Perspectives in Heavy Flavour Spectroscopy at LHCb

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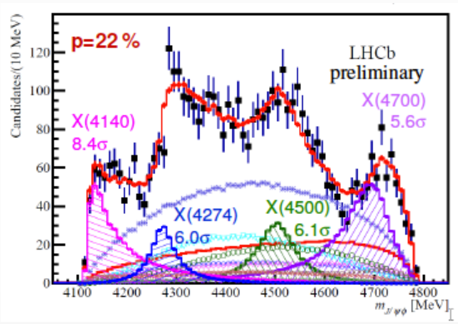
On behalf of LHCb Collaboration

Beyond the LHCb Phase-I Upgrade
28-31 May, La Biodola, Isola d'Elba (Italy)

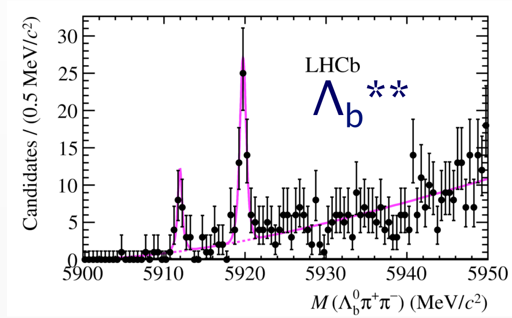
Spectroscopy at LHCb so far

PRL 118 (2017) 022003

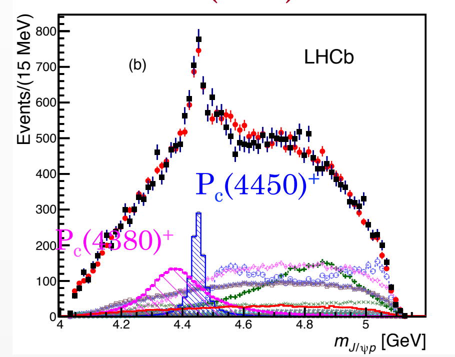
PRD 95 (2017) 012002



PRL 109 (2012) 172003

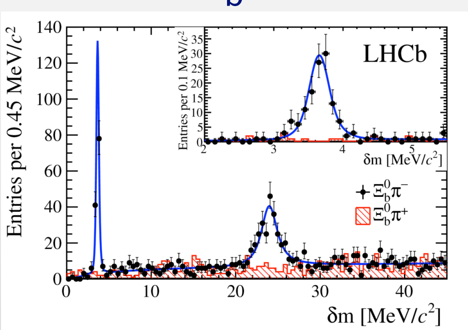


PRL 115 (2015) 072001



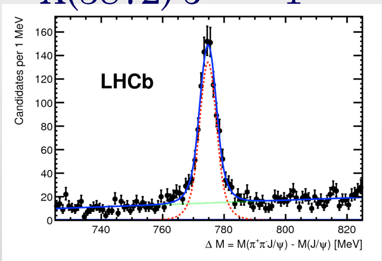
- LHCb has contributed to populate the Zoo of Particles
- Sometimes no cage was ready to welcome them
- …and RUN II not fully exploited

Ξ_b^{**}



PRL 114 (2015) 062004

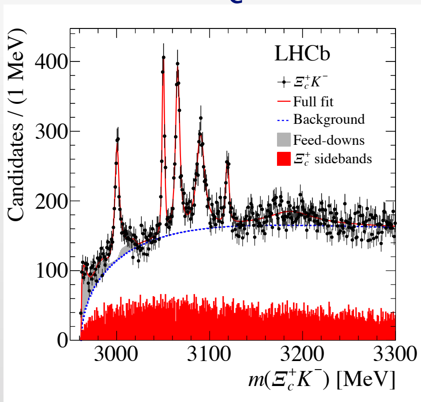
X(3872) $J^{PC} = 1^{++}$



PRD 92 (2015) 011102

PRL 110 (2013) 222001

Ω_c^{**}



PRL 118 (2017) 182001

Phase II Upgrade in a Nutshell

"If we want everything to remain as it is, everything must change" Il Gattopardo

A Phase II upgrade will be installed in Long Shutdown 4 of the LHC:

- It will consist of redesigned subsystems that can operate at a luminosity of 2×10^{34} cm^{-2} s^{-1} (10 x larger than Phase I upgrade)
- It is expected that the experiment collects data corresponding to an integrated luminosity of 300 fb^{-1}
- Extension of the experiment's capabilities into selecting π^0, η, γ and low-momentum tracks

Rule of Thumb

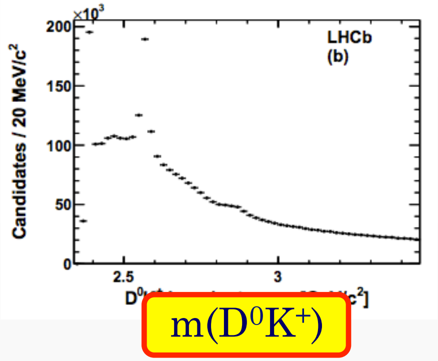
"Scale present Run-1 yields by a factor 360 for hadronic final states and 180 for muonic final states"

- ✓ ….it assumes we known the yields in Run I…but spectroscopy is mainly looking for unobserved states
- ✓ Educated guesses on production cross-sections and branching ratios
- ✓ Numbers in this talk can be wrong by order of magnitudes

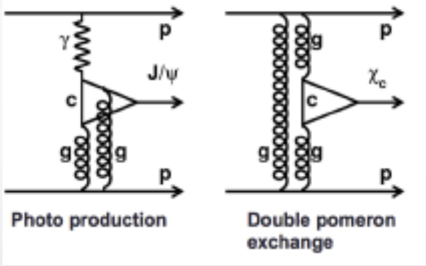
How to do spectroscopy?

Prompt Production: (e.g. $pp \rightarrow D_s^{**}(\rightarrow D^0K) + X$)

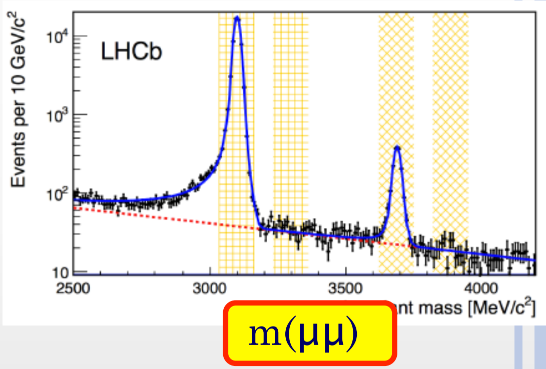
- ✓ Large cross sections
- ✗ Large combinatorial background
- ✗ Hard to disentangle broad structures
- ✗ Difficult to assess spin
- ✗ Presence of "reflections"/"feed-downs"



Central Exclusive Production (CEP)

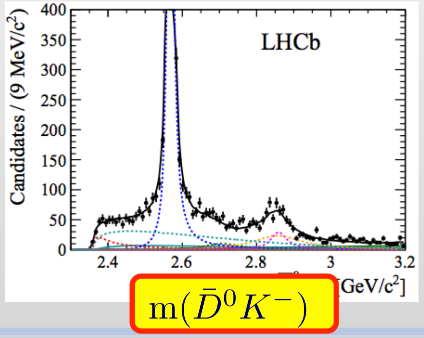


- ✓ Small background
- ✓ $J^{PC} = 1^{--}$, J^{++}
- ✗ Limited cross sections



b-hadron decays (e.g. $B_s \rightarrow D_s^{**}(\rightarrow D^0K)\pi$)

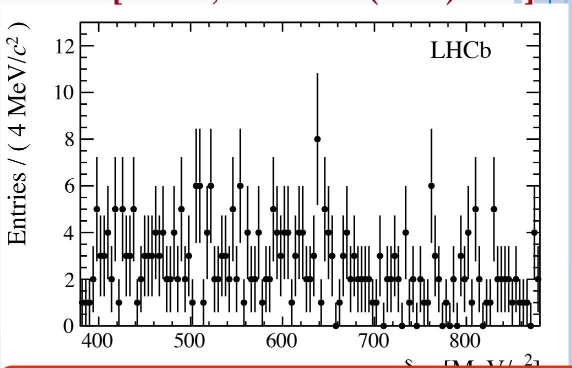
- ✓ Small background
- ✓ Access to the phase of the amplitude and spin-parity
- ✗ Limited cross sections
- ✗ High spin resonances suppressed
- ✗ Presence of "shadows"



Doubly Heavy Baryons: Ξ_{cc}, Ω_{cc}

All the ground states with the charm quantum number C = 0 or C = 1 have been discovered. Three weakly decaying C = 2 states are expected: a Ξ_{cc} isodoublet (ccu; ccd) and an Ω_{cc} isosinglet (ccs), each with $J^P = 1/2^+$. None of these doubly charmed baryons has unambiguous experimental evidence.

[LHCb, JHEP 12 (2013) 090]



$m(\Lambda_c K\pi) - m(\Lambda_c) - m(K) - m(\pi)$

Doubly Heavy Baryons

- No signal found with 0.6 fb^{-1} at LHCb

$$\frac{\sigma(\Xi_{cc}^+)\mathcal{B}(\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} < 1.5 \times 10^{-2} \text{ at the 95\% CL}$$

- Observations of Ξ_{cc} and Ω_{cc} expected with RUN II data or during the upcoming upgrade
- The Phase II upgrade will be useful into studying their production and excited spectra: Ξ^{**}_{cc} and Ω^{**}_{cc}

What about Ξ_{bc}?

- The B_c meson was discovered almost 2 decades ago
  In LHCb, ~5000 $B_c \rightarrow J/\psi \pi$ in Run I

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

Lower production rates, guess $\sigma(X_{bc}) \sim (0.1 - 0.5) \times \sigma(B_c^+)$
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)
Probably no single golden mode: several modes may be required for chance

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

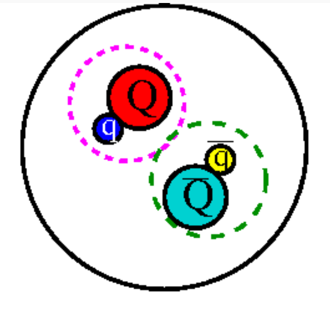
$$N(\Xi_{bc}^0 \to J/\psi \Lambda_c^+ K^-; \mathrm{Run\,5}) \simeq 6 \times 10^2$$

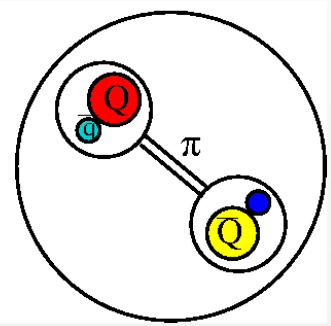
Doubly Charmed Tetraquark: $cc\bar{q}\bar{q}$

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

- 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 into the standard quarkonium scenarios and "exotic" interpretations have been proposed

Tetraquark





Loosely bound molecules

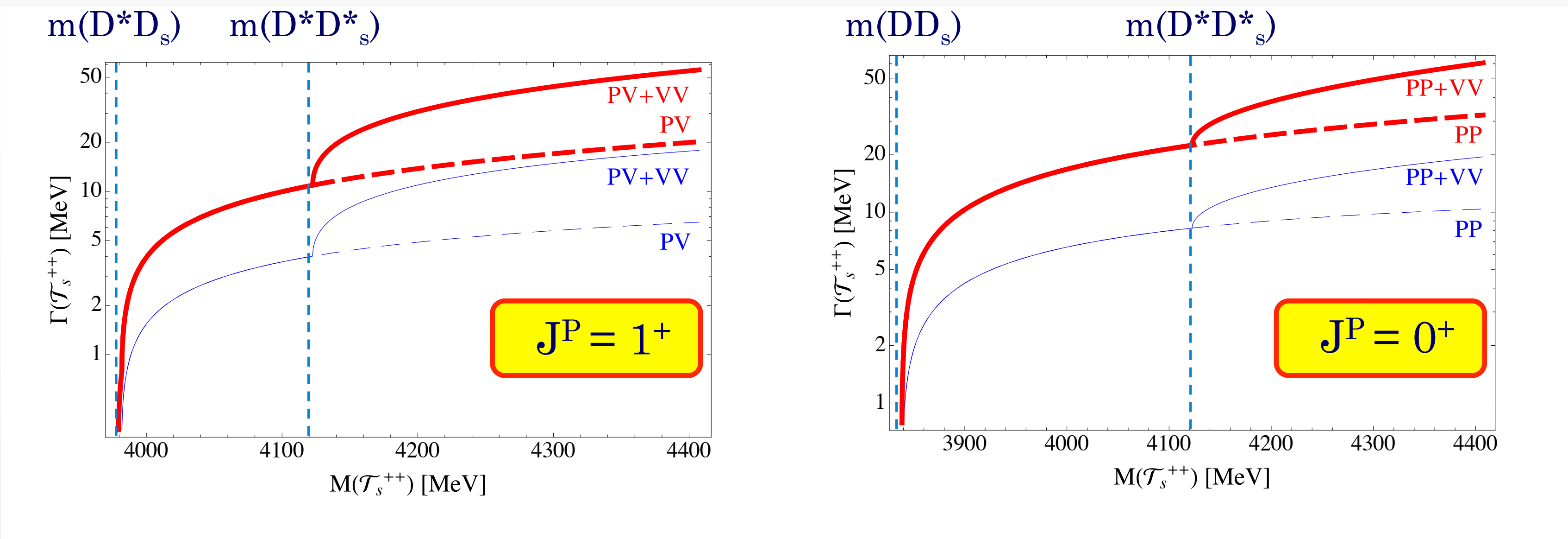
- Doubly charmed particles are a straightforward consequence
- If discovered, they would be almost full-proof states made of 4 quarks

- Observation of doubly charged states would be even more important to understand their nature: indeed in a loosely bound molecule, Coulomb repulsion would induce a fall-apart decay on very short time scales

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

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

- If the masses of such states are below the DD thresholds → strong decays are forbidden and weak decay pattern would be complicated
- If the 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 lighter and more likely to be formed (and observed)

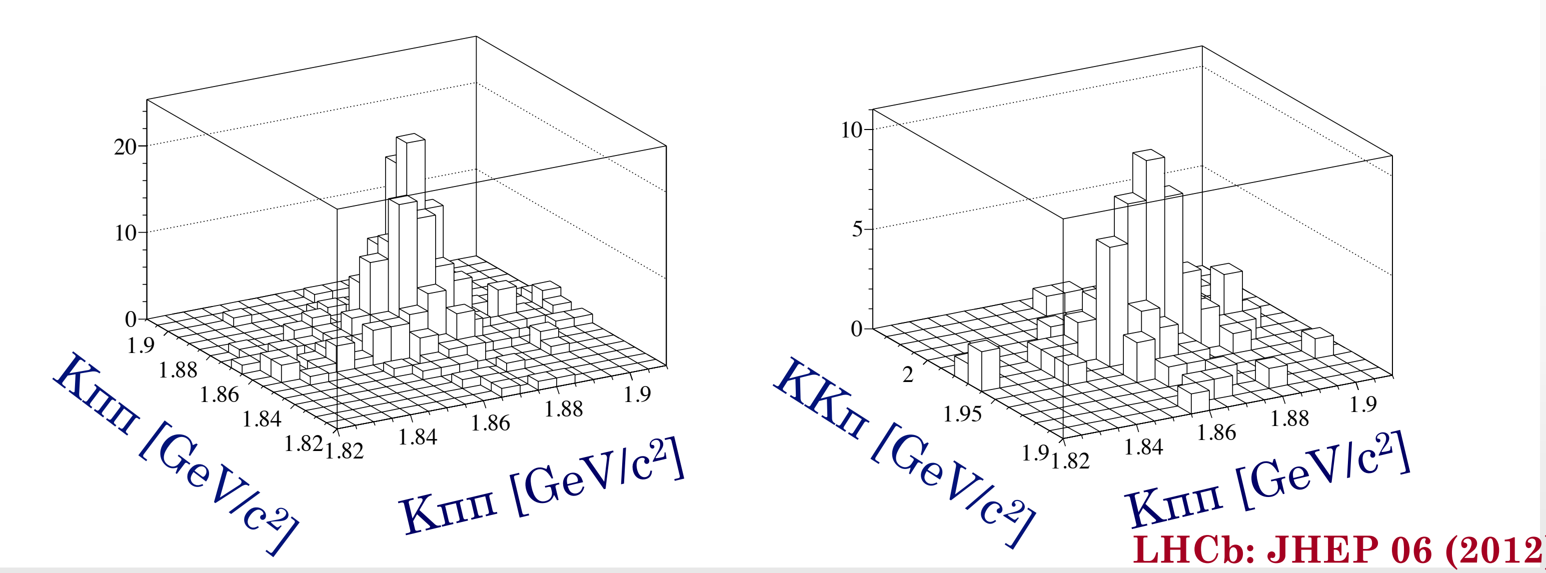


Natural widths as predicted by a pure tetraquark model

Doubly Charmed Tetraquark in Prompt Production

Narrow states could be easily spot in the prompt production

Associate production of D^+D^+ and $D^+D_s^+$ (0.3 fb^{-1})



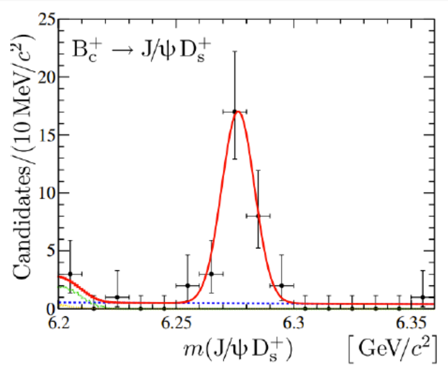
LHCb: JHEP 06 (2012) 141

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

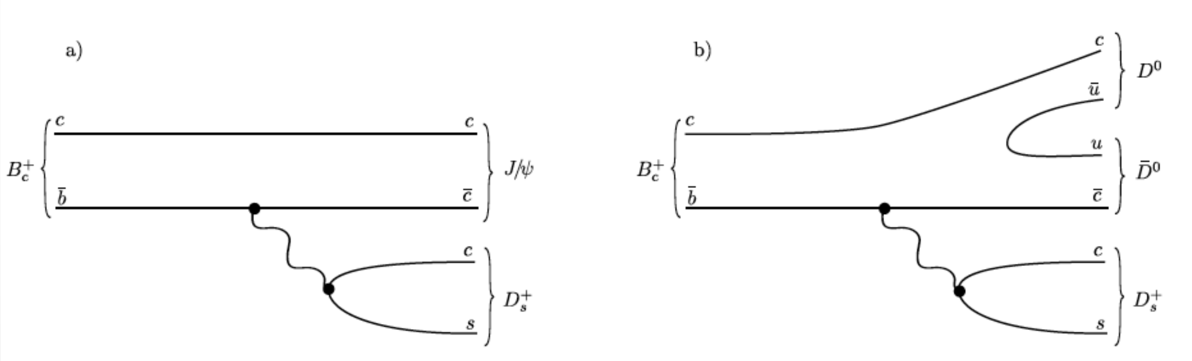
Doubly Charmed Tetraquark in B_c decays

- 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.
- Search for tetraquark: $\mathcal{T}_s^+(cc\bar{u}\bar{s}) \to D^0 D_s^+$

[LHCb: PRD 87 (2013) 112012]



N = 28.9 ± 5.6 (3 fb^{-1})

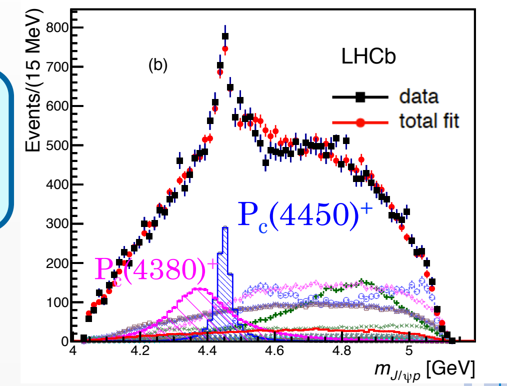


$N(B_c^+ \to D^0 \bar{D}^0 D_s^+; \text{Run5}) \simeq 10^2$ candidates

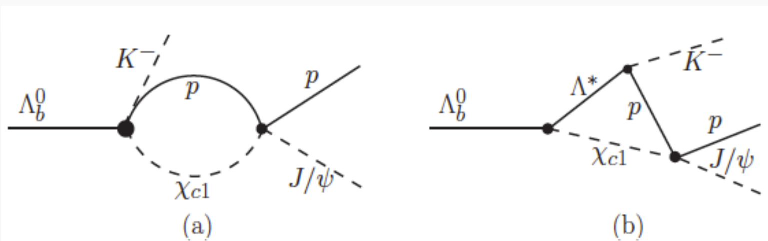
Clear signature. Expected to be background free.
Three pseudoscalar in the final state

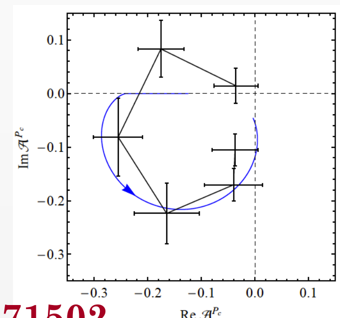
Pentaquarks

[LHCb: PRL 115 (2015) 072001]



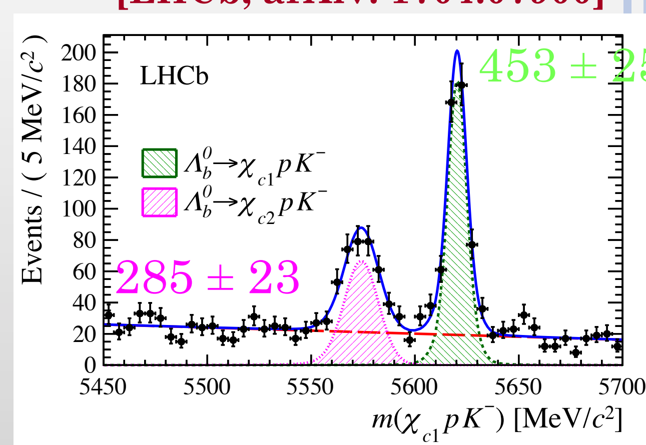
In 2015 LHCb observed two P_c^+ decaying to $J/\psi\ p$
Are they cusps?





F.-K. Guo et al.: PRD 92 (2015) 071502
M. Bayar et al.: PRD 94 (2016) 074039

[LHCb, arXiv: 1704.07900]



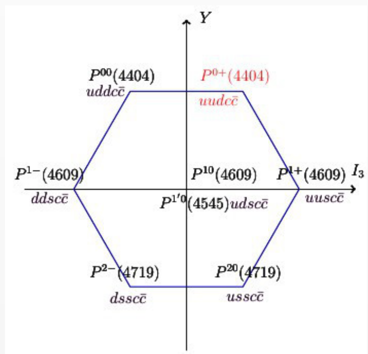
Observation of the χ_{c1} p decay mode will help to clarify the nature of the observed P_c states

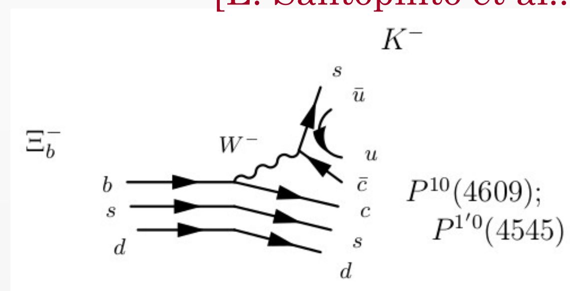
$$N(\Lambda_b^0 \to \chi_{c1} p K^-; \mathrm{Run5}) \simeq 9 \times 10^4$$
$$N(\Lambda_b^0 \to \chi_{c2} p K^-; \mathrm{Run5}) \simeq 6 \times 10^4$$

Multiplet of Pentaquarks

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

[E. Santopinto et al.: arXiv:1604.03769]

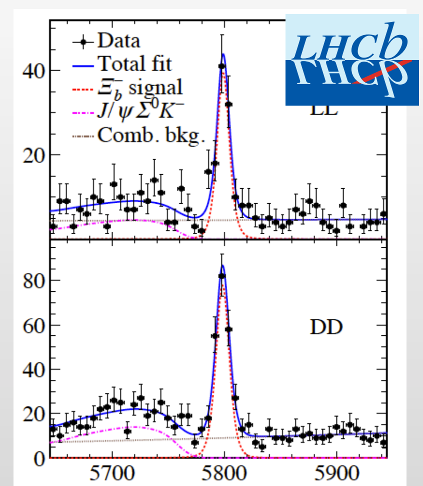




LHCb: arXiv: 1701.05274

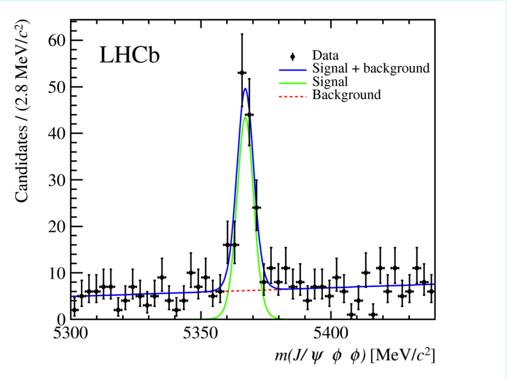
300 candidates of
$\Xi_b^- \rightarrow J/\psi\,\Lambda K^-$ (3 fb^{-1})

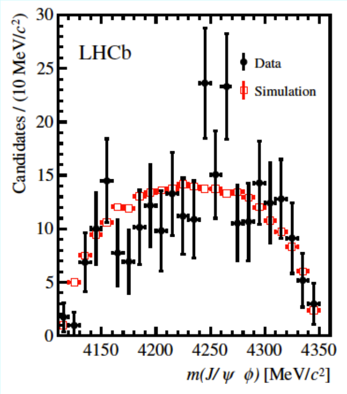
$$N(\Xi_b^- \rightarrow J/\psi\Lambda K^-; \text{Run5}) \simeq 6 \times 10^4$$



Other Exotics

- Search for X(4140) & X(4274) → J/ψ ϕ in B_s → J/ψ ϕϕ decays





LHCb: JHEP 03 (2016) 040

- Exploration of $D_{(s)}\bar{D}^{(*)}_{(s)}$ mass spectra from B decays & Central Exclusive Production

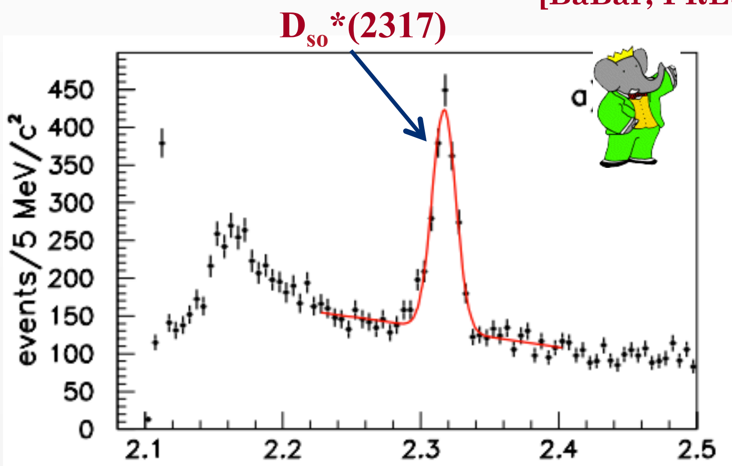
X_b

- Search for Y(1S) ω (→π π π^0, μμ)

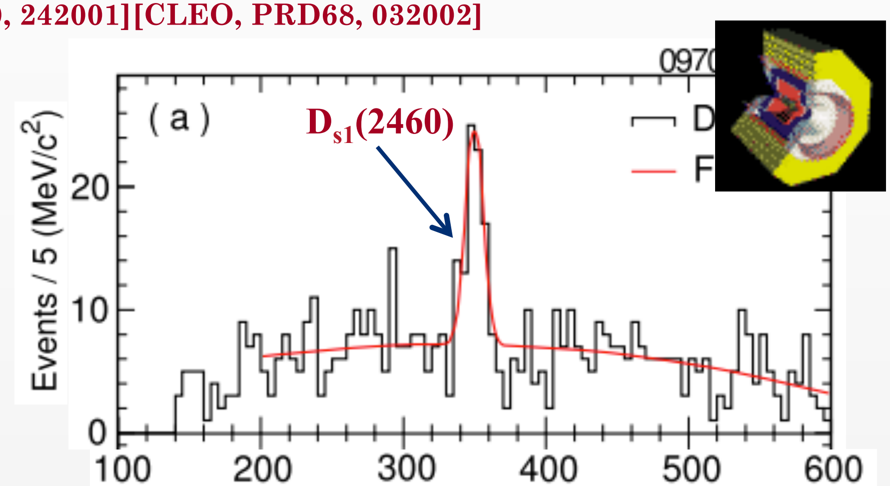
Probing the Exotic Nature of $D_{s0}^*(2317)$ and $D_{s1}(2460)$

2003: Discovery of two narrow states decaying to $D_s^{(*)+}\pi^0$

[BaBar, PRL90, 242001][CLEO, PRD68, 032002]



$M(D_s\pi^0)$



$M(D_s\gamma\pi^0)$-$M(D_s\gamma)$

PDG	Mass (MeV)	Width (MeV)
$D_{s0}^*(2317)^\pm$	2317.7 ± 0.6	< 3.8
$D_{s1}(2460)^\pm$	2459.5 ± 0.6	< 3.5

Surprisingly narrow!

Are they ordinary $c\bar{s}$ or tetraquark/molecules states? Predictions on the natural width vary according to the models

Weak Decays of Excited D_s Mesons

Weak decays have never been observed for any short-lived resonance, although such decay modes of the J/ψ meson have been searched for, with the best limits above $O(10^{-6})$.

For any state which can decay through strong and/or electromagnetic processes, branching ratios of the weak decays are suppressed by the square of the Fermi constant, and are typically $O(10^{-10})$ or less.

$$\Gamma_{(D_s^* \to \ell\nu)} = \frac{G_F^2}{12\pi} |V_{cs}|^2 f_{D_s^*}^2 M_{D_s^*}^3 (1 - \frac{m_\ell^2}{M_{D_s^*}^2})^2 (1 + \frac{m_\ell^2}{2M_{D_s^*}^2})$$

These are, however, enhanced if the total width is suppressed as is the case for the D_{sJ} states.

Search for Weak Decays of Excited D_s Mesons at LHCb

Assuming a production cross-section comparable to that of the D_s meson (500μb at 13 TeV), a branching fraction of 10^{-8} and a reconstruction efficiency of 0.1% results in an expected signal of ***50 decays*** in a 1 fb^{-1} data sample.

Where to look at?

The search for such decays in prompt production will be affected by large combinatorial background and narrow signals (i.e. small Q value) will give the best sensitivity

$$D_s^*(2112)/D_{s0}^*(2317)/D_{s1}(2460) \rightarrow p\bar{p}\pi$$

- Outstanding particle identification performance needed to identify protons with high purity and efficiency
- Background reduction

Spectroscopy with Photons and π^0 in the Final States

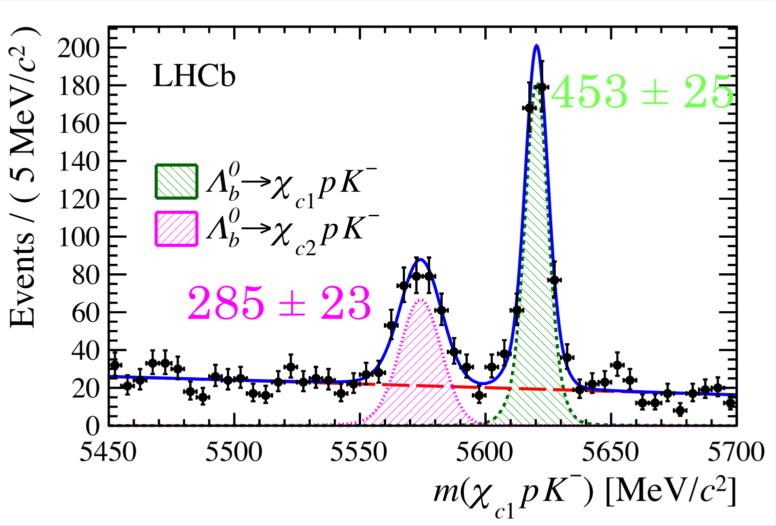
LHCb has already shown the relevance of decay modes with γ and π^0 into final states:

- Measurement of $B(X(3872) \to \psi(2S)\gamma)/B(X(3872) \to J/\psi\gamma)$ **[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 $\chi_{c1} \to J/\psi\gamma$
  [LHCb, arXiv: 1704.07900]



Spectroscopy with Photons and π^0 in the Final States

There are states (not fully exploited) which decay mostly/only into final states with neutrals: (e.g.) D_{s0}*(2317) and D_{s1}(2460)

$D^*_{s0}(2317)$

Decay Mode	BR
$D_s^+\pi^0$	seen

It would be surprising if the only decay mode (isospin-violating)

$D_{s1}(2460)$

Decay Mode	BR (%)
$D_s^{*+}\pi^0$	48 ± 11
$D_s^+\gamma$	18 ± 4
$D_s^+\pi^+\pi^-$	4.3 ± 1.3
TOT	70 ± 12

Room for new decay modes

Heavy quark symmetry predicts states (still missing) with a beauty quark with similar decay patterns: B_{s0}* and B_{s1}'

Summary

- Spectroscopy will benefit of the large dataset collected by looking for heavy states with small production cross-sections and/or small decay rates
- Spectroscopy in B_c decays becomes feasible
- A higher performing Electromagnetic Calorimeter will widen the spectroscopy program by studying the radiative decays which can shed light on the nature of many exotic states or by search the isospin partners of some tetraquark candidates (e.g. $Z(4430)^0 \rightarrow \psi(2S)\ \pi^0$, $J/\psi\ \eta$)
- 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
- Prompt spectroscopy still important: trigger strategy to keep it alive

LHCb vs Belle II

LHCb will be still unique in many sectors:
$B_s^{(**)}$, $B_c^{(**)}$, $\Xi_{bc}^{(**)}$, $\Omega_b^{(**)}$, …