Exotic hadrons at LHCb

Hadron 2019

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On behalf of LHCb

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3. A look to run 3 and beyond

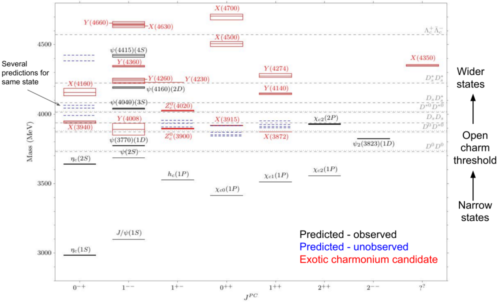
Observation of $\chi_{c1}(3872)$ in baryon decays

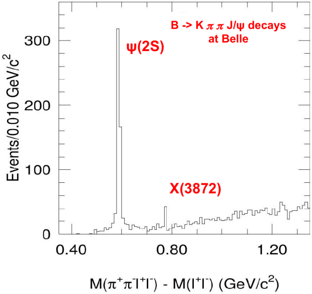
$\chi_{c1}(3872)$ - the first exotic with hidden-charm

(PRL 91, 262001(2003))

Quantum numbers confirmed by LHCb

$J^{PC} = 1^{++}$ (PRL 110, 222001(2013))





PRL 91, 262001(2003)

Far from (well predicted) charmonium states, narrower than expected for above open charm threshold - exotic charmonium state

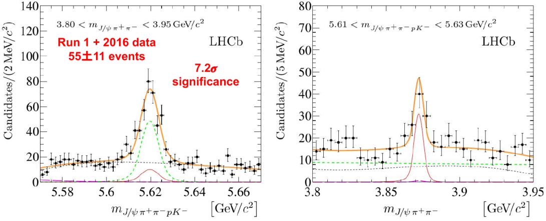
$\chi_{c1}(3872)$ to date studied only in b-meson decays - extend to baryon decays

Observation of $\chi_{c1}(3872)$ in baryon decays

First observation of $\Lambda_b^0 \to \chi_{c1}(3872) p K^-$ with $\chi_{c1}(3872) \to J/\psi \pi^+\pi^-$ decays

Fit to $J/\psi\pi^+\pi^- pK^-$ and $J/\psi\pi^+\pi^-$ spectrums

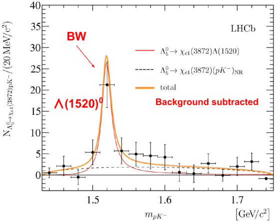
First observation of $\chi_{c1}(3872)$ in a baryon decay at $> 7\sigma$



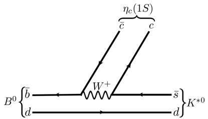
JHEP, arXiv:1907.00954(2019)

$$\mathcal{B}(\Lambda_b^0 \to \chi_{c1}(3872) pK^-) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-) = (1.24 \pm 0.25^{+0.23}_{-0.19}) \times 10^{-6}$$

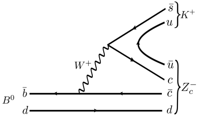
$58 \pm 15\%$ of signal decays proceed through 2-body $\chi_{c1}(3872)\Lambda^0(1520)$ decay compared to a fraction of $6 \pm 2\%$ in the control mode $\Lambda_b^0 \to \psi(2S) pK^-$



Many interpretations of the observed charmonium-like Z_c exotic states predict another exotic state decaying to $\eta_c(1S)\pi^-$ (PRD87,091501(2013), PRL111, 162003(2013), PRD71, 014028(2005))

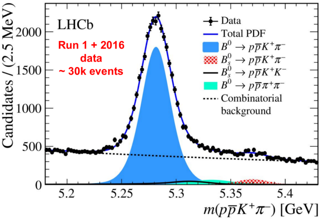


K^{*0} resonances dominate decay

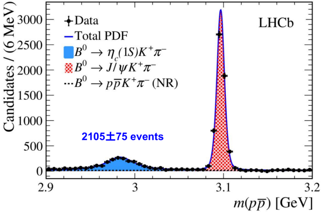


Exotic resonance predicted in $\eta_c(1S)\pi^-$

Dalitz plot analysis of $B^0 \to \eta_c(1S)K^+\pi^-$ decays performed where $\eta_c(1S) \to p\bar{p}$



EPJ. C78 1019(2018)

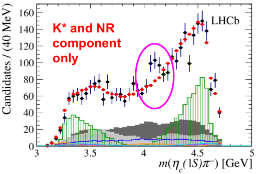


EPJ. C78 1019(2018)

Exotic states in $B^0 \to \eta_c(1S)K^+\pi^-$

K^{*0} resonances and NR component alone cannot describe the data - allow a Z_c component with floating mass and width

Conventional states only



EPJ. C78 1019(2018)

First evidence ($> 3\sigma$) for an exotic state decaying to 2 pseudoscalars

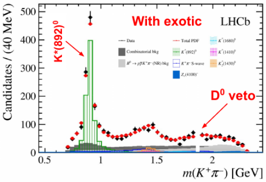
$Z_c(4100)^-$

$M = 4096 \pm 20^{+18}_{-22}$ MeV

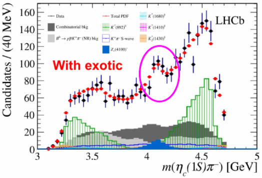
$\Gamma = 152 \pm 58^{+60}_{-35}$ MeV

$J^P = 0^+/1^-$

Exotic contribution



Exotic contribution



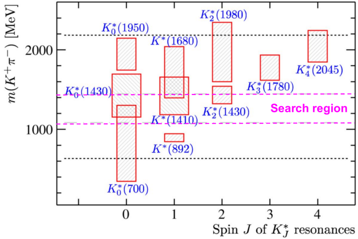
First measurement of branching fraction:

$$\mathcal{B}(B^0 \to \eta_c(1S)K^+\pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$$

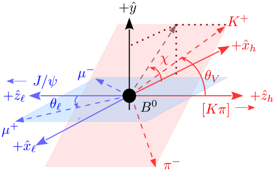
Exotic Contributions to $B^0 \to J/\psi K^+ \pi^-$

Exotic $Z(4430)^- \to \psi(2S)\pi^-$ observed by LHCb in 2014 (PRL 112, 222002)
Belle report another exotic $Z(4200)^-$ in $J/\psi\pi^-$ system (PRD 90, 112009(2014))

$B^0 \to \psi(')K^+\pi^-$ decay dominated by many, overlapping, poorly measured K_J^* states

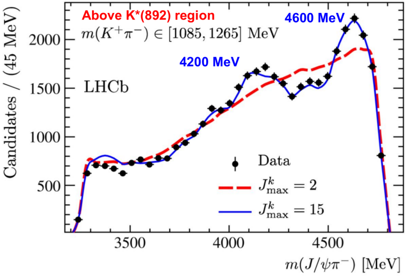


Model independent method only requires knowledge of highest spin K_J^* for given $m_{K^+\pi^-}$

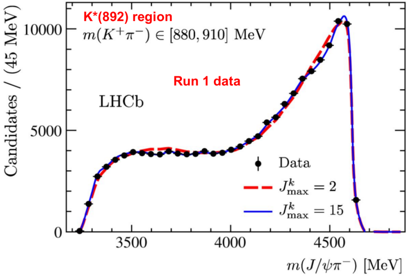


Dataset allows for a 4-D angular analysis in 35 bins of $m_{K^+\pi^-}$.
Significantly greater sensitivity to exotic components than previous 2-D analyses

Exotic Contributions to $B^0 \to J/\psi K^+ \pi^-$

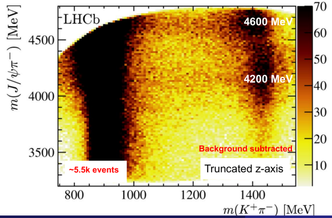


PRL 122 152002(2019)



PRL 122 152002(2019)

Assumption that decay can be described only using K_J^* states ruled out at $> 5\sigma$

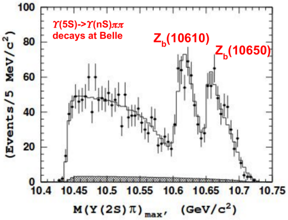


Model independent method can only indicate presence of exotic contributions - need model dependent analysis to determine further properties of these structures

Beautiful tetraquarks

In search for exotics most progress made in charmonium sector - exotics with minimal quark content $c\bar{c}qq'(q'')$ - what about bottomonium?

Two tetraquarks in bottomonium sector seen in decays of $\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-$ decays by Belle - $Z_b(10610)$ and $Z_b(10650)$



PRL 108 122001(2012)

No exotic hadron has been observed composed of more than 2 heavy quarks

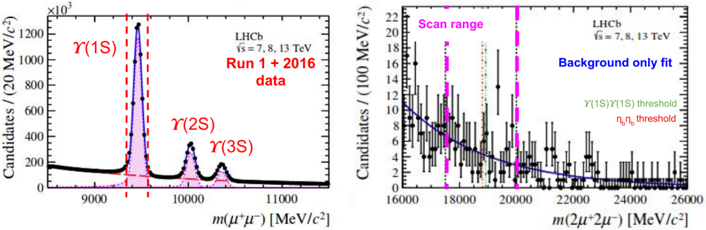
Predictions for a $X_{b\bar{b}b\bar{b}}$ tetraquark state with mass $[18.4, 18.8]$ GeV close to but below $\eta_b\eta_b$ threshold

Implies decay to $\Upsilon(nS)l^+l^-$ $(l = e, \mu)$

Beautiful tetraquarks

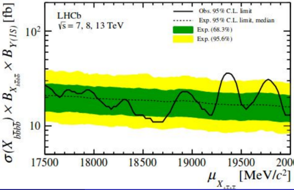
Search for a possible exotic tetraquark state composed of 2 b and 2 $\bar{b}$ quarks decaying to $\Upsilon(1S)\mu^+\mu^-$

Search $17.5 < m(2\mu^+2\mu^-) < 20.0$ GeV range for an excess



JHEP 10 086(2018)

No excess seen at any mass hypothesis
Upper limits set on product of $X_{b\bar{b}b\bar{b}}$ production cross-section and branching fraction as a function of $X_{b\bar{b}b\bar{b}}$ mass



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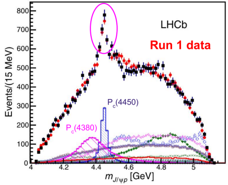
Exotic baryons in $\Lambda_b^0 \to J/\psi p K^-$ - UPDATE

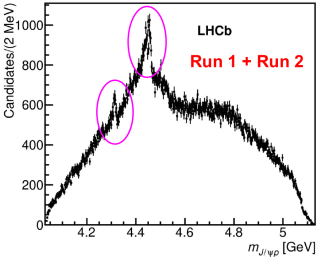
In 2015 LHCb observed exotic contributions decaying to $J/\psi p$ in $\Lambda_b^0 \to J/\psi p K^-$ decays
Exotic contributions near 4450 MeV supported by model independent analysis at more than 9σ

(PRL117.082002 (2016))

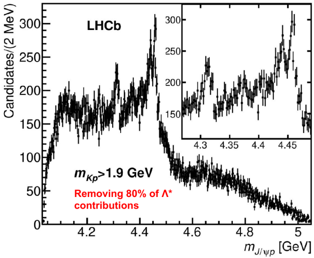


PRL117.082002 (2016)

Nine-fold increase in statistics for 2019 analysis! Structure at 4312 MeV evident and $P_c(4450)^+$ resolved into 2 narrower structures



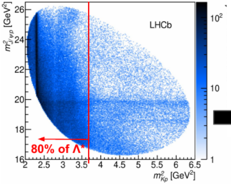
PRL 122, 222001 (2019)

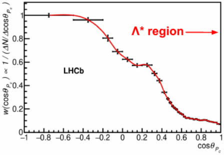


Exotic baryons in $\Lambda_b^0 \to J/\psi p K^-$ - UPDATE

New structures narrow - use 1D mass fit with BW amplitudes to begin to analyse nature.
Three types of fit performed resulting in different background composition/shape :

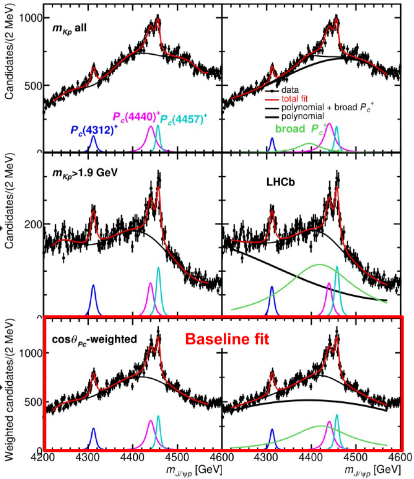
Enhance P_c signal with m_{Kp} cut or weight events according to cosine of the P_c helicity angle



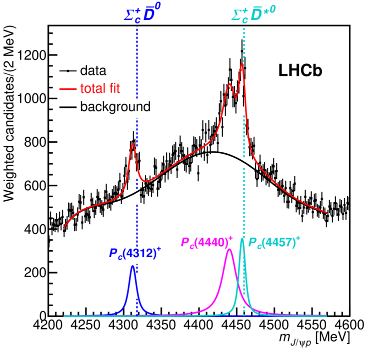


3 BW + h.o polynomial

3 BW + broad P_c + l.o polynomial



Exotic baryons in $\Lambda_b^0 \to J/\psi p K^-$ - UPDATE

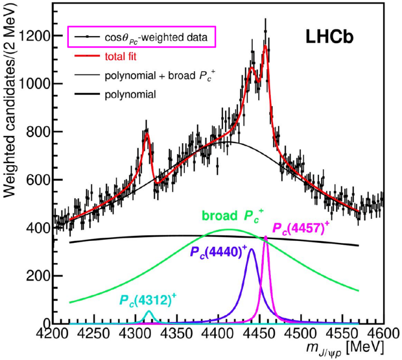


PRL 122, 222001 (2019)

-7.3σ for new $P_c(4312)$
-5.4σ for 2-peak structure rather than single peak at 4450 MeV
-Fits with/without a broad P_c both describe data well-full amplitude analysis required with comprehensive understanding of dominant $\Lambda^* \to pK^-$ spectrum

State	M [MeV]	Γ [MeV]	(95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)

Exotic baryons in $\Lambda_b^0 \to J/\psi p K^-$ - UPDATE



Range of alternative fits performed including ones that take into account interference effects between BW amplitudes

No significant change to fit-quality with respect to incoherent sum of BW, large deviations in P_c parameters - added as systematic uncertainty

Allowing interference between $P_c(4312)$ and broad P_c

PRL 122, 222001 (2019)

State	M [MeV]	Γ [MeV]	(95% CL)
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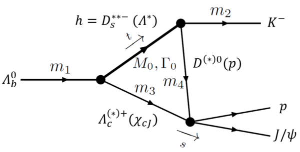
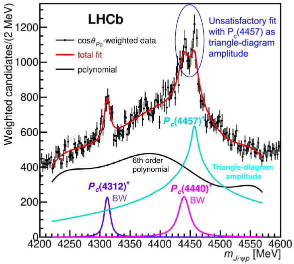
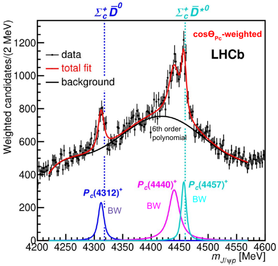
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(< 20)

$P_c(4457)^+$ peaks at $\Lambda_c^+(2595)\bar{D}^0$ threshold... possible triangle diagram involving $D_{s1}(2860)^-$?



PRL 122, 222001 (2019)





PRL 122, 222001 (2019)

Narrow width and proximity to $\Sigma_c^+ \bar{D}^{(*)0}$ thresholds suggests baryon-meson molecules

JPAC analysis of $P_c(4312)^+$ lineshape indicates attractive effect of $\Sigma_c^+ \bar{D}^0$ channel not strong enough to form a bound state (JPAC: arXiv:1904.10021)

See talks "Amplitude Analysis at JPAC" and "Analysis tools in searching for resonances"

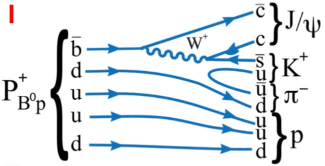
b-flavored pentaquarks

Skyrme model predicts that the heavier the constituent quarks the more tightly bound the pentaquark - more stable state *Proc. R. Soc. A260, 127(1961)*

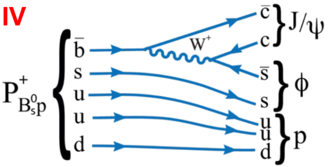
Investigate existence of pentaquark states containing a single b or $\bar{b}$ quark that decays weakly

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0 p} \to J/\psi K^+ \pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b \pi^-} \to J/\psi K^- \pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b \pi^+} \to J/\psi K^- \pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

I



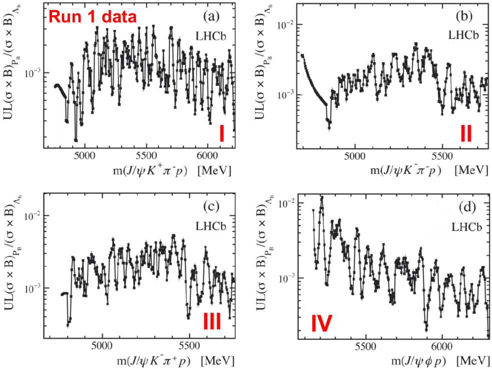
IV



b-flavored pentaquarks

Perform scan in each modes' $m_{J/\psi hhh}$ distribution in 4 MeV steps
No significant evidence for signal - set 90% CL upper limits on R

$$R = \frac{\sigma(pp \to P_B X) \cdot \mathcal{B}(P_B \to J/\psi X)}{\sigma(pp \to \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b^0 \to J/\psi K^- p)}$$

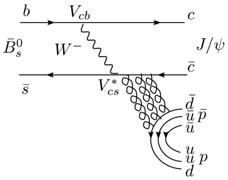


Phys. Rev. D 97, 032010 (2017)

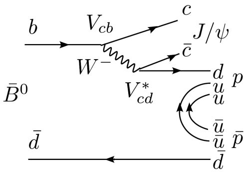
Exotic contributions to $B^0_{(s)} \to J/\psi p\bar{p}$

Decay modes are suppressed

$B^0_s \to J/\psi p\bar{p}$ - OZI-suppressed

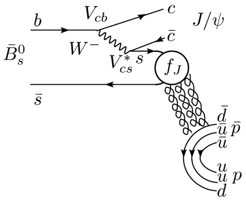


$B^0_d \to J/\psi p\bar{p}$ - Cabibbo suppressed

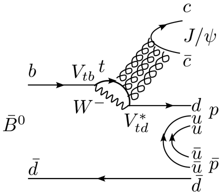


Can be enhanced through

Exotic states in $J/\psi p$ system, glueballs in $p\bar{p}$ system



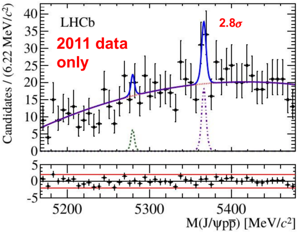
Gluonic penguin diagram



LHCb searches for $B^0_{(s)} \to J/\psi p\bar{p}$

2011 data

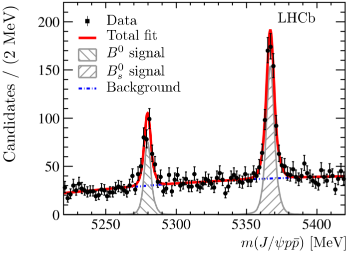
set



JHEP 09 006 (2013)

-2.8σ observed for B^0_s mode
-No $B^0 \to J/\psi p\bar{p}$ observed

Run 1 + 2015 + 2016



PRL 122 191804 (2019)

-11.5σ for B^0 mode
-19.5σ for B^0_s mode

Exotic contributions to $B^0_{(s)} \to J/\psi p\bar{p}$

Branching fraction results:
$\mathcal{B}(B^0_s \to J/\psi p\bar{p}) = (3.58 \pm 0.19 \pm 0.31) \times 10^{-6}$
$\mathcal{B}(B^0 \to J/\psi p\bar{p}) = (4.51 \pm 0.40 \pm 0.43) \times 10^{-7}$

B^0_s mode branching fraction 2 orders of magnitude greater than theory predictions without resonant contributions EPJ. C75, 101(2015)

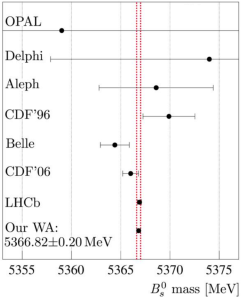
Will perform full Dalitz plot analysis for exotic searches

Perform $B^0_{(s)}$ mass measurements using $B^0_{(s)} \to J/\psi p\bar{p}$ due small Q-value

Worlds best single measurements:

$m(B^0) = 5279.74 \pm 0.30 \pm 0.10\mathrm{MeV}$

$m(B^0_s) = 5366.85 \pm 0.19 \pm 0.13\mathrm{MeV}$



PRL 122 191804 (2019)

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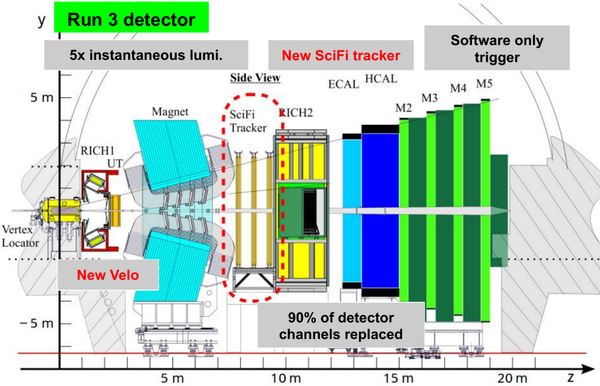
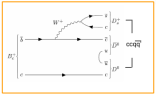
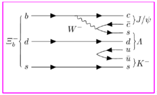
A look to run 3 and beyond



A look to run 3 and beyond





	LHCb			Belle II
Decay mode	$23\,\mathrm{fb}^{-1}$	$50\,\mathrm{fb}^{-1}$	$300\,\mathrm{fb}^{-1}$	$50\,\mathrm{ab}^{-1}$
$B^+ \to X(3872)(\to J/\psi\pi^+\pi^-)K^+$	14k	30k	180k	11k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k	4k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M	140k
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100	—
$\Lambda_b^0 \to J/\psi p K^-$	340k	700k	4M	—
$\Xi_b^- \to J/\psi \Lambda K^-$	4k	10k	55k	—
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k	< 6k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600	—

Study $\chi(3872)$ lineshape with simultaneous fit to multiple channels

Study **charged** exotic mesons such as $Z(4430)^+$. Broad - require amplitude analyses

Explicitly exotic charm states eg. doubly charmed tetraquarks $(cc\bar{q}\bar{q}')$ $\mathcal{T}_{cc}^+ \to D_s^+ D^0$

P_c observation channel - high sensitivity amplitude analysis (J^{PC})

Search for hidden-charm pentaquark with strangeness decaying to $J/\psi/\Lambda$. 1st observation at LHCb with $\approx$ 300 signal decays (PLB 772 265 (2017))

Conclusions

Exotic state searches are very active both in experiment and theory sectors

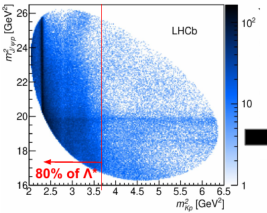
Experimental and theoretical developments moving quickly

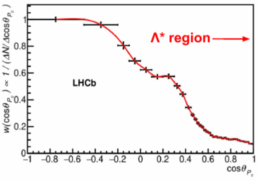
LHCb working on full run 1 and run 2 dataset where statistics are such that more amplitude analyses are possible

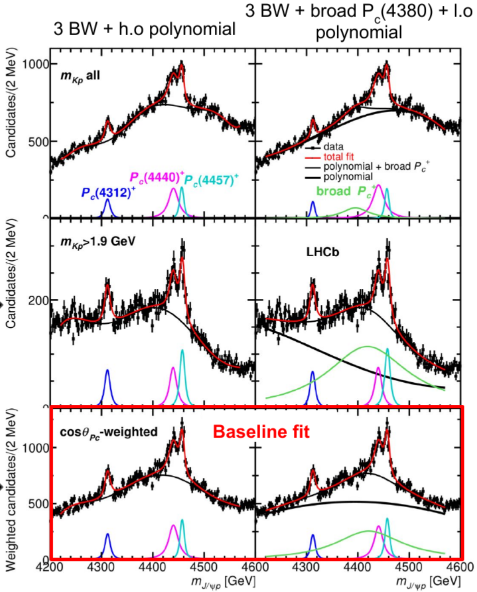
Excellent long term prospects for exotic searches at LHCb

Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$ - UPDATE

Enhance P_c signal with m_{Kp} cut or weight events according to cosine of the P_c helicity angle



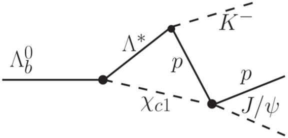




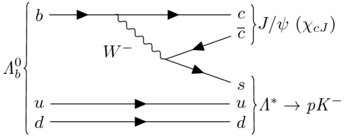
Exotics search in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

Predictions that P_c states observed by LHCb may be due to rescattering effects through triangle diagrams

$m(\chi_{c1} p) \approx m(P_c(4450))$



Could $P_c(4450)$ be explained by $\chi_{c1} p \to J/\psi p$? Note no known S-wave binding mechanism for $p\chi_{cJ}$ combinations.

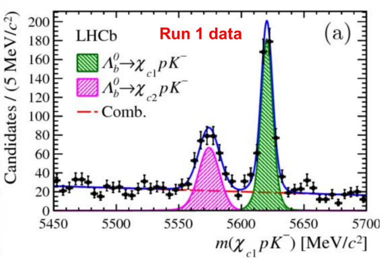


Can be tested by searching for $P_c(4450) \to \chi_{c1} p$ resonance in $\Lambda_b \to \chi_{c1} p K^-$ - requires amplitude analysis

Exotics search in $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$

First observation of $\Lambda_b^0 \to \chi_{c(1,2)} p K^-$ and branching fraction measurement in preparation for amplitude analysis

Reconstruct $\chi_{cJ} \to J/\psi\gamma$
No suppression of χ_{c2} relative to χ_{c1} as observed in B decays



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Significance of χ_{c1} and χ_{c2} decay modes 29σ and 17σ

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

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