Simulation of the $X(3872) \rightarrow J/\psi + \rho$ and $X(3872) \rightarrow J/\psi + \omega$ processes in the PANDA experiment

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**X(3872) state**

**Basic properties:**
1) Neutral charmonium-like particle;
2) Narrow state: $\Gamma < 1.2 \text{ MeV}/c^2$;
3) Mass very close to the $D^0\bar{D}^{*0}$ threshold;
4) Isospin breaking: $Br(J/\psi + \rho) \approx Br(J/\psi + \omega)$;
5) Spin-parity: $1^{++}$.

**Nature:**
- $D^0\bar{D}^{*0}$-molecule?
- Tetraquark?
- Mixture of states: $X(3872) = c\bar{c} + DD^* \rightarrow$ non-Breit-Wigner shape $\rightarrow$ Flatté parameterization for scattering amplitude.
Flatté parametrization for the near threshold resonance of the $D^0 \bar{D}^{*0}$ scattering amplitude defines

$$F(E) = -\frac{1}{2k_1} \frac{g_1 k_1}{D(E)},$$

with

$$D(E) = \begin{cases} 
E - E_f - \frac{g_1 \kappa_1}{2} - \frac{g_1 \kappa_2}{2} + i \frac{\Gamma(E)}{2}, & E < 0 \\
E - E_f - \frac{g_2 \kappa_2}{2} + i \left(\frac{g_1 k_1}{2} + \frac{\Gamma(E)}{2}\right), & 0 < E < \delta \\
E - E_f + i \left(\frac{g_1 k_1}{2} + \frac{g_2 k_2}{2} + \frac{\Gamma(E)}{2}\right), & E > \delta
\end{cases}$$

and

$$\delta = M(D^+D^{*-}) - M(D^0\bar{D}^{*0}) = 7.6 \text{ MeV},$$

$$k_1 = \sqrt{2\mu_1 E}, \kappa_1 = \sqrt{-2\mu_1 E}, k_2 = \sqrt{2\mu_2(E - \delta)}, \kappa_2 = \sqrt{2\mu_2(\delta - E)}.$$
\[ \Gamma(E) = \Gamma_{\pi^+\pi^-J/\psi}(E) + \Gamma_{\pi^+\pi^-\pi^0J/\psi}(E), \]

the \( \gamma J/\psi \) channel is neglected due to its small branching fraction\(^1\).

\[
\Gamma_{\pi^+\pi^-J/\psi}(E) = f_\rho \int_{2m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\rho}{(m - m_\rho)^2 + \Gamma_\rho^2/4},
\]

\[
\Gamma_{\pi^+\pi^-\pi^0J/\psi}(E) = f_\omega \int_{3m_\pi}^{M-m_{J/\psi}} \frac{dm}{2\pi} \frac{q(m)\Gamma_\omega}{(m - m_\omega)^2 + \Gamma_\omega^2/4},
\]

with \( f_\rho \) and \( f_\omega \) being effective couplings.

\(^1\)Belle Collaboration, K. Abe et al., BELLE-CONF-0540. arXiv:hep-ex/0505037, 2005
PANDA experiment is one of the major projects of the FAIR in Darmstadt. The PANDA physics program includes following questions:

- **charmonium spectroscopy** → will able to measure such states as $X(3872)$;
- gluonic excitations, e.g. hybrids and glueballs;
- nucleon structure;
- hadrons in the nuclear medium;
- hypernuclear physics.
The PANDA experiment will be carried out by high-energy storage ring HESR\textsuperscript{2}. An important feature of the HESR is the combination of cooled beams and dense internal targets, comprising challenging beam parameters in two operation modes ($\delta p/p = 4 \cdot 10^{-5}$ and $\delta p/p = 2 \cdot 10^{-4}$).

\textbf{Figure:} HESR storage ring

Width of $X(3872)$ will be measured by energy scan. The term energy scan reflects the procedure to measure the energy dependent cross section of a specific process over a certain range of center-of-mass energies $E_{cm}$. 

**Figure:** Schematic of energy scan
PandaRoot is the official framework for the PANDA for simulation, reconstruction and analysis.

Figure: Scheme of the PandaRoot data flow
Group from IHEP developed \(X(3872)\) production Monte Carlo generator with decays in \(J/\psi + \rho\) and \(J/\psi + \omega\) channels, based on the Flatté parameterization. The following reactions were considered:

- a) \(p\bar{p} \rightarrow X(3872) \rightarrow J/\psi + \rho \rightarrow e^- + e^+ + \pi^+\pi^-\pi^0\);
- b) \(p\bar{p} \rightarrow X(3872) \rightarrow J/\psi + \omega \rightarrow e^- + e^+ + \pi^+\pi^-\),

the lepton decay of \(J/\psi\) was considered in the electron-positron channel due to its registration in the forward shashlyk calorimeter (IHEP group is responsible for the creation of this calorimeter).

The following Flatté parameters were chosen:

- a) \(E_f\) ranging from \(-8\) MeV to \(-3\) MeV;
- b) \(f_\rho = 0.00047, f_\omega = 0.00271\) and \(g = 0.137\) (taken from \(^3\)).

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\(^3\)Klaus Götzen et al., RN-QCD-2016-002, 2016
Simulation of the $X(3872) \rightarrow J/\psi + \rho$ and $X(3872) \rightarrow J/\psi + \omega$

For reconstruction $p\bar{p} \rightarrow X(3872) \rightarrow J/\psi + \rho/\omega$, the following selection criteria were selected:

- **Pion PID:** None (all charged tracks),
- **Electron PID:** None (all charged tracks),
- **$J/\psi \rightarrow e^+e^-$ mass window:** $2.5 \text{ GeV} \leq m(e^+e^-) \leq 4.5 \text{ GeV}$,
- **$\rho \rightarrow \pi^+\pi^-$ mass window:** $0.27 \text{ GeV} \leq m(\pi^+\pi^-) \leq 1.0 \text{ GeV}$,
- **$\omega \rightarrow \pi^+\pi^-\pi^0$ mass window:** $0.27 \text{ GeV} \leq m(\pi^+\pi^-\pi^0) \leq 1.0 \text{ GeV}$,
- **$p\bar{p} \rightarrow e^+e^-\pi^+\pi^-\pi^0$ 4C fit:** $\text{prob} > 0.01$,
- **$\pi^0 \rightarrow \gamma\gamma$ mass window:** $0.075 \text{ GeV} \leq m(\gamma\gamma) \leq 0.175 \text{ GeV}$,
- **$\pi^0 \rightarrow \gamma\gamma$ energy asymmetry:** $\frac{|E_{\gamma_1} - E_{\gamma_2}|}{E_{\gamma_1} + E_{\gamma_2}} > 0.7$.

These selection criteria showed the optimal reconstruction efficiency of events.
Simulation of the $X(3872) \rightarrow J/\psi + \rho$

The resulting resonance curves are shown ($N(\Delta E)$) in Figure obtained for $X(3872) \rightarrow J/\psi + \rho$ with $E_f = -8 \text{ MeV}$, $-5 \text{ MeV}$ and $-3 \text{ MeV}$. 

![Graphs showing resonance curves for $X(3872) \rightarrow J/\psi + \rho$ for different energies.](image-url)
Simulation of the $X(3872) \rightarrow J/\psi + \omega$

The resulting resonance curves are shown ($N(\Delta E)$) in Figure obtained for $X(3872) \rightarrow J/\psi + \omega$ with $E_f = -8\text{ MeV}, -5\text{ MeV}$ and $-3\text{ MeV}$.
Simulation of the $X(3872) \to J/\psi + \rho$ and $X(3872) \to J/\psi + \omega$ taking into account the beam profile

The theoretical shapes have been calculated taking into account the real beam profile of the HESR accelerator for its two modes ($\delta p/p = 4 \cdot 10^{-5}$ and $\delta p/p = 2 \cdot 10^{-4}$).
In conclusion, let us formulate the main results of this work.

- The $X(3872)$ production was simulated with decays in the $J/\psi + \rho$ and $J/\psi + \omega$ channels by scanning the line shape of the resonance curve for Flatté parameter $E_f$ ranging from $-8 \text{ MeV}$ to $-3 \text{ MeV}$. The obtained simulation results well reproduce the embedded theoretical resonance curves. The reconstruction efficiency of $J/\psi + \rho \sim 9\%$, $J/\psi + \omega \sim 3\%$.

- The theoretical shapes have been calculated taking into account the real beam profile of the HESR accelerator.