Spectroscopy and Exotics at LHCb

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2nd May, 2016

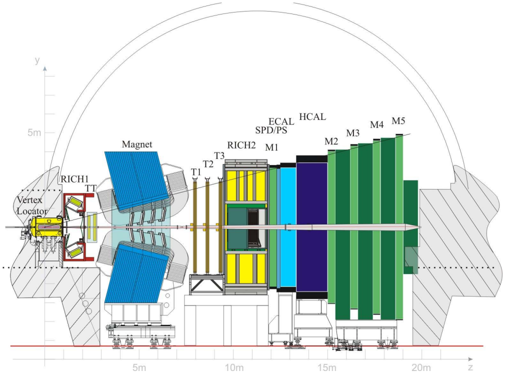
on behalf of the LHCb Collaboration

THE UNIVERSITY of EDINBURGH

Outline

- Wide range of spectroscopy analyses performed at LHCb
- Talk will focus on most recent results
- Will cover meson spectroscopy and exotics
  - D_s^+ spectroscopy in inclusive $D^* K$
  - Light spectroscopy in $D^0 \to K_S^0 K^+ \pi^-$
  - Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$
  - Tetraquark search in $B_s^0 \pi^\pm$
- All results based on analyses of full Run I dataset

The LHCb Detector



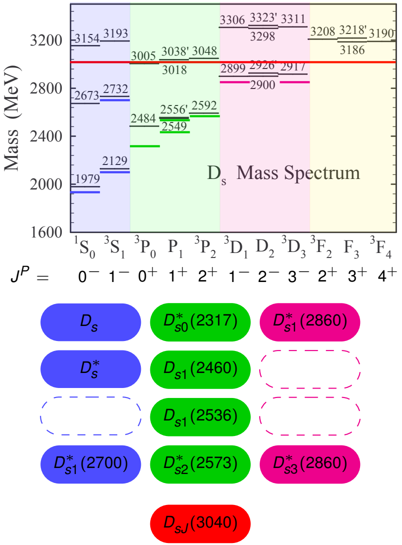
- Instrumentation in the forward region ($2 < \eta < 5$)
- Excellent vertex reconstruction
- Precise tracking before and after magnet
- Good PID separation up to $\sim 100\,\mathrm{GeV}/c$

Int. J. Mod. Phys. A 30 (2015) 1530022

D_s^+ Spectroscopy

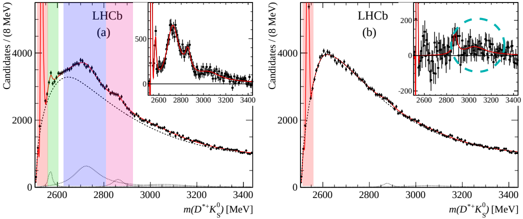
PRD 89 (2014) 074023

- Meson spectroscopy tests refine models of QCD
- D_s^+ mesons particularly interesting with one heavy and one light quark
- Unexpected large mass splitting seen between the 1P states PRL 90 (2003) 242001
- Two states recently observed by LHCb considered two of the four 1D states PRL 113 (2014) 162001
- At least three more states expected up to 3 GeV/c^2
  - all with unnatural J^P



D_s^+ Spectroscopy

- Inclusive analysis of $pp \to D^{*+} K_S^0 X$ and $D^{*0} K^+ X$ decays
- Use $D^{*+} \to D^0 \pi^+$, $D^0 \to K^- \pi^+$ (shown) or $K^- \pi^+ \pi^+ \pi^-$ and $D^{*0} \to D^0 \pi^0$, $D^0 \to K^- \pi^+$ decay chains
- Builds on previous analyses of $D^0 K^+$
- Access to natural (NP) and unnatural (UP) spin-parities
- Plots show (a) $|\cos\theta_H| < 0.5$ and (b) > 0.5 to emphasise NP and UP components
  - Resonant contributions seen due to $\boldsymbol{D_{s1}(2536)^+}$, $\boldsymbol{D^*_{s2}(2573)^+}$, $\boldsymbol{D^*_{s1}(2700)^+}$ and $\boldsymbol{D^*_{s3}(2860)^+}$ resonances
  - Weak evidence for structure around $\mathbf{3\ GeV/}c^2$



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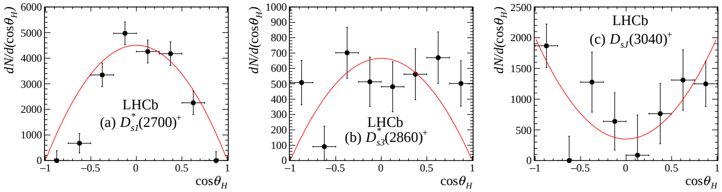
D_s^+ Spectroscopy

- NP and UP resonances identified by helicity angle distribution of D^* decay
- NP resonances follow $\sin^2\theta_H$ distribution
- UP resonances follow $1 + h\cos^2\theta_H$
- Expected distributions seen for (a–c) $D_{s1}^*(2700)^+$, $D_{s3}^*(2860)^+$ and $D_{sJ}(3040)^+$
- Data consistent with additional UP contribution in $2.86\,\mathrm{GeV}/c^2$ region



JHEP 02 (2016) 133

D_s^+ Spectroscopy

- First observation of $D_{s2}^*(2573)^+ \to D^{*+}K_S^0$ decay
- Branching ratio relative to $D_{s2}^*(2573)^+ \to D^+K_S^0$ measured to be

$$\frac{\mathcal{B}(D_{s2}^*(2573)^+ \to D^{*+}K_S^0)}{\mathcal{B}(D_{s2}^*(2573)^+ \to D^+K_S^0)} = 0.044 \pm 0.005\,(\text{stat.}) \pm 0.011\,(\text{syst.})$$

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$D^0 \to K_S^0 K^\pm \pi^\mp$

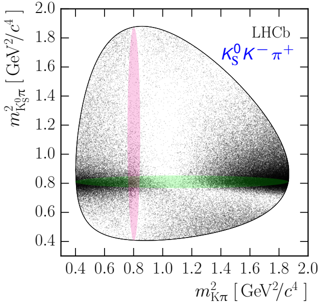
- Dalitz plot (DP) analysis of $D^0 \to K_S^0 K^\pm \pi^\mp$ of interest to determine *CP* violation as a function of position in the phasespace
- Amplitude model would offer improved sensitivity to the CKM angle γ in analyses using these final states compared to the alternative "coherence factor" approach
- Also an excellent environment in which to study light-flavour spectroscopy
- Use $D^{*+} \to D^0 \pi^+_{\rm slow}$, $D^0 \to K_S^0 K^\pm \pi^\mp$ decay chain
- Charge of the slow pion tags flavour of D^0 meson

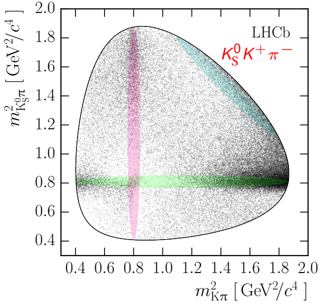
PRD 93 (2016) 052018

- Analysis uses pure sample of 110 000 $D^0 \to K_S^0 K^- \pi^+$ and 80 000 $D^0 \to K_S^0 K^+ \pi^-$ decays
- DP distributions show clear structures in $m(K_S^0 \pi^\pm)$ and in $m(K^\mp \pi^\pm)$
- Structure also in $m(K_S^0 K^+)$
- Model constructed using the isobar formalism

$$\mathcal{M}_{K_S^0 K^\pm \pi^\mp}(m_{K_S^0 \pi^\pm}, m_{K^\mp \pi^\pm}) = \sum_R a_R e^{i\phi_R} \mathcal{M}_R(m_{K_S^0 \pi^\pm}, m_{K^\mp \pi^\pm})$$

- Two alternative models used for complicated $K\pi$ S-wave components – GLASS and LASS





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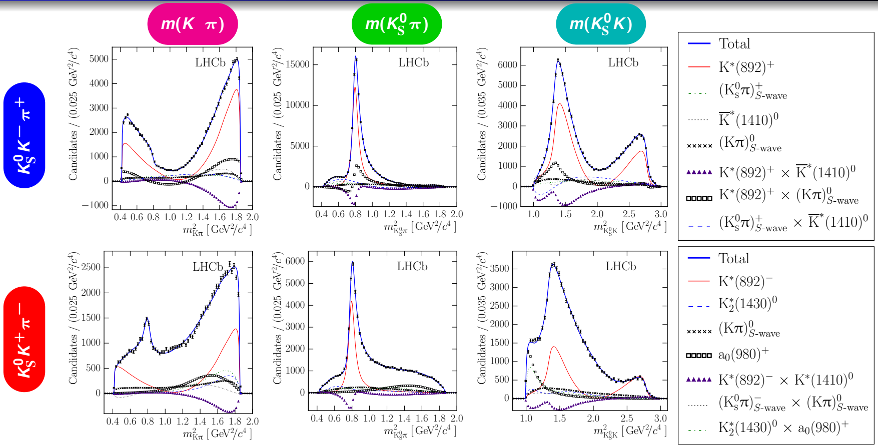
$D^0 \to K^0_S K^\pm \pi^\mp$



- Both fit models (GLASS shown) give good agreement with mass projections of datasets
- Models favour small (~ 1 %) but significant contributions ($2\Delta LL > 150$) from $\rho(1450, 1700)^\pm$ resonances previously seen by OBELIX Eur. Phys. J C26 (2003) 371

PRD 93 (2016) 052018

$D^0 \to K_S^0 K^\pm \pi^\mp$

- No significant *CP* violation observed
- Consistent with *CP* conservation with *p*-value of 0.54 (0.45) for GLASS (LASS) fit model
- BF ratios measured for the full decay and the $K^*(892)^\pm K^\mp$ region

$$\frac{\mathcal{B}(D^0 \to K_S^0 K^+ \pi^-)}{\mathcal{B}(D^0 \to K_S^0 K^- \pi^+)} = 0.655 \pm 0.004\,(\text{stat.}) \pm 0.006\,(\text{syst.})\,,$$

$$\frac{\mathcal{B}(D^0 \to K^{*-} K^+)}{\mathcal{B}(D^0 \to K^{*+} K^-)} = 0.370 \pm 0.003\,(\text{stat.}) \pm 0.012\,(\text{syst.})$$

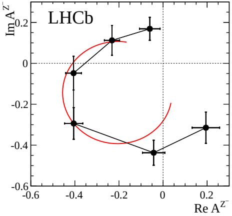
- Improved measurements of coherence factors (shown for GLASS model)

$$R_{K_S^0 K\pi} = 0.573 \pm 0.007 \pm 0.019 \quad R_{K^* K} = 0.831 \pm 0.004 \pm 0.010$$

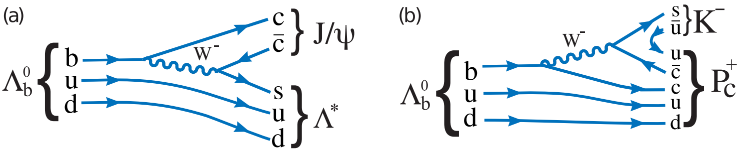
PRD 93 (2016) 052018

Exotics

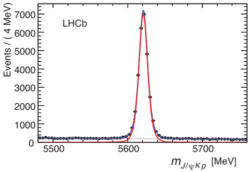
- Various LHCb analyses have observed/confirmed exotic states
- Resonant nature of $Z(4430)$ determined from $B^0 \to \psi(2S)\pi^- K^+$ decays PRL 112 (2014) 222002 PRD 92 (2015) 112009
  - Observation confirmed by model-independent analysis
- Quantum numbers of $X(3872)$ confirmed from $B^+ \to J/\psi\,\rho^0 K^+$ decays PRD 92 (2015) 011102
- Will focus on most recent results...

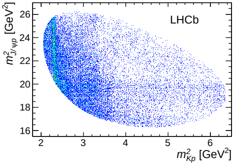


Pentaquarks – $\Lambda_b^0 \to J/\psi\, pK^-$



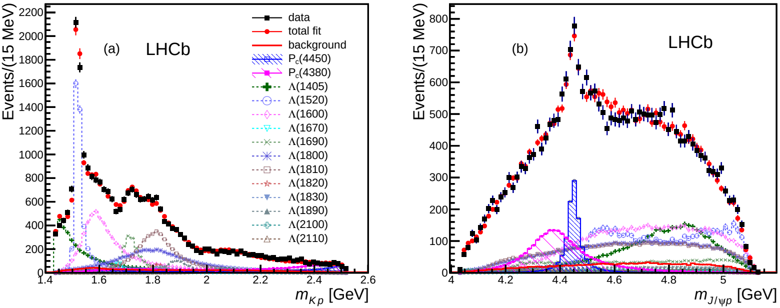
- Feynman diagrams contributing to $\Lambda_b^0 \to J/\psi\, pK^-$ allow for resonant contributions in (a) $m(pK^-)$ or (b) $m(J/\psi\, p)$
- Resonances in $m(J/\psi\, p)$ have a minimum quark content of $c\bar{c}uud$
- Recent LHCb analysis based on a pure sample of 26 000 signal decays
- 6D amplitude analysis performed

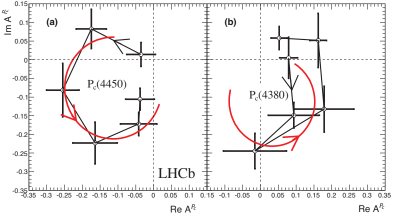




PRL 115 (2015) 072001

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



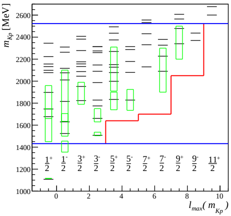


- Two peaking components in $m(J/\psi\, p)$ with opposite parities required to fit data
- Phase motion of each component consistent with that of a resonance

PRL 115 (2015) 072001

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

- Could data be explained entirely by $m(pK^-)$ structures?
- Test hypothesis with model-independent analysis
- Bin data in $m(pK^-)$
- Describe angular distribution in each mass bin with sum of Legendre polynomials $\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{\max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$

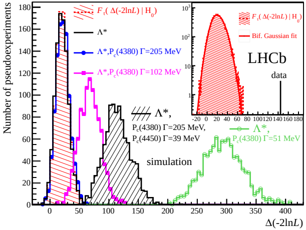


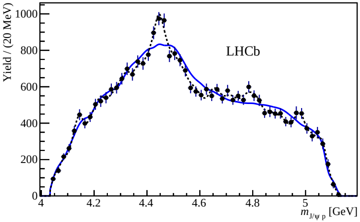
- Λ^* resonances of spin j give non-zero contributions up to $2j^{\text{th}}$ moment $\langle P_{2j}^U \rangle$
- Higher spin resonances are heavier
- Use **theoretical predictions** and **experimental results** to set $\boldsymbol{l_{\max}(m_{pK^-})}$ for all masses within the **kinematically allowed range**

arXiv:1604.05708

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

- Resonances in $m(J/\psi\, K^-)$ or $m(J/\psi\, p)$ introduce sharp structures in the angular distribution
- Compare null hypothesis (moments up to $l_{\rm max}$) with alternative hypothesis (include higher moments)
- Construct DLL from ratio of likelihoods and compare data to toys assuming null hypothesis
- (Left) reject null hypothesis with significance $> 9\sigma$
- (Right) null hypothesis gives poor description of $m(J/\psi\, p)$



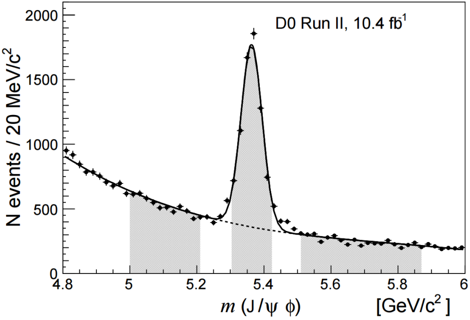


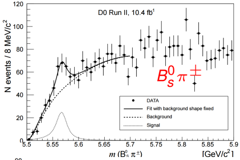
arXiv:1604.05708

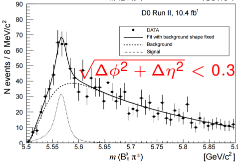
$B_s^0\pi^\pm$ spectroscopy

- $X(5568)^\pm \to B_s^0\pi^\pm$ decay reported by D0 in February with a significance of 5.1σ
- Signal implies large production rate within D0 acceptance

$$\rho_X^{\text{D0}} \equiv \left.\frac{\sigma(p\bar{p}\to X+\text{anything})\times\mathcal{B}(X\to B_s^0\pi)}{\sigma(p\bar{p}\to B_s^0+\text{anything})}\right|_{\text{D0Acc.}}$$
$$= (8.6\pm1.9\pm1.4)\%$$





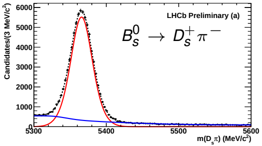


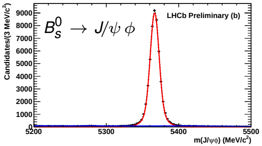
arXiv:1602.07588

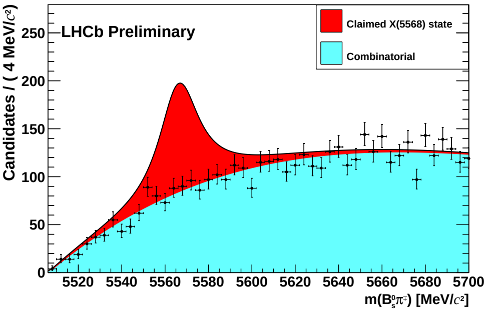
$B_s^0\pi^\pm$ spectroscopy

- LHCb search first reported at Moriond
- Study based on large clean samples of B_s^0 decays
- (Right) no peak observed in $m(B_s^0\pi)$ from $X(5568)$
- Upper limits set on production in the LHCb acceptance

$$\rho_{X,}^{\text{LHCb}} < \begin{cases} 0.009\ (0.010)\ @\ 90\ (95)\ \%\ \text{CL} \\ 0.016\ (0.018)\ @\ 90\ (95)\ \%\ \text{CL} \end{cases} \quad p_{\text{T}\,B_s^0} > \begin{cases} 5\,\text{GeV}/c \\ 10\,\text{GeV}/c \end{cases}$$







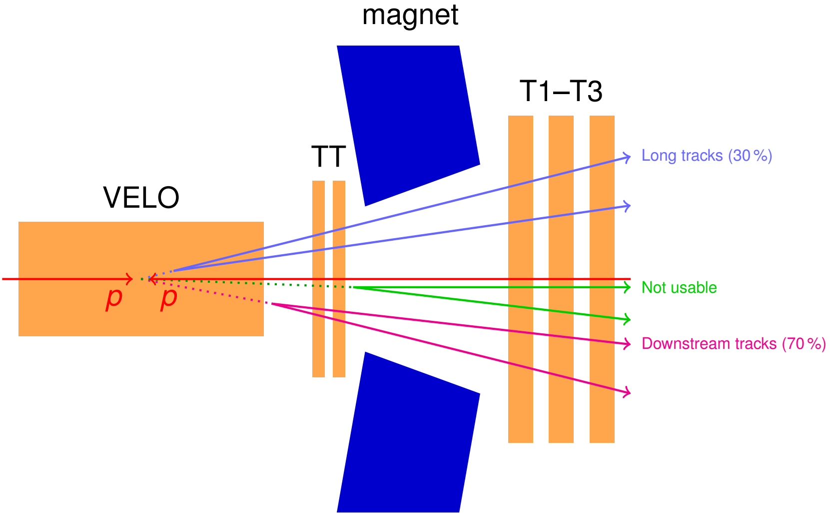
LHCb-CONF-2016-004

Summary

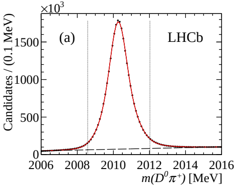
- **Inclusive $D^* K$** spectroscopy gives **first observation** of $D^*_{s2}(2573)^\pm \to D^{*\pm} K^0_S$
- Dalitz plot analysis of $D^0 \to K^0_S K^\pm \pi^\mp$ shows **no significant *CP* violation** but significant $\rho(1450, 1700)^\pm \to K^0_S K^\pm$ contributions
- **Model-independent analysis** supports **pentaquark** hypothesis for structures in $J/\psi\, pK^-$
- **No sign of $X(5568)$** tetraquark candidate within LHCb acceptance with **10× D0 statistics**

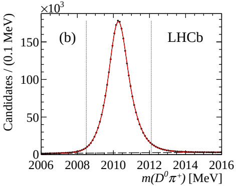
Backup

K_S^0 Categories



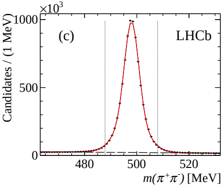
D_s^+ Spectroscopy

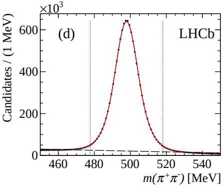


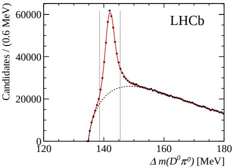


$D^{*+} \to D^0\pi^+$ candidates reconstructed from (a) $D^0 \to K^-\pi^+$ and (b) $D^0 \to K^-\pi^+\pi^+\pi^-$

$K_S^0 \to \pi^+\pi^-$ candidates reconstructed from (c) "long" tracks and (d) "downstream" tracks







$m(D^0\pi^0) - m(D^0) - m(\pi^0)$ for $D^{*0} \to D^0\pi^0$ candidates

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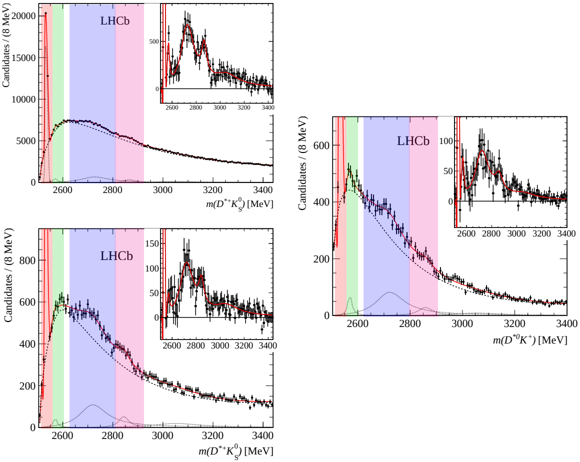
D_s^+ Spectroscopy



(Left) $m(D^{*+}K^0_S)$ for (top) $D^0 \to K^-\pi^+$ and (bottom) $K^-\pi^+\pi^+\pi^-$
(Right) $m(D^{*0}\pi^0)$ for $D^0 \to K^-\pi^+$

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D_s^+ Spectroscopy

Data		$D_{s1}^*(2700)^+$	$D_{sJ}^*(2860)^+$	χ^2/ndf
(a) $D^{*+}K_S^0$	Mass	$2732.3 \pm 4.3 \pm 5.8$	$2867.1 \pm 4.3 \pm 1.9$	
$D^0 \to K^-\pi^+$	Width	$136 \pm 19 \pm 24$	$50 \pm 11 \pm 13$	
	Yield	$(1.57 \pm 0.28) \times 10^4$	$(3.1 \pm 0.8) \times 10^3$	94/103
	Significance	8.3	6.3	
(b) $D^{*+}K_S^0$	Mass	2729.3 ± 3.3	2861.2 ± 4.3	
$D^0 \to K^-\pi^+$	Width	136 (fixed)	57 ± 14	
NP sample	Yield	$(1.50 \pm 0.11) \times 10^4$	$(2.50 \pm 0.60) \times 10^3$	90/104
	Significance	7.6	7.1	
(c) $D^{*+}K_S^0$	Mass	2732.3 (fixed)	2876.7 ± 6.4	
$D^0 \to K^-\pi^+$	Width	136 (fixed)	50 ± 19	
UP sample	Yield	$(0 \pm 0.8) \times 10^3$	$(1.0 \pm 0.4) \times 10^3$	100/105
	Significance	0.0	3.6	
(d) $D^{*+}K_S^0$	Mass	2725.5 ± 6.0	2844.0 ± 6.5	
$D^0 \to K^-\pi^+\pi^+\pi^-$	Width	136 (fixed)	50 ± 15	
	Yield	$(2.6 \pm 0.4) \times 10^3$	490 ± 180	89/97
	Significance	4.7	3.8	
(e) $D^{*0}K^+$	Mass	2728.3 ± 6.5	2860.9 ± 6.0	
	Width	136 (fixed)	50 (fixed)	
	Yield	$(1.89 \pm 0.30) \times 10^3$	290 ± 90	79/99
	Significance	6.6	3.1	

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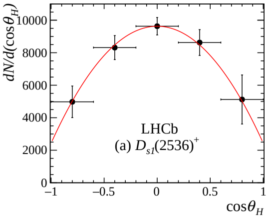
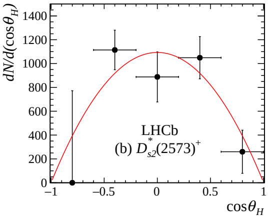
Resonance	J^P	Function	χ^2/ndf
$D_{s1}(2536)^+$	1^+	$1 + h\cos^2\theta_\text{H}$	0.1/3
$D_{s2}^*(2573)^+$	2^+	$\sin^2\theta_\text{H}$	2.2/4
$D_{s1}^*(2700)^+$	1^-	$\sin^2\theta_\text{H}$	11.4/7
$D_{s3}^*(2860)^+$	3^-	$\sin^2\theta_\text{H}$	13.4/7
$D_{sJ}(3040)^+$	UP	$1 + h\cos^2\theta_\text{H}$	8.0/6





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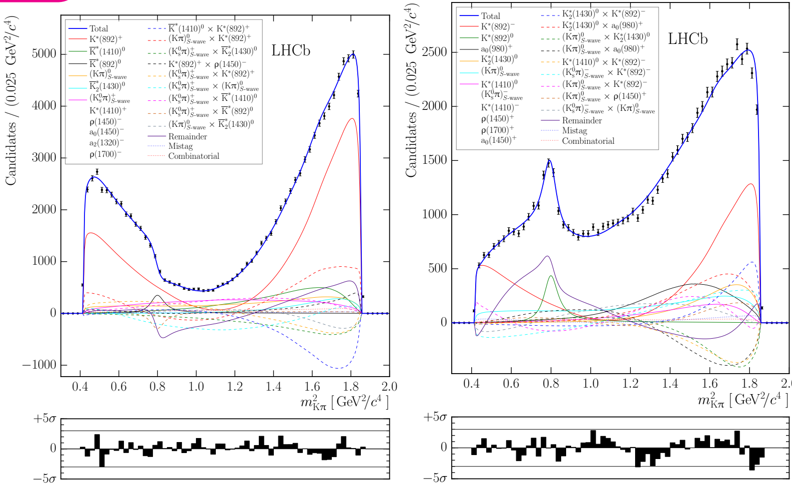
$D^0 \to K^0_S K^{\pm}\pi^{\mp}$

$m(K\ \pi)$

$K^0_S K^- \pi^+$ | $K^0_S K^+ \pi^-$



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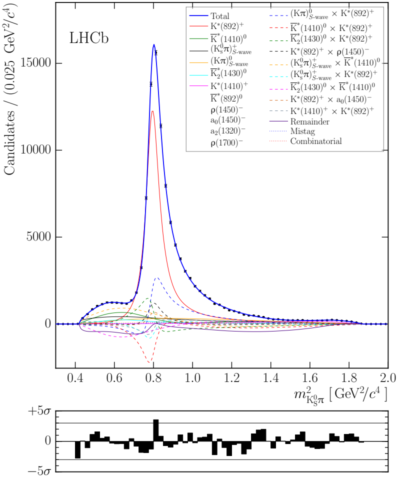
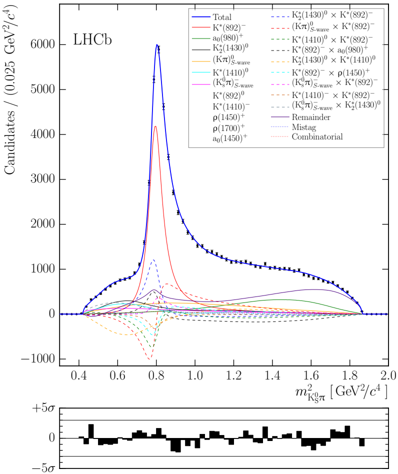
$D^0 \to K^0_S K^\pm \pi^\mp$

$m(K^0_S\pi)$

$K^0_S K^- \pi^+$



$K^0_S K^+ \pi^-$



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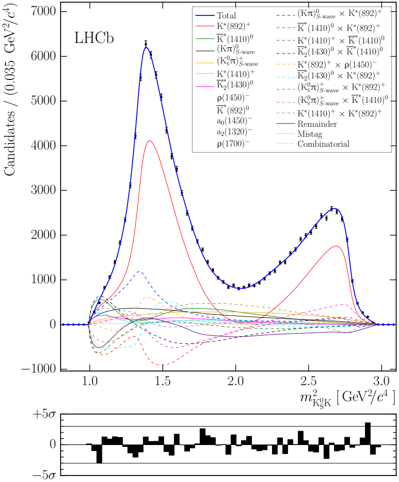
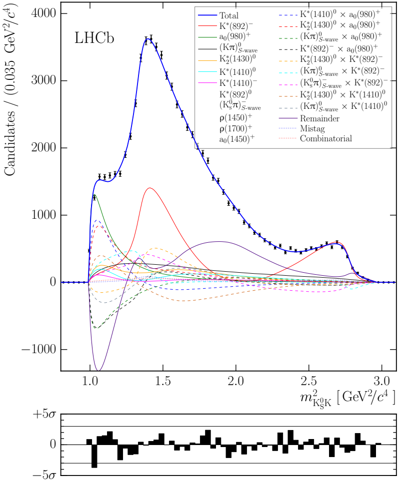
$D^0 \to K^0_S K^\pm \pi^\mp$

$m(K^0_S K)$

$K^0_S K^- \pi^+$ — **$K^0_S K^+ \pi^-$**





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$D^0 \to K^0_S K^\pm \pi^\mp$

Fixed parameters

Parameter		Value	
$K^*(892)^\pm$	m_R	891.66±0.26	MeV/c^2
	Γ_R	50.8±0.9	MeV/c^2
$K^*(1410)^\pm$	m_R	1.414±0.015	GeV/c^2
	Γ_R	0.232±0.021	GeV/c^2
$(K^0_S\pi)^\pm_{S\text{-wave}}$	m_R	1.435±0.005	GeV/c^2
	Γ_R	0.279±0.006	GeV/c^2
$K^*(892)^0$	m_R	895.94±0.22	MeV/c^2
	Γ_R	48.7±0.8	MeV/c^2
$K^*(1410)^0$	m_R	1.414±0.015	GeV/c^2
	Γ_R	0.232±0.021	GeV/c^2
$K^*_2(1430)^0$	m_R	1.4324±0.0013	GeV/c^2
	Γ_R	0.109±0.005	GeV/c^2
$(K\pi)^0_{S\text{-wave}}$	m_R	1.435±0.005	GeV/c^2
	Γ_R	0.279±0.006	GeV/c^2
	r	1.8±0.4	(GeV/c)$^{-1}$
	a	1.95±0.09	(GeV/c)$^{-1}$
$a_0(980)^\pm$	m_R	0.980±0.020	GeV/c^2
	$g_{\eta\pi}$	324±15	MeV
	$\frac{g^2_{K\bar{K}}}{g^2_{\eta\pi}}$	1.03±0.14	
$a_2(1320)^\pm$	m_R	1.3181±0.0007	GeV/c^2
	Γ_R	0.1098±0.0024	GeV/c^2
$a_0(1450)^\pm$	m_R	1.474±0.019	GeV/c^2
	Γ_R	0.265±0.013	GeV/c^2
$\rho(1450)^\pm$	m_R	1.182±0.030	GeV/c^2
	Γ_R	0.389±0.020	GeV/c^2
$\rho(1700)^\pm$	m_R	1.594±0.020	GeV/c^2
	Γ_R	0.259±0.020	GeV/c^2

Floated params (GLASS)

Parameter		Value	
$K^*(892)^\pm$	m_R	$893.1 \pm 0.1 \pm 0.9$	MeV/c^2
	Γ_R	$46.9 \pm 0.3 \pm 2.5$	MeV/c^2
$K^*(1410)^\pm$	Γ_R	$210 \pm 20 \pm 60$	MeV/c^2
$(K^0_S\pi)^\pm_{S\text{-wave}}$	F	1.785 (fixed)	
	a	$4.7 \pm 0.4 \pm 1.0$	(GeV/c)$^{-1}$
	ϕ_F	$0.28 \pm 0.05 \pm 0.19$	rad
	ϕ_S	$2.8 \pm 0.2 \pm 0.5$	rad
	r	$-5.3 \pm 0.4 \pm 1.9$	(GeV/c)$^{-1}$
$K^*(1410)^0$	m_R	$1426 \pm 8 \pm 24$	MeV/c^2
	Γ_R	$270 \pm 20 \pm 40$	MeV/c^2
$(K\pi)^0_{S\text{-wave}}$	F	$0.15 \pm 0.03 \pm 0.14$	
	a	$4.2 \pm 0.3 \pm 2.8$	(GeV/c)$^{-1}$
	ϕ_F	$-2.5 \pm 0.2 \pm 1.0$	rad
	ϕ_S	$-1.1 \pm 0.6 \pm 1.3$	rad
	r	$-3.0 \pm 0.4 \pm 1.7$	(GeV/c)$^{-1}$
$a_0(1450)^\pm$	m_R	$1430 \pm 10 \pm 40$	MeV/c^2
$\rho(1450)^\pm$	Γ_R	$410 \pm 19 \pm 35$	MeV/c^2
$\rho(1700)^\pm$	m_R	$1530 \pm 10 \pm 40$	MeV/c^2

Floated params (LASS)

Parameter		Value	
$K^*(892)^\pm$	m_R	$893.4 \pm 0.1 \pm 1.1$	MeV/c^2
	Γ_R	$47.4 \pm 0.3 \pm 2.0$	MeV/c^2
$K^*(1410)^\pm$	m_R	$1437 \pm 8 \pm 16$	MeV/c^2
$(K^0_S\pi)^\pm_{S\text{-wave}}$	b'_1	$60 \pm 30 \pm 40$	
	b'_2	$4 \pm 1 \pm 5$	
	b'_3	$3.0 \pm 0.2 \pm 0.7$	
$K^*(1410)^0$	m_R	$1404 \pm 9 \pm 22$	MeV/c^2
$(K\pi)^0_{S\text{-wave}}$	b'_1	$130 \pm 30 \pm 80$	
	b'_2	$-6 \pm 1 \pm 14$	
	b'_3	$2.5 \pm 0.1 \pm 1.4$	
	r	$1.2 \pm 0.3 \pm 0.4$	(GeV/c)$^{-1}$
$a_0(980)^\pm$	m_R	$925 \pm 5 \pm 8$	MeV/c^2
$a_0(1450)^\pm$	m_R	$1458 \pm 14 \pm 15$	MeV/c^2
	Γ_R	$282 \pm 12 \pm 13$	MeV/c^2
$\rho(1450)^\pm$	m_R	$1208 \pm 8 \pm 9$	MeV/c^2
$\rho(1700)^\pm$	m_R	$1552 \pm 13 \pm 26$	MeV/c^2

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$D^0 \to K^0_S K^\pm \pi^\mp$

CPV parameters for $D^0 \to K^0_S K^- \pi^+$

	Δa_R		$\Delta\phi_R(^\circ)$		Δ(Fit fraction) [%]	
Resonance	GLASS	LASS	GLASS	LASS	GLASS	LASS
$K^*(892)^+$	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	$0.6 \pm 1.0 \pm 0.3$	$0.9 \pm 1.0 \pm 0.3$
$K^*(1410)^+$	$0.07 \pm 0.06 \pm 0.04$	$0.03 \pm 0.06 \pm 0.04$	$3.9 \pm 3.5 \pm 1.9$	$2.0 \pm 2.9 \pm 1.9$	$1.4 \pm 0.8 \pm 0.2$	$1.2 \pm 1.6 \pm 0.2$
$(K^0_S\pi^+)_{\rm Swave}$	$0.02 \pm 0.08 \pm 0.07$	$-0.05 \pm 0.08 \pm 0.07$	$2.0 \pm 1.7 \pm 0.0$	$2.0 \pm 1.7 \pm 0.0$	$1 \pm 4 \pm 3$	$-2.3 \pm 3.5 \pm 3.3$
$\bar{K}^*(892)^0$	$-0.046 \pm 0.031 \pm 0.005$	$-0.051 \pm 0.030 \pm 0.005$	$1.2 \pm 1.6 \pm 0.3$	$1.5 \pm 1.7 \pm 0.3$	$-0.43 \pm 0.30 \pm 0.03$	$-0.47 \pm 0.29 \pm 0.03$
$\bar{K}^*(1410)^0$	$0.006 \pm 0.034 \pm 0.017$	$0.02 \pm 0.04 \pm 0.02$	$2 \pm 5 \pm 5$	$-3 \pm 6 \pm 5$	$0.3 \pm 1.0 \pm 0.1$	$0.4 \pm 0.7 \pm 0.1$
$(K^-\pi^+)_{\rm Swave}$	$0.05 \pm 0.04 \pm 0.02$	$0.03 \pm 0.04 \pm 0.02$	$0.4 \pm 1.6 \pm 0.6$	$1.0 \pm 1.4 \pm 0.6$	$2.2 \pm 1.3 \pm 0.4$	$2.6 \pm 2.2 \pm 0.4$
$a_2(1320)^-$	$-0.25 \pm 0.14 \pm 0.01$	$-0.24 \pm 0.13 \pm 0.01$	$2 \pm 9 \pm 3$	$-1 \pm 9 \pm 3$	$-0.20 \pm 0.13 \pm 0.05$	$-0.15 \pm 0.10 \pm 0.05$
$a_0(1450)^-$	$-0.01 \pm 0.14 \pm 0.12$	$-0.13 \pm 0.14 \pm 0.12$	$0 \pm 5 \pm 4$	$-4 \pm 6 \pm 4$	$-0.0 \pm 0.4 \pm 0.4$	$-0.4 \pm 0.4 \pm 0.4$
$\rho(1450)^-$	$0.06 \pm 0.13 \pm 0.11$	$-0.05 \pm 0.12 \pm 0.11$	$-13 \pm 10 \pm 9$	$-5 \pm 9 \pm 9$	$0.3 \pm 0.7 \pm 0.6$	$-0.3 \pm 0.7 \pm 0.6$

CPV parameters for $D^0 \to K^0_S K^+ \pi^-$

	Δa_R		$\Delta\phi_R(^\circ)$		Δ(Fit fraction) [%]	
Resonance	GLASS	LASS	GLASS	LASS	GLASS	LASS
$K^*(892)^-$	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	0.0 (fixed)	$-1.1 \pm 0.7 \pm 0.2$	$-0.9 \pm 0.7 \pm 0.2$
$K^*(1410)^-$	$0.05 \pm 0.12 \pm 0.08$	$-0.03 \pm 0.10 \pm 0.08$	$-6 \pm 4 \pm 3$	$-3.0 \pm 3.6 \pm 2.8$	$0.6 \pm 2.7 \pm 2.4$	$-2 \pm 4 \pm 2$
$(K^0_S\pi^-)_{\rm Swave}$	$0.10 \pm 0.25 \pm 0.24$	$-0.14 \pm 0.25 \pm 0.24$	$-7.7 \pm 3.4 \pm 0.0$	$-8 \pm 4 \pm 0$	$2 \pm 6 \pm 6$	$-4 \pm 6 \pm 6$
$K^*(892)^0$	$-0.010 \pm 0.024 \pm 0.001$	$-0.012 \pm 0.022 \pm 0.001$	$-1.4 \pm 2.9 \pm 2.2$	$0.8 \pm 2.8 \pm 2.2$	$-0.4 \pm 0.4 \pm 0.0$	$-0.4 \pm 0.4 \pm 0.0$
$K^*(1410)^0$	$0.10 \pm 0.10 \pm 0.09$	$0.19 \pm 0.13 \pm 0.09$	$-1 \pm 9 \pm 8$	$-9 \pm 9 \pm 8$	$1.9 \pm 1.1 \pm 0.2$	$1.6 \pm 0.8 \pm 0.2$
$(K^+\pi^-)_{\rm Swave}$	$-0.07 \pm 0.06 \pm 0.05$	$-0.12 \pm 0.06 \pm 0.05$	$-2 \pm 4 \pm 4$	$2 \pm 4 \pm 4$	$-4 \pm 5 \pm 5$	$-9 \pm 6 \pm 5$
$a_0(980)^+$	$0.06 \pm 0.04 \pm 0.01$	$0.052 \pm 0.025 \pm 0.008$	$-3 \pm 5 \pm 2$	$-0.9 \pm 3.1 \pm 2.2$	$2.2 \pm 2.8 \pm 2.4$	$4.6 \pm 3.3 \pm 2.4$
$a_0(1450)^+$	$-0.11 \pm 0.10 \pm 0.04$	$-0.07 \pm 0.07 \pm 0.04$	$10 \pm 8 \pm 5$	$5 \pm 6 \pm 5$	$-0.21 \pm 0.30 \pm 0.23$	$-0.4 \pm 0.4 \pm 0.2$
$\rho(1700)^+$	$-0.03 \pm 0.13 \pm 0.09$	$-0.12 \pm 0.13 \pm 0.09$	$4 \pm 6 \pm 2$	$2 \pm 5 \pm 2$	$-0.07 \pm 0.25 \pm 0.19$	$-0.27 \pm 0.27 \pm 0.19$

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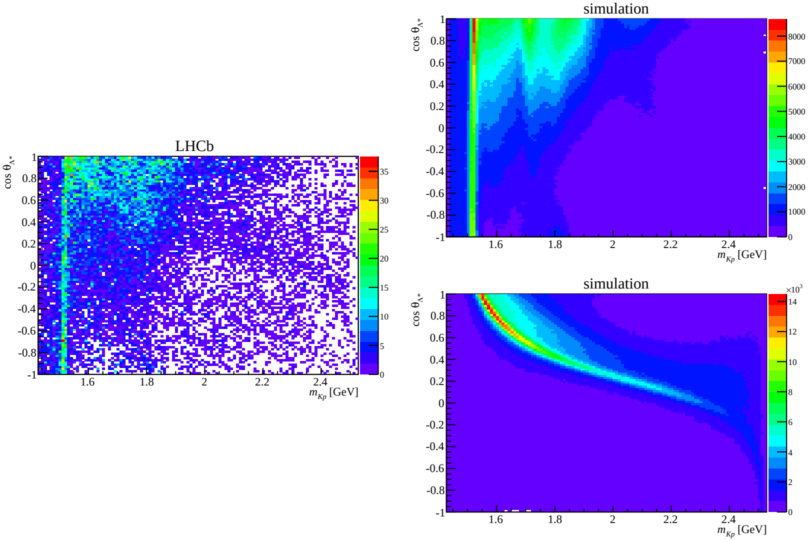
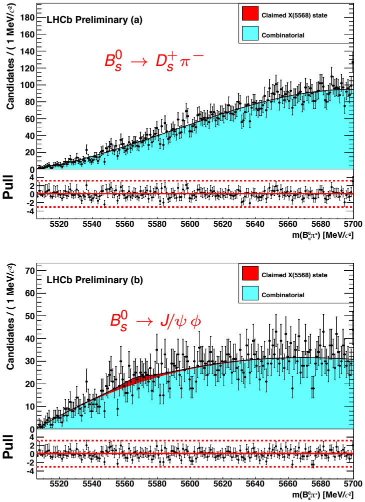
Pentaquarks – $\Lambda_b^0 \to J/\psi\, pK^-$

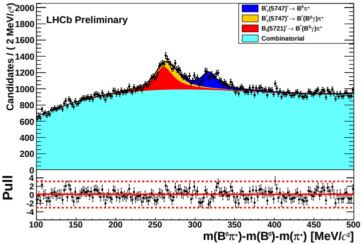


(Left) Dalitz plot distribution of data compared to simulated samples of (top) Λ^* resonances and (bottom) two pentaquarks

arXiv:1604.05708

$B_s^0\pi^\pm$ spectroscopy





(Left) Plots $m(B_s^0\pi^\pm)$ distributions with best-fit signal yields
(Right) Control fit to $m(B^0\pi^+)$ distribution

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$B_s^0\pi^\pm$ spectroscopy

		$B_s^0 \to D_s^-\pi^+$	$B_s^0 \to J/\psi\,\phi$	Sum
$N(B_s^0)$	B_s^0 $p_T > 5\,\mathrm{GeV}/c$ (10^3)	66.3 ± 0.3	46.3 ± 0.2	112.6 ± 0.4
$N(B_s^0)$	B_s^0 $p_T > 10\,\mathrm{GeV}/c$ (10^3)	30.1 ± 0.2	14.1 ± 0.1	44.2 ± 0.2
$N(X)$	B_s^0 $p_T > 5\,\mathrm{GeV}/c$	23 ± 55	-15 ± 37	8 ± 66
$N(X)$	B_s^0 $p_T > 10\,\mathrm{GeV}/c$	70 ± 48	11 ± 30	81 ± 57
$\epsilon^{\mathrm{rel}}(X)$	B_s^0 $p_T > 5\,\mathrm{GeV}/c$	0.141 ± 0.002	0.102 ± 0.001	—
$\epsilon^{\mathrm{rel}}(X)$	B_s^0 $p_T > 10\,\mathrm{GeV}/c$	0.239 ± 0.003	0.230 ± 0.003	—

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