On a Possible Explanation of the DLS-Puzzle

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The enhancement in the dilepton spectrum observed in heavy-ion collisions for invariant electron-positron masses in the range $0.15 \text{ GeV}/c^2 < M_{e^+e^-} < 0.6 \text{ GeV}/c^2$ has recently been traced back to a corresponding enhancement in $pn$ collisions relative to $pp$ collisions. Whereas the dilepton spectra in the latter are understood quantitatively, theoretical descriptions fail to describe the much higher dilepton rate in $pn$ collisions, in particular regarding the region $M_{e^+e^-} > 0.3 \text{ GeV}/c^2$ at beam energies below 2 GeV. We show that the missing strength can be attributed to the $\rho$-channel $\pi^+\pi^-$ production, which is dominated by the $t$-channel $\Delta\Delta$ excitation and the recently found isoscalar dibaryonic resonance structure at 2.37 GeV.

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INTRODUCTION

Dilepton spectroscopy has been established as a valuable tool to explore the conditions of matter at high temperature and high density. Such extreme conditions as found in stars or in the early universe can be probed by relativistic heavy-ion collisions. In measurements of such collision processes a significant excess of lepton pairs over the theoretically expected rate has been observed in the mass region between the pion mass and the $\omega$ mass and interpreted as a possible sign of medium modifications. However, at lower beam energies of (1 - 2) GeV per nucleon still such an enhancement has been observed.

To address this problem the Dilepton Spectrometer (DLS) collaboration was the first to investigate the untriggered dilepton still such an enhancement has been observed.

In these calculations the following lepton-pair production processes have been taken into account:

- pion Dalitz decay $\pi^0 \rightarrow e^+e^-$,
- $\eta$ Dalitz decay $\eta \rightarrow e^+e^-\gamma$,
- leptonic vector meson decay $\nu \rightarrow e^+e^-\gamma$,
- virtual bremsstrahlung $NN \rightarrow NN e^+e^-$ and $NN e^+e^-$
- baryon resonance decay $R \rightarrow Ne^+e^-$, predominantly $\Delta \rightarrow Ne^+e^-$.  

The bremsstrahlung calculations of Ref.\textsuperscript{[7]} overshoot the HADES data for $pp$ collisions. For the $np$ case they overshoot the data for $M_{e^+e^-} < 0.3 \text{ GeV}$ and underpredict them above.

At sufficiently high incident energies both colliding nucleons may get excited. So in addition to the configuration $NR$, where $R$ denotes a nucleon in one of its excited states (resonance), we may have combinations of the form $RR'$. The lowest-lying such configuration is $\Delta\Delta$. In the following we will concentrate on the beam energy 1.25 GeV, where high-precision HADES data are available. As we will argue below the only relevant $RR'$ configuration there is $\Delta\Delta$.

At the energies of interest here, single-pion production in $NN$ collisions is by far the largest inelastic channel. It is dominated by $t$-channel meson exchange in combination with the excitation of one of the nucleons into the $\Delta(1232)$ resonance - or to a lesser extent to the Roper resonance $N^*(1440)$ with subsequent decay into the $\pi N$ system.

In the description of the dilepton spectra two-pion production has not been taken into account in most of the previous works, since its cross section is smaller by an order of magnitude. However, as we will show in the following, due to the relatively large decay branching $\rho^0 \rightarrow e^+e^-$ the $\pi^+\pi^-$ production in the $\rho$ channel contributes significantly to the electron-positron spectrum for $M_{e^+e^-} \geq 0.3 \text{ GeV}/c^2$.

In Ref.\textsuperscript{[4]} two-pion production has been accounted for in some global manner. Here we proceed differently. Since the two-pion channels have been investigated experimentally meanwhile by exclusive and kinematically complete measurements, we know the dominating two-pion production mechanisms in dependence of the energy in detail. In particular, we may perform an isospin decomposition of experimental cross sections and underlying reaction mechanisms, in order to separate their con-
tributions to \( pp \) and \( pn \) induced dilepton production.

**TWO-PION PRODUCTION**

In recent years the two-pion production in \( pp \) and \( pn \) collisions has been measured by exclusive and kinetically complete experiments over the energy region from threshold up to \( T_{lab} = 1.4 \text{ GeV} \) \([8, 22]\).

It has been shown that the \( pp \) induced two-pion production process is dominated by \( t \)-channel Roper and \( \Delta \Delta \) excitation \([8, 18, 23, 24]\). In the latter both nucleons are mutually excited to the \( \Delta \) resonance by \( t \)-channel meson exchange in the collision process. The Roper excitation process dominates at energies close to threshold below 1 GeV, whereas the \( \Delta \Delta \) process takes over above 1 GeV. Hence in the following we will focus on the latter two-pion production process. And since the HADES experiment has been carried out at \( T_p = 1.25 \text{ GeV} \), we will concentrate on this energy.

In \( pn \) induced two-pion production in addition the recently discovered dibaryon resonance structure \( d_r^* \) with \( I(J^P) = (0^+), M = 2.37 \text{ GeV}/c^2 \) and \( \Gamma = 70 \text{ MeV} \) strongly contributes at energies around 1.2 GeV due to its decay \( d_r^* \rightarrow \Delta \Delta \rightarrow NN\pi\pi \) \([14, 22]\).

The total inclusive cross section for \( pp \) induced \( \pi^+\pi^- \) production at \( T_p = 1.25 \text{ GeV} \) is about 700 \( \mu \text{b} \) and for \( np \) induced \( \pi^+\pi^- \) production it is about 1300 \( \mu \text{b} \). The latter contains not only the \( n\pi^+\pi^- \) channel, but also the double-pionic fusion channel \( d\pi^+\pi^- \).

The only sizeable way two-pion production may feed the electron-pair production is via \( \pi^+\pi^- \rightarrow \rho^0 \rightarrow e^+e^- \) with the isovector \( \pi^+\pi^- \) pair being in relative \( p \)-wave (\( \rho \) channel).

In order to filter out the \( \rho \)-channel \( \pi^+\pi^- \) production from the known two-pion production cross sections, we make use of the isospin decomposition of these cross sections in terms of matrix elements \( M_{I_N^*N^*I_{NN}^*I_{NN}^*} \), where \( I_{\pi\pi} \) stands for the isospin of the pion pair and \( I_{NN} \) and \( I_{NN}^* \) for the isospin of the nucleon pair in initial and final states, respectively \([12, 25, 26]\).

For a specific process these matrix elements depend on the isospin coupling coefficients. For the \( \Delta\Delta \) process the matrix elements are proportional to the respective \( 9j \)-symbol for isospin recoupling:

\[
M'_{I_N^*N^*I_{NN}^*I_{NN}^*} \sim I_{\Delta_1}I_{\Delta_2}I_{\Delta_3} I_{N_1}I_{N_2}I_{N_3} I_{\pi_1}I_{\pi_2}I_{\pi_3},
\]

where \( N_i \) and \( \pi_i \) couple to \( \Delta_i \) for \( i = 1, 2 \) and \( I_\alpha = \sqrt{\frac{1}{2}I_\alpha + 1} \).

In \( pp \)-initiated two-pion production only \( M_{111} \) gives rise to \( \rho^0 \)-channel production. However, because \( M_{111} \) is zero for the \( \Delta\Delta \) process — since the corresponding \( 9j \)-symbol in eq. (1) is zero, there is no contribution to \( \rho^0 \)-channel production. Hence the PLUTO \([27]\) generated cocktail for the description of the \( pp \) dilepton production as given in Ref. \([2]\) stays unchanged.

The situation changes dramatically in case of \( pn \)-initiated \( \rho^0 \)-channel production, since here we indeed do have large contributions from the \( \Delta\Delta \)-process. According to Refs. \([25, 26]\) we have for the \( pn \) initiated \( \pi^+\pi^- \) production:

\[
\sigma(pp \rightarrow \rho^0\pi^+\pi^-) = \frac{1}{60}\sqrt{\sum M_{101}^2 - 2M_{111}M_{121} + M_{121}^2} + \frac{1}{8}|M_{011}|^2 + \frac{1}{24}|M_{110}|^2 + \frac{1}{12}|M_{000}|^2,
\]

and since \( I_d = 0 \)

\[
\sigma(pp \rightarrow d\pi^+\pi^-) = \frac{1}{8}|M_{011}|^2 + \frac{1}{24}|M_{110}|^2.
\]

For dilepton production via \( \rho^0 \) production only matrix elements with \( I_{\pi\pi} = 1 \) contribute. Selecting in addition the \( \Delta\Delta \) process we end up with:

\[
\sigma(pp \rightarrow \Delta\Delta \rightarrow nn\pi^+\pi^-)_{I=1} = \frac{1}{8}|M_{011}|^2.
\]

With the relations

\[
M_{011} = \sqrt{\frac{15}{9}}M_{110} = \sqrt{\frac{15}{2}}M_{121}, \quad M_{110} = \frac{15}{2}M_{121},
\]

obtained by angular momentum recoupling according to eq. (1) this leads to

\[
\sigma(pp \rightarrow \Delta\Delta \rightarrow nn\pi^+\pi^-)_{I=1} = \frac{27}{16}M_{121}^2 = \frac{45}{4}\sigma(pp \rightarrow \Delta\Delta \rightarrow nn\pi^+\pi^+),
\]

since \([25, 26]\)

\[
\sigma(pp \rightarrow nn\pi^+\pi^+) = \frac{3}{20}|M_{121}|^2.
\]

The analysis of the \( pp \rightarrow nn\pi^+\pi^+ \) reaction gives about 15 \( \mu \text{b} \) \([13]\) for this cross section at \( T_p = 1.25 \text{ GeV} \), which results in

\[
\sigma(pp \rightarrow \Delta\Delta \rightarrow nn\pi^+\pi^-)_{I=1} \approx 170 \text{\mu b}.
\]
This number roughly corresponds to one fourth of the full \( \Delta\Delta \) production in the \( pn \to p\pi^+\pi^- \) reaction \[23\].

In case the final pn pair fuses to a deuteron we also obtain \( \rho^0 \)-channel production, which is related to the measured \( \pi^+\pi^0 \) (\( \rho^+ \) channel) production in \( pp \) collisions by the isospin relation \[21\]:

\[
\sigma(pn \to d[\pi^+\pi^-]_{I=1}) = \frac{1}{2}\sigma(pp \to d\pi^+\pi^0) \approx 100 \mu b. (10)
\]

In addition, the \( \rho^0 \)-channel production in \( pn \) initiated two-pion production is fed by excitation and decay of the \( d^* \)-resonance. Since its decay proceeds again via the \( \Delta\Delta \) system in the intermediate step, we can use the isospin relation for the \( \Delta\Delta \) system — utilizing again eq. (1) —

\[
M_{1\Delta} = -\sqrt{1\over 2} M_{0\Delta}^\Delta,
\]

in order to connect the \( pn[\pi^+\pi^-]_{I=1} \) decay channel with the \( pn\pi^0\pi^0 \) channel. According to the predictions in Refs. \[28\] - \[29\] the resonance effect in the latter channel should be 85 \% of that in \( d\pi^+\pi^0 \) channel \[21\], which isospin-decomposed reads as \[25\] - \[26\]

\[
\sigma(pn \to pn\pi^0\pi^0) = \frac{1}{30}\sqrt{3 \over 2} M_{101} + M_{121}|^2 + (12)
\]

\[
+ \frac{1}{24}|M_{000}|^2
\]

and for \( I_{NN} = I_{d^*} = 0 \):

\[
\sigma(pn \to d^* \to d\pi^0\pi^0) = \frac{1}{24}|M_{000}|^2. (13)
\]

At the resonance maximum at \( \sqrt{s} = 2.37 \) GeV this cross section is about 240 \( \mu b \), however, at \( \sqrt{s} = 2.42 \) GeV (\( T_p = 1.25 \) GeV) it is already as low as 90 \( \mu b \). Together with eqs. (2), (11) and (13) and the condition \( I_{NN} = I_{d^*} = 0 \) this results in:

\[
\sigma(pn \to d^* \to pn[\pi^+\pi^-]_{I=1}) = \frac{1}{24}|M_{1\Delta}^\Delta(d^*)|^2 = (14)
\]

\[
= \frac{1}{24}|M_{1\Delta}^\Delta(d^*)|^2 = \frac{1}{48}|M_{0\Delta}^\Delta(d^*)|^2 = \frac{1}{2}\sigma(pn \to d^* \to pn\pi^0\pi^0) \approx 40 \mu b.
\]

A cross check of this number is provided by a recent measurement \[22\] of the \( ppp^0\pi^- \) channel, since again by isospin relations we have \[22\] - \[25\] - \[26\]

\[
\sigma(pn \to d^* \to pn[\pi^+\pi^-]_{I=1}) = \sigma(pn \to d^* \to ppp^0\pi^-) . (15)
\]

Though according to Gal and Garciolo \[30\] the \( d^* \) decay into isovector nucleon and pion pairs should be dynamically suppressed, the measurement of the \( pn \to d^* \to ppp^0\pi^- \) reaction and its analysis \[22\] is compatible with a resonance cross section as expected by the isospin relations. However, since in the \( ppp^0\pi^- \) channel the resonance structure sits upon a large background of conventional processes, it cannot be excluded that the resonance contribution actually might be somewhat smaller.

In total we have about 310 \( \mu b \) of \( \rho^0 \)-channel \( \pi^+\pi^- \) production in \( pn \)-initiated reactions at \( T_p = 1.25 \) GeV — compared to none in \( pp \)-initiated reactions. We estimate this number to be correct at least within 20 \%.

**\( \rho^0 \)-CHANNEL \( e^+e^- \) PRODUCTION**

To calculate the \( e^+e^- \) production we assume that the two pions produced in the \( \Delta\Delta \) process undergo final state interaction by forming a \( \rho^0 \), which subsequently decays into an \( e^+e^- \) pair:

\[
pn \to \Delta\Delta \to pn[\pi^+\pi^-]_{I=1} \to pn\rho^0 \to pnn e^+e^- , (16)
\]

see graphs in Fig. 1. The intermediate \( \Delta\Delta \) system is formed either by \( t \)-channel meson exchange or by decay of the \( d^* \) resonance with cross sections as evaluated above.

For the transition from the \( \pi^+\pi^- \) system into the \( e^+e^- \) system by rescattering (final state interaction in the \( \rho \)-channel) we use a Breit-Wigner ansatz \[31\] - \[32\]:

\[
|M(\pi^+\pi^- \to \rho^0 \to e^+e^-)|^2 = \frac{m_{\pi^+\pi^-}^2 \Gamma_{\pi^+\pi^-} \Gamma_{e^+e^-}}{(s - m_{\rho}^2)^2 + m_{\rho}^4 \Gamma_{e^+e^-}^2} . (17)
\]

For the p-wave decay into the \( \pi^+\pi^- \) channel we have \( \Gamma_{\pi^+\pi^-} \sim q^2 \) and for the s-wave decay into the \( e^+e^- \) channel we have \( \Gamma_{e^+e^-} \sim k \), where \( q \) and \( k \) are the momenta in \( \pi^+\pi^- \) and \( e^+e^- \) subsystems, respectively. In a more detailed consideration \[32\] the partial widths depend also on the invariant masses \( M_{\pi^+\pi^-} \) and \( M_{e^+e^-} \) yielding \( \Gamma_{\pi^+\pi^-} = aq^2/M_{\pi^+\pi^-} \Gamma_{\pi^+\pi^-} \) and \( \Gamma_{e^+e^-} = bk/M_{e^+e^-} \). The constants \( a \) and \( b \) in the partial widths are fixed by adjusting them to the known branching ratios and widths at the \( \rho \) mass pole \[33\]. Hence the Monte Carlo (MC) simulation of process (16) is straightforward and free of parameters.

**RESULTS**

The numerical results of this MC simulation are displayed in Fig. 2. At the top panel we show first the \( \rho^0 \)-channel \( \pi^+\pi^- \) spectrum obtained from the processes discussed in eqs. (1) - (15) and scaled by the \( e^+e^- \) branching ratio at the pole of \( \rho^0 \) (dotted line). This gives only a crude estimate. A proper treatment involves the
momentum-dependent transition amplitude in eq. (17) resulting in the solid curve. The enhanced yield of the $e^+e^-$ spectrum relative to the scaled $\pi^+\pi^-$ spectrum at low masses is due to the fact that – in addition to the inverse power dependence on the invariant mass – the pion pair is in relative power dependence on the invariant mass – the pion pair is in relative $p$-wave and therefore suppressed near threshold, whereas the $e^+e^-$ pair is in relative $s$-wave and hence not suppressed. The resulting integral cross section for the process $pn \rightarrow e^+e^-X$ is 72 nb, which is about a factor of four larger than that from the crude estimate.

Since the HADES detector has limited acceptance, this has to be taken into account for comparison with the HADES data. The dashed curve exhibits the final $e^+e^-$ production resulting from $\rho^0$-channel $\pi^+\pi^-$ production in $pn$ collisions within the HADES acceptance.

All other conventional processes due to $\pi^0, \eta$ and $\Delta$ Dalitz decays and bremsstrahlung – mentioned in the introduction – were simulated using the PLUTO generator [27] and filtered with HADES efficiency-acceptance filters. [34] They are shown in Fig. 2, bottom in comparison with the HADES data for $pn$ initiated $e^+e^-$ production at $T_p = 1.25$ GeV. The sum of these processes resulting from Dalitz decays is denoted by the dotted curve. It provides a quantitative description of the data in the region of the $\pi^0$ peak, i.e. for $M_{e^+e^-} < 0.15$ GeV. Above, the sum curve under-predicts the data increasingly with increasing $M_{e^+e^-}$ values. However, if we add the $e^+e^-$ production resulting from $\rho^0$-channel $\pi^+\pi^-$ production (dashed curve both in top and bottom parts of Fig. 2) we obtain a nearly perfect description of the HADES data.

There appears still a slightly underestimated region in the range $0.15 \text{ GeV} < M_{e^+e^-} < 0.3$ GeV. It possibly might be related to direct $d^*$ decay $pn \rightarrow d^* \rightarrow de^+e^-$ or $pn \rightarrow d^* \rightarrow \pi n \delta e^+e^-$ as suggested in Ref. [8]. However, since we know neither shape nor strength of such a $d^*$ form-factor in this channel, we cannot estimate such a contribution reliably. In addition, also the PLUTO generated processes have theoretical uncertainties, which are in the order of the deviation in question. Since we base the dilepton production due to $\rho^0$ channel $\pi^+\pi^-$ production on experimental results for the relevant two-pion production channels, we consider here only the on-shell situation. However, because the two-lepton threshold is much lower than the two-pion threshold also dilepton production via virtual $\rho^0$ formation in the intermediate state will contribute. Taking this into account removes the cut in the $e^+e^-$ spectrum at the $\pi^+\pi^-$ threshold and replaces it by a smooth continuation as depicted, e.g., in Fig. 3 of Ref. [4]. Hence accounting for this will fill...
up the gap below 0.3 GeV – possibly overshoot it even somewhat. We refrain here from doing such a calculation, since in contrast to the on-shell consideration pursued here the off-shell contribution is model-dependent.

Finally we shortly comment on the dependence of the $e^+e^-$ spectrum on the beam energy. The DLS collaboration has measured the $e^+e^-$ production in $pp$ and $pd$ collisions at several beam energies between 1.04 and 4.88 GeV. The ratio $R$ of integrated yields for $M_{e^+e^-} > 0.15$ GeV/$c^2$ exhibits a peak-like structure with a substantial rise from $R \approx 2$ to $R \approx 9$ between $T_p = (1.0 - 1.27)$ GeV, falling off thereafter by a factor of roughly three until $T_p = 2$ GeV. At 2.1 GeV the ratio is somewhat above 2 and at 4.9 GeV a little bit below 2.

Assuming the $pd$ collisions to proceed mainly as quasifree proton-nucleon collisions, we expect a ratio of $R = 2$, if $pp$ and $pn$ collisions contribute equally much. In the quasifree picture the peak region corresponds to $R = 2$, if $pp$ and $pn$ collisions contribute equally much. Whereas the first one with a width of 70 MeV fades away below $\sqrt{s} = 2.3$ GeV and above $\sqrt{s} = 2.5$ GeV, the latter one with a width of about 250 MeV declines much slower fading away above $\sqrt{s} = 2.8$ GeV, which corresponds to beam energies beyond 2 GeV.

For beam energies beyond 1.5 GeV ($\sqrt{s} > 2.5$ GeV) we face substantial contributions from the $\rho^0$ decay of higher-lying $N^*$ and $\Delta$ resonances, which get excited during the collision process. These sources contribute to the dilepton spectra both from $pn$ and $pp$ collisions as demonstrated by Refs. [4, 6], who succeed in a quantitative description of the data for beam energies of 2 GeV and beyond.

**CONCLUSIONS**

It has been shown that the $e^+e^-$ production resulting from $\rho^0$-channel $\pi^+\pi^-$ production gives significant contributions to the dilepton spectrum for $M_{e^+e^-} > 2m_\pi$, which account very well for the missing strength in previous interpretations offering thus a solution of the long-standing DLS puzzle.

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[1] R. J. Porter, et al. (DLS Collaboration), Phys. Rev. Lett. 79 (1997) 1229
[2] G. Ägäkchijev et al. (HADES Collaboration), Phys. Lett. B 690 (2010) 118
[3] R. Shyam, U. Mosel, Phys. Rev. C 82 (2010) 062201
[4] J. Weil, H. van Hees, U. Mosel, Eur. Phys. J. A 48 (2012) 111 and 150
[5] B. V. Martemyanov, M. I. Krivoruchenko, Amand Faessler, Phys. Rev. C 84 (2011) 047601
[6] E. L. Bratkovskaya, J. Aichelin, M. Thomere, S. Vogel, M. Bleicher, Phys. rev. C 87 (2013) 064907
[7] L. P. Kaptari and B. Kämpfer, Nucl. Phys. A 764 (2006) 338
[8] J. Johansson et al. (PROMICE/WASA Collaboration), Nucl. Phys. A 712 (2002) 75
[9] W. Brodowski et al. (PROMICE/WASA Collaboration), Phys. Rev. Lett. 88 (2002) 192301
[10] J. Pätzold et al. (PROMICE/WASA Collaboration), Phys. Rev. C 67 (2003) 052202
[11] T. Skorodko et al. (CELSIUS/WASA Collaboration), Eur. Phys. J. A 35 (2008) 317
[12] T. Skorodko, et al. (CELSIUS/WASA Collaboration), Phys. Lett. B 679 (2009) 30
[13] F. Kren et al. (CELSIUS/WASA Collaboration), Phys. Lett. B 684 (2010) 110 and B 702 (2011) 312; arXiv:0910.0995v2 [nucl-ex]
[14] T. Skorodko et al. (CELSIUS/WASA Collaboration), Phys. Lett. B 695 (2011) 115
[15] T. Skorodko et al. (CELSIUS/WASA Collaboration), Eur. Phys. J. A 47 (2010) 108
[16] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. B 706 (2011) 156
[17] S. Abd El-Bary et al. (COSY-TOF Collaboration), Eur. Phys. J. A 37 (2008) 267
[18] S. Abd El-Sanad et al. (COSY-TOF Collaboration), Eur. Phys. J. A 42 (2009) 159
[19] M. Bashkanov et al. (CELSIUS/WASA Collaboration), Phys. Rev. Lett. 102 (2009) 052301
[20] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Rev. Lett. 106 (2011) 242302
[21] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. B 721 (2013) 229
[22] P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Rev. C 88 (2013) 055208
[23] L. Alvarez-Ruso, E. Oset, E. Hernandez, Nucl. Phys. A 633 (1998) 519
[24] X. Cao, Bing-Song Zou and Hu-Shan Xu, Phys. Rev. C 81 (2010) 065201
[25] L. G. Dakhno et. al., Sov. J. Nucl. Phys. 37 (1983) 540
[26] J. Bystricky et al., J. Physique 48 (1987) 1901
[27] I. Fröhlich et al., arXiv:0708.2382v2
[28] G. Fäldt and C. Wilkin, Phys. Lett. B 701 (2011) 619
[29] M. Albadejo and E. Oset, Phys. Rev. C 88 (2013) 014006
[30] A. Gal and H. Garcilazo, Phys. Rev. Lett. 111 (2013) 172301
[31] C. Q. Li, C. M. Ko and G. E. Brown, Phys. Rev. Lett. 75 (1995) 4007
Note that in PLUTO the bremsstrahlung contributions are taken according to the prescription of Ref. [3], which leads to a good description of the HADES data for the $pp$ case in contrast to that of Ref. [7].