B_c physics at LHCb

Yiming Li 李一鸣 (LAL)
On behalf of the LAL-Tsinghua LHCb group

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LAL-Tsinghua collaboration

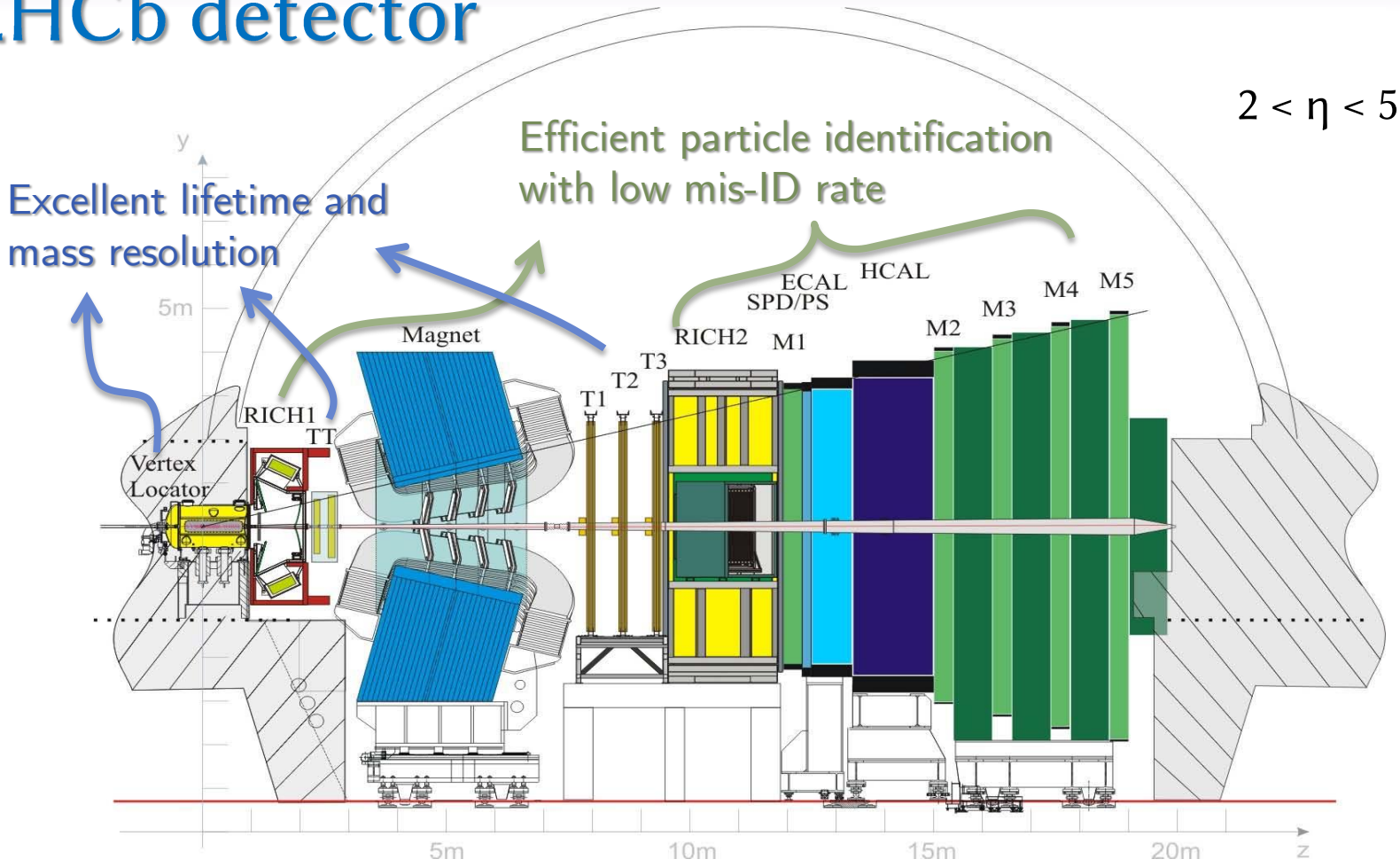
- Started in 2006
- Current members:
  - Tsinghua: Zhenwei Yang, Yuanning Gao, Liupan An
  - LAL: Patrick Robbe, Marie-Hélène Schune, Sergey Barsuk, Yiming Li
- Main research activities in 2015:
  - B_c physics at LHCb
    - in collaboration with Bo Liu, Giulia Manca (Cagliari/LAL) Jibo He (UCAS)
  - Run II commissioning
- In LHCb b-hadrons and quarkonia Working Group:
  - Zhenwei Yang: WG convenor
  - Yiming Li: b-hadrons and Bc subWG convenor
  - Liupan An: Simulation and stripping liaison of the WG

LAL-Tsinghua collaboration

- Long term exchanges
  - Jibo He
    - Tsinghua PhD → LAL postdoc → CERN fellow → UCAS researcher
  - Wenbin Qian
    - Embassy co-tutelle PhD → LAPP Annecy postdoc → Oxford postdoc
  - Bo Liu
    - Tsinghua PhD (CSC student 1 yr @LAL) → Cagliari postdoc
  - Yiming Li
    - Tsinghua postdoc → LAL postdoc

LHCb detector

$2 < \eta < 5$



JINST 3 (2008) S08005

$\mathcal{L}_{\text{int}}$ (*pp* collision) :

Run I : 1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV

Run II: 320 pb^{-1}@ 13 TeV

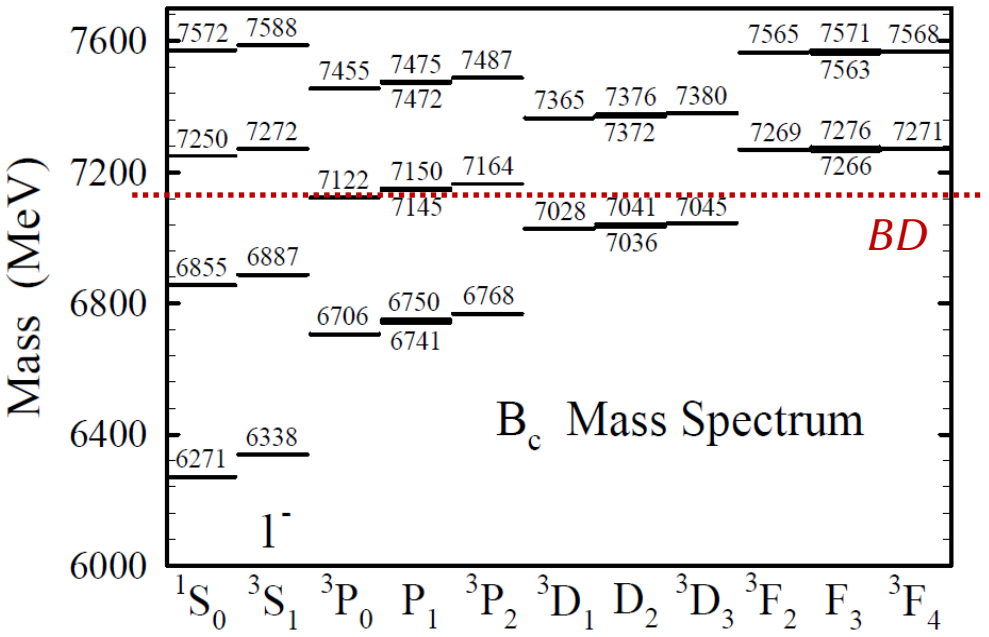
B_c mesons

- B_c is the only meson (family) in SM formed by two different heavy flavour quarks
- Similar to charmonia and bottomonia, a rich spectrum expected

- Below BD threshold all excited states decay to the ground state
- The ground state decays only weakly

- B_c has a much shorter lifetime than other B mesons

Godfrey, PRD70 (2004) 054017



LHCb public results on B_c

Production		New decay and BF ($B_c^+ \to$ …)	
$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+\to J/\psi K^+)}$	PRL 109 (2012) 232001	$J/\psi\pi^+\pi^-\pi^+$	PRL 108 (2012) 251802
$\frac{\sigma(B_c^+)}{\sigma(B_s^0)}\mathcal{B}(B_c^+ \to B_s^0\pi^+)$	PRL 111 (2013) 181801	$\psi(2S)\pi^+$	PRD 87 (2013) 071103 (R)
$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+\to J/\psi K^+)}$ vs. $dp_{\mathrm{T}}dy$	PRL 114 (2015) 132001		PRD 92 (2015) 072007
Mass		$J/\psi K^+$	JHEP 09 (2013) 075
$M(B_c^+ \to J/\psi\pi^+)$	PRL 109 (2012) 232001	$J/\psi D_s^{(*)+}$	PRD 87 (2013) 112012
$M(B_c^+ \to J/\psi D_s^+)$	PRD 87 (2013) 112012	$J/\psi K^+K^-\pi^+$	JHEP 1311 (2013) 094
$M(B_c^+ \to J/\psi p\bar{p}\pi^+)$	PRL 113 (2014) 152003	$J/\psi 3\pi^+2\pi^-$	JHEP 1405 (2014) 148
Lifetime		$J/\psi p\bar{p}\pi^+$	PRL 113 (2014) 152003
$\tau(B_c^+ \to J/\psi\mu\nu)$	EPJC 74 (2014) 2839	$\mathcal{B}(J/\psi\pi^+)/\mathcal{B}(J/\psi\mu\nu)$	PRD 90 (2014) 032009
$\tau(B_c^+ \to J/\psi\pi^+)$	PLB 742 (2015) 39	$B_s^0\pi^+$	PRL 111 (2013) 181801

LAL/Tsinghua's role

Production

$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+\to J/\psi K^+)}$	PRL 109 (2012) 232001
$\frac{\sigma(B_c^+)}{\sigma(B_s^0)}\mathcal{B}(B_c^+\to B_s^0\pi^+)$	PRL 111 (2013) 181801
$\frac{\sigma(B_c^+)\mathcal{B}(B_c^+\to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+\to J/\psi K^+)}$ vs. $dp_T dy$	PRL 114 (2015) 132001

Mass

$M(B_c^+\to J/\psi\pi^+)$	PRL 109 (2012) 232001
$M(B_c^+\to J/\psi D_s^+)$	PRD 87 (2013) 112012
$M(B_c^+\to J/\psi p\bar{p}\pi^+)$	PRL 113 (2014) 152003

Lifetime

$\tau(B_c^+\to J/\psi\mu\nu)$	EPJC 74 (2014) 2839
$\tau(B_c^+\to J/\psi\pi^+)$	PLB 742 (2015) 39

New decay and BF ($B_c^+\to$ ...)

$J/\psi\pi^+\pi^-\pi^+$	PRL 108 (2012) 251802
$\psi(2S)\pi^+$	PRD 87 (2013) 071103 (R)
	PRD 92 (2015) 072007
$J/\psi K^+$	JHEP 09 (2013) 075
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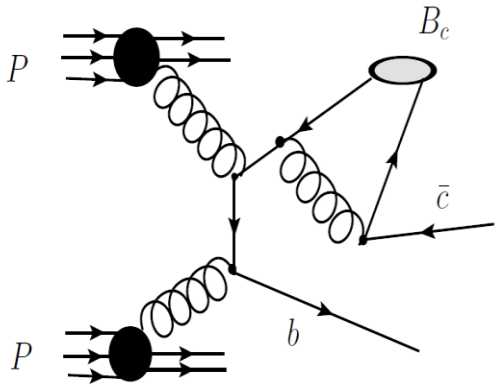
$J/\psi p\bar{p}\pi^+$	PRL 113 (2014) 152003
$\mathcal{B}(J/\psi\pi^+)/\mathcal{B}(J/\psi\mu\nu)$	PRD 90 (2014) 032009
$B_s^0\pi^+$	PRL 111 (2013) 181801

- Involved in many of these
- A few recent ones including:
  - Double differential production
  - First baryonic decay
  - Decay BF of $\psi(2S)\pi^+$

B_c^+ Production

- B_c is produced mainly through gluon-gluon fusion at hadron colliders.
  - Only accessible at high energy hadron colliders with high luminosity
- Production cross-section grows fast wrt $\sqrt{s}$
  - $\sigma_{\mathrm{LHC}}/\sigma_{\mathrm{Tevatron}} \sim \mathcal{O}(10)$
  - $\sigma(B_c^+) \sim 0.47\ \mu\mathrm{b}\ @\ \sqrt{s} = 8\ \mathrm{TeV}$
    $\sim 0.9\ \mu\mathrm{b}\ @\ \sqrt{s} = 14\ \mathrm{TeV}$;
- A considerable fraction of B_c^+ from higher states
  - $\sim 1/3$ from $B_c(2S)$, $\sim 10\%$ from $B_c(1P)$
- Predictions based on NRQCD factorization using fixed-order approach
  - BCVEGPY generator used in LHC simulations



C-H Chang et al,
Comput.Phys.Commun. 174 (2006) 241

Double differential production

PRL 114, 132001 (2015)

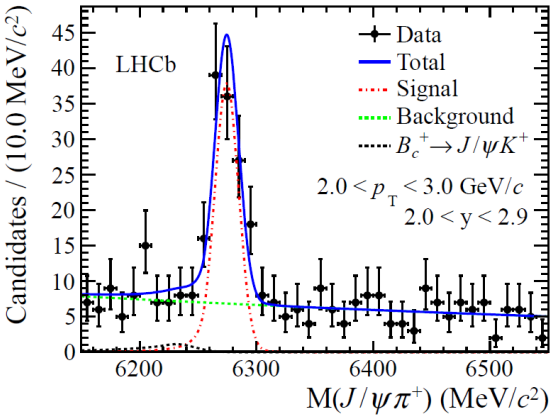
- Cross-section measured in $B_c^+ \to J/\psi\pi^+$ decay, relative to $B^+(\to J/\psi K^+)$
  - 2 fb^{-1}@ 8 TeV, $0 < p_T < 20$ GeV, $2 < y < 4.5$
  - $R = \mathbf{(0.683 \pm 0.018 \pm 0.009)\%}$

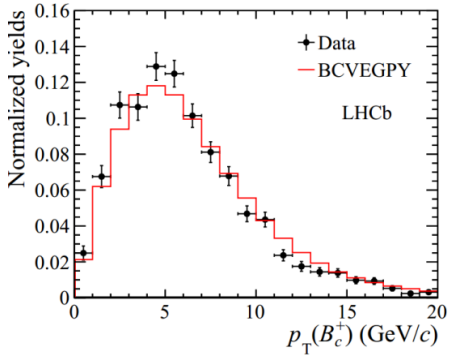
$$R = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

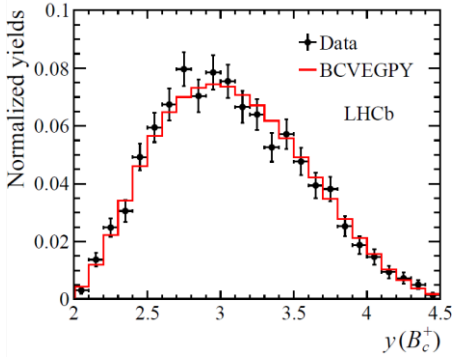
  - Consistent with 7 TeV result

    $(0.68 \pm 0.10 \pm 0.03 \pm 0.05\ (\tau_{B_c}))\%$, $p_T > 4$ GeV, $2.5 < \eta < 4.5$ PRL 109 (2012) 232001
  - Lower than CMS as expected, ∵ B_c^+ p_T softer than B^+

    $(0.48 \pm 0.05 \pm 0.03 \pm 0.05(\tau_{B_c}))\%$, $p_T > 15$ GeV, $|y| < 1.6$ JHEP 01 (2015) 063
- The sufficient statistics allow double differential ratio measurement



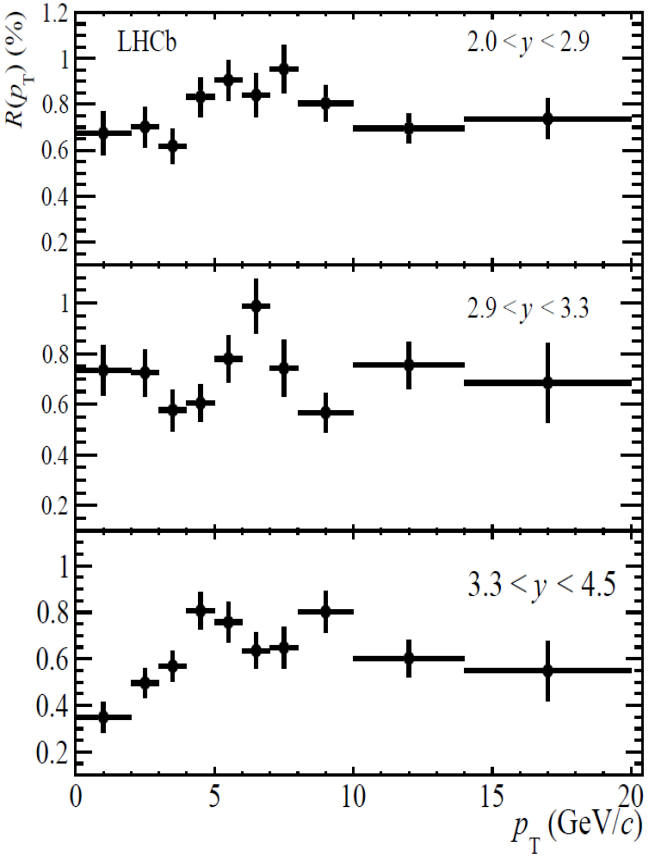




BcVegPy well describes the p_T , y spectrum

Double differential production

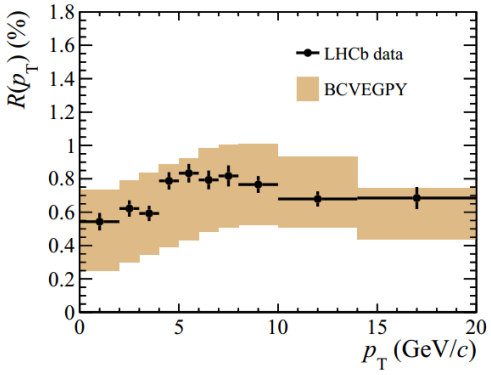
PRL 114, 132001 (2015)

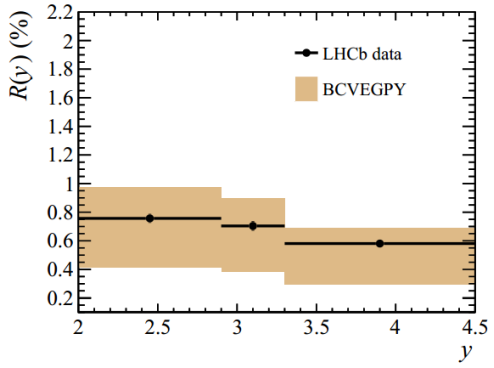


in collaboration with Bo Liu, Giulia Manca (Cagliari/LAL)

$$R(p_{\mathrm{T}}, y) = \frac{\sigma(B_c^+)\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\sigma(B^+)\mathcal{B}(B^+ \to J/\psi K^+)}$$

- R as function of p_{T}, y agrees with theory (FONLL for B, BcVegPy for B_c)





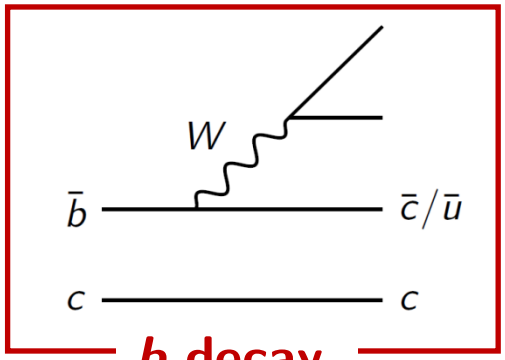
Normalization:

- $\sigma(B_c^+) = 0.47\ \mu$b, theoretical prediction by BcVegPy
- $\mathcal{B}(B_c^+ \to J/\psi\pi^+) = 0.33\%$ [C.-F. Qiao *et al.*, PRD 89 (2014) 034008]
- $\sigma(B^+,\ p_{\mathrm{T}}(B) < 40\ \mathrm{GeV}/c,\ 2.0 < y < 4.5) = 38.9\ \mu$b at $\sqrt{s} = 7$ TeV, measured by LHCb [JHEP 08 (2013) 117], scaled up by 1.2 for 8 TeV
- $\mathcal{B}(B^+ \to J/\psi K^+) = (0.1016 \pm 0.0033)\%$, PDG'12

B_c^+ decays

- With an additional c quark, B_c^+ has a larger variety of decay modes & shorter lifetime than other B mesons

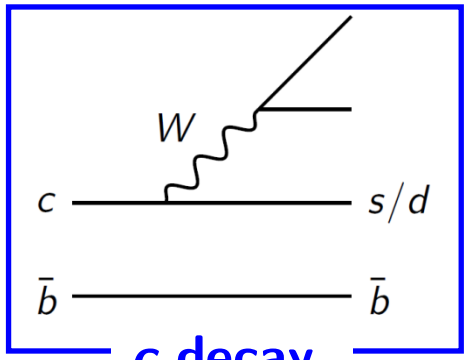
PDG 2015:
$\tau = 0.507 \pm 0.009$ ps



b decay

~ 20%

- with $c\bar{c}$ easier to detect esp. $\rightarrow \mu^+\mu^-$
- Most observed channels in this category

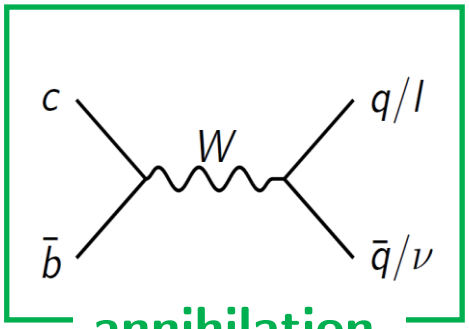


c decay

~ 70%

- $B_c^+ \rightarrow B_s^0 \pi^+$ observed

LHCb, PRL 111, 181801 (2013)



annihilation

~ 10%

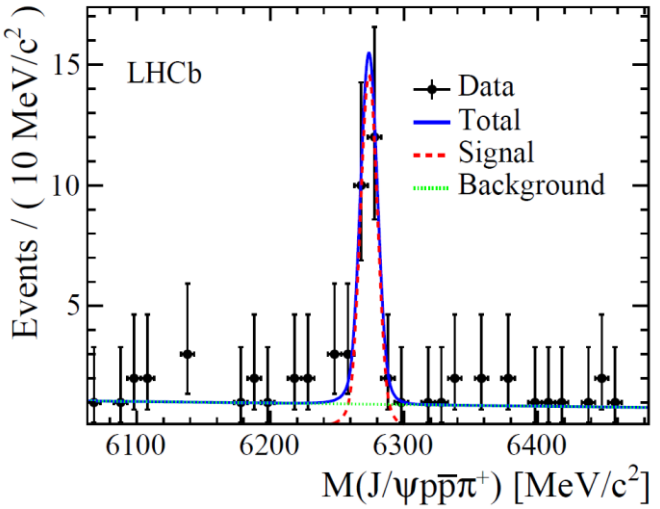
- Not observed yet. K^*K, ϕK...

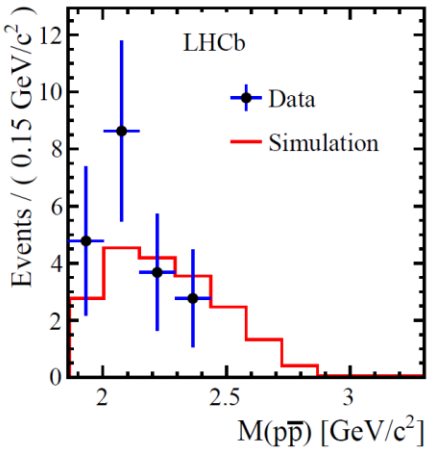
First baryonic decay

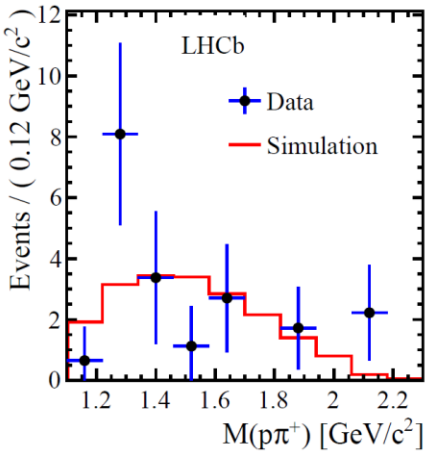
PRL 113, 152003 (2014)

- $B_c^+ \to J/\psi p\bar{p}\pi^+$
- Search using 3 fb^{-1} full Run I data
  - N = 23.9 ± 5.3 (7.3 σ)

$$\frac{\mathcal{B}(B_c^+ \to J/\psi p\bar{p}\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = 0.143^{+0.039}_{-0.034} \pm 0.013$$







- $M(p\bar{p}), M(p\pi^+)$ consistent with phase space decay within statistical uncertainties

Mass measurement

PRL 113, 152003 (2014)

- PDG 2012: 6277 ± **6** MeV
- LHCb measured the mass in several final states:
  - $B_c^+ \to J/\psi\pi^+$: 6273.7 ± **1.3** ± **1.6** MeV (0.37 fb^{-1}) *PRL 109 (2012) 232001*
  - $B_c^+ \to J/\psi D_s^+$: 6276.28 ± **1.44** ± **0.36** MeV (3 fb^{-1}) *PRD 87 (2013) 112012*
- Though statistically limited, $B_c^+ \to J/\psi p\bar{p}\pi^+$ has very small Q-value

$$M = \mathbf{6274.0 \pm 1.8 \pm 0.4\ MeV}$$

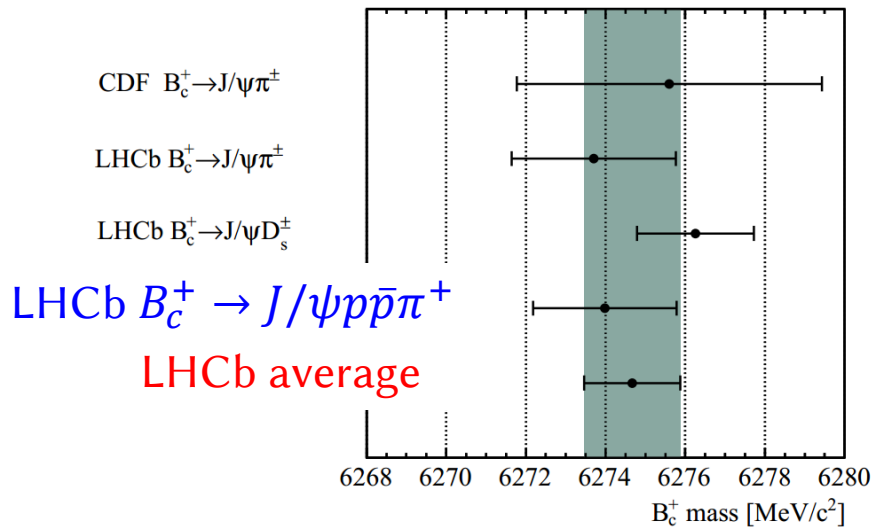
- LHCb average:

  6274.7 ± 1.2 MeV

  - Consistent with lattice QCD

  prediction : 6278(4)(8) MeV

  HPQCD, PRD 86 (2012) 094510



$B_c^+ \to \psi(2S)\pi^+$ relative BF

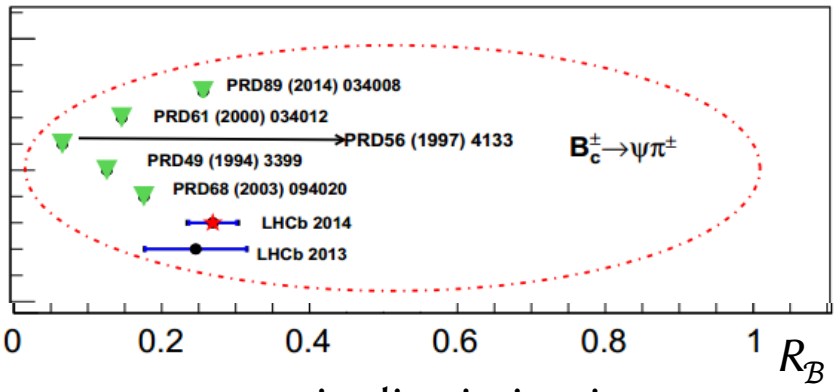
Phys. Rev. D 92 (2015) 072007

- $B_c^+ \to \psi(2S)\pi^+$ first observed with 1 fb^{-1} LHCb data *PRD 87 (2013) 071103(R)*
- Recently updated
  - With full Run I data
  - Improved BDT selection

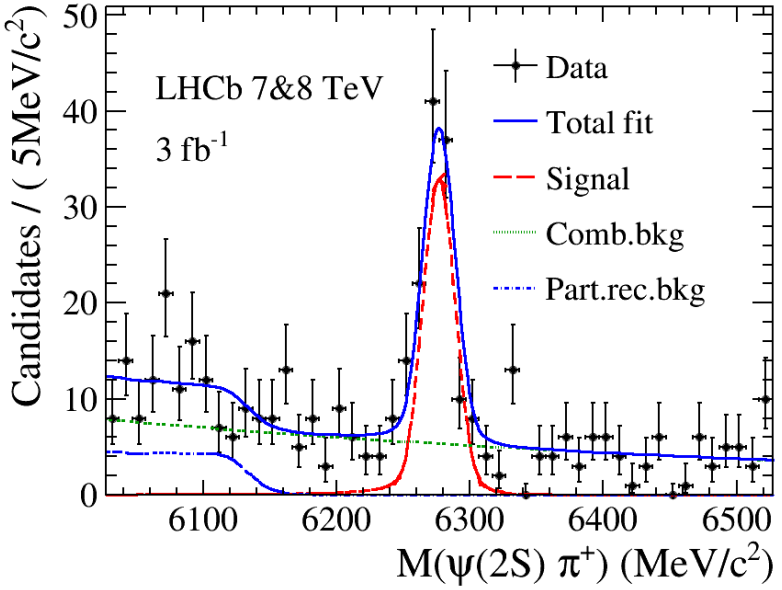
$$R_{\mathcal{B}} = \frac{\mathcal{B}(B_c^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}$$

- $R_{\mathcal{B}} = 0.268 \pm 0.032\ (\text{stat}) \pm 0.007\ (\text{syst}) \pm 0.006\ (\text{BF})$
  - Consistent with 7 TeV result

$0.250 \pm \mathbf{0.068} \pm 0.014 \pm 0.006$

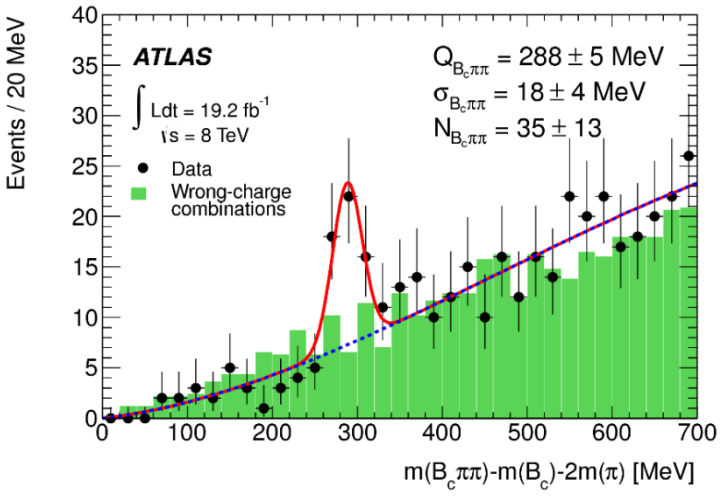


★ start to gain discriminating power between models



Some ongoing work

- Search for excited state
  - ATLAS observe peaking structure in $B_c\pi^+\pi^-$ invariant mass, consistent with $B_c(2S)$ – likely mixture of 2^1S_0 and 2^3S_1
  - $M = \mathbf{6842 \pm 4 \pm 5\ MeV}$
  - Search for similar state @ LHCb



- Search for new decays
  - Triply charmed decay $B_c^+ \to J/\psi D^{(*)} K^{(*)}$
  - Potentials in D_{sJ} study in DK system
  - Very small Q-value, good for mass measurement

Summary and perspectives

- LAL-Tsinghua collaboration keeps active in B_c studies at LHCb
- Run II has started with a smooth commissioning year of 2015
  - Increase in $\sqrt{s}$ could be more surprises than increase in σ
  - Many improvements, e.g. more effective trigger : 5 (Run I) → 12.5kHz (Run II) to storage
- LHCb upgrade planned during LS2 will open more opportunities:
  - Increased luminosity
  - Higher efficiency for hadronic final states by >2
  - Important for B_c hadronic channels, starting working on it