Amplitude analysis in $B \rightarrow J/\psi X$ decays

@GreigCowan (Edinburgh) on behalf of the LHCb collaboration

#beauty2014, 14th July
Overview

• Amplitude analysis of $B^0 \rightarrow J/\psi \pi^+ \pi^-$
  • [arXiv:1404.5673, PRD]
• Amplitude analysis of $B_s \rightarrow J/\psi \pi^+ \pi^-$
  • [PRD 89, 092006 (2014)]

• First observation of $B_c \rightarrow J/\psi \ p\bar{p}\pi^+$
  • [LHCb-PAPER-2014-039]

All results use $1\text{fb}^{-1} @ 7\text{TeV}$ and $2\text{fb}^{-1} @ 8\text{TeV}$ data
Motivation

• $B^0_{(s)} \rightarrow J/\psi \pi^+ \pi^-$ decays very useful for CP violation measurements and new physics searches.
• Also excellent place to study substructure of light mesons that decay to $\pi^+ \pi^-$. 
  • Mass ordering is reversed between the scalar and vector mesons nonets below 2GeV not well understood.
• Are the scalar mesons $[f_0(500), f_0(980)]$ q$\bar{q}$ or tetraquarks or a mixture?

<table>
<thead>
<tr>
<th>Isospin</th>
<th>$I = 0$</th>
<th>$I = 1/2$</th>
<th>$I = 0$</th>
<th>$I = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scalar mesons</td>
<td>$f_0(500)$</td>
<td>$\kappa(800)$</td>
<td>$f_0(980)$</td>
<td>$a_0(980)$</td>
</tr>
<tr>
<td>Vector mesons</td>
<td>$\phi(1020)$</td>
<td>$K^*(892)^0$</td>
<td>$\omega(783)$</td>
<td>$\rho(776)$</td>
</tr>
</tbody>
</table>

![Diagram of $B^0_s \rightarrow J/\psi \pi^+ \pi^-$](image1)

![Diagram of $B^0 \rightarrow J/\psi \pi^+ \pi^-$](image2)
Reminder about Dalitz plots - 3 body decay

Configuration of decay depends on angular momentum of decay products.

All dynamical information contained in $|\mathcal{M}|^2$.

Density plot of $m_{12}^2$ vs. $m_{23}^2$ to infer information on $|\mathcal{M}|^2$.

Constraints

<table>
<thead>
<tr>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 four-vectors</td>
</tr>
<tr>
<td>All decay in same plane ($p_i,z = 0$)</td>
</tr>
<tr>
<td>$E_i^2 = m_i^2 + p_i^2$</td>
</tr>
<tr>
<td>Energy + momentum conservation</td>
</tr>
<tr>
<td>Rotate system in plane</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |\mathcal{M}|^2 \, dm_{12}^2 \, dm_{23}^2$$
4D amplitude analysis (scalar $\rightarrow$ vector scalar scalar)

- $B^0_{(s)} \rightarrow J/\psi \pi^+ \pi^-$, $J/\psi \rightarrow \mu^+ \mu^-$ so need to consider 3-helicities in final state.
- Use 4 variables to describe the system: $m_{hh}$ and 3 angles $\Omega = (\theta_{hh}, \theta_{J/\psi}, \chi)$.
- Use the **Isobar** approach.
- Build amplitude from sum of two-body $\pi^- \pi^+$ resonances.
- Overlapping and interfering Breit-Wigner and Flatté resonances.
- Include efficiency and background.

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 four-vectors</td>
<td>+12</td>
</tr>
<tr>
<td>All decay in same plane ($p_{i,z} = 0$)</td>
<td>-3</td>
</tr>
<tr>
<td>$E_i^2 = m_i^2 + p_i^2$</td>
<td>-3</td>
</tr>
<tr>
<td>Energy + momentum conservation</td>
<td>-3</td>
</tr>
<tr>
<td>Rotate system in plane</td>
<td>-1</td>
</tr>
<tr>
<td>Vector helicity</td>
<td>+2</td>
</tr>
<tr>
<td>Total</td>
<td>+4</td>
</tr>
</tbody>
</table>

![Graph of Breit-Wigner (BW) and Flatté resonances](attachment:image)
Data sample: \( B^{0(s)} \rightarrow J/\psi \pi^+ \pi^- \)

No sign of exotic \( J/\psi \pi^+ \) resonances

See talk from A. Alves on \( Z(4430)^- \)

[arXiv:1404.5673, PRD]

[PRD 89, 092006 (2014)]
**B⁰ \rightarrow J/ψπ⁺π⁻**: background

- Main background is combinatorial, taken from same-sign events.
- Use simulation to get shape of partially reconstructed B⁰ₙ decays and reflections from B⁰ and Λₜ.
- Use mixed sample to get 4D background parameterisation.
$B^0 \rightarrow J/\psi \pi^+ \pi^-$: efficiency

\[ \varepsilon(m_{\pi \pi}, \theta_{\pi \pi}, \theta_{J/\psi}, \chi) = \varepsilon(m_{J/\psi \pi^+}^2, m_{J/\psi \pi^-}^2) \times \varepsilon(\theta_{J/\psi}, m_{\pi \pi}) \times \varepsilon(\chi, m_{\pi \pi}) \]

- LHCb < 100% efficient at reconstructing the decay particles in 4D space.
- Large simulated signal sample used to model 4D efficiency.
- Use simulation to show that efficiency factorises.
$B^0 \rightarrow J/\psi \pi^+ \pi^-$: amplitude model

- Build amplitude from all possible resonances and a non-resonant (NR) component.
- Use Poissonian $\chi^2$ to distinguish models.
- Systematics: alternative models (Bugg and G&S) used for $f_0(500)$ and $\rho$ resonances.
- Fix resonance mass and width to PDG values.

Baseline model
- 6 resonances
- No NR component
- No $f_0(980)$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Spin</th>
<th>Helicity</th>
<th>Resonance formalism</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)$</td>
<td>1</td>
<td>0, ±1</td>
<td>BW</td>
<td>$775.49 \pm 0.34$</td>
<td>$149.1 \pm 0.8$</td>
<td>PDG [18]</td>
</tr>
<tr>
<td>$f_0(500)$</td>
<td>0</td>
<td>0</td>
<td>BW</td>
<td>$513 \pm 32$</td>
<td>$335 \pm 67$</td>
<td>CLEO [26]</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>2</td>
<td>0, ±1</td>
<td>BW</td>
<td>$1275.1 \pm 1.2$</td>
<td>$185.1^{+2.9}_{-2.4}$</td>
<td>PDG [18]</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>1</td>
<td>0, ±1</td>
<td>BW</td>
<td>$782.65 \pm 0.12$</td>
<td>$8.49 \pm 0.08$</td>
<td>PDG [18]</td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>0</td>
<td>0</td>
<td>Flatté</td>
<td>—</td>
<td>—</td>
<td>See text</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>1</td>
<td>0, ±1</td>
<td>BW</td>
<td>$1465 \pm 25$</td>
<td>$400 \pm 60$</td>
<td>PDG [18]</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>1</td>
<td>0, ±1</td>
<td>BW</td>
<td>$1720 \pm 20$</td>
<td>$250 \pm 100$</td>
<td>PDG [18]</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>0</td>
<td>0</td>
<td>BW</td>
<td>$1461 \pm 3$</td>
<td>$124 \pm 7$</td>
<td>LHCb [27]</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>0</td>
<td>0</td>
<td>BW</td>
<td>$1720 \pm 6$</td>
<td>$135 \pm 8$</td>
<td>PDG [18]</td>
</tr>
</tbody>
</table>
B^0 \to J/\psi \pi^+ \pi^- : fit result

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
<th>Transversity fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>\rho(770)</td>
<td>63.1 \pm 2.2^{+3.4}_{-2.2}</td>
<td>\tau = 0: 57.4 \pm 2.0^{+1.3}<em>{-3.1}, \tau = \parallel: 23.4 \pm 1.7^{+1.0}</em>{-1.3}, \tau = \perp: 19.2 \pm 1.7^{+3.8}_{-1.2}</td>
</tr>
<tr>
<td>f_0(500)</td>
<td>22.2 \pm 1.2^{+2.6}_{-3.5}</td>
<td>1</td>
</tr>
<tr>
<td>f_2(1270)</td>
<td>7.5 \pm 0.6^{+0.4}_{-0.6}</td>
<td>62 \pm 4^{+2}<em>{-4}, 11 \pm 5 \pm 2, 26 \pm 5^{+4}</em>{-2}</td>
</tr>
<tr>
<td>\omega(782)</td>
<td>0.68^{+0.20}<em>{-0.14}^{+0.17}</em>{-0.13}</td>
<td>39^{+15}<em>{-13}^{+4}</em>{-3}, 60^{+12}<em>{-15}^{+3}</em>{-4}, 1^{+9}_{-1} \pm 1</td>
</tr>
<tr>
<td>\rho(1450)</td>
<td>11.6 \pm 2.8 \pm 4.7</td>
<td>58 \pm 10^{+14}<em>{-23}, 27 \pm 13^{+7}</em>{-11}, 15 \pm 7^{+28}_{-10}</td>
</tr>
<tr>
<td>\rho(1700)</td>
<td>5.1 \pm 1.2 \pm 3.0</td>
<td>40 \pm 11^{+13}<em>{-23}, 24 \pm 14^{+7}</em>{-10}, 36 \pm 14^{+28}_{-9}</td>
</tr>
</tbody>
</table>

- Baseline model keeps resonances with fit fractions >3\sigma.
- Main systematics come from model variation, efficiency parameterisation and PDG mass/width of resonances.
- **CP-even fraction is 56.0%**.
  - Future CP violation measurements possible.

Transversity basis describes angular momentum states in a basis of CP eigenstates

\[
f_i = \frac{\int |A_i(m_{\pi\pi}, \Omega)|^2 dm_{\pi\pi} d\Omega}{\int |\sum_k A_k(m_{\pi\pi}, \Omega)|^2 dm_{\pi\pi} d\Omega}
\]

<table>
<thead>
<tr>
<th>Spin</th>
<th>\eta_0</th>
<th>\eta_\parallel</th>
<th>\eta_\perp</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
</tr>
<tr>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
</tr>
</tbody>
</table>
$B^0 \rightarrow J/\psi \pi^+ \pi^- :$ fit projections

(a) LHCb

(b) background

[arXiv:1404.5673, PRD]
**B^{0}_s \rightarrow J/\psi \pi^+ \pi^- : amplitude model**

**CP-even fraction < 2.3% @ 95% CL.**
- CP violation measurement with B^{0}_s \rightarrow J/\psi \pi^+ \pi^-
- See talk by P. Clarke, [arXiv:1405.4140]

**Two suitable models**
- Sol-I without NR; Sol-II with NR
- 5 resonances
- No significant f_0(500), \rho(770)
$B^0_s \rightarrow J/\psi\pi^+\pi^- : S$-wave dominates

- Two $S$-wave solutions.
- Plot amplitude and phase in bins of $m(\pi^+\pi^-)$.
  - **Consistent** amplitude but **different** phase
- Phase cannot be well determined due to lack of P&D waves.

<table>
<thead>
<tr>
<th>Component</th>
<th>Solution I</th>
<th>Solution II</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_0(980)$</td>
<td>$70.3 \pm 1.5^{+0.4}_{-5.1}$</td>
<td>$92.4 \pm 2.0^{+0.8}_{-16.0}$</td>
</tr>
<tr>
<td>$f_0(1500)$</td>
<td>$10.1 \pm 0.8^{+1.1}_{-0.3}$</td>
<td>$9.1 \pm 0.9 \pm 0.3$</td>
</tr>
<tr>
<td>$f_0(1790)$</td>
<td>$2.4 \pm 0.4^{+5.0}_{-0.2}$</td>
<td>$0.9 \pm 0.3^{+2.5}_{-0.1}$</td>
</tr>
</tbody>
</table>

Width of curve represents statistical uncertainty
$B^0_s \rightarrow J/\psi\pi^+\pi^-$: fit projections
Light quark spectroscopy with $B^0_{(s)} \rightarrow J/\psi \pi^+ \pi^-$

- Are the scalar mesons $[\sigma = f_0(500), f_0 = f_0(980)]$ $q\bar{q}$ or tetraquarks or a mixture?

Scalar meson mixing

\[
|f_0(980)\rangle = \cos \varphi_m |s\bar{s}\rangle + \sin \varphi_m |n\bar{n}\rangle
\]
\[
|f_0(500)\rangle = -\sin \varphi_m |s\bar{s}\rangle + \cos \varphi_m |n\bar{n}\rangle,
\]
where $|n\bar{n}\rangle \equiv \frac{1}{\sqrt{2}} (|u\bar{u}\rangle + |d\bar{d}\rangle)$.

\[
|f_0(980)\rangle = \frac{1}{\sqrt{2}} (|[su][\bar{s}\bar{u}]\rangle + |[sd][\bar{s}\bar{d}]\rangle)
\]
\[
|f_0(500)\rangle = |[ud][\bar{u}\bar{d}]\rangle.
\]

Light quark spectroscopy with $B^0(s) \rightarrow J/\psi \pi^+ \pi^-$

- Are the scalar mesons $[\sigma = f_0(500), f_0 = f_0(980)]$ q$\bar{q}$ or tetraquarks or a mixture?

**Scalar meson mixing**

$$|f_0(980)\rangle = \cos \varphi_m |s\bar{s}\rangle + \sin \varphi_m |n\bar{n}\rangle$$

$$|f_0(500)\rangle = -\sin \varphi_m |s\bar{s}\rangle + \cos \varphi_m |n\bar{n}\rangle,$$

where $|n\bar{n}\rangle \equiv \frac{1}{\sqrt{2}} (|uu\rangle + |dd\rangle)$.


\[\text{[Stone, Zhang, PRL 111, 062001 (2013)]}\]

$$\Gamma(B^0 \rightarrow J/\psi f_0) \over \Gamma(B^0 \rightarrow J/\psi \sigma) = \frac{|F_{B^0}^{f_0}(m^2_{J/\psi})|^2 \Phi_{B^0}^{f_0}}{|F_{B^0}^{\sigma}(m^2_{J/\psi})|^2 \Phi_{B^0}^{\sigma}} \times r_{B^0}$$

$$\Gamma(B^0_s \rightarrow J/\psi f_0) \over \Gamma(B^0_s \rightarrow J/\psi \sigma) = \frac{|F_{B^0_s}^{\sigma}(m^2_{J/\psi})|^2 \Phi_{B^0_s}^{\sigma}}{|F_{B^0_s}^{f_0}(m^2_{J/\psi})|^2 \Phi_{B^0_s}^{f_0}} \times r_{B^0_s}$$

ratio of form factors = 1 for the interpretation of results

phase space

PREDICTIONS

$q\bar{q}$ tetraquark

$r_{B^0} = \tan^2 \varphi_m \quad 1/2$

$r_{B^0_s} = \tan^2 \varphi_m \quad 0$
Light quark spectroscopy with $B^0_s \rightarrow J/\psi \pi^+ \pi^-$

1. Measure the ratio of branching fractions for $B^0$ and $B^0_s$.
2. Correct for $\text{BR}(f_0 \rightarrow \pi^+ \pi^-)$ and phase space ratio.
3. Compute $r_B$.

\[
\frac{\mathcal{B}(\bar{B}^0 \rightarrow J/\psi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-)}{\mathcal{B}(\bar{B}^0 \rightarrow J/\psi f_0(500), f_0(500) \rightarrow \pi^+ \pi^-)} = (0.6^{+0.7+3.3}_{-0.4-2.8}) \times 10^{-2}.
\]

\[
r_B^0 = (1.1^{+1.2+6.0}_{-0.7-0.7}) \times 10^{-2}
\]

\[
\frac{\mathcal{B}(\bar{B}^0_s \rightarrow J/\psi f_0(500), f_0(500) \rightarrow \pi^+ \pi^-)}{\mathcal{B}(\bar{B}^0_s \rightarrow J/\psi f_0(980), f_0(980) \rightarrow \pi^+ \pi^-)} < 3.4\%
\]

\[
r_B^s < 0.098 @ 90\% CL
\]

Inconsistent with tetraquark prediction for $f_0(500)$ and $f_0(980)$ of $1/2$ by $\sim 8\sigma$

Both consistent with 0
First observation of $B_c \rightarrow J/\psi p\bar{p}\pi^+$

- First observation of baryonic decay mode of $B_c$.
- Study mechanism of baryon production: $\sigma(B_c)/\sigma(B) \sim 10^{-3}$
- BDT: signal from MC, bkg from sidebands.
- $B_c \rightarrow J/\psi p\bar{p}\pi^+$ mass resolution fixed to 6.4 MeV, taken from ratio in MC and fit to $B_c \rightarrow J/\psi \pi^+$ in data.
- Best mass measurement, momentum scale dominates.

$$m(B_c) = 6274.67 \pm 1.20 \text{ MeV}$$
First observation of $B_c \to J/\psi p\bar{p}\pi^+$

$$\frac{\mathcal{B}(B^+_c \to J/\psi p\bar{p}\pi^+)}{\mathcal{B}(B^+_c \to J/\psi \pi^+)} = 0.143^{+0.039}_{-0.034} \text{ (stat)} \pm 0.013 \text{ (syst)}$$

$$\frac{\mathcal{B}(B^0 \to D^{*-} p\bar{p}\pi^+)}{\mathcal{B}(B^0 \to D^{*-}\pi^+)} = 0.17 \pm 0.02$$

Consistent with factorisation

- Ratio of efficiencies = (4.76 ± 0.06)% (mostly from simulation)
- Dominant systematics from $B_c$ decay model in simulation and proton reconstruction (determined from sample of $\Lambda_c \to pK^-\pi^+$).
- Bkgd subtracted mass distributions consistent with phase-space simulation.
- Looking forward to more data that may allow amplitude analysis to be performed.

---

**Figure 1:**

- Left: $\bar{B}^0 \to D^0 p\bar{p}$
  - $N_{\text{candidates}}$ vs. $M(p\bar{p})$ [GeV/c^2]
  - Data (blue dots) vs. Simulation (red line)

- Middle: $LHCb$
  - $N_{\text{candidates}}$ vs. $M(p\pi^+)$ [GeV/c^2]
  - Data (blue dots) vs. Simulation (red line)

- Right: $\bar{B}^0 \to D^0 p\bar{p}$
  - Events/(0.25 GeV/c^2) vs. $M(p\bar{p})$ (GeV/c^2)
  - Data points with error bars
Summary

• LHCb has used $3\text{fb}^{-1}$ of data to study $\B_{0(s)} \to J/\psi \pi^+ \pi^-$ decays.
  • Excellent environment to perform light hadron spectroscopy by studying resonant structure of $\pi^+ \pi^-$ system.
  • Opened up new possibilities for performing CP violation measurements with these decays.
  • Rule out $f_0(980)$ as a pure tetraquark at $8\sigma$.

• LHCb is leading the way with $B_c$ meson physics
  • Most precise mass measurement.
  • First observation of many new (baryonic) decay mode.
  • Opens up potential amplitude analyses in the future.

Stay tuned for more results with Run-2
BACKUP
The LHCb detector

Covers 4% of solid angle but contains 25% of $b\bar{b}$ pairs

Vertex Finder

Particle ID

Calorimetry

Muon detection

$\sigma(\text{IP}) \approx 20\mu m$

$\delta p/p = 0.4 - 0.6\%$

$\varepsilon_{\text{track}} > 96\%$

$\varepsilon_{\text{PID}}(K) \approx 95\%$

$\text{MisID}(K \rightarrow \pi) \approx 5\%$

$\varepsilon_{\text{PID}}(\mu) \approx 97\%$

$\text{MisID}(\pi \rightarrow \mu) \approx 1 - 3\%$
A typical LHCb event

\[ \langle n_{PVs} \rangle \sim 2.0 \]
\[ \langle n_{Tracks} \rangle \sim 200 \]
\[ \sigma(p\bar{p} \rightarrow b\bar{b}X) \sim 80\mu b \]
\[ \frac{\sigma(c\bar{c})}{\sigma(c\bar{c})} \sim 1500\mu b \]

B hadrons fly \( \sim 1 \text{cm} \) in the detector
Flatté amplitude

- Flatté provides better description of line shape when a second channel opens up near resonance mass.
- Constants $g_{\pi\pi}$ and $g_{KK}$ are coupling constants.

$$A_R(s_{23}) = \frac{1}{m_R^2 - s_{23} - i m_R (g_{\pi\pi}\rho_1 + g_{KK}\rho_2)}$$

$$\rho_{\pi\pi} = \frac{2}{3} \sqrt{1 - \frac{4m_{\pi\pi}^2}{m^2(\pi^+\pi^-)}} + \frac{1}{3} \sqrt{1 - \frac{4m_{\pi^0}^2}{m^2(\pi^+\pi^-)}},$$

$$\rho_{KK} = \frac{1}{2} \sqrt{1 - \frac{4m_{K\pi}^2}{m^2(\pi^+\pi^-)}} + \frac{1}{2} \sqrt{1 - \frac{4m_{K^0}^2}{m^2(\pi^+\pi^-)}}.$$
Reminder about Dalitz plots

$$d\Gamma = \frac{1}{(2\pi)^3} \frac{1}{32M^3} |M|^2 \, dm_{12}^2 \, dm_{23}^2$$

Spin-1 resonance

Peaks in distribution do not correspond to a real resonance - just a shadow/reflection

Modelled as product of Breit-Wigner, kinematic and dynamic factors
Amplitude model

- Use the **Isobar** approach.
- Build amplitude from sum of two-body $\pi^-\pi^+$ resonances.
- Overlapping and interfering Breit-Wigner and Flatté resonances.

**Sum over the k resonances**

\[
|M|^2 = \sum_{\Delta\lambda_\mu=-1,1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_k A_{k,\lambda_\psi}(m_{K\pi}, \Omega |m_{0k}, \Gamma_{0k}) \right|^2
\]

In 4D fit, $\mu^+\mu^-$ are final state particles so different dimuon helicity amplitudes are incoherent (cannot interfere)

Different $J/\psi$ helicity amplitudes interfere

Complex amplitude that encodes the mass and angular dependence
Amplitude analysis of $B^0 \rightarrow J/\psi \pi^+ \pi^-$

- Similar analysis to $Z(4430)$
  - Build 4D matrix element from overlapping $\pi^+ \pi^-$ resonances.
  - Correct for efficiency.
- No sign of exotic $J/\psi \pi^+$ resonances...

Sidebands used for background modelling

19k $B^0$ signal

$B_s^0$ signal

LHCb
**B^0 \rightarrow J/\psi \pi^+ \pi^-**: harmonic moments

- Efficiency corrected and background subtracted \(m(\pi\pi)\) distribution, weighted with spherical harmonics, \(Y_1^0(\cos\theta_{\pi\pi})\).

- Structure of each moment gives qualitative picture of spin contributions and their interference.
$B^0_s \rightarrow J/\psi \pi^+ \pi^-$: harmonic moments

- Efficiency corrected and background subtracted $m(\pi\pi)$ distribution, weighted with spherical harmonics, $Y^0_1(\cos \theta_{\pi\pi})$.

- Structure of each moment gives qualitative picture of spin contributions and their interference.
\[ \text{B}_c \rightarrow J/\psi \ X \text{ decays, } J/\psi \rightarrow \mu^+\mu^- \]

- Interesting to study due to \( \text{B}_c \) being made of two heavy quarks (\( \bar{b}c \)).
- Only decays weakly, so has longer lifetime (\( \sim 0.5 \text{ps} \)) than quarkonia, but shorter lifetime than other \( \text{B} \) mesons (\( \sim 1.5 \text{ps} \)) due to \( c \) quark.
- Discovered by CDF, now observed in many different decay modes by LHCb.
- At LHCb, use clean signature of the \( J/\psi \rightarrow \mu^+\mu^- \) to trigger these modes.
- Simulation needed to correct for efficiency of selection and detector acceptance.
  - Use BCVEGPy generator to simulate \( gg \rightarrow \text{B}_c \)
Evidence for $B_c \rightarrow J/\psi \ 3\pi^+ 2\pi^-$

- NN for muon and pion ID.
- $p_T(\pi^+) > 400$ MeV and IP $\chi^2$ cuts.
- Suppress combinatorial bkg by requiring vertex $\chi^2$ of all $J/\psi \ \pi^+$ combinations < 20.
- Measure BR relative to $B_c \rightarrow J/\psi \ \pi^+$ selected with similar selection.
  - From simulation, efficiency to reconstruct 4 extra pions leads to factor 100 lower efficiency.

From simulation, efficiency to reconstruct 4 extra pions leads to factor 100 lower efficiency.
Evidence for $B_c \to J/\psi \, 3\pi^+ 2\pi^-$, $J/\psi \to \mu^+ \mu^-$

- No resonant structure seen in combination of final state particles.
- Dominant systematic from fit model and decay model in simulation.
  - Reweight MC with $m(3\pi^+ 2\pi^-)$ spectrum.
- Good agreement with theory predictions of 0.95 and 1.1 [PRD86 (2012) 074024]
- Consistent with measurements in $B^+$ and $B^0$ sectors, expected from factorisation.
  - $B_c \to J/\psi \, W^+$ form factors and experimental information from $\tau \to n\pi$

$$\frac{B(B_c^+ \to J/\psi \, 3\pi^+ 2\pi^-)}{B(B_c^+ \to J/\psi \, \pi^+)} = 1.74 \pm 0.44 \pm 0.24$$
Factorisation in $B_c$ decays

- Factorise the decay amplitude into two independent parts
  - $B_c \rightarrow J/\psi W^+$
    - form factors
    - experimental information on $W^+$ from $\tau \rightarrow n\pi$