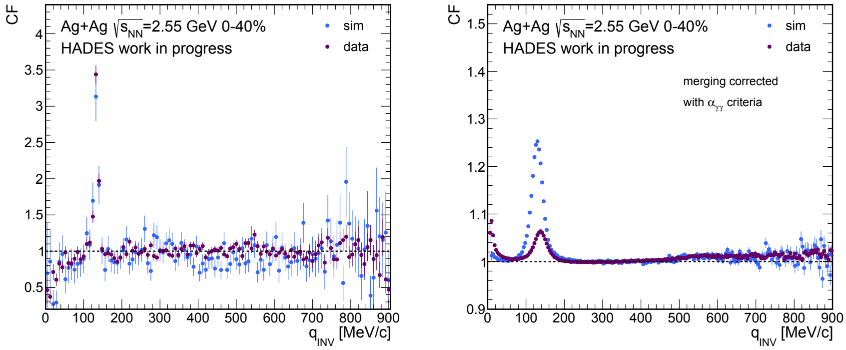

Figure 3: Correlation functions for PCM photons (left), ECAL photons (right).

For the correlation function constructed solely with PCM, limited statistics lead to large errors, preventing any meaningful conclusion. Using photons from ECAL, after accounting for detector effect (known as merging), caused by the limited granularity of modules, a slight hint of a correlation signal can be observed in real data for $q_{INV} < 50$ MeV/c. In simulations, the relevant enhancement is relatively minor, leading us to suspect that a physical phenomenon is observed in data. The observed signal requires further investigation.

References

[1] M.A. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Annual Review of Nuclear and Particle Science **55**, 357 (2005)
[2] *FAIR-GSI webpage*, `https://fair-center.eu/`
[3] *GSI webpage*, `https://www.gsi.de/en/start/news`
[4] *HADES webpage*, `https://hades.gsi.de/`
[5] The HADES collaboration, European Physical Journal A **41**, 243 (2009)
[6] O. Svoboda et al. (HADES), JINST **9**, C05002 (2014)
[7] T. Povar, *Reconstruction of neutral mesons via photon conversion method in Ag-Ag collisions at 1.58A GeV with HADES* (2023), p. 047
[8] *Ultrarelativistic Quantum Molecular Dynamics*, `https://urqmd.org/`
[9] R. Brun, F. Bruyant, M. Maire, A.C. McPherson, P. Zanarini, *GEANT 3: User's Guide Geant 3.10, Geant 3.11; rev. version* (CERN, Geneva, 1987), `https://cds.cern.ch/record/1119728`

Acknowledgement

This work was supported by the Grant of National Science Centre, Poland, No: 2020/38/E/ST2/00019. Studies were funded by IDUB-POB-FWEiTE-3, project granted by Warsaw University of Technology under the program Excellence Initiative: Research University (ID-UB).