Classical and exotic spectroscopy at LHCb

Elisabeth Niel on behalf of the LHCb Collaboration

École Polytechnique Fédérale de Lausanne - EPFL

Les Rencontres de Physique de la Vallée d'Aoste

La Thuile - Italy

5 – 11 March 2023

Mont Blanc from my home

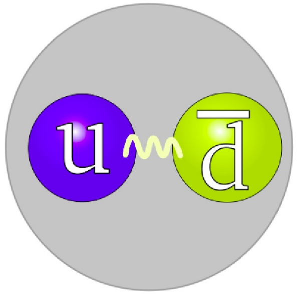
Introduction

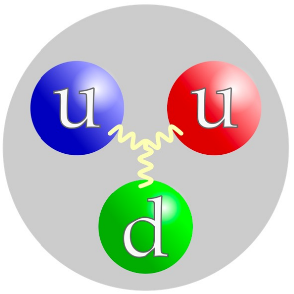
Classical hadrons → mesons [quark + antiquark] or baryons [3 quarks]

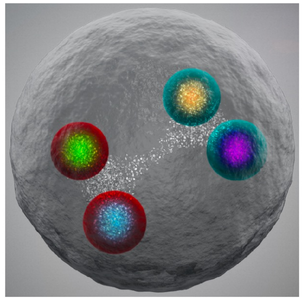
Exotic hadrons → in principle, anything else :
Glueballs, hybrids, tetraquarks, pentaquarks, hexaquarks

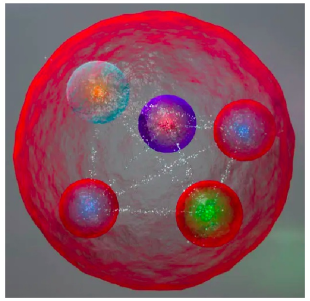
Studied by different experiments:

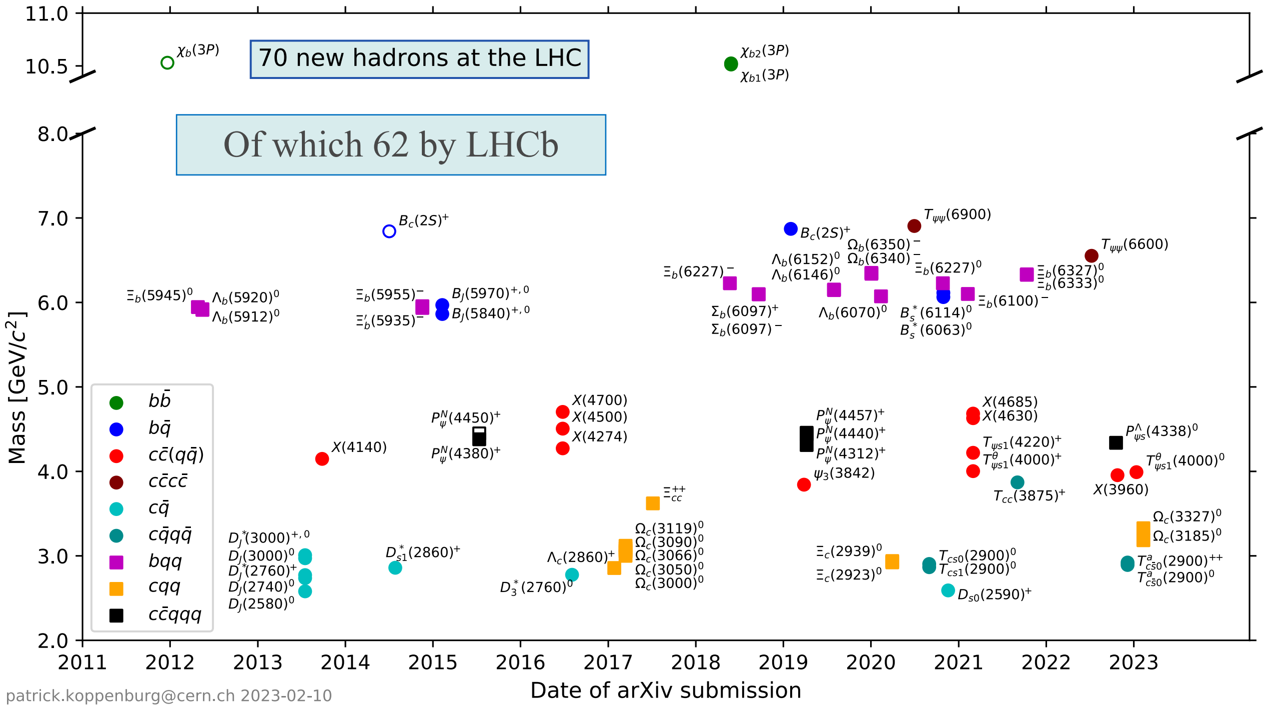
LHCb, BESIII, ATLAS, CMS, Belle, Belle II, BaBar, CDF, D0, ALICE …











LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC.

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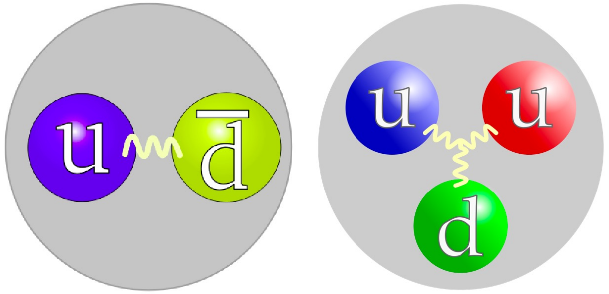

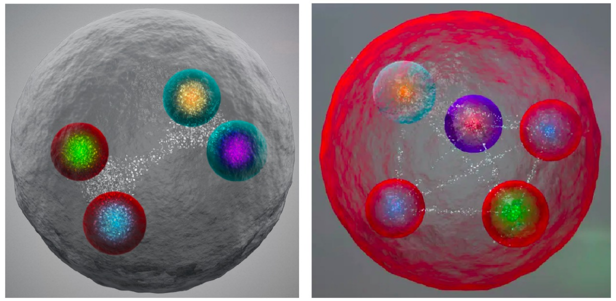

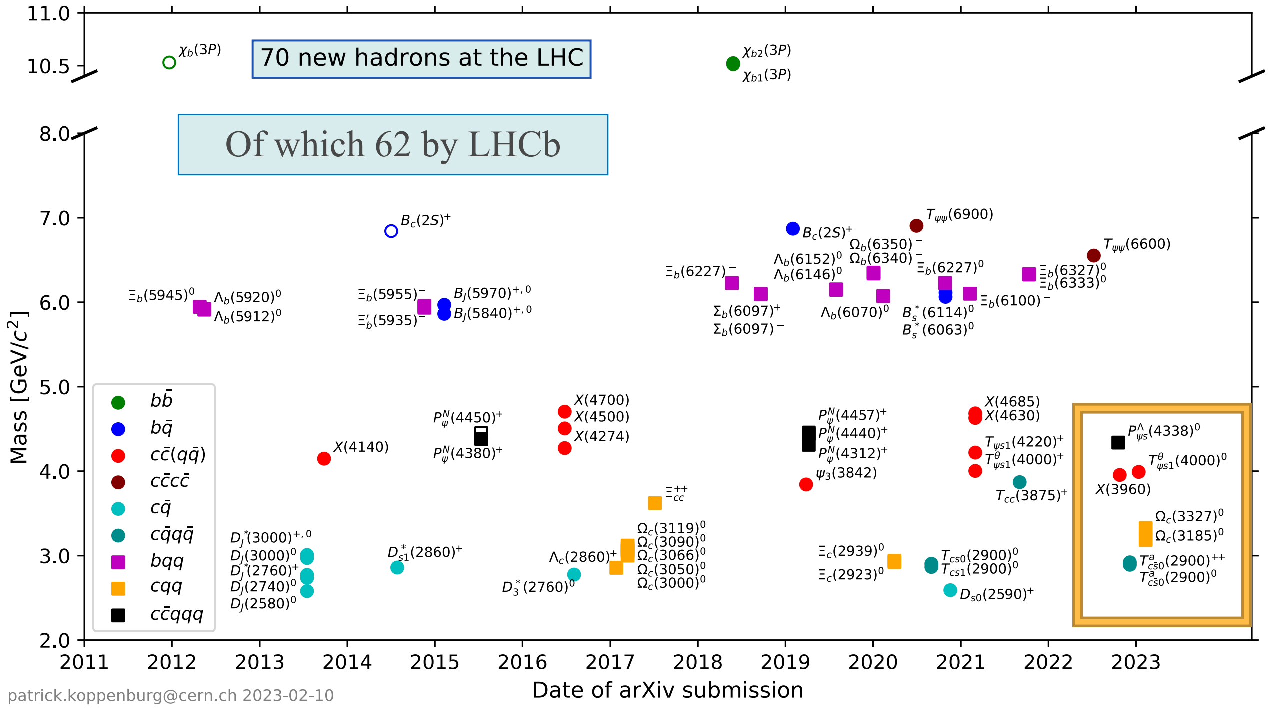

Today: a selection of recent LHCb results

LHCb collaboration, P. Koppenburg, List of hadrons observed at the LHC.

Last year LHCb talk – **La Thuile 2022**

Overview

- Selection of recent LHCb results on classical and exotic spectroscopy

Conventional hadrons

- $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis & Λ_c^+ polarisation measurement (**NEW!**)
- Observation of new excited Ξ_b^0 states in $\Lambda_b^0 K^-\pi^+$
- Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^-\pi^-$ decays
- Study of charmonium contributions in $B^+ \to J/\psi \eta K^+$

Exotics

- $\chi_{c1}(3872)$ production in pp collisions at $\sqrt{s} = 8, 13\,\mathrm{TeV}$
- Observation of exotic tetraquark T_{cc}^+ in $D^0 D^0 \pi^+$
- Evidence of new pentaquark structure in $B_s^0 \to p\bar{p}J/\psi$ decays

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Conventional hadrons for today

- $\Lambda_c^+ \to pK^-\pi^+$ polarimetry
- $D_s^+ \to \pi^+\pi^-\pi^+$
- $D^+ \to \pi^+\pi^-\pi^+$
- Observation of new Ω_c^0 states decaying into $\Xi_c^+ K^-$
- Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^+$ [talk by Gabriele Martelli]

Last year LHCb talk – **La Thuile 2022**

Overview

...al and exotic spectroscopy

Exotics for today

- Observation of the $B_s^0 \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)\pi^+\pi^-$ decay
- $B^0 \to J/\psi\phi K_S^0$ new state : $T_{\psi s1}^{\theta}(4000)^0$ **and** $T_{\psi s1}(4220)^0$
- New doubly charged and neutral open charmed tetraquarks observed in $B^0 \to \bar{D}^0 D_s^+\pi^-$ **and** $B^+ \to D^- D_s^+\pi^+$
- New state from the amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$
- Strange pentaquark candidate in $B^- \to J/\psi\Lambda\bar{p}$

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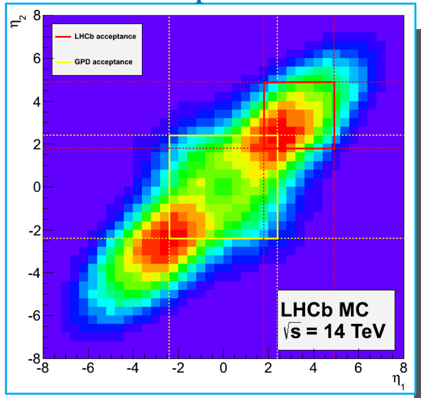
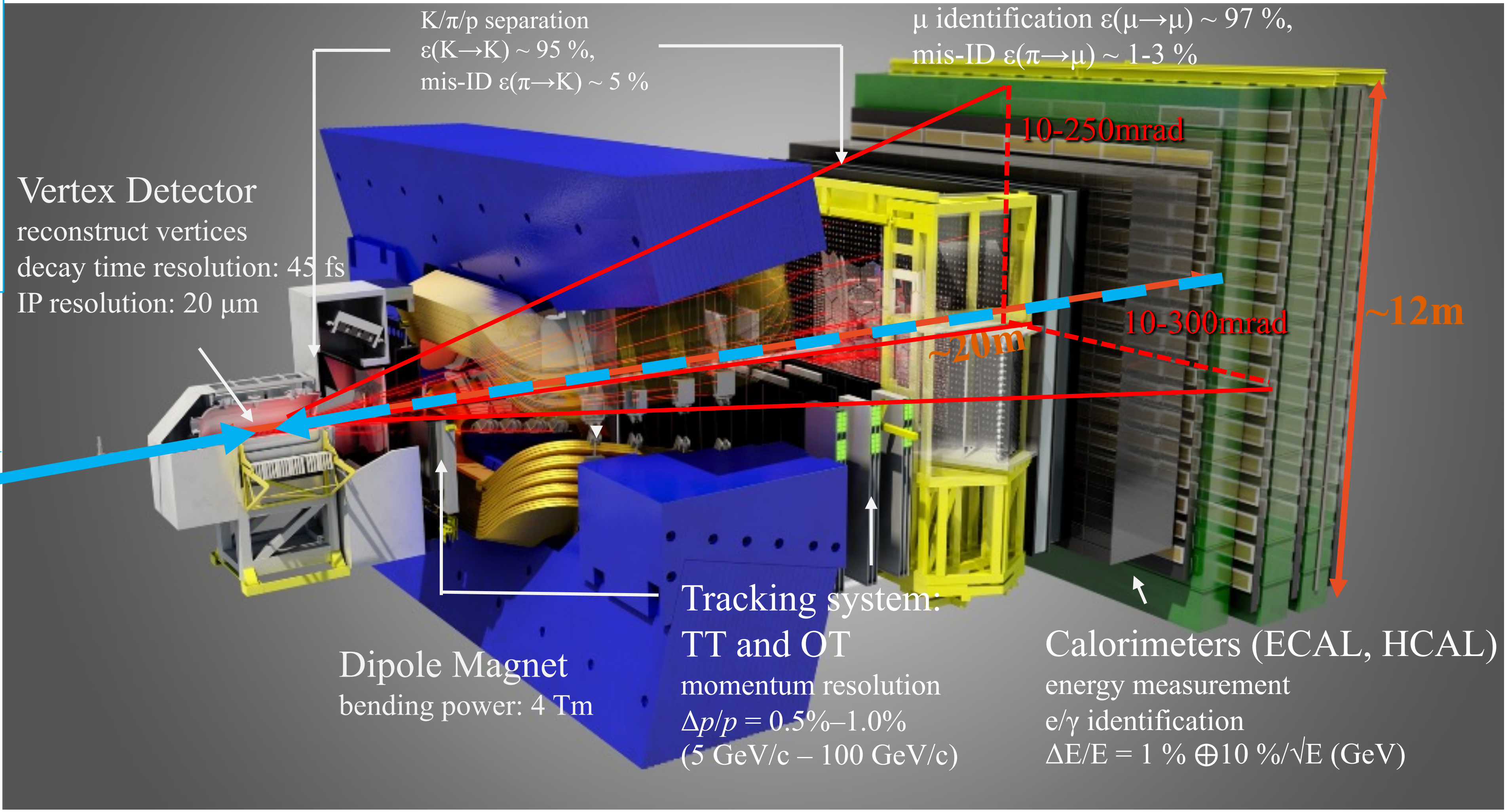
The LHCb experiment

[IJMPA 30 (2015) 1530022]
[JINST 3 (2008) S08005]

$b\bar{b}$ acceptance





Single arm forward spectrometer with excellent vertexing, tracking, PID

Conventional spectroscopy at LHCb

- **heavy baryons:**
  - $\Omega_c^0 \to \Xi_c^+ K^-$
- **doubly heavy baryons**
  - Observation of $\Xi_{cc}^{++} \to \Xi_c'^+ \pi^+$
- **amplitude structures of charm hadron decays**
  - $D_s^+ \to \pi^+ \pi^- \pi^+$
  - $D^+ \to \pi^+ \pi^- \pi^+$
  - $\Lambda_c^+ \to p K^- \pi^+$ polarimetry
  - Observation of the $B_s^0 \to (\chi_{c1}(3872) \to J/\psi \pi^+ \pi^-) \pi^+ \pi^-$ decay

Observation of new Ω_c^0 states decaying into $\Xi_c^+ K^-$

- Single charmed baryons: one charm quark + 2 lighter quarks → large mass difference
- Described by heavy quark effective theory HQET but masses and quantum numbers diverges among different theories, some examples:
  - lattice quantum chromodynamics predicts invariant-mass spectrum with D or F–wave excited states PRL 119, 042001
  - baryon-meson molecular (quasi-bound) states interpretation for $\mathbf{\Omega_c^0(3050)}$ and $\mathbf{\Omega_c^0(3090)}$ PRD 97 (2018) 094035 , EPJ. A54 (2018) 64, Few Body Syst. 61 (2020) 34
  - interpretation as pentaquark states PRD96 (2017) 034012 and Communications in Theoretical Physics 73 (2021) 035201.
- Measurement of BR would help to discriminate internal structure (molecular, pentaquarks,…)

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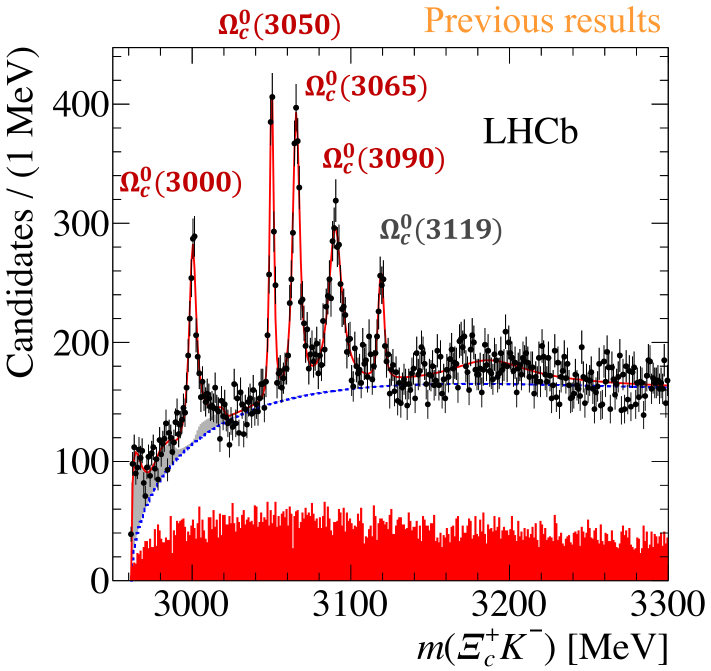
- NEW update of PRL 118 (2017) 182001 → 5 times larger data sample



Previous LHCb measurement

Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.
$\Omega_c(3188)^0$	$3188 \pm 5 \pm 13$	$60 \pm 15 \pm 11$
$\Omega_c(3066)^0_{\rm fd}$		
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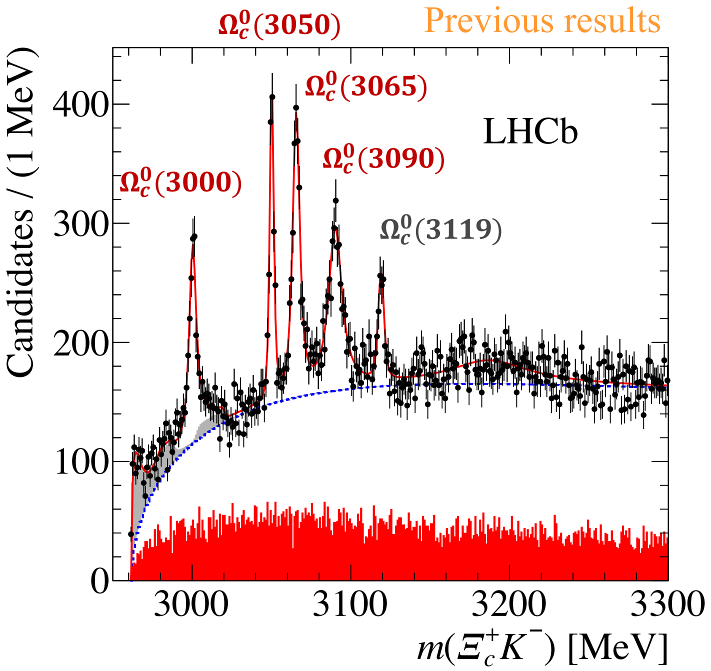
- Measurement of BR would help to discriminate internal structure (molecular, pentaquarks,…)
- NEW update of PRL 118 (2017) 182001 → 5 times larger data sample
- Production from $\Omega_b^- \rightarrow \Xi_c^+ K^- \pi^-$ also studied by LHCb Phys. Rev. D 104, L091102



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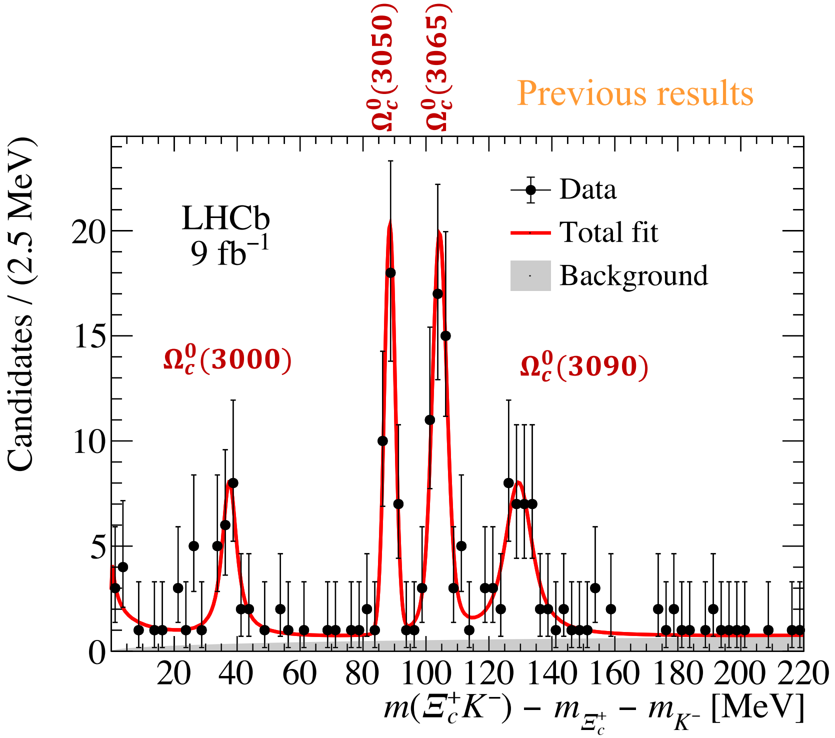
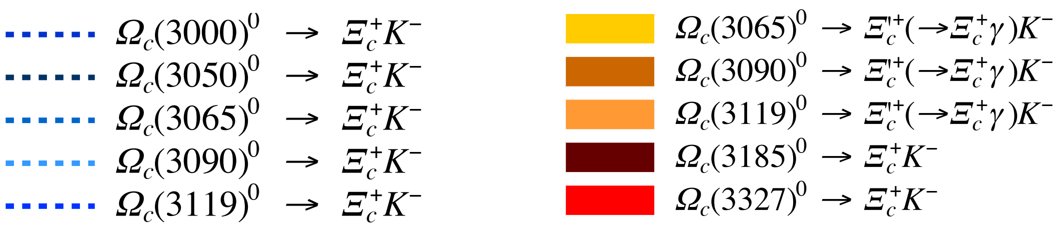


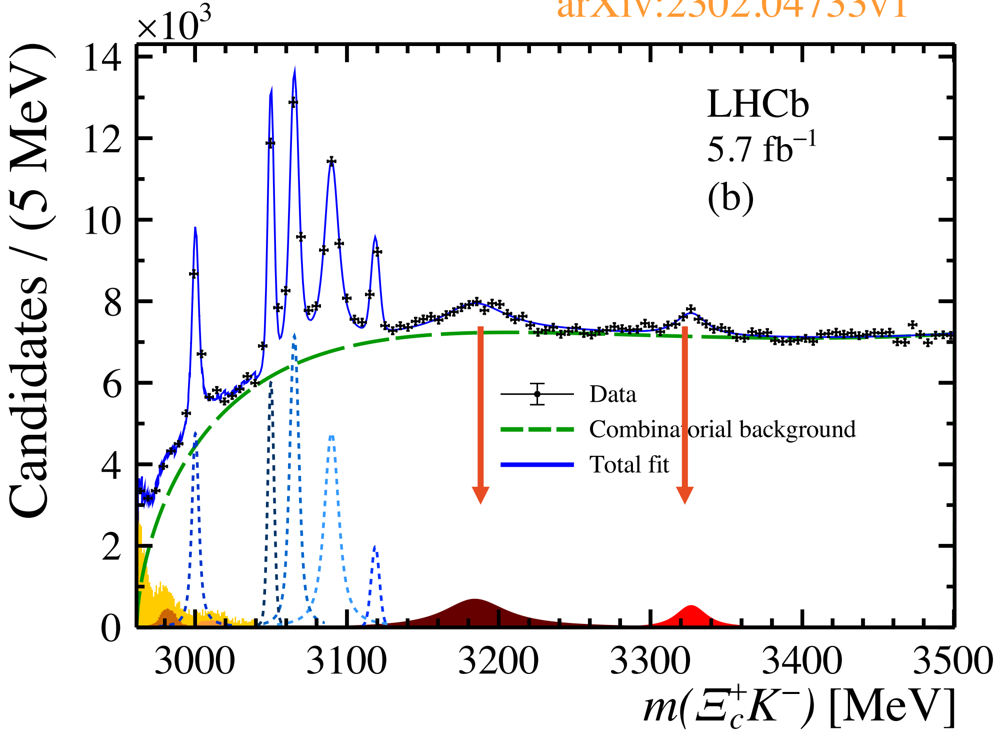
Observation of new Ω_c^0 states decaying into $\Xi_c^+ K^-$

- Two new excited states $\boldsymbol{\Omega_c(3185)^0}$ and $\boldsymbol{\Omega_c(3327)^0}$
- Five states from previous analysis confirmed→masses and widths measured with highest precision to date



Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07\ ^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23\ ^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04\ ^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17\ ^{+0.64}_{-0.72}$
		< 1.8 MeV, 95% C.L.
$\Omega_c(3065)^0$	$3065.63 \pm 0.06\ ^{+0.06}_{-0.06} \pm 0.23$	$3.79 \pm 0.20\ ^{+0.38}_{-0.47}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11\ ^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44\ ^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12\ ^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63\ ^{+0.90}_{-1.05}$
		< 2.5 MeV, 95% C.L.
$\Omega_c(3185)^0$	$3185.1 \pm 1.7\ ^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7\ ^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2\ ^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5\ ^{+13}_{-1}$

arXiv:2302.04733v1



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Partially reconstructed decays with photons determined from simulation (yields vary in the fit)

- Fit at threshold enanchement with BW with or w/o feed down $\boldsymbol{\Omega_c(3065)^0}$, not possible to separate two states but the existence of another hidden state cannot be excluded.
- $\boldsymbol{\Omega_c(3185)^0}$ could be also described by two states

$\Omega_c(3000)^0 \to \Xi_c^+ K^-$
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$\Omega_c(3119)^0 \to \Xi_c^+ K^-$
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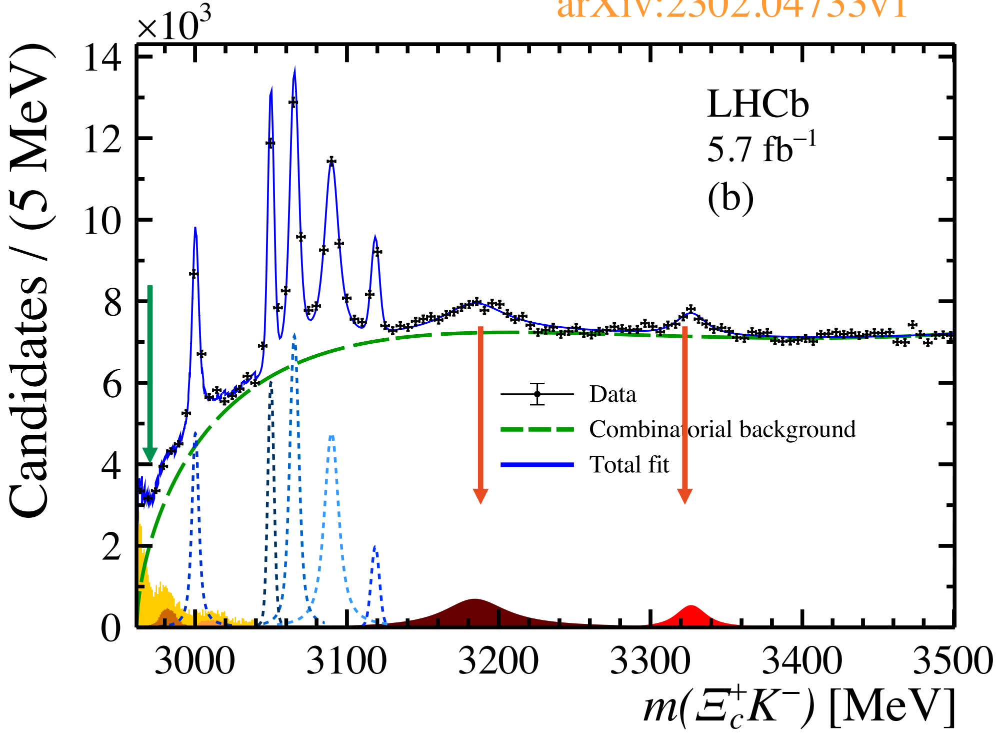


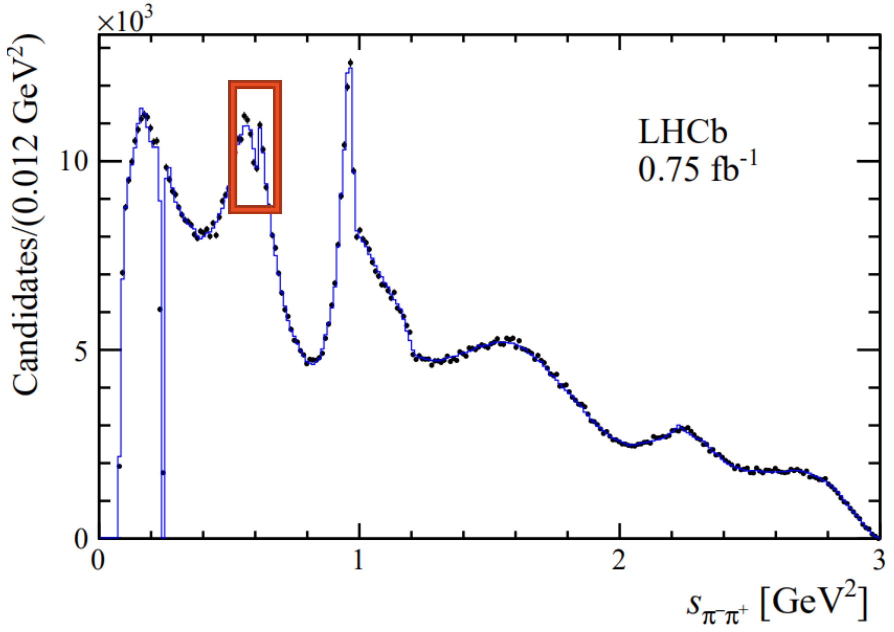
Amplitude analysis $D^+(D_s^+) \to \pi^+\pi^-\pi^+$

- Spectroscopy of scalar states, test glueballs interpretation *J. Phys. G: Nucl. Part. Phys.* **40** 043001
- 2012 data, $\mathcal{L} = 0.75\ \text{fb}^{-1}$. Promptly produced D mesons: $\boldsymbol{N(D^+)\sim 600k}$ and $\boldsymbol{N(D_s^+)\sim 700k}$
- Amplitude description: **S-wave** with Quasi-Model Independent approach (**QMIPWA**) **and isobar model for spin-1, spin-2 components**

$$\mathcal{A}_S(s_{12}, s_{13}) = \mathcal{A}_S(s_{12}) + \mathcal{A}_S(s_{13}) \qquad \mathcal{A}_S^k(s_{\pi^+\pi^-}) = c_k e^{i\phi_k}$$

c_k, ϕ_k: Generic functions determined by fit to data

$D^+ \to \pi^-\pi^+\pi^+$



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]		$-2\log\mathcal{L} = 805622$

Dominated by S-wave, followed by $\rho(770)^0\pi^+$ and $f_2(1270)^0\pi^+$

Contribution from $(\omega(782) \to \pi^+\pi^-)\pi^+$ observed for the first time

arXiv:2208.033

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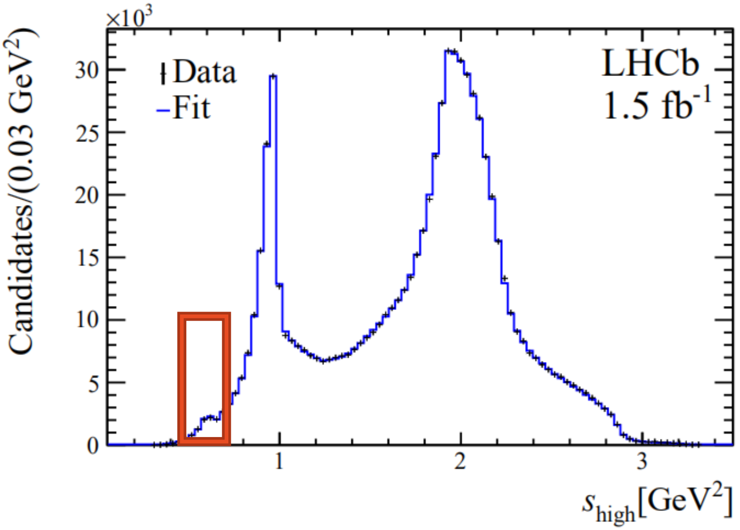
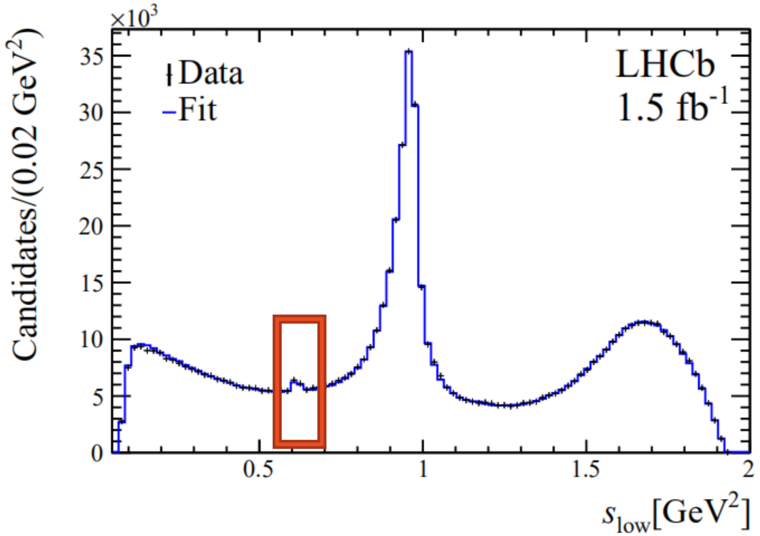
$D_s^+ \to \pi^-\pi^+\pi^+$

$$\mathcal{A}_S(s_{12}, s_{13}) = \mathcal{A}_S(s_{12}) + \mathcal{A}_S(s_{13}) \qquad \mathcal{A}_S^k(s_{\pi^+\pi^-}) = c_k e^{i\phi_k}$$

c_k, ϕ_k: Generic functions determined by fit to data





Resonance	Magnitude	Phase [°]	Fit fraction (FF) [%]
S-wave			84.97 ± 0.14
$\rho(770)^0$	0.1201 ± 0.0030	79.4 ± 1.8	1.038 ± 0.054
$\omega(782)$	0.04001 ± 0.00090	-109.9 ± 1.7	0.360 ± 0.016
$\rho(1450)^0$	1.277 ± 0.026	-115.2 ± 2.6	3.86 ± 0.15
$\rho(1700)^0$	0.873 ± 0.061	-60.9 ± 6.1	0.365 ± 0.050
combined	–	–	6.14 ± 0.27
$f_2(1270)$	1 (fixed)	0 (fixed)	13.69 ± 0.14
$f_2'(1525)$	0.1098 ± 0.0069	178.1 ± 4.2	0.0455 ± 0.0070
sum of fit fractions			104.3
χ^2/ndof (range)	[1.45 – 1.57]		

Dominated by S-wave, followed by spin-2 resonances
Contribution from $(\omega(782) \to \pi^+\pi^-)\pi^+$ observed for the first time

arXiv:2209.09840

$\Lambda_c^+ \rightarrow pK^-\pi^+$ polarimetry

- Polarization measurement: insights on quark hadronisation mechanism, hadron spectroscopy, BSM searches in $\Lambda_b \rightarrow \Lambda_c l^- \nu$ and with the measurement of EDM and MDM of charm baryons.
- Recent LHCb Λ_c^+ polarization measurement in $\Lambda_c^+ \rightarrow p\,K^-\pi^+$ semileptonic decays and amplitude analysis: **6 $\boldsymbol{\Lambda^*}$, 3 $\boldsymbol{\Delta^{*++}}$** states, and **3 $\boldsymbol{K^{*0}}$** states arXiv:2208.03262
- Decay paremetrization is model dependent→new method to express the polarized decay rate in model agnostic way

Reduction of uncertainties on polarization measurement!

arXiv:2301.07010

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Reduction of uncertainties on polarization measurement!

unpolarized intensity

aligned polarimeter vector

$$|\mathcal{M}(\phi,\theta,\chi,\kappa)|^2 = I_0(\kappa)\left(1 + \sum_{i,j} P_i R_{ij}(\phi,\theta,\chi)\alpha_j(\kappa)\right)$$

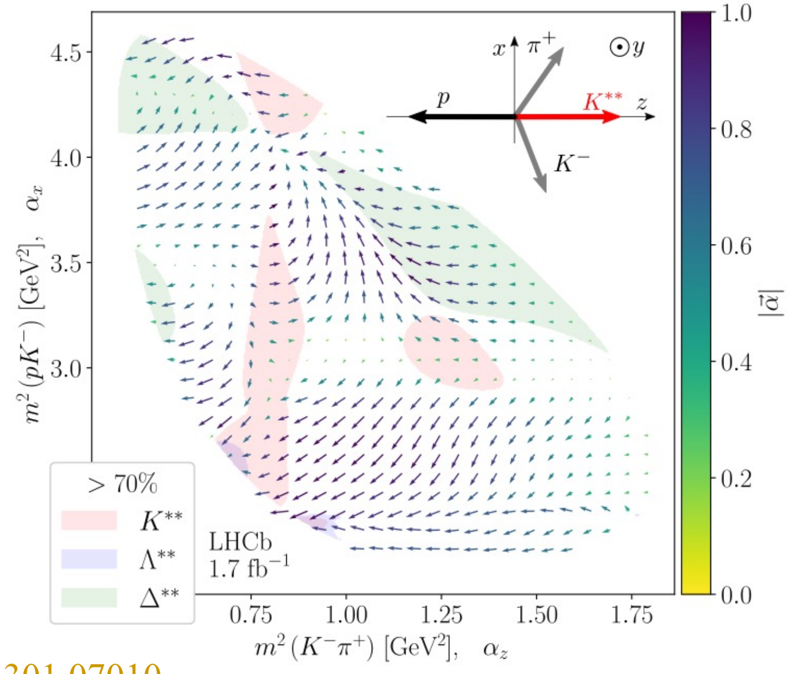
- $\alpha_j(\tau)$ can be computed for any model and represented as an arrow over the x-z plane, where κ denotes the kinematic variables

arXiv:2301.07010

$\Lambda_c^+ \to pK^-\pi^+$ polarimetry

- Polarization measurement: insights on quark hadronisation mechanism, hadron spectroscopy, BSM searches in $\Lambda_b \to \Lambda_c l^- \nu$ and with the measurement of EDM and MDM of charm baryons.
- Recent LHCb Λ_c^+ polarization measurement in $\Lambda_c^+ \to p\, K^-\pi^+$ semileptonic decays and amplitude analysis: **6 Λ^*, 3 Δ^{*++}** states, and **3 K^{*0}** states arXiv:2208.03262
- Decay paremetrization is model dependent→new method to express the polarized decay rate in model agnostic way

Reduction of uncertainties on polarization measurement!



arXiv:2301.07010

unpolarized intensity ↓ aligned polarimeter vector ↓

$$|\mathcal{M}(\phi,\theta,\chi,\kappa)|^2 = I_0(\kappa)\left(1+\sum_{i,j} P_i R_{ij}(\phi,\theta,\chi)\alpha_j(\kappa)\right)$$

- $\alpha_j(\tau)$ can be computed for any model and represented as an arrow over the x-z plane, where κ denotes the kinematic variables
- Length of polarization vector = color axis, > 0.5 over the Dalitz→ significant contribution of both parity conserving and violating currents!
- Averaged on angles→ worse uncertainty on P_i
- Code available at https://lc2pkpi-polarimetry.docs.cern.ch

Observation of the $B_s^0 \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)\pi^+\pi^-$ decay

- Puzzling difference between the branching fractions $B^+ \to \chi_{c1}(3872)K^+$ and $B^0 \to \chi_{c1}(3872)K^0$ arXiv:2302.02127
- Compact-tetraquark interpretation explaining also similar BR $B_s^0 \to \chi_{c1}(3872)\phi$ and $B^0 \to \chi_{c1}(3872)K^0$ Phys. Rev. D102 (2020) 034017
- The ratio of branching fractions measured:

$$\frac{\mathcal{B}\left(B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-\right) \times \mathcal{B}\left(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\right)}{\mathcal{B}\left(B_s^0 \to \psi(2S)\pi^+\pi^-\right) \times \mathcal{B}\left(\psi(2S) \to J/\psi\pi^+\pi^-\right)} = (6.8 \pm 1.1 \pm 0.2) \times 10^{-2}$$

arXiv:2302.10629

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- The signal yields two-dimensional extended unbinned maximum-likelihood fit to the $J/\psi\ \pi^+\ \pi^+\pi^-\ \pi^-$ and $J/\psi\ \pi^+\ \pi^+$ mass distributions

Fit components:

1. Signal template $B_s^0 \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)\pi^+\pi^-$
2. **J/ψππ combination** does not originate from a $\chi_{c1}(3872)$ meson (no interference with first accounted for)
3. **Random combinations** of the $\chi_{c1}(3872)$ state with a π+π− pair,
4. Polynomial background

Parameter		$B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$	$B_s^0 \to \psi(2S)\pi^+\pi$
N		155 ± 23	1301 ± 47
$m_{\chi_{c1}(3872)}$	[MeV/c^2]	3871.57 ± 0.09	—
$m_{\psi(2S)}$	[MeV/c^2]	—	3686.08 ± 0.07
$m_{B_s^0}$	[MeV/c^2]	5366.97 ± 0.23	
$s_{B_s^0}$		1.06 ± 0.03	
$s_{J/\psi\pi^+\pi^-}$		1.12 ± 0.03	

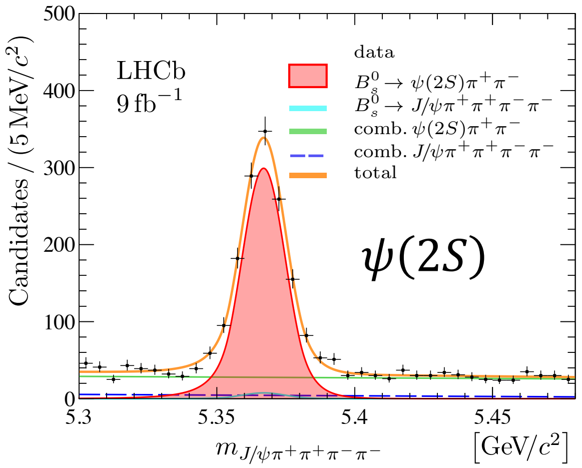
$$\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-) = (1.6 \pm 0.3 \pm 0.1 \pm 0.3) \times 10^{-6},$$

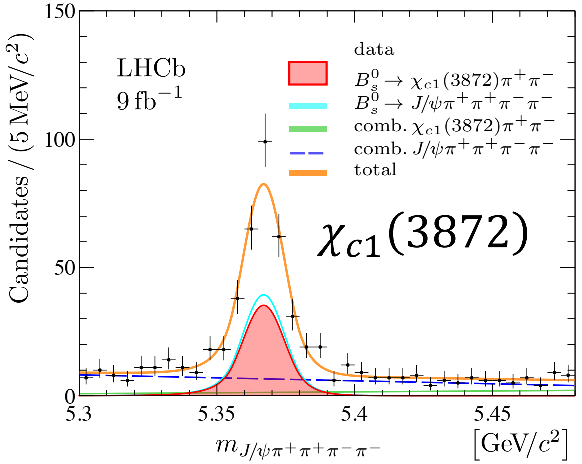
Using PDG input for

$$\mathcal{B}(B_s^0 \to \psi(2S)\pi^+\pi^-) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)$$

arXiv:2302.10629

$3.85 < m_{J/\psi\pi^+\pi^-} < 3.90\ \mathrm{GeV}/c^2$





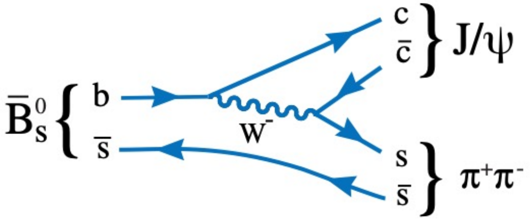
$3.67 < m_{J/\psi\pi^+\pi^-} < 3.70\ \mathrm{GeV}/c^2$

Observation of the $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$ decay

- Mass spectra $(\pi^+\pi^-)$ system recoiling against the $\chi_{c1}(3872)$ and ψ(2S) states obtained using the *sPlot technique* from mass fits
- From $B_s^0 \to J/\psi\pi^+\pi^-$ analysis **f_0(980) and f_0(1500)** contributions dominant confirmed Phys. Rev. D89 (2014) 092006
- Describe the spectra with coherent sum of scalar **f_0(980) and f_0(1500)** + non resonant component

$$F(m) \propto mqp^3 \left| f\mathcal{A}_{f_0(980)}(m) + e^{i\varphi}\mathcal{A}_{f_0(1500)}(m) \right|^2$$

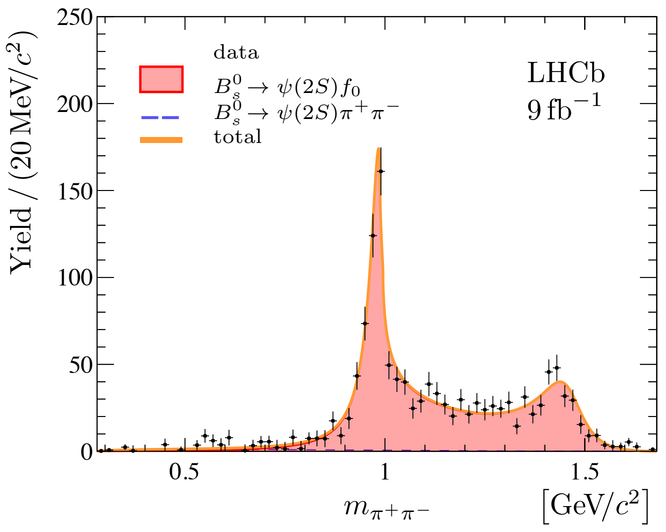
Phase space

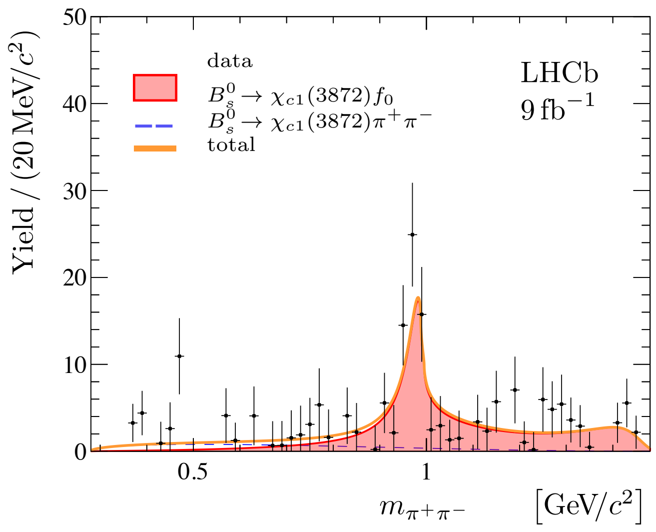


- Fit parameter shared in the simultaneous fit
- Di-pion mass spectrum from $B_s^0 \to \psi(2S)\pi^+\pi^-$ decays decribed → see dominant contribution of 2 S-wave resonances
- Large component $\boldsymbol{B_s^0 \to \chi_{c1}(3872) f_0(980)}$ with significance exceeding 7 standard deviations.

arXiv:2302.10629

Not compatible with phase space only





Exotic Spectroscopy at LHCb

- **Tetraquarks**
  - $B^+ \to J/\psi\phi K^+$ two states : $T_{\psi s1}^{\theta}(4000)^+$ and $T_{\psi s1}(4220)^0$
  - New doubly charged and neutral open charmed tetraquarks observed in $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$
  - New state from the amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

- **Pentaquarks**
  - Strange pentaquark candidate in $B^- \to J/\psi \Lambda \bar{p}$

LHCb naming scheme

We proposed a new exotic hadron naming convention arXiv:2206.15233v1

- ***T*** for tetraquark
- ***P*** for pentaquark
- **superscript**: based on existing symbols, to indicate isospin, parity and G-parity
- **subscript**: heavy quark content

T states zero net S, C, B

(P,G)	$I=0$	$I=1$
$(-,-)$	ω	π
$(-,+)$	η	ρ
$(+,+)$	f	b
$(+,-)$	h	a

T states non-zero net S, C, B

(P)	$I=0$	$I=\frac{1}{2}$	$I=1$
$(-)$	η	τ	π
$(+)$	f	θ	a

P states

$I=0$	$I=\frac{1}{2}$	$I=1$	$I=\frac{3}{2}$
Λ	N	Σ	Δ

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G=1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi 1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon 1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^\Lambda_{\psi s}(4459)^0$	[20]

Evidence of $T_{\psi s1}^{\theta}(4000)^0$ state

Previously $\boldsymbol{B^+ \to J/\psi\phi K^+}$ we observed two states : $\boldsymbol{T_{\psi s1}^{\theta}(4000)^+}$ and $\boldsymbol{T_{\psi s1}(4220)^+}$ Phys. Rev. Lett. **127**, 082001

Here we looked for **the isospin partner decay**, is there a $\boldsymbol{T_{\psi s1}^{\theta}(4000)^0}$ isospin partner in $B^0 \to J/\psi\phi K_S^0$?

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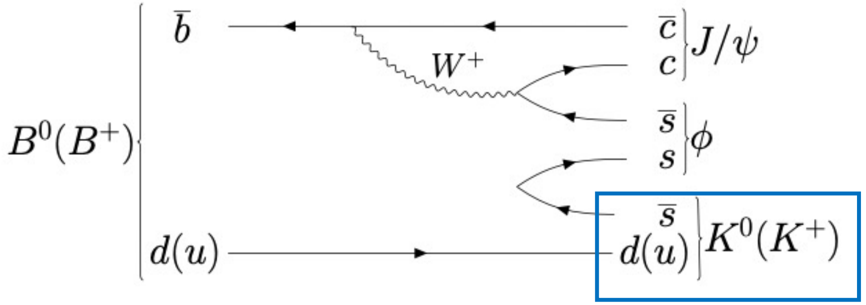
Similar analysis: reconstruct pairs of muons, kaons and pions (+ require long flight distance on the K^0_S)

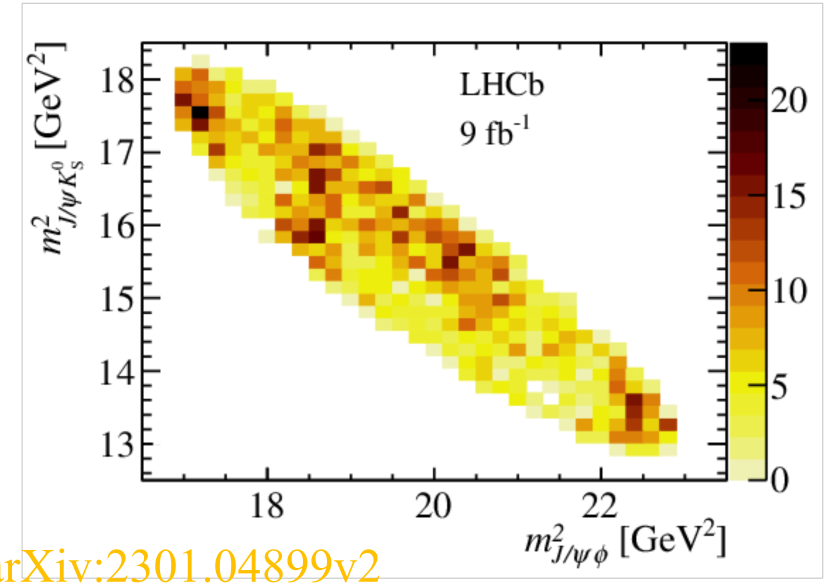
A simultaneous fit on the two modes is performed.

$B^0 \to J/\psi\phi K^0_S$

VS

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





arXiv:2301.04899v2

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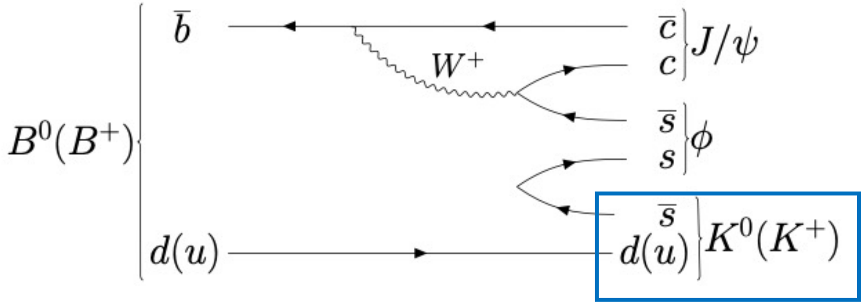
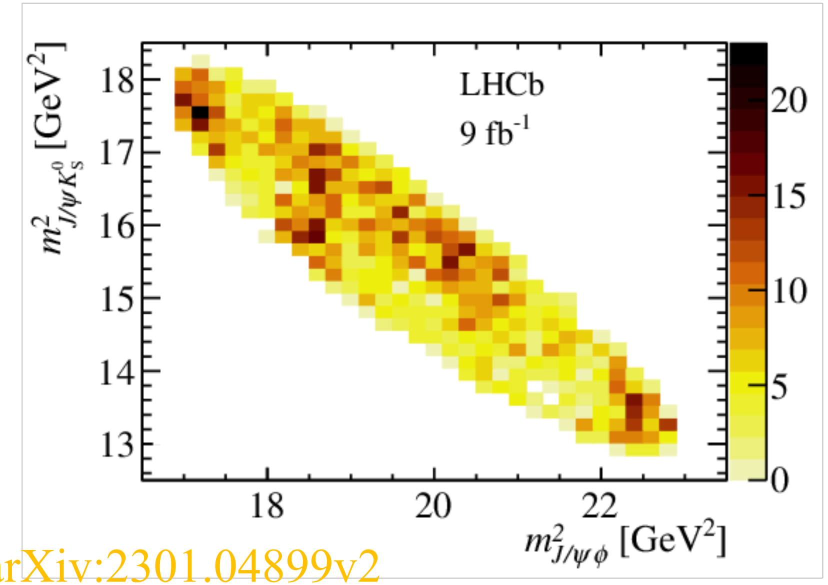




arXiv:2301.04899v2

Default model:

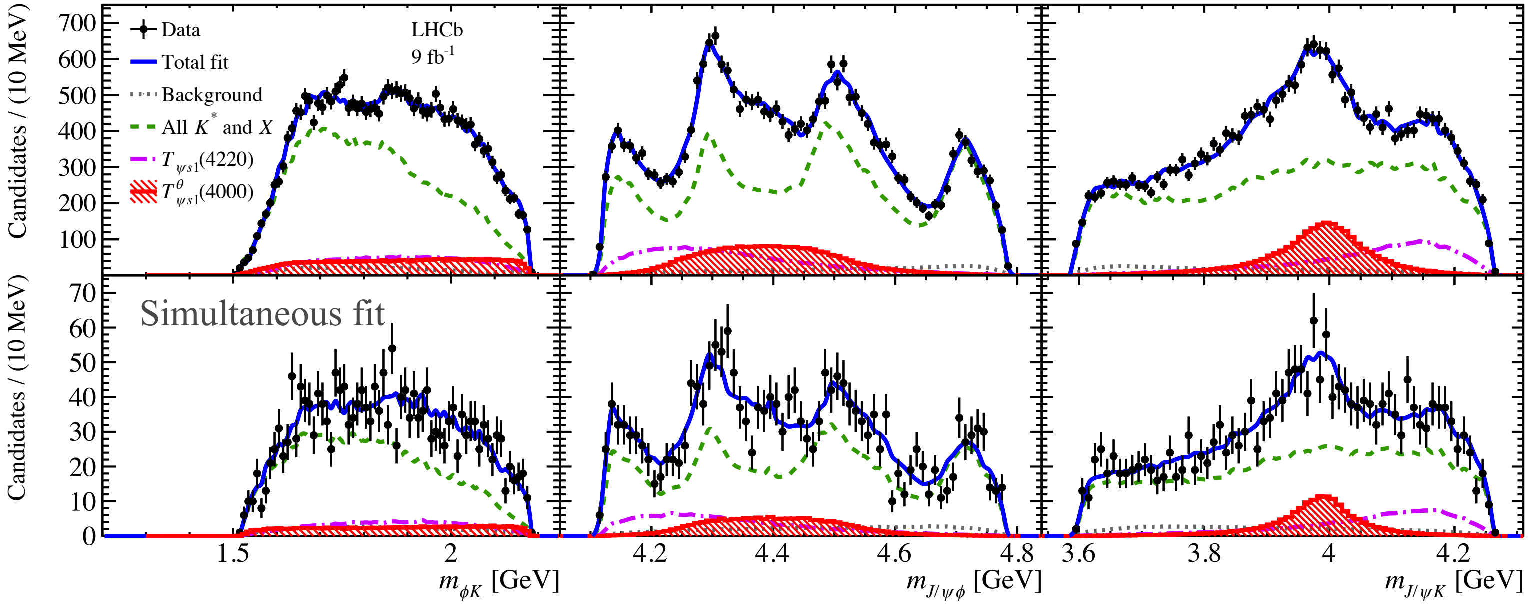
- ➢K^* resonances in (ϕK_S^0) : 9 in total
- ➢X ($\chi_{c\,0,1}$, η_c or $T_{\psi\phi1}^{\eta}$) in $(J/\psi\phi)$: 7 in total
- ➢$T_{\psi s1}^{\theta}$ in $(J/\psi K_S^0)$

Assumption of isospin symmetry→ mass, width and helicity couplings for all the components except $T_{\psi s1}^{\theta}(4000)^0$ constraint to be identical.

<u>$T_{\psi s1}(4220)^0$ constraints to be identical to $T_{\psi s1}(4220)^+$ due to limited size of B^0 sample</u>

Evidence of $T_{\psi s1}^{\theta}(4000)^0$ state

Submitted to PRL



$B^+ \to J/\psi\phi K^+$
and
$B^0 \to J/\psi\phi K_S^0$

Measured mass and width

$$M(T_{\psi s1}^{\theta}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\,\text{MeV}$$
$$\Gamma(T_{\psi s1}^{\theta}(4000)^0) = \ 105\,^{+29}_{-25}\,^{+17}_{-23}\,\text{MeV}$$

- Difference in mass with $T_{\psi s1}^{\theta}(4000)^+$ is small → confirm the isospin partnership $\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}\,\text{MeV}$
- Significance computed with likelihood ratio method with :

$$t \equiv -2\ln[\mathcal{L}(H_0)/\mathcal{L}(H_1)]$$

$H_{0,1}$: default model without or with the new state

- Significance is : **4 σ**, goes up to **5.4 σ** assuming isospin symmetry for the $T_{\psi s1}^{\theta}(4000)$ states

arXiv:2301.04899v2

Doubly charged tetraquark

- **New doubly charged and neutral open charmed tetraquarks** observed in $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ arXiv:2212.02717v1
- Predicted by diquark-antiquark model from X(2900) in $B \to DD^+K^-$

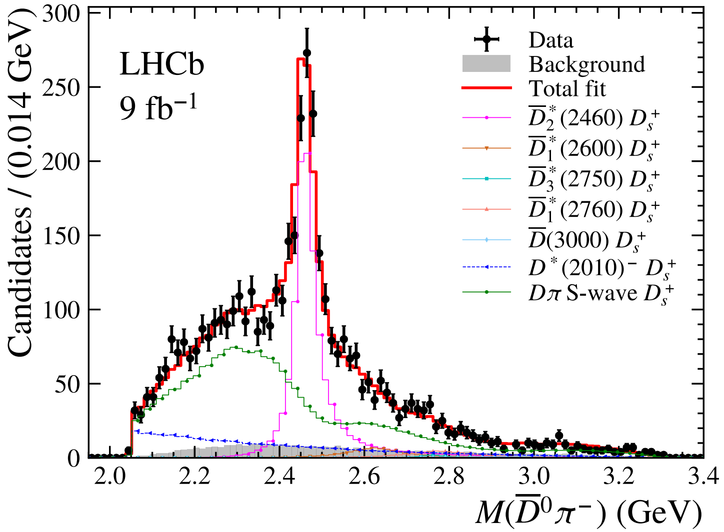
Name	Decay	Content
$T^a_{c\bar{s}0}(2900)^0$	$B^0 \to \bar{D}^0 D_s^+ \pi^-$	$c\bar{s}\bar{u}d$
$T^a_{c\bar{s}0}(2900)^{++}$	$B^+ \to D^- D_s^+ \pi^+$	$c\bar{s}u\bar{d}$

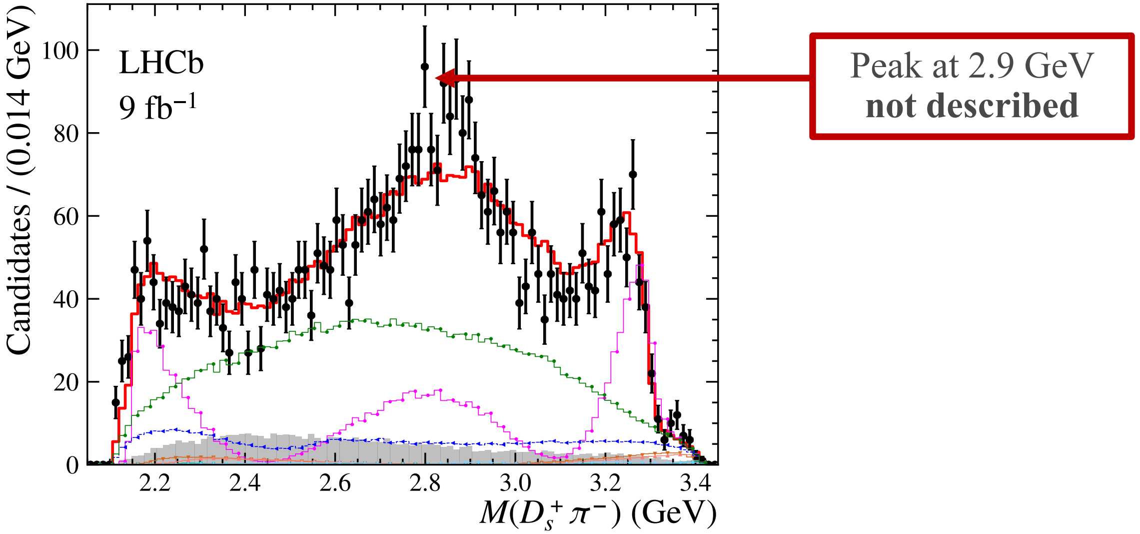
Model:

- Only expect $\bar{D}^*$ resonances
- Spin parity of $\bar{D}(3000)^0$ determined : 4^+
- $\bar{D}\pi$ S-wave with quasi Model Independent splines

Expected resonant content

Resonance	J^P	Mass (GeV)	Width (GeV)	Comments
$\bar{D}^*(2007)^0$	1^-	2.00685 ± 0.00005	$< 2.1 \times 10^{-3}$	Width set to be 0.1 MeV
$D^*(2010)^-$	1^-	2.01026 ± 0.00005	$(8.34 \pm 0.18) \times 10^{-5}$	
$\bar{D}_0^*(2300)$	0^+	2.343 ± 0.010	0.229 ± 0.016	#
$\bar{D}_2^*(2460)$	2^+	2.4611 ± 0.0007	0.0473 ± 0.0008	#
$\bar{D}_1^*(2600)^0$	1^-	2.627 ± 0.010	0.141 ± 0.023	#
$\bar{D}_3^*(2750)$	3^-	2.7631 ± 0.0032	0.066 ± 0.005	#
$\bar{D}_1^*(2760)^0$	1^-	2.781 ± 0.022	0.177 ± 0.040	#
$\bar{D}_J^*(3000)^0$	$?^?$	3.214 ± 0.060	0.186 ± 0.080	# $J^P = 4^+$ is assumed





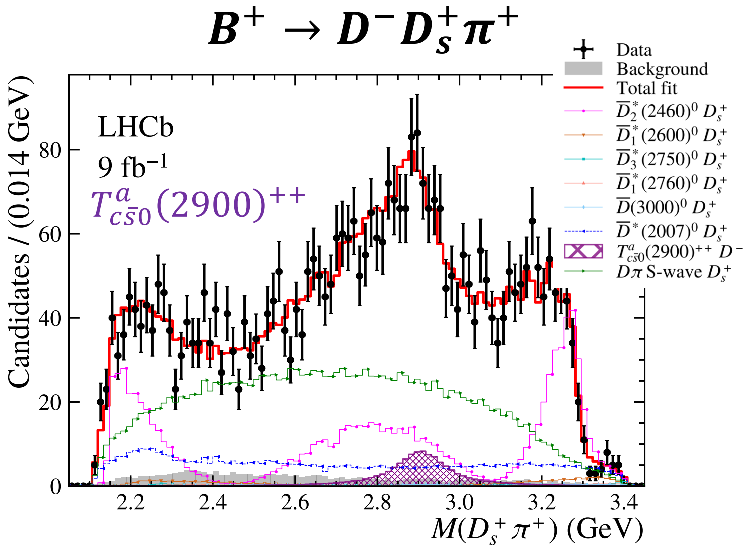
Doubly charged tetraquark

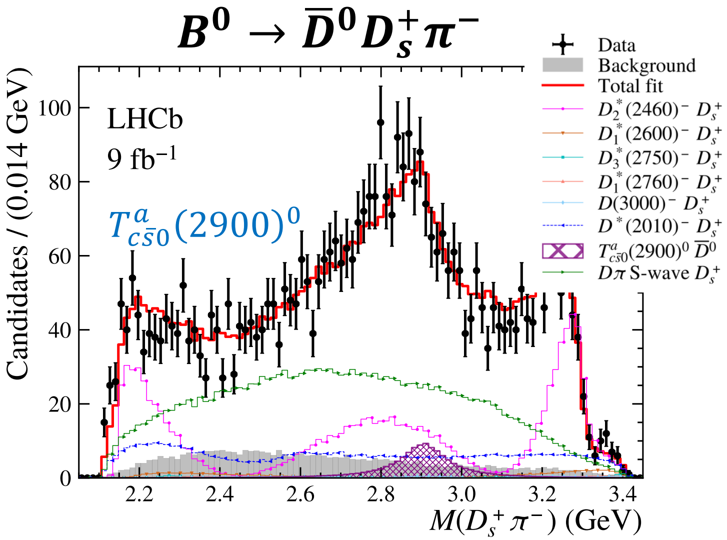
- Simultaneous fit of both channels with isospin relation between two states enforced

arXiv:2212.02717v1

→Model with $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$ preffered

- Fit with only D^* resonances any spin combinations discarded, fit with different masses for the two states compatible results





Particle	Amplitude	Phase	B^0 Fraction (%)	B^+ Fraction (%)
$T^a_{c\bar{s}0}(2900)$	$0.149 \pm 0.031 \pm 0.031$	$-1.26 \pm 0.22 \pm 0.35$	$2.45 \pm 0.65 \pm 0.84$	$2.55 \pm 0.64 \pm 0.83$
$D^*(2007)^0$	$2.58 \pm 0.11 \pm 1.07$	$-3.01 \pm 0.06 \pm 0.31$	–	$14.0 \pm 1.1 \pm 2.7$
$D^*(2010)^-$	$3.05 \pm 0.11 \pm 0.48$	$-2.91 \pm 0.06 \pm 0.28$	$17.0 \pm 1.0 \pm 2.4$	–
$D_2^*(2460)$	1	0	$22.35 \pm 0.76 \pm 0.74$	$22.53 \pm 0.74 \pm 0.54$
$D_1^*(2600)$	$0.218 \pm 0.030 \pm 0.051$	$0.13 \pm 0.16 \pm 0.22$	$1.28 \pm 0.39 \pm 0.60$	$1.32 \pm 0.38 \pm 0.59$
$D_3^*(2750)$	$0.153 \pm 0.032 \pm 0.040$	$-2.80 \pm 0.19 \pm 0.60$	$0.32 \pm 0.15 \pm 0.21$	$0.33 \pm 0.14 \pm 0.20$
$D_1^*(2760)$	$0.119 \pm 0.044 \pm 0.153$	$-0.18 \pm 0.34 \pm 1.01$	$0.26 \pm 0.27 \pm 1.37$	$0.28 \pm 0.26 \pm 1.35$
$D_J^*(3000)$	$1.44 \pm 0.23 \pm 1.15$	$1.40 \pm 0.23 \pm 1.33$	$0.45 \pm 0.16 \pm 0.34$	$0.46 \pm 0.15 \pm 0.33$
$D\pi$ S-wave	$1.142 \pm 0.045 \pm 0.083$	$-0.972 \pm 0.045 \pm 0.084$	$44.9 \pm 1.9 \pm 3.6$	$48.3 \pm 1.8 \pm 3.5$

- Common mass and widths is:

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.013\,\text{GeV}$$

$$T^a_{c\bar{s}0}(2900)^0 : M = (2.892 \pm 0.014 \pm 0.015)\,\text{GeV}$$
$$\Gamma = (0.119 \pm 0.026 \pm 0.013)\,\text{GeV}$$
$$T^a_{c\bar{s}0}(2900)^{++} : M = (2.921 \pm 0.017 \pm 0.020)\,\text{GeV}$$
$$\Gamma = (0.137 \pm 0.032 \pm 0.017)\,\text{GeV}$$

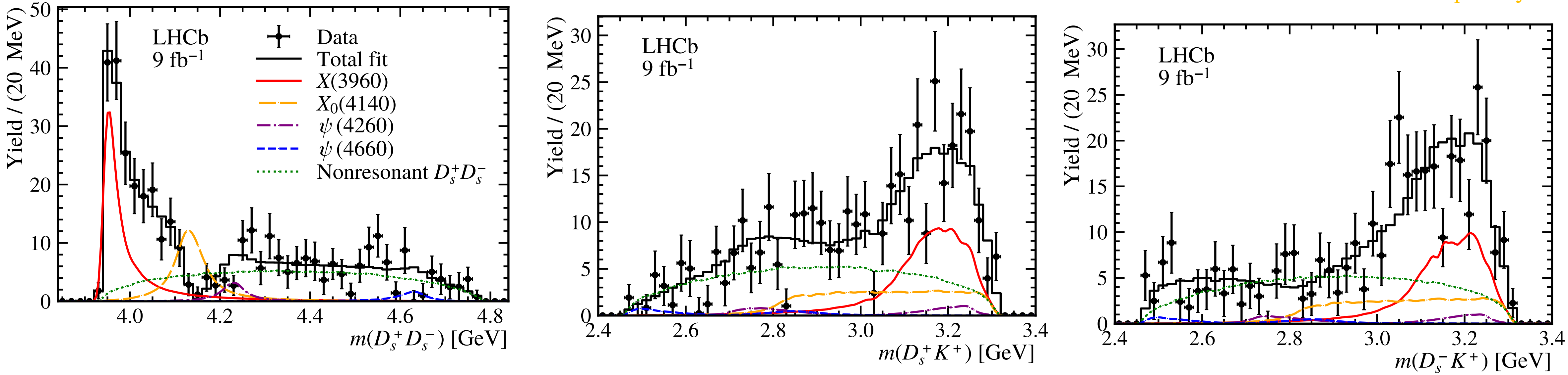
- Significance estimated from $2\Delta LL$

New state has 9 σ
Spin parity: 7.5 σ 0^+ vs 1^-

Observation and amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

- Branching ratio measured: $\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034,$ arXiv:2211.05034 accepted by PRD
- **Observed state: X(3960) with $J^P = 0^{++}$ close to $D_s^+ D_s^-$ threshold**

arXiv:2210.15153 accepted by PRL



Observation and amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

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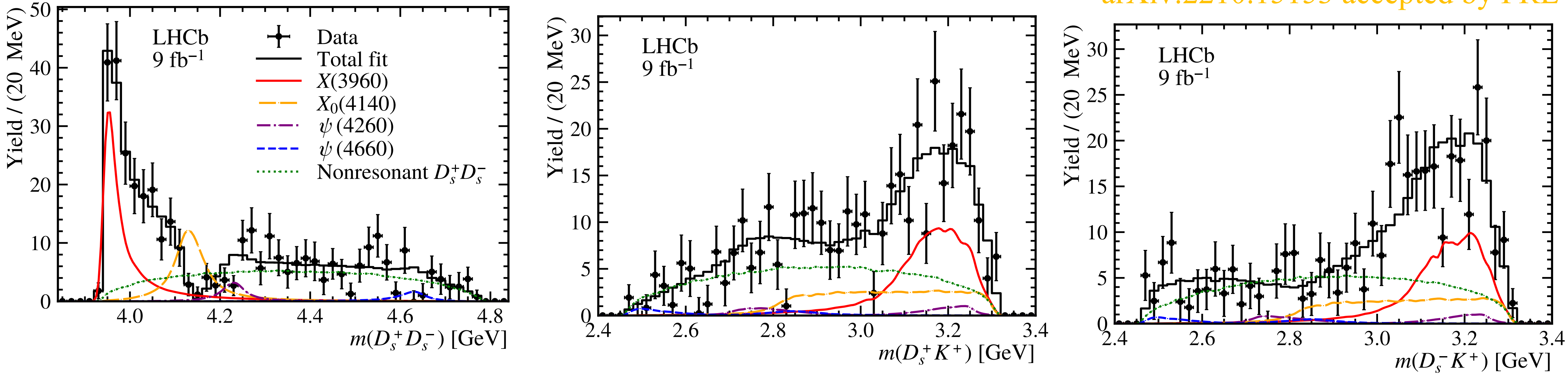
- **Observed state: X(3960) with $J^P = 0^{++}$ close to $D_s^+ D_s^-$ threshold**
- Previously measured $\boldsymbol{\chi_{c0}}$**(3930) in D^+D^- does not fit in** χ_{c0}(2P) [4131–4292 MeV] or χ_{c0}(3P)[3842–3868 MeV] spectrum.
- If $\chi_{c0}(3930)$ and X(3960) are the same particle: $\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = \frac{\mathcal{B}^{(1)} \mathcal{F}_X^{(1)}}{\mathcal{B}^{(2)} \mathcal{F}_X^{(2)}} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$
- If X(3960) had no $s\bar{s}$ content $\Gamma(D^+D^-) >> \Gamma(D_s^+ D_s^-)$ contradicting the ratio above

→either not the same resonance or they are the same non-conventional charmonium-like state [candidate containing the $c\bar{c}s\bar{s}$ dominant constituents]

? → $T_{\psi\phi}^{f}(3960)$

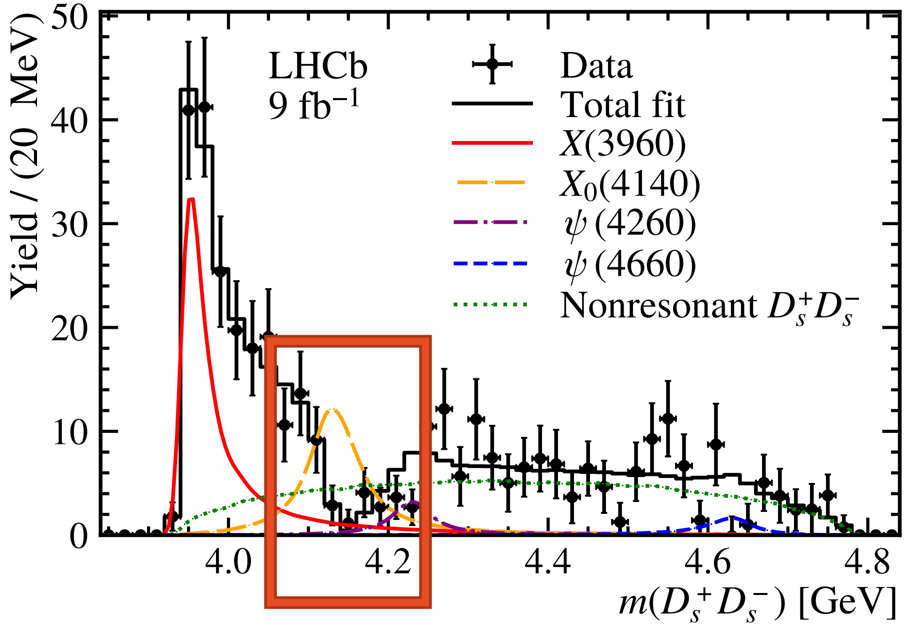
arXiv:2210.15153 accepted by PRL



Observation and amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

- **X(4140)** produces the dip around 4140 MeV via **destructive interference with the 0^{++} NR** and **X(3960) components → with $(-22.4 \pm 6.4)\%$** and **$(-5.2 \pm 3.9)\%$** interference fractions
- If the dip produced by the opening of the nearby **J/ψφ threshold**
  →test with **K matrix** with coupled channels J/ψφ and $D_s D_s$

arXiv:2210.15153 accepted by PRL

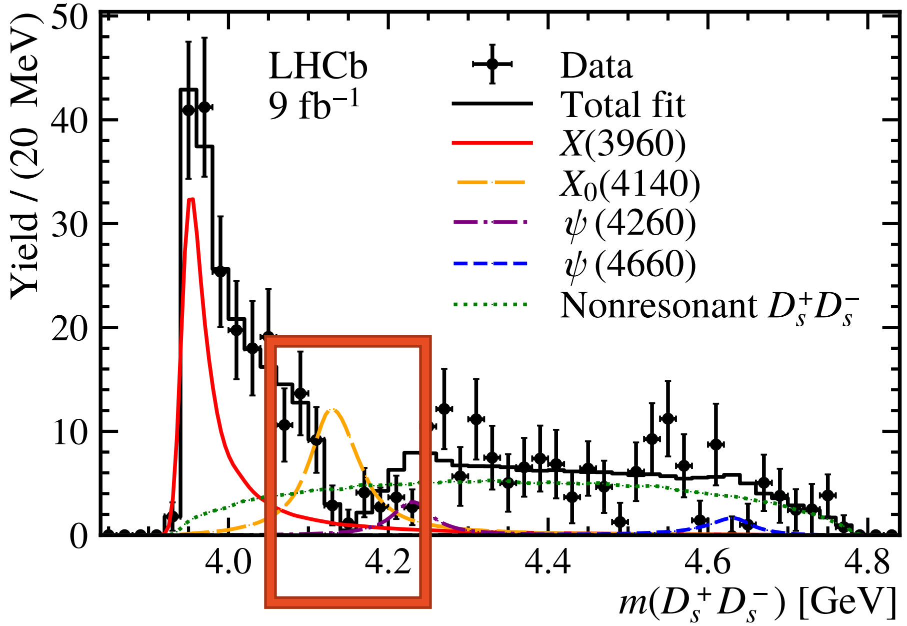


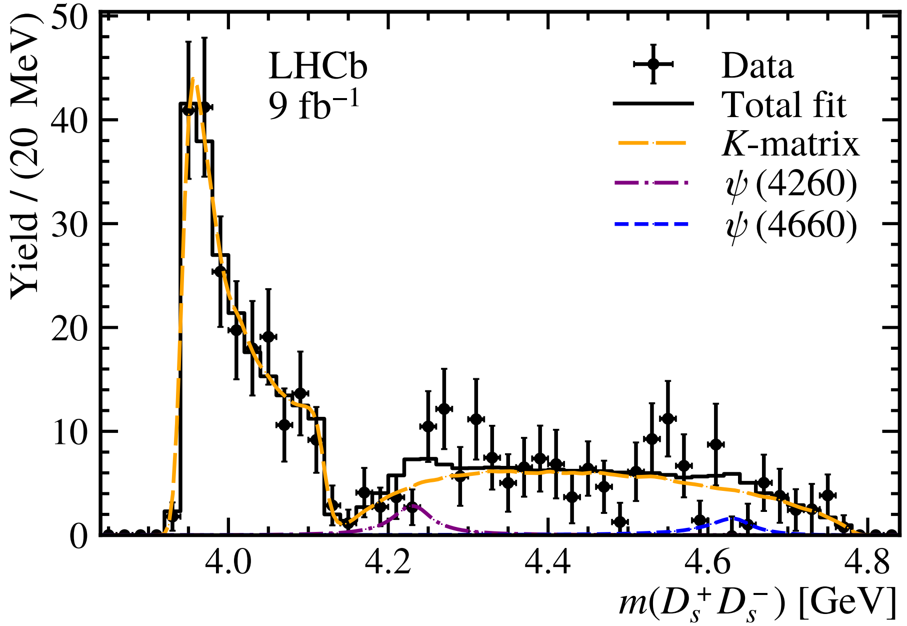
Observation and amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$

- **X(4140)** produces the dip around 4140 MeV via **destructive interference with the 0^{++} NR** and **X(3960) components → with (−22.4 ± 6.4)%** and **(−5.2 ± 3.9)%** interference fractions
- If the dip produced by the opening of the nearby **J/ψφ threshold**
  →test with **K matrix** with coupled channels J/ψφ and $D_s D_s$
- K-matrix parameterisation similar fit quality as baseline model → no strong conclusion whether the dip is due to:
  - destructive interference with the $X_0(4140)$ resonance
  - or caused by the J/ψφ $\to D_s^+ D_s^-$ rescattering.

Need more data to confirm!

arXiv:2210.15153 accepted by PRL





Exotic Spectroscopy at LHCb

- **Tetraquarks**
  - $B^+ \to J/\psi\phi K^+$ two states : $T^{\theta}_{\psi s1}(4000)^+$ and $T_{\psi s1}(4220)^0$
  - New doubly charged and neutral open charmed tetraquarks observed in $B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$
  - New state from the amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$
- **Pentaquarks**
  - Strange pentaquark candidate in $B^- \to J/\psi \Lambda \bar{p}$

Strange pentaquark candidate $P_{\psi s}^{\Lambda}$

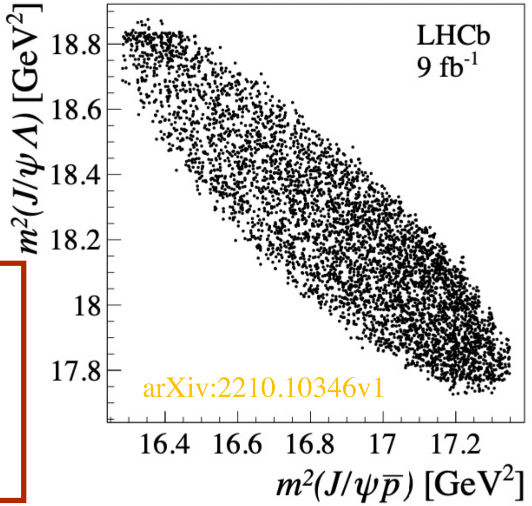
- Amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$
- A new narrow pentaquark state observed
- Close to the mass threshold $\Xi_c^+ D^-$
- **Spin ½** and preferred parity **odd**
- First observation of pentaquark with strange content
- Previous analysis by CMS JHEP12(2019)100

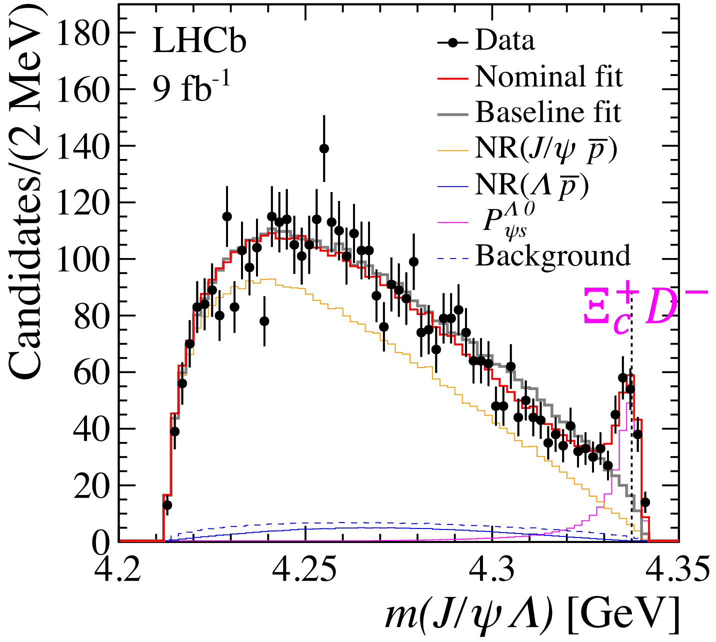
$[c\bar{c}uds]$

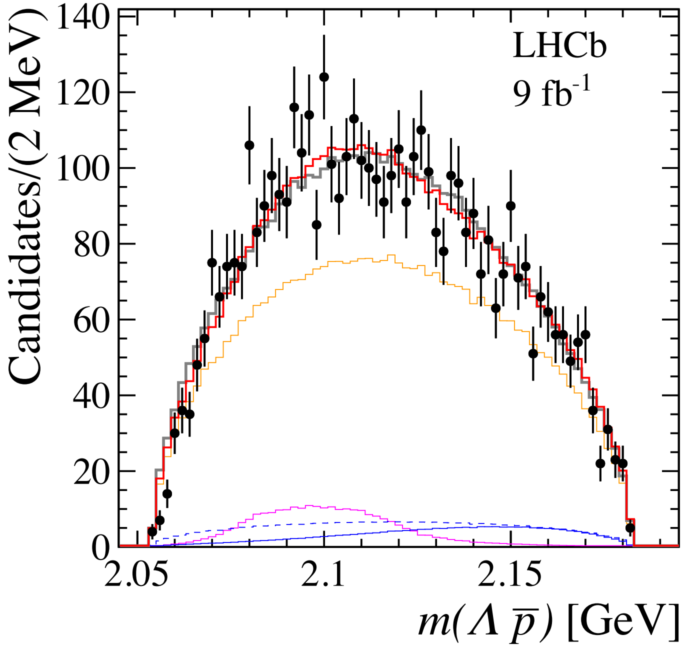
$$M_{P_{\psi s}^{\Lambda}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$
$$\Gamma_{P_{\psi s}^{\Lambda}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$

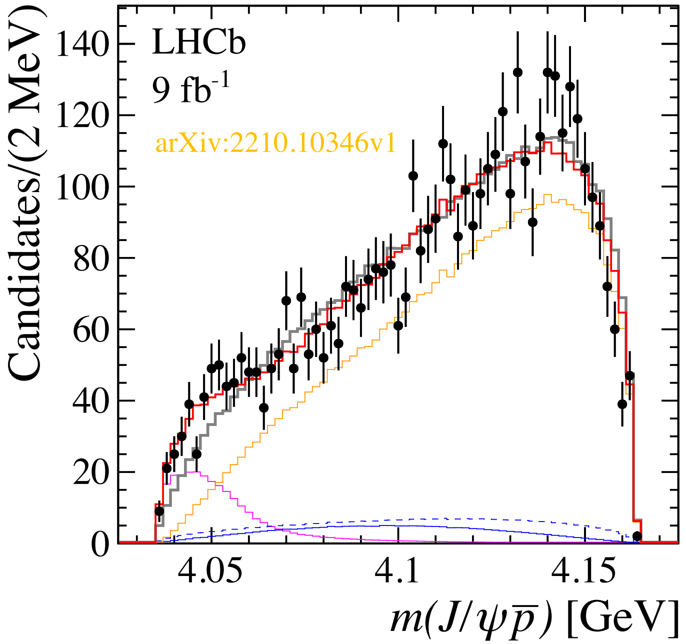
Fit Fractions

$$f_{P_{\psi s}^{\Lambda}} = 0.125 \pm 0.007 \pm 0.019$$
$$f_{\text{NR}(J/\psi\bar{p})} = 0.840 \pm 0.022 \pm 0.014$$
$$f_{\text{NR}(\Lambda\bar{p})} = 0.113 \pm 0.013 \pm 0.017$$









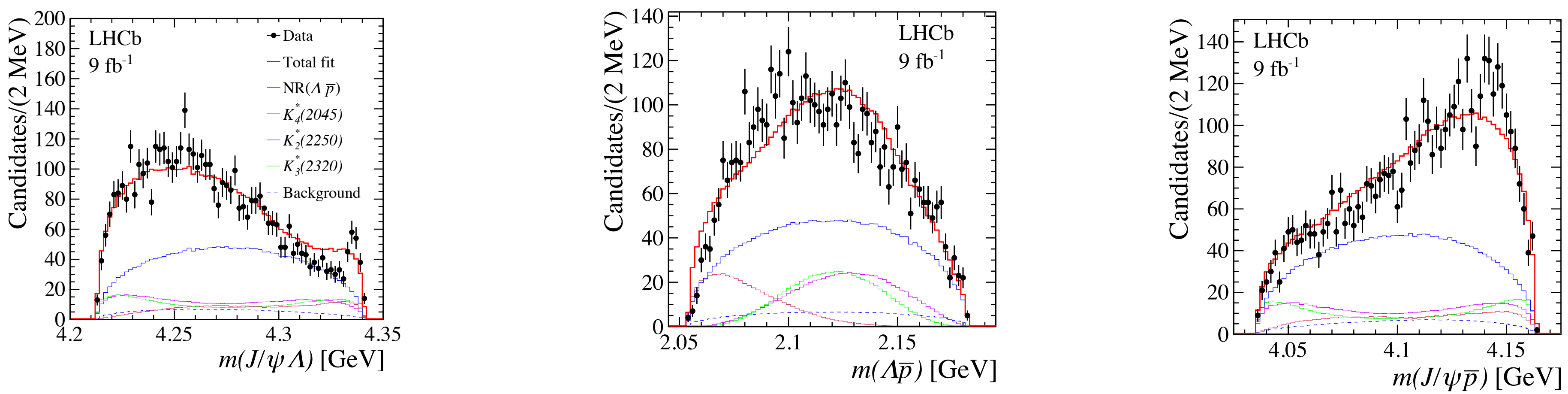
Strange pentaquark candidate $P_{\psi s}^{\Lambda}$

➢ Fit with only the known K* resonances

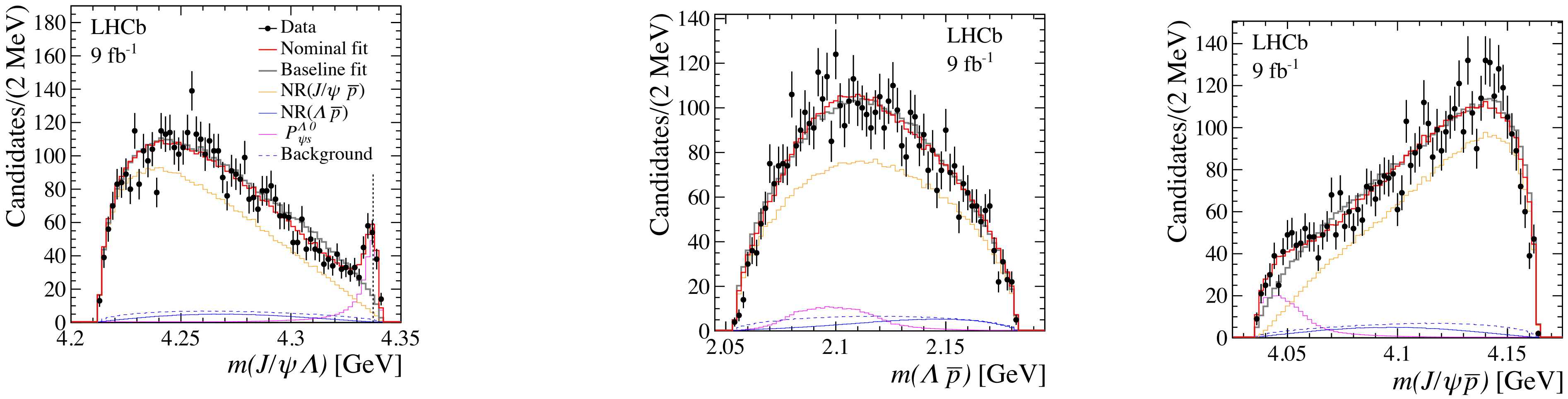
This model does not describe the data well
$\chi^2/\text{ndf} = 123/46$

Resonance	Mass (MeV)	Natural width (MeV)	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

arXiv:2210.10346v1



➢ Nominal fit



Conclusions

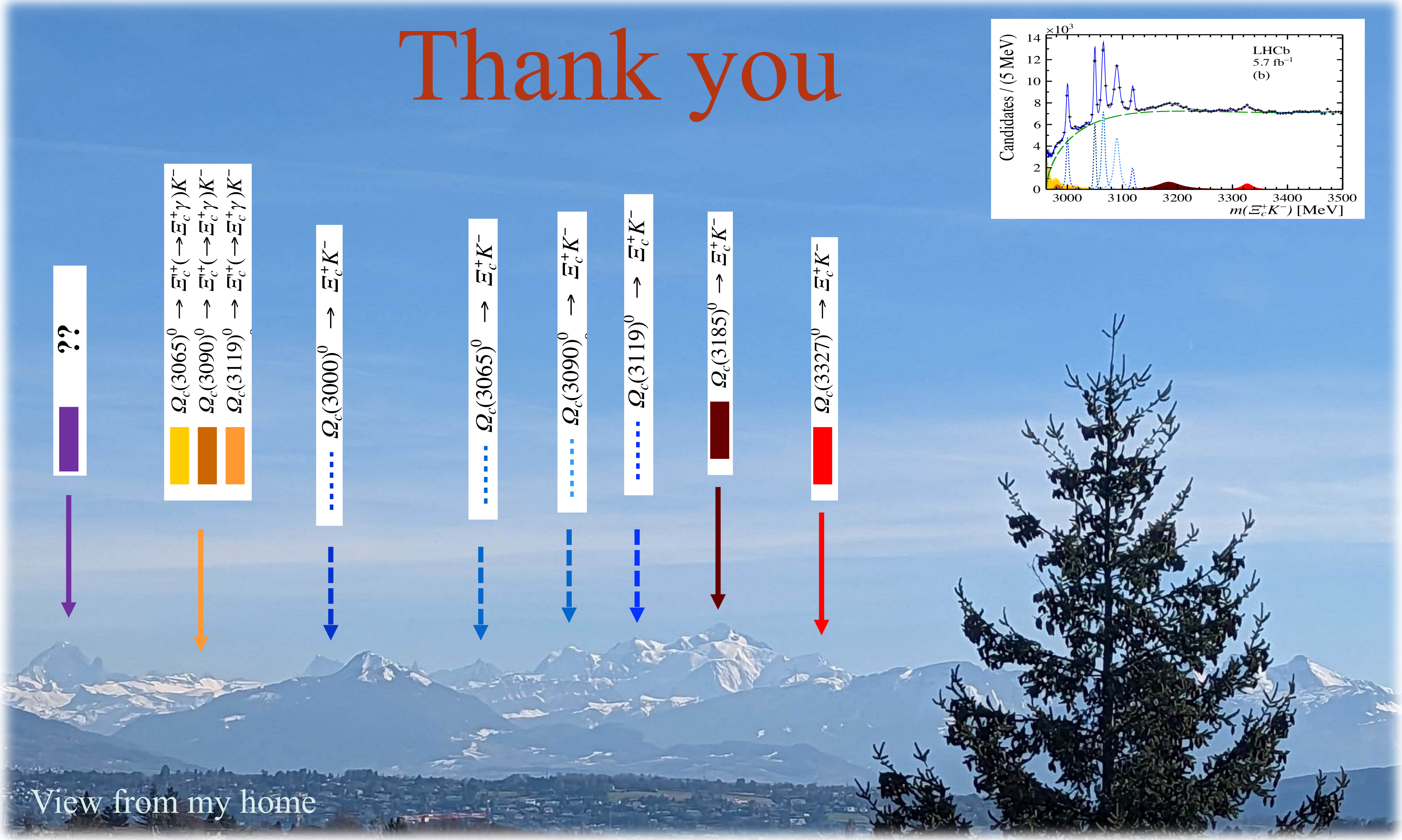
- LHCb leading contributions on conventional and exotic spectroscopy shown today:
  - ✓ New tetraquark and pentaquark candidates shown
  - ✓ New singly and doubly heavy baryons found with high significance
  - ✓ New method for polarization measurement of spin ½ baryons

- Spectroscopy of heavy hadrons is crucial to understand QCD dynamics and binding rules
  → these are valuable inputs for the theory community

- Collaboration theory/experiment is crucial here: need predictions for masses, widths, lifetimes and model to describe/discover exotics.

LHCb Run 3 data will help access decays not yet observed, and more analysis are on-going with LHCb Run1 and Run2 data, so stay tuned!

Thank you

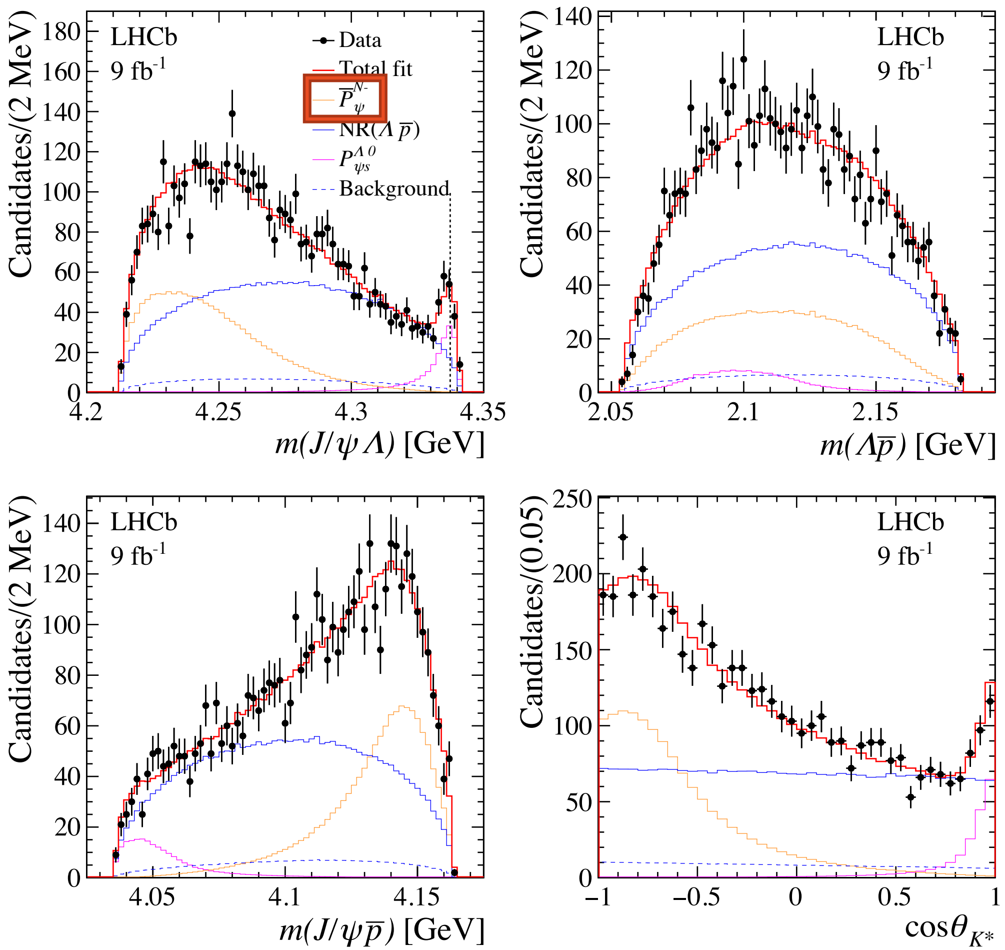


Candidates / (5 MeV)
$\times10^3$
14
12
10
8
6
4
2
0
LHCb
5.7 fb^{-1}
(b)
3000
3100
3200
3300
3400
3500
$m(\Xi_c^+K^-)$ [MeV]
??
$\Omega_c(3065)^0 \to \Xi_c'^+(\to\Xi_c^+\gamma)K^-$
$\Omega_c(3090)^0 \to \Xi_c'^+(\to\Xi_c^+\gamma)K^-$
$\Omega_c(3119)^0 \to \Xi_c'^+(\to\Xi_c^+\gamma)K^-$
$\Omega_c(3000)^0 \to \Xi_c^+K^-$
$\Omega_c(3065)^0 \to \Xi_c^+K^-$
$\Omega_c(3090)^0 \to \Xi_c^+K^-$
$\Omega_c(3119)^0 \to \Xi_c^+K^-$
$\Omega_c(3185)^0 \to \Xi_c^+K^-$
$\Omega_c(3327)^0 \to \Xi_c^+K^-$
View from my home

Stange pentaquark candidate $P_{\psi s}^{\Lambda}$

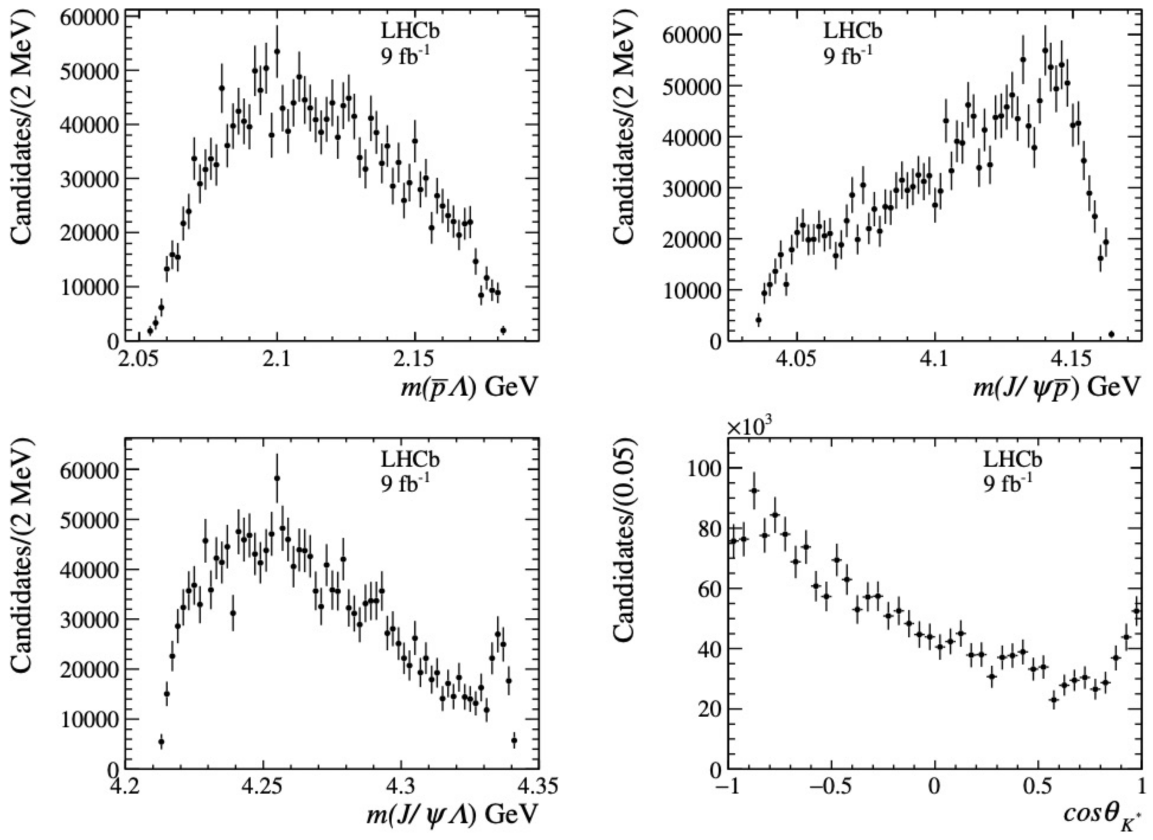
➢Fit with $\bar{P}^{N-}_{\psi}$ contribution

This model is discarded because of an increase in −2 log L around 80



➢Efficiency corrected distributions

arXiv:2210.10346v1

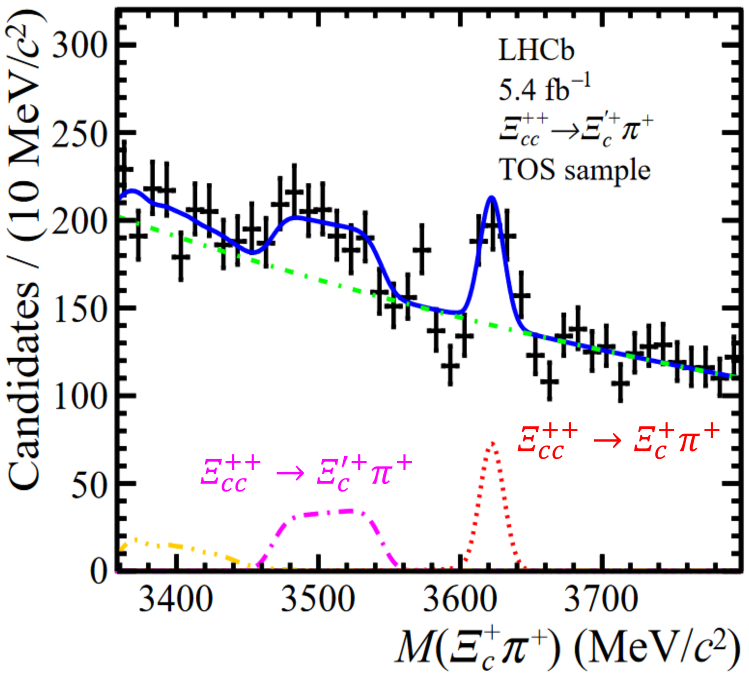


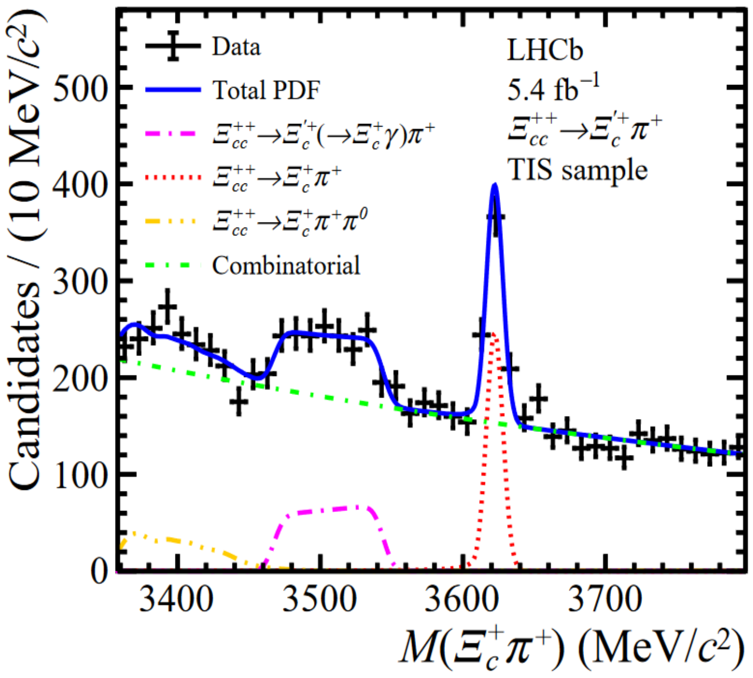
Observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$

Search for $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ and measure branching fraction

- $\Xi_c'^{+} \to \Xi_c^{+}\gamma$, partial reconstructed signal in $m(\Xi_c^{+}\pi^{+})$
- Similar efficiency & comparable production as $\boldsymbol{\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+}}$
- $\frac{B(\Xi_{cc}^{++}\to\Xi_c'^{+}\pi^{+})}{B(\Xi_{cc}^{++}\to\Xi_c^{+}\pi^{+})}$ prediction vary between $\mathbf{0.3 \sim 7}$

1st observation of $\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+}$ with 2016-2018 data, $\mathcal{L}$~5.4 fb^{-1} → statistical significance > 9 σ





JHEP05(2022)038

$$\frac{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c'^{+}\pi^{+})}{\mathcal{B}(\Xi_{cc}^{++} \to \Xi_c^{+}\pi^{+})} = 1.41 \pm 0.17 \pm 0.10.$$

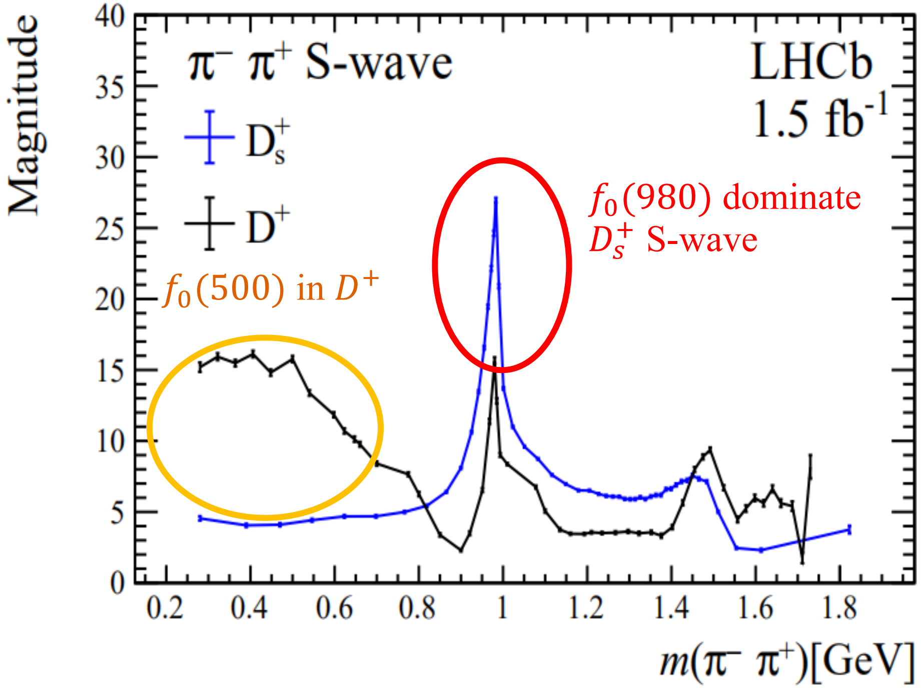
BR is inconsistent with previous theoretical predictions→useful input to improve future calculations

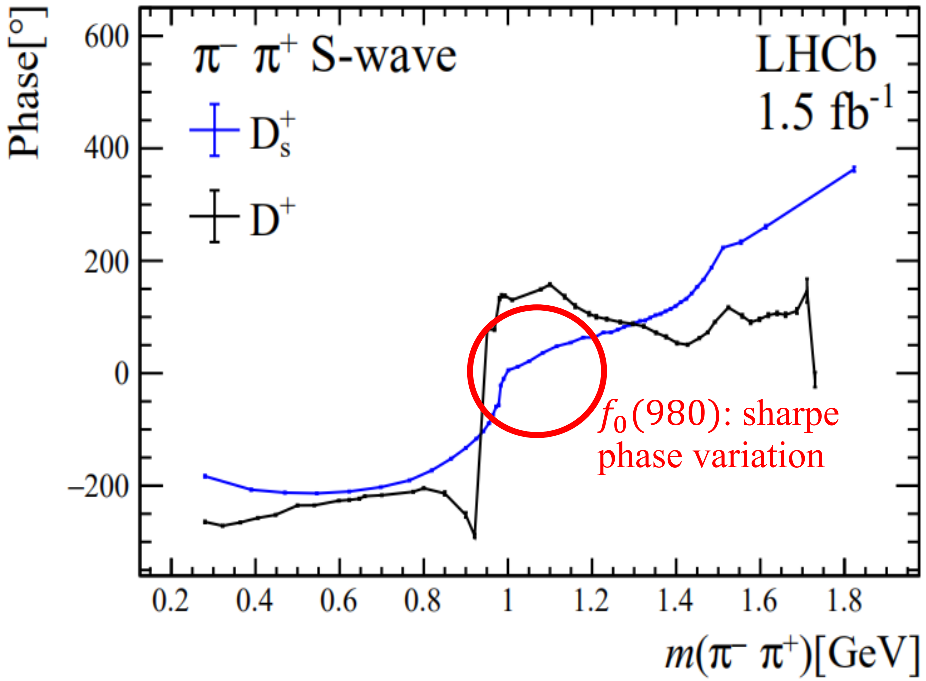
Some examples:

Using light-cone sum rules Yu-ji Shi et.al., PRD 106(2022)034004

With updated spin-flavor structure of $[us]$ in Ξ_c^{+}: Hong-Wei Ke et.al., PRD 105(2022)096011

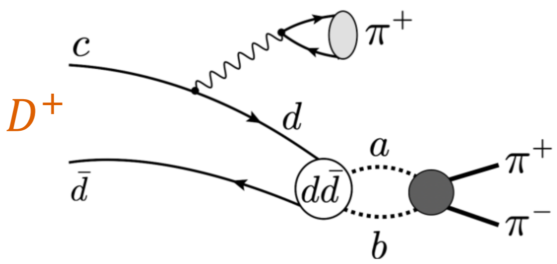
Amplitude analysis $D^+(D_s^+) \to \pi^+\pi^-\pi^+$





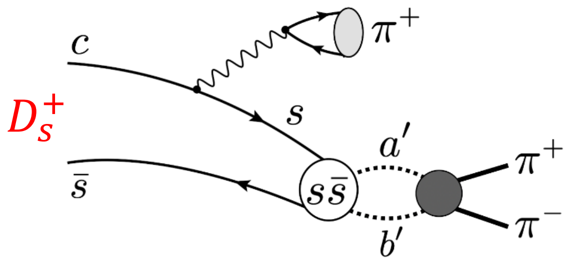
unitary chiral model, Int. J. Mod. Phys. **25**(2016)16300

- Potential interpretation of the difference:



$$\sum_i d\bar{q}_i q_i \bar{d} = \pi^+\pi^- + \frac{1}{2}\pi^0\pi^0 - \frac{2}{\sqrt{6}}\pi^0\eta + K^0\overline{K}^0 + \frac{1}{3}\eta\eta$$

Indicating $f_0(500)$ as dynamical pole of $\pi\pi \to \pi\pi$ rescattering ?



$$\sum_i s\bar{q}_i q_i \bar{s} = K^+K^- + K^0\overline{K}^0 + \frac{1}{3}\eta\eta$$

$f_0(980)$ strongly couples to KK channel

scalar mesons would emerge from the ab ⟶ π+π− scattering