

B_c studies at LHCb

Jibo HE

(on behalf of the LAL-Tsinghua collaboration)

LAL, Orsay

5th FCPPL Workshop @ Orsay/Saclay, 22/03/2012

LAL-Tsinghua collaboration

- Collaboration between the LHCb groups of LAL (Orsay) and Tsinghua University (Beijing) started end of 2004, support from FCPPL in 2007
- Collaboration members (status now)
 - ▶ LAL
 - ★ Marie-Hélène SCHUNE
 - ★ Patrick ROBBE
 - ★ Jibo HE (Post-doc)
 - ▶ Tsinghua
 - ★ Yuanning GAO
 - ★ ZhenWei YANG
 - ★ Bo LIU (PhD student, to defend in June 2012), visited LAL in 2011, supported by CSC (China Scholarship Council)
- Former members
 - ▶ Wenbin QIAN, joint PhD student, defended in Sept 2010
- Supported / backed up by theorists from China and France

- Topics

- ▶ Early physics: J/ψ production
- ▶ B_c physics, main focus now

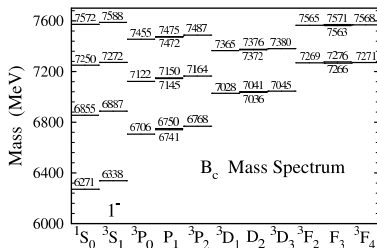
- Journal papers

- ▶ Measurement of the B^\pm production cross-section in pp collisions at $\sqrt{s} = 7$ TeV
[arXiv:1202.4812](#), to appear in JHEP
- ▶ Measurement of J/ψ production in pp collisions at $\sqrt{s} = 7$ TeV
[EPJC 71, 1645 \(2011\)](#)
- ▶ Experimental prospects of the B_c studies of the LHCb experiment
[CPL 27, 061302 \(2010\)](#)
- ▶ Nonleptonic charmless B_c decays and their search at LHCb with S. Descotes-Genon (LPT, Orsay) and E. Kou (LAL)
[PRD 80, 114031 \(2009\)](#)

- Conference talks in 2011 (on behalf of the LHCb collaboration)
 - ▶ B_c studies at LHCb
J. He on QWG 2011, Darmstadt, Germany
 - ▶ J/ψ production studies in LHCb
P. Robbe on Quarkonium Production: Probing QCD at the LHC, Vienna, Austria
 - ▶ Results on charmonium and charmonium-like production from the LHC
Y. Gao on HADRON 2011, Munich, Germany
 - ▶ Exotic spectroscopy and quarkonia at LHCb
B. Liu on HADRON 2011, Munich, Germany
 - ▶ J/ψ and B_c^\pm production at LHCb
J. He on BEAUTY 2011, Amsterdam, Netherlands

B_c spectrum

- B_c : Mesons formed by two different heavy flavor quarks, the \bar{b} quark and the c quark *
 - ▶ Unique in the Standard Model because the top quark is too heavy and decays before forming any bound states
- B_c spectrum
 - ▶ Estimated using potential models
- B_c^+ mass
 - ▶ Potential models: $6.2\text{-}6.4 \text{ GeV}/c^2$
[CERN-2005-005], and refs. therein
 - ▶ pQCD: $6326_{-9}^{+29} \text{ MeV}/c^2$
N. Brambilla & A. Vairo, [PRD 62, 094019 (2000)]
 - ▶ Lattice QCD: $6278(6)(4) \text{ MeV}/c^2$
TWQCD, [arXiv:0704.3495]
 - ▶ PDG'10: $6277 \pm 6 \text{ MeV}/c^2$



S.Godfrey, [PRD 70, 054017 (2004)]

*Charge conjugates implied in this presentation

B_c decays

- B_c mesons' decays

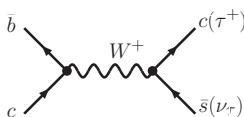
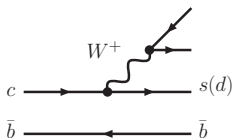
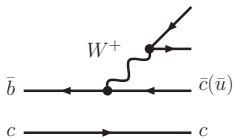
- ▶ Excited states (below BD threshold), decay through the Strong or EM interactions into B_c^+
- ▶ Ground state B_c^+ : decay only weakly

- B_c^+ decay modes

- ▶ $\bar{b} \rightarrow \bar{c} W^+$ ($\sim 20\%$), e.g., $J/\psi \pi^+$, $J/\psi \ell^+ \nu_\ell$
- ▶ $c \rightarrow s W^+$ ($\sim 70\%$), e.g., $B_S^0 \pi^+$, $B_S^0 \ell^+ \nu_\ell$
- ▶ $c \bar{b} \rightarrow W^+$ ($\sim 10\%$), e.g., $\bar{K}^{*0} K^+$, $\tau^+ \nu_\tau$

- B_c^+ lifetime predictions

- ▶ Inclusive rates or Σ (exclusive rates)
- ▶ $\tau(B_c^+)_{\text{SR}} = 0.48 \pm 0.05$ ps
V. V. Kiselev, et. al, [NPB 585, 353 (2000)]
- ▶ PDG'10: 0.45 ± 0.04 ps



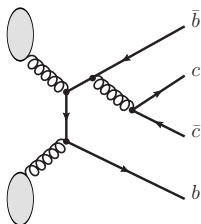
B_c production

- B_c production

- ▶ Difficult to generate at e^+e^- colliders
- ▶ At hadron colliders, B_c generated mainly through $gg \rightarrow B_c + b + \bar{c}$

- B_c^+ production rate

- ▶ Theoretical prediction C.-H.Chang, et al., [\[PRD 71, 074012 \(2005\)\]](#)



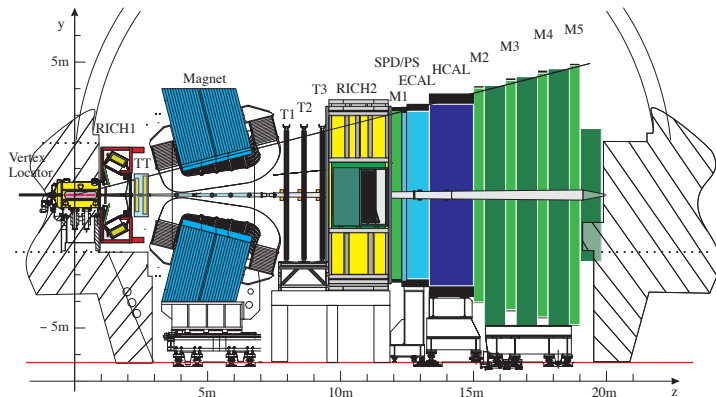
	$ (^1S_0)_1\rangle$	$ (^3S_1)_1\rangle$	$ (^1S_0)_{8g}\rangle$	$ (^3S_1)_{8g}\rangle$	$ (^1P_1)_1\rangle$	$ (^3P_0)_1\rangle$	$ (^3P_1)_1\rangle$	$ (^3P_2)_1\rangle$
LHC [†]	71.1	177.	(0.357, 3.21)	(1.58, 14.2)	9.12	3.29	7.38	20.4
TEVATRON	5.50	13.4	(0.0284, 0.256)	(0.129, 1.16)	0.655	0.256	0.560	1.35

- ★ $\sigma(^3S_1)/\sigma(^1S_0) \sim 2.5$
- ★ Color octets and 1st P -wave contributions are small
- ★ $\sigma(B_c^+)_{\text{LHC}}/\sigma(B_c^+)_{\text{TeVatron}} \sim O(10)$
- ▶ $\sigma(2S)/\sigma(1S)$ would be $|R_{2S}(0)/R_{1S}(0)|^2 \approx 0.6$
- ▶ Considering the contributions of the decays of these states, $\sigma(B_c^+) \sim 0.9 \mu\text{b}$ for $\sqrt{s} = 14 \text{ TeV}$; or $\sim 0.4 \mu\text{b}$ for $\sqrt{s} = 7 \text{ TeV}$

[†] $\sqrt{s} = 14 \text{ TeV}$

The LHCb experiment

- Forward spectrometer ($2 < \eta < 5$) to study heavy-quark physics



Vertex Locator

Tracking (TT, T1-T3)

RICHs

Muon system (M1-M5)

ECAL

HCAL

$$\sigma_{PV,x/y} \sim 10 \mu\text{m}, \quad \sigma_{PV,z} \sim 60 \mu\text{m}$$

$$\Delta p/p: 0.4\% - 0.6\%$$

$$\varepsilon(K \rightarrow K) \sim 95\%, \quad \text{mis-ID rate } (\pi \rightarrow K) \sim 7\%$$

$$\varepsilon(\mu \rightarrow \mu) \sim 97\%, \quad \text{mis-ID rate } (h \rightarrow \mu) \sim 2\%$$

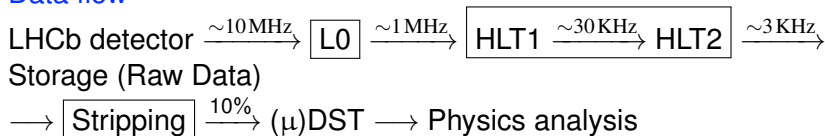
$$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\% \quad (E \text{ in GeV})$$

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

The LHCb data flow

- $L \sim 3 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$, cross-sections @ $\sqrt{s} = 7 \text{ TeV}$
 - $\sigma_{pp}^{\text{inel}} \sim 60 \text{ mb}$
 - $\sigma(pp \rightarrow c\bar{c}X) \sim 6 \text{ mb}$
 - $\sigma(pp \rightarrow b\bar{b}X) \sim 0.3 \text{ mb}$, c.f. $\sigma(e^+e^- \rightarrow b\bar{b}) \sim 1 \text{ nb}$ @ $\Upsilon(4S)$
 - $\sigma(pp \rightarrow J/\psi X) \sim 0.06 \text{ mb}$

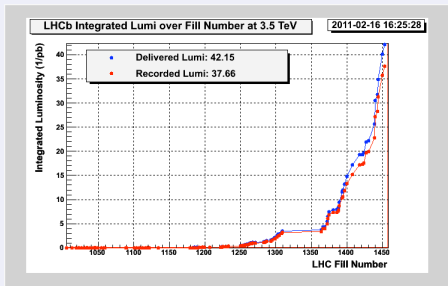
- **Data flow**



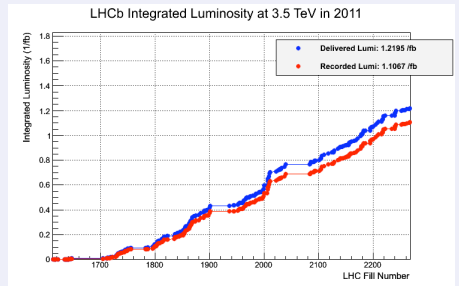
- **Hardware Trigger**, Level-0
 - ▶ Based on information from the calorimeter and muon systems
- **Software Trigger**, High Level Trigger (HLT)
 - ▶ Full event reconstruction
 - ▶ Runs $\sim 26 \text{ K}$ processes, $\sim 20 \text{ ms/event}$ per process
- **Stripping**, also referred as HLT3
 - ▶ Pre-selections of all decay channels under study

The LHCb data-taking

2010 (37 pb^{-1} recorded)



2011 (1.1 fb^{-1} recorded)



- 2010 data

- ▶ B_c^+ mass and production
- ▶ B^+ production

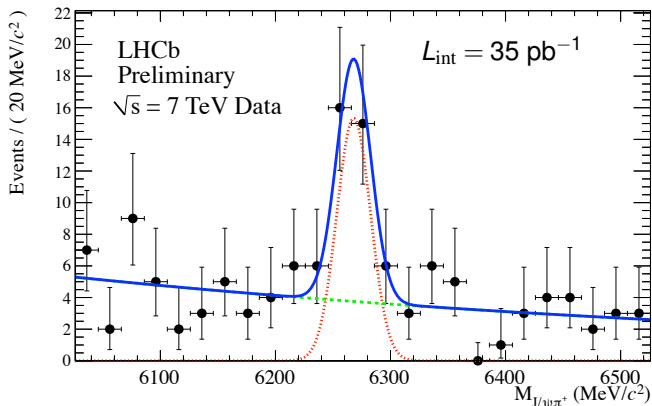
- 2011 data (ongoing analysis)

- ▶ B_c^+ mass, production and lifetime
- ▶ $B_c^+ \rightarrow J/\psi K^+$, $B_c^+ \rightarrow \psi(2S)\pi^+$
- ▶ $B_c^+ \rightarrow B_s^0 \pi^+$
- ▶ b -hadrons production

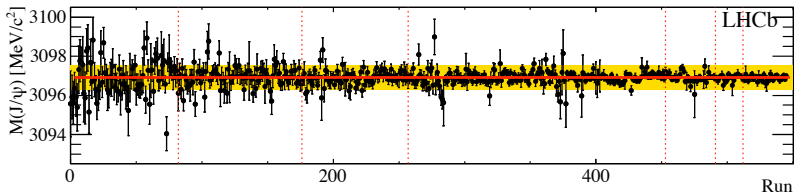
B_c^+ mass measurement

CERN-LHCb-CONF-2011-027

- Based on $\sim 35 \text{ pb}^{-1}$ of data collected in 2010
- Cut based selection. Signal yield, 28 ± 7
- Fit Model
 - ▶ Signal: Gaussian
 - ▶ Background: Exponential



- Momentum scale calibrated using large sample of $J/\psi(\mu^+\mu^-)$. After calibration, J/ψ mass stable, better than 0.02%
- Checked with Υ , D^0 , K_S^0 , and $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$



B_c^+ mass measurement, systematics

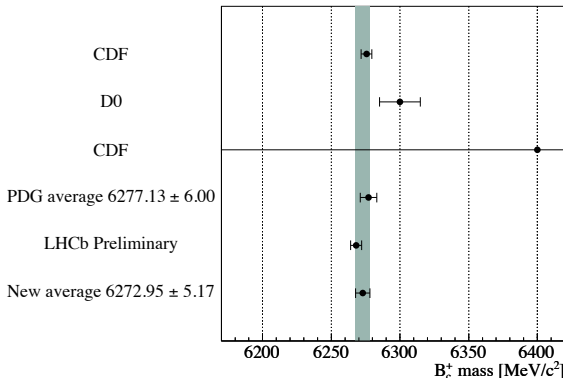
Source of uncertainty	Value [MeV/ c^2]
Mass fitting:	
Background model	0.32
Signal model	0.07
Momentum scale calibration:	
Average momentum scale	0.23
η dependence of momentum scale	0.44
Detector description:	
Energy loss correction	0.11
Detector alignment:	
Vertex detector (track slopes)	0.06
Quadratic sum	0.61

B_c^+ mass measurement, result

- Preliminary result

$$M(B_c^+) = 6268.0 \pm 4.0(\text{stat}) \pm 0.6(\text{syst}) \text{ MeV}/c^2$$

- Comparison with PDG



- Uncertainty dominated by statistics, updated with 2011 data, under internal review

- Based on $\sim 33 \text{ pb}^{-1}$ data collected in 2010
- Use fully reconstructed $B_c^+ \rightarrow J/\psi(\mu^+\mu^-)\pi^+$, relatively clean.
Large control sample $B^+ \rightarrow J/\psi K^+$ available.
- Measure

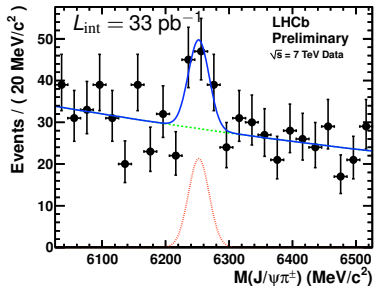
$$\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi\pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = \epsilon_{\text{rel}} \times \frac{N(B_c^+)}{N(B^+)}$$

for $p_T(B) > 4 \text{ GeV}/c$ and $\eta \in (2.5, 4.5)$

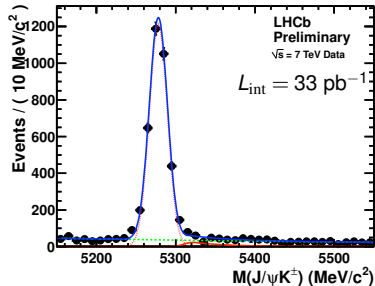
Extraction of $N(B_c^+)$ and $N(B^+)$

- Lifetime unbiased event selection (& trigger), as similar as possible between $B_c^+ \rightarrow J/\psi \pi^+$ and $B^+ \rightarrow J/\psi K^+$
- Cabibbo suppressed background $B^+ \rightarrow J/\psi \pi^+$ considered for $B^+ \rightarrow J/\psi K^+$
- 43 ± 13 $B_c^+ \rightarrow J/\psi(\mu^+ \mu^-)\pi^+$ signal

$B_c^+ \rightarrow J/\psi \pi^+$
 $N_{\text{sig}} = 43 \pm 13$



$B^+ \rightarrow J/\psi K^+$
 $N_{\text{sig}} = 3476 \pm 62$



Ratio of production cross section

- Total efficiencies computed from MC, binned in (p_T, η) to reduce the dependence on theoretical model
- Systematics dominated by B_c^+ lifetime (0.453 ± 0.041) ps, will be reduced after a better lifetime measurement
- Preliminary result

$$\frac{\sigma(B_c^+) \times \mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}{\sigma(B^+) \times \mathcal{B}(B^+ \rightarrow J/\psi K^+)} = (2.2 \pm 0.8|_{\text{stat.}} \pm 0.2|_{\text{sys.}})\%$$

for $p_T(B) > 4 \text{ GeV}/c$ and $\eta \in (2.5, 4.5)$

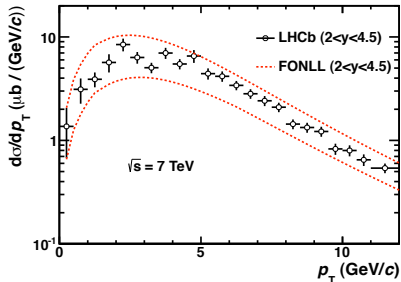
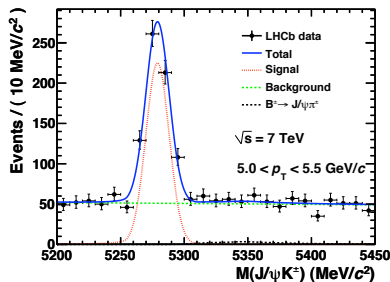
- Updated with 2011 data, under internal review

Measurement of B^+ production cross-section

arXiv:1202.4812, to appear in JHEP

- Powerful test of pQCD
- 35 pb^{-1} (2010), both $d\sigma/dp_T$ and total cross-section measured
 $\sigma(pp \rightarrow B^\pm X, 0 < p_T < 40 \text{ GeV}/c, 2.0 < y < 4.5) = 41.4 \pm 1.5|_{\text{stat.}} \pm 3.1|_{\text{syst.}} \mu\text{b}$
- Good agreement with FONLL prediction

M. Cacciari et al., JHEP. 9805 (1998) 007; JHEP. 0103 (2001) 006

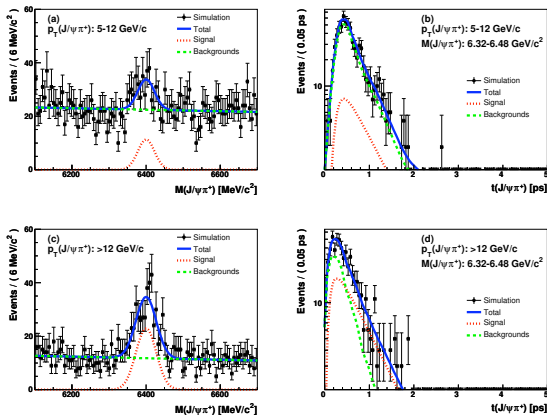


- Extended to $b \rightarrow J/\psi X$ with 2011 data
 - ▶ $B^0 \rightarrow J/\psi \{K^{*0}, K_S^0\}$, $B_s^0 \rightarrow J/\psi \phi$, and $\Lambda_b^0 \rightarrow J/\psi \Lambda$
 - ▶ Extracting b hadronization fractions

Prospects Lifetime measurement with $B_C^+ \rightarrow J/\psi \pi^+$

CERN-LHCb-2008-077

- Based on MC studies, measured with 1 fb^{-1} of data, under internal review (not shown today)
- Acceptance extracted from MC, two $p_T(B_C^+)$ bins (5-12, $> 12 \text{ GeV}/c$) to reduce dependence on $p_T(B_C^+)$ distribution
- Uncertainty below **30 fs** achievable(ed) with 1 fb^{-1} of data



Prospects $B_c^+ \rightarrow J/\psi \mu^+ X$

- $B_c^+ \rightarrow J/\psi(\mu^+ \mu^-) \mu^+ \nu_\mu$, compared to $B_c^+ \rightarrow J/\psi \pi^+$,
 - ▶ **Pro**
 - ★ $O(10)$ larger branching ratio, $\sim 1.9\%$
 - ★ 3 μ in the final states, easier (relatively) to reduce background. Lifetime unbiased selection possible
 - ▶ **Contra**
 - ★ Missing energy caused by neutrino, partially reconstructed. Not easy to use MC-free method to estimate background
- ~ 5 K signal events can be selected from 1 fb^{-1} @ $\sqrt{s} = 7 \text{ TeV}$
- Extensive study of estimating background using data-driven methods
 - ▶ Studied mis-ID rates of $\{\pi, K, p\} \rightarrow \mu$ using $D^{*+} \rightarrow D^0(K^- \pi^+) \pi_S^+$, $\Lambda \rightarrow p \pi^-$, and $K_S^0 \rightarrow \pi^+ \pi^-$
- Developed dedicated **Hlt2 trigger line** to keep enough mass sidebands
- Analysis ongoing to measure B_c^+ lifetime, and $\frac{\mathcal{B}(B_c^+ \rightarrow J/\psi \mu^+ \nu_\mu)}{\mathcal{B}(B_c^+ \rightarrow J/\psi \pi^+)}$

- $B_c^+ \rightarrow J/\psi K^+, B_c^+ \rightarrow \psi(2S)\pi^+$
 - ▶ Measurements with 2011 data ongoing
- $B_c^+ \rightarrow B_s^0 \pi^+$
 - ▶ Self-tagged channel, $\mathcal{B}(B_c^+ \rightarrow B_s^0 \pi^+)$ up to 16%
 - ▶ With $B_s^0 \rightarrow J/\psi \phi$ and $B_s^0 \rightarrow D_s^- \pi^+$
 - ▶ Search with 2011 data ongoing
- Annihilation
 - ▶ Possible channel, e.g., $B_c^+ \rightarrow \bar{K}^{*0} K^+$, with branching ratio of $O(10^{-6})$, c.f., S. Descotes-Genon, et al., [\[PRD 80, 114031 \(2009\)\]](#)
- Excited states
 - ▶ $B_c^{*+} \rightarrow B_c^+ \gamma$ is difficult, $\Delta M = M(B_c^{*+}) - M(B_c^+)$ only 60-70 $\text{MeV}c^2$, very soft γ , difficult for LHCb
 - ▶ $B_c(2^1 S_0) \rightarrow B_c^+ \pi^+ \pi^-$, and $B_c(2^3 S_1) \rightarrow B_c^{*+} \pi^+ \pi^- \rightarrow (B_c^+ \gamma) \pi^+ \pi^-$, possible to see them with 2011/2012 data
 - ▶ P -wave states, low cross-section, small mass differences among four states

- Primary goal, study B_c mesons systematically
 - ▶ Measure B_c^+ mass, lifetime, production rate as precisely as possible
 - ▶ Search for new decay modes of B_c^+ , and measure their branching ratios
 - ▶ Search for excited states
- New members
 - ▶ Yiming LI (Post-doc of Tsinghua)
 - ▶ Xuhao YUAN (Post-doc of Tsinghua)
- Moderate amount of money for travelings and short visits
- Approval of this project will **strengthen our leading role** in **experimental studies of B_c physics**

Summary

- Measured B_c^+ mass and cross section using $B_c^+ \rightarrow J/\psi \pi^+$ with 2010 data collected by LHCb
- Measured B^+ cross-section using $B^+ \rightarrow J/\psi K^+$ with 2010 data, to be published
- Prospects with 2011 data ($\sim 1 \text{ fb}^{-1}$)
 - ▶ $\sim 600 B_c^+ \rightarrow J/\psi \pi^+$ signals, B_c^+ mass, production rate measurements updated, lifetime measured, under internal review
 - ▶ Yield of $B_c^+ \rightarrow J/\psi \mu^+ X$ one order of magnitude higher, lifetime measurement ongoing
 - ▶ Search for $B_c^+ \rightarrow J/\psi K^+$, $B_c^+ \rightarrow \psi(2S)\pi^+$, and $B_c^+ \rightarrow B_s^0 \pi^+$ ongoing
 - ▶ b hadrons cross-section measurements nearly completed
- Supports from FCPPL very helpful and highly acknowledged!