Classical and Exotic Spectroscopy at LHCb

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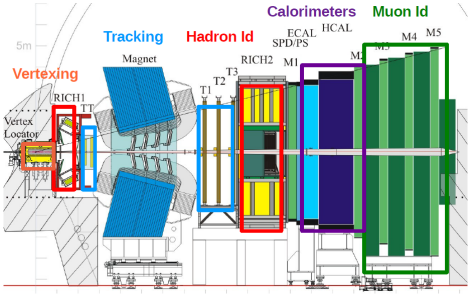
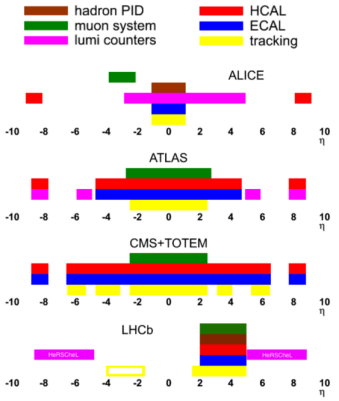
The LHCb detector, Run 1 & 2

- Forward detector fully instrumented in $2 < \eta < 5$
- complementary coverage w.r.t. other LHC experiments
- Excellent tracking, momentum resolution and particle identification



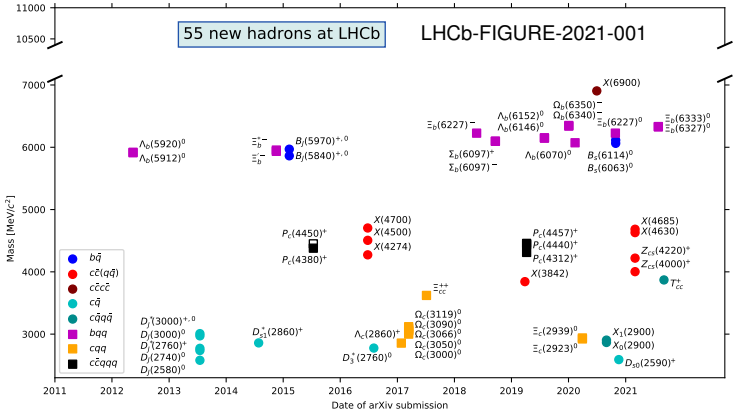


JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

Spectroscopy at LHCb

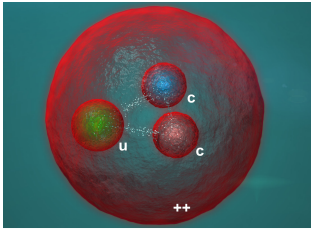
- LHCb primarily designed to study heavy hadron decays

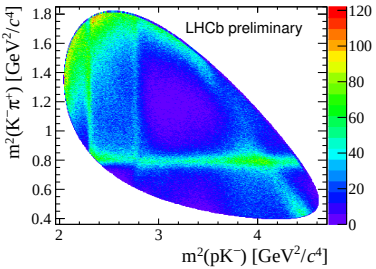
- A real new hadron discovery machine!
  - Conventional (baryons and mesons)
  - Exotic (like tetra/ pentaquarks)
- Major contribution to the hadron taxonomy



Motivation

- Systematic study of hadron production gives info on
  - quark production mechanisms
  - hadron formation from quarks (hadronisation)
  - hadron internal structure
- Important measurements for quantum chromodynamics (QCD), especially at low-energy
  - Discrimination among predictions obtained in different effective low energy QCD approaches
- Detailed study of hadron properties and decays possible at LHCb
  - *e.g.* spin-parity assignments, polarisation, amplitude analyses





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

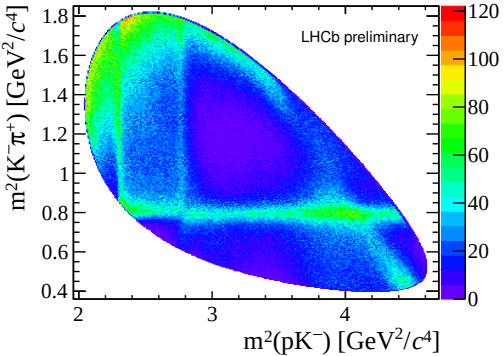
- $\chi_{c1}(3872)$ production in pp collisions at $\sqrt{s} = 8, 13\,\mathrm{TeV}$
- Observation of exotic tetraquark T_{cc}^+ in $D^0 D^0 \pi^+$
- Evidence of new pentaquark structure in $B_s^0 \to p\bar{p}J/\psi$ decays

$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis & polarisation

LHCb-PAPER-2022-002, in preparation

- Full phase-space amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ decays
  - On 400k candidates selected from beauty hadron semileptonic decays
- Amplitude model and polarisation determined simultaneously AHEP (2020) 7463073

- Amplitude model separating resonance contribution in complicated phase space
- First Λ_c^+ polarisation measurement in semileptonic production
  - Probe for baryon production + New Physics tests
- Amplitude model provides Λ_c^+ polarimeter
  - Especially important for systems with smaller datasets

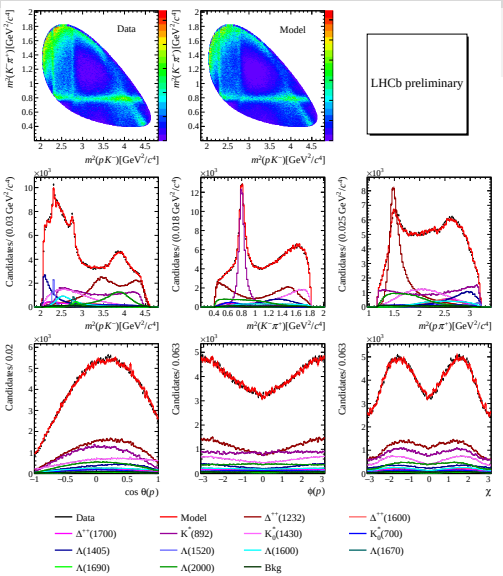


$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis

- Decay model written in terms of helicity amplitudes with general method for matching final particle spin states among different decay chains AHEP (2020) 6674595
- Built amplitude model, measured all parameters

Main contributions	Fit Fraction (%)
$\Delta^{++}(1232)$	$28.60 \pm 0.29 \pm 0.76 \pm 0.16$
$K^*(892)$	$22.14 \pm 0.23 \pm 0.64 \pm 0.04$
$K_0^*(1430)$	$14.7 \pm 0.6 \pm 2.7 \pm 0.1$

Uncertainties divided in statistical, amplitude model choice, systematic



$\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis & polarisation

LHCb-PAPER-2022-002, in preparation

- Large polarisation precisely measured in Λ_c^+ helicity systems
- Normal $\hat{T}$-odd polarisation (P_y) compatible with zero

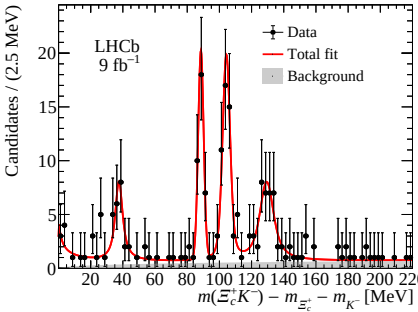
Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x (approx B)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y (approx B)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z (approx B)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

- Established large contribution in $m(pK^-) \approx 2\,\mathrm{GeV}$ region
  - Described as single $J^P = 1/2^-$ state, with Breit-Wigner parameters $m = 1970 \pm 4 \pm 13\ \mathrm{MeV}$ and $\Gamma = 148 \pm 7 \pm 18\ \mathrm{MeV}$
- Closest resonance reported by the PDG is $\Lambda(2000)$

Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

Phys. Rev. D 104 (2021) L091102

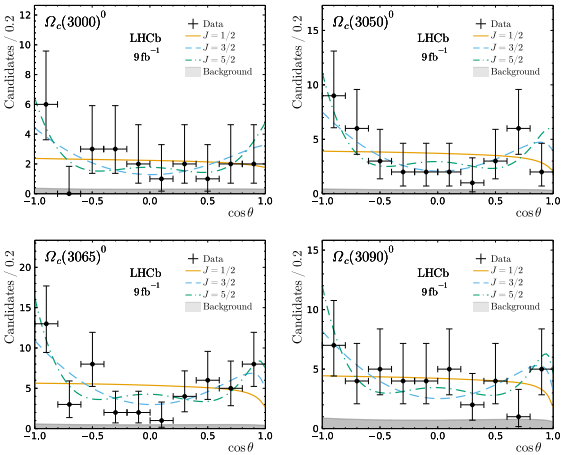
- First observation of $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decay with full LHCb dataset
- Four excited Ω_c^0 baryons observed in $\Xi_c^+ K^-$ mass spectrum
  - $\Omega_c(3000)^0$, $\Omega_c(3050)^0$, $\Omega_c(3065)^0$, $\Omega_c(3090)^0$
  - Previously observed in prompt pp and e^+e^- production
    PRL 118 (2017) 182001, PRD 97 (2018) 051102)
  - Measured mass and widths, with
    $\Gamma_{\Omega_c(3050)^0} < 1.6\ \mathrm{MeV}$ at 95% CL
  - $\Omega_c(3120)^0$ state missing, upper limit given



Observation of excited Ω_c^0 baryons in $\Omega_b^- \to \Xi_c^+ K^- \pi^-$ decays

Phys. Rev. D 104 (2021) L091102

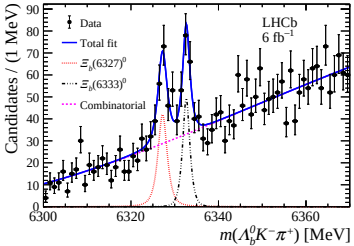
- Threshold enhancement with significance $> 4\sigma$ seen, as in PRD 97 (2018) 051102
  - Interpretation as radiative $\Omega_c(3065)^0$ decay excluded, more data needed to shed light on its nature
- Resonance spin analysed via helicity angle distributions
  - $\frac{1}{2}, \frac{3}{2}, \frac{3}{2}, \frac{5}{2}$ assignment consistent with data
  - $\frac{1}{2}, \frac{1}{2}, \frac{3}{2}, \frac{3}{2}$ assignment rejected at 3.5σ

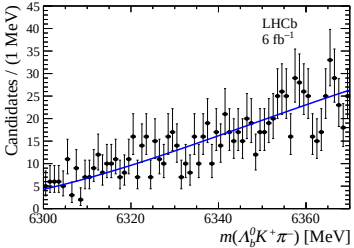


Observation of new excited Ξ_b^0 states in $\Lambda_b^0 K^- \pi^+$

arXiv:2110.04497, submitted to PRL

- Run 2 (2015-18) LHCb data
- New $\Xi_b^0(6327)$, $\Xi_b^0(6333)$ states in $\Lambda_b^0 K^- \pi^+$ mass spectrum, not seen in $\Lambda_b^0 K^+ \pi^-$
  - $m_{\Xi_b^0(6327)} = 6327.28^{+0.23}_{-0.21}(stat) \pm 0.08(syst) \pm 0.24(m_{\Lambda_b^0})\,\mathrm{MeV}$
  - $m_{\Xi_b^0(6333)} = 6332.69^{+0.17}_{-0.18}(stat) \pm 0.03(syst) \pm 0.22(m_{\Lambda_b^0})\,\mathrm{MeV}$
  - $\Delta m = 5.41^{+0.26}_{-0.27}(stat) \pm 0.06(syst)\,\mathrm{MeV}$
- Natural widths consistent with zero
  - $\Gamma_{\Xi_b^0(6327)} < 2.20(2.56)\,\mathrm{MeV}$ at 90(95)% CL
  - $\Gamma_{\Xi_b^0(6333)} < 1.55(1.85)\,\mathrm{MeV}$ at 90(95)% CL
- Two-peak vs no peak significance $> 9\sigma$
- Consistent with doublet of 1D Ξ_b^0 resonances

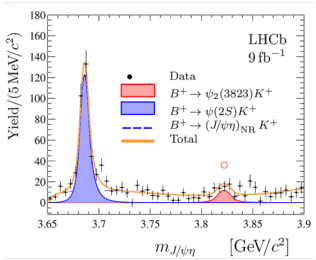


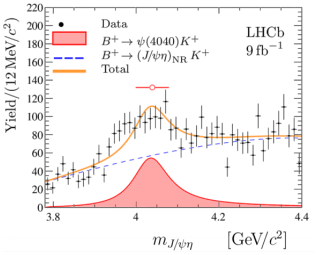


Study of charmonium contributions in $B^+ \to J/\psi\,\eta K^+$

arXiv:2202.04045, submitted to JHEP

- Studied $B^+ \to J/\psi\,\eta K^+$ with $J/\psi \to \mu^+\mu^-$, $\eta \to \gamma\gamma$ with full LHCb dataset
- Investigated $J/\psi\,\eta$ mass spectrum for charmonia and charmonium-like states
- Evidence for $\psi_2(3823)$ and $\psi(4040)$ states
  - Significance of 3.4 and 4.7σ, resp.
- BF ratios w.r.t. $B^+ \to \psi(2S)(\to J/\psi\,\eta)K^+$
  - $F_{\psi_2(3823)} = (5.95^{+3.38}_{-2.55})\%$
  - $F_{\psi(4040)} = (40.6 \pm 11.2)\%$
- Other charmonium(-like) and hypothetical states not seen
  - Upper limit for the C-odd partner of $\chi_{c1}(3872)$ is $F_{X'_c} < 1.9\%$



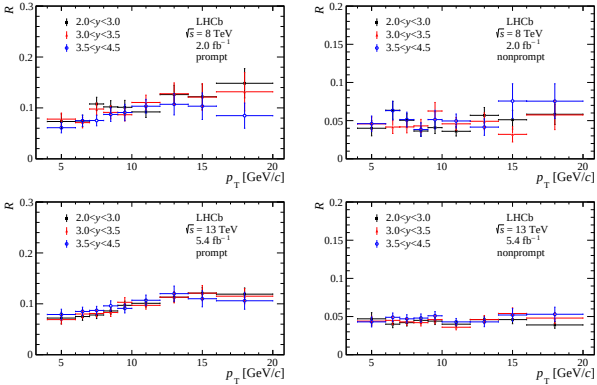


$\chi_{c1}(3872)$ production in pp collisions at $\sqrt{s} = 8, 13\,\mathrm{TeV}$

JHEP 01 (2022) 131

- Exotic $\chi_{c1}(3872)$ structure to be clarified
- Measured differential $pp \to \chi_{c1}(3872)X$ cross-section ratio over $\psi(2S)$ production
- Complements multiplicity-dependent production studied by LHCb PRL 126 (2021) 092001

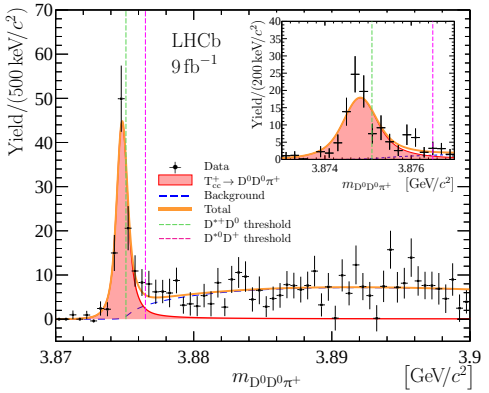
- In prompt pp collisions and from beauty decays (nonprompt)
- 2012 (8 TeV) and 2015-18 data (13 TeV)
- Visible increase of prompt ratio at high p_T, flat behaviour for nonprompt



Observation of exotic tetraquark T_{cc}^{+} in $D^0 D^0 \pi^+$

arXiv:2109.01038; arXiv:2109.01056

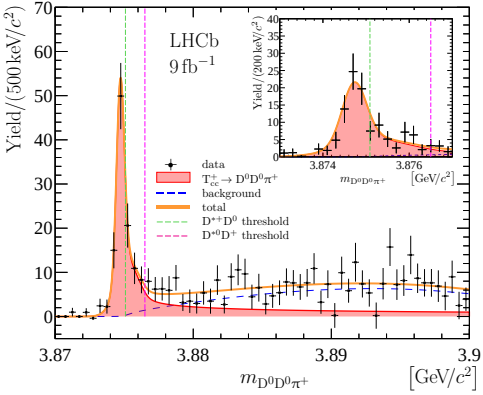
- Very narrow state observed in $D^0 D^0 \pi^+$ mass spectrum, at ≈ 3875 MeV
  - Peak significance of 21.7σ with full LHCb dataset
  - Fit with 2-body Rel. Breit-Wigner
- First double charm tetraquark observed, T_{cc}^{+}
  - minimal quark content $cc\bar{u}\bar{d}$
  - $m_{T_{cc}^{+}} - m_{D^{*+}} - m_{D^0} = -273 \pm 61 \pm 5^{+11}_{-14}$ keV
  - $\Gamma_{T_{cc}^{+}} = 410 \pm 65 \pm 43^{+18}_{-38}$ keV
  - Isoscalar $J^P = 1^+$ ground state
- Close to $D^{*+} D^0$ threshold
  - Significance for below-threshold peak at 4.3σ



Observation of exotic tetraquark T_{cc}^{+} in $D^0 D^0 \pi^+$

arXiv:2109.01038; arXiv:2109.01056

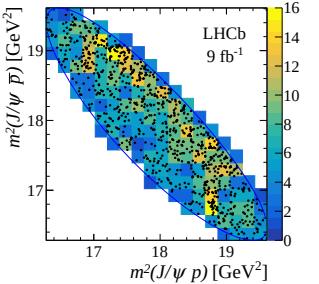
- Properties of new resonance studied using unitarized 3-body BW model
  - Larger tail above $D^{*+} D^0$ threshold w.r.t 2-Body RBW
  - Significance for below-threshold peak at 9σ
- Measured pole parameters, scattering length a and coupling constant $|g|$
  - $\delta m_{pole} = -360 \pm 40^{+4}_{-0}\,\mathrm{keV}$
  - $\Gamma_{pole} = 48 \pm 2^{+0}_{-14}\,\mathrm{keV}$
  - $a = -360 \pm 40^{+4}_{-0}\,\mathrm{keV}$
  - $|g| > 5.1(4.3)\,\mathrm{GeV}$ at 90(95)% CL
- No hint of possible T_{cc}^{0}, T_{cc}^{++} isospin partners
  - Observed T_{cc}^{+} consistent with singlet state

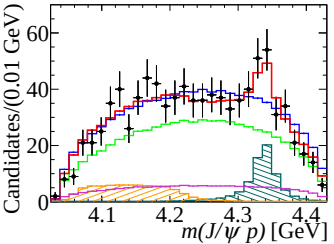


Evidence of new structures in $B_s^0 \to p\bar{p}J/\psi$ decays

Phys. Rev. Lett. 128 (2022) 062001

- Amplitude analysis of flavour-untagged $B_s^0 \to p\bar{p}J/\psi$ decays with full LHCb dataset
- Evidence for new structure in $J/\psi\, p$, $J/\psi\, \bar{p}$ mass spectra
  - $m = 4337^{+7}_{-4} \pm 2\,\mathrm{MeV}$
  - $\Gamma = 29^{+26}_{-12} \pm 14\,\mathrm{MeV}$
- Pentaquark $c\bar{c}uud$ candidate decaying to $P_c^+ \to J/\psi\, p$, $P_c^- \to J/\psi\, \bar{p}$
- Significance $3.1 - 3.7\sigma$ depending on assigned spin-parity
  - J^P indistinguishable with available data
- Differing from P_c states observed in $\Lambda_b^0 \to J/\psi\, pK^-$





Conclusions

- Presented a selection of the latest LHCb results on classical and exotic spectroscopy
  - $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis and Λ_c^+ polarisation measurement
  - Observation of new excited Ω_c^0 and Ξ_b^0 baryons
  - Study of charmonium and $\chi_{c1}(3872)$ contributions
  - New tetra/pentaquark states $T_{cc}^+/P_c^+(4337)$

- Latest findings extend the striking series of hadrons discovered at LHCb
- A wealth of information available for theory community
- The trend is increasing... new hadrons ready for the next harvest?