Studies on B hadron production, spectroscopy and decays at CMS

Kruger 2012

Xin Shi

National Taiwan University

On behalf of CMS collaboration
Outline

• Introduction
• B-Hadron Production
• $\Lambda_b$ lifetime
• $B_s$ lifetime difference ($\Delta \Gamma_s$)
• Summary
Introduction

• CMS is a general purpose detector at the LHC.

• Inner tracker consists of silicon pixel and silicon strip layers.

• Muons are measured by drift tubes (DT), cathode strip chambers (CSC) and resistive plate chambers (RPC).

• The dimuon mass resolution is less than 1%.

• Powerful tool for B-physics study.
Dimuon mass distribution collected with various dimuon triggers.
B-Hadron Production

CMS $\sqrt{s} = 7$ TeV

- $B^+$ (l$^B,l < 2.4$)
- $B^+$ Tsallis fit
- $B^0$ (l$^B,l < 2.2$)
- $B^0$ Tsallis fit
- $B_s^0$ (l$^B,l < 2.4$)
- $B_s^0$ Tsallis fit
- $\bar{\Lambda}_b$ (l$^\bar{\Lambda}_b,l < 2.0$)
- $\bar{\Lambda}_b$ Tsallis fit

CMS Preliminary, $\sqrt{s} = 7$ TeV

- $pp \rightarrow \Lambda_b X \rightarrow J/\psi \Lambda X$
  $p_T > 10$ GeV, |y| < 2.0 (x10000)
  $11.6 \pm 0.6 \pm 1.2 \pm 2.0$
  (1900 pb$^{-1}$)

- $pp \rightarrow B^+ X$
  $p_T > 5$ GeV, |y| < 2.4
  $28.1 \pm 2.4 \pm 2.0 \pm 3.1$
  (6 pb$^{-1}$)

- $pp \rightarrow B^0 X$
  $p_T > 5$ GeV, |y| < 2.2
  $33.3 \pm 2.5 \pm 3.1 \pm 3.6$
  (40 pb$^{-1}$)

- $pp \rightarrow B_s X \rightarrow J/\psi \phi X$
  $8 < p_T < 50$ GeV, |y| < 2.4 (x1000)
  $6.9 \pm 0.4 \pm 0.7 \pm 0.3$
  (40 pb$^{-1}$)

Theory: MC@NLO / POWHEG
CTEQ6M PDF, $\mu = (m_b^2 + p_T^2)^{1/2}$, $m_b = 4.75$ GeV
Observation of $\Xi_b^{*0}$

CMS

$pp, \sqrt{s} = 7\text{ TeV}$
$L = 5.3\text{ fb}^{-1}$

(b)

$M(J/\psi\Xi^-\pi^+) - M(J/\psi\Xi^-) - M(\pi) \ [\text{MeV}]$

$14.84 \pm 0.74 \text{ (stat.)} \pm 0.28 \text{ (syst.) \ MeV}$
$\Gamma = 2.1 \pm 1.7 \text{ (stat.) \ MeV}$

$M(\Xi_b^{*0}) = 5945.0 \pm 0.7 \text{ (stat.)} \pm 0.3 \text{ (syst.)} \pm 2.7 \text{ (PDG) MeV}$

Measured mass and width are compatible with theoretical expectations for the $J^P = 3/2^+$ baryon

Measurement of the $\Lambda_b$ lifetime
Study of b-baryons is an important ingredient in understanding b-hadron production.

The non-perturbative QCD model of Heavy Quark Theory provides predictions.

Recent measurements include those from CDF, D0 and ATLAS.

Use $\Lambda_b \rightarrow J/\psi \Lambda^0$, $J/\psi \rightarrow \mu \mu$, $\Lambda^0 \rightarrow p\pi$. 
Event Selection

- Two oppositely charged muons.
- Constrain the dimuon invariant mass to the known $J/\psi$ mass.
- Select two other oppositely charged tracks as the proton and pion with the $p_T$(proton) $>$ $p_T$(pion).
- Constrain the proton-pion invariant mass to the $\Lambda^0$ mass,
- reject events with $m(p\pi)$ close to $K_s$ mass.
Likelihood Fit and Efficiency

- **2-D unbinned maximum likelihood fit:**
  - **Signal:** Double Gaussian in $m$, decay in $t$  
    $$M_{\text{sig}}(m) \cdot M_{\text{sig}}(t) = G_{\text{sig}}(m; \mu_m, \sigma_1, \sigma_2, f) \cdot D_{\text{sig}}(t; \tau, \sigma_1, \sigma_2, f)$$
  - **Prompt background:** Linear in $m$, Double Gaussian in $t$
    $$M_{\text{prompt}}(m) \cdot M_{\text{prompt}} = (a_0 + a_1 m) \cdot G_{\text{prompt}}(t; \mu_t, \sigma_1, \sigma_2, f)$$
  - **Non-prompt background:** Linear in $m$, decay in $t$
    $$M_{\text{non-prompt}}(m) \cdot M_{\text{non-prompt}} = (a_0 + a_1 m) \cdot D_{\text{non-prompt}}(t; \tau, \sigma_1, \sigma_2, f)$$

- **Constant efficiency**

---

![Graph](image)

**CMS simulation**

$\sqrt{s} = 7$ TeV  \  $L = 5$ fb$^{-1}$

fit with turn-on curve for systematic study.
Fit Projection $\Lambda_b$

CMS preliminary $\sqrt{s} = 7$ TeV $L = 5$ fb$^{-1}$

- **$\Lambda_b$**: 
  - fit function
  - signal
  - prompt background
  - non-prompt background

**Prompt bkgd**

**Non-prompt bkgd**

**Events / (0.006 GeV/c²)**

**Invariant mass $J/\psi \Lambda$ (GeV/c²)**

**Pull**

**Proper decay time (ps)**

**Events / (0.16 ps)**

**B²**

See backup for $B^0$ fits.

Xin Shi

Kruger 2012
Systematic and Results

• Systematic uncertainty sources:
  • Efficiency (main source)
  • Alignment
  • Event selection
  • Fit model

• Final results $\Lambda_b$ lifetime:

$$1.503 \pm 0.052 \text{ (stat.)} \pm 0.031 \text{ (syst.) ps}$$
Comparison with Previous Results

$\Lambda_b$ lifetime

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Year(s)</th>
<th>Decays</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS pre(2011)</td>
<td></td>
<td>$J/\psi\Lambda$</td>
</tr>
<tr>
<td>ATLAS (2011)</td>
<td></td>
<td>$J/\psi\Lambda$</td>
</tr>
<tr>
<td>D0 (02-11)</td>
<td></td>
<td>$J/\psi\Lambda$</td>
</tr>
<tr>
<td>CDF2 (02-09)</td>
<td></td>
<td>$J/\psi\Lambda$</td>
</tr>
<tr>
<td>D0 (02-06)</td>
<td></td>
<td>$J/\psi\Lambda$</td>
</tr>
<tr>
<td>D0 (02-06)</td>
<td></td>
<td>$\Lambda_c^+\mu$</td>
</tr>
<tr>
<td>CDF2 (02-06)</td>
<td></td>
<td>$\Lambda_c^+\pi$</td>
</tr>
<tr>
<td>OPAL (90-95)</td>
<td></td>
<td>$\Lambda_c^+l, \Lambda l^-l^+$</td>
</tr>
<tr>
<td>CDF1 (91-95)</td>
<td></td>
<td>$\Lambda_c^+l$</td>
</tr>
<tr>
<td>ALEPH (91-95)</td>
<td></td>
<td>$\Lambda l^-l^+$</td>
</tr>
<tr>
<td>ALEPH (91-94)</td>
<td></td>
<td>$\Lambda_c^+l$</td>
</tr>
<tr>
<td>DELPHI (91-94)</td>
<td></td>
<td>$\Lambda_c^+l$</td>
</tr>
</tbody>
</table>

Errors in black: statistical only
Errors in grey: syst. added in quadrature
Band: current best value
data from arXiv:1010.1589
prepared for PDG2011
Measurement of the $B_s$ lifetime difference
**B_s lifetime difference**

\[ B_s \rightarrow J/\psi \phi \text{ with } J/\psi \rightarrow \mu^+ \mu^- \text{ and } \phi \rightarrow K^+ K^- \]

- Two flavour eigenstate of B_s oscillate.
- B_s-\bar{B}_s mixing gives rise to a CP violation phase:
  \[ \Phi_s = \Phi_M - 2\Phi_D \]
- The final state is an admixture of the CP-even and CP-odd eigenstates.
• Since $B_s$ is a pseudo-scalar meson, while $J/\psi$ and $\Phi$ are vector mesons, the orbital angular momentum can have the values $L = 0, 1, 2$.

• To measure the lifetime difference ($\Delta \Gamma_s$) for the decay rates of the two $B_s$ mass eigenstates, an analysis is needed to disentangle the two CP eigenstates.

• Decay topology is described by:

$$\Theta = (\theta_T, \psi_T, \varphi_T)$$
Bs Decay Formula

- The differential decay rate:

\[ \frac{d^4\Gamma(B_s(t))}{d\Theta \, dt} = f(\Theta, t; \alpha) = \sum_{i=1}^{6} O_i(\alpha, t) \cdot g_i(\Theta) \]

- Proper decay time
- Kinematics-independent observables
- Angular distributions
- Physics parameters of interest

\[ (\Gamma_s, \Delta\Gamma_s, |A_0|^2, |A_\perp|^2, \delta_\parallel) \]

- Longitudinal amplitudes
- Transverse amplitudes
- Strong phase
Event Selection

- Two oppositely charged muons.
- Two oppositely charged tracks.

- Build $B_s$ from 4-track vertex fit:
  - Constrain the dimuon invariant mass to the known $J/\psi$ mass.
  - Constrain the $K^+K^-$ to the $\phi$ mass.
• The overall efficiency includes: detector acceptance, the trigger conditions, and the selection cuts.
• No sizable correlation between the proper time and the angular variables is found.
• The correlation amongst the angular observables is also negligible.
• The proper decay length efficiency is almost flat in the range [0.02-0.3]cm.
Maximum likelihood fit

- **Event likelihood function:**
  \[
  L = L_{\text{signal}} + L_{\text{background}},
  \]
  \[
  L_{\text{signal}} = (f(\Theta, t; \alpha) \otimes G(t, \kappa, \sigma(t))) \cdot M(m) \cdot \epsilon(t) \epsilon(\Theta),
  \]
  \[
  L_{\text{background}} = b(\Theta, t, m),
  \]
  signal mass PDF (sum of two Gaussian)
  proper decay time uncertainty
  Gaussian resolution function
  Legendre polynomials and sinusoidal function

- **5-D fit procedure**
  - 1-D fit of Bs mass to get the mean and the smaller of the two Gaussian function widths.
  - Fit sideband region for the angular background shapes.
  - Fit the full mass range.
Fit to the Data

Signal yield: $14456 \pm 140$

mass: $5366.8 \pm 0.1$ MeV

PDG $5366.77 \pm 0.24$ MeV

Events / (0.0045 GeV)

Events / (0.0034 cm)

B_s proper decay length [cm]

CMS preliminary, 5 fb$^{-1}$ $\sqrt{s} = 7$ TeV

Data
Signal
Background
Fit
## Systematics

| Uncertainty source                              | $\Delta \Gamma_s$ [ps$^{-1}$] | $c\tau$ [cm] | $|A_0|^2$ | $|A_\perp|^2$ | $\delta ||$ [rad] |
|-------------------------------------------------|-------------------------------|--------------|----------|-----------|-------------|
| **Signal PDF modeling**                         |                               |              |          |           |             |
| Signal mass model                               | 0.00072                       | 0.00012      | 0.0022   | 0.0006    | 0.039       |
| Proper time resolution                         | **0.00170**                   | 0.00006      | 0.0007   | 0.0000    | 0.007       |
| $\phi_s$ approximation                         | 0.00000                       | 0.00001      | 0.0000   | 0.0000    | 0.002       |
| S-wave assumption                              | 0.00109                       | 0.00001      | 0.0130   | 0.0066    | 0.056       |
| **Background PDF modeling**                    |                               |              |          |           |             |
| Background mass model                           | 0.00019                       | 0.00000      | 0.0000   | 0.0001    | 0.003       |
| Background lifetime model                       | 0.00040                       | 0.00000      | 0.0001   | 0.0002    | 0.003       |
| Peaking $B^0$ background                        | 0.00025                       | 0.00006      | 0.0002   | 0.0022    | 0.050       |
| Background angular model                        | **0.00175**                   | 0.00003      | 0.0001   | 0.0064    | 0.161       |
| **Limited simulation statistics**               |                               |              |          |           |             |
| Angular efficiency parameters                   | 0.00019                       | 0.00002      | 0.0057   | 0.0055    | 0.037       |
| Temporal efficiency parameters                  | 0.00000                       | 0.00005      | 0.0000   | 0.0000    | 0.000       |
| Temporal efficiency parametrization             | **0.00181**                   | 0.00014      | 0.0005   | 0.0007    | 0.001       |
| Angular efficiency parametrization             | 0.00063                       | 0.00003      | 0.0021   | 0.0086    | 0.007       |
| Likelihood function bias                        | 0.00000                       | 0.00004      | 0.0004   | 0.0000    | 0.014       |
| **Total uncertainty**                           | **0.00341**                   | **0.00022**  | **0.0146**| **0.0140**| **0.187**   |
B_s lifetime result

\[ \Delta \Gamma_s = 0.048 \pm 0.024 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \text{ ps}^{-1}, \]

\[ c\tau_{B_s} = 0.04580 \pm 0.00059 \text{ (stat.)} \pm 0.00022 \text{ (syst.)} \text{ cm}, \]

\[ |A_0|^2 = 0.528 \pm 0.010 \text{ (stat.)} \pm 0.015 \text{ (syst.)}, \]

\[ |A_\perp|^2 = 0.251 \pm 0.013 \text{ (stat.)} \pm 0.014 \text{ (syst.)}, \]

\[ \delta_{||} = 2.79 \pm 0.14 \text{ (stat.)} \pm 0.19 \text{ (syst.)} \text{ rad}. \]
Summary

- CMS is a powerful detector for studying B physics because of its excellent tracking and lepton identification.

- New measurement of the $\Lambda_b$ lifetime:

  \[ 1.503 \pm 0.052 \text{ (stat.)} \pm 0.031 \text{ (syst.)} \text{ ps} \]

- New measurement of the $B_s$ lifetime difference:

  \[ \Delta \Gamma_s = 0.048 \pm 0.024 \text{ (stat.)} \pm 0.003 \text{ (syst.)} \text{ ps}^{-1} \]

- Stay tuned for more exciting B physics results!

All public results can be found at:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH
Backup
Kinematic observables

\[
\frac{d^4 \Gamma(B_s(t))}{d\Theta \, dt} = f(\Theta, t; \alpha) = \sum_{i=1}^{6} O_i(\alpha, t) \cdot g_i(\Theta)
\]

\begin{align*}
O_1 &= |A_0(t)|^2 = |A_0(0)|^2e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos \phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_2 &= |A_t(t)|^2 = |A_t(0)|^2e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos \phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_3 &= |A_\perp(t)|^2 = |A_\perp(0)|^2e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) + \cos \phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_4 &= \text{Im}(A_{t}^*(t)A_{\perp}(t)) = |A_t(0)||A_\perp(0)|e^{-\Gamma_s t}[-\cos(\delta_\perp - \delta_t) \sin \phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_5 &= \text{Re}(A_{0}^*(t)A_{t}(t)) = |A_0(0)||A_t(0)| \cos \delta_t e^{-\Gamma_s t}[\cosh(\Delta\Gamma_s t/2) - \cos \phi_s \sinh(\Delta\Gamma_s t/2)] \\
O_6 &= \text{Im}(A_{0}^*(t)A_{\perp}(t)) = |A_0(0)||A_\perp(0)|e^{-\Gamma_s t}[-\cos \delta_\perp \sin \phi_s \sinh(\Delta\Gamma_s t/2)],
\end{align*}

\begin{align*}
g_1 &= 2\cos^2(\psi_T)(1 - \sin^2(\theta_T) \cos^2(\varphi_T)), \\
g_2 &= \sin^2(\psi_T)(1 - \sin^2(\theta_T) \sin^2(\varphi_T)), \\
g_3 &= \sin^2(\psi_T) \sin^2(\theta_T), \\
g_4 &= -\sin^2(\psi_T) \sin^2(2\theta_T) \sin(\varphi_T), \\
g_5 &= \frac{1}{\sqrt{2}} \sin(2\psi_T) \sin^2(\theta_T) \sin(2\varphi_T), \\
g_6 &= \frac{1}{\sqrt{2}} \sin(2\psi_T) \sin(2\theta_T) \sin(\varphi_T).
\end{align*}
Fit Projection $B^0$

CMS preliminary
$\sqrt{s} = 7$ TeV  $L = 5$ fb$^{-1}$

- fit function
- signal
- prompt background
- non-prompt background

Events / (0.0059 GeV/c$^2$)

Pull

Pull

Proper decay time (ps)

Invisible mass $J/\psi K_s$(GeV/c$^2$)

Proper decay time (ps)

Events / (0.16 ps)

Ks