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Inclusive e^+e^- pair production in p+p and p+Nb collisions at $E_{kin} = 3.5$ GeV

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Abstract. We report on recent data of e^+e^- pair emission in proton nucleus collisions at energies above the light vector meson production thresholds. Invariant mass distributions for the p+Nb system at $E_{kin} = 3.5\ GeV$ are compared to data from elementary p+p reactions at the same beam energy. We observe a constant π^0/ω yield ratio for both systems but an excess in the mass region above the π^0 mass. Furthermore we present here the normalization procedure that was applied to p+Nb collisions by measuring the production of negative pions in the HADES acceptance.

1. Introduction

The spectroscopy of e^+e^- pairs offers a promising opportunity to study hadron properties inside a strongly interacting medium. Electrons and positrons interact only electromagnetically and their kinematics stays almost undistorted while propagating through matter. Systematic studies in different environments, characterized by different temperatures and densities, are therefore possible, if the respective hadron h has a direct decay branch into e^+e^- pairs: $h \longrightarrow e^+e^-$. For the light vector mesons with the same quantum numbers as virtual photons the branching ratio is approximately 10^{-5}. Background sources of dielectrons like external conversion of real photons, Dalitz decays of hadrons, misidentification of pions as electrons etc. have to be well under control and understood.

Experimentally the highest temperatures and/or densities can be formed in relativistic heavy-ion collisions. Dilepton spectra were measured by CERES [1] and NA60 [2] at CERN-SPS energies. At lower energies (1-2 AGeV) the DLS [3] experiment and recently the HADES collaboration [4, 5, 6, 7] published their data for different collision systems.

Another site in the systematic studies of hadron properties is the so-called cold nuclear matter, i.e. a medium at ground state density and zero temperature. Experimentally it can be tested in heavy nuclei in proton -, pion - or photon - induced reactions. One has two different observables at hand: the spectral shape in the e^+e^- invariant mass and/or the total yield for different nuclei. The measurement of the shape requires the decay taking place inside the nucleus. This is only true for short-lived vector mesons like the ρ or longer lived mesons (ω,ϕ) at small momenta. The measurement of the yield or production cross section can be connected to the total width of the hadron via the so called transparency ratio [8, 9].

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So far, shape measurements in elementary reactions were done for the ρ meson by the CLAS experiment at JLab[10] and the E325 experiment at KEK[11]. However, the results are not conclusive so far. For the ω and ϕ meson several experiments [12, 13, 14, 15] reported a sizable broadening of the total decay width inside the medium using the transparency ratio method.
To contribute to this still unresolved issue the HADES collaboration measured the inclusive e^+e^- pair production in proton induced reactions at E_{kin} = 3.5 GeV. The reference spectrum was obtained in p + p reactions and the in-medium effects on the heavy nucleus Nb.

2. Experimental setup and measured e^+e^- spectra

The High Acceptance Di-Electron Spectrometer HADES is installed at the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt and is provided with a proton or heavy-ion beam by the synchrotron SIS18. A detailed description of the spectrometer can be found in Ref. [4]. For the $e^{\pm}$ identification a hadron blind Ring Imaging CHerenkov detector (RICH) was used. Particle identification was supplemented by a time-of-flight measurement in a plastic scintillator wall (ToF) and an electromagnetic shower pattern in the Pre-Shower detector.
In our experiments a proton beam with a kinetic energy of $E_{kin} = 3.5\ GeV$ was incident on a liquid hydrogen target for the p + p run in 2007 [16] and on a 12-fold Nb target for the p + Nb run in 2008. The event selection was done in two steps. In the first trigger stage (LVL1), events with a charged particle multiplicity in the ToF wall of $M_{ch} \geq 3$ were selected. The second trigger stage (LVL2) selected events with at least one lepton candidate indicated by a ring in the RICH detector.
All possible combinations of identified e^+/e^- tracks have been formed event by event and corrected for detector and reconstruction efficiencies. The latter ones were deduced using Monte-Carlo simulations embedded into real events. Invariant mass spectra of the unlike-sign pairs were constructed from single e^+/e^- tracks. To increase the purity of the e^+/e^- sample a cut on the single track momentum $0.08 < p_e/(GeV/c) < 2.00$ was applied.
The combinatorial background (CB) was extracted from all like-sign pair combinations inside the same event. Since the CB stems predominantly from external γ-conversion it could be reduced by cutting on the pair opening angle $\alpha_{ee} > 9°$ and on the track fitting quality. By subtracting the CB from the unlike-sign pairs the signal spectrum was obtained.
The measured invariant mass distributions of e^+e^- pairs are shown in the left panel of Fig. 1. The data points are normalized to the number of recorded LVL1 events. The signal to background ratio is $S/B \simeq 1$ at $M_{ee} \simeq 200\ MeV/c^2$ and increases up to $S/B \geq 10$ at $M_{ee} \simeq 750\ MeV/c^2$. The low-mass part of the spectrum is dominated by π^0 Dalitz decays ($M_{ee} < 150\ MeV/c^2$), while the intermediate part ($150\ MeV/c^2 < M_{ee} < 550\ MeV/c^2$) can be attributed to $\Delta(1232)$ and η Dalitz decays[16]. The high mass part of the distribution is dominated by the direct decay of the light vector mesons ρ, ω and ϕ. The peak around 780 MeV/c^2 corresponds to the decay of $\omega \rightarrow e^+e^-$ and the peak around 1000 MeV/c^2 reflects the decay of $\phi \rightarrow e^+e^-$. A mass resolution of $\frac{\Delta M}{M} \sim 2\%$ is extracted from a fit with a Gaussian distribution (see inset in Fig. 1). The remaining signal continuum in this mass region may originate from in-medium ρ-decays.

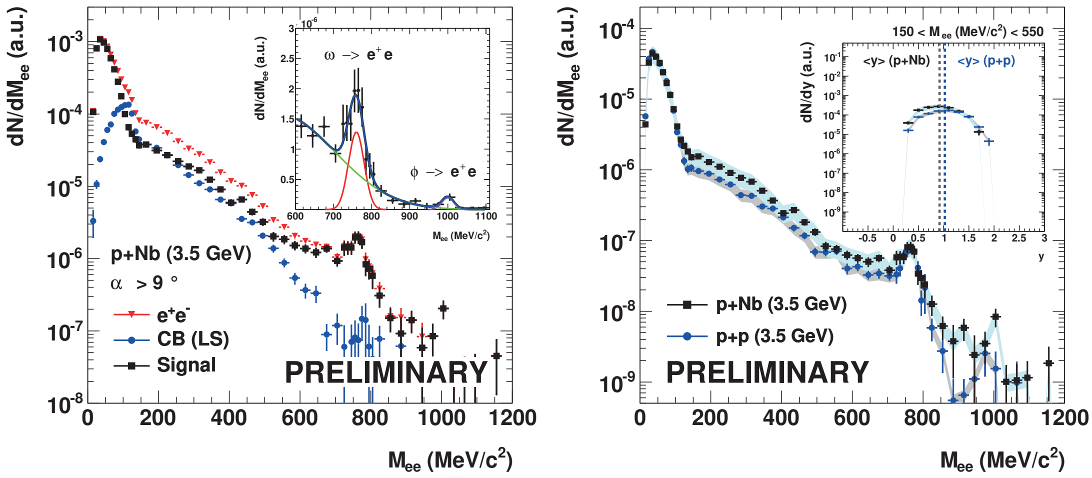

Figure 1. Left: Efficiency corrected invariant mass spectrum of all e^+e^- pairs (red triangles), the combinatorial background (blue dots) and the signal pairs (black squares) for p+Nb collisions at $E_{kin} = 3.5\ GeV$. The inset shows the ω and ϕ meson yield. Right: Efficiency corrected e^+e^- signal spectra for p+p (blue dots) and p+Nb (black squares) collisions. They are normalized to their yield N_π in the π^0 mass region ($50\ MeV/c^2 < M_{ee} < 120\ MeV/c^2$). The systematic uncertainties are shown by the error bands. The inset shows the rapidity distributions, with the mean rapidity values given by the vertical lines.

3. Comparison of the p+p and p+Nb results

In a first step all spectra were scaled to the same yield N_π in the π^0 mass region ($50\ MeV/c^2 < M_{ee} < 120\ MeV/c^2$). In the right panel of Fig. 1 the invariant mass distribution of the signal in p + Nb collisions is compared to the reference spectrum p+p. In the ω/ρ region the yield is comparable for both reaction systems relative to the π^0 yield. This suggests a similar vector meson production rate off the nucleus as for pions.

The yield in the intermediate mass region ($150\ MeV/c^2 < M_{ee} < 550\ MeV/c^2$) is enhanced by about 50%. To further investigate this enhancement different kinematic observables were studied. The inset of Fig. 1 shows the rapidity distributions of e^+e^- pairs in this mass region for both reaction systems. The mean values for both reaction systems are indicated by vertical lines. For p + Nb, it is shifted towards target rapidity. This hints to the presence of an additional slow source, which has to be verified by detailed transport model calculations.

The spectral shape of the ω meson does not exhibit a clear signature of in-medium effects inside the error bars as visible in Fig. 1. The comparison of yields in different mass regions can lead to further insight about the in-medium widths of hadrons.

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4. Cross sections

Total cross sections were obtained via the comparison of the measured yield Y_H of a known physical process inside the HADES acceptance and its measured cross section σ_{Meas}. A global normalization factor

$$F_{NORM} = \frac{\sigma_{Meas}}{Y_H} \tag{1}$$

can then be calculated for e^+e^- spectra.

In p+p collisions F_{NORM} was obtained via the exclusive measurement of elastic p+p collisions and the known integrated cross section inside the HADES acceptance:

$$F_{NORM,pp} = \frac{\sigma_{ACC,elastic}}{Y_{H,elastic}}. \tag{2}$$

In p+Nb collisions such exclusive measurement was not possible. The physical source chosen there is the production of negative pions in proton induced reactions on nuclei. This was measured recently by the HARP-CDP collaboration [17] for a number of nuclei and projectile energies. Differential cross sections $\frac{d^2\sigma}{d\Omega dp}$ are given for bins in $0.1 < p_\perp$ (GeV/c) < 0.9 and $20^\circ < \theta_{HARP-CDP} < 90^\circ$ which covers fully the HADES polar angle range ($18^\circ < \theta_{HADES} < 85^\circ$). The system p + Nb was not measured but the systematics allows for an interpolation for our collision system.

In our experiment, negative pions were identified via their energy loss in the ToF detector. A detailed description of the analysis is given in [18]. A correction for efficiency was done in the same way as for $e^\pm$, additionally an acceptance correction in azimuthal angle was applied. To compare to differential cross sections measured by the HARP-CDP collaboration also the trigger bias was taken into account. This was achieved by a global factor F_{TRIG} obtained from transport model (UrQMD [19]) calculations followed by full scale GEANT [20] simulations of the detector setup. The multiplicity of negative pions $M_{ACC,\pi}$ in the HADES acceptance for different cuts on the charged particle multiplicity M_{ch} was then used to calculate F_{TRIG}:

$$F_{TRIG} = \frac{M_{ACC,\pi}(M_{ch} \geq 3)}{M_{ACC,\pi}(M_{ch} \geq 0)} = 1.42 \pm 0.14, \tag{3}$$

where $M_{ch} \geq 0$ means minimum bias events. The systematic error of 10 % was estimated from different scaling factors obtained from experiment and simulation, which was possible in the cases of $M_{ch} \geq 2$ and $M_{ch} \geq 3$. After correcting the pion spectra for trigger bias the normalization factor $F_{NORM,pNb} = 886 \pm 184$ mb was obtained by fitting the HADES data points bin-by-bin in θ and $p_\perp$ to the HARP-CDP results. Since the shape of the pt distribution turns out to be quite sensitive to both the bombarding energy and the target size, this was done for $0.3 < p_\perp$ (GeV/c) < 0.9 and $30^\circ < \theta < 75^\circ$ only. To interpolate the HARP-CDP data to our reaction system, a global scaling factor of 0.963 was applied to their 4.15 GeV p+Cu data set (interpolation of systematic HARP data to our collision system). The result is shown in the left panel of Fig. 2 for the polar angle region $50^\circ < \theta < 60^\circ$.

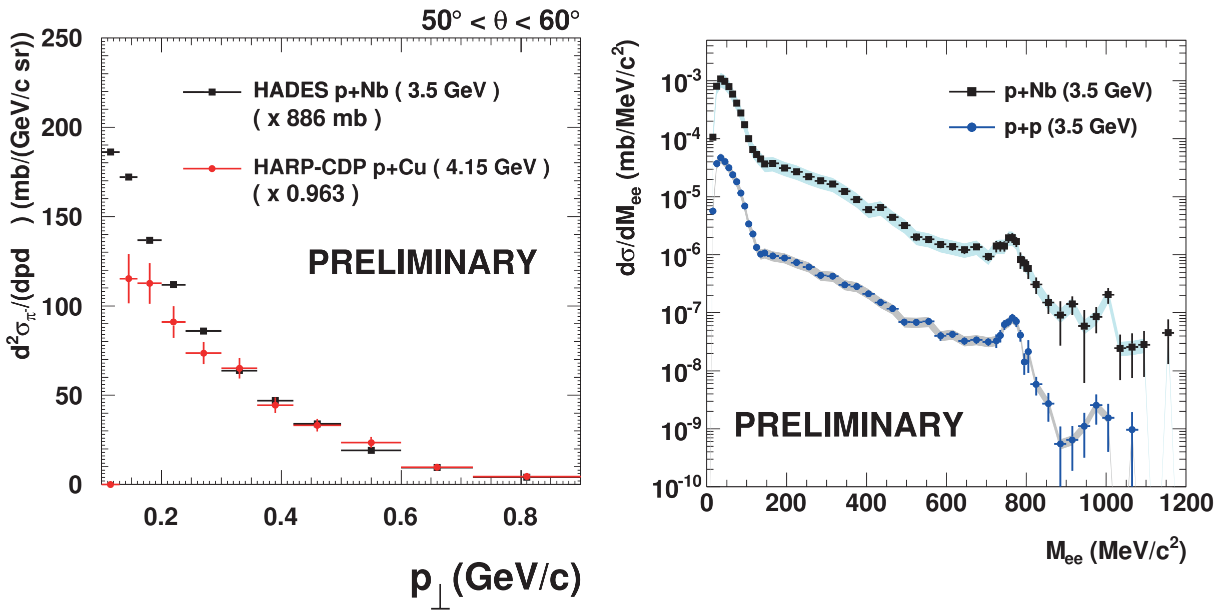

Figure 2. Left: Differential cross sections for the transverse momentum distribution of π^-: HADES data (black squares, only statistical errors) after scaling with the best fit value of $F_{NORM,pNb} = 886$ mb and HARP-CDP data (red circles, systematic and statistical errors) after system size scaling.
Right: Efficiency corrected e^+e^- signal spectra for p+p (blue dots) and p+Nb (black squares) collisions. Given are differential cross sections after applying the normalization procedure. The systematic uncertainties are shown by the error bands.

5. Summary

We have measured inclusive e^+e^- pair production in p+p and p+Nb collisions at $E_{kin} = 3.5\ GeV$. The comparison of invariant mass spectra scaled to their yield in the π^0 region shows the same signal strength in the ω pole mass region, whereas an excess of 50% over the elementary p+p processes is obtained in the intermediate mass region ($200\ MeV/c^2 < M_{ee} < 600\ MeV/c^2$). This excess is located at rapidities closer to target rapidity compared to the elementary processes in this mass interval, which hints to an additional slow source. The spectral shape of the ω meson does not show a significant difference for both reactions. For the analysis of total production cross sections a normalization of the dielectron spectra is needed, which was achieved via elastic collisions in the p+p reaction system and via the π^- production in the p+Nb system. Final conclusions about possible in-medium changes of vector mesons in matter require a comparison to transport models. Work along this line is in progress.

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