Exotic charm hadrons at LHCb

Anton Poluektov

University of Warwick, UK

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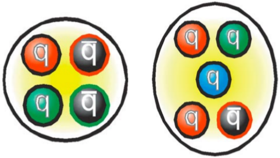
On behalf of LHCb collaboration

Exotic states and interpretations

Exotic hadrons: hadrons with quark content other than well-established $q\overline{q}$ (mesons) and qqq (baryon) states.

- Tightly-bound **multiquark states**:
  - $qq\overline{q}\overline{q}$: tetraquarks
  - $qqqq\overline{q}$: pentaquarks

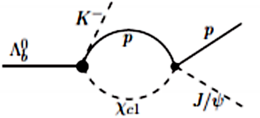


- Loosely-bound **molecules** (meson-meson, meson-baryon, baryon-baryon)

Strong evidence from many analyses for the existence of such states.

However, kinematical effects in rescattering can lead to structures that can resemble resonances

- **Cusps**: rescattering without binding.



Outline

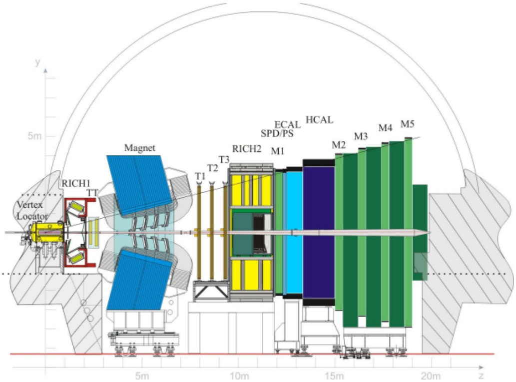
LHCb analyses related to exotic charm hadron spectroscopy:

- Measurements of $X(3872)$
- $Z(4430)$ in $B^0 \to \psi(2S)K^+\pi^-$
- Exotic states in $B^+ \to J/\psi\,\phi K^+$
- Pentaquark states in $\Lambda_b^0 \to J/\psi\,pK^-$
- Exotic states in $\Lambda_b^0 \to J/\psi\,p\pi^-$
- D^0p states in $\Lambda_b^0 \to D^0p\pi^-$
- Excited Ω_c states
- Searches for other exotic contributions

Other related talks at this conference:

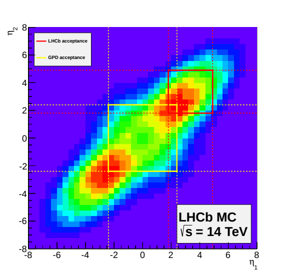
- Prospects with upgraded LHCb [Tomasz Skwarnicki]
- Conventional spectroscopy [Patrick Spradlin]
- Doubly-charmed hadrons [Daniel Vieira]
- Amplitude analysis techniques [Tim Evans]

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Rapidity coverage

$2 < \eta < 5$



- Covers forward region (maximum of *c* and *b* production)

LHCb

[JINST 3 (2008) S08005]

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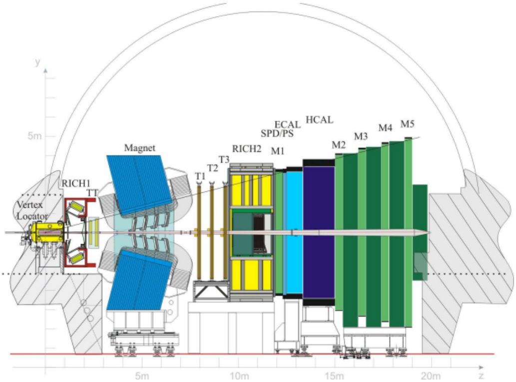
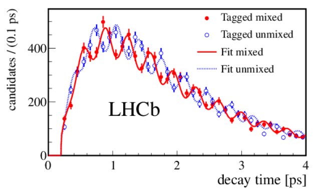


Vertexing

B_s^0 oscillations with $B_s^0 \to D_s\pi$



[New J. Phys. 15 (2013) 053021]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background

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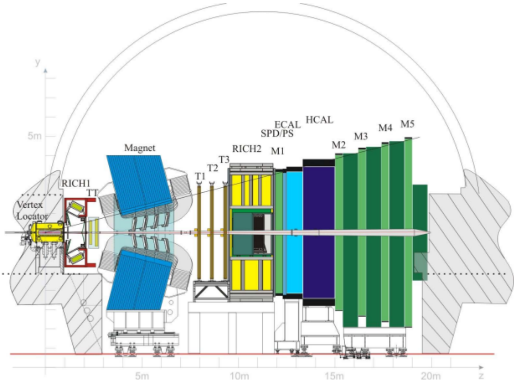
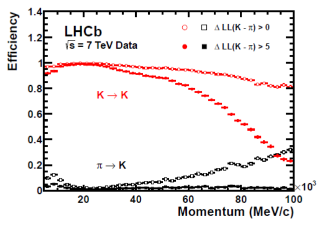


PID

K/π ID efficiency and misID rate



[EPJ C73 (2013) 2431]

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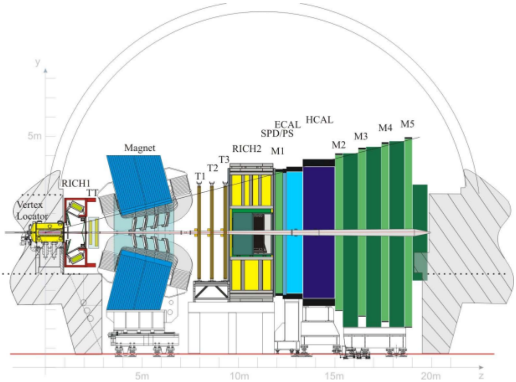
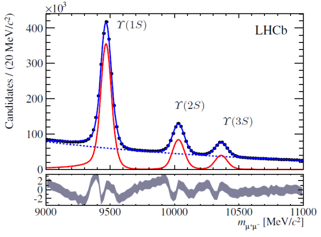


Tracking

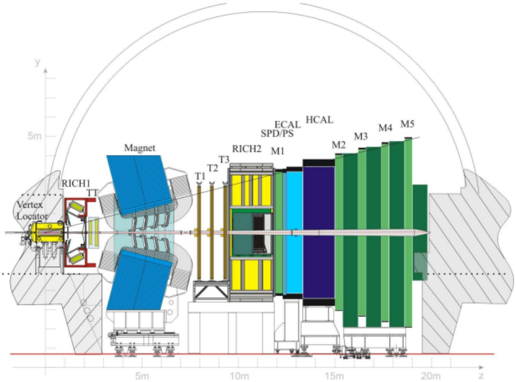
$\mu^+\mu^-$ mass spectrum



[PRL 111 (2013) 101805]

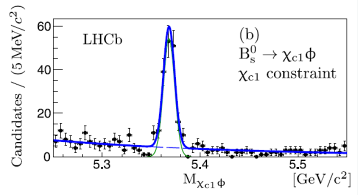
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking

One-arm spectrometer optimised for studies of beauty and charm decays at LHC



Calorimetry

$B_s^0 \to \chi_{c1}\phi$, $\chi_{c1} \to J/\psi\gamma$



[Nucl. Phys. B874 (2013) 663]

- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
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- Calorimetry: reconstruct neutrals (π^0, γ) in the final state

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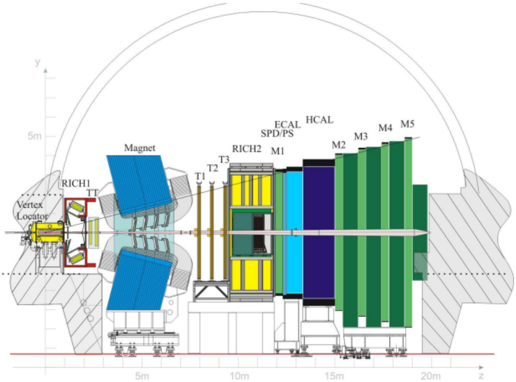

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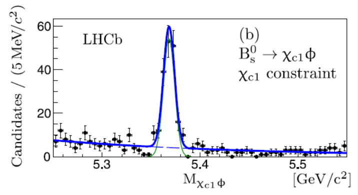

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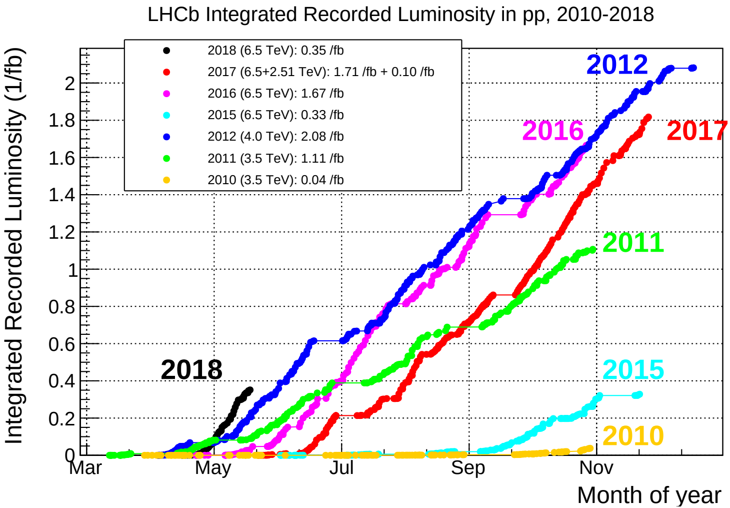
- Covers forward region (maximum of c and b production)
- Good vertexing: measure B^0 and B_s^0 oscillations, reject prompt background
- Particle identification: flavour tagging, misID background
- High-resolution tracking
- Calorimetry: reconstruct neutrals (π^0, γ) in the final state
- Efficient trigger, including fully hadronic modes

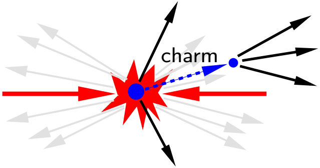


$3\,\mathrm{fb}^{-1}$ in 2011 and 2012 (Run 1, $\sqrt{s} = 7, 8\,\mathrm{TeV}$): All results in this talk

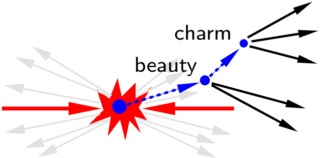
$4\,\mathrm{fb}^{-1}$ in 2015–2018 so far (Run 2, $\sqrt{s} = 13\,\mathrm{TeV}$, higher b cross section)

Conventional and exotic charm states are studied at LHCb in two production regimes:

- **Prompt production** in *pp* collisions
  - High statistics
  - High combinatorial background



- **Weak decays** of beauty hadrons (fully or partially reconstructed)
  - Low background
  - Well-defined initial state, determination of quantum numbers
  - Kinematic constraints



Properties of exotic states which can be determined and tested against theory models

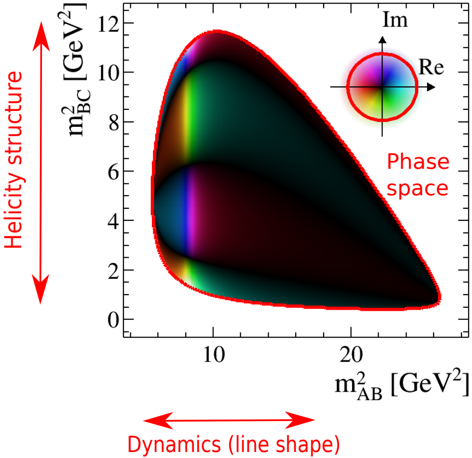
- Mass and width
- Production and decay channels, branching ratios
- Quantum numbers: spin, parity
- Line shape

Amplitude analyses

Many of LHCb exotic measurements use amplitude analysis technique.

Perform fits of the amplitude as a function of phase space variables

- Three-body decays $D \to ABC$: two kinematic variables M^2_{AB}, M^2_{BC} (Dalitz plot)
- Add angular variables if initial/final state not scalar



- Both lineshape parameters and spin can be extracted.
- Complex phases of components can be accessed though interference with other structures.

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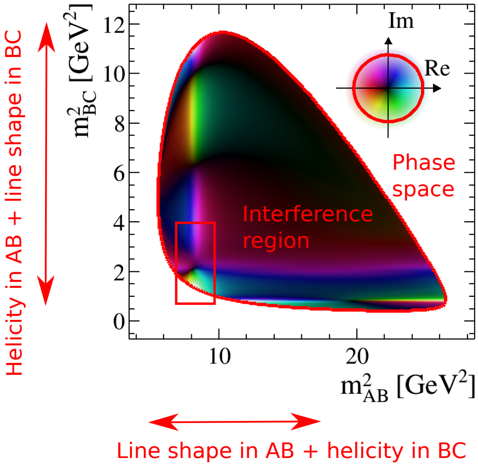

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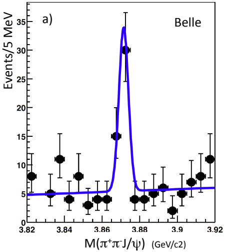
First manifestly exotic candidate: $X(3872)$

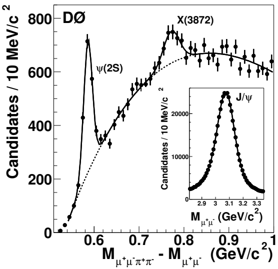
Discovered by Belle in 2003 [PRL 91 262001 (2003)]

- $B^+ \to X(3972)K^+$, $X(3872) \to J/\psi\,\pi^+\pi^-$
- Mass close to $D^0\overline{D}^{*0}$ [PRD 91 (2015), 011102]
  $m(D^0\overline{D}^{*0}) - m(X(3872)) = 3 \pm 192\,\mathrm{keV}$ (sic!)
- Small width ($\Gamma < 1.2\,\mathrm{MeV}$)

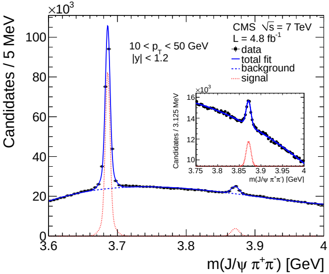


Hadron machines are also active in studies of $X(3872)$ production

D0, [PRL 93:162002,2004]



CMS, $7\,\mathrm{TeV}$ [JHEP 04 (2013) 154]

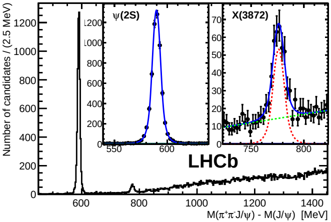


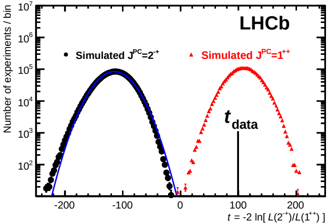
Observation of prompt $X(3872)$ in pp collisions and mass measurement:

$M(X(3872)) = 3871.95 \pm 0.48 \pm 0.12\,\mathrm{MeV}$ with $35\,\mathrm{pb}^{-1}$ [EPJC 72 (2012) 1972]

Quantum numbers: $J^{PC} = 1^{++}$ ($> 8\sigma$ over 2^{-+}) [PRL 110, 222001 (2013)]

$1\,\mathrm{fb}^{-1}$





D-wave decay could invalidate 1^{++}, constrained $< 4\%$ [PRD 92 (2015) 011102]

Branching ratio to $c\bar{c}\gamma$: [Nucl.Phys. B886 (2014) 665-680]

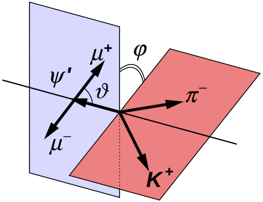
$$R_{\psi\gamma} = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.46 \pm 0.64 \pm 0.29$$

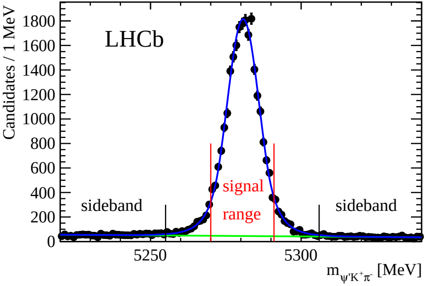
Rules out purely molecular interpretation ($R_{\psi\gamma} \ll 1$)

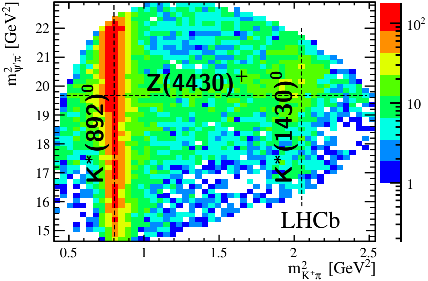
Charged exotic state: $Z(4430)$

[PRL 112, 222002 (2014)]

- Decay $B^0 \to \psi(2S)K^+\pi^-$
- Signal yield: 25k events
- Combinatorial background: $\sim 4\%$
- 4D amplitude analysis: $(m^2(K\pi), m^2(\psi(2S)\pi), \theta_{\psi'}, \phi_{\psi'})$

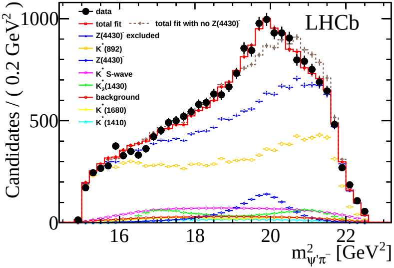






Structure in $\psi(2S)\pi^-$ spectrum

[PRL 112, 222002 (2014)]

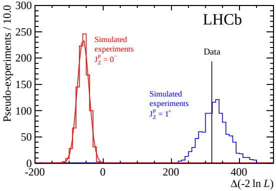


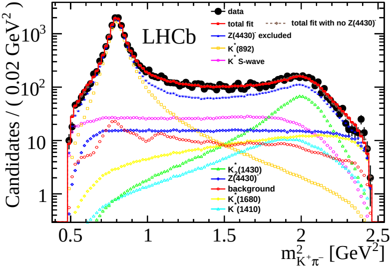
Model-dependent fit prefers resonance-like state with $J^P = 1^+$

$\mathcal{F}(Z(4430)^+) = (5.9 \pm 0.9^{+1.5}_{-3.3}(syst))\%$

Quantum numbers (wrt. favoured $J^P = 1^+$)

J^P	LHCb	Belle
0^-	9.7	3.4
1^-	15.8	3.7
2^+	16.1	5.1
2^-	14.6	4.7



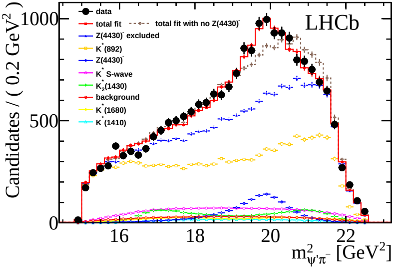


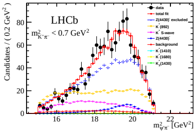
Parameters

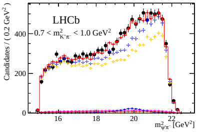
	LHCb	Belle
Mass, MeV	$4475 \pm 7^{+15}_{-25}$	$4485 \pm 22^{+28}_{-11}$
Width, MeV	$172 \pm 13^{+27}_{-34}$	$200^{+41}_{-46}{}^{+26}_{-35}$

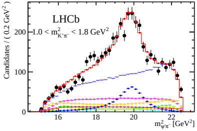
$Z(4430)$ in $B \to \psi(2S)K^+\pi^-$

[PRL 112, 222002 (2014)]









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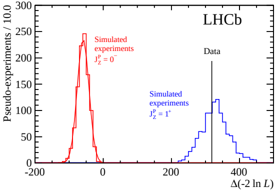

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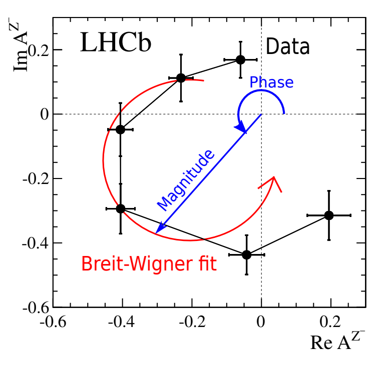
$Z(4430)$: model-independent confirmation

Model-independent test of phase rotation

[PRL 112, 222002 (2014)]



K^* states provide reference amplitude for phase motion measurement.

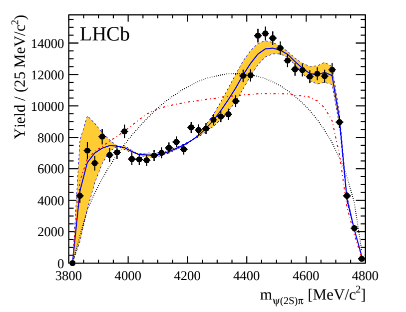
Clockwise rotation: characteristic of a resonant behaviour.

Confirmation of $\psi'\pi^-$ structures

[PRD 92 (2015) 112009]

Check that $K^-\pi^+$ amplitude *only* fails to describe the decay.

$K^-\pi^+$ should contribute to reasonably low moments, while exotic $\psi'\pi^-$ contributes to *all* moments.



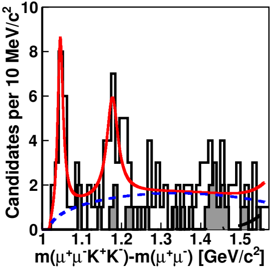
Resonances with spin up to 3 cannot reproduce the features seen in data.

$X(4140)$ and $J/\psi\,\phi$ family

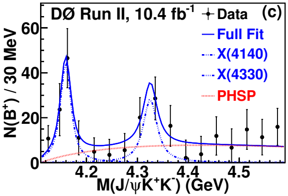
Exotic states in $B^+ \to J/\psi\,\phi K^+$

Peaks in $J/\psi\,\phi$ around 4140 and 4274 MeV are found by CDF and confirmed by D0 and CMS

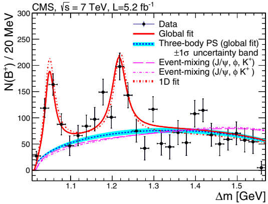
[CDF, PRL 102, 242002 (2009)]



[D0, PRD 89, 012004 (2014)]

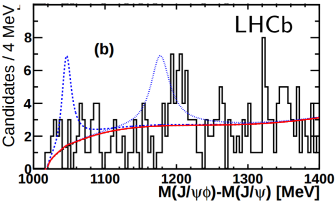


[CMS, PLB 734 (2014) 261]



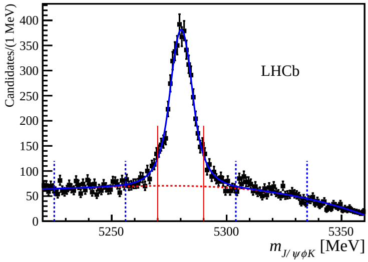
Belle [PRL 104:112004 (2010)]:
no $X(4140)$, but $X(4350)$ in $\gamma\gamma \to J/\psi\,\phi$

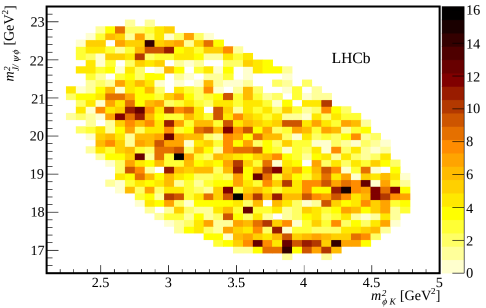
no evidence from:
BaBar [PRD 91, 012003 (2015)],
LHCb ($0.37\,\mathrm{fb}^{-1}$) [PRD 85, 091103(R) (2012)]



Exotic states in $B^+ \to J/\psi\,\phi K^+$

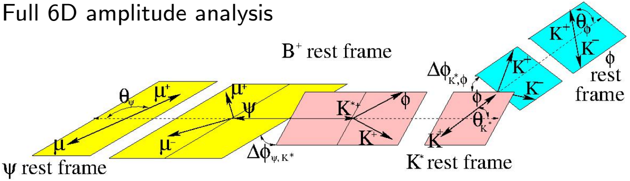
[PRL 118 (2017) 022003], [PRD 95 (2017) 012002]



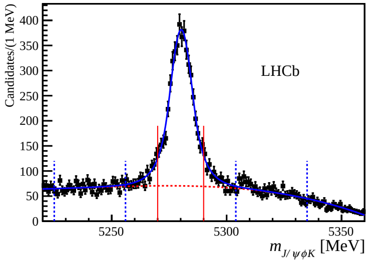


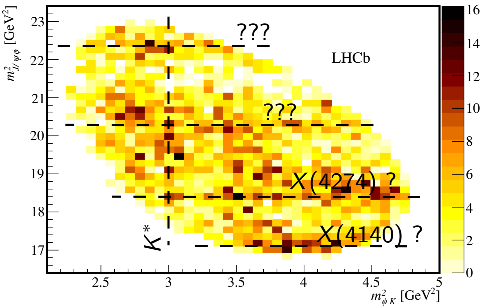
Signal yield: 4289 ± 151 events
Background: $\sim 20\%$

Full 6D amplitude analysis



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





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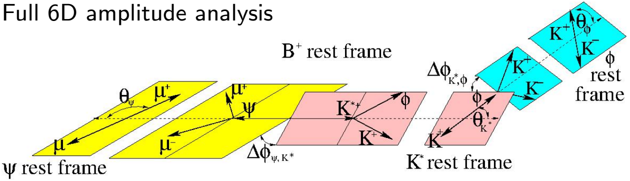

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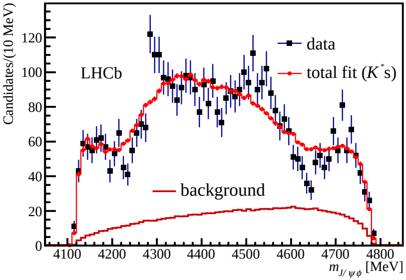
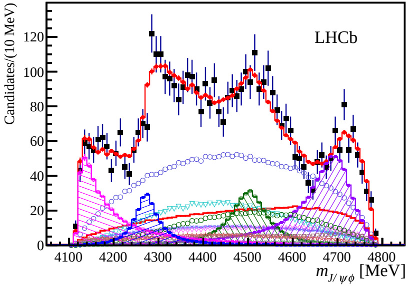


K^* states only



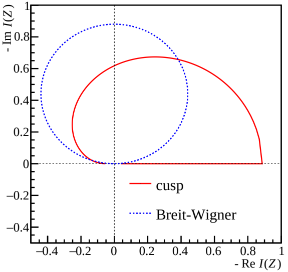
K^* plus 4(!) exotic states in $J/\psi\,\phi$

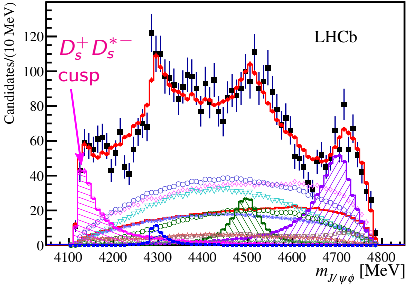
Contribution	J^{PC}	Significance	M_0 [MeV]	Γ_0 [MeV]	FF %
$X(4140)$	1^{++}	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.8}_{-2.0}$
$X(4274)$	1^{++}	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-\ 3.6}$	$56\pm11\,^{+\ 8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
$X(4500)$	0^{++}	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	0^{++}	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm\ 5\,^{+\ 9}_{-\ 5}$

Masses for $X(4140)$ and $X(4274)$ are consistent with previous measurements, but widths significantly larger.

Exotic states in $B^+ \to J/\psi \phi K^+$

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





$J^P = 1^+$ assignment rules out interpretation of $X(4140)$ as a $D_s^{*+} D_s^{*-}$ molecule.

$X(4140)$ could be a $D_s^+ D_s^{*-}$ state, below threshold $\Rightarrow$ line shape differs from a Breit-Wigner ("cusp").

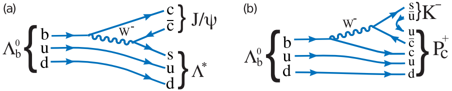
Check one particular "cusp" model by [E.S.Swanson, Phys. Rev. D91 034009, 2015]
Preferred by 3σ over Breit-Wigner fit. Should be able to distinguish BW and "cusp" with larger statistics.

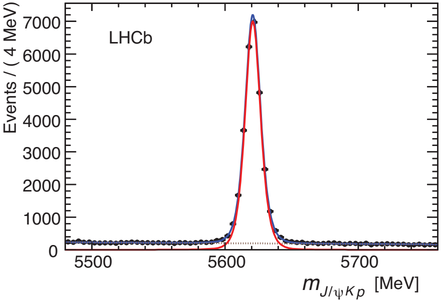
Pentaquarks: $P_c(4380)$ and $P_c(4450)$

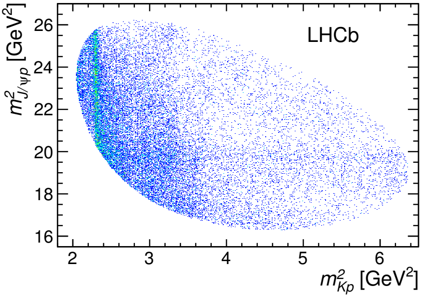
$\Lambda_b^0 \to J/\psi\, pK^-$ decay

[PRL 115 (2015) 072001]

Conventional contributions only in pK^- spectrum (Λ^* states).







Event yield: 26007 ± 166 events
Low background (5.4%)

Dalitz distribution shows an unexpected narrow feature in $J/\psi\, p$ mass.

Not an experimental effect (veto $B \to J/\psi\, Kh$, check part-rec Ξ_b decays, clones and ghosts...)

$\Lambda_b^0 \to J/\psi\, pK^-$ decay

[PRL 115 (2015) 072001]

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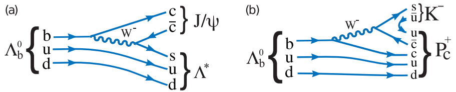

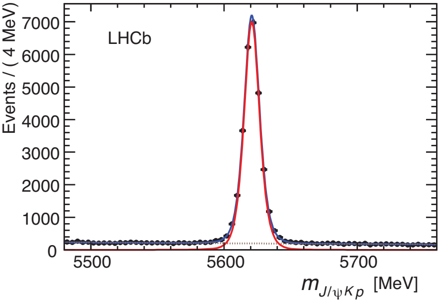

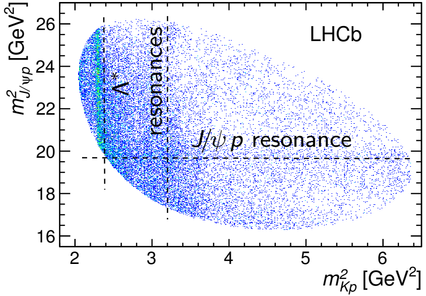

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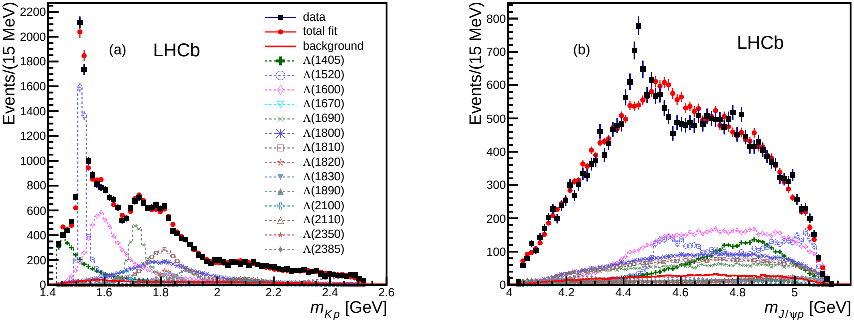
PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi\, pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$

Two models for Λ^* system (both isobar based on Breit-Wigners):

- "Extended": 14 Λ^* states ("**" and higher).
- "Reduced": 12 states, exclude two higher mass (2350, 2585), fewer LS-couplings.



Admixture of all known Λ^* states does not reproduce the peak observed at $m_{J/\psi\, p} = 4450\,\mathrm{MeV}$.

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi\, pK^-$ decay to understand its dynamics.

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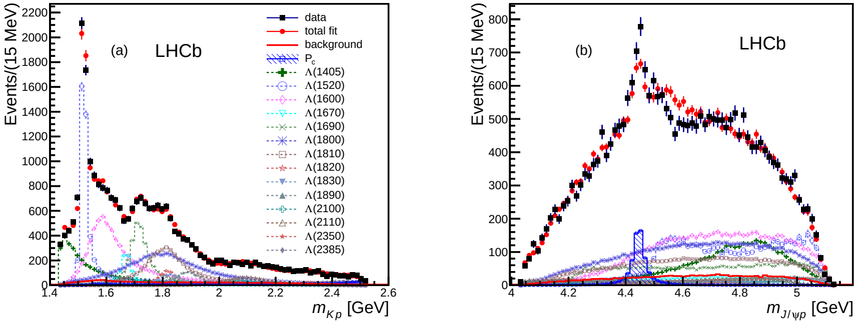

Inclusion of the exotic $J/\psi\, p$ state improves the fit, best $J^P = 5/2^\pm$

PRL 115, 072001 (2015),

Full amplitude analysis of the $\Lambda_b^0 \to J/\psi pK^-$ decay to understand its dynamics.

Fit in 6D phase space: $(M_{Kp}, \theta_{\Lambda_b^0}, \theta_\mu, \phi_\mu, \theta_K, \phi_K)$

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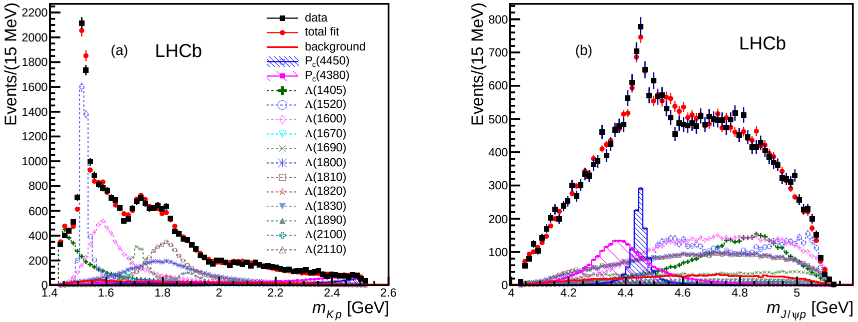
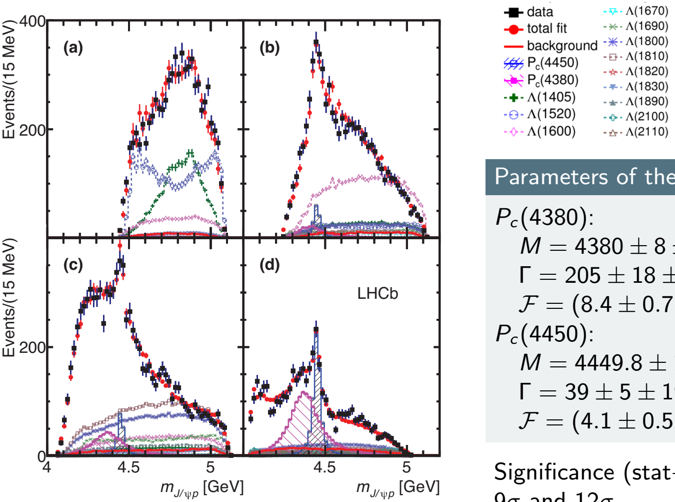


Two $J/\psi\, p$ states give the best fit, $J = 3/2$ and $5/2$ with opposite parities

Pentaquark states in $\Lambda_b^0 \to J/\psi\, pK^-$

PRL 115, 072001 (2015),



Parameters of the pentaquark states

$P_c(4380)$:

$M = 4380 \pm 8 \pm 29\,\mathrm{MeV}$,

$\Gamma = 205 \pm 18 \pm 86\,\mathrm{MeV}$

$\mathcal{F} = (8.4 \pm 0.7 \pm 4.2(\mathrm{syst}))\%$

$P_c(4450)$:

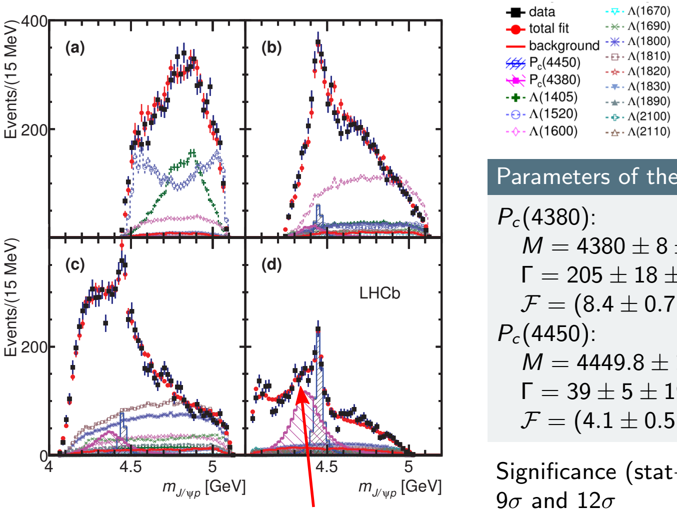
$M = 4449.8 \pm 1.7 \pm 2.5\,\mathrm{MeV}$

$\Gamma = 39 \pm 5 \pm 19\,\mathrm{MeV}$

$\mathcal{F} = (4.1 \pm 0.5 \pm 1.1(\mathrm{syst}))\%$

Significance (stat+syst) is overwhelming: 9σ and 12σ

PRL 115, 072001 (2015),



Apparent need for 2nd, wide, $J/\psi\, p$ state

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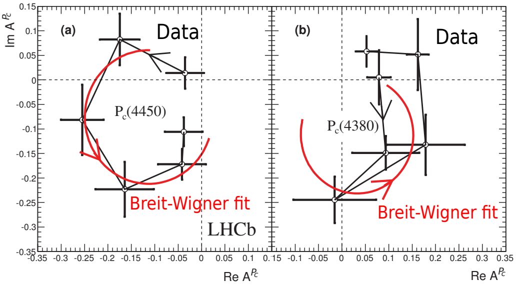
PRL 115, 072001 (2015),

Argand plots: model-independent confirmation of the resonant character of the exotic states.

Interference with Λ^* states allows to extract the phase in bins of $m_{J/\psi\, p}$.



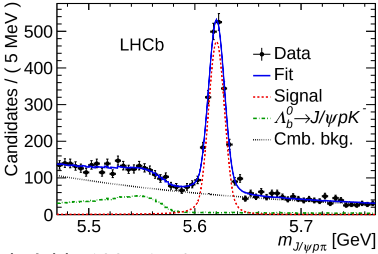
Clear phase rotation for $P_c(4450)$, direction consistent with Breit-Wigner amplitude
Not conclusive for $P_c(4380)$, need more statistics.

[PRL 117 (2016) 082002]

Model-independent PWA analysis (similar to $Z(4430)$): Λ^* resonances *only* cannot describe the data; 10σ significance of exotic contribution.

Exotic contributions in $\Lambda_b^0 \to J/\psi\, p\pi^-$

[PRL 117 (2016) 082003]

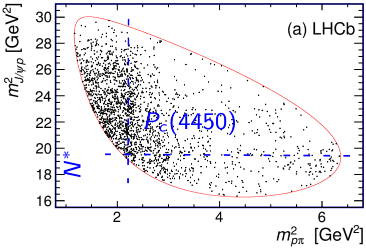


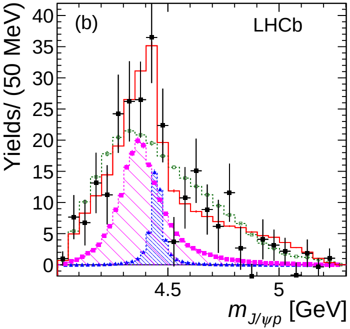
Signal yield: 1885 ± 50 events
Background: $\sim 20\%$

N^* states in $p\pi^-$

Possible exotic contributions:

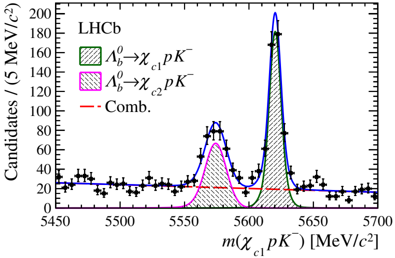
- $P_c(4380, 4450)$ in $J/\psi\, p$
- Z_c in $J/\psi\, \pi^-$ [Belle, PRD 90, 112009 (2014)]
  $M = 4196^{+31+17}_{-29-13}$ MeV
  $\Gamma = 370 \pm 70^{+70}_{-132}$ MeV
- Total significance of exotic contributions: 3.1σ.





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

[PRL 119 (2017) 062001]



Test exotic nature of $P(4450)$

- Mass close to $\chi_{c1}p$ threshold, could be a rescattering effect
- If a kinematic effect, should be absent in $\Lambda_b^0 \to \chi_{c(1)} pK^-$ [PRD 92, 071502 (2015)]

First step :observation of $\Lambda_b^0 \to \chi_{c(1)} pK^-$

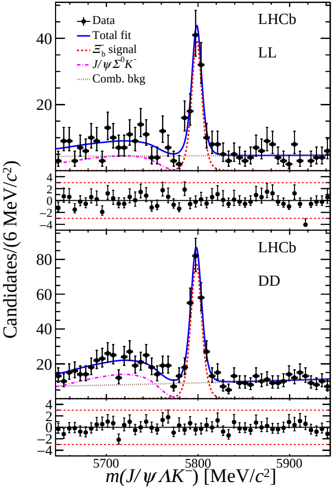
$m(J/\psi\gamma)$ constrained to equal $m(\chi_{c1}) \Rightarrow \Lambda_b^0 \to \chi_{c2} pK^-$ peak is displaced

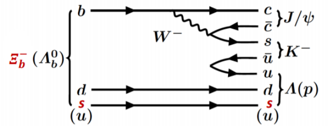
$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c1} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.242 \pm 0.014 \pm 0.013(syst) \pm 0.009(Br), \quad 453 \pm 25 \text{ events}$$

$$\frac{\mathcal{B}(\Lambda_b^0 \to \chi_{c2} pK^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi pK^-)} = 0.248 \pm 0.020 \pm 0.014(syst) \pm 0.009(Br), \quad 285 \pm 23 \text{ events}$$

Next step: amplitude analysis adding Run 2 data

[PLB 772 (2017) 265]



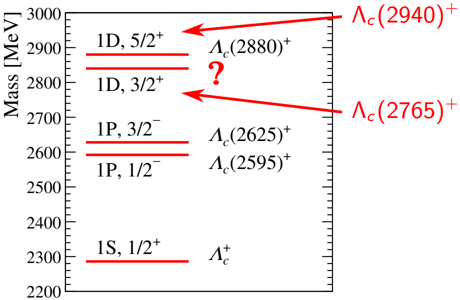


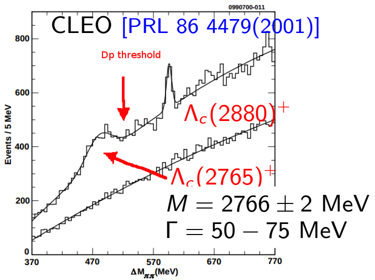
Search for strange hidden-charm pentaquark $udsc\bar{c}$
[PRL 105:232001 (2010)]

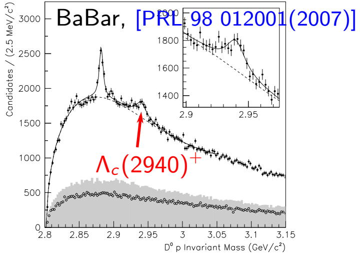
First observation of this decay:
- Λ inside VELO: 99 ± 12 events;
- Λ outside VELO: 209 ± 17 events

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\mathcal{B}(\Xi_b^- \to J/\psi \Lambda K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi \Lambda)} = (4.19 \pm 0.29(\mathrm{stat}) \pm 0.15(\mathrm{syst})) \times 10^{-2},$$

Possible open-charm exotics in Λ_c excitations



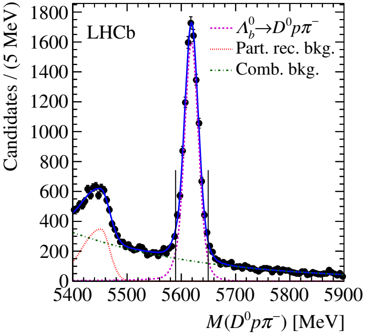




- $J^P = 3/2^+$ state (2nd member of D-wave doublet) is missing in data
- Two experimentally observed states without clear assignment: $\Lambda_c(2765)^+$ and $\Lambda_c(2940)^+$.
- $\Lambda_c(2940)^+$ has mass close to D^*N threshold: possible molecular interpretation.

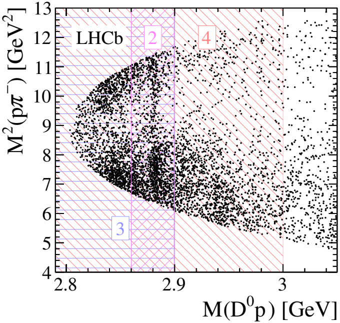
$\Lambda_b^0 \to D^0 p\pi^-$, $D^0 \to K^-\pi^+$ [JHEP 1705 (2017) 030]

Looking at excited Λ_c^+ states in the exclusive b decay for the first time.
Well-defined initial state, low background, access to quantum numbers.



Signal yield: 11212 ± 126 events
Background: $\sim 16\%$

Λ_b^0 unpolarised $\Rightarrow$ two DoF,
2D Dalitz plot phase space.



Amplitude analysis of $\Lambda_b^0 \to D^0 p\pi^-$ decay

$\Lambda_b^0 \to D^0 p\pi^-$, $D^0 \to K^-\pi^+$ [JHEP 1705 (2017) 030]

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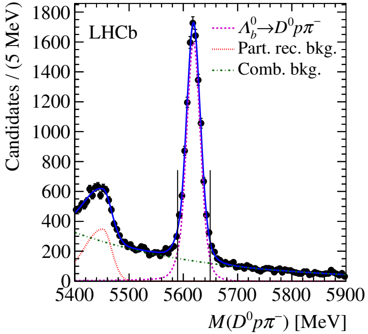

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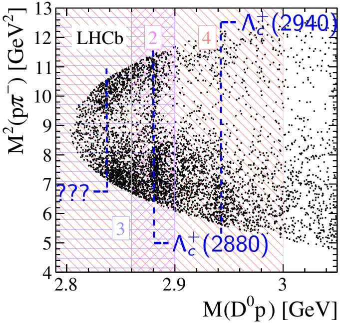


Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ decay

[JHEP 1705 (2017) 030]

- New resonance: $\Lambda_c(2860)^+$, $J^P = 3/2^+$

  $M(\Lambda_c(2860)^+) = 2856.1^{+2.0}_{-1.7} \pm 0.5(\text{syst})^{+1.1}_{-5.6}(\text{model})\,\text{MeV}$

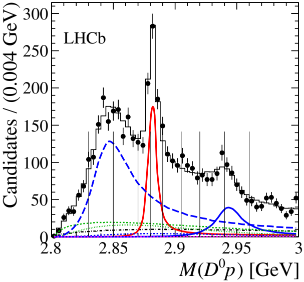
  $\Gamma(\Lambda_c(2860)^+) = 67.6^{+10.1}_{-8.1} \pm 1.4(\text{syst})^{+5.9}_{-20.0}(\text{model})\,\text{MeV}$

  Fits well into Λ_c^+ spectrum as $1D$ state.

- $\Lambda_c(2940)^+$: preferred $J^P = 3/2^-$

  $M(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5} \pm 0.4(\text{syst})^{+0.1}_{-4.6}(\text{model})\,\text{MeV}$

  $\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0} \pm 0.9(\text{syst})^{+5.2}_{-10.4}(\text{model})\,\text{MeV}$



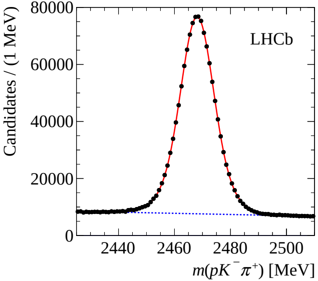
$\Lambda_c(2940)^+$ J^P	Significance wrt $3/2^-$ (stat + syst)	
	Exp NR	Poly NR
None	8.2	5.6
$1/2^+$	7.9	4.1
$1/2^-$	5.6	4.5
$3/2^+$	3.7	3.6
$5/2^+$	4.4	3.1
$5/2^-$	4.5	2.2
$7/2^+$	6.1	6.2
$7/2^-$	6.1	4.0

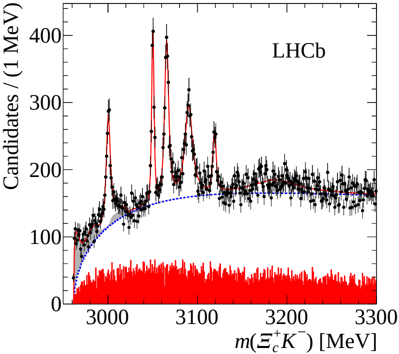
$J^P = 3/2^-$ favours molecular interpretation (P. Ortega, D. Entem, F. Fernandez, [arXiv:1210.2633]; J. Zhang, [arXiv:1212.5325], [arXiv:1405.0919]),
$2P$ radial excitation (B. Chen, K.-W. Wei, A. Zhang, [arXiv:1406.6561]),
or their admixture.

Possible open-charm exotics in Ω_c excitations

Search for $\Omega_c^{*0} \to \Xi_c^+ K^-$
Large sample of $\Xi_c^+ \to pK^-\pi^+$ decays, combine with a K^-

[PRL 118, 182001 (2017)]



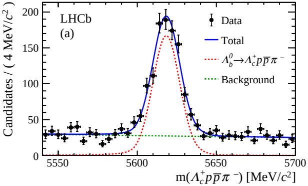


State	Mass, MeV	Width, MeV	Yield
$\Omega_c^0(3000)$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$	$1300 \pm 100 \pm 80$
$\Omega_c^0(3050)$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$	$970 \pm 60 \pm 20$
$\Omega_c^0(3066)$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$	$1740 \pm 100 \pm 50$
$\Omega_c^0(3090)$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$	$2000 \pm 140 \pm 130$
$\Omega_c^0(3119)$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$	$480 \pm 70 \pm 30$

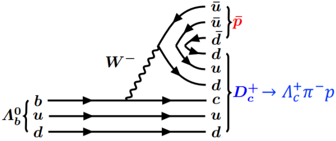
Two of the states are surprisingly narrow (3050, 3119); possible exotic interpretation (meson-baryon molecules, e.g. $K\Xi_c'$, $D\Xi$: [arXiv:1709.08737], [arXiv:1710.04231])

Searches for dibaryons New!

[arXiv:1804.09617]



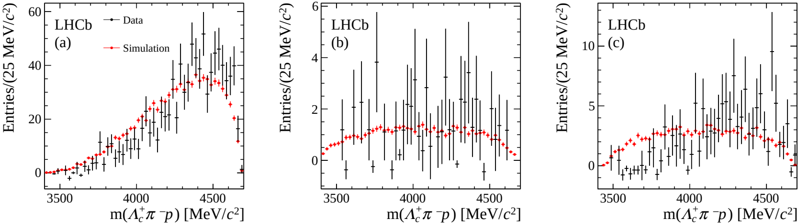
Search for charmed dibaryon *cdudud* [PLB 750 (2015) 37]



First observation of $\Lambda_b^0 \to \Lambda_c^+ p\bar{p}\pi^-$:

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

No evidence of exotic contributions:



Summary

- Exotic spectroscopy is an essential part of LHCb physics programme
- Many important results with $3\,\text{fb}^{-1}$:
  - $X(3872)$ measurements
  - Confirmation and quantum numbers of $Z(4430)$
  - Discovery of hidden-charm pentaquarks
  - Exotic states in $J/\psi\,\phi$
  - Studies of open-charm baryons
- Many more expected after adding Run 2:
  - Updates of present analyses with higher stats, precision measurements
  - Pentaquark searches with open-charm states
  - Prompt production of exotic states
  - Final states with neutrals (χ_c, Λ^0, K^0_S, ω)
  - New initial states (B^0_s, B^+_c, b-baryons)
  - More amplitude analyses; more sophisticated models based on unitarity and analyticity

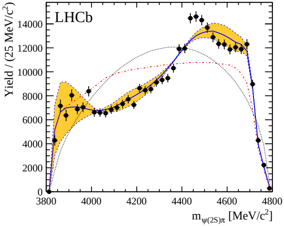
Backup

$Z(4430)$: model-independent confirmation

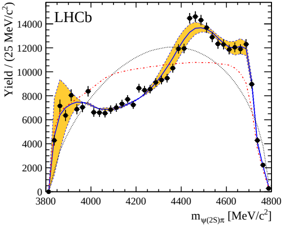
[PRD 92 (2015) 112009]

Model-independent confirmation of a structure in $\psi'\pi^-$.
Check that $K^-\pi^+$ amplitude *only* fails to describe the decay.
$K^-\pi^+$ should contribute to reasonably low moments, while exotic $\psi'\pi^-$ contributes to *all* moments.

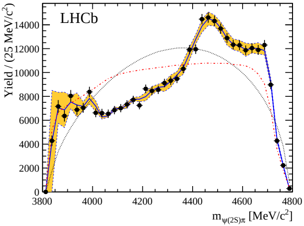
$J_{\max} = 2$
$l_{\max} = 4$
(K^*, K_2^* etc.)



$J_{\max} = 3$
$l_{\max} = 6$
($+K_3^*(1780)$ etc.)



$J_{\max} = 15$
$l_{\max} = 30$
...



Resonances with spin up to 3 cannot reproduce the features seen in data.

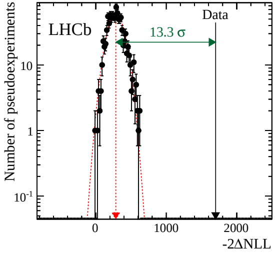
$m_{(\psi(2S)\pi)}$ distribution can only be described by an unreasonable number of Legendre moments.

[PRD 92 (2015) 112009]

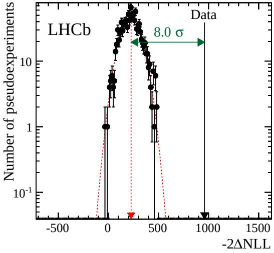
Test statistic:

$$-2\Delta NLL = -2\sum_i \frac{W_i}{\epsilon_i} \log \frac{F_l(m^i_{\psi\pi})}{F_{30}(m^i_{\psi\pi})}$$

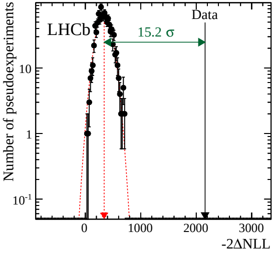
Run toys with $K^+\pi^-$-only model to determine distribution, compare with $-2\Delta NLL$ in data.



$l_{\max} = 4$



$l_{\max} = 6$

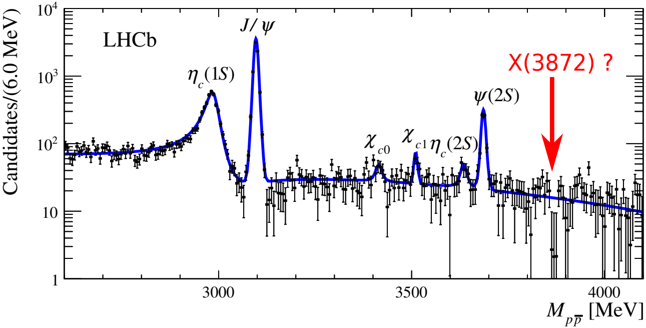


$l_{\max} = 4\ldots6$ depending on $m(K^+\pi^-)$

Resonances with spin up to 3 cannot reproduce the features seen in data.

[arXiv:1607.06446]

- Decay $B^+ \to p\overline{p}K^+$
- First observation of $\eta_c(2S) \to p\overline{p}$
- Mass and width of $\eta_c(1S)$

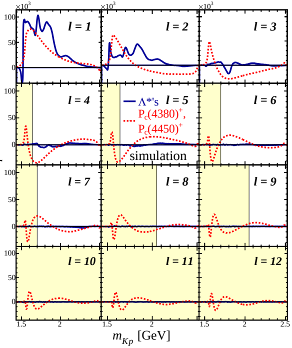


No evidence of $X(3872) \to p\overline{p}$ in $B^+ \to p\overline{p}K^+$:

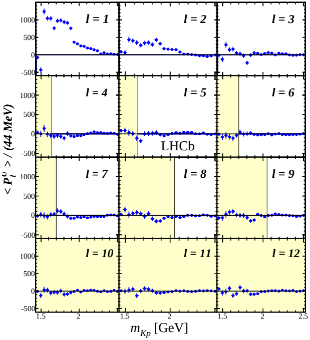
$$\frac{\mathcal{B}(B^+ \to X(3872)K^+) \times \mathcal{B}(X(3872) \to p\overline{p})}{\mathcal{B}(B^+ \to J/\psi\, K^+) \times \mathcal{B}(J/\psi \to p\overline{p})} < 0.25 \times 10^{-2} \quad @\ 95\%\ \text{CL}$$

[PRL 117 (2016) 082002]

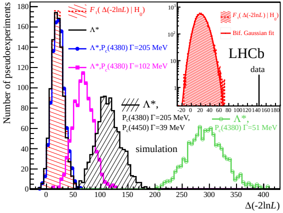
Checking that Λ^* resonances *only* cannot describe the data.
Use Legendre moments in $\cos\theta_{\rm hel}$ as a function of m_{pK}.
Allow $l_{\rm max}$ depending on m_{pK}



Moments from model



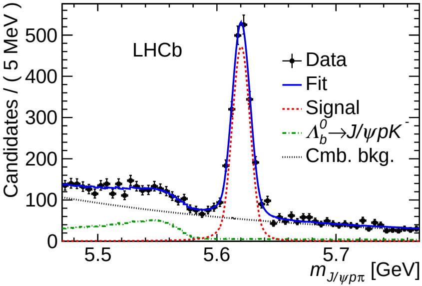
Moments from data



10σ significance

Exotic contributions in $\Lambda_b^0 \to J/\psi\, p\pi^-$

[PRL 117 (2016) 082003]

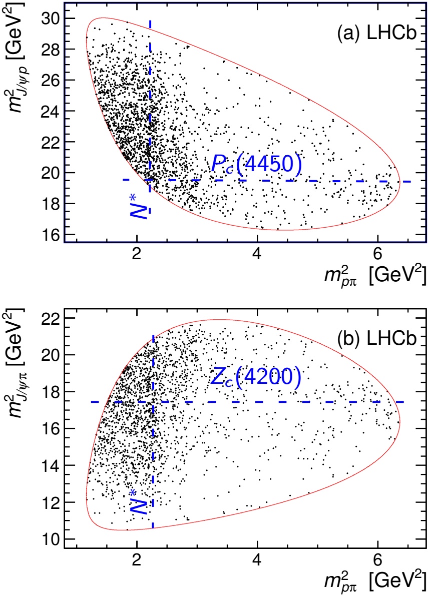


Signal yield: 1885 ± 50 events
Background: $\sim 20\%$

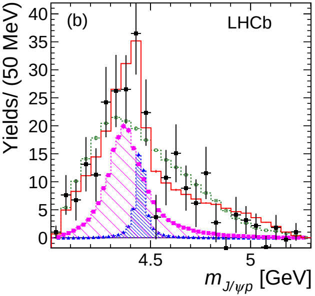
N^* states in $p\pi^-$

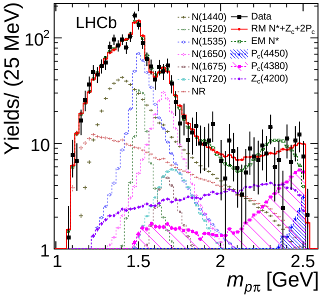
Possible exotic contributions:

- P_c in $J/\psi\, p$
- Z_c in $J/\psi\, \pi^-$ [Belle, PRD 90, 112009 (2014)]
  $M = 4196^{+31+17}_{-29-13}$ MeV
  $\Gamma = 370 \pm 70^{+70}_{-132}$ MeV



Exotic contributions in $\Lambda_b^0 \to J/\psi\, p\pi^-$





[PRL 117 (2016) 082003]

$N^* \to p\pi^-$ contributions:

- Baseline: isobar $p\pi^-$ with 7-14 states.
- Tried BW and Flatté for N(1535) (opening of $n\eta$ threshold)
- Cross-check: K-matrix for $1/2^-$ wave using Bonn-Gatchina parametrisation [A. Anisovich et al., arXiv:0911.5277]

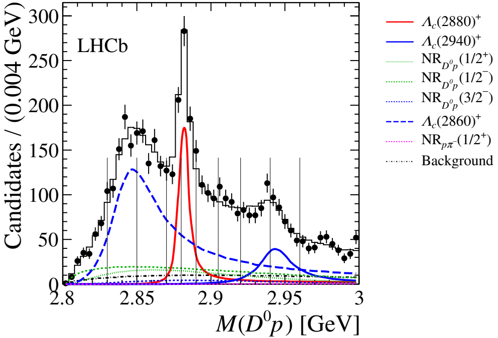
Exotic contributions:

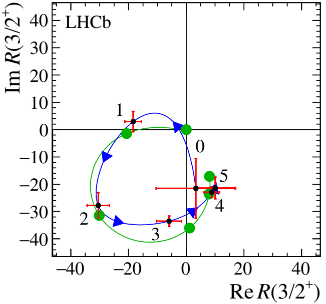
- Considered $P_c(4380)$, $P_c(4450)$ (in $J/\psi\, p$) and $Z_c(4200)$ (in $J/\psi\, \pi^-$).
- Total significance of exotic contributions: 3.1σ.
- Individual contributions are not significant
- Fit fractions:
  - $\mathcal{F}(P_c(4380)) = (5.1 \pm 1.5^{+2.6}_{-1.6})\%$
  - $\mathcal{F}(P_c(4450)) = (1.6^{+0.8}_{-0.6}{}^{+0.6}_{-0.5})\%$
  - $\mathcal{F}(Z_c(4200)) = (7.7 \pm 2.8^{+3.4}_{-4.0})\%$

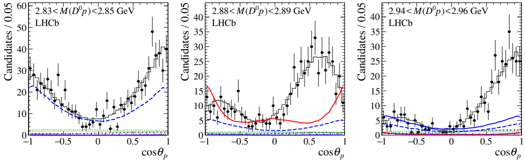
Amplitude analysis of $\Lambda_b^0 \to D^0 p \pi^-$ decay

[JHEP 1705 (2017) 030]

Fit model: $\Lambda_c(2880)^+$ ($J^P = 5/2^+$), $\Lambda_c(2940)^+$, $\Lambda_c(2860)^+$ (J^P varied) and non-resonant (exponential or 2nd-order polynomial, $J^P = 1/2^{\pm}, 3/2^-$).





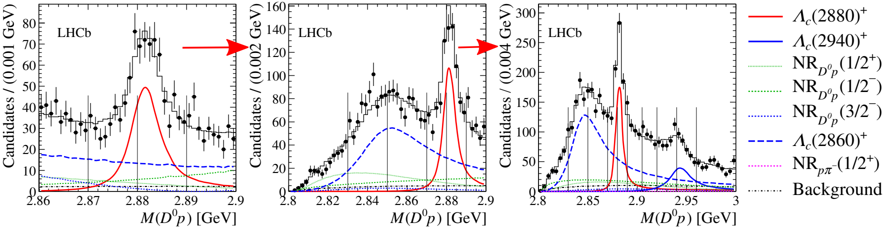


Rotation of phase for $J^P = 3/2^+$ component ($\Lambda_c(2860)^+$) wrt. non-resonant amplitudes.

[JHEP 1705 (2017) 030]

Basically, a PWA in the low-$M(D^0p)$ region (admixture of $p\pi^-$ amplitude is small).

Since no known "reference" amplitude and a large number of unknown parameters, make analysis in steps:



Consider a range of model variations, including:

- Non-resonant amplitude model (exponential, 2nd-order polynomial).
- Helicity formalism vs. covariant tensors [M. Williams, QFT++], e.g.:
  $A(5/2^+) = \bar{u}(p_{\Lambda_b^0}, m_{\Lambda_b^0})\,(C_2 + C_1\gamma^5)\; p^{\alpha}_{\Lambda_b^0} p^{\beta}_{\Lambda_b^0}\; P^{(5/2)}_{\alpha\beta\mu\nu}(q^2)\; p^{\mu}_p p^{\nu}_p\; \gamma^5\; u(p_p, m_p)$