Perspectives of Hadron Spectroscopy at LHCb

[arXiv:1808.08865]

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On behalf of the LHCb Collaboration

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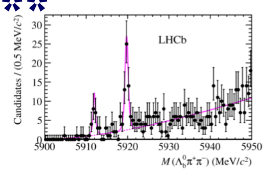
Spectroscopy at LHCb

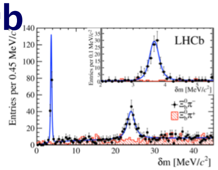
LHCb has largely contributed to populate the zoo of particles.
Some of them have a clear "exotic" signature

Λ_b^{**}



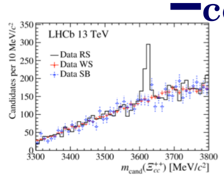
PRL 109 (2012) 172003

Ξ_b^{**}



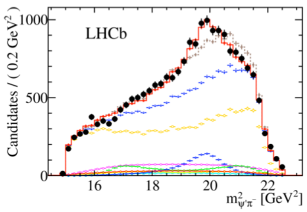
PRL 114 (2015) 062004

Ξ_{cc}^{++}



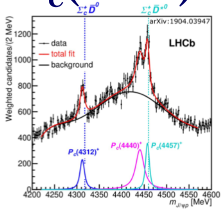
PRL 119 (2017) 112001

$Z_c(4430)^+$



PRL 112 (2014) 222002
PRD 92 (2015) 112009

$P_c(4450)^+$

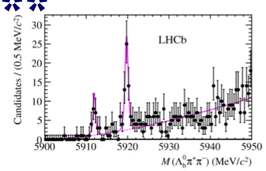


PRL 115 (2015) 072001
arXiv:1904.03947

Spectroscopy at LHCb

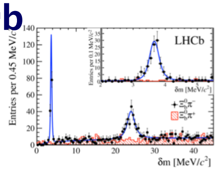
…but many other states have uncertain nature. Goal of the upcoming years is to probe their conventional/exotic nature…and find new candidates of course

Λ_b^{**}



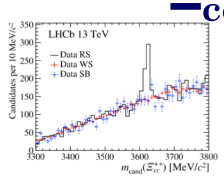
PRL 109 (2012) 172003

Ξ_b^{**}



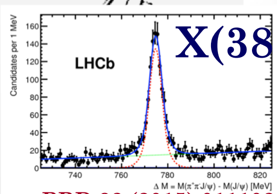
PRL 114 (2015) 062004

Ξ_{cc}^{++}



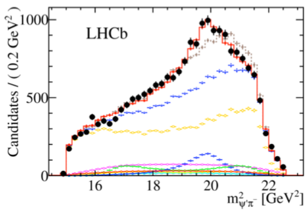
PRL 119 (2017) 112001

X(3872)



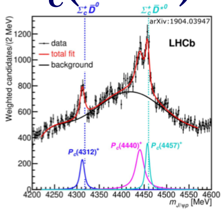
PRD 92 (2015) 011102
PRL 110 (2013) 222001

$Z_c(4430)^+$



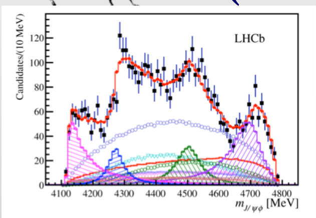
PRL 112 222002 (2014)
PRD 92 112009 (2015)

$P_c(4450)^+$



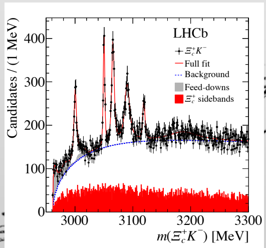
PRL 115 (2015) 072001
arXiv:1904.03947

X(4140)



PRL 118 (2017) 022003
PRD 95 (2017) 012002

Ω_c^{**}(?)



PRL 118 (2017) 182001

LHCb Going to Upgrade

Upgrade I (Approved)

- Main limitation that prevents exploiting higher luminosity with the present detector is the Level-0 (hardware) trigger
  - ✓ Level-0 output rate < 1 MHz (readout rate) requires raising thresholds
- This is particularly problematic for hadronic final states
- Running at $2\text{x}10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ with full software trigger, running at 40 MHz

Upgrade II (Under approval)

To be installed in Long Shutdown 4 of the LHC:

- Subsystems redesigned to operate at a luminosity of $1\text{-}2\ \text{x}\ 10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$
- Integrated luminosity of > $300\ \text{fb}^{-1}$
- Extension of the experiment's capabilities into selecting π^0, η and low-momentum tracks

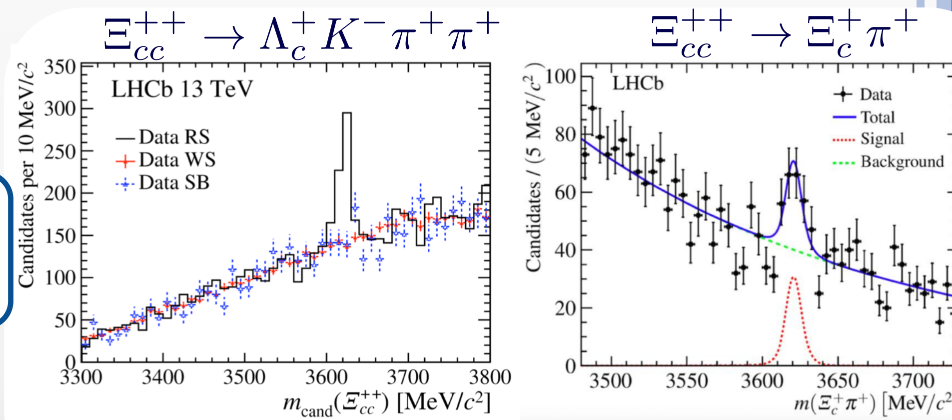
LHC era			HL-LHC era	
Run 1 (2010-12)	Run 2 (2015-18)	Run 3 (2021-24)	Run 4 (2027-30)	Run 5+ (2031+)
$3\ \text{fb}^{-1}$	$9\ \text{fb}^{-1}$	$23\ \text{fb}^{-1}$	$46\ \text{fb}^{-1}$	$>300\ \text{fb}^{-1}$
		Upgrade Ia	Upgrade Ib	Upgrade II

Doubly Heavy Baryons

- Three weakly decaying C = 2 states are expected:
- Ξ_{cc} isodoublet (ccu; ccd) and an Ω_{cc} isosinglet (ccs), each with $J^P = 1/2^+$
- Ξ_{cc}^{++} observed in two different decay modes!

$m(\Xi_{cc}^{++}) = 3621.24 \pm 0.65(\text{stat}) \pm 0.31(\text{syst})$ MeV

$\tau(\Xi_{cc}^{++}) = 0.256^{+0.024}_{-0.022}(\text{stat}) \pm 0.014(\text{syst})$ ps



PRL 119 (2017) 112001 **PRL 121 (2018) 052002**

- Observations of Ξ_{cc}^+ and Ω_{cc}^+ expected with RUN II data or during the upcoming Upgrade I
- Upgrade II will be useful into studying their production and excited spectra: Ξ^{**}_{cc} and Ω^{**}_{cc}. Ω_{ccc} might be also observed

What about Ξ_{bc}?

- The B_c meson was discovered almost two decades ago
  In LHCb, ~5000 $B_c \to J/\psi\pi$ in Run I

So, why have we not yet seen bcq baryons (Ξ_{bc})?

Lower production rates, guess $\sigma(X_{bc}) \sim (0.1\text{ -}0.5) \times \sigma(B_c^+)$

In J/ψ modes, (usually) get a charm baryon: yield reduced by $BF(X_c) \times \varepsilon_{sel}(X_c)$

Shorter lifetime (~0.15 – 0.4 ps range, compared to ~0.5 ps for B_c)

$$
\begin{aligned}
(e.g.)\, N(\Xi_{bc}^0 \to J/\psi \Lambda_c^+ K^-; \mathrm{Run1}) =& N(B_c^+ \to J/\psi D_s^{(*)+}; \mathrm{Run1}) \\
& \times \frac{\sigma(pp \to \Xi_{bc} X)}{\sigma(pp \to B_c^+ X)} \times f_{\Xi_{bc} \to \Xi_{bc}^0} \\
& \times \frac{Br(\Xi_{bc}^0 \to J/\psi \Lambda_c^+ K^-)}{Br(B_c^+ \to J/\psi D_s^{(*)+})} \\
& \times \epsilon_{K^-} \\
& \simeq 3\,\mathrm{candidates}
\end{aligned}
$$

[arXiv:1808.08865]

$$N(\Xi_{bc}^0 \to J/\psi \Lambda_c^+ K^-; \mathrm{Run\,5}) \simeq 6 \times 10^2$$

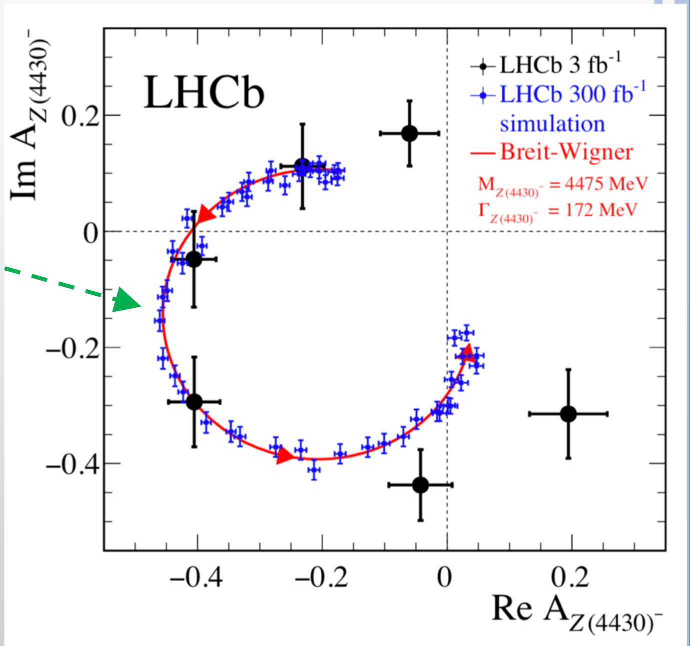
Exclusive Ξ_{bb} are even more unlikely but see later for an alternative approach

Probing the Nature of the Exotic Hadrons

- Observation of several hadronic resonances with hidden charm or beauty (so called X, Y, Z states) in the last decade at LHC and B-factories
- They barely fit to standard quarkonium scenarios and "exotic" interpretations proposed: compact tetraquarks, molecules, cusps, …
- Most of them are quite broad and observed in 3-body decays of *b*-hadrons (e.g. $B^0 \rightarrow Z(4430)^- (\rightarrow \psi(2S)\,\pi^-)\,K^+$)

Upgrade II would allow to test further their nature by:

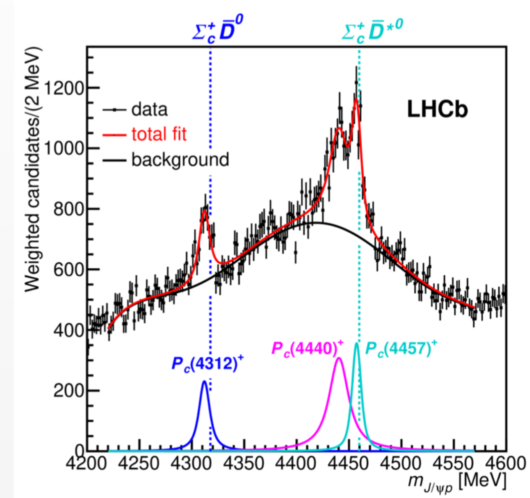
- Probing the resonant character
- Searching for isospin partners
- Measurements of quantum numbers J^P



Such goal relies on amplitude analysis techniques. Refinement of theoretical parametrization of hadronic amplitudes and advanced understanding of the light spectroscopy are required in the meantime

Probing the Nature of the Exotic Hadrons

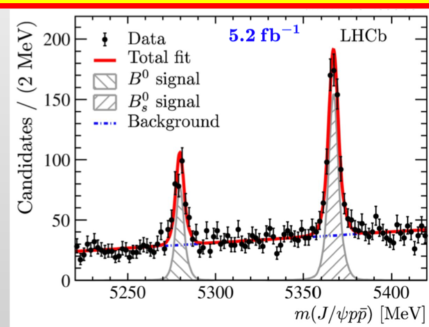
arXiv:1904.03947



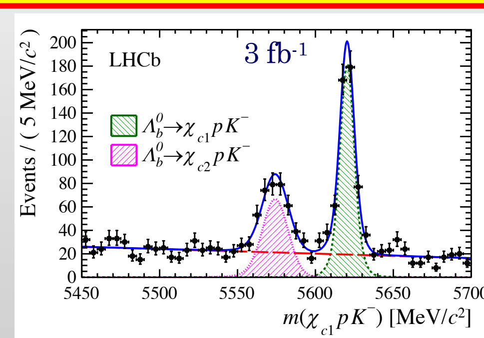
- What about the narrow pentaquarks P_c^+ recently observed? (See Lucio's talk for more details)
  https://agenda.infn.it/event/15632/contributions/89325/
- Determination of quantum numbers is very likely but observation of isospin partners is disfavored ($P_c^0 \rightarrow J/\psi\ n$)

However new insights might come by:

- Studying P_c^+ in different system (e.g. $B^0 \rightarrow J/\psi\ p\bar{p}$) or decay modes (e.g. $\Lambda_b \rightarrow \chi_{c1} pK$)
- Measurements of production in prompt and from *b*-hadron decays



arXiv:1902.05588



PRL 119 (2017) 062001

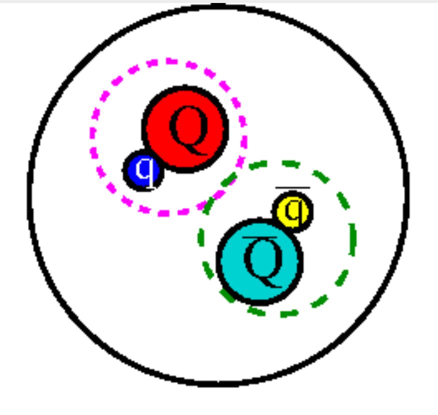
Doubly Charmed Tetraquark: $cc\bar{q}\bar{q}$

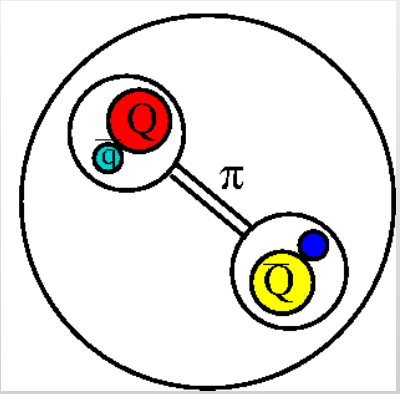
[A. Esposito et al.: PRD 88 (2013) 054029]

- Doubly charmed particles are a straightforward consequence of the hidden charmed exotic hadrons
- If discovered, they would be almost full-proof states made of 4 quarks

Between them, the doubly charged states play an important role into understanding their nature: indeed in a loosely bound molecule, Coulomb repulsion would induce a fall-apart decay on very short time scales

Tetraquark





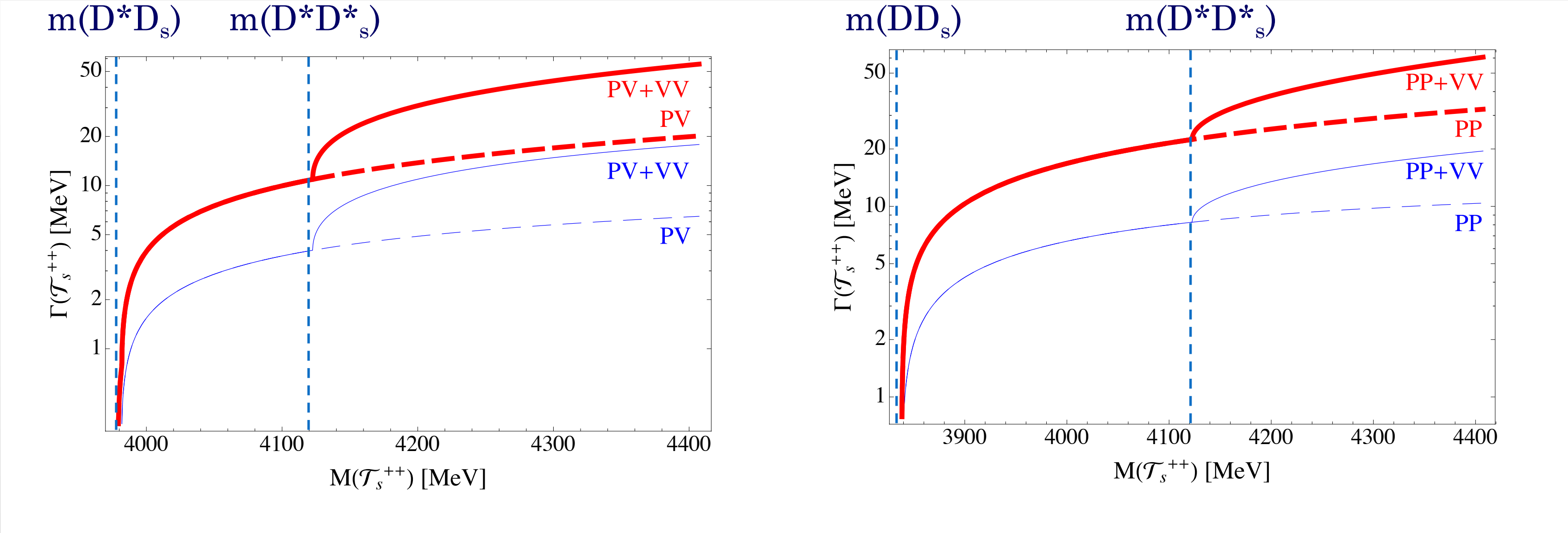
Loosely bound molecules

DOUBLY CHARMED TETRAQUARK: $cc\bar{q}\bar{q}$

[A. Esposito et al.: PRD 88 (2013) 054029]

- If their masses are above the DD thresholds, pure tetraquark models predict (narrow) states with quantum numbers $J^P = 0^+, 1^+$ and 2^+
- 0^+ and 1^+ states expected to be the lightest and most likely to be formed (and observed)

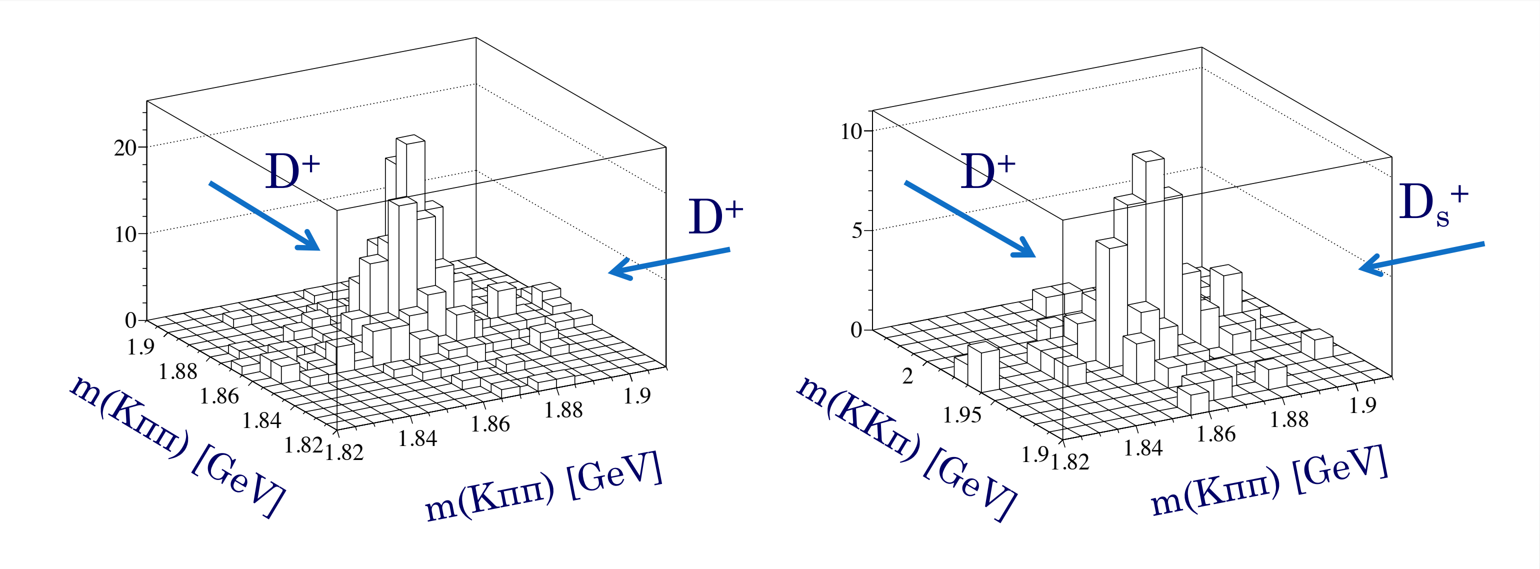
Natural widths as predicted by a pure tetraquark model



Doubly Charmed Tetraquark in Prompt Production

Narrow states could be easily spotted in the prompt production

Associated production of D^+D^+ and $D^+D_s^+$ (0.3 fb^{-1}) **[JHEP 06 (2012) 141]**



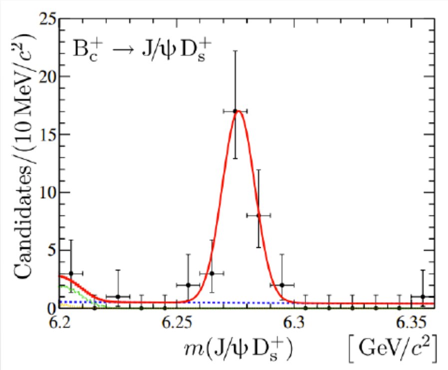
arXiv:1808.08865

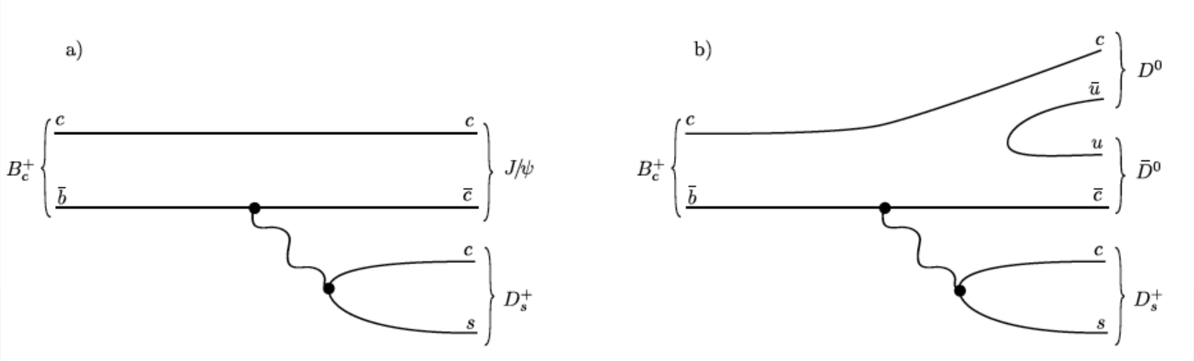
$$N(D^+D^+;\mathrm{Run5}) \simeq 750\mathrm{k\ candidates}$$
$$N(D^+D_s^+;\mathrm{Run5}) \simeq 150\mathrm{k\ candidates}$$

Doubly Charmed Tetraquark in B_c decays

- If the states are broad-ish → Search for them in B_c decays where the quantum numbers can be also measured
- The B_c meson is the lightest state in the standard model that can decay to two same-flavour charmed hadrons: $\mathcal{T}_s^+(cc\bar{u}\bar{s}) \to D^0 D_s^+$

PRD 87 (2013) 112012





N = 28.9 ± 5.6 (3 fb^{-1})

arXiv:1808.08865

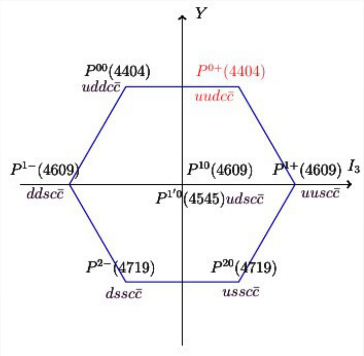
$N(B_c^+ \to D^0 \bar{D}^0 D_s^+; \mathrm{Run5}) \simeq 10^2$ candidates

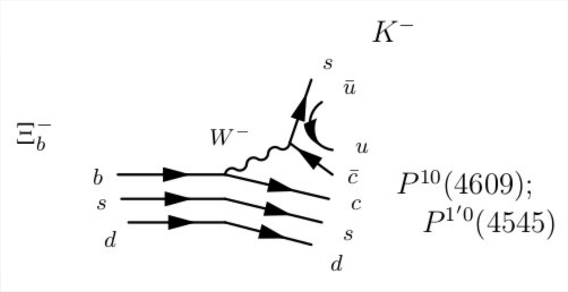
Clear signature. Expected to be background free.
Three pseudoscalars in the final state

MULTIPLETS OF PENTAQUARKS

As for other hadrons, multiplets of pentaquarks should exist. The observed P_c^+ should be states with quark content $uud c\bar{c}$. We could look for strange pentaquark $P_{cs}^0 \to J/\psi\Lambda$ in Ξ_b decays.

[E. Santopinto et al.: PRD 96 (2017) 014014]



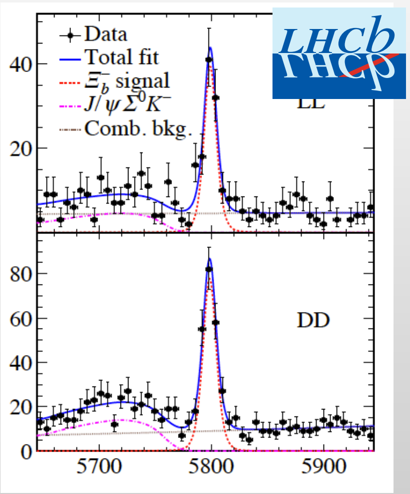


LHCb: PLB 772 (2017) 265

300 candidates of
$\Xi_b^- \to J/\psi\Lambda K^-$ (3 fb^{-1})

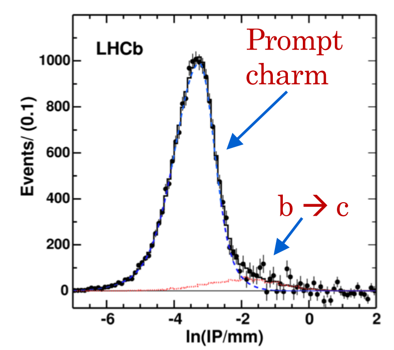
arXiv:1808.08865

$$N(\Xi_b^- \to J/\psi\Lambda K^-; \mathrm{Run5}) \simeq 6 \times 10^4$$



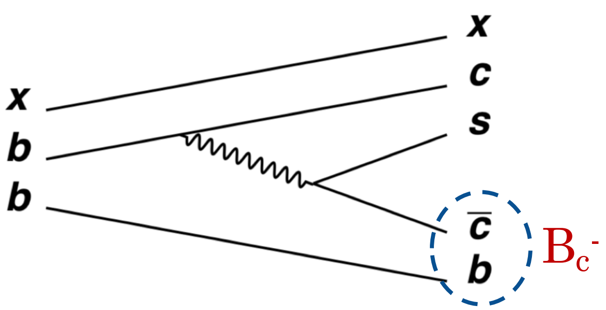
Inclusive Search for Doubly Beauty Hadrons (Ξ_{bb}, Ω_{bb}, $X_{bb\bar{q}\bar{q}}$, etc…)

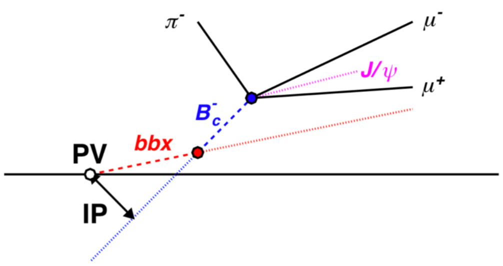
- Exclusive approaches not promising (e.g. $X_{bb\bar{u}\bar{d}} \to B^- D^+ \pi^-$):
  - Curse of BFs: 2 x (b → c) x (c → s) x efficiency
- What about an inclusive approach? E.g. Displaced charm hadrons used to measure inclusive $\boldsymbol{\sigma}(pp \to b\bar{b}X)$

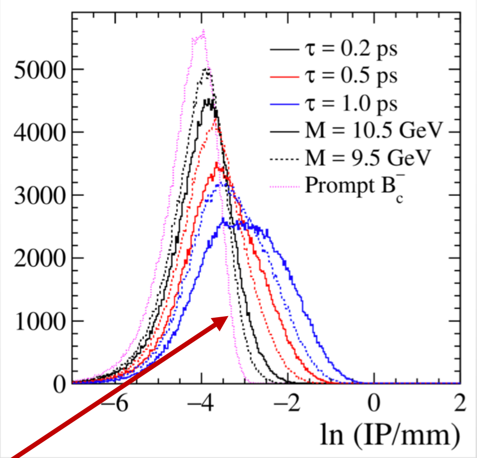


PLB 694 (2010) 209

Weakly decaying double beauty hadrons are the only possible source of displaced B_c^- mesons





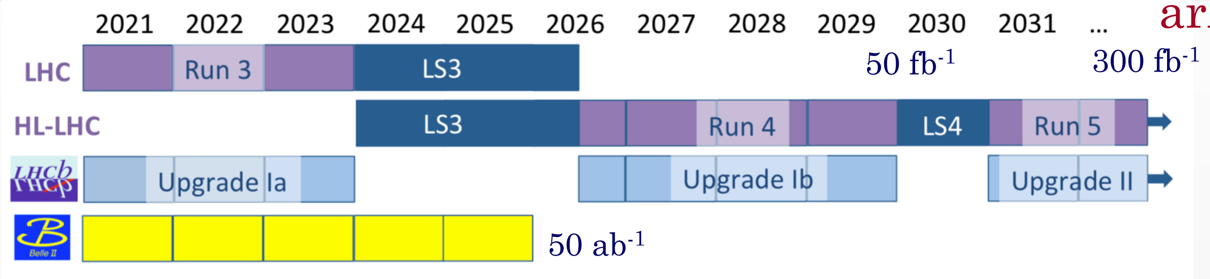


T. Gershon, A. Poluektov
JHEP 01 (2019) 019

Yields and shape can return insights on the cross-section, mass and lifetime
Theoretical inputs required to probe the composition of the *bb*-hadron mixture

Belle II and LHCb at Work

arXiv:1808.08865



Complementarity of the two experiments essential in exploring spectroscopy

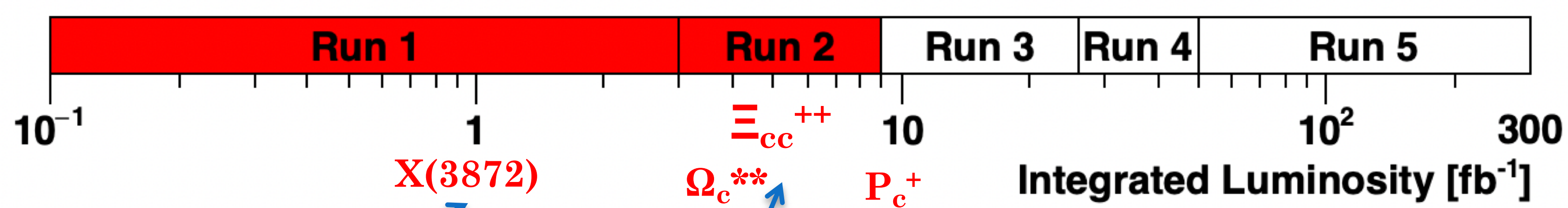
- LHCb: larger production cross-sections, more performant for decay mode involving charged particles (e.g. X(3872)→J/$\psi\pi\pi$, …), unique in many sectors: $B_s^{(**)}$, $B_c^{(**)}$, $\Xi_{bc}^{(**)}$
- Belle II: smaller background, more suitable for decay modes with neutrals in the final state (e.g. X(3872)→J/ψ γ and its isospin/C-odd partners, …)

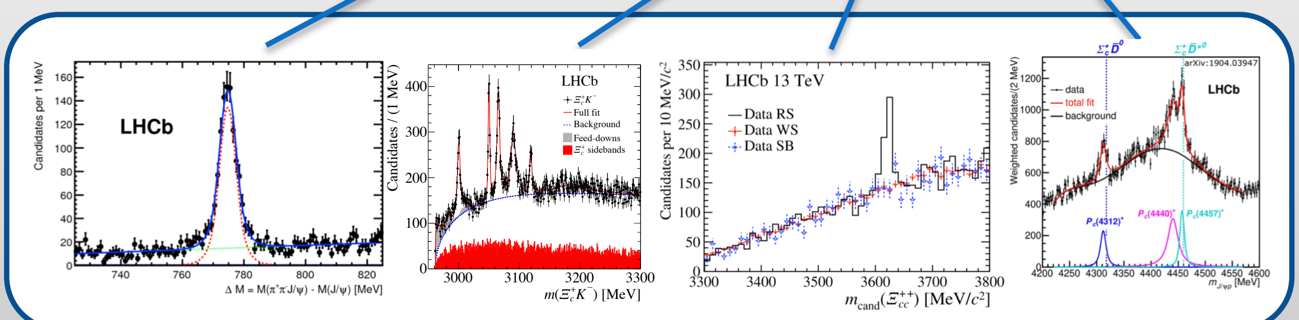
Decay mode	LHCb $23\,\text{fb}^{-1}$	LHCb $50\,\text{fb}^{-1}$	LHCb $300\,\text{fb}^{-1}$	Belle II $50\,\text{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi p K^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k	<6k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600	—

Summary

The large data set collected in the HL-LHC era, together with an upgraded detector, will boost sensitivity in searches for heavy states with small production cross sections and/or small decay rates

Predictions are always complicated…even more when concerning unknown states!



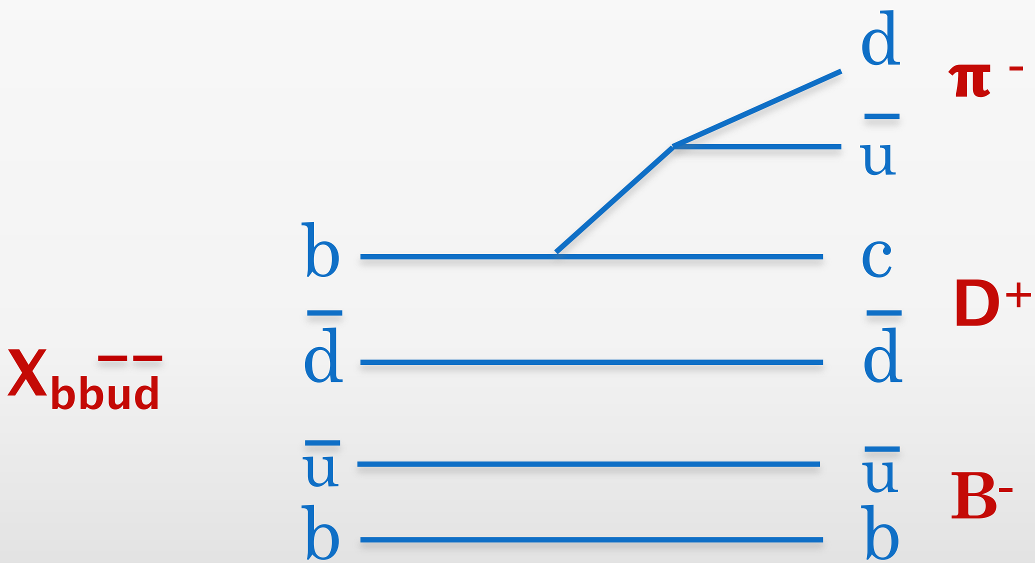


…to be continued

BACK UP

Search for a Stable 1^{++} $bb\bar{u}\bar{d}$ Tetraquark

- It would have observable lifetime, this combinatorial background would be under control
- Unfortunately *bbq* baryons have not been observed yet, reflecting low prompt production rates expected for both *b* quarks to end up in the same hadron, and difficulty in reconstruction of two subsequent weak decays of *b* quark

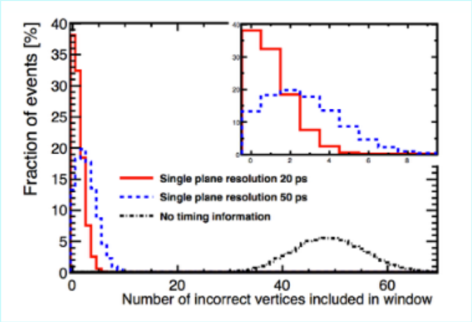


- Inclusive reconstructive efficiencies for B mesons are low at LHCb due to low branching fractions into low multiplicity final states
- Not promising even for Upgrade II!

Impact of Calorimeter Upgrade

See Preema Pais's Talk on Wednesday

- Increased calorimeter resolution
- Reduction in background by a fast timing calorimeter information
- Increased sensitivity to low p_T photon and π^0

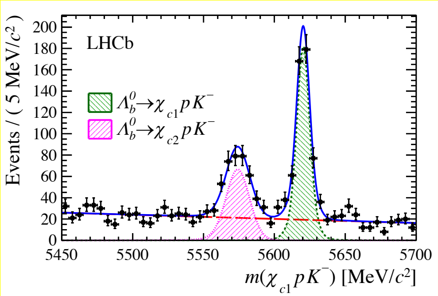


- Measurement of $\mathcal{B}$(X(3872)→ψ(2S) γ)/$\mathcal{B}$(X(3872)→J/ψ γ) **[Nucl.Phys.B886 (2014) 665]**

$$\frac{BR(X(3872) \to \psi(2S)\gamma)}{BR(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

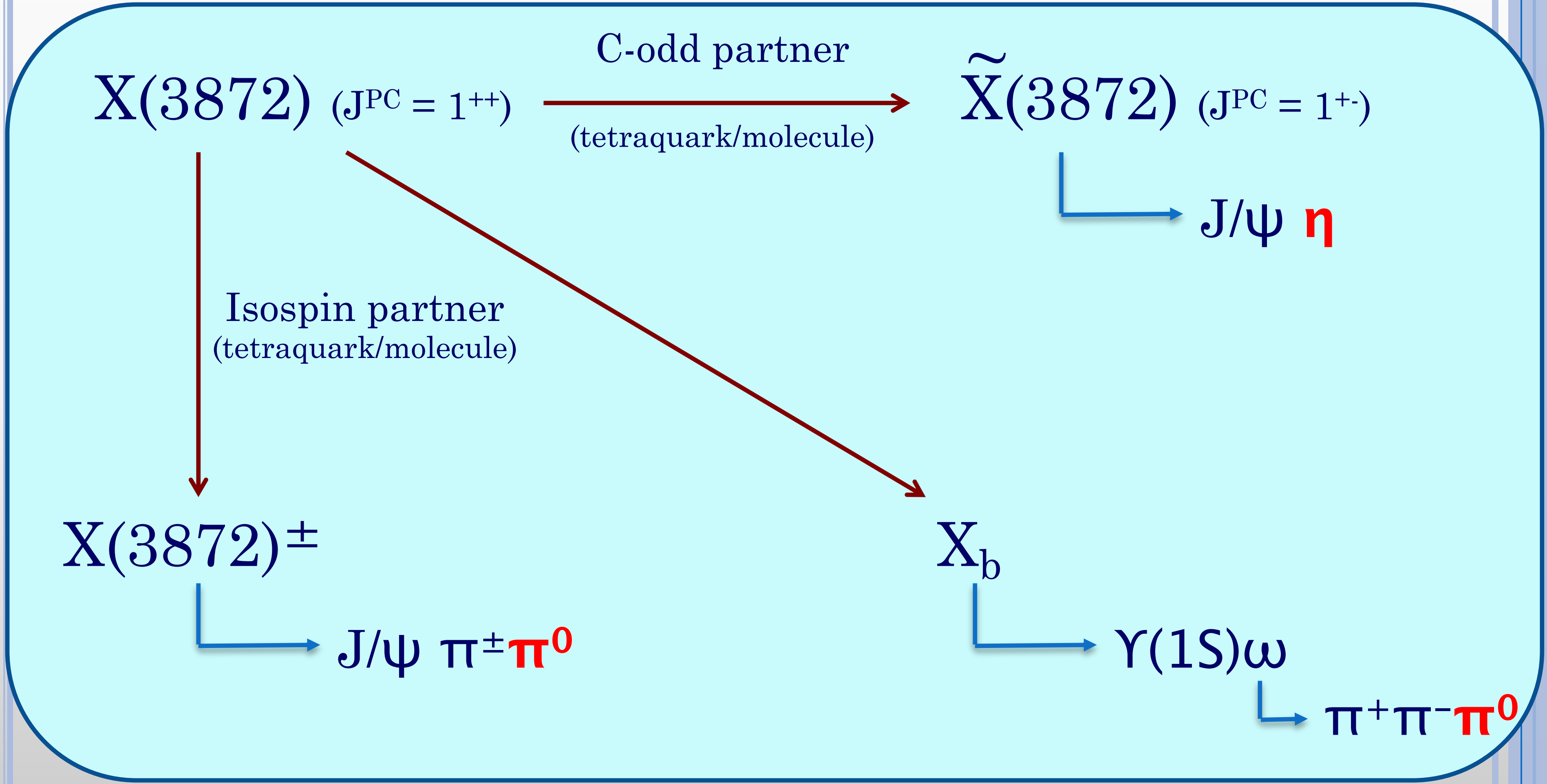
→ *Pure molecule scenario disfavored*

- Search for pentaquarks decaying to $\chi_{c1}p$ where χ_{c1}→J/ψ γ **[LHCb: PRL 119 (2017) 062001]**



Impact of Calorimeter Upgrade

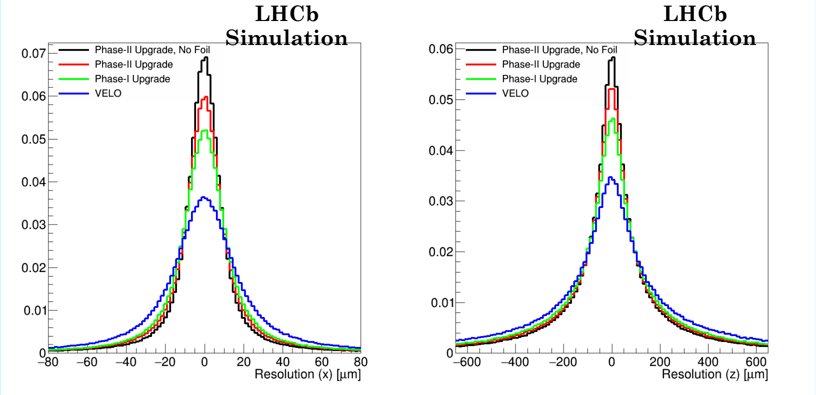
Neutrals will be crucial into probing further the X(3872) meson



IMPACT OF VELO UPGRADE

Removal of RF foil

- Improved vertex resolution
- Higher signal efficiency with large background rejection
- Increased track efficiency
- Reduction in ghost rates



- Better performance into detecting low momentum tracks will contribute into studying/observing excited states decaying through dipion transitions (e.g. $B_c^* \rightarrow B_c \pi \pi$)
- Better reconstruction efficiency for multibody B decays, such as $B \rightarrow \bar{D}DK$ aiming to the search for charmonium-like states
- Improved vertex resolution ➔ Higher efficiency into selecting short-lived particles: B_c, Ξ_{cc}, Ω_{cc}, Ξ_{bc}, Ω_{ccc}

Light Baryon Spectroscopy

- The poor knowledge of the light sector (Λ*, N*, etc…) has had a large impact on the amplitude analyses aiming to the search for the pentaquarks
- LHCb can contribute to study the spectroscopy of the light sector as well