Studies of B_c^+ mesons at LHCb

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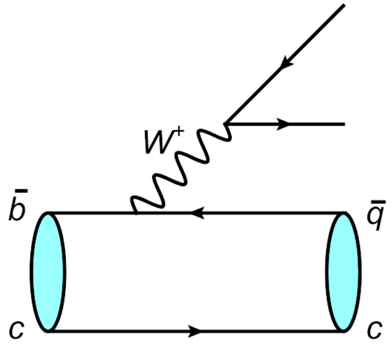
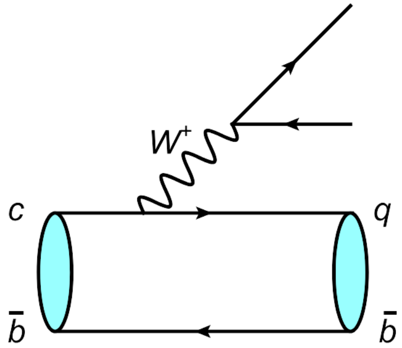
B_c^+ meson

- **Heavy quarkonium:** ideal system to probe QCD both theoretically and experimentally
- **The B_c^+ meson:** only ground-state meson composed of two different heavy quarks ($\bar{b}c$)
  - ✓ Opportunity: unique features to extract information on both QCD dynamics and weak interactions
    - ⇒ the heaviest among known meson (~6.27 GeV), decay time (~0.5 ps) three times shorter than B^+
    - ⇒ rich decay modes through weak interaction

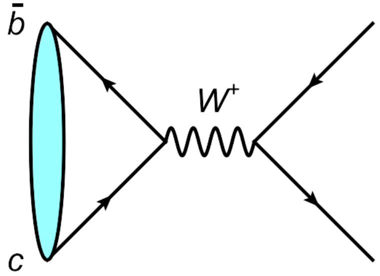
$b \to c$ transition (~30%)	$c \to s$ transition (~60%)	$\bar{b}c \to W^+ \to \bar{q}q$ (~10%)



e.g. $B_c^+ \to J/\psi\, \pi^+$

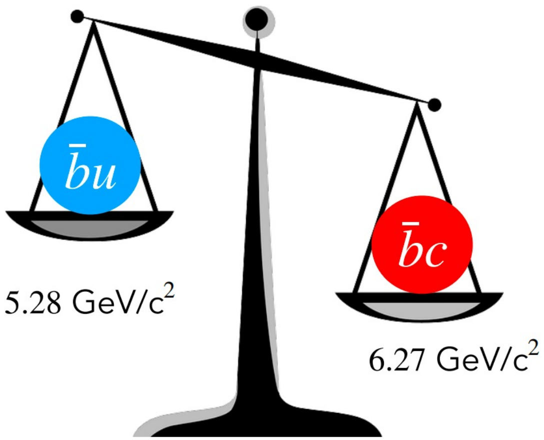


e.g. $B_c^+ \to B_s^0 \pi^+$



e.g. $B_c^+ \to D^0 K^+$

Heavier, shorter-lived than B^+ hence less efficient to detect

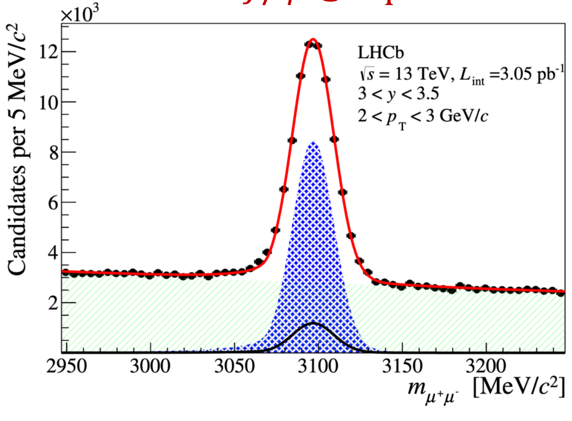


B_c^+ meson

- **The B_c^+ meson:** only ground-state meson composed of two different heavy quarks ($\bar{b}c$)
  - ✓ Opportunity: unique features to extract information on both QCD dynamics and weak interactions
  - ✗ Challenge: limited knowledge in experimental study
    - ⇒ unreachable in current e^+e^- colliders
    - ⇒ suppressed in hadron colliders as it requires simultaneous $\bar{c}c$ and $\bar{b}b$ pair production

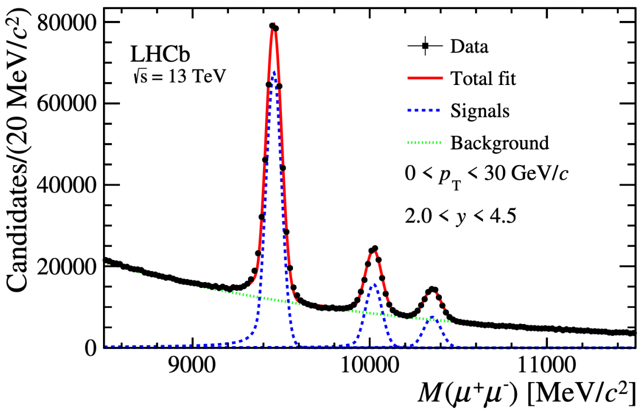
$$N(J/\psi) : N\big(\Upsilon(1S)\big) : N(B_c^+) = 100\text{k} : 0.4\text{k} : 1 \text{ @ LHCb}$$

$\sim$1M J/ψ @ 3 pb^{-1}



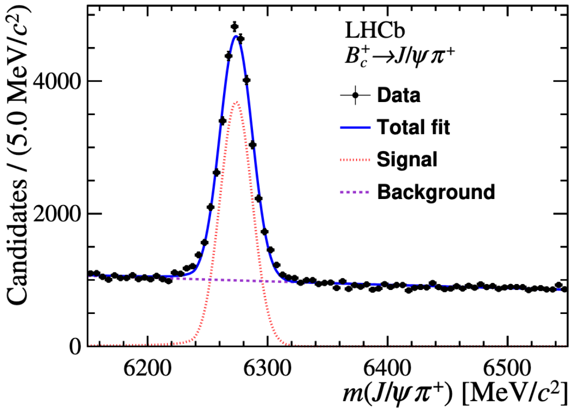
[JHEP 10 (2015) 172]

$\sim$0.44M $\Upsilon(1S)$ @ 277 pb^{-1}



[JHEP 07 (2018) 134]

$\sim$25k $B_c^+(\to J/\psi\,\pi^+)$ @ 9 fb^{-1}



[JHEP 07 (2020) 123]

Studies of B_c^+ mesons at LHCb

- The LHCb plays a leading role in the study of the B_c^+ meson
  - ✓ Mass, lifetime measurements → dominating world average
  - ✓ Various studies of new decay modes and production

- This talk will focus on the **recent progress on B_c^+ studies** at LHCb:
  - New measurement of B_c^+ decays into single charm final states [LHCb-PAPER-2024-035, in prep.] — New decay
  - Observation of $B_c^+ \to D h^+ h^-$ decays [LHCb-PAPER-2025-028, in prep.] — New decay
  - Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay [JHEP 06 (2025) 013] — Exotic related
  - Observation of the orbitally excited B_c^+ states [arXiv:2507.02149] [arXiv:2507.02142] — New state
  - Observation of $B_c^+ \to J/\psi\, \pi^+\pi^0$ decay [Not discussed] [JHEP 04 (2024) 151] — New decay

Γ_1	$J/\psi(1S)\ell^+\nu_\ell$ anything	seen
Γ_2	$J/\psi(1S)\mu^+\nu_\mu$	seen
Γ_3	$J/\psi(1S)\tau^+\nu_\tau$	seen
Γ_4	$J/\psi(1S)\pi^+$	seen
Γ_5	$J/\psi(1S)K^+$	seen
Γ_6	$J/\psi(1S)\pi^+\pi^+\pi^-$	seen
Γ_7	$J/\psi(1S)K^+\pi^-\pi^+$	
Γ_8	$J/\psi(1S)K^+K^-K^+$	
Γ_9	$J/\psi(1S)a_1(1260)$	not seen
Γ_{10}	$J/\psi(1S)K^+K^-\pi^+$	seen
Γ_{11}	$J/\psi(1S)\pi^+\pi^+\pi^+\pi^-\pi^-$	seen
Γ_{12}	$\psi(2S)\pi^+$	seen
Γ_{13}	$\psi(2S)\pi^+\pi^-\pi^+$	
Γ_{14}	$\psi(2S)K^+K^-\pi^+$	
Γ_{15}	$J/\psi(1S)D^0K^+$	seen
Γ_{16}	$J/\psi(1S)D^*(2007)^0K^+$	seen
Γ_{17}	$J/\psi(1S)D^*(2010)^+K^{*0}$	seen
Γ_{18}	$J/\psi(1S)D^+K^{*0}$	seen
Γ_{19}	$J/\psi(1S)D_s^+$	seen
Γ_{20}	$J/\psi(1S)D_s^{*+}$	seen
Γ_{21}	$J/\psi(1S)p\bar{p}\pi^+$	seen
Γ_{22}	$\chi_{c0}\pi^+$	$(2.4^{+0.9}_{-0.8}) \times 10^{-5}$
Γ_{23}	$p\bar{p}\pi^+$	not seen
Γ_{24}	D^0K^+	seen
Γ_{52}	$B_s^0\pi^+$ / $B(\bar{b} \to B_s)$	seen

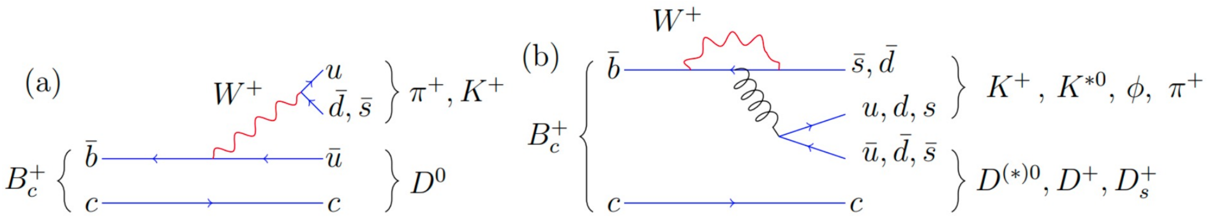
New measurement of B_c^+ decays into single charm final states

[LHCb-PAPER-2024-035, in prep.]

Preliminary

New measurement of $B_c^+ \to DX$ decays

- The $B_c^+ \to D^0 K^+$ was observed with 5.1σ significance of using Run1 data [LHCb-PAPER-2024-035, in prep.]



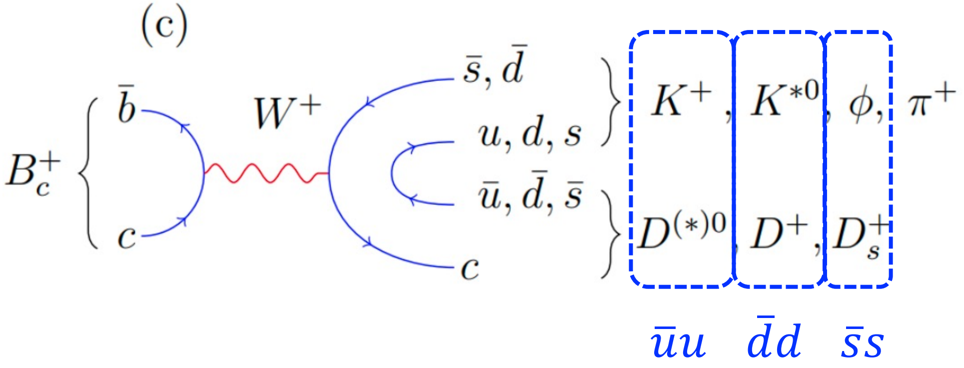
[JHEP 06 (2011) 015]

$R_{D^0K} = (f_c/f_u) \times \mathscr{B}(B_c^+ \to D^0K^+) = (9.3^{+2.8}_{-2.5} \pm 0.6) \times 10^{-7}$ seen

$R_{D^0\pi} = (f_c/f_u) \times \mathscr{B}(B_c^+ \to D^0\pi^+) < 3.9 \times 10^{-7}$ not seen

$\Rightarrow R_{D^0K}$ is nearly an order of magnitude larger than expectations from $b \to u$ and $b \to s$ transitions, and exceeds the theoretical predictions [PRL 118 (2017) 111803]

- The measurement suggests a dominance of **weak annihilation over $b \to u$ transition**



- Motivation: to further establish the dominance of annihilation, the following decays are studied using Run1 + Run2 data
  - ✓ $B_c^+ \to D^0K^+, B_c^+ \to D^0\pi^+$ (follow-up study)
  - ✓ $B_c^+ \to D^{*0}K^+(\bar{u}u),\ B_c^+ \to D^+K^{*0}(\bar{d}d),\ B_c^+ \to D_s^+\phi\ (\bar{s}s)$ (search for new decay modes)

New measurement of $B_c^+ \to DX$ decays

Conclusion

$A_{CP}(B_c^+ \to D^0 K^+) = 0.07 \pm 0.10 \pm 0.03$ *no asymmetry*

$R_{D^+K^{*0}} = (1.42 \pm 0.23 \pm 0.07 \pm 0.11) \times 10^{-6}$, *1st Observe.*

$R_{D^{*0}K^+} = (1.46 \pm 0.30 \pm 0.11 \pm 0.05) \times 10^{-6}$,

$R_{D_s^+\phi} = (4.0 \pm 1.3 \pm 0.2 \pm 0.5) \times 10^{-7}$, } *Evidence*

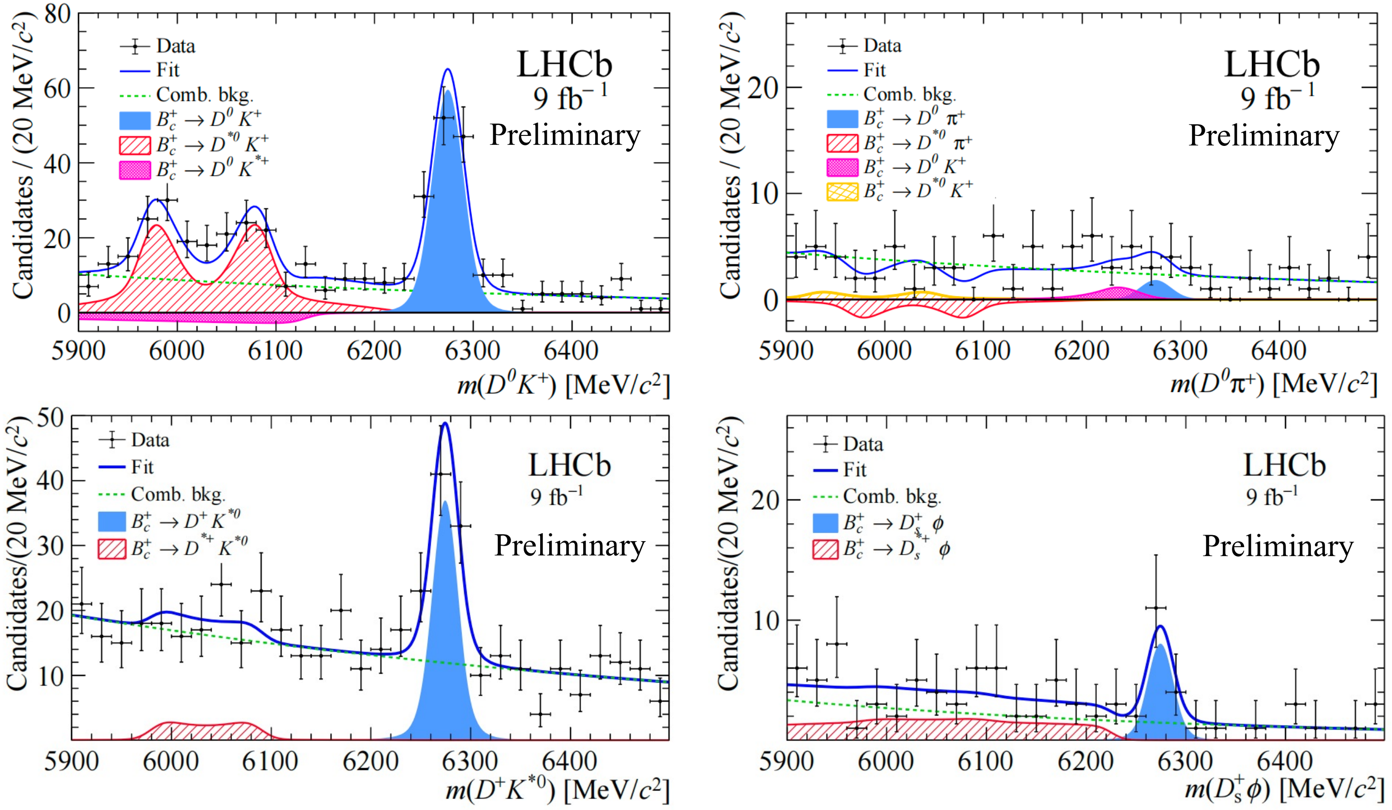
$R_{D^0K^+} = (9.7 \pm 1.0 \pm 0.4 \pm 0.3) \times 10^{-7}$,

$R_{D^0\pi^+} < 1.4 \times 10^{-7}$ (95 % CL). } *Improve.*

- *Final states requiring $\bar{s}s$ are significantly suppressed compared to light-quark states*
- *Vector meson modes ($D^{*0}K^+, D^+K^{*0}$) are about 1.5 × more likely than D^0K^+*

⇒ 2 orders of magnitude higher than expected from W-emission and penguin amplitudes, indicating the weak annihilation dominates in these B_c^+ decays

[LHCb-PAPER-2024-035, in prep.]



	$B_c^+ \to D^0K^+$	$B_c^+ \to D^+K^{*0}$	$B_c^+ \to D^{*0}K^+$	$B_c^+ \to D_s^+\phi$	$B_c^+ \to D^0\pi^+$
Yield	129 ± 14	64 ± 11	152 ± 32	14 ± 4	4 ± 4
Significance	$\sim 14.5\ \sigma$	$8.1\ \sigma$	$4.9\ \sigma$	$4.3\ \sigma$	$1.1\ \sigma$

Observation of $B_c^+ \to D h^+ h^-$ decays

[LHCb-PAPER-2025-028, in prep.]

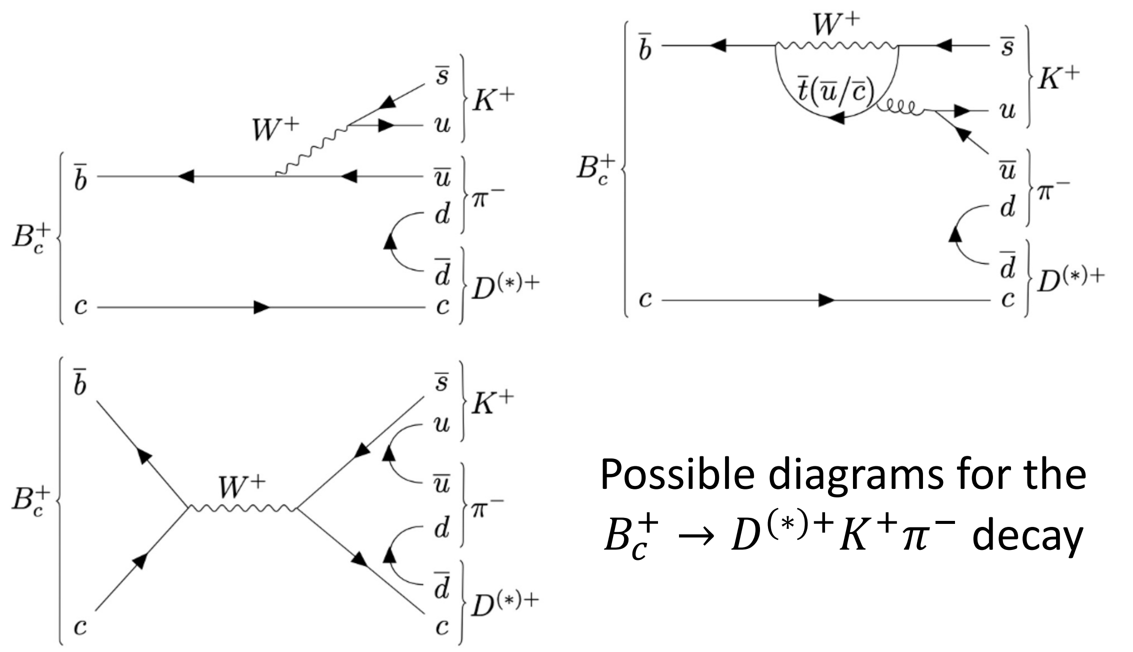
Preliminary

Observation of $B_c^+ \to Dh^+ h^-$ decays

- Complementary to the analysis of previous $B_c^+ \to DX$ decays [LHCb-PAPER-2025-028, in prep.]
  - ✗ Comparing to $B_c^+ \to DX$ decays, the three-body decays are theoretically challenging to predict
  - ✓ Experimentally, this study serves as a pathfinder for future CPV studies via new decay mode searches
- Aim to measure the BFs of $B_c^+ \to D^+K^+\pi^-, B_c^+ \to D^{*+}K^+\pi^-, B_c^+ \to D_s^+K^+K^-$
- Using $B_c^+ \to B_s^0\pi^+$ as the normalization channel
- The BF ratios are measured using Run1+Run2 data

$$\frac{\mathcal{B}(B_c^+ \to Dh^+h^-)}{\mathcal{B}(B_c^+ \to B_s^0\pi^+)} = \frac{N_{B_c^+ \to Dh^+h^-}}{N_{B_c^+ \to B_s^0\pi^+}} \cdot \frac{\varepsilon_{B_c^+ \to B_s^0\pi^+}}{\varepsilon_{B_c^+ \to Dh^+h^-}} \cdot \frac{\mathcal{B}(B_s^0)}{\mathcal{B}(D_{(s)}^{(*)+})}$$

Signal yield | Estimated from simulation | BF rom PDG



Possible diagrams for the $B_c^+ \to D^{(*)+}K^+\pi^-$ decay

Observation of $B_c^+ \to D h^+ h^-$ decays

- Complementary to the analysis of previous $B_c^+ \to DX$ decays [LHCb-PAPER-2025-028, in prep.]
  - ✗ Comparing to $B_c^+ \to DX$ decays, the three-body decays are theoretically challenging to predict
  - ✓ Experimentally, this study serves as a pathfinder for future CPV studies via new decay mode searches
- Aim to measure the BFs of $B_c^+ \to D^+K^+\pi^-, B_c^+ \to D^{*+}K^+\pi^-, B_c^+ \to D_s^+K^+K^-$
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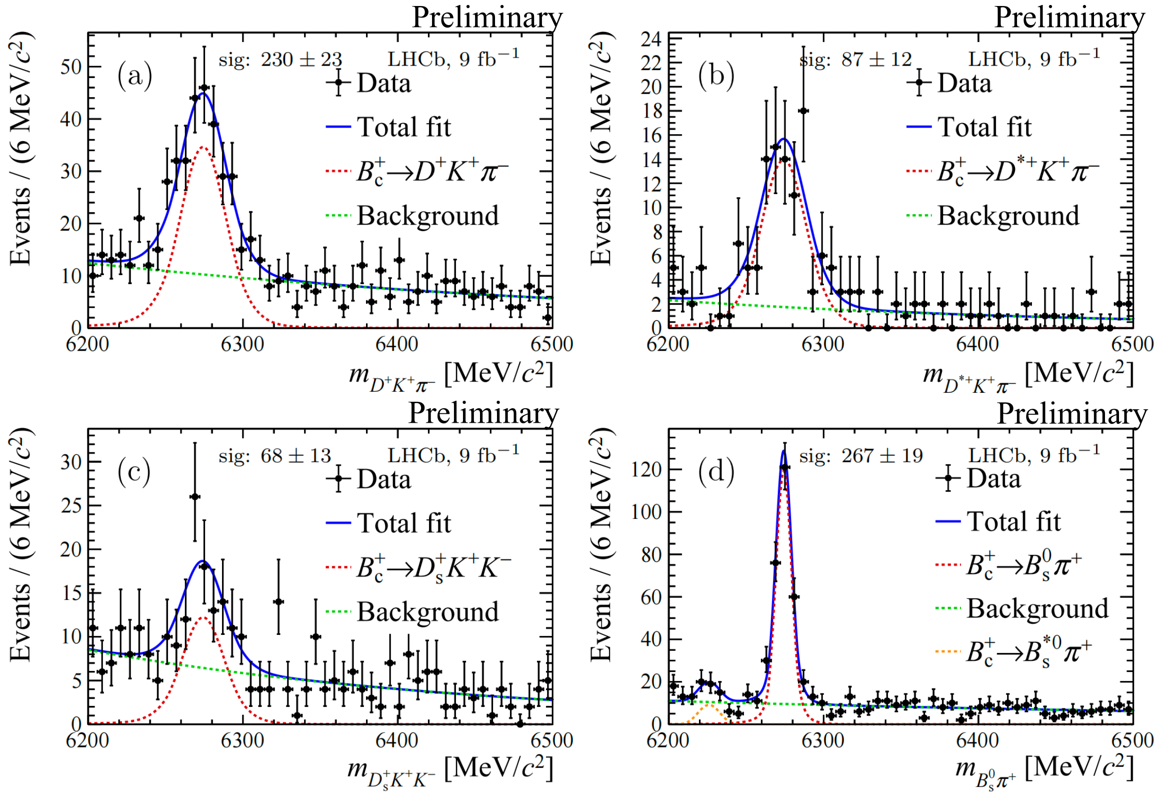


Conclusion

- *All three decay modes are observed with significance above 5σ → 1st Observation*

$$\mathcal{R}(B_c^+ \to D^+K^+\pi^-) = (1.96 \pm 0.23 \pm 0.08 \pm 0.10) \times 10^{-3}$$
$$\mathcal{R}(B_c^+ \to D^{*+}K^+\pi^-) = (3.67 \pm 0.55 \pm 0.24 \pm 0.20) \times 10^{-3}$$
$$\mathcal{R}(B_c^+ \to D_s^+K^+K^-) = (1.61 \pm 0.35 \pm 0.13 \pm 0.07) \times 10^{-3}$$

- *Using $BF(B_c^+ \to B_s^0\pi^+) \sim 16.4\ \%$, the study gives the absolute BFs $\sim 10^{-4}$* [arXiv:hep-ph/0211021]

Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

[JHEP 06 (2025) 013]

Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

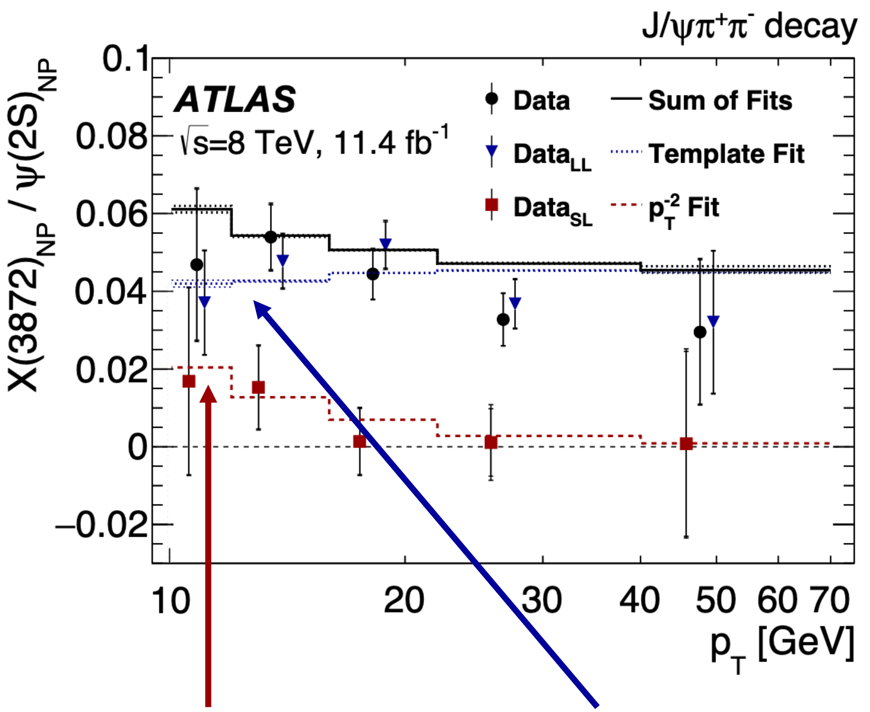
[JHEP 06 (2025) 013]

- $\chi_{c1}(3872)$ has never been seen in any exclusive B_c^+ decays
- Compact-tetraquark interpretation expects a significant enhancement of the $B_c^+ \to \chi_{c1}(3872)\pi^+$ branching fraction [Phys. Rev. D 94 (2016) 034036]

> Again, we expect the decay $B_c^\pm \to X(3872)^{(I=0)}\pi^\pm$ to have a large branching ratio, which is similar to $B_c^\pm \to J/\psi\pi^\pm$, as both are factorizable processes and are proportional to $C^{(-)} + C^{(+)}$. The decays of $B_c^\pm$ to the $[cq][\bar{c}\,\bar{q}']$-tetraquarks have the potential to map out a large number of anticipated states in this sector.

- In 2017, ATLAS measured the cross-section of $\chi_{c1}(3872)$ in pp collisions, the result can be interpretated as a significant enhancement of $\chi_{c1}(3872)$ production in inclusive B_c^+ decays [JHEP01(2017)117]

$$\frac{\sigma_{pp\to B_c^+X} \times \mathcal{B}_{B_c^+\to\chi_{c1}(3872)X}}{\sigma_{pp\to b\bar{b}X} \times \mathcal{B}_{b\to\chi_{c1}(3872)X}} = (25 \pm 13 \pm 2 \pm 5)\,\%$$



Short-lived component (From B_c^+ mesons)

Long-lived component (From other b-hadrons)

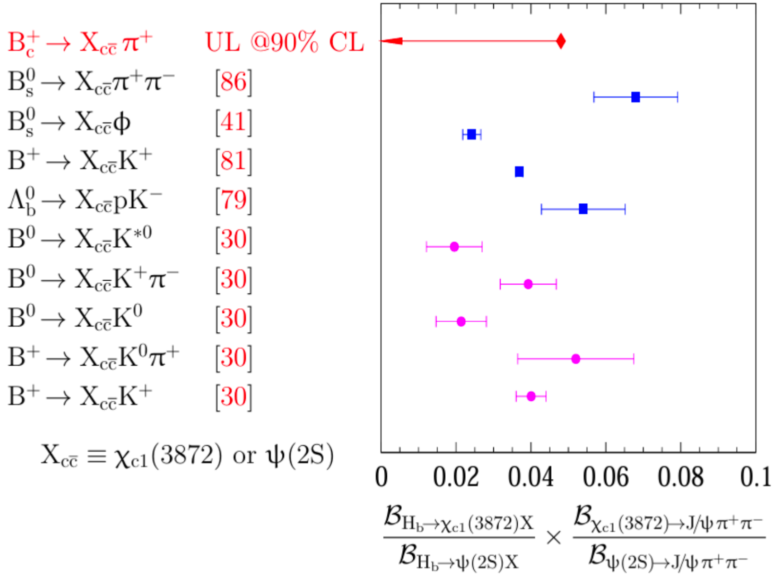
⇒ **aim to provide additional experimental input and impose constraints on theoretical models**

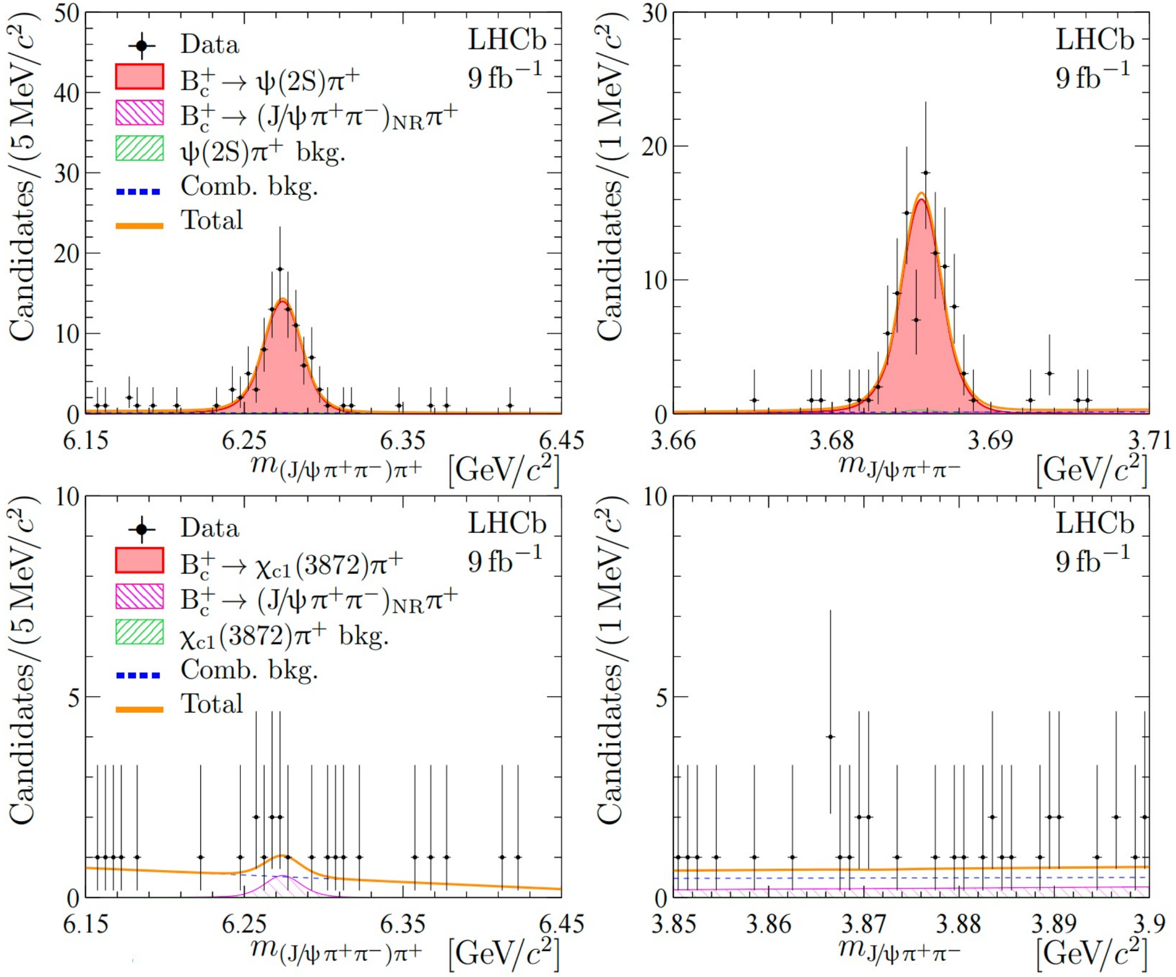
Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

[JHEP 06 (2025) 013]

- Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$, $\chi_{c1}(3872) \to J/\psi\,\pi^+\pi^-$
- Using the normalization channel: $B_c^+ \to \psi(2S)\,\pi^+$
- No $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay mode observed as signal
- An upper limit for the ratio of branching fractions is set at 90 (95) % CL:

$$\mathcal{R}^{\chi_{c1}(3872)}_{\psi(2S)} = \frac{\mathcal{B}_{B_c^+\to\chi_{c1}(3872)\pi^+}}{\mathcal{B}_{B_c^+\to\psi(2S)\pi^+}} \times \frac{\mathcal{B}_{\chi_{c1}(3872)\to J/\psi\,\pi^+\pi^-}}{\mathcal{B}_{\psi(2S)\to J/\psi\,\pi^+\pi^-}} < 0.05\;(0.06)$$





Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay

[JHEP 06 (2025) 013]

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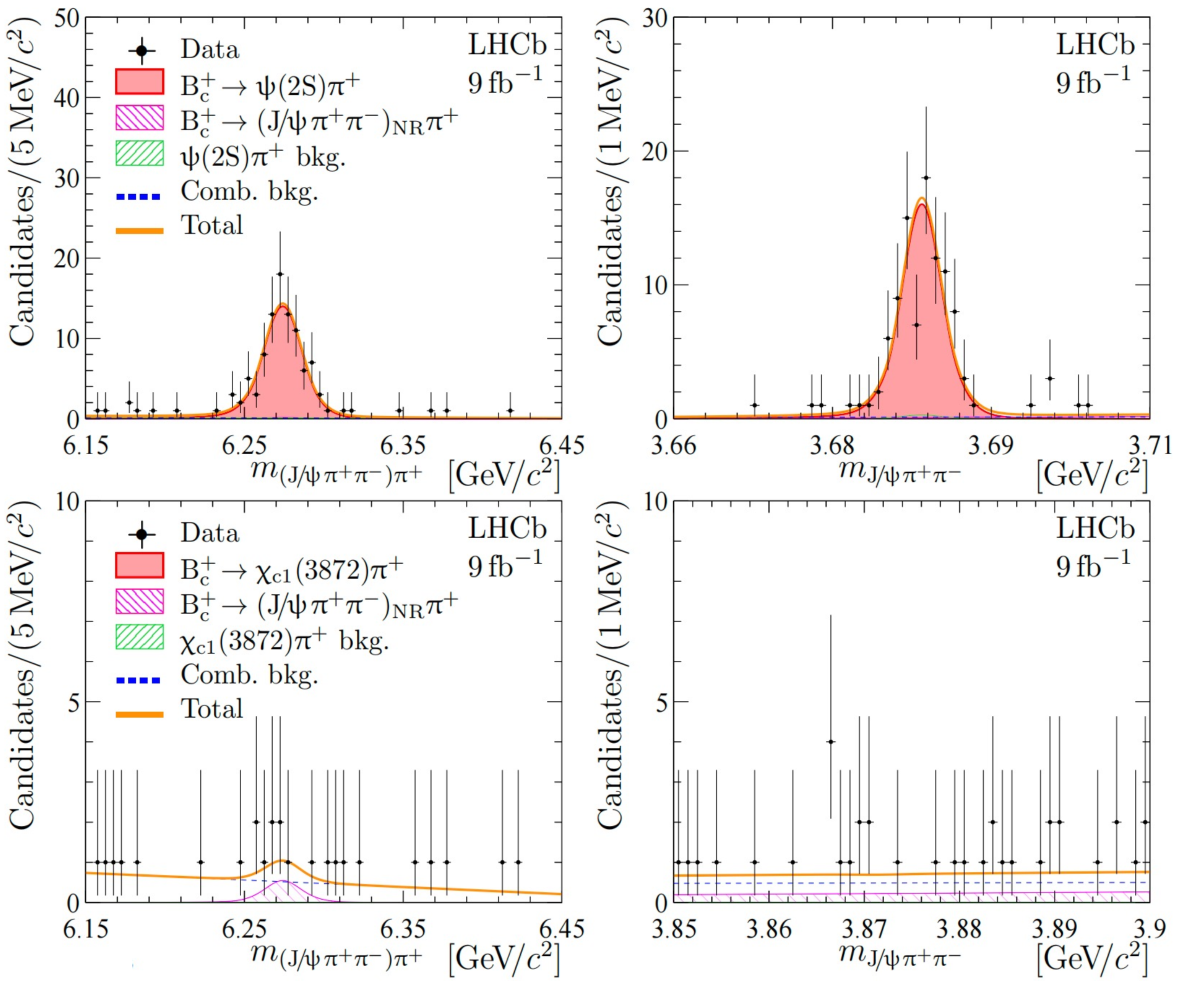


Conclusion

- *No large enhancement for $\chi_{c1}(3872)$ production in B_c^+ decays is observed*
- *Previous expectations based on compact-tetraquark interpretation are not supported by this measurement*

Observation of the orbitally excited B_c^+ states

[arXiv:2507.02149]

[arXiv:2507.02142]

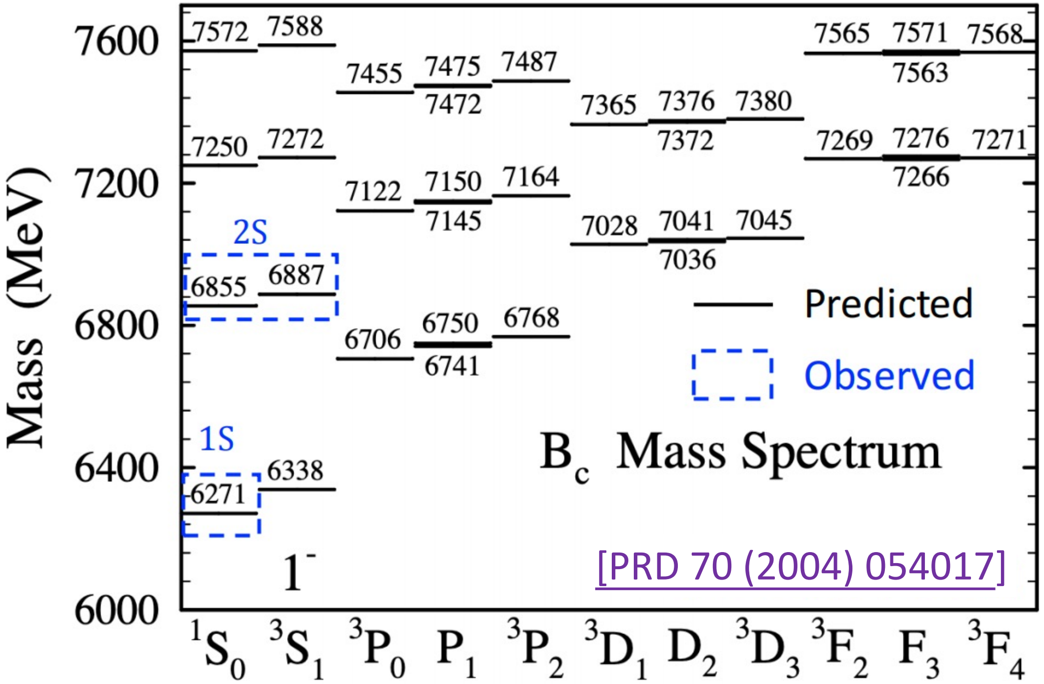
A brief history: expanding the B_c^+ meson family

[arXiv:2507.02149] [arXiv:2507.02142]

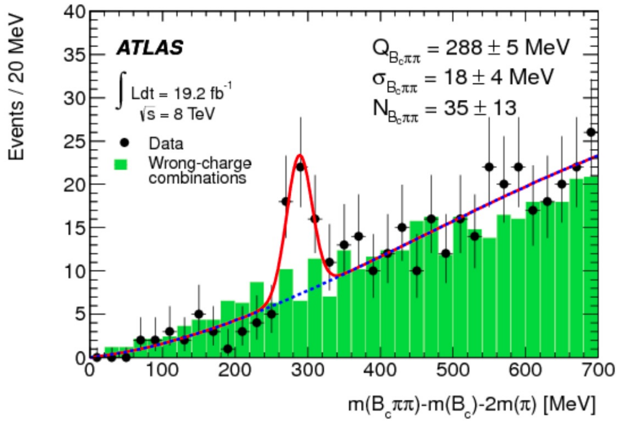
- In 1998, the B_c^+ meson was discovered at the Tevatron
- Despite its ground state, **only the 2S states** have been observed at the LHC in 2014 and 2019

That's all we know so far…

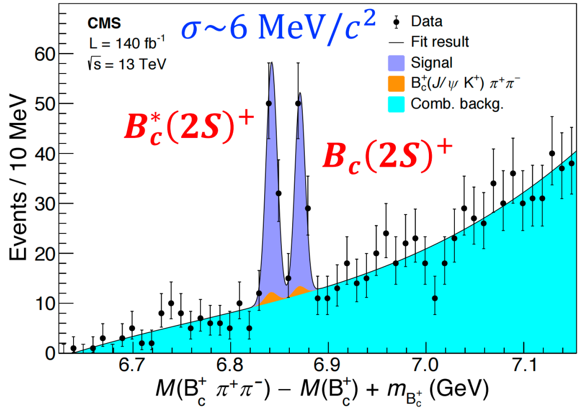
Spectroscopy of Mesons Containing Two Heavy Quarks	PDF
• B_c^+	$0(0^-)$
• $B_c(2S)^\pm$	$0(0^-)$



[PRD 70 (2004) 054017]

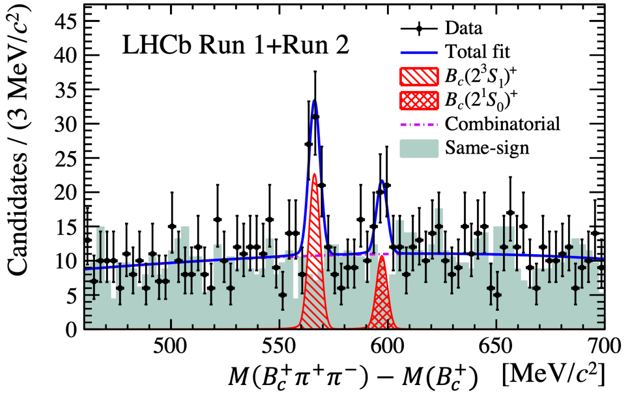


[PRL 113 (2014) 212004]



[PRL 122 (2019) 132001]

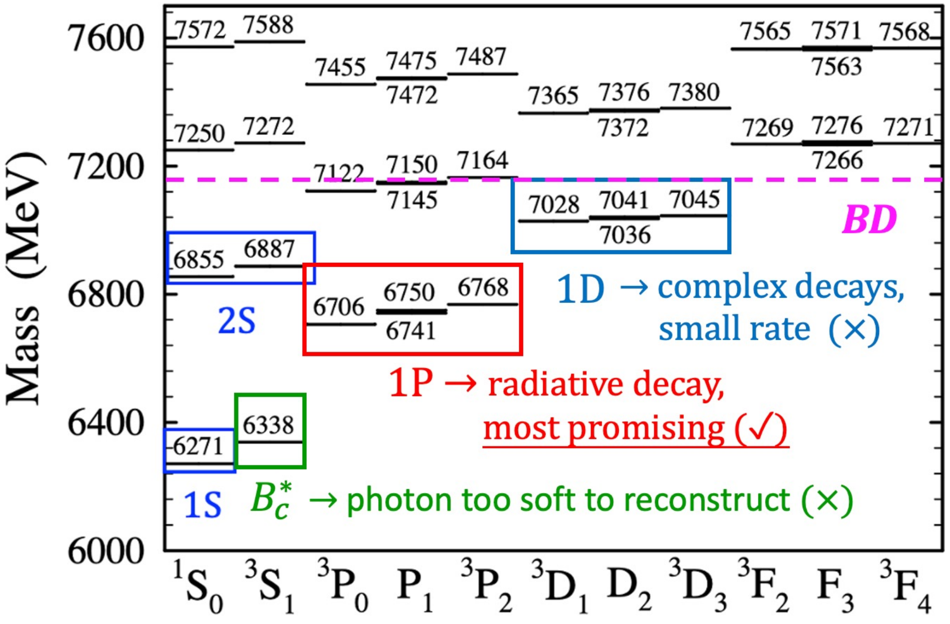
What is next ?



[PRL 122 (2019) 232001]

A brief history: expanding the B_c^+ meson family

- In 1998, the B_c^+ meson was discovered at the Tevatron
- Despite its ground state, **only the 2S states** have been observed at the LHC in 2014 and 2019
- **What is next ?** ⇒ Check the predicted properties of B_c^+ excitations [PRD 70 (2004) 054017]
  - ❑ $M(B_c^{**})$ above the BD threshold : $B_c^{**} \to BD$
  - ❑ $M(B_c^{**})$ below the BD threshold : radiative and pionic decay to B_c^+



⇒ $B_c\ (1P)^+$ is the most likely to be the next !

$B_c(1P)^+$ in theory

(a) States mixing

$$(L=1)\otimes(S=0,1)\begin{cases} S=0 \rightarrow 1^1P_1 \\ S=1 \rightarrow 1^3P_0,\ 1^3P_1,\ 1^3P_2 \end{cases}$$

mixing

Four physical states

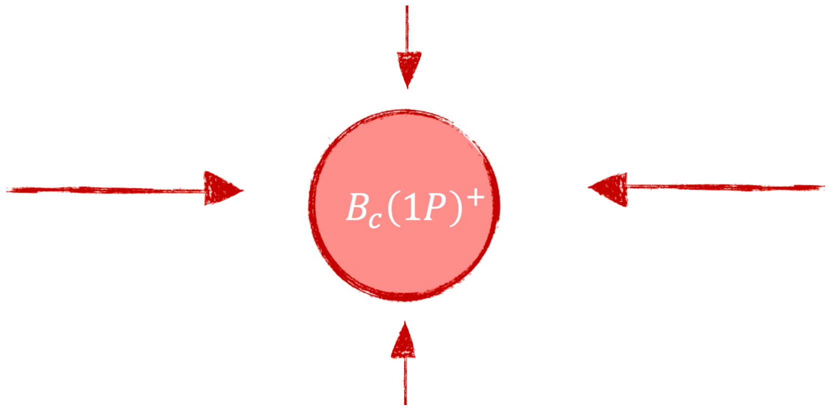
$$1^3P_0,\ 1^3P_2\quad \begin{pmatrix}1P_1'\\1P_1\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}1^1P_1\\1^3P_1\end{pmatrix}$$

(b) Decay branching fraction

$B_c(1\text{P})^+ \rightarrow B_c^{(*)+}\gamma$

Initial state	Final state	Width (keV)	B.F. (%)
1^3S_1	1^1S_0	0.08	100
1^3P_2	1^3S_1	83	100
$1P_1'$	1^3S_1	11	12.1
	1^1S_0	80	87.9
	Total	91	100
$1P_1$	1^3S_1	60	82.2
	1^1S_0	13	17.8
	Total	73	100
1^3P_0	1^3S_1	55	100

$*\ \Gamma \sim O(100\text{ KeV})$
negligible comparing to resolution



(c) Masses and mixing angle

$M \in (6.68, 6.80)$ GeV

State	GI[6]	EFG [12]	FUII [10]
1^3S_1	6338	6332	6341
1^1S_0	6271	6270	6286
1^3P_2	6768	6762	6772
$1P_1'$	6750	6749	6760
$1P_1$	6741	6734	6737
1^3P_0	6706	6699	6701
θ_{1P}	22.4°	20.4°	28.5°

(d) Production rate

	1^1P_1	1^3P_0	1^3P_1	1^3P_2	2^1S_0	2^3S_1
σ_{prod} [nb]	3.5	1.1	2.7	7.2	4.5	11.1

[PRD 70 (2004) 054017]
[Comput. Phys. Commun. 197 (2015) 335]

$B_c(1P)^+$ in experiment

- The mass shift due to the unreconstructed γ_{soft} from B_c^*
  - Spin singlet 1^1P_1 fully decay to $B_c\gamma$:

$$\mathrm{M_{reco}} = \mathrm{M(B_c\gamma)}$$

  - Spin triplet $1^3P_{1,2,3}$ transition to $B_c^*(1^3S_1)$ and then to $B_c\gamma$

$$\mathrm{M_{reco}} = \mathrm{M(B_c\gamma)} - \delta\mathrm{M}$$

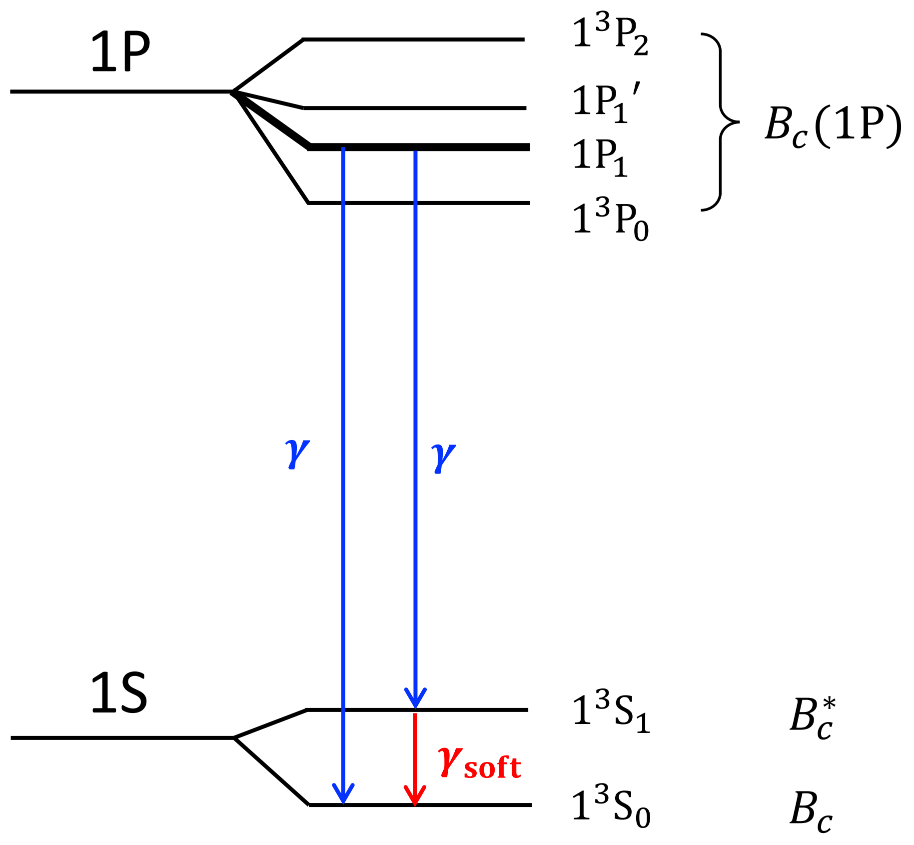
$\Rightarrow$ triplet-derived mass peaks will shift downward by δM

- Recall that the $1P_1'$, $1P_1$ are mixtures of 1^1P_1, 1^3P_1 states

States	1^3P_0	$1P_1$	$1P_1'$	1^3P_2
Decays	$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^+\gamma$	$B_c^+\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$
		$B_c^{*+}(\to B_c^+\gamma)\gamma$	$B_c^{*+}(\to B_c^+\gamma)\gamma$	
#peaks	1	2	2	1

Four states $\Rightarrow$ Six peaks

$\Rightarrow \mathrm{M(B_c\gamma)_{reco}} - \mathrm{M(B_c)}$ is predicted within **(340, 520) MeV**



◎ *The value $\delta M = M(B_c^*) - M(B_c)$ is unknown since B_c^* has not been observed yet*

Observation of the orbitally excited B_c^+ states

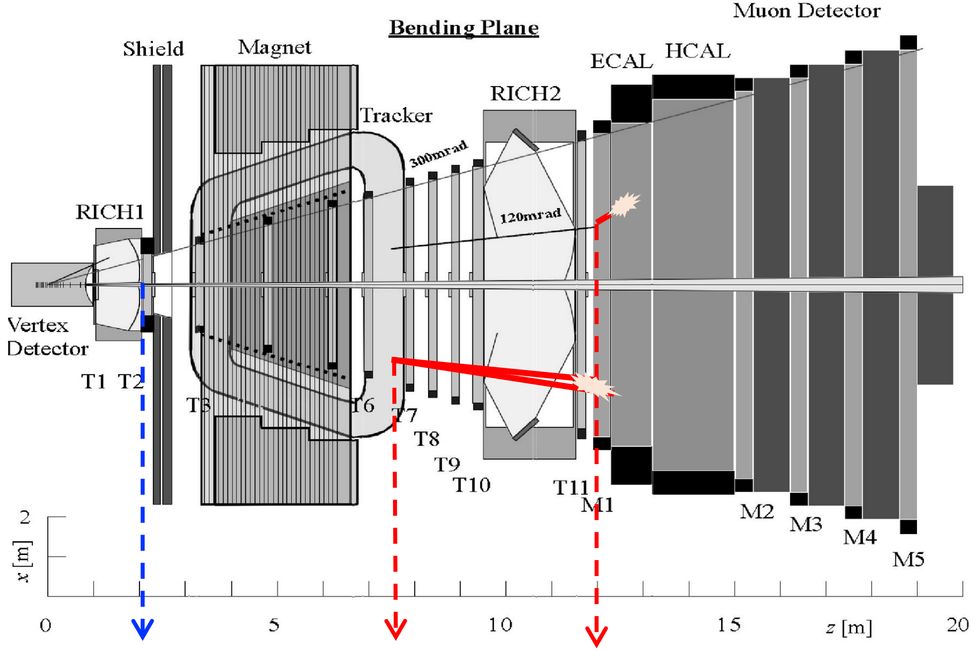
[arXiv:2507.02149]
[arXiv:2507.02142]

◉ Analysis overview

- ❑ Run1 + Run2 dataset at LHCb corresponding to 9 fb^{-1}
- ❑ $B_c(1P)^+$ reconstruction
  - ✓ $B_c(1P)^+ \to B_c^+\gamma$ with $B_c^+ \to J/\psi\pi^+,\ J/\psi \to \mu^+\mu^-$
  - ✓ Calorimeter photon used (worse resolution, larger statistics)
- ❑ $B_c(1P)^+$ selection
  - ✓ BDT classifier used to maximize $S/\sqrt{S+B}$ for B_c^+ candidates
  - ✓ Cut-based selection performed in signal decay mode
- ❑ Simulation
  - ✓ BcVegPy is employed to produce $B_c(1P)^+$ and B_c^+ states
  - ✓ The photon energy is corrected using $\chi_{c1} \to J/\psi\,\gamma$ decay

⇒ following the selection criterion in $B_c(2S)^+$ measurement

[PRL 122 (2019) 232001]



photons convert before magnet

reconstructed as e^+e^- pairs

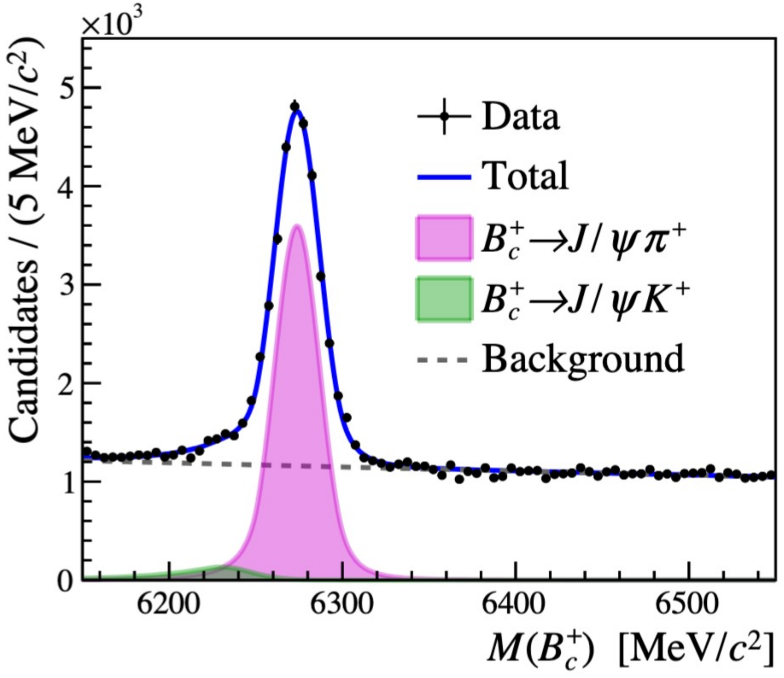
photons convert after magnet | non-convert photons

reconstructed as calorimeter clusters ✓

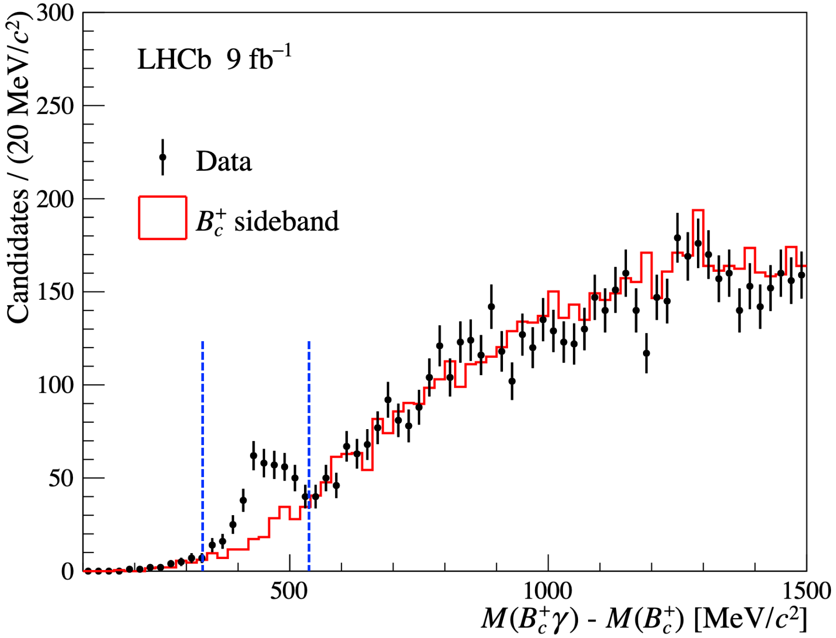
Observation of the orbitally excited B_c^+ states

[arXiv:2507.02149]
[arXiv:2507.02142]

- **A pronounced wide peaking structure is seen within the predicted mass range!**
  - Distribution of B_c^+ sideband ($(6340, 6550)$ MeV) is shown as comparison
  - Structure is confirmed across different data-taking periods, magnet polarities, alternative selection criteria
- How to interpretate the observed structure ? → theory-independent and theory-constraint interpretation!



⇒ ~ 25 K B_c^+ reconstructed, compatible with those in the previous analysis



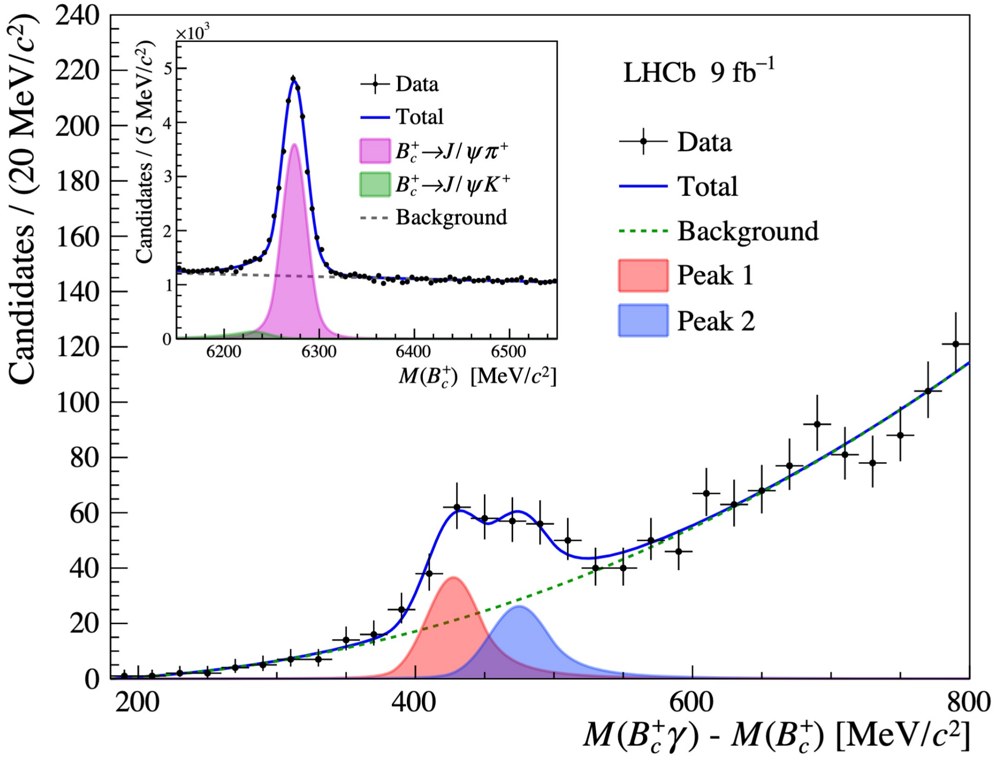
⇒ recall the predicted mass region is $(340, 520)$ MeV

Observation of the orbitally excited B_c^+ states

[arXiv:2507.02149]
[arXiv:2507.02142]

Theory-independent interpretation

- The mass-resolution relation of $B_c(1P)^+$ signal is studied using an ensemble of corrected simulation samples
- The visible width of the peaking structure is ~ 37 MeV, while the width of a single peak is determined to be ~ 20 MeV $\Rightarrow$ **a minimal two-peak model is used to effectively describe the structure**



Conclusion (I)

- *The structure is confirmed with global significance $> 7\sigma$*
- *The signal yield, effective peak positions are measured to be*

$$N = 182 \pm 25$$
$$M_1 = 6704.8 \pm 5.5 \pm 2.8 \pm 0.3 \ \ \mathrm{MeV}/c^2$$
$$M_2 = 6752.4 \pm 9.5 \pm 3.1 \pm 0.3 \ \ \mathrm{MeV}/c^2$$

- *The observed structure is expected to be contributed from multiple $B_c(1P)^+ \to B_c^{(*)+}\gamma$ decays, which have to wait for larger statistics and better resolution to be distinguished.*

Observation of the orbitally excited B_c^+ states

[arXiv:2507.02149]
[arXiv:2507.02142]

◉ Theory-constrained interpretation

- ❑ Considering the possible presence of six peaks using Run2 data at $\sqrt{s} = 13$ TeV
- ❑ For a given theoretical model, several properties constrained to predictions
  - ✓ Fix the position of each peak to the prediction
  - ✓ Fix the relative yields of six peaks, for N_i

$$N_i = L \cdot \sigma_{\mathrm{prod},i} \cdot BR_i \cdot \varepsilon_i$$

- $\sigma_{\mathrm{prod},i}$: calculated using BcVegPy generator
- ε_i: estimated with simulation
- BR_i: obtained from GI model with masses and mixing angle modified for each specific model

- ❑ **Different theoretical models were investigated**
- ❑ The **total signal yield of $B_c(1P)^+$** can be extracted, with the **relative production rate** calculated

$$R = \frac{N(B_c(1P)^+ \to B_c^+\gamma)}{N(B_c^+)} \cdot \frac{\varepsilon(B_c^+)}{\varepsilon(B_c(1P)^+ \to B_c^+\gamma)}$$

⇒ represent the fraction of B_c^+ comes from $B_c(1P)^+$, predicted to be $(0.17, 0.19)$ based on NRQCD-based prediction

Observation of the orbitally excited B_c^+ states

[arXiv:2507.02149]
[arXiv:2507.02142]

◉ Theory-constrained interpretation

- ❑ Considering the possible presence of six peaks with several properties constrained to predictions
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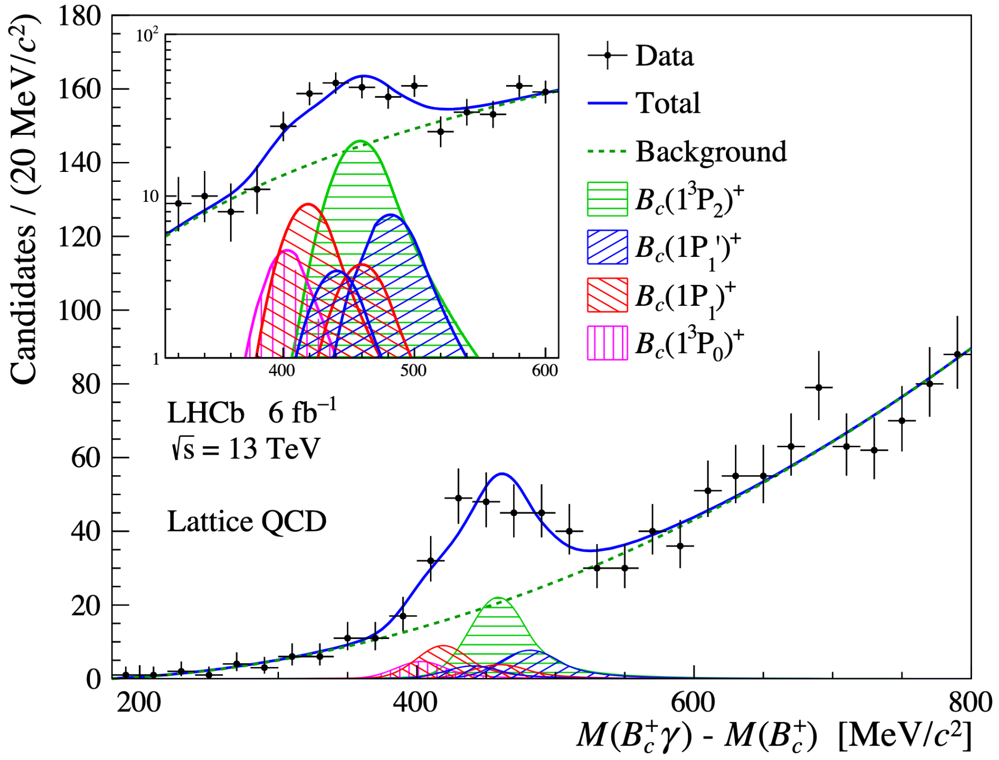


Conclusion (II)

- ◉ *All considered models provide a generally good description with p-values ranging from 15%-90%*
- ◉ *The Lattice QCD calculation is taken as the baseline, with R measured to be*

$$R = 0.20 \pm 0.03 \pm 0.02 \pm 0.03$$

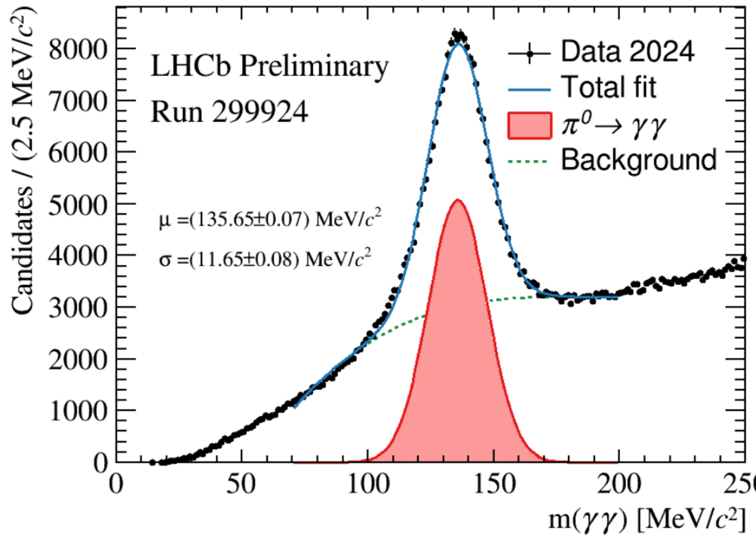
⇒ first-principle & provide highest p-value

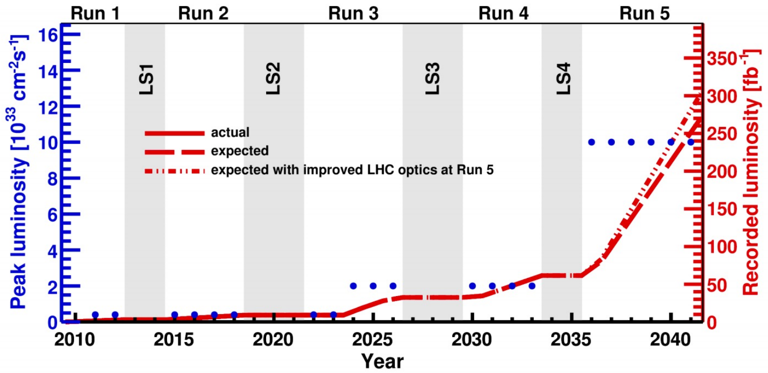
- ◉ *The result is consistent with NRQCD-based prediction*

Summary

- New measurement of B_c^+ decays into single charm final states
  - ✓ New decay mode: $B_c^+ \to D^+ K^{*0}$
  - ✓ Evidence for $B_c^+ \to D^{*0} K^+, B_c^+ \to D_s^+ \phi$ decay
  - ✓ Improved measurement of $B_c^+ \to D^0 K^+$
- Observation of $B_c^+ \to D h^+ h^-$ decays
  - ✓ New decay mode: $B_c^+ \to D^+ K^+ \pi^-, B_c^+ \to D^{*+} K^+ \pi^-, B_c^+ \to D_s^+ K^+ K^-$
- Search for $B_c^+ \to \chi_{c1}(3872)\pi^+$ decay
  - ✓ No enhancement observed, upper limit set
  - ✓ Predictions based on compact-tetraquark models not supported
- Observation of the orbitally excited B_c^+ states
  - ✓ New states observed: $B_c(1P)^+$
  - ✓ Relative production rate measured in theory-constraint interpretation
- With more opportunity in Run3, the LHCb experiment will keep making important contributions to B_c^+ studies with closer collaboration between theorists and experimentalists !

[LHCb-FIGURE-2024-017]





Thanks a lot for your attention!

Backup

Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ decay

[JHEP 04 (2024) 151]

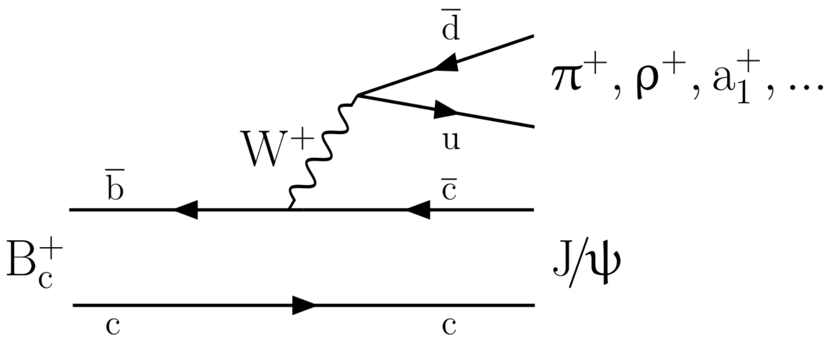
Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ decay

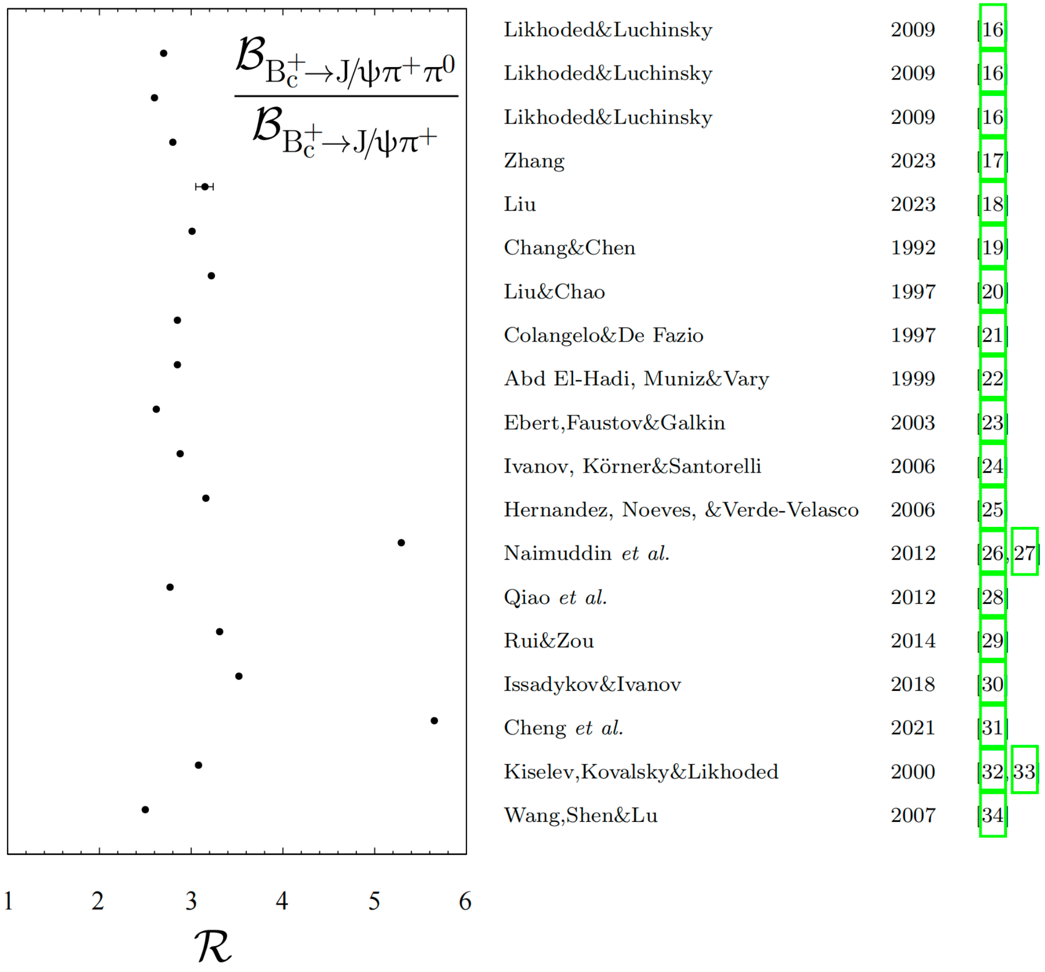
[JHEP 04 (2024) 151]

- Motivation
  - ❒ Tree-level $b \to c$ transition
  - ❒ Various prediction values

  ⇒ spin-counting: $3 \times \mathcal{B}(B_c^+ \to J/\psi\pi^+)$
  - ❒ Study the structure of intermediate states

  ⇒ potential tiny contribution from $\rho(1450)$ [PhysRevD.61.112002]





* Full RunI + RunII dataset: 9 fb^{-1}

Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ decay

[JHEP 04 (2024) 151]

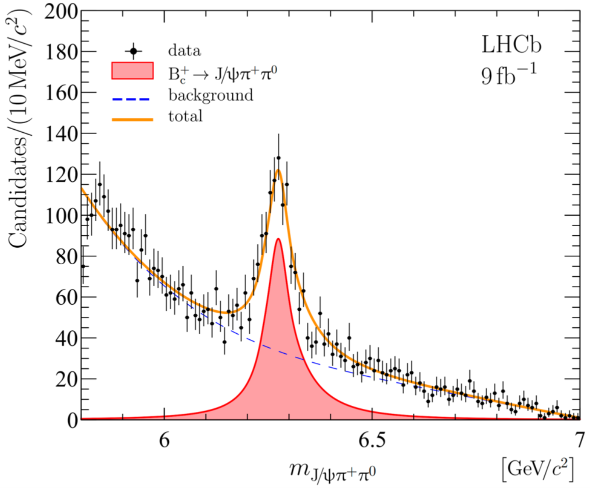
- Strategy
  - Measure the ratio of branching fractions between $B_c^+ \to J/\psi\pi^+\pi^0$ and $B_c^+ \to J/\psi\pi^+$

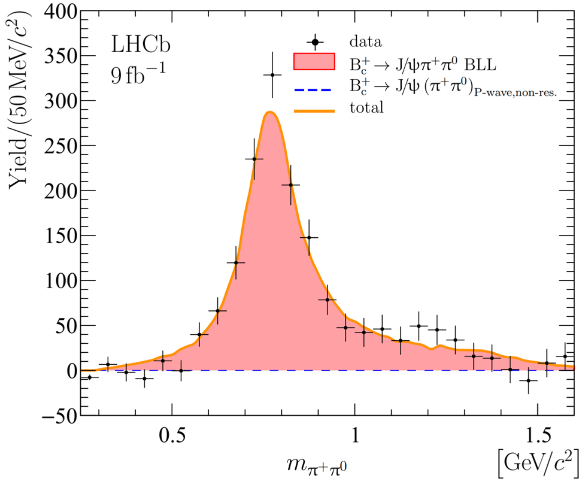
$$\frac{\mathcal{B}(B_c^+ \to J/\psi\rho^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = \frac{N_{\rho^+}}{N_{\pi^+}} \cdot \frac{\epsilon_{\pi^+}}{\epsilon_{\rho^+}}$$

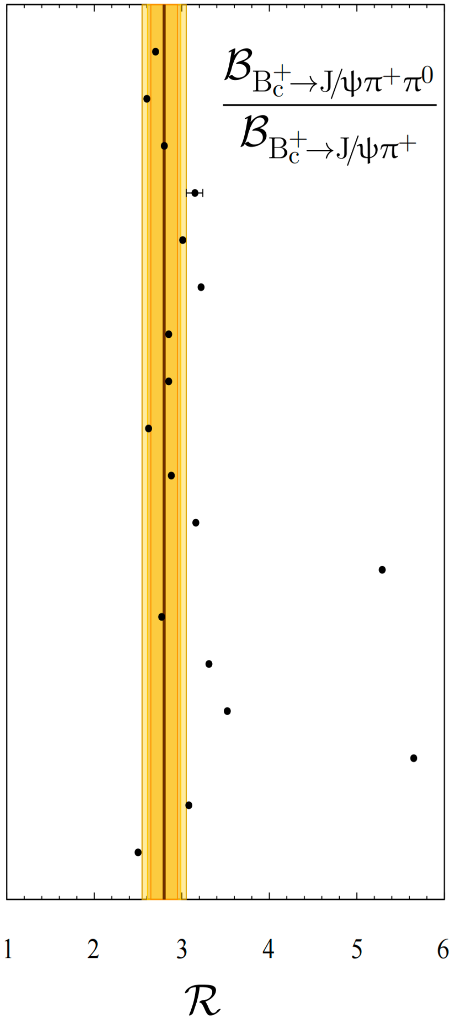
  - The $B^+ \to J/\psi K^{*+}(\to K^+\pi^0)$ decay is used to correct the detector resolution
  - The possible contribution from $\rho(1450)$ is considered in simulation

- Results
  - The $B_c^+ \to J/\psi\pi^+\pi^0$ decay is dominated by $B_c^+ \to J/\psi\rho^+$ with a small admixture of $B_c^+ \to J/\psi\rho(1450)^+$

$$\mathcal{R} = \frac{\mathcal{B}_{B_c^+\to J/\psi\pi^+\pi^0}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = 2.80 \pm 0.15 \pm 0.11 \pm 0.16$$







New measurement of $B_c^+ \to DX$ decays

- Five R_{DX} and one A_{CP} asymmetry are measured

$$A_{CP}(B_c^+ \to D^0 K^+) = \frac{\mathcal{N}(B_c^+ \to D^0 K^+) - \mathcal{N}(B_c^- \to \overline{D}^0 K^-)}{\mathcal{N}(B_c^+ \to D^0 K^+) + \mathcal{N}(B_c^- \to \overline{D}^0 K^-)}$$

Observable	Signal	Normalisation	Common D mode
$R_{D^+K^{*0}}$	$B_c^+ \to D^+[K^+\pi^-]_{K^{*0}}$	$B^+ \to D^+[K^+\pi^-]_{\overline{D}^0}$	$D^+ \to K^-\pi^+\pi^+$
$R_{D_s^+\phi}$	$B_c^+ \to D_s^+[K^+K^-]_\phi$	$B^+ \to D_s^+[K^+K^-]_{\overline{D}^0}$	$D_s^+ \to K^+K^-\pi^+$
$R_{D^{*0}K^+}$	$B_c^+ \to D^{*0}K^+$	$B^- \to D^0\pi^-$	$D^0 \to K^-\pi^+$
$R_{D^0K^+}$	$B_c^+ \to D^0K^+$	$B^- \to D^0\pi^-$	$D^0 \to K^-\pi^+$
$R_{D^0\pi^+}$	$B_c^+ \to D^0\pi^+$	$B^- \to D^0\pi^-$	$D^0 \to K^-\pi^+$

$$R_{D^0h^+} = \frac{\mathcal{N}(B_c^+ \to D^0h^+)}{\mathcal{N}(B^+ \to \overline{D}^0\pi^+)} \cdot \mathcal{B}(B^+ \to \overline{D}^0\pi^+) \cdot \frac{\varepsilon(B^+ \to \overline{D}^0\pi^+)}{\varepsilon(B_c^+ \to D^0h^+)}, \quad h \in \{K, \pi\}$$

$$R_{D^{*0}K^+} = \frac{\mathcal{N}(B_c^+ \to D^{*0}K^+)}{\mathcal{N}(B^+ \to \overline{D}^0\pi^+)} \cdot \mathcal{B}(B^+ \to \overline{D}^0\pi^+) \cdot \frac{\varepsilon(B^+ \to \overline{D}^0\pi^+)}{\varepsilon(B_c^+ \to D^{*0}K^+)},$$

$$R_{D^+K^{*0}} = \frac{\mathcal{N}(B_c^+ \to D^+K^{*0})}{\mathcal{N}(B^+ \to D^+\overline{D}^0)} \cdot \mathcal{B}(B^+ \to D^+\overline{D}^0) \cdot \frac{\varepsilon(B^+ \to D^+\overline{D}^0)}{\varepsilon(B_c^+ \to D^+K^{*0})} \cdot \frac{\mathcal{B}(\overline{D}^0 \to K^+\pi^-)}{\mathcal{B}(K^{*0} \to K^+\pi^-)},$$

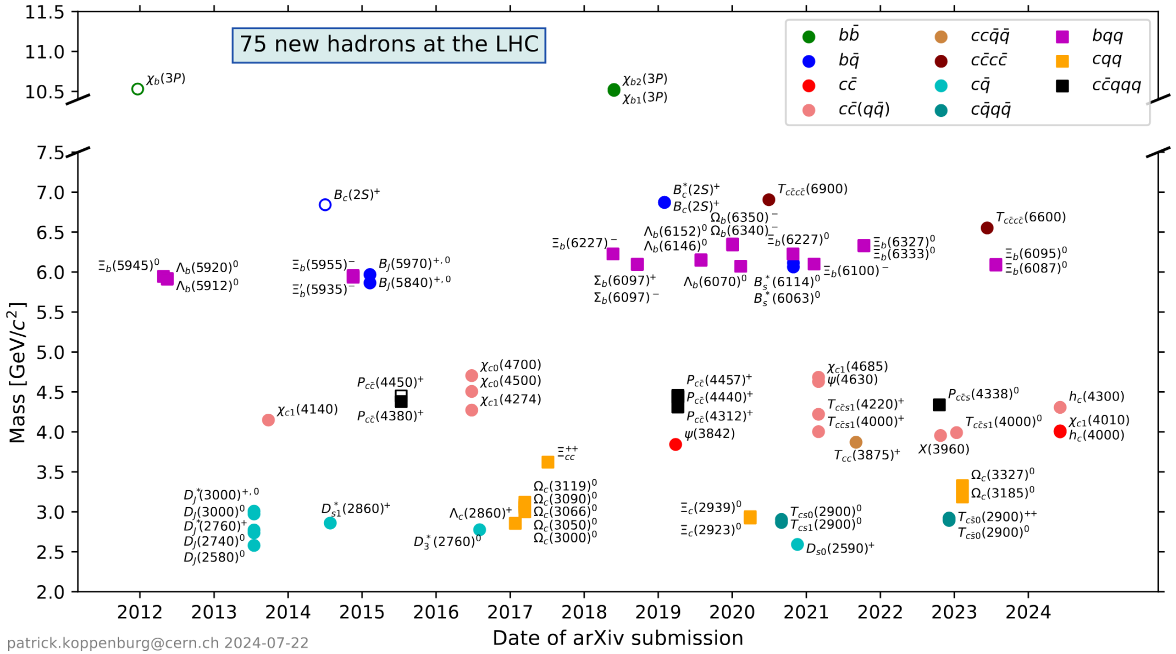
$$R_{D_s^+\phi} = \frac{\mathcal{N}(B_c^+ \to D_s^+\phi)}{\mathcal{N}(B^+ \to D^+\overline{D}^0)} \cdot \mathcal{B}(B^+ \to D^+\overline{D}^0) \cdot \frac{\varepsilon(B^+ \to D^+\overline{D}^0)}{\varepsilon(B_c^+ \to D_s^+\phi)} \cdot \frac{\mathcal{B}(\overline{D}^0 \to K^+K^-)}{\mathcal{B}(\phi \to K^+K^-)}.$$

Yield | PDG | Estimated from simulation

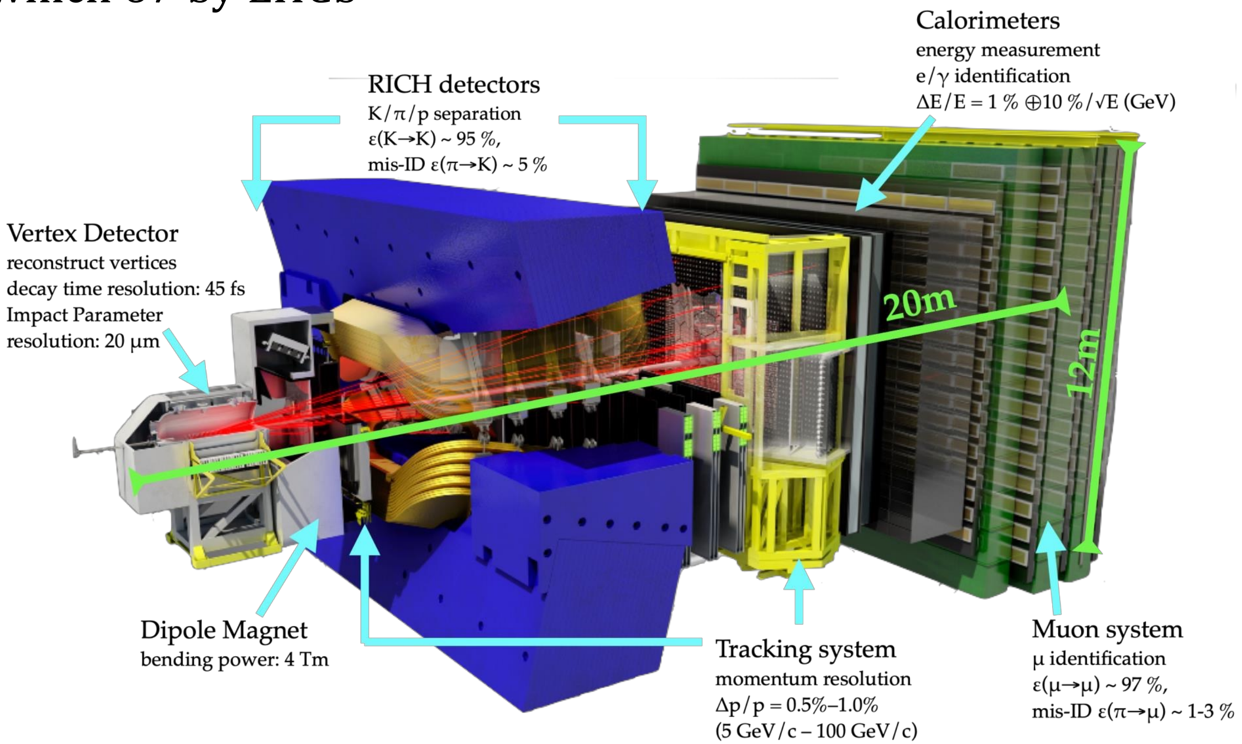
The LHCb detector

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

- A general purpose detector covering the forward region: $2 < \eta < 5$
- **Excellent tracking, particle identification and trigger systems**
- **Perfect conditions for both precision measurements & observations of new states/decays**
- Successful operation in RunI and RunII with various collision systems (pp, p-Pb, Pb-Pb)
- So far 75 hadrons have been discovered at the LHC, of which 67 by LHCb

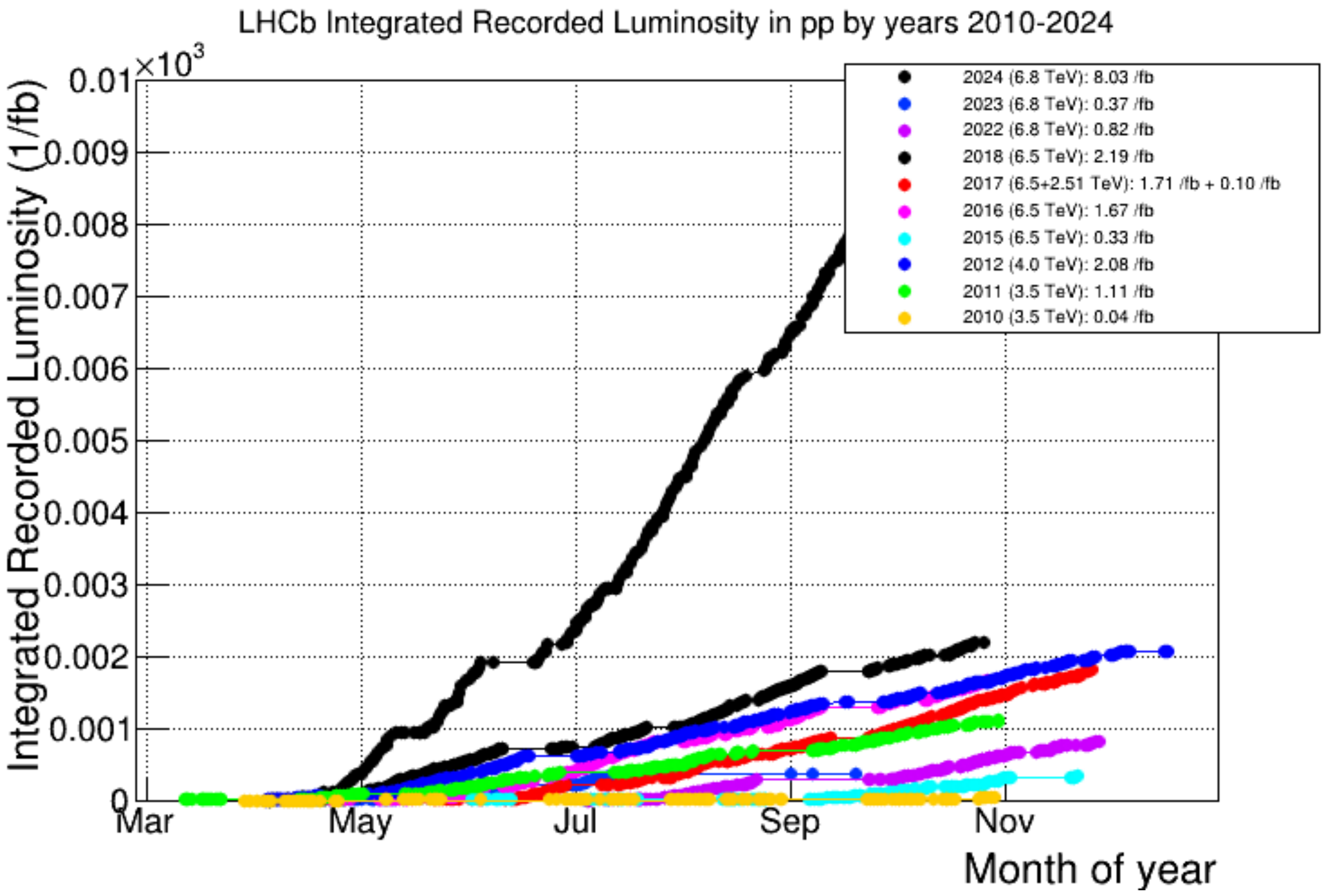


[https://www.nikhef.nl/~pkoppenb/hadrons//Masses.pdf]



LHCb dataset

- RunI: 3 fb^{-1} pp collision @ 7,8 TeV
- RunII: 6 fb^{-1} pp collision @ 13 TeV



https://lbgroups.cern.ch/online/OperationsPlots/index.htm