Spectroscopy of Strange and non-Strange Light Mesons @ LHCb

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Outline

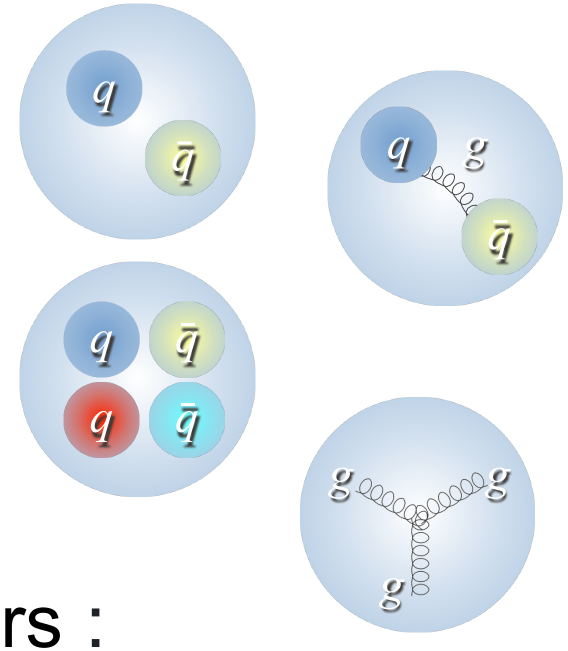
- Non-strange light meson spectroscopy
  - Early works on light mesons
  - Study of light-meson resonances decaying to $K_S^0 K\pi$ in the $B \to (K_S^0 K\pi)K$ channels *[PRD 111 (2025) 092009]*
- Strange meson spectroscopy
  - Studies of the resonance structure in $D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$decays *[Eur. Phys. J. C 78 (2018) 443]*
  - Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$ decays *[JHEP 01 (2025) 054]*
  - Observation of new resonances decaying to $J/\psi K^+$ and $J/\psi\phi$ *[PRL 127 (2021) 082001]*

The precision understanding of the strange and no-strange hadron spectroscopy is important for LHCb in the study of the heavy-flavour exotic states

Light mesons

- Conventional mesons as color-singlet $q\bar{q}$ pairs ($q = u, d, s$) fit into SU(3) flavour multiplets with quantum numbers:

$$\boxed{J^{PC} = 0^{++}, 0^{-+}, 1^{--}, 1^{+\pm}, 2^{++}, \text{etc}}$$



- QCD allows other formations called exotics:
  - Glueballs (pure gluonic states)
  - Hybrids ($q\bar{q}g$)
  - Tetraquarks ($qq\overline{qq}$ or $q\bar{q}q\bar{q}$)
- Experimental signatures of exotic quantum numbers :

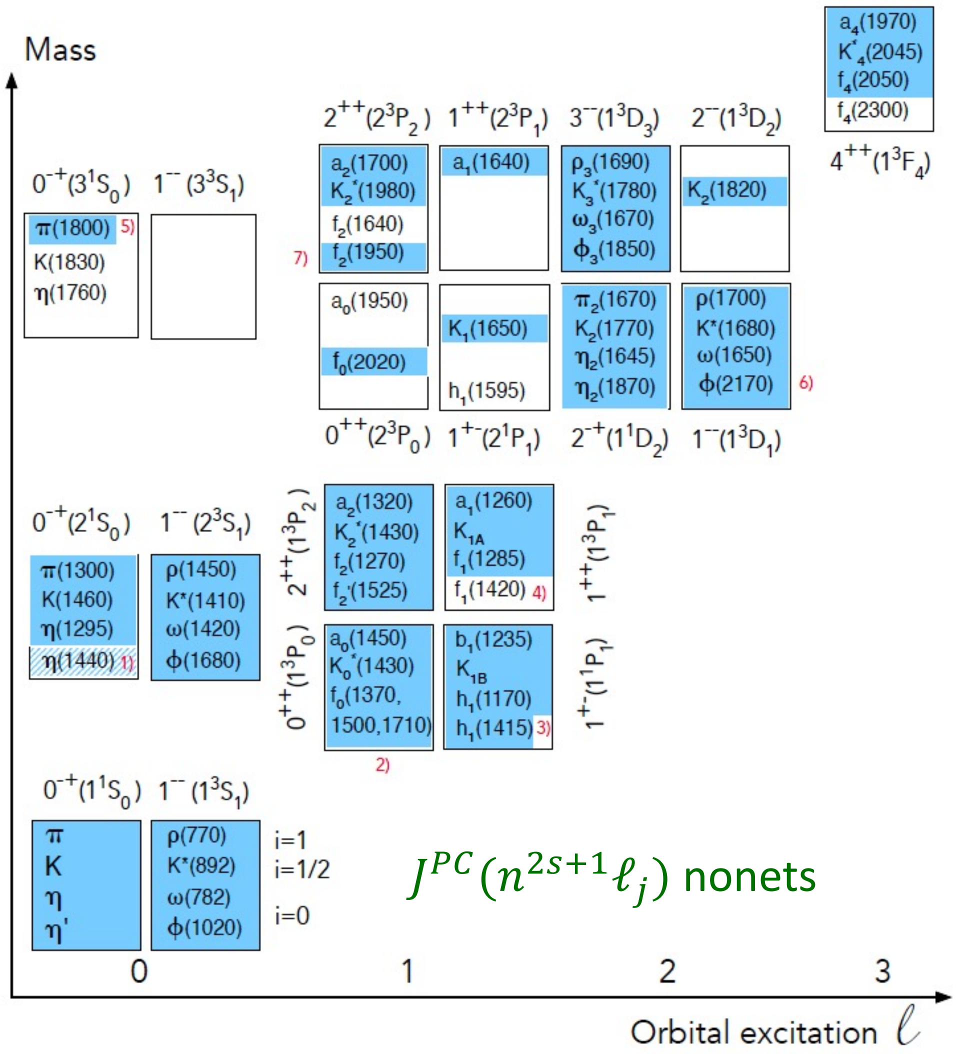
$$\boxed{0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \text{etc}}$$

Open questions

[PDG review "*Spectroscopy of Light Meson Resonances*"]

- Pseudoscalar $\eta(1440)$ 1)
  - Possibly two states $\eta(1405)$ & $\eta(1475)$
- Difficulty accommodating known light scalars in lower $q\bar{q}$ nonets 2)
  - $a_0(980)$, $K_0^*(700)$, $f_0(500)$, $f_0(980)$
- Three observed isoscalars 2)
  - $f_0(1370/1500/1700)$
  - The latter two proposed as glueball candidates
- The axial-vector meson $f_1(1420)$ has another candidate $f_1(1510)$ 4)

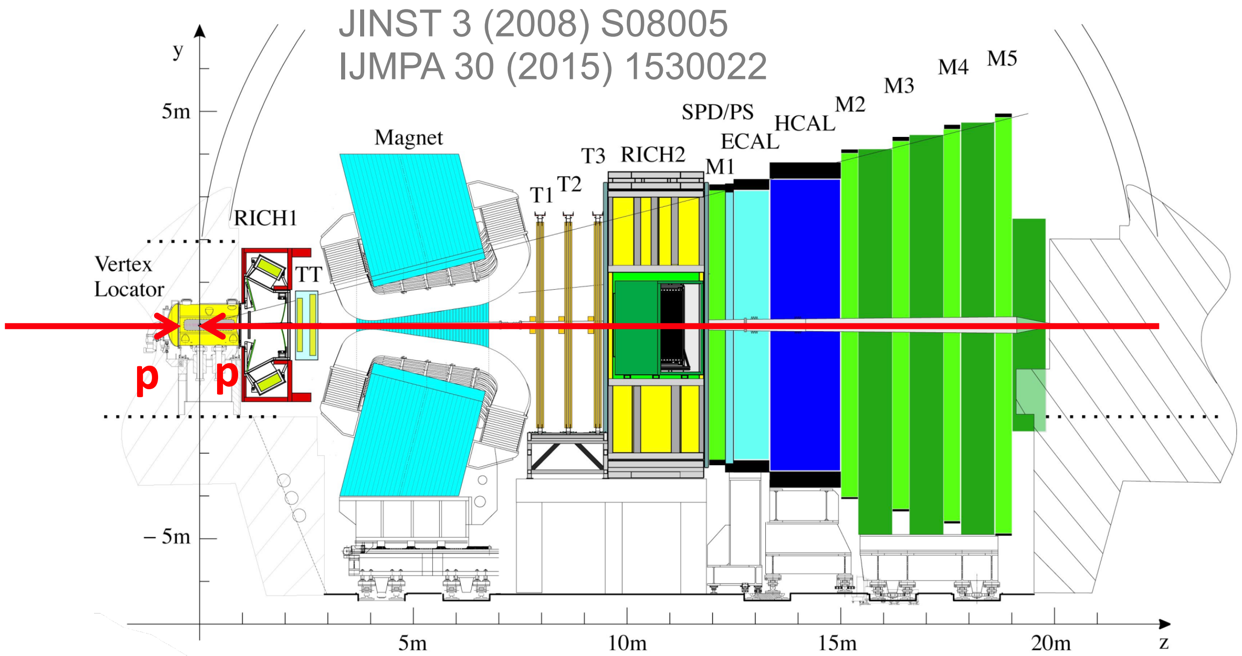
Mass spectrum of $q\bar{q}$ mesons

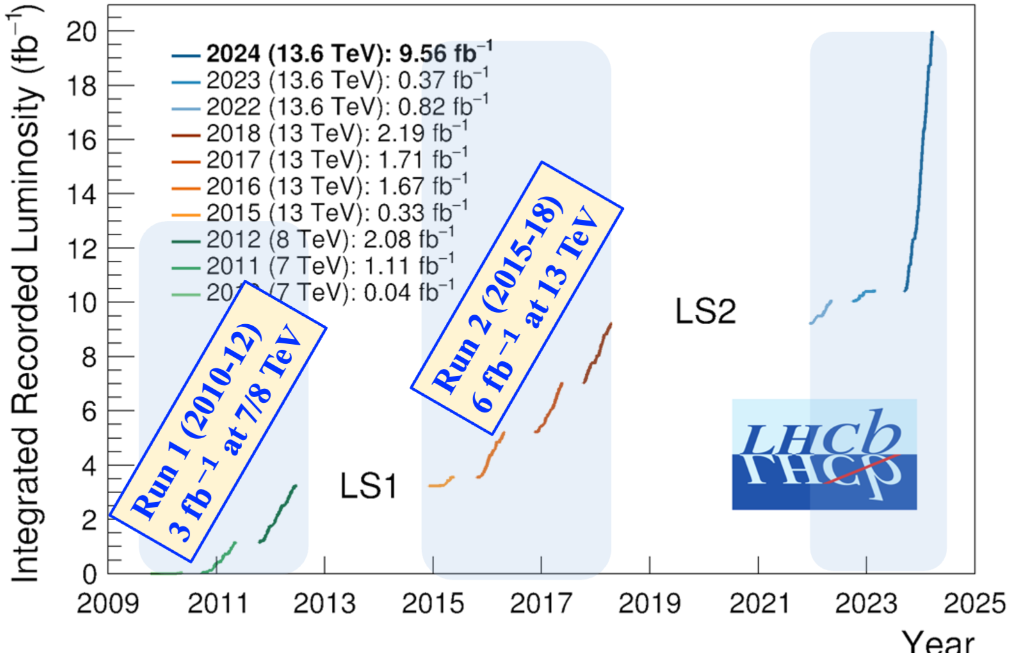


The LHCb Experiment

- LHCb is a dedicated flavour physics experiment at the LHC
  - >10^4 $\times$ larger b production rate than the B factories @ $\Upsilon(4S)$
  - Access to all b-hadrons: B^+, B^0, B_s^0, B_c^+, b-baryons
- Can also study hadron spectroscopy and exotic states
- Acceptance optimised for forward $b\bar{b}$ production

> ➢ All results based on full or part of run-1 and run-2 datasets



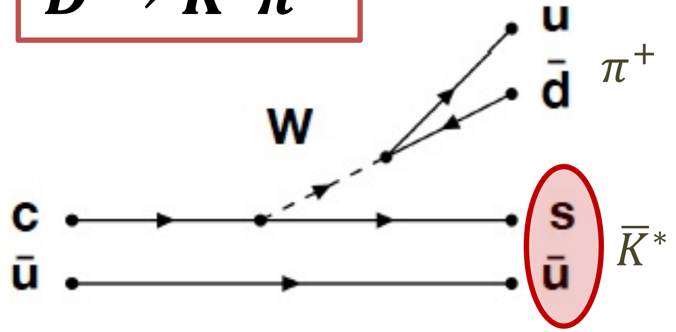


Light-hardon spectroscopy at LHCb

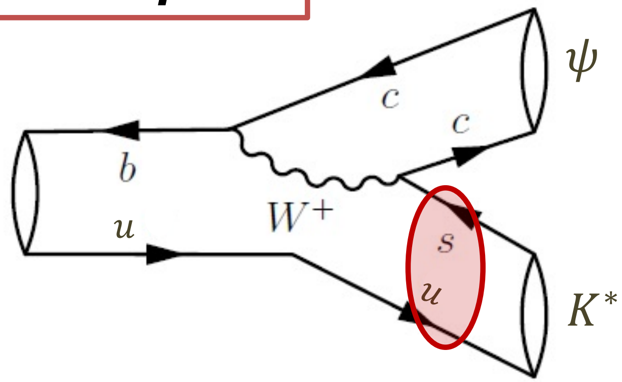
- Amplitude analysis
  - Direct production of light hadrons obviously happens but the multiplicity of tracks is so large that they are covered by large background
  - Rather study resonances in heavy flavored particle decays (D, $B_{(s)}$-hadrons)
  - $B_{(s)}$-decays select pure quark-contents of the light hardon

Strange production

$D \to \bar{K}^{*}\pi^{+}$

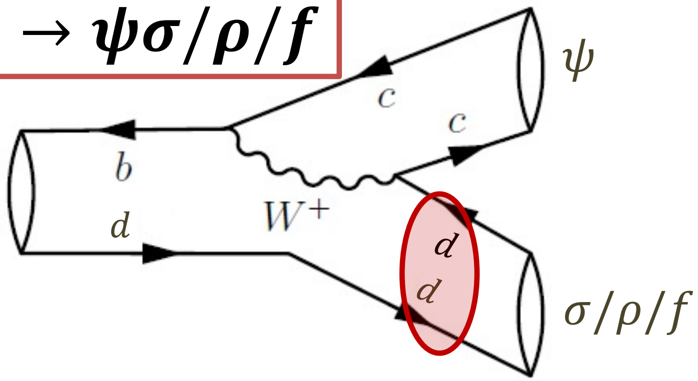


$B \to \psi K^{*}$

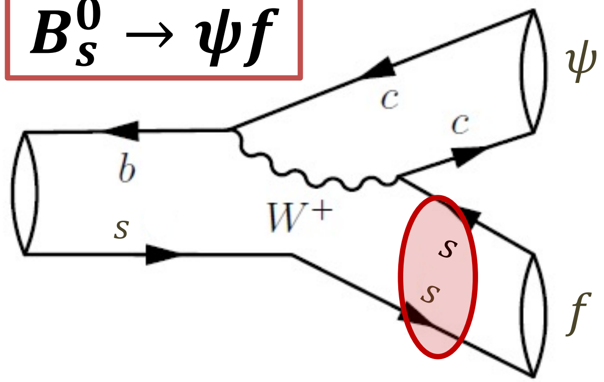


Non-Strange production

$B^0 \to \psi\sigma/\rho/f$



$B_s^0 \to \psi f$



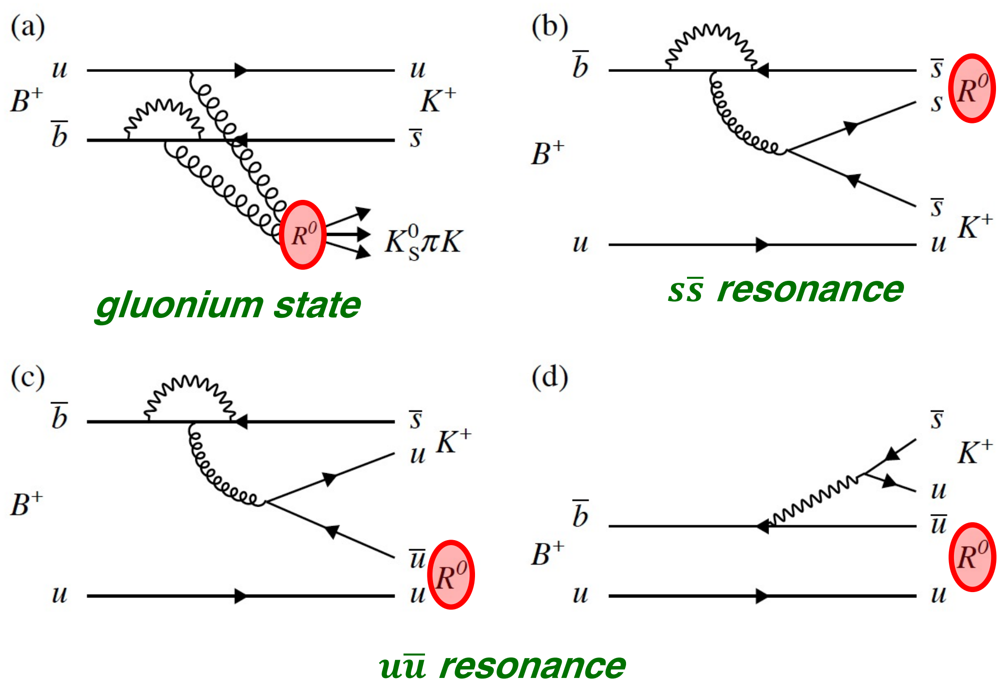
Non-Strange Mesons

Early works on non-strange light mesons

- LHCb, "Resonances and CP violation in B_s^0 and $\overline{B}_s^0 \to J/\psi K^+K^-$ decays in the mass region above the φ(1020)", *JHEP 08 (2017) 037*.
- LHCb, "Measurement of the resonant and CP components in $B^0 \to J/\psi\pi^+\pi^-$ decays", *PRD 90 (2014) 012003*.
- LHCb, "Measurement of resonant and CP components in $B_s^0 \to J/\psi\pi^+\pi^-$ decays", *PRD 89 (2014) 092006*.
- LHCb, "Observation of $B_{(s)}^0 \to J/\psi f_1(1285)$ decays and measurement of the $f_1(1285)$ mixing angle", *PRL 112 (2014) 091802*.
- Sheldon Stone and Liming Zhang, "Use of $B \to J/\psi f_0$ decays to discern the $q\bar{q}$ or tetraquark nature of scalar mesons", *PRL 111 (2013) 062001*.
- LHCb, "Amplitude analysis and branching fraction measurement of $B_s^0 \to J/\psi K^+K^-$", *PRD 87 (2013) 072004*.
- LHCb, "Analysis of the resonant components in $B^0 \to J/\psi\pi^+\pi^-$", *PRD 87 (2013) 052001*.
- Liming Zhang and Sheldon Stone, "Time-dependent Dalitz-plot formalism for $B_q^0 \to J/\psi h^+h^-$", *PLB 719 (2013) 383-387*.
- LHCb, "Analysis of the resonant components in $B_s^0 \to J/\psi\pi^+\pi^-$", *PRD 86 (2012) 052006*.
- LHCb, "Observation of $B_s^0 \to J/\psi f_2'(1525)$ in $J/\psi K^+K^-$ final states", *PRL 108 (2012)151801*.
- LHCb, "First observation of $B_s^0 \to J/\psi f_0(980)$ decays", *PLB 698 (2011) 115-122*.
- S. Stone and L. Zhang "S-waves and the measurement of CP violating phases in B_s decays", *PRD 79 (2009) 074024*.

$R^0 \to K_S^0 K^\pm \pi^\mp$ system in $B^+ \to R^0 K^+$ decays

- The process b → s gluon has been suggested as possible source of gluonium states [H. Fritzsch, PLB 415, 83-89 (1997)]
- However contributions from $s\bar{s}$ and $u\bar{u}$ resonances are expected.



- Pseudoscalar glueball:
  - Phenomenological models: ≈ 1.4 GeV
  - Lattice QCD: ≈ 2.5 GeV

    [J Phys G40 (2013) 043001]

- Mass region (<1.6 GeV) can study:
  - Two overlapping 1^{++} states: $f_1(1420)$ and $f_1(1510)$
  - Two states $\eta(1405)$ & $\eta(1475)$

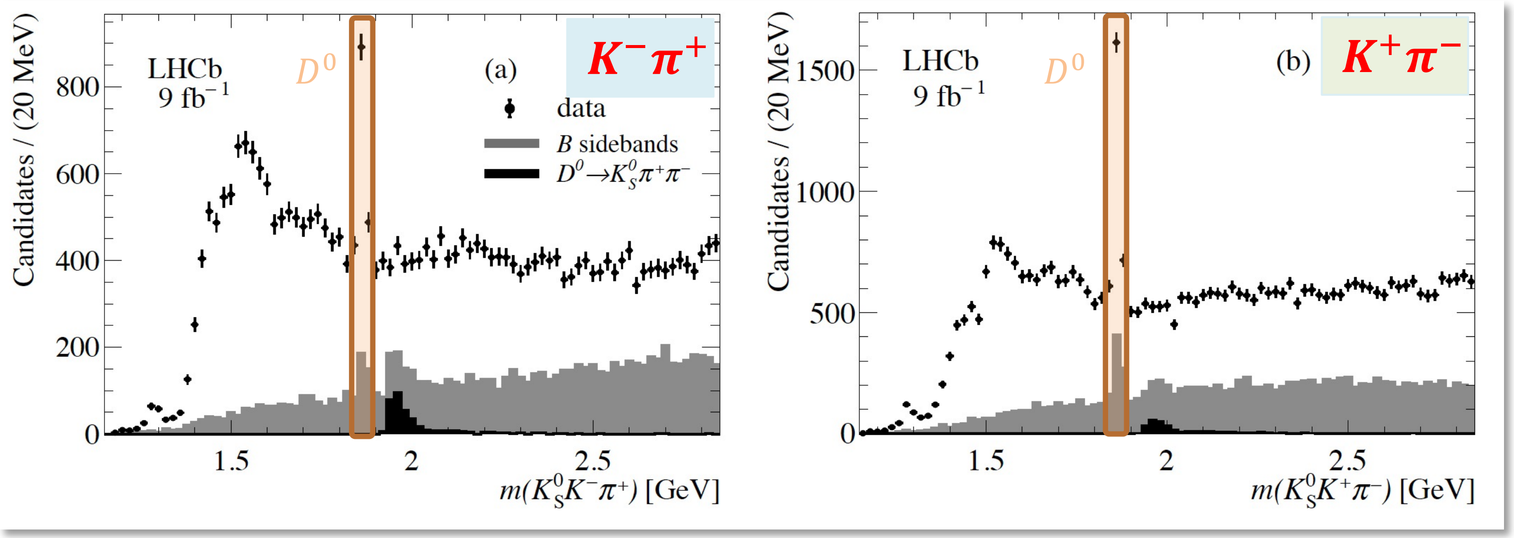
$K_S^0 K^\pm \pi^\mp$ mass spectra

[PRD 111 (2025) 092009]

- Selection re-optimized in the $K_S^0 K^\pm \pi^\mp$ threshold region
- Event yields for $m(K_S^0 K^\pm \pi^\mp) < 1.85$ GeV

Final state	Signal Events	Background	Purity
$B^+ \to K_S^0 K^+ K^- \pi^+$	10430	1454	87.8 ± 0.3
$B^+ \to K_S^0 K^+ K^+ \pi^-$	12320	2180	85.0 ± 0.3

- Complex superposition of resonances in the threshold region



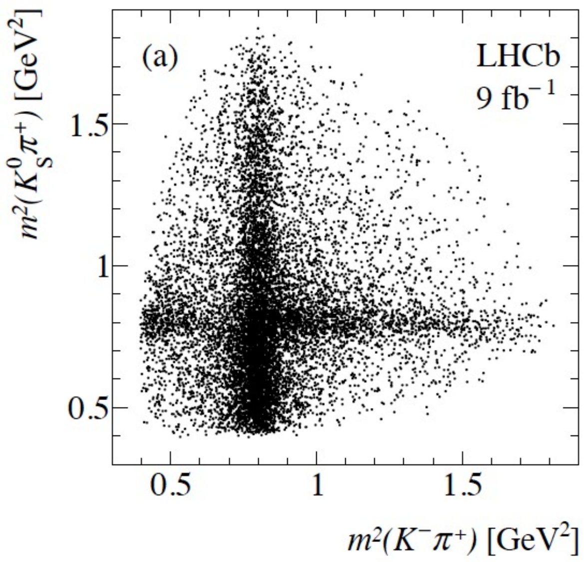
Comparison of two decay modes

[PRD 111 (2025) 092009]

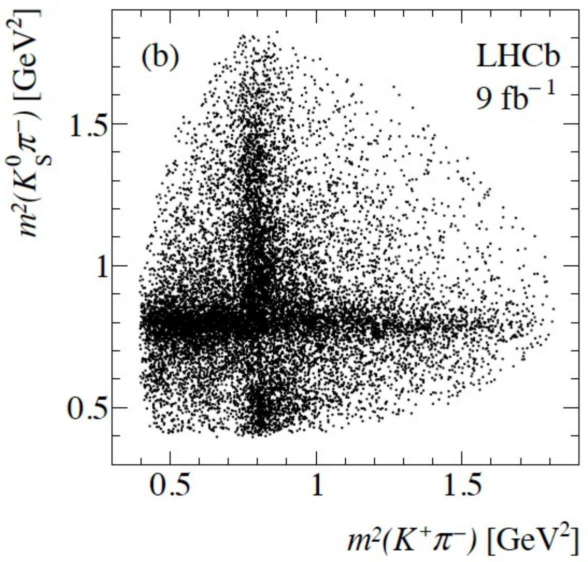
- Dalitz plot for the two different B^+ decays for $1.3 < m\left(K_S^0 K^\pm \pi^\mp\right) < 1.85$ GeV

$B^+ \to \left(K_S^0 K^- \pi^+\right) K^+$

$K^{*+}K^-$ vs $\overline{K}^{*0}K^0$



$B^+ \to \left(K_S^0 K^+ \pi^-\right) K^+$



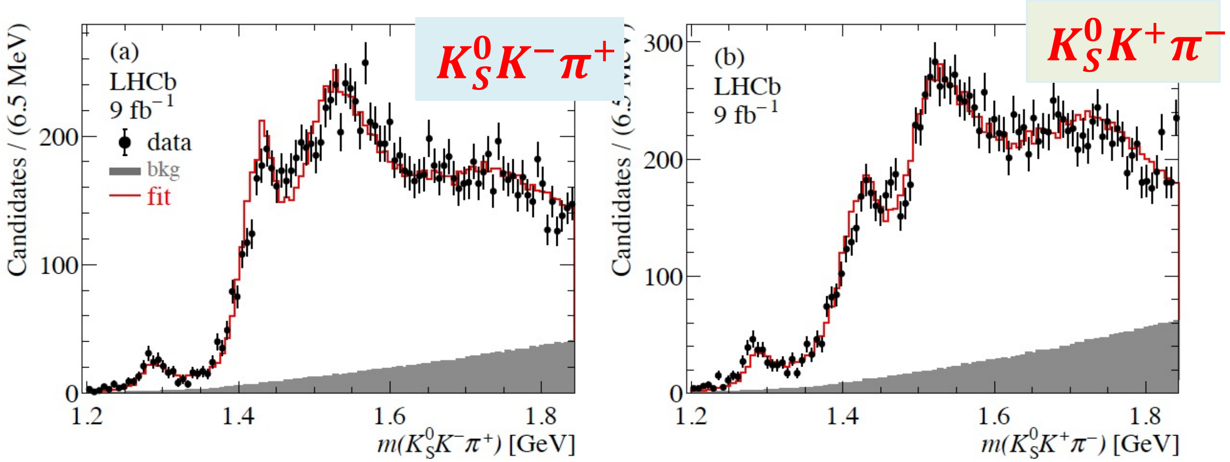
$K^{*-}K^+$ vs $K^{*0}\overline{K}^0$

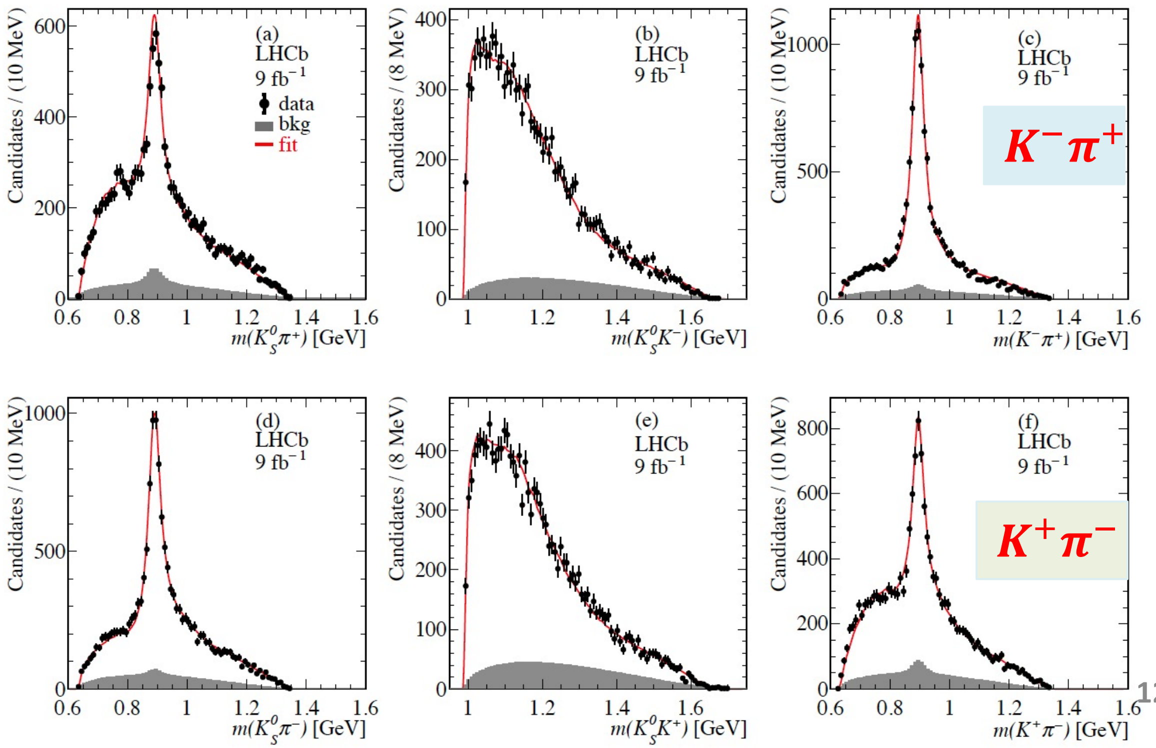
- Asymmetric K^{*+}/K^{*0} distributions
- The Dalitz plots for $B^+ \to \left(K_S^0 K^- \pi^+\right) K^+$ and $B^+ \to \left(K_S^0 K^+ \pi^-\right) K^+$ are different
- Neutral K^{*0} and charged K^{*+} bands are somewhat inverted

Ampitude analysis

[PRD 111 (2025) 092009]

- Decay chains via $a_0(980)\pi$, $K^*(892)\bar{K}$ and direct $K^0K\pi$
- Resonant parameters are fixed to those from PDG
- Reference amplitude is the $J^{PC} = 0^{-+}\ \eta(1475) \to K^*\bar{K}$, parameter fixed to BESIII analysis on $J/\psi \to \gamma K_S^0 K_S^0 \pi^0$ [JHEP 03 (2023) 121]
- 19 contributions include $J^{PC} = 0^{-+}, 1^{++}, 1^{+-}$ and $\eta_2(1645)$





Fit results

[PRD 111 (2025) 092009]

Contribution	Decay	$B^+ \to K_S^0 K^- \pi^+ K^+$ Fraction [%]	$B^+ \to K_S^0 K^- \pi^+ K^+$ Phase [rad]	$B^+ \to K_S^0 K^+ \pi^- K^+$ Fraction [%]	$B^+ \to K_S^0 K^+ \pi^- K^+$ Phase [rad]
$\eta(1475)$	$K^*\bar{K}$	$10.7 \pm 1.1 \pm 1.1$	0	$10.3 \pm 1.1 \pm 1.4$	0
	$a_0\pi$	$1.4 \pm 0.4 \pm 0.4$	$3.18 \pm 0.19 \pm 0.15$	$1.8 \pm 0.4 \pm 0.4$	$2.92 \pm 0.14 \pm 0.13$
	PS	$15.2 \pm 2.1 \pm 2.1$	$3.33 \pm 0.10 \pm 0.12$	$8.9 \pm 1.4 \pm 2.7$	$3.57 \pm 0.11 \pm 0.13$
	Total	$27.4 \pm 2.4 \pm 2.4$	–	$21.0 \pm 1.8 \pm 3.1$	–
$\eta(1760)$	$K^*\bar{K}$	$1.9 \pm 0.4 \pm 0.3$	$-1.53 \pm 0.16 \pm 0.28$	$3.1 \pm 0.4 \pm 0.5$	$-1.16 \pm 0.13 \pm 0.20$
	$a_0\pi$	$2.0 \pm 0.4 \pm 0.3$	$2.11 \pm 0.15 \pm 0.20$	$1.7 \pm 0.4 \pm 0.3$	$3.06 \pm 0.12 \pm 0.24$
	PS	$11.9 \pm 1.8 \pm 2.7$	$1.60 \pm 0.10 \pm 0.19$	$23.2 \pm 2.4 \pm 5.1$	$1.92 \pm 0.07 \pm 0.22$
	Total	$15.8 \pm 1.9 \pm 2.7$	–	$27.9 \pm 2.5 \pm 5.1$	–
$\eta(1405)$	$K^*\bar{K}$	$3.5 \pm 0.6 \pm 1.9$	$-0.10 \pm 0.10 \pm 0.20$	$2.3 \pm 0.5 \pm 0.7$	$-0.01 \pm 0.11 \pm 0.18$
	PS	$5.2 \pm 0.5 \pm 0.8$	$1.77 \pm 0.11 \pm 0.28$	$6.4 \pm 0.5 \pm 0.9$	$1.96 \pm 0.13 \pm 0.20$
	Total	$8.7 \pm 0.8 \pm 2.0$	–	$8.6 \pm 0.7 \pm 1.1$	–
$f_1(1285)$	$a_0\pi$	$2.0 \pm 0.2 \pm 0.2$	$-0.35 \pm 0.13 \pm 0.26$	$2.0 \pm 0.2 \pm 0.2$	$-0.47 \pm 0.11 \pm 0.12$
$f_1(1420)$	$K^*\bar{K}$	$11.4 \pm 0.7 \pm 2.1$	$4.25 \pm 0.08 \pm 0.23$	$6.6 \pm 0.5 \pm 1.7$	$4.67 \pm 0.10 \pm 0.27$
$h_1(1415)$	$K^*\bar{K}[S]$	$10.0 \pm 0.9 \pm 2.0$	$4.59 \pm 0.08 \pm 0.20$	$18.6 \pm 1.2 \pm 3.5$	$1.57 \pm 0.08 \pm 0.55$
	$K^*\bar{K}[D]$	$3.3 \pm 0.3 \pm 0.2$	$-0.13 \pm 0.08 \pm 0.16$	$2.4 \pm 0.3 \pm 0.2$	$-2.57 \pm 0.08 \pm 0.42$
	Total	$13.3 \pm 1.0 \pm 2.0$	–	$21.0 \pm 1.2 \pm 3.6$	–
$f_1(1510)$	$K^*\bar{K}$	$2.9 \pm 0.4 \pm 1.2$	$-3.23 \pm 0.09 \pm 0.47$	$2.6 \pm 0.3 \pm 2.7$	$-2.88 \pm 0.09 \pm 0.23$
$h_1(1595)$	$K^*\bar{K}[S]$	$5.3 \pm 0.8 \pm 1.4$	$1.44 \pm 0.08 \pm 0.19$	$14.8 \pm 1.4 \pm 2.8$	$4.20 \pm 0.06 \pm 0.48$
$\eta_2(1645)$	$K^*\bar{K}$	$1.6 \pm 0.2 \pm 0.8$	$2.28 \pm 0.10 \pm 0.09$	$0.8 \pm 0.2 \pm 0.2$	$2.15 \pm 0.12 \pm 0.09$
PS		$18.2 \pm 2.4 \pm 2.9$	$3.13 \pm 0.09 \pm 0.15$	$25.1 \pm 2.6 \pm 5.0$	$2.85 \pm 0.07 \pm 0.16$
$K^*_{\rm ne}$		$3.2 \pm 0.4 \pm 0.3$	$-0.87 \pm 0.08 \pm 0.22$	$2.0 \pm 0.3 \pm 0.3$	$-1.36 \pm 0.08 \pm 0.16$
$K^*_{\rm ch}$		$8.4 \pm 0.7 \pm 0.9$	$-0.86 \pm 0.07 \pm 0.19$	$2.8 \pm 0.4 \pm 1.0$	$-0.82 \pm 0.07 \pm 0.10$
Sum		$118.0 \pm 4.3 \pm 6.2$	–	$135.5 \pm 4.6 \pm 9.7$	–

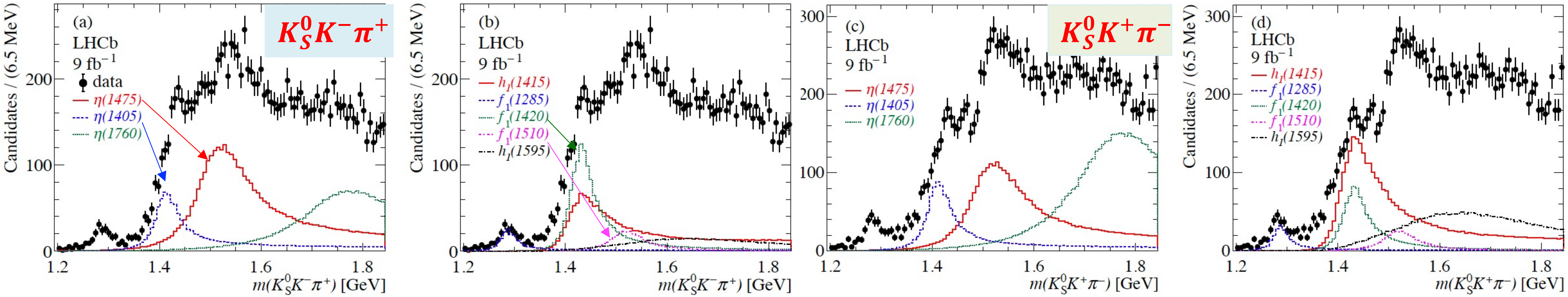
For the two channels

- $J^{PC} = 0^{-+}, 1^{++}$ K^*K contributions are in similar phase.
- $J^{PC} = 1^{+-}$ K^*K contributions are shifted by $\approx \pi$
- These phase differences are responsible for the observed “inversion” of the Dalitz plots

Partial waves contributions

[PRD 111 (2025) 092009]

- Significant 0^{-+} signal has been established, comprising $\eta(1405)$, $\eta(1475)$ and $\eta(1760)$.
- The concurrent observation of these states in both J/ψ radiative decays *[BESIII, JHEP 03 (2023) 121]* and B^+ decays implies potential commonalities in their production mechanisms.
- Presence of $f_1(1420)$ and $f_1(1510)$, both with $I = 0$, $J^{PC} = 1^{++}$ challenges their physical interpretation, as they both compete for identification as the $s\bar{s}$ member of the axial-vector nonet



Strange Mesons

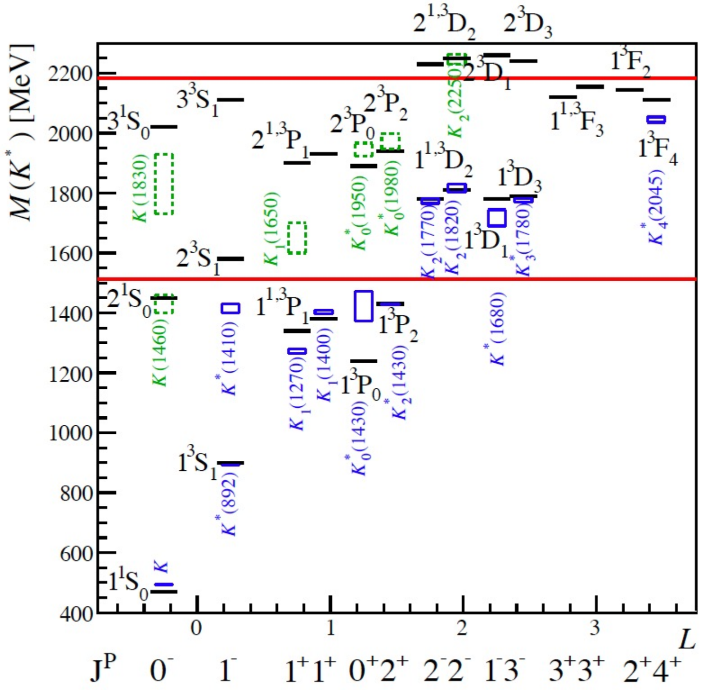
$D^0 \to K^{\mp}\pi^{\pm}\pi^{\pm}\pi^{\mp}$ decays

7,8 TeV; 3 fb^{-1}

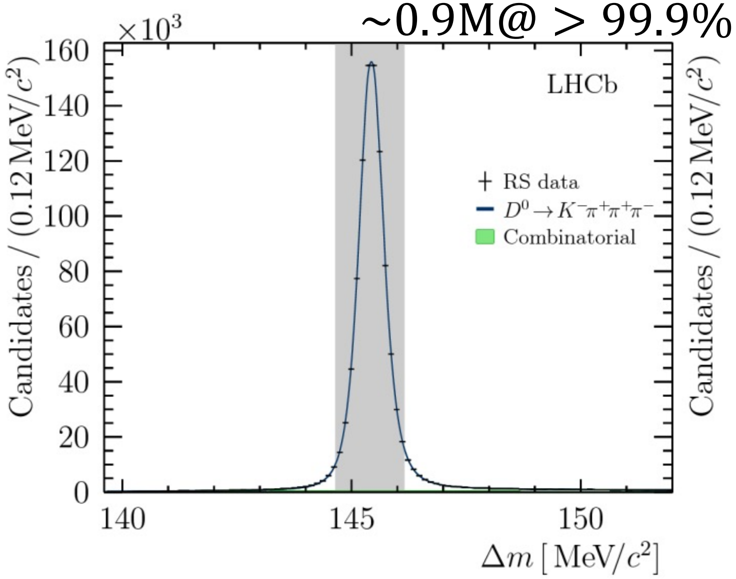
[EPJC 78 (2018) 443]

- Poor known higher K^* resonances

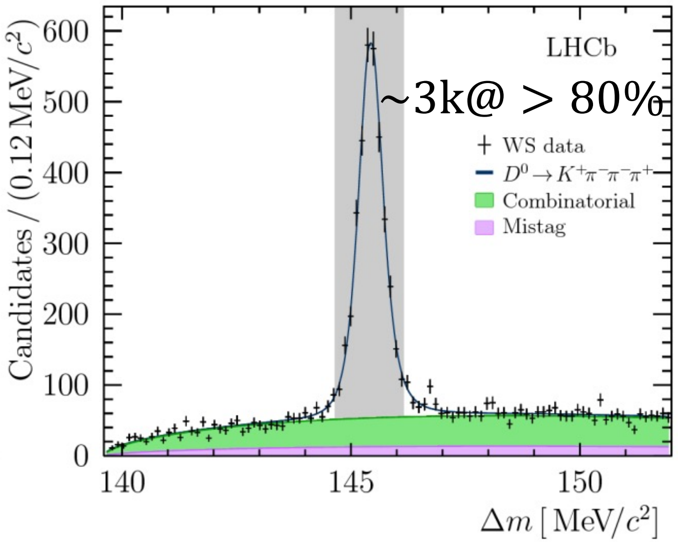
Prediction [Godfrey-Isgur model]
Confirmed
Not-confirmed



~0.9M@ > 99.9%



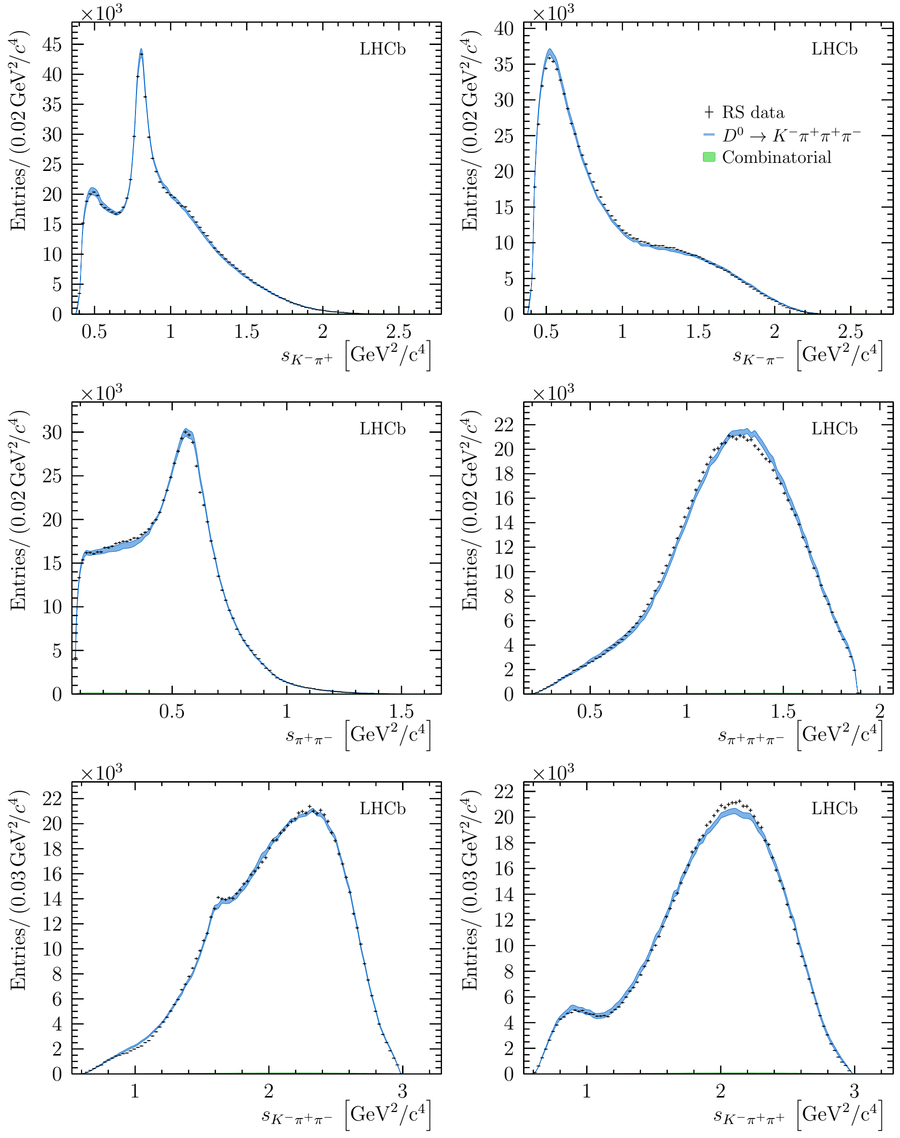
~3k@ > 80%



- Strategy:
  - Purity sample selected with double tag $B^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ where $D^{*+} \to D^0\pi^+$

$D^0 \to K^-\pi^+\pi^+\pi^-$ AmAn results

[EPJC 78 (2018) 443]



	Fit Fraction [%]	$\lvert g\rvert$	$\arg(g)[^o]$
$[\overline{K}^*(892)^0\rho(770)^0]^{L=0}$	$7.34 \pm 0.08 \pm 0.47$	$0.196 \pm 0.001 \pm 0.015$	$-22.4 \pm 0.4 \pm 1.6$
$[\overline{K}^*(892)^0\rho(770)^0]^{L=1}$	$6.03 \pm 0.05 \pm 0.25$	$0.362 \pm 0.002 \pm 0.010$	$-102.9 \pm 0.4 \pm 1.7$
$[\overline{K}^*(892)^0\rho(770)^0]^{L=2}$	$8.47 \pm 0.09 \pm 0.67$		
$[\rho(1450)^0\overline{K}^*(892)^0]^{L=0}$	$0.61 \pm 0.04 \pm 0.17$	$0.162 \pm 0.005 \pm 0.025$	$-86.1 \pm 1.9 \pm 4.3$
$[\rho(1450)^0\overline{K}^*(892)^0]^{L=1}$	$1.98 \pm 0.03 \pm 0.33$	$0.643 \pm 0.006 \pm 0.058$	$97.3 \pm 0.5 \pm 2.8$
$[\rho(1450)^0\overline{K}^*(892)^0]^{L=2}$	$0.46 \pm 0.03 \pm 0.15$	$0.649 \pm 0.021 \pm 0.105$	$-15.6 \pm 2.0 \pm 4.1$
$\rho(770)^0\,[K^-\pi^+]^{L=0}$	$0.93 \pm 0.03 \pm 0.05$	$0.338 \pm 0.006 \pm 0.011$	$73.0 \pm 0.8 \pm 4.0$
$\alpha_{3/2}$		$1.073 \pm 0.008 \pm 0.021$	$-130.9 \pm 0.5 \pm 1.8$
$\overline{K}^*(892)^0\,[\pi^+\pi^-]^{L=0}$	$2.35 \pm 0.09 \pm 0.33$		
$f_{\pi\pi}$		$0.261 \pm 0.005 \pm 0.024$	$-149.0 \pm 0.9 \pm 2.7$
β_1		$0.305 \pm 0.011 \pm 0.046$	$65.6 \pm 1.5 \pm 4.0$
$a_1(1260)^+K^-$	$38.07 \pm 0.24 \pm 1.38$	$0.813 \pm 0.006 \pm 0.025$	$-149.2 \pm 0.5 \pm 3.1$
$K_1(1270)^-\pi^+$	$4.66 \pm 0.05 \pm 0.39$	$0.362 \pm 0.004 \pm 0.015$	$114.2 \pm 0.8 \pm 3.6$
$K_1(1400)^-\,[\overline{K}^*(892)^0\pi^-]\,\pi^+$	$1.15 \pm 0.04 \pm 0.20$	$0.127 \pm 0.002 \pm 0.011$	$-169.8 \pm 1.1 \pm 5.9$
$K_2^*(1430)^-\,[\overline{K}^*(892)^0\pi^-]\,\pi^+$	$0.46 \pm 0.01 \pm 0.03$	$0.302 \pm 0.004 \pm 0.011$	$-77.7 \pm 0.7 \pm 2.1$
$K(1460)^-\pi^+$	$3.75 \pm 0.10 \pm 0.37$	$0.122 \pm 0.002 \pm 0.012$	$172.7 \pm 2.2 \pm 8.2$
$[K^-\pi^+]^{L=0}\,[\pi^+\pi^-]^{L=0}$	$22.04 \pm 0.28 \pm 2.09$		
$\alpha_{3/2}$		$0.870 \pm 0.010 \pm 0.030$	$-149.2 \pm 0.7 \pm 3.5$
$\alpha_{K\eta'}$		$2.614 \pm 0.141 \pm 0.281$	$-19.1 \pm 2.4 \pm 12.0$
β_1		$0.554 \pm 0.009 \pm 0.053$	$35.3 \pm 0.7 \pm 1.6$
$f_{\pi\pi}$		$0.082 \pm 0.001 \pm 0.008$	$-147.0 \pm 0.7 \pm 2.2$
Sum of Fit Fractions	$98.29 \pm 0.37 \pm 0.84$		
χ^2/ν	$40483/32701 = 1.238$		

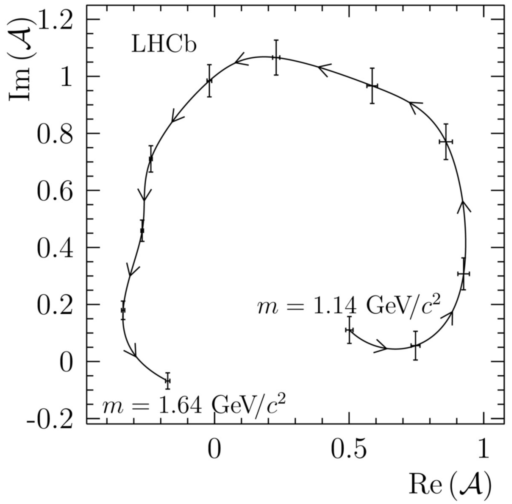
Strange resonances in $D^0 \to K^-\pi^+\pi^-\pi^+$

[EPJC 78 (2018) 443]

- $K_1(1270)^-$

$K_1(1270)^-$ $m_0 = 1289.81 \pm 0.56 \pm 1.66$ MeV/c^2; $\Gamma_0 = 116.11 \pm 1.65 \pm 2.96$ MeV/c^2	Partial Fractions [%]	$\lvert g\rvert$	$\arg(g)$[°]
$\rho(770)^0K^-$	$96.30 \pm 1.64 \pm 6.61$		
$\rho(1450)^0K^-$	$49.09 \pm 1.58 \pm 11.54$	$2.016 \pm 0.026 \pm 0.211$	$-119.5 \pm 0.9 \pm 2.3$
$\overline{K}^*(892)^0\pi^-$	$27.08 \pm 0.64 \pm 2.82$	$0.388 \pm 0.007 \pm 0.033$	$-172.6 \pm 1.1 \pm 6.0$
$[K^-\pi^+]^{L=0}\pi^-$	$22.90 \pm 0.72 \pm 1.89$	$0.554 \pm 0.010 \pm 0.037$	$53.2 \pm 1.1 \pm 1.9$
$[\overline{K}^*(892)^0\pi^-]^{L=2}$	$3.47 \pm 0.17 \pm 0.31$	$0.769 \pm 0.021 \pm 0.048$	$-19.3 \pm 1.6 \pm 6.7$
$\omega(782)[\pi^+\pi^-]K^-$	$1.65 \pm 0.11 \pm 0.16$	$0.146 \pm 0.005 \pm 0.009$	$9.0 \pm 2.1 \pm 5.7$

- $K(1460)^-$
  - The presence of this resonance is further justified by the Argand diagram from the Model Independent Partial Wave Analysis



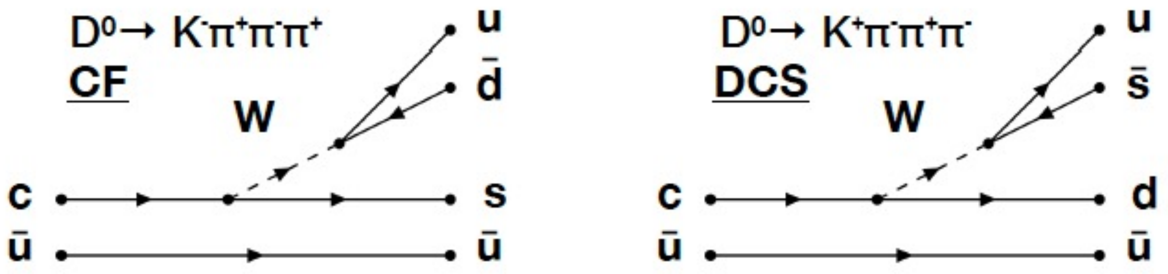
$K(1460)^-$ $m_0 = 1482.40 \pm 3.58 \pm 15.22$ MeV/c^2 ; $\Gamma_0 = 335.60 \pm 6.20 \pm 8.65$ MeV/c^2	Partial Fractions [%]	$\lvert g\rvert$	$\arg(g)$[°]
$\overline{K}^*(892)^0\pi^-$	$51.39 \pm 1.00 \pm 1.71$		
$[\pi^+\pi^-]^{L=0}K^-$	$31.23 \pm 0.83 \pm 1.78$		
f_{KK}		$1.819 \pm 0.059 \pm 0.189$	$-80.8 \pm 2.2 \pm 6.6$
β_1		$0.813 \pm 0.032 \pm 0.136$	$112.9 \pm 2.6 \pm 9.5$
β_0		$0.315 \pm 0.010 \pm 0.022$	$46.7 \pm 1.9 \pm 3.0$

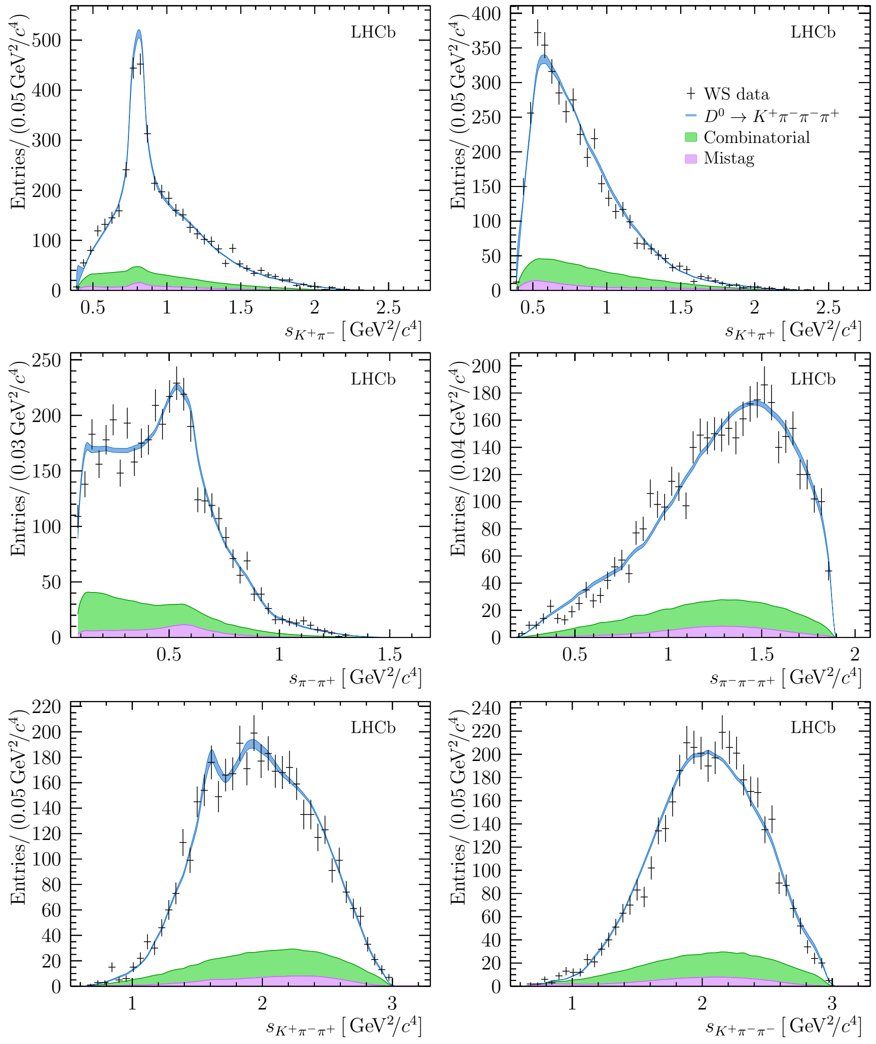
$D^0 \to K^+\pi^-\pi^-\pi^+$ AmAn results

[EPJC 78 (2018) 443]

- **3-body resonances parameters fixed to RS fit**
- **Largest fraction from $K_1\pi$**

	Fit Fraction [%]	$\lvert g \rvert$	$\arg(g)[^\circ]$
$[K^*(892)^0\rho(770)^0]^{L=0}$	$9.62 \pm 1.58 \pm 1.03$	$0.205 \pm 0.019 \pm 0.010$	$-8.5 \pm 4.7 \pm 4.4$
$[K^*(892)^0\rho(770)^0]^{L=1}$	$8.42 \pm 0.83 \pm 0.57$	$0.390 \pm 0.029 \pm 0.006$	$-91.4 \pm 4.7 \pm 4.1$
$[K^*(892)^0\rho(770)^0]^{L=2}$	$10.19 \pm 1.03 \pm 0.79$		
$[\rho(1450)^0 K^*(892)^0]^{L=0}$	$8.16 \pm 1.24 \pm 1.69$	$0.541 \pm 0.042 \pm 0.055$	$-21.8 \pm 6.5 \pm 5.5$
$K_1(1270)^+\pi^-$	$18.15 \pm 1.11 \pm 2.30$	$0.653 \pm 0.040 \pm 0.058$	$-110.7 \pm 5.1 \pm 4.9$
$K_1(1400)^+ [K^*(892)^0\pi^+]\,\pi^-$	$26.55 \pm 1.97 \pm 2.13$	$0.560 \pm 0.037 \pm 0.031$	$29.8 \pm 4.2 \pm 4.6$
$[K^+\pi^-]^{L=0}[\pi^+\pi^-]^{L=0}$	$20.90 \pm 1.30 \pm 1.50$		
$\alpha_{3/2}$		$0.686 \pm 0.043 \pm 0.022$	$-149.4 \pm 4.3 \pm 2.9$
β_1		$0.438 \pm 0.044 \pm 0.030$	$-132.4 \pm 6.5 \pm 3.0$
$f_{\pi\pi}$		$0.050 \pm 0.006 \pm 0.005$	$74.8 \pm 7.5 \pm 5.3$
Sum of Fit Fractions	$101.99 \pm 2.90 \pm 2.85$		
χ^2/ν	$350/239 = 1.463$		





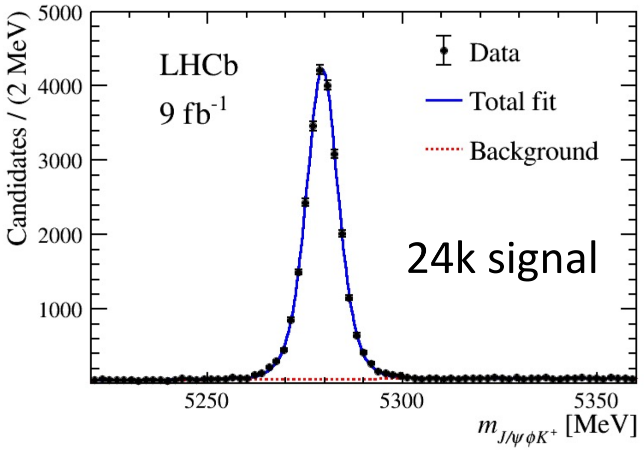
$B^+ \to J/\psi\phi K^+$ decays

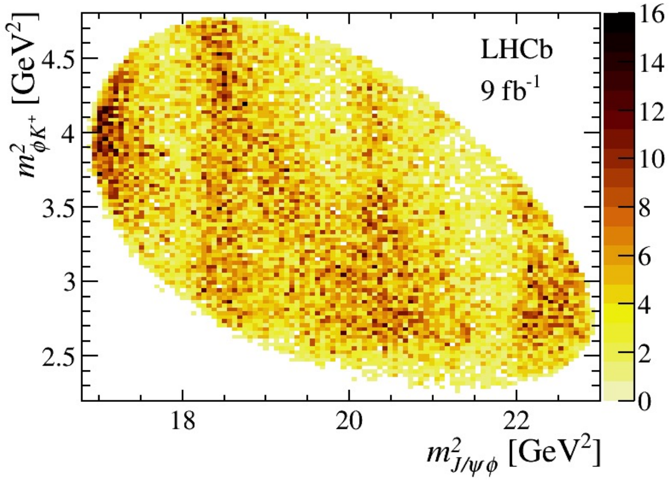
[PRL 127 (2021) 082001]

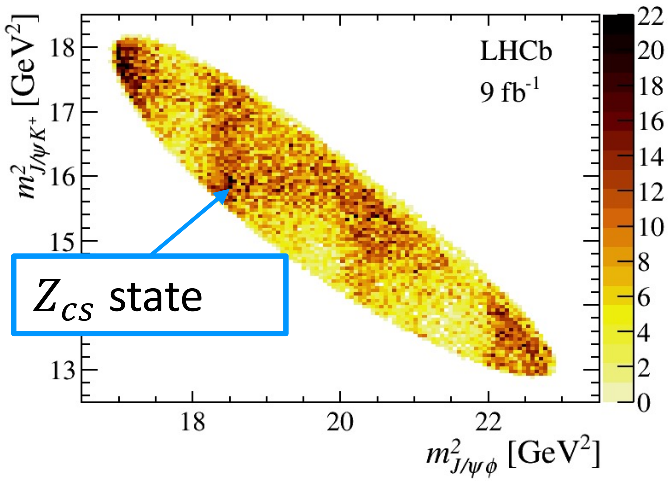
- 24k $B^\pm$ signal and purity 96% in signal window ($\pm$15 MeV)
- Dalitz-plot in the signal region shows 4 structures in $J/\psi\phi$ mass and an obvious $J/\psi K^+$ band
- Amplitude analysis is performed to study various resonant contributions

$B^+ \to$
- $\boldsymbol{Z_{cs}^+[c\bar{c}u\bar{s}](\to J/\psi K^+)\phi}$
- $\boldsymbol{X[c\bar{c}s\bar{s}](\to J/\psi\phi)K^+}$
- $\boldsymbol{J/\psi K^{*+}[\bar{s}u](\to K^+\phi)}$

$\to \boldsymbol{J/\psi\phi K^+}$





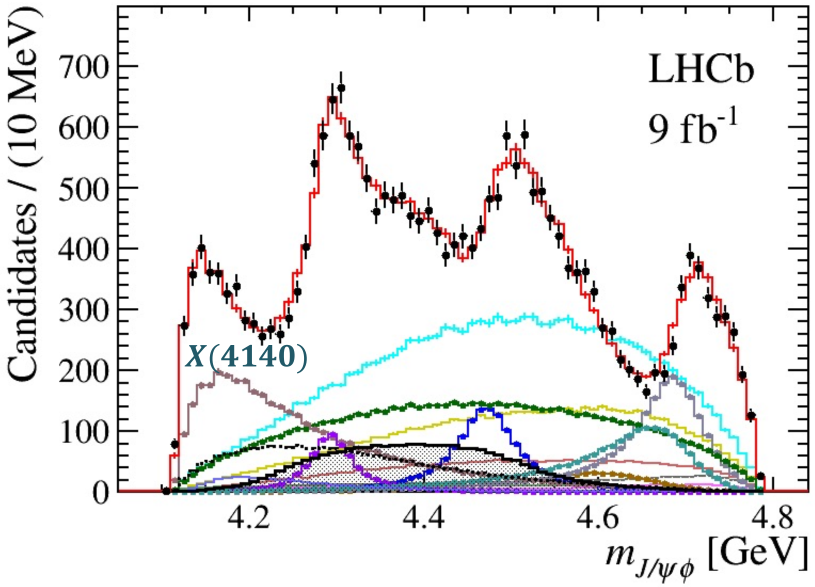


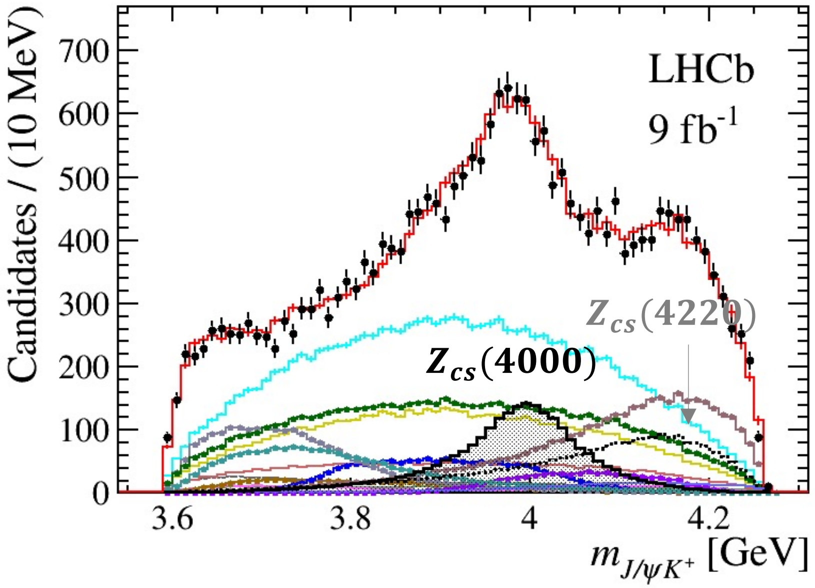
Amplitude results

[PRL 127 (2021) 082001]

- Observed four new tetraquark candidates
- Confirmed previous observed four $X \to J/\psi\phi$
- Main systematics from non-well known high-mass K*

Tetraquark	Mass [MeV]	Width [MeV]
$Z_{cs}(4000)^+$	$4003 \pm 6^{+\ 4}_{-14}$	$131 \pm 15 \pm 26$
$Z_{cs}(4200)^+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$
$X(4630)$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$
$X(4685)$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$

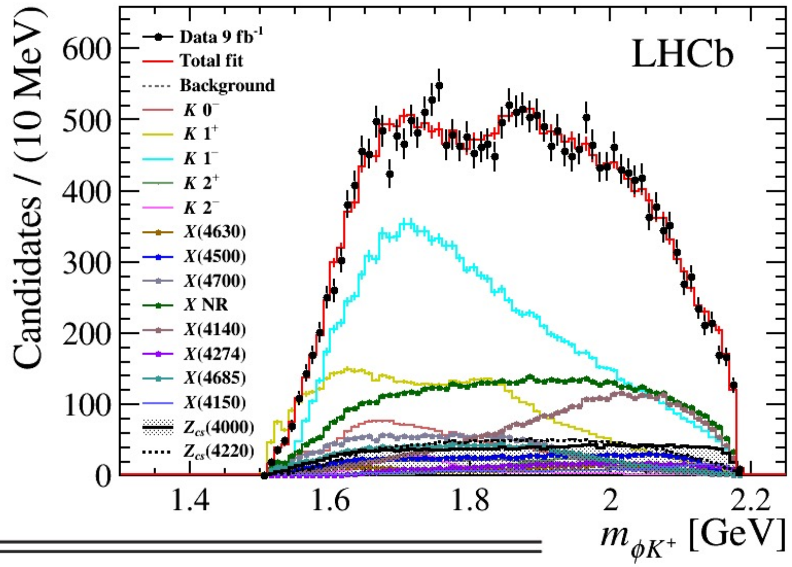




Strange meson results

[PRL 127 (2021) 082001]

- Default resoance model included 9 K*
- Measured the mass and widths of three K*
  - Parameters of other well known K* are fixed to PDG values
- Extended model included more higher mass K* as systemetic uncertainty

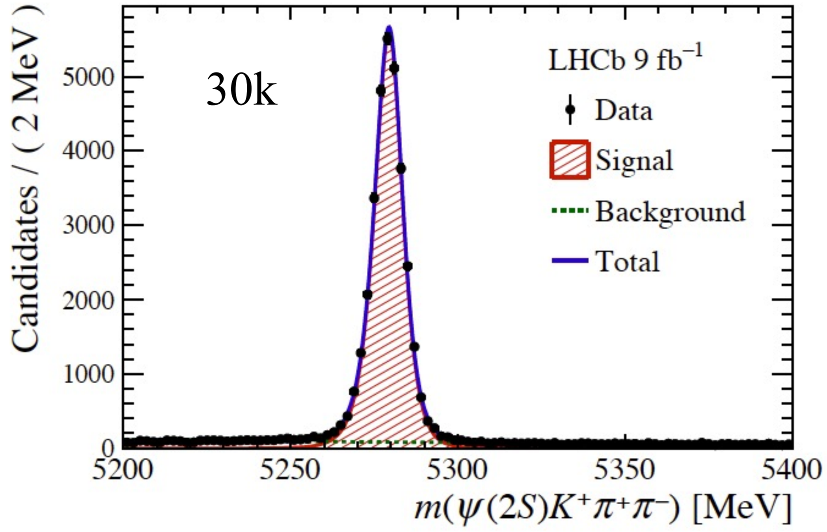


J^P	Contribution		Significance (σ)	M_0 (MeV)	Γ_0 (MeV)	FF (%)
1^+	2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
	2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
	1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
2^-	1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
	1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}_{-8}$
	2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5^{+11}_{-17}$
2^-	2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	$318 \pm 82^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2^{+1.0}_{-3.8}$

$B^+ \to \psi(2S)K^+\pi^+\pi^-$: amplitude analysis

[JHEP 01 (2025) 054]

- Can study $K^+\pi^+\pi^-$ system, crucial for NP studies of $B \to K\pi\pi(\gamma/\mu\mu)$
- Can also study charmonium-like exotic states
- With ~1000 signal decays, Belle only studied the $K^+\pi^+\pi^-$ system [PRD 83 (2011) 032005]
- LHCb performed the first full amplitude analysis on this decay
- Baseline fit contributions
  - 6 K'^+ states
  - 11 exotic states: most are very broad



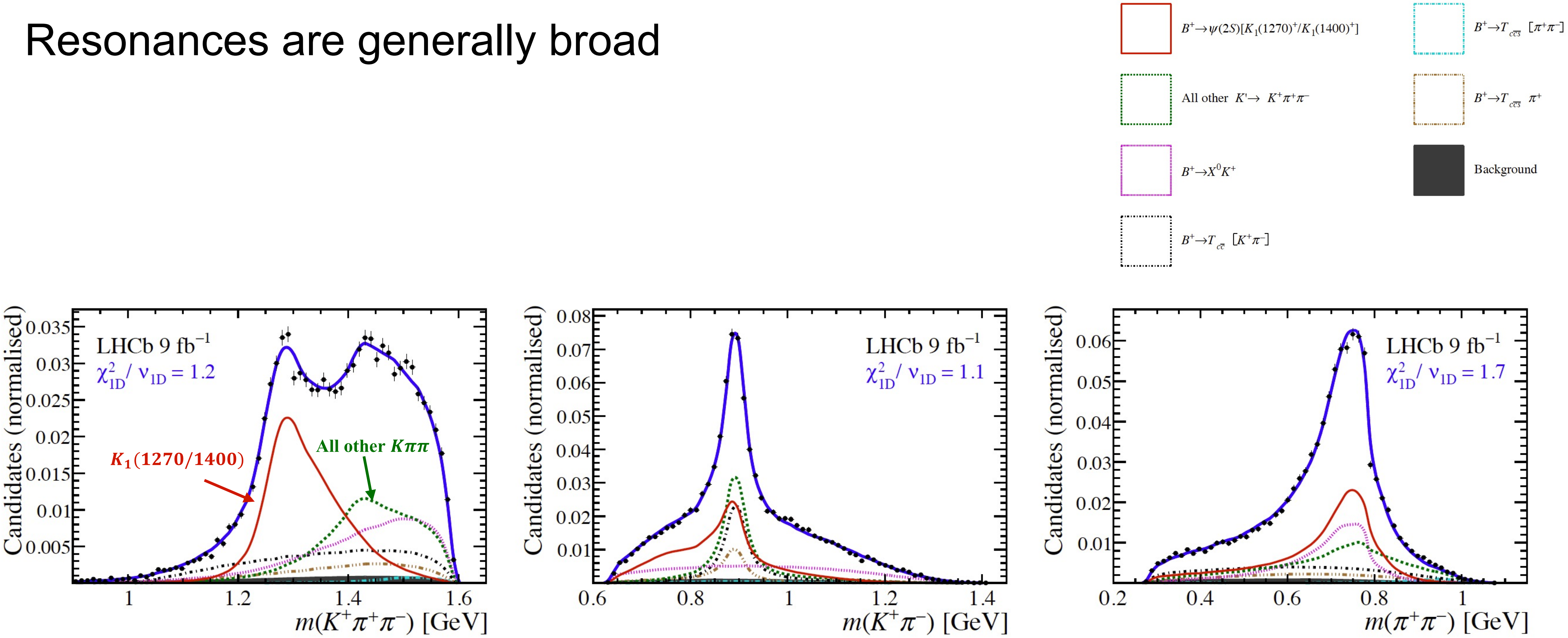
Decay channel	Fit fraction [%]
$B^+ \to \chi_{c0}(4475)K^+$	$18.45 \pm 1.31 \pm 2.92$
$B^+ \to \psi(2S)\ K^*(1680)^+$	$8.15 \pm 1.31 \pm 3.51$
$B^+ \to \psi(2S)\ K_1(1270)^+$	$7.60 \pm 0.85 \pm 1.35$
$B^+[P] \to \psi(2S)\ K_1(1270)^+$	$7.52 \pm 0.60 \pm 1.08$
$B^+[D] \to \psi(2S)\ K_1(1270)^+$	$6.81 \pm 0.45 \pm 1.18$
$B^+ \to \psi(2S)\ K_1(1400)^+$	$5.78 \pm 0.62 \pm 0.92$
$B^+ \to \psi(2S)\ K(1460)^+$	$5.26 \pm 0.48 \pm 0.87$
$B^+[P] \to T_{c\bar{c}1}(4200)^+\ K^*(892)^0$	$4.60 \pm 0.54 \pm 2.17$
$B^+ \to T_{c\bar{c}\bar{s}1}(4600)^0\pi^+$	$4.42 \pm 0.98 \pm 2.17$

……

Fit projections

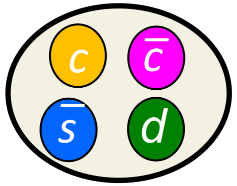
[JHEP 01 (2025) 054]

- Fit quality is acceptable, 7D $\chi^2/ndof = 1.2$
- Resonances are generally broad



Exotic contributions

[JHEP 01 (2025) 054]



- 3 new $T_{c\bar{c}\bar{s}} \to \psi(2S)K\pi$ states are observed
- $\psi(2S)K$ mass above $Z_{cs}(4000)^+$, only tail of $Z_{cs}(4000)^+$ can contribute

	Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
	$\chi_{c0}(4475)$	0^+	$4475\pm 7\pm 12$	$231\pm 19\pm 32$	$\chi_{c0}(4500)$	4474 ± 4	77^{+12}_{-10}
	$\chi_{c1}(4650)$	1^+	$4653\pm 14\pm 27$	$227\pm 26\pm 22$	$\chi_{c1}(4685)$	4684^{+15}_{-17}	126 ± 40
	$\chi_{c0}(4710)$	0^+	$4710\pm 4\pm 5$	$64\pm 9\pm 10$	$\chi_{c0}(4700)$	4694^{+16}_{-5}	87^{+18}_{-10}
	$\eta_{c1}(4800)$	1^-	$4785\pm 37\pm 119$	$457\pm 93\pm 157$	$X(4630)$	4626^{+24}_{-110}	174^{+140}_{-80}
	$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)	$T_{c\bar{c}}(4055)^+$	4054 ± 3.2	45 ± 13
	$T_{c\bar{c}1}(4200)^+$	1^+	$4257\pm 11\pm 17$	$308\pm 20\pm 32$	$T_{c\bar{c}1}(4200)^+$	4196^{+35}_{-32}	370^{+100}_{-150}
	$T_{c\bar{c}1}(4430)^+$	1^+	$4468\pm 21\pm 80$	$251\pm 42\pm 82$	$T_{c\bar{c}1}(4430)^+$	4478^{+15}_{-18}	181 ± 31
	$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578\pm 10\pm 18$	$133\pm 28\pm 69$			
new	$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925\pm 22\pm 47$	$255\pm 55\pm 127$			
	$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225\pm 86\pm 181$	$226\pm 76\pm 374$			
	$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

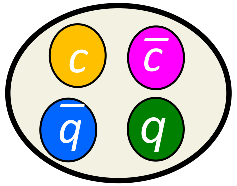
Summary

- LHCb has great potential to study strange and no-strange hadrons with different decay final state
- We have studied the X resonances from $B \to J/\psi X$ decays
  - More final states, such as $B \to J/\psi K_S^0 K\pi$, to be tried
- More studies are preformed from D decays
- We also have a good start with light hadrons final state such as $B \to \left(K_S^0 K\pi\right)K$ decays
- For higher K* states, we can also try with B radiate decays

The precision understanding of the strange and no-strange hadron spectroscopy is important for LHCb in the study of the heavy-flavour exotic states

Exotic contributions

[arXiv: 2407.12475]



- 4 $X^0 \to \psi(2S)\pi^+\pi^-$ states are identified
  - Main decay mode is $\boldsymbol{\psi(2S)\rho^0}$
  - Similar but broader that the states observed in $B^+ \to \boldsymbol{J/\psi\phi}K^+$
  - But they might not the same, $\psi(2S)\rho^0$ has I=1, $J/\psi\phi$ has I=0

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]	Res. PDG	m_0 [MeV]	Γ_0 [MeV]
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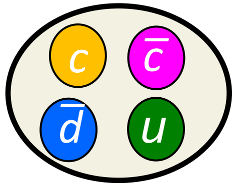
States in $B^+ \to J/\psi\phi K^+$

Exotic contributions

[arXiv: 2407.12475]



- 3 $T_{c\bar{c}}^{(*)} \to \psi(2S)\pi$ states are identified
  - Confirmed $\boldsymbol{Z_c(4430)^+}$ seen in $\bar{B}^0 \to \psi(2S)\pi^+K^-$
  - Confirmed $\boldsymbol{Z_c(4200)^+}$ seen in $\bar{B}^0 \to J/\psi\pi^+K^-$, and $J^P = 1^+$ is determined for the 1st time
  - $T_{c\bar{c}}(4055)^+$ seen in $e^+e^- \to \psi(2S)\pi^+\pi^-$ is also needed

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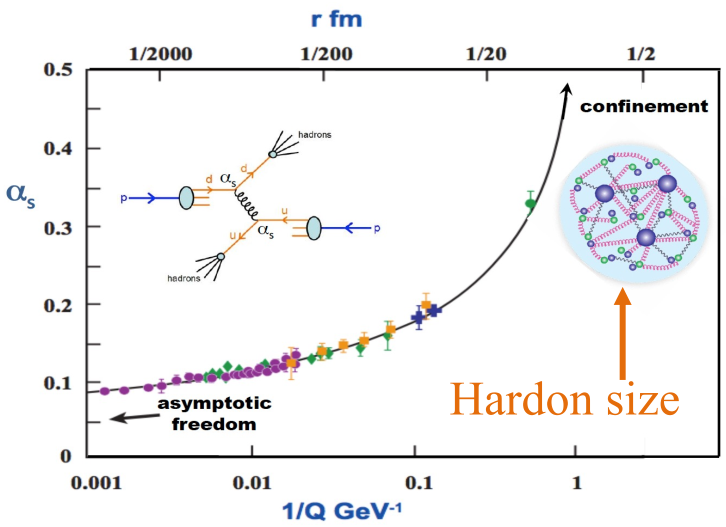
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)	$T_{c\bar{c}\bar{s}1}(4000)^+$	4003^{+7}_{-15}	131 ± 30

Introduction

- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD



- Exotic hadrons provide unique probe to QCD
  - Predicted in quark model
  - Recent results show strong evidence for their existence