Recent results on exotic hadrons at LHCb

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on behalf of the LHCb collaboration

EMMI Workshop
Anti-Matter, Hyper-Matter and Exotica Production at the LHC
Bologna
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Conventional and exotic hadrons

Conventional hadrons: mesons (quark+antiquark), hadrons (3 quarks)
Exotic hadrons: **virtually anything else**

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

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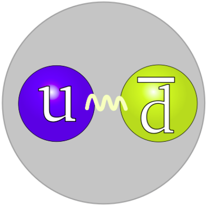

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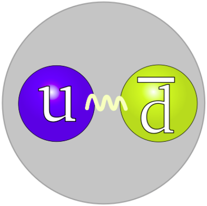

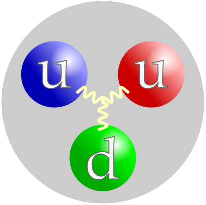

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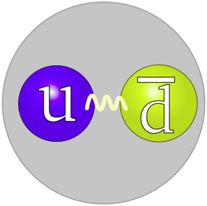

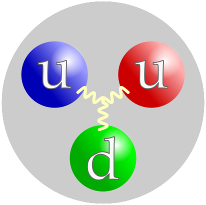

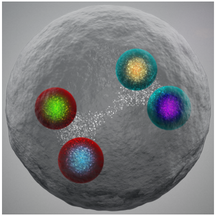

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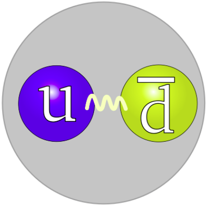

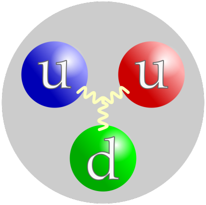

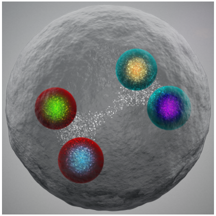
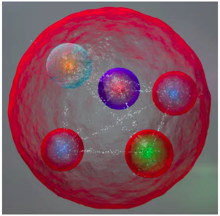

Hidden and explicit exotics

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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: $[c\bar{c}uud]$, $[c\bar{c}uds]$

Studied by many different experiments: LHCb, BESIII, ATLAS, CMS, Belle, Belle II, BaBar, CDF, D0, ALICE...

HIDDEN TETRAQUARKS

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

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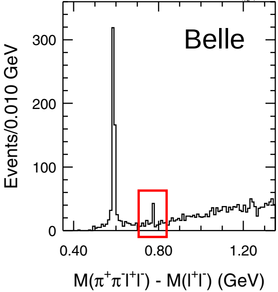
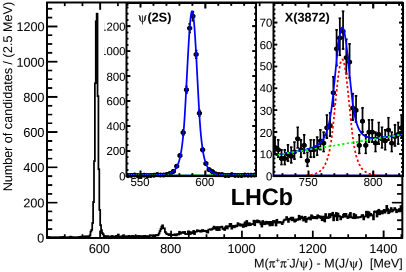
- $X(3872)$ is the first well-established exotic candidate ever discovered
- Observed by Belle in 2003 as a narrow peak in $m_{J/\psi\pi\pi}$ from $B^+ \to K^+ J/\psi \pi^+\pi^-$ decays
- Observed in the following years by many other experiments
- $m_{\chi_{c1}} - m_{\overline{D}^0} - m_{D^{*0}} = 0.01 \pm 0.18$ 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

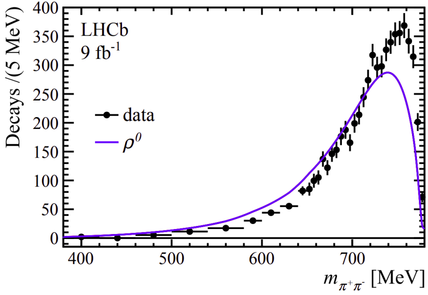




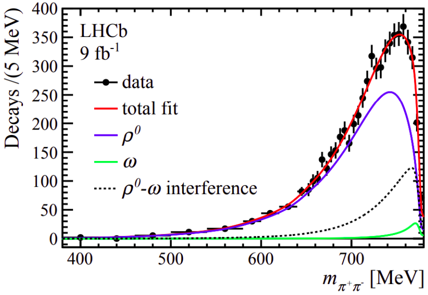
[PRL 91, 262001 (2003)], [PRL 110, 222001 (2013)], [PRD 92, 011102 (2015)]

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

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 pPb

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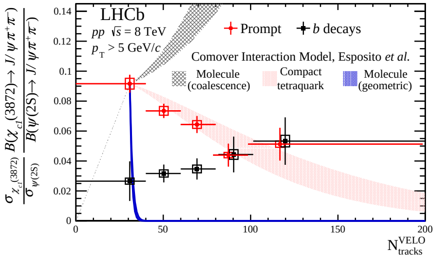
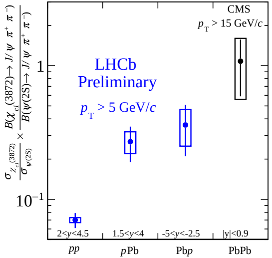
Observation of multiplicity-dependence prompt production

- 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 pPb collisions

- Different dynamics in the nuclear medium than conventional charmonia?



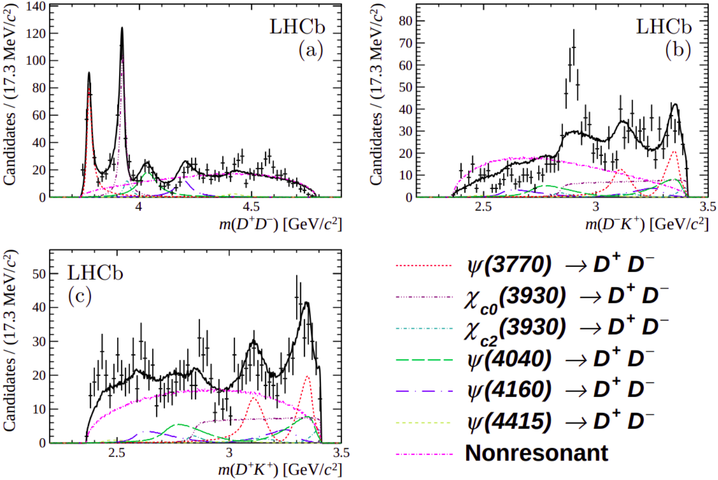


[PRL 126 (2021) 092001], [LHCB-CONF-2022-001]

CHARGED AND OPEN-FLAVOUR TETRAQUARKS

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

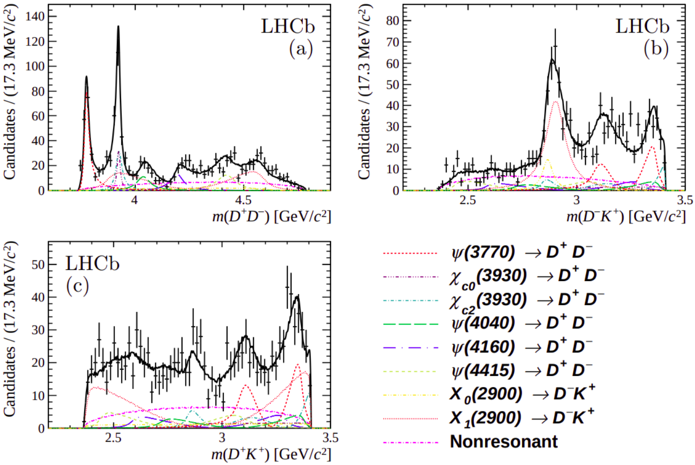
- Amplitude model constructed with the isobar formalism
- Total amplitude dominated by coherent sum of subsequent 2-body decays
- All well-motivated DD resonances are included



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

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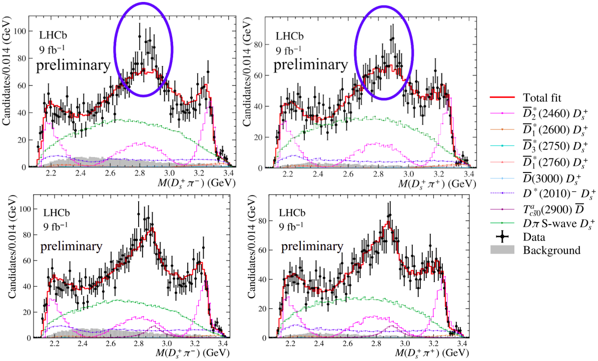
- No evidence for the $\chi_{c0}(3860) \to D^+ D^-$ state reported by Belle
- $\chi_{c2}(3930)$ contribution better described by 2 states: $\chi_{c0}(3930)$, $\chi_{c2}(3930)$
- Reasonable agreement with data when including 2 $D^- K^+$ Breit-Wigners
- $m_{X_0(2900)} = 2886 \pm 7 \pm 2$ MeV, $\Gamma_{X_0(2900)} = 57 \pm 12 \pm 4$ 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], [arXiv:2212.02716]

Observation of a doubly-charmed tetraquark

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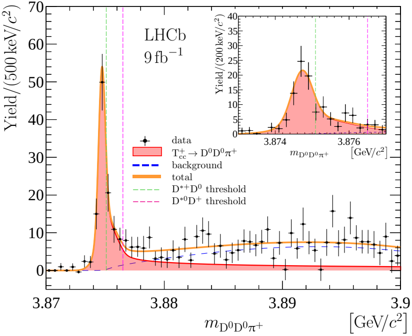
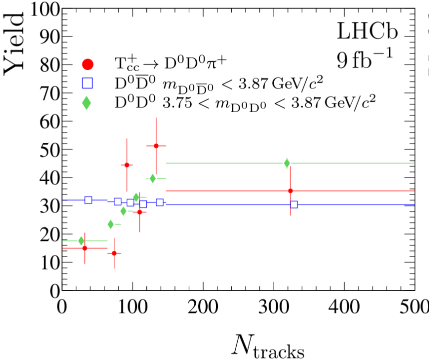




Narrow peak in the $D^0D^0\pi^+$ spectrum just below the $D^{*+}D^0$ threshold

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

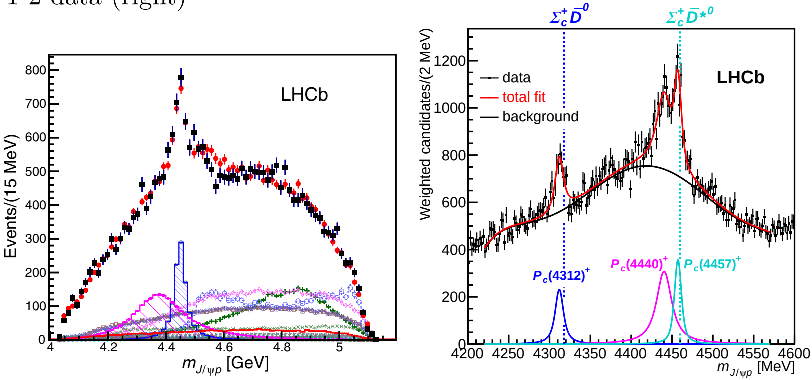
- Measured pole position and width, scattering length, effective range...
- Weinberg compositeness parameter: $Z < 0.52$ at 90% CL
- Unexpected behaviour: no production cross-section suppression at high multiplicity, although large size is measured - like for $\chi_{c1}(3872)$

[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)

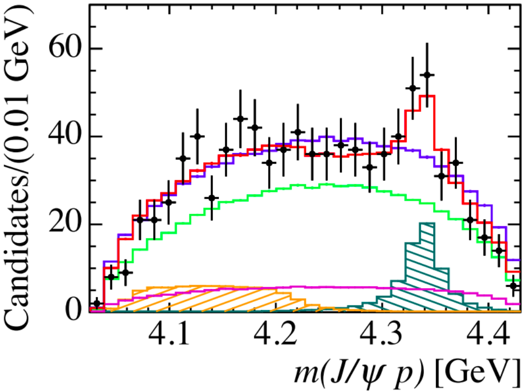


- 14 well established $\Lambda^* \to pK^-$ resonances in the amplitude model
- The large $Pc(4450)^+$ contribution is resolved into two separate peaks
- All states lie just below some mass threshold - molecules?
- Confirmed also with Legendre polynomial expansion

[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: $P_{cs}(4459)^0$

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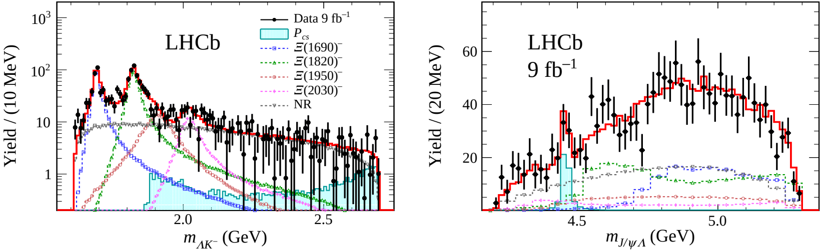
Amplitude analysis of $\Xi_b^0 \to J/\psi \Lambda K^-$ decays

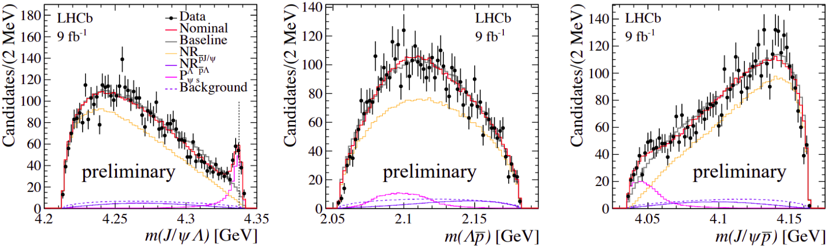


- Two new Ξ^{*-} states observed: $\Xi(1690)^-$ and $\Xi(1820)^-$
- Evidence for a new pentaquark with strangeness
- Mass is 19 MeV below the $\Xi_c^0 \bar{D}^{*0}$, J^P not yet determined
- Limited yield, improvements foreseen in the next years

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

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

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

[arXiv:2210.10346], submitted to PRL

CONCLUSIONS AND PROSPECTS FOR THE FUTURE

Conclusions

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- Heavy meson 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!
- Most important aspect is to continue the close cooperation between the major players (LHC experiments, BelleII, BESIII) and theory community

Prospects for the future

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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 will be accessible allowing studies on open-flavour exotic states
- Prompt production still unobserved
- Amplitude analysis is challenging now and it will get worse!

Also, increasing interest in the theory community on multiplicity-dependence in production $\Longrightarrow$ to add in our priority list!

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