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Multi-strange-quark states at ultra-relativistic heavy-ion collisions

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Abstract. We examine the possibility of producing and evidencing exotic strange matter (strangelets and metastable multi-hypernuclear objects, MEMO's), including also pure hyperonic bound states ($(\Lambda\Lambda)_b$, $(\Xi\Lambda)_b$), at RHIC and LHC. Simulations are presented to estimate the sensitivity of the STAR and ALICE experiments to the detection of these objects, focusing mainly on metastable short-lived (weak decaying) strange dibaryons, with a particular emphasis on the H-dibaryon, a six quark-bag bound state (*uuddss*).

Keywords. Strangeness; heavy-ions; quark gluon plasma.

1. Strange cluster production at RHIC and LHC

It is often speculated [1–3] that strange quark matter could be produced in heavy-ion collisions via two different scenario: by coalescence of hyperons and nucleons in a hadronic medium [4] or by a strangeness distillation process [5] in a quark gluon plasma (QGP). The latter mechanism requires in principle a large baryonic chemical potential (μ_B). But the mid-rapidity region covered by the central barrel of STAR or ALICE does not, *a priori*, offer such conditions. Nevertheless, the first measurements at RHIC show that the free net baryon regime is still not reached. Moreover, some calculations [6] indicate that, even at LHC where μ_B is expected to be almost zero, there might be non-negligible fluctuations of μ_B between different rapidity bins in the central region. Hence distillation could take place locally.

Beside this possible hindrance, we have to consider that the overall conditions for QGP formation and existence should be better at RHIC and even more at LHC than at all other accelerators. Consequently, if a strangelet really needs a QGP to be created, its production probability could be enhanced at the new colliders.

Coming back to the first scenario, relativistic heavy-ion collisions provide a prolific source of hyperons which could, together with nucleons, coalesce during the later stage of the reaction and form MEMO's or purely hyperonic clusters, creating a doorway state to strangelets. For example, a dilambda could be formed by the coalescence of two Λ's and transform to a H-dibaryon.

2. The search for strange dibaryons at RHIC and LHC

The search for exotic strange clusters is in progress at the new colliders. The central barrel of STAR and ALICE offer in principle the possibility to investigate both situations: long and short lifetime objects. But this central apparatus is much better suited to the second case which implies the search for weak decay topologies like the H-dibaryon or the dilambda decay. It covers the pseudorapidity domain of $|\eta| < 1$. This large angular acceptance of $45° < \theta < 135°$ is well adapted to the search of specific decay patterns, via secondary track reconstruction, secondary vertices and kink finding.

In order to estimate the sensitivity of STAR and ALICE to the H^0, we will study the capability of the apparatus for reconstructing the two following decay channels: $H^0 \longrightarrow \Sigma^- p \longrightarrow n\pi^- p$ and $H^0 \longrightarrow \Lambda p\pi^- \longrightarrow p\pi^- p\pi^-$. The first one is difficult to see in the huge background environment of STAR and ALICE because of the very short Σ^- track length and because of the undetected neutron. For this reason, at first, we will focus on the second mode, in which the sequential decay leads to the reconstruction of two successive vertices, each connecting a proton track with a π^- track. After mixing of the H^0 daughters with the simulated event products and full event reconstruction, one has to develop specific H^0 finding algorithms and produce the H^0 invariant mass distribution. From this simulation, the detector efficiency and sensitivity will be derived.

2.1 *The $H^0 \longrightarrow \Lambda p\pi^-$ weak hadronic decay in STAR*

As a first attempt, we have considered a mass of 2210 MeV for the H^0, the same lifetime as for the Λ ($\tau = 2.6 \times 10^{-10}$ s), a constant rapidity distribution limited to the mid-rapidity region ($-1 < y < +1$) and an exponential transverse mass distribution. After H^0 mixing within realistic simulated events, detector digitization and full event reconstruction (space point finding, tracking and particle identification) in TPC, we have to find, from the secondary track analysis, all the secondary $p\pi^-$ vertex (the so-called V^0) candidates. Then, among this background of V^0s, one has to find the V^0–V^0 pairs that could correspond to a H^0 decay.

We have obtained the first estimate of those quantities by simulating 10^4 events with 700 charged particles per unit of rapidity. This number corresponds roughly to the measured rapidity density in STAR for central Au+Au events at 200 A·GeV. A mean multiplicity of seven H^0s per event, in the $-1 < y < +1$ rapidity range, has been considered for this purpose. This represents a total of 7×10^4 generated H^0s.

Among them, 140 are correctly reconstructed, corresponding to an efficiency $\varepsilon = 2 \times 10^{-3}$. They generate a clear peak in the $\Lambda p\pi^-$ invariant mass distribution shown in figure 1. This preliminary result can be improved by optimizing the set of selection cuts, at the V^0 finding level as well as at the V^0 association procedure step. The background level in the H^0 mass domain ($m_{H^0} \pm 7$ MeV) is about 100 counts. The shape of the background (see figure 1), which shows large fluctuations, has to be investigated more. Nevertheless, by extrapolating the background to full statistics expected in STAR, $N_{\text{event}} \sim 10^7$ central events, one may deduce the detector sensitivity. Observing a H^0 signal, above the background at 3σ confidence level, implies about 960 H^0s (n_{H^0}) reconstructed.

Taking into account the total number of analyzed events and the efficiency, the estimated sensitivity is $\mathrm{d}N_{H^0}/\mathrm{d}y = 2.5 \times 10^{-2} H^0$ per event (for $|y| < 1$). In order to get more accurate estimates, it is foreseen to perform H^0 embedding into real data.

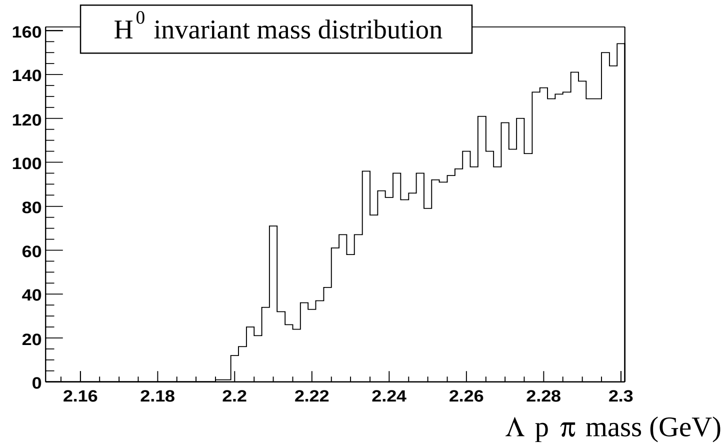

Figure 1. $\Lambda p\pi^-$ invariant mass spectrum for $H^0 \longrightarrow \Lambda p\pi^-$ obtained from reconstruction of STAR simulated events.

2.2 *The H^0 decay in ALICE*

The sensitivity of ALICE to the $H^0 \longrightarrow \Lambda p\pi^-$ decay is estimated here at a fast simulation level, without full tracking and V^0 finding. This essentially means that we have to make some assumptions on the expected V^0 background.

First of all, we have calculated the acceptance of the H^0 decay chain integrated over rapidity and transverse momentum, for various lifetimes, considering again an initial H^0 phase space distribution restricted to $-1 < y < +1$ with $\mathrm{d}N_{H^0}/\mathrm{d}y =$ constant in this rapidity range. Then, the rate (R) of reconstructable H^0s is given by this acceptance factor (Acc) times the secondary track and V^0 finding efficiency ($\varepsilon_{\rm sec}$): $R = \varepsilon_{\rm sec} *$ Acc. The quantity $\varepsilon_{\rm sec}$ represents the probability to get the four secondary tracks correctly reconstructed and to find the two V^0s of the H^0 decay. This number is approximated by the square of the Λ reconstruction efficiency. The rate of reconstructable H^0s computed in this way depends on the H^0 lifetime, for $\tau = 2.6 \times 10^{-10}$ s, R is equal to 0.2%.

The next step is to estimate the global reconstruction efficiency, including the $V^0 - V^0$ association algorithm described in the previous section and to get a reasonable estimate of the combinatoric background. For this purpose, a total amount of 5×10^4 events has been simulated, with an initial H^0 yield of 2 per event on the average. Each of these events contains an average number of about 100 $p\pi^-$ secondary vertex candidates. The rate R being of 0.2%, the total number of reconstructable H^0 present in this set of events is equal to 200, i.e. one candidate every 250 events.

The H^0 reconstruction is applied to all the simulated V^0s, event by event, assuming the momentum, angular and vertex position resolutions which are currently used in the ALICE fast simulations. We get an efficiency of 1.7×10^{-3}: a total of about 170 true reconstructed H^0s (the peak in the invariant mass distribution shown in figure 2, and a background of about 200 counts. For the statistics of 10^7 events, the extrapolated sensitivity per unit of rapidity in the central region ($|y| < 1$) is of about $1.75 \times 10^{-2} H^0$ per event.

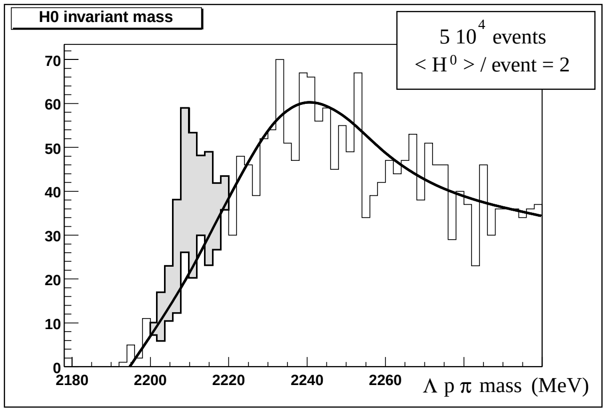

Figure 2. $\Lambda p\pi^-$ invariant mass spectrum for $H^0 \longrightarrow \Lambda p\pi^-$ obtained from reconstruction of ALICE simulated events.

3. Summary and outlook

The preliminary study of the detectability of exotic strange clusters in the central barrel of STAR and ALICE exhibits encouraging results for short-lived objects. In particular, the discovery of the H-dibaryon or dilambda weak hadronic decay to $\Lambda p\pi^-$ seems to be possible if the production rate of these hypothetical particles is higher than 2×10^{-2} per rapidity unit in the mid rapidity ($|y| < 1$) region of a central heavy-ion collision at RHIC or LHC. This sensitivity level may be improved substantially by optimizing the reconstruction methods and selection cuts used to recognize the decay topology, in order to reduce as much as possible the combinatorial background. Furthermore, the possibility of looking for the $H^0 \longrightarrow \Sigma^- p$ weak decay will be examined soon. Besides, two other priorities must be mentioned: the search for $H^0 \longrightarrow \Xi^- p$ strong interaction resonances and the investigation of other possible hadronic dibaryon decays, the $(\Xi^0 p)_b$ for example, for which we hope to reach at least comparable sensitivities.

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