Precision measurement of the B_c^+ mass

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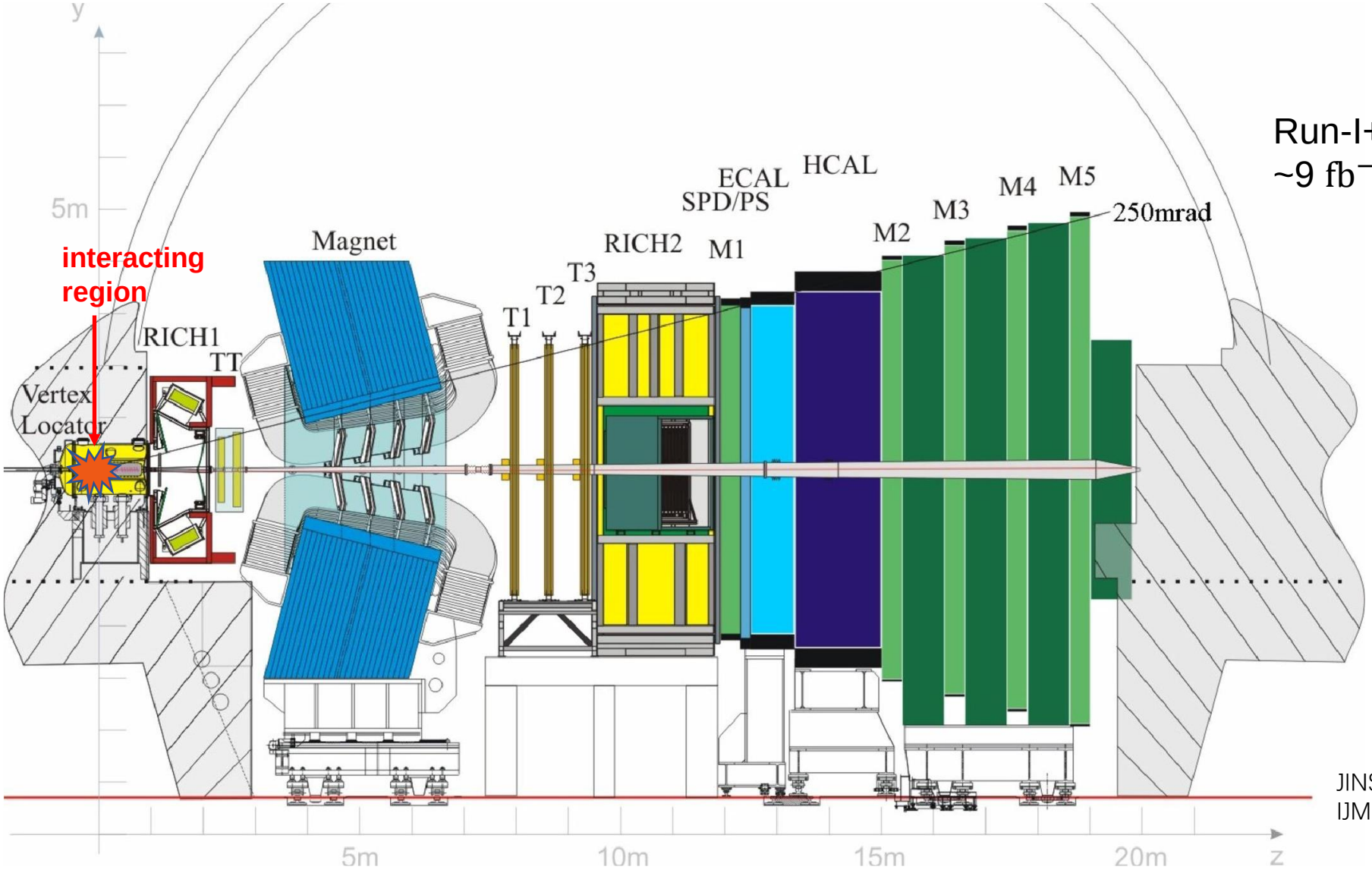
Outline

- Introduction
- Event selection
- Mass fit
- Systematic uncertainties
- Combination

LHCb Detector

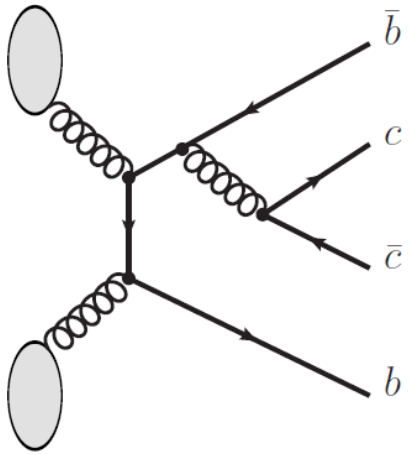


Run-I+Run-II
~9 fb^{-1} for data-taking

JINST 3 (2008) S08005)
IJMPA 30 (2015) 1530022

Introduction

- B_c^+ meson: Ground state of the only meson family consists of different heavy-flavor quarks, ideal testing for QCD models.
- Decays weakly, first observed in CDF[PRL 81(1998)2432].



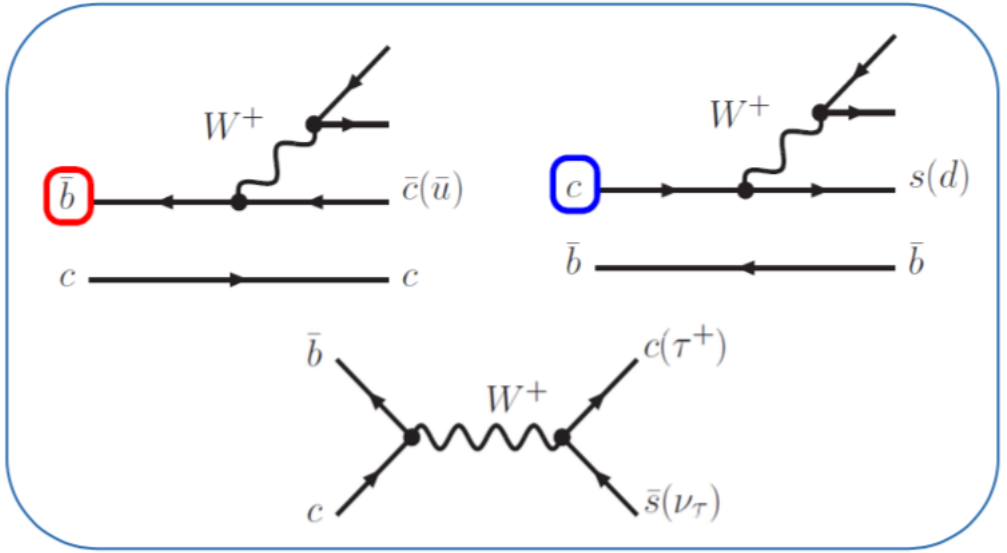
- B_c^+ produced mainly through

$gg \to B_c^+ + b + \bar{c}$

$\sigma(B_c^+) \sim 50\text{nb}$ for $\sqrt{s} = 14$ TeV[EPJC**38**,267–276(2004)]

$\sigma(B_c^+)_{\text{LHC}} / \sigma(B_c^+)_{\text{Tevatron}} \sim \mathcal{O}(10)$

- B_c^+ decay modes:
  - $\bar{b} \to \bar{c} W^+$ (~20%)
    - $J/\psi\, \pi^+$, $J/\psi D_s^+$, etc.
  - $c \to s W^+$ (~70%)
    - $B_s^0 \pi^+$, semileptonic, etc.
  - $c\bar{b} \to W^+$ (~10%)
    - leptonic decays, etc.



Motivation

- With large cross-section, many new B_c^+ decay modes discovered and studied.

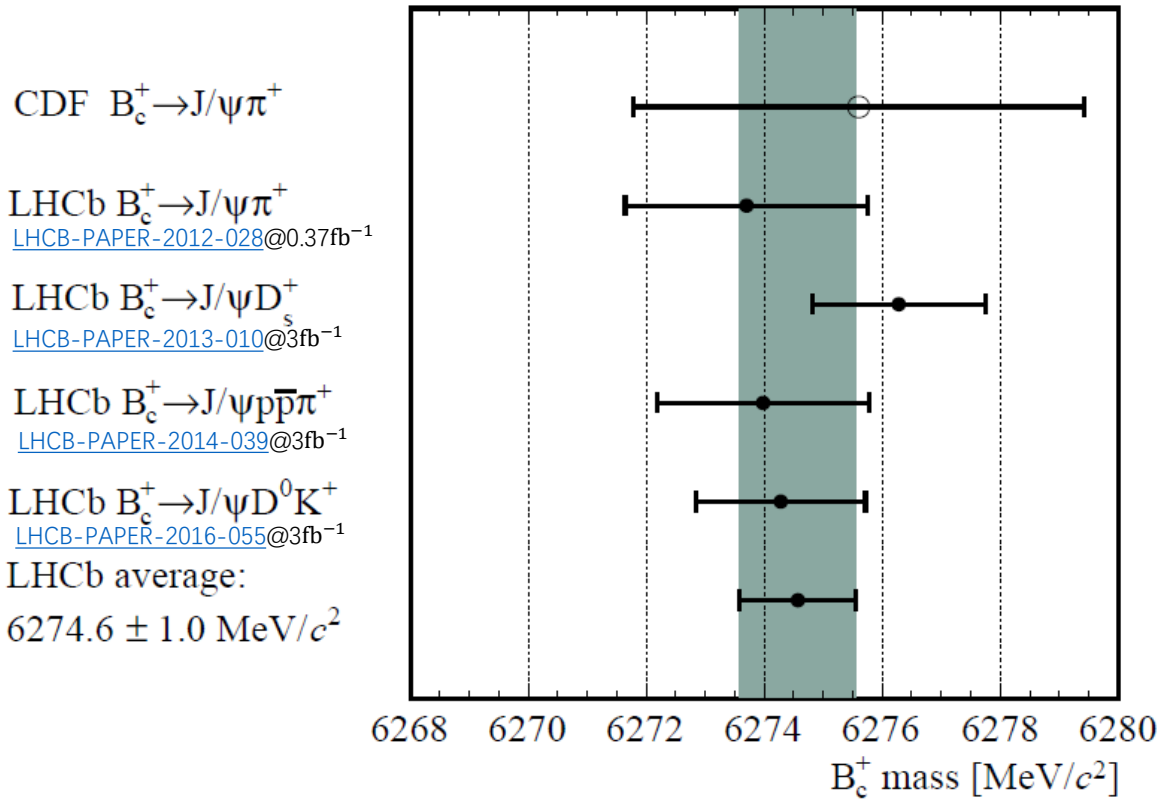
- Previous LHCb results
  6274.6 ± 1.0 MeV
- Lattice QCD results is
  $\mathrm{M}(B_c^+) = 6278(6)(4)\mathrm{MeV}$

- Dominating systematic uncertainty in $B_c\ (2S)$ mass measurement, e.g.,
  - [LHCB-PAPER-2019-007-001]

  $\mathrm{M}\left(B_c^+(2S)\right) = 6872.1 \pm 1.3\ (\mathrm{stat.}) \pm 0.1(\mathrm{syst.})$
  $\pm 0.8\ (B_c^+)$ MeV
  - CMS: [CMS-BPH-18-007]

  $\mathrm{M}\left(B_c^+(2S)\right) = 6871.0 \pm 1.2\ (\mathrm{stat.}) \pm 0.8(\mathrm{syst.})$
  $\pm 0.8\ (B_c^+)$ MeV

[HPQCD, PRD 86 (2012) 094510]



- With more data and more decay modes, we can improve the precision further.

B_c^+ decays used in this analysis

- Include most of the B_c^+ decays observed so far.
  - $J/\psi D^0(\pi^+K^-)K^+$
  - $J/\psi D_s^+$
    - $D_s^+ \to 3\pi$
    - $D_s^+ \to KK\pi$
  - $B_s^0\pi^+$
    - $B_s^0 \to D_s^-\pi^+$
    - $B_s^0 \to J/\psi\phi$
  - $J/\psi p\bar{p}\pi^+$
  - $J/\psi 3\pi$
  - $J/\psi\pi$

Small Q value

Also used to measure the mass difference between B_c^+ and B_s^0

High statistics

Analysis strategy

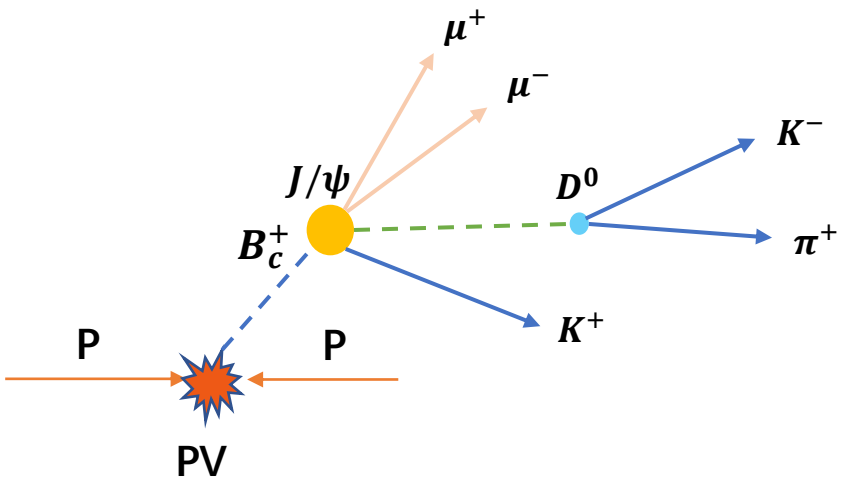
Take $B_c^+ \to J/\psi D^0 K^+$ as an example

Blinded analysis

- Event Selection
  - Pre-selection (stripping), BDT-based selection, and optimization
- Signal line shape
- Mass fit
- Systematic uncertainties
  - Uncertainties and correction
- Combination

Cut-based preselection

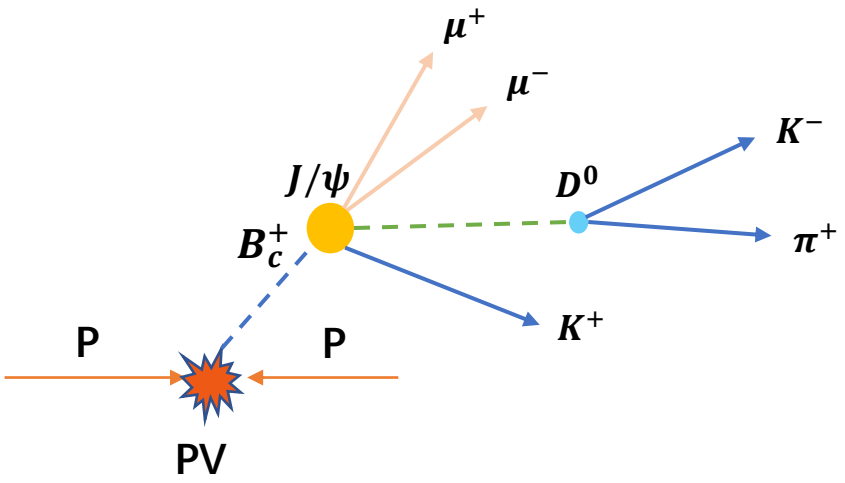
- For $B_c^+ \to J/\psi D^0 K^+$
  - Starting from detached J/ψ, loose pre-selection on pions and kaons.
- Each selection efficiencies > 90%
  - Vertex fit quality, p_T, track quality, etc.

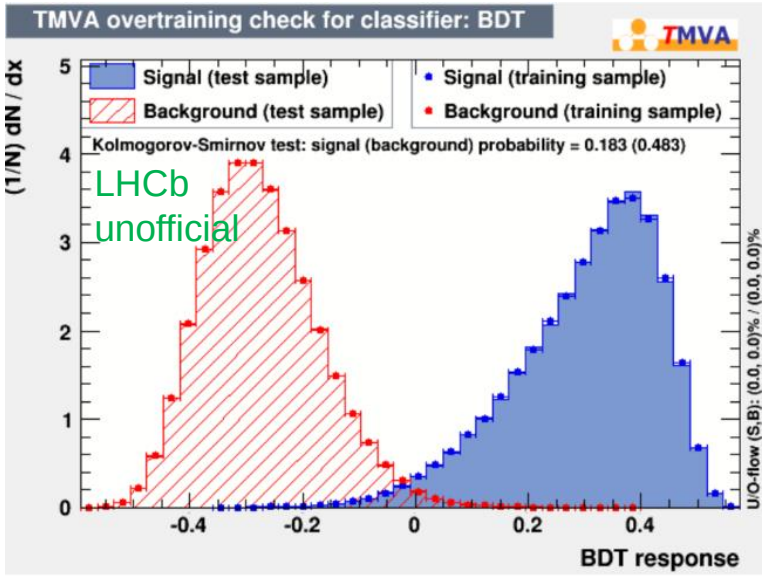


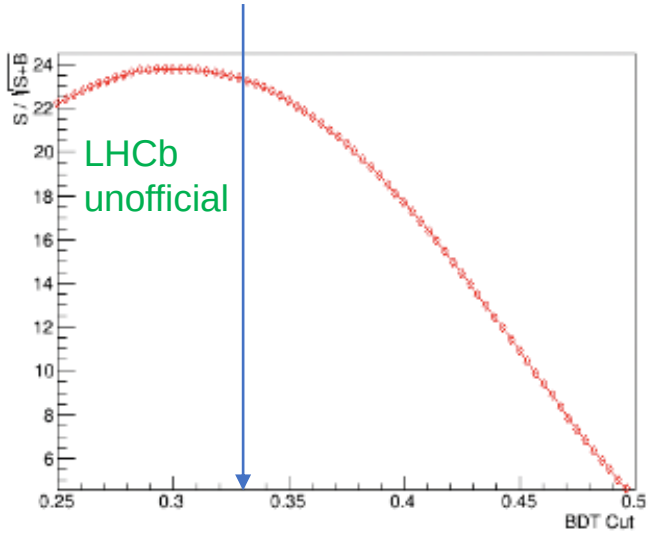
cut	number of events	efficiency[%]
without cut	176751	$(100.00 \pm 0.00)\%$
$\mu^\pm\ p_T > 550 MeV$	167487	$(94.76 \pm 0.05)\%$
$\mu^\pm\ Track_{\chi^2/ndf} < 5$	167487	$(100.00 \pm 0.00)\%$
$\mu^\pm\ PIDmu > 0$	157379	$(93.96 \pm 0.06)\%$
J/ψ *mass window* $(2996.916, 3196.916) MeV/c^2$	151154	$(96.04 \pm 0.05)\%$
J/ψ *EndVertex* $\chi^2/ndf < 20$	150290	$(99.43 \pm 0.02)\%$
J/ψ *LOKI FDS* > 3	106549	$(70.90 \pm 0.12)\%$
J/ψ *mass window* $(3040, 3150) MeV/c^2$	104699	$(98.26 \pm 0.04)\%$
π^+ *TRACK* $\chi^2/ndf < 3, K^-$ *Track* $\chi^2/ndf < 3$	104699	$(100.00 \pm 0.00)\%$
$\pi^+\ \chi^2_{IP} > 0.5, K^-\ \chi^2_{IP}) > 0.5$	99304	$(94.85 \pm 0.07)\%$
$\pi^+\ p_T > 100, K^-\ p_T > 100$	99168	$(99.86 \pm 0.01)\%$
$\pi^+\ hasRich == 1, K^-\ hasRich == 1$	98471	$(99.30 \pm 0.03)\%$
$\pi^+\ ProbNNghost < 0.3, K^-\ ProbNNghost < 0.3$	92547	$(93.98 \pm 0.08)\%$
$(K^-\ ProbNNk/\pi^+\ ProbNNpi) > 0.1$	88466	$(95.59 \pm 0.07)\%$
$D^0\ EndVertex\ \chi^2/ndf < 9$	85311	$(96.43 \pm 0.06)\%$
D^0 *mass window* $(1834.83, 1894.83) MeV/c^2$	81926	$(96.03 \pm 0.07)\%$
$K^+\ Track\ \chi^2/ndf < 3$	81926	$(100.00 \pm 0.00)\%$
$K^+\ \chi^2_{IP} > 0.25$	77699	$(94.84 \pm 0.08)\%$
$K^+\ p_T > 100$	77515	$(99.76 \pm 0.02)\%$
$K^+\ hasRich == 1$	77154	$(99.53 \pm 0.02)\%$
$K^+\ ProbNNghost < 0.3$	74128	$(96.08 \pm 0.07)\%$
$K^+\ ProbNNk > 0.1$	68999	$(93.08 \pm 0.09)\%$
$B_c^+\ EndVertex\ \chi^2/ndf) < 20$	68676	$(99.53 \pm 0.03)\%$
B_c^+ *mass window* $(5575.1, 6975.1) MeV/c^2$	68676	$(100.00 \pm 0.00)\%$
total cut	68676	$(38.85 \pm 0.12)\%$

BDT-based final selection

- For $B_c^+ \to J/\psi D^0 K^+$
  - BDT trained with signal from MC, and background from far upper side-band data.
  - Training variables: χ^2_{IP} of all particles, p_T of all particles, B_c^+ and long-lived daughters' decay time and its significance, χ^2_{vertex} of B_c^+, and B_c^+ pointing angle.
- BDT cut value determined by maximizing $S/\sqrt{S+B}$.







(f) $J/\psi D^0 K^+$ (Cut value: 0.33)

Signal line shape

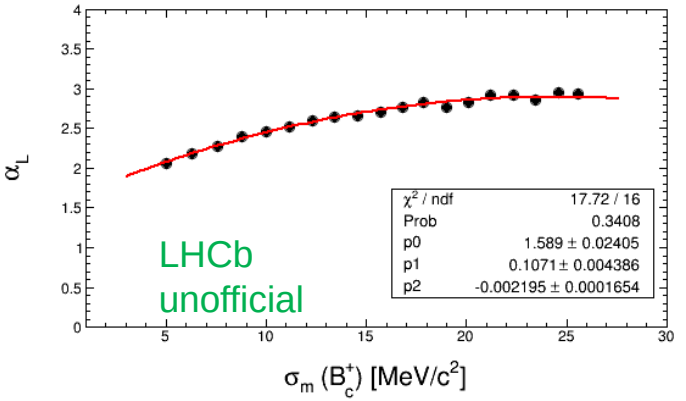
- Double-sided Crystal Ball (DSCB) function to describe signal, with left tail caused by final state radiation, and right tail caused by mass constraint.

$$f(x; M, \sigma, a_l, n_l, a_r, n_r) = \begin{cases} e^{-a_l^2/2}\left(\frac{n_l}{a_l}\right)^{n_l} \cdot \left(\frac{n_l}{a_l} - a_l - \frac{x-M}{\sigma}\right)^{-n_l}, & \frac{x-M}{\sigma} < -a_l \\ \exp\left(-\frac{1}{2}\left(\frac{x-M}{\sigma}\right)^2\right), & -a_l \le \frac{x-M}{\sigma} \le a_r \\ e^{-a_r^2/2}\left(\frac{n_r}{a_r}\right)^{n_r} \cdot \left(\frac{n_r}{a_r} - a_r + \frac{x-M}{\sigma}\right)^{-n_r}, & \frac{x-M}{\sigma} > a_r \end{cases}$$

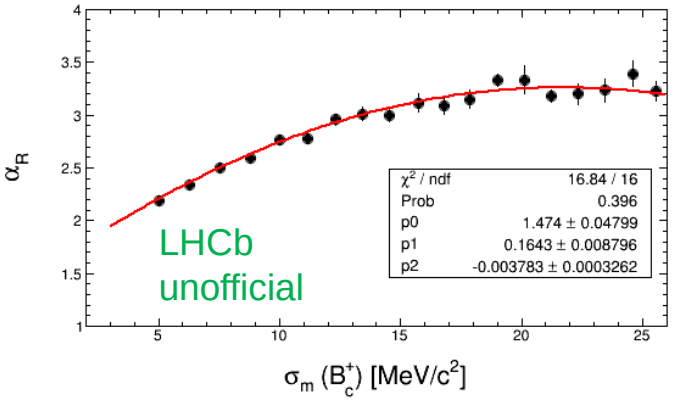
- Fixed n_l, n_r, with α_l, α_r parameterized as 2^{nd} order polynomial function of mass resolution.

$B_c^+ \to J/\psi D^0(\pi^+K^-)K^+$:

α_l vs. resolution ($n_l = 2.6$)

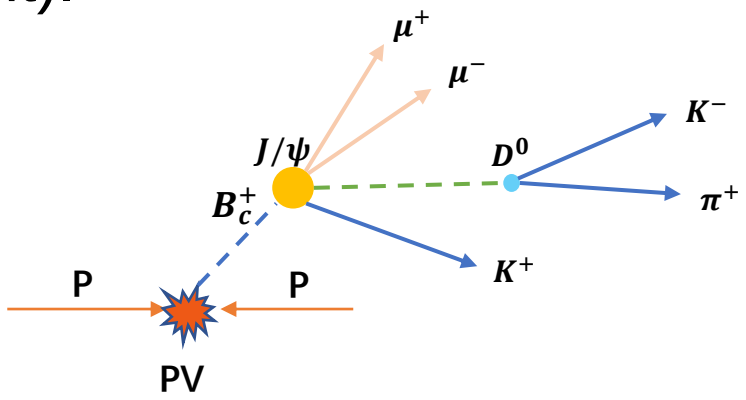


α_r vs. resolution ($n_r = 4.7$)



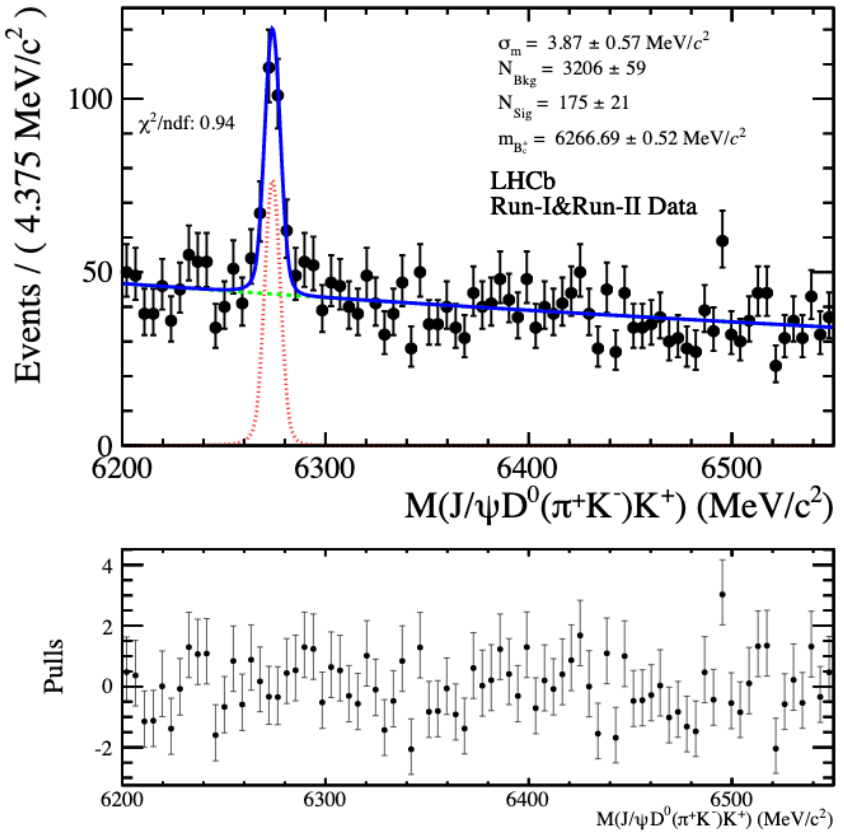
Mass fit

- Using both Run-I and Run-II data.
- Using DecayTreeFilter mass (daughters' mass constraint & PV constraint).



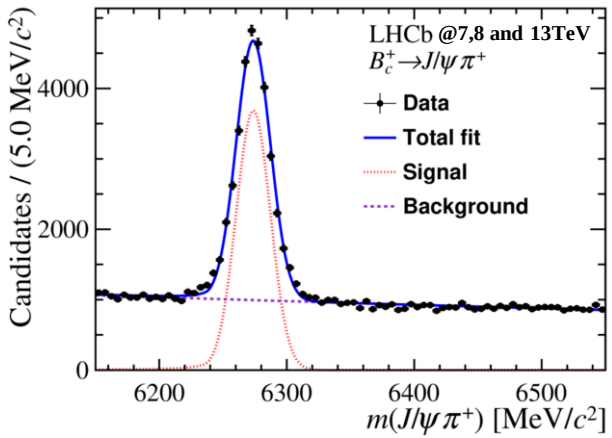
- Signal line shape:
  - Double-sided Crystal Ball
- Background line shape:
  - exponential function

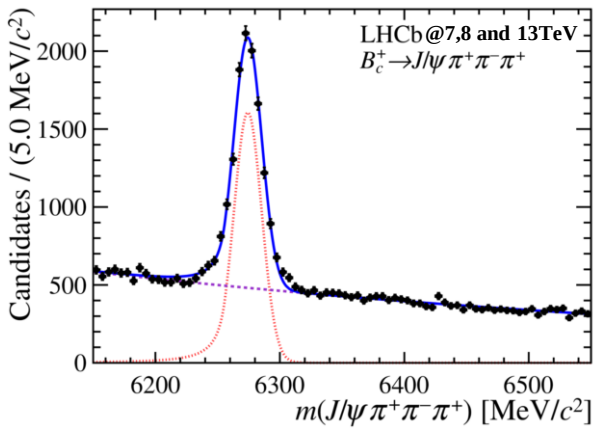
$B_c^+ \to J/\psi D^0(\pi^+K^-)K^+$:

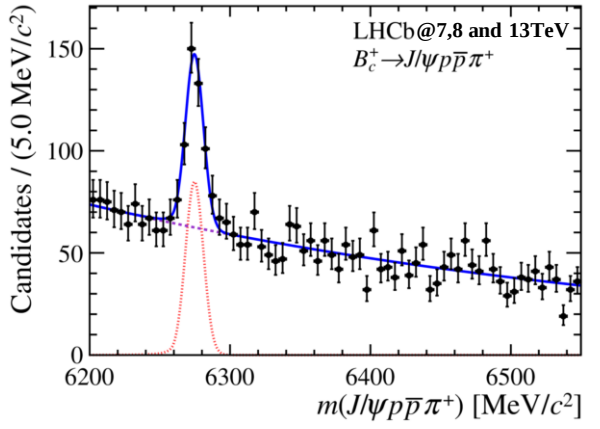


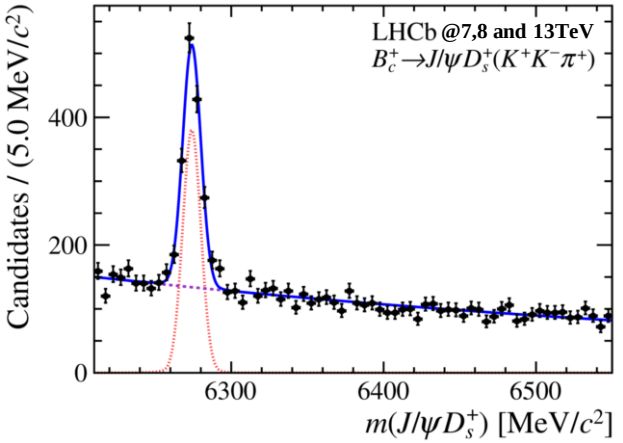
Mass distributions and fits

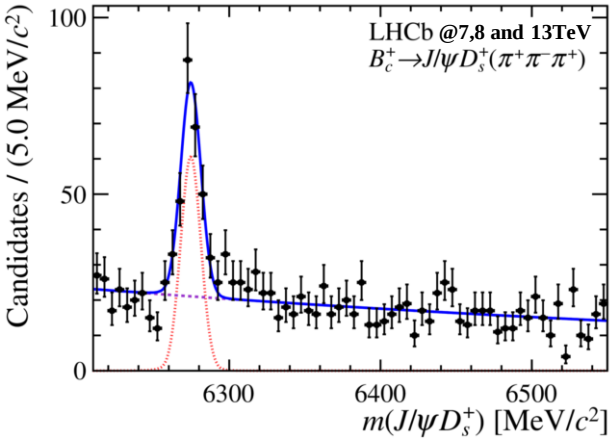
B_c^+ mass spectrum

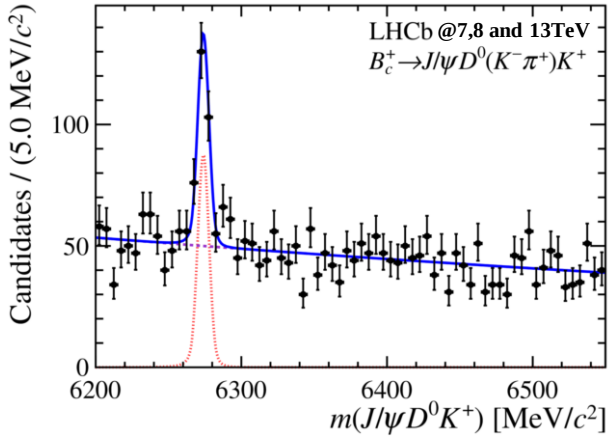


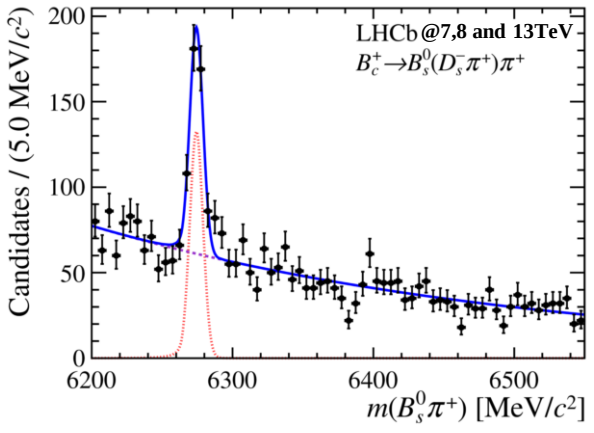


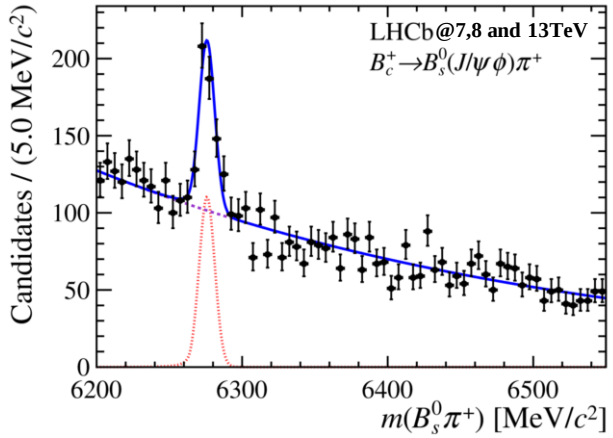






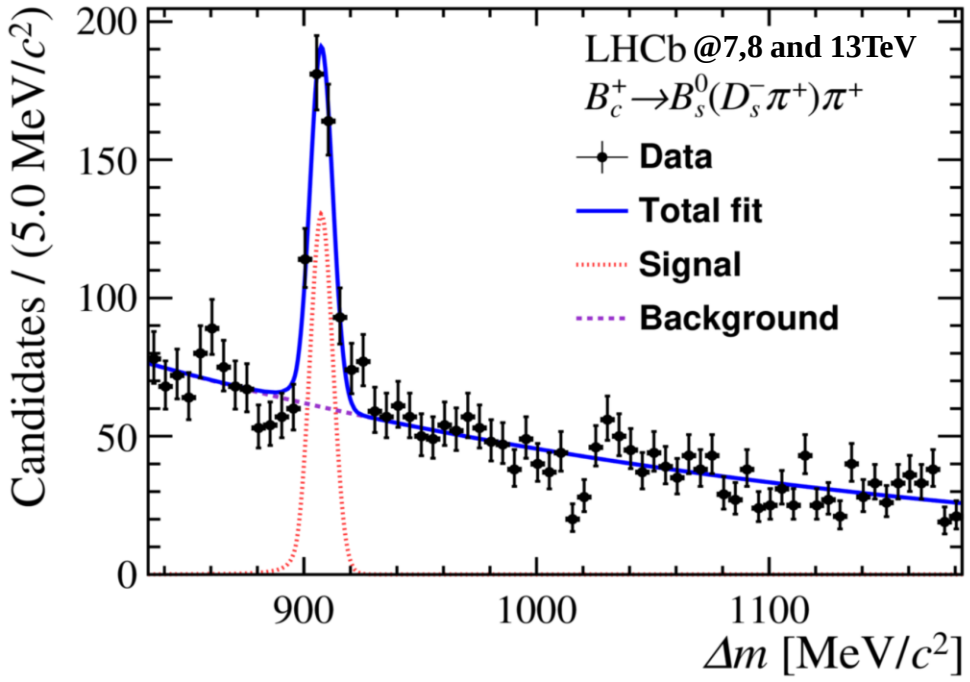


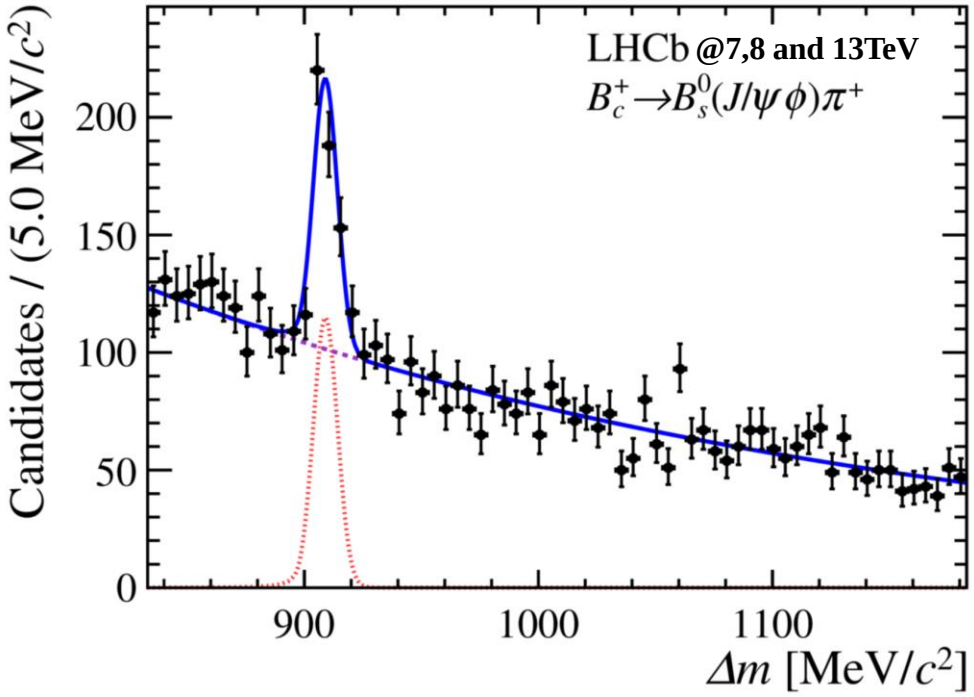




Mass difference

$B_c^+ - B_s^0$ mass difference





Correction & systematic uncertainties

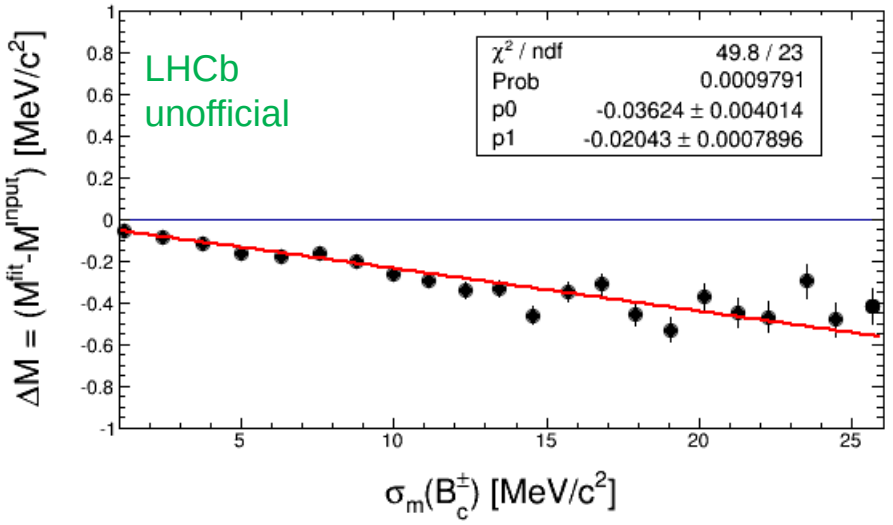
- **Correction**
  - Signal line shape (Final state radiation)
  - Bias caused by event selection
- **Uncertainties**
  - Momentum scale calibration
  - Energy loss correction
  - Fit model
    - Signal line shape
    - Background line shape
  - Particle mass uncertainties
  - Selection bias

Correction due to FSR

- Signal line shape (Final state radiation)
- Bias caused by event section

- Mass bias due to the loss energy of gamma. ΔM = M (measured mass) - M (generated mass) as a function of resolution.

- $\text{Correction} = -(p0 + p1 * x)$
- Uncertainty is related to signal line shape.



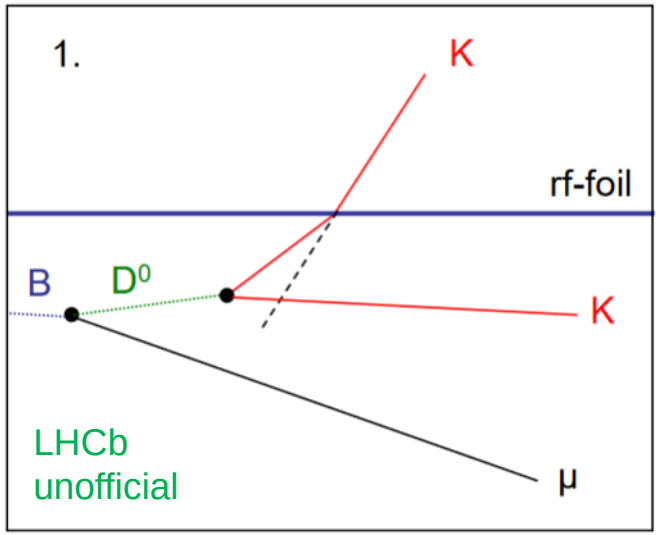
$B_c^+ \to J/\psi D^0(\pi^+K^-)K^+$:
Correction=0.13 MeV.

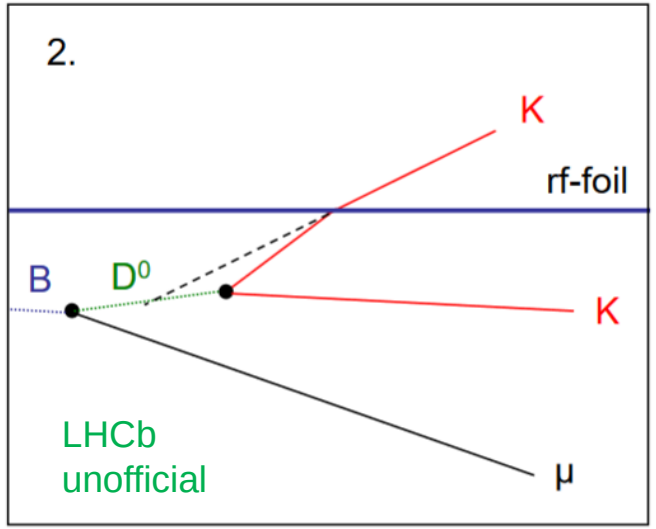
Correction due to event-selection

- Signal line shape (Final state radiation)

- Bias caused by event selection

- Multiple scattering in RF foil. Cause the correlation between mass and event selection.
- Estimated by fitted mass with events before and after all the event selection.





Summary of corrections

Correction of all decays:

$$\mathrm{M}_{B_c^+}(fitted\ mass) = \mathrm{M}_{B_c^+}(original\ mass) + \mathrm{Cor.(FSR)} + \mathrm{Cor.(Selection)}$$

Mass spectrum

Final states	Source [MeV/c^2]	
	FSR	Selection bias
$J/\psi\,\pi^+$	0.24	-0.17
$J/\psi\,2\pi^+\pi^-$	0.27	-0.15
$J/\psi\,p\bar{p}\pi^+$	0.05	-0.10
$J/\psi\,D_s^+(\pi^+K^+K^-)$	-0.01	0.03
$J/\psi\,D_s^+(\pi^+\pi^+\pi^-)$	-0.31	0.03
$J/\psi\,D^0(\pi^+K^-)K^+$	0.13	-0.02
$B_s^0(D_s^+\pi^-)\pi^+$	0.09	-0.37
$B_s^0(J/\psi\,\phi)\pi^+$	0.05	-0.46

Mass difference

Final states	Source [MeV/c^2]	
	FSR	Selection bias
$B_s^0(D_s^+\pi^-)\pi^+$	0.09	-0.36
$B_s^0(J/\psi\,\phi)\pi^+$	0.05	-0.44

Systematic uncertainties

Uncertainties of all decays:

Mass spectrum

Table 3: Summary of systematic uncertainties (in MeV/c^2) on the B_c^+ mass.

dominant

Decay mode	Momentum scale calibration	Energy loss correction	Signal model	Background model	Intermediate states	Selection	Total
$J/\psi\pi^+$	0.91	0.02	0.10	0.01	<0.01	0.01	0.92
$J/\psi\pi^+\pi^-\pi^+$	0.83	0.04	0.10	0.02	<0.01	0.05	0.84
$J/\psi p\bar{p}\pi^+$	0.35	0.04	0.10	0.01	<0.01	0.06	0.37
$J/\psi D_s^+(K^+K^-\pi^+)$	0.36	0.04	0.10	0.02	0.07	0.02	0.38
$J/\psi D_s^+(\pi^+\pi^-\pi^+)$	0.36	0.04	0.10	0.02	0.07	0.03	0.38
$J/\psi D^0(K^-\pi^+)K^+$	0.25	0.04	0.10	0.01	0.05	0.02	0.28
$B_s^0(D_s^-\pi^+)\pi^+$	0.23	0.04	0.10	<0.01	0.21	0.12	0.43
$B_s^0(J/\psi\phi)\pi^+$	0.23	0.04	0.10	0.01	0.21	0.02	0.41

Mass difference

Table 4: Summary of systematic uncertainties on the mass difference ΔM (in MeV/c^2) for the $B_s^0(D_s^-\pi^+)\pi^+$ and $B_s^0(J/\psi\phi)\pi^+$ decays.

Decay mode	Momentum scale calibration	Energy loss	Signal model	Background model	Intermediate states	Selection	Total
$B_s^0(D_s^-\pi^+)\pi^+$	0.23	0.04	0.10	0.01	<0.01	0.13	0.29
$B_s^0(J/\psi\phi)\pi^+$	0.23	0.04	0.10	<0.01	<0.01	0.02	0.25

Combination

[JHEP 07(2020)123]

- Combination method: BLUE (Best linear unbiased estimates)
- B_c^+ mass measured with 8 decay channels with Run-I & Run-II data.

- Combined results:

$M(B_c^+) = 6274.47 \pm 0.27\ (stat.) \pm 0.17\ (syst.)$ MeV/c^2
$= 6274.47 \pm 0.32$ MeV/c^2

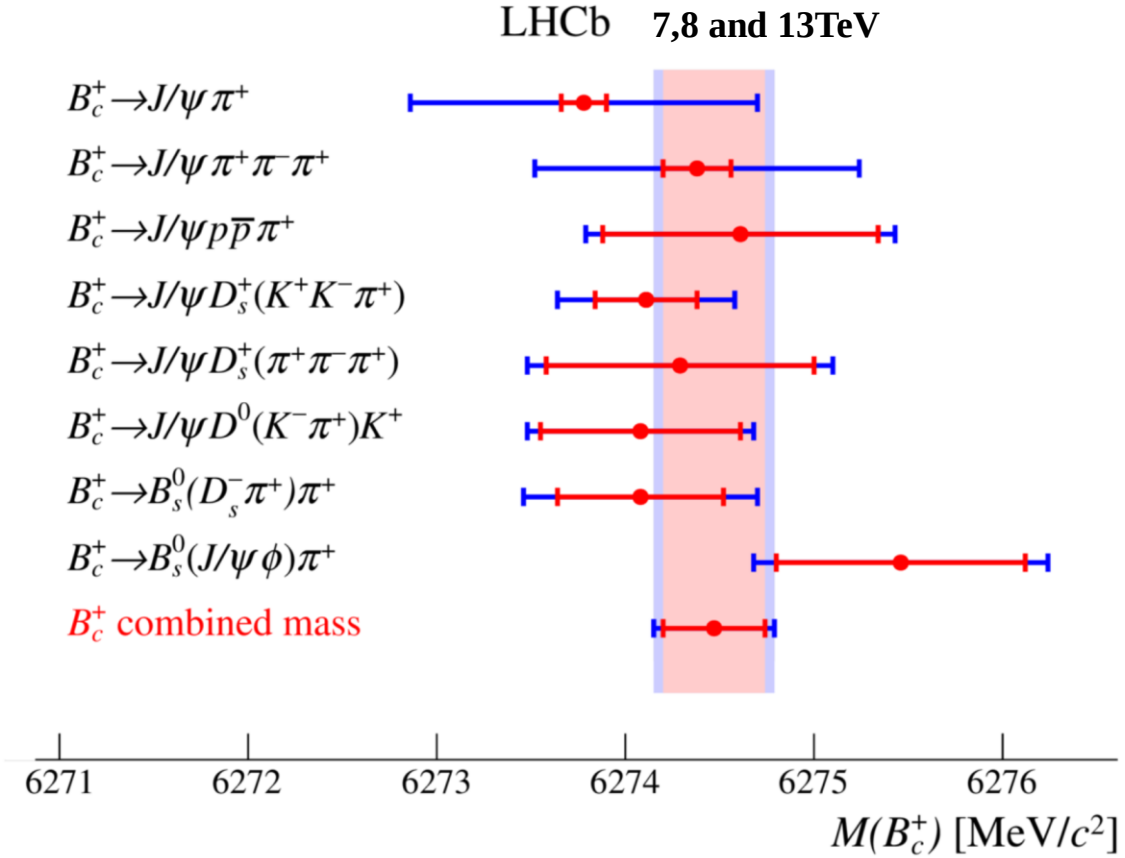
- Compare with current result by PDG:

$M(B_c^+) = 6274.9 \pm 0.8$ MeV/c^2

- Compare with Lattice QCD result:

$M(B_c^+) = 6278(6)(4)$MeV /c^2

Most precise measurement of B_c^+ mass to date.

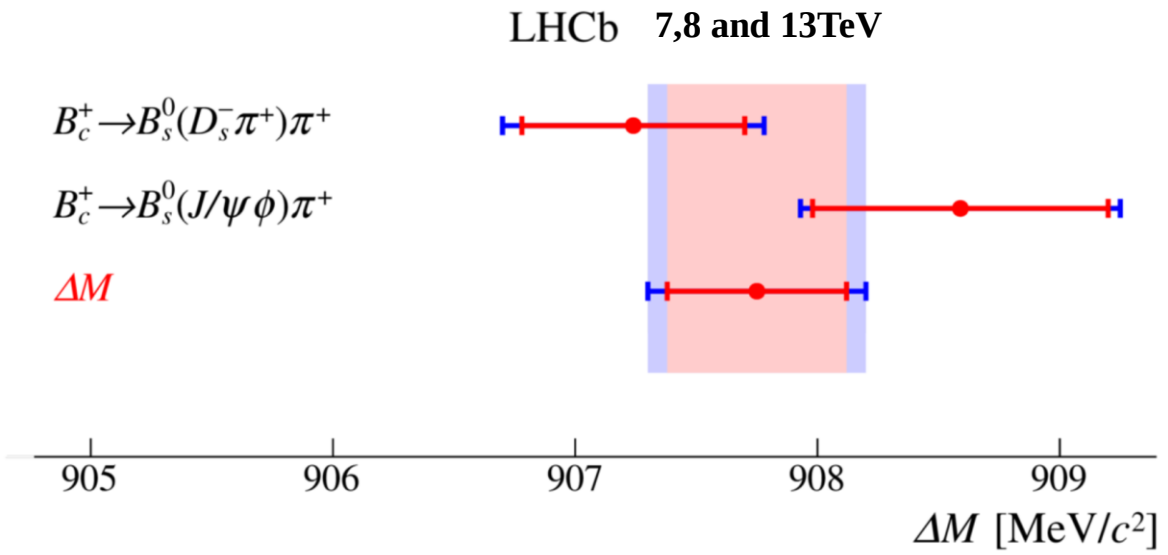


Combination of mass difference

[JHEP 07(2020)123]

- First measurement of $B_c^+ - B_s^0$ mass difference with 2 decay channels with Run-I & Run-II data.
- Combined results:

$$\Delta M(B_c^+) = 907.75 \pm 0.37\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{MeV}/c^2 = 907.75 \pm 0.46\ \text{MeV}/c^2$$



Thank you!

Backup

B_c^+ spectrum

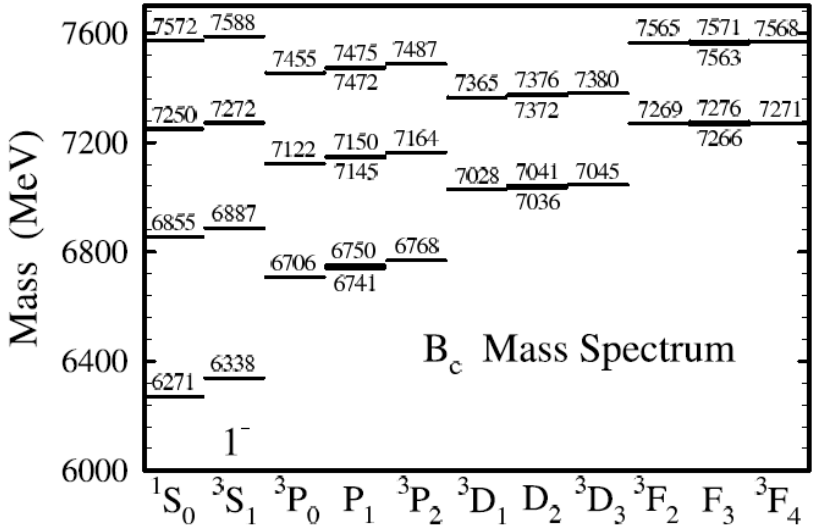
- Rich spectrum for B_c^+
- Theory model: potential model, lattice QCD, pQCD, etc.

Potential model: $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r$

Lattice QCD: non-perturbative QCD

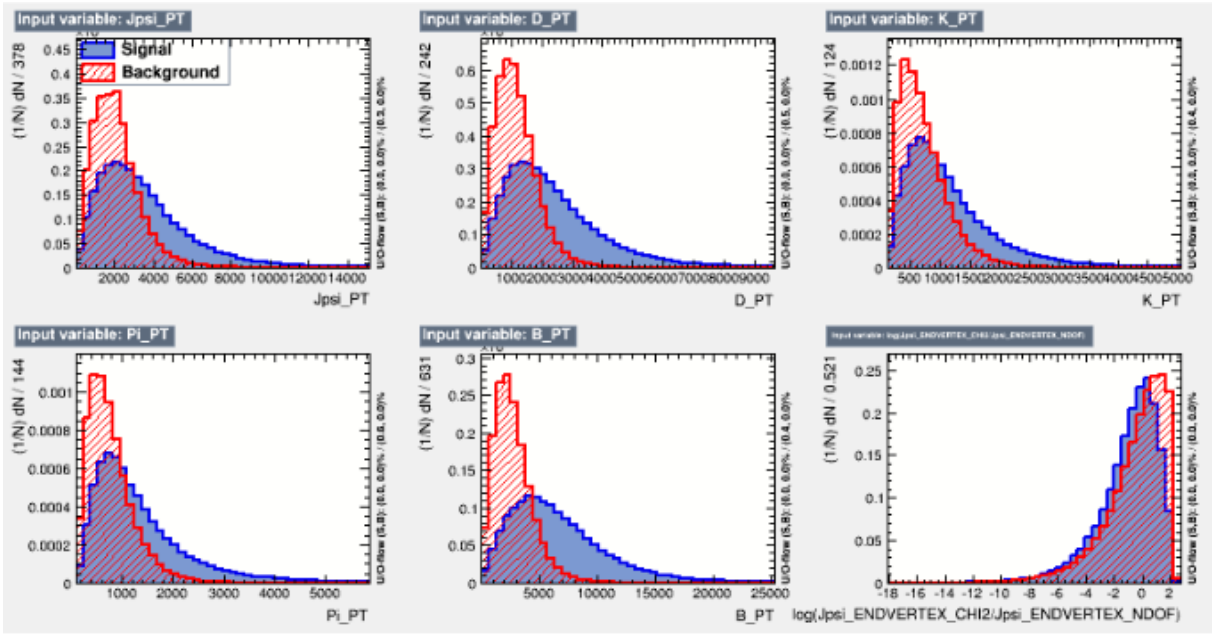
State	Present	[46]	[27]	[63]	[95]	PDG [7]
1^1S_0	6.272	6.278	6.272	6.271	6.275	6.275
1^3S_1	6.321	6.331	6.333	6.338	6.314	–
2^1S_0	6.864	6.863	6.842	6.855	6.838	6.842
2^3S_1	6.900	6.873	6.882	6.887	6.850	–
3^1S_0	7.306	7.244	7.226	7.250	–	–
3^3S_1	7.338	7.249	7.258	7.272	–	–
4^1S_0	7.684	7.564	7.585	–	–	–
4^3S_1	7.714	7.568	7.609	–	–	–
5^1S_0	8.025	7.852	7.928	–	–	–
5^3S_1	8.054	7.855	7.947	–	–	–
6^1S_0	8.340	8.120	–	–	–	–
6^3S_1	8.368	8.122	–	–	–	–

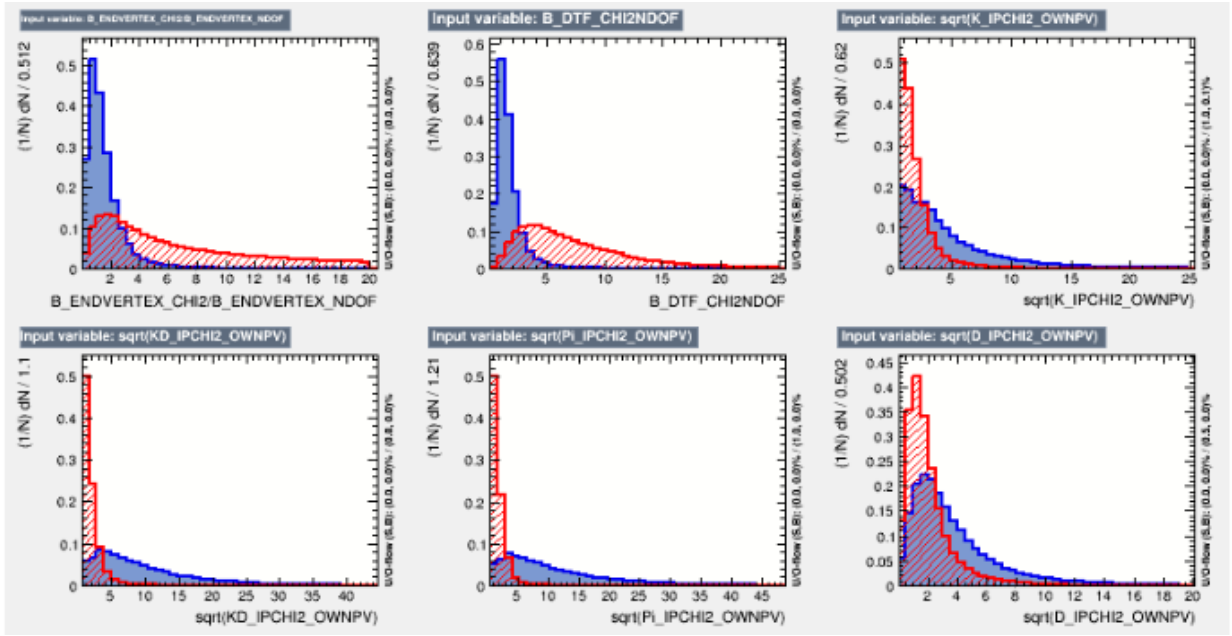
[Eur. Phys. J. C (2018) 78:592]

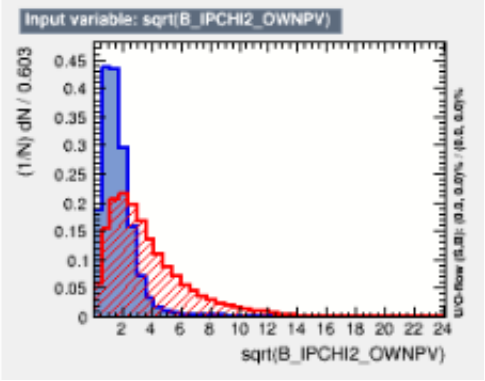


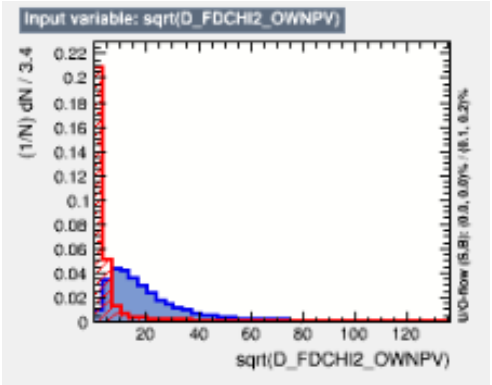
[PRD 70 (2004) 054017]

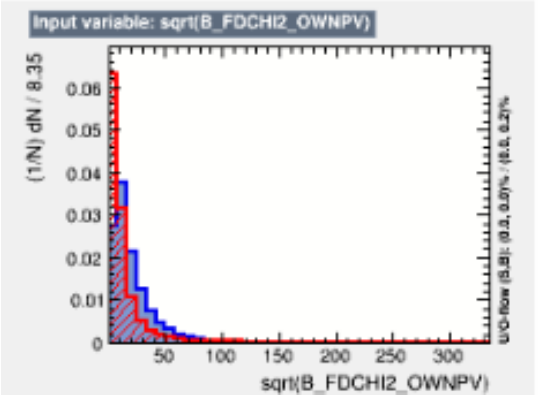
Training variables

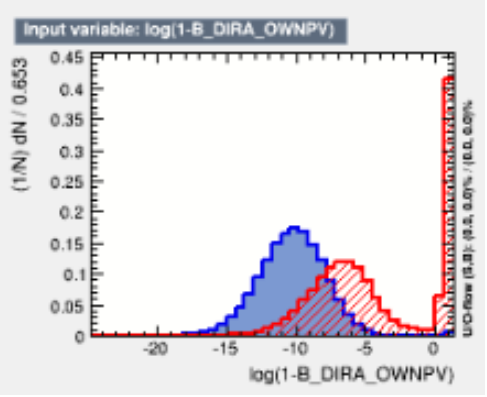




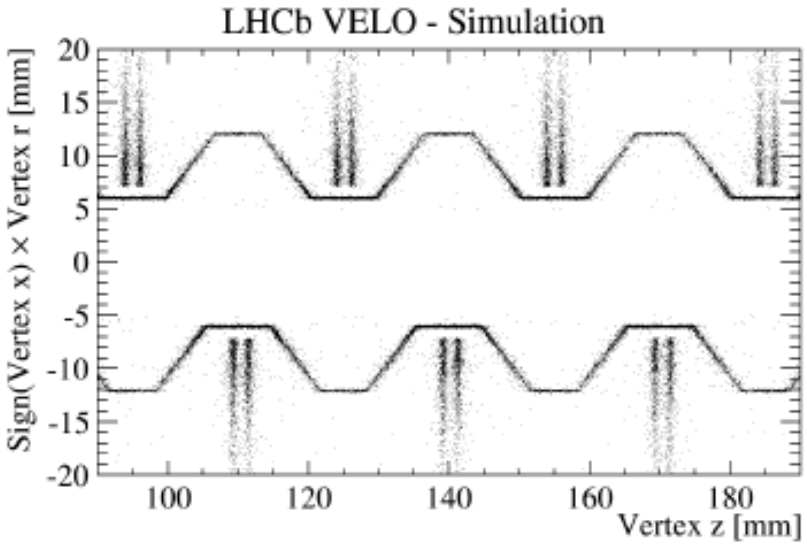






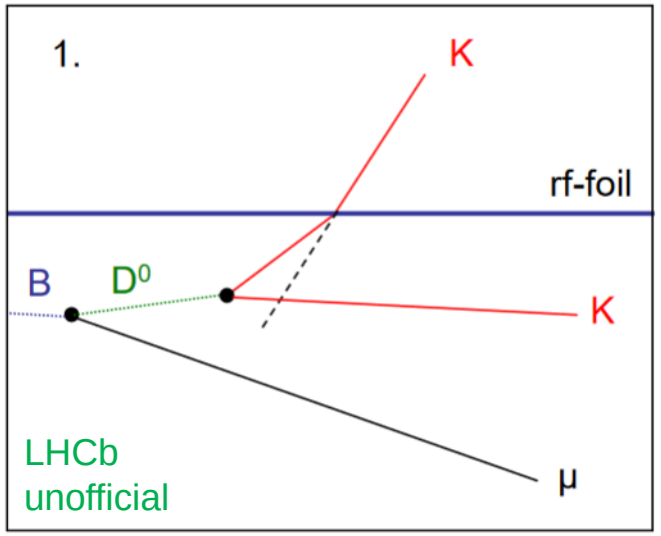


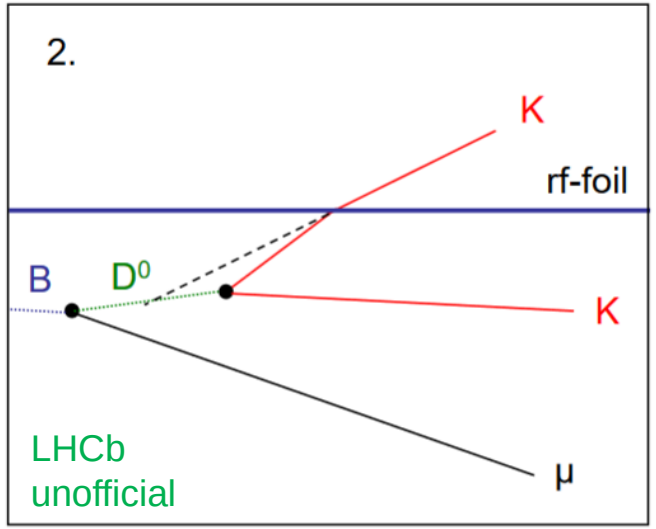
RF foil



[CERN-LHCb-DP-2014-001]

- RF-foil is the dominant material in VELO, in which different open angle can lead to a shift in lifetime that refers to a bias in mass measurement.





Yields

Mass spectrum

Decay mode	Yield	Fitted mass $[\mathrm{MeV}/c^2]$	Corrected mass $[\mathrm{MeV}/c^2]$	Resolution $[\mathrm{MeV}/c^2]$
$J/\psi\pi^+$	25181 ± 217	6273.71 ± 0.12	6273.78 ± 0.12	13.49 ± 0.11
$J/\psi\pi^+\pi^-\pi^+$	9497 ± 142	6274.26 ± 0.18	6274.38 ± 0.18	11.13 ± 0.18
$J/\psi p\bar{p}\pi^+$	273 ± 29	6274.66 ± 0.73	6274.61 ± 0.73	6.34 ± 0.76
$J/\psi D_s^+(K^+K^-\pi^+)$	1135 ± 49	6274.09 ± 0.27	6274.11 ± 0.27	5.93 ± 0.30
$J/\psi D_s^+(\pi^+\pi^-\pi^+)$	202 ± 20	6274.57 ± 0.71	6274.29 ± 0.71	6.63 ± 0.67
$J/\psi D^0(K^-\pi^+)K^+$	175 ± 21	6273.97 ± 0.53	6274.08 ± 0.53	3.87 ± 0.57
$B_s^0(D_s^-\pi^+)\pi^+$	316 ± 27	6274.36 ± 0.44	6274.08 ± 0.44	4.67 ± 0.48
$B_s^0(J/\psi\phi)\pi^+$	299 ± 37	6275.87 ± 0.66	6275.46 ± 0.66	5.32 ± 0.74

Mass difference

Decay mode	Yield	Fitted ΔM $[\mathrm{MeV}/c^2]$	Corrected ΔM $[\mathrm{MeV}/c^2]$	Resolution $[\mathrm{MeV}/c^2]$
$B_s^0(D_s^-\pi^+)\pi^+$	325 ± 27	907.51 ± 0.46	907.24 ± 0.46	4.88 ± 0.47
$B_s^0(J/\psi\phi)\pi^+$	300 ± 32	908.98 ± 0.61	908.59 ± 0.61	5.12 ± 0.62

Systematic uncertainties

- Momentum scale calibration
- Energy loss correction
- Fit model
  - Signal line shape
  - Background line shape
- Particle mass Uncertainties
- Selection bias

- Uncertainties = $Q * 0.3 * 10^{-3}$.

[JHEP06 (2013) 065]

Decay channels	Q value [MeV]	Mass uncertainties [MeV]
$B_c^+ \to J/\psi D^0 K^+$	819	0.25
$B_c^+ \to B_s^0 \pi^+$	768	0.23
$B_c^+ \to J/\psi D_s^+$	1210	0.36
$B_c^+ \to J/\psi 3\pi$	2759	0.83
$B_c^+ \to J/\psi \pi$	3038	0.91
$B_c^+ \to J/\psi p\bar{p}\pi^+$	1162	0.35

Systematic uncertainties

- Momentum scale calibration
- Energy loss correction
- Fit model
  - Signal line shape
  - Background line shape
- Particle mass Uncertainties
- Selection bias

- Scale from the D^0 mass measurement.

[JHEP06 (2013) 065]

Decay channels	$N_{final\ states}$	Mass uncertainties [MeV]
$B_c^+ \to J/\psi D^0 K^+$	5	0.04
$B_c^+ \to B_s^0 \pi^+$	5	0.04
$B_c^+ \to J/\psi D_s^+$	5	0.04
$B_c^+ \to J/\psi 3\pi$	5	0.04
$B_c^+ \to J/\psi \pi$	3	0.02
$B_c^+ \to J/\psi p\bar{p}\pi^+$	5	0.04

Systematic uncertainties

- Momentum scale calibration
- Energy loss correction
- Fit model
  - Signal line shape
  - Background line shape
- Particle mass Uncertainties
- Selection bias

- Study with different modes in $J/\psi\pi^+$ decay:

	Mass (in MeV/c^2)	
	Fitted	Corrected
DSCB	6276.731 ± 0.017	6277.057 ± 0.017
Double gaussian	6276.616 ± 0.017	6277.088 ± 0.017
Hypatia	6276.722 ± 0.017	6277.060 ± 0.017

- Applying correction due to FSR.
- Agree within 0.1 MeV, taken as systematic uncertainty.

Systematic uncertainties

- Momentum scale calibration
- Energy loss correction
- Fit model
  - Signal line shape
  - Background line shape
- Particle mass Uncertainties
- Selection bias

- For Background line shape, the difference measurement between exponential and Chebyshev function has been compared.

Decay channels	Sig shape[MeV]	Bkg shape [MeV]
$B_c^+ \to J/\psi D^0(\pi^+K^-)K^+$	0.1	0.01
$B_c^+ \to B_s^0(D_s^-\pi^+)\pi^+$		0
$B_c^+ \to B_s^0(J/\psi\phi)\pi^+$		0.01
$B_c^+ \to J/\psi D_s^+(3\pi)$		0.02
$B_c^+ \to J/\psi D_s^+(KK\pi)$		0.02
$B_c^+ \to J/\psi 3\pi$		0.02
$B_c^+ \to J/\psi\pi$		0.01
$B_c^+ \to J/\psi p\bar{p}\pi^+$		0.01

Systematic uncertainties

- Momentum scale calibration
- Energy loss correction
- Fit model
  - Signal line shape
  - Background line shape
- Particle mass Uncertainties
- Selection bias

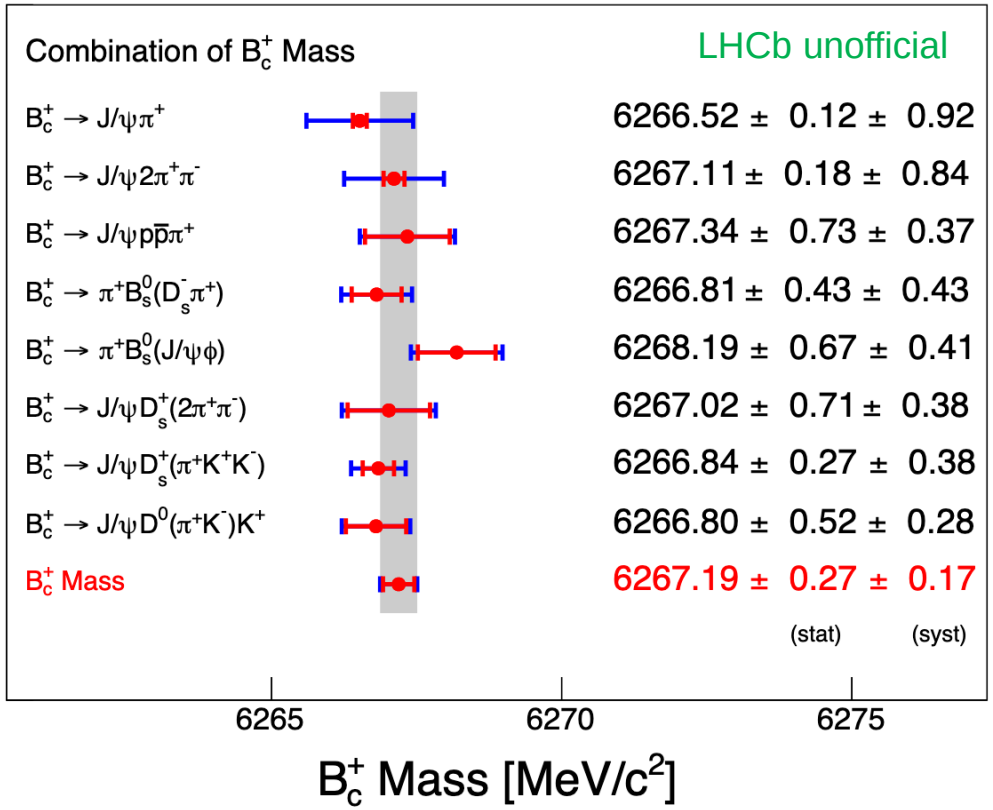
- The mass uncertainty of B_s^0, D^0, and D_s^+ taken into account, propagated to M(B_c^+).

Decay channels	Mass uncertainties [MeV]
$B_c^+ \to J/\psi D^0 K^+$	0.05
$B_c^+ \to B_s^0 \pi^+$	0.21
$B_c^+ \to J/\psi D_s^+$	0.07
$B_c^+ \to J/\psi 3\pi$	0
$B_c^+ \to J/\psi \pi$	0
$B_c^+ \to J/\psi p\bar{p}\pi^+$	0

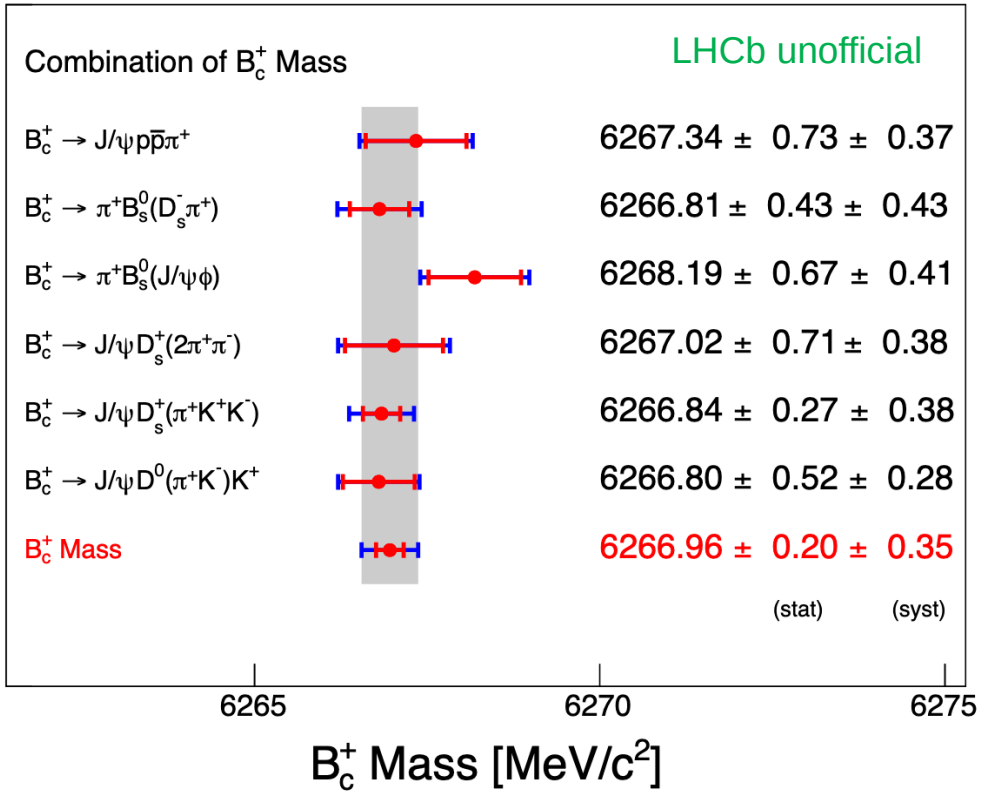
BLUE method

Excluding decays with negative weight, check with unblinded results

All decays



Only positive weights

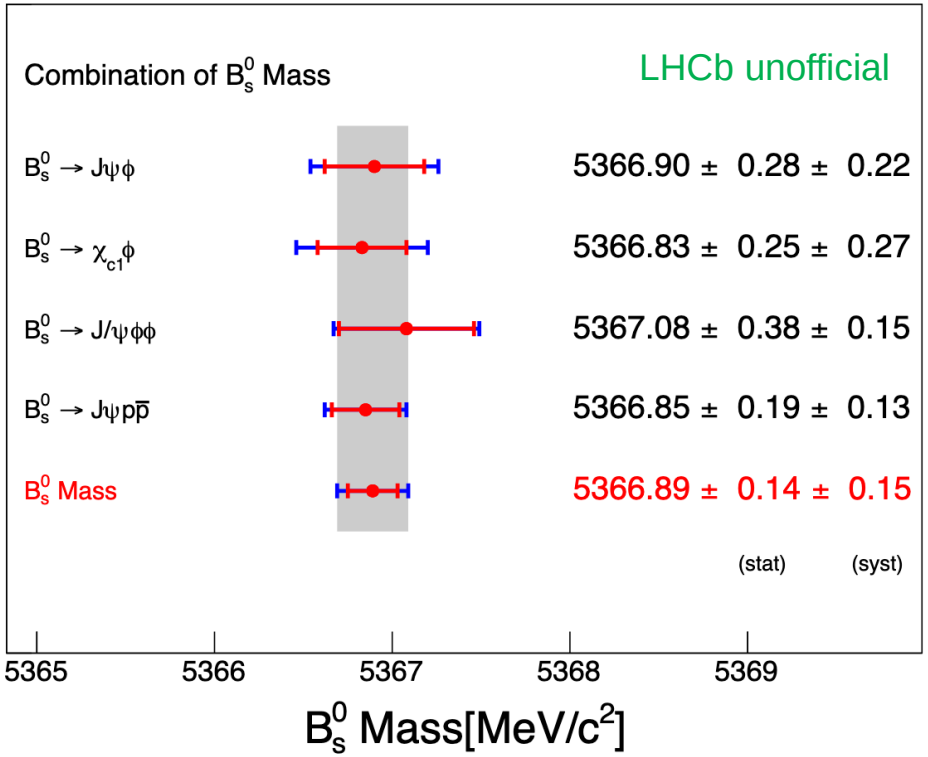


Mass uncertainty

- Only the mass of B_s^0 dominated by LHCb

Particle	Measurement [MeV/c^2]	Dominant collaboration
$D_s^{\pm}$	1968.34±0.07	ACCMOR
D^0	1864.83±0.05	CLEO
B_s^0	5366.88±0.17	LHCb

- Combine with LHCb measurements of B_s^0 mass

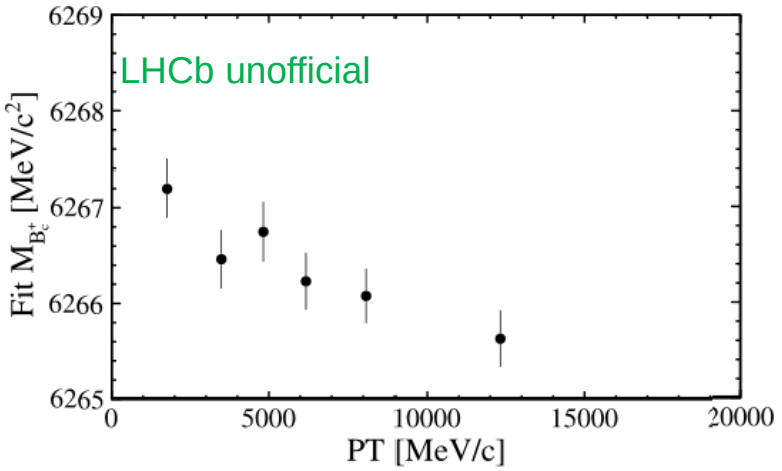


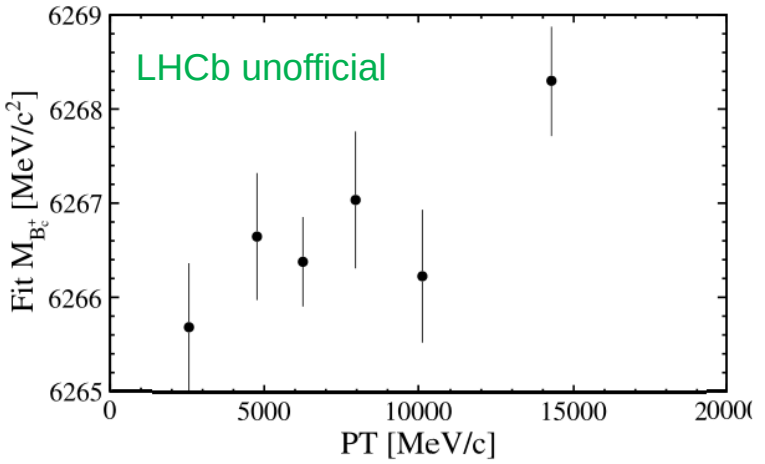
$$\mathrm{M}(B_s^0) = 5366.89 \pm 0.14\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst})\,\mathrm{MeV}/c^2 = 5366.89 \pm 0.21\,\mathrm{MeV}/c^2.$$

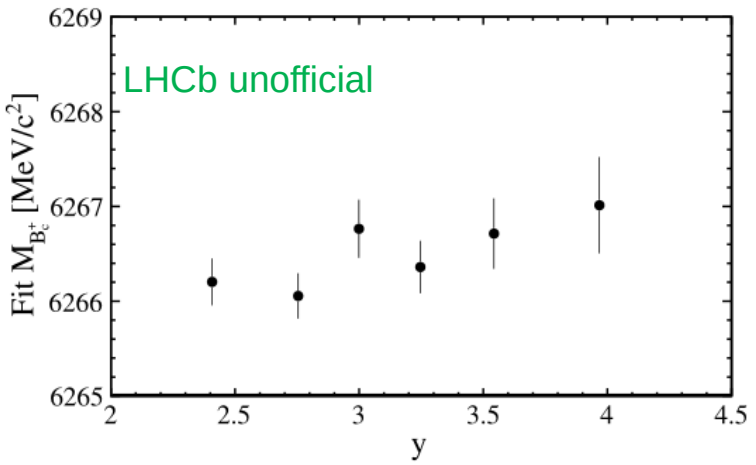
p_T dependence

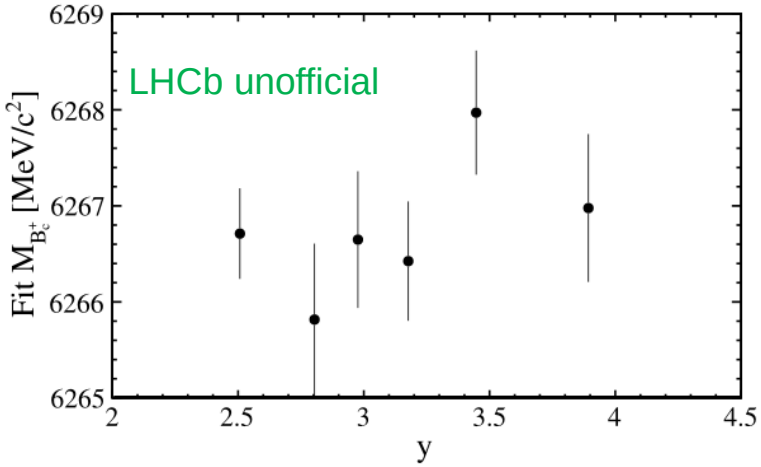
Mainly caused by material budget description in the reconstruction.

The fitted mass averaged over p_T range away from the true mass of B_c^+: p_T dependence can be included in momentum scale calibration(0.03%).



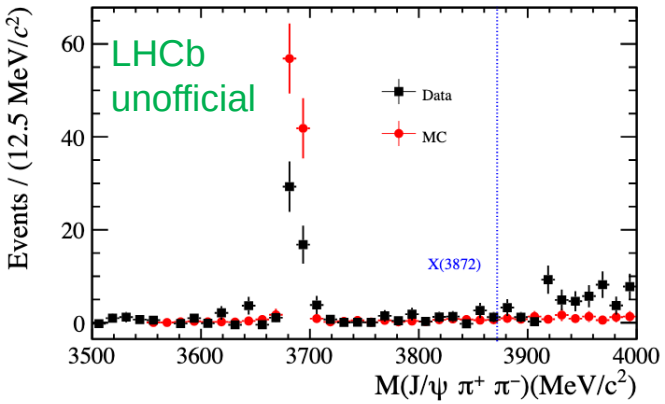




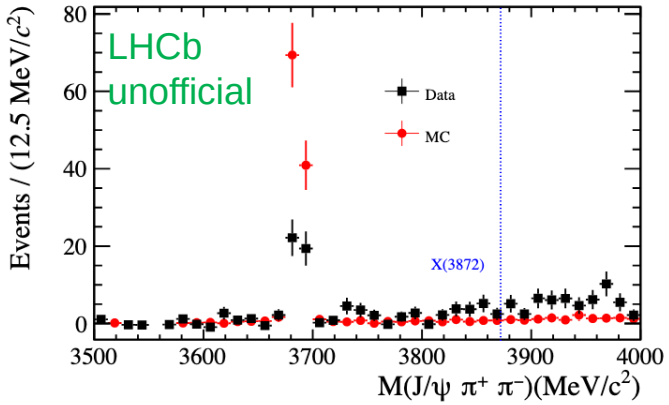


Exotic states

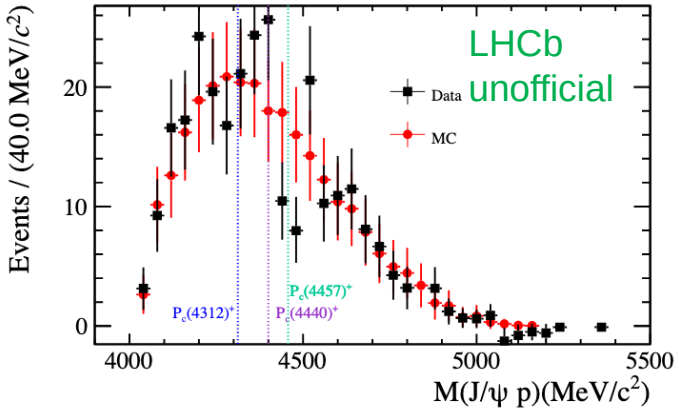
- Check exotic states in B_c^+ decays



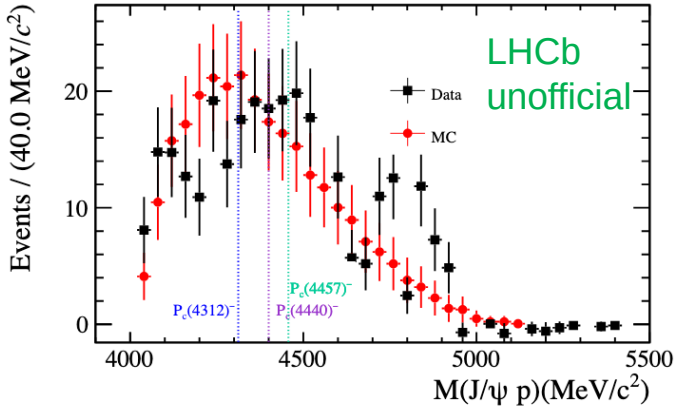
(a) $\mathrm{M}(J/\psi\pi^+{}_1\pi^-)$



(b) $\mathrm{M}(J/\psi\pi^+{}_2\pi^-)$



(a) $\mathrm{M}(J/\psi p)$



(b) $\mathrm{M}(J/\psi\bar{p})$

Combination

- Combination method: BLUE (Best linear unbiased estimates)
  Nucl. Instrum. Meth.A270(1988) 110&Nucl. Instrum. Meth.A500(2003) 391.

- Correlation for different sources of systematics:
  - Between decays
    - Correction = 100%:
      - Momentum scale calibration
      - Energy loss
      - Signal line shape
    - Correlation = 0%
      - Background line shape
      - Mass uncertainty
      - Event Selection
  - Between different sources
    - Momentum scale calibration and B_s^0 mass uncertainty: 100%