Search for the $\chi_{c1}(3872) \to \chi_{c1}(1P)\pi^+\pi^-$ Decay in LHCb

James Martello-Gallagher

Ivan Polyakov, Mengzhen Wang, Aravindhan Venkateswaran, Vanya Belyaev

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NOTE: To abide by LHCb guidelines on preliminary results, no figures depicting results or explicit calculation results are included.

1 Introduction

1.1 Motivation

Spectroscopy of hadrons with heavy quarks, especially exotic hadrons, is one of the most promising ways to advance understanding of QCD in the non-perturbative regime.

The nature of $\chi_{c1}(3872)$ is still under discussion, displaying behaviour of pure charmonium ($c\bar{c}$), compact tetraquark (4 quark) and molecular (2 loosely bound mesons) components.

Measuring the branching fraction of its decay into $\chi_{c1}(1P)\pi^+\pi^-$ will provide further experimental input.

Currently, only upper limits and theoretical estimates have been set:

Theoretical Predictions	$BF(\chi_{c1}(3872) \to \chi_{c1}\pi^+\pi^-)$
Dubinsky & Voloshin (pure charmonium) [Phys.Rev.D 77, 014013 (2008)]	$\sim 0.1\%$
Estimation based on bottomonium	$\sim 0.05 - 0.3\%$

Experimental Results	$BF(\chi_{c1}(3872) \to \chi_{c1}\pi^+\pi^-)$
Belle [Phys.Rev.D 93,052016(2016)]	$< 0.8\%$
BESIII [Phys.Rev.D 109,L071101(2024)]	< 0.8 %

Conventional photon reconstruction (calorimeter or converted photons) suffers efficiency suppression of $\mathcal{O}(0.1)$.

1.2 Outline

- Via partial reconstruction of a particular B^+ decay, physical constraints were used to obtain the missing photon momentum, avoiding the suppression and increasing the signal event count.
- Using a simulation sample, the expected signal and background yields were calculated, and preliminary branching fraction upper limits were set based on simulation.
- Various improvement methods were explored to improve the mass resolution.

2 Method

2.1 Missing γ reconstruction

To create the photon solutions mathematically, the following physical constraints are used:

$B^+ \to \chi_{c1}(3872)\ K^+$
$\quad \hookrightarrow \chi_{c1}\,\pi^+\pi^-$
$\quad\quad \hookrightarrow J/\psi$
$\quad\quad\quad \hookrightarrow \mu^+\ \mu^-$

$$\tilde{P}_{\text{Tot}} = \tilde{P}_{\text{Miss}} + \tilde{P}_{\text{Rec}}\ (\parallel r_B) \qquad m_{\text{Miss}} = m_\gamma = 0$$
$$m_{\text{Tot}} = m_B \qquad \text{or} \qquad m_{\mu,\mu,\text{Miss}} = m_{\chi_{c1}}$$

where we define a "B mode" solution as one using the $m_{\text{Tot}} = m_B$ constraint and a "χ_{c1} mode" solution as one using $m_{\mu,\mu,\text{Miss}} = m_{\chi_{c1}}$.

Since each mode produces two solutions, the chosen solution going forward is the one which has lower $|\Delta m|$:

$$\Delta m = \begin{cases} m(J/\psi\gamma) - m_{\text{PDG}}(\chi_{c1}) & \text{for B modes} \\ m(J/\psi\pi\pi K\gamma) - m_{\text{PDG}}(B) & \text{for } \chi_{c1} \text{ modes} \end{cases}$$

2.2 Mass resolution improvements

To explore potential areas for improvement in the signal mass resolution, the effects from 3 variables were studied:

$$(\text{B-vertex}, J/\psi\ \text{4-momentum}, \pi\pi K\ \text{4-momentum})$$

These were individually varied between Monte-Carlo (M) and reconstructed (R) values (e.g. MRR for a Monte-Carlo PV but reconstructed J/ψ and $\pi\pi K$ 4-momenta).

Comparing the RMS of each variation, the B-vertex clearly showed the most promise for improvements, whereas the J/ψ 4-momentum had small margins for improvement.

2.3 Selections & Fits

As further selections beyond the standard working group selections, a cut on the mass shift $|\Delta m|$ and determinant (of the photon solutions) were explored.

The mass cut of $|\Delta m| < 100$ MeV (3σ) showed little improvement, whereas the cut on the determinant, ensuring it was > 0, greatly reduced asymmetry. This determinant cut also has physical requirements, as a non-negative determinant means real solutions. Only the photon determinant cut was retained going forward.

For the signal data, a 2-sided crystal ball function fit best. Since the background data was a cocktail of B meson decays with missing π^0 or γ, a phasespace function modulated by a 1st order polynomial was used for analysis. This described the background well, as no peaking structure was found. Combinatorial background was not considered for the analysis.

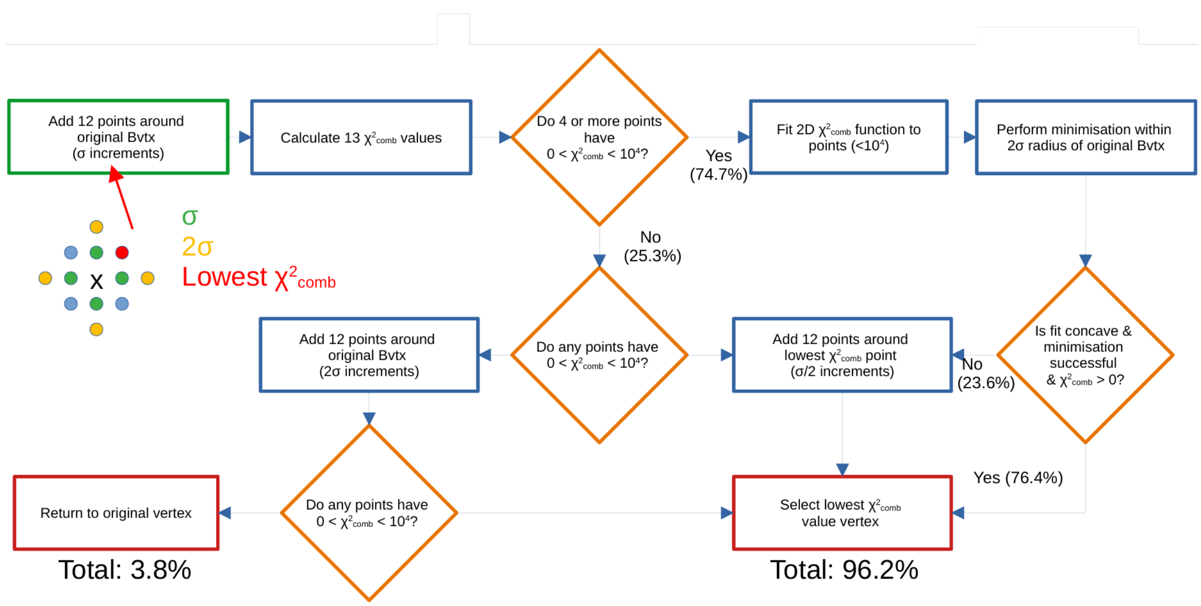
3 Improvements

Since B-vertex location was found to be the area of greatest potential improvement, 2 algorithms were implemented to try to improve the mass resolution, and final results.

3.1 DecayTreeFitter

The DecayTreeFitter algorithm varies parameters simultaneously in the system to automatically optimise results. Here the photon was masked as a neutrino (as it is a particle not detected by the LHCb), and combined with the $J/\psi\pi\pi K$ system. Constraints were applied to the primary vertex and momenta of J/ψ, χ_{c1} and B^+.

3.2 Custom χ^2 algorithm



A custom χ^2_{comb} was created, given by:

$$\chi^2_{comb} = \left[\frac{B_{\text{vtx,original}} - B_{\text{vtx,new}}}{\sigma_{\text{vtx}}}\right]^2 + \left[\frac{m_{\text{new}} - m_{\text{PDG}}}{\sigma_{\text{m}}}\right]^2$$

The custom algorithm sampled B-vertex positions, and selected the one which produced lowest χ^2_{comb}. The algorithm dealt with various scenarios accordingly during the sampling, including a χ^2_{comb} function fit and minimisation process from the sampled points (see figure).

3.3 Comparison

With standard cuts implemented on the 2 algorithms and the original method, a similar increase in efficiency was found in the algorithms, although the widths in the mass distribution increased. Because of this mixed outcome, all 3 were retained throughout the analysis, each providing their own set of efficiencies, yields, and branching fraction upper limits.

4 Results

4.1 Efficiencies & Branching Fractions

To calculate the expected signal and background yields the efficiencies of signal, background, and normalisation channel (see Section 4.2) were required. These can be split into 3 components: generator level efficiency - ratio of events that pass the generation stage where samples are created from decay files, reconstruction efficiency - ratio of events that pass the tupling stage, including the partial reconstruction, and selection efficiency - ratio of events that pass additional cuts and restrictions put on the data after tupling.

4.2 Expected yields

The estimated event yield was calculated via:

$$\frac{\text{Events}_i}{\text{Events}_{\text{Norm}}} = \frac{\text{BR}_i}{\text{BR}_{\text{Norm}}} \times \frac{\epsilon_i}{\epsilon_{\text{Norm}}}$$

where the index i is for signal or background. A normalisation channel is a channel that has a known number of events in real data. Here the decay channel $B^+ \to \chi_{c1}(3872)K^+,\ \chi_{c1}(3872) \to J/\psi\pi^+\pi^-$ was used as it is well studied and very similar to the signal.

Using the calculated efficiencies and known branching fractions, along with an assumed signal branching fraction range of 0.05 - 0.3% (range from bottomonium estimates), a range for expected signal yield was calculated, along with a background expected yield.

Modelling this by reweighing the simulation data, an expected mass distribution was created. From this an upper limit was calculated for 90 and 95 confidence level with a likelihood profile on the background data.

5 Improvements & Future Avenues

The signal to background ratio is quite small, so further study is needed to validate the estimations.

Improvements include:

- Improving the mass resolution.
- More comprehensive selection.
- Greater background suppression.
- Investigating other methods to boost sensitivity.
- Including further background contributions.

The eventual objective is analysis on Run data, so that a value for the branching fraction for $\chi_{c1}(3872) \rightarrow \chi_{c1}(1P)\pi^+\pi^-$ can be calculated, or an improvement can be made on its current upper limit.