$B^+_c$ physics at LHCb

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Outline

- Introduction

- Selected recent $B_c^+$ results at LHCb
  
  ✓ Observation of $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$
  
  ✓ $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+\nu_\mu)$
  
  ✓ Lifetime measurement using $B_c^+ \rightarrow J/\psi \mu^+\nu_\mu X$
  
  ✓ Evidence of $B_c^+ \rightarrow J/\psi 3\pi^+2\pi^-$

- Summary
The only meson composed of different heavy flavor quarks: $c$ & $b$

Rich spectroscopy
- LHCb: $M(B_c^+(1S)) = 6276.3 \pm 1.4 \pm 0.4 \text{ MeV}/c^2$
- ATLAS: $M(B_c^+(2S)) = 6842 \pm 4 \pm 5 \text{ MeV}/c^2$

A wide range of decay modes
- Tevatron: $J/\psi\pi^+, J/\psi\mu^+\nu$\mu$
- LHCb: $J/\psi\pi^+\pi^-\pi^+, \psi(2S)\pi^+, J/\psi K^+, J/\psi D_s^{(*)+}, J/\psi K^+K^-\pi^+, B_S^0\pi^+, ...$

More studies on $B_c^+$ physics are needed
- Large uncertainty in $\tau(B_c^+)$
- Many other $B_c^+$ decays not observed, especially annihilation decays
- No absolute branching ratio measurement
First observation of $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$

LHCb-PAPER-2014-039
Baryonic $B_c^+$ decay: $B_c^+ \to J/\psi p\bar{p} \pi^+$

- Baryonic decay of $b$ hadron important
  - To understand baryon production mechanism
  - To search for new baryons and tetra-quarks
  - Special behavior observed in baryonic $B_{u,d}$ decays, not understood yet

- This analysis presents
  - First observation of $B_c^+ \to J/\psi p\bar{p} \pi^+$
  - Precise measurement of $B_c^+$ mass
Observation of $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$

- Pre-selection + multivariate selection based on boosted decision tree (BDT)
  - Proton identification optimised

First observation

$$N_{\text{sig}} = 23.9 \pm 5.3 \ (7.3 \sigma)$$

$$N_{\text{sig}} = 2835 \pm 58$$
Most efficiencies determined from simulation
Proton identification efficiency estimated from data sample

Branching fraction measured as

\[
\frac{\mathcal{B}(B_c^+ \to J/\psi p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = \frac{N(B_c^+ \to J/\psi p\bar{p}\pi^+)}{N(B_c^+ \to J/\psi \pi^+)} \times \frac{\epsilon(B_c^+ \to J/\psi \pi^+)}{\epsilon(B_c^+ \to J/\psi p\bar{p}\pi^+)}
\]

\[= 0.143^{+0.039}_{-0.034}\text{(stat)} \pm 0.013\text{(syst)}\]

Consistent with \(B^0\) baryonic decay

\[
\frac{\mathcal{B}(B_c^+ \to J/\psi p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} \approx \frac{\mathcal{B}(B^0 \to D^{*-} p\bar{p}\pi^+)}{\mathcal{B}(B^0 \to D^{*-} \pi^+)} = 0.17 \pm 0.02
\]
Mass of $B^+_c$ meson

- Low Q-value provides a precise measurement of $B^+_c$ mass

The fitted $M(B^+_c) = 6273.8 \pm 1.8$ MeV/$c^2$

FSR correction: $0.20 \pm 0.03$ MeV/$c^2$

$M(B^+_c) = 6274.0 \pm 1.8\text{(stat)} \pm 0.4\text{(syst)}$ MeV/$c^2$

Previous results

- LHCb $J/\psi\pi^+$
- LHCb $J/\psi D^+_s$
- LHCb $J/\psi p\bar{p}\pi^+$
- LHCb combined

- CDF $J/\psi\pi^+$

Dominant by Momentum scale

- $M(B^+_c) = 6276.3 \pm 1.4\text{(stat)} \pm 0.4\text{(syst)}$ MeV/$c^2$

- $M(B^+_c) = 6274.7 \pm 0.9\text{(stat)} \pm 0.8\text{(syst)}$ MeV/$c^2$

The most precise measurement

LHCb-PAPER-2014-039
The measurement of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$

arXiv:1407.2126
\[ \mathcal{B}(B_c^+ \to J/\psi \pi^+)/\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu) \]

- No experimental determination of the relative size of these decays

\[ R \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \]

- Testing theoretical predictions
  - Large spread among different calculations: 0.050-0.091
    - PRD49,3399, PRD61,034012, PRD68,094020, PRD73,054024, PRD89,017501...

- Providing comparison between \( B_c^+ \) cross sections measured at Tevatron (using \( B_c^+ \to J/\psi \mu^+ \nu_\mu \))

\[ \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = \left( 29.5 \pm 4.0 \text{(stat)}^{+10.7}_{-7.6} \text{(syst)} \pm 3.6(p_T \text{ spec}) \right) \%
\]

and at LHCb (using \( B_c^+ \to J/\psi \pi^+ \))

\[ \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi \pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)} = \left( 0.68 \pm 0.10 \text{(stat)} \pm 0.03 \text{(syst)} \pm 0.05(\tau_{B_c^+}) \right) \%
\]

See Iain’s talk
Main challenge: undetected neutrino

\[ m(J/\psi\mu^+) > 5.3 \text{ GeV}/c^2 \text{ required} \]

\[ \Rightarrow B_{u,d,s} \rightarrow J/\psi X \text{ suppressed} \]

Signal-to-background likelihood-ratio used with 4 variables

\[
\text{DLL} = -2 \sum_{i=1}^{4} \ln \left( \frac{P_{\text{sig}}(x_i)}{P_{\text{bkg}}(x_i)} \right)
\]

\( B_{c}^+ \rightarrow J/\psi \mu^+ \nu_{\mu} \)
Signal yields determined from fitting to invariant mass distributions

\[ B_c^+ \rightarrow J/\psi \pi^+ \]

\[ J/\psi \pi^+ \]

LHCb 1 fb\(^{-1}\)

\[ J/\psi K^+ \]

\[ N_{J/\psi \pi} = 839 \pm 40 \]

\[ B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu \]

\[ J/\psi \mu^+ \nu_\mu \]

LHCb 1 fb\(^{-1}\)

\[ B_{u,d,s} \rightarrow J/\psi X \text{ bkg} \]

Combinatorial bkg

\[ N_{J/\psi \mu} = 3537 \pm 125 \]

feeddown bkg

arXiv:1407.2126
Result of $\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$

- With efficiencies estimated from simulation

$$R(m(J/\psi\mu^+) > 5.3\text{GeV}/c^2)$$

$$\equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)} = \frac{N(B_c^+ \to J/\psi\pi^+)}{N(B_c^+ \to J/\psi\mu^+\nu_\mu)} \times \frac{\epsilon(B_c^+ \to J/\psi\mu^+\nu_\mu)}{\epsilon(B_c^+ \to J/\psi\pi^+)}$$

$$= 0.271 \pm 0.016(\text{stat}) \pm 0.016(\text{syst})$$

- Extrapolated to full mass range

$$R = f \ast R(m(J/\psi\mu^+) > 5.3\text{GeV}/c^2) = 0.0469 \pm 0.0028(\text{stat}) \pm 0.0046(\text{syst})$$

$R$ factor from theoretical prediction

Uncertainty from $f$ factor

Consistent with predictions of

- Bethe-Salpeter equation
  - PRD62,014019
- Light-front quark model
  - PRD89,017501
- Potential model
  - PRD68,094020
Measurement of $B^+_c$ lifetime with $B^+_c \rightarrow J/\psi \mu^+ \nu_\mu X$

EPJC74,2839
$B_c^+$ lifetime

- $\tau(B_c^+) \sim \tau(\text{Charm})$
  - Decay mechanism dominated by $c$ decay

- Large spread in $B_c^+$ lifetime prediction: 0.3 – 0.7 ps

- Large uncertainty in previous measurements:
  - D0 & CDF measured with $B_c^+ \rightarrow J/\psi \pi^+$ and $B_c^+ \rightarrow J/\psi l^+\nu$
  - PDG2012: $\tau(B_c^+) = 0.452 \pm 0.033$ ps
  - Dominates systematics in most of $B_c^+$ analyses

Precise measurement of $B_c^+$ lifetime required:
- Powerful test for $B_c^+$ dynamics
- Improving measurements of $B_c^+$ physics
\( \tau(B_c^+) \) measurement with \( B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X \)

- Compared to \( B_c^+ \) hadronic decay
  - 😊 Advantage
    - High statistics: \( \sim 20\times \) larger than \( B_c^+ \rightarrow J/\psi \pi^+ \)
    - 😞 But
      - Partial reconstruction
      - Model dependent
  - Clear 3\( \mu \) signature
  - Model dependent

- 2D fits to \((M_{J/\psi \mu}, t_{ps})\)
  - ✓ Pseudo decay time \( t_{ps} = M_{J/\psi \mu} \times (\vec{p} \cdot \vec{L})/|\vec{p}|^2 \)
  - ✓ Correction factor & resolution from simulation
  - ✓ Bkg shapes from simulation or data sample
  - ✓ Decay model: little effects observed

2D fits to \((M_{J/\psi \mu}, t_{ps})\):
- LHCb
  - Candidates per 0.2 ps
  - 2 fb\(^{-1}\)

- LHCb
  - Candidates per 50 MeV/c\(^2\)
  - 2 fb\(^{-1}\)
Result of $\tau(B_c^+)$

$\tau(B_c^+) = 509 \pm 8\text{(stat)} \pm 12\text{(syst)}$ fs

- Main systematic uncertainty:
  - BKG model ($\pm 10$ fs)
  - Signal model ($\pm 5$ fs)

- Most precise measurement of $\tau(B_c)$ to date

- Consistent with PDG value

- Higher precision can be achieved

Combining with independent measurement of $\tau(B_c^+)$ with $B_c^+ \rightarrow J/\psi \pi^+$

EPJC74, 2839
Evidence of $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$

JHEP1405,148
Evidence of $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$

- Powerful tests
  - Form factors of $B_c^+ \rightarrow J/\psi W^+$ transition
  - Spectral functions for virtual $W^+$ boson into light hadrons

- 1 fb$^{-1}$ (7 TeV) + 2 fb$^{-1}$ (8 TeV) data used

$$N_{\text{sig}} = 32 \pm 8 \ (4.5 \sigma)$$

$$\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)} = 1.74 \pm 0.44 \pm 0.24$$

Consistent with theoretical predictions (0.95 ~ 1.1)

In agreement with $B^0$ and $B^+$ meson decays:

$$\frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^+ 2\pi^-)}{\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+)} = 1.70 \pm 0.34$$

$$\frac{\mathcal{B}(B^+ \rightarrow \bar{D}^{*0} 3\pi^+ 2\pi^-)}{\mathcal{B}(B^+ \rightarrow \bar{D}^{*0} \pi^+)} = 1.10 \pm 0.24$$

In agreement with $B^0$ and $B^+$ meson decays:

PRD86,074024

JHEP1405,148

3 fb$^{-1}$
Summary

- LHCb provide good opportunities for $B_c^+$ physics
- Many $B_c^+$ new decays observed and properties measured

1. First observation of $B_c^+ \rightarrow J/\psi p\bar{p}\pi^+$
   - Firstly observed baryonic decay of $B_c^+$
   - The most precise $B_c^+$ mass measurement

2. First measurement of $\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)/\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)$
   - Consistent with theoretical predictions

3. Measurement of $\tau(B_c^+)$ with $B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu X$
   - Most precise measurement

4. Evidence of $B_c^+ \rightarrow J/\psi 3\pi^+ 2\pi^-$

More studies still ongoing
Thanks for your attentions
Backup
LHCb detector

- A single-arm forward spectrometer covering $2 < \eta < 5$
- Focusing on $b/c$ physics
  - Separating PV and SV of $B$ decays:
    - $B$ meson flying distance $\sim$ cm
    - VELO: $\sigma_{PV,x/y} \sim 10 \mu m$, $\sigma_{PV,x/y} \sim 60 \mu m$
  - Reconstructing $J/\psi \rightarrow \mu^+ \mu^-$ effectively:
    - Good muon identification: $\epsilon(\mu \rightarrow \mu) \sim 95 \%$, $\pi - \mu$ misID $\sim 5 \%$
    - Trigger system: 90 \% efficiency
Successful data taking since 2010

- 2012: 2 fb$^{-1}$ @ 8 TeV
- 2011: 1 fb$^{-1}$ @ 7 TeV
- 2010: 37 pb$^{-1}$ @ 7 TeV

Analyses mostly based on 2011, 2012 data
Experimental studies of $B_c^+$ physics

- $B_c^+$ production dominant by $gg \rightarrow B_c^+ + \bar{c} + b$
  - Production fraction $\sim 0.1\%$ of other B mesons
  - Few decays observed at Tevatron: $J/\psi\pi^+, J/\psi\mu^+\nu_\mu$

- LHCb: good opportunity for $B_c^+$ physics
  - Large production: $\sigma(B_c^+)_\text{LHC}/\sigma(B_c^+)_\text{Tevatron} \sim \mathcal{O}(10)$
  - More decays observed:
    $$J/\psi\pi^+\pi^-\pi^+, \psi(2S)\pi^+, J/\psi K^+, J/\psi D_s^{(*)+}, J/\psi K^+K^-\pi^+, B_S^0\pi^+ \ldots$$
  - $B_c^+$ properties measured more precisely:
    $$M(B_c^+) = 6276.28 \pm 1.44 \pm 0.36 \text{ MeV}/c^2$$

- More studies on $B_c^+$ physics are in need
  - Large uncertainty in $\tau(B_c^+)$
  - Many other $B_c^+$ decays not observed especially annihilation decay modes
  - No absolute branching ratio measured
Special behavior in $B^{0,\pm}$ baryonic decays

Baryon-antibaryon effective mass peaks at very low values
Similar results observed in $B^0 \to p\bar{\Lambda}\pi^-$, $B^+ \to p\bar{p}\pi^+$, $B^0 \to p\bar{p}K^0$, $B^+ \to p\bar{p}K^{*+}$

PRL88,181803

PRL90,201802, PRL92,131801
Optimisation of BDT and PID

Punzi function

\[ f_{\text{Punzi}}(t, d) = \frac{\epsilon_{\text{sig}}(t, d)}{a/2 + \sqrt{B(t, d)}} \]

- \( t, d \): BDT & PID selection
- \( \epsilon_{\text{sig}} \): efficiency of signals
- \( B(t, d) \): BKG events left with \( t \) & \( d \)
- \( a = 3 \): 3-sigma significance search

BDT_response > 0

PID1*PID2 > 0.42
Systematics

FSR correction: estimated from simulation

✓ $\delta M = \text{observed } Bc \text{ mass} - \text{input value}$
✓ $\delta M$ related to resolution
✓ $0.2 \pm 0.03 \text{ MeV}/c^2$
Fitted $B_c^+$ mass need to be calibrated:

- Scale on the track momentum
- The scale $\alpha$ makes $B^+ \rightarrow J/\psi(\mu^+\mu^-)K^+$ mass to PDG 2012
- Variation of scales studied with a variety of decays
  - $3 \times 10^{-4}$
  - Propagated to uncertainty of $B_c^+$ mass: $\pm 0.030$ MeV/c$^2$
Signals for $B_c^+ \to J/\psi \mu^+ \nu\mu$

Feeddown: $\psi(2S)\mu^+ \nu\mu$, $\chi_{cJ}\mu^+ \nu\mu$, $J/\psi \tau^+ \nu\tau$
Analysis strategy

2D data-model \( m(J/\psi \mu^+) \oplus t_{ps} \) to enhance sig/bkg separation

- \( B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu \) kinematics dependent on form factor
- Three different decay models used in simulation
- Only small differences observed
- Feed-down effects:
  - To be small after selection
  - Considered as a source of systematics

- Partial reconstruction (missing neutrino)
  - Cannot reconstruct \( B_c^+ \) proper decay time \( t \)
  - Using pseudo decay time \( t_{ps} \) instead:
    - \( t_{ps} \equiv \) decay time in \( J/\psi \mu^+ \) rest frame
  - Correction between \( t_{ps} \) and \( t \) (\( k=t_{ps}/t \)) obtained from simulation
2D fits to $m(J/\psi\mu)$ and $t_{ps}$

- Decay time signal model: determined from simulation study
  - $J/\psi$ + hadron misidentified as a $\mu$
  - Fake $J/\psi$ + real $\mu$
  - Combinatorial: $J/\psi$ + $\mu$ not coming from a $B_{c+}$
    - Prompt bkg: decays close to PV
    - Detached bkg from simulation of $H_b \rightarrow J/\psi X$, $H_b \equiv B_d$, $B_u$, $B_s$, $\Lambda_b$

All background sources modelled on data (except for detached combinatorial)