Observation of a new charmonium and evidence of a new charged charmonium-like state at LHCb

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on behalf of the LHCb collaboration

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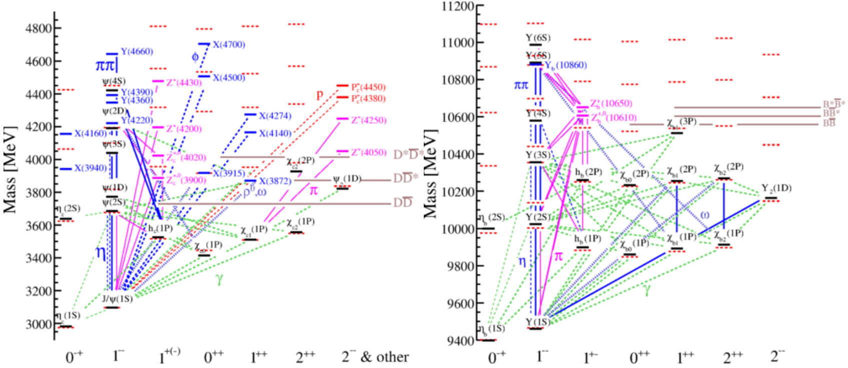
Heavy flavour spectroscopy at LHCb

- Thanks to the large centre-of-mass energy, LHC provides a large amount of $b\bar{b}$ and $c\bar{c}$ pairs
  - $\sim 10^{11} b\bar{b}$/yr in forward region
  - 20 times more for $c\bar{c}$
- Important as tests and inputs to QCD models
  - Various theoretical models make predictions on the heavy hadron production and properties
  - New states/decays provide inputs to theory
  - Many observed states still lack of interpretation: exotic states which are not fitting the standard picture

Exotic spectroscopy

- The observation of states with properties inconsistent with pure $c\bar{c}$ and $b\bar{b}$ states raised the interest of the so-called exotic (non-standard) quarkonium states from both the theoretical and experimental point of view starting from the discovery of the $X(3872)$ state
- Since then, a plethora of unexpected neutral (X, Y) and charged (Z^+, P_c^+) states have been discovered
- The nature and the internal structure of these states are still unclear (molecular/tightly bound): many efforts needed to uncover their nature



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

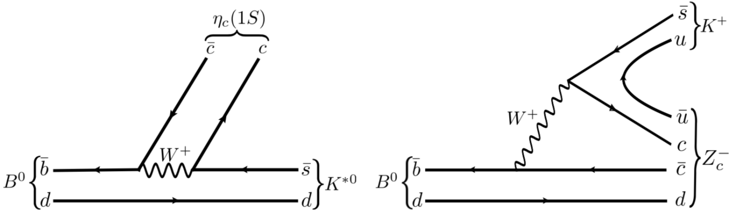
Evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays

EPJC 78 (2018) 1019

$\eta_c\pi^-$ resonance in $B^0 \to \eta_c K^+\pi^-$: motivations

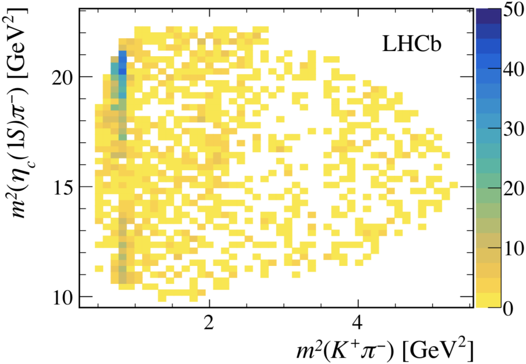
- Predictions of $\eta_c\pi^-$ states depending on the model used to describe the $Z_c(3900)^-$ discovered by BESIII [PRL 110 (2013) 252001]
  - hadrocharmonium state: charged charmonium-like state of mass $\sim 3800\,\mathrm{MeV}$ [PRD87 (2013) 091501]
  - quarkonium hybrids: prediction of states with quantum numbers allowing the decay into the $\eta_c\pi^-$ system
- Using the diquark model: a $J^P = 0^+$ exotic candidate below the open-charm threshold decaying to $\eta_c\pi^-$ [PRD71 (2005) 014028]

Search for possible exotic states in the $\eta_c\pi^-$ invariant mass using $B^0 \to \eta_c K^+\pi^-$ decays



$B^0 \to \eta_c(1S)K^+\pi^-$: analysis strategy [EPJC 78 (2018) 1019]

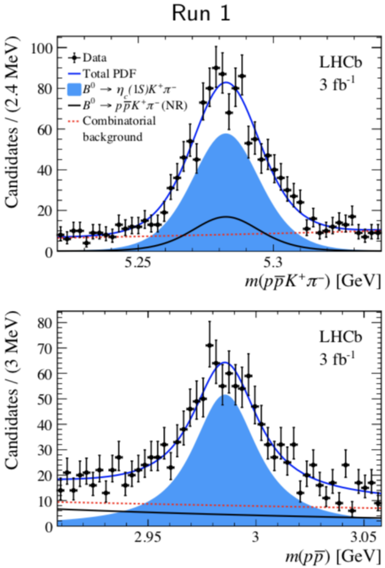
- Using $L \sim 4.7\,\mathrm{fb}^{-1}$, Run1+Run2 data (2011-2016)
- η_c reconstructed in $p\bar{p}$ final state (fully hadronic mode thanks to the excellent performance of the charged hadron identification by the RICH detectors)
- Isolate $B^0 \to \eta_c K^+\pi^-$ signal candidates from non-resonant $B^0 \to p\bar{p}K^+\pi^-$ and combinatorial background candidates
- Perform a Dalitz plot (DP) analysis to search for exotic hadrons



Dalitz analysis strategy [EPJC 78 (2018) 1019]

- The $B^0 \to \eta_c(1S)K^+\pi^-$ decay involves only pseudo-scalar particles: fully described by only two independent kinematic quantities $[m^2(K^+\pi^-), m^2(\eta_c\pi^-)]$
- Dalitz plot analysis using the Laura++ package
- Sizeable natural width of the η_c meson $[(32.0 \pm 0.8)\,\mathrm{MeV}]$:
  - Kinematic quantities ($m^2(K^+\pi^-), m^2(\eta_c\pi^-)$ + helicity angles) calculated using the $m(p\bar{p})$ instead of the known value of the η_c mass
  - Natural width of the η_c is set to zero when computing the DP normalisation (taken into account in the systematic uncertainties)
- Isobar model used to write the decay amplitude: $K^+\pi^-$ S-wave at low mass ($m(K^+\pi^-) \lesssim 1.7\,\mathrm{GeV}$) parametrised using the LASS PDF, Breit Wigner PDFs for the other $K^+\pi^-$ resonances
- Run1 and Run2 subsamples fitted simoultaneously using the JFIT framework: free parameters are in common, signal and background yields and the efficiency maps are different between the two subsamples

$B^0 \to \eta_c(1S)K^+\pi^-$: signal [EPJC 78 (2018) 1019]

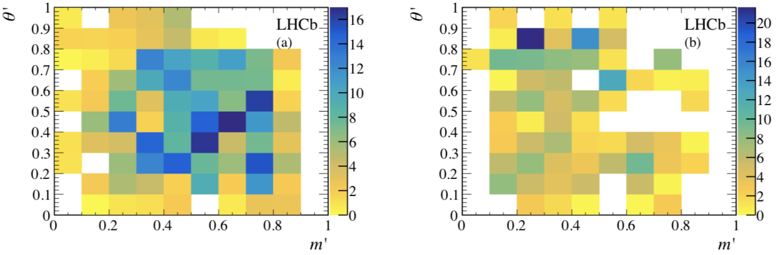


- 2D fit to $m(p\bar{p}K^+\pi^-)$ and $m(p\bar{p})$ distributions
- to subtract non-resonant $B^0 \to p\bar{p}K^+\pi^-$ and combinatorial background candidates
- fitting separately Run1 and Run2 data
- D^0 and Λ_c^+ vetoes

Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	805 ± 48	1065 ± 56
$B^0 \to p\bar{p}K^+\pi^-$ (NR)	234 ± 48	273 ± 56
Combinatorial background	409 ± 36	498 ± 41

Dalitz analysis strategy: background [EPJC 78 (2018) 1019]

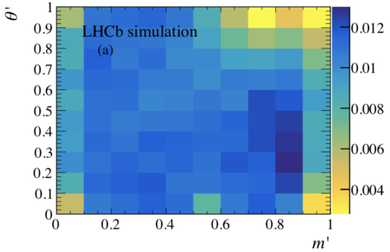
- Background parametrisation
  - sPlot technique from the joint 2D $m(p\bar{p}K^{+}\pi^{-}), m(p\bar{p})$ fit is used to extract combinatorial and nonresonant background histograms (which are then included in the amplitude fit)
  - Histograms are built using the Square Dalitz plot (SDP) in order to avoid artefacts related to the curved boundaries of the DP
  - Smoothing procedure applying a 2D cubic spline interpolation



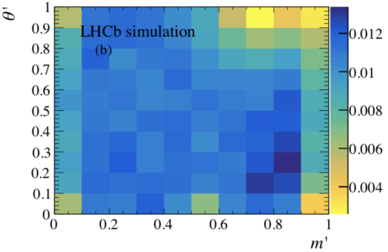
Combinatorial bkg NR bkg

Dalitz plot analysis: efficiency [EPJC 78 (2018) 1019]

- Efficiency variation across the SDP caused by the detector acceptance and the (trigger, offline) selection procedure
- Evaluated with simulated samples generated uniformly across the SDP
- Reweighting procedure to take into account known differences between data and simulation
- Efficiency studied separately for the Run1 and Run2 subsamples
- Smoothing procedure using a 2D cubic spline interpolation



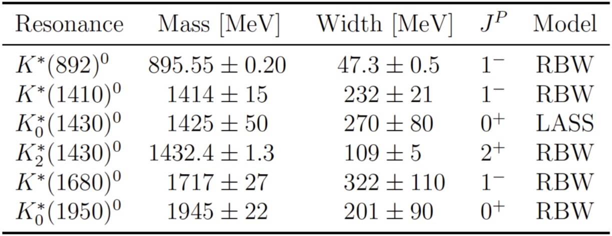
Run 1 efficiency



Run2 efficiency

Dalitz plot analysis: contributions [EPJC 78 (2018) 1019]

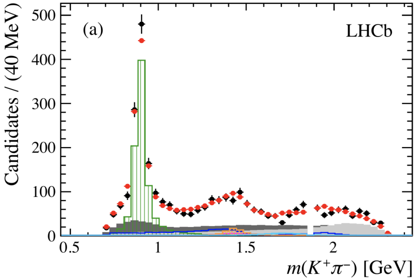
- Non-exotic contributions from K^* resonances with $m(K^*) \lesssim m(B^0) - m(\eta_c)$
- Only amplitudes giving significant improvements in the description of the data are retained
- Baseline model includes 6 K^{*0} resonances

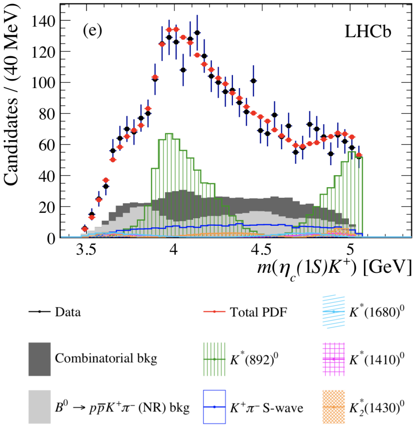


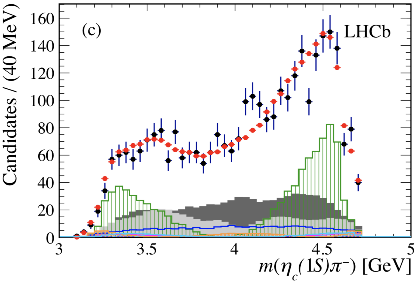
Resonance	Mass [MeV]	Width [MeV]	J^P	Model
$K^*(892)^0$	895.55 ± 0.20	47.3 ± 0.5	1^-	RBW
$K^*(1410)^0$	1414 ± 15	232 ± 21	1^-	RBW
$K_0^*(1430)^0$	1425 ± 50	270 ± 80	0^+	LASS
$K_2^*(1430)^0$	1432.4 ± 1.3	109 ± 5	2^+	RBW
$K^*(1680)^0$	1717 ± 27	322 ± 110	1^-	RBW
$K_0^*(1950)^0$	1945 ± 22	201 ± 90	0^+	RBW

- $+$ low mass $K^+\pi^-$ S-wave

Model with only $K^+\pi^-$ contributions [EPJC 78 (2018) 1019]

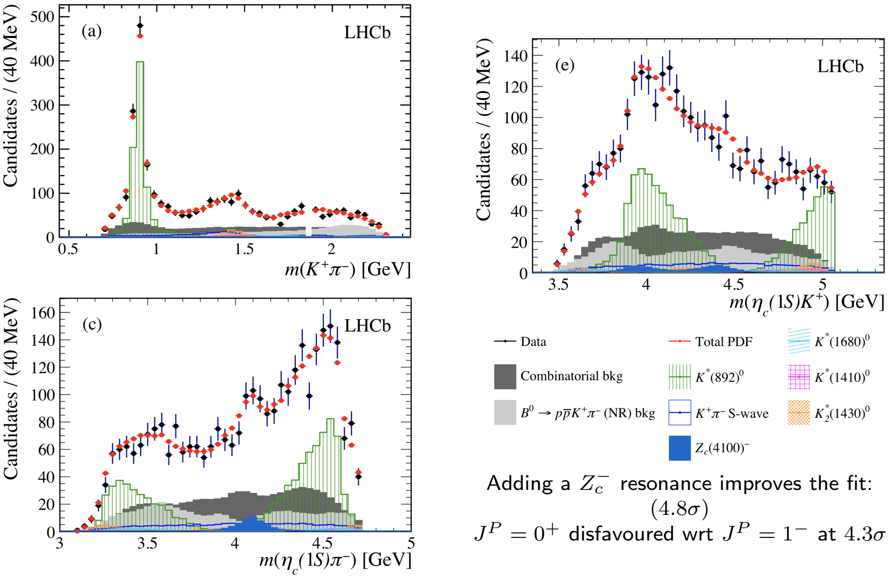






Discrepancy around $4100\,\mathrm{MeV}$ in the $m(\eta_c(1S)\pi^-)$ spectrum

Model with $K^+\pi^- + \eta_c(1S)\pi^-$ [EPJC 78 (2018) 1019]



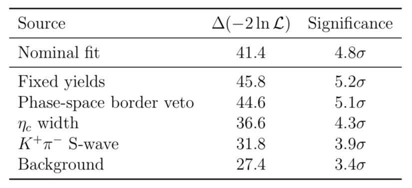
Adding a Z_c^- resonance improves the fit: (4.8σ)

$J^P = 0^+$ disfavoured wrt $J^P = 1^-$ at 4.3σ

Systematic uncertainties

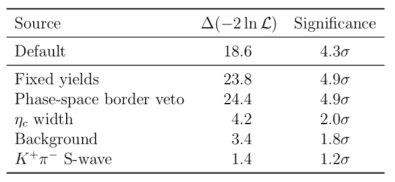
- Experimental uncertainties
  - Fixed signal and background yields
  - Background parametrisation
  - Phase-space border veto applied on the parametrisation of the efficiencies
  - Efficiency variations across the SDP
  - Amplitude fit bias
- Model uncertainties
  - treatment of the $\eta_c(1S)$ natural width
  - $K^+\pi^-$ S-wave parametrisation
  - Fixed parameters of the resonances
  - Addition or removal of marginal components
- The systematic variations producing the largest deviations on the $Z_c(4100)$ parameters (mass, width and fit fraction) are used to evaluate the systematic effects on the significances

$Z_c(4100)$ significance including systematic uncertainties and correlations: 3.2σ



Source	$\Delta(-2\ln\mathcal{L})$	Significance
Nominal fit	41.4	4.8σ
Fixed yields	45.8	5.2σ
Phase-space border veto	44.6	5.1σ
η_c width	36.6	4.3σ
$K^+\pi^-$ S-wave	31.8	3.9σ
Background	27.4	3.4σ

Discrimination between $J^P = 0^+$ and $J^P = 1^-$ is not significant



Source	$\Delta(-2\ln\mathcal{L})$	Significance
Default	18.6	4.3σ
Fixed yields	23.8	4.9σ
Phase-space border veto	24.4	4.9σ
η_c width	4.2	2.0σ
Background	3.4	1.8σ
$K^+\pi^-$ S-wave	1.4	1.2σ

Cross-checks

- No significant improvement adding further high-mass K^{*0} states
  - the $K_3^*(1780)^0$ and $K_4^*(2045)^0$ states
  - the high mass $K_5^*(2380)^0$ which falls outside the phase space limits
  - the $K_2^*(1980)^0$ which has not been seen in the $K^+\pi^-$ final state thus far
  - the unestablished P-, D- and F-wave $K^+\pi^-$ states predicted by the Godfrey-Isgur model
- No significant additional amplitude decaying to $\eta_c\pi^-$
- No significant additional exotic amplitude decaying to $\eta_c K^+$
- Negligible effect due to the η_c meson resonant phase motion due to the sizeable natural width introducing interference effects with the NR $p\bar{p}$ contribution
  - data sample is divided in two, containing candidates with masses below and above the η_c meson peak

Evidence for an exotic $Z_c(4100)^-$ [EPJC 78 (2018) 1019]

- Resonance parameters:
  $m_{Z_c^-} = 4096 \pm 20^{+18}_{-22}\,\text{MeV} \qquad \Gamma_{Z_c^-} = 152 \pm 58^{+60}_{-35}\,\text{MeV}$
- Fit fraction of the Z_c^-: $3.3 \pm 1.1^{+1.2}_{-1.1}\%$
- Significance is 3.2σ after considering systematic uncertainties
- Discrimination between $J^P = 0^+$ and $J^P = 1^-$ is not significant
- Need more data to conclusively determine the nature of the $Z_c(4100)$ state

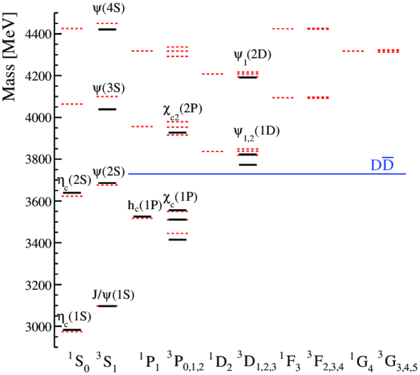
Decay mode	Branching fraction (10^{-5})
$B^0 \to \eta_c K^*(892)^0$	$29.5 \pm 1.6 \pm 0.6 \; ^{+1.0}_{-2.8} \pm 3.4$
$B^0 \to \eta_c K^*(1410)^0$	$1.20 \pm 0.63 \pm 0.02 \pm 0.63 \pm 0.14$
$B^0 \to \eta_c K^+ \pi^-$ (NR)	$5.90 \pm 0.84 \pm 0.11 \; ^{+0.57}_{-0.69} \pm 0.68$
$B^0 \to \eta_c K_0^*(1430)^0$	$14.50 \pm 2.10 \pm 0.28 \; ^{+2.01}_{-1.60} \pm 1.67$
$B^0 \to \eta_c K_2^*(1430)^0$	$2.35 \pm 0.87 \pm 0.05 \; ^{+0.57}_{-0.92} \pm 0.27$
$B^0 \to \eta_c K^*(1680)^0$	$1.26 \pm 1.15 \pm 0.02 \; ^{+0.86}_{-0.97} \pm 0.15$
$B^0 \to \eta_c K_0^*(1950)^0$	$2.18 \pm 1.04 \pm 0.04 \; ^{+0.80}_{-1.43} \pm 0.25$
$B^0 \to Z_c(4100)^- K^+$	$1.89 \pm 0.64 \pm 0.04 \; ^{+0.69}_{-0.63} \pm 0.22$

(statistical, branching fraction systematic, fit fraction systematic, external branching fractions uncertainties)

Standard spectroscopy

Near-threshold $D\bar{D}$ spectroscopy and observation of a new charmonium state
arXiv: 1903.12240, submitted to JHEP

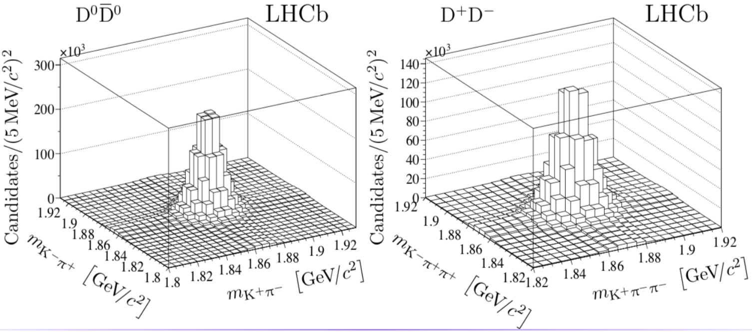
Charmonium spectrum status



- Charmonium spectrum and properties well described by potential models
- A lot of not yet observed states above the $D\bar{D}$ threshold
- Only few states with large L states known
- $\psi_3(1^3D_3)$ state not yet discovered: expected to be narrow since even if it is above $D\bar{D}$ threshold, the decay is suppressed due to the F-wave centrifugal barrier factor
- Mass predictions: $3815\text{-}3863\,\mathrm{MeV}$
- Width predictions: $1\text{-}2\,\mathrm{MeV}$

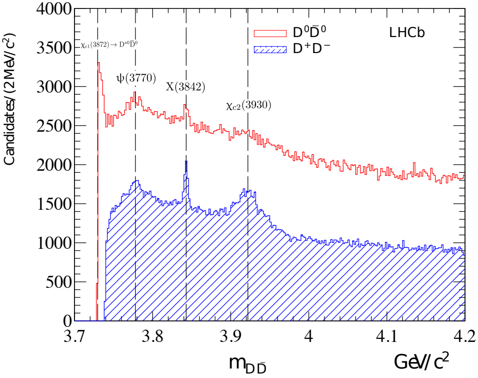
New charmonium in $D\bar{D}$ [arXiv: 1903.12240]

- Run1 + Run2 data: $9\,\mathrm{fb}^{-1}$: first analysis using the complete dataset!
- Select promptly produced D^+D^- and $D^0\bar{D}^0$ candidates
- Using $D^+ \to K^-\pi^+\pi^+$ and $D^0 \to K^-\pi^+$
- To reduce combinatorial background, exploit D meson decay time
- Select only D candidates with mass within $\pm 20\,\mathrm{MeV}$ (approximately $\pm 3\sigma$) of the known D-meson
- Purity: 88% for $D^0\bar{D}^0$ and 83% for the D^+D^-



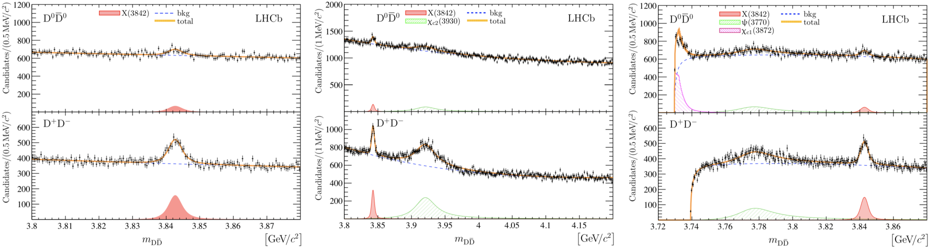
$D\bar{D}$ spectra [arXiv: 1903.12240]

- To improve $D\bar{D}$ resolution: D mass constrained to the known values
- To better model background, fits performed in three different overlapping mass regions
  - Narrow region around a new state: $X(3842)$: $3.80 < m_{D\bar{D}} < 3.88\,\mathrm{GeV}$
  - High-mass region: $3.80 < m_{D\bar{D}} < 4.2\,\mathrm{GeV}$
  - Near-threshold region $m_{D\bar{D}} < 3.88\,\mathrm{GeV}$



$D\bar{D}$ spectra [arXiv: 1903.12240]

- Simultaneous fit to the D^+D^- and the $D^0\bar{D}^0$ spectra
- Relativistic Breit-Wigner convoluted with resolution (from 0.9 to 1.9 MeV) for signal
- Background: pol2/pol2*expo/two-body phase-space*pol2
- For the $D^0\bar{D}^0$ mass spectrum: $\chi_{c1}(3872) \to D^{*0}\bar{D}^0$, $D^{*0} \to D^0\pi^0$ or $D^{*0} \to D^0\gamma$



- $X(3842)$: $m = (3842.71 \pm 0.16 \pm 0.12)\,\mathrm{MeV}$ $\Gamma = (2.79 \pm 0.51 \pm 0.35)\,\mathrm{MeV}$
- $\psi(3770)$: $m(\psi(3770)) = (3778.1 \pm 0.7 \pm 0.6)\,\mathrm{MeV}$ Γ constrained to $(27.2 \pm 1.0)\,\mathrm{MeV}$ (PDG)
- $\chi_{c2}(3930)$: $m(\chi_{c2}(3930)) = (3921.9 \pm 0.6 \pm 0.2)\,\mathrm{MeV}$
  $\Gamma(\chi_{c2}(3930)) = (36.6 \pm 1.9 \pm 0.9)\,\mathrm{MeV}$

$D\bar{D}$ results [arXiv: 1903.12240]

- New narrow charmonium state: X(3842)
- Most probable interpretation as spin-3 D-wave state $\psi_3(1^3D_3)$ with $J^{PC} = 3^{--}$

$$m = 3842.71 \pm 0.16 \pm 0.12\,\mathrm{MeV} \qquad \Gamma = 2.79 \pm 0.51 \pm 0.35\,\mathrm{MeV}$$

- First observation of hadroproduction of $\psi(3770)$ and of $\chi_{c2}(3930)$

$$m(\psi(3770)) = 3778.1 \pm 0.7 \pm 0.6\,\mathrm{MeV}$$
$$m(\chi_{c2}(3930)) = 3921.9 \pm 0.6 \pm 0.2\,\mathrm{MeV}$$
$$\Gamma(\chi_{c2}(3930)) = 36.6 \pm 1.9 \pm 0.9\,\mathrm{MeV}$$

$D\bar{D}$ results [arXiv: 1903.12240]

	$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle PRL 96 (2006) 082003	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$
BaBar PRD 81 (2010 092003	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$
This analysis	$3921.9 \pm 0.6 \pm 0.2$	$36.6 \pm 1.9 \pm 0.9$

	$m_{\psi(3770)}$ [MeV/c^2]
Shamov and Todyshev PLB 769 (2017) 187	3779.8 ± 0.6
PDG average	3778.1 ± 1.2
PDG fit	3773.13 ± 0.35
This analysis	$3778.1 \pm 0.7 \pm 0.6$

- The mass of the $\chi_{c2}(3930)$ is 2σ lower than the current world average
- The natural width of the $\chi_{c2}(3930)$ is 2σ higher than the current world average
- Mass value is midway between the mass for this state and for the X(3915) meson: two distinct charmonium states in this region or only one? [PRL 115 (2015) 0220001]
- For $\psi(3770)$, mass is compatible with PDG average dominated by KEDR experiment
- Disagreement with the PDG fit value (which includes BES measurement)

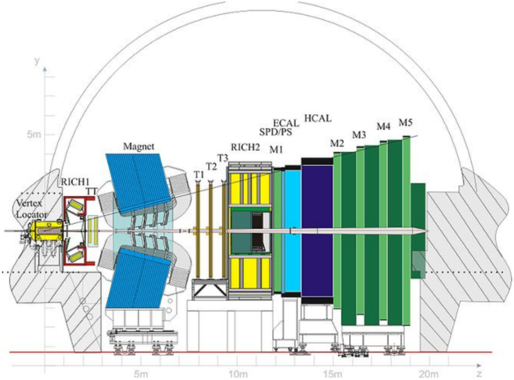
Conclusions

- A wide range of interesting spectroscopy measurements performed by the LHCb experiment
- Exotic spectroscopy is quite a rich field where LHCb is contributing significantly with the confirmation of already observed states or with the observation of new states
- An overall picture of these states is still missing: experimental effort is needed
- Standard spectroscopy results provide a perfect benchmark for tests of effective theories of the strong interaction
- A lot of states have not observed yet
- Long Shutdown 2 started, the detectors are going to be upgraded: collect a larger data sample with high efficiency starting in 2021!

Spare slides

The LHCb detector

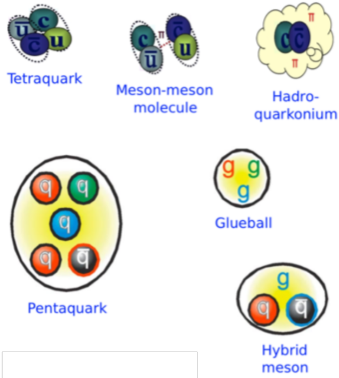
Designed to study CP-violating processes and rare b- and c-hadrons decays



Impact parameter:	$\sigma_{IP} = 20\ \mu\mathrm{m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\ \mathrm{GeV}/c)$
Mass :	$\sigma_m = 8\ \mathrm{MeV}/c^2$ for $B \to J/\psi X$ (constrained $\mathrm{m}_{J/\psi}$)
RICH $K - \pi$ separation:	$\epsilon(K \to K) \sim 95\%$ mis-ID $\epsilon(\pi \to K) \sim 5\%$
Muon ID:	$\epsilon(\mu \to \mu) \sim 97\%$ mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

Interpretations of exotic hadrons

- Different models have been proposed about the quark composition and binding mechanisms of these exotic hadrons



Predictions of a $\eta_c\pi^-$ exotic state

- $Z_c(3900)^-$ as hadrocharmonium state (where the compact heavy quark-antiquark pair interacts with the surrounding light quark mesonic excitation by a QCD analogue of the van der Waals force): predicts an as-yet-unobserved charged charmonium-like state with a mass of approximately $3800\,\mathrm{MeV}$ whose dominant decay mode is to the $\eta_c\pi^-$ system
- $Z_c(3900)^-$ as quarkonium hybrids where the excitation of the gluon field (the valence gluon) is replaced by an isospin-1 excitation of the gluon and light-quark fields
  - prediction of different multiplets of charmonium tetraquarks, comprising states with quantum numbers allowing the decay into the $\eta_c\pi^-$ system.
  - The $\eta_c\pi^-$ system carries isospin $I = 1$, G-parity $G = 1$, spin $J = L$ and parity $P = (-1)^L$, where L is the orbital angular momentum between the η_c and the π^- mesons. Lattice QCD calculations predict the mass and quantum numbers of these states, comprising a $I^G(J^P) = 1(0^+)$ state of mass $4025 \pm 49\,\mathrm{MeV}$, a $I^G(J^P) = 1^-(1^-)$ state of mass $3770 \pm 42\,\mathrm{MeV}$, and a $I^G(J^P) = 1^-(2^+)$ state of mass $4045 \pm 44\,\mathrm{MeV}$. The $Z_c(4430)$ resonance, discovered by the Belle collaboration and confirmed by LHCb, could also fit into this scenario.
- Diquark model: a $J^P = 0^+$ exotic candidate below the open-charm threshold decaying to $\eta_c\pi^-$

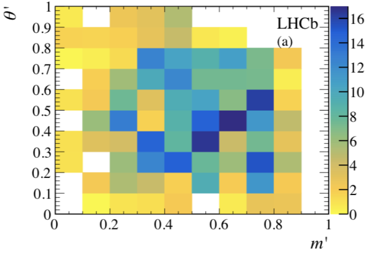
Branchi

Parametrisation of the backgrounds

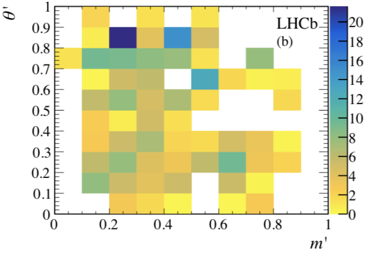
- sPlot technique from the joint 2D $m(p\bar{p}K^+\pi^-), m(p\bar{p})$ fit is used to extract combinatorial and NR background histograms
- Smoothing procedure using a 2D cubic spline interpolation
- Parametrised using the Square Dalitz plot (SDP) using the variables m' and θ' defined in the range 0 to 1 and given by

$$m' \equiv \frac{1}{\pi}\arccos(2\frac{m(K^+\pi^-)-m^{\min}_{K^+\pi^-}}{m^{\max}_{K^+\pi^-}-m^{\min}_{K^+\pi^-}}-1) \qquad \theta' \equiv \frac{1}{\pi}\theta(K^+\pi^-)$$

where $m^{\max}_{K^+\pi^-} = m_{B^0} - m_{\eta_c}$, $m^{\min}_{K^+\pi^-} = m_{K^+} + m_{\pi^-}$ and $\theta(K^+\pi^-)$ is the helicity angle of the $K^+\pi^-$ system (the angle between the K^+ and the η_c mesons in the $K^+\pi^-$ rest frame

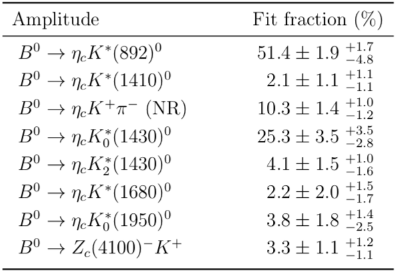


Combinatorial bkg

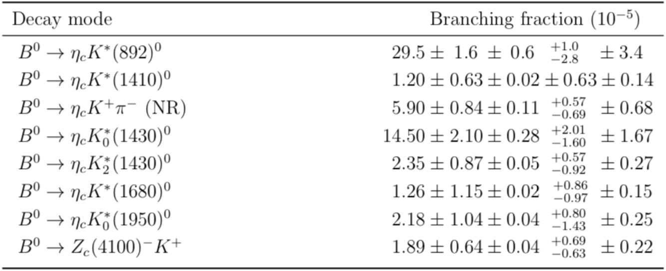


NR bkg

Quasi-two-body branching fractions



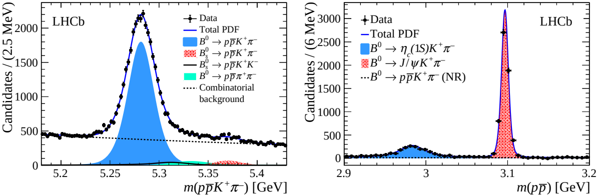
Amplitude	Fit fraction (%)
$B^0 \to \eta_c K^*(892)^0$	$51.4 \pm 1.9\ ^{+1.7}_{-4.8}$
$B^0 \to \eta_c K^*(1410)^0$	$2.1 \pm 1.1\ ^{+1.1}_{-1.1}$
$B^0 \to \eta_c K^+\pi^-$ (NR)	$10.3 \pm 1.4\ ^{+1.0}_{-1.2}$
$B^0 \to \eta_c K_0^*(1430)^0$	$25.3 \pm 3.5\ ^{+3.5}_{-2.8}$
$B^0 \to \eta_c K_2^*(1430)^0$	$4.1 \pm 1.5\ ^{+1.0}_{-1.6}$
$B^0 \to \eta_c K^*(1680)^0$	$2.2 \pm 2.0\ ^{+1.5}_{-1.7}$
$B^0 \to \eta_c K_0^*(1950)^0$	$3.8 \pm 1.8\ ^{+1.4}_{-2.5}$
$B^0 \to Z_c(4100)^- K^+$	$3.3 \pm 1.1\ ^{+1.2}_{-1.1}$



Decay mode	Branching fraction (10^{-5})
$B^0 \to \eta_c K^*(892)^0$	$29.5 \pm 1.6 \pm 0.6\ ^{+1.0}_{-2.8} \pm 3.4$
$B^0 \to \eta_c K^*(1410)^0$	$1.20 \pm 0.63 \pm 0.02 \pm 0.63 \pm 0.14$
$B^0 \to \eta_c K^+\pi^-$ (NR)	$5.90 \pm 0.84 \pm 0.11\ ^{+0.57}_{-0.69} \pm 0.68$
$B^0 \to \eta_c K_0^*(1430)^0$	$14.50 \pm 2.10 \pm 0.28\ ^{+2.01}_{-1.60} \pm 1.67$
$B^0 \to \eta_c K_2^*(1430)^0$	$2.35 \pm 0.87 \pm 0.05\ ^{+0.57}_{-0.92} \pm 0.27$
$B^0 \to \eta_c K^*(1680)^0$	$1.26 \pm 1.15 \pm 0.02\ ^{+0.86}_{-0.97} \pm 0.15$
$B^0 \to \eta_c K_0^*(1950)^0$	$2.18 \pm 1.04 \pm 0.04\ ^{+0.80}_{-1.43} \pm 0.25$
$B^0 \to Z_c(4100)^- K^+$	$1.89 \pm 0.64 \pm 0.04\ ^{+0.69}_{-0.63} \pm 0.22$

Branching fraction measurement

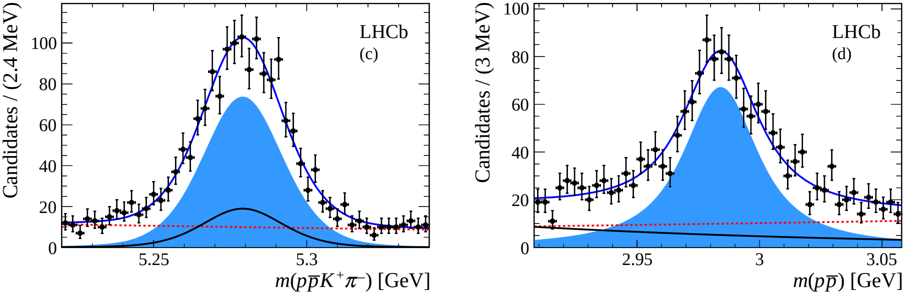
- Measurement of the $B^0 \to \eta_c K^+ \pi^-$ wrt $B^0 \to J/\psi K^+ \pi^-$ (normalisation channel)
  $R = \frac{N_{\eta_c}}{N_{J/\psi}} \times \frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}}$
- Two-stage procedure:
  - Fit to the $m(p\bar{p}K^+\pi^-)$ to separate $B^0 \to p\bar{p}K^+\pi^-$ from background contributions
  - Fit to the sPlot weighted $m(p\bar{p})$ distribution to extract η_c, J/ψ and nonresonant contributions



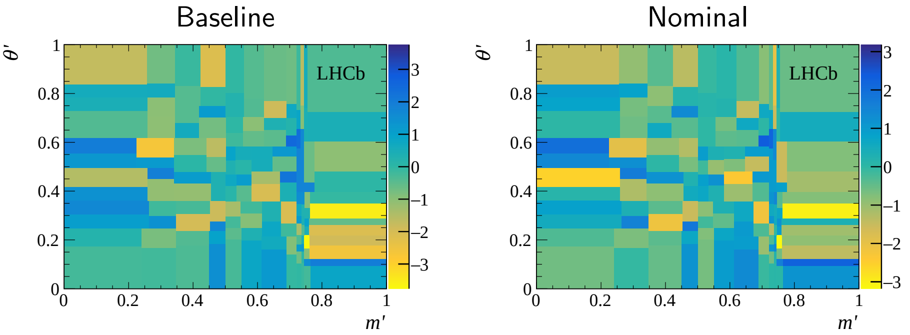
- Ratio of efficiencies between signal and normalization channel expected to be close to unity: evaluated using simulated samples reweighted using calibration samples
- Systematic uncertainties due to fit model and due to effect of efficiency variation

$$R = 0.357 \pm 0.015 \pm 0.008$$
$$\mathcal{B}(B^0 \to \eta_c K^+ \pi^-) = (5.73 \pm 0.24 \pm 0.13 \pm 0.66) \times 10^{-4}$$

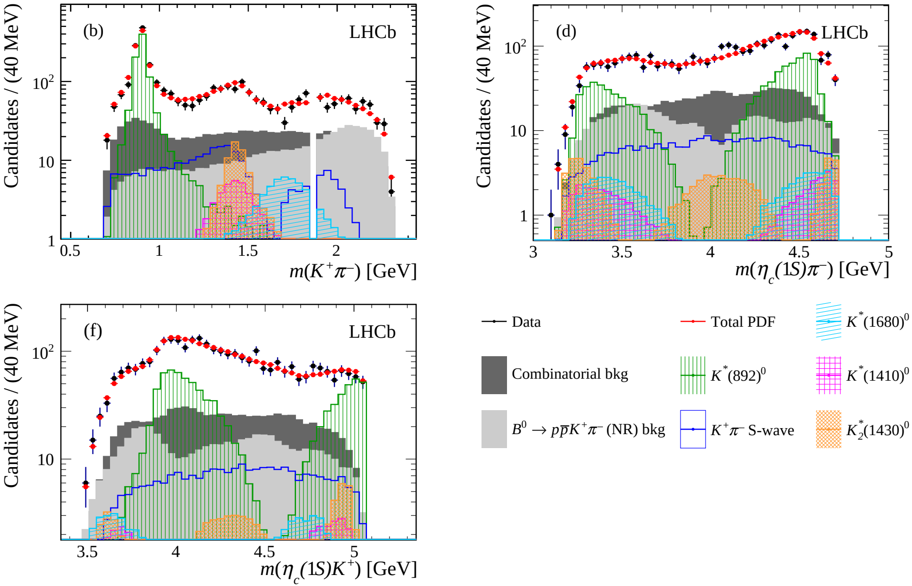
Run-2 signal


Candidates / (2.4 MeV)
LHCb
(c)
0
20
40
60
80
100
5.25
5.3
$m(p\overline{p}K^{+}\pi^{-})$ [GeV]
Candidates / (3 MeV)
LHCb
(d)
0
20
40
60
80
100
2.95
3
3.05
$m(p\overline{p})$ [GeV]

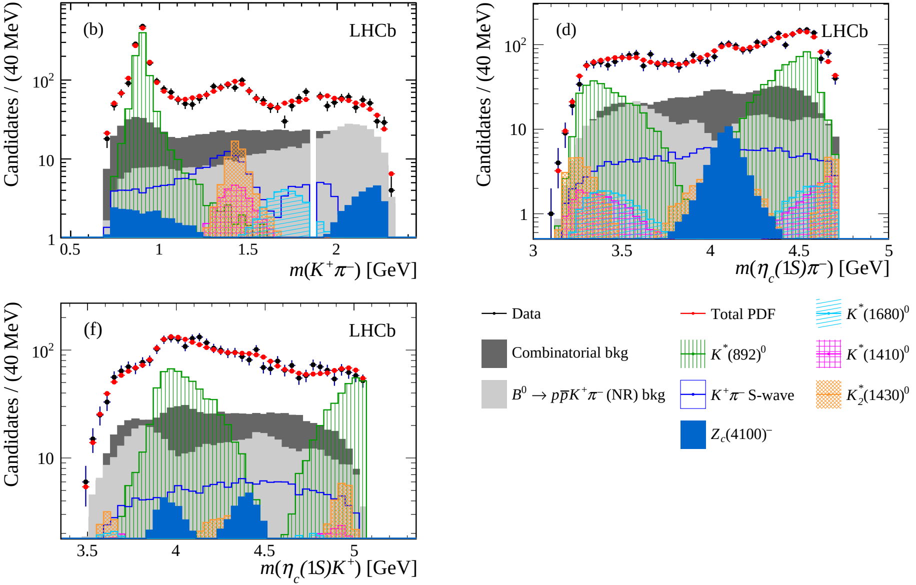
Fit quality: 2D pull



Baseline: log

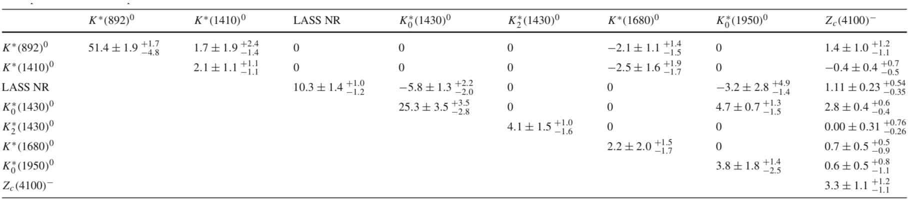


Nominal: log


(b)
LHCb
Candidates / (40 MeV)
1
10
10^2
0.5
1
1.5
2
$m(K^+\pi^-)$ [GeV]
(d)
LHCb
Candidates / (40 MeV)
1
10
10^2
3
3.5
4
4.5
5
$m(\eta_c(1S)\pi^-)$ [GeV]
(f)
LHCb
Candidates / (40 MeV)
10
10^2
3.5
4
4.5
5
$m(\eta_c(1S)K^+)$ [GeV]
Data
Total PDF
$K^*(1680)^0$
Combinatorial bkg
$K^*(892)^0$
$K^*(1410)^0$
$B^0 \to p\overline{p}K^+\pi^-$ (NR) bkg
$K^+\pi^-$ S-wave
$K_2^*(1430)^0$
$Z_c(4100)^-$

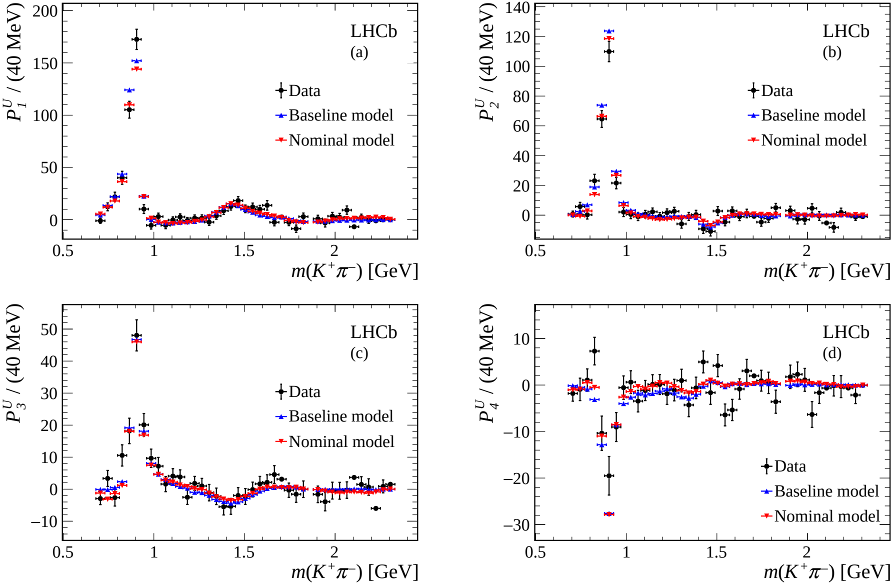
$Z_c(4100)^-$ significance

Fit fractions

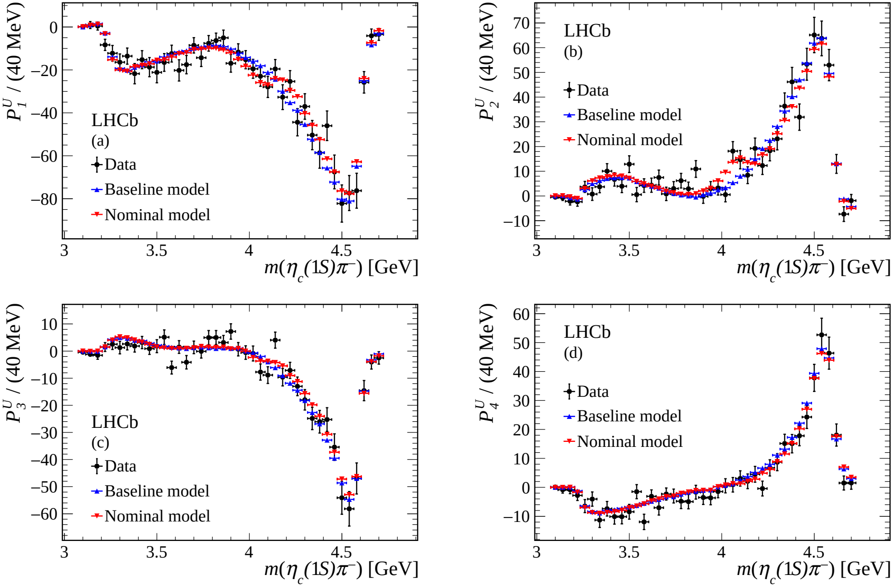


	$K^*(892)^0$	$K^*(1410)^0$	LASS NR	$K_0^*(1430)^0$	$K_2^*(1430)^0$	$K^*(1680)^0$	$K_0^*(1950)^0$	$Z_c(4100)^-$
$K^*(892)^0$	$51.4 \pm 1.9\ ^{+1.7}_{-4.8}$	$1.7 \pm 1.9\ ^{+2.4}_{-1.4}$	0	0	0	$-2.1 \pm 1.1\ ^{+1.4}_{-1.5}$	0	$1.4 \pm 1.0\ ^{+1.2}_{-1.1}$
$K^*(1410)^0$		$2.1 \pm 1.1\ ^{+1.1}_{-1.1}$	0	0	0	$-2.5 \pm 1.6\ ^{+1.9}_{-1.7}$	0	$-0.4 \pm 0.4\ ^{+0.7}_{-0.5}$
LASS NR			$10.3 \pm 1.4\ ^{+1.0}_{-1.2}$	$-5.8 \pm 1.3\ ^{+2.2}_{-2.0}$	0	0	$-3.2 \pm 2.8\ ^{+4.9}_{-1.4}$	$1.11 \pm 0.23\ ^{+0.54}_{-0.35}$
$K_0^*(1430)^0$				$25.3 \pm 3.5\ ^{+3.5}_{-2.8}$	0	0	$4.7 \pm 0.7\ ^{+1.3}_{-1.5}$	$2.8 \pm 0.4\ ^{+0.6}_{-0.4}$
$K_2^*(1430)^0$					$4.1 \pm 1.5\ ^{+1.0}_{-1.6}$	0	0	$0.00 \pm 0.31\ ^{+0.76}_{-0.26}$
$K^*(1680)^0$						$2.2 \pm 2.0\ ^{+1.5}_{-1.7}$	0	$0.7 \pm 0.5\ ^{+0.5}_{-0.9}$
$K_0^*(1950)^0$							$3.8 \pm 1.8\ ^{+1.4}_{-2.5}$	$0.6 \pm 0.5\ ^{+0.8}_{-1.1}$
$Z_c(4100)^-$								$3.3 \pm 1.1\ ^{+1.2}_{-1.1}$

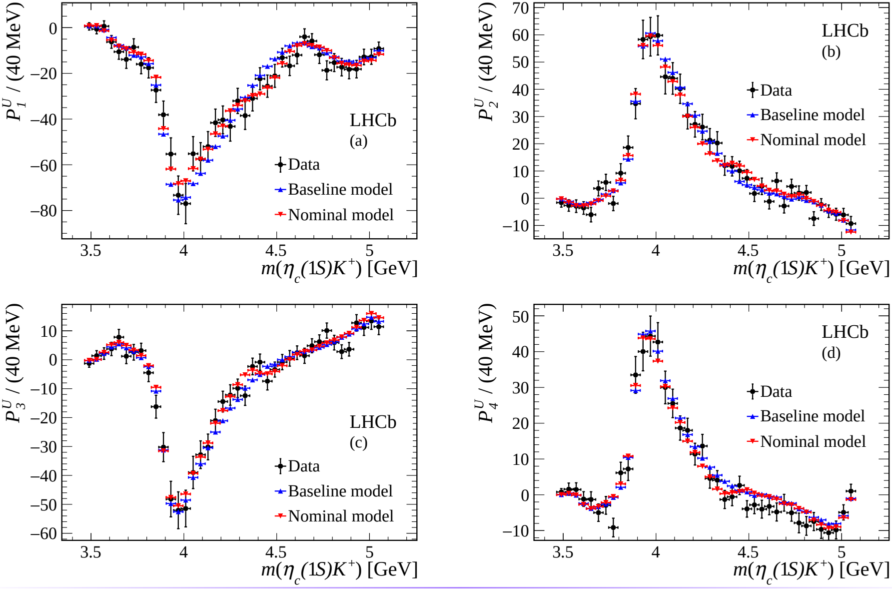
$K^+\pi^-$ Legendre moments



$\eta_c\pi^-$ Legendre moments



$\eta_c K^+$ Legendre moments



Width of the $\eta_c(1S)$

- Necessary to take into account the sizeable natural width of the $\eta_c(1S)$ meson $(\Gamma \sim 32\,\mathrm{MeV})$:
  - Kinematic quantities such as $m^2(K^+\pi^-)$, $m^2(\eta_c\pi^-)$ and the helicity ancles are calculated using the invariant mass $m(p\bar{p})$ instead of the known value of the η_c mass
  - When computing the DP normalisation the width of the η_c meson is set to zero: the effect of this simplification is determined when assessing the systematic uncertainties
  - Amplitude fits are repeated computing the DP normalisations by using the $m_{\eta_c} + \Gamma_{\eta_c}$ and $m_{\eta_c} - \Gamma_{\eta_c}$

LASS model

- The amplitude parametrisations using RBW functions lead to unitarity violation within the isobar model if there are overlapping resonances or if there is a significant interference with a NR component, both in the same partial wave
- For the $K^+\pi$ S-wave at low $K^+\pi$ mass, where the $K_0(1430)^0$ resonance interferes strongly with a slowly varying NR S-wave component: LASS lineshape

$$T(m) = \frac{m}{|\vec{q}|\cot\delta_B - i|\vec{q}|} + e^{2i\delta_B}\frac{m_0\Gamma_0\frac{m_0}{q_0}}{m_0^2 - m^2 - im_0\Gamma_0\frac{|\vec{q}|}{m}\frac{m_0}{q_0}}$$

$$\cot\delta_B = \frac{1}{a|\vec{q}|} + \frac{1}{2}r|\vec{q}|$$

and where m_0 and Γ_0 are the pole mass and width of the $K_0(1430)^0$ state, and a and r are the scattering length and the effective range, respectively.

- The LASS model replaced with $K_0^*(1430)^0$ and $K_0^*(800)^0$ resonances parametrised with RBW functions, and a NR S-wave $K^+\pi^-$ component parametrised with a uniform amplitude within the DP.

Charmonium spectrum