Heavy Flavour Spectroscopy

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University of Edinburgh

On behalf of LHCb Collaboration

Workshop on the physics of HL-LHC, and perspectives at HE-LHC
30 October-1 November, CERN

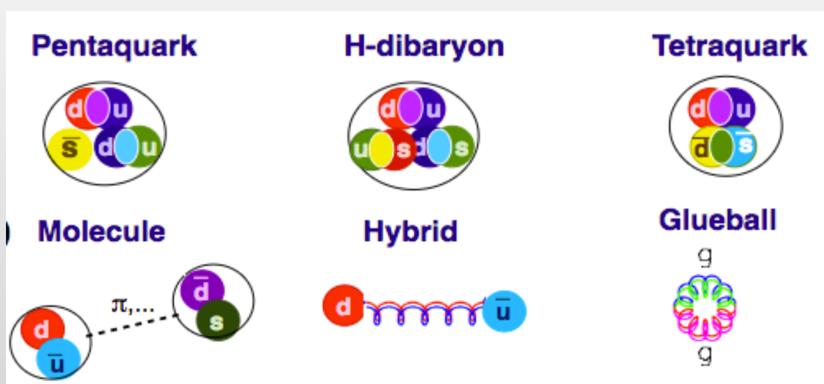
SPECTROSCOPY AND QCD

Standard Model — Colored quarks and gluons

Long-distance effects ⟷

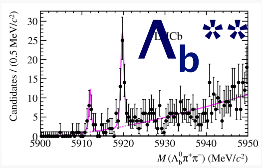
Nature — Color-singlet mesons and baryons

- ➢ Long-distance regime of QCD is the least understood aspect of QCD
- ➢ Many models predict states beyond the standard $q\bar{q}$ and qqq

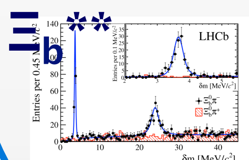


SPECTROSCOPY AT LHCb

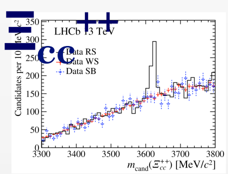
Exotic candidates have been already observed? Many other?
Are they really exotic states? Which kind?



PRL 109 (2012) 172003

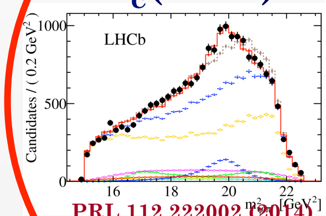


PRL 114 (2015) 062004



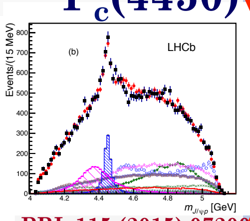
PRL 119 (2017) 112001

$Z_c(4430)^+$



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

$P_c(4450)^+$

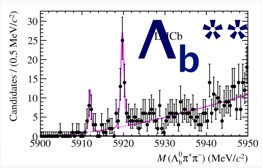


PRL 115 (2015) 072001

SPECTROSCOPY AT LHCb

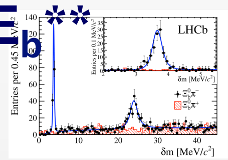
Exotic candidates have been already observed? Many other?
Are they really exotic states? Which kind?

Λ_b^{**}



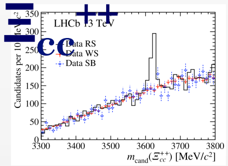
PRL 109 (2012) 172003

Ξ_b^{**}



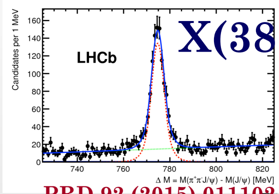
PRL 114 (2015) 062004

Ξ_{cc}^{++}



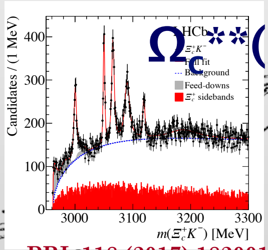
PRL 119 (2017) 112001

X(3872)



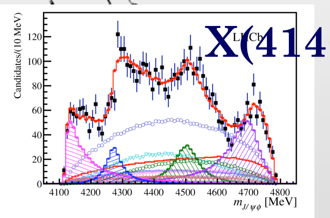
PRD 92 (2015) 011102
PRL 110 (2013) 222001

Ω_c^{**}(?)



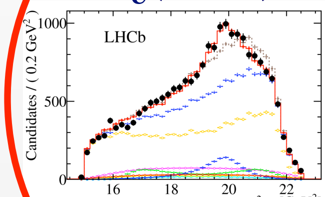
PRL 118 (2017) 182001

X(4140)



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

$Z_c(4430)^+$



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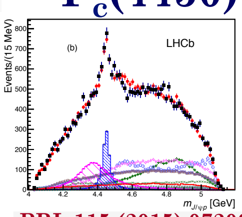


PRL 115 (2015) 072001

Upgrade II in a Nutshell

An Upgrade II will be installed in Long Shutdown 4 of the LHC:

- ➢ It will consist of redesigned subsystems that can operate at a luminosity of 1-2 x 10^{34} cm^{-2} s^{-1} (10 x larger than Upgrade I)
- ➢ 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 [CERN−LHCC−2017−003]

Rule of Thumb

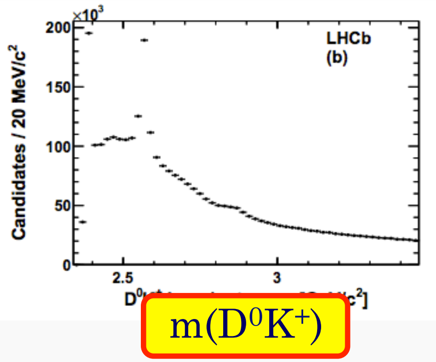
"Scale present Run-1 yields by a factor ~400 for hadronic final states and ~200 for muonic final states"

- ✓ But it assumes states have been already observed in Run I…
- ✓ Educated guesses on unknown production cross-sections and branching ratios

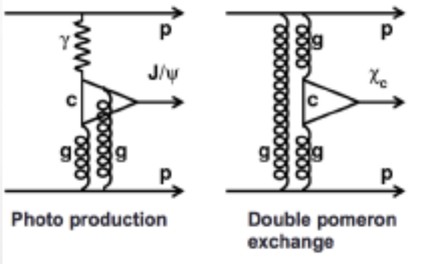
How to do spectroscopy?

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

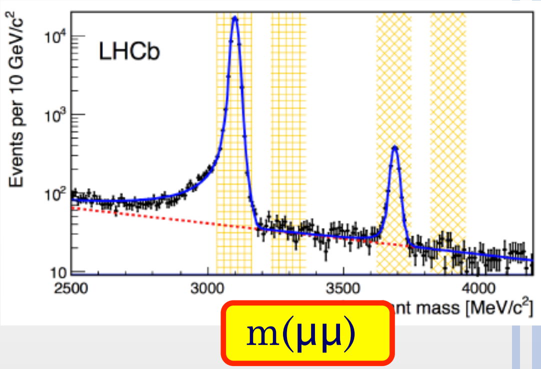
- ✓ Large cross sections
- ✗ Large combinatorial background
- ✗ Hard to disentangle broad structures
- ✗ Difficult to assess spin
- ✗ Presence of "reflections"/"feed-downs"



Central Exclusive Production (CEP)

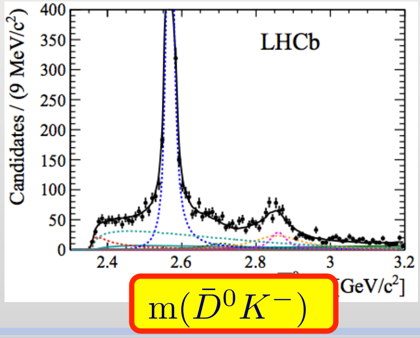


- ✓ Small background
- ✓ $J^{PC} = 1^{--}$, J^{++}
- ✗ Limited cross sections



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

- ✓ 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

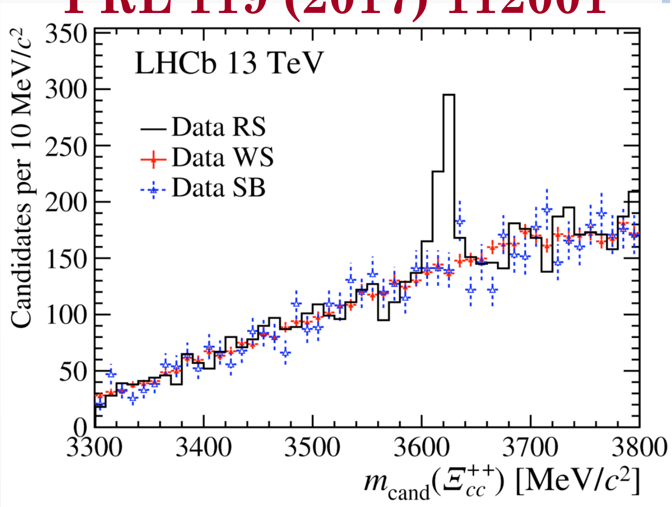
All the ground states with the charm quantum number C = 0 or C = 1 have been discovered. Three weakly decaying C = 2 states are expected: a Ξ_{cc} isodoublet (ccu; ccd) and an Ω_{cc} isosinglet (ccs), each with $J^P = 1/2^+$.
Ξ_{cc}^{++} recently observed by LHCb!

$$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+, \; \Lambda_c^+ \to p K^- \pi^+$$

Highly significant signal observed (>12σ) consistent with a state decaying weakly

$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72$ (stat) ± 0.27 (syst) ± 0.14 (Λ_c^+) MeV

PRL 119 (2017) 112001



- 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}. Ω_{ccc} is also likely to be observed

What about Ξ_{bc}?

- The B_c meson was discovered almost two 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 $\sigma(X_{bc}) \sim (0.1\text{ -}0.5) \times \sigma(B_c^+)$

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)

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

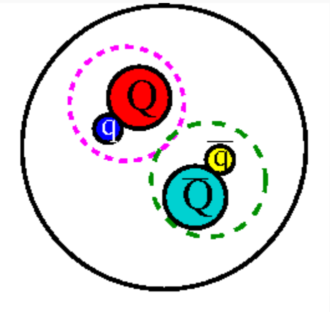
$$N(\Xi_{bc}^0 \to J/\psi \Lambda_c^+ K^-;\mathrm{Run\,5}) \simeq 6 \times 10^2$$

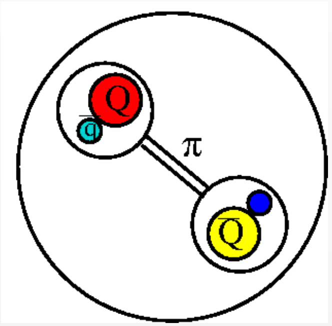
DOUBLY CHARMED TETRAQUARK: $cc\bar{q}\bar{q}$

[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

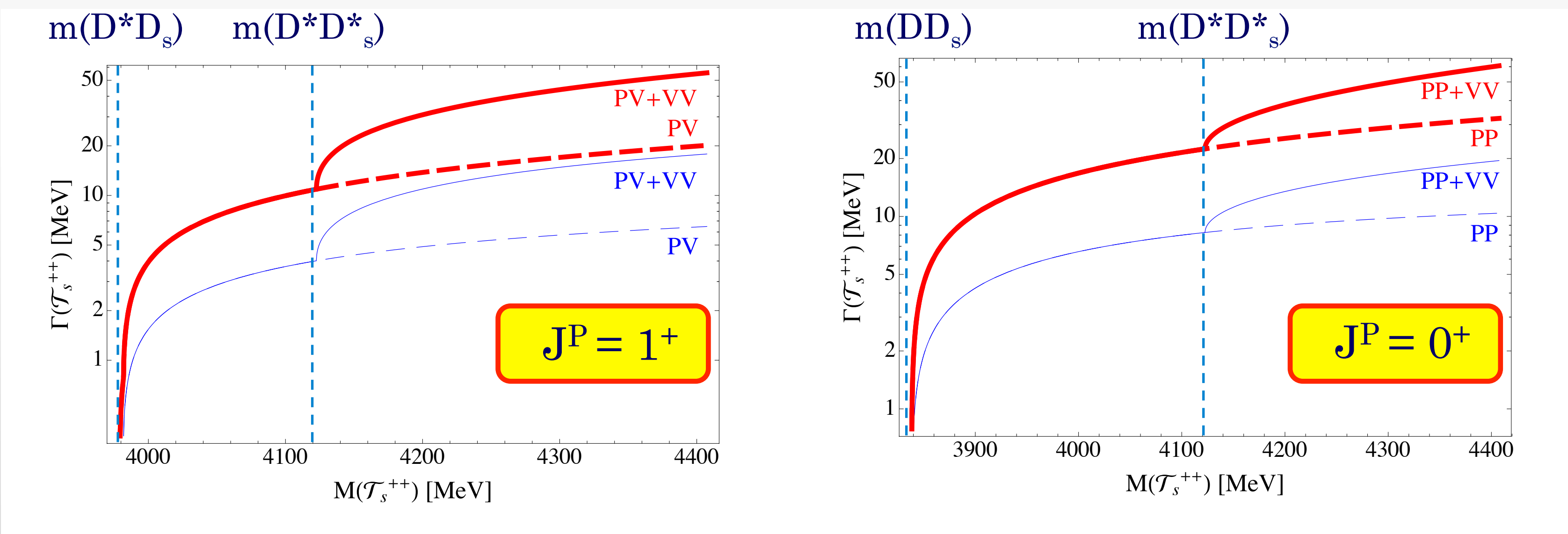
- Doubly charmed particles are a straightforward consequence
- If discovered, they would be almost full-proof states made of 4 quarks

- 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)

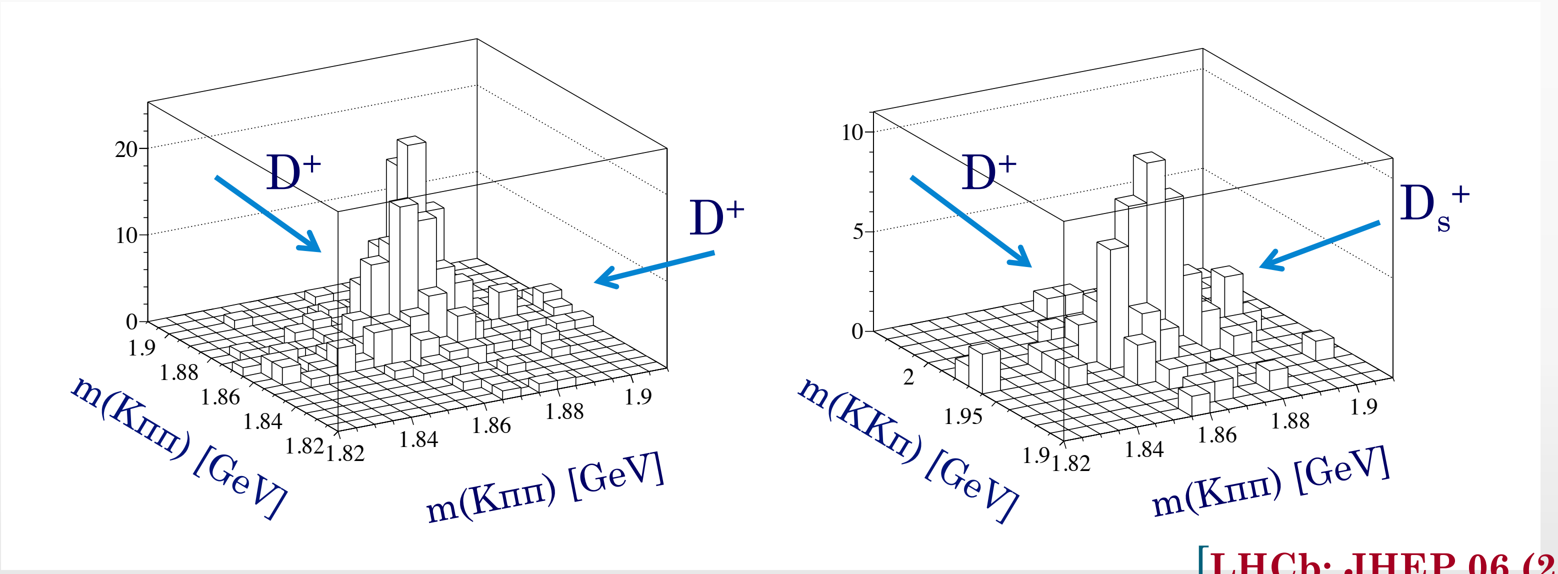


Natural widths as predicted by a pure tetraquark model

Doubly Charmed Tetraquark in Prompt Production

Narrow states could be easily spotted in the prompt production

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



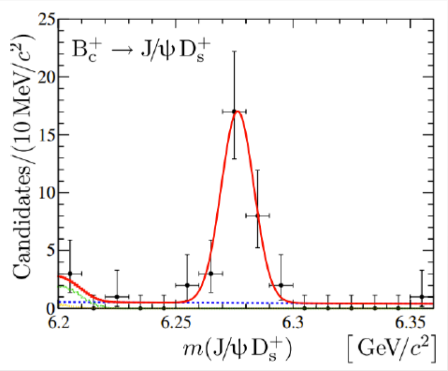
[LHCb: JHEP 06 (2012) 141]

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

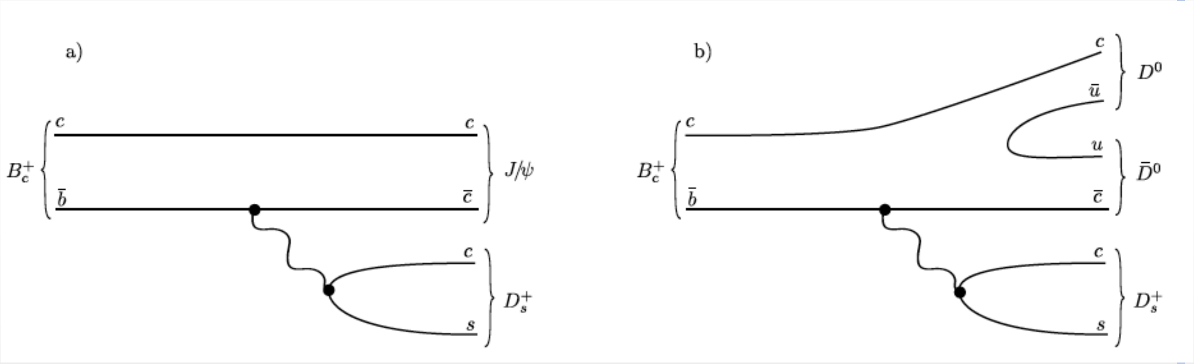
DOUBLY CHARMED TETRAQUARK IN B_c DECAYS

- 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])



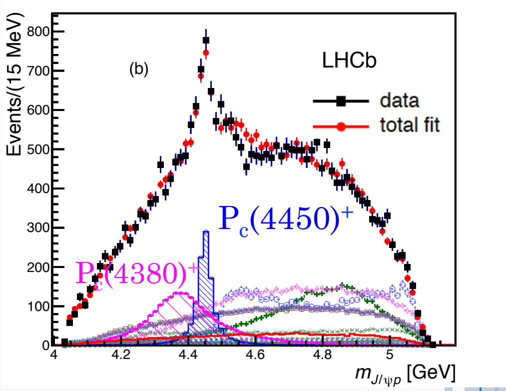
$$N(B_c^+ \to D^0 \bar{D}^0 D_s^+; \text{Run5}) \simeq 10^2 \text{ candidates}$$

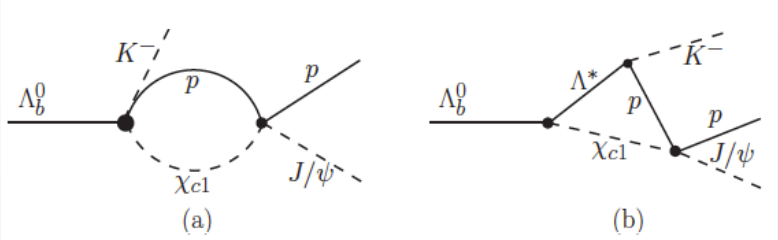
Clear signature. Expected to be background free.
Three pseudoscalars in the final state

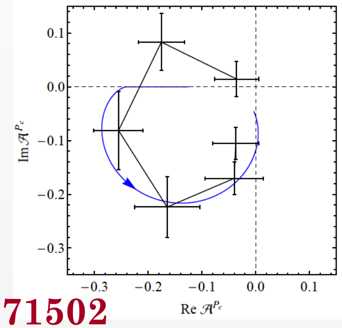
PENTAQUARKS

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

[LHCb: PRL 115 (2015) 072001]

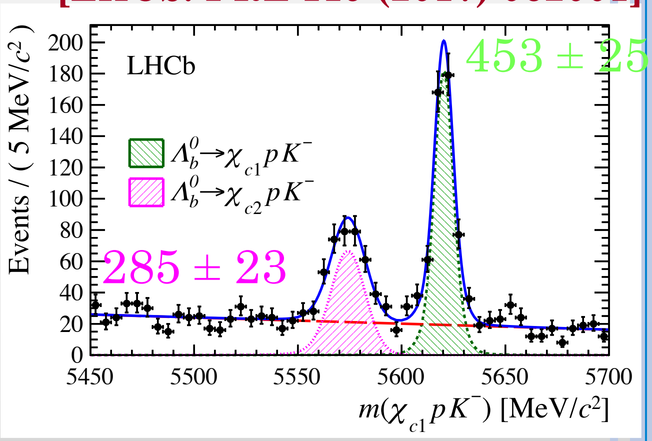






F.-K. Guo et al.: PRD 92 (2015) 071502
M. Bayar et al.: PRD 94 (2016) 074039

[LHCb: PRL 119 (2017) 062001]



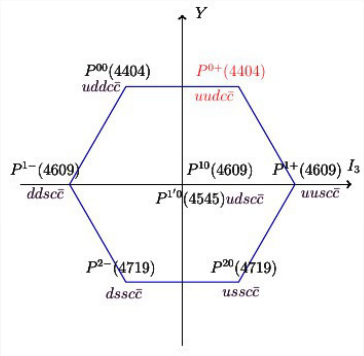
Observation of the χ_{c1} p decay mode will help to clarify the nature of the observed P_c states

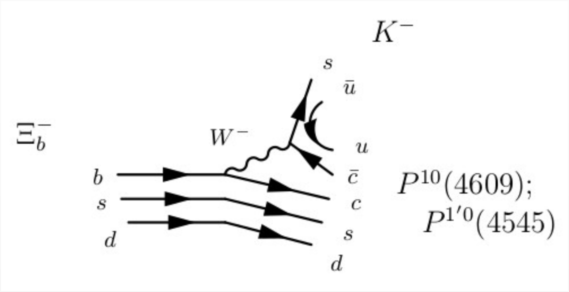
$$N(\Lambda_b^0 \to \chi_{c1} p K^-; \text{Run5}) \simeq 9 \times 10^4$$
$$N(\Lambda_b^0 \to \chi_{c2} p K^-; \text{Run5}) \simeq 6 \times 10^4$$

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 $P_{cs}^0 \to J/\psi\Lambda$ in Ξ_b decays.

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

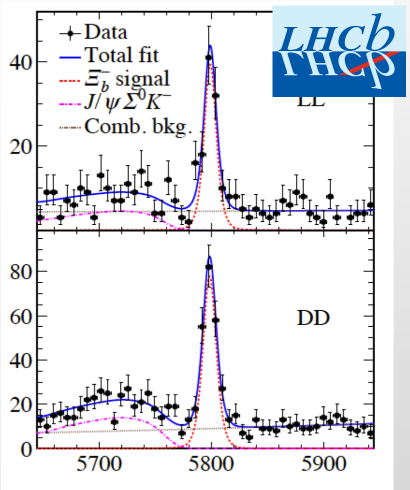




LHCb: PLB 772 (2017) 265

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

$$N(\Xi_b^- \to J/\psi\Lambda K^-; \mathrm{Run5}) \simeq 6\times10^4$$

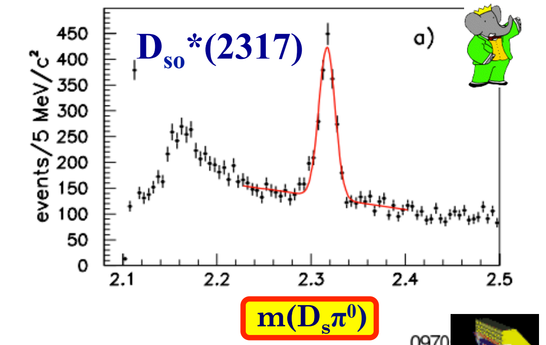


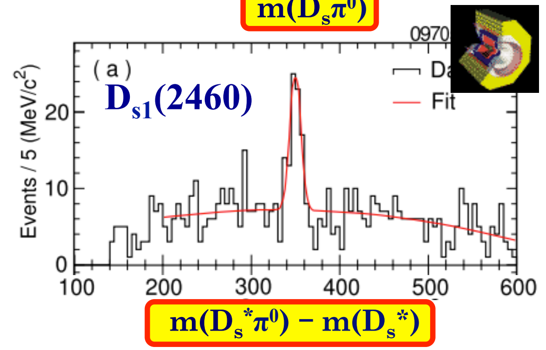
Weak Decays of Excited D_s Mesons

2003: Discovery of two narrow states decaying to $D_s^{(*)+}\pi^0$
[BaBar, PRL90 (2003) 242001][CLEO, PRD68 (2003) 032002]

	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 not observed for any short-lived resonance.

- Best limits ($O(10^{-6})$) are measured for the J/ψ meson
- If strong and/or electromagnetic processes are allowed, weak decays are suppressed by the square of the Fermi constant ($<O(10^{-10})$)

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

[PRL 112 (2014) 212002]

- Rates enhanced if the total width is suppressed as for the excited D_s 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?

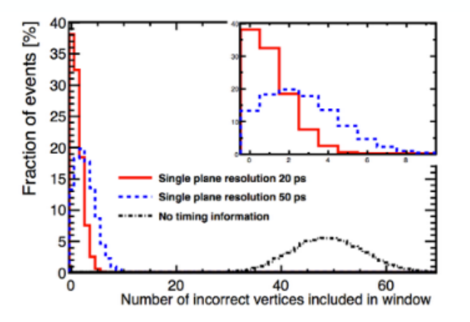
The search for such decays in prompt production will be affected by large combinatorial background and narrow signals (i.e. small Q value) will give the best sensitivity

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

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

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

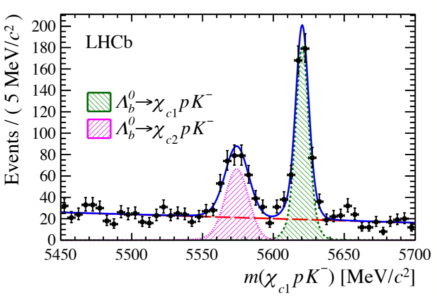
- Measurement of $B(X(3872)\to\psi(2S)\,\gamma)/B(X(3872)\to J/\psi\,\gamma)$ **[Nucl.Phys.B886 (2014) 665]**

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

➡ *Pure molecule scenario disfavored*

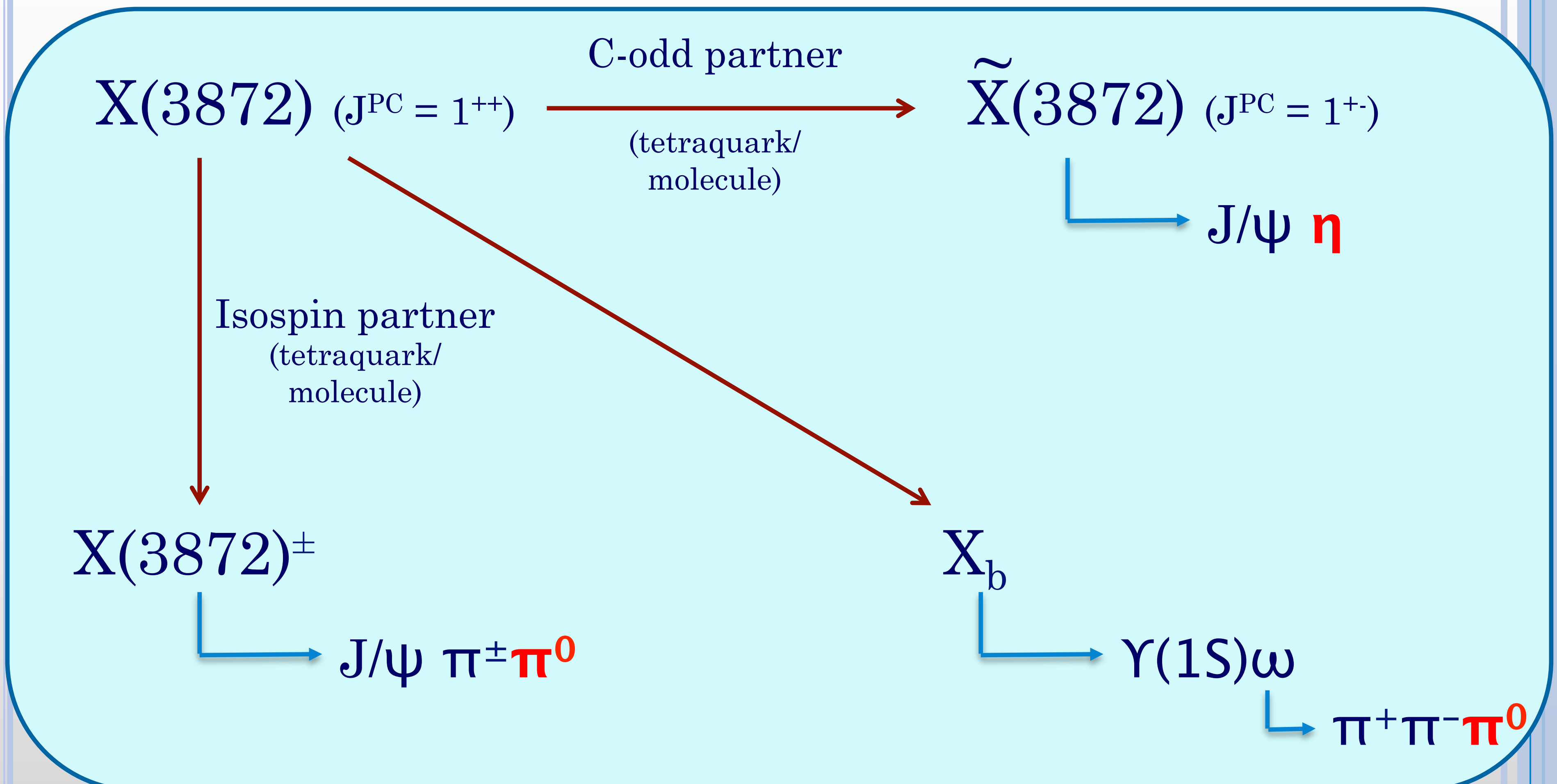
- Search for pentaquarks decaying to $\chi_{c1}p$ where $\chi_{c1}\to J/\psi\,\gamma$

[LHCb: PRL 119 (2017) 062001]



Impact of Calorimeter Upgrade

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

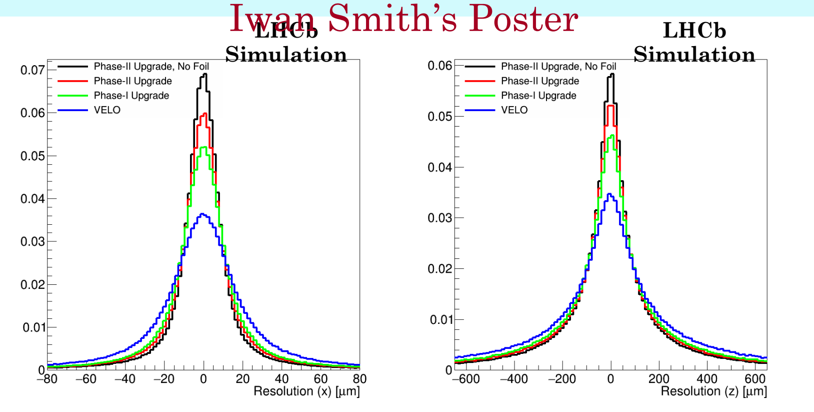


Impact of VELO Upgrade

See: Gregory Ciezarek's talk on Wednesday
Iwan Smith's Poster

Removal of RF foil

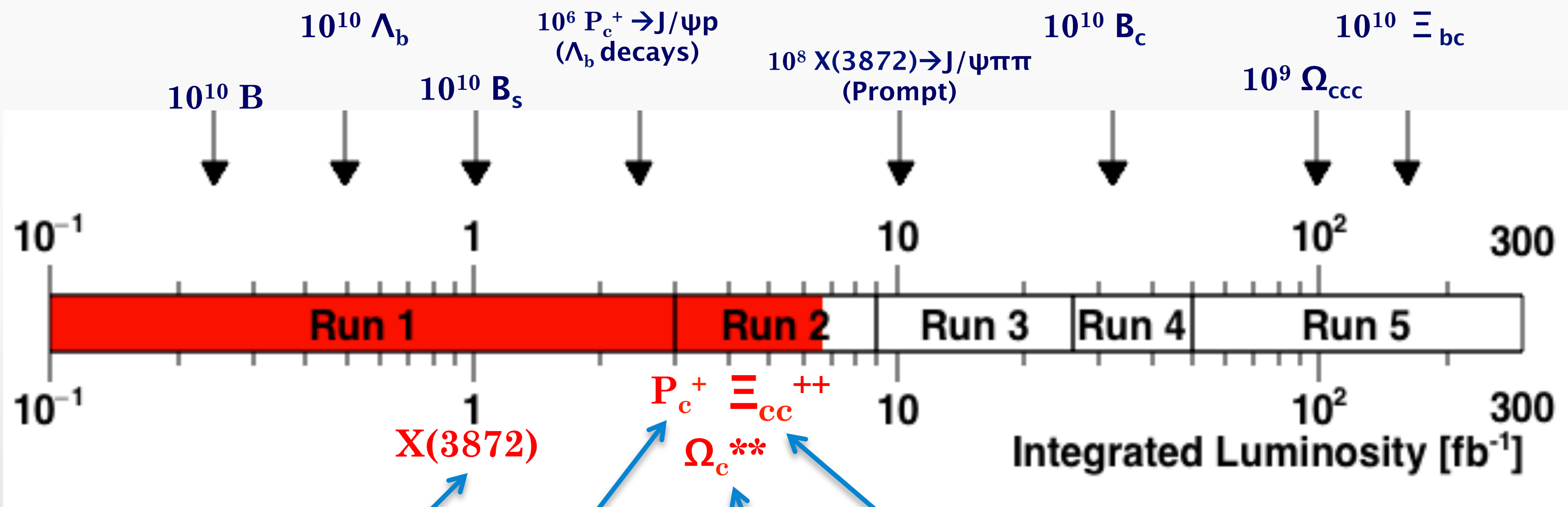
- Improved vertex resolution
- Higher signal efficiency with large background rejection
- Increased track efficiency
- Reduction in ghost rates

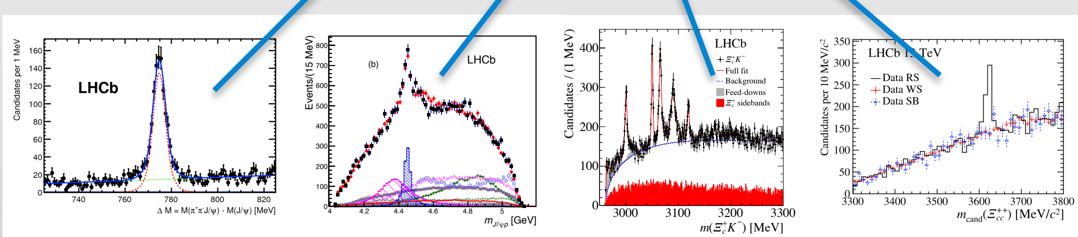


- Better performance into detecting low momentum tracks will contribute into studying/observing excited states decaying through dipion transitions (e.g. $B_c^* \rightarrow B_c \pi \pi$)
- Better reconstruction efficiency for multibody B decays, such as $B \rightarrow \bar{D}DK$ aiming to the search for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

SUMMARY

- Great interest into spectroscopy
- The observation of the two pentaquarks is the most cited LHCb paper
- 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





...to be continued