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Vector mesons in matter

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Abstract. One consequence of the chiral restoration is the mixing of parity partners. We look for a possible signature of the mixing of vector and axial vector mesons in heavy-ion collisions. We suggest an experimental method for its observation. The dynamical evolution of the heavy-ion collision is described by a transport equation of QMD-type evolving nucleons, N^* and Δ resonances, Λ's and Σ baryons, and furthermore, π's, η's ρ's σ's ω's and kaons with their isospin degrees of freedom. The input cross-sections and resonance parameters of the model are fitted to the available nucleon–nucleon and pion–nucleon cross-sections.

Keywords. Vector mesons; chiral symmetry; medium effects.

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1. Introduction

The in-medium properties of hadrons is a topic of current interest. There is a long-standing and controversial discussion about the vector meson properties in dense nuclear matter [1–7]. Some of the models [1,2] suggest that the vector meson masses can be used to measure the chiral condensate providing information about the partial chiral restoration. However, QCD sum rule calculations do not necessarily lead to that conclusion [5]. Models based on hadronic degrees of freedom, on the other hand, do not see substantial mass reduction even at normal nuclear density [6,7].

Chiral symmetry requires that in the restored phase the spectral functions of parity partners are the same. This may happen in several ways. The possibility that the masses become the same in the restored phase is studied in several calculations. In this paper we study the possibility that the mass of the ρ- and A_1-mesons do not change substantially, but there is a mixing between their spectral functions. We look for an experimental signal of such a phenomenon.

Heavy-ion collisions in the energy regime from a few hundreds of A MeV up to about 2 A GeV offer a possibility to create and study hot, dense nuclear matter. We study heavy-ion collisions using a transport equation system of the QMD-type.

For the long-range interaction between nucleons we use a momentum-dependent force worked out in [8]. Using the small acceleration approximation they derive a relativistic scalar–vector force from a modified Zimányi–Moszkowski Lagrangian based on σ-, ω- and ρ-meson exchanges. The momentum dependence of the force is fixed automatically by the theory. They could describe the flow data of the FOPI Collaboration for bombarding energies of 150, 250 and 400 A MeV.

In the next section we show the details of our collision term. In §3 we study the consequence of the mixing of ρ- and A_1-mesons.

2. QMD model

At bombarding energies of a few GeV range several baryon resonances are excited, and thus we need to include them in our model. We use all four star resonances and some of the three star ones up to about 2.3 GeV. We include in our model the nucleons, 24 baryon resonances, Λ and Σ baryons, π-, η-, σ-, ρ-, ω- and K-mesons.

For elastic baryon–baryon cross-section we use the usual Cugnon parametrization [9].

We assume that the inelastic cross-sections are resonance dominated, and added incoherently. Meson absorption cross-section on a nucleon to a given resonance R is given by

$$\sigma_{\pi N \to R} = \frac{4\pi}{p^2} \frac{2S_R + 1}{2} \mathrm{CG} \frac{\Gamma_{\mathrm{in}} \Gamma_{\mathrm{tot}}}{(s - m_R^2) + s\Gamma_{\mathrm{tot}}^2}, \tag{1}$$

where $(2S_R+1)/2$ counts for the spin degrees of freedom ($(2S_R+1)$ for the resonance and 2 for the nucleon), CG is the appropriate Clebsh–Gordan coefficient, p is the center of mass momentum in the pion nucleon system. We use energy-dependent width for the resonances:

$$\Gamma(M)_{BM} = \Gamma_0 Br_{BM} \frac{\rho(M)_{BM}}{\rho(M_{\mathrm{r}})_{BM}}, \tag{2}$$

where $\Gamma(M)_{BM}$ is the partial decay-width of the resonance R with mass M to decay to the state BM, the resonance peak mass is M_{r}, and $\rho(M)$ is the phase-space factor with a cut-off:

$$\rho(M)_{BM} = \frac{p}{M} \frac{p^{2l}}{(\beta^2 + p^2)^{l+1}}, \tag{3}$$

where l is the partial wave and p is the c.m.s. momentum of the BM channel, β is a cut-off parameter. Special care is taken for such channels where the resonance with its peak mass cannot decay to a given channel. In our model these channels can be $N\omega$, ΣK and ΛK. In this case Br_{BM} does not have the meaning of a branching ratio, since that is defined at the peak mass. It is only a parameter describing the coupling strength. It can be even larger than 1 as one can see in table 1. In this case in eq. (2) instead of $\rho(M_{\mathrm{r}})_{BM}$ which is not defined, we use $\rho(M_{\mathrm{r}})_{N\pi}$.

The baryon resonance parameters such as mass, width and branching ratios are fitted by describing the meson production channels in πN collisions:

$$\sigma_{\pi N \to BM} = \sum_R \sigma_{\pi N \to R} \frac{\Gamma_{R \to BM}}{\Gamma_{\mathrm{tot}}}. \tag{4}$$

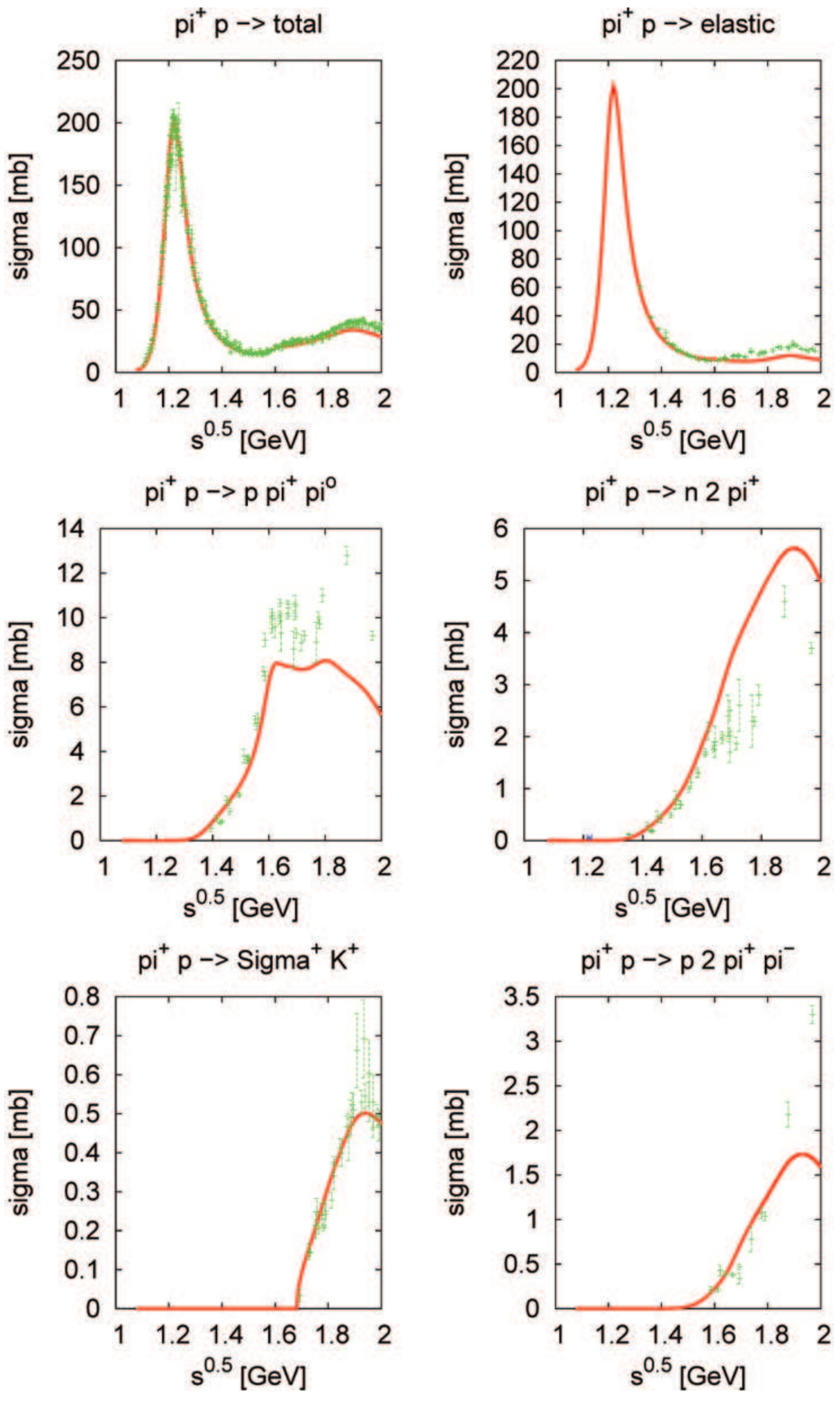

Figure 1. Results of the fit for π^+p reactions.

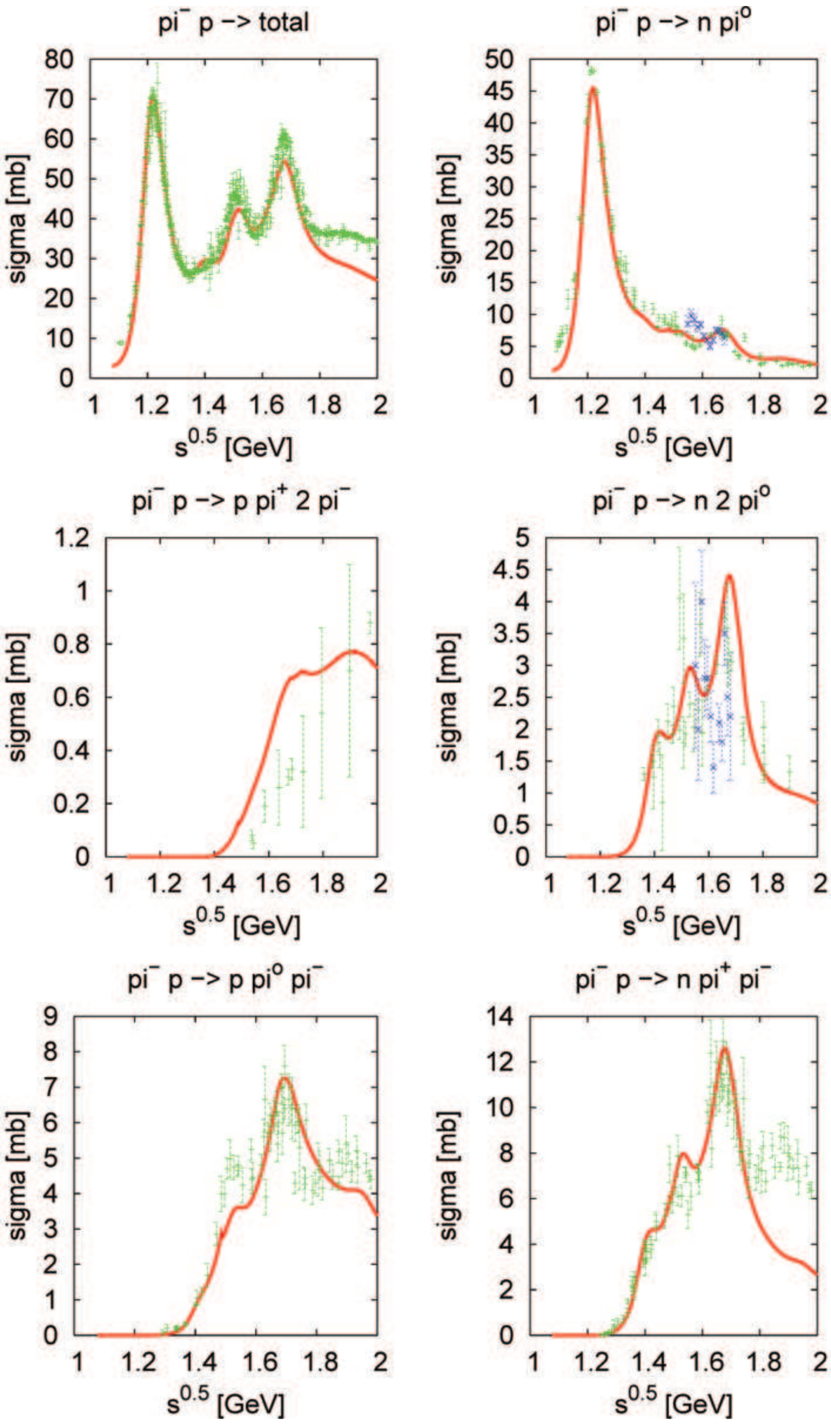

Figure 2. Results of the fit for $\pi^- p$ reactions.

Table 1. Resonance parameters, masses, widths and branching ratios. In the first column the masses of the resonances are given according to the Particle Data Book. Columns 2 and 3 give the fitted mass and width, and rest of the columns show the fitted branching ratios. For resonances where the peak mass is smaller than the masses of the decay products, for that decay channel the branching ratio has a different meaning. Explanation is in the text.

Mass (PD)	Mass	Width	$N\pi$	$N\eta$	$N\sigma$	$N\rho$	$\Delta\pi$	$P_{11}\pi$	$D_{13}\pi$	$S_{11}\pi$	ΣK	ΛK	$N\omega$
$N1440$	1.421	0.140	0.500	0.037	0.405	0.01	0.001	0.079	0.000	0.000	0.380	0.400	3.14
$N1520$	1.535	0.105	0.500	0.001	0.261	0.04	0.098	0.009	0.000	0.090	0.000	0.162	0.16
$N1535$	1.535	0.233	0.375	0.351	0.004	0.13	0.001	0.001	0.139	0.001	0.256	0.029	0.00
$N1650$	1.649	0.168	0.550	0.102	0.003	0.11	0.065	0.054	0.119	0.000	0.151	0.001	0.10
$N1675$	1.681	0.121	0.330	0.007	0.315	0.11	0.236	0.001	0.000	0.000	0.015	0.000	6.40
$N1680$	1.688	0.110	0.571	0.013	0.161	0.12	0.121	0.000	0.000	0.000	0.000	0.011	3.43
$N1700$	1.744	0.250	0.035	0.001	0.167	0.00	0.115	0.000	0.000	0.000	0.087	0.023	0.57
$N1710$	1.760	0.337	0.050	0.000	0.219	0.06	0.185	0.002	0.002	0.004	0.001	0.225	0.25
$N1720$	1.770	0.348	0.118	0.099	0.021	0.49	0.084	0.047	0.004	0.000	0.049	0.078	0.01
$N2000$	1.952	0.105	0.082	0.000	0.041	0.61	0.000	0.001	0.000	0.000	0.081	0.023	0.16
$N2080$	1.814	0.258	0.132	0.233	0.001	0.00	0.000	0.157	0.000	0.000	0.091	0.048	0.34
$N2190$	2.130	0.380	0.038	0.002	0.027	0.57	0.000	0.316	0.000	0.000	0.014	0.026	0.01
$N2220$	2.340	0.519	0.053	0.059	0.369	0.02	0.000	0.404	0.000	0.000	0.000	0.000	0.10
$N2250$	2.266	0.393	0.053	0.047	0.341	0.34	0.000	0.131	0.000	0.000	0.000	0.001	0.08
$D1232$	1.232	0.120	1.000	0.000	0.000	0.00	0.000	0.000	0.000	0.000	0.000	0.000	0.00
$D1600$	1.663	0.180	0.100	0.000	0.000	0.00	0.900	0.000	0.000	0.000	0.166	0.000	0.00
$D1620$	1.625	0.120	0.223	0.000	0.000	0.63	0.100	0.045	0.000	0.000	0.245	0.000	0.00
$D1700$	1.798	0.181	0.109	0.000	0.000	0.07	0.793	0.000	0.000	0.000	0.030	0.000	0.00
$D1900$	1.883	0.272	0.827	0.000	0.000	0.00	0.000	0.069	0.090	0.000	0.010	0.000	0.00
$D1905$	1.940	0.498	0.154	0.000	0.000	0.57	0.210	0.000	0.000	0.000	0.069	0.000	0.00
$D1910$	1.930	0.180	0.150	0.000	0.000	0.25	0.007	0.019	0.502	0.000	0.069	0.000	0.00
$D1920$	2.020	0.350	0.305	0.000	0.000	0.00	0.000	0.000	0.695	0.000	0.000	0.000	0.00
$D1930$	1.970	0.373	0.285	0.000	0.000	0.00	0.000	0.019	0.695	0.000	0.000	0.000	0.00
$D1950$	1.970	0.400	0.303	0.000	0.000	0.00	0.001	0.242	0.454	0.000	0.000	0.000	0.00

Here $\sigma_{\pi N\to BM}$, where BM denotes $N1\pi$, $N2\pi$, $N3\pi$, $N\eta$, $N\omega$, ΣK and ΛK states, is measured, the parameters of the right hand-side are fitted.

Resonance production cross-section $NN\to NR$ is given by the fit of

$$\sigma_{NN\to BM} = \sum_R \sigma_{NN\to NR}\frac{\Gamma_{R\to BM}}{\Gamma_{\rm tot}}. \tag{5}$$

Here BM denote the same states as before. The left-hand side is measured again. In the right-hand side the branching ratios are obtained by the previous πN fit, and the $\sigma_{NN\to NR}$'s are fitted. Here the resonance mass is not fixed by the input channel as in the πN case, and so we have to average over the kinematically allowed resonance masses.

For the fitting we use the Minuit package from the CERN library.

The resulting model describes the experimental data rather well. In figure 4 we compare our calculation with the experimental data of the KAOS Collaboration

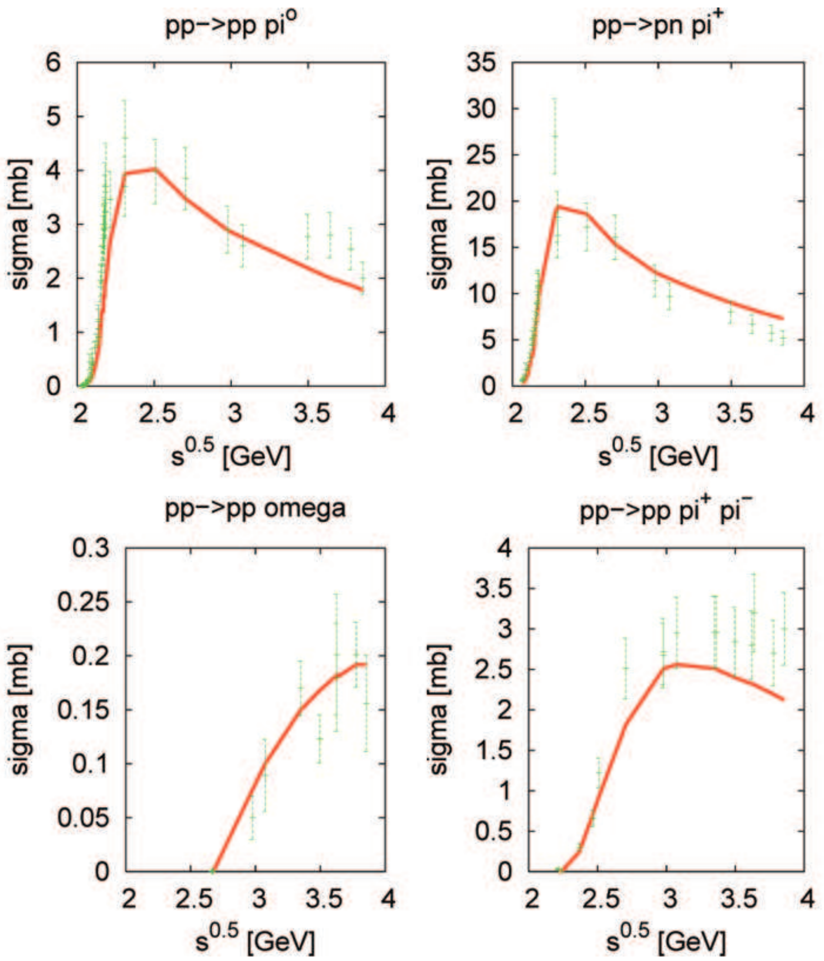

Figure 3. Results of the fit for pp reactions in the nonstrange sector.

[10]. The agreement is excellent, although in the heavy-ion case the experimental spectrum is somewhat stiffer.

3. ρ-A1 mixing

Due to the presence of real or virtual pions in nuclear matter the vector and axial vector correlators mix.

Krippa [11] derived a mixing theorem for a zero-temperature gas of noninteracting nucleons using soft pion theorems and current algebra,

$$\Pi_V^{\mu\nu}(q) = (1-\xi)\ \Pi_V^{\circ\mu\nu}(q) + \xi\ \Pi_A^{\circ\mu\nu}(q)$$
$$\Pi_A^{\mu\nu}(q) = (1-\xi)\ \Pi_A^{\circ\mu\nu}(q) + \xi\ \Pi_V^{\circ\mu\nu}(q). \quad (6)$$

Here, the mixing parameter

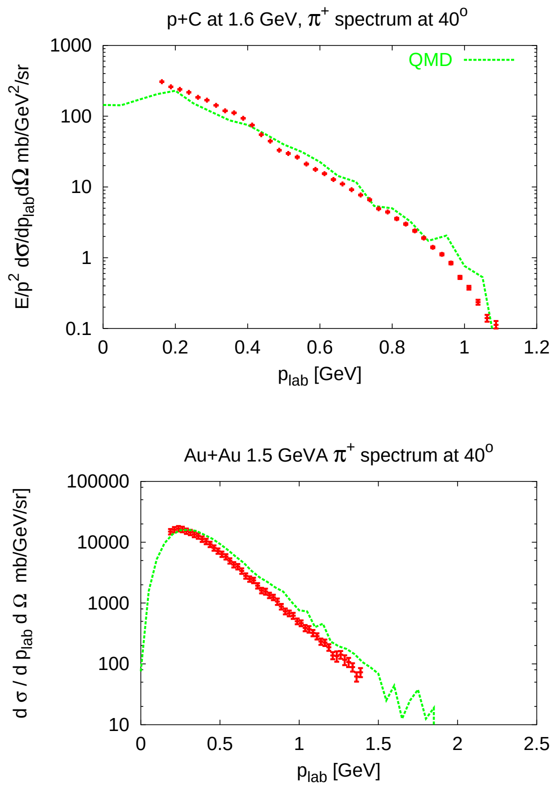

Figure 4. π^+ spectra at 40° measured by the KAOS Collaboration at SIS GSI. Upper panel: $p+\mathrm{C}$ at a bombarding energy of 1.6 GeV; lower panel: Au + Au at 1.5 GeVA bombarding energy.

$$\xi \equiv \frac{4\varrho_N \bar{\sigma}_{\pi N}}{3 f_\pi^2 m_\pi^2} \approx \frac{1}{2} 0.4 * \frac{\varrho_N}{\varrho_N^\circ}. \tag{7}$$

We use a more conservative estimate in our calculation: $\frac{1}{2}0.3 * \frac{\varrho_N}{\varrho_N^\circ}$ [12].

This mixing has two experimental signals: there should be a peak in the 3π invariant mass spectrum at the ρ mass or an A_1 peak in the dilepton mass spectrum. None of these two decays may happen without mixing. Observing one of them is a clear signature of mixing. (It is not necessarily a signal of partial restoration of chiral symmetry, since mixing may have different origin as well.)

At the experimental facilities of these days a broad dilepton peak at the A_1 mass cannot be observed. Therefore, we study the possibility of observing a peak at the ρ mass in the 3π invariant mass spectrum. Since pions have strong final state interaction we do not consider heavy ion, but rather $\pi + A$ collisions. In table 2 we studied the energy and mass number dependence of A_1 production. Results of 1 million events are shown. In the first two columns we define the system and energy, in the third we give how many A_1 are produced during the collision. The fourth column shows the background, the total number of exclusive 3π events, and finally

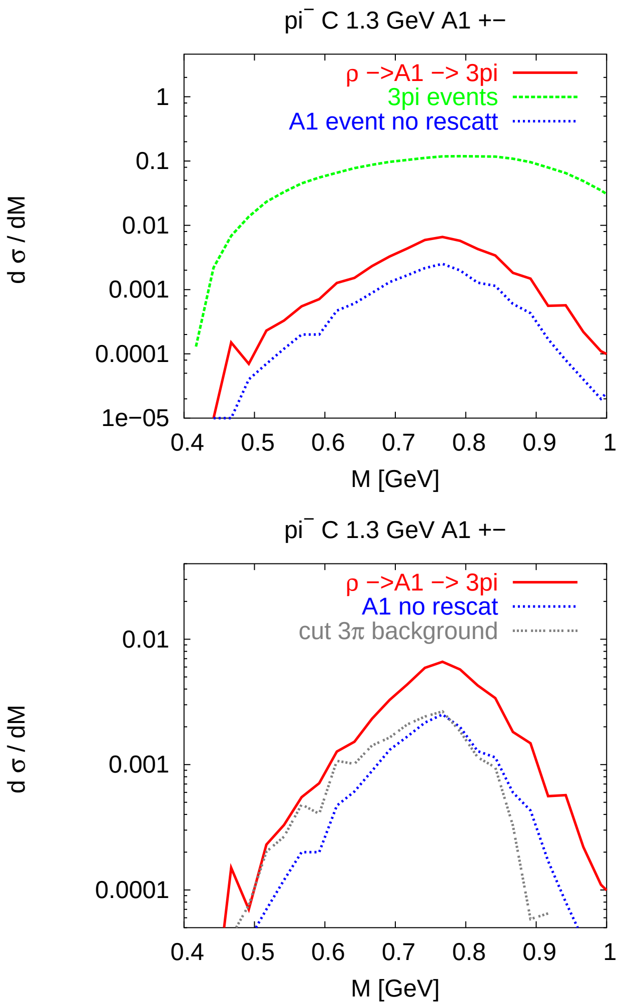

Figure 5. In the upper panel we show the total 3π invariant mass spectrum (dotted line), the mass spectrum of the produced A_1 (solid line) and the mass spectrum of those three pions, which leaves the system without final state interaction (dashed–dotted) line.

the last column shows in how many events the 3π decaying from an A_1 leave the system without any further interaction.

Although in heavy system many A_1's are produced, because of the strong final state interaction of the pions a light system is preferred, since pions have a much larger escape probability, and there the signal-to-background ratio is the highest ($\approx$1%). Although this ratio is rather small, there is a chance to observe it. In figure 5 we show the 3π invariant mass spectrum for $\pi+$ C collision at 1.3 GeV bombarding energy where the sum of the charges of the $3\pi = \pm 1$ (0 is excluded because of the large ω contribution). In the upper panel we show the total mass

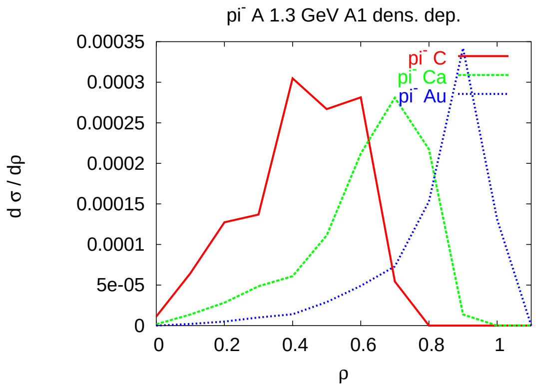

Figure 6. Density dependence of the A_1 production for π^- on C, Ca and Au nuclei.

Table 2. π-nucleus collisions; 1 million central events.

System	Energy (GeV)	$A1$	3 Pions	$A1$ no rescatt.
π^- Au	1.3	6400	56 000	100
π^- C	1.3	1200	43 000	450
π^- Ca	1.3	3200	54 000	400
π^- Ca	1.1	3100	46 000	350
π^- Ca	1.5	2400	55 000	360

spectrum (dashed line), the A_1 mass spectrum (solid line) and the mass spectrum of those 3 pions, which leaves the system without final state interaction (dotted line). The total spectrum is flat without any structure. On the other hand, if we cut off the uncorrelated background (calculable by event mixing), we obtain the dashed–dotted line of the lower panel of figure 5. If there is no mixing – there is no correlated 3π event – that line should be identically zero. In our calculation it shows the structure of the ρ meson, somewhat shifted to lower masses. This slight shift comes from rescattering one of the three pions. This result is still very preliminary. Before drawing conclusions we have to study further correlations in the 2π sector as well. But it seems there is a reasonable chance to observe the vector–axial vector mixing in pion-induced collisions at SIS.

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