

PERSPECTIVES OF SCALAR- AND VECTOR-MESON PRODUCTION IN HADRON–NUCLEUS REACTIONS* **

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The production and decay of vector mesons (ρ, ω) in pA reactions at COSY energies is studied with particular emphasis on their in-medium spectral functions. It is explored within transport calculations, if hadronic in-medium decays like $\pi^+\pi^-$ or $\pi^0\gamma$ might provide complementary information to their dilepton (e^+e^-) decays. Whereas the $\pi^+\pi^-$ signal from the ρ -meson is found to be strongly distorted by pion rescattering, the ω -meson Dalitz decay to $\pi^0\gamma$ appears promising even for more heavy nuclei. The perspectives of scalar meson (f_0, a_0) production in pp reactions are investigated within a boson-exchange model indicating that the f_0 -meson might hardly be detected in these collisions in the $K\bar{K}$ or $\pi\pi$ decay channels whereas the exclusive channel $pp \rightarrow da_0^+$ looks very promising.

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1. Introduction

The modification of the vector meson properties [1–7] in nuclear matter has become a challenging subject in dilepton physics from π^-A , pA and AA collisions. Here the dilepton (e^+e^-) radiation from ρ 's and ω 's propagating in finite density nuclear matter is directly proportional to their spectral function which becomes distorted in the medium due to the interactions with nucleons [8–13]. Apart from the vacuum width Γ_V^0 ($V = \rho, \omega$) these modifications are described by the real and imaginary part of the retarded self energies Σ_V , where the real part $\text{Re } \Sigma_V$ yields a shift of the

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meson mass pole and the additional imaginary part $\text{Im } \Sigma_V$ (half) the collisional broadening of the vector meson in the medium. We recall that the meson self energy in the $t - \rho$ approximation is proportional to the complex forward VN scattering amplitude $f_{VN}(P, 0)$ and the nuclear density $\rho(X)$, *i.e.* $\Sigma_V(P, X) = -4\pi\rho(X)f_{VN}(P, 0)$. The scattering amplitude itself, furthermore, obeys dispersion relations between the real and imaginary parts [14–16] while the imaginary part can be determined from the total VN cross section according to the optical theorem. Thus the vector meson spectral function

$$A_V(X, P) = \frac{\Gamma_V(X, P)}{(P^2 - M_V^2 - \text{Re } \Sigma_V(X, P))^2 + \Gamma_V(X, P)^2/4}, \quad (1)$$

where $\Gamma_V(X, P) = -2\text{Im } \Sigma_V(X, P)$, can be constructed once the VN elastic and inelastic cross sections are known. Note that in (1) all quantities depend on space-time X and four-momentum P .

2. Production and decay of vector mesons at finite density

As mentioned before, the in-medium vector meson spectral functions can be measured directly by the leptonic decay $V \rightarrow e^+e^-$ or the Dalitz decay $\omega \rightarrow \pi^0\gamma$, respectively. The vector meson production in pA collisions can be considered as a natural way [17] to study the ρ - and ω -properties at normal nuclear density under rather well controlled conditions. This also holds for the photo-production of vector mesons on nuclei [18].

The following calculations have been performed for $p+A$ collisions at 2.4–2.5 GeV by introducing a real and imaginary part of the vector meson self energy as

$$U_V = \frac{\text{Re } \Sigma_V}{2M_0} \simeq M_0 \beta \frac{\rho(X)}{\rho_0} \quad (2)$$

and width

$$\Gamma^* = \frac{\text{Im } \Sigma_V}{2M_0} \simeq \Gamma_V^0 + \Gamma_{\text{coll}} \frac{\rho(X)}{\rho_0} \quad (3)$$

in the $t - \rho$ -approximation. Here M_0 and Γ_V^0 denote the bare mass and width of the vector meson in vacuum while $\rho(X)$ is the local baryon density and $\rho_0 = 0.16 \text{ fm}^{-3}$. The parameter $\beta \simeq -0.16$ was adopted from the models in Refs. [1–7]. The predictions for the ω -meson collisional width Γ_{coll} at density ρ_0 range from 20 to 50 MeV [1, 2, 19] — depending on the number of ωN final channels taken into account — while the collisional width of the ρ -meson should be about 100–120 MeV at ρ_0 due to the strong coupling to baryon resonances (*cf.* Fig. 6 of Ref. [16]).

2.1. ρ^0 -mesons

In Ref. [20] the $\pi^+\pi^-$ decays of ρ^0 -mesons produced in pA reactions has been investigated with the aim of testing the in-medium ρ^0 -spectral function at normal nuclear matter density.

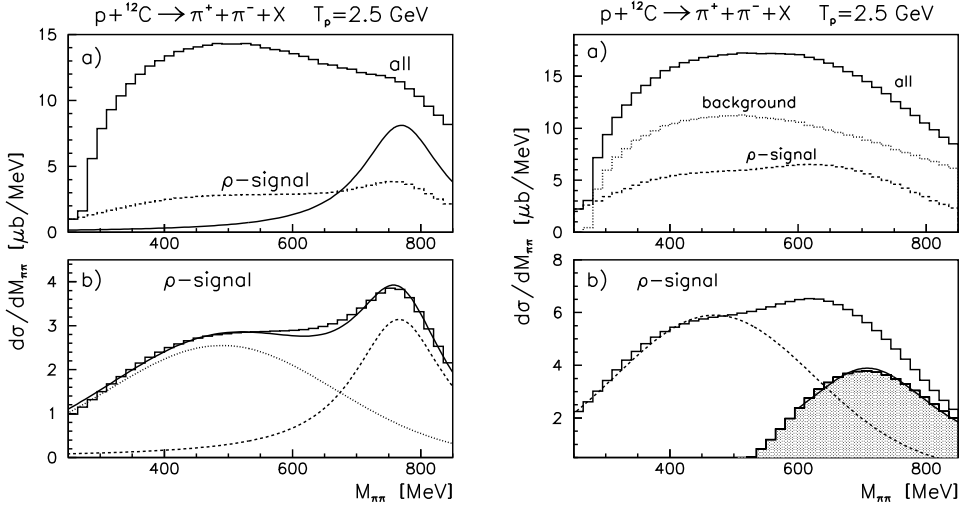


Fig. 1. (l.h.s.) The invariant mass distribution of two pions from $p + {}^{12}\text{C}$ collisions at 2.5 GeV using the bare spectral function of the ρ -meson for $p_z \leq 2$ GeV/c and $p_T \leq 0.8$ GeV/c. Displayed are the total $\pi^+\pi^-$ invariant mass spectrum (all), the ρ signal after subtraction of the combinatorial background (dashed line) as well as a Breit-Wigner distribution with the bare ρ -meson properties normalized to the total ρ -production cross section from the transport approach (see text).

(r.h.s.) The invariant mass distribution of two pions from $p + {}^{12}\text{C}$ at 2.5 GeV ($p_z \leq 2$ GeV/c and $p_T \leq 0.8$ GeV/c) employing the in-medium modification of the ρ -meson according to Eq. (2) for $\beta = -0.16$. In (b) the solid histogram shows the ρ -meson signal from (a); the dashed line is a statistical fit while the hatched histogram is the difference between the ρ signal and the statistical fit, which can be described again by a Breit-Wigner function (solid line) with $M_0^* = 708$ MeV and $\Gamma = 270$ MeV (see text).

Some results of the transport model studies from Ref. [20] are displayed in Fig. 1 for the reaction $p + {}^{12}\text{C}$ at 2.5 GeV. The l.h.s. displays the invariant mass distribution of two pions using the bare spectral function of the ρ -meson for $p_z \leq 2$ GeV/c and $p_T \leq 0.8$ GeV/c. In (a) the solid histogram shows the total $\pi^+\pi^-$ invariant mass spectrum while the dashed histogram indicates the ρ signal after subtraction of the combinatorial background. The solid line is a Breit-Wigner distribution with the bare ρ -meson properties normalized to the total ρ -production cross section from the trans-

port approach as expected in case of no final state interactions. In (b) the histogram shows the ρ -meson signal from (a) while the dotted line is the “statistical spectrum”; the dashed line is a Breit–Wigner function with the ρ -meson properties $M_0 = 766.9$ MeV and $\Gamma_0 = 173$ MeV while the solid line shows the sum. The dashed histogram in the r.h.s. of Fig. 1(a) represents the ρ -signal as obtained by background subtraction from uncorrelated $\pi^-\pi^-$ pairs in case of the in-medium modification (2) with $\beta = -0.16$. It is seen that not only the shape of the mass spectra, but also the absolute normalization are different from the calculations with the bare ρ -properties (l.h.s.). The ρ -meson signal is shown again in Fig. 1(b) (r.h.s.) in terms of the solid histogram, which at first glance is quite complicated to analyze in order to extract in-medium properties of the ρ -meson. To this aim we have fitted the spectrum with a statistical distribution [20] as shown in Fig. 1(b) by the dashed line. The hatched histogram in Fig. 1(b) then shows the difference between the ρ -mass spectrum and the statistical distribution; it can be fitted by a Breit–Wigner distribution with $M_0^* = 708$ MeV and $\Gamma = 270$ MeV.

In comparison with the l.h.s. of Fig. 1(b) a dropping of the ρ -meson mass thus might be extracted from the invariant mass distribution of two pions for light nuclei such as ^{12}C . However, the analysis is partly model dependent and the experiment requires large area detectors.

2.2. ω -mesons

The situation changes for the in-medium ω -meson Dalitz decay since here only a single pion might rescatter whereas the photon escapes practically without reinteraction. Again the calculations are performed within the transport model used before for ρ^0 and $K^\pm$ studies [15,20] by taking into account both the direct $pN \rightarrow \omega pN$, $pN \rightarrow \omega pN\pi$ and secondary $pN \rightarrow \pi NN$, $\pi N \rightarrow \omega N$ production mechanisms employing the cross sections from Ref. [21] as well as ωN elastic and inelastic interactions in the target nucleus (with cross sections from Ref. [19]) and accounting for $\pi^0 N$ rescattering. Here the ω propagation is described by the Hamilton’s equation of motion and its Dalitz decay to $\pi^0\gamma$ by Monte Carlo according to the survival probability $P_\omega(t-t_0) = \exp(-\Gamma_V^0(t-t_0))$ in the rest frame of the meson that was created at time t_0 .

We first present the results without employing any medium modifications for the ω -meson. The l.h.s. of Fig. 2 shows the resulting $\pi^0\gamma$ invariant mass spectrum for $p+\text{C}$ and $p+\text{Cu}$ collisions at a beam energy of 2.4 GeV. The solid histogram displays the spectral function of ω ’s, which decay outside the nucleus at densities $\rho \leq 0.05 \text{ fm}^{-3}$; the distribution from the $\omega \rightarrow \pi^0\gamma$ decay for $\rho > 0.05 \text{ fm}^{-3}$ for events without π^0 -rescattering is shown by the light hatched areas while events that involve $\pi^0 N$ elastic or inelastic scattering

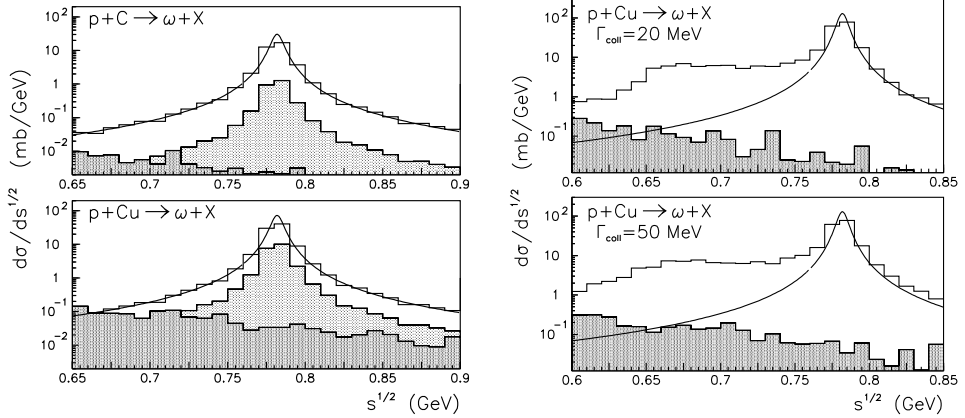


Fig. 2. (l.h.s.) The $\pi^0\gamma$ invariant mass spectra from $p+C$ and $p+Cu$ collisions at a beam energy of 2.4 GeV calculated without in-medium modifications of the ω -meson. The different contributions are explained in the text. (r.h.s.) The $\pi^0\gamma$ invariant mass spectra from $p+Cu$ collisions at 2.4 GeV calculated for $\Gamma_{\text{coll}} = 20$ and 50 MeV (open histograms) when employing the potential (2) for $\beta = -0.16$. The hatched histograms indicate the contributions from ω -mesons, that decay at finite density and include π^0 rescattering, while the solid lines show the ω -spectral function in vacuum for comparison.

are displayed in terms of the dark areas. The solid lines show the Breit-Wigner distribution determined by the pole mass and width for the free ω -meson. As can be seen from Fig. 2 (l.h.s.) most of the ω -mesons from the ^{12}C target decay in the vacuum (92%) and consequently ω decays in the medium as well as π^0 rescattering are rather scarce. The situation changes for a Cu target where $\pi^0\gamma$ coincidences from finite density are more frequent (19% ω 's decay inside the target), however, also π^0 rescattering gives a substantial background which in the invariant mass range of interest can approximately be described by an exponential tail in $\sqrt{s} = M_\omega$. Note, that experimentally the in-medium ω spectral function can only be observed by the $\pi^0\gamma$ invariant mass distribution from ω -mesons decaying inside the nucleus without π^0 -rescattering.

Now we examine the feasibility of a direct detection of an in-medium modification of the ω -spectral function via the $\pi^0\gamma$ invariant mass spectrum. The solid histograms in Fig. 2 (r.h.s.) show the calculated $\pi^0\gamma$ invariant mass spectra from $p+Cu$ collisions at 2.4 GeV calculated with $\Gamma_{\text{coll}} = 20$ MeV (upper part) and $\Gamma_{\text{coll}} = 50$ MeV (lower part) while employing the potential (2) with $\beta = -0.16$. The results are shown for an 'experimental' mass resolution of 10 MeV. The solid lines indicate the Breit-Wigner distribution given by

the mass and width for the vacuum ω -meson for comparison. The results indicate a substantial enhancement of the low mass $\pi^0\gamma$ spectra due to the contribution from ω -mesons decaying inside the nucleus while feeling the attractive potential (2). Apparently, there is no substantial difference between the $\pi^0\gamma$ spectra calculated with $\Gamma_{\text{coll}} = 20$ and 50 MeV since the shape of the low invariant mass spectrum is dominated by the (density dependent) in-medium shift of the ω -pole. Only above the vacuum ω -pole mass one can see a slightly enhanced yield in case of the higher collisional broadening. Moreover, the contribution from ‘distorted’ ω -mesons (due to π^0 rescattering), which is shown in Fig. 2 by the dark hatched histograms, is small and represents an approximately exponential background in the available $\pi^0\gamma$ energy.

As demonstrated in Ref. [22] ω -meson mass shifts comparable to Fig. 2 (r.h.s.) may also be observed for targets as light as ^{12}C or heavy as ^{208}Pb . Such experiments might be carried out at COSY with neutral particle detectors looking for the 3γ invariant mass distribution and gating on events where 2 γ ’s yield the invariant mass of a π^0 . This program is complementary to dilepton studies in pA reactions with the HADES detector at GSI Darmstadt [23].

3. Scalar meson production

The scalar meson sector plays a very important role in the physics of hadrons. Nevertheless, the structure of the lightest scalar mesons $a_0(980)$ and $f_0(980)$ is not yet understood and is one of the most important topics of hadronic physics ([24,25] and references therein). It has been discussed that they could be either “ $q\bar{q}$ states”, “Four-quark cryptoexotic states”, $K\bar{K}$ molecules or vacuum scalars ([24]). Nowadays, theory gives some preference to the Unitarized Quark Model (UQM) proposed by Tornqvist [26], however, other options cannot be ruled out experimentally. Moreover, there is a strong mixing between the uncharged $a_0(980)$ and the $f_0(980)$ due to a coupling to $K\bar{K}$ intermediate states. It is, therefore, important to study independently the uncharged and charged components of the $a_0(980)$ because the latter are not mixed with the $f_0(980)$ and preserve their original quark content.

3.1. The reaction $NN \rightarrow f_0 NN$

The production of scalar mesons (f_0, a_0) in pp reactions is investigated within a meson-exchange approximation. The relevant diagrams for the $NN \rightarrow f_0 NN \rightarrow K\bar{K} NN$ reaction are those involving pion emission from the nucleons with s -channel production of the f_0 -meson and its subsequent decay to $K\bar{K}$ or $\pi\pi$ (for details the reader is referred to Ref. [27]). The coupling constant at the $\pi\pi f_0$ vertex is determined from a fit to the reaction

$\pi^- p \rightarrow f_0 n \rightarrow n K^+ K^-$ [27]. A form factor at the $f_0 \pi \pi$ vertex has to be incorporated since both pions are off their mass-shell; we use the form

$$F_{f_0 \pi \pi}(q_1^2, q_2^2) = F_{\pi N N}(q_1^2) F_{\pi N N}(q_2^2), \quad (4)$$

where the $\pi N N$ form factor is taken as $F(t) = (\Lambda^2 - m_\pi^2)/(\Lambda^2 - t)$ with a cut-off parameter $\Lambda = 1.05$ GeV. The form factor (4) is normalized to unity at $q_1^2 = m_\pi^2$ and $q_2^2 = m_\pi^2$, which is consistent with the kinematical conditions for the determination of the $f_0 \pi \pi$ coupling constant.

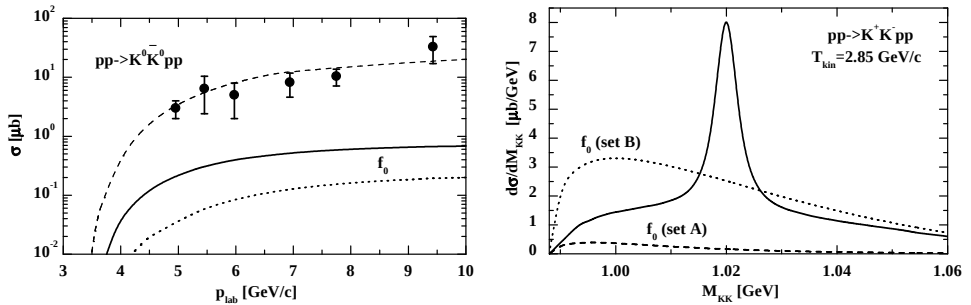


Fig. 3. (l.h.s.) The $pp \rightarrow f_0 pp \rightarrow K^0 \bar{K}^0 pp$ cross section calculated with coupling constants from *set A* with (dotted line) and without form factor (solid line) at the $f_0 \pi \pi$ vertex. The experimental data for the $pp \rightarrow K^0 \bar{K}^0 pp$ reaction are taken from Ref. [29], while the dashed line shows the corresponding calculation within the one-boson exchange model from Ref. [30]. (r.h.s.) The $K^+ K^-$ invariant mass distribution from pp collisions at 2.85 GeV. The solid line shows the calculated contribution from the ϕ decays and $K^+ K^-$ background according to Ref. [30]. The dashed line shows the contribution from the $pp \rightarrow f_0 pp \rightarrow K^+ K^- pp$ reaction calculated with constants from *set A* (lower), while the dotted (upper) line shows the result obtained with *set B* (see text).

The dotted line in Fig. 3 (l.h.s.) shows the $pp \rightarrow f_0 pp \rightarrow K^0 \bar{K}^0 pp$ cross section calculated with the coupling constants $g_{f_0 \pi \pi} = 1.49$ GeV and $g_{f_0 K K} = 0.82$ GeV (*set A*) and with the form factor (4) in comparison to the experimental data [29] for the $pp \rightarrow K^0 \bar{K}^0 pp$ reaction. The dashed line shows the calculations within the pion and kaon exchange model from Ref. [30] for $K \bar{K}$ production. To estimate the maximal f_0 production cross section we neglect the form factor at the $f_0 \pi \pi$ vertex and show the result in terms of the solid line in Fig. 3 (l.h.s.). Actually, the contribution from f_0 production to the total $pp \rightarrow K^0 \bar{K}^0 pp$ cross section is almost negligible at high energies. However, a possible way for f_0 observation is due to the low energy part of the $K \bar{K}$ invariant mass spectrum.

We thus calculate the K^+K^- invariant mass spectrum from the $pp \rightarrow K^+K^-pp$ reaction at a beam energy of 2.85 GeV, which corresponds to the kinematical conditions for the DISTO experiment at SATURNE [28]. Since at this energy the ϕ -meson production becomes possible we include its contribution to the K^+K^- spectrum. The $pp \rightarrow \phi pp$ total cross section was taken from Ref. [31] and the K^+K^- invariant mass was distributed according to the Breit-Wigner resonance prescription with a full ϕ -meson width $\Gamma_\phi = 4.43$ MeV and a branching ratio $Br(\phi \rightarrow K^+K^-) = 49.1\%$.

The solid line in Fig. 3 (r.h.s.) shows the K^+K^- invariant mass spectrum for the $pp \rightarrow \phi pp$ reaction as well as the background spectrum from the $pp \rightarrow K^+K^-pp$ reaction, which was calculated as in Ref. [30] on the basis of pion and kaon exchange diagrams. The dashed line indicates the K^+K^- spectrum calculated with the coupling constants from *set A* and without form factor at the $f_0\pi\pi$ vertex. For these coupling constants it is quite obvious that the f_0 -meson cannot be directly detected in pp collisions by using the K^+K^- -mode. Note, that when introducing a form factor (4) at the $f_0\pi\pi$ vertex the contribution from $pp \rightarrow f_0 pp \rightarrow K^+K^-pp$ becomes even smaller.

To test the sensitivity of the model to the f_0 parameters we also performed a calculation with $g_{f_0\pi\pi} = 3.05$ GeV and $g_{f_0KK} = 4.3$ GeV (*set B*) [27] and show the result in terms of the dotted line in Fig. 3 (r.h.s.). Indeed, in this case the f_0 contribution is very strong at low K^+K^- invariant mass, however, the experimental data from DISTO [32] exclude this possibility.

3.2. The reaction $pp \rightarrow da_0^+$

The missing mass spectrum in the reaction $pp \rightarrow d(MM)^+$ for deuterons produced at 0° in the laboratory and incident momenta of 3.8, 4.5 and 6.3 GeV/ c has been measured at LBL (Berkeley) [33]. It is interesting that apart from the peaks corresponding to π and ρ production, there is a distinctive structure in the missing mass spectrum at 0.95 GeV² which was identified as a_0 production.

In order to estimate the cross section of the reaction $pp \rightarrow da_0^+$ at lower momenta — which are available at COSY — the two-step model (TSM) described by the triangle diagram is used ([34,35]). For the deuteron wave function we take the parameterization from Ref. [36] and neglect the D -wave part which gives only a small contribution compared to the S -wave term.

The amplitudes taken into account are: (i) the a_0 coupling to two nucleons through the $f_1(1285)$ and π -meson exchanges; (ii) the a_0 coupling through η - and π -meson exchanges; (iii) the production of a_0 -mesons through pion exchange with s - and u -channel nucleon currents. The coupling constants and cut-off parameters Λ_i for π - and η -meson exchanges are taken

from the Bonn potential model; for the a_0 - and $f_1(1285)$ -mesons the values from Ref. [37] are employed while the cut-off Λ at the nucleon exchange vertex was considered as a free parameter within the interval 1.2–1.3 GeV. Within this model the mechanisms (i) and (ii) are of minor importance and the dominant contribution comes from the nucleon u -channel exchange.

The results of the calculations for the forward differential cross section at various beam momenta [35] match with the data from [33] for a cut-off $\Lambda = 1.3$ GeV and indicate that cross sections of 50–100 nb/sr should be reached at a bombarding energy of 2.6 GeV, which provides very promising perspectives for exploring the a_0 properties and dynamics at COSY.

4. Summary

In this contribution the production and decay of vector mesons (ρ, ω) in pA reactions at COSY energies has been studied with particular emphasis on their in-medium spectral functions. It is found within transport calculations, that hadronic in-medium decays like $\pi^+\pi^-$ or $\pi^0\gamma$ might provide complementary information to their dilepton (e^+e^-) decays. However, the $\pi^+\pi^-$ signal from the ρ -meson is strongly distorted by pion rescattering on nucleons even for light nuclei like ^{12}C . On the other hand, the ω -meson Dalitz decay to $\pi^0\gamma$ appears promising even for more heavy nuclei since only the neutral pion may rescatter and 3-photon events ($\pi^0 \rightarrow \gamma\gamma$) have a very small background at high invariant mass.

Furthermore, the perspectives of scalar meson (f_0, a_0) production in pp reactions have investigated within a boson-exchange model indicating that the f_0 -meson might hardly be detected in the $K\bar{K}$ or $\pi\pi$ decay channels in these collisions whereas the exclusive channel $pp \rightarrow da_0^+$ looks very promising when detecting the deuteron and analyzing the missing mass spectrum in the range 0.9–1 GeV².

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