Study of b-hadron to J/$\psi hh$ decays

Liming Zhang (Syracuse University)
on behalf of the LHCb Collaboration

ICHEP 2014
(July 2-9, Valencia, Spain)
Outline

• Amplitude analysis of $B_s^0 \rightarrow J/\psi \pi^+ \pi^-$
  PRD 89, 092006 (2014)

• Amplitude analysis of $B^0 \rightarrow J/\psi \pi^+ \pi^-$

• Precision measurement of $\Lambda_b^0 / B^0$ lifetime ratio
  PLB, 734, (2014) 122

• First observation of Cabibbo-suppressed decay
  $\Lambda_b^0 \rightarrow J/\psi p \pi^-$
  arXiv: 1406.0755

All use 3fb$^{-1}$ LHCb data
• Amplitude analysis of $B_{s}^{0} \rightarrow J/\psi \pi^{+}\pi^{-}$
  
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All use 3fb$^{-1}$ LHCb data
Motivation

- $B_{(s)}^0 \rightarrow J/\psi\pi^+\pi^-$ is useful for CPV measurements & search for New Physics in mixing
- Also provide excellent environment for studying of the light scalar mesons, such as $f_0(980)$, $\sigma$ or called $f_0(500)$
- Time-integrated amplitude analysis: to understand the resonant structure and CP components of the decays

\[ B_s \left\{ \begin{array}{c} b \\ \bar{s} \end{array} \right\} J/\psi \left\{ \begin{array}{c} c \\ \bar{c} \end{array} \right\} \pi^+\pi^- \]

\[ \bar{B}^0 \left\{ \begin{array}{c} b \\ \bar{d} \end{array} \right\} J/\psi \left\{ \begin{array}{c} c \\ \bar{c} \end{array} \right\} \pi^+\pi^- \]

$ss$ system has $I=0$
Analysis approach

- Because of spin-1 $J/\psi$, need to consider three-helicities
- $B_{(s)}^0 \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) h^+ h^-$ is described by 4 variables
  - choose $m_{hh}$ and three angles ($\theta_{hh}$, $\theta_{J/\psi}$, $\chi$)
- No obvious exotic $J/\psi \pi^+$ resonance seen in data of both decays
- Then decays are described by coherent sum of $\pi^+ \pi^-$ resonances
- A new theoretical approach allows to include all four variables and measure the fractions of CP-even and CP-odd states. Details see Zhang&Stone, "Time-dependent Dalitz-plot formalism for $B_q^0 \rightarrow J/\psi \ h^+ \ h^-$", Phys. Letters B 719 (2013) 383-387.
Invariant mass of $J/\psi \pi^+ \pi^-$

- $\pm 20$ MeV of peaks: 27,400 $B_s$ signal and 18,800 $B^0$ signal
m(π⁺π⁻)

- Fit considers all possible resonances and Non-resonance (NR)
- Baseline model keeps resonances which have contribution >3σ
- Breit-Wigner function is used for most of resonances
  - Except for Flatté function for f₀(980).
  - Alternative models used for f₀(500) and ρ as systematic evaluation
Fit fractions in $B^0$ decays

<table>
<thead>
<tr>
<th>Component</th>
<th>Fit fraction (%)</th>
<th>Transversity fractions (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau = 0$</td>
<td>$\tau =</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>$63.1 \pm 2.2^{+3.4}_{-2.2}$</td>
<td>$57.4 \pm 2.0^{+1.3}_{-3.1}$</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>$62 \pm 4^{+2}_{-4}$</td>
</tr>
<tr>
<td>$\omega(782)$</td>
<td>$0.68^{+0.20+0.17}_{-0.14-0.13}$</td>
<td>$39^{+15+4}_{-13-3}$</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>$11.6 \pm 2.8 \pm 4.7$</td>
<td>$58 \pm 10^{+14}_{-23}$</td>
</tr>
<tr>
<td>$\rho(1700)$</td>
<td>$5.1 \pm 1.2 \pm 3.0$</td>
<td>$40 \pm 11^{+13}_{-23}$</td>
</tr>
</tbody>
</table>

- 6 resonances
- $f_0(500)$ is large
- CP-even fraction is 56%

Transversity describes angular momentum states in a basis of CP eigenstates

| Spin | $\eta_0$ | $\eta_{||}$ | $\eta_{\perp}$ |
|------|----------|-------------|----------------|
| 0    | $-1$     | $-$         | $-$            |
| 1    | $1$      | $1$         | $-1$           |
| 2    | $-1$     | $-1$        | $1$            |

Fit projections with three angles are shown in backup
Fit fractions in $B_s^0$ decays

<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>
<tr>
<td>$f_2(1270)_{0}$</td>
<td>$0.36 \pm 0.07 \pm 0.03$</td>
<td>$0.42 \pm 0.07 \pm 0.04$</td>
</tr>
<tr>
<td>$f_2(1270)_{</td>
<td></td>
<td>}$</td>
</tr>
<tr>
<td>$f_2(1270)_{\perp}$</td>
<td>$0.63 \pm 0.34^{+0.16}_{-0.08}$</td>
<td>$0.60 \pm 0.36^{+0.12}_{-0.09}$</td>
</tr>
<tr>
<td>$f_2'(1525)_{0}$</td>
<td>$0.51 \pm 0.09^{+0.05}_{-0.04}$</td>
<td>$0.52 \pm 0.09^{+0.05}_{-0.04}$</td>
</tr>
<tr>
<td>$f_2'(1525)_{</td>
<td></td>
<td>}$</td>
</tr>
<tr>
<td>$f_2'(1525)_{\perp}$</td>
<td>$0.26 \pm 0.18^{+0.06}_{-0.04}$</td>
<td>$0.26 \pm 0.22^{+0.06}_{-0.05}$</td>
</tr>
<tr>
<td>NR</td>
<td>-</td>
<td>$5.9 \pm 1.4^{+0.7}_{-4.6}$</td>
</tr>
<tr>
<td>Sum</td>
<td>$85.2$</td>
<td>$110.6$</td>
</tr>
<tr>
<td>$-\ln\mathcal{L}$</td>
<td>$-93738$</td>
<td>$-93739$</td>
</tr>
<tr>
<td>$\chi^2/\text{ndf}$</td>
<td>$2005/1822$</td>
<td>$2008/1820$</td>
</tr>
</tbody>
</table>

- 5 resonances + possible NR
- Two solutions: when including NR. One with NR~0, one with significant NR
- Same D-wave fraction 2.3%
- CP-even fraction $<2.3\%$ at 95% CL. Dominate systematics by including $\rho(770)$. 

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\[ f_0(500) = \sigma \text{ and } f_0(980) = f_0 \]

- The two light scalar meson states are not well understood.

\[ |f_0 \rangle = \cos \phi |s\bar{s} \rangle + \sin \phi |n\bar{n} \rangle \]
\[ |\sigma \rangle = -\sin \phi |s\bar{s} \rangle + \cos \phi |n\bar{n} \rangle, \]

where \[ |n\bar{n} \rangle = \frac{1}{\sqrt{2}} (|u\bar{u} \rangle + |d\bar{d} \rangle). \]

**Predictions**

<table>
<thead>
<tr>
<th>B_s ratio</th>
<th>tetraquark model</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma(\bar{B}_s^0 \rightarrow J/\psi \sigma) ) ( \Gamma(\bar{B}_s^0 \rightarrow J/\psi f_0) )</td>
<td>( \frac{</td>
</tr>
<tr>
<td>B^0 ratio</td>
<td>( \frac{\Gamma(\bar{B}_s^0 \rightarrow J/\psi f_0) \Gamma(\bar{B}_s^0 \rightarrow J/\psi \sigma)}{\Gamma(\bar{B}_s^0 \rightarrow J/\psi \sigma)} )</td>
</tr>
</tbody>
</table>

\[ r_{B_s^0} = \tan^2 \phi \quad 0 \]
\[ r_{B^0} = \tan^2 \phi \quad \frac{1}{2} \]

The form factor ratio = 1 is used for the interpretations of the measurements consistent with a measurement using \( \Gamma (\bar{B}_s^0 \rightarrow J/\psi f_0) / \Gamma (\bar{B}_s^0 \rightarrow J/\psi \sigma) \)

Fleischer arXiv:1109.1112

Stone&Zhang [PRL 111, 062001 (2003)]
$f_0(500)$ and $f_0(980)$

- Measurements, both ratios consistent with 0

$$\frac{B \left( B^0_s \to J/\psi f_0(500), \ f_0(500) \to \pi^+\pi^- \right)}{B \left( B^0_s \to J/\psi f_0(980), \ f_0(980) \to \pi^+\pi^- \right)} < 3.4\%$$

@90% CL

$$\frac{B \left( B^0 \to J/\psi f_0(980), \ f_0(980) \to \pi^+\pi^- \right)}{B \left( B^0 \to J/\psi f_0(500), \ f_0(500) \to \pi^+\pi^- \right)} = (0.6_{-0.4}^{+0.7+3.3})\%$$

- Correcting for $\mathcal{B}(f_0 \to \pi^+\pi^-)$ and phase space ratio $\frac{\Phi(500)}{\Phi(980)} = 1.25$.

<table>
<thead>
<tr>
<th>Model</th>
<th>$B^0_s \to J/\psi \pi^+\pi^-$</th>
<th>$B^0 \to J/\psi \pi^+\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$qq$</td>
<td>$</td>
<td>\phi</td>
</tr>
<tr>
<td>Tetraquark</td>
<td>$r_{B^0_s} &lt; 1.8% \ @ \ 90% \ CL$ (consistent with prediction 0)</td>
<td>$r_{B^0} = (1.1_{-0.7}^{+1.2+6.0})%$ (inconsistent with prediction of 50% by $\sim 8\sigma$)</td>
</tr>
</tbody>
</table>

- Consistent picture of $qq$ model with mixing angle $< 7.7^\circ \ @ \ 90\% \ CL$.

- Rules out that $f_0(980)$ & $f_0(500)$ are pure tetraquark states at $8\sigma$. 

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ICHEP'2014

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All use 3fb$^{-1}$ LHCb data
Motivation

• One theoretical tool, HQE, is used to measure $|V_{cb}|$ & $|V_{ub}|$. It can be tested by using its predictions for relative $b$-hadron lifetimes (Lenz arXiv:1405.3601)

• Predictions given using the HQE in 1986:
  $\tau(B_s)/\tau(B^0) \approx 1.0$,  $\tau(B^-)/\tau(B^0) \approx 1.1$,  
  $\tau(\Lambda_b)/\tau(B^0) \approx 0.96$ [M. A. Shifman and M. B. Voloshin, Sov. Phys. JETP 64 (1986) 698]

• Problem from $\Lambda_b$ lifetime. Early measurements were $(80 \pm 3)\%$ of the $B^0$ lifetime (HFAG 2003)

• New LHCb measurement determines relative $\Lambda_b/B^0$ lifetime directly
• Same decay topologies, many systematic uncertainties are eliminated
• $\Lambda_b \to J/\psi pK^-$, previously unknown decay mode, 50,000 signal events in 3/fb
• $B^0 \to J/\psi K^{*0}$ 340,000 signal events
Rates & acceptances

Method

• Measure $\Lambda_b^0/B^0$ yield ratio in bins of decay time $t$

• Fit function:

$$R(t) = R(0)[1 + at]e^{-t(1/\tau_{\Lambda_b^0} - 1/\tau_{B^0})}$$

Results

$$\frac{\tau(\Lambda_b^0)}{\tau(B^0)} = 0.974 \pm 0.006 \pm 0.004$$

$$\tau(\Lambda_b^0) = 1.479 \pm 0.009 \pm 0.010 \text{ ps}$$
\( \Lambda_b \) Lifetimes

- The most precise single measurement.
- Consistent with other recent measurements.
- Consistent with the original predictions of the HQE.

Experiment
- LHCb (2014) Average
- LHCb 1/fb (2014) [J/\(\psi\)\(\Lambda\)]
- LHCb 3/fb (2014) [J/\(\psi\)K\(^-\)]
- LHCb 1/fb (2013) [J/\(\psi\)K\(^-\)]
- CMS (2012) [J/\(\psi\)\(\Lambda\)]
- ATLAS (2012) [J/\(\psi\)\(\Lambda\)]
- D0 (2012) [J/\(\psi\)\(\Lambda\)]
- CDF (2011) [J/\(\psi\)\(\Lambda\)]
- CDF (2010) [\(\Lambda_c^+\pi^-\)]
- D0 (2007) [J/\(\psi\)\(\Lambda\)]
- D0 (2007) [Semileptonic decay]
- DLPH (1999) [Semileptonic decay]
- ALEP (1998) [Semileptonic decay]
- OPAL (1998) [Semileptonic decay]
- CDF (1996) [Semileptonic decay]
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Observation of $\Lambda_b^0 \to J/\psi p\pi^-$

- Measured relative $\mathcal{B}$ is consistent with ratio of CKM matrix elements times of ratio of phase space factors $\sim 0.08$

$$\frac{\mathcal{B}(\Lambda_b^0 \to J/\psi p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.0824 \pm 0.0025 \text{ (stat)} \pm 0.0042 \text{ (syst)}$$

- CP asymmetry difference: $2.2\sigma$ from 0

$$A_{CP}(\Lambda_b^0 \to J/\psi p\pi^-) - A_{CP}(\Lambda_b^0 \to J/\psi pK^-) = (+5.7 \pm 2.3 \text{ (stat)} \pm 1.2 \text{ (syst)})\%$$
Summary

• Amplitude analysis applied to $B^0_{(s)} \rightarrow J/\psi \pi^+\pi^-$
  – The resonant structure and CP components are studied
  – Rule out $f_0(980)$ is a pure tetraquark at $8\sigma$ level

• Towards CPV measurement in $B^0_{(s)} \rightarrow J/\psi \pi^+\pi^-$
  – CPV phase $\phi_s$ measurement in $B^0_s \rightarrow J/\psi \pi^+\pi^-$ using the new approach
  – $B^0 \rightarrow J/\psi \pi^+\pi^-$ study is ongoing

• The most precise measurement of $\Lambda^0_b/B^0$ lifetime ratio, consistent with HQE prediction

• A new observation of $\Lambda^0_b$ decay
BACKUP
Fit projections of $B_s^0$ decays

From Solution II (Solution I has similar projects)

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Fit projections of $B^0$ decays
Total PDF

Efficiency function from MC

Signal function

\[ F(m_{hh}, \theta_{hh}, \theta_{J/\psi}, \chi) = \frac{f_{\text{sig}}}{N_{\text{sig}}} \epsilon(m_{hh}, \theta_{hh}, \theta_{J/\psi}, \chi) S(m_{hh}, \theta_{hh}, \theta_{J/\psi}, \chi) + (1 - f_{\text{sig}}) B(m_{hh}, \theta_{hh}, \theta_{J/\psi}, \chi), \]

Signal fraction

Background PDF, obtained from like-sign combination + small \( \rho \) background

Normalization for \( \epsilon S \)

First integrate \( \chi \) and \( \cos\theta_{J/\psi} \) analytically, then \( \cos\theta_{hh} \) and \( m_{hh} \) numerically.
Spherical harmonic moments

- Efficiency corrected and background subtracted $m(\pi\pi)$ distribution, weighted by $Y_l^0 (\cos \theta_{hh})$.
- Can test different spin contributions.
- $\langle Y_1^0 \rangle$ and $\langle Y_3^0 \rangle$ are 0 because of opposite contributions from $B_S^0$ and $\bar{B}_S^0$.

$B_S^0 \to J/\psi\pi^+\pi^-$

Baseline fit (Solution II)
Spherical harmonic moments

- Efficiency corrected and background subtracted m(ππ) distribution, weighted by $Y_l^0 (\cos \theta_{hh})$.
- Can test different spin contributions.
- $\langle Y_1^0 \rangle$ and $\langle Y_3^0 \rangle$ are 0 because of opposite contributions from $B^0$ and $B^0$.

$B^0 \rightarrow J/\psi \pi^+ \pi^-$
Other fit parameters

\[ B_s^0 \rightarrow J/\psi \pi^+ \pi^- \]

**Table 6: Fitted resonance phase differences (°).**

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Model I</th>
<th>Model II</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0(1500) - f_0(980) )</td>
<td>138 ± 4</td>
<td>177 ± 6</td>
</tr>
<tr>
<td>( f_0(1790) - f_0(980) )</td>
<td>78 ± 9</td>
<td>95 ± 16</td>
</tr>
<tr>
<td>( f_2(1270)_0 - f_0(980) )</td>
<td>96 ± 7</td>
<td>123 ± 8</td>
</tr>
<tr>
<td>( f_2(1270)</td>
<td></td>
<td>- f_0(980) )</td>
</tr>
<tr>
<td>( f'_2(1525)_0 - f_0(980) )</td>
<td>−132 ± 6</td>
<td>−97 ± 7</td>
</tr>
<tr>
<td>( f'_2(1525)</td>
<td></td>
<td>- f_0(980) )</td>
</tr>
<tr>
<td>NR - ( f_0(980) )</td>
<td>−</td>
<td>−104 ± 5</td>
</tr>
<tr>
<td>( f'<em>2(1525)</em>\perp - f_2(1270)_\perp )</td>
<td>149 ± 46</td>
<td>145 ± 51</td>
</tr>
</tbody>
</table>

**Table 12: Other fit parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Model I</th>
<th>Model II</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m_{f_0(980)} ) (MeV)</td>
<td>945.4 ± 2.2</td>
<td>949.9 ± 2.1</td>
</tr>
<tr>
<td>( g_{\pi\pi} ) (MeV)</td>
<td>167 ± 7</td>
<td>167 ± 8</td>
</tr>
<tr>
<td>( g_{KK}/g_{\pi\pi} )</td>
<td>3.47 ± 0.12</td>
<td>3.05 ± 0.13</td>
</tr>
<tr>
<td>( m_{f_0(1500)} ) (MeV)</td>
<td>1460.9 ± 2.9</td>
<td>1465.9 ± 3.1</td>
</tr>
<tr>
<td>( \Gamma_{f_0(1500)} ) (MeV)</td>
<td>124 ± 7</td>
<td>115 ± 7</td>
</tr>
<tr>
<td>( m_{f_0(1790)} ) (MeV)</td>
<td>1814 ± 18</td>
<td>1809 ± 22</td>
</tr>
<tr>
<td>( \Gamma_{f_0(1790)} ) (MeV)</td>
<td>328 ± 34</td>
<td>263 ± 30</td>
</tr>
</tbody>
</table>
A new theoretical approach allows to include all angular information and measure the fraction of CP-even and CP-odd states.


Time-integrated decay rate is sum of functions for $B_{(s)}^0$ and $\bar{B}_{(s)}^0$, and small contribution from their interference due to non-zero $\Delta \Gamma_s$ in $B_s^0$ case.

$$
|\overline{A}(m_{hh}, \theta_{hh}, \theta_{J/\psi}, \chi)|^2 = 
|\overline{H}_0(m_{hh}, \theta_{hh})|^2 \sin^2 \theta_{J/\psi} + \frac{1}{2} \left( |\overline{H}_+(m_{hh}, \theta_{hh})|^2 + |\overline{H}_-(m_{hh}, \theta_{hh})|^2 \right) 
\times (1 + \cos^2 \theta_{J/\psi}) + \text{Re} \left[ \overline{H}_+(m_{hh}, \theta_{hh}) \overline{H}_-(m_{hh}, \theta_{hh}) e^{2i\chi} \right] \sin^2 \theta_{J/\psi}
+ \sqrt{2} \text{Re} \left[ \left( \overline{H}_0(m_{hh}, \theta_{hh}) \overline{H}_+(m_{hh}, \theta_{hh}) - \overline{H}_0(m_{hh}, \theta_{hh}) \overline{H}_-(m_{hh}, \theta_{hh}) \right) e^{-i\chi} \right] 
\times \sin \theta_{J/\psi} \cos \theta_{J/\psi}.
$$

$\overline{H}_\lambda$ functions for three helicities $\lambda$ are defined next.
Amplitude formula II

\[ \mathcal{H}_\lambda(m_{hh}, \theta_{hh}) = \sum_R h^R_\lambda A_R(m_{hh}) d^{JR}_{-\lambda,0}(\theta_{hh}). \]

Helicity (\(\lambda\)) amplitude \(\rightarrow\) Transversity (\(\tau\))

\[ h_0^R = a_0^R, \]
\[ h_+^R = \frac{1}{\sqrt{2}} (a_\parallel^R + a_\perp^R), \]
\[ h_-^R = \frac{1}{\sqrt{2}} (a_\parallel^R - a_\perp^R). \]

We fit the complex numbers of \(a_0, a_\parallel\) and \(a_\perp\) for each of resonance \(R\)

Neglecting direct CPV

\[ \bar{a}_\tau^R = \eta_\tau^R a_\tau^R \]

<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>-1</td>
<td>-1</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>

\(a\) and \(\bar{a}\) only contain strong phases

\[ A_R(m_{hh}) = \sqrt{2J_R + 1} \sqrt{P_R P_B F_B^{(L_B)} F_R^{(L_R)}} A_R(m_{hh}) \left( \frac{P_B}{m_B} \right)^{L_B} \left( \frac{P_R}{m_{hh}} \right)^{L_R}. \]

Dalitz-plot part as function of \(m_{hh}\), originates from Belle PRD 78, 072004 (2008)
Data

$B_s^0 \to J/\psi \pi^+ \pi^-$

- No evident exotic in $J/\psi \pi^+$.
- Possible resonance at $m(\pi^+\pi^-) \sim 1.8$ GeV. Could be $f_0(1790)$ seen in $J/\psi \to \phi \pi^+ \pi^-$ by BES [PLB 607, 243 (2005)].

within $\pm 20$ MeV of $B_s$ peak
Data

$B^0 \to J/\psi \pi^+ \pi^-$

- No obvious exotic in $J/\psi \pi^+$.
- Favored $B^0 \to J/\psi K_S$ decays are almost rejected by the $B^0$ vertex selection. While some are remains.

within $\pm 20$ MeV of $B^0$ peak
S-wave $\pi^+\pi^-$ in $B_s^0$ decays

- The decay is dominated by S-wave.
- Two S-wave solutions: consistent amplitude strength, but different phase.
  - Phase cannot be well determined because of lack of P&D-waves.

Total S-wave amplitude and phase

Curves’ width reflects the statistical uncertainty

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Vertex Locator \( \sigma_{PV,x/y} \sim 10 \, \mu m, \sigma_{PV,z} \sim 60 \, \mu m \)

Tracking (TT, IT+OT) \( \Delta p/p: 0.4\% @ 5 \, GeV, 0.6\% @ 100 \, GeV \)

RICHs \( \varepsilon (K \rightarrow K) \sim 95\%, \text{mis-ID rate} (\pi \rightarrow K) \sim 5\% \)

Muon system (M1-M5) \( \varepsilon (\mu \rightarrow \mu) \sim 95\%, \text{mis-ID rate} (\pi \rightarrow \mu) \sim 1-3\% \)

ECAL \( \sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\% (E \text{ in GeV}) \)

HCAL \( \sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\% (E \text{ in GeV}) \)