Evidence for $\pi^+\pi^-$ scattering in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV

P. Fachini, R. S. Longacre, Z. Xu and H. Zhang
Brookhaven National Laboratory, Upton, NY, 11973, USA
E-mail: pfachini@bnl.gov

Abstract. A $\rho(770)^0$ mass shift of about 40 MeV/$c^2$ was measured in $p+p$ collisions at $\sqrt{s_{NN}} = 200$ GeV at RHIC. Previous mass shifts have been observed at CERN-LEBC-EHS and CERN-LEP. We will show that phase space does not account for the $\rho(770)^0$ mass shift measured at RHIC, CERN-LEBC-EHS and CERN-LEP and conclude that there are significant scattering interactions in $p+p$ collisions.
1. Introduction

The \( \rho^0 \) was measured via its hadronic decay channel in minimum bias \( p+p \) and Au+Au collisions at RHIC and a mass shift of -40 and -70 MeV/\( c^2 \) of the position of the \( \rho^0 \) was observed, respectively. While no explanations were explicitly attributed to the mass shift in \( p+p \) collisions, the possible explanations for the apparent modification of the \( \rho^0 \) meson properties in Au+Au collisions were attributed to dynamical interactions with the surrounding matter, interference between various \( \pi^+\pi^- \) scattering channels, phase space distortions due to the rescattering of pions forming \( \rho^0 \) and Bose-Einstein correlations between \( \rho^0 \) decay daughters and pions in the surrounding matter [1].

The \( \rho^0 \) meson measured in the dilepton channel probes all stages of the system formed in relativistic heavy-ion collisions because the dileptons have negligible final state interactions with the hadronic environment. Heavy-ion experiments at CERN show an enhanced dilepton production cross section in the invariant mass range of 200-600 MeV/\( c^2 \), showing that the \( \rho^0 \) is broadened rather than shifted [2, 3]. The hadronic decay measurement at RHIC [1], \( \rho(770)^0 \rightarrow \pi^+\pi^- \), was the first of its kind in heavy-ion collisions. Since the \( \rho^0 \) lifetime of \( c\tau = 1.3 \) fm is small with respect to the lifetime of the system formed in Au+Au collisions, the \( \rho^0 \) meson is expected to decay, regenerate, and rescatter all the way through kinetic freeze-out. Therefore, the measured \( \rho^0 \) mass at RHIC should reflect conditions at the late stages of the collisions [5]. However, its has been shown that the \( \rho^0 \) width goes to zero with the \( \rho^0 \) mass dropping near the chiral phase transition, which is called the vector manifestation and it can occur near \( T_c \) in the hot and dense matter [7]. In this scenario, the \( \rho^0 \) lifetime becomes very large and the \( \rho^0 \) produced at the early stages can also be measured in the hadronic channel.

The modification of the \( \rho^0 \) properties in heavy-ion collisions has been expected [4], contrary to the modifications of the \( \rho^0 \) properties in \( p+p \) collisions. Similar modifications of that measured in \( p+p \) collisions at RHIC has been observed before at CERN-LEBC-EHS and CERN-LEP. Until now, the mass shift measured in \( p+p \) at CERN-LEBC-EHS has been attributed to phase space. The process of hadron-hadron collisions at low \( p_T \) is not well understood. These collisions are viewed as a complicated interaction, where a perturbative treatment of the interaction dynamics is not possible. As a consequence, only phenomenological models with assumptions about the partonic subprocess dynamics can be used to interpret the data. By studying soft hadronic interactions we may be able to explain the interaction dynamics of hadron collisions and possibly understand the parton hadronization mechanism, which is important in jet studies. One way of probing the dynamics of hadron-hadron collisions is to study the production of resonances, in particular, the \( \rho^0 \) meson.

In this paper, we will show that phase space does not account for the \( \rho(770)^0 \) mass shift measured at RHIC [1], CERN-LEBC-EHS [8] and CERN-LEP [9, 10, 12, 11] and conclude that there are significant scattering interactions in \( p+p \) collisions.
2. Discussion $\rho$ mass average from the Particle Data Group (PDG)

We will first discuss the $\rho$ mass average from the PDG [14]. The $\rho^0$ mass average $775.8 \pm 0.5$ MeV/$c^2$ from $e^+e^- \rightarrow \pi^+\pi^-$ was obtained from either $e^+e^- \rightarrow \pi^+\pi^-$ or $e^+e^- \rightarrow \pi^+\pi^-\pi^0$. This means that the $\rho^0$ mass average was obtained from \textit{exclusive leptonic reactions}. Similarly, the $\rho^\pm$ mass average $775.5 \pm 0.5$ MeV/$c^2$ was also obtained from \textit{exclusive leptonic reactions}.

The $\rho$ averages reported by the PDG from reactions other than leptonic interactions are systematic lower than the value obtained from \textit{leptonic exclusive interactions} by $\sim 10$ MeV/$c^2$ [14]. The $\rho$ production in these hadronic reactions are inclusive and exclusive. In the case of inclusive productions, the phase space was take into account when the $\rho$ mass was measured (e.g. [8]).

These observations lead us to conclude that the $\rho$ mass depends on specific interactions, e.g. whether the $\rho$ is produced in inclusive or exclusive reactions. Since a leptonic reaction and exclusive measurement of the $\rho^0$ lead to a negligible modification of any kind of the $\rho^0$ mass, the average $775.8 \pm 0.5$ MeV/$c^2$ [14] from $e^+e^-$ should correspond to the $\rho^0$ mass in the vacuum.

3. $\rho^0$ mass shifts at RHIC, CERN-LEBC-EHS, and CERN-LEP

The $\rho^0$ was measured in the hadronic decay channel $\rho^0 \rightarrow \pi^+\pi^-$ at RHIC, CERN-LEBC-EHS, and CERN-LEP in inclusive production. At RHIC, the STAR collaboration measured the $\rho^0$ at $\sqrt{s_{NN}} = 200$ GeV at midrapidity ($|y| < 0.5$) and observed mass shifts of the position of the $\rho^0$ peak of about -40 MeV/$c^2$ and -70 MeV/$c^2$ in minimum bias $p+p$ and peripheral Au+Au collisions, respectively [1]. The invariant mass distributions from [1] is shown in Fig. 1. The solid black line in Fig. 1 is the sum of all the contributions in the hadronic cocktail. The $K^0_S$ was fit to a Gaussian (dotted line). The $\omega$ (light grey line) and $K^*(892)^0$ (dash-dotted line) shapes were obtained from the HIJING event generator [15], with the kaon being misidentified as a pion in the case of the $K^*^0$. The $\rho^0(770)$ (dashed line), the $f_0(980)$ (dotted line) and the $f_2(1270)$ (dark grey line) were fit by relativistic Breit-Wigner functions (BW) times the Boltzmann factor (PS) to account for phase space [5, 16, 17, 18, 19, 20, 21, 22],

\[
\text{BW} = \frac{M_{\pi\pi}M_0\Gamma}{(M_0^2 - M_{\pi\pi}^2)^2 + M_0^2\Gamma^2} \tag{1}
\]

\[
\Gamma = \Gamma_0 \times \frac{M_0}{M_{\pi\pi}} \times \left[ \frac{M_{\pi\pi}^2 - 4m^2_{\pi}}{M_0^2 - 4m^2_{\pi}} \right]^{(2\ell+1)/2} \tag{2}
\]

\[
\text{PS} = \frac{M_{\pi\pi}}{\sqrt{M_{\pi\pi}^2 + p_T^2}} \times \exp \frac{-\sqrt{M_{\pi\pi}^2 + p_T^2}}{T} \tag{3}
\]

where $M_0$ and $\Gamma_0$ are the natural resonance mass and width, respectively [14]. The masses of $K^0_S$, $\rho^0$, $f_0$, and $f_2$ were free parameters in the fit, and the widths of $\rho^0$, $f_0$ and
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Figure 1. The raw $\pi^+\pi^-$ invariant mass distributions after subtraction of the like-sign reference distribution for minimum bias $p+p$ (top) and peripheral Au+Au (bottom) interactions measured by STAR. For details see [1].

$f_2$ were fixed according to [14]. The uncorrected yields of $K_S^0$, $\rho^0$, $\omega$, $f_0$, and $f_2$ were free parameters in the fit while the $K^{*0}$ fraction was fixed according to the $K^{*}(892)^0 \rightarrow \pi K$ measurement [23]. The $\rho^0$, $\omega$, $K^{*0}$, $f_0$, and $f_2$ distributions were corrected for the detector acceptance and efficiency determined from a detailed simulation of the TPC response using GEANT [1]. The number of degrees of freedom (d.o.f.) from the fits was 196 and the typical $\chi^2$/d.o.f. was 1.4. The $\rho^0$ mass obtained from the BW×PS fit is depicted in Fig. 2 where it is clear that the phase space does not account for the measured mass shifts of the position of the $\rho^0$ peak.

At CERN-LEBC-EHS, NA27 measured the $\rho^0$ in minimum bias $p+p$ at $\sqrt{s} = 27.5$ GeV for $x_F > 0$, where $x_F$ is the ratio between the longitudinal momentum and the maximum momentum of the meson, and reported a mass of $762.6 \pm 2.6$ MeV/$c^2$ [8]. The $\rho^0$ signal can be seen even before background subtraction. The invariant $\pi^+\pi^-$ mass distribution was fit to the BW(NA27)×PS(NA27) plus a background function [8]

$$BW(NA27) = \frac{2M_{\pi\pi}}{(M^2_{\pi\pi} - 4m^2_\pi)^{1/2}} \times$$

$$\Gamma \frac{(M_0^2 - M^2_{\pi\pi})^2 + M_0^2 \Gamma^2}{(M_0^2 - M^2_{\pi\pi})^2 + M_0^2 \Gamma^2}$$

$$\Gamma = \Gamma_0 \times \frac{M_0}{M_{\pi\pi}} \times \left[\frac{M^2_{\pi\pi} - 4m^2_\pi}{M_0^2 - 4m^2_\pi}\right]^{(2\ell+1)/2}$$

(4)

(5)
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Figure 2. The $\rho^0$ mass as a function of $p_T$ for minimum bias $p+p$ (filled circles), high multiplicity $p+p$ (open triangles), and peripheral Au+Au (filled squares) collisions measured by STAR. The error bars indicate the systematic uncertainty. Statistical errors are negligible. The $\rho^0$ mass was obtained by fitting the data to the BW×PS functional form described in [1]. The dashed lines represent the average of the $\rho^0$ mass measured in $e^+e^-$ [14]. The shaded areas indicate the $\rho^0$ mass measured in $p+p$ collisions [8]. The open triangles have been shifted downward on the abscissa by 50 MeV/c for clarity.

$$\text{PS(NA27)} = \text{BG} = \frac{\alpha_1}{(M_{\pi\pi})^{\alpha_2}} \left[ \frac{M_{\pi\pi}^2 - 4m_{\pi}^2}{M_{\pi\pi}} \right]^\alpha_{2/2} \times$$

$$\exp\left(-\alpha_3\left[\frac{M_{\pi\pi}^2 - 4m_{\pi}^2}{M_{\pi\pi}}\right]^{1/2} - \alpha_4\left[\frac{M_{\pi\pi}^2 - 4m_{\pi}^2}{M_{\pi\pi}}\right]^{1/2}\right)$$

where $\alpha_1, \alpha_2, \alpha_3$, and $\alpha_4$ are free parameters in the fit. In this analysis, the phase space function (PS(NA27)) used is the same as the combinatorial background (BG). The invariant $\pi^+\pi^-$ mass distribution after subtraction of the mixed-event reference distribution is shown in Fig. 3. The vertical dashed line represent the average of the $\rho^0$ mass measured in $e^+e^-$ [14]. The vertical solid line is the $\rho^0$ mass 762.6 ± 2.6 MeV/$c^2$ reported by NA27 [8]. As shown in Fig. 3 the position of the $\rho^0$ peak is shifted by $\sim 30$ MeV/$c^2$ compared to the $\rho^0$ mass in the vacuum 775.8 ± 0.5 MeV/$c^2$ [14]. The shift of the $\rho^0$ peak can be quantified by fitting the NA27 $\pi^+\pi^-$ mass distribution after subtraction of the mixed-event reference distribution to the BW function (equation 1). The fit is depicted in Fig. 4 and the value of the maximum of the distribution obtained from the fit is 747.6 ± 2.0 MeV/$c^2$ with $\chi^2/ndf = 1.9$. If equation 4 is used instead, the value of the maximum of the distribution is 754.3 ± 2.1 MeV/$c^2$ with $\chi^2/ndf = 1.2$. The difference of a few MeV between the two values is due to the different BW functions used in the analyzes.

As mentioned, NA27 obtained the $\rho^0$ mass by fitting the invariant $\pi^+\pi^-$ mass distribution to the BW×PS function, and they reported a mass of 762.6 ± 2.6 MeV/$c^2$, which is $\sim 10$ MeV/$c^2$ lower than the $\rho^0$ mass in the vacuum. Ideally, the PS factor should have accounted for the shift on the $\rho^0$ peak, and the mass obtained from the fit should have agreed with the $\rho^0$ mass in the vacuum. However, just like in the STAR measurement, this was not the case, since the phase space did not account for the mass
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Figure 3. The invariant $\pi^+\pi^-$ mass distribution after background subtraction (equation 5) for minimum bias $p + p$ collisions measured by NA27. For details see [8]. The vertical dashed line represents the average of the $\rho^0$ mass $775.8 \pm 0.5$ MeV/$c^2$ measured in $e^+e^-$ [14]. The vertical solid line is the $\rho^0$ mass $762.6 \pm 2.6$ MeV/$c^2$ reported by NA27 [8].

Figure 4. The invariant $\pi^+\pi^-$ mass distribution after background subtraction (equation 5) for minimum bias $p + p$ collisions measured by NA27 [8] fit to the BW function (equation 1). For details see [8].

shift on the position of the $\rho^0$ peak.

At CERN-LEP, OPAL, ALEPH and DELPHI measured the $\rho^0$ in inclusive $e^+e^-$ reactions at $\sqrt{s} = 90$ GeV [9, 10, 11, 12]. Even though OPAL never reported the value of the $\rho^0$ mass, OPAL reported a shift on the position of the $\rho^0$ peak by $\sim 70$ MeV/$c^2$ at low $x_p$, where $x_p$ is the ratio between the meson and the beam energies, and no shift at high $x_p$ ($x_p \sim 1$) [9, 10]. OPAL also reported a shift in the position of the $\rho^\pm$ peak from -10 to -30 MeV/$c^2$, which was consistent with the $\rho^0$ measurement [11]. ALEPH reported the same shift on the position of $\rho^0$ peak observed by OPAL [12]. Both OPAL and ALEPH used the like-sign method to subtract the background. DELPHI fit the raw invariant $\pi^+\pi^-$ mass distribution to the $(\text{BW} \times \text{PS} + \text{BG})$ function

$$\text{PS(DELPHI)} = \text{BG} = (M - M_{th})^{\gamma_1} \times$$
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**Figure 5.** The $p_T$ distribution at $|y| < 0.5$ for minimum bias $p + p$ collisions [4]. The black circles are the data, the dashed line is the power-law fit and the solid line is the exponential fit. See [4] for the fit functions. The errors shown are statistical only and smaller than the symbols.

\[ \exp(\gamma_2 M + \gamma_3 M^2 + \gamma_4 M^3 + \gamma_5 M^4), \]  
where $M_{th}$ is the threshold mass and BW is a relativistic Breit-Wigner function, for $x_p > 0.05$ and reported a $\rho^0$ mass of $757 \pm 2$ MeV/$c^2$ [13], which is five standard deviations below the $\rho^0$ mass in the vacuum (775.8 ± 0.5 MeV/$c^2$). As one can see, similarly to NA27, DELPHI assumed that the phase space was described by the background function. Bose-Einstein correlations were used to describe the shift on the position of $\rho^0$ peak. However; high (even unphysical) chaoticity parameters ($\lambda \sim 2.5$) were needed [9, 10, 12].

4. Phase space in $p + p$ collisions

In $p+p$ collisions, most models assume that particles are born at hadronization according to phase space without any final state interaction. In multiparticle production processes, single-inclusive (e.g. $p + p$), invariant particle spectra are typically exponential in $p_T$ [24]. The exponential behavior does not require final state interactions and it can be due to phase space population at hadronization. The slope parameter in $p + p$ collisions are independent of the particle species [25]. At RHIC, the $\rho^0$ spectra in minimum bias and high multiplicity $p + p$ are exponential in $p_T$ up to 1.1 GeV/$c^2$ with slope parameters of $\sim 180$ MeV. The $\rho^0$ spectrum in minimum bias $p + p$ is depicted in Fig. 5. For reference, the slope parameter of $\pi^-$ is $\sim 160$ MeV [26]. Note that the slope parameter in $p + p$ is independent of the particle rest mass and shows $m_T$ scaling. These results are also independent of the multiplicity.

However, the $\rho^0$ mass measured in $p + p$ at RHIC is multiplicity dependent (the mass shift in high multiplicity is higher than in minimum bias $p + p$ collisions) [4], which is opposite to the slope parameter that is multiplicity independent. Note that the systematic errors are correlate among themselves and between the two measurements. We will demonstrate that the mass should be independent of $p_T$ as well as multiplicity.
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at hadronization without final state interactions. According to quantum mechanics, a resonance at rest is described by the wave function,

$$\Psi(x, t) \propto \exp\left(-\frac{E_0}{\hbar}t\right) \times \exp\left(-\frac{t}{2\tau}\right)$$  \hspace{1cm} (8)

where $\tau$ is the lifetime and $E_0$ is the energy at rest. The probability amplitude of the resonance decay can be written as

$$\tilde{\Psi}(E, x) \propto \int_0^\infty (\exp(-\frac{E_t}{\hbar}))^* \Psi(x, t) dt$$  \hspace{1cm} (9)

$$\tilde{\Psi}(E, x) \propto \frac{1}{i \frac{E-E_0}{\hbar} - \frac{i}{2\tau}} \Psi(x)$$  \hspace{1cm} (10)

$$P(E) \propto \left| \frac{1}{i \frac{E-E_0}{\hbar} - \frac{i}{2\tau}} \right|^2 \int |\Psi(x)|^2 dx$$  \hspace{1cm} (11)

$$P(E) \propto \frac{\Gamma/2}{(E - E_0)^2 + \frac{\Gamma^2}{4}}$$  \hspace{1cm} (12)

where $\Gamma = \hbar/\tau$, and the probability amplitude is a non-relativistic Breit-Wigner distribution. When the energy conservation law is imposed in the partition of string fragmentation into multiple hadrons, a phase space factor, similar to the Boltzmann factor in thermal distribution, has to be added to equation 12. Replacing $E$ by the invariant mass ($M$), the phase space is $\exp\left(-\frac{m_{T}}{T}\right)$, where $m_{T}$ equals $\sqrt{M^2 + p_{T}^2}$ and $T$ equals 160 MeV. Equation 12 is then rewritten as

$$P(M, p_{T}) \propto \frac{\Gamma/2}{(M - M_0)^2 + \frac{\Gamma^2}{4}} \times \exp\left(-\frac{m_{T}}{T}\right).$$  \hspace{1cm} (13)

However; as discussed previously, the phase space does not describe the mass shift of the $\rho$ meson measured at RHIC, CERN, and LEP.

Most event generators (e.g. PYTHIA \[27\] and HIJING \[28\]) create resonances according to a non-relativistic Breit-Wigner function at a given $p_{T}$ (equation 12). However, we just showed that a more reasonable way to produce resonances is to use equation 13.

Since the phase space of a non interacting multiparticle state cannot explain the distortion of the $\rho^0$ line shape, we can conclude that the phase space in $p + p$ collisions also accounts for hadrons scattering and forming resonances. In the case of the $\rho^0$, $\pi^+\pi^- \rightarrow \rho^0 \rightarrow \pi^+\pi^-$. This can be pictured in the string fragmentation particle production scenario, where the string breaks several times, two pions are formed, they scatter, and form a $\rho^0$. Such interactions are significant and modify the $\rho^0$ spectral shape in $e^+e^-$ and $p + p$ from a relativistic $p$-wave Breit-Wigner function.

Using the $p + p$ data from the top plot of Fig. 1 and the rescattering formalism of \[29\], we can test the ideas of a mass shift having a $\pi^+\pi^-$ scattering component. The di-pion production is given by equation 21 of \[29\]. For the $\rho^0$ which is $p$-wave $\ell = 1$ equation 21 becomes

$$|T|^2 = |D|^2 \frac{\sin^2(\delta_1)}{PS'} + |A|^2 \frac{\alpha \sin(\delta_1) + PS' \cos(\delta_1)}{PS'}$$  \hspace{1cm} (14)
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The $\delta_1$ is the p-wave phase shift ($\rho^0$) and $\frac{\sin^2(\delta)}{\text{PS}'}$ in our case becomes the Breit-Wigner times phase space equation [13] $|D|^2$ becomes the direct production of $\rho^0$ for the $p_T$ range 600 to 800 MeV/c. $|A|^2$ is the phase space overlap of di-pions in the $\ell = 1$ partial waves. The pions emerge from a close encounter in a defined quantum state with a random phase. The emerging pions can re-interact or re-scatter through the p-wave quantum state or a phase shift. The phase space overlap comes from sampling the $\pi$ spectrum from $p + p$ collisions, where the sum of the $\pi^+\pi^-$ has the correct $p_T$ range. The di-pion mass spectrum for this $p_T$ range falls with increasing di-pion invariant mass. The variable $\alpha$ is related to the real part of the di-pion rescattering diagram and measures the range of interaction [29]

$$\alpha = (1.0 - \frac{r^2}{r_0^2})$$

(15)

The $r$ is the radius of rescattering in fm and $r_0$ is 1.0 fm or the limiting range of the strong interaction. The PS’ is the phase space factor

$$\text{PS'} = \frac{2q(q/q_0)^2}{M(q/q_0)^2(1+(q/q_0)^2)}$$

(16)

where $q$ is the momentum of the pions in the center-of-mass and $q_0$ is the size of interaction for the $\rho^0$ system and we use 1.0 fm distance to set $q_0$ at 200 MeV/c.

In order to fit the $p + p$ data we need to add the rest of the cocktail of resonances used by STAR [1]. Such a fit is shown in Fig. 6 (solid line), where the direct $\rho^0$ term time the phase space (dotted line) and the rescattered term (dash-dotted line) plus the sum (dashed line) are also depicted. In equation [14] we have three parameters which are fitted. A scale factor on the phase space overlap of the di-pions. The direct production $D$ and $\alpha$. The value for $\alpha$ form the fit is 0.47, which implies $r = 0.73$ fm.

We see that the mass shift is a rescattering effect coming from a $\pi\pi$ source which is not the $\rho$. This $\pi\pi$ source becomes a $\rho^0$ through reinteraction. The mass shift of the $\rho$ seen in [30], where the $\rho^0$ is photoproduced, is due to the same rescattering effect, except that the direct production of the $\rho^0$ in this case is coherent with the $\pi\pi$ source.

**Figure 6.** Fit to the data using equation [13] (solid line), the direct $\rho^0$ contribution term times the phase space (dashed line), the rescattering term (dash-dotted line) and the sum of the both (dashed line).
STAR measured the $\rho^0$ at midrapidity and NA27 measured at the forward region. In addition, there is the energy difference of $\sqrt{s_{NN}} = 200$ and 27.5 GeV, respectively. All these facts are consistent our model, the difference between the $\rho^0$ mass shift measure by STAR and NA27 is due to pion multiplicity. Similar arguments is valid for the $\rho$ measurements at CERN-LEP at $\sqrt{s_{NN}} = 90$ GeV indicating that there is also significant scattering interactions in $e^+e^-$ reactions.

5. Conclusions

We discussed that the natural mass of the $\rho$ meson should be measured in exclusive reactions only. We showed that a shift on the position of the $\rho^0$ peak has been measured before and that the phase space does not account for the $\rho(770)^0$ mass shift measured at RHIC, CERN-LEBC-EHS, and CERN-LEP. In addition, we discussed the phase space in $p+p$ collisions and concluded that there are significant scattering interactions in $p+p$ reactions. These interactions modify the $\rho^0$ line shape in $p+p$ and $e^+e^-$ interactions from a Breit-Wigner function. Using the rescattering formalism of [29], we can reproduce the $\rho^0$ mass shift measured by the STAR collaboration in minimum bias $p+p$ collisions.

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