Exotic hadronic states at LHCb

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UW High Energy Physics Seminar, 28 October 2016

Outline

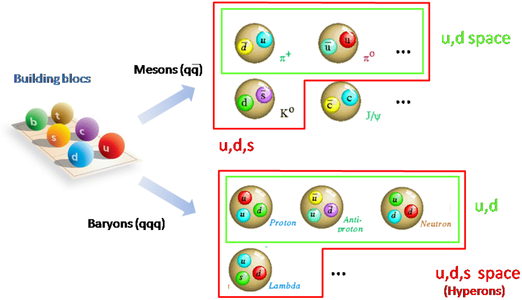
- Introduction
- LHCb experiment
- Confirmation of the resonant nature of $Z(4430)^-$ state
- Determination of $X(3872)$ properties
- Family of $J/\Psi\phi$ resonances
- Non-confirmation of $B_s\pi$ resonance
- Discovery of $P_c^+(4380)$ and $P_c^+(4450)$ states

QCD and exotic hadrons

It is impossible to derive the hadron spectrum analytically from the QCD Lagrangian, and besides Lattice QCD, which tries to solve the problem numerically, many phenomenological models were proposed.

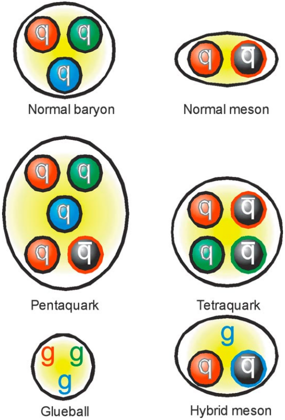
$$\mathcal{L}_{QCD} = -\frac{1}{4} F^{A}_{\alpha\beta} F^{\alpha\beta}_{A} + \sum_{flavors} \bar{q}_A (i\gamma^{\mu} D_{\mu} - m)_{AB} q_B + \mathcal{L}_{gauge-fixing} + \mathcal{L}_{ghost}$$

The quark model categorised hadrons successfully into two families: mesons and baryons, composed of a quark-antiquark pair or three quarks correspondingly.



QCD and exotic hadrons

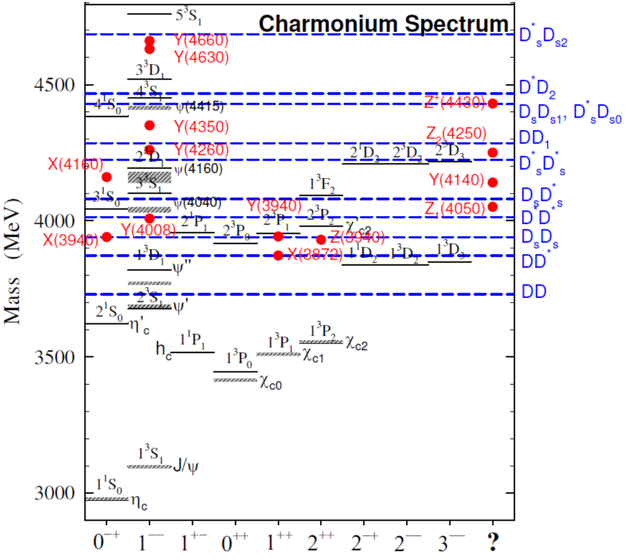
- The QCD allows much richer hadron spectrum. Even in 1964 Gell-Mann and Zweig proposing a quark model expected not only existence of mesons $q\bar{q}$ and baryons qqq but also the possible existence of tetraquarks $q\bar{q}q\bar{q}$ and pentaquarks $qqqq\bar{q}$.
- In QCD gluons not only mediate interactions but also carry a color charge and may form a color singlet called glueball. Excited glue can also contribute to the quantum numbers of $q\bar{q}$ system forming hybrid mesons.
- "Exotic" states or "exotic" quantum numbers are such only in the context of naive quark model are truly legitimate QCD states.



In the quark model the parity of a neutral meson is $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$. The sequence of quantum numbers J^{PC}: 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} is not allowed in a simple $q\bar{q}$ system and they are known as explicitly exotic.

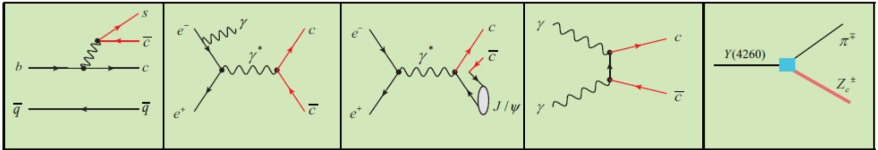
The charmonium spectrum

[S.Godfrey, arXiv:0910.3409v2]



X,Y,Z - states

Since 2003 many charmonium-like states not fitting well into conventional charmonium spectra have been observed in different production mechanisms:

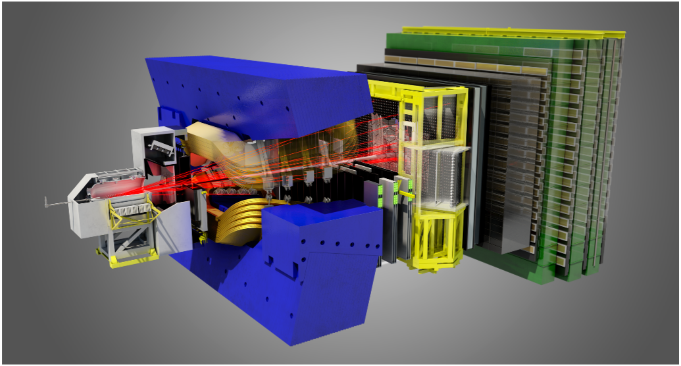


$X(3872)$	$Y(4260)$	$X(3940)$	$X(3915)$	$Z_c(3900)$
$Y(3940)$	$Y(4008)$	$X(4160)$	$X(4350)$	$Z_c(4025)$
$Z^+(4430)$	$Y(4360)$		$Z(3930)$	$Z_c(4020)$
$Z^+(4051)$	$Y(4630)$			$Z_c(3885)$
$Z^+(4248)$	$Y(4660)$			
$Y(4140)$				
$Y(4274)$				
$Z_c^+(4200)$				
$Z^+(4240)$				arXiv:1001.02092v1
$X(3823)$				

Recently the family of exotic mesons resonances has been increased by exotic baryon resonances in $J/\Psi p$ discovered by LHCb.

The LHCb experiment [Int. J. Mod. Phys. A 30 (2015) 1530022]

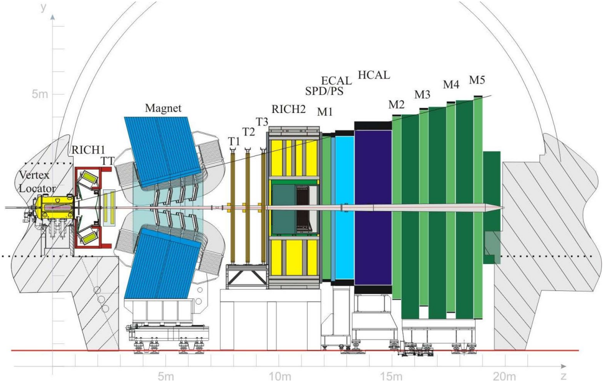
- LHCb is a single-arm spectrometer which exploits the correlated production of $b\bar{b}$ and $c\bar{c}$pairs in the LHC environment.
- Covering 4 % of solid angle ($2 < \eta < 5$) it contains 25% of $b\bar{b}$ pairs.
- The detector was designed for CP violation measurements and search for rare decays.



In years 2011-2012 (Run I) 3 fb^{-1} of integrated luminosity has been collected.

The LHCb experiment [Int. J. Mod. Phys. A 30 (2015) 1530022]

- High precision tracking system: $\sigma(IP) = 20\,\mu m$, $\delta p/p = 0.4 - 0.6\%$
- Excellent particle ID with two RICH detectors ($\epsilon_{PID}(K) \approx 95\%$, $MisID(K \to \pi) \approx 5\%$)

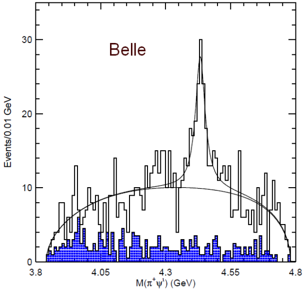


Despite the high background level inherent to hadronic collisions the detector allows to study exotic hadrons produced in heavy flavour decays.

The $Z^-(4430)$

- The Belle collaboration found an evidence [PRL 100(2008)142001] for a narrow $Z^-(4430)$ peak with width $\Gamma = 45^{+18}_{-13}{}^{+30}_{-13}$ MeV and $M = 4433 \pm 4 \pm 2$ MeV in the $\Psi'\pi^+$ mass distribution in the $B \to \Psi' K\pi$ decays.

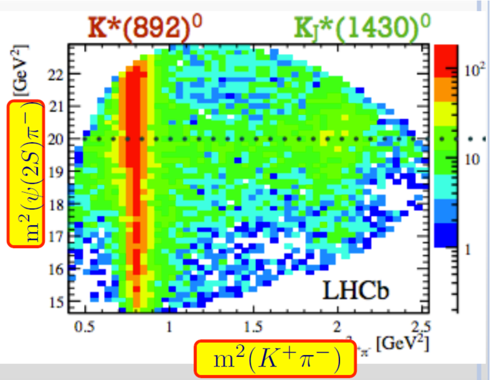
  $(121 \pm 30$ events)
- The minimal quark content of such a state is $c\bar{c}d\bar{u}$.
- However the Babar collaboration was able to describe the observed $m_{\Psi'\pi^-}$ in terms of reflections of K^* states with a spin $J \leq 3$.
- Belle updated the results [PRD88(2013)074026] with 4D amplitude analysis with $Z^-(4430)$ significance more than 5.2 σ and $J^P = 1^+$ favoured by more than 3.4 σ. $(2010 \pm 50 \pm 40$ events)

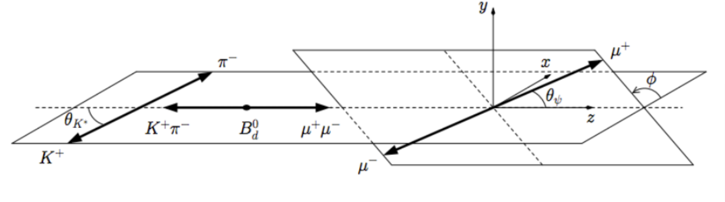


$$M = 4485 \pm 22^{+28}_{-11}\ MeV$$
$$\Gamma = 200^{+41}_{-46}{}^{+26}_{-35}\ MeV$$

The $Z^{-}(4430)$

- LHCb analysed 3 fb^{-1} with about 25000 $B \rightarrow \Psi' K\pi$ candidates.
- 2 analysis methods were used: 4D amplitude analysis [PRL112(2014)222002] and model independent confirmation of Z(4430) existence [PRD92(2015)112009].





Amplitude Analysis

$$\vec{\Phi} = (m^2_{K\pi}, m^2_{\psi\pi}, \cos\theta_\psi, \phi) \Rightarrow \frac{d\Gamma}{d\vec{\Phi}} \propto |\mathcal{M}(\vec{\Phi})|^2$$

Model Independent Analysis

$$\vec{\Phi} = (m^2_{K\pi}, \cos\theta_{K*}, \cos\theta_\psi, \phi) \Rightarrow \frac{d\Gamma}{d\vec{\Phi}} \propto |\mathcal{M}(\vec{\Phi})|^2 p(\vec{\Phi}) q(\vec{\Phi})$$

Can the reflections of the structures in m(Kπ) and cos ϑ_{K^*} reproduce the m(ψ'π) distribution?

If no exotics in ψK and ψπ → Partial wave expansion in a given bin of m²(Kπ)

Legendre Polynomials

$$\mathcal{M}(\theta_{K^*}) = \underbrace{\mathcal{S}_{wave}}_{J(K^*)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(K^*)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(K^*)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(K^*)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(K^*)=4} P_4 + \ldots$$

$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0\rangle P_0 + \langle P_1\rangle P_1 + \langle P_2\rangle P_2 + \langle P_3\rangle P_3 + \langle P_4\rangle P_4 + \langle P_5\rangle P_5 + \langle P_6\rangle P_6 + \ldots$$

where the moments <P_N> determined from data: $\langle P_N\rangle = \sum_{i=1}^{N_{data}} \frac{1}{\epsilon_i} P_N(\cos\theta^i_{K^*})$

The $Z^-(4430)$

(e.g.) If only K* resonances up to J = 2

$$\mathcal{M}(\theta_{K^*}) = \underbrace{\mathcal{S}_{wave}}_{J(K^*)=0} P_0 + \underbrace{\mathcal{P}_{wave}}_{J(K^*)=1} P_1 + \underbrace{\mathcal{D}_{wave}}_{J(K^*)=2} P_2 + \underbrace{\mathcal{F}_{wave}}_{J(K^*)=3} P_3 + \underbrace{\mathcal{G}_{wave}}_{J(K^*)=4} P_4 + \ldots$$

$$|\mathcal{M}(\theta_{K^*})|^2 = \langle P_0\rangle P_0 + \langle P_1\rangle P_1 + \langle P_2\rangle P_2 + \langle P_3\rangle P_3 + \langle P_4\rangle P_4 + \langle P_5\rangle P_5 + \langle P_6\rangle P_6 + \ldots$$

Sum of the terms up to $P_{N_{max}}$, where $N_{max} = 2^*J(K^*)$,
has to describe the data projections

Should it not happen →

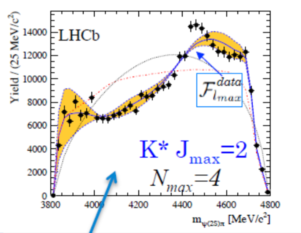
There are K* resonances with J > 2
or
There are exotic(s) which make the high order terms non-zero!

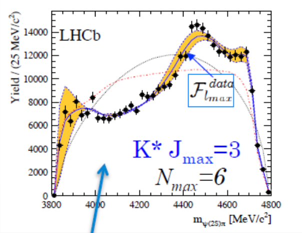
The $Z^-(4430)$

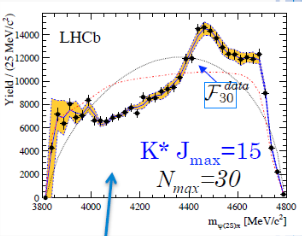
Resonance	Mass (MeV/c^2)	Γ (MeV/c^2)	J^P
$K^*(892)^0$	895.81 ± 0.19	47.4 ± 0.6	1^-
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+
$B^0 \to \psi(2S)K^+\pi^-$ phase space limit (1593 MeV)			
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-
$K_3^*(1780)^0$	1776 ± 7	159 ± 21	3^-
...	...	...	...
$K_4^*(2045)^0$	2045 ± 9	198 ± 30	4^+

Unlikely a contribution from K* resonances with J > 3

Allows for K* states up to $K^*_2(1430)$	Allows for a tail of $K^*_3(1780)$	Allows implausible K* contributions







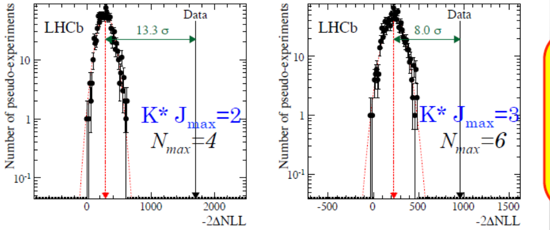
Clear discrepancy at ~4430 MeV	It may look OK but…	No discrepancy as expected

The yellow bands related to the uncertainty on normalized moments (due to the statistical uncertainty from the data)

Test significance of implausible $N_{max} < N < 30$ moments using the log-likelihood ratio:

$$\Delta(-2\mathrm{NLL}) = -2\log\frac{\mathcal{L}_{N_{max}}}{\mathcal{L}_{30}} = -2\log\frac{\prod_i \mathcal{F}_{N_{max}}(m^i_{\psi'\pi})}{\prod_i \mathcal{F}_{30}(m^i_{\psi'\pi})}$$

Statistical simulations of pseudo-experiments generated from the $N < N_{max}$ hypotheses

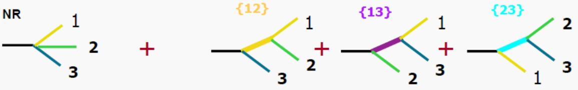


Explanation of the data with plausible K* contributions is ruled at high significance without assuming anything about K* resonance shapes or their interference patterns!

The $Z^-(4430)$

THE ISOBAR MODEL

Isobar model: total decay amplitude as a coherent sum of processes where one daughter is spectator



Three-body amplitude for $B^0 \to \psi(2S)\, K\, \pi$

Sum over all K* resonances

Z(4430) component

$$|\mathcal{M}(\Phi)|^2 = \sum_{\Delta\lambda_\mu=1,-1} \left| \sum_{\lambda_\psi=-1,0,1} \sum_{K^*} A^{K^*}_{\lambda_\psi \Delta\lambda_\mu}(m_{K\pi},\Omega) + \sum_{\lambda^Z_\psi=-1,0,1} A^{Z}_{\lambda^Z_\psi \Delta\lambda_\mu}(m_{\psi\pi},\Omega^Z)\, e^{i\Delta\lambda_\mu \alpha} \right|^2$$

Defined unless a phase and a constant

Rotation by α due to different helicity frame

The $Z^-(4430)$

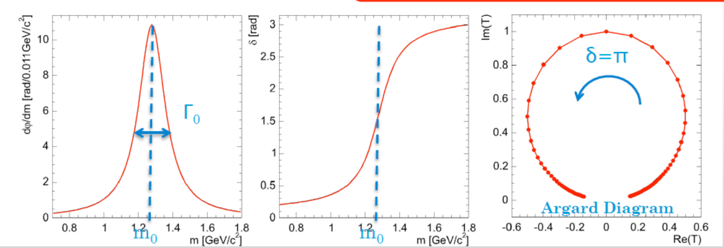
HOW TO MODEL A SINGLE TERM

$$A^{K^*}_{\lambda_\psi,\Delta\lambda_\mu}(m_{K\pi},\Omega) = H^{K^*}_{\lambda_\psi} A^{K^*}(m_{K\pi}) d^{J(K^*)}_{\lambda_\psi,0}(\theta_{K^*}) \times e^{i\lambda_\psi\phi} d^1_{\lambda_\psi,\Delta\lambda_\mu}(\theta_\psi)$$

Free parameters
+
m_0, Γ_0 (in case of a new state)

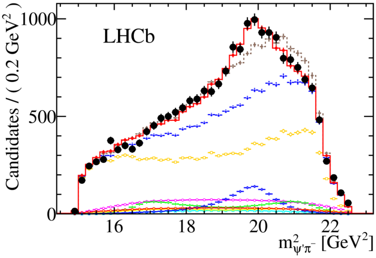
Relativistic Breit-Wigner

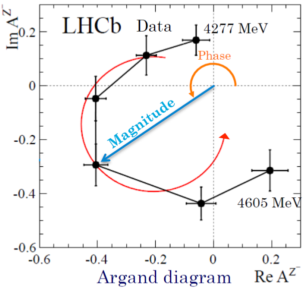
$$A^{K^*}(m_{K\pi}) = \frac{1}{m_0^2 - m_{K\pi}^2 - i m_o \Gamma_0}$$



The $Z^-(4430)$

- The significance of a resonance $\Delta(-2\ln\mathcal{L}) > 13.9\sigma$.
- The $J^P = 1^+$ hypothesis is favoured with others ruled out at significance $> 9\sigma$.
- The positive parity rules out the possibility that $Z(4430)^-$ is a $\bar{D}^*(2007)D_1(2420)$.
- The Argand plot demonstrates behaviour characteristic for a resonance, i.e. a circular trajectory in the complex plane with a fast change of phase crossing the maximum of amplitude.

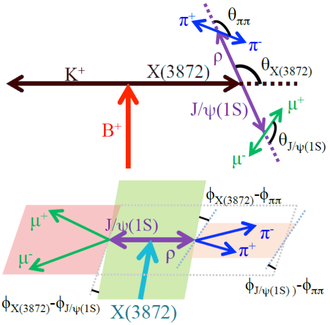




The X(3872) before LHCb measurements

- The X(3872) was discovered by Belle in 2003 as a resonance in $X(3872) \to J/\Psi \pi^+ \pi^-$ and later confirmed by Babar, CDF, D0.
- The state is narrow $\Gamma < 1.2\,MeV$ and its mass $3871.69 \pm 0.17\,MeV$ [PDG2015] is close to $D\bar{D}^*$ threshold $(3871.81 \pm 0.09\,MeV)$.
- Observation of decays $X(3872) \to \rho J/\Psi$ and $X(3872) \to \omega J/\Psi$ with comparable branching fraction indicates violation of isospin symmetry.
- Observation of $X(3872) \to \gamma J/\Psi$ imposes positive C-parity.
- Measurements by Belle, Babar and CDF left 2 options for quantum number assignment $J^{PC} = 1^{++}$ and $J^{PC} = 2^{-+}$.

Measurements of X(3872) quantum numbers by LHCb



- The angular correlations in the decay $B^+ \to J/\Psi\pi^+\pi^-K^+$ carry information about $X(3872)$ quantum numbers.
- To discriminate between 1^{++} and 2^{-+} assignments we use a likelihood-ratio test with PDF defined 5D angular space $\Omega = (\cos\theta_X, \cos\theta_{\pi\pi}, \Delta\phi_{X,\pi\pi}, \cos\theta_{J/\Psi}, \Delta\phi_{X,J/\Psi})$
- Analysis on 3 fb^{-1} [PRD92(2015)011102] with 1011 ± 38 $B^+ \to X(3872)K^+$ candidates considered full amplitude model including D-wave.
- $J^{PC} = 1^{++}$ was established (significance more than 16 σ) and no significant D-fraction was found ($<$ 4% at 95% C.L.).

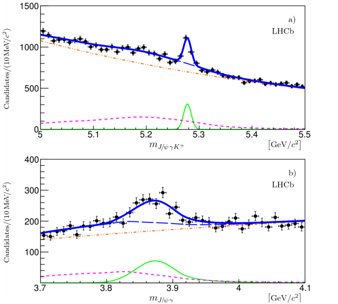
$X(3872) \to \Psi(2S)\gamma$

Radiative decays of $X(3872)$ provide a valuable information for its interpretation (molecule, tetraquark, hybrid meson and mixed state).

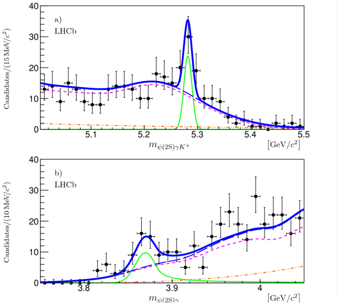
$$R_{\Psi\gamma} = \frac{B(X(3872)\to\Psi(2S)\gamma)}{B(X(3872)\to J/\Psi\gamma)}$$

The $R_{\Psi\gamma}$ is predicted to be in the range $(3-4)\times10^{-3}$ for a $D\bar{D}^*$ molecule, 1.2-15 for pure charmonium state and 0.5-5 for a molecule-charmonium mixture.

$B \to X(3872)K \to J/\Psi\gamma K$

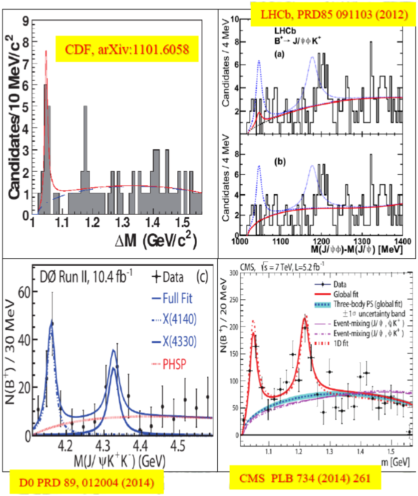


$B \to X(3872)K \to \Psi(2S)\gamma K$



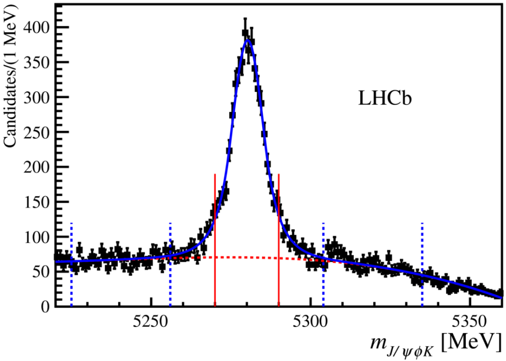
The measured $R_{\Psi\gamma} = 2.46 \pm 0.64 \pm 0.29$ does not support pure $D\bar{D}^*$ molecular interpretation.

Exotics in $J/\Psi\phi$ final state



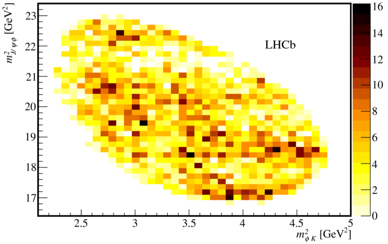
- 2008 - Observation of narrow structure X(4140) in $J/\Psi\phi$ by CDF, Γ= 12 MeV ($> 5\sigma$) in $B^+ \to J/\Psi\phi K^+$ decay.
- Narrow and above $D_s D_s$ threshold, therefore exotic interpretation.
- Confirmed by CMS ($> 5\sigma$) and D0 (3.1σ).
- Not confirmed by Belle, Babar and early LHCb (0.37 fb^{-1})
- Evidence for a second peak by CDF (4274 MeV) and CMS (4314 MeV).

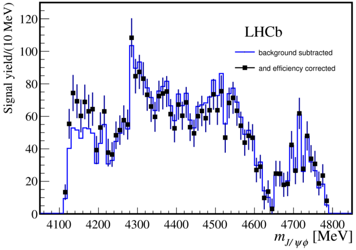
Exotics in $J/\Psi\phi$ final state

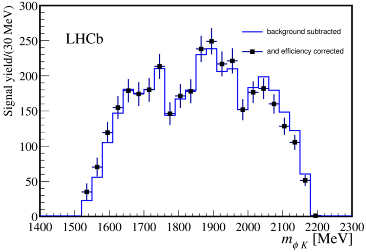


- arXiv: 1606.07895, arXiv:1606.07898
- Analysis with 3 fb^{-1} of data at 7 and 8 TeV centre-of-mass energy.
- 4289 ± 151 $B^+ \to J/\Psi\phi K^+$ were reconstructed with background fraction of 23%.

Exotics in $J/\Psi\phi$ final state

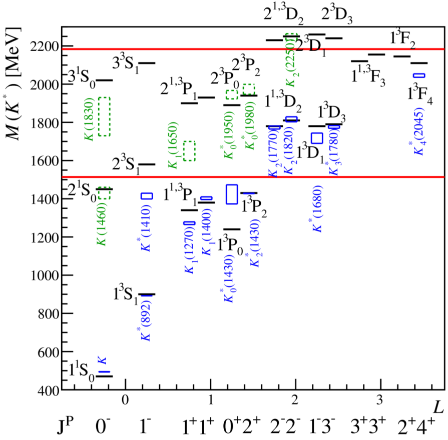


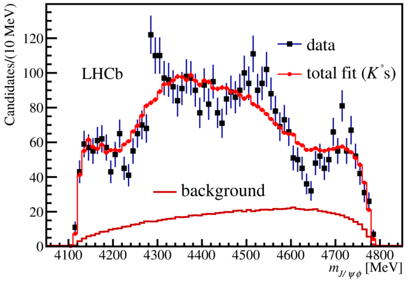




Can J/Ψ structure be reflection from non-trivial interference pattern in $B^+ \to J/\Psi(K^* \to \phi K^+)$ decay?
Full amplitude analysis is needed.

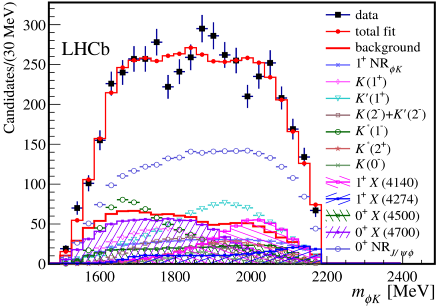
If genuine $J/\Psi\phi$ states are present, it is crucial to determine their quantum numbers for theoretical interpretation.

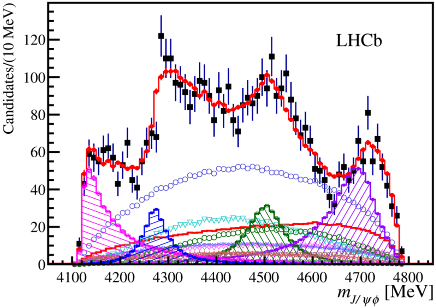




- 6D amplitude model with $m_{\phi K}$, θ_{K^*}, $\theta_{J/\Psi}$, $\Delta\phi_{K^*,J/\Psi}$ and $\Delta\phi_{K^*,\phi}$ idependent variables.
- K^* resonances from Godfrey-Isgur model (PRD 32,189(1985)) with masses and widths floating.
- Data cannot be described by K^* only (p-value=10^{-7}).

Significant improvement in fit with 4 additional resonances.





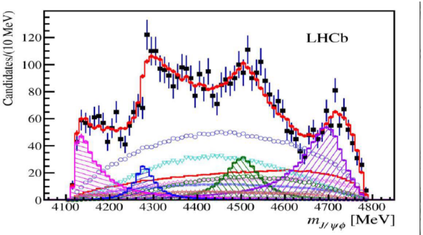
Exotics in $J/\Psi\phi$ final state

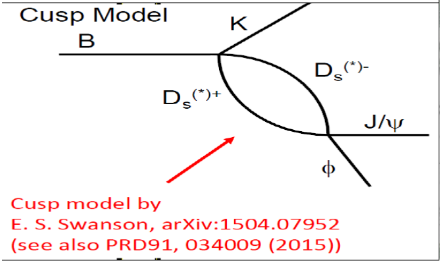
X(4180)&X(4274) $J^{PC} = 1^{++}$ at >5σ

X(4500)&X(4700) $J^{PC} = 0^{++}$ at >4σ

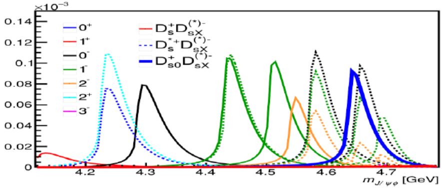
Contri-bution	sign.	Fit results M_0 [MeV]	Γ_0 [MeV]	FF %
All $X(1^+)$				$16\pm3\,^{+6}_{-2}$
$X(4140)$	8.4σ	$4146.5\pm4.5\,^{+4.6}_{-2.8}$	$83\pm21\,^{+21}_{-14}$	$13\pm3.2\,^{+4.8}_{-2.0}$
ave.		4143.4 ± 1.9	15.7 ± 6.3	
$X(4274)$	6.0σ	$4273.3\pm8.3\,^{+17.2}_{-3.6}$	$56\pm11\,^{+8}_{-11}$	$7.1\pm2.5\,^{+3.5}_{-2.4}$
CDF		$4274.4\,^{+8.4}_{-6.7}\pm1.9$	$32\,^{+22}_{-15}\pm8$	
CMS		$4313.8\pm5.3\pm7.3$	$38\,^{+30}_{-15}\pm16$	
All $X(0^+)$				$28\pm5\pm7$
$NR_{J/\psi\phi}$	6.4σ			$46\pm11\,^{+11}_{-21}$
$X(4500)$	6.1σ	$4506\pm11\,^{+12}_{-15}$	$92\pm21\,^{+21}_{-20}$	$6.6\pm2.4\,^{+3.5}_{-2.3}$
$X(4700)$	5.6σ	$4704\pm10\,^{+14}_{-24}$	$120\pm31\,^{+42}_{-33}$	$12\pm5\,^{+9}_{-5}$

X(4140) as cusp

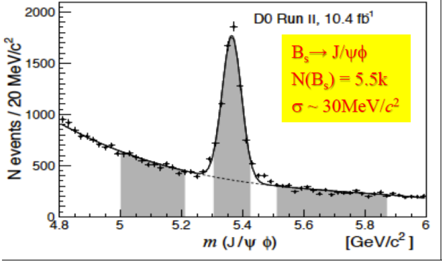


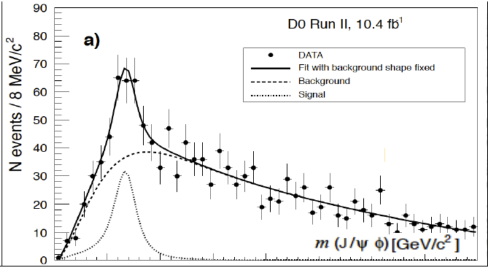


- Since 4 states in this decay channel seems rather odd, the “CUSP” model of Swanson was used to to explain the state just above $D_s D_s^*$ threshold.
- X(4140) cusp prefered over Breit-Wigner with 1.6 σ
- Many cusps at higher masses are expected.

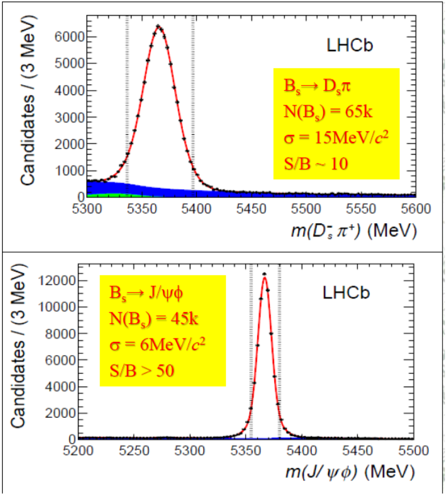


- In February 2016 D0 reported evidence of the narrow structure $X(5568) \to B_s\pi^{\pm}$ produced in $p\bar{p}$ collisions with $M = 5568$ MeV and $\Gamma = 22$ MeV. Statistical significance 6.1 σ.
- Fraction of B_s from X decay $\rho = (8.6 \pm 1.9 \pm 1.4)\%$
- If confirmed it would differ from any of the previous observations, as it must have constituent quarks with four different flavours (b, s, u, d).
- It would be unique in having its mass dominated by a single constituent quark rather than by a quark-antiquark pair.





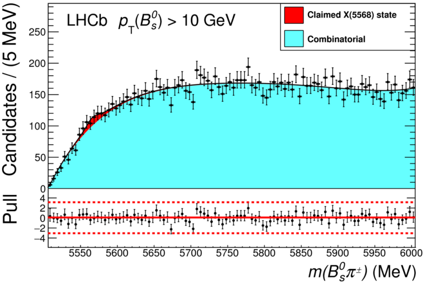
$X(5568) \to B_s\pi^{\pm}$



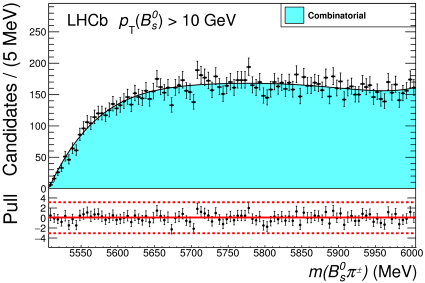
- LHCB data corresponding to 3 fb^{-1} of integrated luminosity were analysed.
- Two decay modes: $B_s \to D_s\pi$ and $B_s \to J/\Psi\phi$ with 20 times larger B_s yield.
- arXiv:1608.00435v1 (accepted by PRL)

$X(5568) \to B_s\pi^{\pm}$

Fit with "signal"

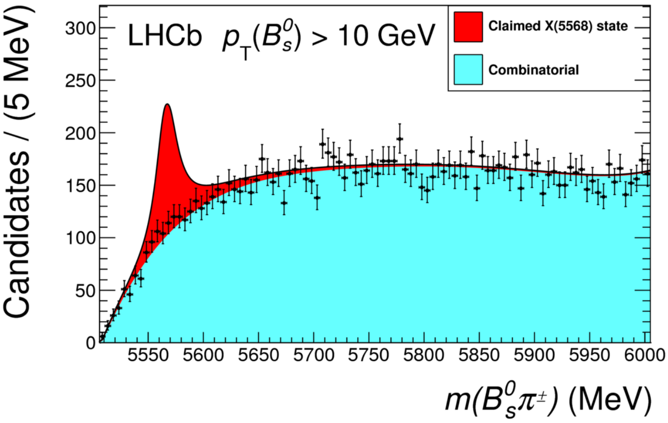


Fit with no signal



$X(5568) \to B_s\pi^{\pm}$

How we should see signal if $\rho = 8.6\%$ is a universal parameter?



Fit results and upper limits

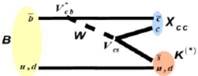
		$B_s^0 \to D_s^- \pi^+$	$B_s^0 \to J/\psi\,\phi$	Sum
$N(B_s^0)/10^3$	$p_T(B_s^0) > 5$ GeV	62.2 ± 0.3	43.6 ± 0.2	105.8 ± 0.4
	$p_T(B_s^0) > 10$ GeV	28.4 ± 0.2	13.2 ± 0.1	41.6 ± 0.2
	$p_T(B_s^0) > 15$ GeV	8.8 ± 0.1	3.7 ± 0.1	12.5 ± 0.1
$N(X)$	$p_T(B_s^0) > 5$ GeV	3 ± 64	-33 ± 43	-30 ± 77
	$p_T(B_s^0) > 10$ GeV	75 ± 52	12 ± 33	87 ± 62
	$p_T(B_s^0) > 15$ GeV	14 ± 31	-10 ± 17	4 ± 35
$\epsilon^{\rm rel}(X)$	$p_T(B_s^0) > 5$ GeV	0.127 ± 0.002	0.093 ± 0.001	—
	$p_T(B_s^0) > 10$ GeV	0.213 ± 0.003	0.206 ± 0.002	—
	$p_T(B_s^0) > 15$ GeV	0.289 ± 0.005	0.290 ± 0.004	—

$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 5\,{\rm GeV}) = -0.003 \pm 0.006 \pm 0.002\,,$$
$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 10\,{\rm GeV}) = 0.010 \pm 0.007 \pm 0.005\,,$$
$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 15\,{\rm GeV}) = 0.000 \pm 0.010 \pm 0.006\,,$$

$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 5\,{\rm GeV}) < 0.011\ (0.012)\,,$$
$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 10\,{\rm GeV}) < 0.021\ (0.024)\,,$$
$$\rho_X^{\rm LHCb}(p_T(B_s^0) > 15\,{\rm GeV}) < 0.018\ (0.020)\,.$$

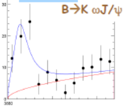
CL= 95%

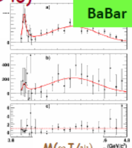
Other tetraquark candidates



Belle Y(3940) BaBar

$B \to K\ \omega J/\psi$

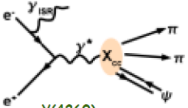




$M(\omega J/\psi)$ $M(\omega J/\psi)$

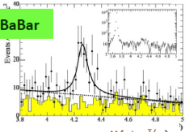
Z(4430)

Thus far, no amplitude analyses for these states

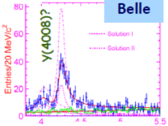


Y(4260)

BaBar



Belle

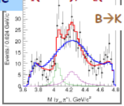


$M(\pi^+\pi^- J/\psi)$ $M(\pi^+\pi^- J/\psi)$

Y(4350) & Y(4660)

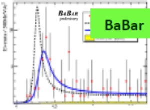
Belle $Z_1(4050)$, $Z_2(4250)$

$B \to K\ \pi^+\chi_{c1}$

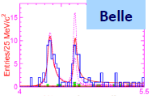


$M(\pi^{\pm}\chi_{c1})$

BaBar

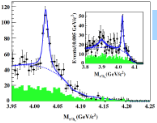


Belle



$M(\pi^+\pi^-\psi')$ $M(\pi^+\pi^-\psi')$

All current candidates contain a $c\bar{c}$ or $b\bar{b}$



BES

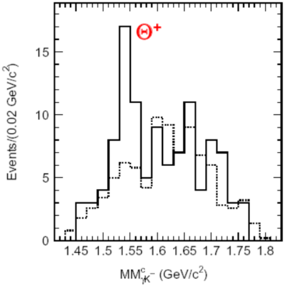
$e^+e^- \to Y(4260) \to \pi^+ Z_c(4020)^- \to \pi^- h_c$

Search for strange pentaquarks

- Pentaquarks come in two types, exotic and nonexotic. Exotic pentaquarks have an antiquark with a different flavor than any of its four quarks.
- The lightest exotic pentaquark is made of ($\bar{s}uudd$) quarks, first called the Z^+ and later renamed as the Θ^+.
- In 1987, Praszalowicz made a prediction, based on the skyrme model of baryons, that the Z^+ could exists with a mass of about 1.54 GeV/c^2, followed in 1997 by Diakonov, Petrov and Polyakov (DPP) that the Z^+ could have a narrow mass width of 0.01 GeV/c^2 or less.

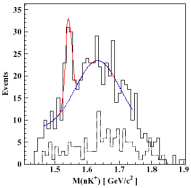
- In the process $\gamma n \to nK^+K^-$, LEPS observed peak in $m(nK^+)$ spectrum.
- $m = 1540 \pm 10 \pm 5$ MeV.
- $\Gamma < 25$ MeV at 90% CL.
- No. of events N = 43.
- Significance ~ 4.6 σ ($S/\sqrt{B}$).
- Minimum quark content $uudd\bar{s}$.
- Mass and width consistent with chiral soliton model prediction.

- LEPS 2000...2001 data:



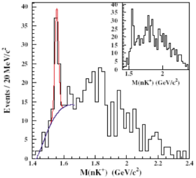
Search for strange pentaquarks

- CLAS (1999) $\gamma d \to npK^+K^-$:



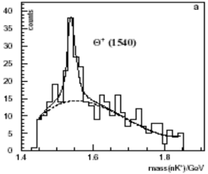
- $m = 1542 \pm 5$ MeV.
- $\Gamma < 21$ MeV.
- N = 43, significance ~ 5.2 σ.

- CLAS, $\gamma p \to n\pi^+K^+K^-n$:



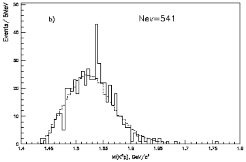
- $m = 1555 \pm 10$ MeV.
- $\Gamma < 26$ MeV.
- N = 41, significance ~ 7.8 σ.

- SAPHIR (1997...1998) $\gamma p \to nK^+K_S^0$:



- $m = 1540 \pm 4 \pm 2$ MeV.
- $\Gamma < 21$ MeV
- $N = 63 \pm 13$, significance ~ 4.8 σ.

- DIANA (1986) $K^+Xe \to pK_S^0Xe$:

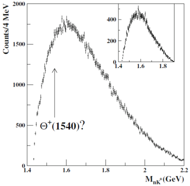


- $m = 1539 \pm 4 \pm 2$ MeV
- $\Gamma < 9$ MeV
- N = 29, significance ~ 4.4 σ.
- pK_S^0 so not necessarily exotic state!

Also confirmation by Hermes, Zeus, SVD-2, COSY-TOF with significances given as 4.6, 5.2, 7.8, 4.8, 4.4, 3...4, 3.9...4.6, 6.7, 5.6 and 3.7...5.9.

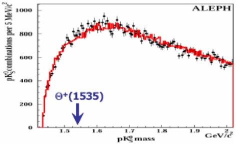
Search for strange pentaquarks

Negative results

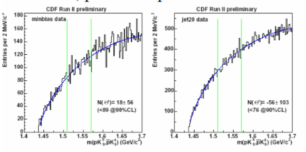


Null results

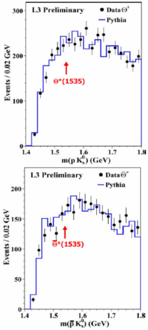
- ALEPH, e^+e^-:



- CDF, proton antiproton:



- L3, $\gamma\gamma$:



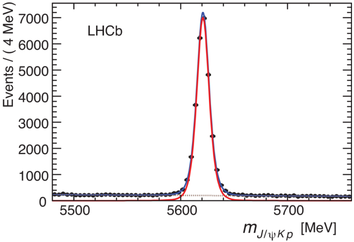
The experiment at CLAS called the g11 run was a search for the same reaction published in 2003 by SAPHIR, $\gamma p \to K^+ K_0 p$, with a goal of obtaining better statistics than SAPHIR by a factor of 100 or more.

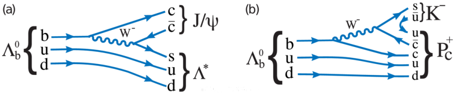
(Kenneth Hicks. On the conundrum of the pentaquark, Eur. Phys. J.(2012))

$\Lambda_b \to J/\Psi K^- p$

- Large yields of $\Lambda_b \to J/\Psi K^- p$ available at LHCb have been used for a precise measurement of Λ_b lifetime.
- This decay is expected to be dominated by $\Lambda^* \to K^- p$ resonances; however, it could also have exotic contribution that results in resonant structure in the $J/\Psi p$ mass spectrum.

[PRL115(2015)072001]

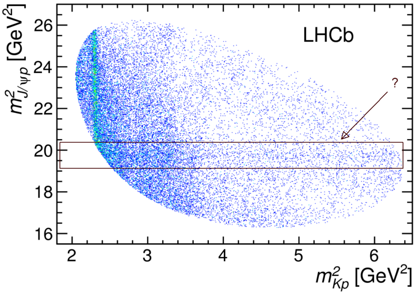




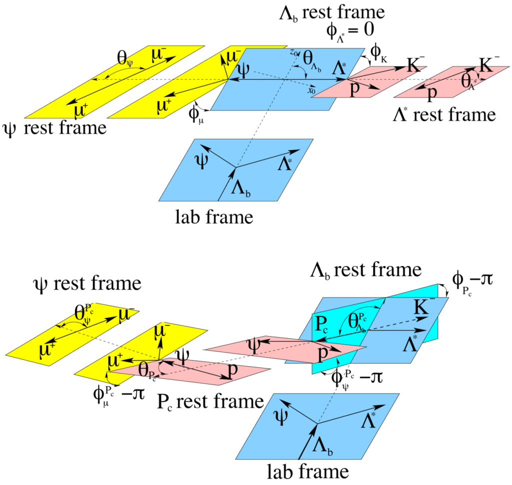
26007 ± 166 Λ_b candidates have been collected with 3 fb^{-1} of data

$\Lambda_b \to J/\Psi K^- p$

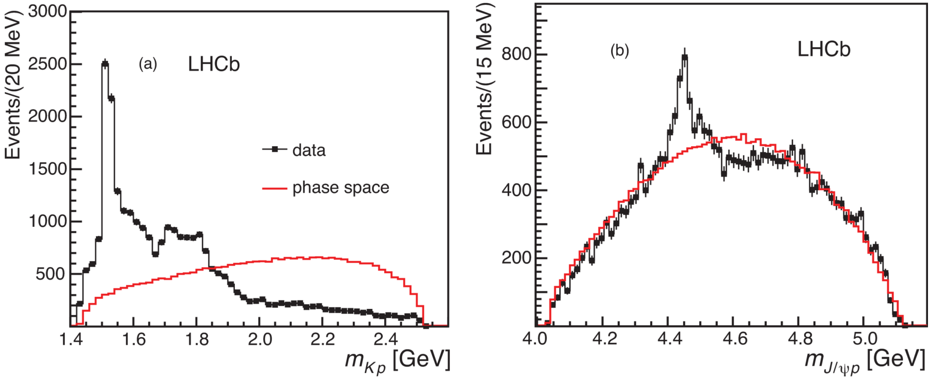
- With 3 fb^{-1} a resonant structure has been observed in the Dalitz plot [PRL115(2015)072001] in a $J/\Psi p$ channel.
- A resonance decaying strongly to $J/\Psi p$ must have a $c\bar{c}uud$ quark content.
- Irrespective of the internal binding mechanism we label it as P_c^+.
- To exclude reflections generated by the Λ^* states a full amplitude analysis is necessary.

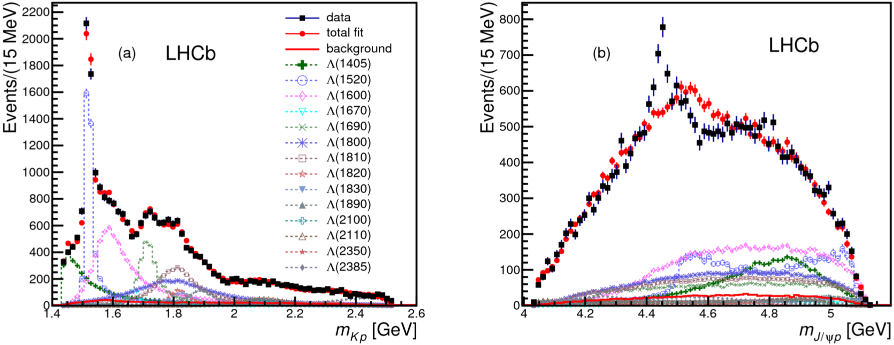


6D amplitude analysis (5 angles and m^2_{pK}) with 14 (16) Λ^* states included



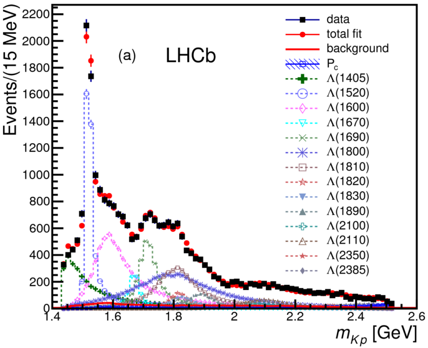
$\Lambda_b \to J/\Psi K^- p$ [PRL115(2015)072001]

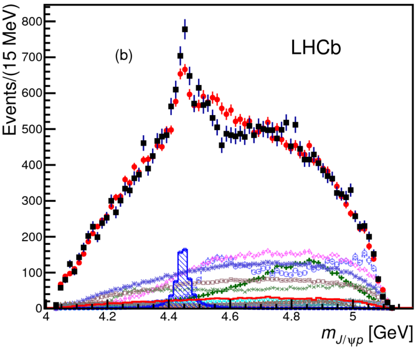




Λ^* reflections don't explain the structure in $m_{J/\Psi p}$ (with extended model including 2 additional Λ).

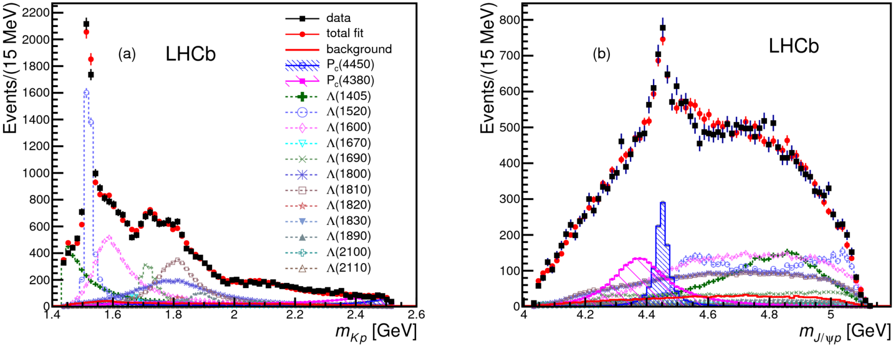
Extended Λ^* model with 1 P_c resonance ($J^P = 5/2^+$)





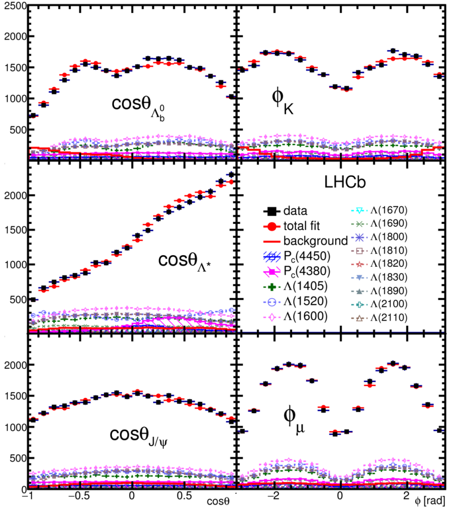
The $\Delta(-2\ln\mathcal{L})$ is reduced by 14.7^2 w.r.t to fit with only Λ states.

Reduced Λ^* model with 2 P_c resonances



- The $\Delta(-2\ln\mathcal{L})$ is reduced by 18.7^2 w.r.t to fit with only Λ states.
- Adding further states did not improve the fit significantly.

Fits to the angular distributions.



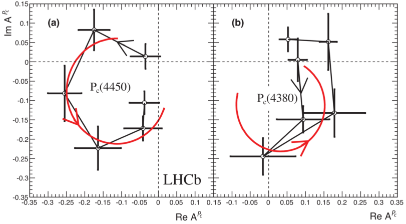
The amplitude fit of $\Lambda_b \to J/\Psi K^- p$ cannot be satisfactory described without two Breit-Wigner shaped resonances in the $J/\Psi p$ mass spectrum $P_C(4380)^+$ and $P_c(4450)^+$.

State	Mass [MeV]	Width [MeV]	fav. J^P	Fit fraction	Sign.
$P_c(4380)^+$	$4380 \pm 8 \pm 29$	$205 \pm 18 \pm 86$	$3/2^-$	$(8.4 \pm 0.7 \pm 4.2)\%$	9σ
$P_c(4450)^+$	$4449.8 \pm 1.7 \pm 2.5$	$39 \pm 5 \pm 19$	$5/2^+$	$(4.1 \pm 0.5 \pm 1.1)\%$	12σ

The branching fractions have been determined [Chin.Phys.C 40(2016)011001]:

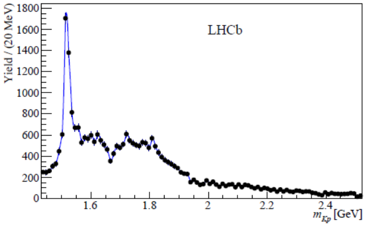
$$\mathcal{B}(\Lambda_b \to P_c^+ K^-)\mathcal{B}(P_c^+ \to J/\Psi p) = \begin{cases} (2.66 \pm 0.22 \pm 1.33^{+0.48}_{-0.38}) \times 10^{-5} & \text{for} \quad P_c(4380)^+ \\ (1.30 \pm 0.16 \pm 0.35^{+0.23}_{-0.18}) \times 10^{-5} & \text{for} \quad P_c(4450)^+ \end{cases}$$

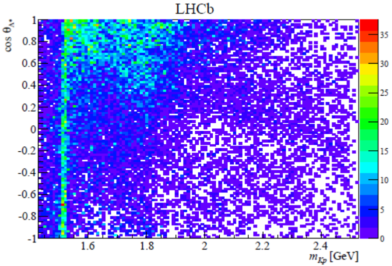
For the $P_c(4450)^+$ the Argand diagram is consistent with a rapid counter-clockwise change of phase.



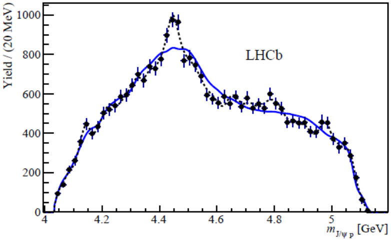
$\Lambda_b \to J/\Psi K^- p$ [Phys. Rev. Lett. 117, 082002 (2016)]

- The goal of this analysis is explain the structures observed in the pJ/Ψ invariant mass as a reflection of the activity of the conventional resonances on the $K^- p$ system.
- No model dependent assumptions are made. Instead, the $m_{K^- p}$ distribution is taken from data as it is.
- The angular structure of the $K^- p$ system is acquired via Legandre polynomials calculated from the Λ^* helicity angle.

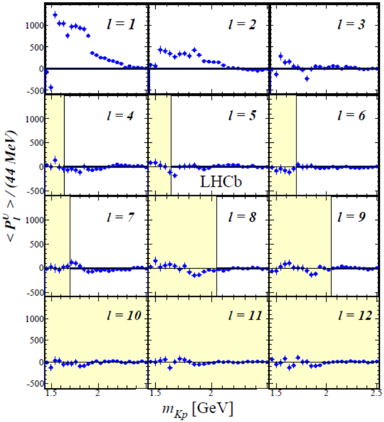




- The maximum order of the Legendre polynomials considered in each m_{K-p} slice is limited by the maximum spin of the Λ^* expected to give local contributions.
- A normalized weight is calculated and used to reweight simulated events to obtain a prediction for $m_{J/\psi\, p}$ distribution consistent with the conventional resonances contributions.
- The predicted distribution does not provide a satisfactory description of LHCb data.

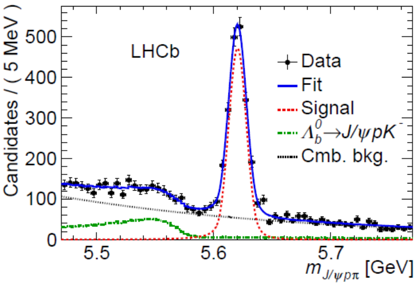


Legendre polynomials in function of m_{K-p}. Yellow shadowed areas are filtered out.

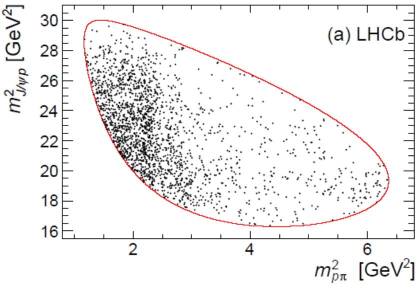


Evidence for exotic contribution to $\Lambda_b \to J/\Psi p\pi^-$

- Sample with 1885 ± 50 $\Lambda_b^0 \to J/\psi\, p\pi^-$ signal candidates,
- Analysis: six-dimensional amplitude fit (invariant masses, helicity and decay planes angles).
- Combinatorial background modeled by an exponential function and events from $\Lambda_b^0 \to J/\psi\, pK^-$ modeled using simulated samples.
- Six-dimensional efficiency calculated using complete simulation of the detector.

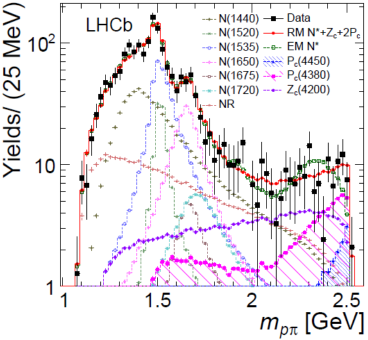


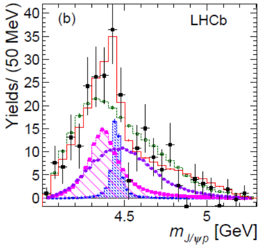
background subtracted Dalitz plot

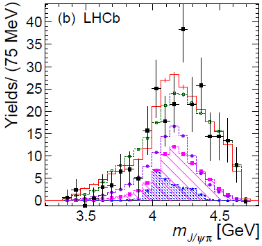


Evidence for exotic contribution to $\Lambda_b \to J/\Psi p \pi^-$

- Reduced Model. Including only well estabilished N^* resonances.
- Extended Model. Used to calculate systematic uncertainties and the significances.
- Exotic states contributions are necessary to achieve acceptable fit quality, mainly in the $m_{p\pi^-} > 1.8\,\mathrm{GeV}/c^2$ region.





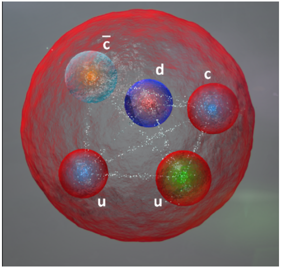


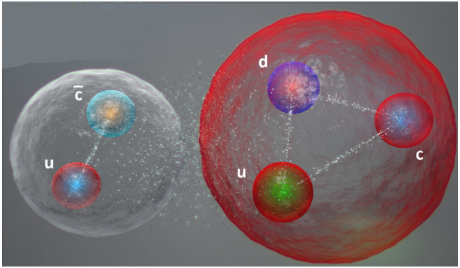
Evidence for exotic contribution to $\Lambda_b \to J/\Psi p \pi^-$

- Fit fractions from the RM + exotic states.
  - $P(4380)_c^+$: $(5.1 \pm 1.5^{+2.6}_{-1.6})\%$
  - $P(4450)_c^+$: $(1.6^{+0.8}_{-0.6}{}^{+0.6}_{-0.5})\%$
  - $Z_c(4200)^+$: $(7.7 \pm 2.8^{+3.4}_{-4.0})\%$
- When the two P_c^+ states are not considered, the fraction for the $Z_c(4200)^+$ state is $(17.2 \pm 3.5)\%$.
- Conversely, the fit fractions of the two P_c^+ states remain stable regardless of the inclusion of the $Z_c(4200)^+$ state.
- If both types of exotic resonances are included, the total significance for them is 3.1σ.
- Assuming that the $Z_c(4200)^+$ contribution is negligible, there is a 3.3σ significance for the two P_c^+ states taken together.

The P_c interpretations

- Tightly bound pentaquarks
  Jaffe, PRD15(1977)267
  Strottman, PRD20(1979)748
  Maiani et al., PRD71(2005)014028
- Molecular model with meson exchange for binding
  Törnqvist, Z.Phys.C61(1994)525
- Others:
  Rescattering
  PRD92(2015)071502





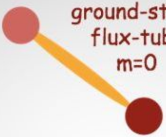
Summary and future perspective

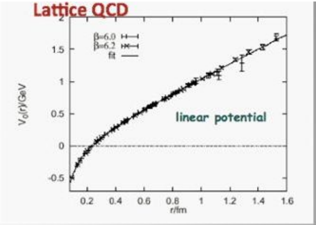
- With 3 fb^{-1} of data collected in Run I the LHCb provided a valuable contribution to the spectroscopy of exotic hadrons:
  - The quantum numbers of $X(3872)$ $J^{PC} = 1^{++}$ have been established.
  - The study of $X(3872)$ radiative decays disfavours their pure molecular interpretation.
  - The resonant nature of $Z(4430)^{-}$ has been confirmed.
  - Two exotic states in the $J/\Psi p$ channel with charmonium pentaquark interpretation have been discovered.
  - Family of $J/\Psi\phi$ resonances were studied with amplitude anaslysis and extended by 2 new states X(4500) and X(4700).
  - $B_s\pi^{\pm}$ state claimed by D0 was not confirmed with higher statistics.
- In Run 2 started in 2015 with an energy growth from 8 TeV to 13 TeV the $\sigma(c\bar{c})$ and $\sigma(b\bar{b})$ increased by $\approx$ 60%.
- The improvements in trigger system increased an output bandwidth $5\,\mathrm{kHz} \to 12\,\mathrm{kHz}$, which allows to record more data.
- Run 2 promises about twice as much $b\bar{b}$ and $c\bar{c}$ pair per fb^{-1}, and $\mathcal{L} \sim 5\, fb^{-1}$ compared to 3 fb^{-1} in Run 1.

Backup

Hybrid mesons

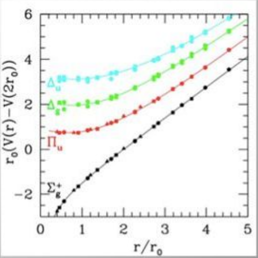
The normal mesons are built up from a "quark-antiquark pair" with a "ground-state" flux tube.





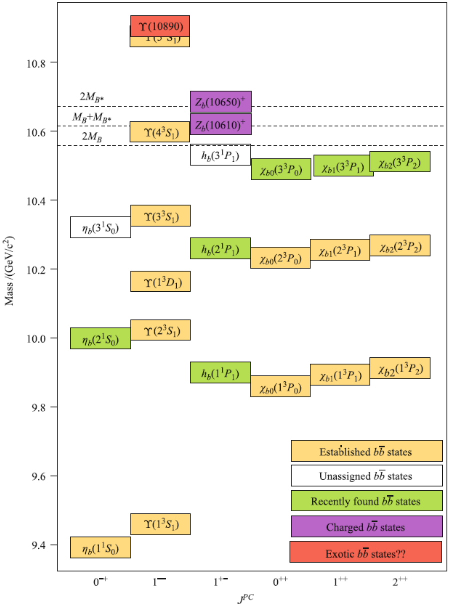
(π, K, η, η')	$(\rho, K^*, \omega, \Phi)$	(b_1, K_1, h_1, h_1')	$(\cdots)$
$J^{PC}=0^{-+}$	$J^{PC}=1^{--}$	$J^{PC}=1^{+-}$	$0^{++},1^{++},2^{++},2^{--},2^{-+},3^{++},3^{--},3^{+-}$
$\langle S=0, L=0 \rangle$	$\langle S=1, L=0 \rangle$	$\langle S=0, L=1 \rangle$	$\langle S\neq 0, L\neq 1 \rangle$

Gluonic Excitations provide an experimental measurement of the excited QCD potential



July 7, 2009 GlueX - ACTS 2009 - David Lawrence 3

Bottomonium mesons



Future perspectives for pentaquark search

- Search for isospin partners (replace $u\bar{u}$ with $d\bar{d}$): $\Lambda_b \to P_c^0 K^0 \to J/\Psi n K^0$ *or* $J/\Psi p \pi^- K^0$
- Search for strange partners (replace $u\bar{u}$ with $s\bar{s}$): $\Lambda_b \to P_{cs}^0 \phi \to J/\Psi \Lambda \phi$
- Di-quark model suggestion: $\Lambda_b \to \pi J/\Psi \Sigma(1385)$ $\Lambda_b \to K J/\Psi \Sigma(1385)$

$\Lambda_b \to J/\Psi K^- p$

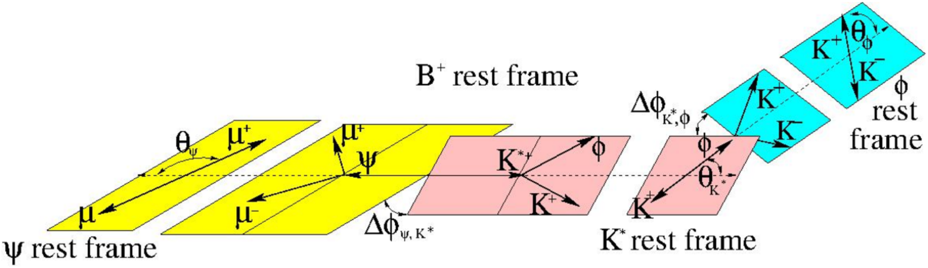
State	J^P	M_0 (MeV)	Γ_0 (MeV)	# Reduced	# Extended
$\Lambda(1405)$	$1/2^-$	$1405.1^{+1.3}_{-1.0}$	50.5 ± 2.0	3	4
$\Lambda(1520)$	$3/2^-$	1519.5 ± 1.0	15.6 ± 1.0	5	6
$\Lambda(1600)$	$1/2^+$	1600	150	3	4
$\Lambda(1670)$	$1/2^-$	1670	35	3	4
$\Lambda(1690)$	$3/2^-$	1690	60	5	6
$\Lambda(1800)$	$1/2^-$	1800	300	4	4
$\Lambda(1810)$	$1/2^+$	1810	150	3	4
$\Lambda(1820)$	$5/2^+$	1820	80	1	6
$\Lambda(1830)$	$5/2^-$	1830	95	1	6
$\Lambda(1890)$	$3/2^+$	1890	100	3	6
$\Lambda(2100)$	$7/2^-$	2100	200	1	6
$\Lambda(2110)$	$5/2^+$	2110	200	1	6
$\Lambda(2350)$	$9/2^+$	2350	150	0	6
$\Lambda(2585)$	?	$\approx$2585	200	0	6

$\Lambda_b \to J/\Psi K^- p$

- Two Λ^* models: extended (146 fit parameters) - to explore model space and reduced (64 fit parameters) - to keep non-vanishing components for final results.
- Two fitters to cross-check background treatment:
  - sFit : subtract background with the sWeight method
  - cFit : explicitly model background from sidebands (default)

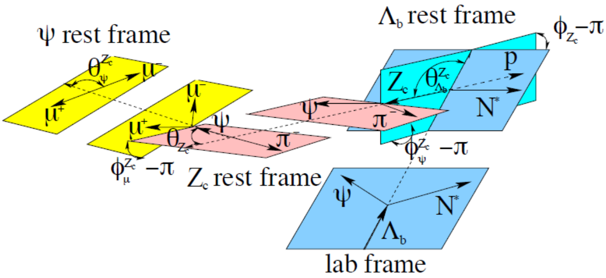
Exotics in $J/\Psi\phi$ final state

Definition of the θ_{K^*}, $\theta_{J/\Psi}$, θ_ϕ, $\Delta\phi_{K^*,J/\Psi}$ and $\Delta\phi_{K^*,\phi}$ angles describing angular correlations in $B^+ \to J/\Psi K^{*+}$, $J/\Psi \to \mu^+\mu^-$, $K^* \to \phi K^+$, $\phi \to K^+K^-$ decays.



Evidence for exotic contribution to $\Lambda_b \to J/\Psi p\pi^-$

- Three parametizations: $\Lambda_b^0 \to (P_c^+ \to J/\psi\, p)\pi^-$, $\Lambda_b^0 \to (Z_c(4200)^+ \to J/\psi\, \pi^-)p$ and $\Lambda_b^0 \to J/\psi\, (N^* \to p\pi^-)$, with $J/\psi \to \mu^+\mu^-$.
- Six-dimensional amplitude fit: resonance invariant mass, three helicities angles, and two differences between decay planes.
- Lorentz transformations relates the two helicity representantions.



- Resonances described by Breit-Wigner.
- Angular distribution calculated using helicity formalism.