Beauty Meson Spectroscopy at LHCb

LHCb Implication Workshop

CERN

Oct.24th, 2024

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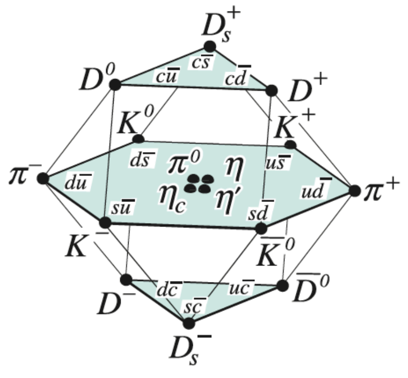
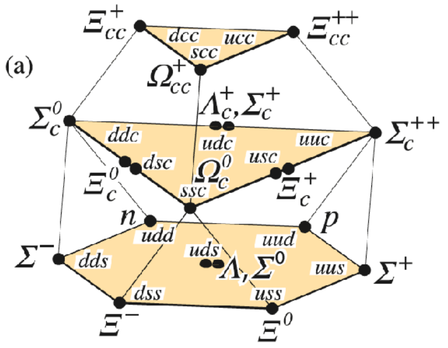
on behalf of the LHCb collaboration

QCD and Hadron Spectroscopy

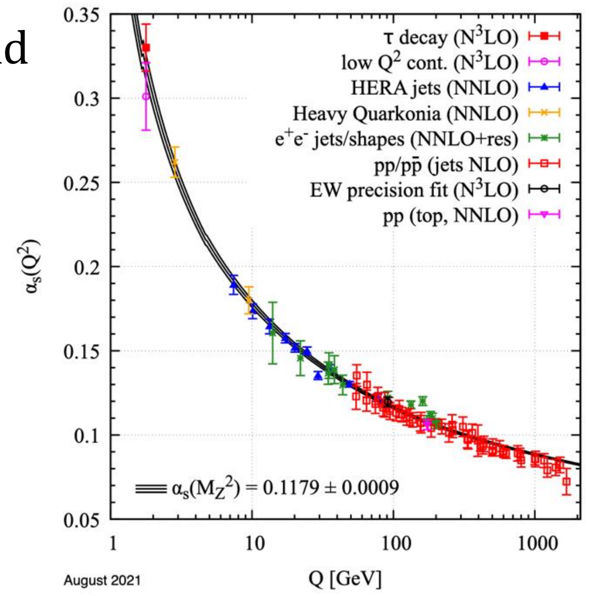
- QCD is in principle expected to fully describe the spectrum and properties of hadrons
  ⇒ shows non-perturbative behavior at such energy scale

- **Experimental measurements in hadron spectroscopy**
  - ❒ Extend the knowledge of QCD
  - ❒ Provide crucial inputs to reduce the uncertainties in theory
  - ❒ Help to understand the ways in which QCD forms bound states and about their internal structure





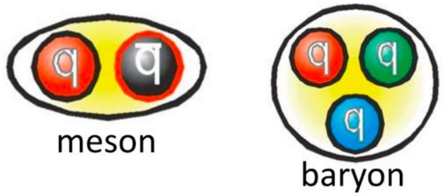
[PDG Appendix]



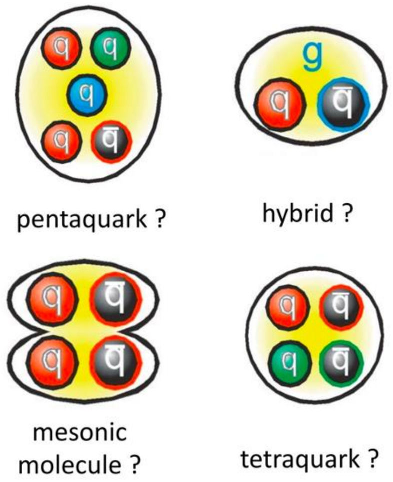
Hadron properties

- ❍ New state
- ❍ New decay
- ❍ Mass & Width (lifetime)
- ❍ Production
- ❍ Branching ratio
- ❍ Quantum numbers
- ❍ ……

CONVENTIONAL

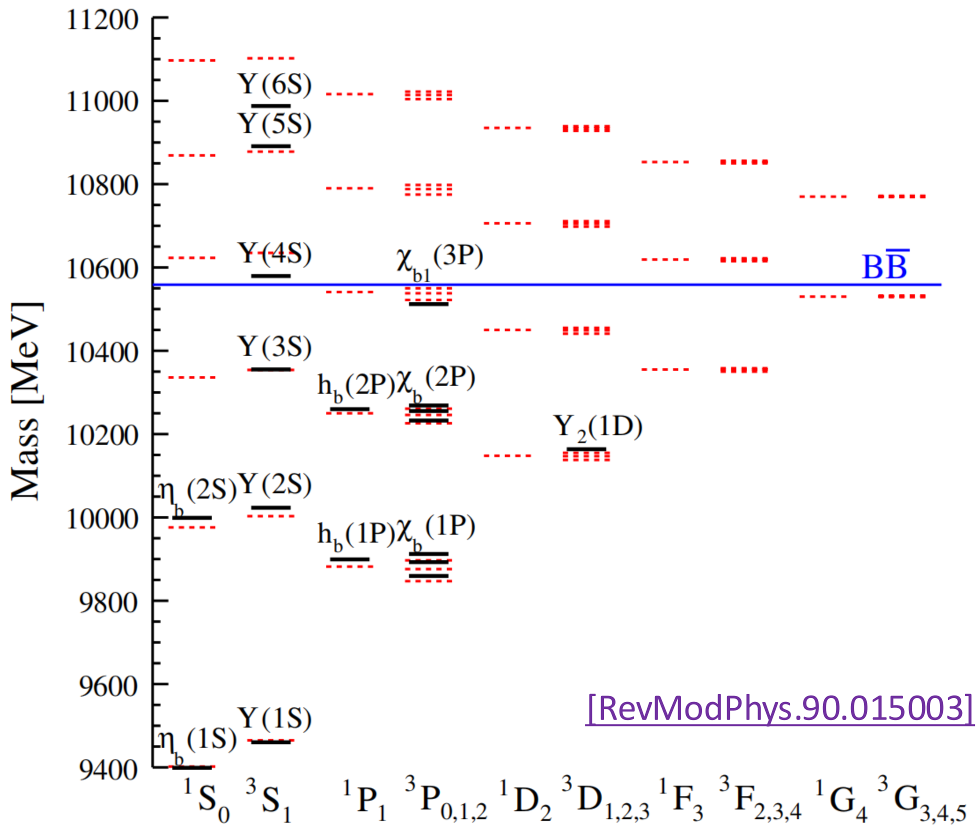


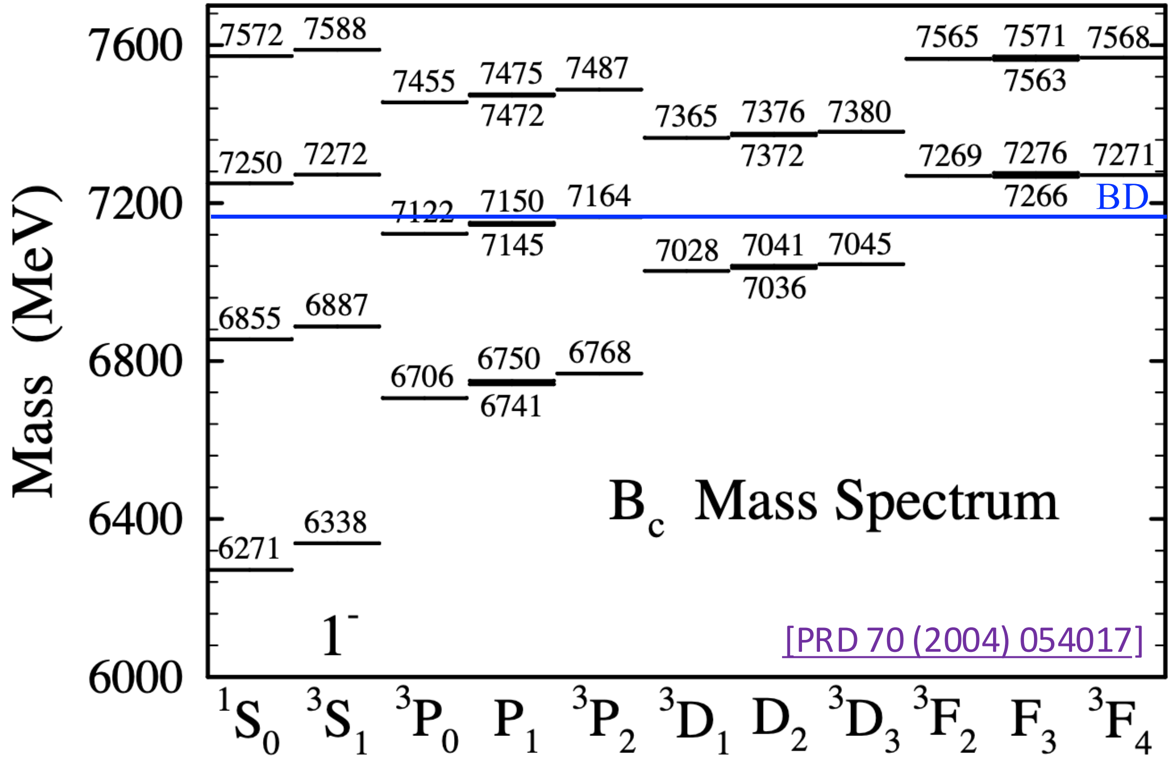
EXOTIC



Quarkonium and Beauty Meson Spectrum

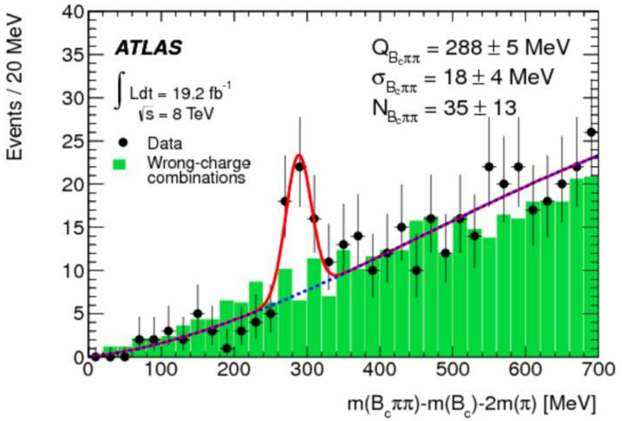
- The charmonium spectrum is well-known, as is the bottomonium spectrum.
- For B mesons, and in particular for B_s or B_c, the knowledge is limited.



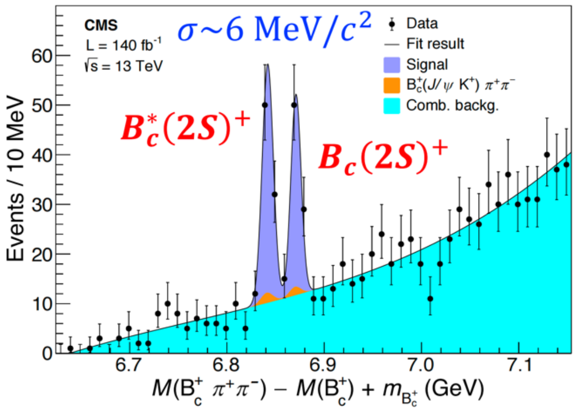


Quarkonium and Beauty Meson Spectrum

- Charmonium spectrum is pretty well know. Bottomonium spectrum as well.
- For B mesons, and in particular for B_s or B_c, the knowledge is limited.

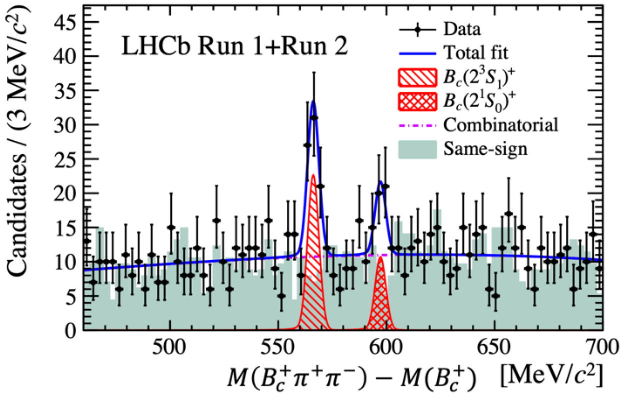


[PRL 113 (2014) 212004]

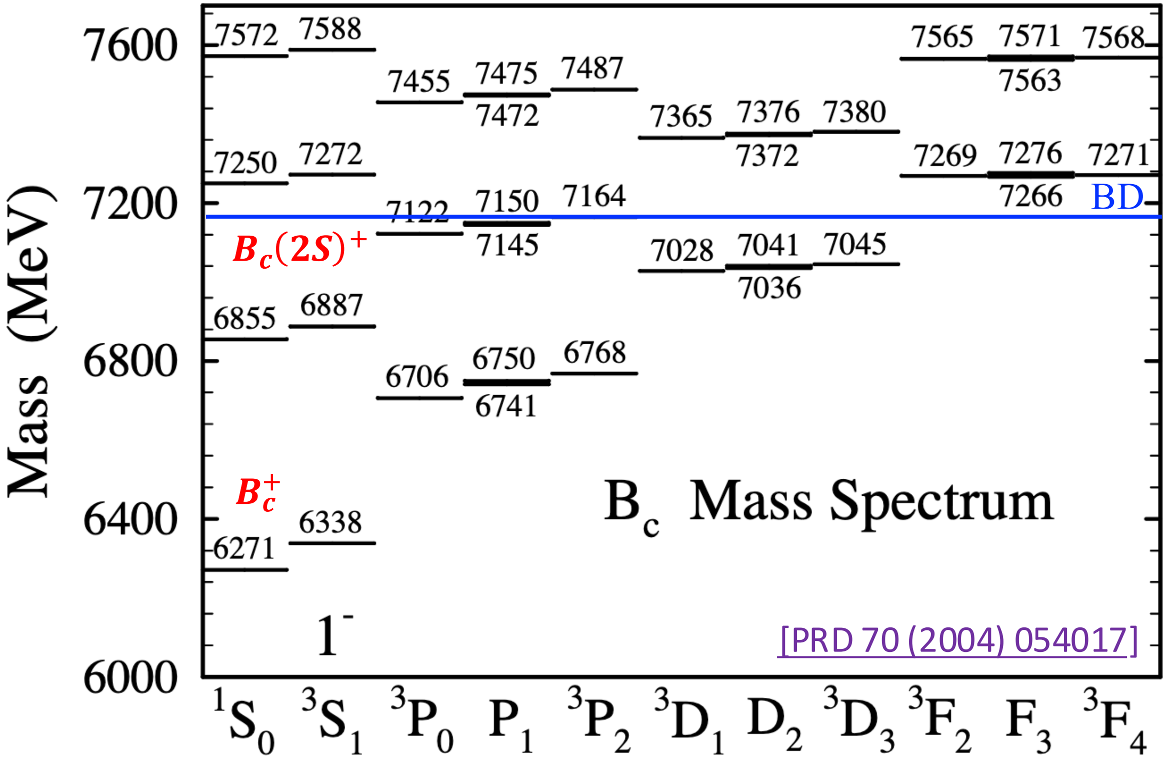


[PRL 122 (2019) 132001]

What is next ?

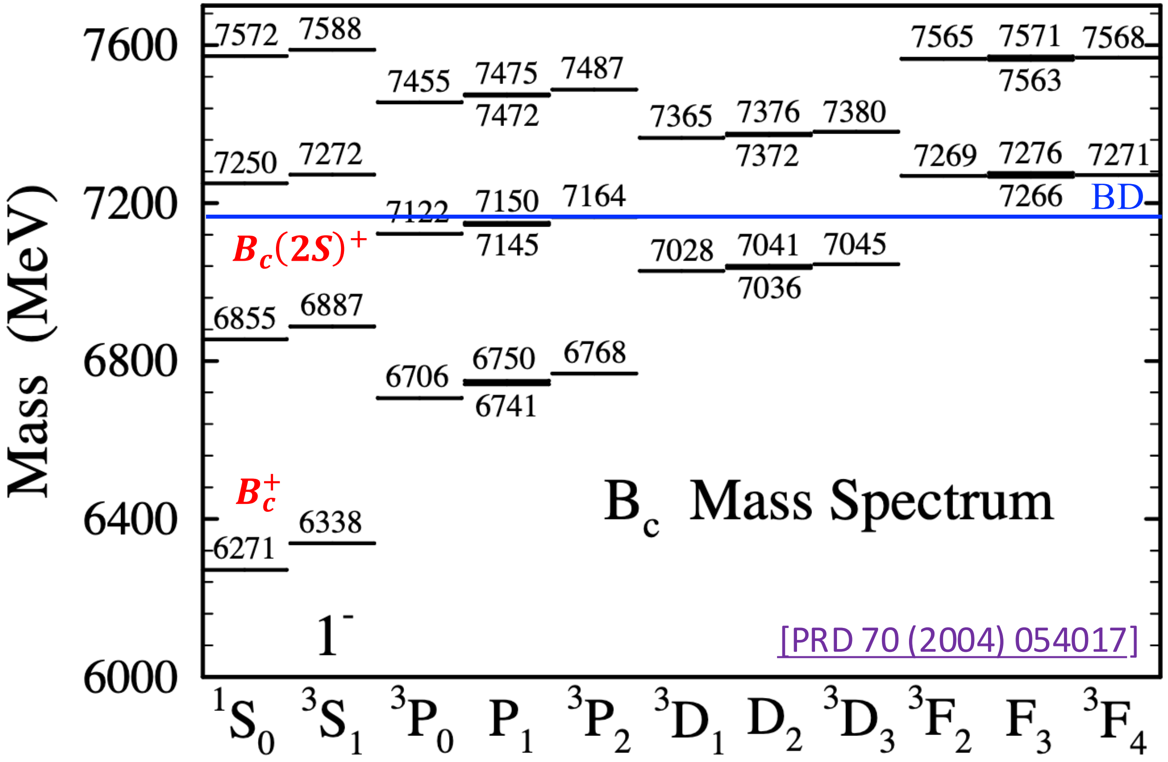


[PRL 122 (2019) 232001]



Quarkonium and Beauty Meson Spectrum

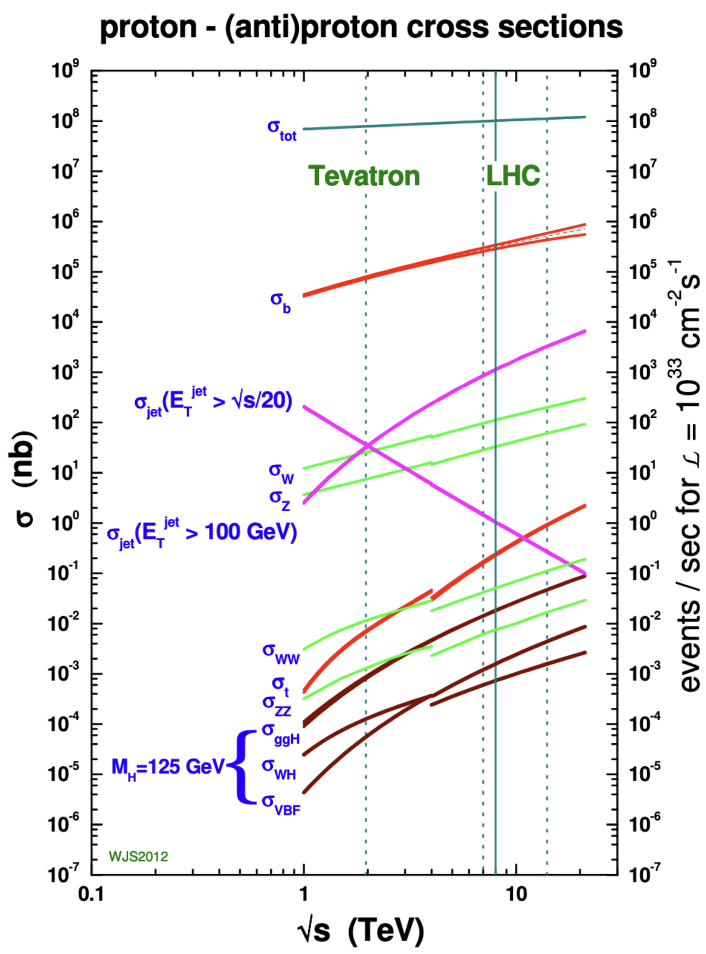
- Charmonium spectrum is pretty well know. Bottomonium spectrum as well.
- For B mesons, and in particular for B_s or B_c, the knowledge is limited.
- **This talk will focus on the latest topics of beauty meson spectroscopy, includes**
  - Study of hidden beauty spectroscopy [JHEP 10 (2024) 12]
  - Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays [LHCb-PAPER-2024-045] in preparation
  - Observation of $B_c^+ \to J/\psi\, \pi^+\pi^0$ decay [JHEP 04 (2024) 151]
  - Measurement of the BF of $B^0 \to J/\psi\pi^0$ decay [JHEP 05 (2024) 065]



b-hadron production at the LHC

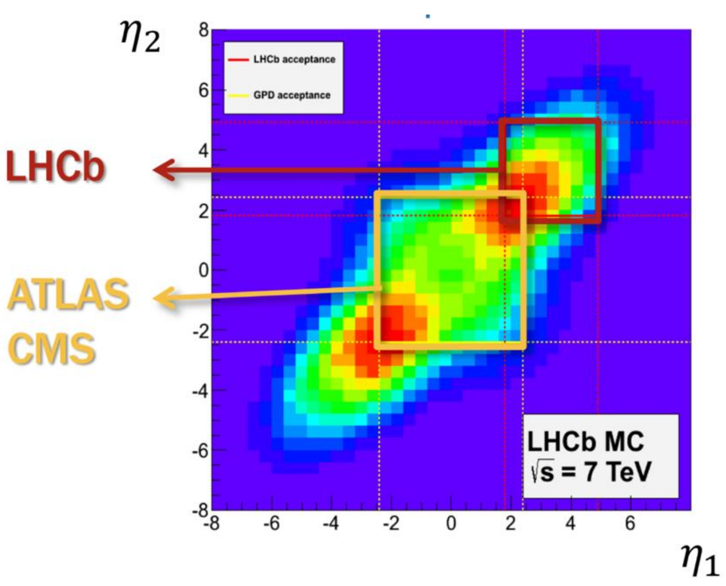
- All types of b-hadrons, and their excitations, can be produced at the LHC
  - ❒ $B^0 = |\bar{b}d>,\ B^+ = |\bar{b}u>,\ B_s^0 = |\bar{b}s>,\ B_c^+ = |\bar{b}c>\ \ldots$

[LHC highlights and prospects]



- $\sigma(pp \to b\bar{b}X) \sim$ 154.3 μb at 13 TeV in the forward region

  $\Rightarrow$ **~60k $b\bar{b}/s$ inside LHCb acceptance** [PhysRevLett.118.052002]



- Two approaches to study the spectroscopy
  - ❒ **Inclusive analysis**
    - ✓ no spin analysis for two body decays
    - ✓ large cross sections
    - ✓ signal purity may be poor
  - ❒ **Exclusive analysis**
    - ✓ quantum numbers assignment is possible (model-dependent)
    - ✓ limited statistics
    - ✓ small background

Study of hidden beauty spectroscopy

[JHEP 10 (2024) 12]

Study of hidden beauty spectroscopy

[JHEP 10 (2024) 12]

- Υ states
  - Masses measured in 1990s (CESR, DORIS, VEPP) , relied on photon energy of $\Upsilon(2S)$ and $\Upsilon(3S)$
    → standing tensions between CESR and DORIS on $\Upsilon(1S)$ mass
  - Shamov et al resolved by reanalysing the data with interference and radiative corrections considered correctly
  - Quoted error in PDG 2024 for $\Upsilon(1S)$ decreased: 0.26 MeV → 0.1 MeV ☺ [Phys. Lett. B839 (2023), 137766]
  - DORIS data is removed for $\Upsilon(2S)$, error increased: 0.31 MeV → 0.5 MeV ☹
- χ_b states
  - Mass knowledge largely comes from study of photon energy in feed-down from Υ decays
  - Measurement of mass splitting are dominated by BaBar experiment

State	Measured mass [MeV/c^2]	
	PDG2024	PDG2022
$\Upsilon(1S)$	9460.4 ± 0.1	9460.30 ± 0.26
$\Upsilon(2S)$	10023.4 ± 0.5	10023.26 ± 0.31
$\Upsilon(3S)$	10355.2 ± 0.5	10355.2 ± 0.5

Study of hidden beauty spectroscopy

[JHEP 10 (2024) 12]

- Measurement of the mass and mass splittings using
  - Full RunI + RunII dataset: 9 fb^{-1}
  - Di-muon mode: $\Upsilon \to \mu^-\mu^+$
  - Di-pion mode: $\Upsilon(2S) \to \Upsilon(1S)\pi^-\pi^+$, $\Upsilon(3S) \to \Upsilon(2S)\pi^-\pi^+$

Agree with PDG. Most precise result for $\Upsilon(2S)$

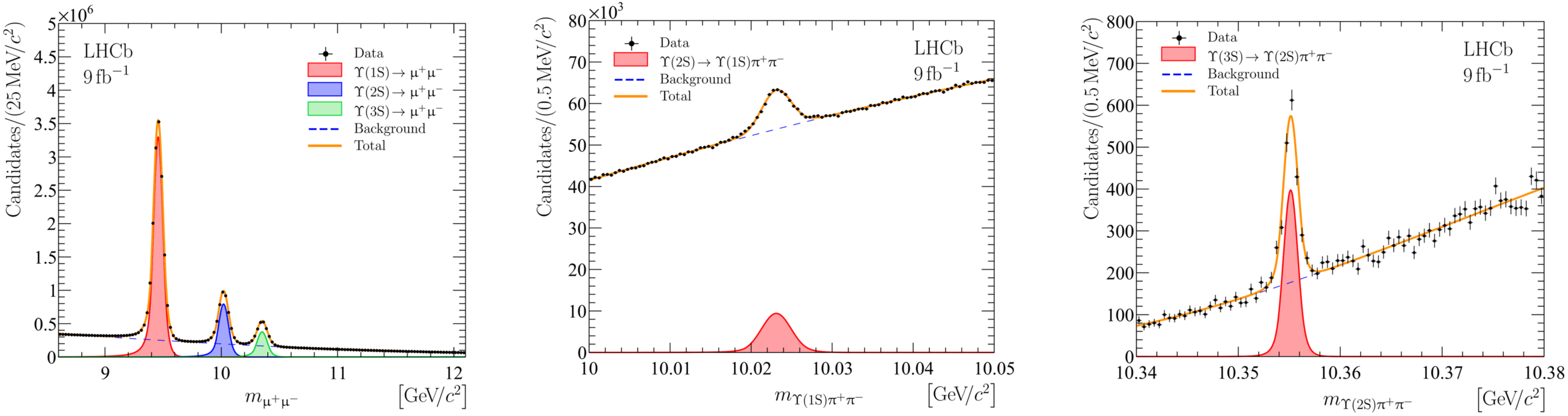
$$m_{\Upsilon(2S)} = 10\,023.25 \pm 0.03 \pm 0.12 \pm 0.09\ \text{MeV}/c^2$$

$$m_{\Upsilon(3S)} = 10\,355.28 \pm 0.03 \pm 0.04 \pm 0.48\ \text{MeV}/c^2$$

Similar precision to BaBar, with deviations in $2-4\,\sigma$

$$m_{\Upsilon(2S)} - m_{\Upsilon(1S)} = 562.84 \pm 0.02 \pm 0.13\ \text{MeV}/c^2,$$

$$m_{\Upsilon(3S)} - m_{\Upsilon(2S)} = 331.86 \pm 0.03 \pm 0.05\ \text{MeV}/c^2.$$



Study of hidden beauty spectroscopy

[JHEP 10 (2024) 12]

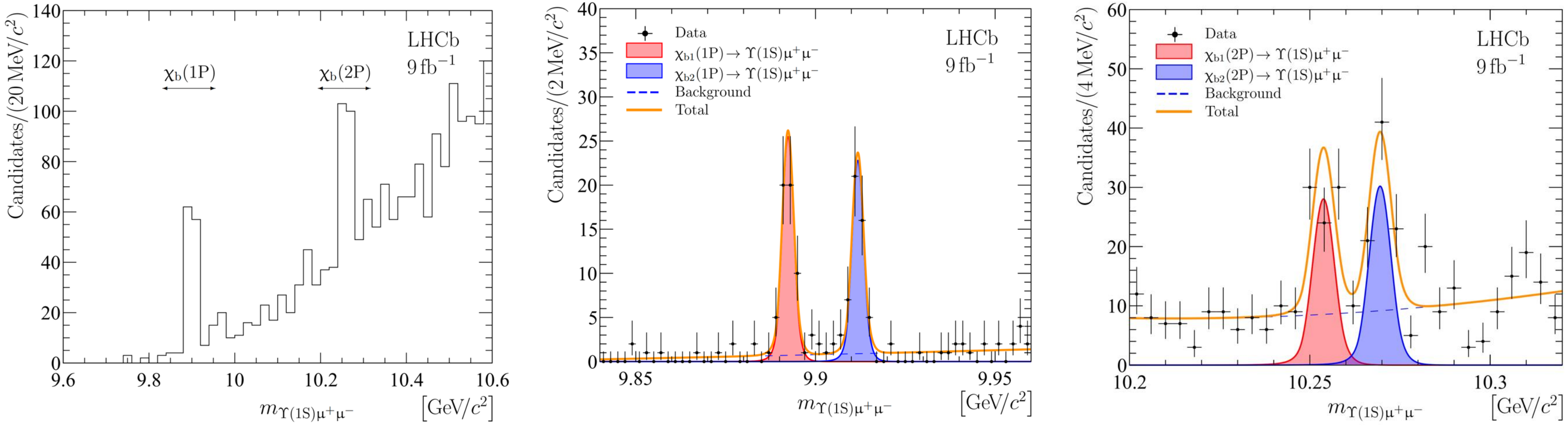
- First observation of muonic Dalitz decay $\chi_{b1,2} \to \Upsilon(1S)\mu^-\mu^+$

$$
\begin{aligned}
m_{\chi_{b1}(1P)} &= 9\,892.50 \pm 0.26 \pm 0.10 \pm 0.10\,\mathrm{MeV}/c^2 \\
m_{\chi_{b2}(1P)} &= 9\,911.92 \pm 0.29 \pm 0.11 \pm 0.10\,\mathrm{MeV}/c^2 \\
m_{\chi_{b1}(2P)} &= 10\,253.97 \pm 0.75 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2 \\
m_{\chi_{b2}(2P)} &= 10\,269.67 \pm 0.67 \pm 0.22 \pm 0.09\,\mathrm{MeV}/c^2
\end{aligned}
$$

1P: world best value
2P: Slightly worse precision than PDG24

$$
\begin{aligned}
m_{\chi_{b2}(1P)} - m_{\chi_{b1}(1P)} &= 19.4 \pm 0.4\,\mathrm{MeV}/c^2 \\
m_{\chi_{b2}(2P)} - m_{\chi_{b1}(2P)} &= 15.7 \pm 1.0\,\mathrm{MeV}/c^2
\end{aligned}
$$

1P: central value agree, precision is 1.6 times worse than PDG24
2P: central value agree at the level of 2.6 σ, precision is 4 times worse



Study of light meson resonances in the $B \rightarrow (K_S^0 K \pi) K$ decays

[LHCb-PAPER-2024-045] in preparation

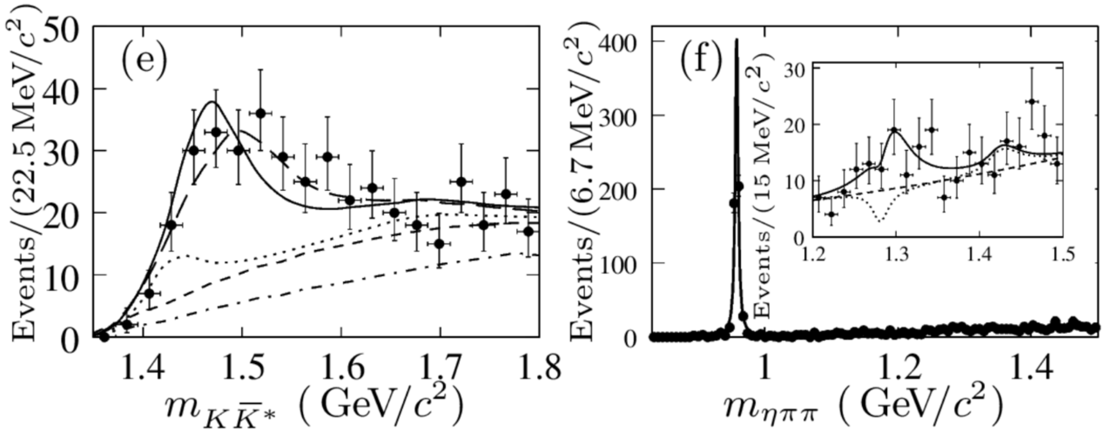
New

Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

- Previous studies in $B^+ \to R^0 K^+$ decay

[LHCb-PAPER-2024-045] in preparation

  - BaBar: interpreted as signals from $\eta(1475) \to K^*\bar{K}$ and $\eta(1295) \to \eta\pi^+\pi^-$ Phys.Rev.Lett.101(2008)091801



  - PDG branching fractions for pseudoscalars and axial mesons

Resonance	$\mathcal{B} \times 10^{-6}$
$\eta(1295)K^+ \times \mathcal{B}(\eta(1295) \to \eta\pi\pi)$	$2.9^{+0.8}_{-0.7}$
$\eta(1405)K^+ \times \mathcal{B}(\eta(1405) \to \eta\pi\pi)$	< 1.3 CL=90%
$\eta(1405)K^+ \times \mathcal{B}(\eta(1405) \to K^*\bar{K}$	$< 1.2)$ CL=90%
$\eta(1475)K^+ \times \mathcal{B}(\eta(1475) \to K^*\bar{K})$	$13.8^{+2.1}_{-1.8}$
$f_1(1285)K^+$	< 2.0 CL=90%
$f_1(1420)K^+ \times \mathcal{B}(f_1(1420) \to \eta\pi\pi)$	< 2.9 CL=90%
$f_1(1420)K^+ \times \mathcal{B}(f_1(1420) \to K^*\bar{K})$	< 4.1 CL=90%

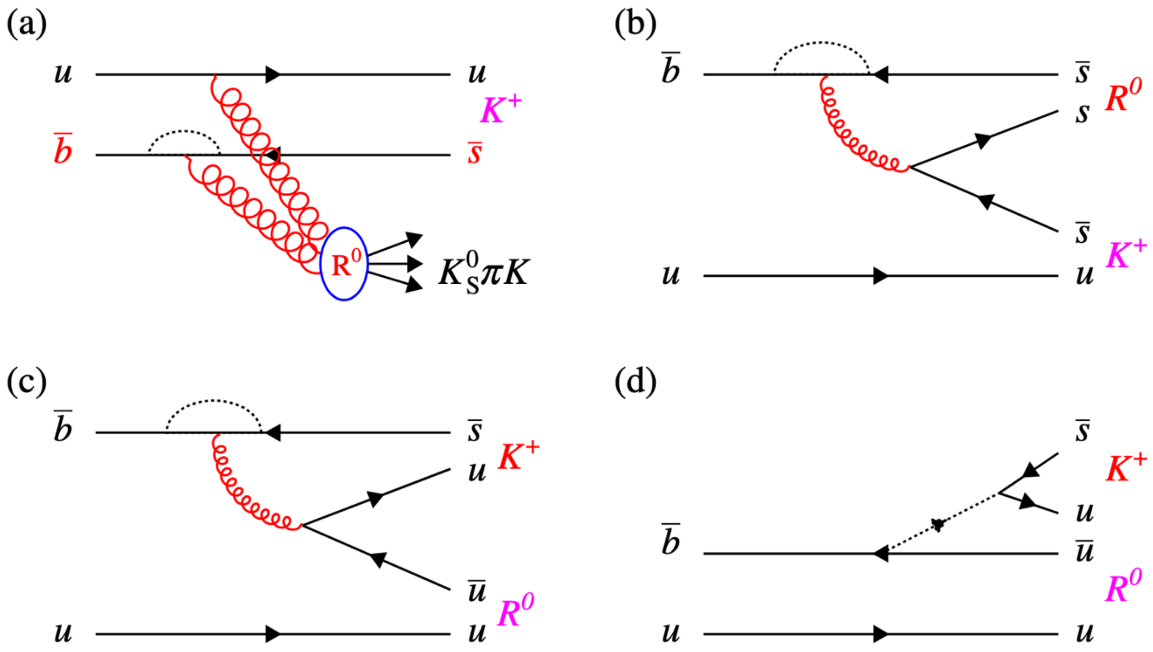
LHCb preliminary

Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

[LHCb-PAPER-2024-045] in preparation

- Motivation
  - Study the light meson spectroscopy in the threshold region of the $\boldsymbol{K_S^0 K\pi}$ mass spectrum in the decays of

    $B^+ \to (K_S^0 K^+ \pi^-) K^+$ $\qquad$ $B^+ \to (K_S^0 K^- \pi^+) K^+$
  - The interest is related to the identification of the pseudoscalar glueball and possible improvements in the understanding of the composition of the $J^{PC} = 0^{-+}, J^{PC} = 1^{++}, J^{PC} = 1^{+-}$ multiplets
  - The exclusive production of resonances in B decays may be calculable and help in evaluating the quark content



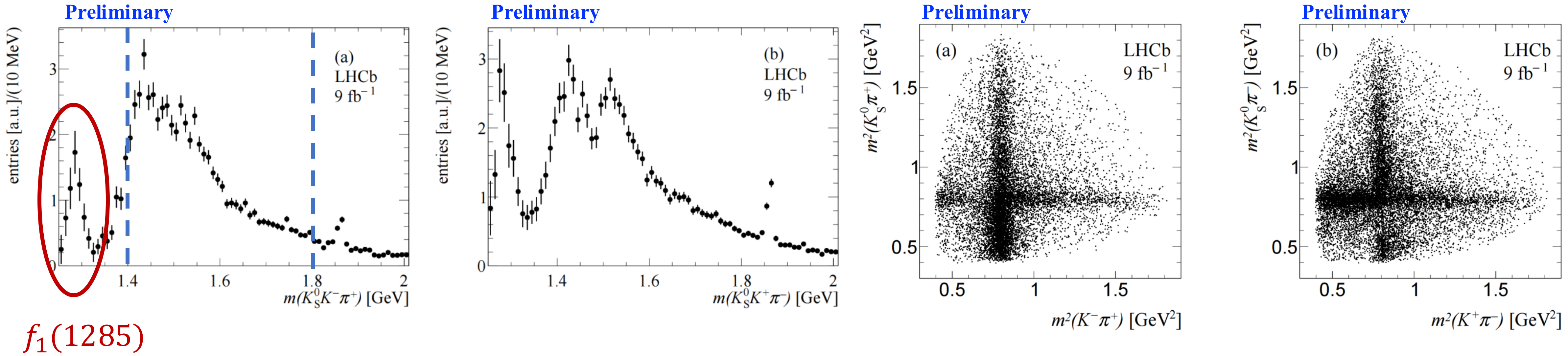
✓ possible source of gluonium states for $b \to s\, g$ process

✓ expected contributions from $s\bar{s}$ and $u\bar{u}$

Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

[LHCb-PAPER-2024-045] in preparation

- Full RunI + RunII dataset with $K_S^0{}_{LL}$ and $K_S^0{}_{DD}$ datasets
- Signal of $f_1(1285)$ in the threshold region
- Complex superposition of resonances in the 1.4-1.8 GeV mass region
- Asymmetric $K^{*+}(892)/K^{*0}(892)$ distributions.
- The Dalitz plots for $B^+ \to (K_S^0 K^+ \pi^-)K^+$ and $B^+ \to (K_S^0 K^- \pi^+)K^+$ are different.



⇒ Followed by a amplitude analysis

Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

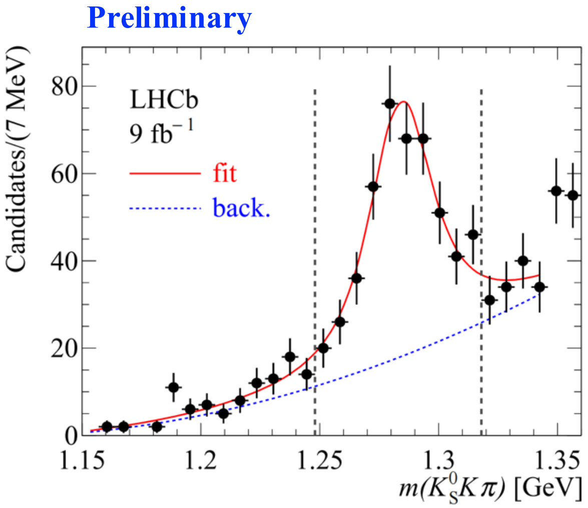
[LHCb-PAPER-2024-045] in preparation

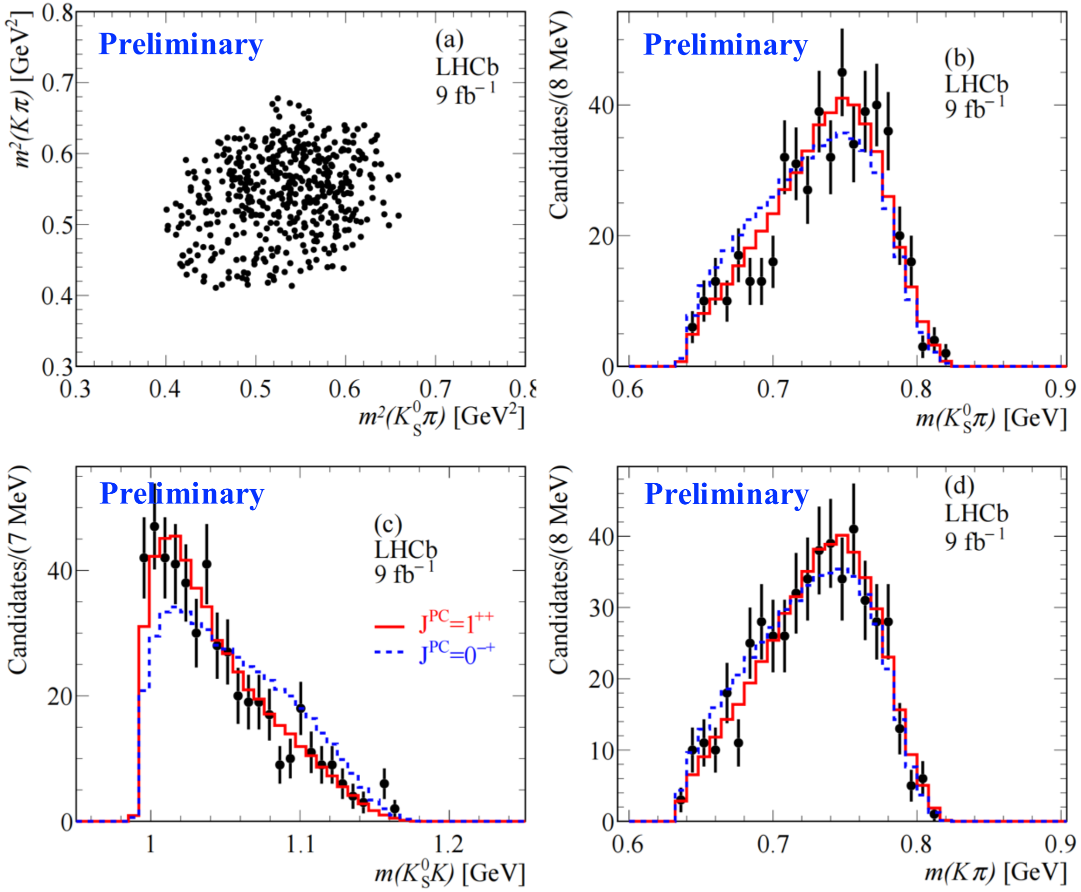
- Study of the $f_1(1285)$ mass region
  - Well known: $J^P = 1^+$; decay to $K_S^0 K\pi$ mainly through $a_0(980)\pi$
  - Fit with BW $\otimes$ R or single BW ; Amplitude analysis under three hypo.

Fitting method	χ^2/ndf	m_0 [MeV]	Γ [MeV]
Conv	13.3/22	1283.5 ± 1.5	27.4 ± 5.6
noConv	13.6/22	1283.5 ± 1.6	32.3 ± 5.4

Amplitudes	$-2log\mathcal{L}$	Fractions
(a) $f_1(1285), 1^+, PS$	-629.8	$0.601 \pm 0.042,\ 0.392 \pm 0.042$
(b) $f_1(1285), 0^-, PS$	-224.5	$0.164 \pm 0.041,\ 0.784 \pm 0.104$
(c) $f_1(1285)1^+, PS,$	-649.5	$0.577 \pm 0.043,\ 0.766 \pm 0.101$
$\eta(1295)0^-$		0.129 ± 0.050

PDG averages:
- $m = 1281.9 \pm 0.5$ MeV
- $\Gamma = 22.7 \pm 1.1$ MeV





Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

[LHCb-PAPER-2024-045] in preparation

- Amplitude analysis of the full low-mass
  - Evaluate the differences in fractions and relative phases between the two B^+ decay modes.

LHCb preliminary

Resonance	Decay	Δf	σ_1	σ_2	$\Delta\phi$	σ_1	σ_2
$\eta(1475)$	$K^*\overline{K}$	$0.5 \pm 1.5 \pm 1.8$	0.35	0.23	-	-	-
	$a_0\pi$	$-0.4 \pm 0.6 \pm 0.5$	0.72	0.54	$0.26 \pm 0.24 \pm 0.20$	1.10	0.84
	PS	$6.3 \pm 2.5 \pm 3.5$	2.53	1.47	$-0.24 \pm 0.15 \pm 0.18$	1.61	1.04
	Total	$6.4 \pm 3.0 \pm 3.9$	2.16	1.30	-	-	-
$\eta(1760)$	$K^*\overline{K}$	$-1.1 \pm 0.6 \pm 0.6$	1.92	1.37	$-0.37 \pm 0.21 \pm 0.34$	1.79	0.92
	$a_0\pi$	$0.3 \pm 0.5 \pm 0.4$	0.51	0.41	$-0.95 \pm 0.19 \pm 0.31$	4.95	2.59
	PS	$-11.3 \pm 3.0 \pm 5.8$	3.76	1.74	$-0.32 \pm 0.12 \pm 0.29$	2.62	1.01
	Total	$-12.1 \pm 4.4 \pm 5.8$	2.78	1.67	-	-	-
$\eta(1405)$	$K^*\overline{K}$	$1.2 \pm 0.8 \pm 2.0$	1.50	0.55	$-0.09 \pm 0.15 \pm 0.27$	0.61	0.29
	PS	$-1.1 \pm 0.8 \pm 1.2$	1.47	0.78	$-0.19 \pm 0.17 \pm 0.34$	1.12	0.49
	Total	$0.1 \pm 1.1 \pm 2.3$	0.05	0.02	-	-	-
$f_1(1285)$	$a_0\pi$	$-0.1 \pm 0.3 \pm 0.3$	0.31	0.21	$0.1 \pm 0.2 \pm 0.3$	0.70	0.36
$f_1(1420)$	$K^*\overline{K}$	$4.8 \pm 0.9 \pm 2.7$	5.62	1.66	$-0.4 \pm 0.1 \pm 0.4$	3.28	1.11
$h_1(1415)$	$K^*\overline{K}S$	$-8.6 \pm 1.5 \pm 4.01$	5.80	2.00	$3.0 \pm 0.1 \pm 0.6$	26.69	5.07
	$K^*\overline{K}D$	$1.0 \pm 0.4 \pm 0.3$	2.51	1.96	$2.4 \pm 0.11 \pm 0.5$	21.57	5.26
	Total	$-7.7 \pm 1.5 \pm 4.1$	5.00	1.77	-	-	-
$f_1(1510)$	$K^*\overline{K}$	$0.3 \pm 0.5 \pm 3.0$	0.57	0.09	$-0.35 \pm 0.13 \pm 0.52$	2.75	0.65
$h_1(1595)$	$K^*\overline{K}S$	$-9.6 \pm 1.7 \pm 3.1$	5.78	2.74	$-2.76 \pm 0.10 \pm 0.52$	27.60	5.25
$\eta_2(1645)$	$K^*\overline{K}$	$0.8 \pm 0.3 \pm 0.8$	2.97	0.91	$0.13 \pm 0.16 \pm 0.13$	0.83	0.65
PS		$-6.8 \pm 3.5 \pm 5.8$	1.95	1.01	$0.28 \pm 0.11 \pm 0.22$	2.46	1.13

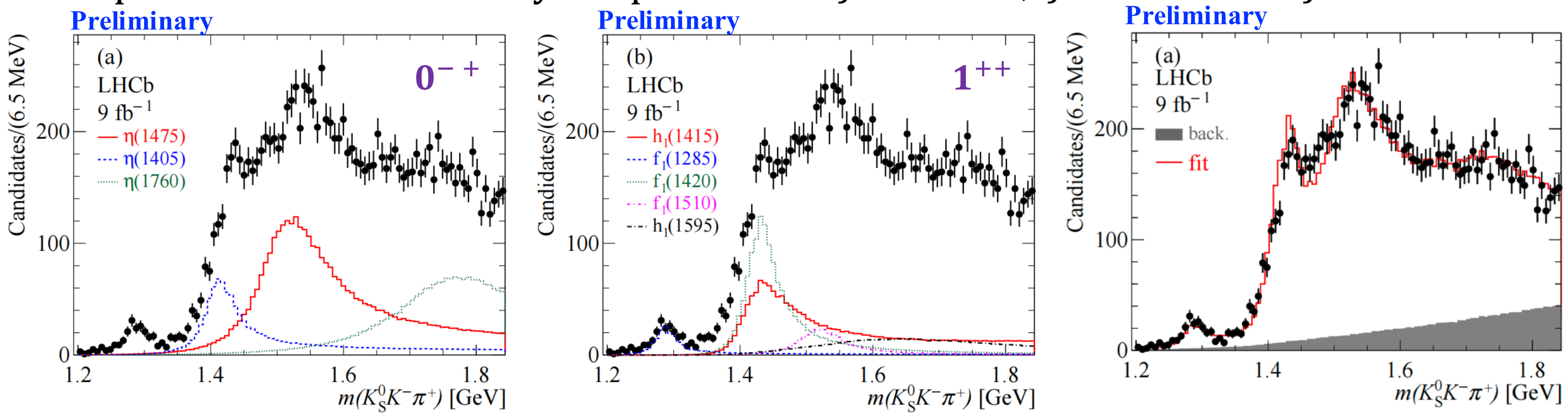
Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

- Partial waves decomposition

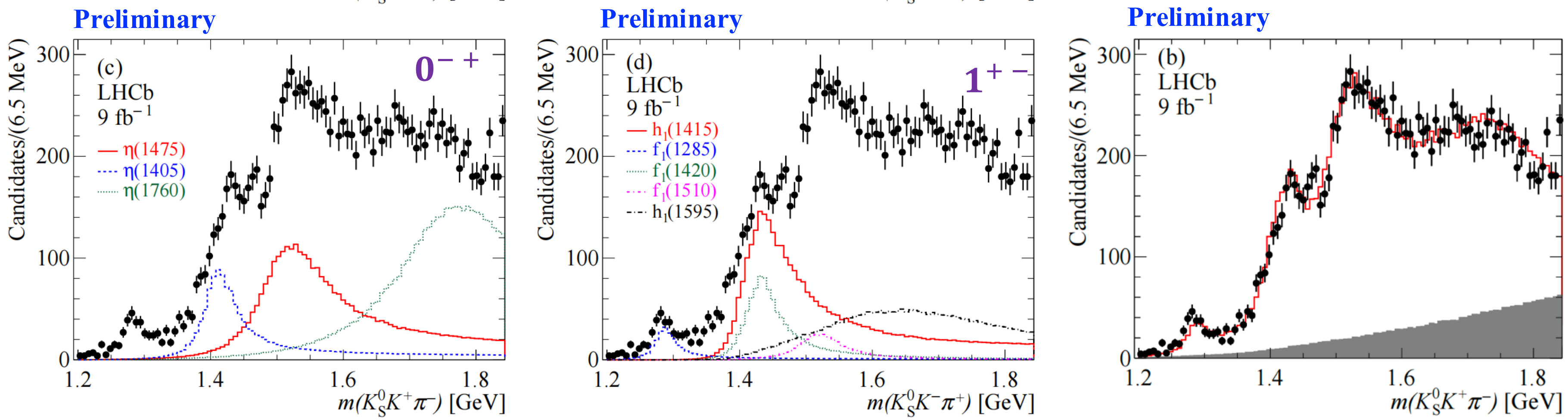
[LHCb-PAPER-2024-045] in preparation

  - The $K_S^0 K\pi$ mass spectrum is dominated by the presence of $J^{PC} = 0^{-+}$, $J^{PC} = 1^{++}$ and $J^{PC} = 1^{+-}$

$B^+ \to (K_S^0 K^- \pi^-)K^+$



$B^+ \to (K_S^0 K^+ \pi^-)K^+$



Study of light meson resonances in the $B \to (K_S^0 K\pi)K$ decays

[LHCb-PAPER-2024-045] in preparation

- Measurements of branching fraction
  - In LHCb-PAPER-2022-051, the total branching fractions have been measured
  - The BF for resonance R^0 in $B^+ \to R^0 K^+$ with $R^0 \to \overline{K^0} K^+ \pi^-$

Final state	reference	$\mathcal{B}(\times 10^{-5})$
$B^+ \to K^0 K^+ K^- \pi^+$	η_c	$32.28 \pm 0.33 \pm 1.97 \pm 7.17$
	J/ψ	$34.01 \pm 0.74 \pm 0.91 \pm 3.10$
	average	$32.57 \pm 0.30 \pm 0.83 \pm 2.85$
$B^+ \to \overline{K}^0 K^+ K^+ \pi^-$	η_c	$26.56 \pm 0.31 \pm 0.68 \pm 5.90$
	J/ψ	$28.01 \pm 0.68 \pm 1.35 \pm 2.55$
	average	$26.81 \pm 0.28 \pm 0.61 \pm 2.34$

LHCb preliminary

Contributions	$\mathcal{B}(B^+ \to R^0 K^+) \times 10^{-5}$
$B^+ \to \eta(1475)K^+ \to (K^*\overline{K})K^+$	$1.49 \pm 0.15 \pm 0.15 \pm 0.13$
$B^+ \to \eta(1475)K^+ \to (a_0(980)^-\pi^+)K^+$	$0.19 \pm 0.05 \pm 0.05 \pm 0.02$
$B^+ \to \eta(1475)K^+ \to (K^0K^-\pi^+)K^+$	$2.10 \pm 0.29 \pm 0.30 \pm 0.18$
$B^+ \to \eta(1760)K^+ \to (K^*\overline{K})K^+$	$0.27 \pm 0.05 \pm 0.04 \pm 0.02$
$B^+ \to \eta(1760)K^+ \to (a_0(980)^-\pi^+)K^+$	$0.28 \pm 0.05 \pm 0.03 \pm 0.02$
$B^+ \to \eta(1760)K^+ \to (K^0K^-\pi^+)K^+$	$1.64 \pm 0.25 \pm 0.37 \pm 0.14$
$B^+ \to \eta(1405)K^+ \to (K^*\overline{K})K^+$	$0.48 \pm 0.08 \pm 0.26 \pm 0.04$
$B^+ \to \eta(1405)K^+ \to (K^0K^-\pi^+)K^+$	$0.73 \pm 0.08 \pm 0.11 \pm 0.06$
$B^+ \to f_1(1285)K^+ \to (a_0(980)^-\pi^+)K^+$	$0.27 \pm 0.03 \pm 0.02 \pm 0.02$
$B^+ \to f_1(1420)K^+ \to (K^*\overline{K})K^+$	$1.58 \pm 0.10 \pm 0.30 \pm 0.14$
$B^+ \to f_1(1510)K^+ \to (K^*\overline{K})K^+$	$0.40 \pm 0.05 \pm 0.16 \pm 0.03$
$B^+ \to h_1(1415)K^+ \to (K^*\overline{K})K^+$	$1.84 \pm 0.14 \pm 0.27 \pm 0.16$
$B^+ \to h_1(1595)K^+ \to (K^*\overline{K})K^+$	$0.73 \pm 0.11 \pm 0.12 \pm 0.06$
$B^+ \to \eta_2(1645)K^+ \to (K^*\overline{K})K^+$	$0.22 \pm 0.03 \pm 0.11 \pm 0.02$

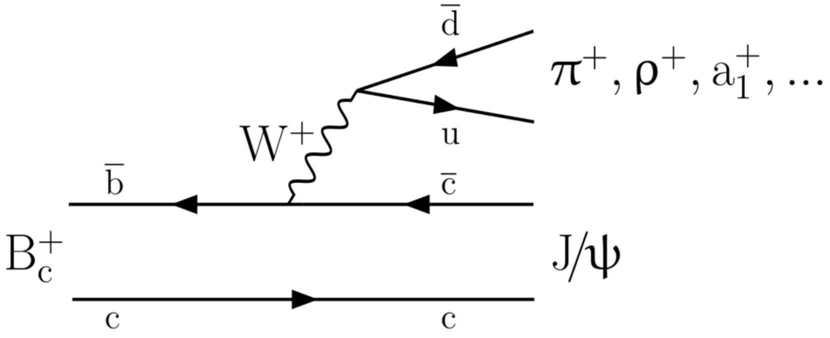
Observation of $B_c^+ \to J/\psi\pi^+\pi^0$ decay

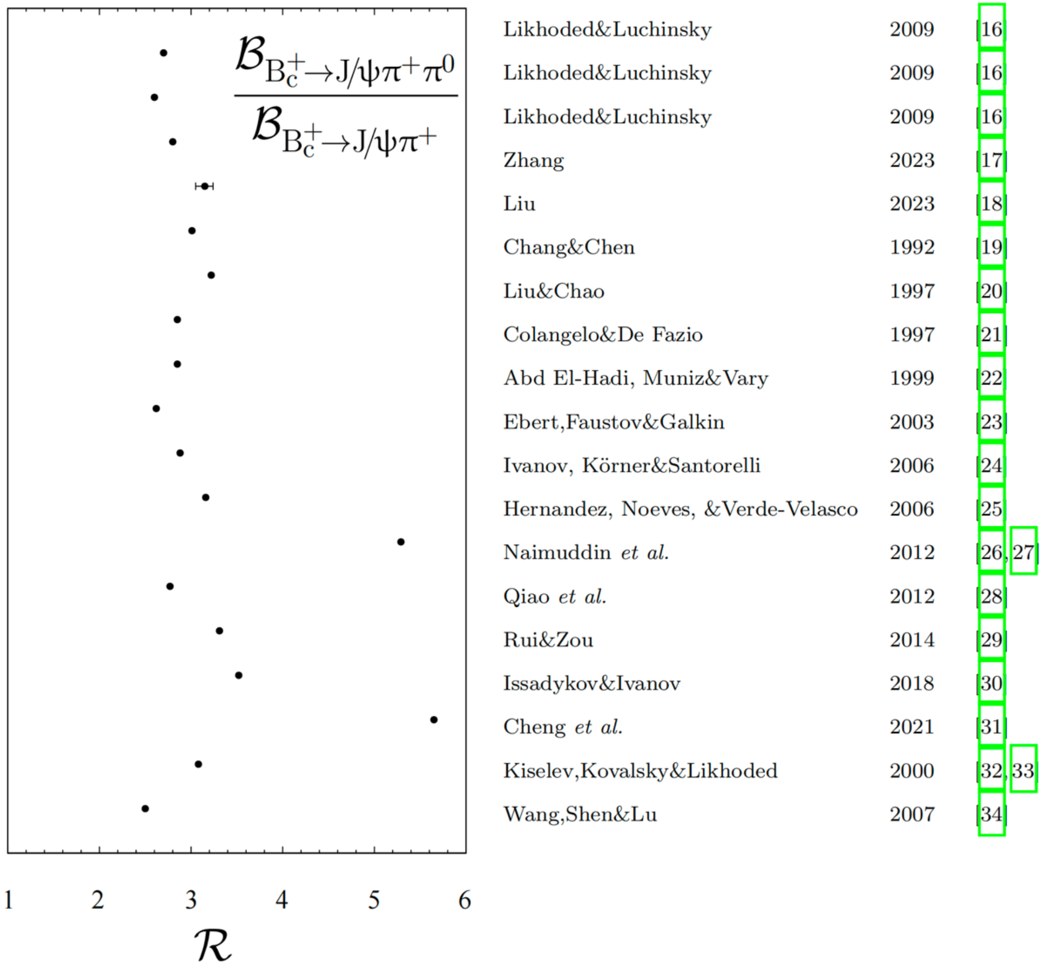
[JHEP 04 (2024) 151]

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

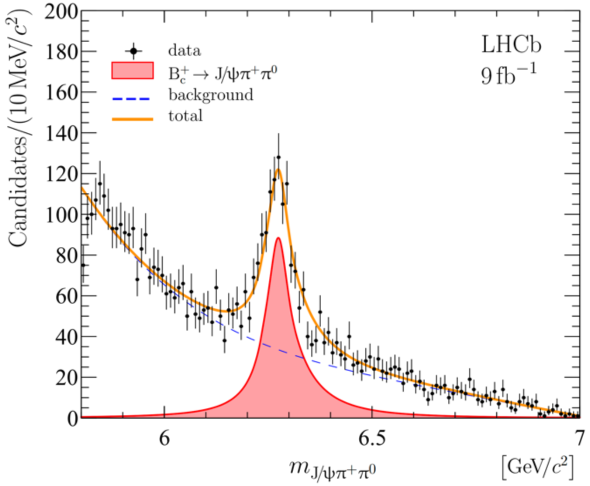
- Strategy
  - Measure the ratio of branching fractions between $B_c^+ \to J/\psi\pi^+\pi^0$ and $B_c^+ \to J/\psi\pi^+$

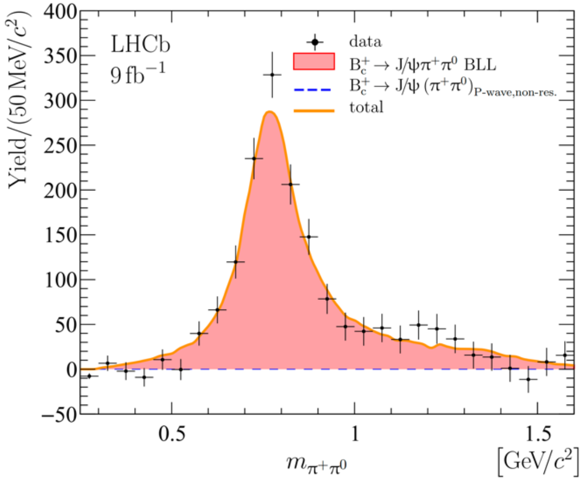
$$\frac{\mathcal{B}(B_c^+ \to J/\psi\rho^+)}{\mathcal{B}(B_c^+ \to J/\psi\pi^+)} = \frac{N_{\rho^+}}{N_{\pi^+}} \cdot \frac{\epsilon_{\pi^+}}{\epsilon_{\rho^+}}$$

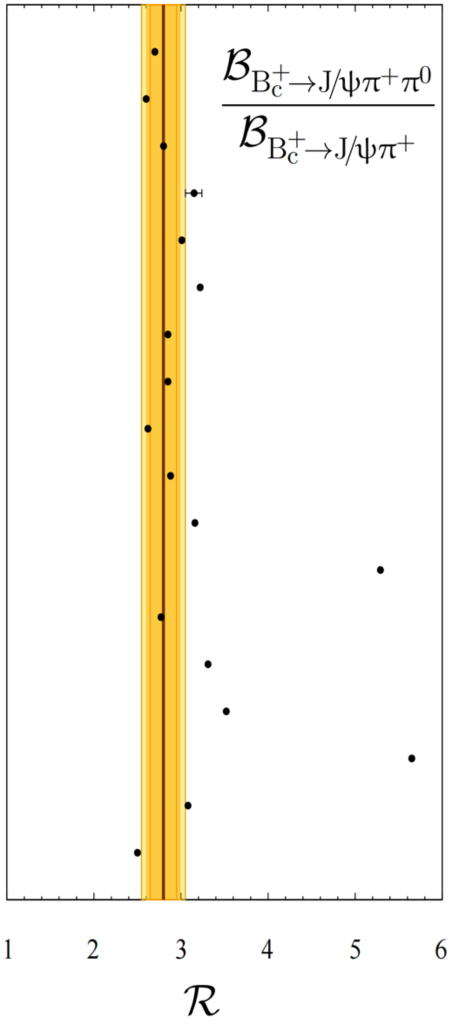
  - The $B^+ \to J/\psi K^{*+}(\to K^+\pi^0)$ decay is used to correct the detector resolution
  - The possible contribution from $\rho(1450)$ is considered in simulation

- 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 $B_c^+ \to J/\psi\rho(1450)^+$

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







Measurement of the BF of $B^0 \to J/\psi\pi^0$ decay

[JHEP 05 (2024) 065]

Measurement of the BF of $B^0 \to J/\psi\pi^0$ decay

[JHEP 05 (2024) 065]

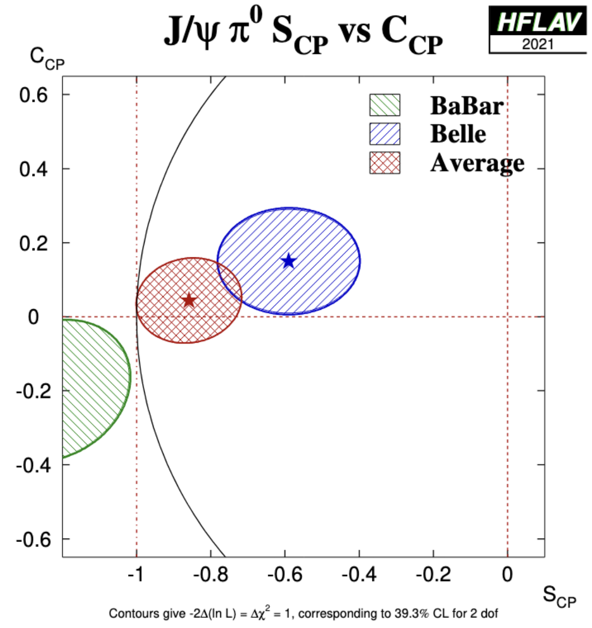
- Motivation
  - Constrain the phase shift from hadronic penguin topologies to improve the precision of CPV measurements (sin(2β)) in the golden channel $B^0 \to J/\psi K_S^0$
  - The BaBar and Belle collaborations reported evidence of indirect CP-violation in $B^0 \to J/\psi\pi^0$ decays (comparable with $B^0 \to J/\psi K_S^0$), as well as the branching fraction.

- Goal: new measurement competitive with Belle 2018 results using RunI & II dataset

[Phys. Rev. D 107 (2023) 052008]

$\Gamma(B^0 \to J/\psi(1S)\pi^0)/\Gamma_{total}$ — Γ_{223}/Γ

VALUE	CL%	DOCUMENT ID		TECN	COMMENT
1.66 ± 0.10	OUR AVERAGE				
1.62 ±0.11 ±0.06		[1] PAL	2018	BELL	$e^+ e^- \to \Upsilon(4S)$
1.69 ±0.14 ±0.07		[1] AUBERT	2008AU	BABR	$e^+ e^- \to \Upsilon(4S)$
$2.5\ ^{+1.1}_{-0.9}$ ±0.2		[1] AVERY	2000	CLE2	$e^+ e^- \to \Upsilon(4S)$



Measurement of the BF of $B^0 \to J/\psi\pi^0$ decay

[JHEP 05 (2024) 065]

- Strategy
  - Measure the ratio of branching fractions between $B^0 \to J/\psi\pi^0$ and $B^+ \to J/\psi K^{*0}$

$$\frac{\mathcal{B}(B^0 \to J/\psi\pi^0)}{\mathcal{B}(B^+ \to J/\psi K^{*+})} = \frac{N_{B^0}}{N_{B^+}} \cdot \frac{\epsilon_{B^+}}{\epsilon_{B^0}} \cdot \mathcal{B}(K^{*+} \to K^+\pi^0)$$

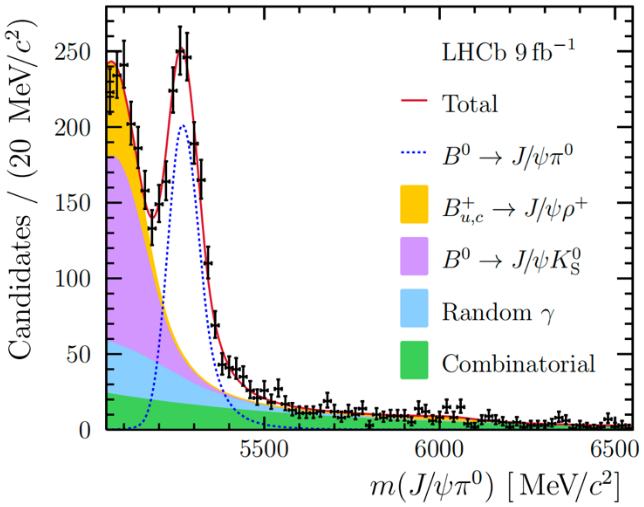
  - Enlarge the π^0 mass window to part-reco, combinatorial and random photon background

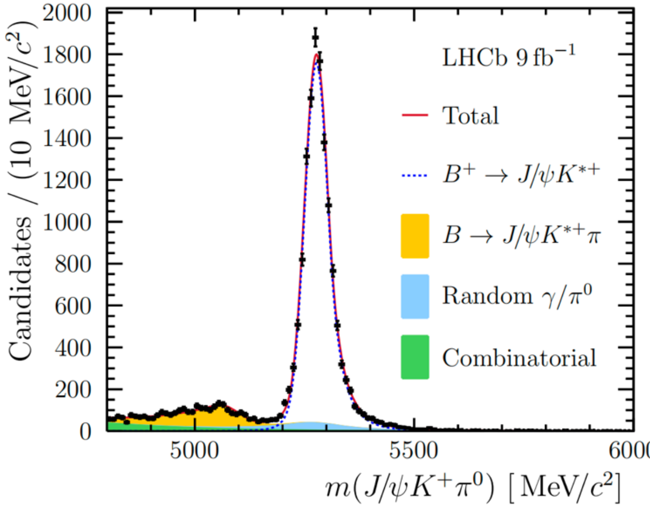
- Results

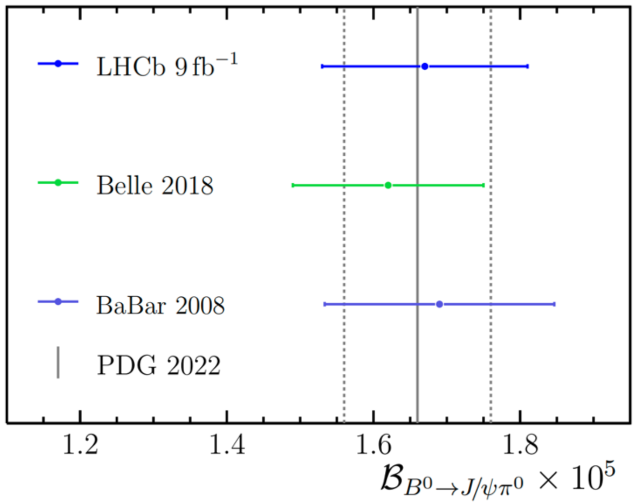
$$\frac{\mathcal{B}_{B^0\to J/\psi\pi^0}}{\mathcal{B}_{B^+\to J/\psi K^{*+}}} = (1.153 \pm 0.053 \pm 0.048) \times 10^{-2}$$

Competitive with the most precise single measurement

$$\mathcal{B}_{B^0\to J/\psi\pi^0} = (1.670 \pm 0.077 \pm 0.069 \pm 0.095) \times 10^{-5}$$

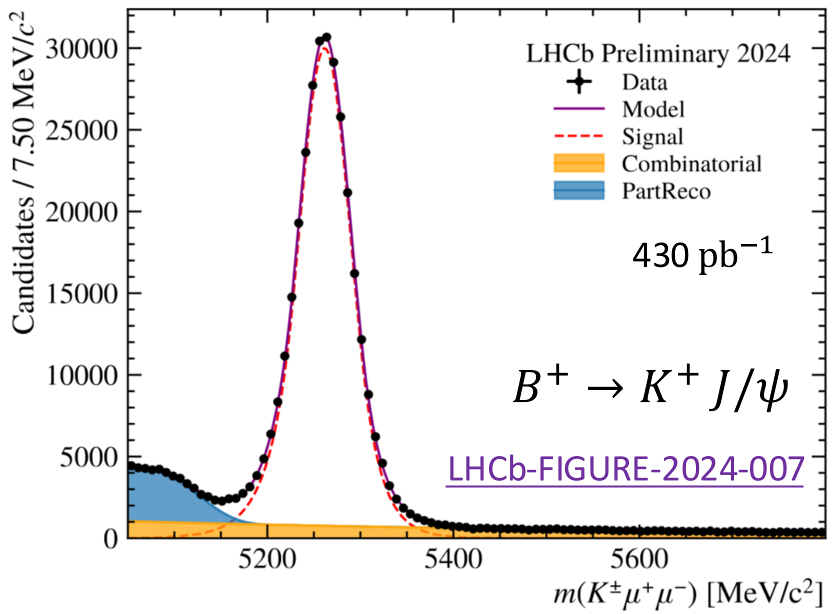




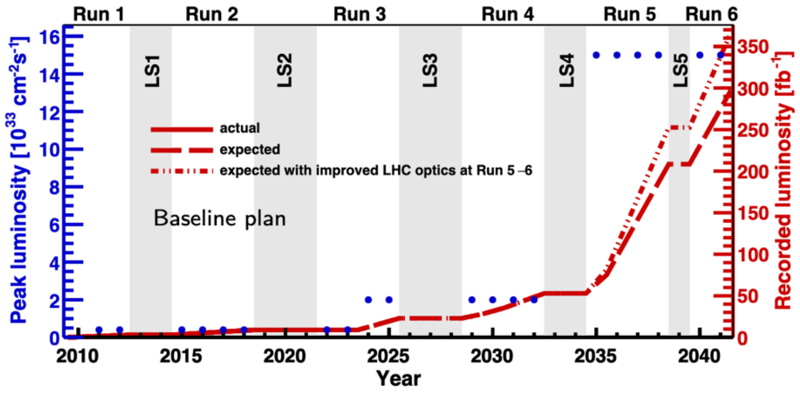


Summary and prospect

- Recent beauty meson spectroscopy results presented in this talk
  - Mass measurements:
    - ✓ $\Upsilon(2S), \Upsilon(3S), \chi_b(1P), \chi_b(2P)$
  - New decay modes:
    - ✓ $B_c^+ \to J/\psi\pi^+\pi^0$
    - ✓ $\chi_b \to \Upsilon(1S)\mu^-\mu^+$
  - $BR(B^0 \to J/\psi\pi^0)$ (improved)
  - New information in light meson spectroscopy



- In RunIII, the LHCb experiment will keep making important contributions to heavy hadron spectroscopy with
  - Higher luminosity
  - Upgraded detector (e.g. UT)
  - Improved techniques (e.g. full reconstruction in software trigger)
  - …



- **Today's discovery, tomorrow's precision tool to test QCD**

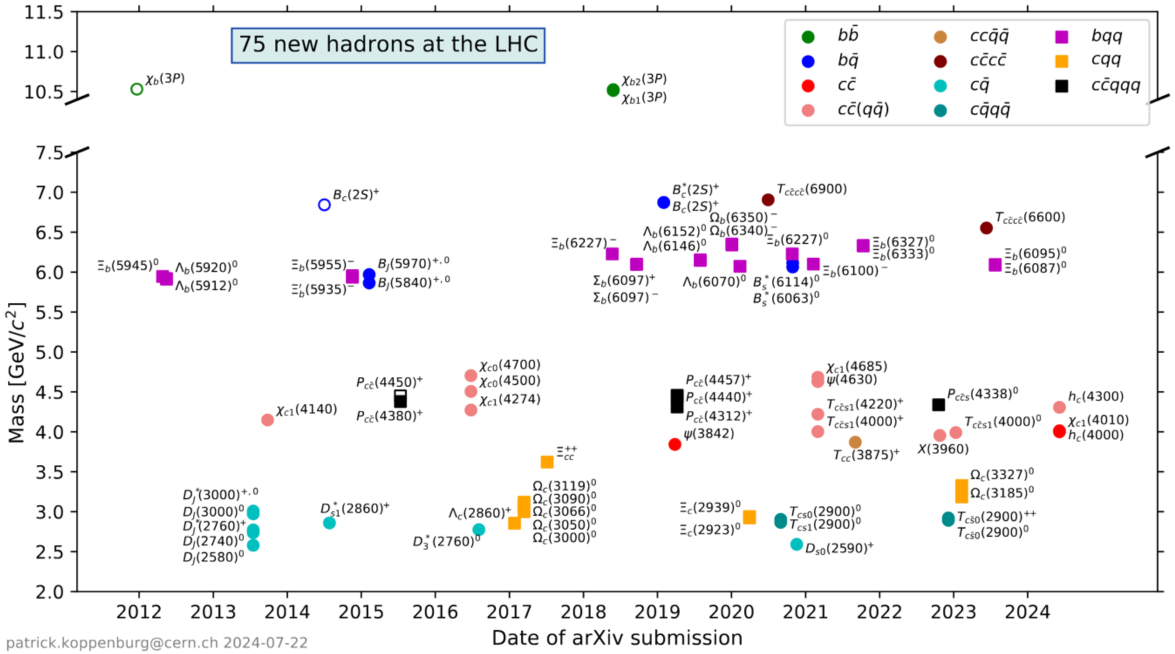
Thanks a lot for your attention!

Backup

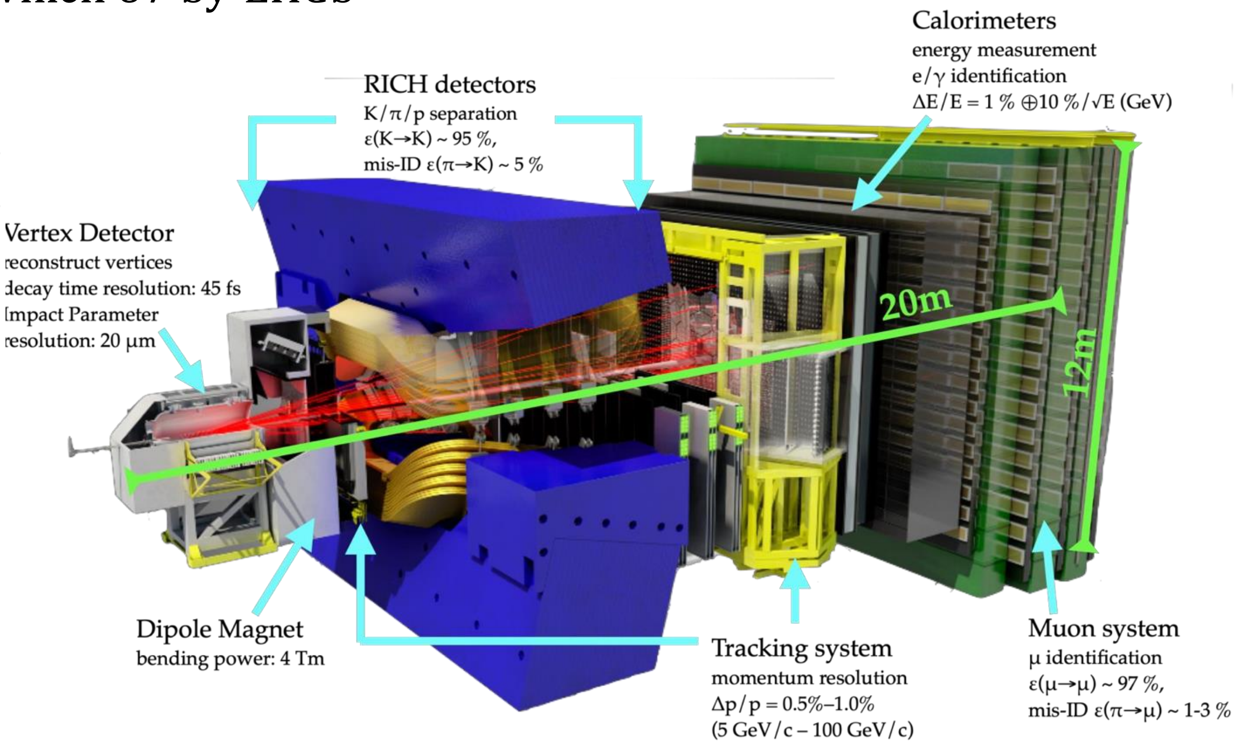
The LHCb detector

[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

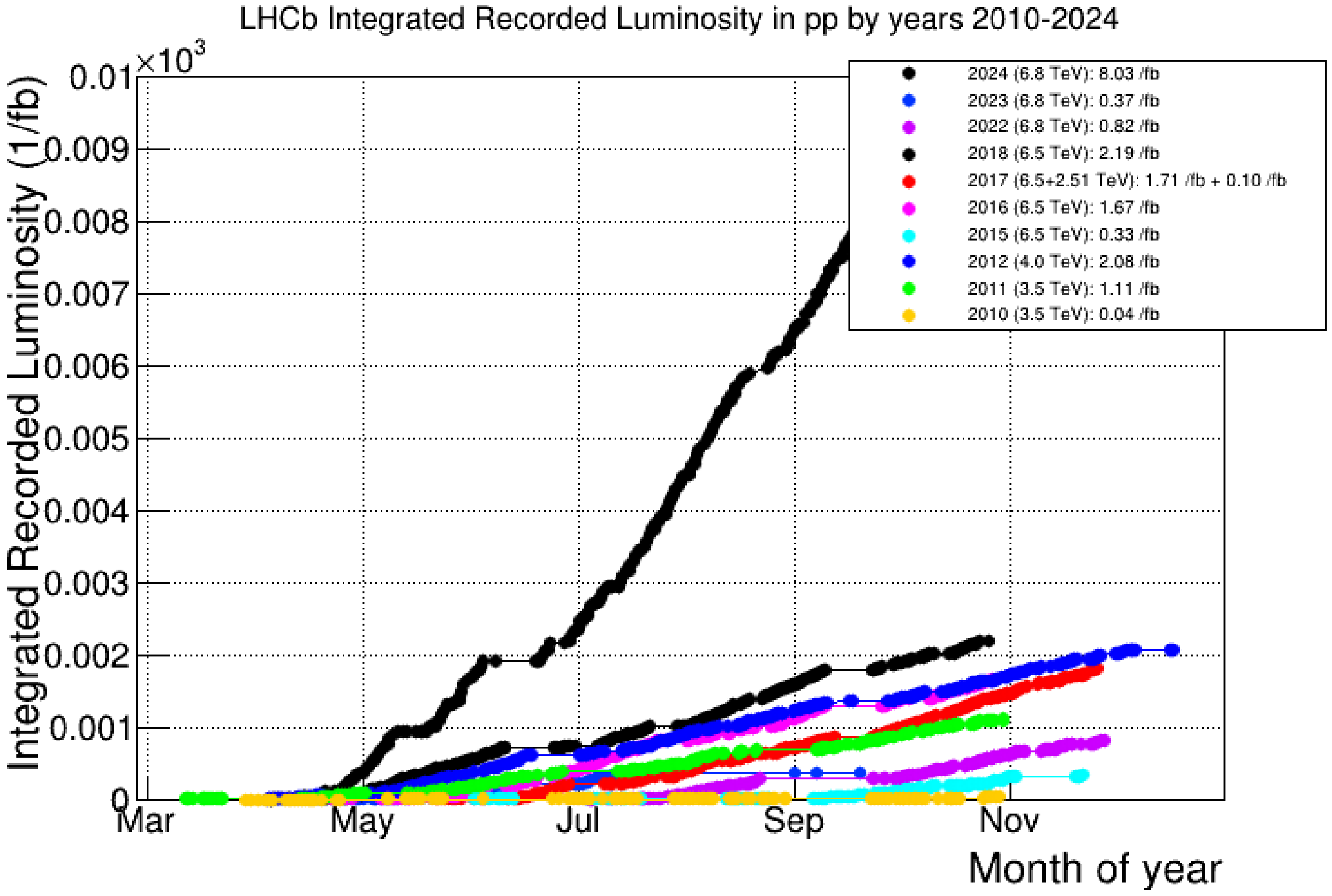


[https://www.nikhef.nl/~pkoppenb/hadrons//Masses.pdf]



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

Observation of $B_c^+ \to \chi_c \pi^+$ decay

[JHEP 02 (2024) 173]

Observation of $B_c^+ \to \chi_c \pi^+$ decay

[JHEP 02 (2024) 173]

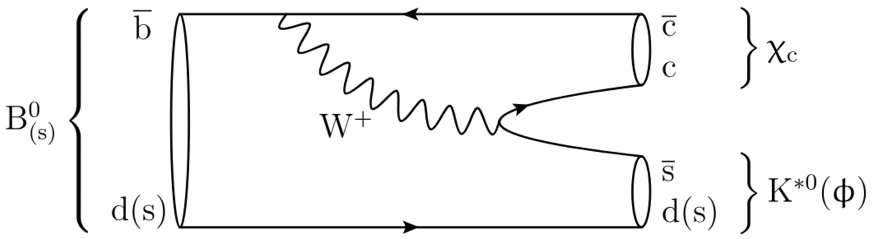
- Motivation
  - The $B_c^+ \to \chi_{c1,2}\pi^+$ decay with $\chi_{c1,2} \to J/\psi\gamma$ channel never were studied (only evidence for $B_c^+ \to \chi_{c0}(\to K^+K^-)\pi^+$)
  - The partial width ratio of $\Lambda_b^0 \to \chi_{c2} pK^- / \Lambda_b^0 \to \chi_{c1} pK^-$ or $\Lambda_b^0 \to \chi_{c2} p\pi^- / \Lambda_b^0 \to \chi_{c1} p\pi^-$ are measured to be almost equal

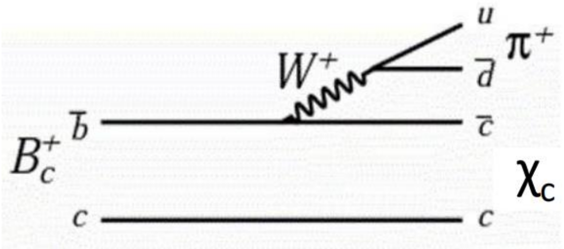
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} p\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} p\pi^-)} = 0.95 \pm 0.30 \pm 0.04 \pm 0.04$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)} = 1.06 \pm 0.05 \pm 0.04 \pm 0.04$$

  - The partial widths for $B^0 \to \chi_{c2} K^{*0}$ show significant suppression compared to $B^0 \to \chi_{c1} K^{*0}$

$$\frac{\mathcal{B}(B^0 \to \chi_{c2} K^{*0})}{\mathcal{B}(B^0 \to \chi_{c1} K^{*0})} = \left(9.74 \pm 2.86\,(\text{stat}) \pm 0.97\,(\text{syst})\right) \times 10^{-2} \times \frac{\mathcal{B}(\chi_{c1} \to J/\psi\gamma)}{\mathcal{B}(\chi_{c2} \to J/\psi\gamma)}$$
$$= \left(17.1 \pm 5.0\,(\text{stat}) \pm 1.7\,(\text{syst}) \pm 1.1\,(\mathcal{B})\right) \times 10^{-2},$$





⇒ additional measurements are required to test the theory predictions and clarify the role of QCD factorization

Observation of $B_c^+ \to \chi_c \pi^+$ decay

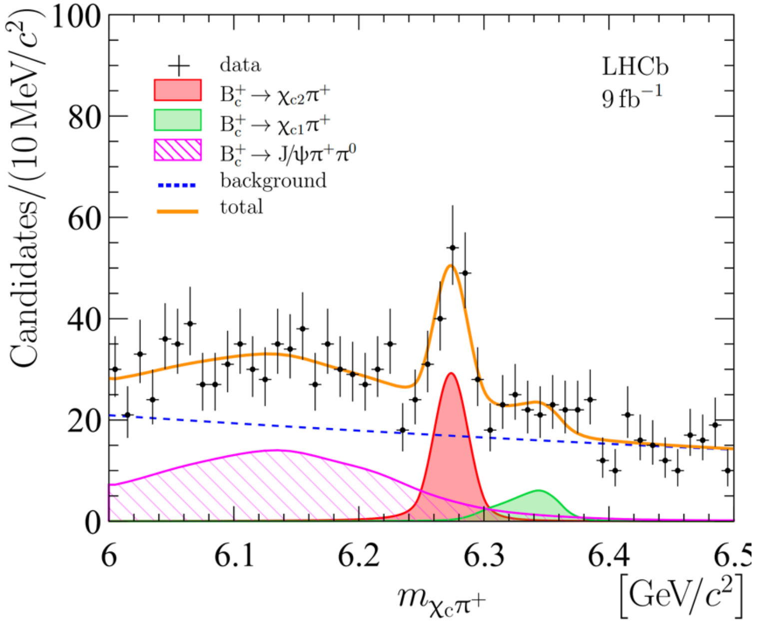
[JHEP 02 (2024) 173]

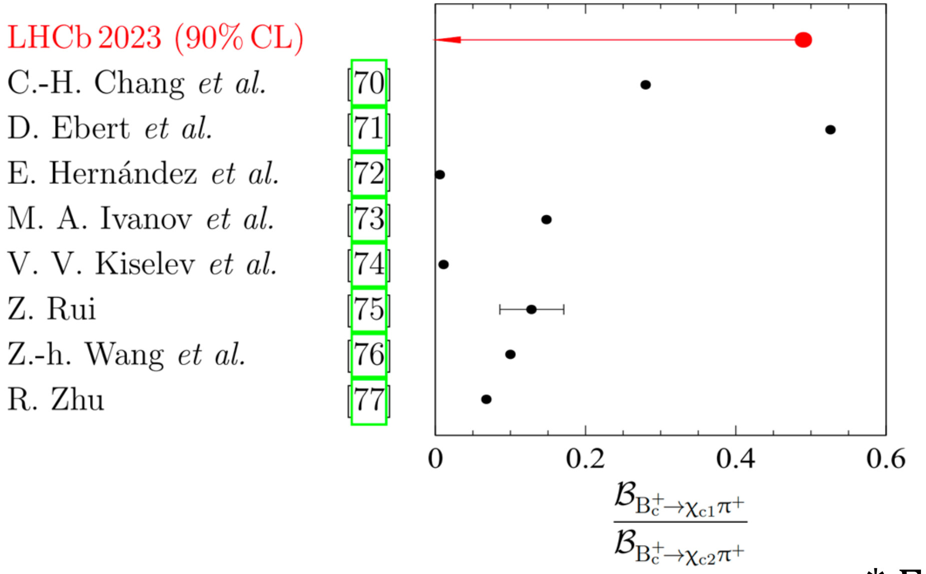
- Strategy
  - Measure the ratio of branching fractions between $B_c^+ \to \chi_{c1,2}\pi^+$ and $B_c^+ \to J/\psi\pi^+$

$$\frac{\mathcal{B}_{B_c^+\to\chi_{c1,2}\pi^+}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = \frac{N_{B_c^+\to\chi_{c1,2}\pi^+}}{N_{B_c^+\to J/\psi\pi^+}} \times \frac{\varepsilon_{B_c^+\to J/\psi\pi^+}}{\varepsilon_{B_c^+\to\chi_{c1,2}\pi^+}}$$

  - The $B^+ \to J/\psi K^{*+}(\to K^+\pi^0)$ decay is used to correct the detector resolution

- Results





$$\frac{\mathcal{B}_{B_c^+\to\chi_{c2}\pi^+}}{\mathcal{B}_{B_c^+\to J/\psi\pi^+}} = 0.37 \pm 0.06 \pm 0.02 \pm 0.01$$

$$\frac{\mathcal{B}_{B_c^+\to\chi_{c1}\pi^+}}{\mathcal{B}_{B_c^+\to\chi_{c2}\pi^+}} < 0.49 \text{ at } 90\%\ \text{CL}$$

Agree with theory expectation for the suppression

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