Formation and decay of hadronic resonances in the QGP

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Hadronic resonances can play a pivotal role in providing experimental evidence for partial chiral symmetry restoration in the deconfined quark-gluon phase produced at RHIC. Their lifetimes, which are comparable to the lifetime of the partonic plasma phase, make them an invaluable tool to study medium modifications to the resonant state due to the chiral transition. In this paper we show that the heavier, but still abundant, light and strange quark resonances $K^*$, $\phi$, $\Delta$ and $\Lambda^*$ have large probability to be produced well within the plasma phase due to their short formation times. We demonstrate that, under particular kinematic conditions, these resonances can be formed and will decay inside the partonic state, but still carry sufficient momentum to not interact strongly with the hadronic medium after the QCD phase transition. Thus, $K^*$, $\phi$, $\Delta$ and $\Lambda^*$ should exhibit the characteristic property modifications which can be attributed to chiral symmetry restoration, such as mass shifts, width broadening or branching ratio modifications.

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I. INTRODUCTION

Measurements of experimental observables in hadron-nucleus collisions at relativistic energies strongly suggest that final-state hadrons are not produced at the moment of collisions $\tau_{\text{coll.}} \sim R_A/\gamma$, $\gamma = E_N/m_N$. Instead, they require a finite formation time, which can be viewed as the time needed to build up the hadronic wave function, i.e. the time to establish wavefunction overlap between the constituent partons. Based on the uncertainty principle and time dilation, the production of relativistic particles is supposed to follow a simple particle energy dependence, i.e. low energy particles are produced first, high energy particles - last. In elementary particle physics this is known as the ‘inside-outside cascade’. Its main features have been verified in many deep inelastic scattering experiments \cite{1}. The measured dependence of hadron production modification on the mass of the nuclear target shows how important the interplay of this simple hadronization time dependence and the space-time evolution of the parton-nucleus interaction can be. Several model calculations have argued that ‘pre-hadron’ formation is a possible mechanism that can account for the scaling of hadron multiplicity ratios in cold nuclear matter \cite{2, 3}.

In relativistic heavy ion collisions (A+A) the hadron formation time is of even greater importance because, here, a portion of the hadrons are likely formed during the partonic lifetime of the quark-gluon plasma (QGP), and therefore will generate a mixed phase with the QGP. The interactions of these hadrons with the plasma phase could potentially be used to elucidate both fundamental physics concepts and specific physics mechanisms, such as the existence of chiral symmetry restoration in high energy nuclear collisions or the nature of heavy flavor energy loss in the plasma. Adil and Vitev \cite{4} have recently shown that early hadronization of heavy quarks triggers a new type of interaction between the charm and beauty mesons and the hot partonic medium. Collisional dissociation of heavy mesons in the QGP emulates large energy loss and leads to significant suppression of their experimentally observed cross sections, as measured through semi-leptonic decay channels by STAR and PHENIX \cite{5, 6}.

In this paper we build upon the recent developments toward incorporating the space-time picture of hadronization in heavy ion phenomenology and evaluate the formation time of light- and strange-quark heavy-mass hadronic resonances, such as the $K^*$, $\phi$, $\Delta$ and $\Lambda^*$, in order to determine the probability of interaction between early-formed resonances and the partonic medium. In the second part of the paper we propose, based on the encouraging model results, a specific triggered jet correlation measurement for RHIC and the LHC, which could resolve the question of resonance modification \cite{7, 8, 9}, including baryon states \cite{10}, through partial chiral symmetry restoration.
II. TREATMENT OF FORMATION TIME IN HIGH ENERGY COLLISIONS

The simplest formulation of the energy and mass dependence of the inside-outside cascade [11] can be written as:

$$\tau_{\text{form}} = \frac{\tau_0 E}{m},$$  \hspace{1cm} (1)

where $\tau_{\text{form}}$ is the formation time, $\tau_0$ is the proper formation time in the hadron’s rest frame, $E$ is the energy of the hadron and $m$ is its mass. Eq. (1) has the transparent interpretation of a Lorentz-dilated interval $\tau_0 \sim R_h \sim 1 \text{ fm/c}$. In such a model high energy particles are produced later, and heavy mass particles are produced earlier.

The space-time picture of hadronization was re-examined for string fragmentation models, such as the Lund model [12], to point out that different hadron constituents are produced at different times [13, 14]. One can then distinguish between a constituent length, which is the time ($c = 1$) after which the valence quarks of the hadron are formed through color string breaking, and the formation length, which is the time when the quarks coalesce to form a hadron. Between constituent length and formation length the structure can be envisioned as a pre-hadron. The constituent length itself vanishes when the hadron is near the kinematic limit $z \to 1$ and this inverted formation hierarchy is known as an inside-outside cascade. If final-state hadron (or pre-hadron) absorption in cold nuclear matter is the origin of the measured cross section attenuation in the HERMES semi-inclusive DIS measurements [15], constituent length would appear to more accurately capture the dynamics of meson and baryon production in high energy collisions.

In this paper we are primarily interested in the production of leading strange-quark resonances and their baryon production in high energy collisions. Consequently, let us revisit the formation time evaluation [4], which is most easily understood in the context of independent fragmentation [16, 17]. In momentum space, in lightcone coordinates, the fragmentation of a parton of mass $m_q$ into a hadron of mass $m_h$ and a light secondary parton can be represented as:

\[
\begin{bmatrix}
p^+, \frac{m_q^2}{2p^+} \ 0 \end{bmatrix} \rightarrow \begin{bmatrix}
p_{\text{hadron}}^+, \frac{k^2 + m_h^2}{2p^+} \ 0 \ \ 0 \ 0 \ 0 \end{bmatrix} \rightarrow \begin{bmatrix}
p_{\text{form}}^+, \frac{k^2}{2(1-z)p^+} \ 0 \end{bmatrix} \ \ (2)
\]

Here $p^+$ is the large lightcone momentum of the parent parton and $|k| \sim \Lambda_{\text{QCD}} \sim 200 \text{ MeV/c}$ is the deviation from collinearity. We can evaluate the lightcone $\Delta y^+ = \tau_{\text{form}} + l_{\text{form}}$ that is conjugate to the non-conserved lightcone momentum component $\Delta p^- = (p^-)_{\text{final}} - (p^-)_{\text{initial}}$ of the evolving system:

\[
\begin{align*}
\Delta y^+ &\simeq \frac{1}{\Delta p^-} \\
&= \frac{zp^+}{m_h} \times 2 \left[ m_h + \frac{k^2}{(1-z)m_h} - \frac{z m_h^2}{m_h^2} \right]^{-1} \ . \hspace{1cm} (3)
\end{align*}
\]

The formation time then reads:

\[
\tau_{\text{form}} = \frac{\Delta y^+}{1 + \beta_g}, \hspace{0.5cm} \beta_g = \frac{p_0}{E_0} \ . \hspace{1cm} (4)
\]

We note that Eq. (4) exhibits features of both inside-outside and outside-inside cascades. It can be interpreted, similarly to Eq. (1), as a boost to a proper formation time, which now depends on the details of the parent parton decay. Our results, however, also shows that $\tau_{\text{form}} \to 0$ when $z \to 1$. This effect is most pronounced for light pions, where $m_\pi < \Lambda_{\text{QCD}}$, and there is absolute scale sensitivity to the choice of the non-perturbative physics parameter $|k| \sim \Lambda_{\text{QCD}}$. For heavy resonances such sensitivity and the kinematic region of outside-inside cascade are strongly reduced.

III. QGP EVOLUTION

At present there is no reliable dynamical mechanism that can qualitatively describe the formation of a deconfined state, the quark-gluon plasma, in ultra-relativistic heavy ion collisions. Nuclear stopping, which at the partonic level is described by inelastic quark and gluon interactions in cold nuclear matter [18], plays a major role in the liberation of partonic degrees of freedom. However, for center of mass energies $\sqrt{s_{NN}} > \sqrt{s_{\text{QCD}}} \approx 17$ GeV the collision time $\tau_{\text{coll}} \approx 2R_A/\gamma$ is generally considered insufficient for isotropisation and/or equilibration of the QGP, should such state of matter be formed. For example, in central Pb+Pb collisions at the LHC $\tau_{\text{coll}} = 5 \times 10^{-3} \text{ fm/c}$ ($\to 0$) and can be used to mark the beginning of final-state evolution with very little uncertainty. We can gain insight in the timescale of medium formation using the approximate parton-hadron duality [19] and the uncertainty principle. In high energy hadronic collisions light pions dominate multiplicities and $\tau_0 \approx 1/(p_T)_{\pi}$. In our evaluation we take $(p_T)_{\pi} = 450 \text{ MeV/c}$ for central Au+Au collisions at RHIC [20] and note that there is approximately 25% variation of the mean transverse momentum in going from central to peripheral collisions. Extrapolations to LHC energies have been made using Monte Carlo event generator results, fit to the CDF collaboration data from $\sqrt{s} = 1.8 \text{ GeV} \ p + \bar{p}$ collisions [21].

Accounting for the above-mentioned variation in going from $N + N$ to $A + A$ collisions we find $(p_T) = 850 \text{ MeV/c}$ for central Pb+Pb collisions at the LHC. Consequently, $\tau_0^{\text{RHIC}} = 0.44 \text{ fm/c}$ and $\tau_0^{\text{LHC}} = 0.23 \text{ fm/c}$.

Gluon degrees of freedom (8 colors, 2 polarizations) dominate soft parton multiplicities at RHIC and the LHC.
and their density can be related to charged hadron rapidity density in a Bjorken expansion scenario as follows [19]:

\[ \rho(\tau) = \frac{1}{\tau A_\perp} \frac{dN^g}{dy} \approx \frac{1}{\tau A_\perp} \frac{3}{2} \frac{dN^{ch}}{dy} \frac{dN^{ch}}{d\eta}. \]  

(5)

Assuming local thermal equilibrium one finds:

\[ T(\tau) = \frac{3}{\sqrt{\pi^2 \rho(\tau)/16 \zeta(3)}}. \]  

(6)

In Eqs. (5) and (6) the average over the distribution of densities, and correspondingly temperatures, in the plane transverse to the collision axis is implicit. For \( b = 3 \) fm, \( dN^g/dy = 1100 \) at RHIC and \( dN^g/dy = 2800 \) at the LHC in Au+Au and Pb+Pb collisions, respectively, we find \( T(\tau)_{RHIC} = 435 \) MeV and \( T(\tau)_{LHC} = 713 \) MeV.

The lifetime of the QGP itself depends on the details of the expansion. Different hydrodynamic scenarios, including initial conditions and type of expansion, appear to be approximately consistent with the low \( p_T \) data. In general, the faster the transverse expansion \( \tau_T \neq 0 \), the shorter the lifetime of the plasma will be. Thus, we can relyably give only the upper time limit of the transition from the QGP phase to a hot hadron gas, corresponding to the case of longitudinal Bjorken expansion:

\[ \tau_{QGP} = \tau_0 (T_0/T_c)^3. \]  

(7)

For a critical temperature \( T_c \approx 180 \) MeV, we find at RHIC \( \tau_{QGP} = 6.2 \) fm/c and at the LHC \( \tau_{QGP} = 14 \) fm/c. We emphasize again that these are mean values over the reaction geometry and the hottest densest central region of the collision will have larger QGP lifetimes. On the other hand, transverse expansion will reduce the QGP lifetime, bringing the RHIC estimate in accord with the measurement of hadronic resonance suppression in conjunction with HBT measurements [22].

The qualitative dependence of leading hadron formation times on the mass of the particle and the momentum and mass of the parent areon are given in Figure 1. When compared to the lifetime of the QGP at RHIC and the LHC we observe that for a wide range of momenta, hadron formation times are well within the anticipated lifetime of the plasma.

This is of particular interest for hadronic resonances, i.e. states that might be formed and decay within the lifetime of the partonic medium. Here, the hadron formed in the QGP will experience in-medium interactions with the partonic system and decay off-shell if chiral symmetry restoration reduces its mass. Consequently, intermediate momentum resonances which are formed early and decay into particles that escape the partonic medium with little hadronic reinteration could be used to test chiral symmetry restoration. According to UrQMD calculations [23], hadronic reinteraction (rescattering and regeneration) processes only affect the low momentum region (\( p_T = 0-2 \) GeV/c) of the resonance spectra. Therefore, for higher momentum resonances, experimentally observable effects, such as reduced production rates, modification of the branching ratios, mass shifts and broadening of the widths in the QGP phase are expected to be detectable. We take this as an indication that a more detailed study of their production and decay is justified to help guide experimental searches at RHIC and the LHC.

**IV. FORMATION TIME OF HEAVY MASS RESONANCES IN THE PARTONIC MEDIUM**

The study of particle formation in high energy heavy ion collisions requires information about the distribution of the observed hadron momentum fraction relative to the parent quark or gluon, \( P(z) \). At fixed momenta \( \{ p_T \} = p_T, \cdots p_T, \cdots p_T \) and rapidities \( \{ y \} = y, \cdots y, \cdots y \), for a perturbative n-particle production event, including the simplest case of inclusive hadrons, this probability is given by:

\[ P(z) = \frac{1}{d\sigma^{h}(p_T, \{ y \})/d\sigma^{h}(p_T, \{ y \})} \frac{d\sigma^{h}(p_T, \{ y \})}{d\sigma^{h}(p_T, \{ y \})} dz. \]  

(8)

The principal theoretical difficulty in obtaining \( P(z) \) for resonances is their unknown fragmentation functions, \( D(z, Q^2) \). Limited experimental data on resonance production has hindered their inclusion in a global QCD analysis [10, 17]. The approach that we here undertake is to use as a guideline the known pion, kaon, proton, neutron and lambda decay probabilities in approximating fragmentation into resonant states, \( D_h(z, Q^2) \propto D_h(z, Q^2) \). One notes that the overall normalization of \( D_h(z, Q^2) \) cancels in Eq. (8) and it would require decay probabilities of drastically different shape to significantly alter \( P(z) \) and, consequently, the hadron formation times for \( m_h > \Lambda_{QCD} \).

To lowest order, the perturbative QCD cross sections of hard, \( p_T > \text{few GeV}/c \), inclusive and jet- or hadron-triggered (\( \Delta \varphi = \varphi_2 - \varphi_1 \approx \pi \) particle production are...
Formation time [fm/c] at a fixed momentum $p_T = 8 \text{ GeV/c}$.

In Eqs. (9) and (10) vacuum and medium-induced acoplanarity can also be incorporated [26], but these have a very small effect on the hadron formation in the kinematic region of interest. It is important to note that for triggered back-to-back correlations to lowest order $p_T/z_1 = p_T/z_2$ [27]. For our choice of fragmentation functions, Ref. [16], the small $z < 0.05$ region has to be extrapolated.

Results for the mean formation time of hadronic resonances as a function of their $p_T$,

$$\langle \tau_{\text{form}} \rangle = \int_0^1 dz P(z) \tau_{\text{form}}(z; p_T, m_h, m_q, k_T = \Lambda_{QCD}) \ ,$$

compared to the estimated lifetime of the plasma at RHIC, are given in Figure 2. We note that at fixed transverse momentum $\langle \tau_{\text{form}} \rangle$ is controlled primarily by the particle mass. At higher $p_T$ there is a systematic bias toward larger mean values of $z$ but these only affect the formation time of the lightest particles, such as $\pi$ and $K$. We also studied the validity of our assumption that we can get guidance for the formation times of resonant particles from the known $P(z)$ momentum fraction distributions for $\pi, K, p$, and $\Lambda$, shown in the insert of Figure 2 for $p_T = 8 \text{ GeV/c}$ at RHIC. $\tau_{\text{form}}$ for the $\phi$ meson was evaluated with all available momentum fraction distributions and the uncertainty, presented in Figure 2 is not significant. In the perturbative regime, $p_T > \text{few GeV/c}$ light hadron production takes place largely at times that exceed the QGP lifetime and the observed nuclear modification is dominated by inelastic interactions of the parent parton [19]. Heavy particles, however, tend to be produced inside the plasma and would undergo broadening or dissociation [2]. Depending on their $p_T$ range, $K^*$, $\phi$, $\Delta$ and $\Lambda^*$ are ideally suited to prove the early stages of the collision when the medium is hot and dense. We finally note that in the region $\langle \tau_{\text{form}} \rangle \sim \tau_{\text{col}} \ll \tau_0$ our separation of scales between hard and soft physics, upon which this study is based, is violated. Furthermore, only high momentum resonances ($p_T > 2 \text{ GeV/c}$) from the

\[ \frac{d\sigma_{hN}}{dy_1 dp_{T_1}} \bigg|_{p_T} = K_{NLO} \sum_{abcd} 2\pi \int_{x_{1,2} \leq 1} dy_1 \int_{x_{1,2} \leq 1} dy_2 \times \frac{D_{h_1/c}(z_1)\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \frac{\alpha_s^2}{S^2} |M_{ab\rightarrow cd}|^2 \cdot \left( 9 \right) \]

\[ \frac{d\sigma_{hN}}{dy_1 dp_{T_1} dp_{T_2}} = K_{NLO} \sum_{abcd} 2\pi \int_{x_{1,2,3,4} \leq 1} dy_1 dy_2 \times \frac{D_{h_1/c}(z_1)D_{h_2/d}(z_2)\phi_{a/N}(x_a)\phi_{b/N}(x_b)}{x_a x_b} \times \frac{\alpha_s^2}{S^2} |M_{ab\rightarrow cd}|^2 \cdot \left( 10 \right) \]
perturbative regime are considered, because low momentum bulk resonances from a thermal QGP phase will be formed later and are more likely, according to UrQMD simulation, to undergo large rescattering in the hadronic medium.

Calculations of the formation times of the resonant states of interest at the LHC are shown in Figure 3. It is remarkable that over a very large $p_T$ range (for $\Lambda^*$ almost to $p_T \sim 100$ GeV/c) these hadrons can provide information for the in-medium modification of particles in the background of hot dense matter. Our conclusion is also facilitated by the longer lifetime of the plasma created at the LHC. However, one has to take into account that the plasma density and thus the resonance-parton interaction probability will drop according to Bjorken expansion. Thus high momentum resonances formed late in a rather dilute plasma will not exhibit much of a medium modification. Furthermore the additional decay time of the resonances has to be taken into account, therefore a smaller momentum range will enrich the decays inside the dense medium.

V. RESONANCE INTERACTION AND DECAY IN THE PARTONIC MEDIUM

Medium modification of the resonance properties requires interaction with the partonic medium. There are no detailed models of parton-hadron interactions, but one can use an estimate of the collisional wavefunction broadening for the propagating resonance, characterized by $\Delta k_T^2$, $\Delta k_T = k_{\perp 1} - k_{\perp 2}$, as has been done previously for propagating heavy mesons [4]. The amount of broadening depends on the path length in the medium, the resonance formation time, the resonance lifetime, and the time-dependent medium density. For a meson it reads:

$$\Delta k_T^2 = 4 \left\langle \mu^2 \frac{L}{\Lambda} \right\rangle \xi \int_{\tau_{\text{form}}}^{\tau_{\text{decay}}} \alpha_s^2 \rho(z) dz . \quad (12)$$

In Eq. (12) $\mu$ sets the scale of typical momentum transfers from the medium to a valence quark and $\xi$ simulates the effect of the power law tails in Moliere multiple scattering. One notes that $\tau_{\text{decay}} = (\tau_{\text{decay}})^* \gamma$ depends both on the in-medium modification of the resonance lifetime and its momentum.

Given the small in-vacuum decay widths of heavy resonances, $\Gamma(K^*) = 50.8$ MeV, $\Gamma(\phi) = 4.65$ MeV, $\Gamma(\Delta) \approx 120$ MeV and $\Gamma(\Lambda^*) = 15.6$ MeV, in order to observe any effect of partial chiral symmetry restoration a self-consistent reduction in their lifetime, related to the width broadening, is critical. Otherwise, even if the partonic medium is radially co-moving with velocity as large as $\langle \beta > \gamma \sim 0.7c$ [28], it is likely that high momentum resonances with moderate in-vacuum lifetime (e.g. $K^*$, $\Lambda^*$) will have their decay point boosted outside of the QGP. This sets the constraint that the medium-modified lifetime of the resonance can not exceed a few fm/c. Several models have been applied in the past [7, 8] to calculate the broadening of the in-medium spectral functions and, although these calculations are based on interactions in a dense hadronic medium, parton-hadron duality arguments can hopefully allow to generalize the results to a quark-gluon plasma. It has been argued [9], on the example of the $\phi$ meson, that at $T = 250$ MeV the shortening of its in-vacuum lifetime can be as large as a factor of 10.

Furthermore, care should be taken in ensuring that the resonance propagates through an extended volume of hot and dense matter. Triggering on a strongly interacting particle biases the partonic hard scattering toward the surface of the fireball and guarantees that the away-side resonance must traverse a medium of larger spatial extent. The higher the trigger $p_T$, the more effective this
technique is expected to be. Ideally, one needs two handles to control $\tau_{\text{form}}$ and the trigger bias. Naively, one may expect that energetic hadron triggers that lead to sizable partonic $p^+$ will entail resonance formation outside of the QGP, see Eq. (3). However, the selection of an associated $p_T$ correlates the near-side and away-side momentum fractions, $p_Tz/p_Tt \approx z_2/z_1$. This relation is exact to lowest order and is illustrated for back-to-back particles of significantly different momenta, on the example of their probability distributions $P(z_1)$ and $P(z_2)$, in the top panel of Figure 1. The bottom panel of Figure 1 shows that for massive hadrons, $m_h \gg \Lambda_{\text{QCD}}$, the resonance momentum determines its formation time independent of the trigger $p_T$.

The 10-fold broadening of the $\phi$ meson decay width in medium at $T=250$ MeV, which was modeled in [2], implies $\Delta \Gamma_{\text{th}} \approx 50$ MeV. Using this thermal contribution to the decay width as a rough guidance, one can obtain estimates for the reduced lifetime of hadronic resonances. Subsequent accounting for the Lorentz time dilation and the time dependence of the QGP temperature at RHIC and LHC suggests that experimental studies should focus on hadronic resonances below 5 GeV/c (RHIC) or 10 GeV/c (LHC), respectively, assuming that the lifetime of the partonic medium has to at least equal the total resonance propagation time, including formation and decay. Due to the convolution of many dynamical effects, a more quantitative estimate on how many of the produced resonances will decay in the medium is near impossible at present. For example, there is a time distribution of formation and decay, $\propto [1 - \exp(-t/\tau_{\text{form}, \text{decay}})]$, suggestive that there will always be a small fraction of resonances, affected by the medium. But as has been the case in all previous studies, short lifetime resonances are more likely to exhibit a larger effect. Therefore studies of the $K^*$ ($c\tau = 3.88$ fm) and $\Lambda$ ($c\tau = 1.64$ fm) will yield stronger signatures than the $\Lambda^*$ ($c\tau = 12.6$ fm) and the $\phi$ ($c\tau = 46.5$ fm).

Finally, we address the question of dissociation of lightly bound resonances in the partonic medium, see e.g Eq. (12). Theoretically, this may lead to very strong resonance suppression, but experimental evidence at RHIC [29, 30] has shown that although the resonant over non-resonant particle ratios decrease in going from proton-proton to central Au+Au collisions, the survival rate of direct resonance production is large. It is difficult to quantify the rate because generation of resonances in the hadronic phase has also been experimentally verified [29]. A semi-quantitative analysis of direct $\phi$-production vs. $\phi$-production from $K^+ + K^-$ coalescence has shown that for longer lived resonances the hadronic contribution is small [31], but the relative strength of the hadronically generated resonance contribution changes with lifetime and hadronic interaction probabilities [32]. Recent measurements by PHENIX in the di-lepton sector [33] might be a first indicator that resonances are indeed medium modified in the hot partonic phase at RHIC. These results need to be evaluated in accordance with other RHIC measurements by STAR, though, which have shown that cold nuclear matter effects already modify the in-vacuum resonance properties, albeit on a small scale [30, 34].

VI. AN EXPERIMENTAL METHOD TO SEARCH FOR CHIRAL SYMMETRY RESTORATION

In order to experimentally verify the impact of the partonic medium on resonance properties we need to reconstruct intermediate momentum resonances which are produced early. This might be possible through the selection of resonances in the away-side jet of a triggered di-jet or $\gamma$-jet event. The trigger can be based on a reconstructed high momentum (leading) particle or the full near-side jet energy reconstructed in a calorimeter. Both methods lead to the identification of a near-side jet which is less affected by the medium due to the surface bias in the trigger. The $(\Delta \phi = \pi)$ correlations with the away-side associated particles will determine the modified jet. Full jet reconstruction on the near side is preferred, because it determines not only the exact $z$-distribution of the away-side jet fragments but also the jet axis. However, back-to-back jet simulations based on the reconstruction of leading trigger particles already show that the overall $z$-distribution of the leading particle on the near-side constrains the $z$-distribution of the associated particles on the away-side, as shown if Figure 4.

In order to study the chiral transition we propose a $\Delta \phi$ quadrant analysis (see Figure 5).

![Figure 5](image-url)

FIG. 5: Sketch of jet fragmentation into resonances ($\Lambda^*$ is taken as an example for all hadronic resonances) in the medium created in a heavy-ion collision. Same-side correlations of resonances are not affected by the medium, whereas the away-side high $p_T$ resonance might be affected by the early-time (chirally restored) medium. Thermal resonances, which are affected by the late-time hadronic medium are at $\pi/2$ with respect to the trigger particle.

The medium modification of resonance properties should be strongest in the away-side ($\Delta \phi = \pi$) quad-
rant using reconstructed resonances with momentum of $p_T > 2$ GeV/c which are correlated to the same-side jet axis or leading particle. They are likely to be produced early and thus will interact with the partonic medium, but their decay products will also escape the medium sufficiently fast to not exhibit much interaction in the late hadronic phase.

The low momentum resonances produced at an angle of $\Delta \phi = 1/2\pi$ or $3/2\pi$ with respect to the jet axis or leading particle are identified as thermal resonances produced late from the bulk matter of the collision. They do not populate the spectrum in proton-proton collisions, as shown in Figure 6, but they will be a dominant source in A+A collisions. In the proposed analysis they will be used as a reference, because they predominantly interact in the late hadronic medium. Therefore, their masses and widths are expected to not be altered much relative to the vacuum, unless phase space effects from late regeneration change the shape of the invariant mass signal.

The high $p_T$ same-side jet resonances are also expected to exhibit the vacuum width and mass because the initial quark is expected to fragment outside of the medium (surface bias effect). Therefore a differential measurement of high momentum resonances as a function of the angle to the jet axis might have a built-in reference system and may not require comparison to measurements in p+p collisions, which are very statistics limited for the rare hadronic resonance channels.

Figure 6 shows a simulation of the $\Delta \phi$ distribution for correlations between a trigger hadron and associated $\Delta$ resonances based on PYTHIA. The four quadrants proposed in Figure 4 are highlighted in the plot. Reconstructing the invariant mass in these specific $\Delta \phi$ ranges will yield information on mass shifts, width broadening and branching ratios. Quantitative studies of these properties as a function of resonance momentum, emission angle, jet energy, and jet tag, will directly address the question of chiral symmetry restoration in collisions of heavy nuclei. Early studies of this method have been reported recently based on a statistics limited data set at RHIC [33].

VII. SUMMARY AND CONCLUSIONS

The enhanced jet cross sections at the LHC will enable the heavy ion experimentalists to carry out an in-depth triggerable intermediate- and high-momentum resonance correlation program, which will scan the relevant kinematic domain to look for chiral symmetry restoration effects in hadronic resonances through the method described in this paper. We recognize the inherent uncertainties associated with the estimates of the formation and decay of hadrons in a highly relativistic, possibly strongly-coupled, quark-gluon plasma at high density and temperature, the possibility that resonances can be dissociated in the medium, and the finite probability that even at intermediate and high momentum hadronic rescattering of their decay products might mimic QGP effects. Nevertheless, this is the most complete study to date which uses theoretical input to guide the experimental searches for the chiral transition in QCD in conjunction with the deconfinement phase transition, one of the original drivers of the heavy ion programs at SPS, RHIC and the LHC. Based on our results, we anticipate that this method can yield a definitive measurement of the modification (or lack thereof) of the properties of hadronic resonances in the QGP. The fact that our proposed technique has a built-in reference by simply analyzing off-axis low momentum resonances in the same event makes it even more attractive experimentally.

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