Beauty in ATLAS: New physics searches, spectroscopy and decay properties of $B$-hadrons

Hok-Chuen Cheng (hccheng@umich.edu)
(University of Michigan, Ann Arbor)
On behalf of the ATLAS collaboration

May 5-7, Phenomenology 2014 Symposium
Outline

• B-physics in a nutshell
• The ATLAS experiment at LHC
• Parity violation in the decay $\Lambda_b^0 \to J/\psi \Lambda^0$
• $CP$ violation in $B_s^0 \to J/\psi \phi$ (Brief summary)
• Rare decay of $B_s^0 \to \mu^+ \mu^-$ (Brief summary)
• Summary and outlook
B-physics in a nutshell

- **B-physics investigates physics of mesons and baryons containing at least one bottom quark**
- **B-physics at ATLAS:**
  - Large beauty production cross section and high luminosity provide high sensitivity to B-hadrons
  - Focus on competitive topics:
    - Testing $CP$ Violation through decay parameters that influence CKM matrix elements
    - Studying heavy flavor meson and baryon production and decay properties, e.g. cross section, lifetime, etc
    - Testing predictions of heavy quark interaction models, e.g. HQET, factorization, heavy quark expansion, etc
    - New physics searches through rare and very rare decays which are highly suppressed in SM
Tracking system (Pixel, SCT & TRT) reconstruct trajectories and momenta of charged particles; **crucial for identifying the b decay products**

**EM/hadronic calorimeters** energy deposition of particles and missing energy

**Muon spectrometer** precise tracking and momentum measurement of muons; for study of b-jets containing $J/\psi$ (final products are a muon pair)
Triggers & data taking at ATLAS

Triggers for B-physics

• Reduce huge collision data rate from ~40MHz to ~500Hz
• Most B-physics channels studied at ATLAS have di-muon signature ($B \rightarrow J/\psi(\mu\mu)X$, $B \rightarrow \mu\mu$, etc.)
• Main B-physics triggers in ATLAS
  ◦ single or di-muon triggers
  ◦ topological triggers (invariant mass window for $J/\psi$, $B_s$, Upsilon($\Upsilon$), etc)

Data taking

• Run 1 (2010-2012) ended. Upgrades and preparation for Run 2 in 2015 are ongoing
• Data recorded for $pp$-collisions:
  ◦ **45 fb$^{-1}$ in 2010** ($\sqrt{s} = 7$ TeV, max lumi $2.1 \times 10^{32}$ cm$^{-2}$s$^{-1}$)
  ◦ **5.1 fb$^{-1}$ in 2011** ($\sqrt{s} = 7$ TeV, max lumi $3.6 \times 10^{33}$ cm$^{-2}$s$^{-1}$)
  ◦ **21.3 fb$^{-1}$ in 2012** ($\sqrt{s} = 8$ TeV, max lumi $7.7 \times 10^{33}$ cm$^{-2}$s$^{-1}$)
• Excellent acquisition efficiency (>90%) and detector performance
• More suitable triggers for heavy quark physics in 2010 and 2011 data due to lower thresholds. Updates of analyses using 2012 data are ongoing
Parity violation in the decay $\Lambda_b^0 \to J/\psi \Lambda^0$

- Parity violation is a well-known feature of weak interactions. It is **not maximal in decays of hadrons** due to the presence of **strongly coupled spectator quarks**.
- Results of parity violation measurement can be used to test predictions made by different **quark interaction models**.

### Four possible helicity amplitudes:

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>$\lambda_{J/\psi}$</th>
<th>$\lambda_{\Lambda}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_+$</td>
<td>0</td>
<td>$1/2$</td>
</tr>
<tr>
<td>$a_-$</td>
<td>0</td>
<td>$-1/2$</td>
</tr>
<tr>
<td>$b_+$</td>
<td>$-1$</td>
<td>$-1/2$</td>
</tr>
<tr>
<td>$b_-$</td>
<td>1</td>
<td>$1/2$</td>
</tr>
</tbody>
</table>

Normalization condition

$$|a_+|^2 + |a_-|^2 + |b_+|^2 + |b_-|^2 = 1.$$  

Parity violating asymmetry parameter

$$\alpha_b = |a_+|^2 - |a_-|^2 + |b_+|^2 - |b_-|^2$$
Full angular PDF$^{1,2,3}$:

$$w(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A}) f_{2i}(P, \alpha_\Lambda) F_i(\Omega)$$

$f_{1i}$: bilinear functions of the four helicity amplitudes $\vec{A}$

$f_{2i}$: functions of polarization $P$ of $\Lambda_b$ and decay parameter $\alpha_\Lambda$ of $\Lambda$, where $\alpha_\Lambda = 0.642 \pm 0.013$

$F_i$: functions of decay angles $\Omega(\theta, \phi, \theta_1, \phi_1, \theta_2, \phi_2)$

<table>
<thead>
<tr>
<th>$i$</th>
<th>$f_{1i}$</th>
<th>$f_{2i}$</th>
<th>$F_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$a_+a_+^* + a_-a_-^* + b_+b_+^* + b_-b_-^*$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>$a_+a_+^* - a_-a_-^* + b_+b_+^* - b_-b_-^*$</td>
<td>$\alpha_\Lambda$</td>
<td>$\cos \theta_1$</td>
</tr>
<tr>
<td>4</td>
<td>$-a_+a_+^* - a_-a_-^* + b_+b_+^* + b_-b_-^*$</td>
<td>1</td>
<td>$\frac{1}{2} \left( 3 \cos^2 \theta_2 - 1 \right)$</td>
</tr>
<tr>
<td>6</td>
<td>$-a_+a_+^* + a_-a_-^* - b_+b_+^* + b_-b_-^*$</td>
<td>$\alpha_\Lambda$</td>
<td>$\frac{1}{2} \left( 3 \cos^2 \theta_2 - 1 \right) \cos \theta_1$</td>
</tr>
<tr>
<td>18</td>
<td>$3/\sqrt{2} \text{Re}(b_-a_-^* - a_+b_+^*)$</td>
<td>$\alpha_\Lambda$</td>
<td>$\sin \theta_1 \sin \theta_2 \cos \theta_2 \cos(\phi_1 + \phi_2)$</td>
</tr>
<tr>
<td>19</td>
<td>$-3/\sqrt{2} \text{Im}(b_-a_-^* - a_+b_+^*)$</td>
<td>$\alpha_\Lambda$</td>
<td>$\sin \theta_1 \sin \theta_2 \cos \theta_2 \sin(\phi_1 + \phi_2)$</td>
</tr>
</tbody>
</table>

Parity violation in the decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

- 4.9 fb$^{-1}$ of 2011 data at $\sqrt{s} = 7$ TeV collected with topological $J/\psi$ trigger
- $\Lambda_b^0$ reconstructed through cascade decay topology $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ fit (with $J/\psi \rightarrow \mu^+\mu^-$ and $\Lambda^0 \rightarrow p\pi^-$)
- Selection results

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{sig}}$</td>
<td>$1400 \pm 50$</td>
<td>$1240 \pm 40$</td>
</tr>
<tr>
<td>$N_{\text{Comb}}$</td>
<td>$1090 \pm 80$</td>
<td>$234 \pm 16$</td>
</tr>
<tr>
<td>$N_{B_0^d}$</td>
<td>$210 \pm 90$</td>
<td>$73 \pm 30$</td>
</tr>
</tbody>
</table>

- Parameter extraction

$\alpha_b$ and helicity amplitude parameters can be found by solving:

$$\langle F_i \rangle_{\text{expected}} = \langle F_i \rangle, \quad \text{for } i = 2, 4, 6, 18, \text{ and } 19$$

Imaginary exact solutions were found. $\chi^2$ minimization fit is used to constraint the helicity amplitude parameters to real values that are statistically closest to the exact solution:

$$\chi^2 = \sum_i \sum_j (\langle F_i \rangle_{\exp} - \langle F_i \rangle)V_{ij}^{-1}(\langle F_j \rangle_{\exp} - \langle F_j \rangle), \quad \text{for } i, j = 2, 4, 6, 18, 19$$

where $V_{ij}$ is the covariance matrix of measured $\langle F_i \rangle$, and $\langle F_i \rangle_{\exp}$ is evaluated from models including detector effects.
Fit results

- The weighted MC and the background distributions of $F_i$ variables are added and compared with data.
- The background is estimated by adding the left and right sidebands.
- Main systematics came from detector effect estimation & background contribution.

arXiv:1404.1071
Parity violation in decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$

**Results**

$$\alpha_b = 0.30 \pm 0.16(\text{stat}) \pm 0.06(\text{syst})$$

$$|a_+| = 0.17^{+0.12}_{-0.17}(\text{stat}) \pm 0.09(\text{syst}),$$

$$|a_-| = 0.59^{+0.06}_{-0.07}(\text{stat}) \pm 0.03(\text{syst}),$$

$$|b_+| = 0.79^{+0.04}_{-0.05}(\text{stat}) \pm 0.02(\text{syst}),$$

$$|b_-| = 0.08^{+0.13}_{-0.08}(\text{stat}) \pm 0.06(\text{syst}).$$

$\Lambda^0$ hyperons are more likely to carry a negative helicity

Consistent with the latest LHCb result$^1$

$$\alpha_b = 0.05 \pm 0.17 \pm 0.07$$

Results deviated from two theoretical predictions

$pQCD^2$: $-(0.14\sim0.17)$ at 2.6 s.d.

$HQET^3,4$: 0.78 at 2.8 s.d.

Analysis using 2012 data is ongoing

---

CP violation in $B_s^0 \rightarrow J/\psi \phi$ (Brief summary)

- Small theoretical uncertainty → well predicted in the SM
- New particles can contribute to $B_s - B_s$ box diagrams and significantly modify the SM prediction
- Update to previous measurement using flavor tagging
- 4.9 fb$^{-1}$ data collected in 2011 with topological $J/\psi$ trigger is used
  - Signal region defined to retain 99.8% of $J/\psi$ candidates (see backup slides)
  - An unbinned maximum likelihood fit (MLF) is performed on the selected events to extract decay parameters
  - Tag information is used in the MLF

**SM prediction**

$\phi_s = -2\beta_s = -0.0368 \pm 0.0018$ rad

where $\beta_s = \text{arg}[-(V_{ts}V_{tb}^{*})/(V_{cs}V_{cb}^{*})]$

$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 0.087 \pm 0.021$ ps$^{-1}$

**Results**

$\phi_s = 0.12 \pm 0.25$ (stat.) $\pm 0.11$ (syst.) rad

$\Delta\Gamma_s = 0.053 \pm 0.021$ (stat.) $\pm 0.009$ (syst.) ps$^{-1}$

Results are consistent with CDF$^2$, D0$^3$ and LHCb$^4$

References:

Rare decay of $B_s^0 \rightarrow \mu^+ \mu^-$ (Brief summary)

- Flavor changing neutral current highly suppressed in SM
- Of particular interest in search of new physics, complementary to direct search for physics beyond the SM

- 4.9 fb$^{-1}$ data collected in 2011 by the ATLAS detector is used
- Update to previous result using 2.4 fb$^{-1}$ data
  - $\mu$: $p_T > 4$ GeV and $|\eta| < 2.5$  
  - $B_s$: $p_T > 8$ GeV and $|\eta| < 2.5$
  - $\mu\mu$: $4.0 < m(\mu\mu) < 8.5$ GeV and $\chi^2/n.d.f. < 2.0$
  - Signal Region: [5.066, 5.666] GeV
  - 390K $B_s$ candidates were selected

- Decay $B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm$ used as reference channel for normalization of integrated luminosity, acceptance and efficiency

$$BR(B_s^0 \rightarrow \mu^+ \mu^-) = BR(B^\pm \rightarrow J/\psi K^\pm \rightarrow \mu^+ \mu^- K^\pm) \times \frac{f_{B_s}}{f_B} \times \frac{N_{\mu^+ \mu^-}}{N_{J/\psi K^\pm}} \times \frac{A_{J/\psi K^\pm}}{A_{\mu^+ \mu^-}} \times \frac{\epsilon_{J/\psi K^\pm}}{\epsilon_{\mu^+ \mu^-}}$$

- Main systematics came from PDG branching fractions and acceptance x efficiency ratio between the rare decay and reference channel
Rare decay of $B_s^0 \rightarrow \mu^+ \mu^-$ (Brief summary)

Main backgrounds:
- Combinatorial bkg $b \rightarrow \mu^+ \mu^- X$
- Resonant bkg due to $B$-hadron decay with 1 or 2 hadrons misidentified as muon

Signal selection optimization:
- Performed to select best performing BDTs and final selection cuts in the BDT output variables and invariant mass window for best sensitivity to the signal
- By maximizing estimator of separation power: $P = \frac{\varepsilon}{1 + \sqrt{B}}$, where $\varepsilon$ is the signal efficiency and $B$ is the number of bkg events

$BR(B_s^0 \rightarrow \mu^+ \mu^-)$ branching fraction
- SM prediction$^1$ $(3.56 \pm 0.30) \times 10^{-9}$
- LHCb result$^2$ $(2.9 \pm 1.1) \times 10^{-9}$
- CMS result$^3$ $(3.0 \pm 1.0) \times 10^{-9}$

Results
- Observed limit is set to be $< 15 \times 10^{-9}$ at 95% CL
- compatible with expected limits at $< 16 \pm 7 \times 10^{-9}$ at 95% CL


ATLAS-CONF-2013-076
Summary and outlook

- Excellent muon identification and measurement allow ATLAS to study a wide range of B-physics topics at high energy which are out of reach of B factories.

- **Parity violation** in decay $\Lambda_b^0 \rightarrow J/\psi \Lambda^0$ result consistent with LHCb result, which lies between two theoretical predictions (pQCD & HQET). Updates with 2012 data ongoing.

- **Update on CP violation** measurement in $B_s \rightarrow J/\psi \phi$ with flavor tagging consistent with SM predictions.

- **Improved upper limits set on rare decay** $B_s^0 \rightarrow \mu^+ \mu^-$ consistent with expected values. Update with 2012 data needed to obtain a comparable result with other experiments.

- More public results available on [ATLAS B-physics twiki page](#).

- More results from dedicated analyses using 2012 data are ongoing.
More B-physics public results...

**ATLAS EXPERIMENT - Public Results**

B-physics public results

- Publications
- CONF notes
- PUB notes
- Stand-alone plots
- CSC B-physics chapter
- Daily updated table...

### Publications

Publications appearing in or submitted to peer-reviewed journals are listed below.

<table>
<thead>
<tr>
<th>Short Title</th>
<th>Int L</th>
<th>Journal</th>
<th>Preprint</th>
<th>Plots</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NEW</strong> Associated production of prompt J/µ mesons and W boson in at ( \sqrt{s} = 7 \text{ TeV} )</td>
<td>4.6 fb-1</td>
<td>To be submitted to JHEP</td>
<td>arXiv:1401.2831</td>
<td>Link</td>
</tr>
<tr>
<td><strong>NEW</strong> Production cross section of B⁺ at ( \sqrt{s} = 7 \text{ TeV} )</td>
<td>2.4 fb-1</td>
<td>JHEP.10 (2013) 042</td>
<td>arXiv:1307.0126v2</td>
<td>Link</td>
</tr>
<tr>
<td>( \phi_b ) and ( \Delta \Gamma_b ) from time dependent angular analysis of ( b \to \phi \rightarrow J/\mu \phi )</td>
<td>4.9 fb-1</td>
<td>JHEP.12 (2012) 072</td>
<td>arXiv:1208.0572</td>
<td>Link</td>
</tr>
<tr>
<td>Search for the decay ( B_\phi \rightarrow \mu \mu )</td>
<td>2.4 fb-1</td>
<td>Phys. Lett. B713 (2012) 180-196</td>
<td>arXiv:1204.0735</td>
<td>Link</td>
</tr>
<tr>
<td>Observation of a new ( X_0 ) state in radiative transitions to Y(1S) and Y(2S)</td>
<td>4.4 fb-1</td>
<td>Phys. Rev. Lett. 108 (2012) 152001</td>
<td>arXiv:1112.5154</td>
<td>Link</td>
</tr>
</tbody>
</table>

Analyses performed within other ATLAS Physics Groups:


[https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysPublicResults)
THANK YOU
BACK UP SLIDES
The ATLAS experiment at LHC

ATLAS is a general purpose detector, designed for a wide range of physics scenario (SM, Higgs, SUSY, BSM, etc.)
\[
W(\Omega, \vec{A}, P) = \frac{1}{(4\pi)^3} \sum_{i=0}^{19} f_{1i}(\vec{A})f_{2i}(P, \alpha_L)F_i(\Omega)
\]

<table>
<thead>
<tr>
<th>(i)</th>
<th>(f_{1i})</th>
<th>(f_{2i})</th>
<th>(F_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(a_+ a_<em>^</em> + a_- a_<em>^</em> + b_+ b_<em>^</em> + b_- b_<em>^</em>)</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>(a_+ a_<em>^</em> - a_- a_<em>^</em> + b_+ b_<em>^</em> - b_- b_<em>^</em>)</td>
<td>(P)</td>
<td>(\cos \theta)</td>
</tr>
<tr>
<td>2</td>
<td>(a_+ a_<em>^</em> - a_- a_<em>^</em> - b_+ b_<em>^</em> + b_- b_<em>^</em>)</td>
<td>(\alpha_L)</td>
<td>(\cos \theta_1)</td>
</tr>
<tr>
<td>3</td>
<td>(a_+ a_<em>^</em> + a_- a_<em>^</em> - b_+ b_<em>^</em> - b_- b_<em>^</em>)</td>
<td>(P\alpha_L)</td>
<td>(\cos \theta \cos \theta_1)</td>
</tr>
<tr>
<td>4</td>
<td>(-a_+ a_<em>^</em> - a_- a_<em>^</em> + \frac{1}{2} b_+ b_<em>^</em> + \frac{1}{2} b_- b_<em>^</em>)</td>
<td>1</td>
<td>(\frac{1}{2} (3 \cos^2 \theta_2 - 1))</td>
</tr>
<tr>
<td>5</td>
<td>(-a_+ a_<em>^</em> + a_- a_<em>^</em> + \frac{1}{2} b_+ b_<em>^</em> - \frac{1}{2} b_- b_<em>^</em>)</td>
<td>(P)</td>
<td>(\frac{1}{2} (3 \cos^2 \theta_2 - 1) \cos \theta)</td>
</tr>
<tr>
<td>6</td>
<td>(-a_+ a_<em>^</em> + a_- a_<em>^</em> - \frac{1}{2} b_+ b_<em>^</em> + \frac{1}{2} b_- b_<em>^</em>)</td>
<td>(\alpha_L)</td>
<td>(\frac{1}{2} (3 \cos^2 \theta_2 - 1) \cos \theta_1)</td>
</tr>
<tr>
<td>7</td>
<td>(-a_+ a_<em>^</em> - a_- a_<em>^</em> - \frac{1}{2} b_+ b_<em>^</em> - \frac{1}{2} b_- b_<em>^</em>)</td>
<td>(P\alpha_L)</td>
<td>(\frac{1}{2} (3 \cos^2 \theta_2 - 1) \cos \theta \cos \theta_1)</td>
</tr>
<tr>
<td>8</td>
<td>(-3 \text{Re}(a_+ a_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\sin \theta \sin \theta_1 \sin^2 \theta_2 \cos \phi_1)</td>
</tr>
<tr>
<td>9</td>
<td>(3 \text{Im}(a_+ a_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\sin \theta \sin \theta_1 \sin^2 \theta_2 \sin \phi_1)</td>
</tr>
<tr>
<td>10</td>
<td>(-\frac{3}{2} \text{Re}(b_+ b_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\sin \theta \sin \theta_1 \sin^2 \theta_2 \cos (\phi_1 + 2 \phi_2))</td>
</tr>
<tr>
<td>11</td>
<td>(\frac{3}{2} \text{Im}(b_+ b_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\sin \theta \sin \theta_1 \sin^2 \theta_2 \sin (\phi_1 + 2 \phi_2))</td>
</tr>
<tr>
<td>12</td>
<td>(-\frac{3}{2} \text{Re}(b_- a_<em>^</em> + a_- b_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\sin \theta \cos \theta_1 \sin \theta_2 \cos \theta_2 \cos \phi_2)</td>
</tr>
<tr>
<td>13</td>
<td>(\frac{1}{\sqrt{3}} \text{Im}(b_- a_<em>^</em> + a_- b_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\sin \theta \cos \theta_1 \sin \theta_2 \cos \theta_2 \sin \phi_2)</td>
</tr>
<tr>
<td>14</td>
<td>(-\frac{1}{\sqrt{2}} \text{Re}(b_- a_<em>^</em> + a_+ b_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\cos \theta \sin \theta_1 \sin \theta_2 \cos \theta_2 \cos (\phi_1 + \phi_2))</td>
</tr>
<tr>
<td>15</td>
<td>(\frac{1}{\sqrt{2}} \text{Im}(b_- a_<em>^</em> + a_+ b_<em>^</em>))</td>
<td>(P\alpha_L)</td>
<td>(\cos \theta \sin \theta_1 \sin \theta_2 \cos \theta_2 \sin (\phi_1 + \phi_2))</td>
</tr>
<tr>
<td>16</td>
<td>(\frac{3}{\sqrt{3}} \text{Re}(a_- b_<em>^</em> - b_- a_<em>^</em>))</td>
<td>(P)</td>
<td>(\sin \theta \sin \theta_2 \cos \theta_2 \cos \phi_2)</td>
</tr>
<tr>
<td>17</td>
<td>(-\frac{3}{\sqrt{2}} \text{Im}(a_- b_<em>^</em> - b_- a_<em>^</em>))</td>
<td>(P)</td>
<td>(\sin \theta \sin \theta_2 \cos \theta_2 \sin \phi_2)</td>
</tr>
<tr>
<td>18</td>
<td>(\frac{3}{\sqrt{2}} \text{Re}(b_- a_<em>^</em> - a_+ b_<em>^</em>))</td>
<td>(\alpha_L)</td>
<td>(\sin \theta_1 \sin \theta_2 \cos \theta_2 \cos (\phi_1 + \phi_2))</td>
</tr>
<tr>
<td>19</td>
<td>(-\frac{3}{\sqrt{2}} \text{Im}(b_- a_<em>^</em> - a_+ b_<em>^</em>))</td>
<td>(\alpha_L)</td>
<td>(\sin \theta_1 \sin \theta_2 \cos \theta_2 \sin (\phi_1 + \phi_2))</td>
</tr>
</tbody>
</table>
**CP violation in $B_s^0 \rightarrow J/\psi \phi$**

**Event selection**

- $J/\psi \rightarrow \mu^+ \mu^-$ candidates
  - at least one pair of oppositely charged muon candidates
  - pair of muon tracks refitted to a common vertex
  - $\chi^2$/d.o.f. < 10
  - $2.959 < m(\mu^+ \mu^-) < 3.229$ GeV for both muons with $|\text{eta}| < 1.05$
  - $2.913 < m(\mu^+ \mu^-) < 3.273$ GeV for one muon with $1.05 < |\text{eta}| < 2.5$
  - $2.852 < m(\mu^+ \mu^-) < 3.332$ GeV for both muons with $1.05 < |\text{eta}| < 2.5$

- $\phi \rightarrow K^+K^-$ candidates
  - reconstructed from oppositely charged tracks not identified as muon
  - $p_T > 0.5$ GeV
  - $|\text{eta}| < 2.5$

- $B_s^0 \rightarrow J/\psi \phi$ candidates
  - reconstructed by fitting four tracks each with
    - at least 1 hit in pixel detector
    - at least 4 hits silicon strip detector
    - $\chi^2$/d.o.f. < 3
    - fitted $p_T(K^+/K^-) > 1$ GeV
    - $1.0085 < m(K^+K^-) < 1.0305$ GeV

**ATLAS-CONF-2013-039**

Hok-Chuen Cheng (Michigan) Pheno2014 20
\section*{CP violation in $B_s^0 \rightarrow J/\psi \phi$}

\subsection*{Likelihood function}

An unbinned maximum likelihood fit is performed on the selected events to extract the parameters of the $B_s^0 \rightarrow J/\psi (\mu^+ \mu^-) \phi (K^+ K^-)$ decay. The fit uses information about the reconstructed mass $m$, the measured proper decay time $t$, the measured mass and proper decay time uncertainties $\sigma_m$ and $\sigma_t$, the tag probability, and the transversity angles $\Omega$ of each $B_s^0 \rightarrow J/\psi \phi$ decay candidate. There are three transversity angles; $\Omega = (\theta_T, \psi_T, \phi_T)$ and these are defined in section 5.1.

The likelihood function is defined as a combination of the signal and background probability density functions as follows:

\begin{equation}
\ln \mathcal{L} = \sum_{i=1}^{N} \left\{ w_i \ln (f_s \cdot \mathcal{F}_s(m_i, t_i, \Omega_i)) + f_s \cdot f_{B^0} \cdot \mathcal{F}_{B^0}(m_i, t_i, \Omega_i) \\
+ (1 - f_s \cdot (1 + f_{B^0})) \mathcal{F}_{bkg}(m_i, t_i, \Omega_i) \right\}
\end{equation}

where $N$ is the number of selected candidates, $w_i$ is a weighting factor to account for the trigger efficiency, $f_s$ is the fraction of signal candidates, $f_{B^0}$ is the fraction of peaking $B^0$ meson background events calculated relative to the number of signal events; this parameter is fixed in the likelihood fit. The mass $m_i$, the proper decay time $t_i$ and the decay angles $\Omega_i$ are the values measured from the data for each event $i$. $\mathcal{F}_s$, $\mathcal{F}_{B^0}$ and $\mathcal{F}_{bkg}$ are the probability density functions (PDF) modelling the signal, the specific $B^0$ background and the other background distributions, respectively. A detailed description of the
**CP violation in $B_s^0 \rightarrow J/\psi \phi$**

\[ \phi_s = 0.12 \pm 0.25 \text{ (stat.)} \pm 0.11 \text{ (syst.) rad} \]

\[ \Delta \Gamma_s = 0.053 \pm 0.021 \text{ (stat.)} \pm 0.009 \text{ (syst.) ps}^{-1} \]

\[ \Gamma_s = 0.677 \pm 0.007 \text{ (stat.)} \pm 0.003 \text{ (syst.) ps}^{-1} \]

\[ |A_0(0)|^2 = 0.529 \pm 0.006 \text{ (stat.)} \pm 0.011 \text{ (syst.)} \]

\[ |A_{\parallel}(0)|^2 = 0.220 \pm 0.008 \text{ (stat.)} \pm 0.009 \text{ (syst.)} \]

\[ \delta_{\perp} = 3.89 \pm 0.46 \text{ (stat.)} \pm 0.13 \text{ (syst.) rad} \]

**Full results:**

---

**Table 7: Summary of systematic uncertainties assigned to parameters of interest.**

|                  | $\phi_s$ (rad) | $\Delta \Gamma_s$ (ps$^{-1}$) | $\Gamma_s$ (ps$^{-1}$) | $|A_{\parallel}(0)|^2$ | $|A_0(0)|^2$ | $|A_S(0)|^2$ | $\delta_{\perp}$ (rad) | $\delta_{\parallel}$ (rad) | $\delta_{\perp} - \delta_S$ (rad) |
|------------------|----------------|-------------------------------|------------------------|-----------------------|-------------|----------------|------------------------|-------------------------------|---------------------------------|
| **ID alignment** | $<10^{-2}$     | $<10^{-3}$                    | $<10^{-3}$             | $<10^{-3}$            | $<10^{-3}$  | -              | $<10^{-2}$             | $<10^{-2}$                         | -                               |
| **Trigger efficiency** | $<10^{-2}$     | $<10^{-3}$                    | 0.002                  | $<10^{-3}$            | $<10^{-3}$  | $<10^{-2}$    | $<10^{-2}$             | $<10^{-2}$                         | $<10^{-2}$                        |
| **$B_d^0$ contribution** | 0.03           | 0.001                         | $<10^{-3}$             | $<10^{-3}$            | 0.005       | 0.001         | 0.02                   | $<10^{-2}$                         | $<10^{-2}$                        |
| **Tagging**     | 0.10           | 0.001                         | $<10^{-3}$             | $<10^{-3}$            | 0.002       | 0.05          | $<10^{-2}$             | $<10^{-2}$                         | $<10^{-2}$                        |
| **Models:**     |                |                               |                        |                      |             |               |                       |                                |                                  |
| **default fit** | $<10^{-2}$     | 0.002                         | $<10^{-3}$             | 0.003                 | 0.002       | 0.006         | 0.07                   | 0.01                           | 0.01                            |
| **signal mass** | $<10^{-2}$     | 0.001                         | $<10^{-3}$             | 0.001                 | 0.001       | 0.002         | 0.06                   | 0.02                           | 0.02                            |
| **background mass** | $<10^{-2}$     | 0.001                         | 0.001                  | $<10^{-3}$            | 0.002       | 0.004         | 0.02                   | 0.02                           | 0.02                            |
| **resolution**  | 0.02           | $<10^{-3}$                    | 0.001                  | $<10^{-3}$            | 0.002       | 0.04          | 0.02                   | 0.02                           | 0.02                            |
| **background time** | 0.01           | 0.001                         | $<10^{-3}$             | 0.001                 | 0.002       | 0.01          | 0.02                   | 0.02                           | 0.02                            |
| **background angles** | 0.02           | 0.008                         | 0.002                  | 0.008                 | 0.009       | 0.027         | 0.06                   | 0.07                           | 0.03                            |
| **Total**       | 0.11           | 0.009                         | 0.003                  | 0.009                 | 0.011       | 0.028         | 0.13                   | 0.09                           | 0.04                            |
# Rare decay of $B_s^0 \to \mu^+ \mu^-$

## Discriminative variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{xy}$</td>
<td>Scalar product in the transverse plane of vectors</td>
<td>1</td>
</tr>
<tr>
<td>$I_{0.7}$ isolation</td>
<td>Ratio of $</td>
<td>\not{p}B_T</td>
</tr>
<tr>
<td>$</td>
<td>\alpha_{2d}</td>
<td>$</td>
</tr>
<tr>
<td>$p_{L \text{ min}}$</td>
<td>Minimum momentum of the two muon candidates along the $B$ direction</td>
<td>4</td>
</tr>
<tr>
<td>$p_{TB}$</td>
<td>$B$ transverse momentum</td>
<td>5</td>
</tr>
<tr>
<td>ct significance</td>
<td>Proper decay length divided by its uncertainty</td>
<td>6</td>
</tr>
<tr>
<td>$\chi^2_{z}$, $\chi^2_{xy}$</td>
<td>Significance of the separation between production (PV) and decay vertex (SV)</td>
<td>7</td>
</tr>
<tr>
<td>$</td>
<td>D_{xy}</td>
<td>_{\text{min}},</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>$R$-parameter in two dimensions, $R=\sqrt{\Delta \eta^2 + \Delta \phi^2}$</td>
<td>9</td>
</tr>
<tr>
<td>$</td>
<td>d0</td>
<td>_{\text{max}},</td>
</tr>
</tbody>
</table>