B_c^+ physics at LHCb

Xuhao Yuan @ Tsinghua University
on behalf of the LHCb collaboration

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Outline

- Introduction
- Selected <u>recent</u> B_c^+ results at LHCb
  - ✓ Observation of $B_c^+ \to J/\psi p\bar{p}\pi^+$ LHCb-PAPER-2014-039 New
  - ✓ $\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ arXiv:1407.2126 New
  - ✓ Lifetime measurement using $B_c^+ \to J/\psi\mu^+\nu_\mu X$ EPJC74,2839
  - ✓ Evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ JHEP1405,148
- Summary

B_c^+ meson

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

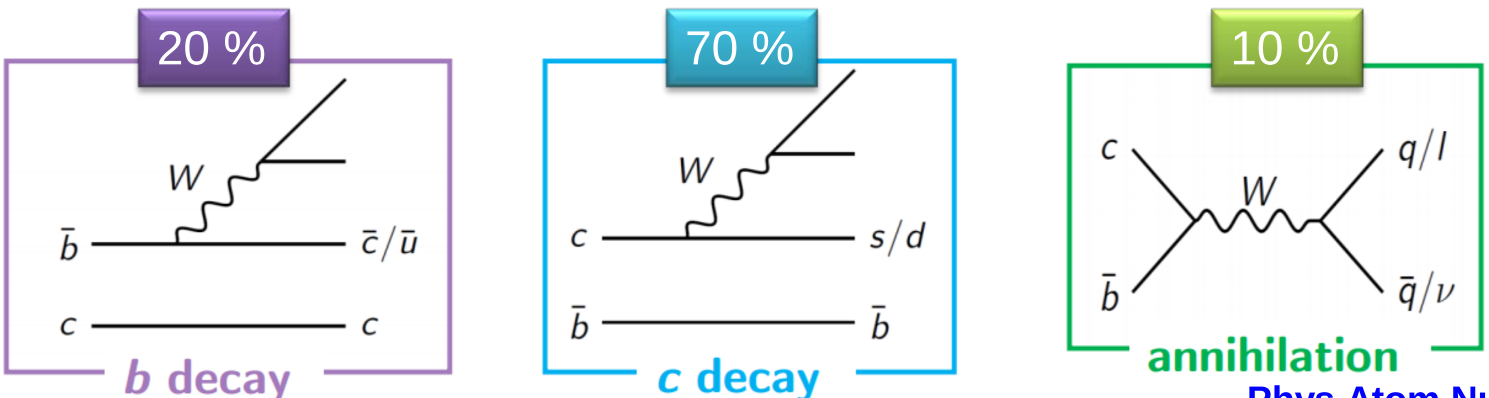
Rich spectroscopy

- LHCb: $M(B_c^+(1S)) = 6276.3 \pm 1.4 \pm 0.4\ \mathrm{MeV}/c^2$ **Phys.Rev.D87,112012**
- ATLAS: $M\big(B_c^+(2S)\big) = 6842 \pm 4 \pm 5\mathrm{MeV}/c^2$

Evelina Bouhova-Thacker's talk

A wide range of decay modes **arXiv:1407.1032**

- Tevatron: $J/\psi\pi^+, J/\psi\mu^+\nu_\mu$
- LHCb: $J/\psi\pi^+\pi^-\pi^+,\ \psi(2S)\pi^+,\ J/\psi K^+,\ J/\psi D_s^{(*)+},\ J/\psi K^+K^-\pi^+,\ B_s^0\pi^+ \ldots$



Phys.Atom.Nucl.67,1559

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

New result of LHCb

First observation of $B_c^+ \to J/\psi p\overline{p}\pi^+$

LHCb-PAPER-2014-039

Baryonic B_c^+ decay: $B_c^+ \to J/\psi p\bar{p}\pi^+$

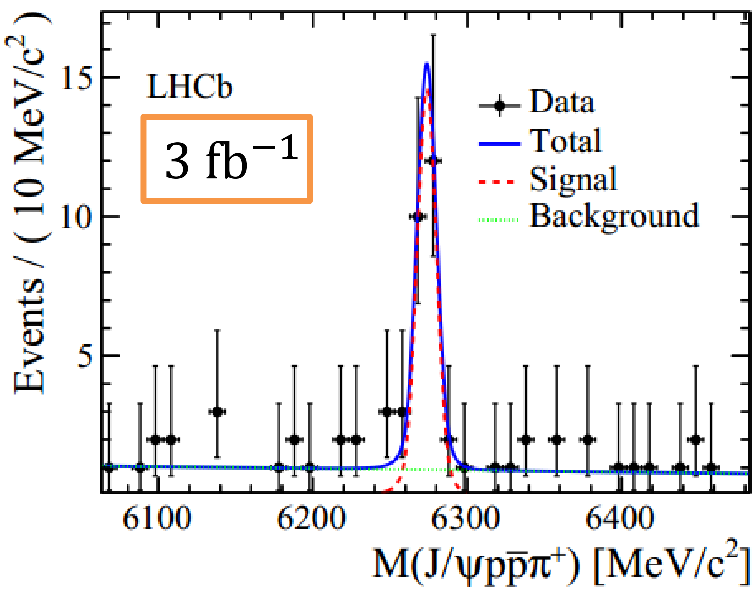
- Baryonic decay of b hadron important
  - To understand baryon production mechanism
  - To search for new baryons and tetra-quarks
  - Special behavior observed in baryonic $B_{u,d}$ decays, not understood yet
- This analysis presents
  - First observation of $B_c^+ \to J/\psi p\bar{p}\pi^+$
  - Precise measurement of B_c^+ mass

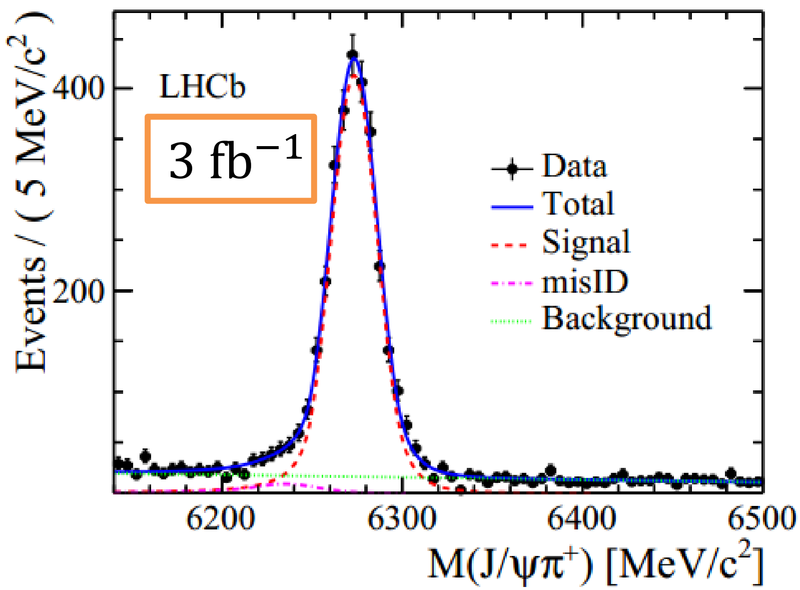
Observation of $B_c^+ \to J/\psi p\bar{p}\pi^+$

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

Invariant mass distribution

LHCb-PAPER-2014-039





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

$N_{\text{sig}} = 2835 \pm 58$

First observation

$\mathcal{B}(B_c^+ \to J/\psi p\bar{p}\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\pi^+)$

- Most efficiencies determined from simulation
- Proton identification efficiency estimated from data sample

Branching fraction measured as

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

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

Dominant by unknown decay model

- 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 $M(B_c^+) = 6273.8 \pm 1.8\ \mathrm{MeV}/c^2$

FSR correction: 0.20±0.03 MeV/c^2

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

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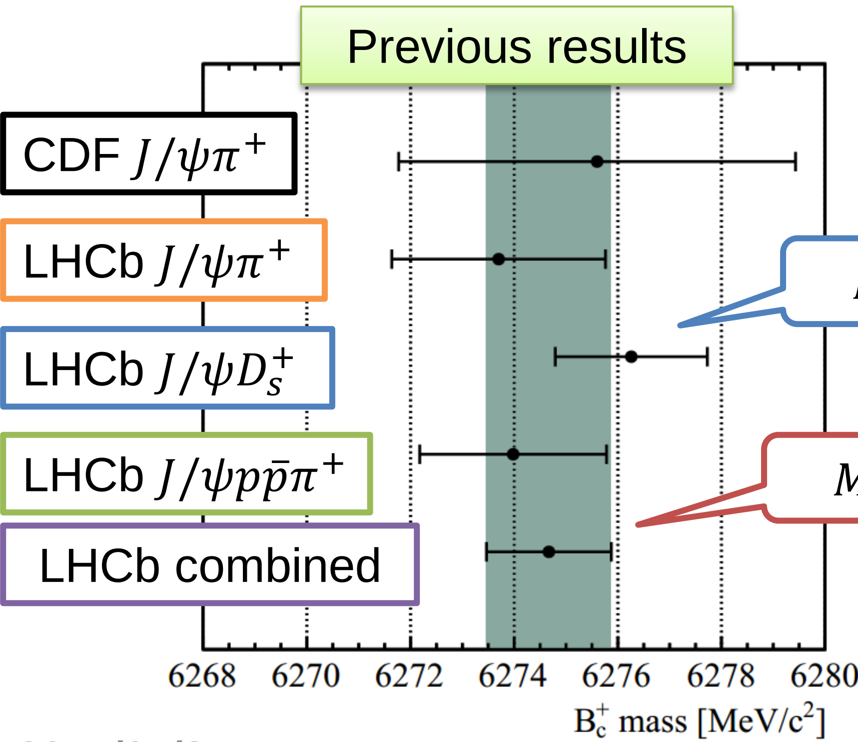
Dominant by Momentum scale



$M(B_c^+) = 6276.3 \pm 1.4(\mathrm{stat}) \pm 0.4(\mathrm{syst})\ \mathrm{MeV}/c^2$

$M(B_c^+) = 6274.7 \pm 0.9(\mathrm{stat}) \pm 0.8(\mathrm{syst})\mathrm{MeV}/c^2$

The most precise measurement

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New result of LHCb

The measurement of $\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$

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 $B_c^+ \to J/\psi\mu^+\nu_\mu$)

See Iain's talk

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

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

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

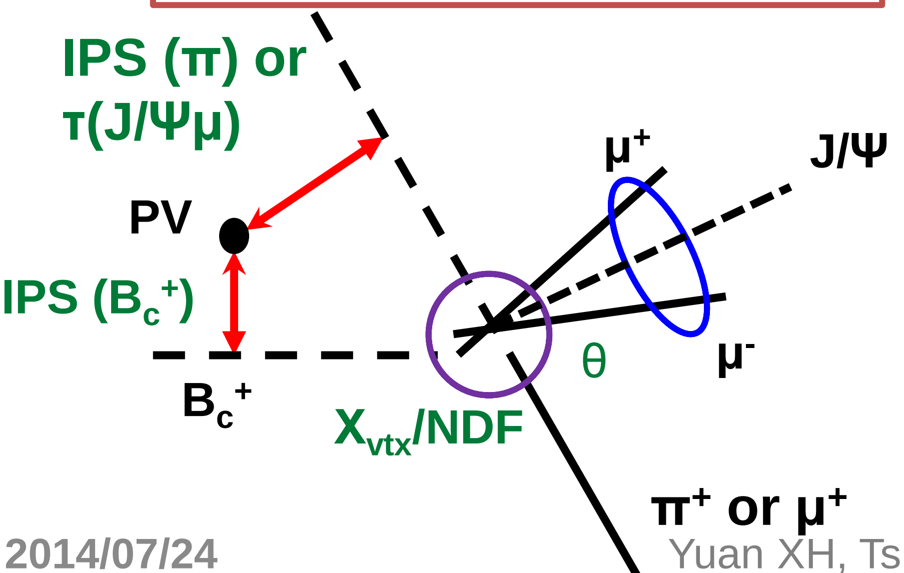
Analysis strategy

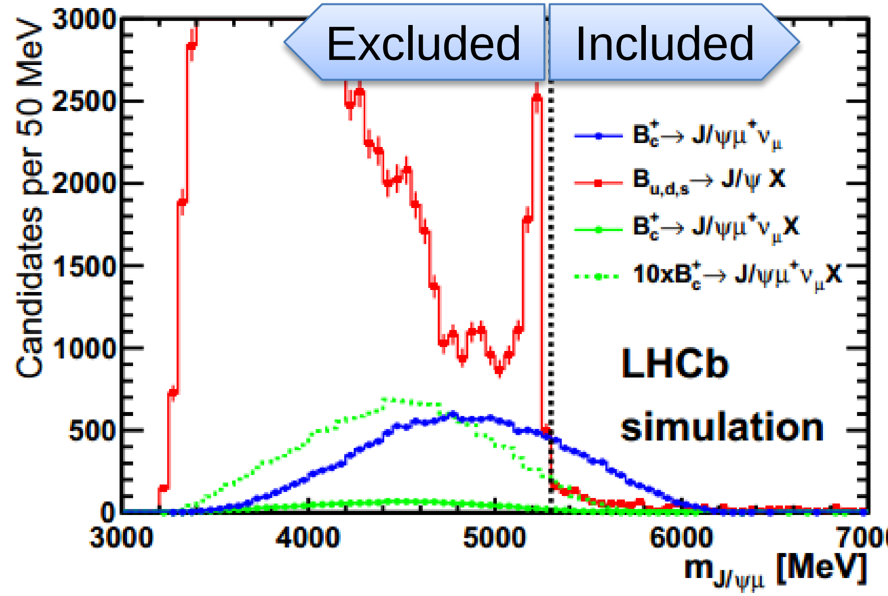
- Main challenge: undetected neutrino

  $m(J/\psi\mu^+) > 5.3\ \mathrm{GeV}/c^2$ required
  ➔ $B_{u,d,s} \to J/\psi X$ suppressed

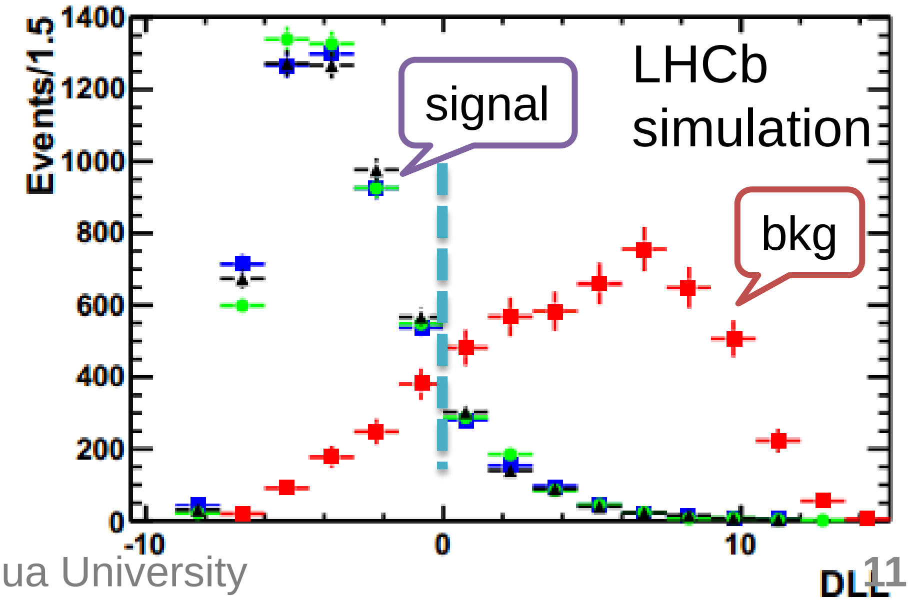
  Signal-to-background likelihood-ratio used with 4 variables

$$\mathrm{DLL} = -2\sum_{i=1}^{4} \ln\left(\frac{\mathcal{P}_{\mathrm{sig}}(x_i)}{\mathcal{P}_{\mathrm{bkg}}(x_i)}\right)$$



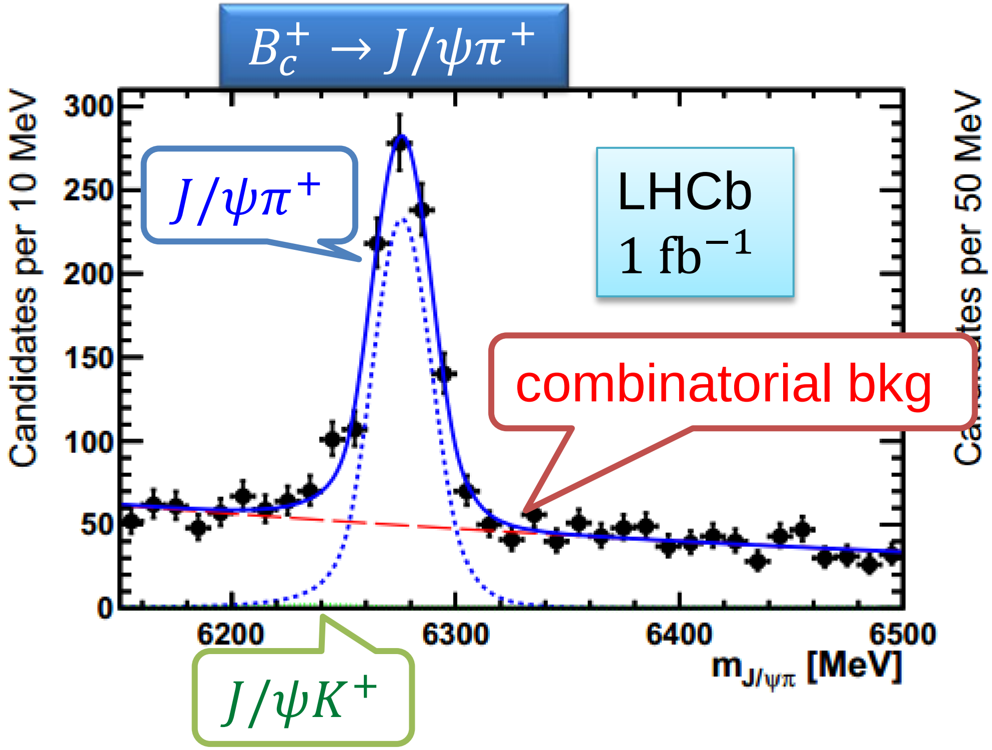


DLL distribution for $B_c^+ \to J/\psi\mu^+\nu_\mu$

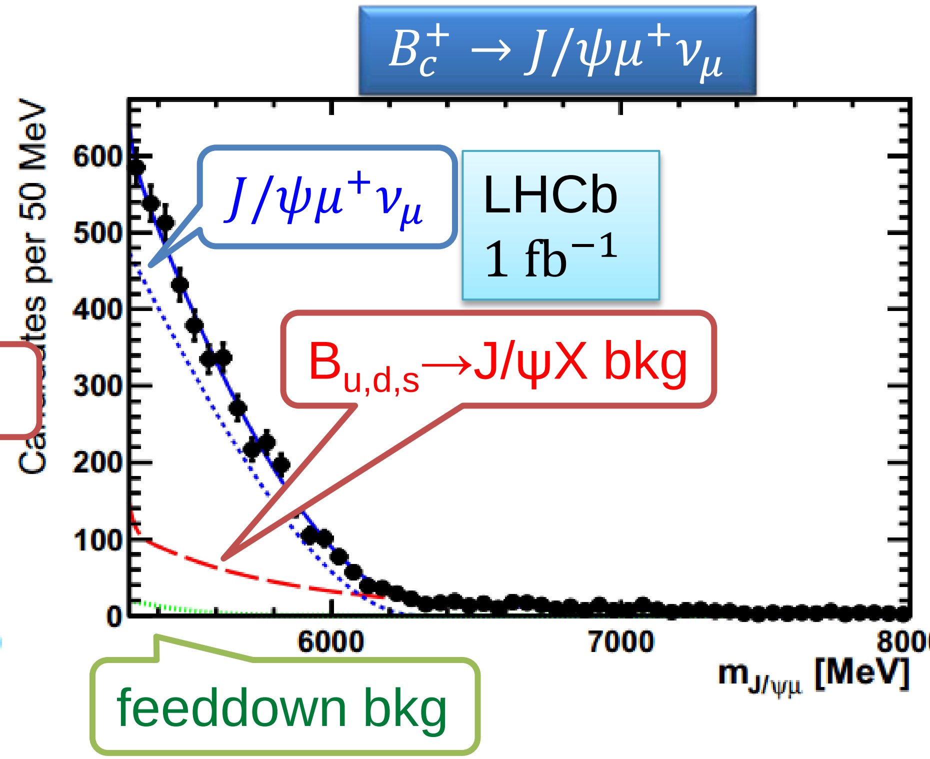


Signal yields for $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi\mu^+\nu_\mu$

- Signal yields determined from fitting to invariant mass distributions



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



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

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

arXiv:1407.2126

$$R(m(J/\psi\mu^+) > 5.3\mathrm{GeV}/c^2) \equiv \frac{\mathcal{B}(B_c^+ \to J/\psi\pi^+)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)} = \frac{N(B_c^+ \to J/\psi\pi^+)}{N(B_c^+ \to J/\psi\mu^+\nu_\mu)} \times \frac{\epsilon(B_c^+ \to J/\psi\mu^+\nu_\mu)}{\epsilon(B_c^+ \to J/\psi\pi^+)}$$

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

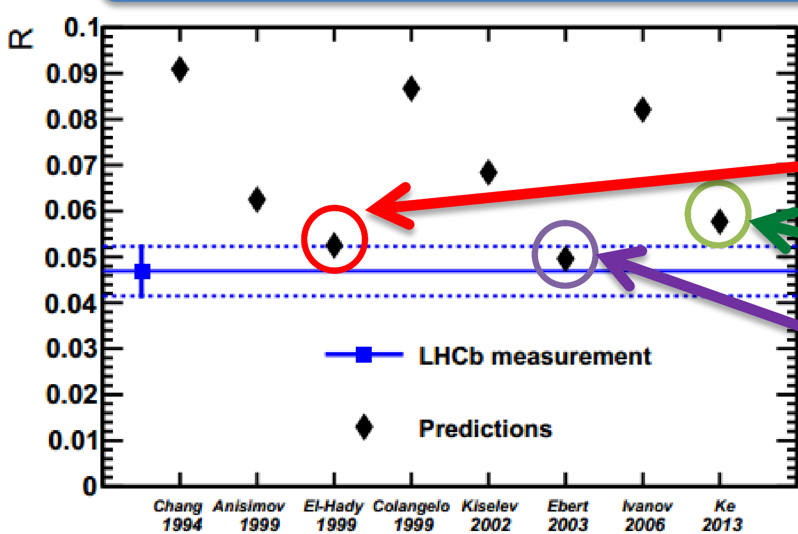
Signal shape
Trigger selection

- Extrapolated to full mass range

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

f 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

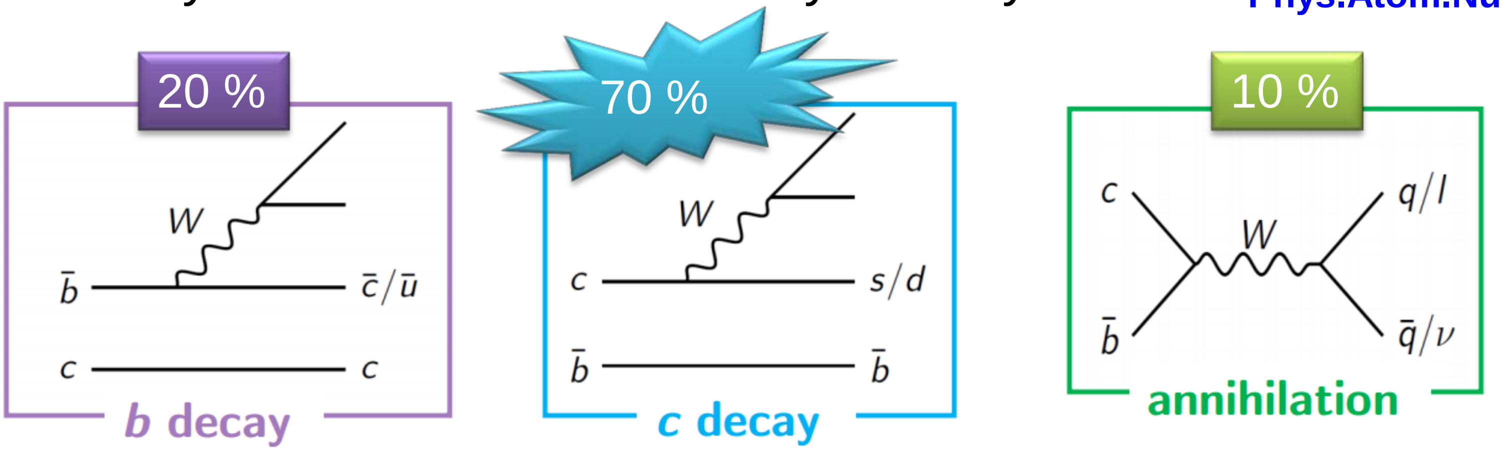
Measurement of B_c^+ lifetime with $B_c^+ \to J/\psi\mu^+\nu_\mu X$

EPJC74,2839

B_c^+ lifetime

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

Phys.Atom.Nucl.67,1559



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

PRD53,4991, PLB452,129, NPB585,353, PRD64,014003

- Large uncertainty in previous measurements
  - D0 & CDF measured with $B_c^+ \to J/\psi\pi^+$ and $B_c^+ \to J/\psi l^+\nu$
  - 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 $B_c^+ \to J/\psi\mu^+\nu_\mu X$

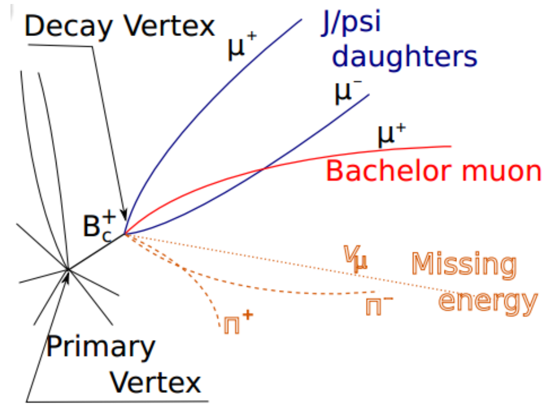
- Compared to B_c^+ hadronic decay

☺ Advantage

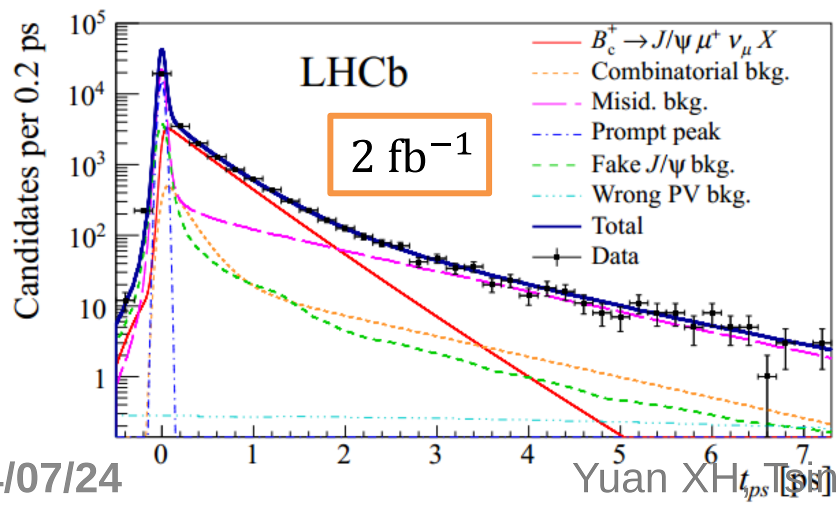
- High statistics:
  ~ 20x larger than $B_c^+ \to J/\psi\pi^+$
- Clear 3μ signature

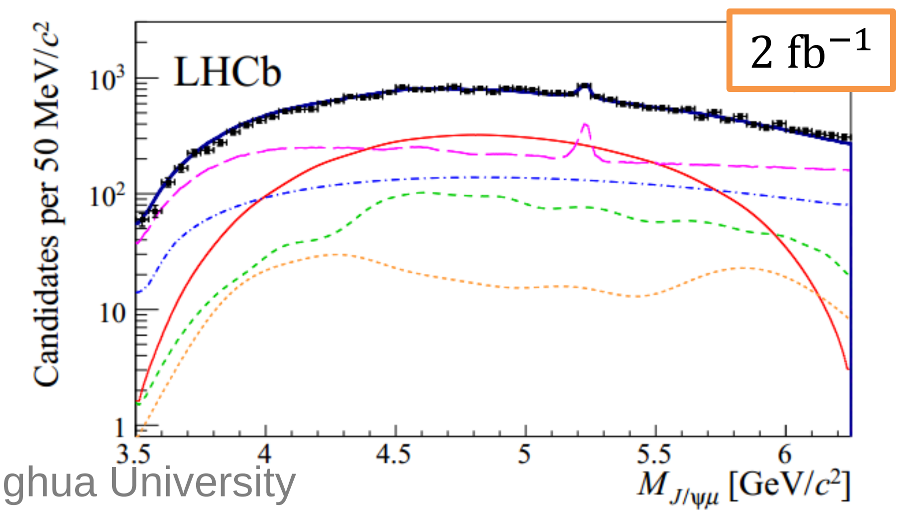
☹ But

- Partial reconstruction
- 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





Result of τ(B_c^+)

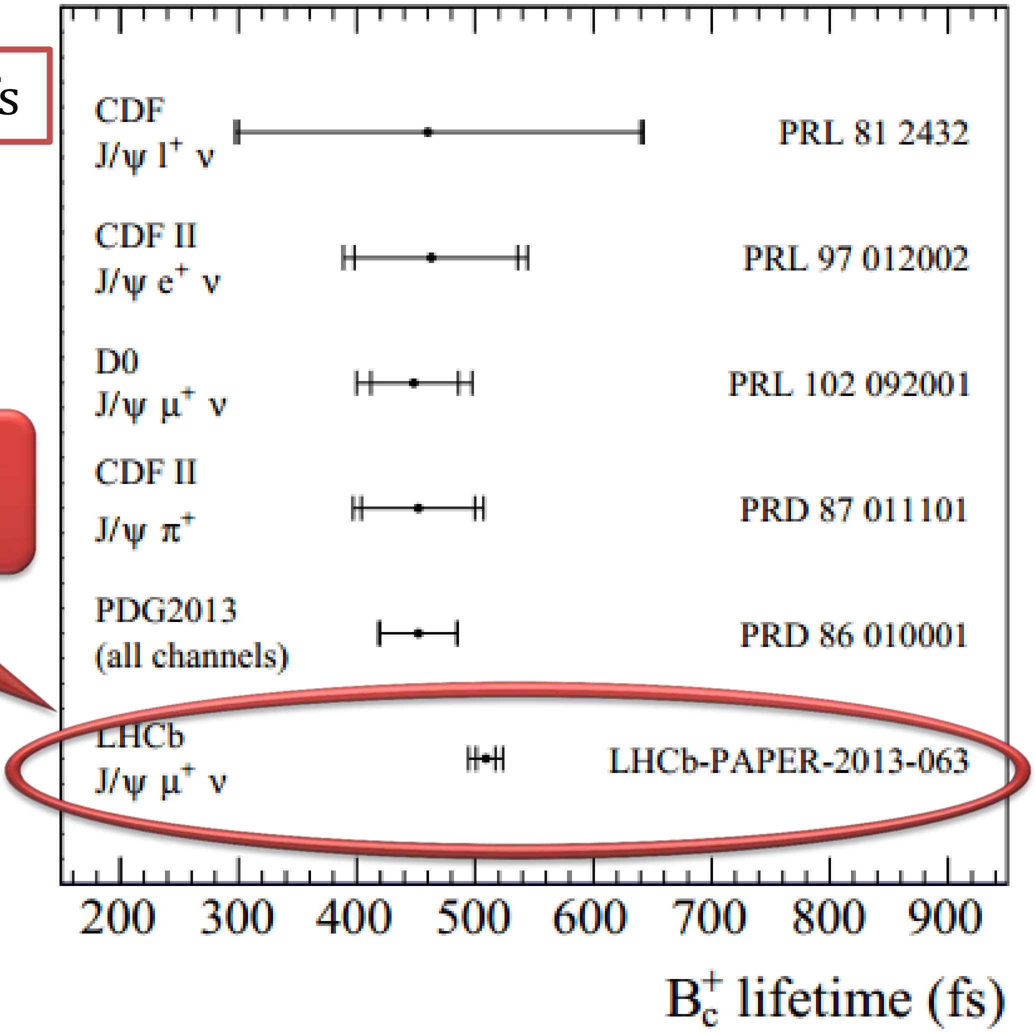
- $\tau(B_c^+)$ measured by LHCb with $B_c^+ \to J/\psi\mu^+\nu_\mu$ EPJC74,2839

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

- 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



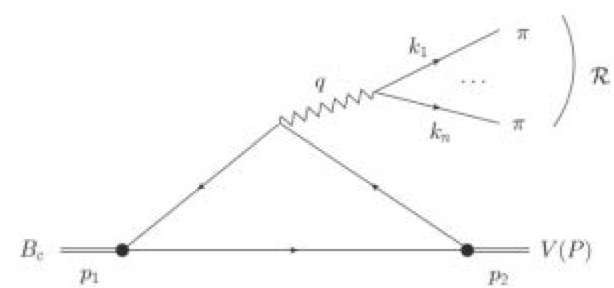
- Higher precision can be achieved
  Combining with independent measurement of $\tau(B_c^+)$ with $B_c^+ \to J/\psi\pi^+$

Evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$

JHEP1405,148

Evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$

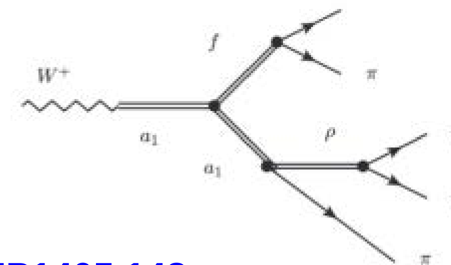
- Powerful tests
  - ✓ Form factors of $B_c^+ \to J/\psi W^+$ transition
  - ✓ Spectral functions for virtual W^+ boson into light hadrons



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

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

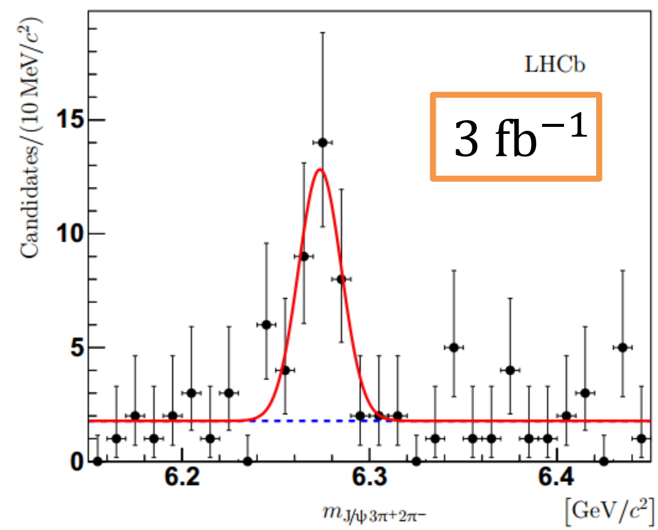
$$\frac{\mathcal{B}(B_c^+ \to J/\psi 3\pi^+ 2\pi^-)}{\mathcal{B}(B_c^+ \to J/\psi \pi^+)} = 1.74 \pm 0.44 \pm 0.24$$



Consistent with theoretical predictions (0.95 ~ 1.1)

PRD86,074024

JHEP1405,148



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

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

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

Summary

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

1. First observation of $B_c^+ \to J/\psi p\bar{p}\pi^+$ **LHCb-PAPER-2014-039**
   - ✓ Firstly observed baryonic decay of B_c^+
   - ✓ The most precise B_c^+ mass measurement
2. First measurement of $\mathcal{B}(B_c^+ \to J/\psi\pi^+)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$ **arXiv:1407.2126**
   - ✓ Consistent with theoretical predictions
3. Measurement of $\tau(B_c^+)$ with $B_c^+ \to J/\psi\mu^+\nu_\mu X$ **EPJC74,2839**
   - ✓ Most precise measurement
4. Evidence of $B_c^+ \to J/\psi 3\pi^+ 2\pi^-$ **JHEP1405,148**

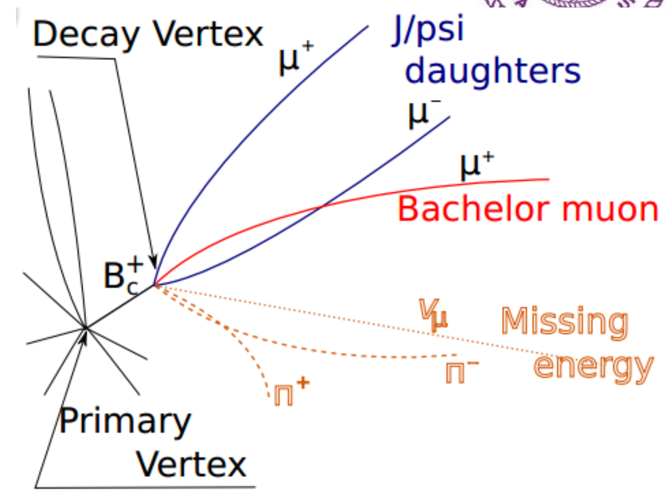
More studies still ongoing

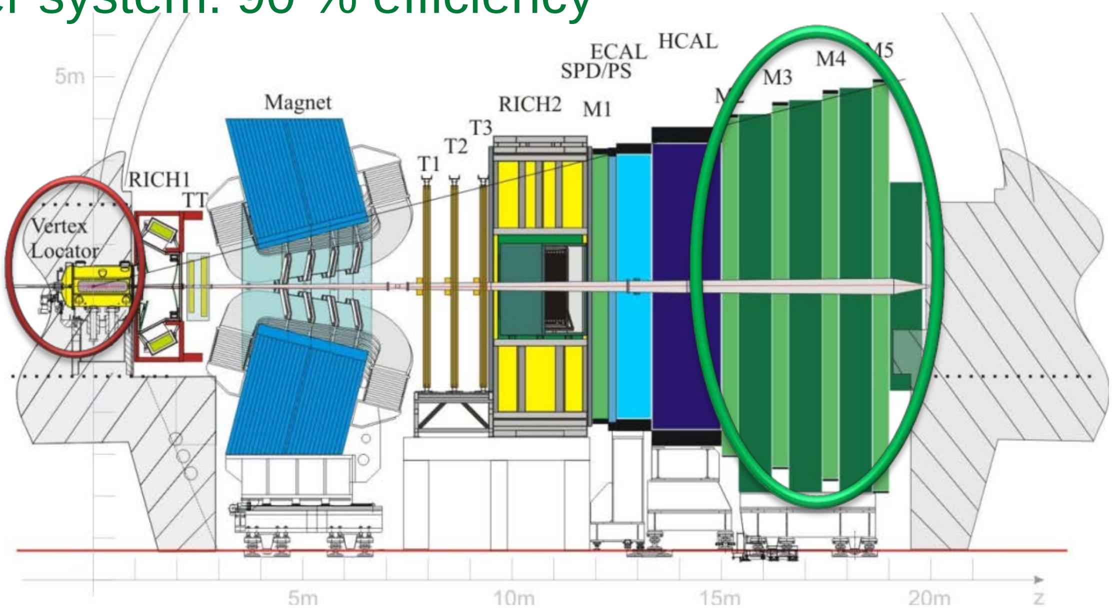
Thanks for your attentions

Backup

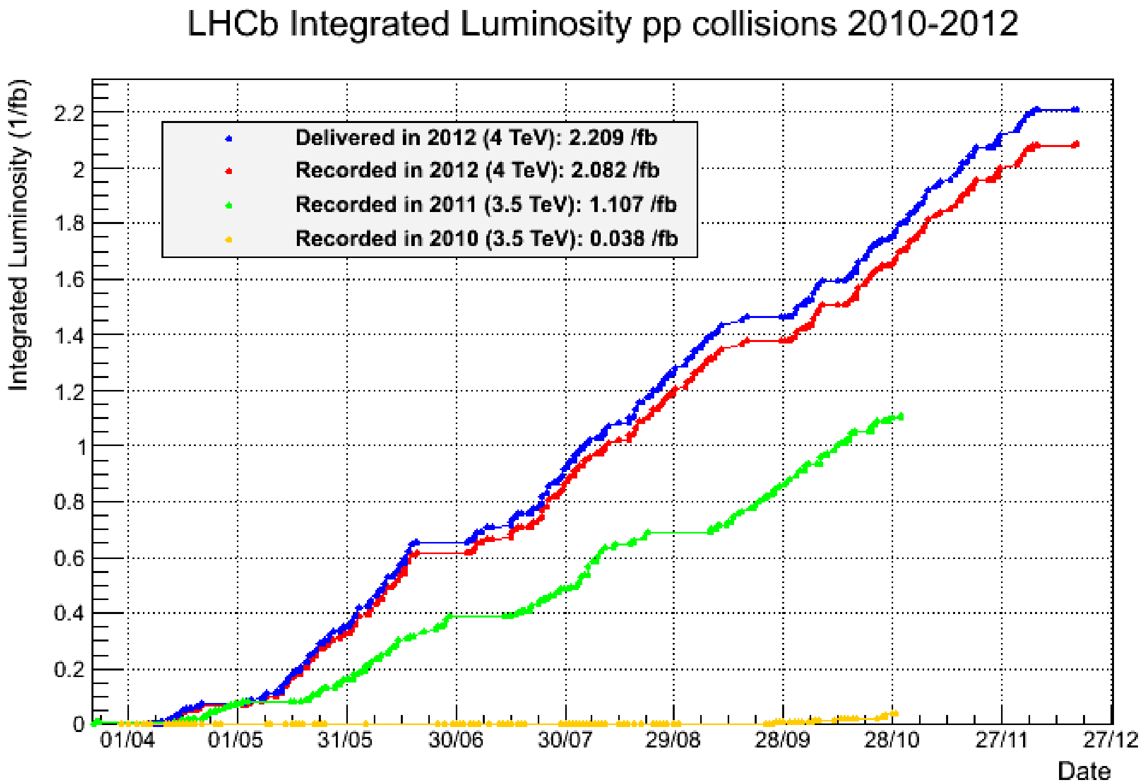
LHCb detector

- 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 ~ cm
    VELO: $\sigma_{\mathrm{PV,x/y}} \sim 10\ \mu\mathrm{m}$, $\sigma_{\mathrm{PV,x/y}} \sim 60\ \mu\mathrm{m}$
  - ✓ Reconstructing $J/\psi \to \mu^+\mu^-$ effectively:
    Good muon identification: $\epsilon(\mu \to \mu)$ ~ 95 %, $\pi - \mu$ misID ~ 5 %
    Trigger system: 90 % efficiency





LHCb data taking



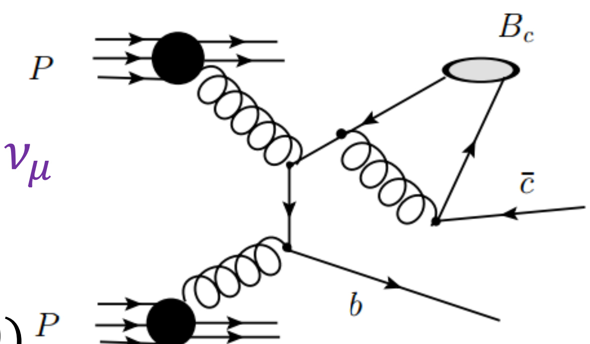
Successful data taking since 2010

- 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 ~ 0.1 % of other B mesons
  - Few decays observed at Tevatron: $J/\psi\pi^+, J/\psi\mu^+\nu_\mu$



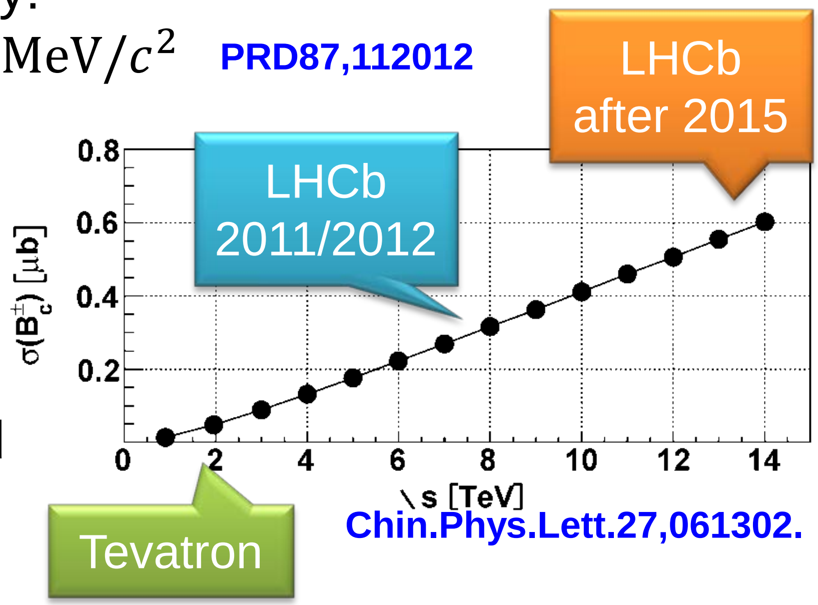
Phys.Atom.Nucl.67,1559

- LHCb: good opportunity for B_c^+ physics
  - Large production: $\sigma(B_c^+)_{\mathrm{LHC}}/\sigma(B_c^+)_{\mathrm{Tevatron}} \sim \mathcal{O}(10)$
  - More decays observed:

    $J/\psi\pi^+\pi^-\pi^+$, $\psi(2S)\pi^+$, $J/\psi K^+$, $J/\psi D_s^{(*)+}$, $J/\psi K^+K^-\pi^+$, $B_s^0\pi^+$…
  - B_c^+ properties measured more precisely:

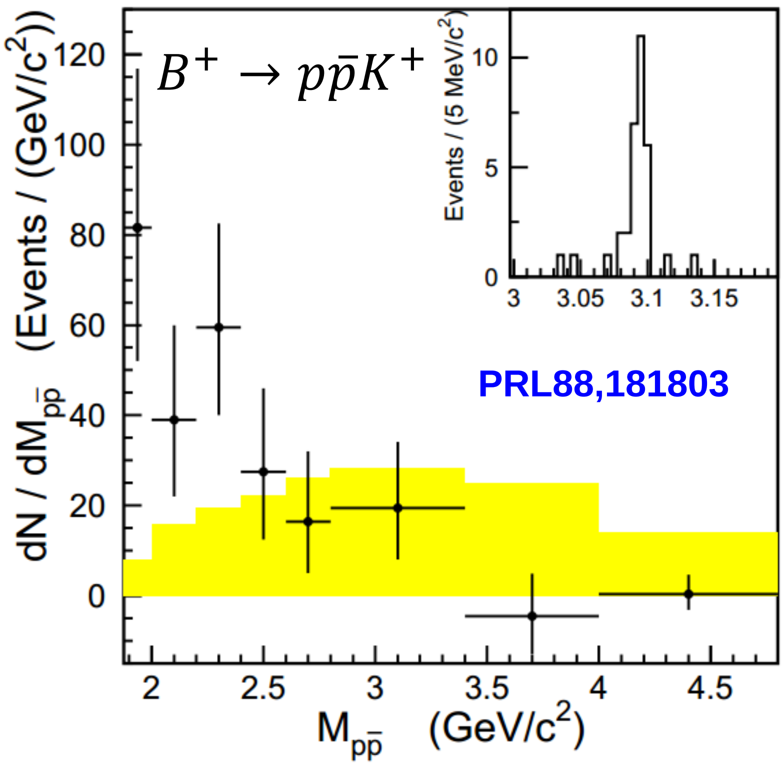
    $$M(B_c^+) = 6276.28 \pm 1.44 \pm 0.36\ \mathrm{MeV}/c^2$$ PRD87,112012

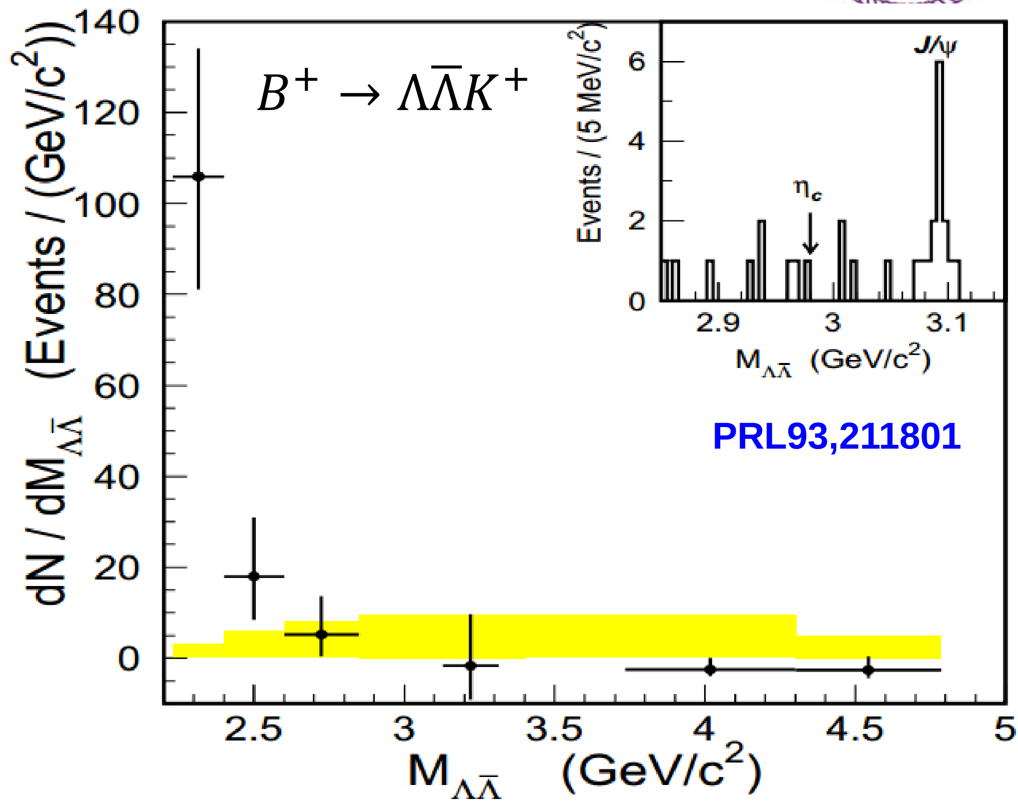
- More studies on B_c^+ physics are in need
  - Large uncertainty in $\tau(B_c^+)$
  - Many other B_c^+ decays not observed especially annihilation decay modes
  - No absolute branching ratio measured



Chin.Phys.Lett.27,061302.

Special behavior in $B^{0,\pm}$ baryonic decays





Baryon-antibaryon effective mass peaks at very low values

Similar results observed in $B^0 \to p\bar{\Lambda}\pi^-$, $B^+ \to p\bar{p}\pi^+$, $B^0 \to p\bar{p}K^0$, $B^+ \to p\bar{p}K^{*+}$

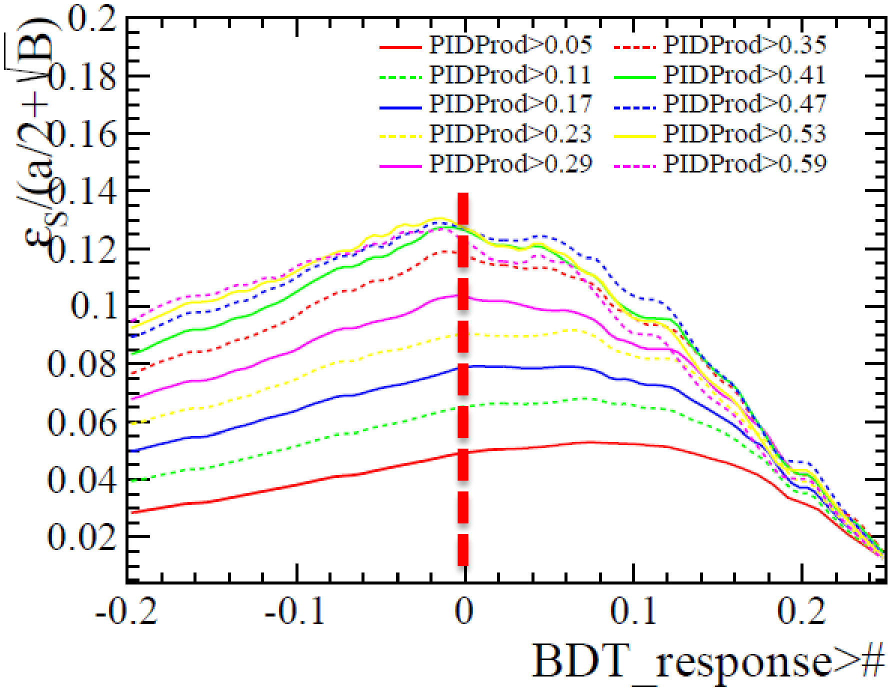
PRL90,201802, PRL92,131801

Optimisation of BDT and PID

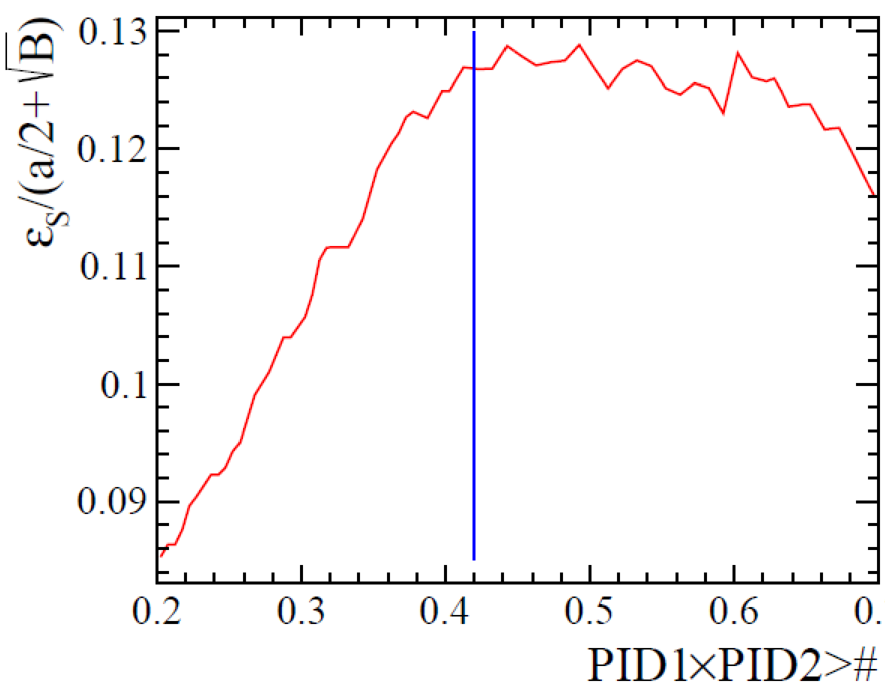
Punzi function $$f_{Punzi}(t,d) = \frac{\epsilon_{sig}(t,d)}{a/2 + \sqrt{B(t,d)}}$$

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

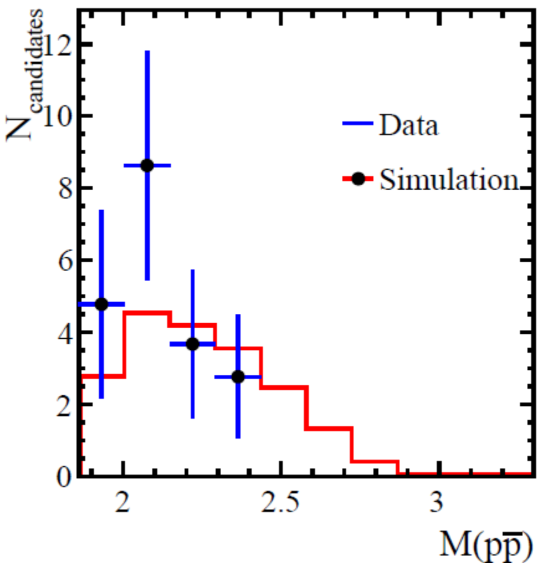
BDT_response>0

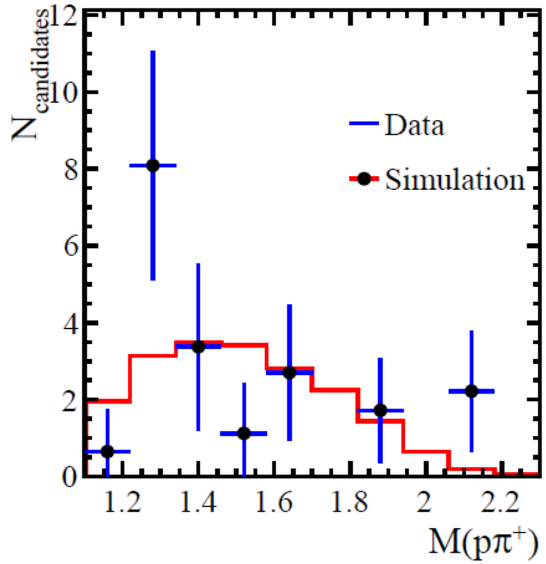


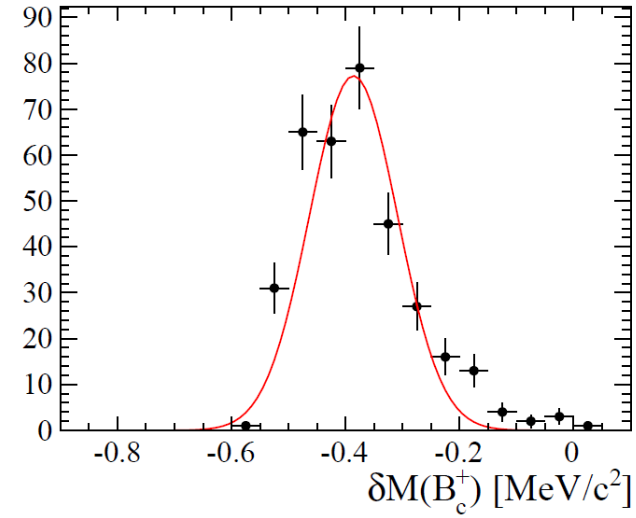
PID1*PID2>0.42



Systematics

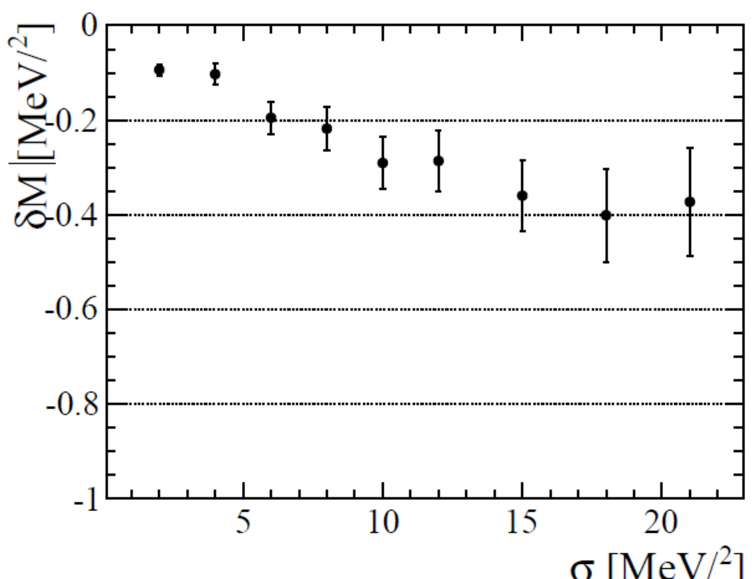




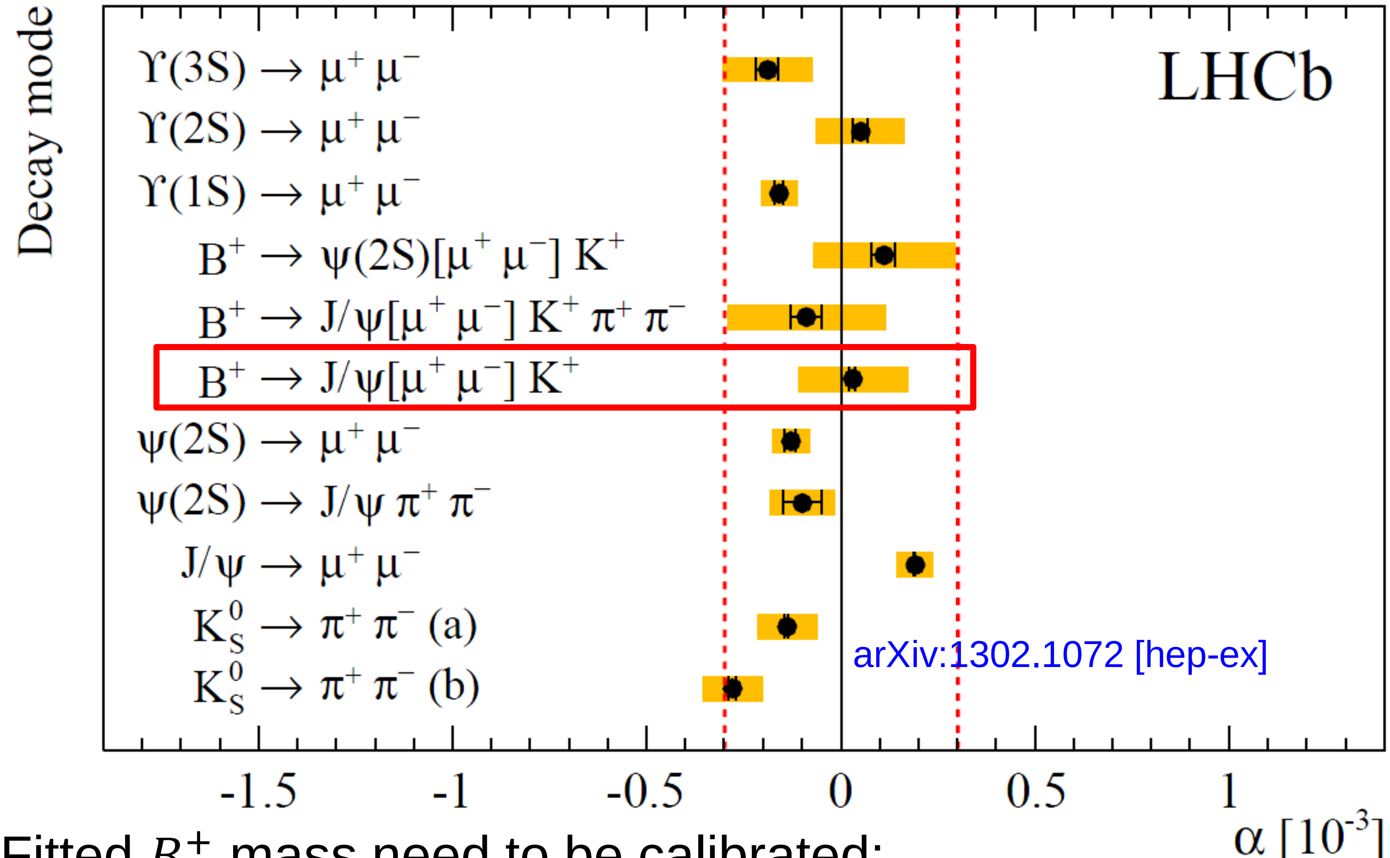


FSR correction: estimated from simulation

- ✓ δM = observed Bc mass – input value
- ✓ δM related to resolution
- ✓ $0.2 \pm 0.03\ \mathrm{MeV}/c^2$

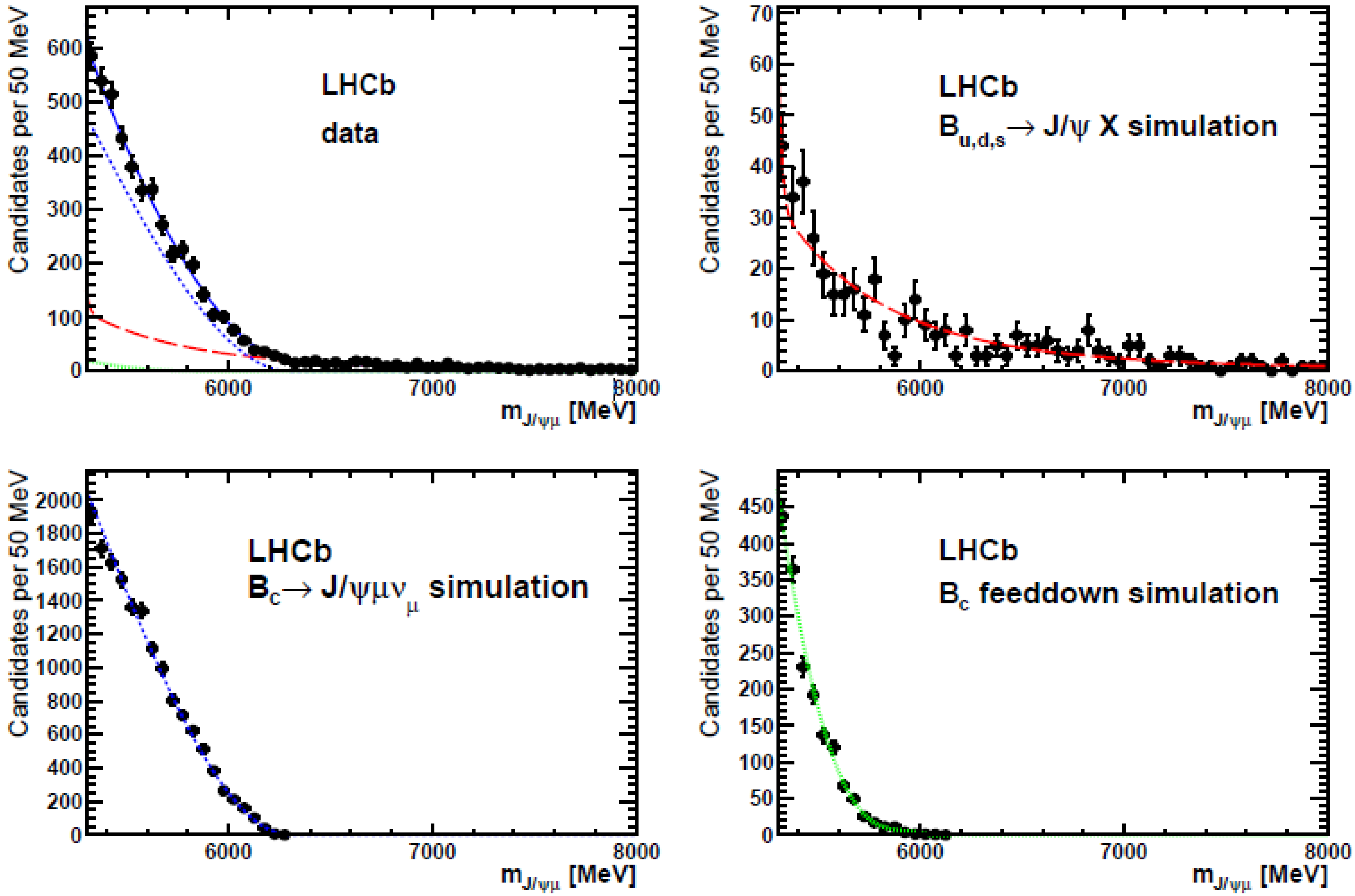


B_c^+ mass determination



- Fitted B_c^+ mass need to be calibrated:
  - Scale on the track momentum
  - The scale α makes $B^+ \to J/\psi(\mu^+\mu^-)K^+$ mass to PDG 2012
  - Variation of scales studied with a variety of decays
    - ✓ 3×10^{-4}
    - ✓ Propagated to uncertainty of B_c^+ mass: $\pm 0.030\ \mathrm{MeV}/c^2$

Signals for $B_c^+ \to J/\psi\mu^+\nu_\mu$

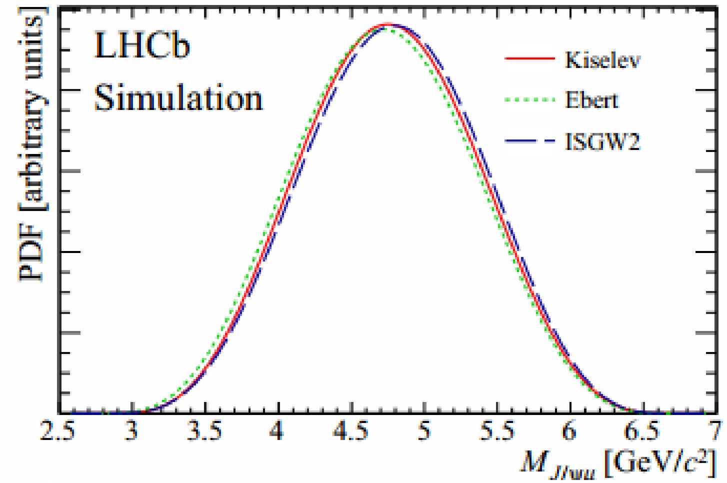


Feeddown: $\psi(2S)\mu^+\nu_\mu$, $\chi_{cJ}\mu^+\nu_\mu$, $J/\psi\tau^+\nu_\tau$

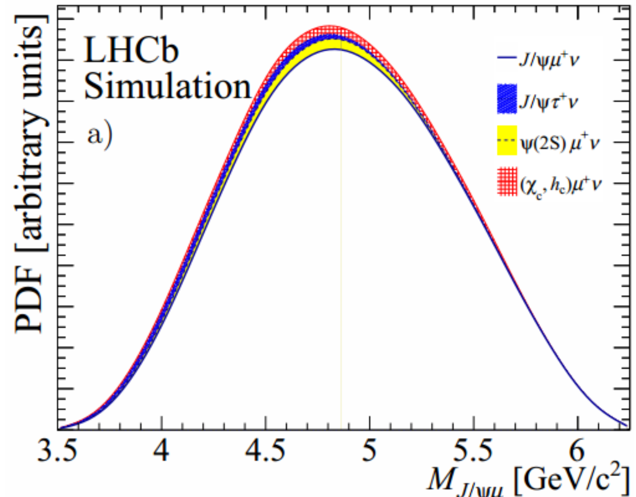
Analysis strategy

2D data-model m(J/ψμ+) ⊕ t_{ps} to enhance sig/bkg separation

- $B_c^+ \to J/\psi\mu^+\nu_\mu$ 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} ≡ 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/ψμ) and t_{ps}

- Decay time signal model: determined from simulation study

- J/ψ + hadron misidentified as a μ
- Fake J/ψ + real μ
- Combinatorial: J/ψ + μ not coming from a Bc+
  - 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, Λ_b

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