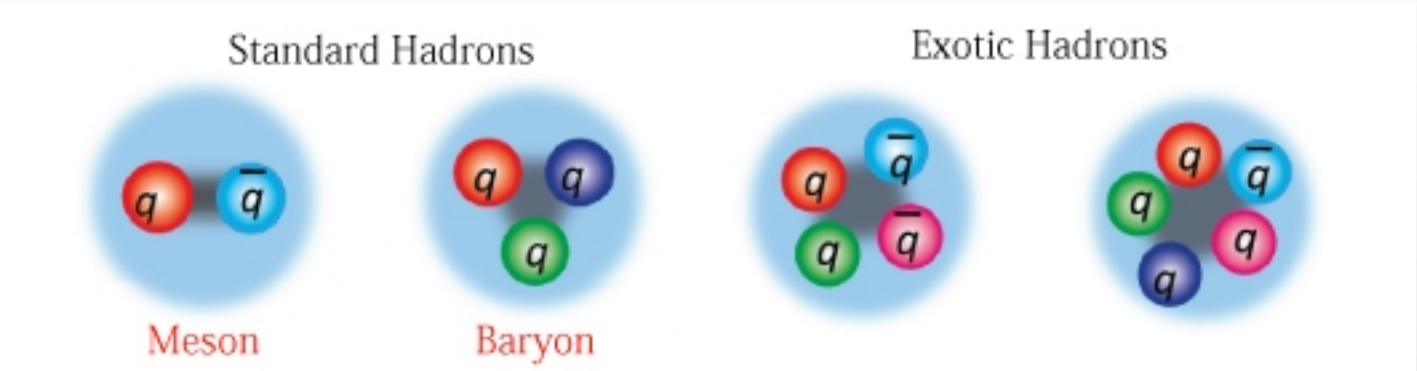
Spectroscopy at LHCb
Status & Prospect

Marco Pappagallo
INFN & University of Bari

Implications of LHCb measurements and future prospects
12-14 October 2016, CERN, Switzerland

Outline

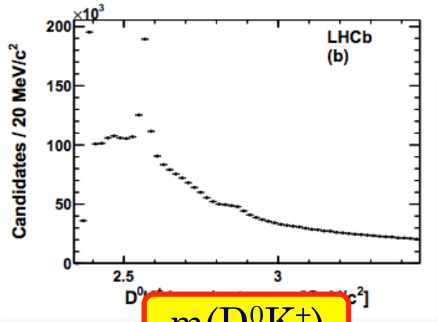
- Introduction
- Standard Spectroscopy
- Exotic Spectroscopy
- Summary



How to do spectroscopy?

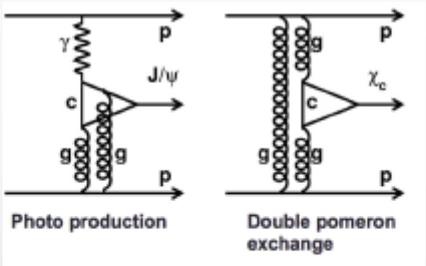
Prompt Production: (e.g. $pp \rightarrow D_s^{**}(\rightarrow D^0K) + X$)

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

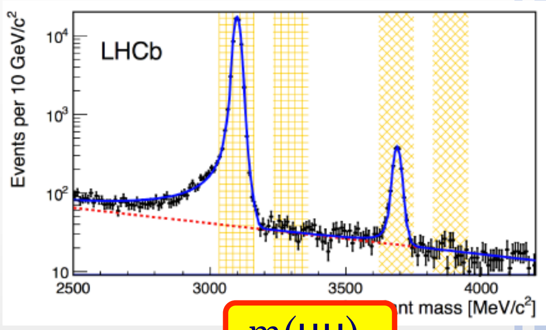


m(D^0K^+)

Central Exclusive Production (CEP)



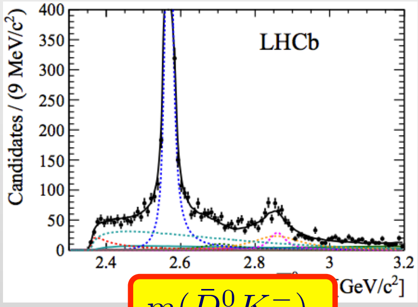
- ✓ Small background
- ✓ $J^{PC} = 1^{--}$, J^{++}
- ✗ Difficult to assess the rapidity gaps
- ✗ Limited cross sections



m(μμ)

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"



m($\bar{D}^0 K^-$)

Standard Spectroscopy: Status

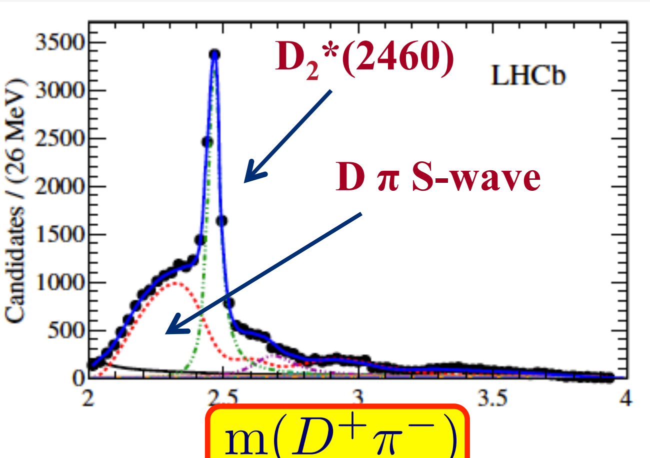
Open-Charm Mesons

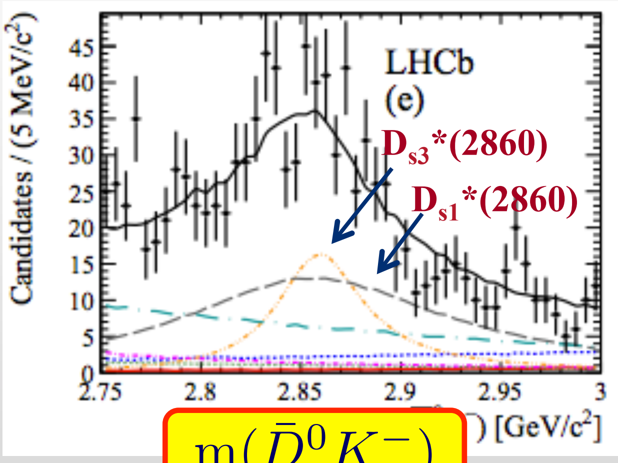
Excited $D_{(s)}$** studied in prompt production ($D^{(*)}\pi/K$) and from B decays ($B \to D\,\pi/K\,X$)

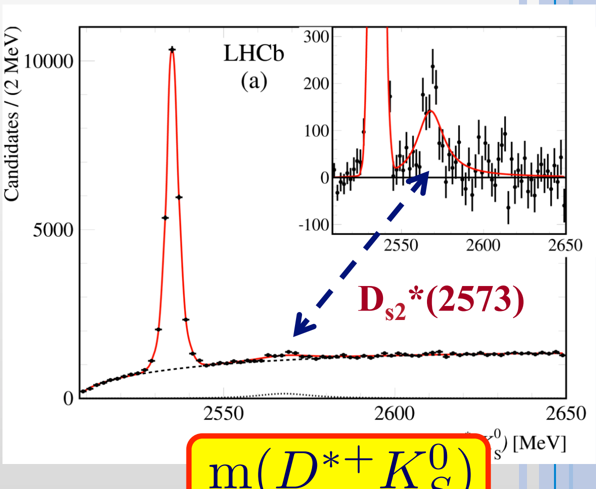
- ✓ Determination of spin-parity (e.g. $D^0*(2400)^-$: $J^P=0^+$)
- ✓ First observation of spin-3 resonances in B decays
- ✓ Observation of new states/ decays modes

[JHEP 09 (2013) 145]
[JHEP 10 (2012) 151]
[PRD 92 (2015) 012012]
[PRD 91 (2015) 092002]
[PRD 92 (2015) 032002]

$B^+ \to D^+\pi^+\pi^-$	$B_s^0 \to \bar{D}^0\pi^+K^-$	Inclusive D^*K
PRD 94 (2016) 072001	PRL 113 (2014) 162001, PRD 90 (2014) 072003	JHEP 02 (2016) 133



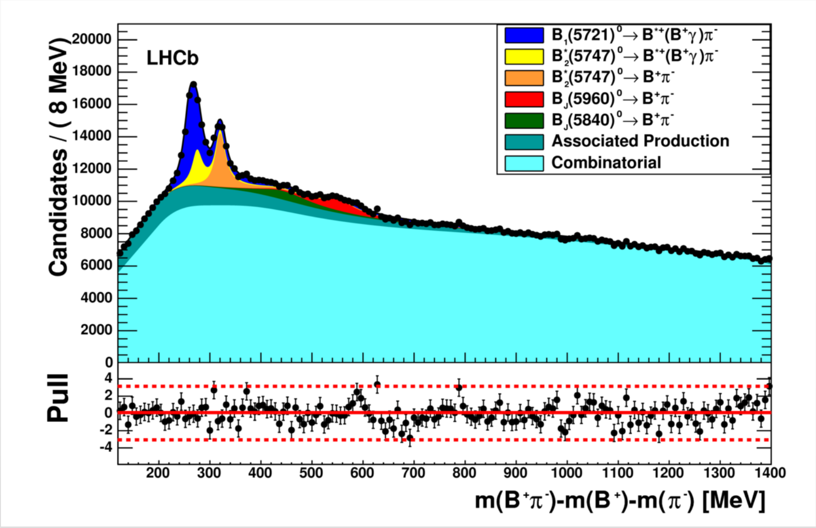




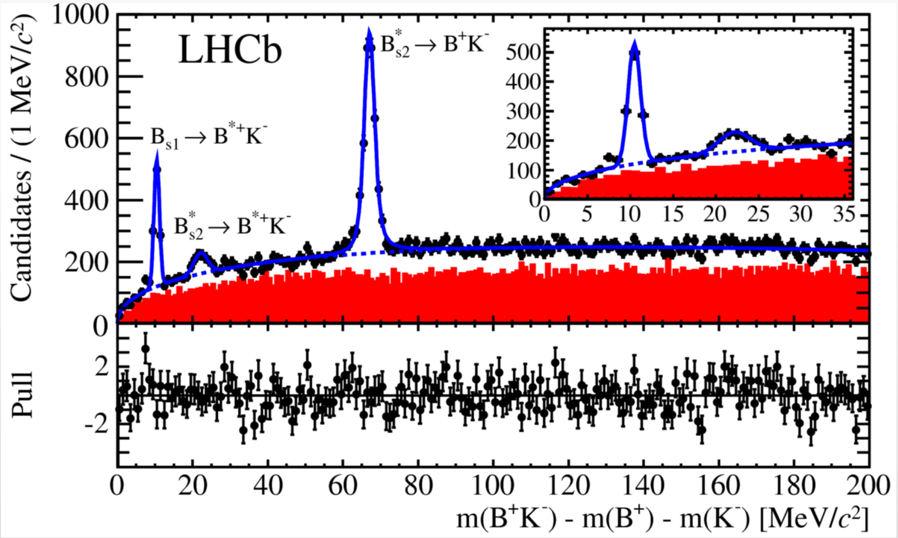
Open-Beauty Mesons

Excited $B_{(s)}^{**}$ studied in prompt production (Bπ/K)
✓ Precise measurements of masses and width
✓ Observation of new decays modes

JHEP 04 (2015) 024



PRL 110 (2013) 151803



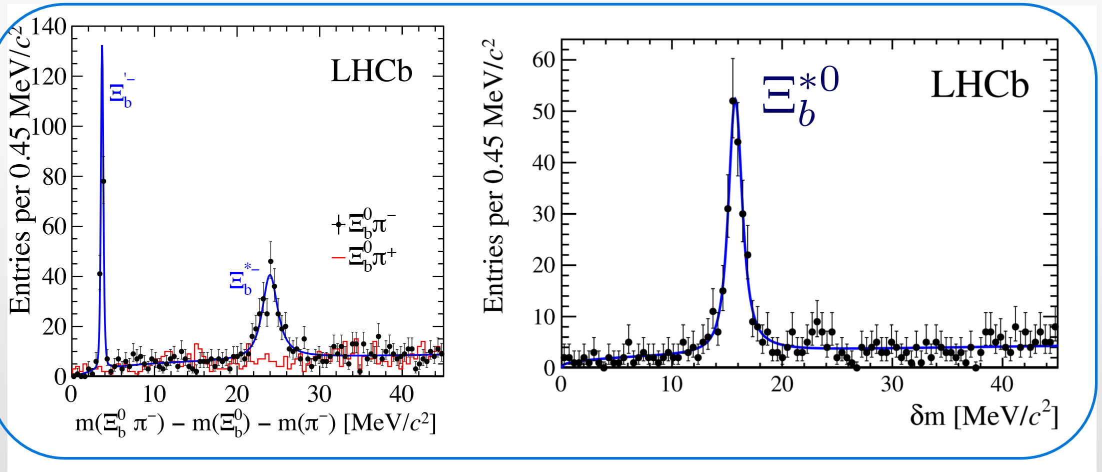
Beauty Baryons Spectroscopy

Large production cross-section of baryons at LHC

- ✓ Filling the gaps of the missing ground states
- ✓ First observation of excited beauty baryons

[PRL 114 (2015) 062004, JHEP 05 (2016) 161]

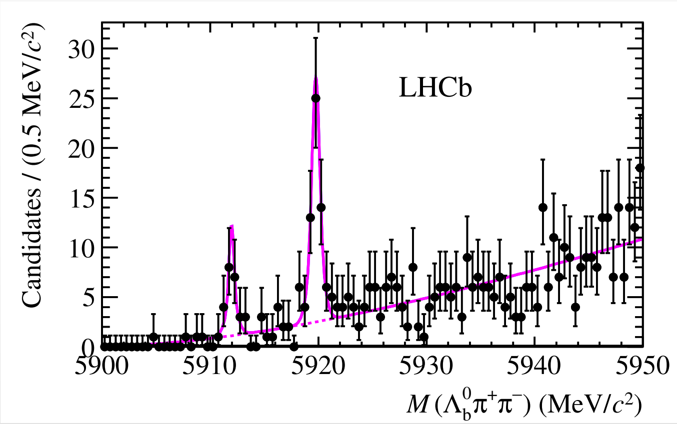
$\Xi_b^{**} \rightarrow \Xi_b\pi$, where $\Xi_b \rightarrow \Xi_c\pi$



Three narrow peaks interpreted as $\Xi_b'^-$ ($J^P = 1/2^+$), Ξ_b^{*-} ($J^P = 3/2^+$) , Ξ_b^{*0} ($J^P = 3/2^+$)

[PRL 109 (2012) 172003]

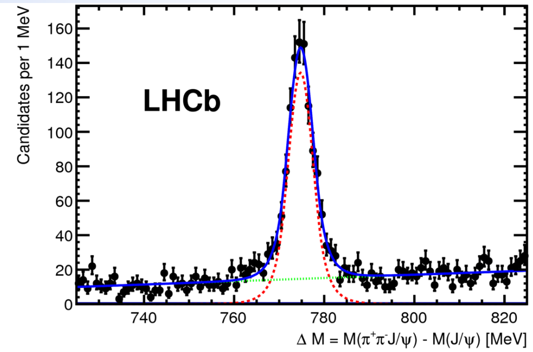
$\Lambda_b^{**0} \rightarrow \Lambda_b^0\pi^+\pi^-$, where $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^-$



Two new peaks are interpreted as the orbitally L=1 excited Λ_b^0 states

Exotic Spectroscopy: Status

The X(3872) State



LHCb experiments has largely contributed to shed light on the nature of the X(3872) state

- Determination of the quantum numbers $J^{PC} = 1^{++}$ ➡ *η_{c2}(2D) ruled out*
  D-wave component f_D < 4% @ 95% C.L. **[PRL 110, 222001 (2013)][PRD92, 011102 (2015)]**
- Precise mass measurement **[EPJC 72 (2012) 1972] [JHEP 06 (2013) 065]**

$$E_B = m(D^0) + m(D^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV/c^2}$$

➡ *Loosely bound in the molecule scenario*

- Production cross-section in *pp* collisions at √s = 7 TeV **[EPJC 72 (2012) 1972]**
- 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*

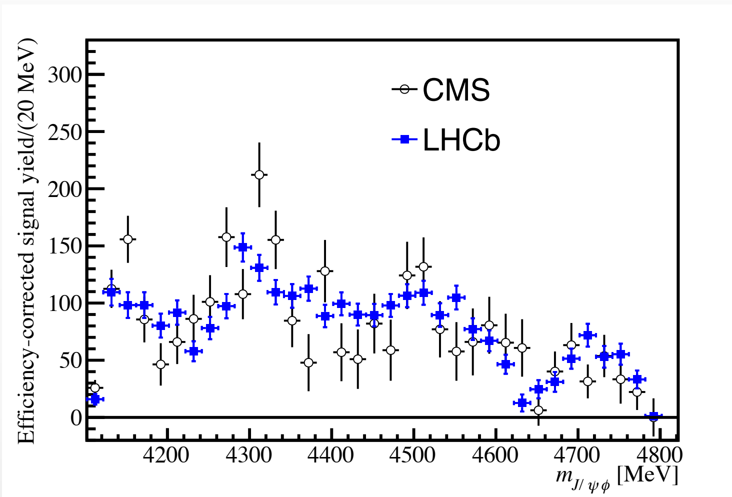
- Search for new decay modes (e.g. X(3872) →pp) **[arXiv: 1607.06446]**

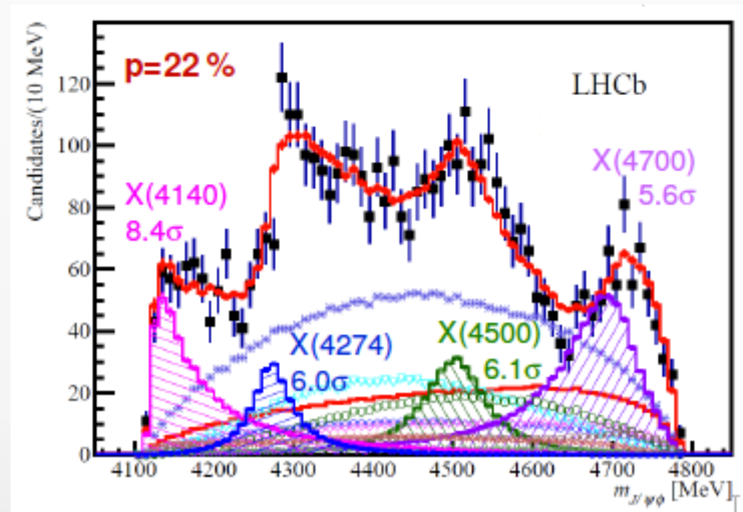
$$\frac{\mathcal{B}(B^+ \to X(3872) K^+) \times \mathcal{B}(X(3872) \to p\bar{p})}{\mathcal{B}(B^+ \to J/\psi K^+) \times \mathcal{B}(J/\psi \to p\bar{p})} < 0.25 \times 10^{-2} \,@\, 95\%\,\mathrm{CL}$$

X(4140) & X(4274)

[LHCb: arXiv: 1606.07895]
[LHCb: arXiv: 1606.07898]

- "Observed" by CDF and later "confirmed" by other experiments (CMS, DØ). Some tension between the measurements of masses/widths
- LHCb performed a 6D amplitude analysis for the first time





	M_0 [MeV]	Γ_0 [MeV]
$X(4140)$	$4146.5 \pm 4.5\,^{+4.6}_{-2.8}$	$83 \pm 21\,^{+21}_{-14}$
$X(4274)$	$4273.3 \pm 8.3\,^{+17.2}_{-\ 3.6}$	$56 \pm 11\,^{+\ 8}_{-11}$
$X(4500)$	$4506 \pm 11\,^{+12}_{-15}$	$92 \pm 21\,^{+21}_{-20}$
$X(4700)$	$4704 \pm 10\,^{+14}_{-24}$	$120 \pm 31\,^{+42}_{-33}$

X(4140) ($J^{PC} = 1^{++}$)
- Mass consistent with the previous measurements but <u>the width substantially larger</u>

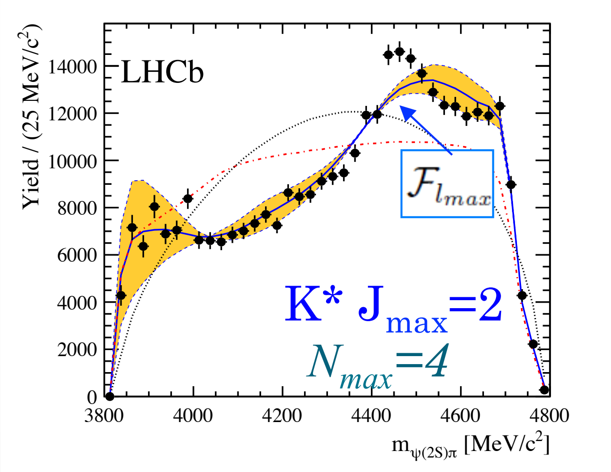
X(4274) ($J^{PC} = 1^{++}$)
- Consistent with the unpublished CDF results.

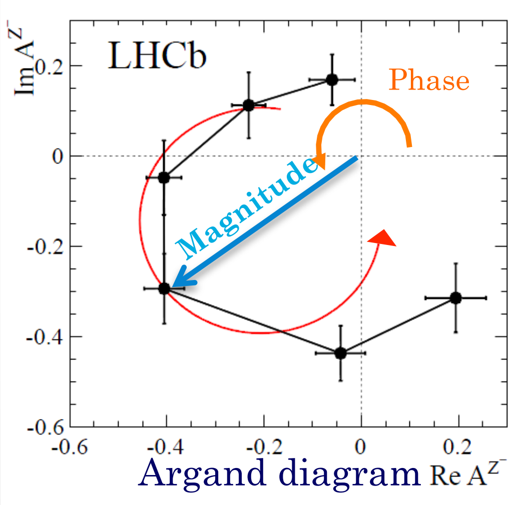
Two new states : **X(4500)** and **X(4700)** with ($J^{PC} = 0^{++}$)

$Z_c(4430)^+$

[PRL 112 (2014) 222002, PRD 92 (2015) 112009]

- Before LHCb era, there was a tension between the B-factories: Amplitude analysis vs Model Independent analysis
- $Z_c(4430)$ is the only exotic confirmed by two experiments by an amplitude analyses





Model independent Analysis:
- Due to a larger sample, LHCb is more sensitive to the presence of exotics. Clear discrepancy at m ~ 4430 MeV

Amplitude Analysis:
- Determination of spin parity of $Z_c(4430)$: $J^P = 1^+$
- The measured mass and width are consistent with the values reported by Belle
- Resonant character shown through an Argard diagram test

PENTAQUARKS

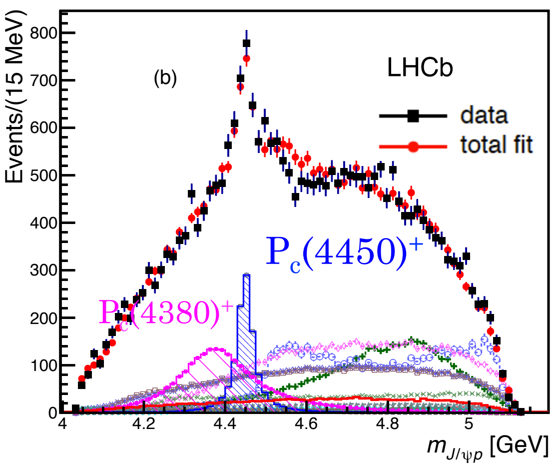
PRL 115 (2016) 072001
PRL 117 (2016) 082003
PRL 117 (2016) 082002

The two Pentaquarks P_c^+ observed in $\Lambda_b \rightarrow J/\psi$ p K are getting support

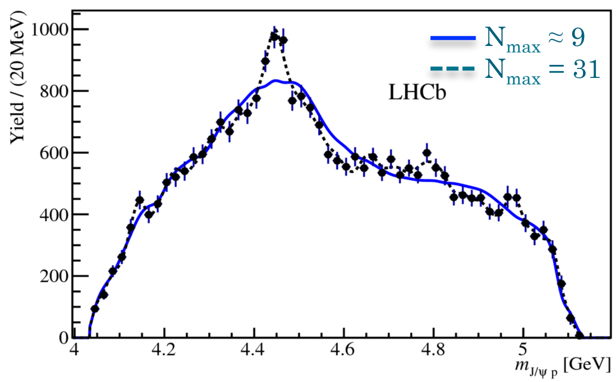
- Model independent analysis of $\Lambda_b \rightarrow J/\psi$ p K decay and amplitude analyses of $\Lambda_b \rightarrow J/\psi$ p π suggest the presence of exotic

$\Lambda_b \rightarrow J/\psi$ p K

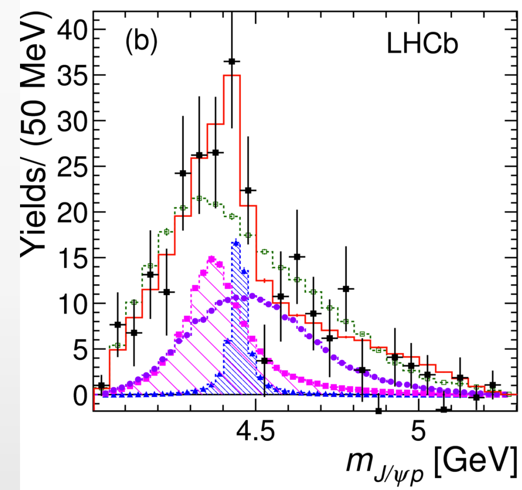
Amplitude Analysis



Model Independent



$\Lambda_b \rightarrow J/\psi$ p π



State	Mass (MeV)	Γ (MeV)
$P_c(4380)^+$	4380 ±8±29	205±18±86
$P_c(4450)^+$	4449.8±1.7±2.5	39 ± 5±19

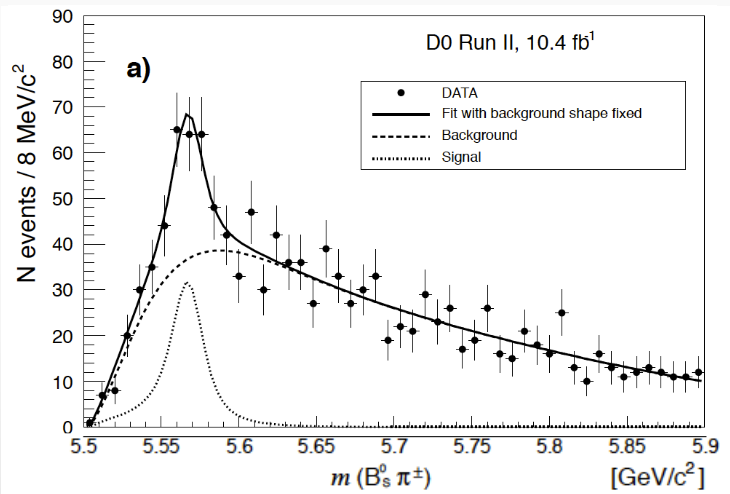
3.1σ for $P_c(4380)^+$, $P_c(4450)^+$, $Z_c(4200)^-$ taken together → Evidence for exotic hadrons

SEARCH FOR X(5568)$^{\pm}$ → $B^0_s\pi^{\pm}$

[Phys. Rev. Lett. 117 (2016) 152003]

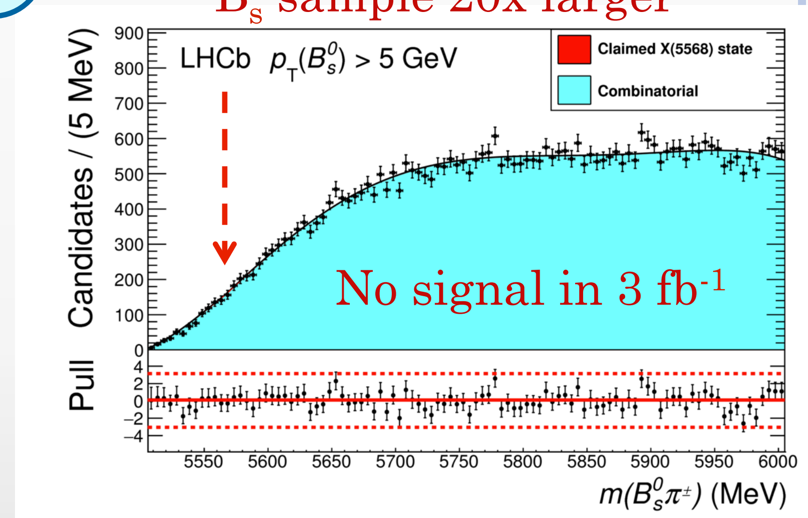
"Observed" by DØ (5.1 σ) with relative high production ($\rho_X^{D\O} = (8.6 \pm 1.9 \pm 1.4)$ %)

$$M = 5567.8 \pm 2.9^{+0.9}_{-1.9}\ \mathrm{MeV}/c^2 \quad < m(\Xi_b)$$
$$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5}\ \mathrm{MeV}/c^2$$



4 weeks later

B_s sample 20x larger



$$\rho_X^{LHCb}(B^0_s\ p_T > 5\ \mathrm{GeV}/c) < 0.011\ (0.012)\ @\ 90\ (95)\ \%\ \mathrm{CL}$$
$$\rho_X^{LHCb}(B^0_s\ p_T > 10\ \mathrm{GeV}/c) < 0.021\ (0.024)\ @\ 90\ (95)\ \%\ \mathrm{CL}$$
$$\rho_X^{LHCb}(B^0_s\ p_T > 15\ \mathrm{GeV}/c) < 0.018\ (0.020)\ @\ 90\ (95)\ \%\ \mathrm{CL}$$

ICHEP Update: No signal in CMS data but DØ showed a signal peaking in same mass region by using B_s semileptonic decays

Standard Spectroscopy: Prospect

RUN II, Upgrade & Beyond

Open-Flavour Mesons

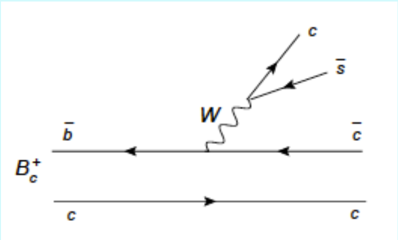
Charm

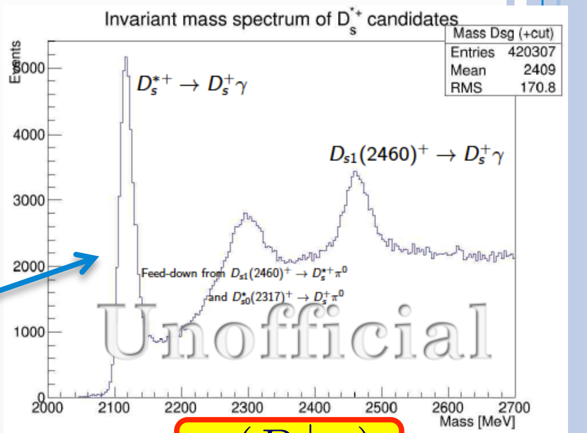
D_{s0}(2317) & D_{s1}(2460)*

- ✓ Determination of spin-parity of $D_{s0}^*(2317)$ by $B_s \rightarrow D_s^- \pi^0 \pi^+$
- ✓ $\mathcal{B}(D_{s0}^*(2317) \rightarrow D_s^- \pi^0) \sim 100\%$. Search for $D_s^* \gamma$ and $D_s e^+e^-$
- ✓ Production studies (e.g. $D_s \gamma$)

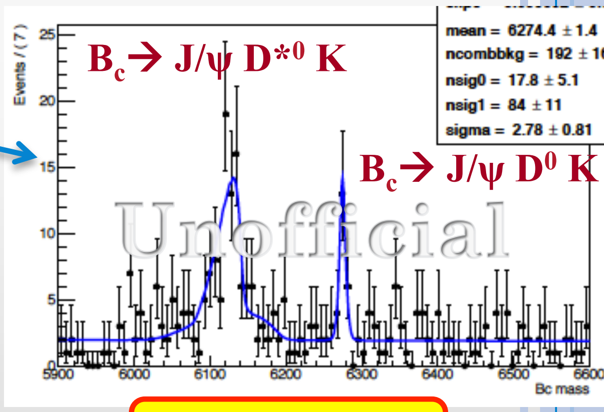
Other $D_{(s)J}$ states

- ✓ Spectroscopy from B_c decays





$m(D_s^+ \gamma)$



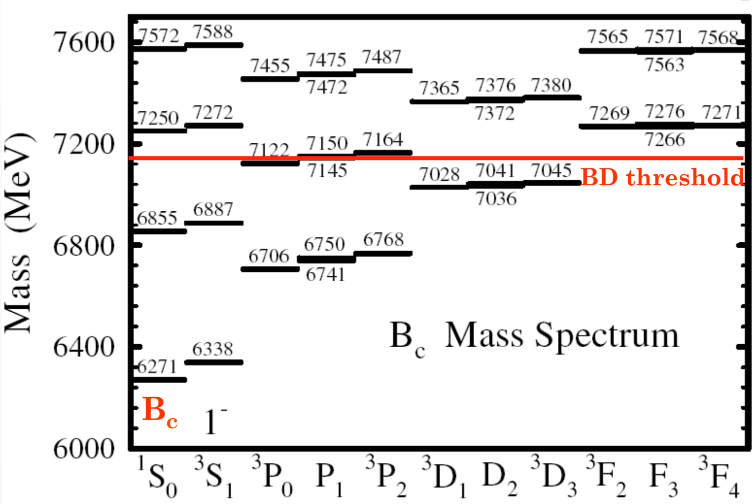
$m(J/\psi D^0 K^+)$

Beauty

Search for the missing B_{s0}^* and B_{s1}'

EXCITED B_c SPECTROSCOPY

- B_c is the only meson is SM formed by two different heavy flavour quarks
- Many excited states predicted below the BD threshold
- $B_c^{**} \rightarrow B_c + X$ where $X = \gamma, \pi^+\pi^-, \ldots$
- $B_c^{**} \rightarrow BD$ (RUN 5)



Phys.Rev.D70, 054017

Baryons Spectroscopy

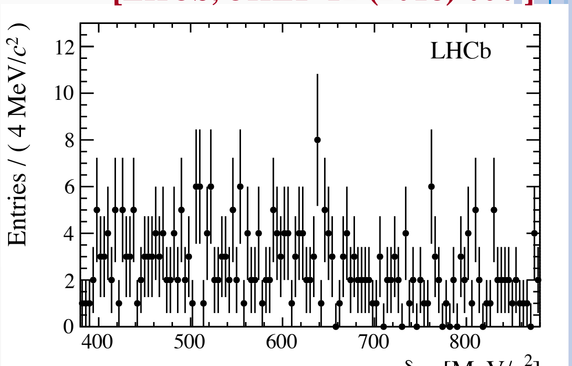
Doubly Heavy Baryons

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

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

- Likely the observation of Ξ_{cc} and Ξ_{bc} (RUN II/Upgrade) and Ω_{ccc}, Ω_{bc}, Ξ_{bb} (> Upgrade)

[LHCb, JHEP 12 (2013) 090]



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

Single Heavy Baryons

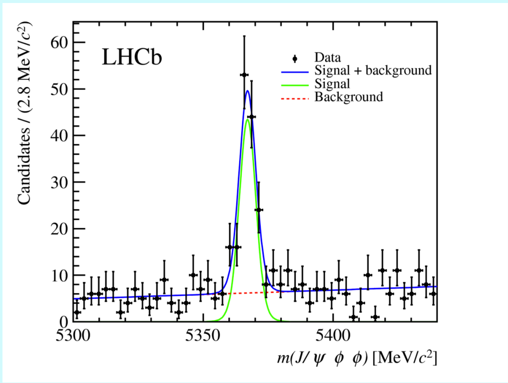
- Charmed spectroscopy boosted in RUN II due to dedicated trigger lines
- Observation of many more excited beauty states: Λ_b^{**}, Ξ_b^{**}, Ω_b^{**}

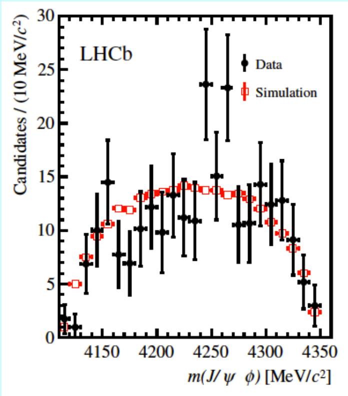
Exotic Spectroscopy: Prospect

RUN II, Upgrade & Beyond

Charmonia-like States

- Precise measurement of mass and width of X(3872)
- Search for new decays mode for X(3872): (e.g.) χ_{c1} π π, $\bar{p}p$
- Search for X(4140) & X(4274) → J/ψ ϕ in B_s → J/ψ ϕϕ decays





JHEP 03 (2016) 040

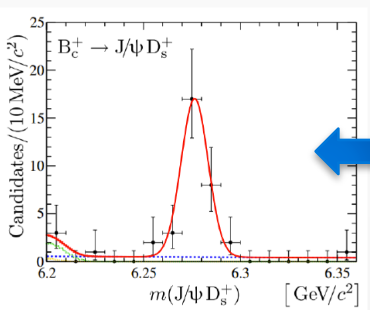
- Exploration of $D_{(s)}\bar{D}^{(*)}_{(s)}$ mass spectra from B decays & Central Exclusive Production

X_b

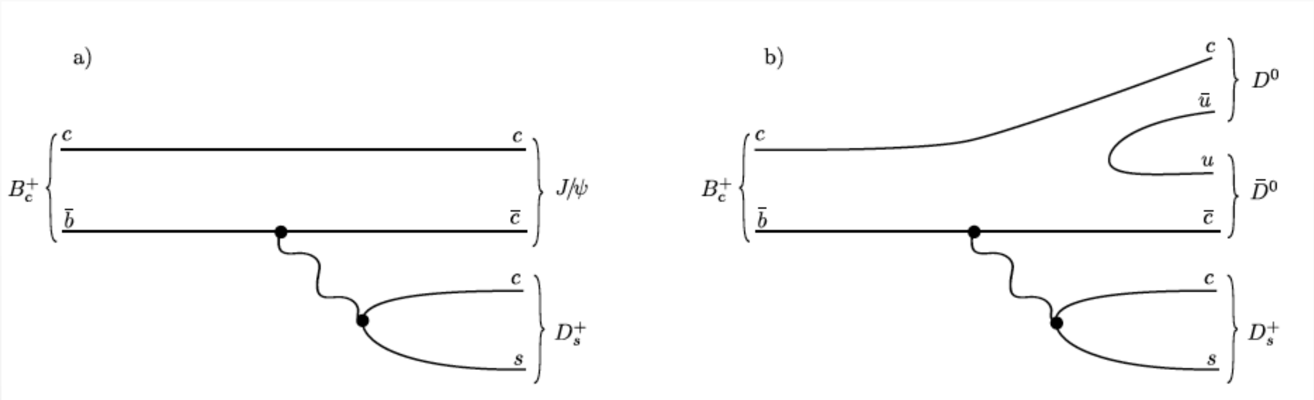
- Search for Y(1S) ω (→π π π^0, μμ)

Charged Tetraquark in B_c decays

- The B_c meson is the lightest state in the standard model that can decay to two same-flavour charmed hadrons.
- Search for tetraquark: $\mathcal{T}_s^+(cc\bar{u}\bar{s}) \to D^0 D_s^+$



N = 28.9 ± 5.6 (3 fb^{-1})

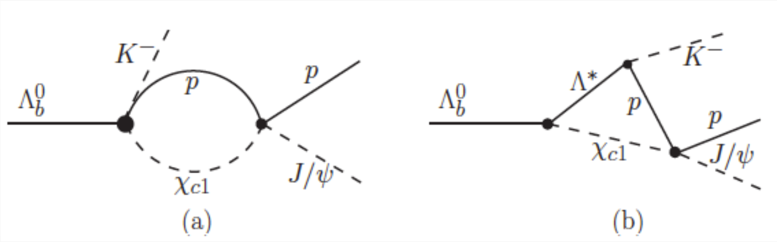


$$N(B_c^+ \to D^0 \bar{D}^0 D_s^+; \text{Run5}) \simeq 10^2 \text{ candidates}$$

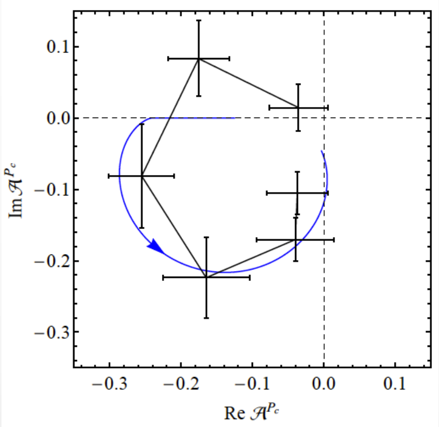
Clear signature. Expected to be background free

PENTAQUARK

- Are the observed P_c^+ states cusps?
- The observation of the χ_{c1} p decay mode would rule out such scenario



PRD 92 (2015) 7, 071502



- Search for the other members of the expected multiplet
- Search for pentaquarks with quark beauty

Summary

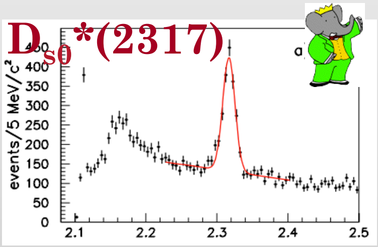
Standard Spectroscopy

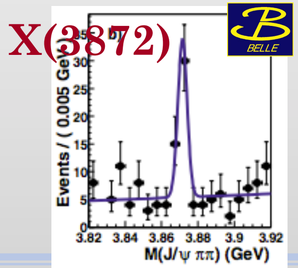
- Charmed broad states observed in prompt production and in B decays
- Charmed baryon spectroscopy will benefit on new trigger strategy
- Large potentiality in the beauty sector (meson and baryon)

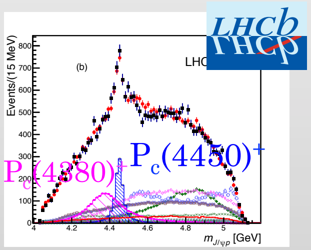
Exotic Spectroscopy

- Observation of two pentaquarks decaying to J/ψ p
- Confirmation/disprove of many exotic states
  - Precise measurements of resonance parameters
  - Determination of quantum numbers
- Robustness of the results enhanced by amplitude techniques which can probe the resonant character and the quantum numbers
  - Need inputs from theoretical community to improve the models

"There are things we don't know we don't know"







To be continued…

Back-up slides

Light 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