Exotic Spectroscopy at LHCb

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Beauty 2018,
May 6-11, La Biodola, Isola d'Elba

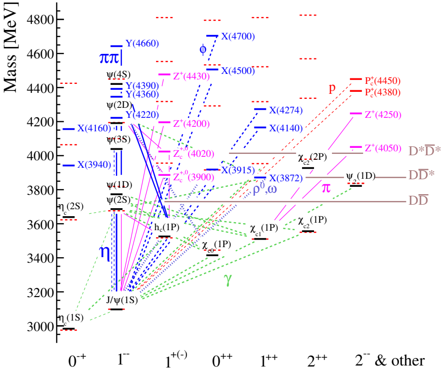
Outline

- introduction
- pentaquark studies
- search for weakly decaying *b*-flavoured pentaquarks
- search for dibaryon states
- future perspectives

All the presented analyses used the $3\,\mathrm{fb}^{-1}$ sample collected by LHCb in Run 1

Introduction

- hadrons beyond conventional mesons and baryons already predicted by the Constituent Quark Model in 1964
- they are allowed by QCD as long as they form color-singlet configurations
- no evidence for almost 40 years
- since 2003 about thirty hadrons not fitting with conventional heavy quarkonium states, well predicted by QCD-motivated potential models, have been observed



[Rev. Mod. Phys. 90 (2018) 015003]

Exotic Spectroscopy

- searches for exotic hadrons in the light-quarks spectroscopy sector are complicated by the presence of broad and overlapping states
- the discovery of states in the heavy quarkonium spectra having **mass, electrical charge and/or decay properties inconsistent with pure $c\bar{c}$ or $b\bar{b}$ states** could be identified with non-standard quarkonium like states
- lack of good understanding of the nature of these states implies that more theoretical and experimental work are required
- discovery of and searches for new exotic hadrons will improve our knowledge of the non-perturbative QCD regime and they will have an indirect impact on searches for New Physics
- the excellent performance of the LHC and of the LHCb detector allowed to obtain important results in the exotic spectroscopy sector
- **especially the discovery of two pentaquark candidates by LHCb triggered a lot of interest and new searches for exotic candidates**

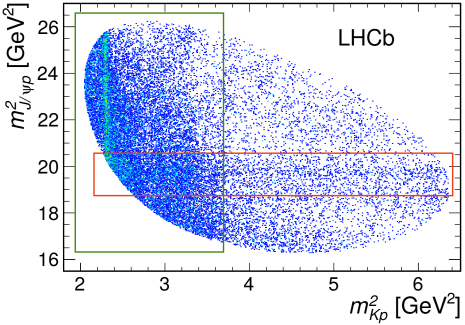
Pentaquark studies

$\Lambda_b^0 \to J/\psi p K^-$ decay channel

[PRL 115 (2015) 072001]

- decay mode with unexpected large yield ($\sim$ 26000 events) and low background rate (5.4% of combinatorial background within $\pm 2\sigma$ of the peak)

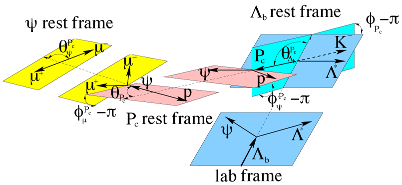
- the decay is expected to be dominated by $\Lambda^* \to pK^-$ interfering resonances
- unexpected and distinct horizontal band near $19.5\,\mathrm{GeV}^2$

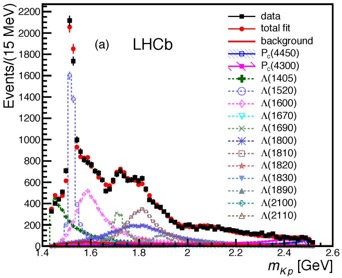


Reflections from Λ^* states or $\left|\mathbf{P_c^+}\right\rangle_\mathbf{f} = |\mathbf{uudc\bar{c}}\rangle$ resonance(s)?

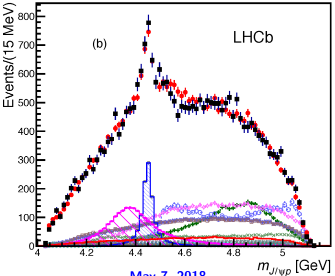
Amplitude fit

[PRL 115 (2015) 072001]





- helicity formalism to perform the full 6D amplitude fit to $m_{pK}, \theta_{\Lambda_b}, \theta_{\Lambda^*}, \phi_K, \theta_\psi, \phi_\mu$
- dynamical amplitudes given by relativistic Breit-Wigners plus the Flatté parameterization for the $\Lambda(1405)$
- well motivated Λ^* states and decay amplitudes allowed
- new $\Lambda_b^0 \to P_c^+ K^-$ decay sequence allowed to interfere with $\Lambda_b^0 \to J/\psi \Lambda^*$ chain



Properties of the pentaquarks

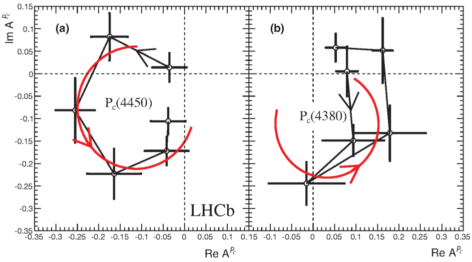
[PRL 115 (2015) 072001]

- two interfering P_c^+ states with **opposite parities** are necessary to obtain good fits

State	M_0 [MeV]	Γ_0 [MeV]	J^P
$P_c(4380)^+$ @ 9 σ	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$\frac{3}{2}^-$ $(\frac{3}{2}^+, \frac{5}{2}^+)$
$P_c(4450)^+$ @ 12 σ	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$\frac{5}{2}^+$ $(\frac{5}{2}^-, \frac{3}{2}^-)$

$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4380)K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (2.56 \pm 0.22 \pm 1.28^{+0.46}_{-0.36}) \times 10^{-5}$$
$$\mathcal{B}(\Lambda_b^0 \to P_c^+(4450)K^-)\mathcal{B}(P_c^+ \to J/\psi p) = (1.25 \pm 0.15 \pm 0.33^{+0.22}_{-0.18}) \times 10^{-5}$$

- **resonant character**:

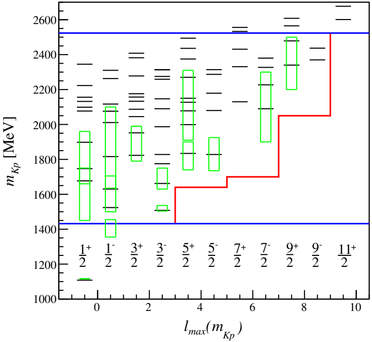


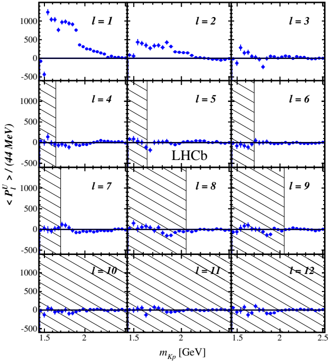
Model-independent approach

[PRL 117 (2016) 082002]

- large density of predicted Λ^* states, possible presence of nonresonant pK^- contributions or Σ excitations $\Rightarrow$ model-independent approach to assess the level of consistency of data with the $\Lambda_b^0 \to J/\psi\Lambda^*$ null hypothesis
- 2D method using the information contained in $(m_{pK}, \cos\theta_{\Lambda^*})$ with minimal assumptions on the spin and lineshape of pK^- contributions
- expand the $\cos\theta_{\Lambda^*}$ distribution in Legendre polynomials

$$\mathbf{L_{max}(m_{pK}) = 2J_{max}(m_{pK})}$$





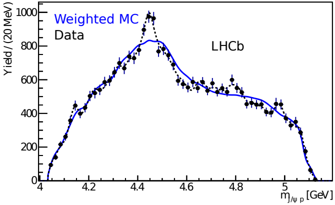
non zero values in the shaded areas means non-Λ^* activity

Results of the model-independent approach

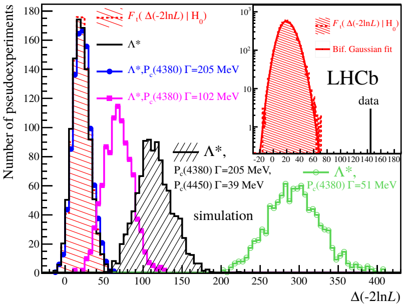
[PRL 117 (2016) 082002]

- generate events flat in $(m_{pK}, \cos\theta_{\Lambda^*})$, apply the 6D efficiency correction and weight them by the m_{pK} and Legendre moment distributions

- hypothesis test through likelihood ratio using pseudoexperiments (H_1: $L \leq 31$)



Λ^* reflections alone cannot describe the decay dynamics

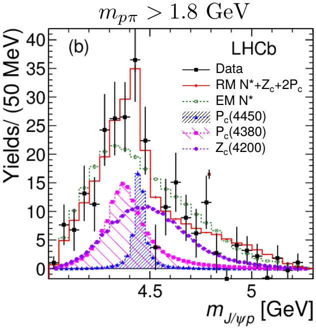


It demonstrates at more than 9σ that $\Lambda_b^0 \to J/\psi pK^-$ decays cannot be described by pK^- contributions alone

Confirmation through the $\Lambda_b^0 \to J/\psi p\pi^-$ decay channel

[PRL 117 (2016) 082003]

- exotic contributions (two P_c^+ or $Z_c(4200)^- \to J/\psi\pi^-$, or both) are required to obtain an acceptable fit in the $m_{p\pi} > 1.8\,\mathrm{GeV}$ region



- the significance for the model with 2 P_c^+ and no $Z_c(4200)^-$ is 3.3σ
- the significance for the model with 2 $P_c^+ + Z_c(4200)^-$ is 3.1σ

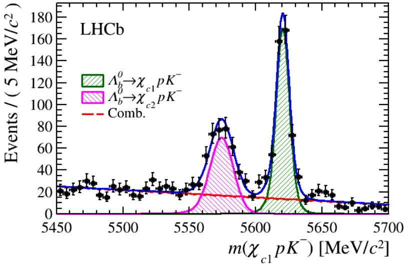
Observations of $\Lambda_b^0 \to \chi_{c(1,2)} pK^-$ decays

[PRL 119 (2017) 062001]

- test the hypothesis of $P_c(4450)^+$ as a kinematic effect of the rescattering from $\chi_{c1}p$ to $J/\psi p$ [PRD 92 (2015) 071502(R)]
- approach challenged by [PRD 94 (2016) 074039]: reduced strength of the $\chi_{c1}p$ threshold peak given the favoured J^P assignments for the $P_c(4450)^+$
- first observation and measurement of the branching ratios
- reconstruct $\chi_{cJ} \to J/\psi\gamma$
- waiting for more statistics to perform the amplitude analyses

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.242 \pm 0.014 \pm 0.013 \pm 0.009$$

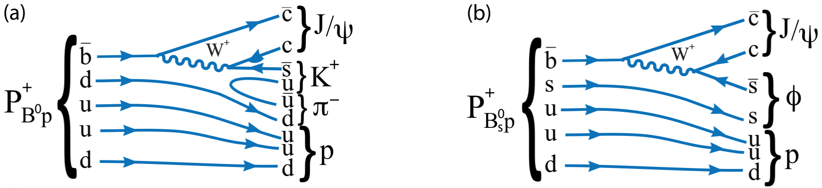
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.248 \pm 0.020 \pm 0.014 \pm 0.009$$



Search for weakly decaying b-flavoured pentaquarks

[PRD 97 (2018) 032010]

- Skyrme model has been used to predict that the heavier the constituent quarks, the more tightly bound the pentaquark state **[Phys. Lett. B 331 (1994) 362], [Phys. Lett. B 590 (2004) 185], [Phys. Lett. B 586 (2004) 337]**
- search for long-lived pentaquarks with a lifetime of the same order of other B-hadrons
- open-flavoured pentaquarks where the b quark decays via the weak interaction



Analysis strategy

[PRD 97 (2018) 032010]

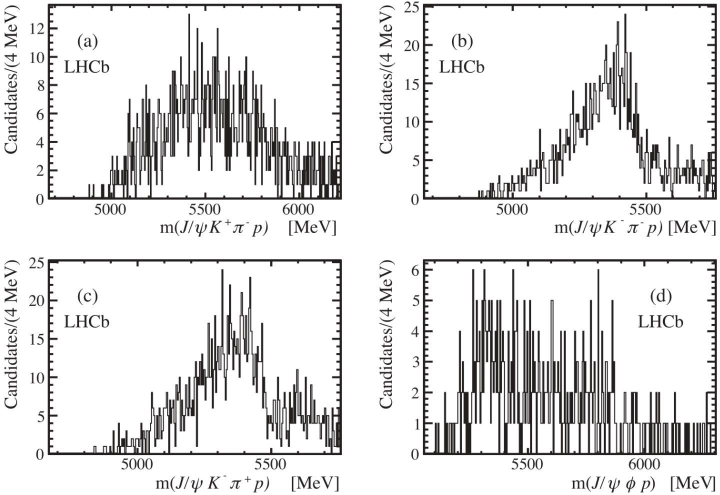
- focus on modes involving a J/ψ in the final state because of the relatively large efficiencies and reduced backgrounds in the LHCb experiment
- restrict the search to below the threshold mass for the corresponding strong decays
- measure the product of production cross section and branching ratio with respect to $\Lambda_b^0 \to J/\psi p K^-$ measured by the LHCb Collaboration **[Chin. Phys. C 40 (2016) 011001]**

Quark content	Decay mode	Search window [MeV]
$\bar{b}duud$	$P^+_{B^0 p} \to J/\psi K^+ \pi^- p$	4668-6220
$b\bar{u}udd$	$P^-_{\Lambda_b^0 \pi^-} \to J/\psi K^- \pi^- p$	4668-5760
$b\bar{d}uud$	$P^+_{\Lambda_b^0 \pi^+} \to J/\psi K^- \pi^+ p$	4668-5760
$\bar{b}suud$	$P^+_{B_s^0 p} \to J/\psi \phi p$	5055-6305

- states labelled with a subscript indicating the final states the pentaquark would predominantly decay into if it had sufficient mass to decay strongly in these states

Upper limits on weakly decaying pentaquarks

[PRD 97 (2018) 032010]



No evidence for signal

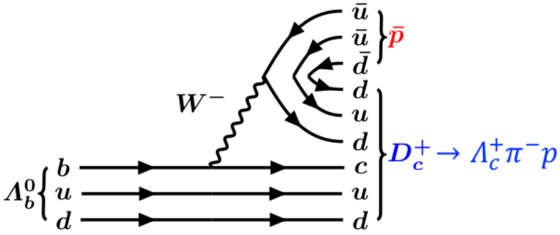
$$90\%\ \text{CL limits} < 10^{-2}\ -\ 10^{-3}\ \text{on}\ R = \frac{\sigma(pp \to P_b X)\mathcal{B}(P_b \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X)\mathcal{B}(\Lambda_b^0 \to J/\psi p K^-)}$$

Search for dibaryon states

Search for dibaryon states in $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$

[arXiv:1804.09617]

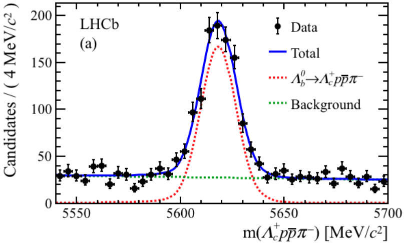
- if diquarks are good building blocks to assemble hadrons, the missing structures to discover are dibaryons [Phys. Lett. B 750 (2015) 37]
- the lightest charmed dibaryon $D_c^+ = [cd][ud][ud]$ with a mass below $4682\,\mathrm{MeV}$ could manifest via $\Lambda_b^0 \to \bar{p}D_c^+$ decays
- the D_c^+ could proceed either via string breaking to the $pP_c^0(\to \Lambda_c^+\pi^-)$ final state, where P_c^0 is a lighter yet undiscovered pentaquark state, or via quark rearrangement to the $p\Sigma_c^0(\to \Lambda_c^+\pi^-)$ final state



Observation of $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$ decays

[arXiv:1804.09617]

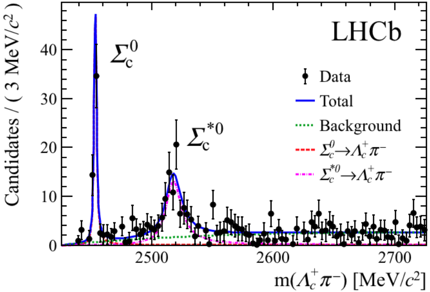
$N_{\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-} = 926 \pm 43$



$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-)} = 0.0540 \pm 0.0023 \pm 0.0032$$

Resonance structures in $\Lambda_c^+\pi^-$

$N_{\Lambda_b^0 \to \Sigma_c^0 p\bar{p}} = 59 \pm 10$, $N_{\Lambda_b^0 \to \Sigma_c^{*0} p\bar{p}} = 104 \pm 17$

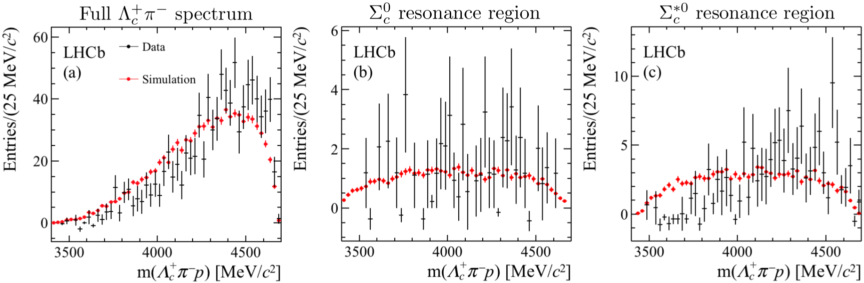


$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^0(\to \Lambda_c^+\pi^-)p\bar{p})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.089 \pm 0.015 \pm 0.006$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Sigma_c^{*0}(\to \Lambda_c^+\pi^-)p\bar{p})}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-)} = 0.119 \pm 0.020 \pm 0.014$$

Search for dibaryon resonances in $\Lambda_c^+\pi^-p$

[arXiv:1804.09617]



- background-subtracted data using the sPlot technique
- **no peak structures are observed**
- the two dimensional distribution of $m_{\Lambda_c^+\pi^-p}$ versus $m_{\Lambda_c^+\pi^-}$ does not exhibit any clear structure

Conclusions

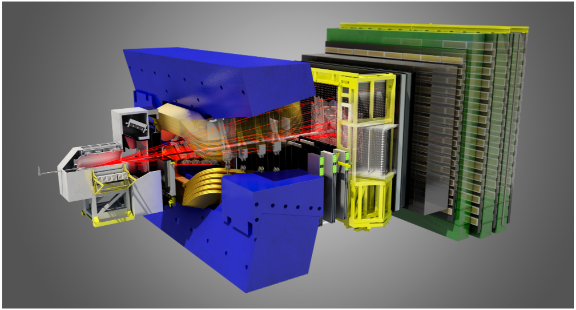
- a coherent picture concerning the nature and the binding mechanism of exotic hadrons is missing and it requires inputs from both the theoretical and experimental sides
- analyses involving both Run1 and Run2 data collected by the LHCb detector will provide a crucial role on the subject, with both eventual observations and non-observations of new exotic hadrons
- the upgraded LHCb will be able to cope with a five-fold increase in the instantaneous luminosity and with increased efficiencies in decay modes involving fully hadronic final states, opening exciting opportunities for the exotic spectroscopy sector (see Paula's talk on Friday)

Thanks and stay tuned for new results!

Extra slides

The LHCb experiment

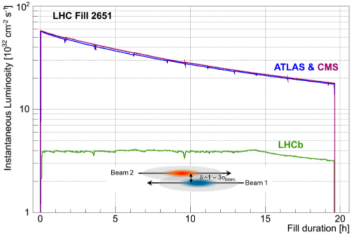
By design: study CP-violating processes and rare b- and c-hadrons decays



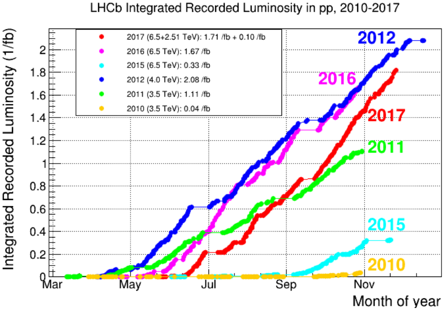
- single arm spectrometer, $2 < \eta < 5$: $\sim$ **25% of $b\bar{b}$ pairs inside the LHCb acceptance**
- **precise primary and secondary vertex reconstruction**: 20 $\mu\mathrm{m}$ for high-p_T tracks
- **excellent momentum resolution**: $\Delta p/p = 0.5\%$ at low momentum to 1.0 % at 200 GeV
- **very good particle identification (PID)** (separation of charged π, K and p and muon identification) over the $10 < p < 100\,\mathrm{GeV}$ range

The LHCb data taking and physics

- **Levelled luminosity**: ~ 1 interaction per bunch crossing
- $\mathcal{L} \sim 4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$



- Run1: $\sim 3\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\text{-}8\,\mathrm{TeV}$
- Run2: $\sim 3.5\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ ($\sigma_{b\bar{b}} \propto \sqrt{s} \Rightarrow$ 2x $b\bar{b}$ pairs with respect to Run1)



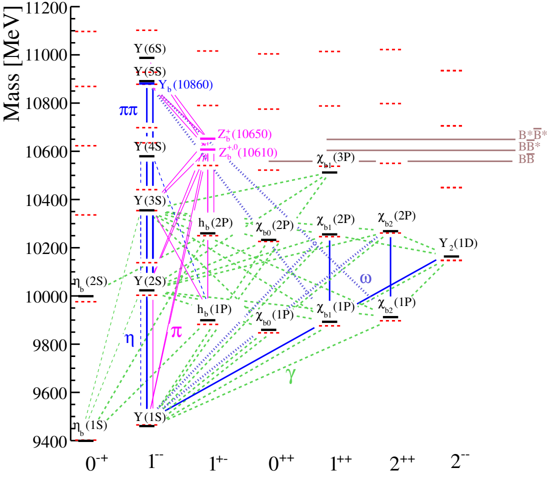
Excellent tracking and PID performance $\Rightarrow$ extended Physics programme

$\Rightarrow$ not only CP violation and rare decays measurements, but also LFU tests, exotic and conventional spectroscopy, production and polarization measurements, EW and QCD physics, dark photon searches, p-Pb and p-He physics, ...

Summary of main LHCb results on exotic states

- search for $X(5568)^- \to B_s^0\pi^-$ **[PRL 118 (2017) 109904]**
- observation of exotic hadrons in $B^+ \to J/\psi\phi K^+$
  [PRD 95 (2017) 012002], [PRL 118 (2017) 022003]
- evidence for exotic hadrons in $\Lambda_b^0 \to J/\psi p\pi^-$ **[PRL 117 (2016) 082003]**
- observation of pentaquarks in $\Lambda_b^0 \to J/\psi pK^-$
  - model independent analysis **[PRL 117 (2016) 082002]**
  - amplitude analysis and resonant character **[PRL 115 (2015) 072001]**
- $Z(4430)^-$ confirmation in $B^0 \to \psi(2S)K^+\pi^-$
  - model independent analysis **[PRD 92 (2015) 112009]**
  - amplitude analysis and resonant character **[PRL 112 (2014) 222002]**
- $X(3872)$ studies
  - quantum numbers measurement $\Rightarrow J^{PC} = 1^{++}$
    [PRD 92 (2015) 011102(R)], [PRL 110 (2013) 222001]
  - measurement of $\mathcal{B}(X(3872) \to \psi(2S)\gamma)/\mathcal{B}(X(3872) \to J/\psi\gamma))$
    [Nucl. Phys. B 886 (2014) 665-680]
  - mass measurement **[JHEP 06 (2013) 065]**
  - search for new decay modes **[EPJC (2013) 73:2462], [Phys. Lett. B 769 (2017) 305-313]**
  - direct production in pp collisions **[EPJC (2012) 72:1972]**

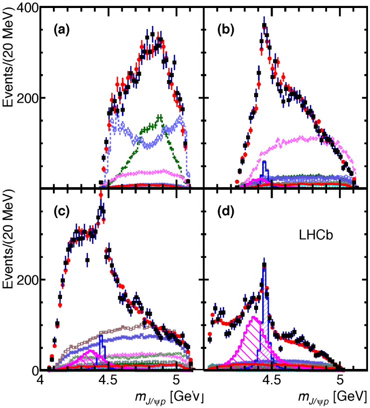
Bottomonium-like spectrum



[Rev. Mod. Phys. 90 (2018) 015003]

$\Lambda_b^0 \to J/\psi p K^-$ amplitude fit projections

[PRL 115 (2015) 072001]



- (a): $m_{pK} < 1.55\,\mathrm{GeV}$, (b): $1.55 < m_{pK} < 1.70\,\mathrm{GeV}$, (c): $1.70 < m_{pK} < 2.00\,\mathrm{GeV}$, (d): $m_{pK} > 2.00\,\mathrm{GeV}$
- negative interference between the P_c^+ states for high m_{pK} ($\Rightarrow \cos\theta_{P_c^+} < 0$)
- positive interference between the P_c^+ states for low m_{pK} ($\Rightarrow \cos\theta_{P_c^+} > 0$)
- consequence of the opposite parities

The model-independent approach in $\Lambda_b^0 \to J/\psi p K^-$ decays

[PRL 117 (2016) 082002]

- 2D method using the information contained in $(m_{pK}, \cos\theta_{\Lambda^*})$
- expand the $\cos\theta_{\Lambda^*}$ distribution in Legendre polynomials:

$$\frac{dN}{dcos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(cos\theta_{\Lambda^*}) \tag{1}$$

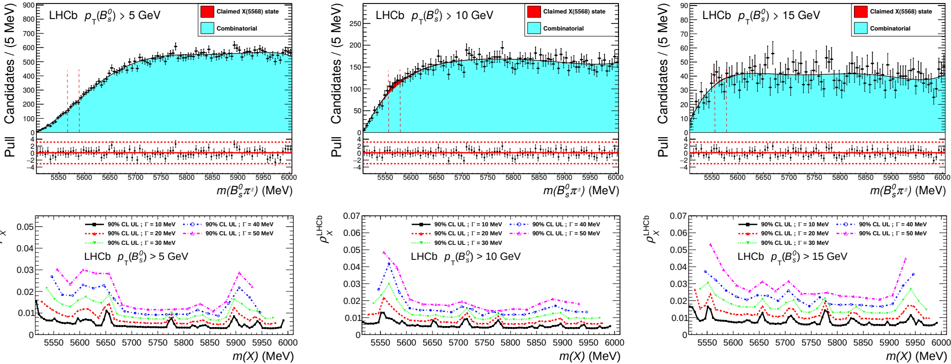
$$\langle P_l^U \rangle^k = \sum_{i=1}^{N^k} \frac{w_i}{\epsilon_i} P_l(cos\theta_{\Lambda^*}^i) \tag{2}$$

- under the H_0 hypothesis, pK^- components can contribute to moments of rank up to $l_{\rm max} = 2J_{\rm max}$, where $J_{\rm max}$ is the highest spin of any pK^- contribution at the given m_{pK} value

Search for structure in the $B_s^0\pi^-$ spectrum

[PRL 117 (2016) 152003]

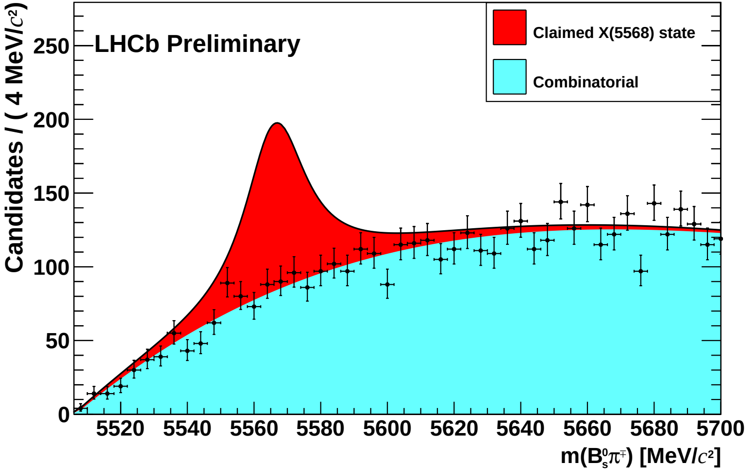
greater cut on $p_T(B_s^0) \Rightarrow X(5568)^-$ produced in a harder process



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

How the X(5568) would appear if $\rho^{\mathrm{LHCb}} = \rho^{\mathrm{D0}}$?

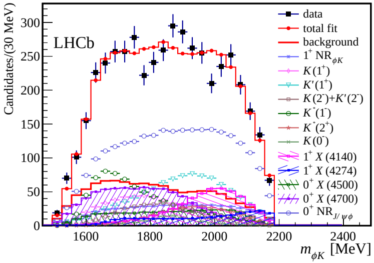
[PRL 117 (2016) 152003]

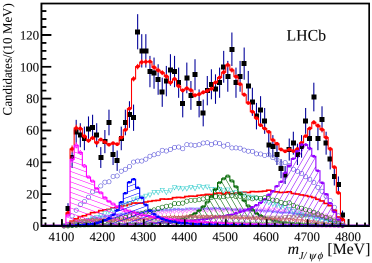


Observation of exotic hadrons in $B^+ \to J/\psi\phi K^+$

[PRD 95 (2017) 012002], [PRL 118 (2017) 022003]

- added $B^+ \to XK^+$ and $B^+ \to Z^+\phi$ decay chains
- only $B^+ \to XK^+$ provides significant improvements in the description of data
- **7 K^* + 4 X + ϕK^+ + $J/\psi\phi$ nonresonant components**



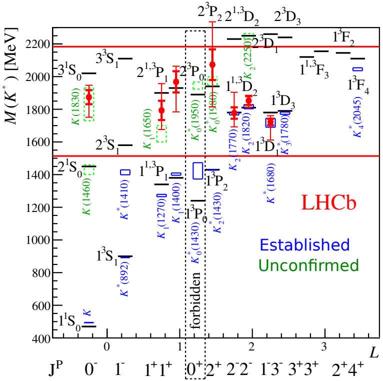


successful description of $m_{J/\psi\phi}$ spectrum: p-value = 22%

Observation of exotic hadrons in $B^+ \to J/\psi\phi K^+$

[PRD 95 (2017) 012002], [PRL 118 (2017) 022003]

State	M_0 [MeV]	Γ_0 [MeV]	J^{PC}
$X(4140)$ @ 8.4 σ	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{21}_{-14}$	1^{++} @ 5.7 σ
$X(4274)$ @ 6.0 σ	$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{8.4}_{-11.1}$	1^{++} @ 5.8 σ
$X(4500)$ @ 6.1 σ	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{21}_{-20}$	0^{++} @ 4.0 σ
$X(4700)$ @ 5.6 σ	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{42}_{-33}$	0^{++} @ 4.5 σ



- excellent agreement of $X(4140)$ mass with previous observations, but width is much larger $M_{CDF} = 4143.4 \pm 3.0 \pm 0.6\,\mathrm{MeV}$, $\Gamma_{CDF} = 15.3^{+10.4}_{-6.1} \pm 2.5\,\mathrm{MeV}$
- confirmation of $X(4274)$ state, first observation of two 0^{++} states
- K^{*+} spectroscopy: excellent agreement with theory and previous experiments