Recent results on exotic hadrons at LHCb

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on behalf of the LHCb collaboration

University of Genova and INFN

CERN-LHC seminar,
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Outline

- overview on exotic hadrons
- the LHCb detector
- highlights of LHCb results on exotic spectroscopy
- evidence for an $\eta_c(1S)\pi^-$ resonance in $B^0 \to \eta_c(1S)K^+\pi^-$ decays
- model-independent evidence for exotic contributions in $B^0 \to J/\psi K^+\pi^-$ decays

Introduction

- hadrons beyond conventional mesons and baryons foreseen since the formulation of the constituent quark model in 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowes

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

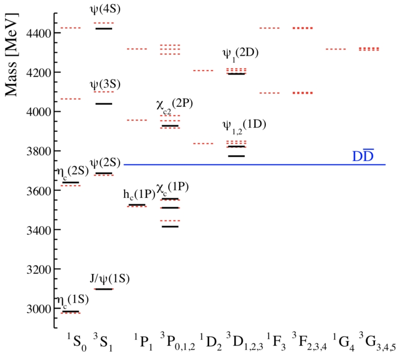
G. Zweig **)
CERN---Geneva

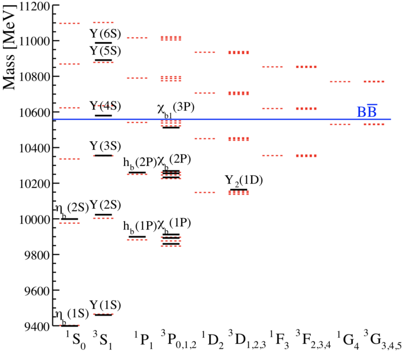
6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}$AAAA, $\bar{A}\bar{A}$AAAAA, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}$A, $\bar{A}\bar{A}$AA etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}$A and AAA, that is, "deuces and treys".

- not forbidden by QCD as long as they form colour-singlet configurations
- many searches for exotic hadrons in the light-spectroscopy sector without success:
  - experimentally difficult given the high density of broad and overlapping states, and the large backgrounds
  - theoretical predictions are challenging given the relativistic u, d and s constituents
- since 2003, about thirty hadrons not fitting with the conventional heavy-quarkonium states have been observed

Heavy-quarkonium spectra

[S. L. Olsen, T. Skwarnicki, and D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003]

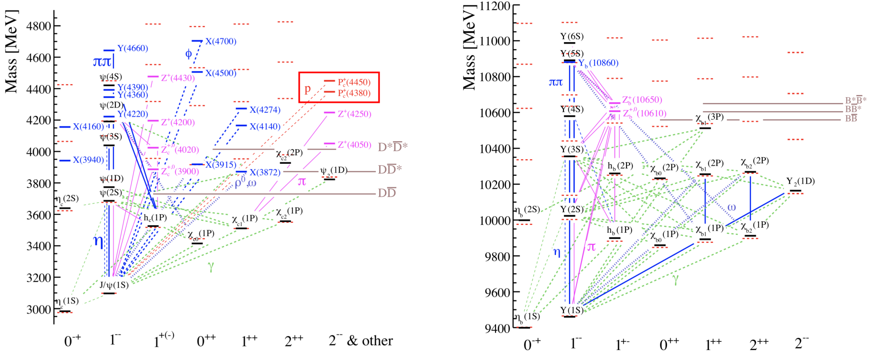




- large c- and b-quark masses allow to treat charmonium ($c\bar{c}$) and bottomonium ($b\bar{b}$) mesons as **non-relativistic systems** $\Rightarrow$ simpler systems $\Rightarrow$ spectra of observed states well described by QCD motivated potential models with corrections provided by the NRQCD framework (dashed lines)
- narrow and non-overlapping states
- limited number of unassigned states below open-flavour thresholds
- no mixing with lighter quarkonium states

Heavy-quarkonium-like spectra

[S. L. Olsen, T. Skwarnicki, and D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003]



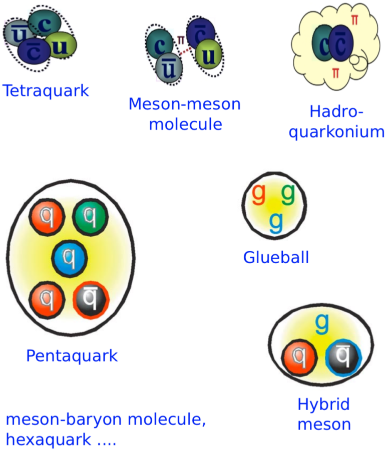
- plethora of unexpected neutral (X, Y) and charged (Z^+, P_c^+) states discovered by B-, c- and τ- factories and by experiments at hadronic colliders
- their decay modes indicate they must contain an heavy quark-antiquark pair in their internal structure
- but either their mass, decay properties or electric charge are not consistent with unassigned charmonium or bottomonium levels

$\Rightarrow$ **more complex substructure than heavy-quarkonium states**

Interpretations of exotic hadrons

- four-quark candidates classified as X (neutral), Y (neutral and $J^{PC} = 1^{--}$) and Z (charged); pentaquark candidates named P

- different models have been proposed about the quark composition and binding mechanisms of these exotic hadrons
- a clear pattern is missing: experimental and theoretical efforts are needed to understand their nature
- it is important to search for new exotic candidates along with new production mechanisms and decay modes of already observed unconventional states
- many contributions from the LHCb experiment

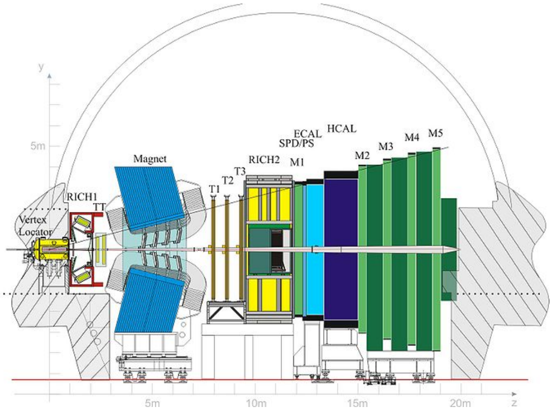


The LHCb experiment

The LHCb experiment

[JINST 3 (2008) S08005]

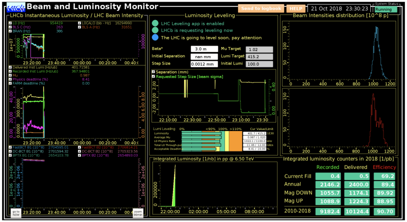
By design: study CP-violating processes and rare *b*- and *c*-hadrons decays

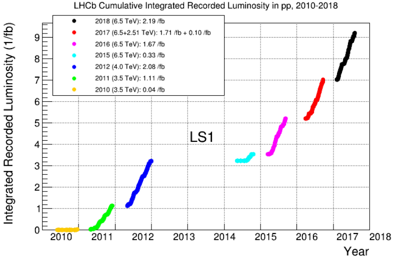


- **VELO**: excellent resolution on primary and secondary vertex separation
- **RICH 1 and 2**: optimal charged hadrons discrimination over the $10 < p < 100\,\mathrm{GeV}$ range
- **Muon stations**: $\sim 90\%$ efficiency on muon triggers

The LHCb data taking and physics

- Run 1: $\sim 3\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\text{-}8\,\mathrm{TeV}$
- Run 2: $\sim 6\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$
  ($\sigma_{b\bar{b}} \propto \sqrt{s} \Rightarrow$ 4x $b\bar{b}$ pairs with respect to Run 1)





Thanks to the LHC!

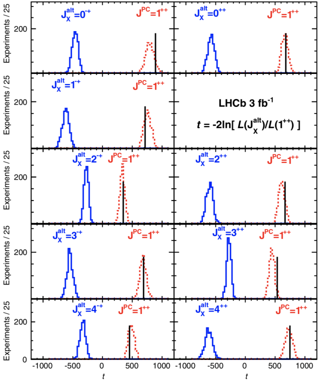
Excellent tracking and PID performance $\Rightarrow$ extended Physics programme

$\Rightarrow$ not only CP violation and rare decays measurements, but also LFU tests, **exotic and conventional spectroscopy**, production and polarisation measurements, EW and QCD physics, dark photon searches, p-Pb and p-He physics, ...

Exotic hadrons at LHCb: highlights

LHCb contributions to the understanding of the $X(3872)$ state

- first exotic candidate observed by Belle in 2003 **[Belle collaboration, Phys. Rev. Lett. 91 (2003) 262001]**
- quantum numbers measurements $\Rightarrow J^{PC} = 1^{++}$ **[Phys. Rev. D92 (2015) 011102], [Phys. Rev. Lett. 110 (2013) 222001]**
- search for new decay modes **[EPJC 73 (2013) 2462], [Phys. Lett. B 769 (2017) 305]**
- direct production in *pp* collisions **[EPJC 72 (2012) 1972]**



- measurement of $\mathcal{B}(X(3872) \to \psi(2S)\gamma)/\mathcal{B}(X(3872) \to J/\psi\gamma)$): **disfavors the pure $D\bar{D}^*$ molecular intepretation** **[Nucl. Phys. B 886 (2014) 665]**

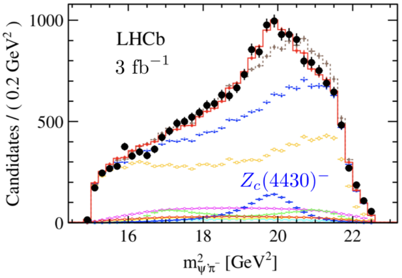
$\Rightarrow$ strong indications that the $X(3872)$ is a **quantum mixture** of the $\chi_{c1}(2P)$ charmonium state (accounting for the prompt production rate) with a $D^0\bar{D}^{*0}$ **molecule** state (accounting for the isospin violation coming from the observation of the decays to $J/\psi\rho$ and $J/\psi\omega$)

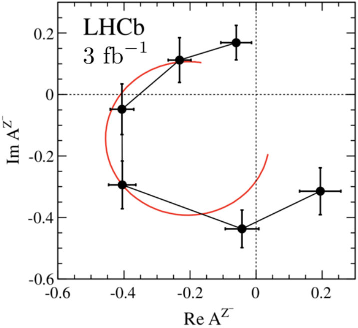
[M. Padmanath, C. B. Lang, and S. Prelovsek, Phys. Rev. D92 (2015) 034501]

Confirmation of the $Z_c(4430)^+$ state in $B^0 \to \psi(2S)K^+\pi^-$ decays

[Phys. Rev. Lett. 112 (2014) 222002]

- confirmation of the existence of the $Z_c(4430)^+$ charged charmonium-like state, and determination of its $J^P = 1^+$ quantum numbers with very high significance
- first unambiguous exotic state
- demonstration of its **resonant character** through the study of the Argand diagram
- model-independent approach used to demonstrate that the $\psi(2S)\pi^-$ structures can not be explained by reflections from $K^+\pi^-$ contributions alone [Phys. Rev. D92 (2015) 112009]

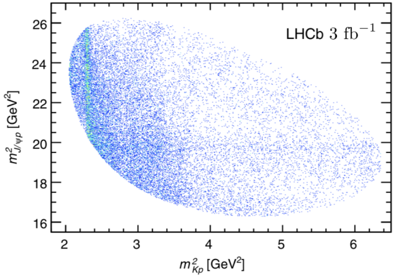


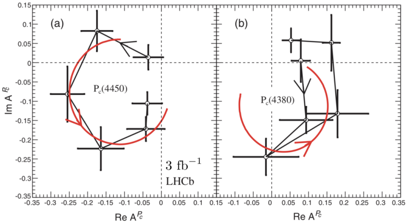


Discovery of two pentaquark candidates in $\Lambda_b \to J/\psi p K^+$ decays

[Phys. Rev. Lett. 115 (2015) 072001]

- first observation of two pentaquark candidates $P_c(4450)^+$ and $P_c(4380)^+$ using Run 1 data (≈ 26000 $\Lambda_b \to J/\psi p K^+$ decays)
- Argand plot consistent with a resonance for the $P_c(4450)^+$, not conclusive for the $P_c(4380)^+$
- P_c^+ states have opposite parities
- supported by a model-independent analysis **[Phys. Rev. Lett. 117 (2016) 082002]**
- evidence for pentaquark contributions also in the Cabibbo-suppressed $\Lambda_b \to J/\psi p \pi^+$ decay mode **[Phys. Rev. Lett. 117 (2016) 082003]**

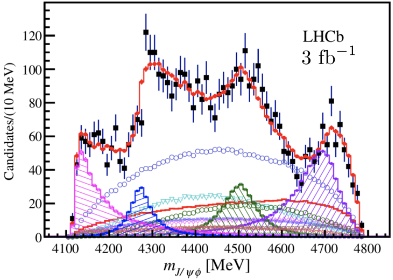


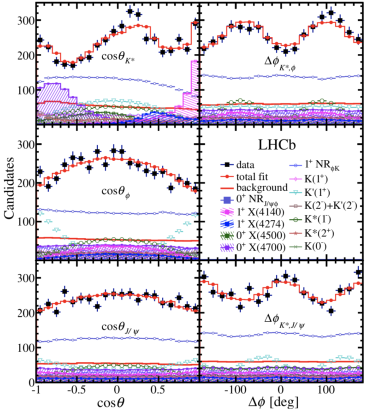


Neutral exotics in $B^+ \to J/\psi\phi K^+$ decays

[Phys. Rev. Lett. 118 (2016) 022003], [Phys. Rev. D95 (2016) 012002]

- confirmation of the $X(4140)$ and $X(4274)$ states
- discovery of two higher mass states: $X(4400)$ and $X(4700)$
- quantum numbers assignments





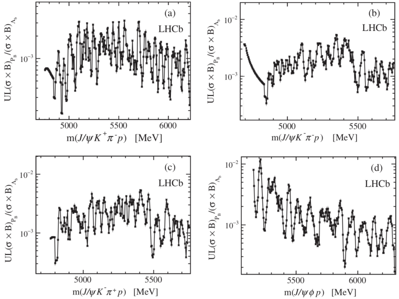
- $D_s^+ D_s^{*-}$ cusp model included among systematic variations **[E. S. Swanson, Int. J. Mod. Phys. E25 (2016) 1642010]**
  - indications that the $X(4140)$ may not be a bound state that can be described by the Breit–Wigner function

Searches for exotic hadrons containing b quarks

Search for weakly decaying b-flavoured pentaquarks
[Phys. Rev. D97 (2018) 032010]

Run 1 data $\Rightarrow L \sim 3\,\mathrm{fb}^{-1}$

No evidence for signal

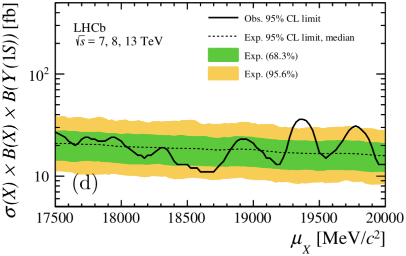


Upper limits relative to Λ_b production times its branching fraction to $J/\psi pK^+$ of $\mathcal{O}(10^{-3})$

Search for $X_{b\bar{b}b\bar{b}} \rightarrow \Upsilon(1S)\mu^+\mu^-$
[JHEP 10 (2018) 086]

2011–2017 data $\Rightarrow L \sim 6.3\,\mathrm{fb}^{-1}$

No significant excess for any mass hypothesis between 17.5 and 20.0 GeV



Upper limits on production cross section of $\mathcal{O}(10\,\mathrm{fb})$

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

[arXiv:1809.07416]

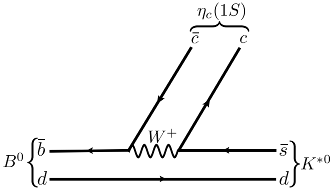
Accepted by EPJC

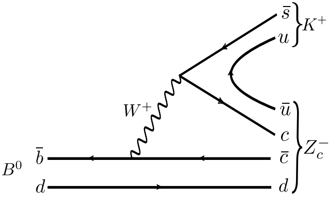
Motivations

[arXiv:1809.07416]

- prediction of states decaying to $\eta_c(1S)\pi^-$ **depending on the model** used to described the $Z_c(3900)^-$, discovered by BESIII **[BESIII collaboration, Phys. Rev. Lett. 110 (2013) 252001]**:
  - $Z_c(3900)^-$ as an hadrocharmonium state $\Rightarrow$ charged charmonium-like state of mass $\approx 3800\,\mathrm{MeV}$ **[M. B. Voloshin, Phys. Rev. D87 (2013) 091501]**
  - $Z_c(3900)^-$ as analogues of quarkonium hybrids $\Rightarrow$ states with quantum numbers allowing the decay to $\eta_c(1S)\pi^-$ **[E. Braaten, Phys. Rev. Lett. 111 (2013) 162003]**
- the diquark model predicts a $J^P = 0^+$ exotic candidate decaying to $\eta_c(1S)\pi^-$ below the open-charm threshold **[L. Maiani, F. Piccinini, A. D. Polosa, and V. Riquer, Phys. Rev. D71 (2005) 014028]**

$\Rightarrow$ **search for an $\eta_c(1S)\pi^-$ resonance studying $B^0 \to \eta_c(1S)K^+\pi^-$ decays**



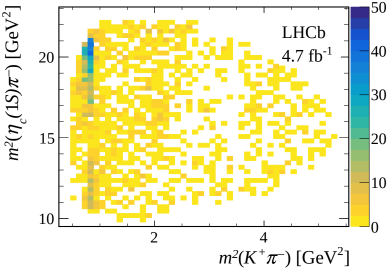


Analysis strategy

[arXiv:1809.07416]

- the $\eta_c(1S)$ is reconstructed into the $p\bar{p}$ decay mode
- charged hadrons discrimination provided by the RICH detectors are of crucial importance to select and correctly identify $B^0 \to p\bar{p}K^+\pi^-$ decays
- isolate $B^0 \to \eta_c(1S)K^+\pi^-$ events from combinatorial and nonresonant $B^0 \to p\bar{p}K^+\pi^-$ decays

- perform a Dalitz plot analysis to search for exotic hadrons and measure quasi-two-body branching fractions
- use 2011–2016 data $\Rightarrow L \sim 4.7\,\mathrm{fb}^{-1}$

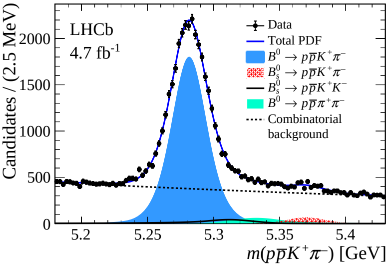


- Dalitz plot analysis performed separately for Run 1 and 2 data to take into account possible differences in the two data taking periods

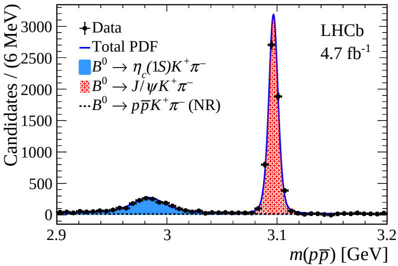
Signal yields

[arXiv:1809.07416]

$\approx 3 \times 10^4\ B^0 \to p\bar{p}K^+\pi^-$ decays



$\approx 2100\ B^0 \to \eta_c(1S)K^+\pi^-$ decays



- fit to the $m(p\bar{p})$ used to determine the $B^0 \to \eta_c(1S)K^+\pi^-$ branching fraction with respect to the $B^0 \to J/\psi K^+\pi^-$ normalisation channel
- reconstruction and selection efficiencies largely cancel in the ratio
- $R = \frac{N_{\eta_c}}{N_{J/\psi}} \times \frac{\epsilon_{J/\psi}}{\epsilon_{\eta_c}} = 0.357 \pm 0.015 \pm 0.008$

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

Amplitude analysis strategy

[arXiv:1809.07416]

- the $B^0 \to \eta_c(1S)K^+\pi^-$ decay involves only pseudoscalar particles $\Rightarrow$ Dalitz plot (DP) analysis using the Laura++ package **[Comput. Phys. Commun. 231 (2018) 198]**

- the sizeable natural width of the $\eta_c(1S)$ meson ($\Gamma_{\eta_c} \sim 32\,\mathrm{MeV}$) complicates the formalism:
  - the kinematic quantities entering the DP formalism are computed using $m(p\bar{p})$ instead of the known value of the $\eta_c(1S)$ mass
  - the natural width of the $\eta_c(1S)$ is set to zero when computing the DP normalisation (the effect of this simplification is taken into account when assessing systematic uncertainties)

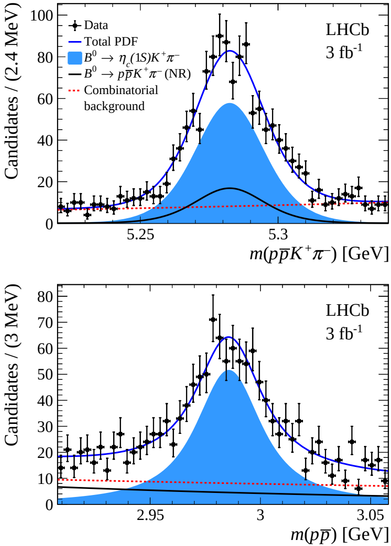
- the isobar model is used to write the decay amplitude: $K^+\pi^-$ S-wave at $m(K^+\pi^-) \lesssim 1.7\,\mathrm{GeV}$ parametrised with the LASS function, other resonances with relativistic Breit–Wigner functions

- simultaneous fit to Run 1 and Run 2 data using the JFIT framework **[arXiv:1409.5080]**: the signal and background yields, and the efficiency maps, are different between the two subsamples

Signal and background yields

[arXiv:1809.07416]

Run 1



- 2D fit to the joint $m(p\bar{p}K^+\pi^-) \times m(p\bar{p})$ distribution
- separate fit to Run 1 and 2 data samples
- D^0 and Λ_c^+ vetoes
- nonresonant and combinatorial backgrounds to be subtracted

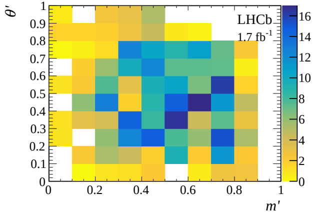
Component	Run 1	Run 2
$B^0 \to \eta_c K^+\pi^-$	805 ± 48	1065 ± 56
$B^0 \to p\bar{p}K^+\pi^-$ (NR)	234 ± 48	273 ± 56
Combinatorial background	409 ± 36	498 ± 41

Parametrisation of the backgrounds

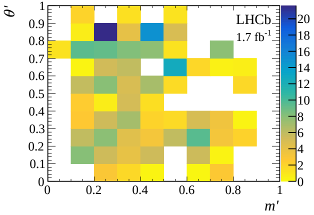
[arXiv:1809.07416]

- use the sPlot technique to build the histograms for the nonresonant and combinatorial backgrounds
- parametrised using the Square Dalitz plot coordinates to avoid artefacts related to the curved boundaries of the DP
- smooth histograms through a cubic spline interpolation

Run 2



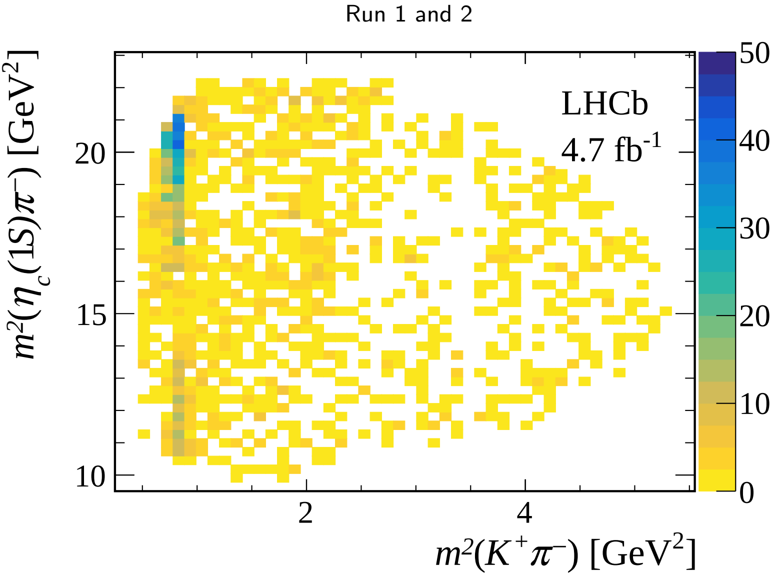
combinatorial background



nonresonant background

Background subtracted Dalitz plot

[arXiv:1809.07416]

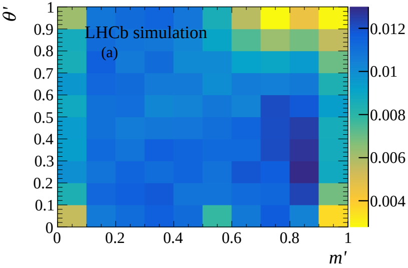


Efficiency parametrisation

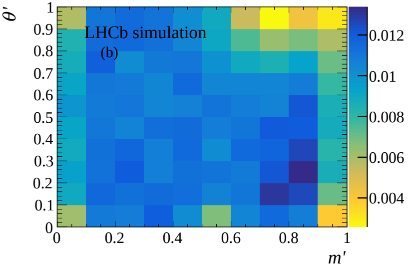
[arXiv:1809.07416]

- the efficiency variation is caused by the detector acceptance and selection procedure
- use simulated samples generated uniformly across the Square Dalitz plot and correct for differences between data and simulation in the PID efficiencies using calibration samples
- smooth histograms through a cubic spline interpolation

Run 1

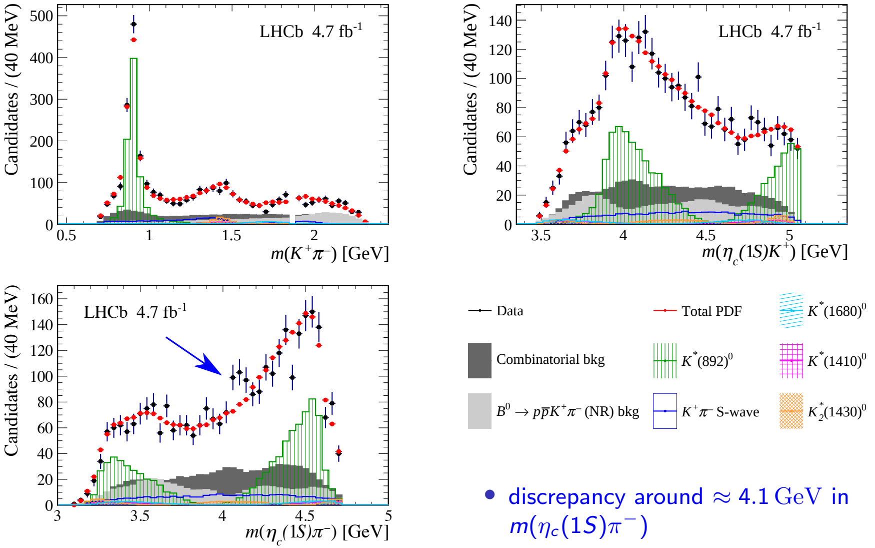


Run 2



Model with only $K^+\pi^-$ contributions

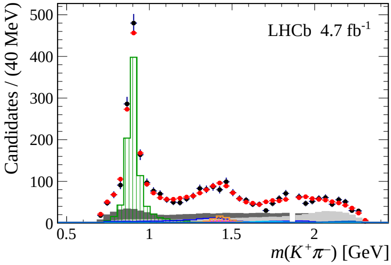
[arXiv:1809.07416]

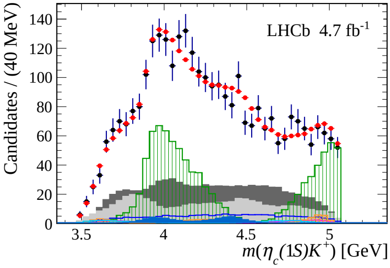


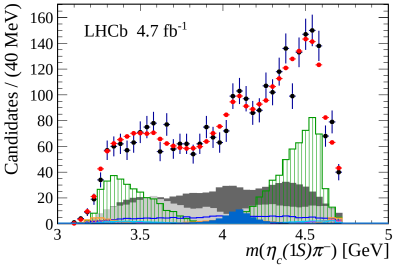
- discrepancy around $\approx 4.1\,\mathrm{GeV}$ in $m(\eta_c(1S)\pi^-)$

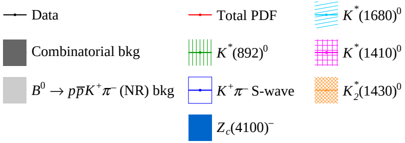
Model with $K^{+}\pi^{-}$ and $\eta_c(1S)\pi^{-}$ contributions

[arXiv:1809.07416]









- **statistical significance** determined through the profile likelihood ratio test, using toys and taking into account the look-elsewhere effect

$Z_c(4100)^{-}$ at $\Rightarrow 4.8\sigma$; $J^P = 0^{+}$ is rejected with respect to $J^P = 1^{-}$ at 4.3σ

Systematic uncertainties

[arXiv:1809.07416]

- **experimental uncertainties**:
  - signal and background yields
  - backgrounds parametrisation
  - efficiency parametrisation
  - 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

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

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

- 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 (top table) when including systematic uncertainties and correlations between them: 3.2σ**
- **Discrimination between $J^P = 0^+$ and $J^P = 1^-$ (bottom table) is not significant**

Cross-checks

[arXiv:1809.07416]

- addition of further high-mass K^{*0} states does not improve the quality of the fit
- additional amplitude decaying to $\eta_c(1S)\pi^-$ is not significant, nor an amplitude decaying to $\eta_c(1S)K^+$
- possible effect of the $\eta_c(1S)$ resonant phase motion in the overall amplitude is found negligible

$Z_c(4100)^-$ parameters and quasi-two-body branching fractions

[arXiv:1809.07416]

- $m_{Z_c^-} = 4096 \pm 20^{+18}_{-22}$ MeV, $\Gamma_{Z_c^-} = 152 \pm 58^{+60}_{-35}$ MeV
- quasi-two-body branching fractions measured by multiplying

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

with the fit fractions resulting from the Dalitz plot fit

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

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

Model-independent evidence for exotic contributions in $B^0 \to J/\psi K^+\pi^-$ decays

LHCb-PAPER-2018-043, in preparation

Motivations

LHCb-PAPER-2018-043, in preparation

- $Z_c(4430)^-$ discovered in the $Z_c(4430)^- \to \psi(2S)\pi^-$ decay mode
- $Z(4430)^- \to J/\psi\pi^-$ decay mode not yet confirmed: the understanding of this would provide insights into the internal structure of the $Z(4430)^-$
- in the dynamical diquark picture, this suppression is explained by a better overlap of the $Z(4430)^-$ radial wavefunction with the $\psi(2S)$ with respect to the radial ground J/ψ state **[S. J. Brodsky, D. S. Hwang, and R. F. Lebed, Phys. Rev. Lett. 113 (2014) 112001]**
- the Belle collaboration observed the $Z_c(4200)^- \to J/\psi\pi^-$ at 6.2σ **[Belle collaboration, Phys. Rev. D90 (2014) 112009]**

Analysis strategy

LHCb-PAPER-2018-043, in preparation

- the $B^0 \to J/\psi K^+\pi^-$ decay mode is dominated by $K^{*0} \to K^+\pi^-$ intermediate contributions
- given the low $Z(4430)^-$ fit fraction expected in this decay mode, an optimal description of the K^{*0} contributions would be required
- adopt the model-independent approach, only requiring the knowledge of the highest spin of the K^{*0} contributions for a given $m(K^+\pi^-)$ interval, to bypass the problem
- 4D angular analysis of $B^0 \to J/\psi K^+\pi^-$ decays to analyse the differential decay rate as a function of $m(K^+\pi^-)$ and of the three angles defining the decay
- test the hypothesis that the K^{*0} contributions alone can describe all the structures seen in the data using a novel 3D moments technique

Angular moments technique

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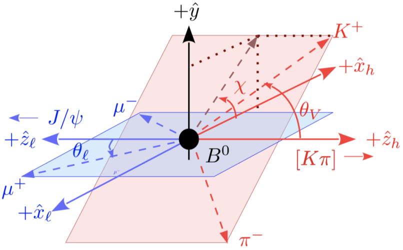

- $\Omega = \{\theta_l, \theta_V, \chi\}$ characterise the decay for a $m(K^+\pi^-)$ value
- θ_V is the K^{*0} helicity angle tagging the spin J of the resonance

$$\left[\frac{d\Gamma^k}{d\Omega}\right]_{J^k_{\max}} \propto \sum_{i=1}^{n^k_{\max}} f_i(\Omega)\Gamma^k_i$$

- $f_i(\Omega)$ is an element of a set of orthonormal functions built starting from spherical harmonics of the three decay angles
- Γ^k_i are angular moments in the k^{th} bin of $m(K^+\pi^-)$ extracted from data (the dependence on $m(K^+\pi^-)$ can be neglected if the intervals are narrow)

Signal yields and K^{*0} states

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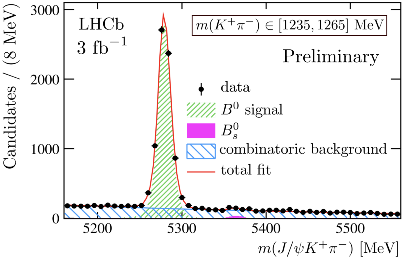
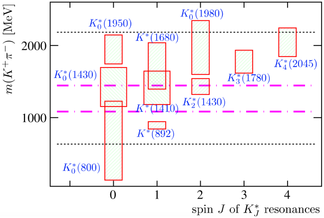
- large statistics of $\sim 500k$ events with Run 1 data
- allows for independent fits in fine $m(K^+\pi^-)$ intervals (purity is larger than 90% for all of them)



- $J_{\max} = 2$ for $m(K^+\pi^-) < 1265\,\text{MeV}$
- $J_{\max} = 3$ for $m(K^+\pi^-) > 1265\,\text{MeV}$
- if only K^{*0} states contribute to the decay $\Rightarrow$ data described by an expansion in angular moments with the sum truncated to $J_{\max}$
  - if the data can be described only truncating the sum to unphysical high values for $J_{\max}$, it is an indication of other dynamical processes contributing to the decay



Model from angular moments

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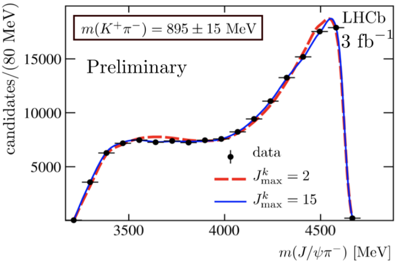
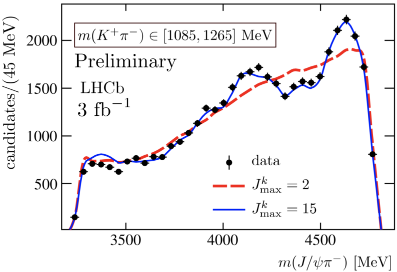
- use simulated events generated flat in the angular space and including efficiency effects
- weight events using normalised moments determined from data



Region dominated by the $K^*(892)^0$
$\Rightarrow$ well described by $J_{\max} = 2$



$\Rightarrow$ Higher moments are required

Significance and results

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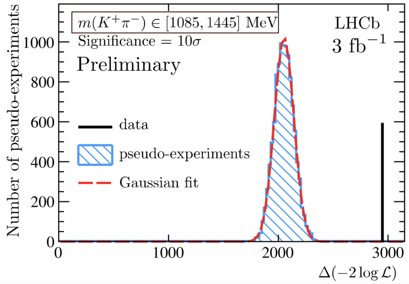
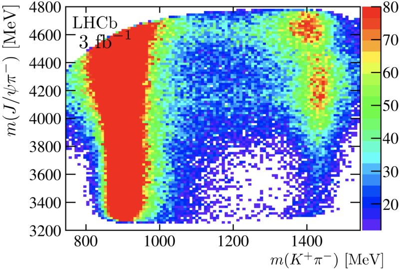


$\Rightarrow$ the profile likelihood ratio test demonstrates at more than 5σ that K^{*0} contributions alone cannot describe the dynamics of the $B^0 \rightarrow J/\psi K^+\pi^-$ decay



By inspecting the DP, structures are visible at $m(J/\psi\pi^-) \approx 4200\,\mathrm{MeV}$ and $m(J/\psi\pi^-) \approx 4600\,\mathrm{MeV}$

The nature of the non-K^{*0} contributions can be investigated with a future amplitude analysis

Conclusions

- the study of exotic spectroscopy is important to improve the understanding of the non-perturbative regime of QCD
- the LHCb collaboration already provided important results in this sector, and will contribute further in the near future with important updates using the Run 2 data sample
- LHCb is going to be upgraded, *i.e.* a brand new detector will be built, implementing an innovative software-based trigger system, that will improve the efficiency on hadronic final states and will make it possible to collect a larger data sample exploiting the increased instantaneous luminosity

Thanks!

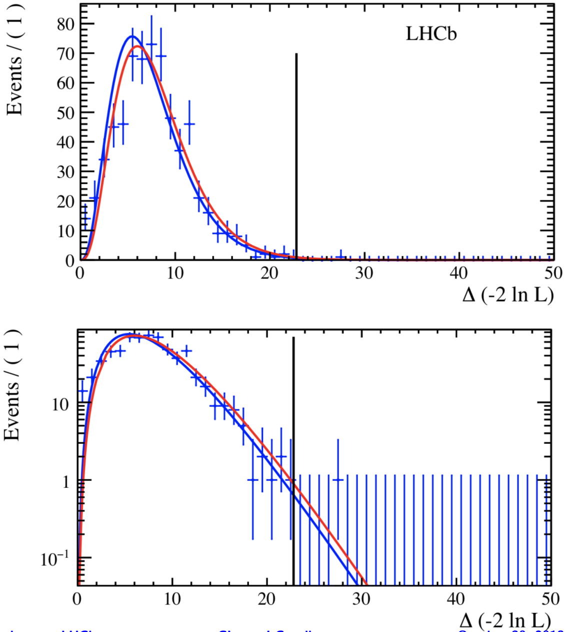
Backup slides

$Z_c(4100)^-$ significance determination strategy

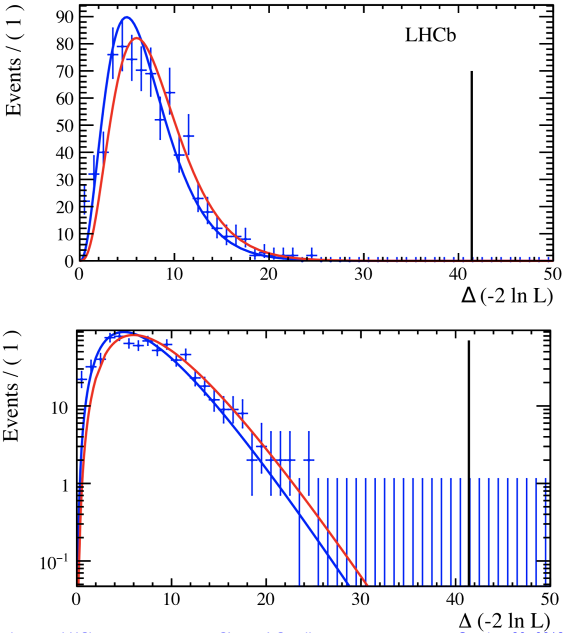
- generate 1000 toys according to the no-Z model
- fit with both the no-Z (H_0) and Z (H_1) models and determine $\lambda = -2 \ln \frac{\mathcal{L}(H_0)}{\mathcal{L}(H_1)} = \Delta(-2 \log \mathcal{L})$
- when fitting with H_0 , add the $Z_c(4100)^-$ component but fixing its isobar coefficients to zero (assure the regularity of the likelihood around the point of constraint)
- when fitting with H_1 , $Z_c(4100)^-$ mass and width are left floating $\Rightarrow$ look-elsewhere effect taken into account
- check $\Delta(-2 \log \mathcal{L})$ follows a χ^2 distribution
- fit $\Delta(-2 \log \mathcal{L})$ to determine the number of degrees of freedom: a χ^2 with ndof=8 describes well $\Delta(-2 \log \mathcal{L})$

$$n_\sigma(\Delta(-2 \ln \mathcal{L}) = \sqrt{2}\ \text{TMath::ErfcInverse}(\text{TMath::Prob}(\Delta(-2 \ln \mathcal{L}), 8)) \quad (1)$$

$\Delta(-2\ln\mathcal{L})$ for $J^P = 0^+$



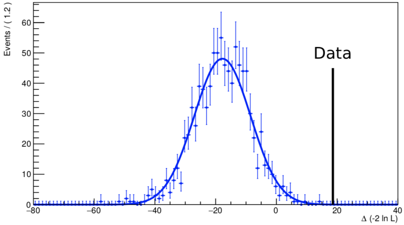
$\Delta(-2\ln\mathcal{L})$ for $J^P = 1^-$



$Z_c(4100)^-$ quantum numbers: significance determination strategy

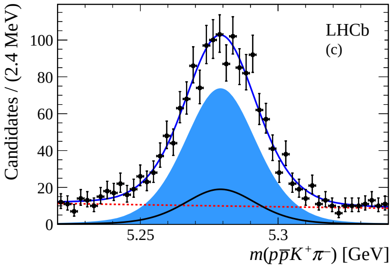
- generate 1000 toys according to $J^P = 0^+$ hypothesis
- fit with both the $J^P = 0^+$ (H_0) and $J^P = 1^-$ (H_1) models and determine $\lambda = -2\ln\frac{\mathcal{L}(H_0)}{\mathcal{L}(H_0)} = \Delta(-2\log\mathcal{L})$
- lower limit on the significance of the rejection of the $J^P = 0^+$ hypothesis:

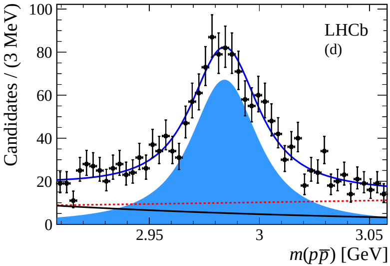
$$n_\sigma = \sqrt{\Delta(-2\ln\mathcal{L})} \qquad (2)$$



Signal and background yields: 2D fit for Run 2

[arXiv:1809.07416]

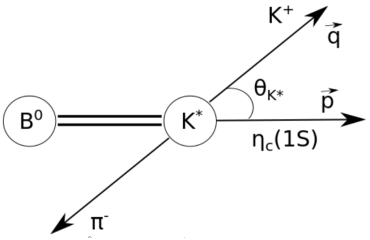




Square Dalitz plot coordinates and helicity angle

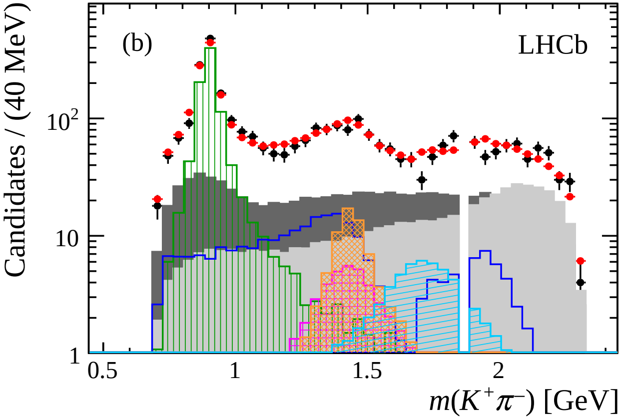
$$m' \equiv \frac{1}{\pi} \arccos\left(2\frac{m(K^+\pi^-) - m^{\min}_{K^+\pi^-}}{m^{\max}_{K^+\pi^-} - m^{\min}_{K^+\pi^-}} - 1\right)$$

$$\theta' \equiv \frac{1}{\pi}\theta(K^+\pi^-),$$



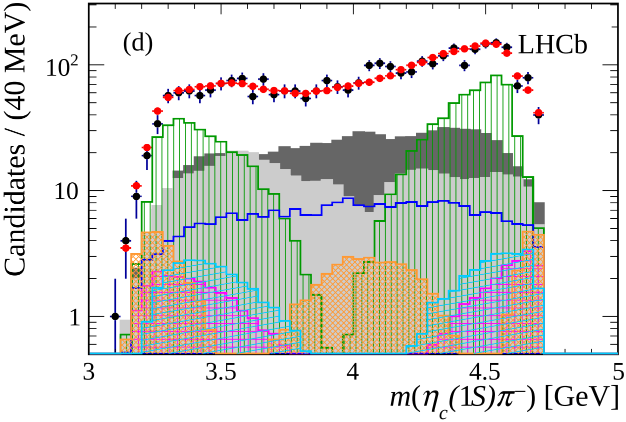
$K^+\pi^-$ model: log $m(K^+\pi^-)$

[arXiv:1809.07416]



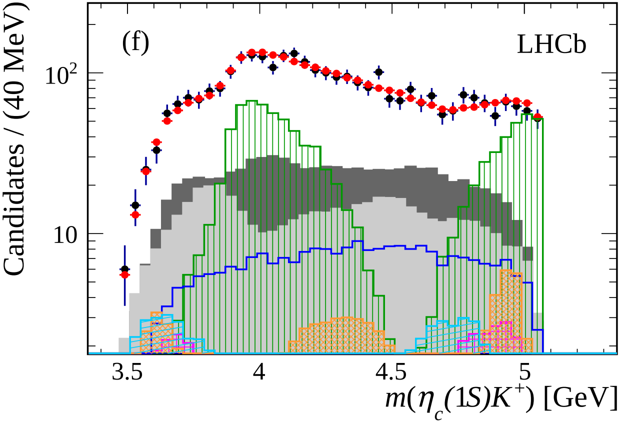
$K^+\pi^-$ model: log $m(\eta_c(1S)\pi^-)$

[arXiv:1809.07416]



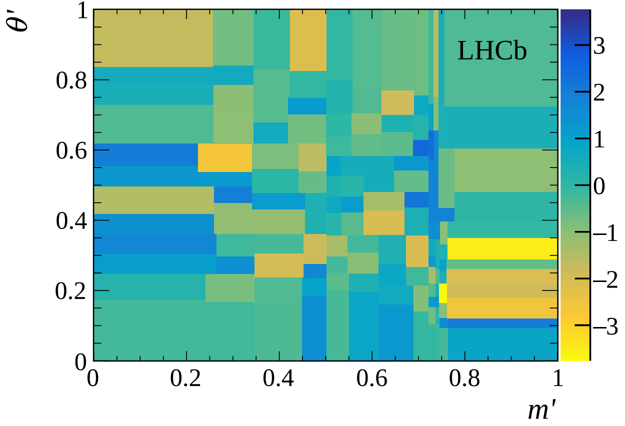
$K^+\pi^-$ model: log $m(\eta_c(1S)K^+)$

[arXiv:1809.07416]



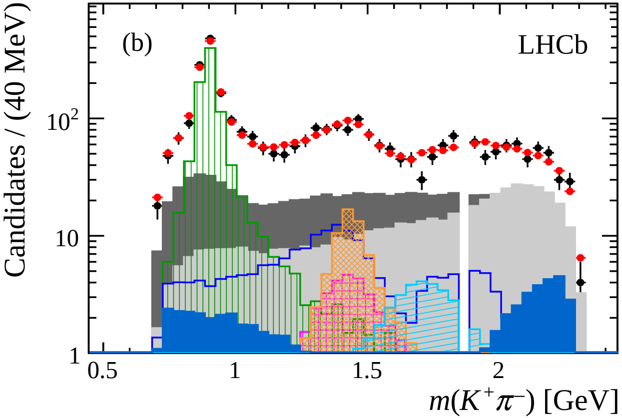
$K^+\pi^-$ model: 2D pull

[arXiv:1809.07416]



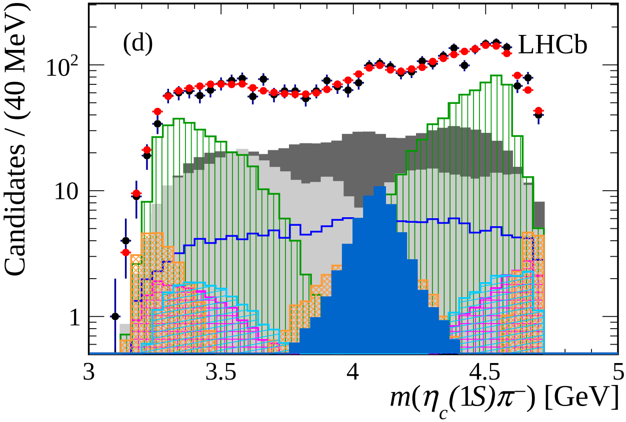
$K^+\pi^-$ and $\eta_c(1S)\pi^-$ model: log $m(K^+\pi^-)$

[arXiv:1809.07416]



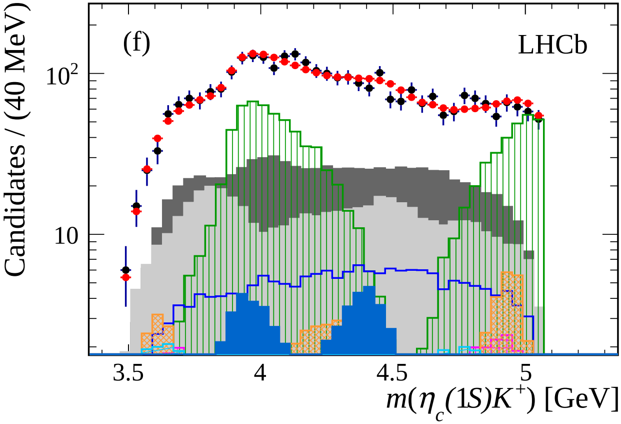
$K^+\pi^-$ and $\eta_c(1S)\pi^-$ model: log $m(\eta_c(1S)\pi^-)$

[arXiv:1809.07416]



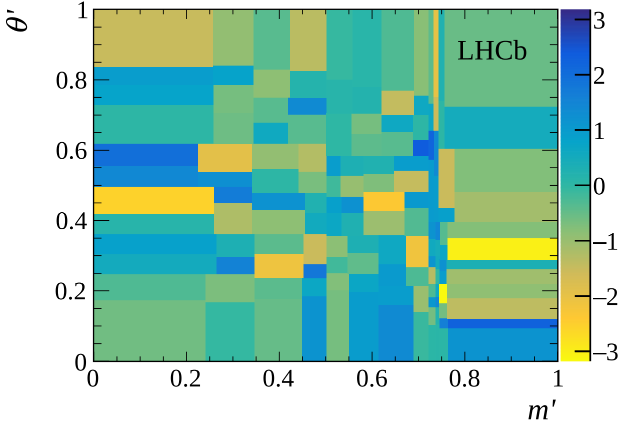
$K^+\pi^-$ and $\eta_c(1S)\pi^-$ model: log $m(\eta_c(1S)K^+)$

[arXiv:1809.07416]



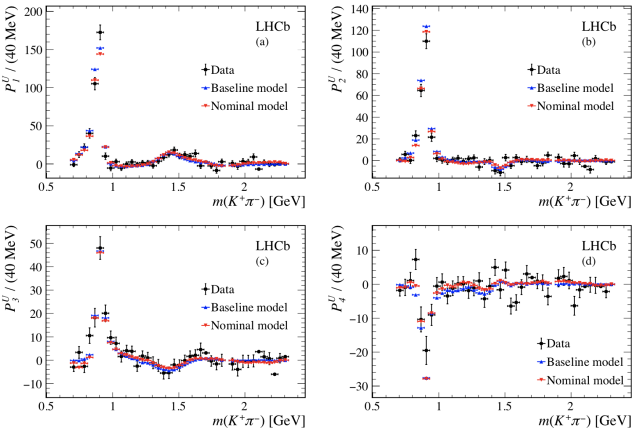
$K^+\pi^-$ and $\eta_c(1S)\pi^-$ model: 2D pull

[arXiv:1809.07416]



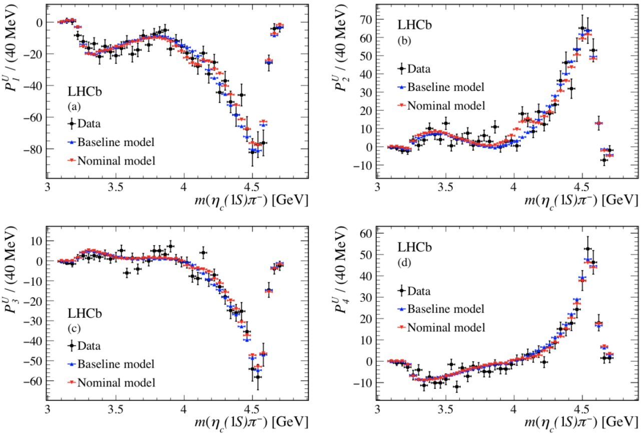
$K^+\pi^-$ Legendre moments

[arXiv:1809.07416]



$\eta_c(1S)\pi^-$ Legendre moments

[arXiv:1809.07416]



$\eta_c(1S)K^+$ Legendre moments

[arXiv:1809.07416]