Exotic multiquark states at LHCb

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LHCb collaboration

Lake Louise Winter Institute
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Conventional and exotic hadrons

Conventional hadrons: mesons (quark+antiquark), baryons (3 quarks)
Exotic hadrons: **virtually any other possible bound state**

- Glueballs
- Hybrids
- Tetraquarks
- Pentaquarks
- Hexaquarks
- ...and other possible combination

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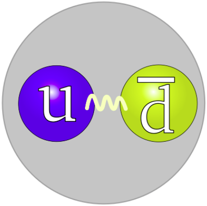

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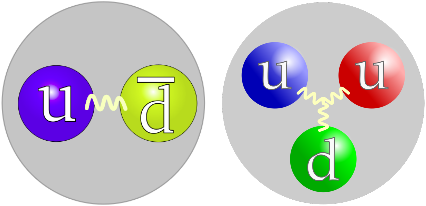

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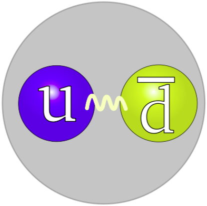

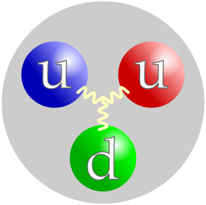

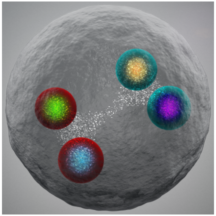

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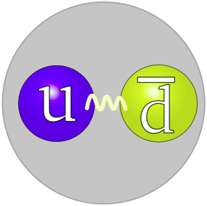
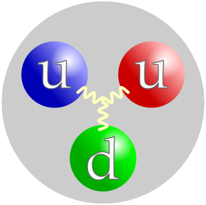
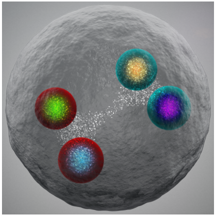
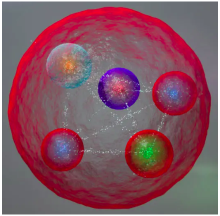
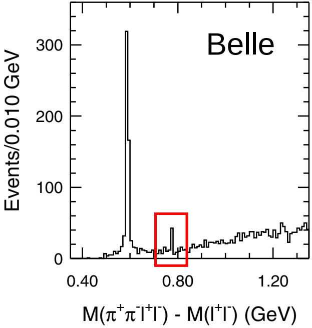


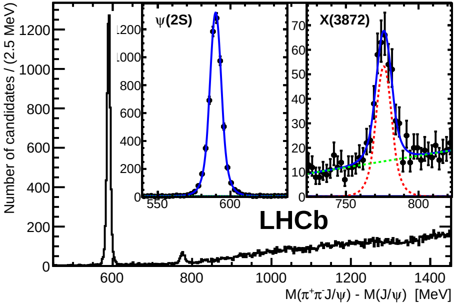


The first exotic candidate

The $X(3872)$, aka $\chi_{c1}(3872)$, is the first exotic candidate ever observed





Today we have more than 40 exotic heavy-hadron candidates!

[Phys. Rev. Lett. 91, 262001 (2003)], [Phys. Rev. Lett. 110, 222001 (2013)]

The spectroscopy programme at LHCb

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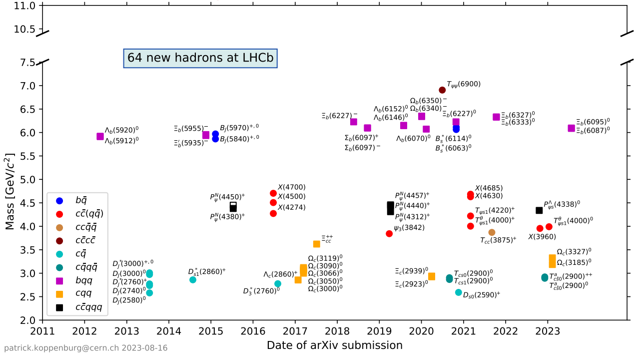

Conventional heavy-hadron spectroscopy

- Excited open-flavour mesons
- Excited conventional charmonia
- Excited heavy baryons
- Discovery and searches
- Precision measurements

Exotic heavy-hadron spectroscopy

- 21 new exotic states discovered
- $\chi_{c1}(3872)$ studies
- Charged, cc, $cc\bar{c}\bar{c}$, open flavour
- Pentaquark candidates
- Search for unexpected contributions

Today: focus on most recent results on exotic spectroscopy

Hidden and explicit heavy exotics

Hidden exotics

- Minimal quark content "mimics" regular hadrons structure
- $[c\bar{c}u\bar{u}]$, $[c\bar{c}d\bar{d}]$...
- Careful study needed
- Quantum numbers
- Production cross-section
- Unusual mass and/or width
- Unusual decay pattern

Explicit exotics

- Minimal quark content manifestly exotic
- "Charged quarkonia" such as Z_c^+, Z_b^+ with $[c\bar{c}u\bar{d}]$ or $[b\bar{b}u\bar{d}]$
- Open-flavour tetraquarks: $[cs\bar{u}\bar{d}]$
- Doubly charm tetraquarks: $[cc\bar{u}\bar{d}]$
- Fully charm tetraquarks: $[cc\bar{c}\bar{c}]$
- Pentaquarks: $[c\bar{c}uud]$, $[c\bar{c}uds]$

The LHCb experiment at CERN

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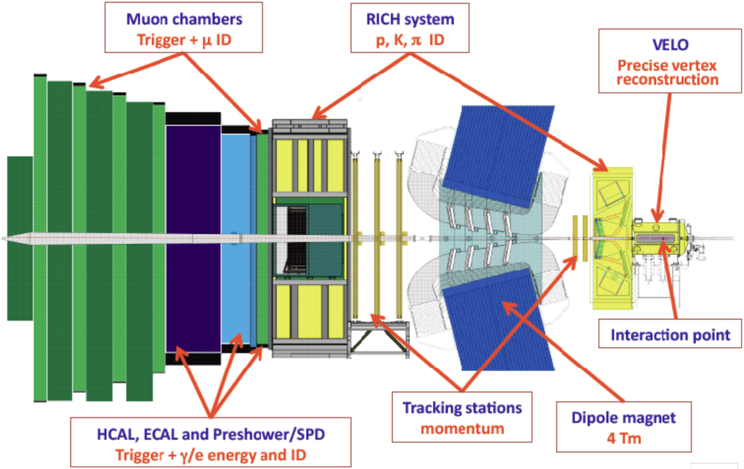
Single-arm spectrometer designed for high precision flavour physics measurements

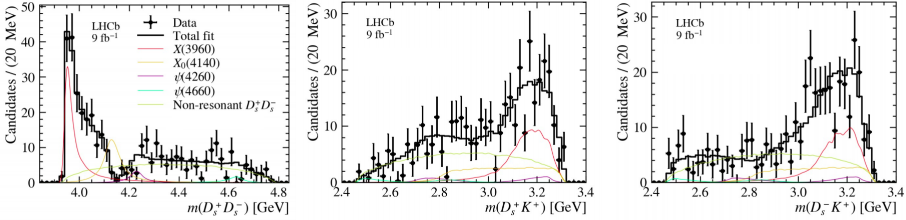


[JINST 3 (2008) S08005], [IJMPA 30 (2015) 1530022]

HIDDEN TETRAQUARKS

Observation of $X(3960)$

Amplitude analysis of the $B^+ \to D_s^+ D_s^- K^+$ decay

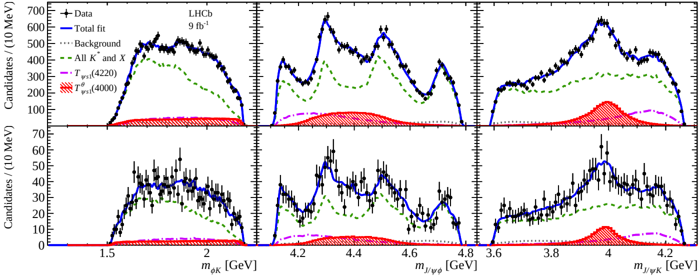


- Threshold enhancement in the $D_s^+ D_s^-$ mass spectrum
- $X(3960)$ (14σ) and $X_0(4140)$ (3.9σ) both with preferred $J^{PC} = 0^{++}$
- Alternatively, the dip can be explained by $J/\psi\phi \to D_s^+ D_s^-$ rescattering
- $X(3960)$ state is the same as $\chi_{c0}(3930)$ observed in $B^+ \to D^+ D^- K^+$?
- Exotic candidate with minimal quark content $[c\bar{c}s\bar{s}]$
- More precise measurement of its mass will be performed

[PRD 102 (2020) 112003], [PRL 131 (2023) 071901]

Evidence for a $J/\psi K_s^0$ structure

Amplitude analysis of $B^0 \to J/\psi \phi K_s^0 \implies$ search for the isospin partners of the $T_{\psi s}^{\theta +}$ states observed in the $B^+ \to J/\psi \phi K^+$ channel



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

$B^0 \to J/\psi \phi K_s^0$

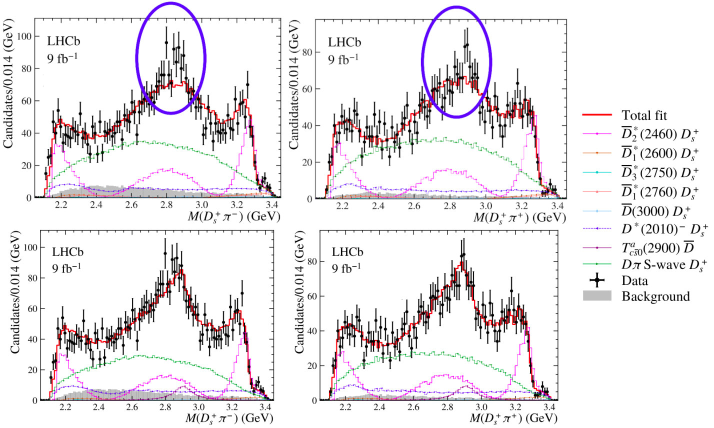
- Amplitude model includes 9 excited K states and the 9 already observed $J/\psi \phi$ exotics
- Evidence for a new state $T^{\theta}_{\psi s1}(4000)^0$ at 4σ significance
- Mass difference between $T^{\theta 0}_{\psi s1}$ and $T^{\theta +}_{\psi s1}$ is $\Delta M = 12^{+11+6}_{-10-4}$ MeV which is consistent with the two states being isospin partners

[PRL 127 (2021) 082001], [PRL 131 (2023) 131901]

CHARGED AND OPEN-FLAVOUR TETRAQUARKS

New open-charm tetraquarks

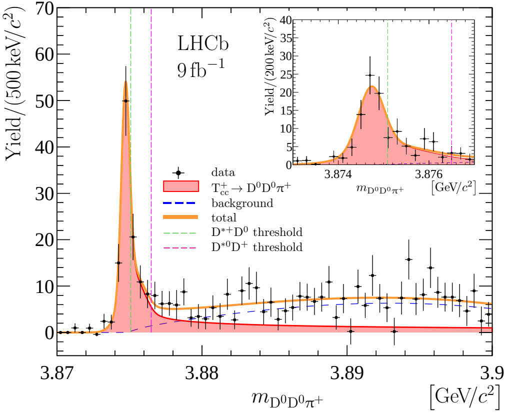
Study of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$ channels



- 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], [PRL 131 (2023) 041902]

Observation of a doubly-charmed tetraquark



Narrow peak in the $D^0 D^0 \pi^+$ spectrum just below the $D^{*+}D^0$ threshold

Consistent with the ground isoscalar T_{cc}^{+} tetraquark with quark content $cc\bar{u}\bar{d}$

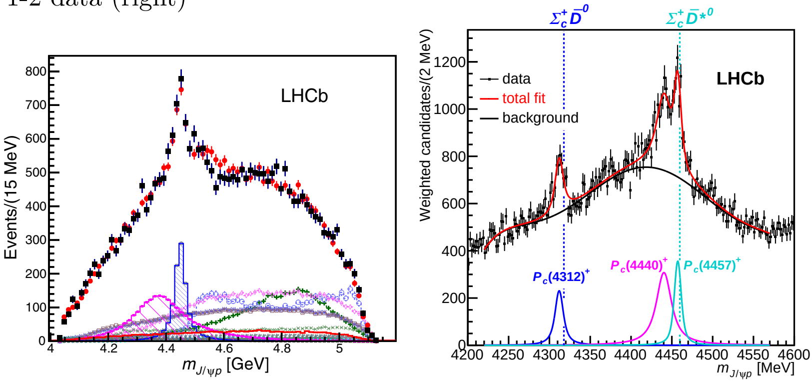
This discovery opens a new world of opportunities - how about T_{bc} or T_{bb}?

[Nature Physics 18 (2022) 751–754], [Nature Comm. 13 (2022) 3351]

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)

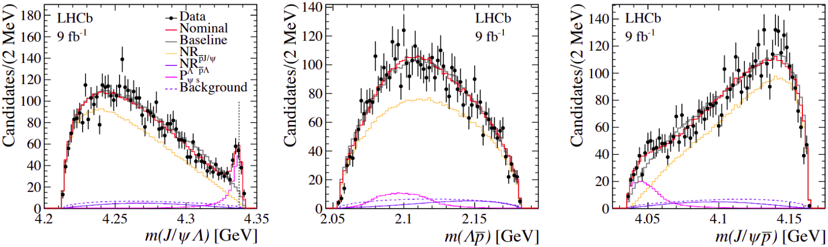


- 14 well established $\Lambda^* \to pK^-$ resonances in the amplitude model
- The large $Pc(4450)^+$ contribution is resolved into two separate peaks
- All states lie just below some mass threshold - molecules?

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

New pentaquarks: $P^{\Lambda}_{\psi s}$

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: $J^P = \frac{1}{2}^+$ excluded 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

[PRL 131 (2023) 031901]

Prompt pentaquarks in charm final states

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The mass of observed pentaquarks is close to some charm baryon-meson threshold
$\Longrightarrow$ search for pentaquark decays into a wide range of Σ_c, Λ_c^+ and D combinations

$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$	$\Sigma_c^{*++}D^0$	$\Sigma_c^{*++}D^-$	$\Sigma_c^{*++}D^+$	$\Sigma_c^{*++}D^{*-}$	~~$\Sigma_c^{*++}D^{*+}$~~
$\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*0}D^0$	$\Sigma_c^{*0}D^-$	$\Sigma_c^{*0}D^+$	$\Sigma_c^{*0}D^{*-}$	~~$\Sigma_c^{*0}D^{*+}$~~
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$	$\Lambda_c^+D^0\pi^+$	$\Lambda_c^+D^-\pi^+$	$\Lambda_c^+D^+\pi^+$	$\Lambda_c^+D^{*-}\pi^+$	$\Lambda_c^+D^{*+}\pi^+$
$\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^-$

42 different modes, 10 of which are too statistically limited $\Longrightarrow$ 32 modes tested

- Simultaneous fit to Σ_c/Λ_c^+ and D^0 signal region and sideband region
- Scan of the mass in 4 MeV steps to search for peaks, calculate p-value
- No clear signal observed, upper limits on all modes are set as function of mass

[LHCb-PAPER-2023-018] in preparation

CONCLUSIONS AND PROSPECTS FOR THE FUTURE

Prospects for the future

Doubly-flavoured tetraquarks T_{cc}, T_{bc} and T_{bb}

- What is their production mechanism? Study production also in pA and AA environments
- Based on existence and properties of T_{cc} there is consensus in theory community that T_{bb} $[bb\bar{u}\bar{d}]$ must be stable
- Binding energy $\mathcal{O}(100 \text{ MeV})$
- T_{bc} $[bc\bar{u}\bar{d}]$ might be stable

Open-flavour tetraquarks and pentaquarks

- Many new states are expected to exist
- In Run 3, with the removal of the L0 trigger, fully-hadronic final states are accessible allowing studies on open-flavour exotic states
- Prompt production still unobserved

[arXiv:2001.01446], [PLB 814 (2021) 136095], [arXiv:2008.11146]

Conclusions

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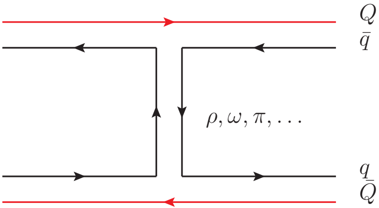
- Heavy hadron spectroscopy is an extremely rich and productive field, both for conventional and exotic states
- New exotic hadrons are discovered every year, both hidden and explicit
- Spectroscopy of heavy hadrons is crucial to understand QCD dynamics and binding rules
- Exotics are not rare!
- However, still mostly unexplored territory!
- A crucial ingredient is the close cooperation between the major experimental players and theory community

BACKUP

Models for multiquark states

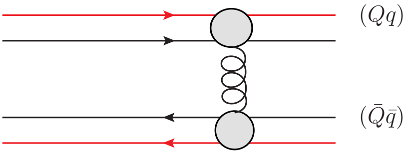
Mesonic (baryonic) molecule

- Low binding energy, narrow states
- Only S-wave, few states predicted
- Independently decaying components
- Mass close to two-body threshold



Compact multiquark

- Tightly bound states
- Large prompt production at high p_T
- Rich isospin splitting (charged states)
- Isospin partners never observed

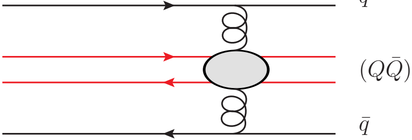


[arXiv:1905.13156], [Phys. Rep. 668, 1-97 (2017)]

Models for multiquark states

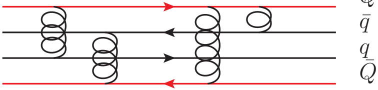
Hadroquarkonium

- Open heavy flavour decays suppressed
- Binded quarkonium and light quarks
- No requirements on mass
- Not clear whether binding can happen



A mess

- ????
- ????
- ????
- You have made poor life choices



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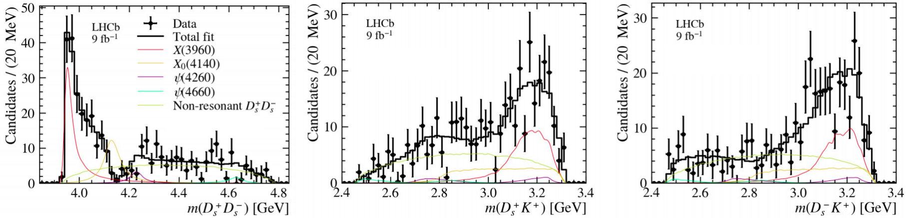
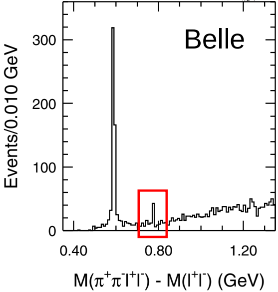


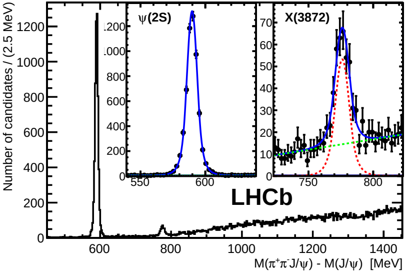
- Threshold enhancement in the $D_s^+ D_s^-$ mass spectrum
- $X(3960)$ (14σ) and $X_0(4140)$ (3.9σ) both with preferred $J^{PC} = 0^{++}$
- Alternatively, the dip can be explained by $J/\psi\phi \to D_s^+ D_s^-$ rescattering
- $X(3960)$ state could be the same as $\chi_{c0}(3930)$ observed in D^+D^-?
- $\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09(\text{stat.}) \pm 0.10(\text{syst.}) \pm 0.08(\mathcal{B} \text{ \& fit frac.})$
- Incompatible with the suppression of $s\bar{s}$ pair from vacuum (wrt $u\bar{u}$ or $d\bar{d}$) and the smaller phase-space volume of $D_s^+ D_s^-$
- Exotic candidate with minimal quark content $[c\bar{c}s\bar{s}]$
- More precise measurement of its mass will be performed

[PRD 102 (2020) 112003], [PRL 131 (2023) 071901]

A brief history of $\chi_{c1}(3872)$

- $X(3872)$ is the first well-established exotic candidate ever discovered
- Observed by Belle in 2003 as a narrow peak in $m_{J/\psi\pi\pi}$ from $B^+ \to K^+ J/\psi \pi^+\pi^-$ decays
- Observed in the following years by many other experiments
- $m_{\chi_{c1}} - m_{\overline{D}^0} - m_{D^{*0}} = 0.01 \pm 0.18$ MeV
- $\Gamma < 1.2$ MeV$/c^2$
- $J^{PC} = 1^{++}$ measured by LHCb
- No clear description of its nature: compact tetraquark, mesonic molecule, admixture...
- Precise measurement of its mass and width is paramount





[PRL 91, 262001 (2003)], [PRL 110, 222001 (2013)], [PRD 92, 011102 (2015)]

Mass, width and lineshape of $\chi_{c1}(3872)$

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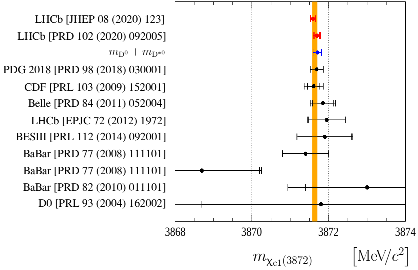
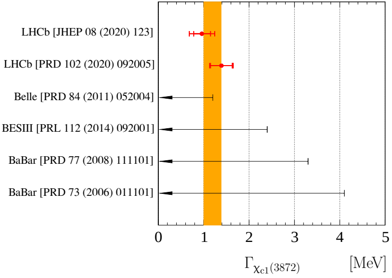
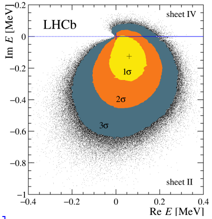
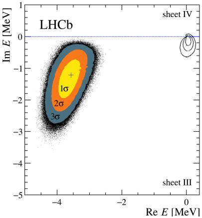




First non-zero determination of the width of this exotic state!

- Lineshape study finds 2 poles in the Riemann surface of the decay amplitude
- Only $\overline{D}^0 D^{*0}$ channel considered
- Bound state preferred, virtual assignment cannot be ruled out





[JHEP 08 (2020) 123], [PRD 102 (2020) 092005]

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

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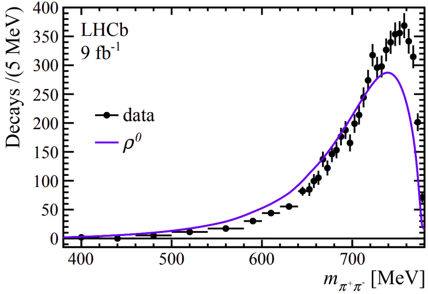
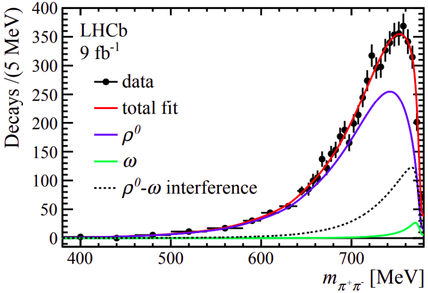
Study of the resonant $\pi^+\pi^-$ structure in the $\chi_{c1}(3872)$ "golden channel"





Using a single Breit-Wigner with a Blatt-Weisskopf radius of 1.45 GeV^{-1}

Adding an ω contribution with a 2-channel K-matrix model

Ratio of couplings

$$\frac{g_{\chi_{c1}(3872)\to\rho J/\psi}}{g_{\chi_{c1}(3872)\to\omega J\psi}} = 0.29 \pm 0.04$$

is one order of magnitude larger than expected for pure $c\bar{c}$ states

[arXiv:2204.12597], submitted to PRL

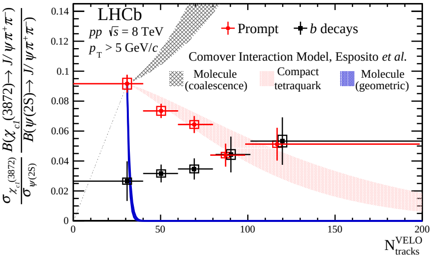
$\chi_{c1}(3872)$ production in *pp* and *p*Pb

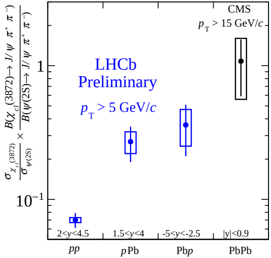
Observation of multiplicity-dependence prompt production

- Decreasing production wrt increasing # of tracks in the event
- Comover Interaction Model: interaction with other produced particles
- Breakup cross-section determined by radius and binding energy
- Coalescence mechanism inconsistent with data, compact preferred
- Cross-check: production from *b* decays seems flat

Furthermore, increased cross-section ratio from *pp* to *p*Pb collisions

- Different dynamics in the nuclear medium than conventional charmonia?





[PRL 126 (2021) 092001], [LHCB-CONF-2022-001]

Hidden exotics in $B^+ \to J/\psi\phi K^+$

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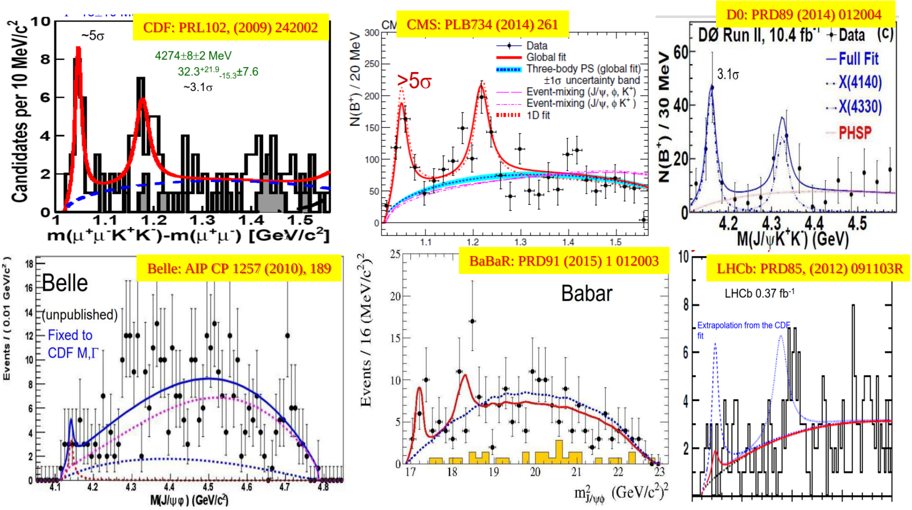
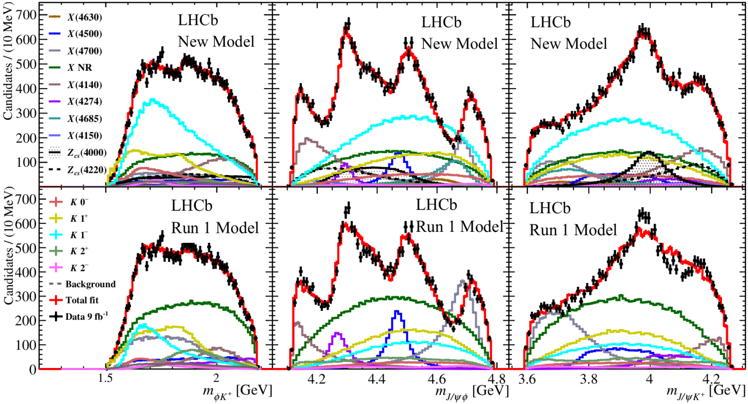


Observation of $X(4140)$ and evidence for $X(4274)$ by CDF, confirmed by D0 and CMS, not confirmed by Belle, BaBar, LHCb

Hidden exotics in $B^+ \to J/\psi\phi K^+$



Run 1 analysis: $X(4150)$, $X(4500)$, $X(4700)$, $X(4140)$, $X(4274)$

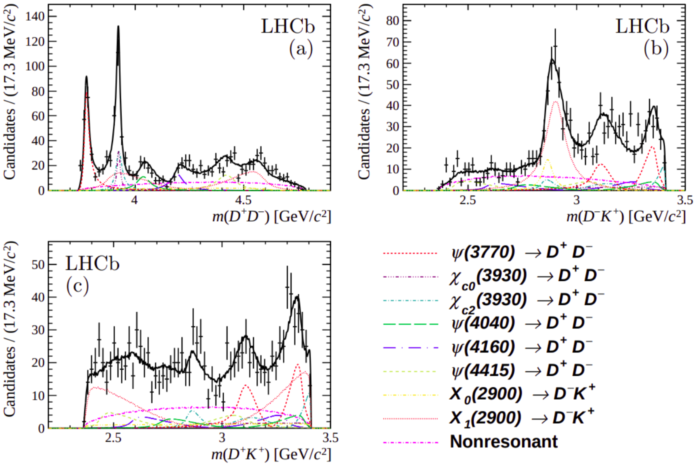
Run 2 analysis: $X(4630)$, $X(4685)$, $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$

First observation of exotic states with $c\bar{c}u\bar{s}$ content in the $J/\psi K^+$ final state

[PRL 127 (2021) 082001]

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 $B^+ \to D^+ D^- K^+$

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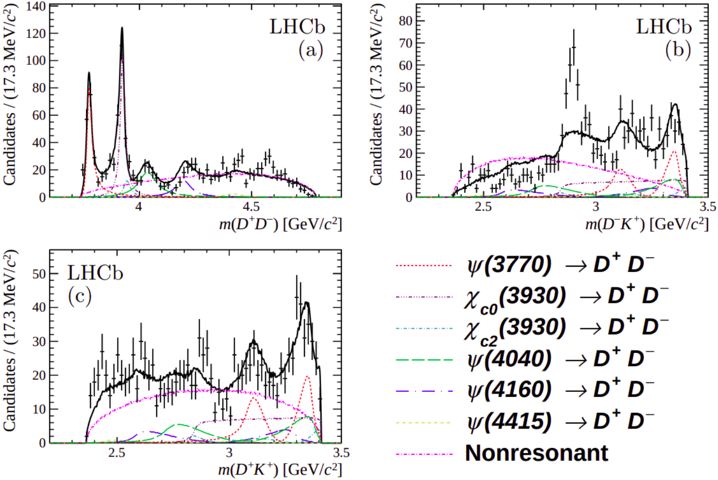
- Amplitude model constructed with the isobar formalism
- Total amplitude dominated by coherent sum of subsequent 2-body decays
- All well-motivated DD resonances are included



[arXiv:2009.00026]

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

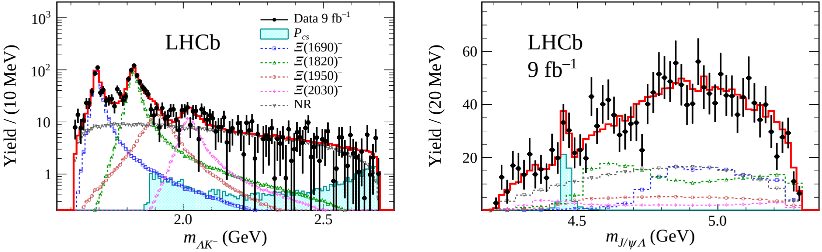
- No evidence for the $\chi_{c0}(3860) \to D^+ D^-$ state reported by Belle
- $\chi_{c2}(3930)$ contribution better described by 2 states: $\chi_{c0}(3930)$, $\chi_{c2}(3930)$
- Reasonable agreement with data when including 2 $D^- K^+$ Breit-Wigners
- $m_{X_0(2900)} = 2886 \pm 7 \pm 2$ MeV, $\Gamma_{X_0(2900)} = 57 \pm 12 \pm 4$ 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 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]