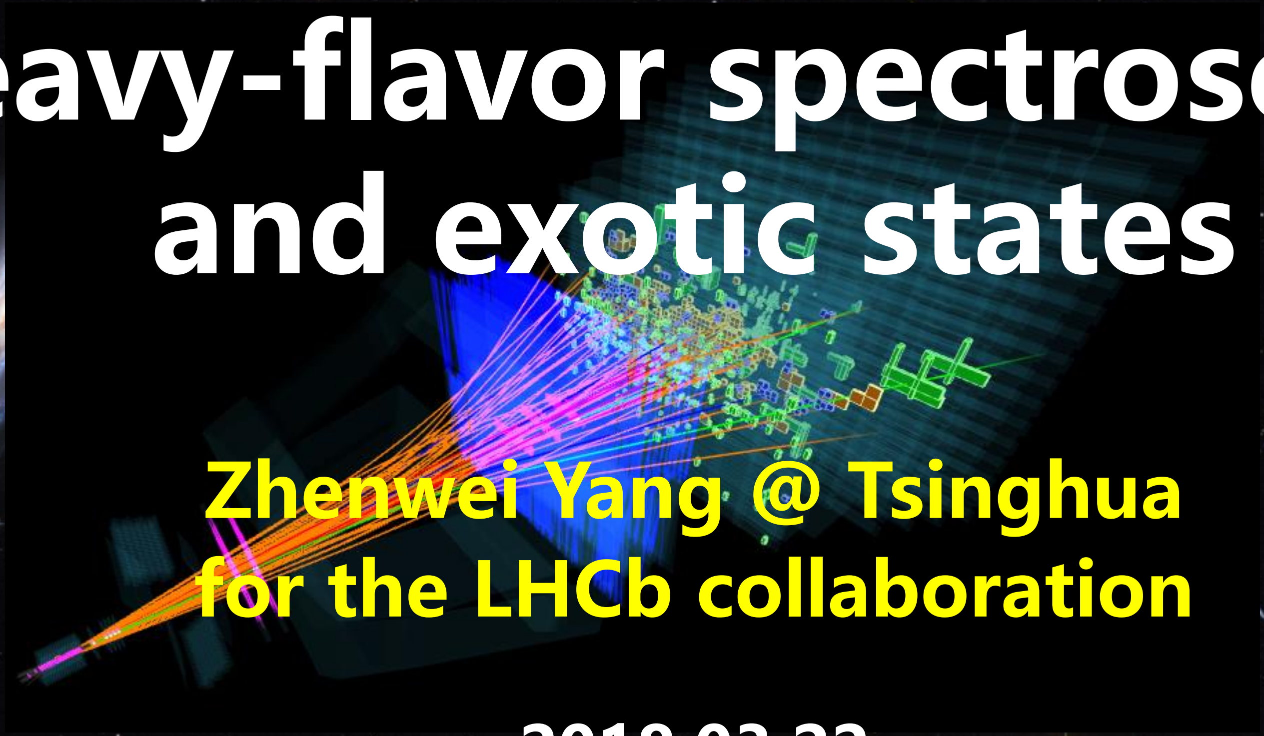
The 3rd Workshop on LHCb Upgrade II

21-23 March, 2018, LAPP Annecy

Heavy-flavor spectroscopy and exotic states

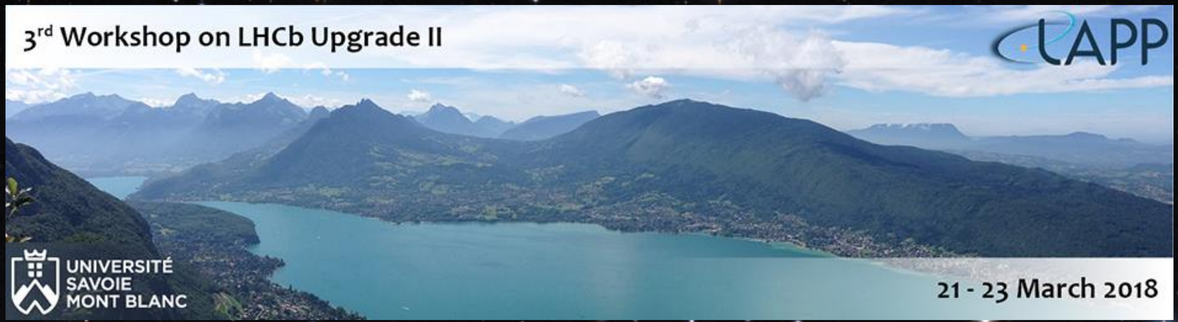


Zhenwei Yang @ Tsinghua
for the LHCb collaboration

2018.03.22

Great thanks to Liming, Lucio, Marco, Patrick, Sebastian, Steve, Tomasz, Vanya, and Yanxi for the nice inputs

Center for High Energy Physics – 2004 – Tsinghua University



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Outline

- Introduction
- Conventional hadrons
- Exotic hadrons
- Summary

Hadron spectroscopy

- Spectroscopy: collecting and sorting energy levels from the viewpoint of quantum mechanics
- An indispensable procedure to elucidate the underlying dynamics from complex phenomena
- Study of hadron spectroscopy can reveal properties of strong interactions between quarks
- New particles and decays are potentially new tools of the search of NP

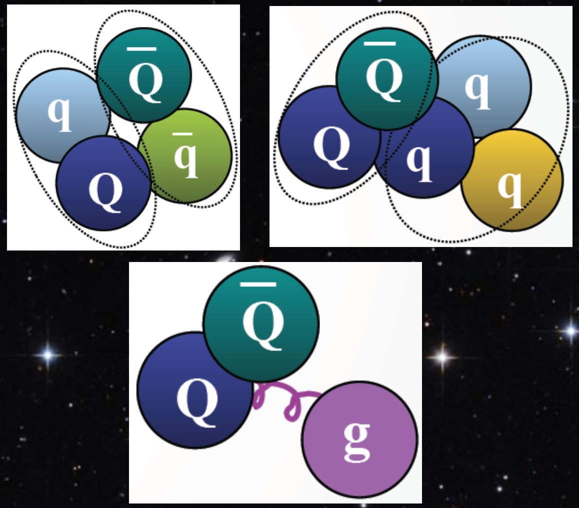
Renaissance of spectroscopy in heavy flavor

- States observed in 2003: do not fit in available models
  - $X(3872) \to J/\psi\pi^+\pi^-$ by Belle as the poster child

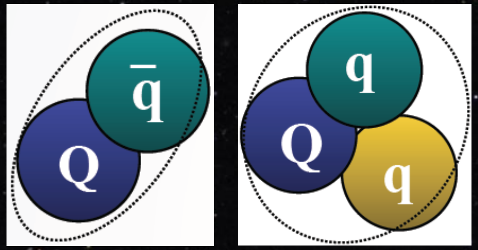
Belle, PRL91 (2003) 262001

- The particle zoo is now proliferated with new hadrons, exotic or conventional

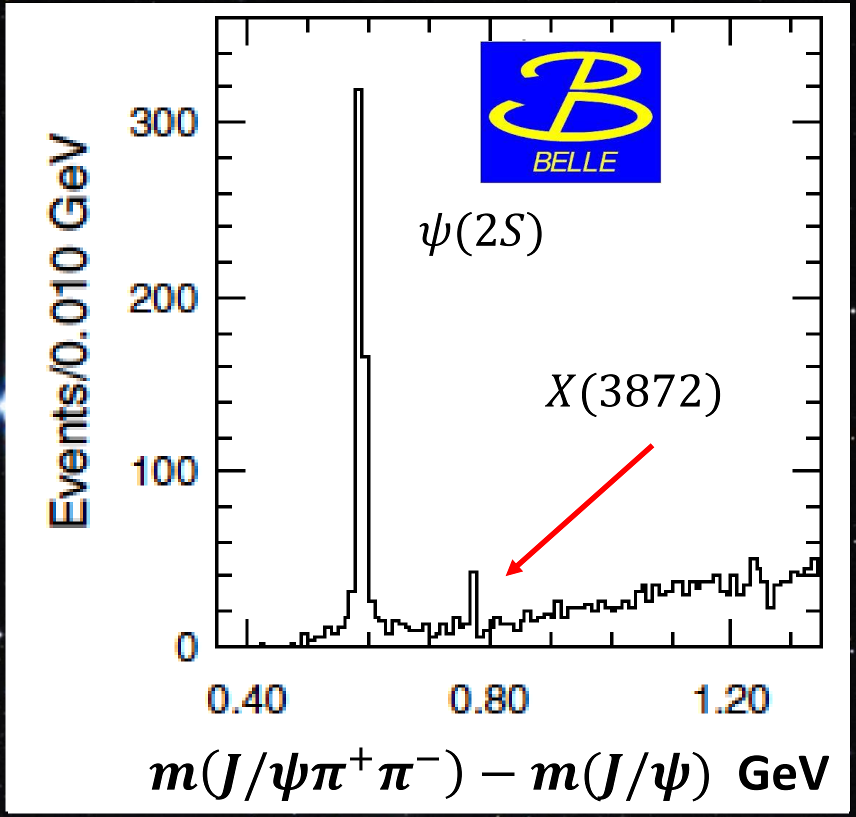
Exotic hadrons



Conventional hadrons



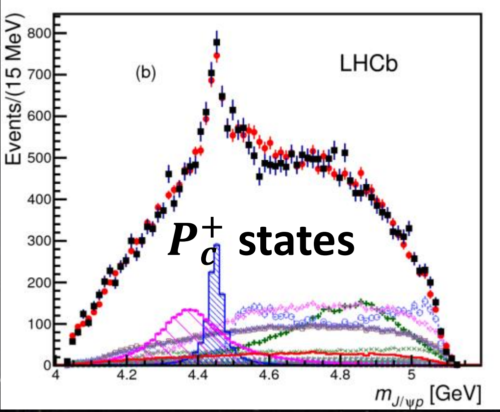
Poster Child



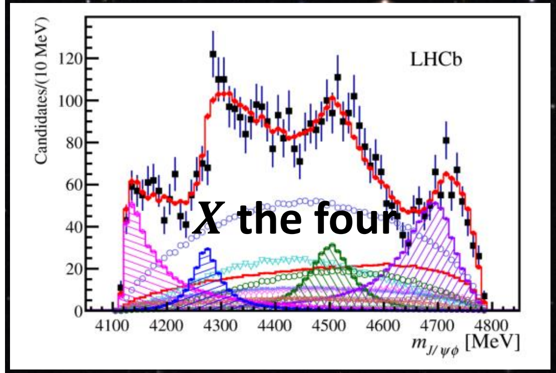
Contributions at LHCb

- LHCb has been playing a crucial role to the proliferated particle zoo
  - $P_c(4380)^+$, $P_c(4450)^+$, X the four, ……
  - J^P of $X(3872)$, ……
  - Ω_c^0 the five, Ξ_{cc}^{++}, ……
- More and more excited (complex)
  - More amplitude analyses performed/needed
  - Precise measurements of the properties: masses, widths, J^P, production, transitions, …

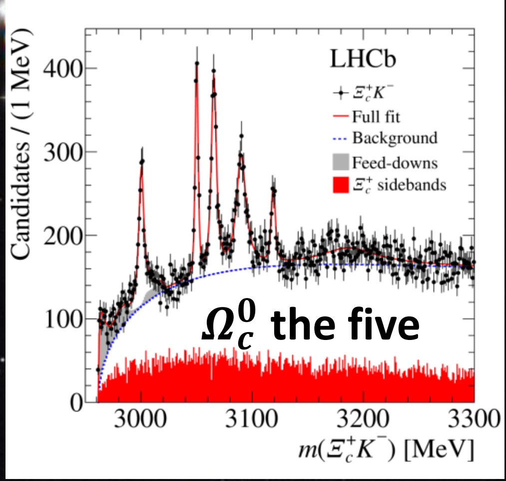
PRL115 (2015) 072001



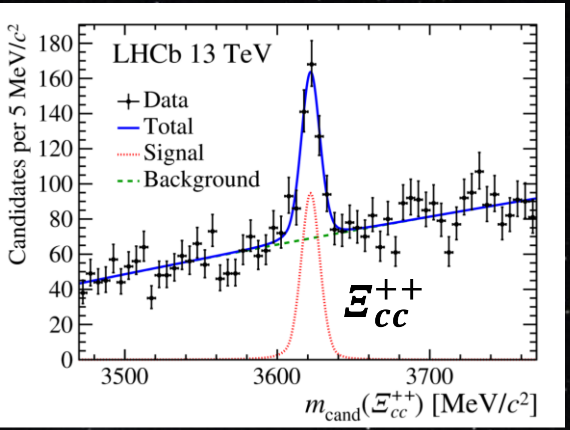
PRL118 (2017) 022003
PRD95 (2017) 012002



PRL118 (2017) 182001



PRL119 (2017) 112001



LHCb upgrade-II & the perspectives

➢ Upgrade-II in a nutshell

- The upgraded detector will be installed in LS4 (2030) of the LHC
- The new detector can operate at a luminosity of $2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$, ten times that of the Upgrade-I
- An integrated luminosity of $300\ \mathrm{fb}^{-1}$ is expected
- Capabilities of the experiment will be extended to selecting γ, π^0, η and low-momentum tracks, bottlenecks of many physics

➢ Perspectives of hadron spectroscopy

- A rule-of-thumb estimate is to scale the Run-I yields by a factor of 360 for hadronic final states and 180 for muonic final states
- Difficult in general to predict spectroscopy
- Estimated numbers could be wrong by order of magnitudes

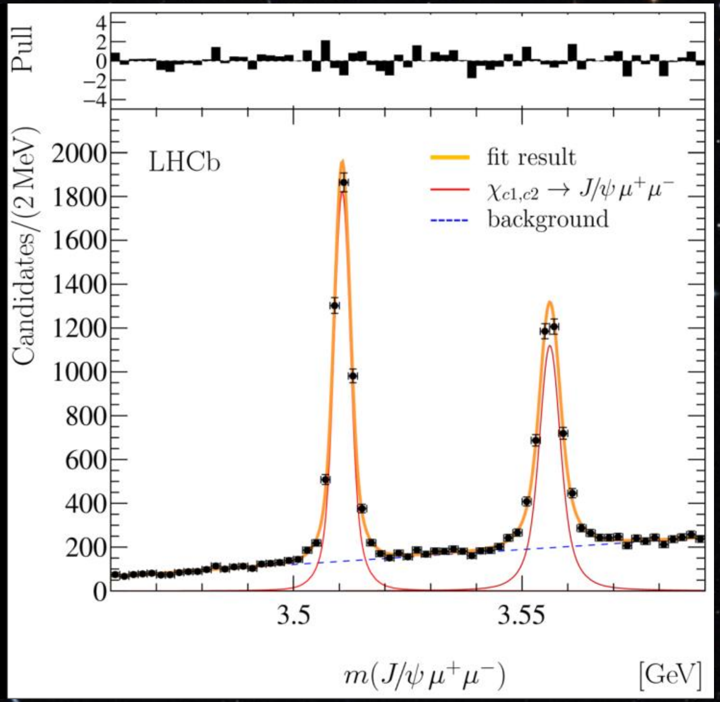
Conventional hadrons

- A lot of physics cases of conventional hadrons that LHCb can explore with the Upgrade-II detector, e.g.
  - Precision measurements of conventional heavy quarkonia
  - (Almost) unexplored B_c spectrum
  - Doubly/triply heavy flavour baryons and their excited states, e.g.
    - ✓ Ω_{cc}^{+}, Ω_{ccc}^{+++}, Ξ_{bc}, Ω_{bc}, Ω_{bcc}^{+}, Ω_{bbb}^{-}
  - Excited c- and b- hadrons, especially baryons

Some of these states could be discovered/studied before Run5, however, most of them need a much larger sample and more powerful detector to be fully explored.

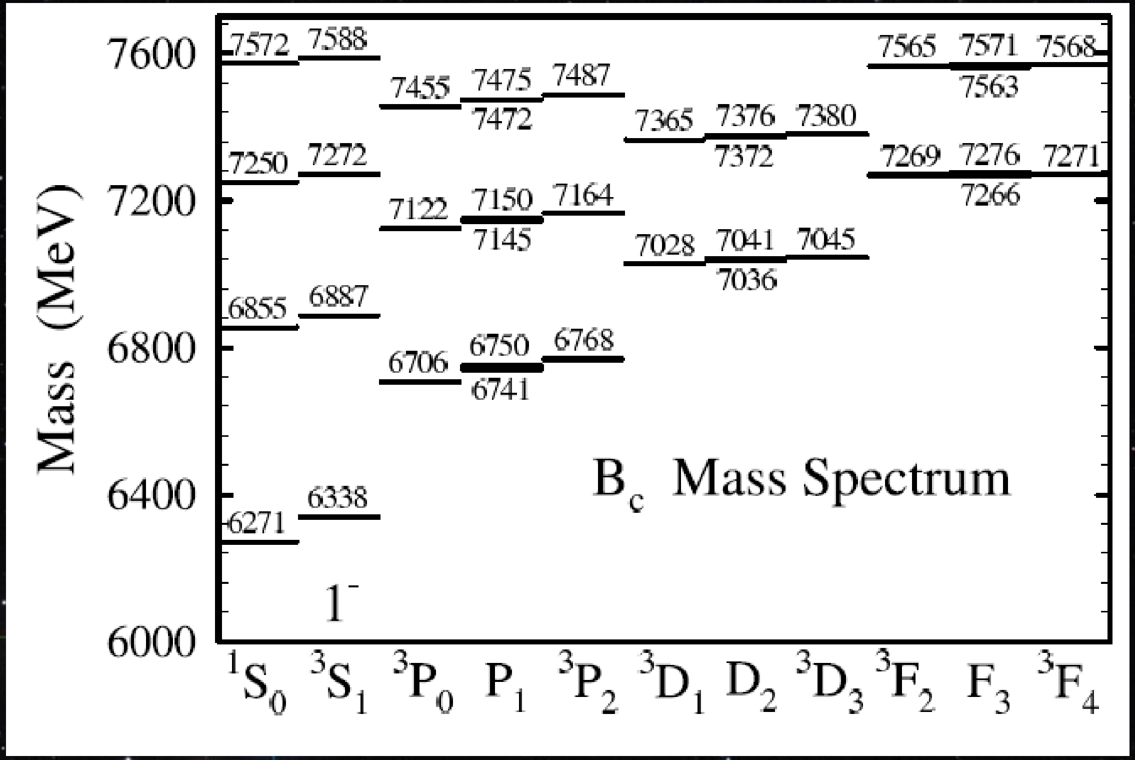
Production & polarization with heavy quarkonia

- Observation of $\chi_{c1,2} \to J/\psi\mu^+\mu^-$ decays is fundamental, which opens a window to detailed studies of $\chi_{c1,2}$
  - Excellent mass resolution to separate χ_{c1} and χ_{c2}
  - Almost background free
- With Upgrade-II, the yields are expected to be around 500k
  - Allow precise measurements of production and polarization to high p_{T} ($> 12\ \mathrm{GeV}/c$) region, providing powerful tests to theoretical models
- This also applies to $\chi_{b1,2} \to \Upsilon(1S)\mu^+\mu^-$ decays
- Precise studies of double heavy quarkonia also need Run5



B_c spectrum

S. Godfrey, PRD 70, 054017 (2004)

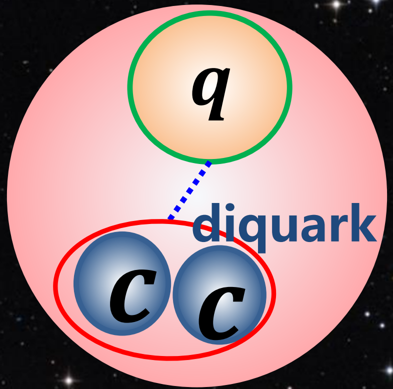


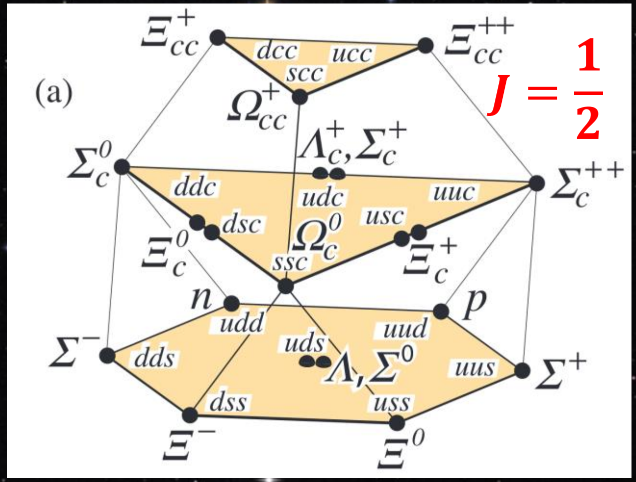
- $(\bar{b}c)$ is a unique meson family in SM with two open heavy flavors
- Rich spectrum and decay modes
- Only the background state B_c^+ is observed unambiguously
- The lowest excited states could be observed with Run2 plus Run3/4 data
- Upgrade-II with $300\ \mathrm{fb}^{-1}$ and improved selections of γ, π^0 and low-momentum tracks would allow the excited states to be largely explored

Doubly/triply charmed baryons: Ξ_{cc}^{++}, Ξ_{cc}^{+}, Ω_{cc}^{+}, Ω_{ccc}^{++}

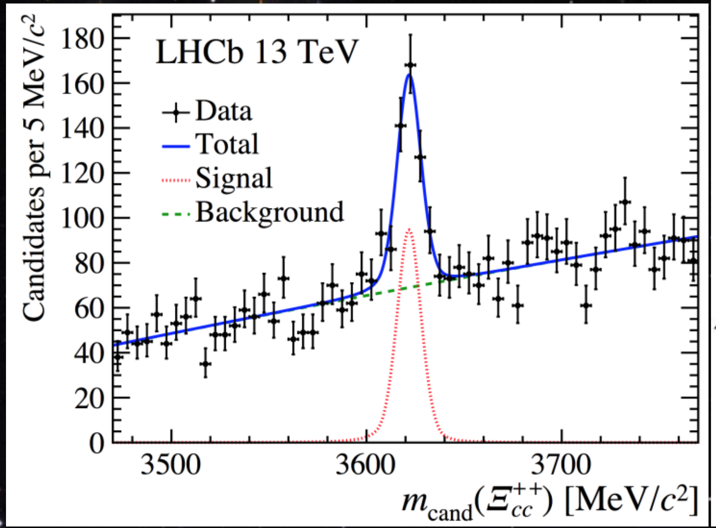
- LHCb observed the doubly charmed baryon Ξ_{cc}^{++} using the 2016 data, confirmed with the 2012 data

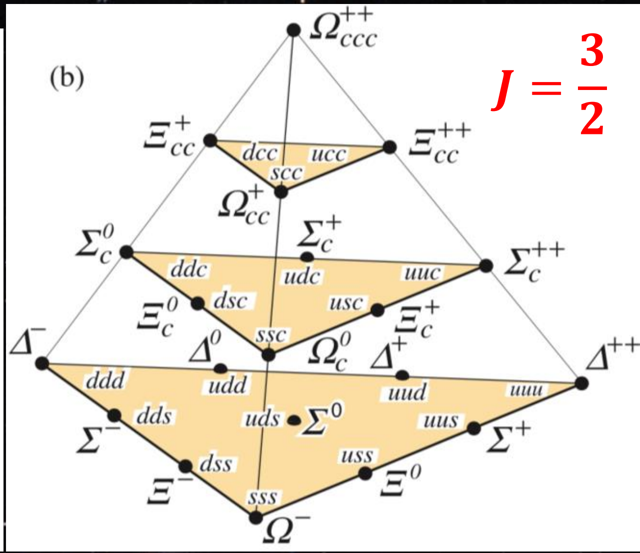
$m = 3621.80 \pm 0.72\ \mathrm{MeV}/c^2$
Yield at 2016: $N_{\mathrm{sig}} = 313 \pm 33$
Yield at 2012: $N_{\mathrm{sig}} = 113 \pm 21$





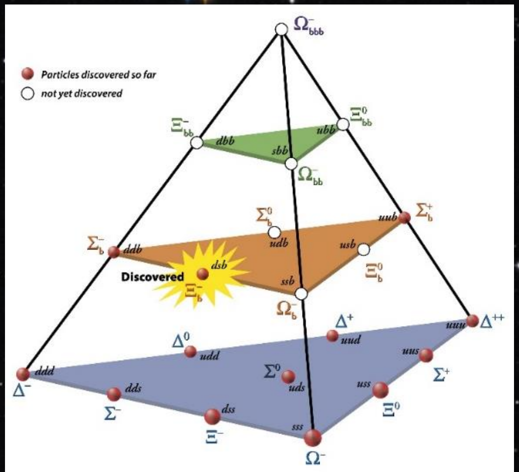
- Observation of Ξ_{cc}^{+} and Ω_{cc}^{+} expected with Run2+Run3/4
- Upgrade-II will be useful to study their properties and to search for the excited states, and could be needed for an observation of Ω_{ccc}^{++}





Searches for Ξ_{bc}, Ω_{bc}, Ξ_{bb}, Ω_{bb}, Ω_{bbb}^{-}…

- Searches for such baryons suffer from **low production rate**, **small branching fractions**, and **low efficiencies**
- Possible decay modes to detect:
  - $J/\psi X_c$ modes such as $J/\psi\Xi_c^+$, $J/\psi\Xi_c^0$, $J/\psi\Lambda_c^+$, $J/\psi\Lambda_c^+K^-$
  - Ξ_{cc} modes, double charm-hadron modes,
  - penguin topologies, H_b modes



- **Yields at Run5** can be estimated by $N(B_c^+ \to J/\psi D_s^+) = 30 \pm 6$ at Run1, theoretical predictions, et al:

$$\boxed{N(\Xi_{bc}^+ \to J/\psi\Xi_c^+) \approx 3000}$$

Largely depends on unknown BF and cross-sections, and upgrade-II will allow us to be fully armed for discoveries of these (excited) states

Exotic hadrons

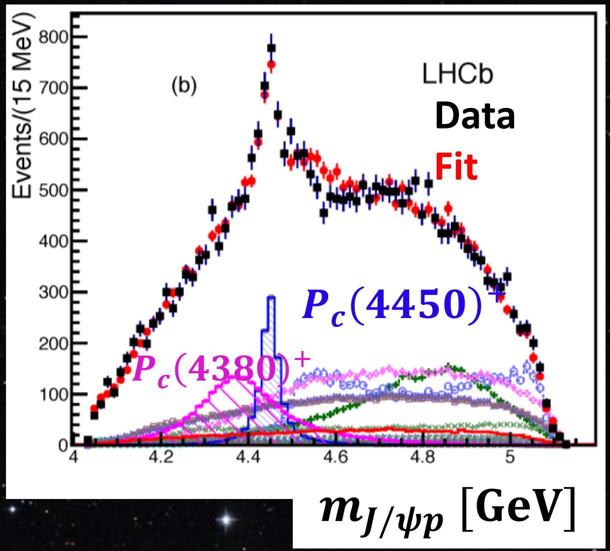
- A large amount of studies are under way and/or prospected to understand the nature of exotic hadrons, e.g.
  - Establishing multiplets of observed tetraquarks, pentaquarks
  - Prompt production of exotic hadrons
  - Amplitude of analysis to precisely establish properties of exotic hadrons and ordinary mesons
  - Tetraquarks with open heavy flavor(s): $(bb)(\bar{u}\bar{d})$, $(cc)(\bar{q}\bar{q}')$, $(bs)(\bar{u}\bar{d})$, $(cs)(\bar{u}\bar{d})$
  - Searching for analogs in the beauty sector

Some of these states could be discovered/studied before Run5, however, most of them need a much larger sample and more powerful detector to be fully explored.

Pentaquarks

- Two P_c^+ states observed in $\Lambda_b^0 \to J/\psi p K^-$ decays
- A lot of open questions
  - Nature of the structures: tightly or loosely?
  - Multiplets?
- Efficiencies of slow γ, π^0 and π^+ are essential for some studies

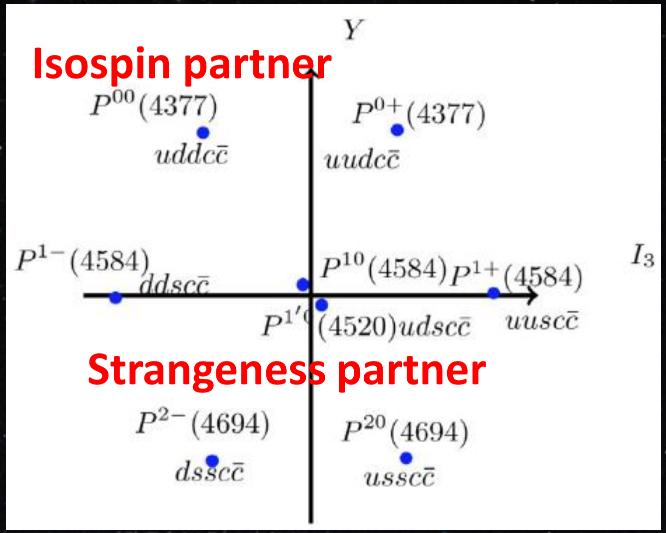
LHCb, PRL115 (2015) 072001



An incomplete list of decays for (possible) pentaquark studies

- ✓ $B_c^+ \to J/\psi p \bar{p} \pi^+$
- ✓ $\Upsilon(1S) \to J/\psi p \bar{p}$
- ✓ $B_s^0 \to J/\psi p \bar{p}$
- ✓ $\Xi_b^- \to J/\psi \Lambda K^-$
- ✓ $B^+ \to J/\psi p \bar{\Lambda}$
- ✓ Prompt $P_c^+ \to J/\psi p$
- ✓ $\Lambda_b^0 \to \eta_c p K^-$
- ✓ $\Lambda_b^0 \to \chi_{c1} p K^-$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^0 K^-$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ \bar{D}^{*0} K^-$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ D^- K^*$
- ✓ $\Lambda_b^0 \to \Lambda_c^+ D_s^- \phi$
- ✓ $\Lambda_b^0 \to J/\psi p \pi^+ \pi^- K^-$
- ✓ $\Lambda_b^0 \to \Sigma_c^{++} D^- K^-$
- ✓ $\Lambda_b^0 \to J/\psi \Lambda \eta$
- ✓ $\Lambda_b^0 \to J/\psi \Lambda \phi$

E. Santopinto et al, PRD 96 (2017) 014014



Pentaquark study in $\Lambda_b^0 \to \chi_{cJ} p K^-$

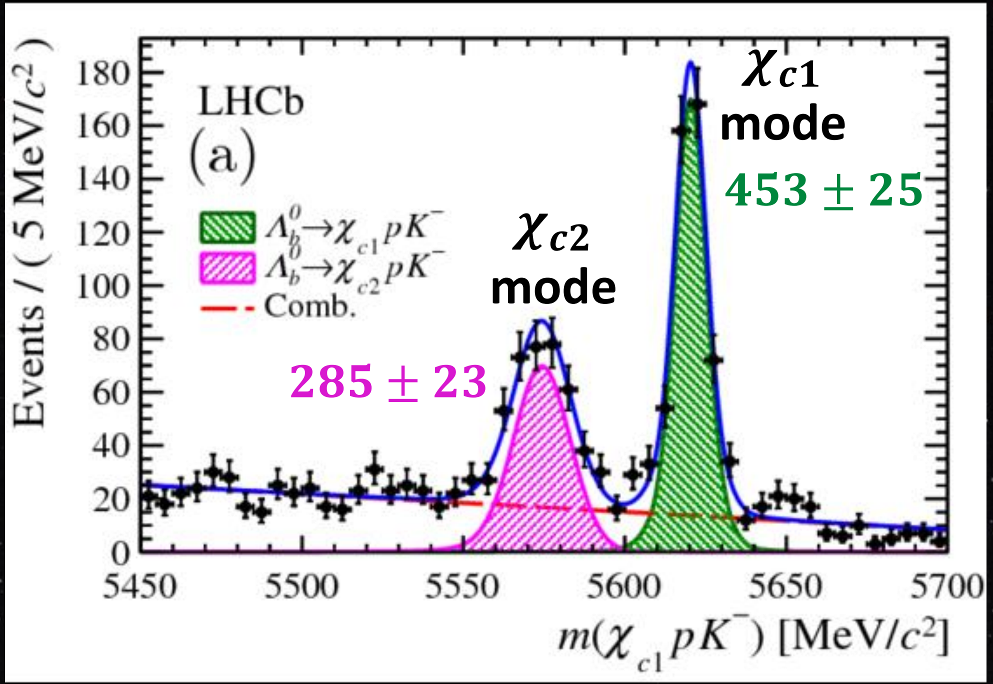
- Observation of the $P_c(4450)^+ \to \chi_{c1} p$ contribution would help to clarify the nature of $P_c(4450)^+$ states F.-K. Guo et al, PRD 92 (2015) 071502 M. Bayar et al, PRD 92 (2016) 074039
- LHCb observed the decays $\Lambda_b^0 \to \chi_{c1,2} p K^-$ with the Run1 data LHCb, PRL 119 (2017) 062001

- **Expected yields at Run5**

$$N(\Lambda_b^0 \to \chi_{c1} p K^-) \approx 8 \times 10^4$$
$$N(\Lambda_b^0 \to \chi_{c2} p K^-) \approx 5 \times 10^4$$

  - Allowing precise amplitudes analysis

- **Observation of $\Lambda_b^0 \to \chi_{c0}(\to J/\psi\gamma) p K^-$ is expected at Run5: $N \simeq 3000$**



Multiplet of pentaquarks

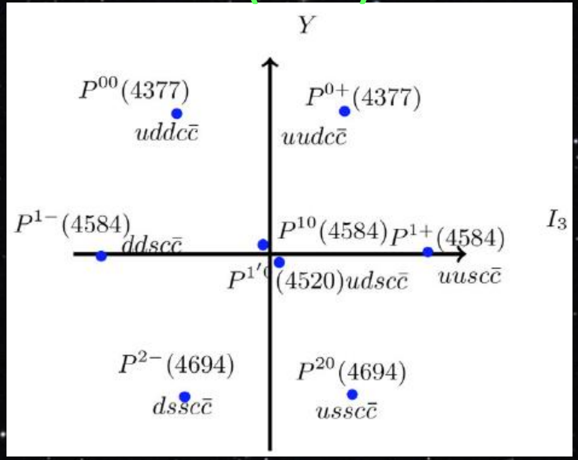
- Multiplets of the observed P_c^+ states ($c\bar{c}uud$) should exist
- E.g. $P_{cs}^0 \to J/\psi\Lambda$ ($c\bar{c}uds$) to be explored in $\Xi_b^- \to J/\psi\Lambda K^-$ decays

  J.-J. Wu et al, PRL105(2010)232001
  H.-X. Chen et al, PRC93(2016)065203
  E. Santopinto et al, PRD 96 (2017) 014014

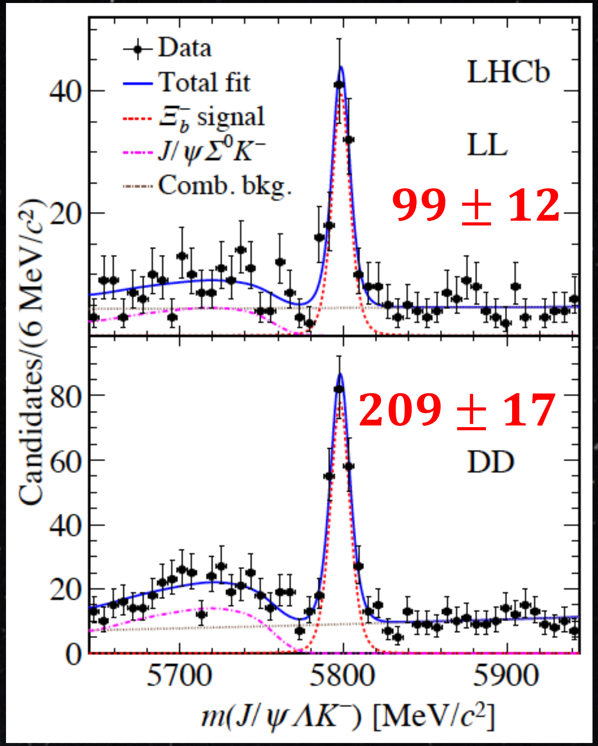
- 300 candidates of $\Xi_b^- \to J/\psi\Lambda K^-$ observed in Run1 data
- **Expected yields at Run5**

$$\boxed{N(\Xi_b^- \to J/\psi\Lambda K^-) \approx 6\times 10^4}$$

E. Santopinto et al, PRD 96 (2017) 014014



LHCb, PLB 772 (2017) 265

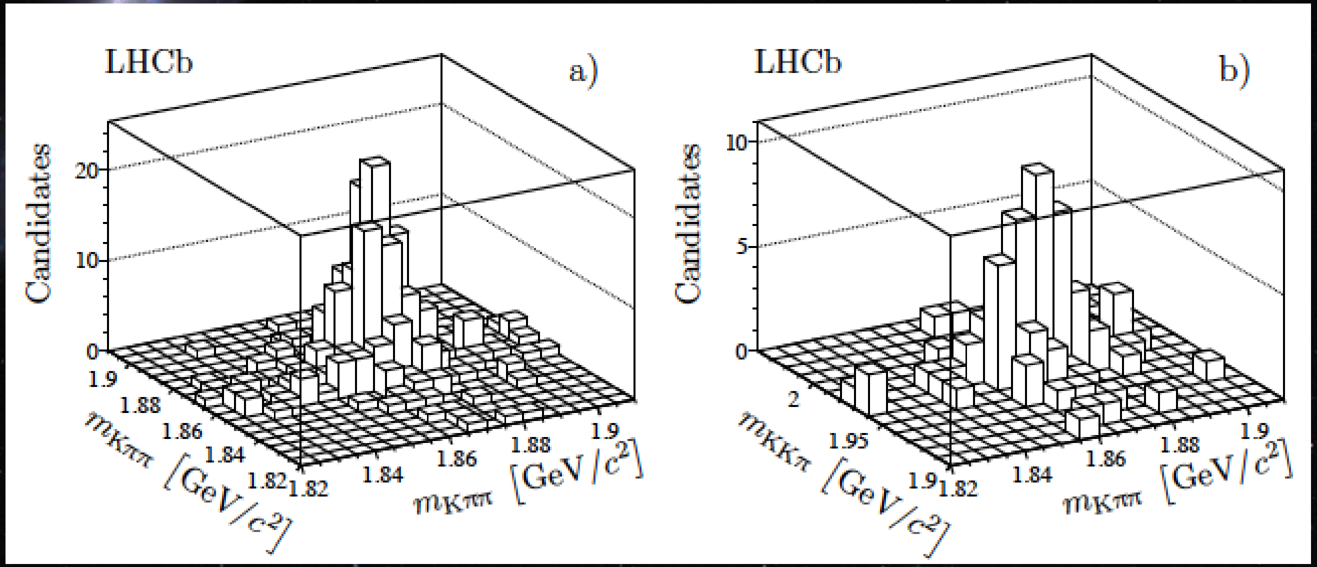


Tetraquarks with double charm/beauty flavors

- Mesons with double charm or beauty flavors, such as $(bb)(\overline{q}\overline{q}')$, $(cc)(\overline{q}\overline{q}')$, would unambiguously be states with four quarks
  - $(bb)(\overline{u}\overline{d})$ is predicted by LQCD and pheno models
  - $(cc)(\overline{q}\overline{q}')$ is proposed in PRD 88 (2013) 054029
  - $(bs)(\overline{u}\overline{d})$ and $(cs)(\overline{u}\overline{d})$ proposed in arXiv:1709.02571 are also good candidates
- If $(bb)(\overline{q}\overline{q}')$, $(cc)(\overline{q}\overline{q}')$ have masses below BB or DD thresholds, they will decay via weak interactions, otherwise strong interactions
  - For strong decays, their widths could be narrow (pure tetraquark), which is helpful to be observed in prompt production, or broad (doubly charged molecular states)

Searches for $(cc)(\overline{q}\overline{q}')$ states

- If $(cc)(\overline{q}\overline{q}')$, which decay into D^+D^+ or $D^+D_s^+$, are narrow states, they could be easily observed in prompt production
- Associate production of D^+D^+ and $D^+D_s^+$ with $0.3\ \mathrm{fb}^{-1}$ data



LHCb, JHEP 06 (2012) 141

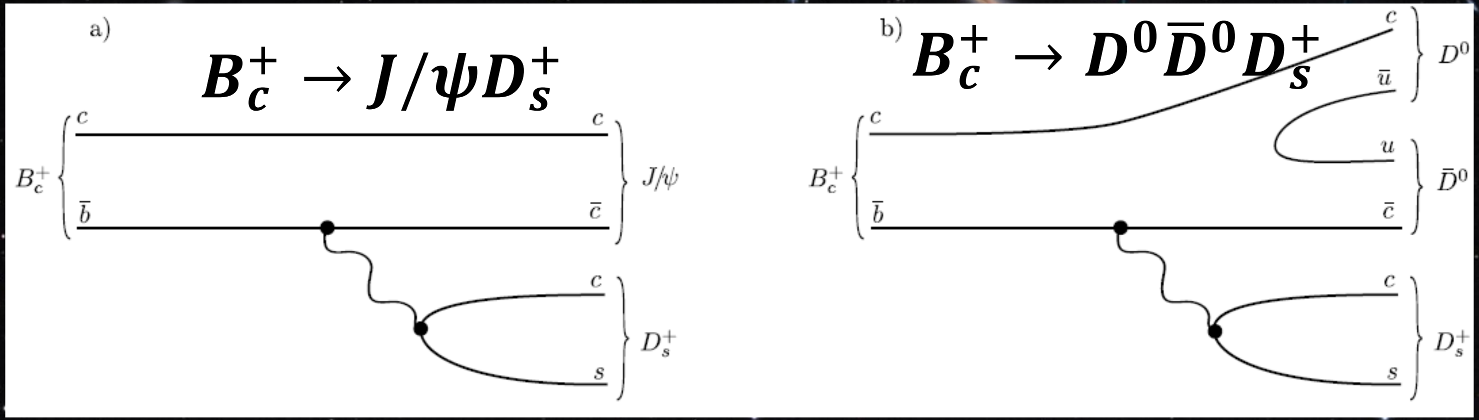
- **Expected yields at Run5:**

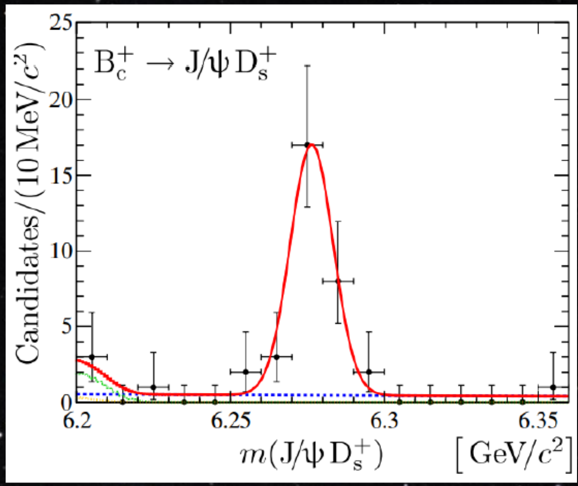
$$N(D^+D^+) \approx 750\ \mathrm{k}$$
$$N(D^+D_s^+) \approx 150\ \mathrm{k}$$

Searches for $(cc)(\overline{q}\overline{q}')$ states in B_c^+ decays

- If $(cc)(\overline{q}\overline{q}')$ are broad states, searching in B_c^+ decays is a good opportunity, $B_c^+ \to D^0\overline{D}^0D_s^+$
- $N(B_c^+ \to J/\psi D_s^+) = 30 \pm 6$ in Run1, and to be $\mathcal{O}(10^4)$ in Run5
- **Expected yield of $B_c^+ \to D^0\overline{D}^0D_s^+$ in Run5: ≈ 100**
  - Clear signal for observation
  - Sample size marginal for AmAn

LHCb, PRD 87 (2013) 112012





Summary

- LHCb Upgrade-II will be very helpful to studies of spectroscopy of heavy flavor hadrons
- A lot of studies suffer from small production rate, low decay rate, and low efficiencies, a much larger sample is essential
- Many studies are difficult, if not impossible, without the Upgrade-II detector to allow the detection of slow γ, π^0, and low-p_{T} charged tracks
  - E.g. Measuring baryon magnetic moment with radiative decay $P_c(4450)^+ \rightarrow P_c(4380)^+\gamma$ [G.-J. Wang et al PRD94(2016)094018]
- With Upgrade-II we can hopefully establish a new landscape of hadron spectroscopy

Summary (cont.)

- *The Experimental Foundations of Particle Physics* by Robert Cahn and Gerson Goldhaber

neutral atom has, as well, Z electrons, each with a mass only 1/1836 that of a proton. The chemical properties of the atom are determined by Z; atoms with equal Z but differing A have the same chemistry and are known as isotopes.

This school-level description did not exist at all in 1895. Atoms were the creation of chemists and were still distrusted by many physicists. Electrons, protons, and neutrons were yet to be discovered. Atomic spectra were well studied, but presented a bewildering catalog of lines connected, at best, by empirical rules like the Balmer formula for the hydrogen atom. Cathode rays had been studied, but many regarded them as uncharged, electromagnetic waves. Chemists had determined the atomic weights of the known elements and Mendeleev had produced the periodic table, but the concept of atomic number had not yet been developed.

THE EXPERIMENTAL FOUNDATIONS OF PARTICLE PHYSICS

Second Edition

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- Looking forward to an updated chapter of spectroscopy in textbooks of particle physics in 2030s

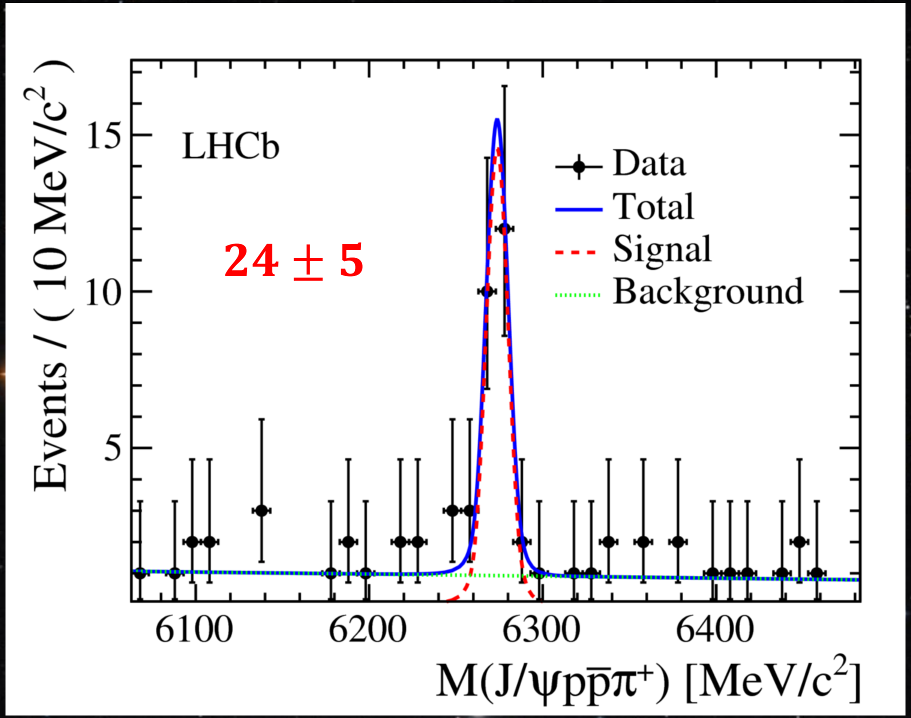
Thank you！

Backup slides

Pentaquark study in $B_c^+ \to J/\psi p\bar{p}\pi^-$

- The baryonic decay $B_c^+ \to J/\psi p\bar{p}\pi^-$ was observed by LHCb using the Run1 data
- A large sample of $B_c^+ \to J/\psi p\bar{p}\pi^-$ decays would allow an exploration of the $P_c^+ \to J/\psi p$ contribution

LHCb, PRL 113 (2014) 152003



- Expected yields at Run5

$$\boxed{N(B_c^+ \to J/\psi p\bar{p}\pi^-) \approx 5 \times 10^3}$$

allowing an amplitude analysis

How to do spectroscopy at LHCb

- **Prompt production**
  - ☺ Large production cross-sections
  - ☹ Large combinatorial background
  - ☹ Difficult to disentangle broad structures
  - ☹ Difficult to assess spin
- **Central exclusive production (CEP)**
  - ☺ Small background
  - ☺ $J^{PC} = 1^{--}, J^{++}$
  - ☹ Small cross-sections
- **b-hadron decays**
  - ☺ Small background
  - ☺ Amplitude analysis can be performed to access J^P quantum numbers
  - ☹ Limited cross-sections