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$\phi(1020)$-meson identification with the HMPID detector in the ALICE experiment

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Summary. — The ALICE experiment at CERN is devoted to study hadronic matter at extreme conditions of temperature, energy density and its phase transition to QGP. The $\phi_{(1020)}$-meson is a good probe for studying the features of the quark-gluon plasma. The ALICE detectors will identify particles at high momenta. In particular the HMPID would identify kaons with $1 \leq p \leq 3$ GeV/c, therefore it will be possible to identify ϕ-mesons through the channel $\phi \to K^+K^-$ up to 6 GeV/c. In this paper will be shown the physical motivations for the study of ϕ-meson and its invariant mass spectrum.

PACS 12.38.Mh – Quark-gluon plasma.
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Hadronic matter at high energy density and high temperature undergoes a phase transition and a new state of matter, named Quark-Gluon Plasma (QGP), is formed. By relativistic heavy-ion collisions it is possible to reach the physical conditions to have such a phase transition. One of the main problems to study the quark-gluon plasma is that it should be created for a very short time, 4 fm/c, and subsequebtly the hadronic matter undergoes further interactions so that the QGP signals are hidden in the measured observables. This means that the features of the plasma can only by inferred by data. The highest energy ever reached so far is $\sqrt{s_{NN}} = 200$ GeV for Au-Au collisions at the Brookhaven National Laboratory. The collider used is named RHIC and four experiments were built up: STAR, PHOBOS, PHENIX and BRAHMS. One of the main results coming from RHIC data is that these collisions cannot be considered as a superposition of single pp collisions [1], so there is a new dynamics to be understood and it seems that their evolution consists of three main phases.

When the two nuclei collide [2] during the first phase (the *thermalization phase*) the system reaches a very high temperature in less than 1 fm/c and a phase transition occurs. This implies that the hadronic matter loses its identity, that is baryons and mesons do not exist anymore, and their quarks and gluons interact in a volume as big as the nuclear one (the quark-gluon plasma state). Subsequently the system starts expanding (the *expansion phase*) and it cools until the physical conditions for the existence of baryons and mesons

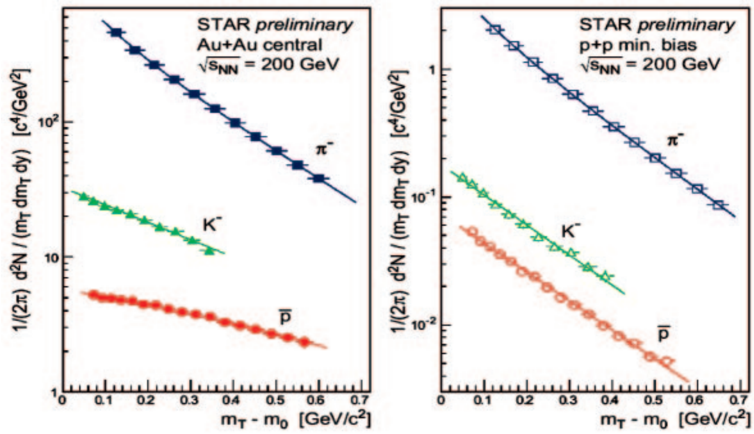

Fig. 1. – Left: hadron spectra from Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Right: hadron spectra from pp collisions at $\sqrt{s_{NN}} = 200$ GeV. The data are from the STAR experiment at BNL (see [2]).

occur again. After more or less 10 fm/c from the beginning of the collision the quarks rearrange themselves into hadrons and the hadronization phase begins. The hadrons form and interact among themselves. When all the particles formed do not interact anymore the *freeze out phase* begins so the barions and the mesons travel undisturbed and reach the detectors. This means that whatever is observed, it comes from the freez eout phase and the QGP signals are hidden. An evidence of how different heavy-ion collisions are from pp collisions is shown in fig. 1. The transverse mass spectra of protons, kaons and pions in Au-Au and pp are shown at the same energy. In a static fireball, as the one formed in pp collisions, the behaviour of such spectra is described by the formula $\mathrm{d}N/(\mathrm{d}ym_\perp \mathrm{d}m_\perp) \sim m_\perp^{1/2} e^{-m_\perp/T}$, where $m_\perp = \sqrt{p_\perp^2 + m^2}$ and T is the temperature of the freeze out.

In pp the particles are formed at the same T and this value corresponds to the temperature of the freeze out, that is the phase during which no more interactions occur.

In the case of the heavy-ion collisions, at the same energy, something new breaks the scaling of the hadron production introducing a blueshifted freeze out temperature at low $m_\perp$.

The new feature of heavy-ion collisions is that the particles are in a collective flow that push them away. This implies a relativistic blueshift factor that reflects the boost of the thermal radiation *towards* the detectors with radial-flow velocity v_T. The spectrum was calculated [3] and the result is the following:

$$\frac{\mathrm{d}N}{\mathrm{d}ym_T\mathrm{d}m_T} \sim e^{-\frac{m_T}{T_{\mathrm{slope}}}} . \tag{1}$$

At low $m_\perp$ the slope depends on the mass, whereas at high $m_\perp$ the scaling is restored. In fact, if $i =$ *proton, kaon, pion*,

– $\sqrt{m_\perp^2 - m_i^2} \ll m_i$, $\qquad T_{\mathrm{slope}} \approx T_f + \frac{1}{2} m_i \langle v_\perp \rangle^2$,

– $\sqrt{m_\perp^2 - m_i^2} \gg m_i$, $T_{\text{slope}} \approx T_f \sqrt{\frac{1+v_\perp}{1-v_\perp}}$.

The momentum spectra provide important information about the freeze-out phase but not about the QGP formation, its signals are exctracted by comparisons of the detected particles. One of the main features of the plasma formation is the strangeness enhancement. The strange hadron formation from QGP is a two-step mechanism [4]: gluon fusion into strangeness, followed by QGP recombinant hadronization. The strange quanrks produced by gluon fragmentation coalescence in hadrons so mass thresholds and the OZI rule is not valid anymore and an enhanchement with respect to pp collisions is observed.

The identity of strange particle-antiparticle yields and spectra implies that both strange matter and antimatter must have been produced from a common source by the same fundamental mechanism. The ϕ-meson is an $s\bar{s}$ bound state (without low-mass resonances) so its production is influenced by QGP formation.

Furthermore statistical models about the chemical properties of the plasma show that also the ratio $2\phi/(h^+ + h^-)$ is important to understand QGP [5]. In general the ϕ-meson is a good probe for the QGP [6]. Its lifetime is about 45 fm/c ($\tau_{\text{collision}} < 15$ fm/c) and it has a small cross-section for scattering with nonstrange hadrons. This means that its $m_\perp$ spectrum provides useful information on freeze-out conditions. A good decay channel for ϕ-meson identification is the $\phi \to K^+K^-$ because it is not influenced by the early stages of the collision as the electromagnetic one. The ALICE experiment at CERN will study the quark-gluon plasma formation and the identification of ϕ-meson via K^+K^- pairs by TOF and HMPID detectors. The latter device is a RICH detector and it can identify kaons in the momentum range $1 < p < 3$ GeV/c ($\phi(1020)$ up to 6 GeV/c). The RICH identifies protons, kaons and pions at momenta higher than 1 GeV/c, but its acceptance is 8% in $-0.5 < \eta < 0.5$. The analysis done is based on simulated data in the AliRoot framework [7]. The limited acceptance and the momentum thresholds due to the Cherenkov effect do now allow to generate a useful number of full Hijing reconstruceted events to have a good statistics for the mesons. A simulation strategy was used to overcome the problem. To study the ϕ detection using RICH detector, 175000 Hijing events were generated in the AliRoot framework, simulating Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. Only kinematics was generated, the reconstruction was made lately on selected particles and according to HMPID performances. Each particle was considered as a track and its momentum, coming from kinematical calculations by Hijing generator, was smeared according to the data in ref. [8] and then two selection cuts were applied to kaons, pions and protons. Only the hadrons having $p > 1.3$ GeV/c and η within the interval $[-0.9, 0.9]$ were considered as good candidates for the reconstruction by HMPID. The identification implies an assignment of a probability to each particle, so a selection about probability was done. By previous analysis it was shown that a contamination of 10% for kaons was present if a probability cut at 80% was applied, so this value was the one chosen to consider a kaon a good candidate for the ϕ invariant-mass calculation. The ϕ-meson invariant-mass spectrum is a small signal masked by an enormous background. In fig. 2 the invariant-mass spectrum of the pairs K^+K^- is shown using the kinematical momenta of kaons generated by 50000 Hijing events without any selection.

The total yield can be considered a sum of the background and the signal, so exctracting the signal means subtracting the background, so in order to have the signal yield, it is necessary to estimate how the background is.

There are several methods to calculate the background yield and it is important to study what is the best time by time. The remaining signal is eventually fitted by a Breit-

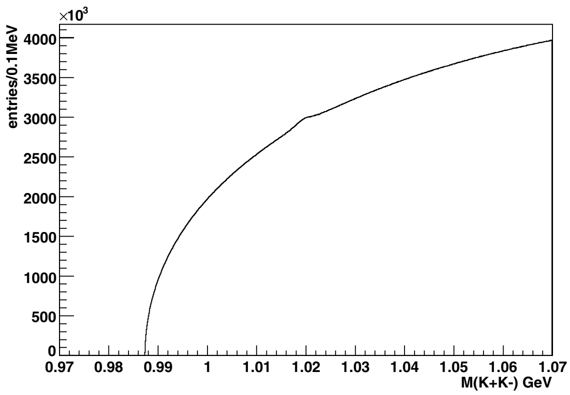

Fig. 2. – The invariant-mass spectrum obtained by kaon momenta without any cut and perfect identification.

Wigner convoluted with a Gaussian. Furthermore there is another approach to avoid the background estimate. The total yield is fitted with a function that provides *a priori* a shape for the background and the total yield can be either a sum of the signal and the background or a function of both.

In the analysis it was used the second approach and the formula chosen to fit the spectrum is the same as the one used in WA77 Collaboration for ϕ-mesons having momentum $p > 2$ GeV/c [9].

$$\frac{\mathrm{d}N}{\mathrm{d}m} \sim BKG(m) \cdot \left(1 + \frac{m}{q(m)} \cdot BW(m)\right) . \tag{2}$$

$q(m) = p^*(m) = \frac{\sqrt{[(m^2+(m_1+m_2)^2)\cdot(m^2-(m_1-m_2)^2)]}}{2\cdot m}$,

$BKG(m) \sim (m - m_{\mathrm{threshold}})^{\alpha} \cdot e^{-b\cdot m}$,

$BW(m) \sim \frac{\Gamma(m)}{(m^2-M^2_{\phi PDG})^2+\Gamma^2 M^2_{\phi PDG})^2}$,

$\Gamma(m) = \frac{q(m)}{p^*_{PDG}} \cdot \frac{M_{\phi PDG})}{m} \cdot \Gamma_{\phi PDG} + RSL$.

RSL is the sperimental resolution and $m_{\mathrm{threshold}} = 2m_{\mathrm{kaon}}$. The free parameters are six: the normalization factors (one for $\mathrm{d}N/\mathrm{d}m$ and the other for the Breit-Wigner), α, b, Γ, RSL. They were reduced to five by imposing that the parameter of the $\mathrm{d}N/\mathrm{d}m$ was such that the integral of the function was equal to the number of entries in the histogram. In the analysis both HMPID geometrical acceptance in $-0.5 < \eta < 0.5$, that is 8%, and the tracking efficiency were not taken into account. The latter was supposed to be costant in the momentum range $1 < p < 3$ GeV/c so both of them are just a scale factor in the yields. The result is shown in fig. 3.

The number of ϕ's produced in the simulation was $N^{\phi}_{\mathrm{AliRoot}} = 198704$, whereas the number obtained integrating the Breit-Wigner is $N^{\phi}_{\mathrm{fit}} = 197327 \pm 16364$. The signal over background value was $S/B = 0.04$, whereas the significance of such a fit was $S/\sqrt{(S+B)} = 91$. This means that the signal extracted by this fitting procedure is well separated by the background. Furthermore the width of the Breit-Wigner was $\Gamma_{\phi} = 4.39 \pm 0.05$

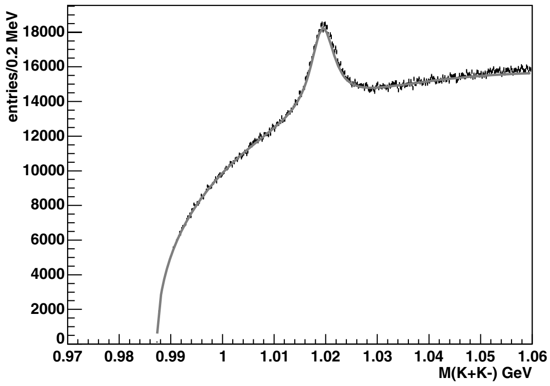

Fig. 3. – The invariant-mass spectrum and the fitted function.

MeV according to the AliRoot value of $\Gamma = 4.43$. The experimental resolution, *RSL*, was 1.8 MeV. In fig. 4 it is shown how both the fitted Breit-Wigner and the background subtracted yield look like. Such a small error (0.05 MeV) is important in comparison with theoretical predictions that show a modification of the width value and the mass value of the meson due to the QGP formation [10-12]. A contribution at lower values should appear in the mass spectrum, mostly in the $\phi \to e^+e^-$ channel, and the width may change up to $\Gamma_\phi \sim 10$ MeV. The small experimental resolution allows to measure such a difference in the width. In the analysis the ϕ mass was fixed but it is possible also to leave the mass as another free parameter to fit. The study of ϕ-meson from simulated data was also performed by another group of the ALICE Collaboration at lower momenta [8]. In the analysis the signal coming from the background subtraction of the total yield was considered. The simulation of background was done by the *event mixing technique* and the fit was done as a convolution of a Breit-Wigner and a Gaussian. So far the PHENIX Collaboration at BNL performed the identification of ϕ [13] making many efforts to know how the background should be calculated. They made a comparison between two different techniques and used the *event mixing technique* to exctract the ϕ

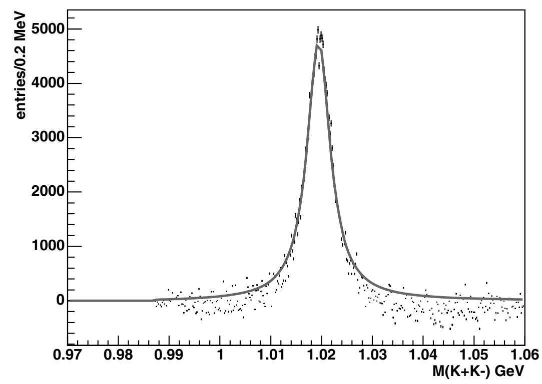

Fig. 4. – The invariant-mass spectrum obtained by backround subctration. The background was calculated using the event-mixing technique.

signal. Their fitting technique was done using a convolution of a Breit-Wigner and a Gaussian. Their results do not show any modification in the mass value and the width.

1. – Conclusions

In this work the physical motivations were shown that lead to the study of the $\phi(1020)$ in heavy-ion physics, the invariant-mass spectrum coming from $\phi \to K^+K^-$ and the fitting procedure used to identify the meson itself. The kaons were identified by the HMPID detector in the ALICE experiment. The simulation procedure and the reconstruction took into account the limited acceptance region of the HMPID. The fitting procedure was chosen in order to avoid background subtraction for the exctraction of the ϕ signal. Such a procedure gives a good separation between signal and background and it is sentitive to changes of the width of the ϕ as it was predicted theoretically.

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