Can We Resolve the Nature of $\chi_{c1}(3872)$ with PANDA?

EMMI Workshop - Experimental and theoretical status of and perspectives for XYZ states

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Study of the lineshape of the $\chi_{c1}(3872)$ state

Abstract

A study of the lineshape of the $\chi_{c1}(3872)$ state is made using a data sample corresponding to an integrated luminosity of 3 fb$^{-1}$ collected in $pp$ collisions at centre-of-mass energies of 7 and 8 TeV with the LHCb detector. Candidate $\chi_{c1}(3872)$ mesons from $b$-hadron decays are selected in the $J/\psi\pi^+\pi^-$ decay mode. Describing the lineshape with a Breit–Wigner function, the mass splitting between the $\chi_{c1}(3872)$ and $\psi(2S)$ states, $\Delta m$, and the width of the $\chi_{c1}(3872)$ state, $\Gamma_{BW}$, are determined to be

$$\Delta m = 185.588 \pm 0.067 \pm 0.068 \text{ MeV},$$

$$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10 \text{ MeV},$$

where the first uncertainty is statistical and the second systematic. Using a Flatté-inspired lineshape, two poles for the $\chi_{c1}(3872)$ state in the complex energy plane are found. The dominant pole is compatible with a quasi-bound $D^0\bar{D}^{*0}$ state but a quasi-virtual state is still allowed at the level of 2 standard deviations.
LHCb Findings

- **Breit Wigner fit**

\[ m_{\chi_c(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010 \text{ MeV} \]
\[ \Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10 \text{ MeV} \]

[previous Belle result: \( \Gamma < 1.2 \text{ MeV (CL90)} \)]

- **Flatté model fit**

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<td>3871.69^{+0.09+0.05}_{-0.04-0.13}</td>
<td>3871.66^{+0.07+0.11}_{-0.06-0.13}</td>
<td>0.22^{+0.06+0.25}_{-0.08-0.17}</td>
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\[ g \quad f_p \times 10^3 \quad \Gamma_0 \text{ [MeV]} \quad m_0 \text{ [MeV]} \]
\[ 0.108 \pm 0.003 \quad 1.8 \pm 0.6 \quad 1.4 \pm 0.4 \quad 3864.5 \text{ (fixed)} \]

(Flatté energy \( E_f = -7.2 \text{ MeV} \))
LHCb Findings

• Breit Wigner fit

\[ m_{\chi c_1(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010 \text{ MeV} \]
\[ \Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10 \text{ MeV} \]

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Factor 6.3, analysis dependent

• Flatté model fit

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(Flatte energy \( E_f = -7.2 \text{ MeV} \))

→ Need to fix the model!
J/ψπ⁺π⁻ Lineshapes

- Flatté Model by Hanhart et al. [PRD 76 (2007) 034007]
- Lineshape for various Flatté energies $E_f$ (other parms. const)

$$E_f = -8.7 \text{ MeV}$$

Fixed by LHCb

$$E_f = -7.2 \text{ MeV}$$

$$E_f = -5.7 \text{ MeV}$$

FWHM = 526 keV

FWHM = 220 keV

FWHM = 217 keV

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LHCb Lineshapes (incl Resolution)

Original lineshapes

Lineshapes with resolution

- **Quote LHCb:**

7.3 **Comparison between Breit–Wigner and Flatté lineshapes**

Figure 4 shows the comparison between the Breit–Wigner and the Flatté lineshapes. While in both cases the signal peaks at the same mass, the Flatté model results in a significantly narrower lineshape. However, after folding with the resolution function and adding the background, the observable distributions are indistinguishable.
Overcome Detector Resolution with Formation

- **Production** with recoils dominated by detector resolution (~ MeV)
- **Formation reaction** → produce $\chi_{c1}(3872)$ [$J^{PC} = 1^{++}$] w/o recoils

- Beam energy spread → resolution
- Measure yield at different $E_{\text{cms}}$

LHCb Detector Resolution $\approx 2.6$ MeV
PANDA Beam Resolution $\approx 0.05$ MeV

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**PANDA at FAIR**

**Facility for Antiproton and Ion Research**
(GSI, Darmstadt, Germany)

- **HESR**
  High Energy Storage Ring

- **PANDA**

- anti-proton production

- existing facility
- new facility
- experiments

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Resolve Nature of \( \chi_c(3872) \) with PANDA
FAIR Construction Site

• Good progress despite pandemic
FAIR Construction Site

- Good progress despite pandemic
PANDA and HESR

<table>
<thead>
<tr>
<th>HESR mode</th>
<th>$dp/p$</th>
<th>$L_{\text{max}}$ [1/cm$^2$·s]</th>
<th>$dE_{\text{cm}}$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Luminosity (HL)</td>
<td>$1 \cdot 10^{-4}$</td>
<td>$2.0 \cdot 10^{32}$</td>
<td>168</td>
</tr>
<tr>
<td>High Resolution (HR)</td>
<td>$2 \cdot 10^{-5}$</td>
<td>$2.0 \cdot 10^{31}$</td>
<td>34</td>
</tr>
<tr>
<td>Phase 1 Mode (P1)</td>
<td>$5 \cdot 10^{-5}$</td>
<td>$2.0 \cdot 10^{31}$</td>
<td>84</td>
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@ $E_{\text{cm}} = 3872$ MeV
What can PANDA do?

Due to precise beam resolution → Breit-Wigner and Flatté-model are distinguishable

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Flatté (-7.2 MeV)

BW (1.4 MeV)

PANDA HL

d$_{cm}$ = 168 keV

PANDA HL resolution $\sigma = 168$ keV (dp/p=1E-4)

PANDA P1

d$_{cm}$ = 84 keV

PANDA P1 resolution $\sigma = 84$ keV (dp/p=5E-5)

PANDA HR

d$_{cm}$ = 34 keV

PANDA HR resolution $\sigma = 34$ keV (dp/p=2E-5)
Strategy
Ingredients from our Simulation Study

- Reaction: \( \bar{p}p \rightarrow \chi_{c1}(3872) \rightarrow J/\psi (\rightarrow e^+e^-/\mu^+\mu^-) \rho^0 (\rightarrow \pi^+\pi^-) \)

- Take parameters \((\sigma, L, B, \varepsilon_{\text{reco}}, \ldots)\) from study to estimate expected yields

\[
N_{\text{exp}}(E_{\text{cms}}) = \sigma(E_{\text{cms}}) \cdot L \cdot t \cdot \prod B_i \cdot \varepsilon_{\text{reco}}
\]

- Investigate separation power between Flatté & BW lineshapes

Total beam time: \( T = 40 \times 2d = 80 \text{ d} \)

Cross section assumption: \( \sigma_{\text{peak}}(\bar{p}p \rightarrow \chi_{c1}) = 50 \text{ nb} \)

Flatté energy: \( E_f = [ -8.7, -8.2, -7.7, -7.2, -6.7, -6.2, -5.7, -5.2 ] \text{ MeV} \)

BW Width: \( \Gamma = [ 100, 150, 200, 250, 300, \ldots, 550 ] \text{ keV} \)
Procedure

We use the following approach:

1. Use key parameters from EPJ A 55 (2019) 42
2. Generate many (toy) spectra for Flatté (BW) model
3. Fit both BW and Flatté to each generated distribution and determine fit probabilities $P_{BW}$ and $P_{F}$
4. Identification considered correct, if $P_{F} > P_{BW}$ ($P_{BW} > P_{F}$)
5. Count fraction of incorrect assignments → $P_{mis}$
6. $P_{mis}$ measure for separation power
7. $P_{mis} = 50\%$ means: models indistinguishable
Scan Procedure Principle (Example)

Example: Breit-Wigner, $\Gamma = 300$ keV (P1 mode)

1. Compute true lineshape reflecting the expected yields
2. Generate poisson random number $N_{\text{poisson}}$ for each $E_{cm}$ and fill into graph
3. Fit lineshapes to extract fit probabilities $P_{BW}$ and $P_F$
Scan Time Optimization
Scan Time Optimisation

• Idea: **Find better scan time distribution** than constant time per energy

• Simple idea for optimisation approach:
  → **Keep 40 equidistant energies in fixed energy range**
  → **Enhance the scan precision in center**

• For that purpose:
  – Choose number $n_{\text{core}}$ of central energy points
  – Take factor $f_{\text{core}}$ more data at expense of tails to
  – Keep total beam time constant ($T = 80d$)

• Perform 2-dimensional grid search to identify optimum combination of $(n_{\text{core}}, f_{\text{core}})$
Scan Optimisation Example (P1)

- **P1 Mode**: Generated with Flatté model \((E_f = -7.2 \text{MeV})\)

Fit Example

- **Breit-Wigner Flatté**

* yields scaled, errors adapted

mis-ID from 10000 fits

\(P_{\text{mis}} = 23.2\%\) vs \(P_{\text{mis}} = 5.6\%\) - 4.1 \times better

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Overall Optimisation

- Compute $P_{\text{mis}}$ for 15 different scenarios with 91 $(f,n)_{\text{core}}$ combi's each
  
  $(\text{HL, P1, HR}) \otimes (E_f = [-6.2, -7.2, -8.2] \text{ MeV} \ & \Gamma = [0.3, 0.5] \text{ MeV})$

- Combine plots of 15 scenarios

Example scenario: $P1, E_f = -7.2 \text{ MeV}$

Combined plot of 15 scenarios

Selected optimum:

$n_{\text{core, opt}} = 12$

$f_{\text{core, opt}} = 2.5$

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RESULTS
Parameter Dependent Performance

- Performance across Flatté energy $E_f$ range

For Mis-match of Flatté as BW we see

- for the three beam modes HL, HR, P1
- the mis-identification probability $P_{mis}$
- across range of input parameters $E_f$
- with LHCb best fit $E_f = -7.2$ MeV
- and $P_{mis} = 50\%$ for "indistinguishable"
Parameter Dependent Performance

- Performance across Flatté energy $E_f$ / Breit-Wigner $\Gamma$ range

![Flatté → BW](image1)

![BW → Flatté](image2)
Parameter Dependent Performance

- Performance across Flatté energy $E_f$ / Breit-Wigner $\Gamma$ range

<table>
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<tr>
<th>Mode</th>
<th>Performance</th>
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<tbody>
<tr>
<td>HL Mode</td>
<td>$\geq 98%$ correct</td>
</tr>
<tr>
<td>HR Mode</td>
<td>$\geq 95%$ correct</td>
</tr>
<tr>
<td>P1 Mode</td>
<td>$\geq 90%$ correct</td>
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N.B.: For BW $\Gamma = 1.4$ MeV we find 0% mis-ID in all modes...

LHCb fit →
Performance - Alternative Representation

- How much better than "indistinguishable" is it?
- **Idea**: Consider so-called *odds* = correct identifications per wrong one

\[ \text{odds} = \frac{1 - P_{\text{mis}}}{P_{\text{mis}}} \]

**Flatté → BW**

**BW → Flatté**

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Performance - Alternative Representation

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\[
\text{odds} = \frac{(1 - P_{\text{mis}})}{P_{\text{mis}}}
\]

- At least \(~10\times\) better than **indistinguishable** across full range!
Summary and Conclusion

- Simulation of line shape measurement of $\chi_{c1}(3872)$ at PANDA ⇒ Different models can be well distinguished

- Correct assignment of fit model over full range between $\geq 90\%$ (P1) and $\geq 98\%$ (HL) depending on beam mode

- At least $\sim 10x$ higher odds to identify correct model than LHCb

- First attempt of scan optimization shows further potential
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Thank you very much for your attention!