Electron-positron annihilation into four pions and the $\mathbf{a_1}\rho\pi$ Lagrangian

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Properties of $\mathbf{a_1(1260)}$

- $I^G = 1^-$
- $J^P = 1^+$
- $m = 1230 \pm 40$ MeV
- $\Gamma =$ 250 to 600 MeV
- Decays ("seen", no info about branching fractions)

  $\rho\pi$ (S and D waves)
  $\rho(1450)\pi$ (S and D waves)
  $\sigma\pi$
  $f_0(1370)\pi$
  $f_2(1270)\pi$
  $K\bar{K}^*$ + c.c.
  $\pi\gamma$

$\mathbf{a_1(1260)}$ in low-energy processes

- Hadronic processes

  diffractive production $\pi^- p \to \pi^-\pi^-\pi^+ p$
  charge-exchange reaction $\pi^- p \to \pi^+\pi^-\pi^0 n$
  central production $pp \to p_f(\pi^+\pi^-\pi^0)p_s$
  decays, e.g. $\rho(1700) \to a_1\pi$

- Electromagnetic processes

  $e^+e^- \to \pi^+\pi^-\pi^+\pi^-$
  $e^+e^- \to \pi^+\pi^-\pi^0\pi^0$

- Weak decays

  $\tau^- \to \nu_\tau\pi^-\pi^-\pi^+$
  $\tau^- \to \nu_\tau\pi^-\pi^0\pi^0$
  $\tau^- \to \nu_\tau\pi^-\pi^-\pi^+\pi^0$
  $D^+ \to K^0_S a_1^+$, etc.

Elmag. radiation from hadron gas

- Photons

  $\pi + \rho \to \gamma + \pi$
  $\pi + \pi \to \gamma + \rho$
  $\rho \to \gamma + \pi + \pi$
  $a_1 \to \gamma + \pi$

- Dileptons

  As above with γ replaced by e^+e^-, and
  $\pi^\pm + a_1^\mp \to e^+e^-$
  $a_1^+ + a_1^- \to e^+e^-$
  $\pi^+\pi^-\pi^+\pi^- \to e^+e^-$
  $\pi^+\pi^-\pi^0\pi^0 \to e^+e^-$

- Calculated rate strongly depends on the choice of the $a_1\rho\pi$ Lagrangian!

Phenomenological $\mathbf{a_1\rho\pi}$ Lagrangian

$$\mathcal{L} = \frac{\mathbf{g_{a_1\rho\pi}}}{\sqrt{\mathbf{2}}} \left(\mathcal{L}_\mathbf{1} \cos\theta + \mathcal{L}_\mathbf{2} \sin\theta\right)$$

$\sin\theta$, $\mathbf{g_{a_1\rho\pi}}$
to be determined

$$\mathcal{L}_1 = \mathbf{A}^\mu \cdot (\mathbf{V}_{\mu\nu} \times \partial^\nu \phi)$$

Xiong, Shuryak, Brown
PRD 46, 3798 (1992)

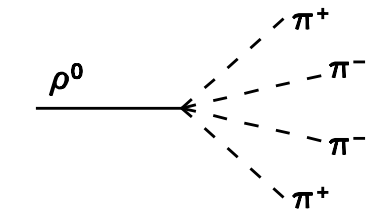
$$\mathcal{L}_2 = \mathbf{V}_{\mu\nu} \cdot (\partial^\mu \mathbf{A}^\nu \times \phi)$$

Janssen, Holinde, Speth
PRC 49, 2763 (1994)

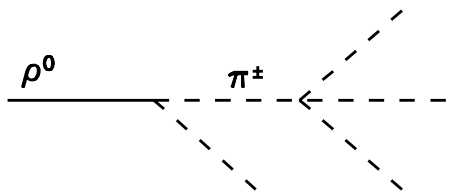
$$\mathbf{V}_{\mu\nu} = \partial_\mu \mathbf{V}_\nu - \partial_\nu \mathbf{V}_\mu$$

$$\Gamma(a_1 \to \rho\pi) = g^2_{a_1\rho\pi} f(\sin\theta)$$

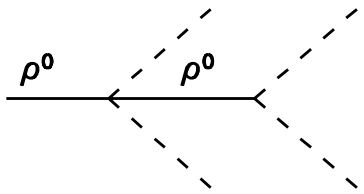
$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ below 1 GeV



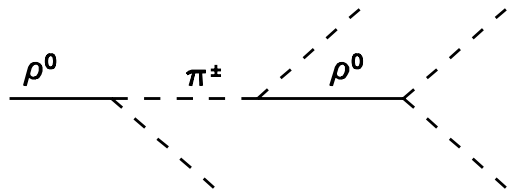
(a1), 1 diagram



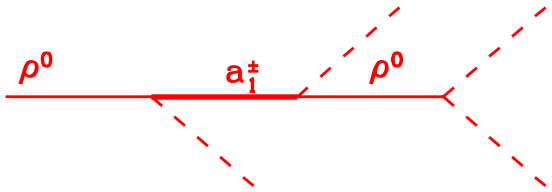
(a2), 4 diagrams



(b1), 4 diagrams



(b2), 8 diagrams

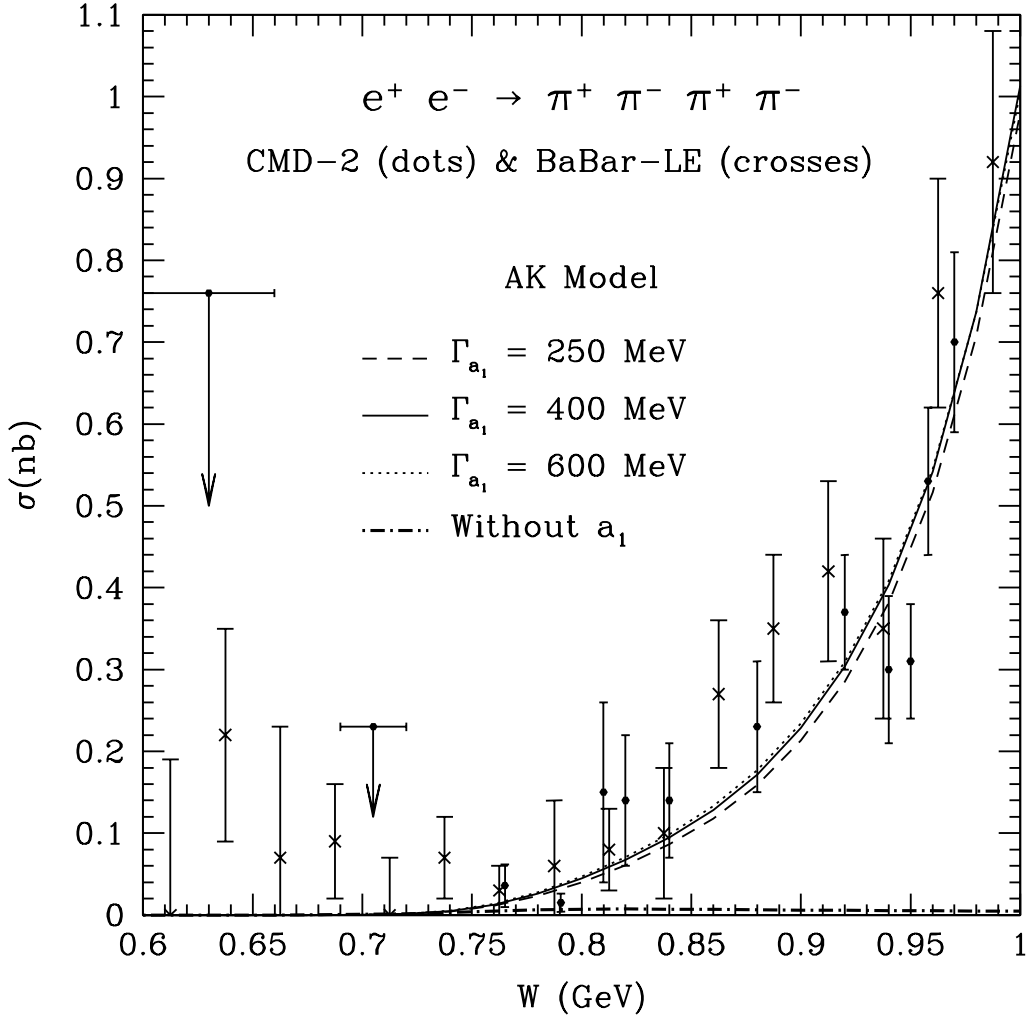


(d), 8 diagrams

Corresponding decay diagrams of ρ^0

P.L.&J.J, Phys. Rev. D 76, 094030 (2007)

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ below 1 GeV



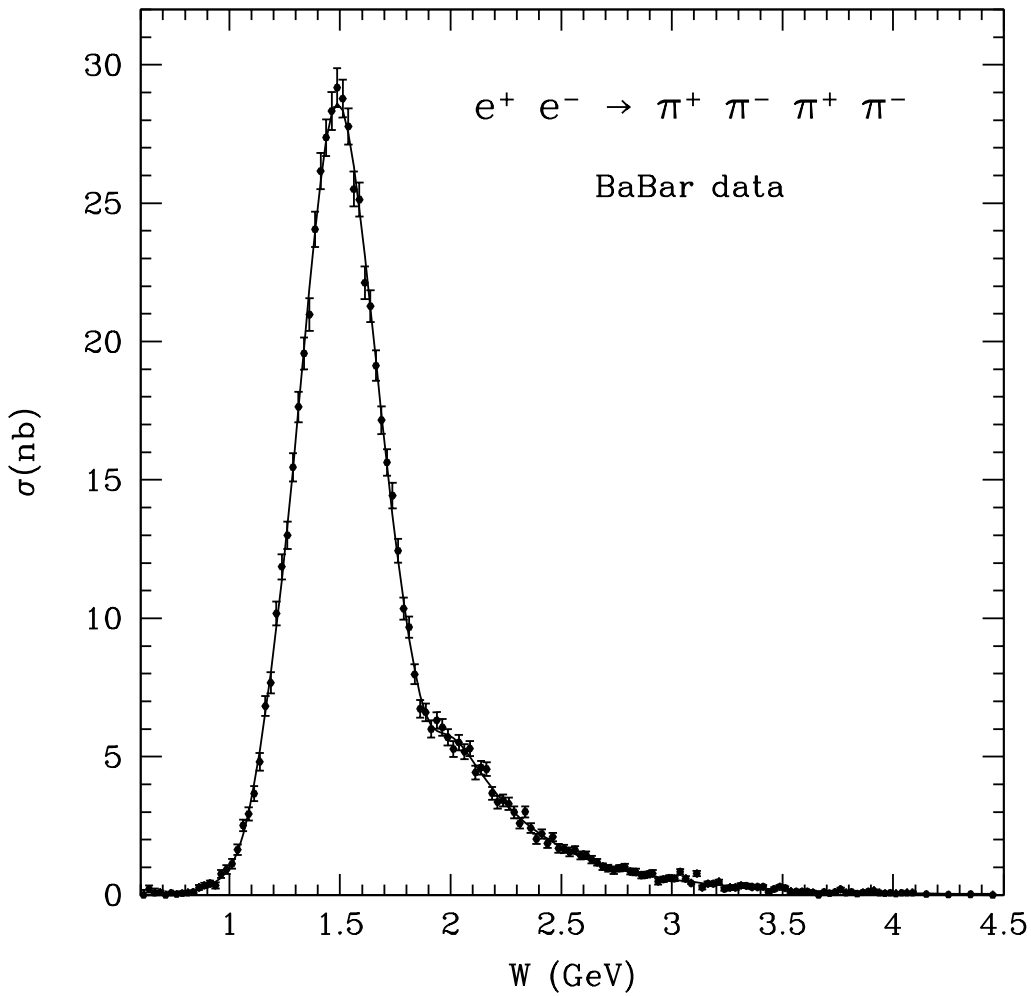
$\chi^2/NDF = 1.18$

$\sin\theta = 0.5022(41)$

Comparison with CMD-2 and low-energy part of BaBar data

Basic model: Achasov and Kozhevnikov, PRD 62, 077904

$e^+e^- \to \pi^+\pi^-\pi^+\pi^-$ up to 4.5 GeV



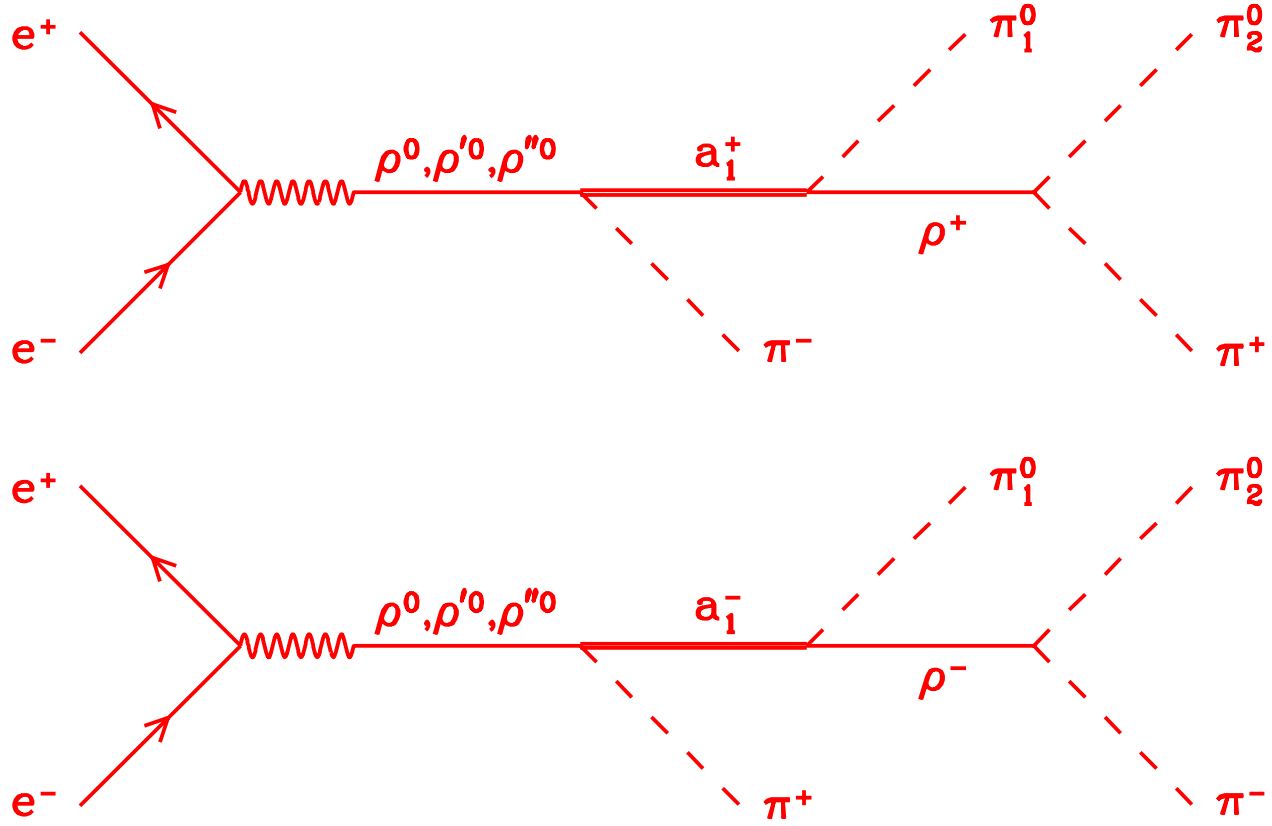
$\chi^2/NDF = 1.12$

$\sin\theta = 0.4603(28)$

Comparison of the pure $\mathbf{a_1}$ model with BaBar data
Form factor includes also $\rho(1450)$ and $\rho(1700)$ resonances

$\mathbf{e^+e^- \to \pi^+\pi^-\pi^0\pi^0}$

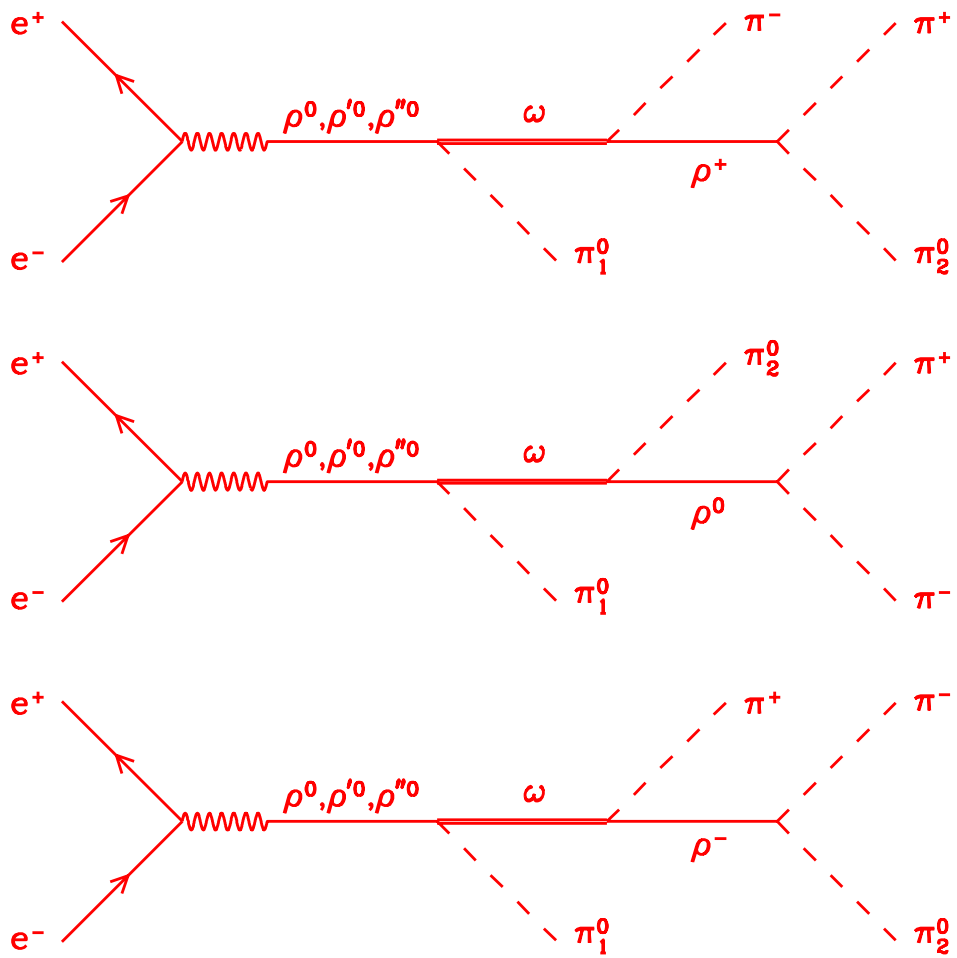
arXiv:0802.4229[hep-ph]



Two Feynman diagrams of a pure $\mathbf{a_1}$ model.

$\mathbf{a_1}\rho\pi$ Lagrangian parameters from the previous analysis.

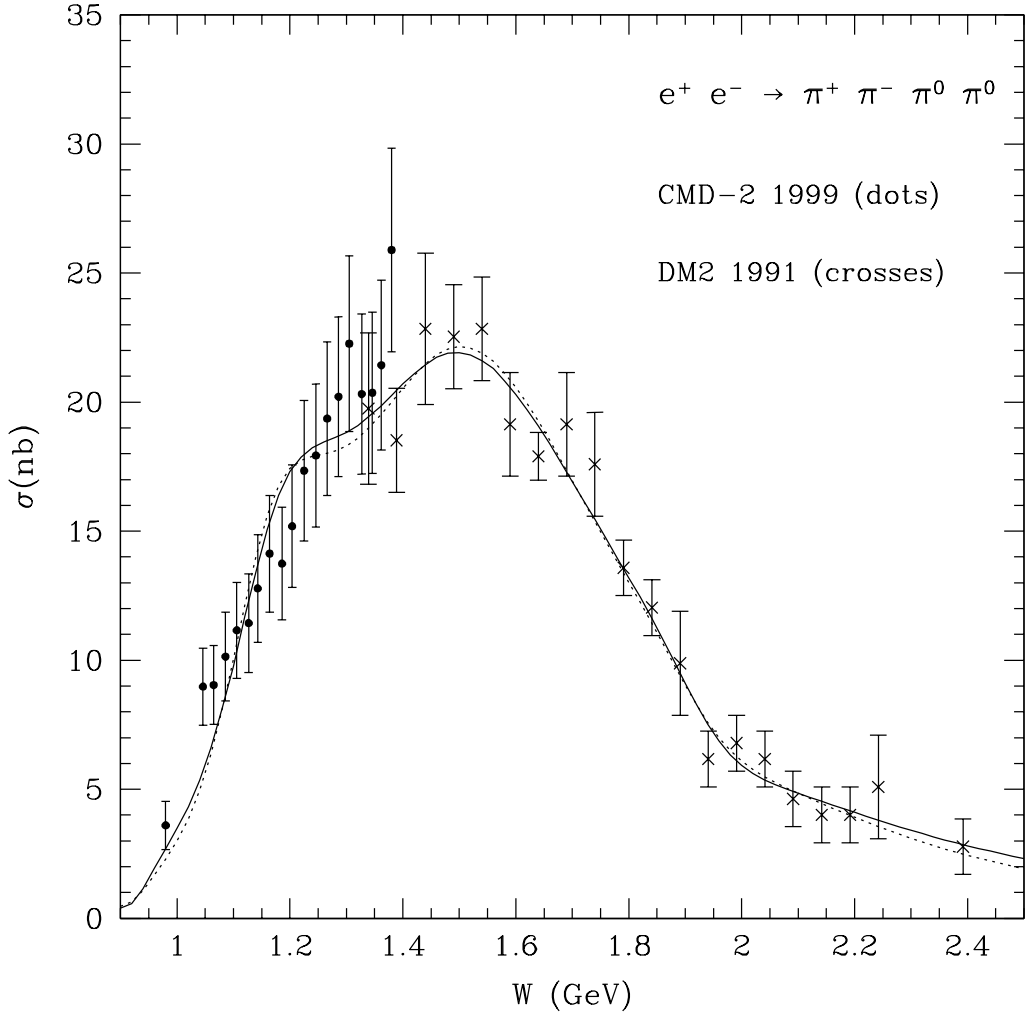
$\mathbf{e^+e^- \longrightarrow \pi^+\pi^-\pi^0\pi^0}$



Three Feynman diagrams describing the ω contribution.

$\omega\rho\pi$ coupling fixed by analysis of the ω decays.

$\mathbf{e^+e^- \to \pi^+\pi^-\pi^0\pi^0}$



Pure $\mathbf{a_1}$ model:
$\chi^2/NDF = 11.2$

$\mathbf{a_1} + \omega$ model:
$\chi^2/NDF = 0.79$

$\mathbf{a_1} + \omega + \mathbf{h_1}$ model:
$\chi^2/NDF = 0.75$

$a_1 + \omega + h_1$ model versus CMD-2 and DM2 data.
$a_1\rho\pi$ Lagrangian parameters same as in $\pi^+\pi^-\pi^+\pi^-$

Joint fit to $\pi^+\pi^-\pi^+\pi^-$ and $\pi^+\pi^-\pi^0\pi^0$

$\chi^2/NDF = 0.99$
$\sin\theta = 0.4632(43)$

$\sin\theta = 0.4603(28)$ from $\pi^+\pi^-\pi^+\pi^-$ above 1GeV
$\sin\theta = 0.5132(55)$ from $\pi^+\pi^-\pi^+\pi^-$ below 1GeV

The results of this study have already been utilized in the evaluation of the dimuon production from the four-pion annihilation in In-In collisions at 158A GeV (comparison with the NA60 experiment):
J. Ruppert, C. Gale, T. Renk, P. Lichard, and J. I. Kapusta, Phys. Rev. Lett. 100, 162301 (2008).