HADES EXPERIMENT: DI-LEPTON SPECTROSCOPY IN $p+p$ (2.2 GeV) AND C+C (1 AND 2 A GeV) COLLISIONS*

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(Received November 14, 2005)

* Presented at the XXIX Mazurian Lakes Conference on Physics
August 30–September 6, 2005, Piaski, Poland.

The HADES (High Acceptance Di-Electron Spectrometer) is a tool designed for lepton pair (e^+e^-) spectroscopy in pion, proton and heavy ion induced reactions in the 1–2 A GeV energy range. One of the goals of the HADES experiment is to study in-medium modifications of hadron properties like effective masses, decay widths, electromagnetic form factors *etc.* Such effects can be probed with vector mesons (ρ, ω, ϕ) decaying into e^+e^- channel. The identification of vector mesons by means of a HADES spectrometer is based on invariant mass reconstruction of e^+e^- pairs. The combined information from all spectrometer sub-detectors is used to reconstruct the di-lepton signal. The recent results from 2.2 GeV $p+p$, 1 A GeV and 2 A GeV C+C experiments are presented.

PACS numbers: 25.75.Dw, 13.60.Le

1. Physical motivations

The dependence of hadron properties on medium effects is one of the most important issues, as from a fundamental point of view, the partial restoration of the QCD chiral symmetry is expected to lead to a mass reduction of vector mesons at finite temperature and/or finite nuclear density. Brown and Rho proposed an in-medium scaling law which predicted a decrease of the vector meson mass [1]. Hatsuda and Lee calculated the density dependence of the mass vector mesons based on the QCD sum rule [2]. Various hadronic models [3] predict significant changes in mass and resonance width of vector mesons, like ρ, ω and ϕ, when embedded in nuclear matter. Besides photon- and hadron-induced reactions, these mesons are produced in heavy-ion collisions and they are short-lived enough to decay to a large extent while still inside the reaction volume.

The perfect method for the vector meson mass description in nuclear matter is the invariant mass reconstruction of mesons from the di-electron pairs. Di-lepton decay channels provide the unique possibility of the investigation of nuclear collisions, because leptons do not interact strongly and are able to carry out undistorted information about the properties of a meson decaying in the dense and hot nuclear matter. From the experimental point of view, electromagnetic signals are very difficult to handle, because they must be separated from a huge hadronic background, and e^+e^- pair production takes place at each collision stage. It is necessary to classify all production mechanisms and their contribution to the signal. One of the key problems is very careful combinatorial background reconstruction, deriving from various vertices of decaying π^0 meson, which is produced copiously in heavy ion reactions. Measurement of di-electron signal makes high demands for a detection setup from the point of view of efficiency and invariant mass resolution.

2. Di-lepton experiments

Due to experimental difficulties in e^+e^- pair identification, there is data from very few experiments available with low mass resolution and insufficient statistics of gathered di-electron events.

The first systematical research of di-electron invariant mass spectra comes from the DLS Collaboration [4]. The results are the most intriguing for d+C, He+Ca, C+C and Ca+Ca at 1 A GeV beam energy. Invariant mass spectra from d+C @ 1.06 A GeV and He+Ca @ 1.04 A GeV reveal the discrepancy between experimental data and theoretical description which is notably pronounced in collisions: C+C @1.04 A GeV and Ca+Ca @ 1.04 A GeV (Fig. 1). Theoretical description embodies the following channels: Dalitz decays $\pi^0 \to e^+e^-\gamma$, $\eta \to e^+e^-\gamma$, $\Delta \to Ne^+e^-$, $\omega \to \pi^0 e^+e^-$, $N(1520) \to Ne^+e^-$, $N(1700) \to Ne^+e^-$, two-body decays $\omega \to e^+e^-$, $\rho \to e^+e^-$, plus *bremstrahlung* πN, and also important above $2m_\pi$ mass region, annihilation channel $\pi\pi \to \rho \to e^+e^-$. Free spectral function of ρ meson has been used in the transport calculation. The sum of all contributions clearly underestimates di-electron production (6–7 times in HSD model [5]) in the invariant mass range of $0.15 \leq M_{e^+e^-} \leq 0.65\,\mathrm{GeV}/c^2$. The excess of measured di-electrons compared to theoretical yields is present also in UrQMD description [6].

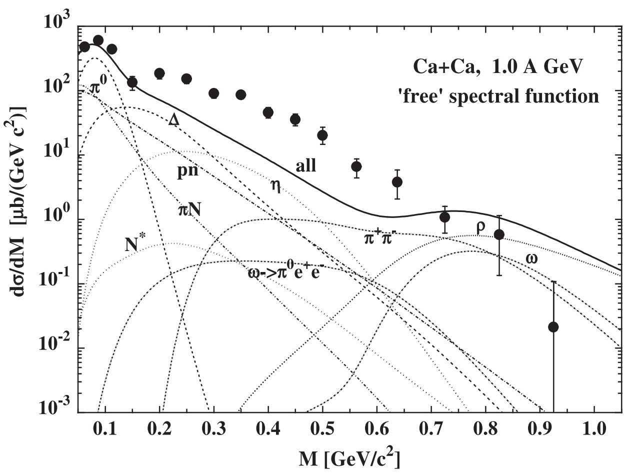

Fig. 1. Di-electron invariant mass spectrum for Ca+Ca collisions at 1 A GeV calculated (HSD model) assuming free spectral function of ρ meson and taking into account the DLS acceptance filter. Mass resolution $\Delta M/M = 10\%$ [5] also taken into account.

There are various theoretical attempts in solving the situation. Shekhter, Fuchs and Faessler [7] describe vector meson production through excitations of nuclear resonances within the framework of an extended VMD model.

ω cross section depends crucially on the role of $N^*(1535)$, therefore, two parameterizations, strong and weak $N^*(1535) - N\omega$ coupling, are introduced, leading to larger (favored in the case of Ca+Ca data) or smaller (better for C+C) off-shell contributions. The collisional broadening in heavy-ion collisions suppresses the ρ/ω peak in the di-lepton spectra and reproduction of the DLS data requires the empirical estimates for the collision widths $\Gamma_\rho^{\rm coll} = 150\,{\rm MeV}$ and $\Gamma_\omega^{\rm coll} = 100$–$300\,{\rm MeV}$. The second medium effect concerns the problem of destructive interference of intermediate ρ and ω mesons with their excited states, which can be partially destroyed by the presence of the medium. The account for decoherence improves the agreement with the DLS data in the low mass region (Fig. 2).

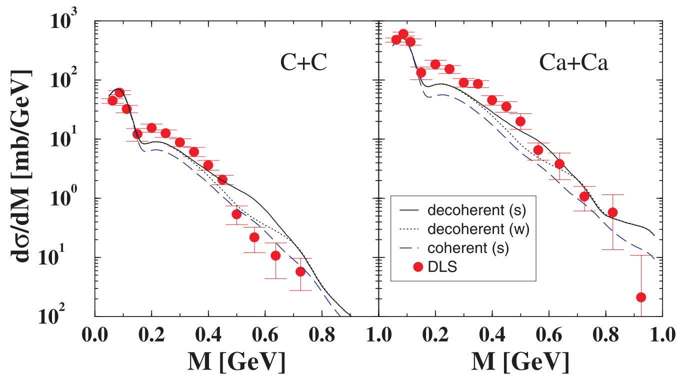

Fig. 2. Influence of the microscopically determined decoherent emission in C+C and Ca+Ca reactions with strong (s) and weak (w) $N^*(1535) - N\omega$ interactions. Coherent case (s) shown for comparison [7].

There is very interesting di-lepton data in a high energy region provided by the CERES/NA45 [8] experiment (S+Au @200 $A\,$GeV, Pb+Au @40 $A\,$GeV, Pb+Au @ 80 $A\,$GeV, Pb+Au @ 158 $A\,$GeV). Similar to DLS data, the difficulties in theoretical description reveal in the nucleus–nucleus collisions, where simple rescaling of $p + p$ collisions contribution is not sufficient. For the first such data, S+Au @ 200 $A\,$GeV, the total excess of measured pairs (sum over the invariant mass range of 0.2–1.5 GeV/c^2) compared to the theoretical cocktail contribution amounts to 5.0 ± 0.7 (statistical errors) ± 2.0 (systematical errors) times. The excess in di-electron pair production is pronounced the most at invariant mass $M_{e^+e^-} \approx 0.45\,{\rm GeV}/c^2$, exceeding the theoretical contribution almost 10 times. In order to improve the mass resolution, CERES spectrometer has been upgraded by addition of a Time Projection Chamber and new results for Pb+Au @ 158 $A\,$GeV, after a laborious calibration process completion, have been published (Fig. 3). Like in previous experiments, in the mass range $0.2\,{\rm GeV}/c^2 < M_{e^+e^-} < 1.1\,{\rm GeV}/c^2$

an excess of di-electron pairs is observed, which amounts to 2.35 ± 0.31 (statistical errors) in comparison to hadronic cocktail contribution. The signal consists of 2571 ± 224 e^+e^- pairs with the signal to background ratio $S/B = 1/21$ [9]. As shown in Fig. 3, the ρ-propagator is treated in 3 ways: vacuum ρ, modifications following Brown–Rho scaling, and modifications via ρ hadron interactions. The data clearly indicate the modification of the properties of vector mesons in the nuclear matter. However, the available experimental data do not allow making the final statement.

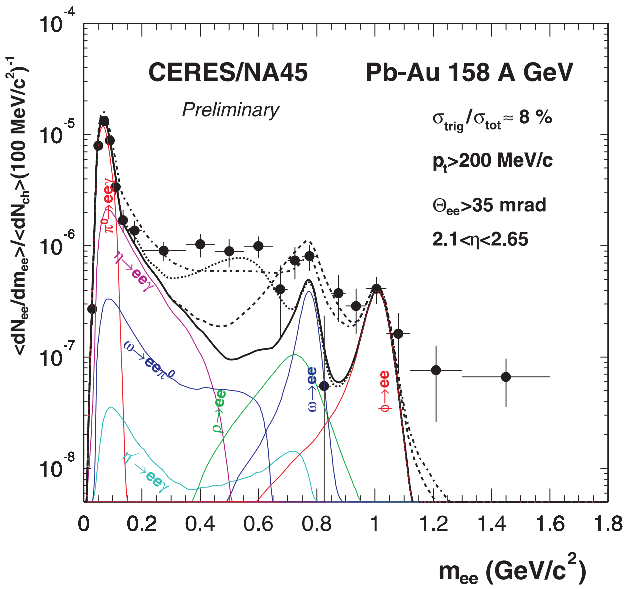

Fig. 3. Invariant mass spectrum of e^+e^- pairs normalized to the expectation from the hadron decay cocktail (thick solid line) in π^0 Dalitz peak using the mixed-event background rejection. The expectation from model calculations assuming the vacuum ρ spectra function (dashed), a dropping mass (dotted) or a in-medium spread ρ width (dashed-dotted) are also shown. Brown–Rho scaling (dotted) is less favored by the data.

It is worth mentioning two more experiments. The experiment E325 at the KEK 12-GeV Proton Synchrotron [10] measured the invariant mass spectra of $\rho, \omega, \phi \to e^+e^-$ in p+C and p+Cu reactions. They observed the excess over the known hadronic sources on the low-mass side of the ω meson peak in the e^+e^- invariant mass spectra. The excess can be described by the model (QCD sum rule) in which the mass of ρ/ω meson decreases by 9% at the normal nuclear density. The NA60 Collaboration reported recently very interesting *di-muon* data from In+In @ 158 A GeV [11]. ω and ρ meson peaks are measured with remarkably good statistics and clearly visible in the di-lepton channel. Clear excess over the cocktail ρ is unraveled, rising with the collision centrality. The ρ meson spectral function is broadened (consistent with Rapp and Wambach calculations [3]) with no mass shift, contrary to Brown–Rho scaling (however, see [12]).

In view of discrepancies between existing experimental spectra and their theoretical descriptions it is necessary to have possibility to measure data with a very good invariant mass resolution, high signal to background ratio and with good statistics. This is why the HADES spectrometer has been designed and built.

3. HADES spectrometer and experimental runs

HADES (High Acceptance Di-Electron Spectrometer) [13] has been designed to measure invariant mass of di-electrons with an excellent mass resolution (1%) in pp, πp, pA, πA and AA collisions at 1–2 A GeV. In this energy range, the dominant sources of di-electrons are Dalitz decays of π^0 and η mesons, however, the most interesting are extremely rare, direct decays of vector mesons ρ^0, ω and ϕ. A comparison of invariant mass spectra of di-electrons produced in pp, πp with pA, πA and AA collisions allow us to investigate the modification of vector meson spectral functions as a function of the density of nuclear matter.

The HADES spectrometer (Fig. 4) consists of 6 identical sectors covering a full azimuthal angle and polar angles from 18° to 85° measured according to the beam direction. Each sector of the spectrometer can work independently and contains: RICH (Ring Imaging Cherenkov Detector), inner MDCs (Multi-wire Drift Chambers) in front of magnetic field, outer MDCs behind the magnetic field, TOF and TOFino time of flight detectors and the electromagnetic cascade detector Pre-Shower. The magnetic field is provided by Coils of superconducting magnet.

The RICH [14] registers UV Cherenkov radiation, which is produced in the gaseous radiator while an electron is passing it. A radiator gas has been selected in such a way that for the beam energies 1–2 A GeV only fast electrons can emit Cherenkov photons, which are reflected from a spherical mirror and focused on the position sensitive photo-cathodes, in a form of a ring. A construction of MDCs [15] allows precisely determine a position and direction of particle tracks in front of and behind the magnetic field what leads to an excellent momentum and invariant mass resolution of the HADES spectrometer. A position resolution measured for a single MDC chamber amounts to $\Delta x = 40\,\mu$m and $\Delta y = 70\,\mu$m and corresponds to the invariant mass resolution $\Delta M/M(\sigma) \approx 1\%$ for vector mesons. Time-of-flight detectors TOF and TOFino and electromagnetic cascade detector Pre-Shower are placed behind the magnetic spectrometer creating META (Multiplicity and Electron Trigger Array) subsystem. The TOF [16] detec-

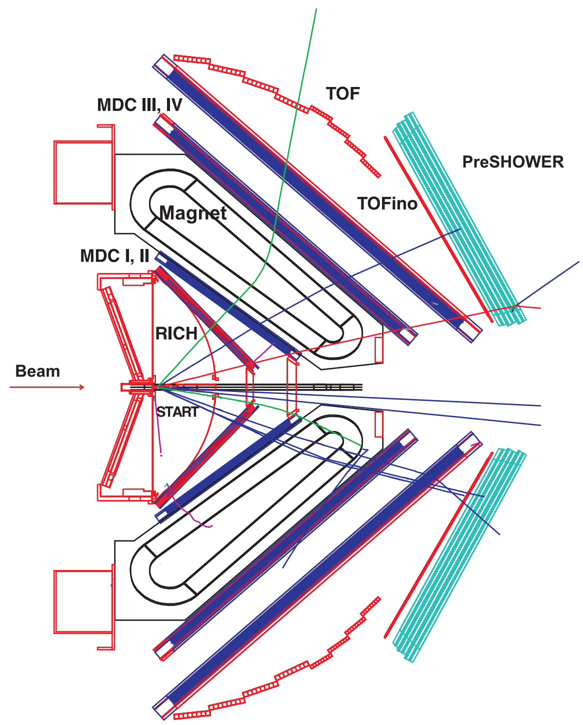

Fig. 4. Side cross section of the HADES spectrometer. A beam is directed to the target placed inside the Cherenkov detector (RICH) which identifies electrons. Two layers of drift chambers (MDCs) are placed in front of and behind the magnetic field provided by Coils of superconducting magnet and are used to determine momentum of charged particles. The whole system is closed by TOF and TOFino time of flight detectors and the electromagnetic cascade detector Pre-Shower improving an electron identification.

tor located for polar angles $\theta > 45°$ has a good time resolution $\sigma_{\mathrm{TOF}} = 150\,\mathrm{ps}$. For smaller polar angles ($\theta < 45°$) it is very difficult to distinguish electrons from fast pions by using only time of flight information (TOFino detector). Thus, the electromagnetic cascade detector Pre-Shower is used in this angular region to improve electron identification. Each sector of the Pre-Shower detector [17] consists of three gaseous chambers separated by two lead converters. The ratio of charge accumulated in the chamber placed behind the lead converter to the corresponding charge in the chamber in front of converter is much larger for e^+/e^- than for hadrons which do not produce electromagnetic cascades.

The most important features which favor of the HADES spectrometer among other instruments measuring e^+e^- pairs are:

- excellent invariant mass resolution ($\Delta M/M(\sigma) = 1\%$);
- large geometric acceptance (35%) for di-electrons from direct decays of vector mesons;
- two level trigger [18] which allows to select online events containing di-electrons and reduces substantially the amount of useless data written on the storage devices. The first trigger level LVL1 selects quasi-central collisions by requiring large particle multiplicities on TOF and TOFino detectors. Then, data is read from the RICH, TOF and the Pre-Shower detectors and online preprocessed in order to find electron hits. Finally, the electron hits are online correlated in the spatial window to find electron tracks in the event. For the events with at least 1 or 2 electron tracks the signal of the second trigger level LVL2 is triggered.

The following production runs has been performed with the events statistics collected:

- November 2002: C+C 2 A GeV, 220×10^6 events,
- January 2004: $p + p$ 2.2 GeV, 400×10^6 events,
- August 2004: C+C 1 A GeV, 650×10^6 events,
- September 2005: Ar+KCl 1.75 A GeV, 800×10^6 events.

4. Heavy-ion collisions C+C @ 2 *A* GeV

In November 2002 the spectrometer was not fully equipped with all outer MDC chambers. Therefore, the data of 2 A GeV ^{12}C + ^{12}C collisions have been analyzed in the so-called low-resolution mode for which tracking relies on the inner MDC planes only, as well as on position information from the TOF and Pre-Shower counters. The mass resolution $\Delta M/M(\sigma)$ amounts to about 10%. The TOF wall also provided a fast LVL1 trigger decision, whereas the lepton content of the recorded events was enriched by a factor of 8 in a LVL2 trigger. A total of 150 million events (50% LVL1 downscaled 1:10 and 50% LVL2) was thus recorded and analyzed. Detailed account of the experimental conditions and of the data analysis procedures are given in [19]. In parallel to analysis the simulation was done, based on UrQMD [20] as well as thermal fireball PLUTO event generator [21]. The average number of participants in the events selected by the LVL1 trigger was estimated from simulation to be $A_{\text{part}} = 8.6$. The measured pion yield extrapolated to 4π amounts to $N_\pi = 1.27 \pm 0.12$ and hence the average yield of positive and negative pions $N_\pi/A_{\text{part}} = 0.148 \pm 0.015$ (systematical uncertainties).

This value is in good agreement with the result reported by the TAPS Collaboration which for neutral pions amounts to 0.138 ± 0.014 [22].

The analysis can be described in a few steps. First, single lepton spectra are generated for e^+ and for e^-, then opposite sign (e^+e^-) and like sign (e^+e^+, e^-e^-) lepton pairs are reconstructed, and combinatorial background is subtracted using the geometric mean of both like sign spectra to obtain the e^+e^- signal. The resulting mass spectrum, background and signal are depicted in Fig. 5 (left). Shown are only the statistical error bars, on top of which an estimated systematic error of the procedure of ±30–40% has to be added quadratically. There is also experimental signal-to-background (S/B) ratio shown in Fig. 5 (right).

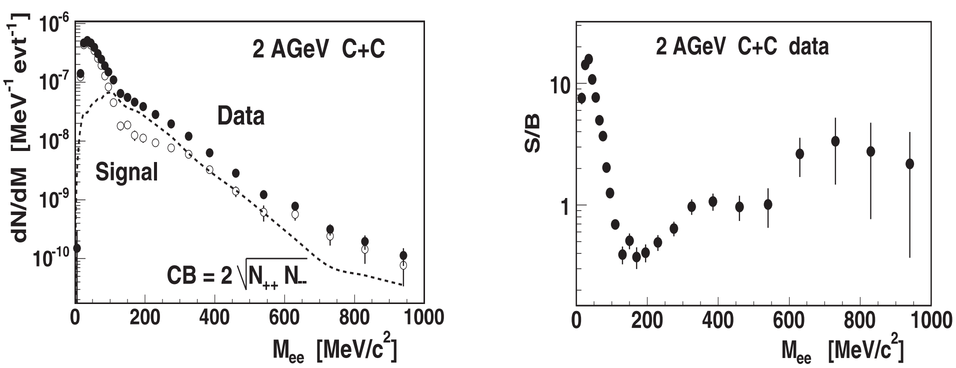

Fig. 5. Reconstructed e^+e^- invariant mass spectrum for 2 *A* GeV C+C. Open circles are signal, dashed line is combinatorial background (left). In the signal reconstruction procedure the condition on the opening angle $\theta_{e^+e^-} > 9°$ between the e^+ and e^- track directions was applied to reject unlike-sign pairs arising from γ conversion. The di-electron signal yields to 19000 pairs (1500 pairs above $0.2\,\mathrm{MeV}/c^2$). The signal to background (S/B) ratio (right) is much better than in the CERES experiment.

In Fig. 6 the pair signal is compared with a simulated cocktail of meson and baryon decays transported through the full detector simulation, *i.e.* folded with the spectrometer acceptance and efficiency. The π^0 and η multiplicities used, with quoted errors of 10% and 16%, respectively, have been taken from [23], whereas vector meson production was estimated with an m_t-scaling ansatz. From this figure it is clear that the data agree with the cocktail, within our 30–40% systematic errors, at low masses (dominated by π^0 Dalitz decays), but show an excess at intermediate masses, indicative of effects due to the collision dynamics and/or the nuclear medium. Simulations with better statistics are still ongoing and a comparison with various transport theories has been started.

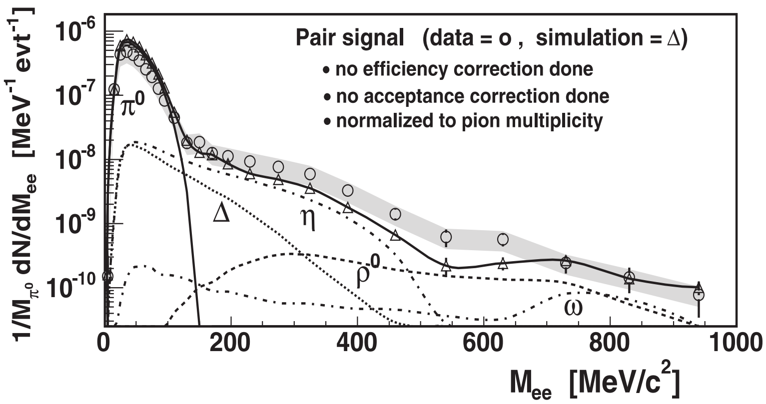

Fig. 6. Comparison of data normalized to π^0 multiplicity with a simulated cocktail of various pair sources. Systematic errors (shaded band) are shown for data.

Even more interesting data, from the point of view of direct comparison with the DLS results were gathered during 1 A GeV C+C run. The analysis is under way and the preliminary spectra with 3 times larger (than in 2 A GeV C+C run) statistics are available.

5. Elementary collisions $p + p$ @ 2.2 GeV

There are three dominant classes of decays which contribute to the di-electron yield in pp reactions at beam energies 1–4 GeV:

- Δ Dalitz decay $pp \to p\Delta^+ \to ppe^+e^-$;
- meson Dalitz decays $pp \to pp\eta(\pi^0) \to ppe^+e^-\gamma$ and $pp \to pp\omega \to ppe^+e^-\pi^0$;
- vector meson two-body decays $pp \to pp\rho/\omega \to ppe^+e^-$.

Large acceptance of HADES allows the simultaneous exclusive measurement of the η production in the pp reactions using η identification via the three-pion and di-electron decays. Since the exclusive cross sections for the η production in pp reactions are well known [24], the absolute normalization can be provided by the η reconstruction via pion decay channel. Thus, the reconstruction of the $\eta \to e^+e^-\gamma$ Dalitz decay can be used as a stringent test for the HADES di-electron acceptance corrections [25].

The η production cross section can be exclusively measured via the Dalitz decay branch. By measuring both protons and both leptons the reconstruction of this decay mode is kinematically complete without requiring an additional photon detector. The existing measurement of the η-Dalitz decay [26] is rather poor as it is based on a sample of 80 counts. It is important to have an accurate measurement of not only the partial width but also the electromagnetic form factor of this decay mode [27].

In January 2004 the data were gathered with the spectrometer equipped with 4 (out of 6) sectors with all MDC chambers (full resolution tracking) and 2 sectors with middle resolution tracking. The analysis strategy is based on various kinematical cuts:

1. veto on elastic pp pairs — pp missing mass is zero, therefore, fitting the background and signal from elastic scattering we reject them,

2. similar procedure of fitting signal and background in pp missing mass spectrum around π^0 mass allows to retrieve π^0 signal (from $pp \to pp\pi^0$ channel). There are various possibilities of background fitting leading to systematical error estimation. The background contains also channels with more than one pion (missing mass of two, three pions),

3. in the case of η meson two decay channels are interesting:

   - hadron channel $\eta \to \pi^+\pi^-\pi^0$ (branching ratio 0.226),
   - lepton channel $\eta \to e^+e^-\gamma$ (branching ratio 0.006),

   Measuring 4 charged particles, we are able to identify π^0 missing mass from $pp\pi^+\pi^-\pi^0$ channel and, therefore, the number of η mesons from hadronic decay. On the other hand, identifying γ missing mass from $ppe^+e^-\gamma$ channel we can retrieve the number of η mesons from electromagnetic channel. Subtracting background in pp missing mass spectrum (Fig. 7) with the cuts as above we directly obtain η signal.

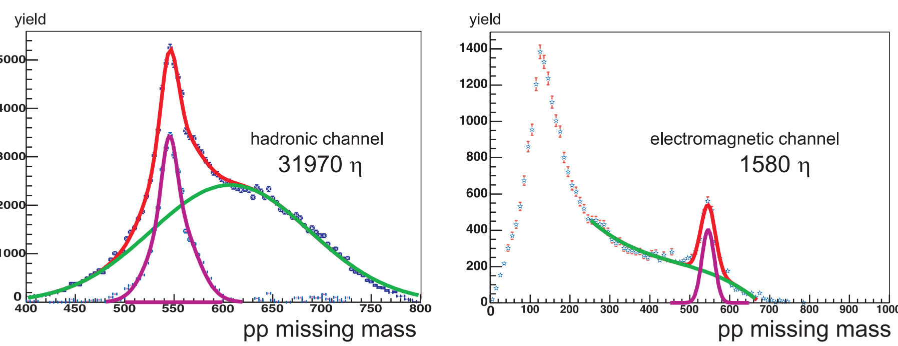

Fig. 7. η meson signal retrieved from pp missing mass spectrum for hadronic (left) and electromagnetic (right) channels (no acceptance corrections). For each track the minimization procedure (kinematical fit, varying momentum, θ, φ) was done.

Obtained missing mass resolution is very good, even in the case of high momentum particles (protons) amounts to 2.4%. Further analysis is under way.

The future program for elementary *pp* collisions (2006 year) will cover studies of the Δ Dalitz (exclusive $\Delta+$ production) decay and ω production.

6. Summary

The recently finished (October 2005) experimental run (Ar+KCl) proved that the HADES spectrometer can operate during a long time (one month) and collect large amounts of data. The heavy-ion data C+C @ 2 A GeV show that with only inner MDC chambers we get the invariant mass resolution on the level of the DLS experiment but with much better statistics. The data will be corrected with respect to the HADES reconstruction efficiency soon, and then compared with various theoretical models. The C+C @ 1 A GeV data will enable direct comparison with the DLS measurements. Elementary reactions $p + p$ @ 2.2 GeV help to prove that the spectrometer measures efficiently all charged particles. The calibration with respect to well known reaction channels will allow to decrease systematical errors and to determine the realistic spectrometer acceptance.

The collaboration gratefully acknowledges support by the German BMBF (06TM970I) and GSI (TM-FR1), by grants GA CR 202/00/1668 and GA AS CR IAA1048304 (Czech Republic), by the Polish State Committee for Scientific Research (KBN) grant 5P03B 140 20, by the INFN (Italy, by the CNRS/IN2P3 (France), by grants MCYT FPA2000-2041-C02-02 and XUGA PGID T02PXIC20605PN (Spain) and by INTAS grant 03-51-3208 (EU).

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