Searches for exotic multiquarks at LHCb

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The hunt for exotic multi-quarks
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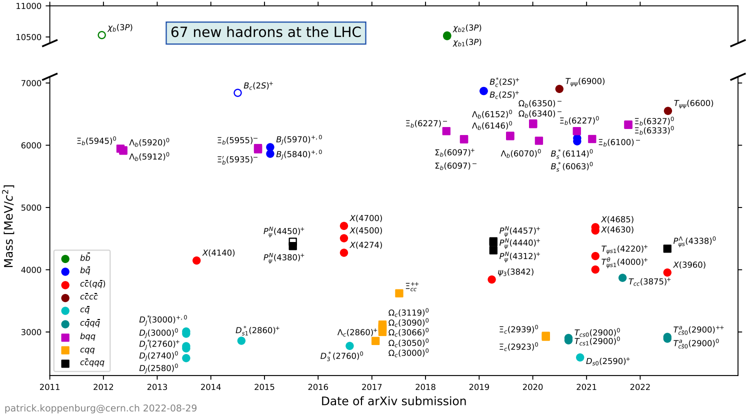
Spectroscopy at LHCb

High luminosity, high b/c production cross-section, a unique dedicated design

LHCb: major player in the field of heavy hadron spectroscopy



From [P. Koppenburg]

Spectroscopy at LHCb

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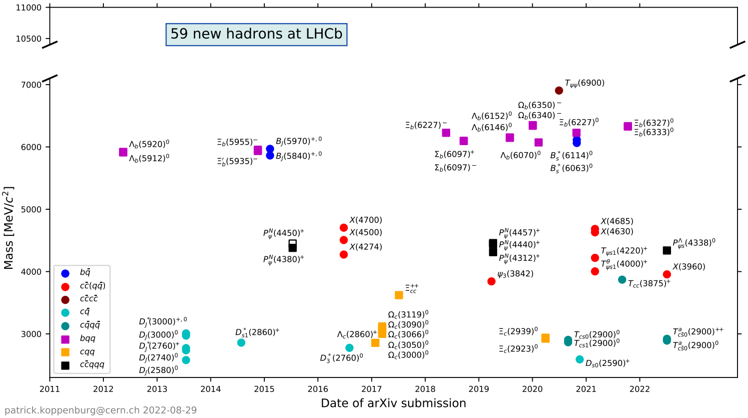

From [P. Koppenburg]

The spectroscopy programme

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Conventional heavy-hadron spectroscopy

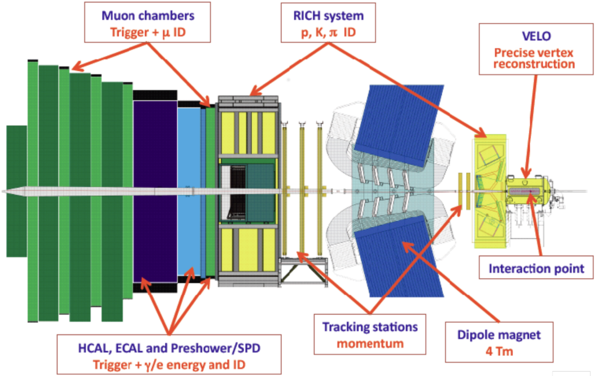
- Excited open-flavour mesons: $B^{+,0}$, B_s^0, B_c^+, $D^{+,0}$, D_s^+...
- Excited conventional charmonia
- Excited baryons: Ξ_b^0, Λ_b^0, Σ_b^+, Ω_c^0, Ω_b^-...
- Discovery and searches of new particles and decay modes
- Precise mass, width, BR measurements and more

Exotic spectroscopy

- $\chi_{c1}(3872)$: production and decay, lineshape, mass, width
- Neutral exotic tetraquarks: $[c\bar{c}u\bar{u}]$, ...
- Charged exotic tetraquarks: $[c\bar{c}u\bar{d}]$, ...
- Doubly charmed: T_{cc}, $T_{cc\bar{c}\bar{c}}$
- Open-flavour tetraquarks: $[c\bar{s}d\bar{u}]$, ...
- Pentaquarks: $[uudc\bar{c}]$, ...
- Searches for unexpected contributions

The LHCb experiment at CERN

Single-arm spectrometer designed for high precision flavour physics measurements



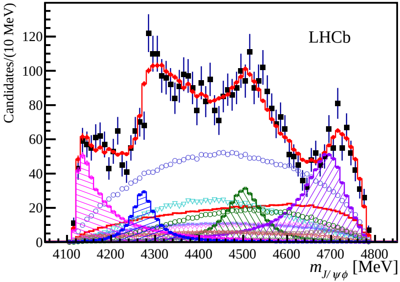
Total recorded luminosity:

- Run 1: 1 fb^{-1} at $\sqrt{s} = 7$ TeV + 2 fb^{-1} at $\sqrt{s} = 8$ TeV
- Run 2: 6 fb^{-1} at $\sqrt{s} = 13$ TeV

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

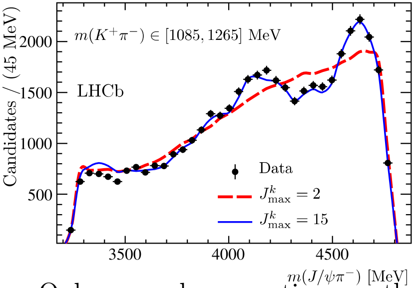
How do we spot exotic states?

Full amplitude analysis



- Each contribution is modeled
- Total amplitude is coherent sum of all contributions
- Takes into account phases and interferences
- Can extract J^{PC}, width...

Model independent expansion



- Only general assumptions on the possible contibutions
- Can only test if known states can explain the mass spectra
- Cannot extract properties
- Usually faster and easier

...or, if we are lucky, we observe a narrow peak where we do not expect one!

OPEN-FLAVOUR TETRAQUARKS

Model-independent study of $B^+ \to D^+ D^- K^+$

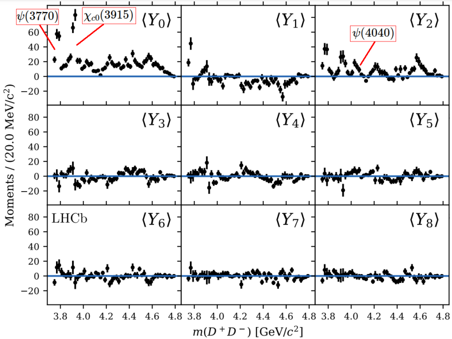
Study of the resonant structure of the decay $B^+ \to D^+ D^- K^+$

Legendre polynomial expansion: decompose the $D^+ D^-$ helicity angle distribution $\cos\theta$ in terms of Legendre polynomials to obtain a PDF:

$$\mathcal{P}(\cos\theta) \propto \sum_{J=0}^{J_{max}} \langle Y_J \rangle P_J(\cos\theta),$$

where $\langle Y_J \rangle$ is extracted from data in slices of $m(D^+ D^-)$:

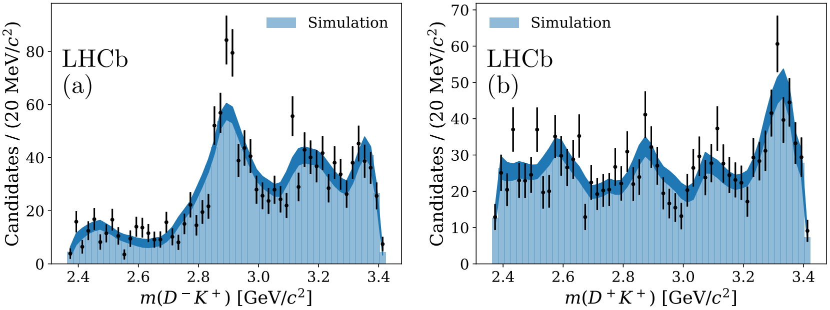
$$\langle Y_J \rangle = \sum_{n=1}^{N} w_J P_J(\cos\theta_n)$$



- J_{max} is the maximum spin of allowed known resonances
- w_J is a weight incorporating background subtraction and efficiency
- N is the total number of candidates in the mass slice
- θ_n is the $D^+ D^-$ helicity angle per candidate n

[PRL 125 (2020) 242001]

Model-independent study of $B^+ \to D^+ D^- K^+$

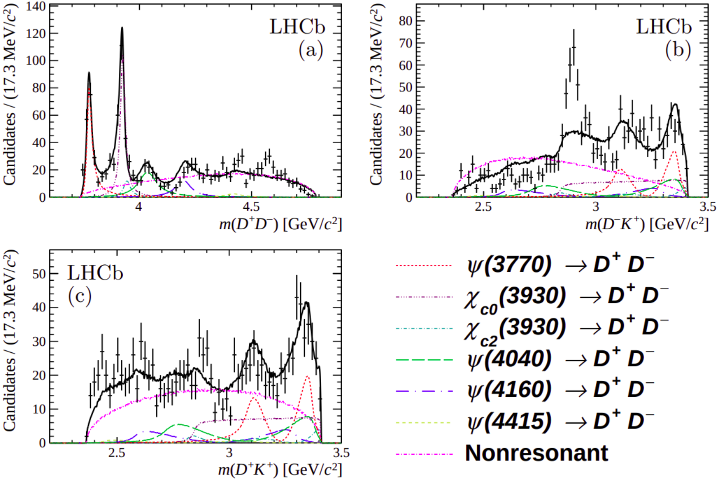


- Data not well described by Legendre moments from resonances up to $J = 2$
- Higher-spin resonances are suppressed
- The D^+K^+ spectrum does not present any unexplained structure
- The hypothesis that only D^+D^- resonances up to spin 2 are present is rejected with a significance of 3.9σ

[PRL 125 (2020) 242001]

Amplitude analysis of $B^+ \to D^+ D^- K^+$

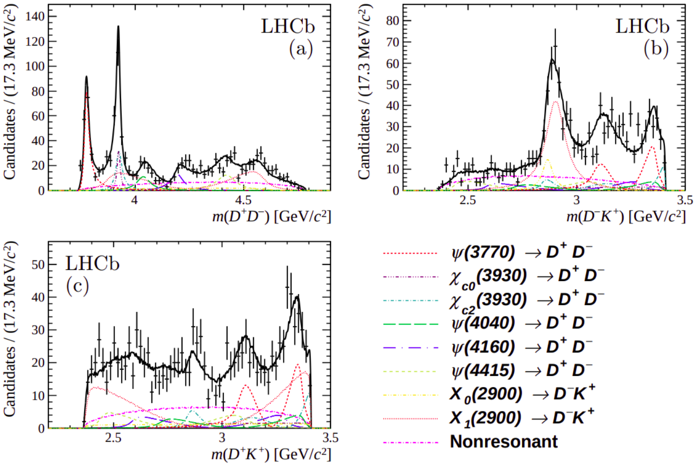
- Amplitude model constructed with the isobar formalism
- Total amplitude dominated by coherent sum of subsequent 2-body decays
- All well-motivated DD resonances are included



[arXiv:2009.00026]

Amplitude analysis of $B^+ \to D^+ D^- K^+$

- Data not well described by considering only DD resonances
- Two $D^- K^+$ Breit-Wigners added to improve significantly the fit
- Spin-0 and spin-1, roughly the same mass



[PRD 102 (2020) 112003]

Amplitude analysis of $B^+ \to D^+ D^- K^+$

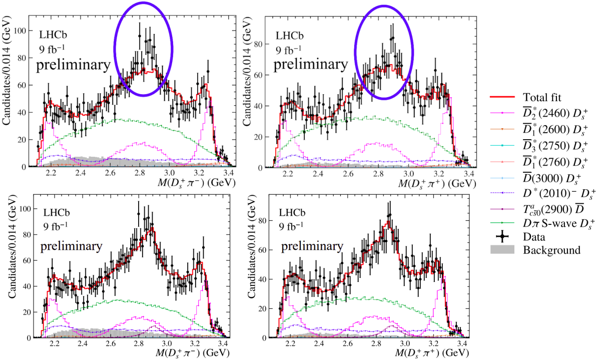
- No evidence for the $\chi_{c0}(3860) \to D^+ D^-$ state reported by Belle
- $\chi_{c2}(3930)$ contribution better described by 2 states: $\chi_{c0}(3930)$, $\chi_{c2}(3930)$
- Reasonable agreement with data when including 2 $D^- K^+$ Breit-Wigners
- $m_{X_0(2900)} = 2886 \pm 7 \pm 2$ MeV, $\Gamma_{X_0(2900)} = 57 \pm 12 \pm 4$ MeV
- $m_{X_1(2900)} = 2904 \pm 5 \pm 1$ MeV, $\Gamma_{X_1(2900)} = 110 \pm 11 \pm 4$ MeV
- However, other models (i.e. rescattering) may also explain the discrepancy

If interpreted as resonances $\Longrightarrow$ first clear observation of exotic hadrons with open flavour, and without a heavy quark-antiquark pair

Minimal quark content: $[cd\bar{s}\bar{u}]$

New open-charm tetraquarks

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



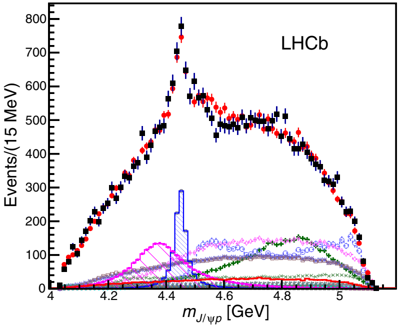
- Joint amplitude analysis linked through isospin symmetry
- Two new states necessary (9σ) to describe the peaking structure
- $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$, $J^P = 0^+$ favoured by $>7.5\sigma$

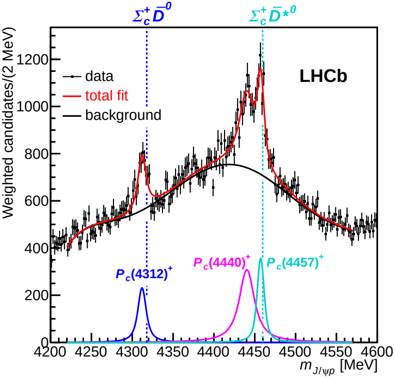
[PRL 125 (2020) 242001], [PRD 102 (2020) 112003], [LHCb-PAPER-2022-026]

PENTAQUARKS

Pentaquarks: the origins

Amplitude analysis of $\Lambda_b^0 \to J/\psi K^- p$ for Run 1 data (left), narrow peaks for Run 1-2 data (right)



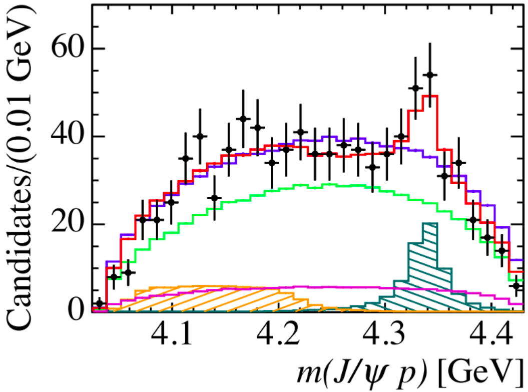


- 14 well established $\Lambda^* \to pK^-$ resonances in the amplitude model
- The large $Pc(4450)^+$ contribution is resolved into two separate peaks
- All states lie just below some mass threshold - molecules?
- Confirmed also with Legendre polynomial expansion

[PRL 115, 072001 (2015)], [PRL 122, 222001 (2019)]

New pentaquarks: $P_c(4337)^+$

Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$ decays



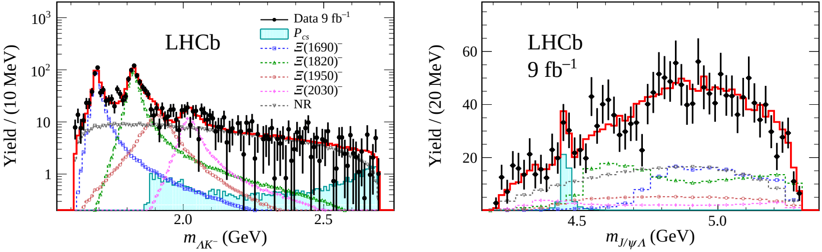
Evidence for a structure in $J/\psi p$ and $J/\psi \bar{p}$

- Statistical significance is $> 3\sigma$
- $m_{P_c} = 4337^{+7+2}_{-4-2}$ MeV, $\Gamma_{P_c} = 29^{+26+14}_{-12-14}$ MeV
- No evidence for $P_c(4312)^+$ nor for $f_J(2220)$ (glueball)

[Eur. Phys. C75 (2015) 101], [PRL 128 (2022) 062001]

New pentaquarks: $P_{cs}(4459)^0$

Amplitude analysis of $\Xi_b^0 \to J/\psi \Lambda K^-$ decays



- Two new Ξ^{*-} states observed: $\Xi(1690)^-$ and $\Xi(1820)^-$
- Evidence for a new pentaquark with strangeness
- Mass is 19 MeV below the $\Xi_c^0 \bar{D}^{*0}$, J^P not yet determined
- Limited yield, improvements foreseen in the next years

[Sci. Bull. 2021 66(13) 1278]

New pentaquarks: $P_{\psi s}^{\Lambda}$

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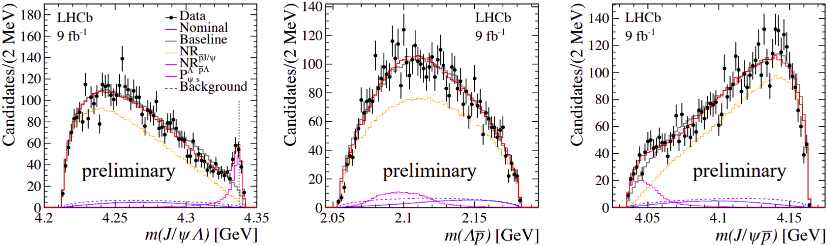
Amplitude analysis of $B^- \to J/\psi \Lambda \bar{p}$



- Observation of a narrow pentaquark state with high significance
- $J = \frac{1}{2}$, odd parity preferred: $J^P = \frac{1}{2}^+$ escluded at 90% CL
- First observation of a pentaquark with strange quark content: $[c\bar{c}uds]$
- Very close to the $\Xi_c^+ D^-$ mass threshold

[LHCb-PAPER-2022-031]

CONCLUSIONS AND PROSPECTS

Conclusions

- Heavy meson spectroscopy is an extremely rich and productive field, both for conventional and exotic states
- New conventional (excited) and exotic hadrons are discovered every year
- LHCb has established itself to be a major player due to high luminosity, high b/c production cross-section and a unique, dedicated design
- Spectroscopy of heavy hadrons is crucial to understand QCD dynamics and binding rules
- New "non-conventional" exotic states have been discovered recently
- Still mostly unexplored territory!
- In Run 3, with the removal of the L0 trigger, fully-hadronic final states will be accessible allowing studies on open-flavour exotic states
- Maybe access to bc tetraquarks and pentaquarks and $b\bar{b}$ spectroscopy