Recent LHCb results on multiquark states

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on behalf of the LHCb collaboration

Excited QCD 2022 – Giardini Naxos
Sicily, Oct 23-29, 2022

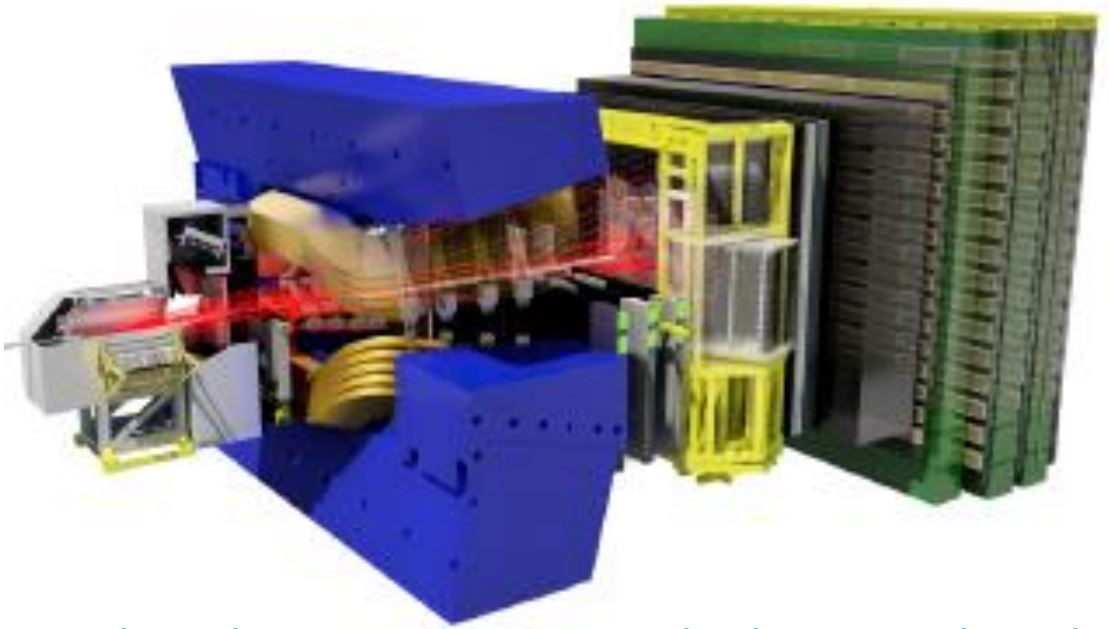
Outline

- Introduction on LHCb experiment
- Recent results on Tetraquarks and Pentaquarks at LHCb
- Prospects and summary

The LHCb experiment at LHC

A forward spectrometer designed for the study of heavy flavour physics

Pseudorapidity coverage: $2 < \eta < 5$, $\eta = -\log(\tan(\theta/2))$
(θ = polar angle relative to the beam line)



[LHCb, JINST 3 (2008) S08005, Int. J. Mod. Phys. A30 (2015) 1530022]

LHCb performance

Precision studies of b and c-hadron decays

Low background
good mass resolution
& particle identification

+

High yields

efficient trigger and selection

Vertexing & Tracking:
$\sigma_p/p \sim 0.4\%$-0.6%
(p from 5 GeV/*c* to 100 GeV/*c*),
$\sigma_{IP} < 20\mu m$

Particle identification:
π/K/p (RICH),
π^0/e/γ (E/HCAL),
μ (MUON)

Trigger L0 hardware,
high p_t *e*/γ/*h*/μ

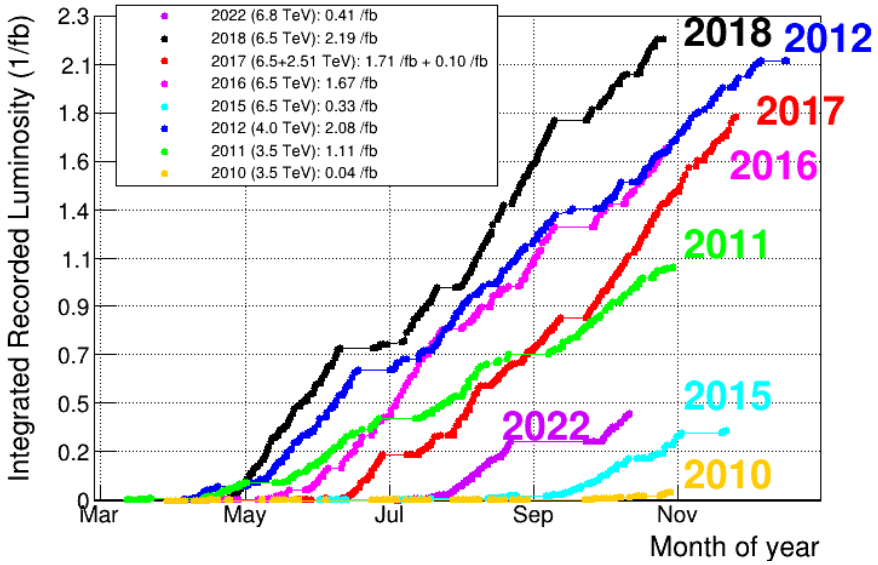
HLT1&HLT2 software,
event reconstruction
~90% efficient for
dimuon channels

LHCb Data Taking

p-p collisions @ LHC
(levelled inst. lumi $\mathcal{L}$~4x10^{32}cm^{-2}s^{-1})

Run 1 (2011-2012): 3 fb^{-1} @ 7-8 TeV
Run 2 (2015-2018): 6 fb^{-1} @ 13 TeV

- More than 9 fb^{-1} accumulated in Run1 + Run 2



$\sigma_{c\bar{c}}$ ~2.4 mb [LHCb, JHEP 1603 (2016) 159]
$\sigma_{b\bar{b}}$ ~110 mb [LHCb, PRL 118 (2017) 052002]
(13 TeV, LHCb acceptance)

- A huge amount of $b\bar{b}$ and $c\bar{c}$ pair have been produced:

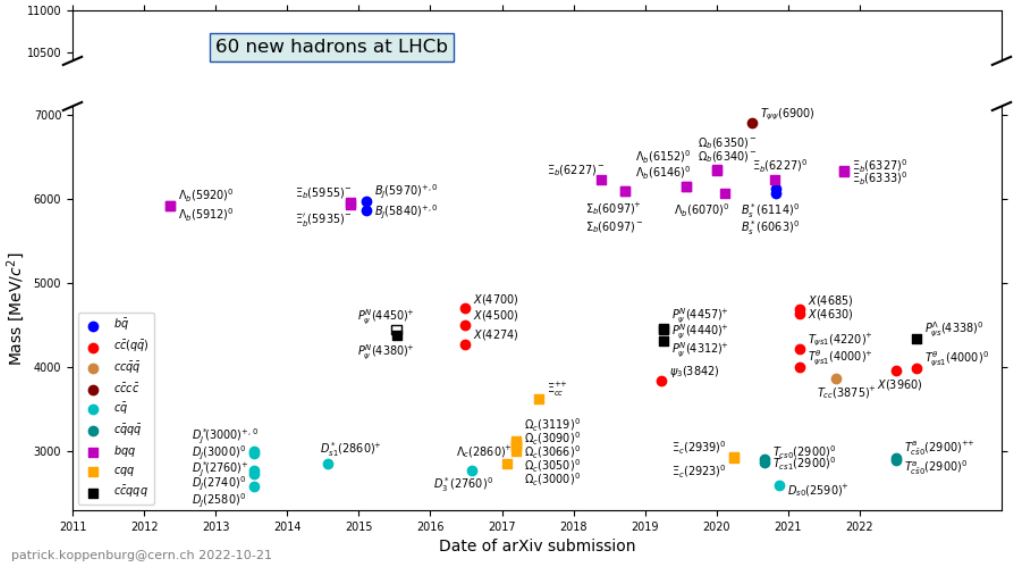
$$\sim 10^{12} b\bar{b}, \sim 10^{13} c\bar{c}$$

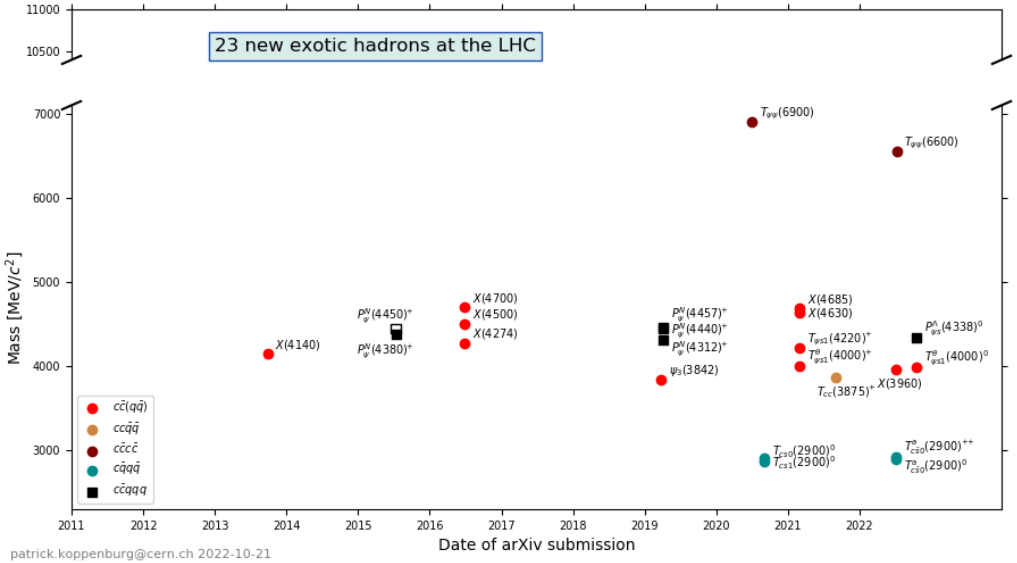
LHCb Physics

- Indirect search for New Physics via precision measurements of CKM, CPV and RD (Lepton Flavour Universality Violation)
- Direct search of new particles beyond SM
- QCD + EW precision measurements at large rapidity
- Heavy-ion and fixed target physics

➢ Hadron spectroscopy:

60 new hadrons at LHCb, 23 new exotic hadrons at LHC


60 new hadrons at LHCb
Mass [MeV/c^2]
Date of arXiv submission
patrick.koppenburg@cern.ch 2022-10-21


23 new exotic hadrons at the LHC
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Exotic hadrons

Search/Observations of exotic states, i.e. Particles with an alternative quark content with respect to conventional mesons (made of quarks-antiquarks pairs) and baryons (made of three quarks).

Hadronic states containing four quarks (tetraquarks) and five quarks (pentaquarks) have been observed/discovered by LHCb during last years.

A discovery of a long-lived exotic state, stable with respect to the strong interactions, would be intriguing.

Tetraquarks at LHCb

- **Study of the doubly charmed tetraquark T_{cc}^+**, LHCb Collaboration, R. Aaij *et al.*, Nature Commun. 13 (2022) 1, 3351
- **Observation of an exotic narrow doubly charmed tetraquark**, LHCb Collaboration, R. Aaij *et al.*, Nature Phys. 18 (2022) 7, 751-754
- **Observation of Multiplicity Dependent Prompt $\chi_{c1}(3872)$ and $\psi(2S)$ Production in pp Collisions**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 126 (2021) 9, 092001
- **Observation of structure in the J/ψ-pair mass spectrum**, LHCb Collaboration, R. Aaij *et al.*, Sci.Bull. 65 (2020) 23, 1983-1993
- **Search for beautiful tetraquarks in the $\Upsilon(1S)\mu^+\mu^-$ invariant-mass spectrum**, LHCb Collaboration, R. Aaij *et al.*, JHEP 10 (2018) 086
- **Dalitz plot analysis of $B^0 \to \overline{D}^0\pi^+\pi^-$ decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.D 92 (2015) 3, 032002
- **Measurement of the resonant and CP components in $\overline{B}^0 \to J/\psi\pi^+\pi^-$ decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.D 90 (2014) 1, 012003
- **Measurement of resonant and CP components in $\bar{B}_s^0 \to J/\psi\pi^+\pi^-$ decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.D 89 (2014) 9, 092006
- **Observation of $\bar{B}_{(s)} \to J/\psi f_1(1285)$ Decays and Measurement of the $f_1(1285)$ Mixing Angle**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 112 (2014) 9, 091802
- **Determination of the $X(3872)$ meson quantum numbers**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 110 (2013) 222001

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Doubly charmed tetraquark

Search for a long-lived exotic state

A hadron with two heavy quarks and two light antiquarks can be a good candidate (1)

The observation of the Ξ_{cc}^{++} baryon containing two *c* quarks [LHCb: Phys. Rev. Lett. 119 (2017) 112001, Phys. Rev. Lett. 121 (2018) 162002, J. High Energy Phys. 02 (2020) 049] stimulated the search of a tetraquark with mass close to the sum of the masses of the D^0 and D^{*+} mesons (2)

(1) A.V. Manohar and M. B. Wise, Nucl. Phys. B399 (1993) 17-33, L. Heller and J.A. Tjon, Phys. Rev D35 (1987) 969-974

(2) M. Karliner and J. L. Rosner, Phys. Rev. Lett. 119 (2017) 202001

Search in the D^0 $D^0\pi^+$ mass spectrum

p-p collision data at centre of mass energies of 7, 8, 13 TeV

Full Run1+Run2 sample: integrated Luminosity of 9 fb^{-1}

Selection of events with two good quality D^0 candidates

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

combined with good quality π^+ candidates and requiring that all originate from the same primary vertex (kinematic fit on the D^0 $D^0\pi^+$ system).

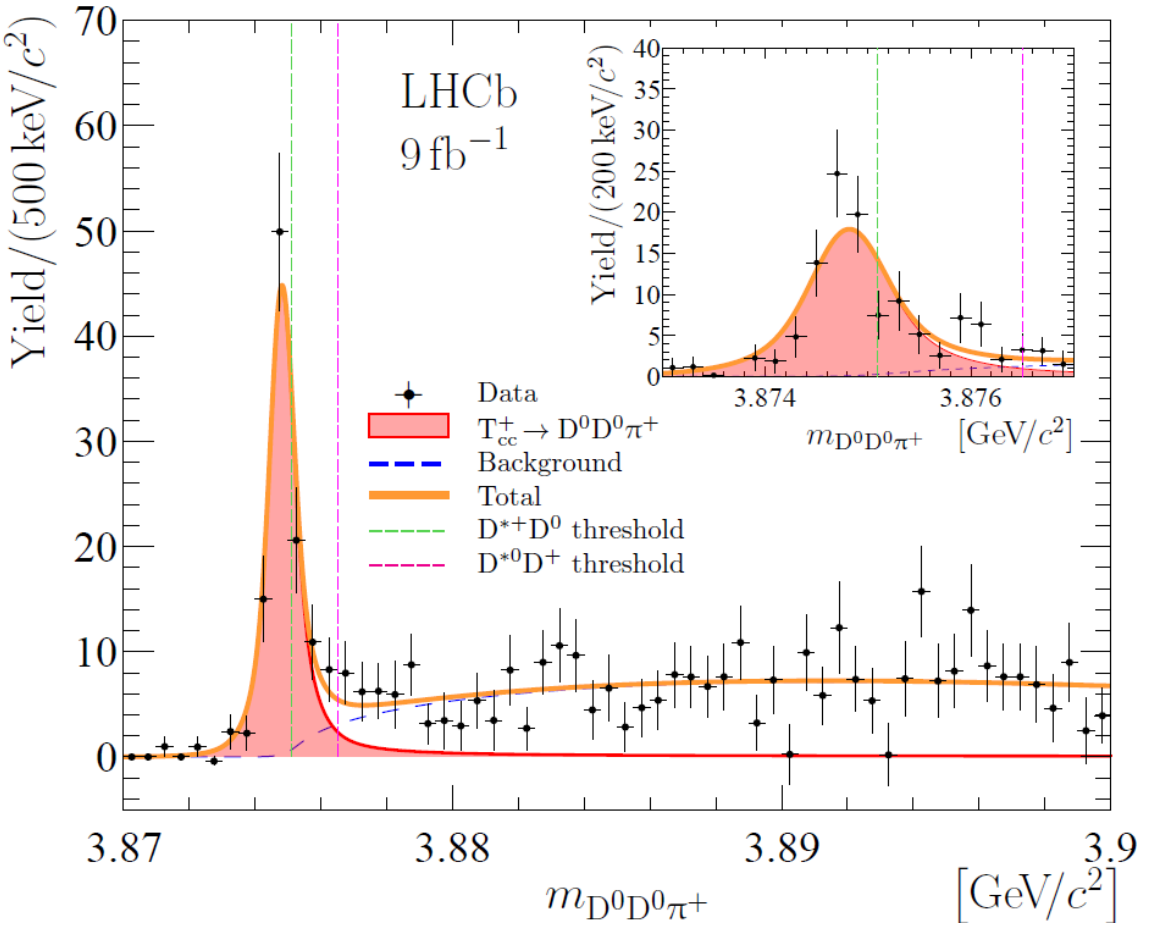
Mass of each D^0 candidate constrained to the known value (improve mass resolution)

Observation of $T^+_{cc} \to D^0 D^0 \pi^+$

Narrow peak near $D^{*+}D^0$ mass threshold

Maximum-likelihood fit:

Signal (convolution of the detector resolution assumed gaussian with a resonant shape relativistic P-wave BW) +
Background (two-body phase space above $D^{*+}D^0$ mass and a positive-second order polynomial)



LHCb, Nature Commun. 13 (2022) 1, 3351

Study of T^+_{cc} state

LHCb, Nature Commun. 13 (2022) 1, 3351

Location of the peak relative to the $D^{*+}D^0$ mass threshold:

$$\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14} keV\, c^{-2}$$

statistical systematic related to the assignment of J^p

$$\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38} keV$$

Consistent with a T^+_{cc} tetraquark ground state with $J^p=1^+$

Narrowest exotic state observed to date, mass = 3,875 MeV

Minimal quark content is: $cc\bar{u}\bar{d}$

Double-charged tetraquark

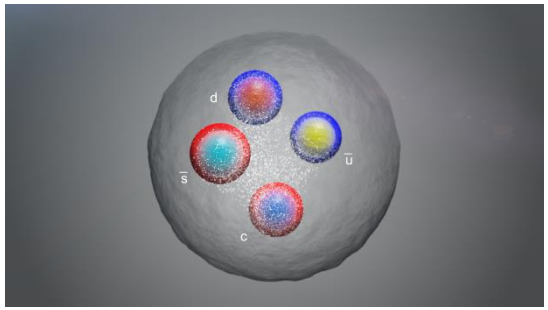
LHCb-PAPER-2022-026

First observation of a doubly charged open-charm tetraquark state $T(2900)^{++}$

and its isospin partner $T(2900)^{0}$ (paper in preparation)

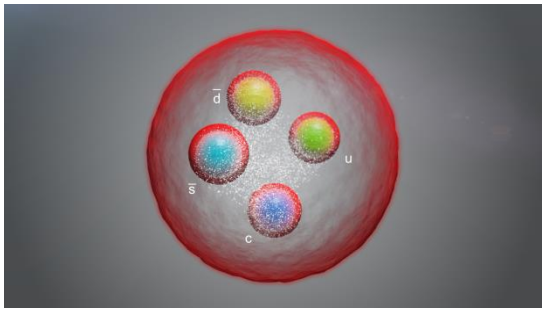
Joint analysis of $B^0 \to D^0 D_s^+ \pi^-$

and $B^+ \to D^- D_s^+ \pi^+$

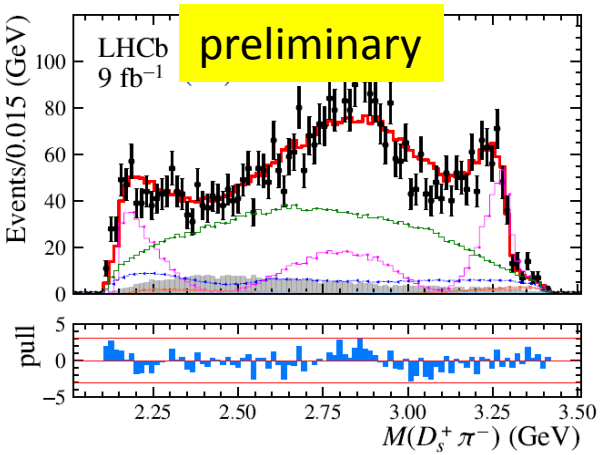


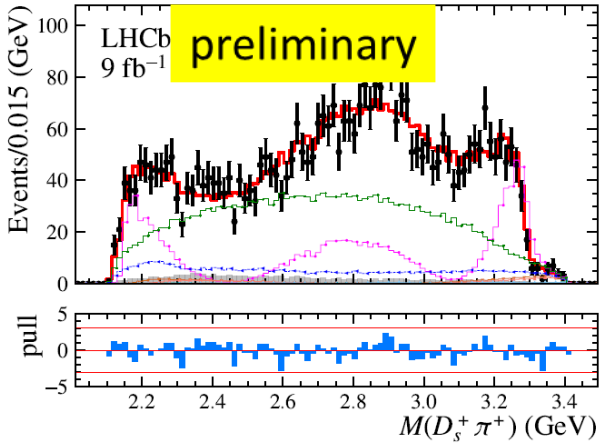
$c\bar{s}u\bar{d}$

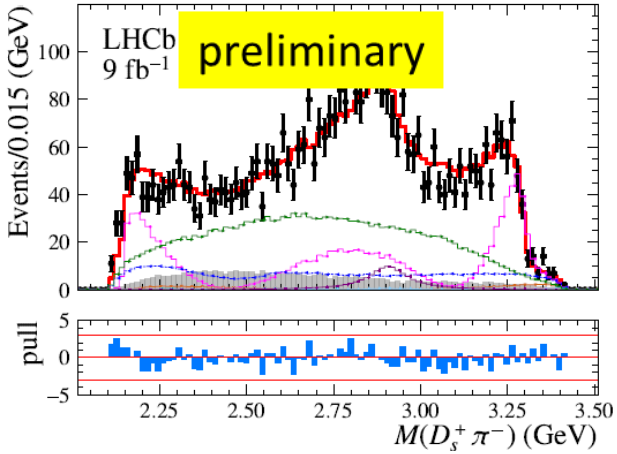
$c\bar{s}\bar{u}d$

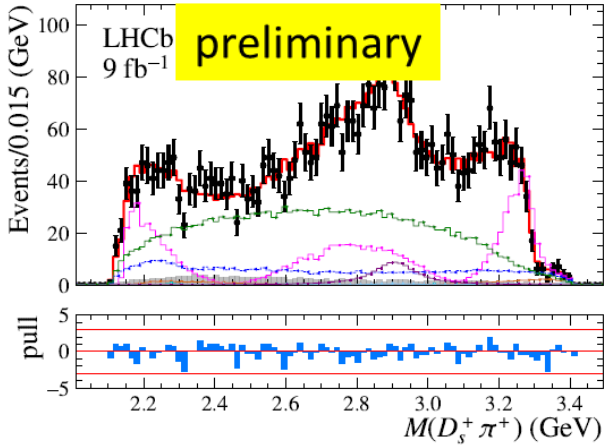


$D_s^+\pi^+$ and $D_s^+\pi$ mass spectra









LHCb-PAPER-2022-026, LHCb-PAPER-2022-027

Pentaquarks at LHCb

- **Evidence for a new structure in the $J/\psi p$ and $J/\psi\overline{p}$ systems in $B_s^0 \to J/\psi p\overline{p}$ decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 128 (2022) 062001
- **Evidence of a $J/\psi\Lambda$ structure and observation of excited Ξ^- states in the $\Xi_b^- \to J/\psi\Lambda K^-$ decay**, LHCb Collaboration, R. Aaij *et al.*, Sci.Bull. 66 (2021) 1278-1287
- **Observation of the $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay**, LHCb Collaboration, R. Aaij *et al.*, Phys.Lett.B 815 (2021) 136172
- **First observation of the decay $\Lambda_b^0 \to \eta_c(1S)pK^-$**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.D 102 (2020) 11, 112012
- **Observation of a narrow pentaquark state, $P_c(4312)^+$, and of two-peak structure of the $P_c(4450)^+$**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 122 (2019) 22, 222001
- **Observation of the decay $\Lambda_b^0 \to \Lambda_c^+ p\overline{p}\pi^-$**, LHCb Collaboration, R. Aaij *et al.*, Phys.Lett.B 784 (2018) 101-111
- **Search for weakly decaying b-flavored pentaquarks**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.D 97 (2018) 3, 032010
- **Evidence for exotic hadron contributions to $\Lambda_b^0 \to J/\psi p\pi^-$ decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 117 (2016) 8, 082003, Phys.Rev.Lett. 117 (2016) 10, 109902 (addendum), Phys.Rev.Lett. 118 (2017) 119901 (addendum)
- **Model-independent evidence for $J/\psi p$ contributions to $\Lambda_b^0 \to J/\psi pK^-$ decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 117 (2016) 8, 082002
- **Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \to J/\psi K^- p$ Decays**, LHCb Collaboration, R. Aaij *et al.*, Phys.Rev.Lett. 115 (2015) 072001

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Pentaquarks in $J/\psi p$ system

Search for pentaquarks in(*)

$$B_s^0 \to J/\psi p \bar{p}$$

p-p collision data at centre of mass energies of 7, 8, 13 TeV
Full Run1+Run2 sample: integrated Luminosity of 9 fb^{-1}

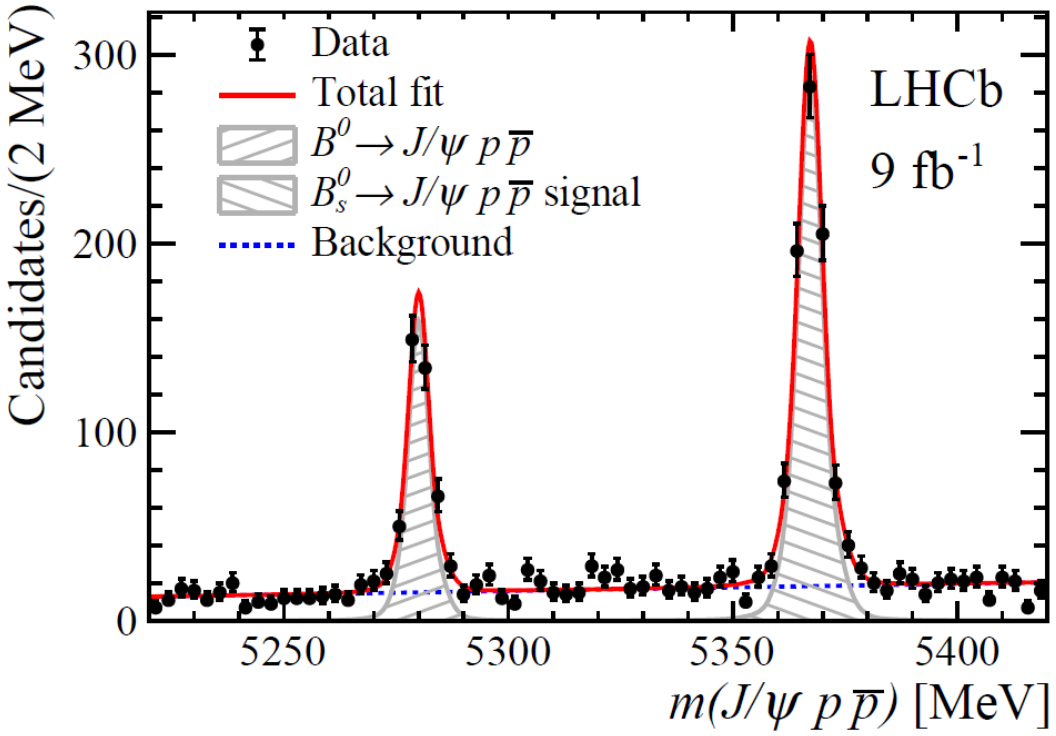
Selection of events with two pairs of oppositely charged tracks:

- first pair consistent with muons from J/ψ decay
- second pair identified as protons

Common vertex significantly displaced from its associated primary *p-p* vertex (PV)

(*) Observed for the first time by LHCb: Phys. Rev. Lett. 122 (2019) 191804

B^0 and B^0_s mass spectra



B^0_s signal decay from fit:

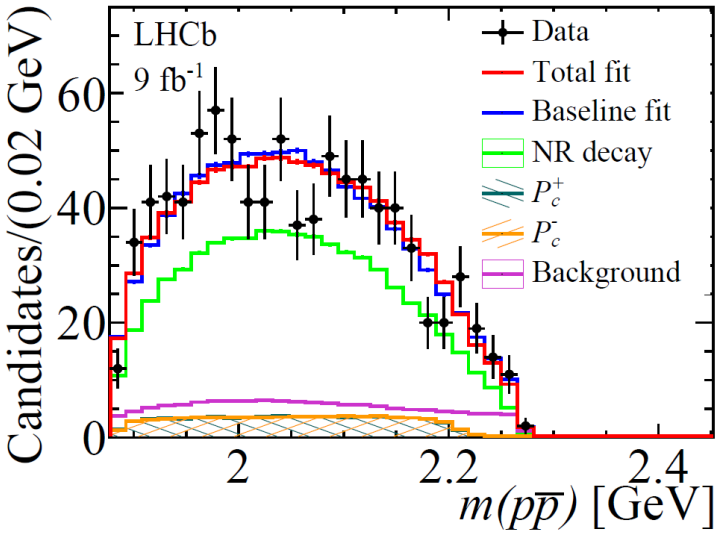
797 +/- 31 events

Backgound
3σ around mass peak:

(14.9 +/- 0.6)%

LHCb, Phys. Rev. Lett. 128 (2022) 062001

Analysis of B^0_s signal

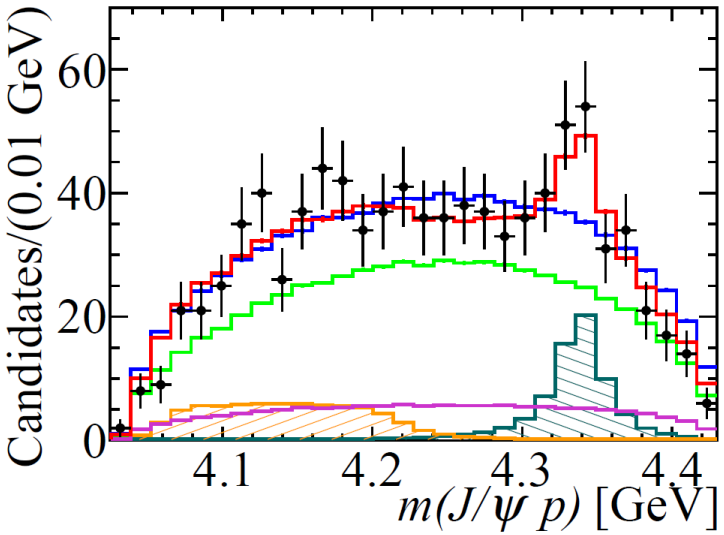


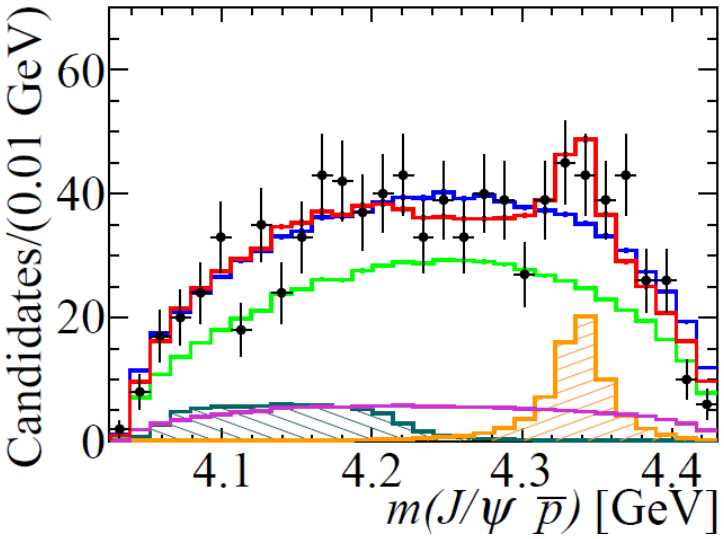
LHCb, Phys. Rev. Lett. 128 (2022) 062001

Evidence for a BW resonance state
Pentaquarklike J^p=1/2$^+$ hypotesis:

$$M_{P_c} = 4337^{+7+2}_{-4-2} MeV$$

$$\Gamma_{P_c} = 29^{+26+14}_{-12-14} MeV$$





Strange pentaquark candidate

Study of the decay:

$$B^- \to J/\psi \Lambda \overline{p}$$

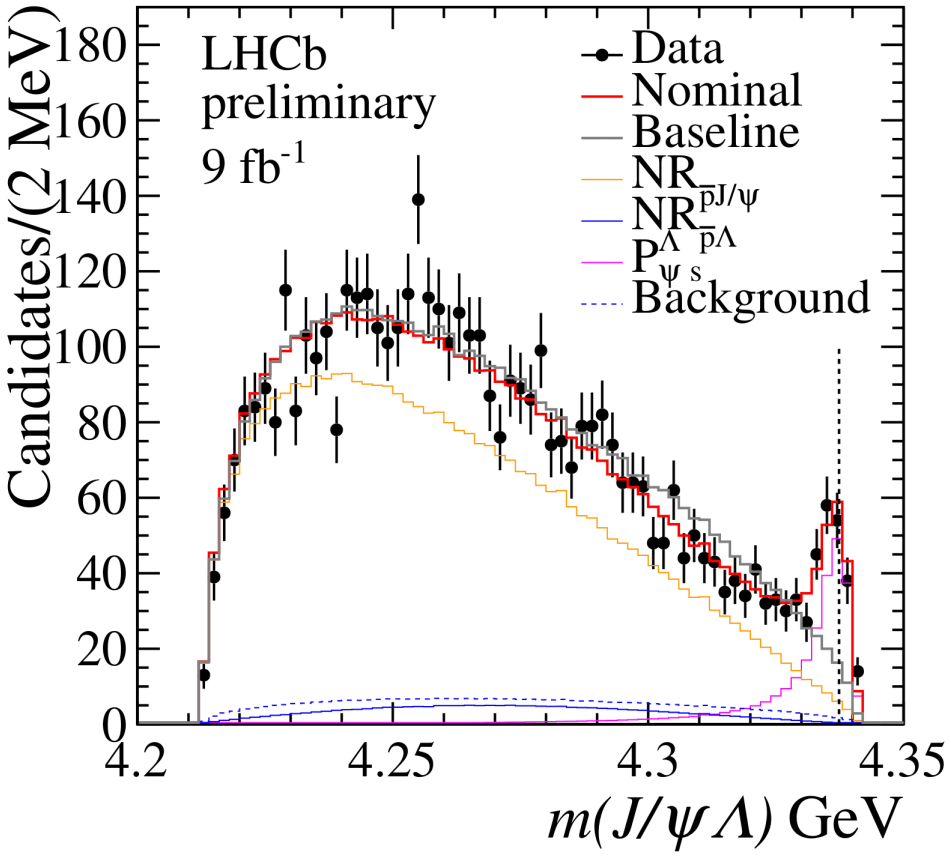
(in preparation)

Narrow resonance in $J/\psi\Lambda$ system consistent with a strange Pentaquark $J^p=1/2^-$

$$M_{P_c} = 4338.2 \pm 0.7 \pm 0.4 MeV$$

$$\Gamma_{P_c} = 7.0 \pm 1.2 \pm 1.3 MeV$$

LHCb-PAPER-2022-031



Conclusions and Outlook

LHCb has been continually producing interesting results in exotic states

The full Run 1 + Run 2 data still not fully exploited

Run 3 started this year with LHCb upgraded detector

- 50 fb^{-1} expected at the end of Run4

LHCb physics program for new Upgrade 2 approved

- 300 fb^{-1} expected at the end of Run5

Precision determination of the characteristics of observed hadrons and observation of new states expected next years

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