Spectroscopy results from LHCb

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On behalf of the LHCb collaboration

CERN

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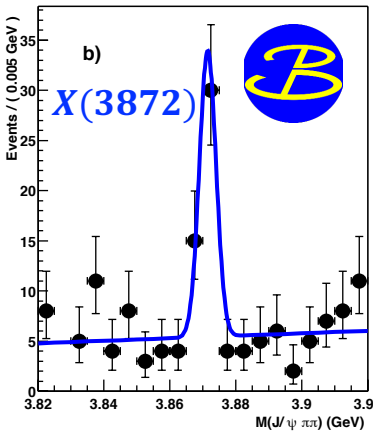
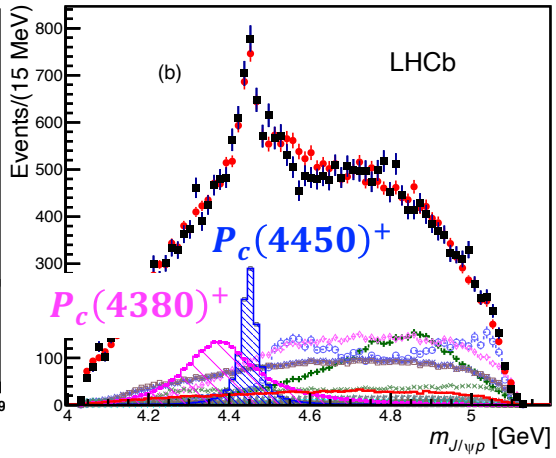
Introduction

- QCD dilemma:
  no rigorous first-principle translation of QCD Lagrangian into observables
  - ✓ Non-perturbative method like **Lattice QCD** is hopeful treatment but with yet limited application
  - ✓ Effective theory and phenomenological models proposed
  - ✓ Hadron spectroscopy provides primary tests and inputs to QCD models

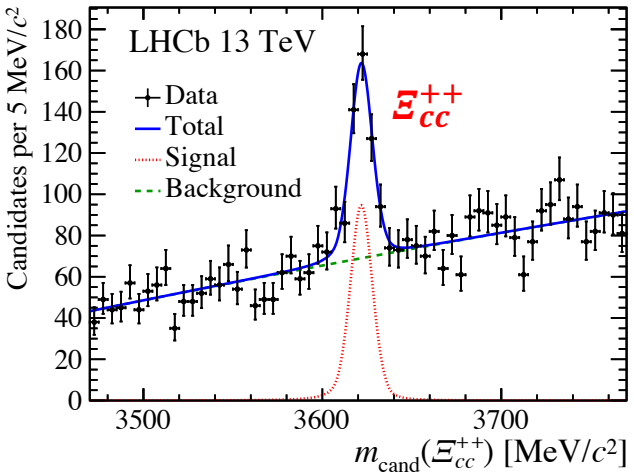
- Striking news keep emerging in recent years, e.g.
  - ✓ $X(3872)$
  - ✓ Pentaquarks
  - ✓ Ξ_{cc}^{++}
  - ✓ …



[PRL 91 (2003) 262001]



[PRL 115 (2015) 072001]

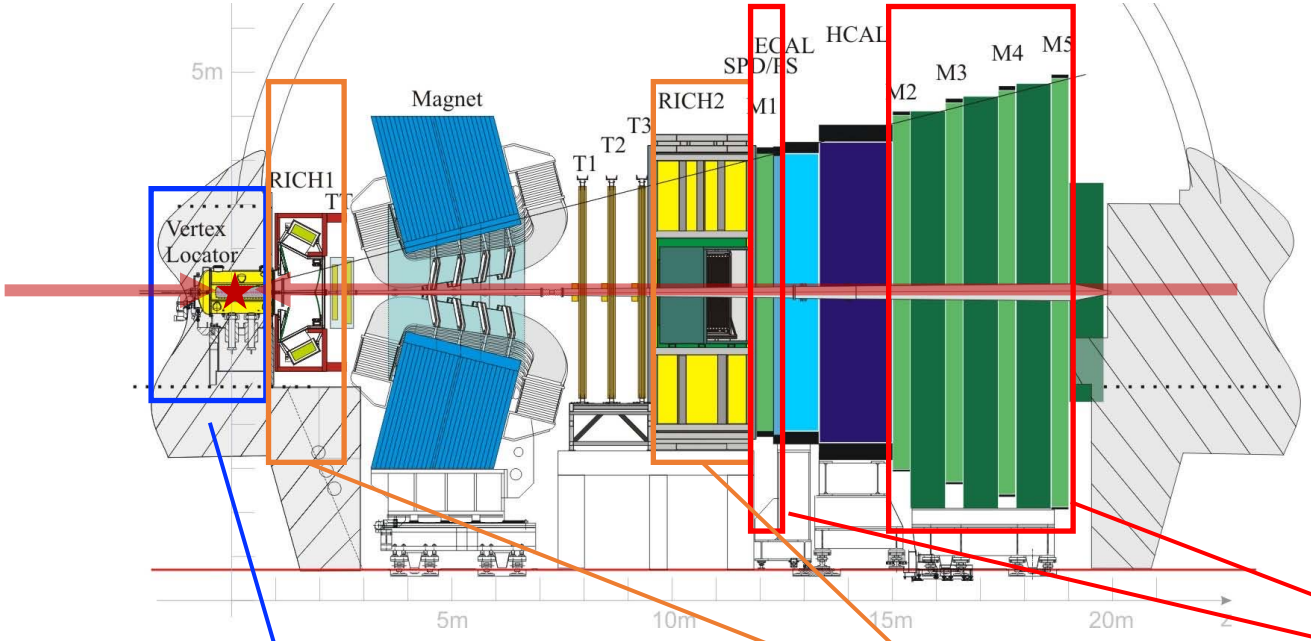


[PRL 119 (2017) 112001]

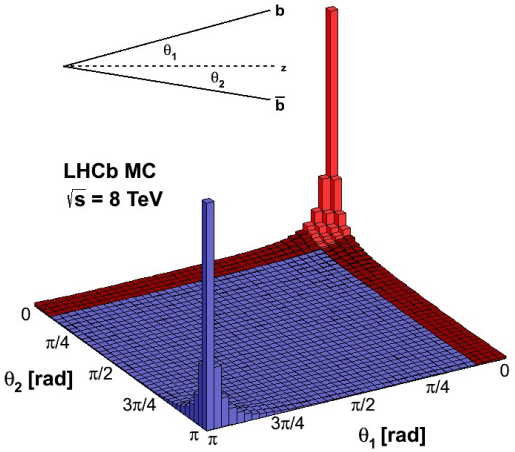
The LHCb detector

- LHCb is a single-arm forward region spectrometer covering $2 < \eta < 5$, dedicated to heavy flavor physics at the Large Hadron Collider

[JINST 3 (2008) S08005]



2.4% 4π angle
$\Rightarrow 25\%$ $b\bar{b}$



Vertex Locator: high precision; capable of separating b/c hadron production and decay vertices

$\sigma_{\mathrm{PV},x/y}\sim 10$ μm, $\sigma_{\mathrm{PV},z}\sim 60$ μm

RICHs: efficient identification of pions, kaons and protons

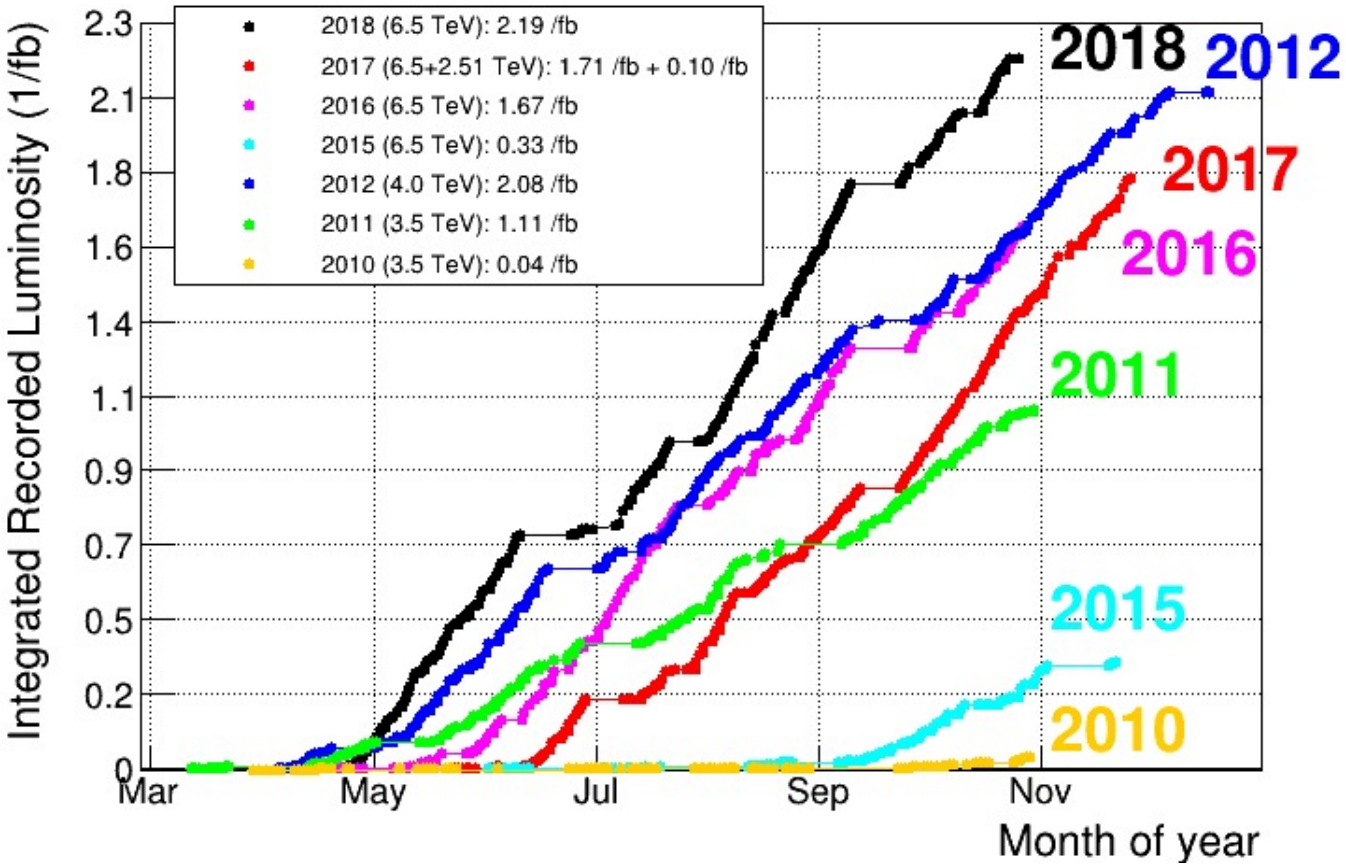
$\varepsilon(K \to K)\sim 95\%$
@ misID rate $(\pi \to K)\sim 5\%$

Muon system (M1-M5): efficient muon identification and trigger

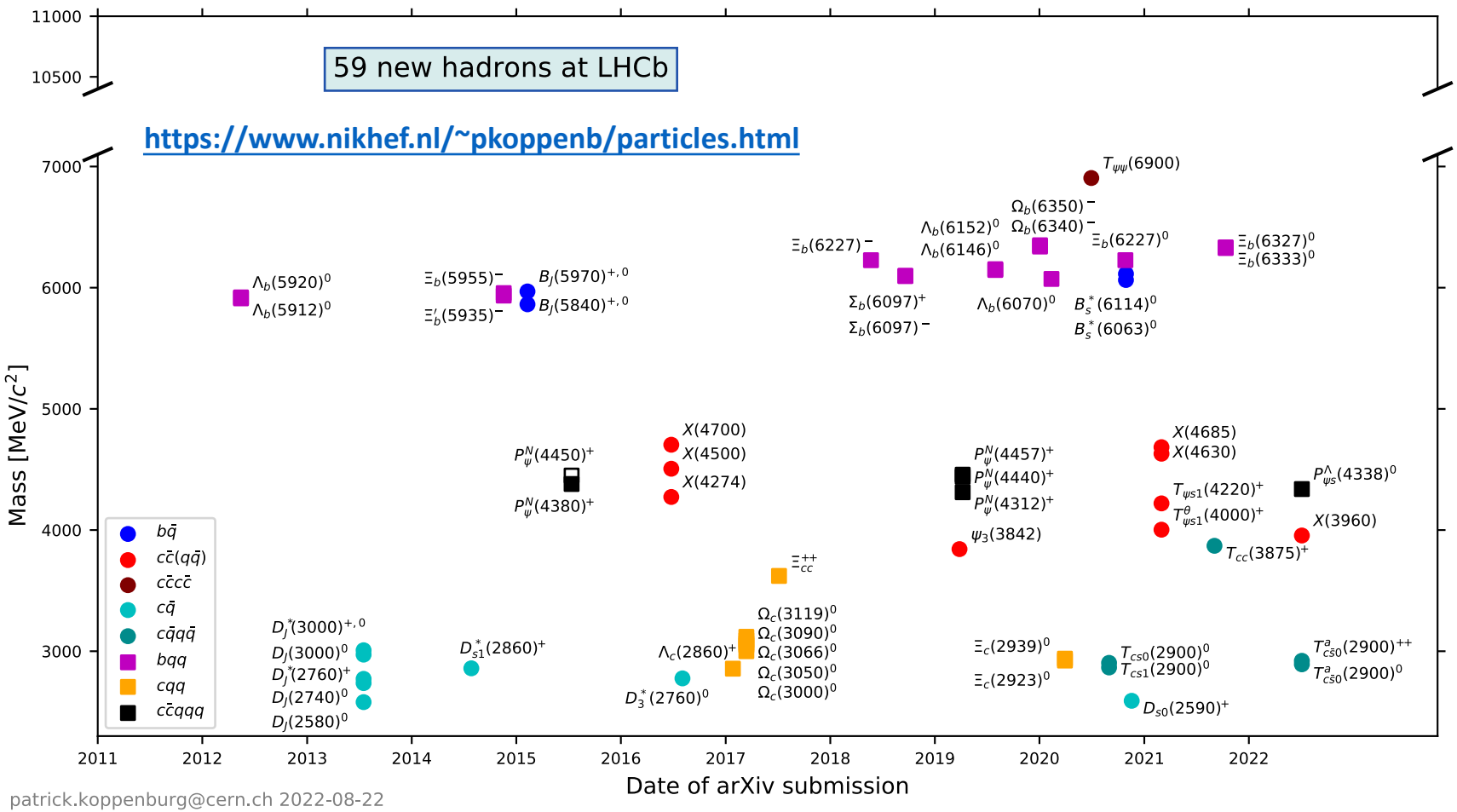
$\varepsilon(\mu \to \mu)\sim 97\%$
@ misID rate $(\pi \to \mu)\sim 1-3\%$

LHCb data taking

- Run 1 (2011-2012): $\mathcal{L}_{\text{int}} = 1\ \text{fb}^{-1}$ @ 7 TeV & $2\ \text{fb}^{-1}$ @ 8 TeV
- Run 2 (2015-2018): $\mathcal{L}_{\text{int}} = 6\ \text{fb}^{-1}$ @ 13 TeV
- Run 3: emerging now @ 13.6 TeV



Hadrons observed at LHCb



- Following “Exotic hadron naming convention” proposed by LHCb recently

[arXiv: 2206.15233]

Incomplete list of recent results

- **Heavy hadrons**

  Conventional (mesons and baryons):
  - ✓ Study of $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$ [LHCb-PAPER-2022-028] in preparation
  - ✓ B_c^+ decay to charmonia plus multihadron [arXiv:2208.08660]
  - ✓ Search for $\Xi_{bc}^+ \to J/\psi \Xi_c^+$ [arXiv:2204.09541]
  - ✓ Observation of $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$ [JHEP 05 (2022) 038]

  Exotic (hadrons beyond $q\bar{q}$ and qqq):
  - ✓ Observation of $T_{c\bar{s}0}^a(2900)^{0/++}$ [LHCb-PAPER-2022-026] in preparation
  - ✓ Observation of $D_s^+ D_s^-$ threshold resonance [LHCb-PAPER-2022-018] in preparation
  - ✓ Observation of $P_{\psi s}^{\Lambda}$ in $B^- \to J/\psi \Lambda \bar{p}$ [LHCb-PAPER-2022-031] in preparation
  - ✓ Observation of ω contribution to $\chi_{c1}(3872) \to J/\psi \pi^+ \pi^-$ [arXiv:2204.12597]

- **Light hadrons**
  - ✓ Amplitude analysis of $D^+ \to \pi^- \pi^+ \pi^+$ [arXiv:2208.03300]
  - ✓ Amplitude analysis of $\Lambda_c^+ \to p K^- \pi^+$ [arXiv:2208.03262]

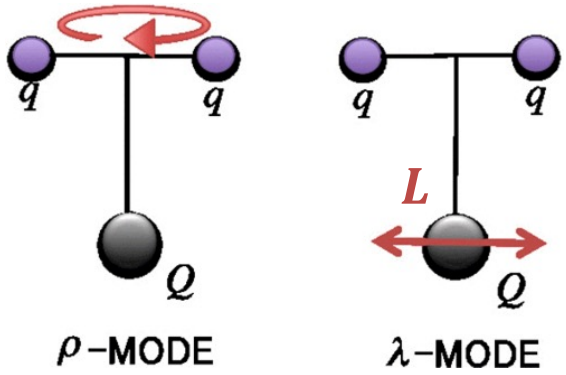
* This talk will focus on the most recent measurements

History of Ξ_c^{**}

- Heavy quark-light diquark $Q[qq]$ model is widely used to describe Qqq systems
  - ✓ λ-mode: low-lying states well established
  - ✓ ρ-mode: no firm assignment yet

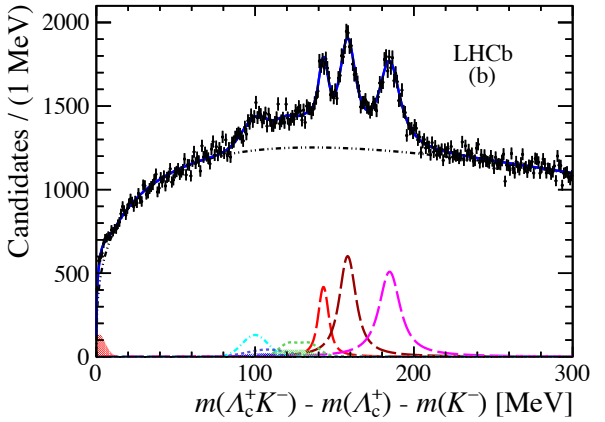
	$J^P_{[qq]} = 0^+$	$J^P_{[qq]} = 1^+$
$L = 0$	$\left(\frac{1}{2}\right)^+$	$\left(\frac{1}{2}\right)^+, \left(\frac{3}{2}\right)^+$
$L = 1$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-$	$\left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$
$L = 2$	$\left(\frac{3}{2}\right)^+, \left(\frac{5}{2}\right)^+$	.....

[PRD 77 (2008) 031101] [EPJC 78 (2018) 252] [EPJC 78 (2018) 928]



[PRD 92 (2015) 114029]

- $\Xi_c(2930)^{0/+}$ seen by BaBar and Belle in $B \to \Lambda_c^+ \overline{\Lambda}_c^- K$
- Prompt $\Lambda_c^+ K^-$ studied at LHCb
  - ✓ $\Xi_c(2930)^0$ resolved into $\Xi_c(2923)^0 + \Xi_c(2939)^0$
  - ✓ Peak at ~2880 MeV but suffer from feed-down

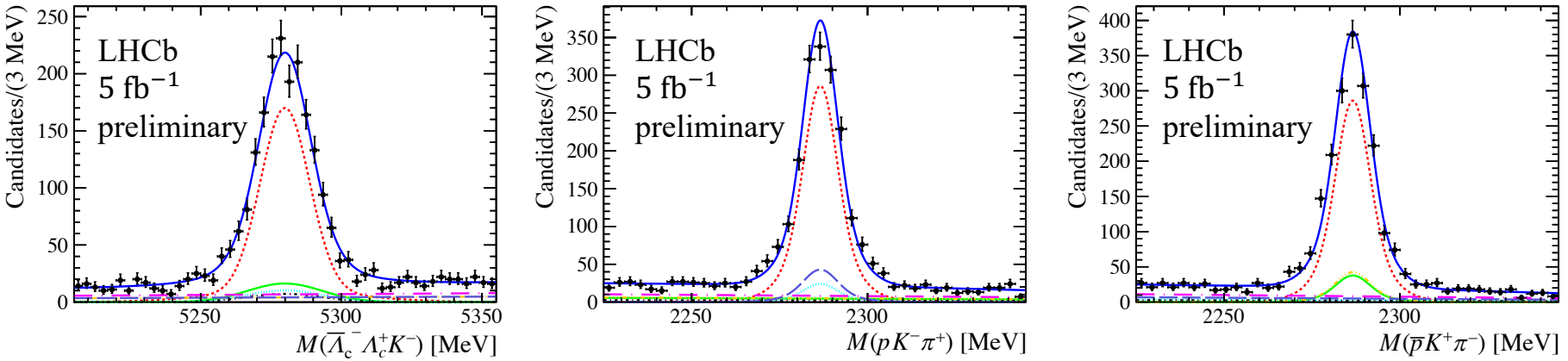


[PRL 124 (2020) 222001]

Study of $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$

[LHCb-PAPER-2022-028]
In preparation

- $B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-$ provides opportunities for
  - ✓Search for $\Xi_c^{0**} \to \Lambda_c^+ K^-$ with lower background level & feed-down contribution in prompt $\Lambda_c^+ K^-$ spectrum will not present
  - ✓Search for possible exotics in $\Lambda_c^+ \overline{\Lambda}_c^-$ and $\overline{\Lambda}_c^- K^-$ systems
- 5 fb^{-1} LHCb data at $\sqrt{s} = 13$ TeV used
- Signals extracted using $(m_{B^-}, m_{\Lambda_c^+}, m_{\overline{\Lambda}_c^-})$ 3D fit: $N_{\text{sig}} = 1365 \pm 42$

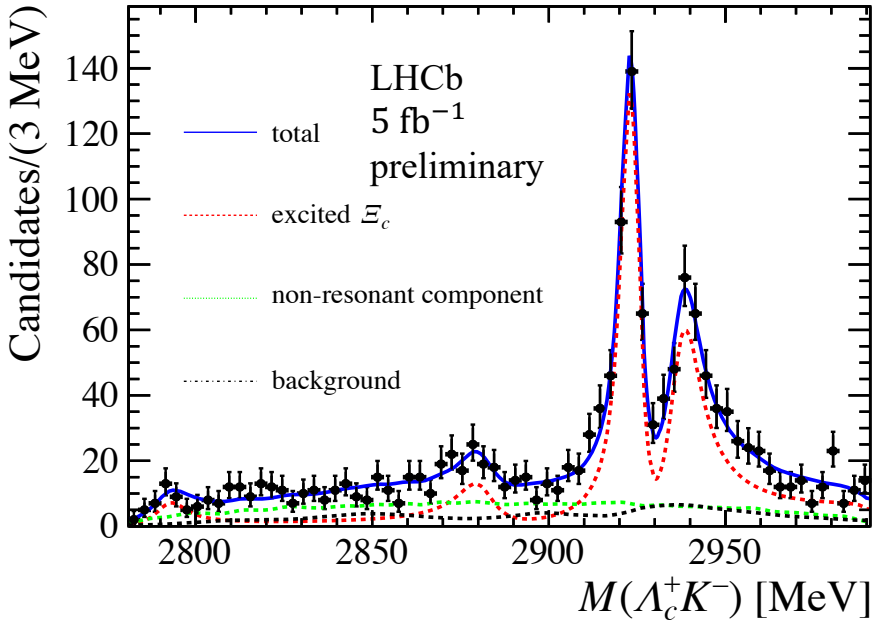


$$\frac{\mathcal{B}(B^- \to \Lambda_c^+ \overline{\Lambda}_c^- K^-)}{\mathcal{B}(B^- \to D^+ D^- K^-)} = 2.36 \pm 0.11 \pm 0.22 \pm 0.25(\mathcal{B})$$

$\Lambda_c^+ K^-$ mass spectrum

[LHCb-PAPER-2022-028]
In preparation

- $\Xi_c(2790)^0, \Xi_c(2880)^0, \Xi_c(2923)^0, \Xi_c(2939)^0$ included in the nominal fit
  - ✓ $J^P = 1/2^-$ (known), $1/2^-, 3/2^-, 3/2^-$ (1P $J^P_{[qq]} = 1^+$ multiplets; alternatives studied in systematics); interference considered
  - ✓ $\Xi_c(2790)^0$: 3.7σ ⇒ evidence of new decay mode
  - ✓ $\Xi_c(2880)^0$: 3.8σ ⇒ evidence of a new state
  - ✓ $\Xi_c(2923)^0, \Xi_c(2939)^0$: confirm prompt $\Lambda_c^+ K^-$ observation
- No significant structure in $M(\bar{\Lambda}_c^- K^-)$ and $M(\Lambda_c^+ \bar{\Lambda}_c^-)$



$$M(\Xi_c(2880)^0) = 2881.8 \pm 3.1 \pm 8.5 \text{ MeV}$$
$$\Gamma(\Xi_c(2880)^0) = 12.4 \pm 5.3 \pm 5.8 \text{ MeV}$$

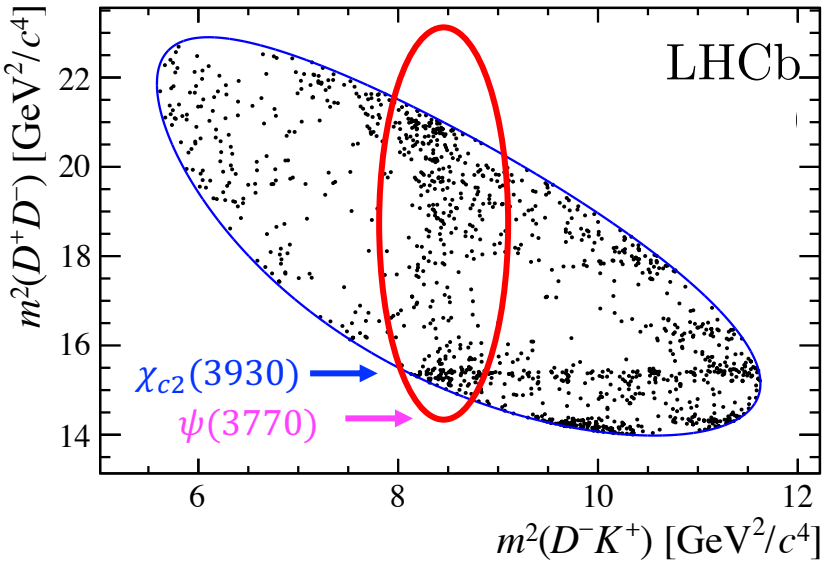
$$M(\Xi_c(2923)^0) = 2924.5 \pm 0.4 \pm 1.1 \text{ MeV}$$
$$\Gamma(\Xi_c(2923)^0) = 4.8 \pm 0.9 \pm 1.5 \text{ MeV}$$

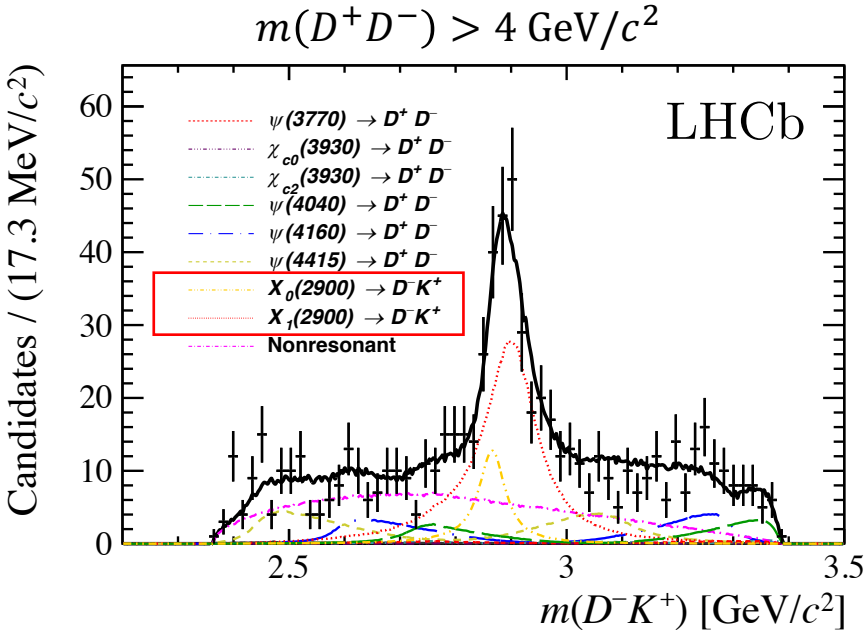
$$M(\Xi_c(2939)^0) = 2938.5 \pm 0.9 \pm 2.3 \text{ MeV}$$
$$\Gamma(\Xi_c(2939)^0) = 11.0 \pm 1.9 \pm 7.5 \text{ MeV}$$

T_{cs} in $B^+ \to D^+D^-K^+$

[PRL 125 (2020) 242001]
[PR D102 (2020) 112003]

- Resonant structures observed in the D^-K^+ system from an amplitude analysis of the $B^+ \to D^+D^-K^+$ decay





$$X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\text{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\text{MeV}$$
$$X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\text{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\text{MeV}$$

- First discovery of open-charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$!
- The observation motivates study of $B \to \bar{D}D_s\pi$

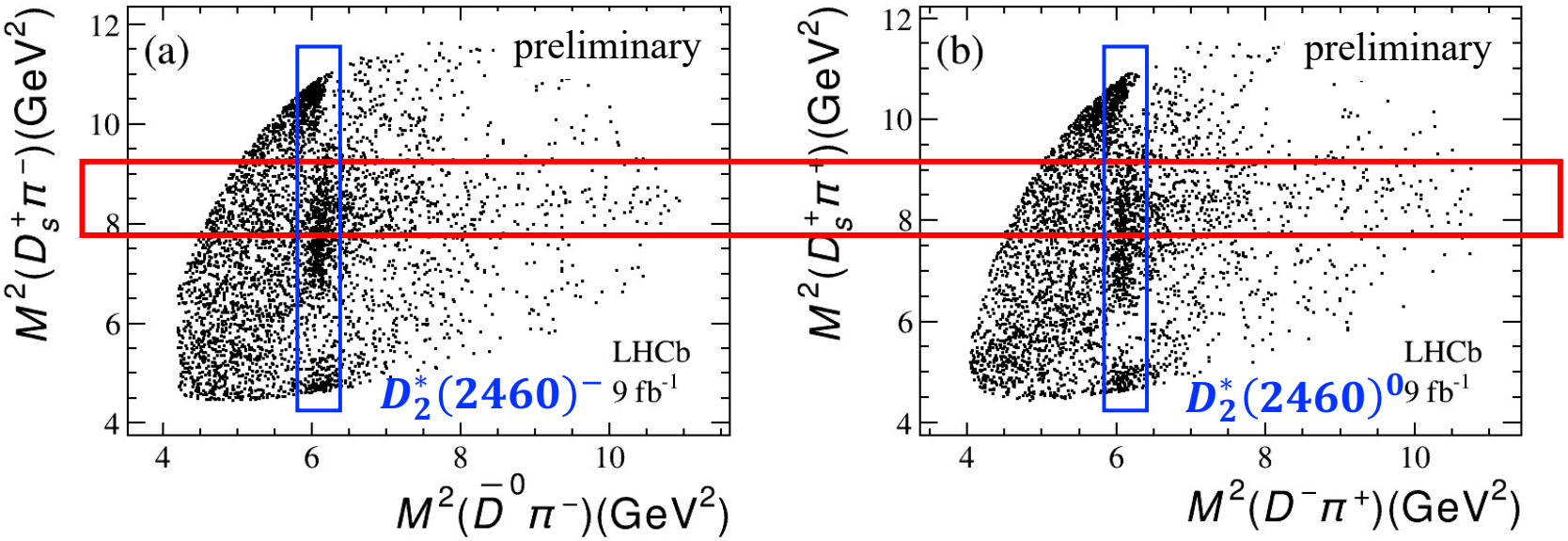
Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

[LHCb-PAPER-2022-026]
In preparation

➢Full 9 fb^{-1} Run1+Run2 LHCb data

⇒ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%

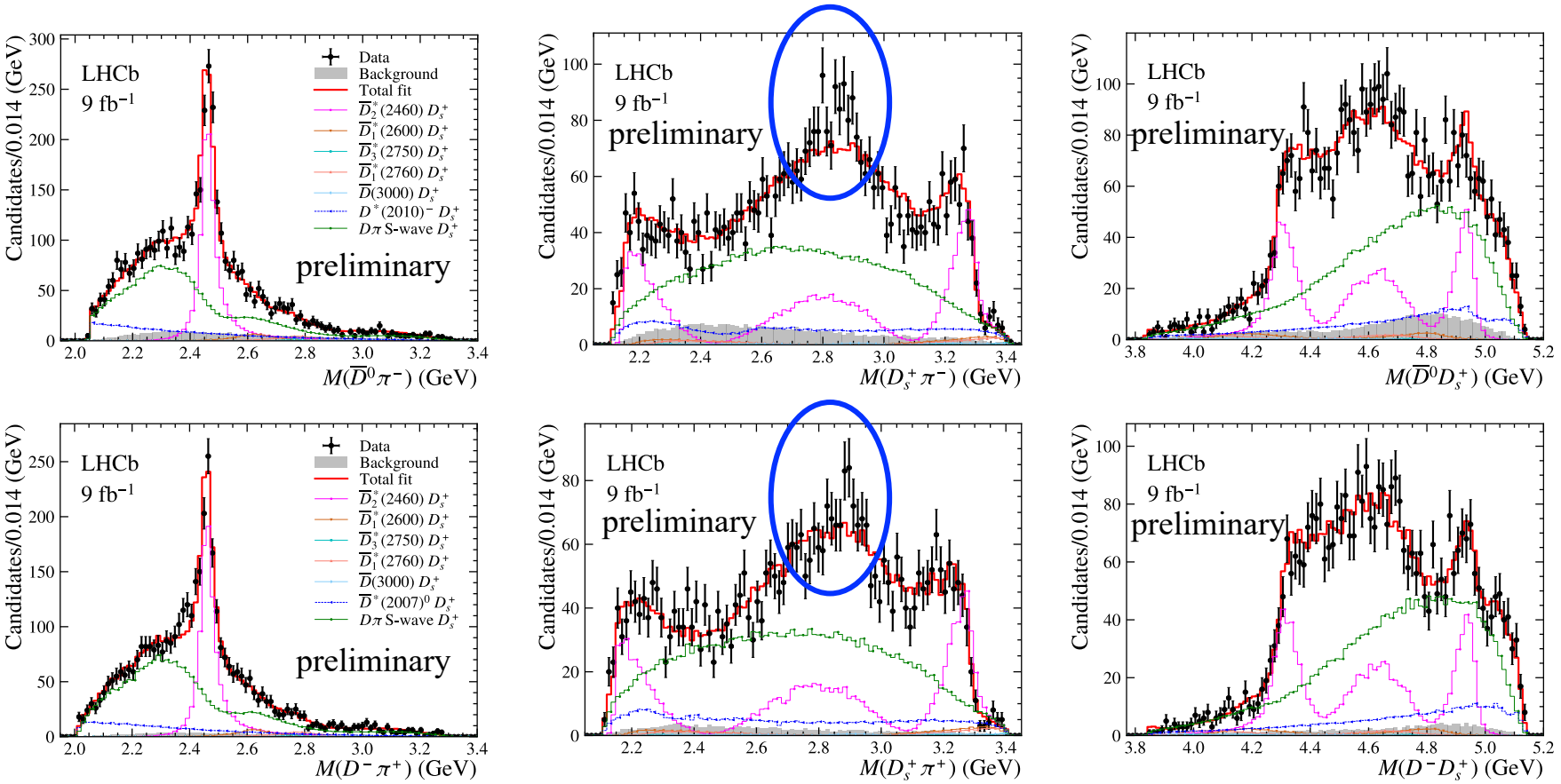


✓Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \text{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

⇒ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

$\overline{D}^{**}$-only fit

[LHCb-PAPER-2022-026]
In preparation

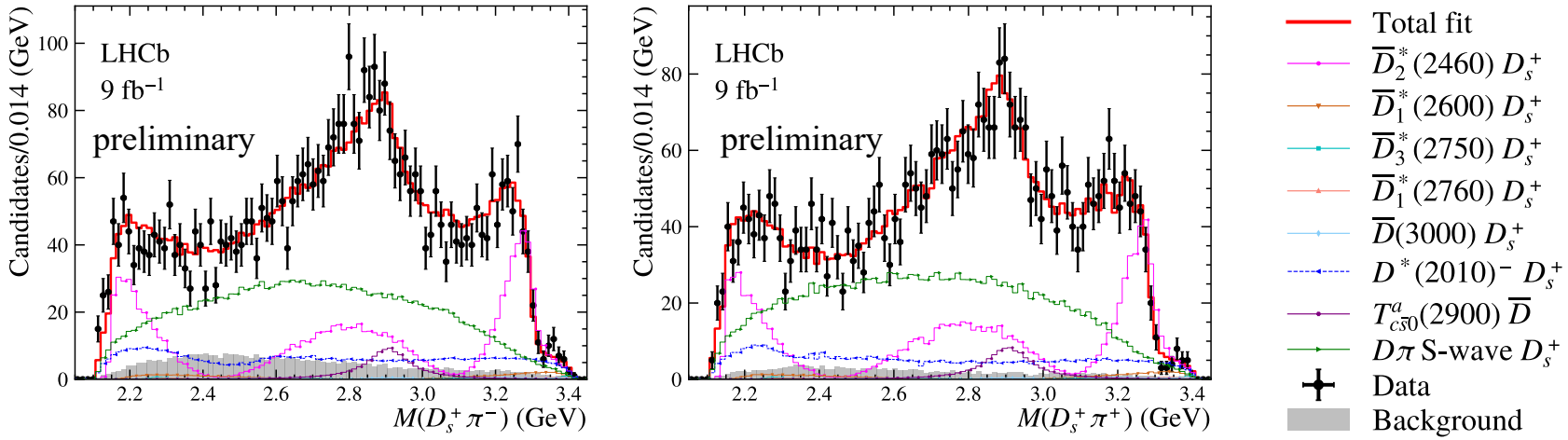


- Fits with new $\overline{D}^{**}$ states included cannot give satisfactory description of peaking structure near 2.9 GeV in $M(D_s^+\pi^{+/-})$ as well

Observation of $T^a_{c\bar{s}0}(2900)^{0/++}$

[LHCb-PAPER-2022-026]
In preparation

- Fit with two $D_s^+\pi$ states sharing resonance parameters



- $T^a_{c\bar{s}0}(2900)^0 \to D_s^+\pi^-$ & $T^a_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$ significance $> 9\sigma$
  - ✓A second 1^- $D_s^+\pi$ state yields significance of only 1.3σ
  - ✓Additional $D\pi, D_s^+\pi, DD_s^+$ resonances disfavored
- $J^P = 0^+$ favored over other spin-parity by more than 7.5σ

$$M = 2.908 \pm 0.011 \pm 0.020\ \text{GeV}$$

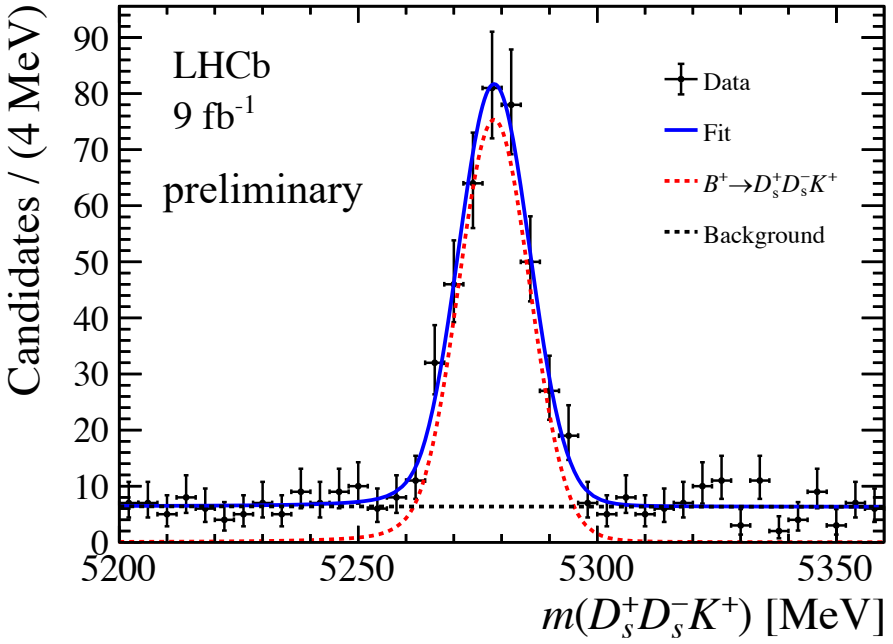
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\ \text{GeV}$$

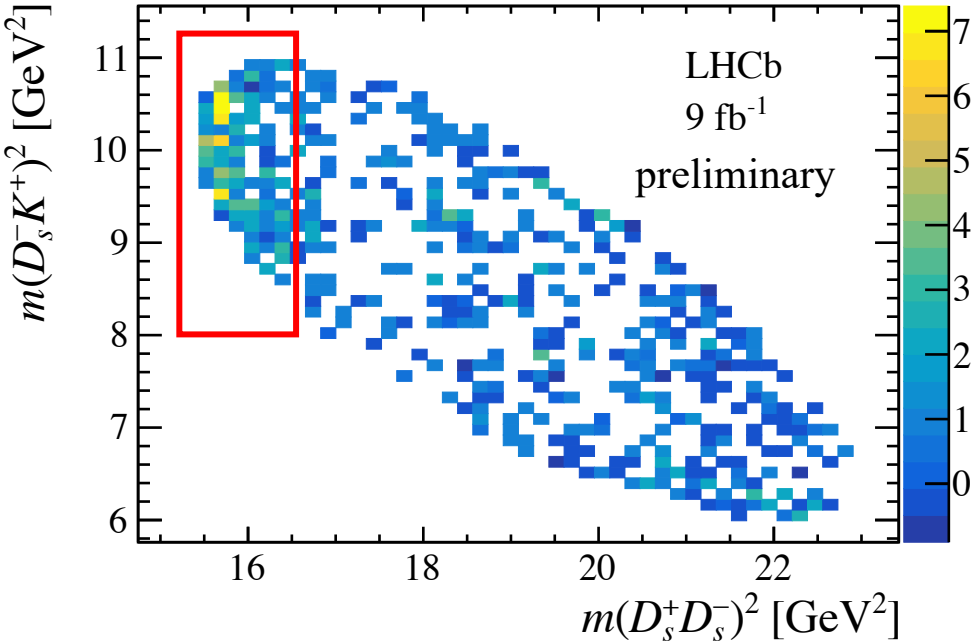
- Flavor partner of $T_{cs0}(2900)$? Multiplets to be revealed in the future.

Observation of $B^+ \to D_s^+ D_s^- K^+$

[LHCb-PAPER-2022-018]
[LHCb-PAPER-2022-019]
In preparation

➢Full 9 fb^{-1} Run1+Run2 LHCb data





$N_{\text{sig}} = 360 \pm 22$

Purity: 84%

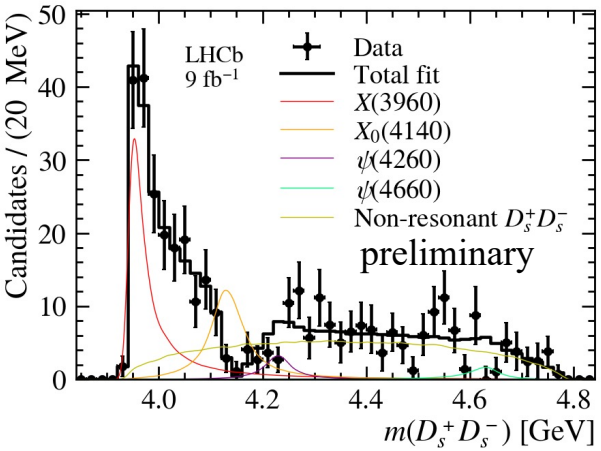
✓Near-threshold enhancement in $m(D_s^+ D_s^-)$

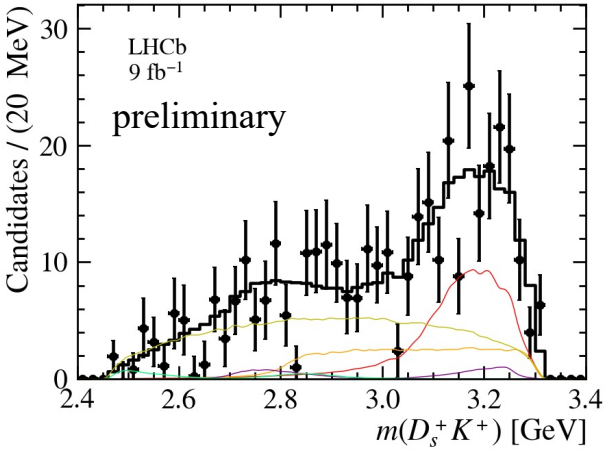
⇒ amplitude analysis

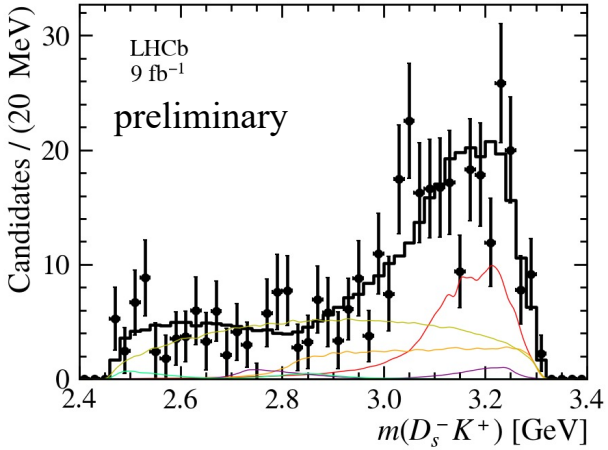
Observation of $X(3960) \to D_s^+ D_s^-$

[LHCb-PAPER-2022-018]
In preparation

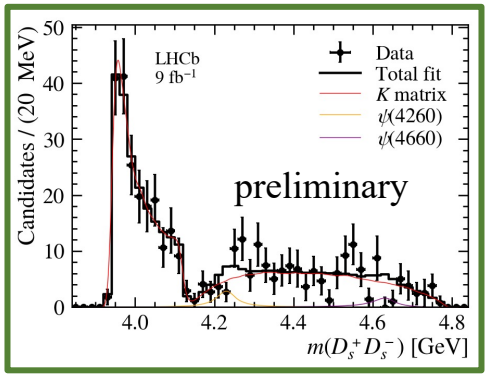
- Baseline model well describes data
  - ✓ 0^{++}: $X(3960)$ (14.3σ), $X_0(4140)$ (3.9σ), Non-resonant
  - ✓ 1^{--}: $\psi(4260), \psi(4660)$







- **$X(3960)$**: threshold enhancement
  - ✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 9.3σ and 12.3σ
- **$X_0(4140)$**: dip at ~4.14 GeV via interference
  - ✓ $J^{PC} = 0^{++}$ preferred over 1^{--} and 2^{++} by 3.5σ and 4.2σ
  - ✓ the dip can also be described by $J/\psi\phi \to D_s^+ D_s^-$ scattering



$X(3960)$ and $\chi_{c0}(3930)$

[LHCb-PAPER-2022-018]
In preparation

	M [MeV]	Γ [MeV]	J^{PC}
$X(3960)$	$3955 \pm 6 \pm 12$	$48 \pm 17 \pm 10$	0^{++}
$\chi_{c0}(3930)$	3924 ± 2	17 ± 5	

➢ Same particle?

$\mathcal{FF}$: Fit fraction

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+) \times \mathcal{FF}^X_{B^+ \to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+) \times \mathcal{FF}^X_{B^+ \to D_s^+D_s^-K^+}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

✓ Creation of $s\bar{s}$ from vacuum is suppressed wrt $u\bar{u}$ or $d\bar{d}$

✓ $X \to D_s^+D_s^-$ has smaller phase-space factor than $X \to D^+D^-$

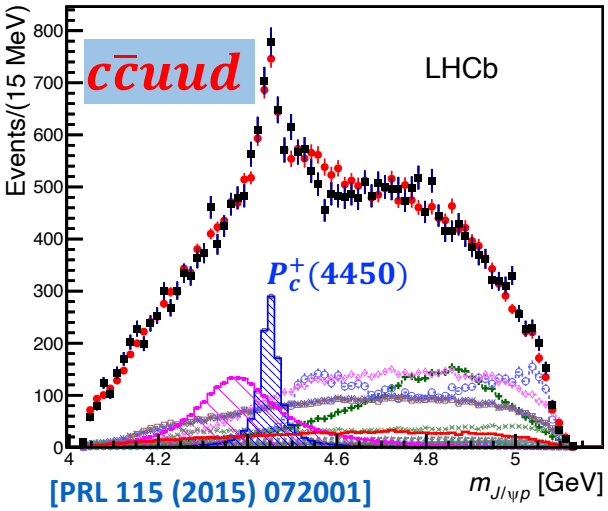
⇒ X has an exotic nature! Candidate for $c\bar{c}s\bar{s}$

➢ Different particles?

✓ No obvious candidate within conventional charmonium multiplets for them; likely to be exotic

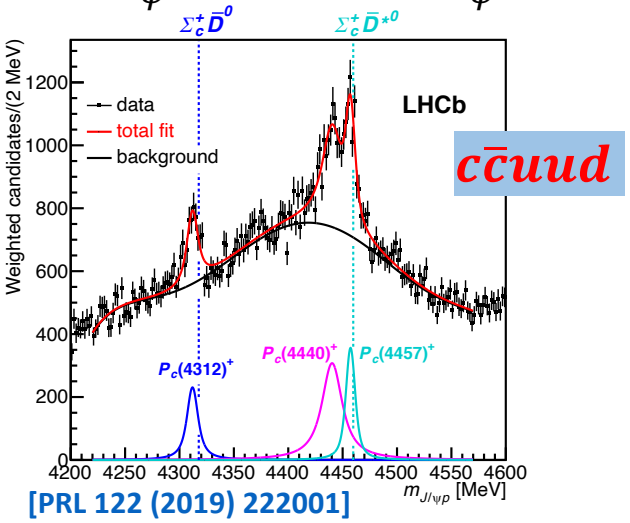
Story of pentaquarks

- Observation of a narrow $P_\psi^N(4450)^+$ in $\Lambda_b^0 \to J/\psi p K^-$



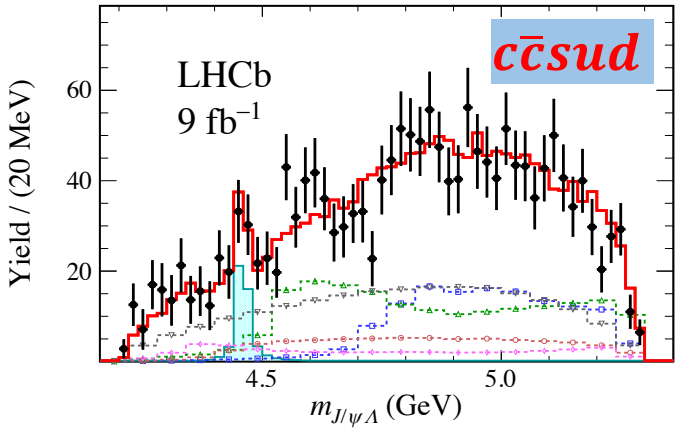
[PRL 115 (2015) 072001]

- A new $P_\psi^N(4312)^+$ and $P_\psi^N(4450)^+$ resolved into $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$



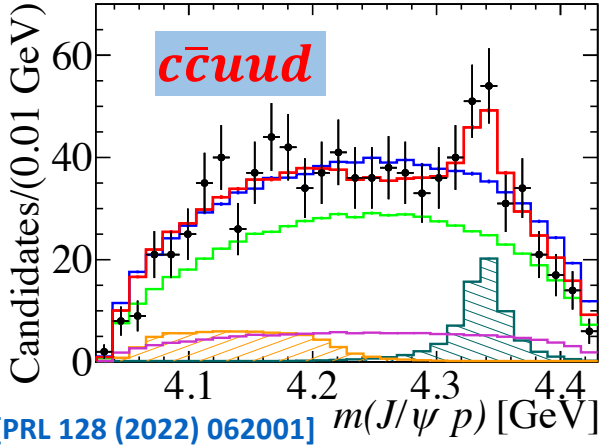
[PRL 122 (2019) 222001]

- Evidence for $P_{\psi s}^\Lambda(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$



[Science Bulletin 66 (2021) 1278]

- Evidence for $P_\psi^N(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$

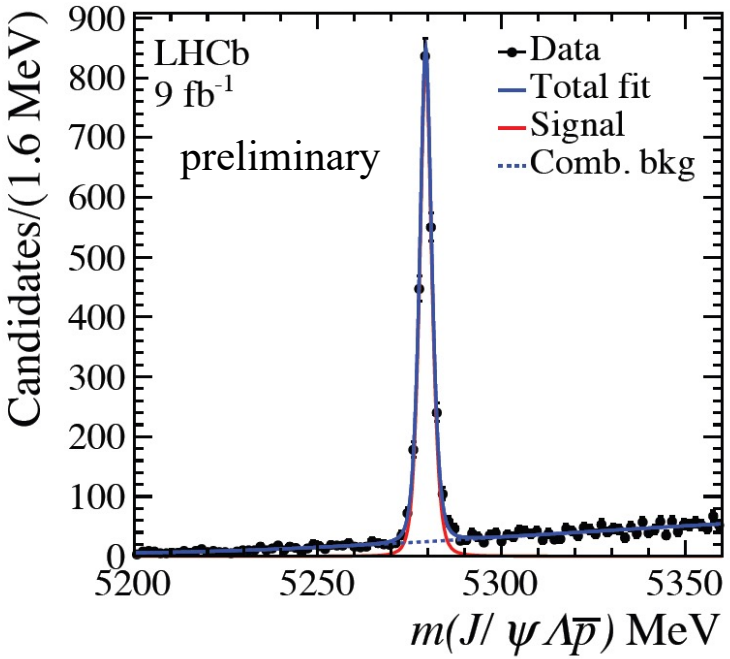


[PRL 128 (2022) 062001]

Study of $B^- \to J/\psi\Lambda\bar{p}$ [LHCb-PAPER-2022-031] In preparation

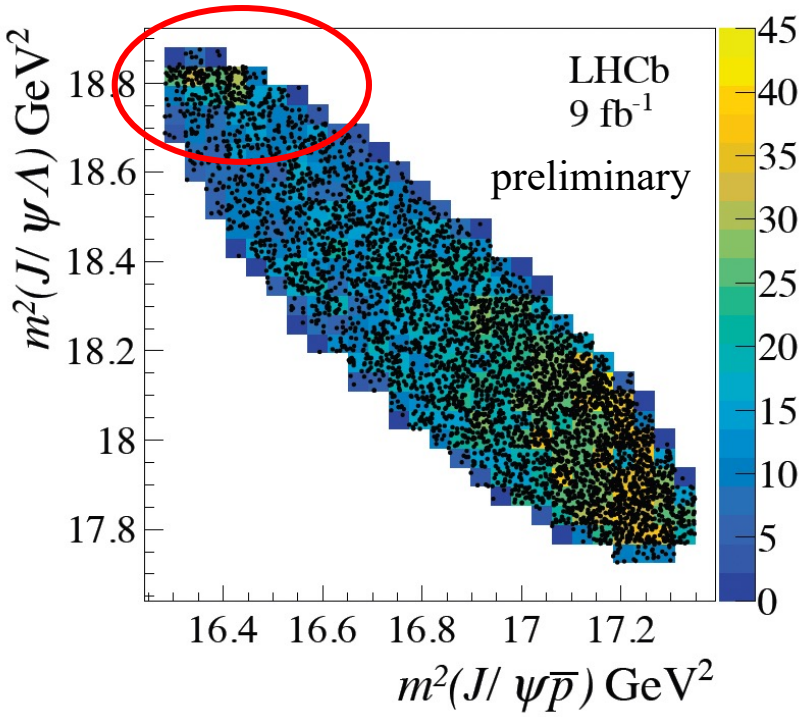
- $B^- \to J/\psi\Lambda\bar{p}$: 1) search for pentaquarks in both $J/\psi\Lambda$ and $J/\psi\bar{p}$;
  2) excellent invariant mass resolution ⇒ narrow resonances

- Full 9 fb^{-1} Run1+Run2 LHCb data



$N_{\text{sig}} = 4617 \pm 73$

Purity: 93%



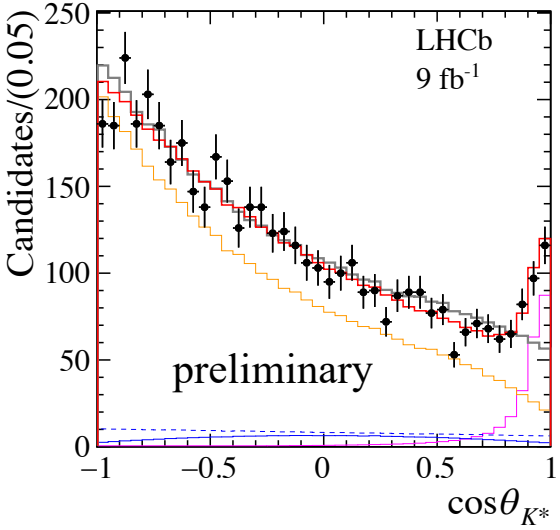
✓Horizontal band at 18.8 GeV^2 in $m^2(J/\psi\Lambda)$

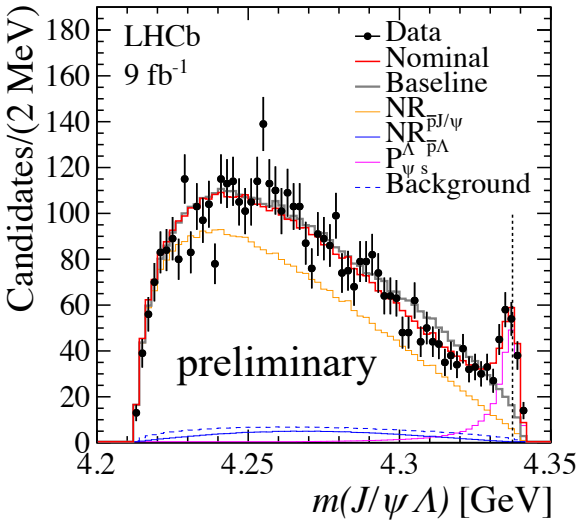
⇒ amplitude analysis

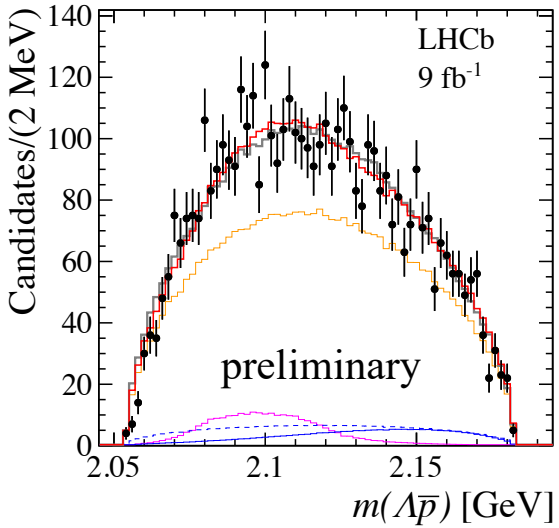
Amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$

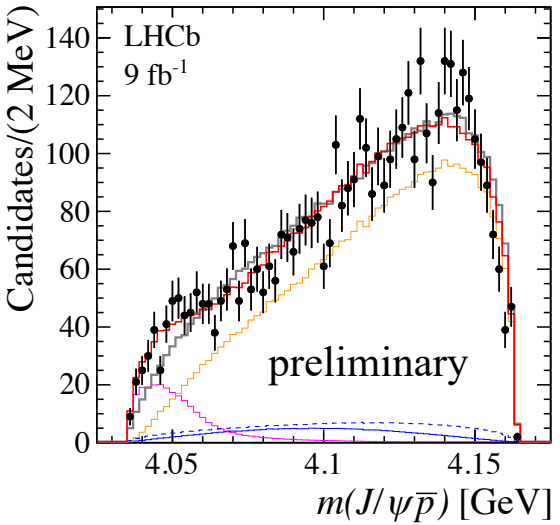
[LHCb-PAPER-2022-031]
In preparation

- Amplitude contributions
  - ✓ $\Lambda\bar{p}$: $\bar{K}_4^*(2045), \bar{K}_2^*(2250), \bar{K}_3^*(2320)$ and $J^P = 1^-$ non-resonant (NP) component ($\bar{K}^*$-only model cannot describe data)
  - ✓ $J/\psi\bar{p}$: $J^P = 1/2^-$ NR component (preferred over resonant lineshape)
  - ✓ $J/\psi\Lambda$: $\boldsymbol{P_{\psi s}^{\Lambda}}$









Observation of $P_{\psi s}^{\Lambda} \to J/\psi\Lambda$

[LHCb-PAPER-2022-031]
In preparation

- $P_{\psi s}^{\Lambda}$ observed with significance $> 10\sigma$
- $J = 1/2$ is established
- $P = -1$ preferred; $J^P = 1/2^+$ excluded at 90% CL

$$M\left(P_{\psi s}^{\Lambda}\right) = 4338.2 \pm 0.7 \pm 0.4 \text{ MeV}$$
$$\Gamma\left(P_{\psi s}^{\Lambda}\right) = 7.0 \pm 1.2 \pm 1.3 \text{ MeV}$$

- Key properties
  - ✓First observation of pentaquark with strange quark content $c\bar{c}uds$
  - ✓Narrow
  - ✓Close to $\Xi_c^+ D^-$ threshold and in S-wave

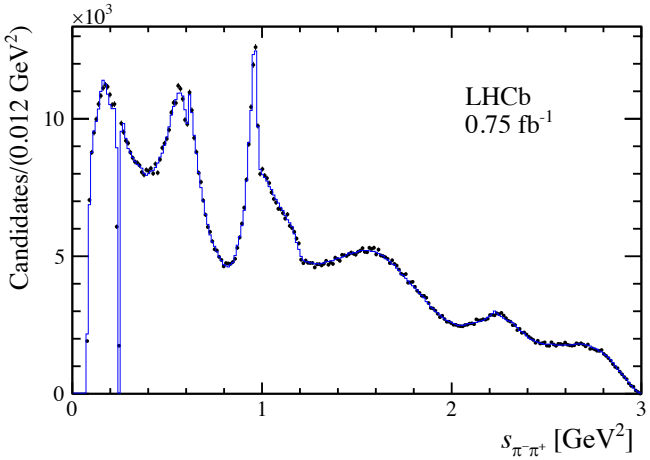
- The most precise single measurement of B^- mass

$$M(B^-) = 5279.44 \pm 0.05 \pm 0.07 \text{ MeV}$$

Amplitude analysis of $D^+ \to \pi^-\pi^+\pi^+$

[arXiv:2208.03300]

- LHCb has the largest samples of charm decays currently
- Multi-body hadronic decays of charm particles offer an interesting environment for light hadron spectroscopy study
- 1.5 fb^{-1} LHCb data at $\sqrt{s} = 8$ TeV used ⇒ 601,171 candidates with purity ~95%
- Method: quasi-model-independent partial wave analysis (QMIPWA) for $\pi^+\pi^-$ S-wave (no model assumed; parameterized as a generic complex function determined by fit to data) & isobar model for spin-1 and spin-2 states



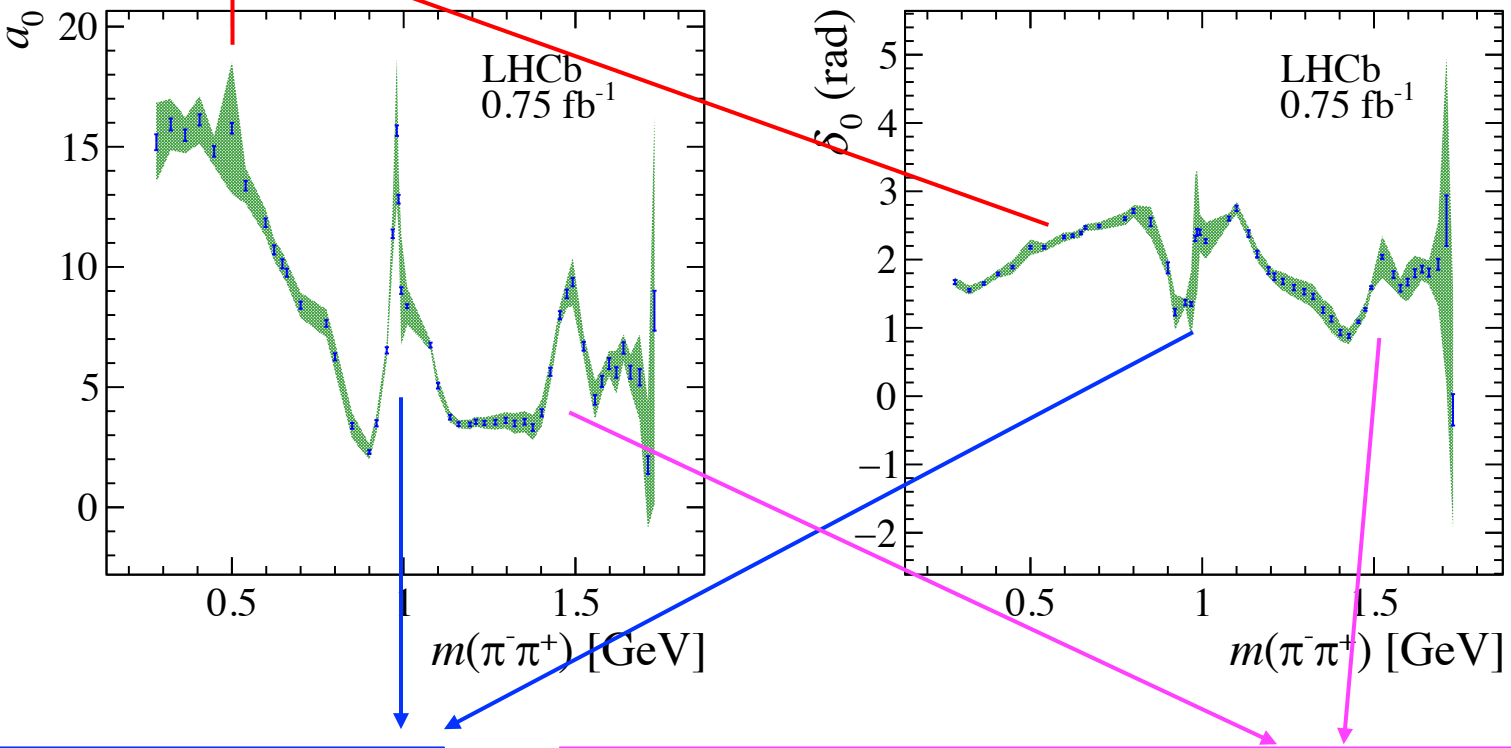
Component	Magnitude	Phase [°]	Fit fraction [%]
$\rho(770)^0\pi^+$	1 [fixed]	0 [fixed]	$26.0 \pm 0.3 \pm 1.6 \pm 0.3$
$\omega(782)\pi^+$	$(1.68 \pm 0.06 \pm 0.15 \pm 0.02) \times 10^{-2}$	$-103.3 \pm 2.1 \pm 2.6 \pm 0.4$	$0.103 \pm 0.008 \pm 0.014 \pm 0.002$
$\rho(1450)^0\pi^+$	$2.66 \pm 0.07 \pm 0.24 \pm 0.22$	$47.0 \pm 1.5 \pm 5.5 \pm 4.1$	$5.4 \pm 0.4 \pm 1.3 \pm 0.8$
$\rho(1700)^0\pi^+$	$7.41 \pm 0.18 \pm 0.47 \pm 0.71$	$-65.7 \pm 1.5 \pm 3.8 \pm 4.6$	$5.7 \pm 0.5 \pm 1.0 \pm 1.0$
$f_2(1270)\pi^+$	$2.16 \pm 0.02 \pm 0.10 \pm 0.02$	$-100.9 \pm 0.7 \pm 2.0 \pm 0.4$	$13.8 \pm 0.2 \pm 0.4 \pm 0.2$
S-wave			$61.8 \pm 0.5 \pm 0.6 \pm 0.5$
$\sum_i \text{FF}_i$			112.8
χ^2/ndof (range)	[1.47 - 1.78]		$-2\log\mathcal{L} = 805622$

- ✓S-wave dominates; followed by $\rho(770)^0\pi^+$ and $f_2(1270)\pi^+$
- ✓A small $\omega(782) \to \pi^-\pi^+$ contribution seen for the first time in $D^+ \to \pi^-\pi^+\pi^+$
- ✓The inclusion of $\rho(1700)^0$ greatly improves the fit quality

$\pi^+\pi^-$ S-wave amplitude

[arXiv:2208.03300]

Large magnitude close to threshold and decrease until ~0.9 GeV + steady phase increase ⇒ dominant contribution from $f_0(500)$



Signiture of $f_0(980)$: sharp increase of magnitude + rapid variation in the phase

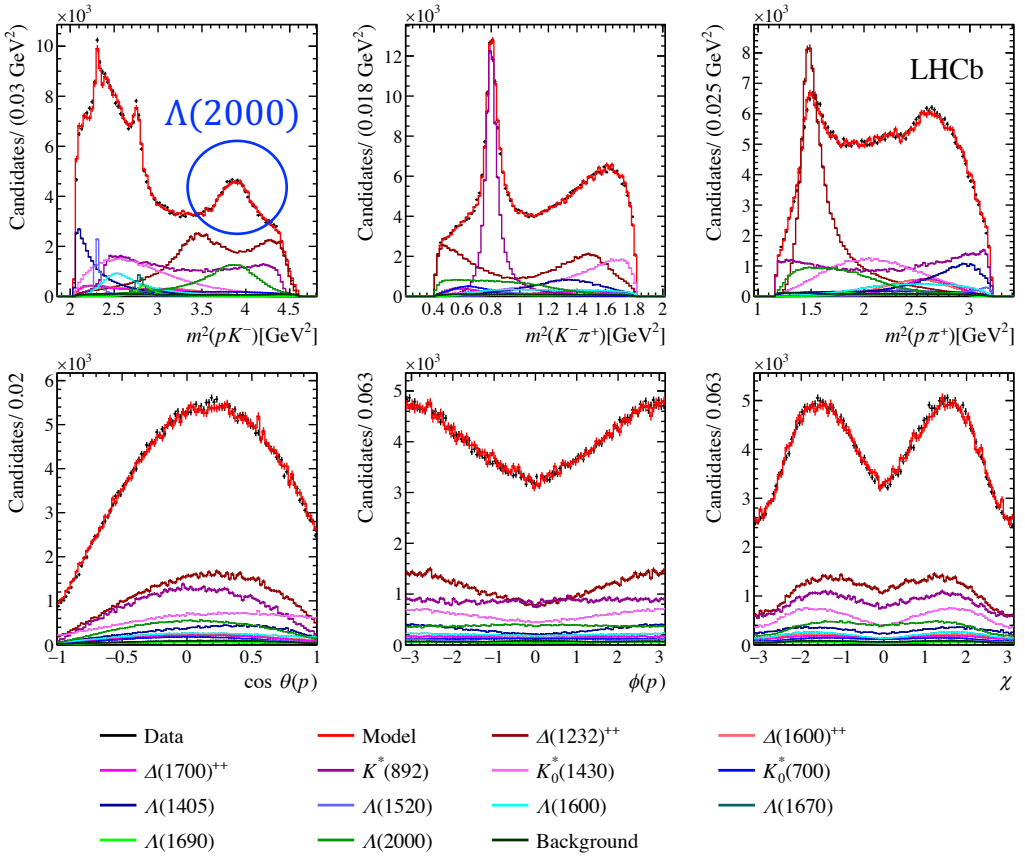
Structure starting at ~1.4 GeV and peaking near ~1.5 GeV with corresponding phase movement, indicating at least one more scalar, possibly $f_0(1370)$ or $f_0(1500)$

Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$

[arXiv:2208.03262]

- A sample of 400,000 candidates with purity of ~98.3% from semi-leptonic b-decays at $\sqrt{s} = 13$ TeV is used

Resonance	J^P	Mass (MeV)	Width (MeV)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5
$\Lambda(1520)$	$3/2^-$	$1515 - 1523$	$10 - 20$
$\Lambda(1600)$	$1/2^+$	1630	250
$\Lambda(1670)$	$1/2^-$	1670	30
$\Lambda(1690)$	$3/2^-$	1690	70
$\Lambda(2000)$	$1/2^-$	$1900 - 2100$	$20 - 400$
$\Delta(1232)^{++}$	$3/2^+$	1232	117
$\Delta(1600)^{++}$	$3/2^+$	1640	300
$\Delta(1700)^{++}$	$3/2^-$	1690	380
$K_0^*(700)$	0^+	824	478
$K^*(892)$	1^-	895.5	47.3
$K_0^*(1430)$	0^+	1375	190



- ✓Largest contributions come from $\Delta(1232)^{++}, K^*(892), K_0^*(1430)$
- ✓Significant contribution from a $J^P = 1/2^-$ state identified as $\Lambda(2000)$

$$M = 1988 \pm 2 \pm 21 \text{ MeV}; \Gamma = 179 \pm 4 \pm 16 \text{ MeV}$$

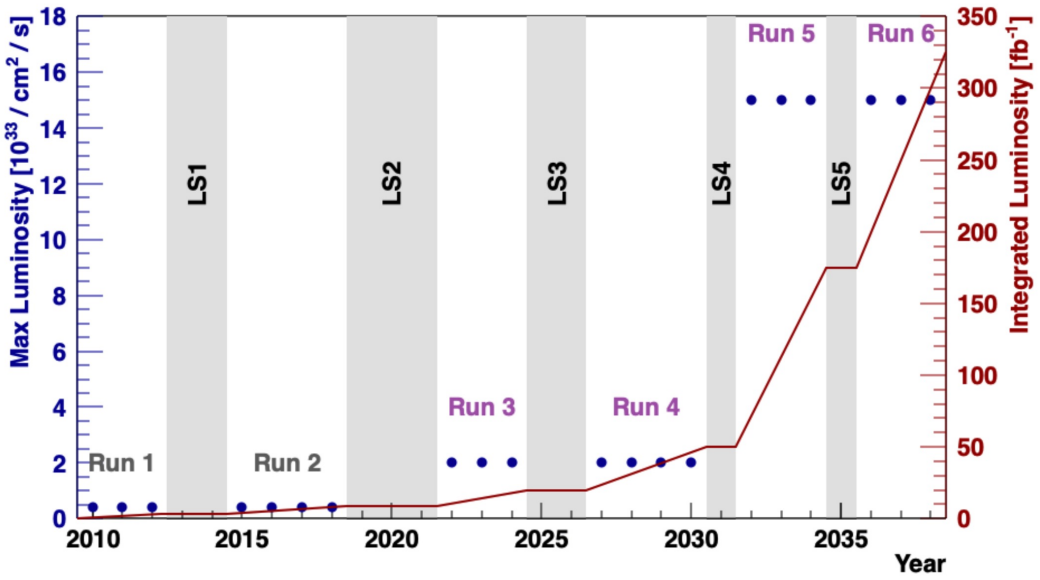
- ✓All parameters of the amplitude model reported

Summary and prospects

- LHCb keeps making important contributions to spectroscopy study
  - ✓**Conventional heavy hadron:** new Ξ_c^{**} states
  - ✓**Exotic heavy hadron:** discovery of $T_{c\bar{s}0}^{a}(2900)^{0/++}$, $X(3960) \to D_s^+ D_s^-$, $P_{\psi s}^{\Lambda}$
  - ✓**Light hadron:** amplitude study of $D^+ \to \pi^-\pi^+\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$

  ……

- In Run 3, the upgraded LHCb detector and an improved software-only trigger system will be implemented

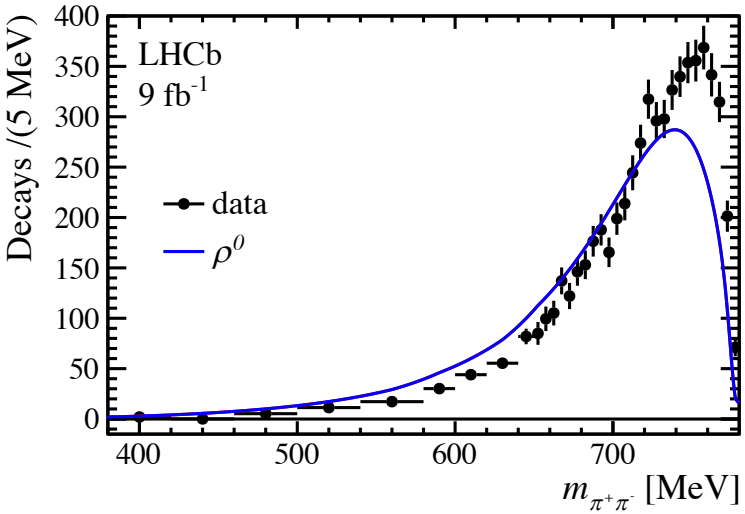


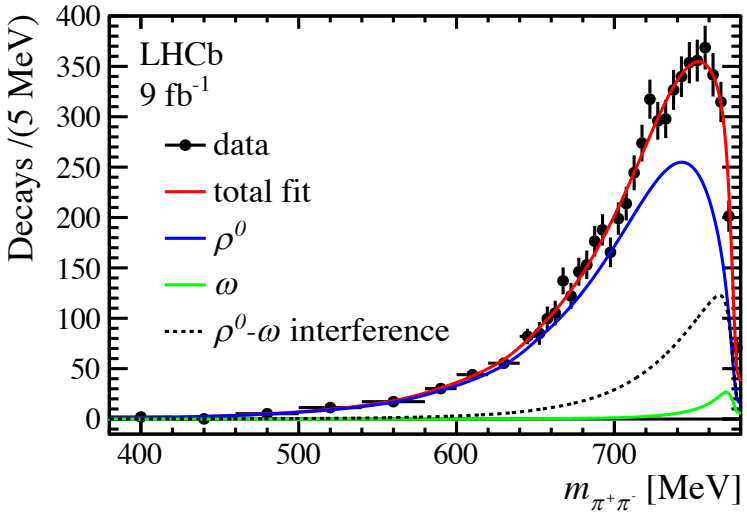
More exciting results are to come!

Back up

ω contribution to $\chi_{c1}(3872) \to J/\psi\pi^+\pi^-$

- $\chi_{c1}(3872)$ is the first observed hidden-charm exotic hadron with most abundant experimental information, but no consensus on its nature yet!
- $\chi_{c1}(3872) \to J/\psi\rho^0$ is isospin violating;
  quantifying the isospin violation is important to understand its nature
- Full 9 fb^{-1} Run1+Run2 LHCb data
  $\Rightarrow 6788 \pm 117$ $B^+ \to \chi_{c1}(3872)(\to J/\psi\pi^+\pi^-)K^+$ signal candidates





[arXiv: 2204.12597]

- Total ω contribution: $(21.4 \pm 2.3 \pm 2.0)\%$
  Excluding interference: $(1.9 \pm 0.4 \pm 0.3)\%$
- ρ^0 contribution an order of magnitude too large for pure charmonium