

Experimental overview on exotic spectroscopy

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LHCb collaboration

with results from CDF, D0, BaBar, BelleII, BESIII, ATLAS, CMS collaborations



**Università
degli Studi
di Ferrara**

QCD challenges from pp to AA collisions
Padova
14/02/2023

Conventional and exotic hadrons

Conventional hadrons: mesons (quark+antiquark), hadrons (3 quarks)

Exotic hadrons: **virtually anything else**

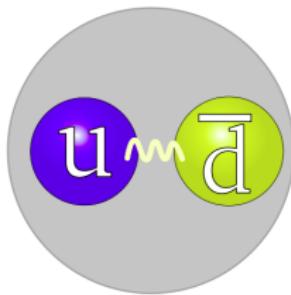
- Glueballs
- Hybrids
- Tetraquarks
- Pentaquarks
- Hexaquarks
- ...and any other possible combination

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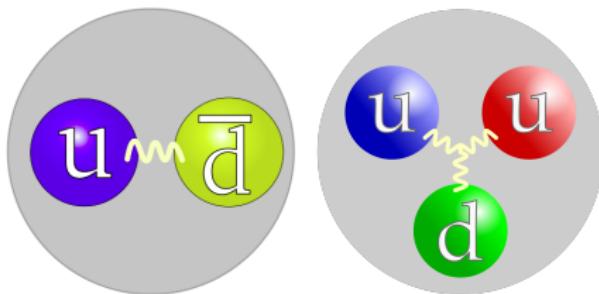


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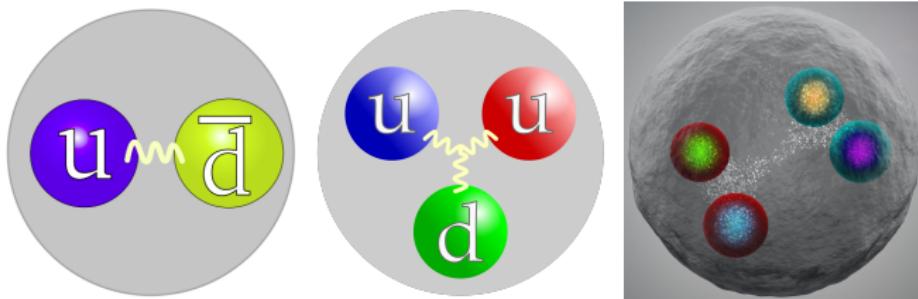


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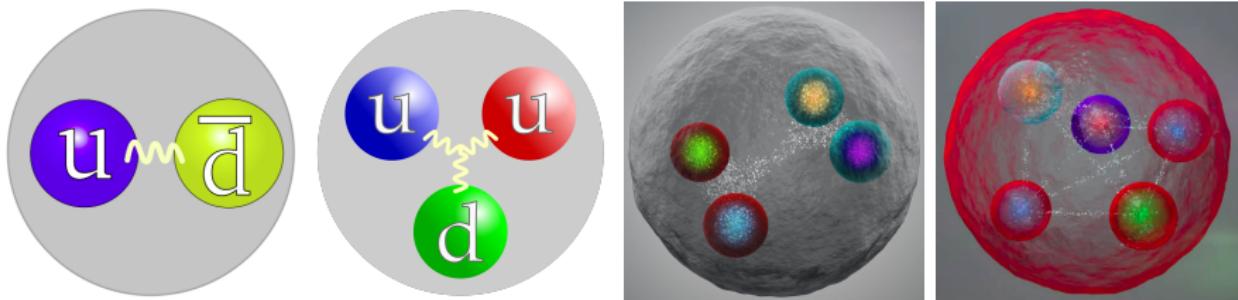


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Hidden and explicit exotics

Hidden exotics

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

Explicit exotics

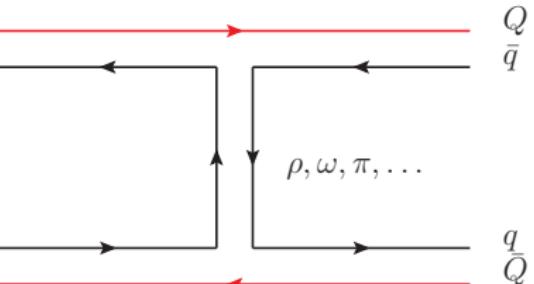
- Minimal quark content manifestly exotic
- "Charged quarkonia" such as Z_c^+ , Z_b^+ with $[c\bar{c}u\bar{d}]$ or $[b\bar{b}u\bar{d}]$
- Open-flavour tetraquarks: $[csu\bar{d}]$
- Doubly charm tetraquarks: $[cc\bar{u}\bar{d}]$
- Fully charm tetraquarks: $[cc\bar{c}\bar{c}]$
- Pentaquarks: $[c\bar{c}uud]$,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

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

Models for multiquark states

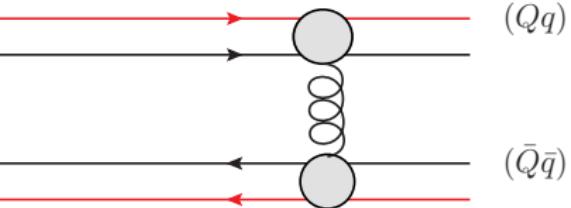
Mesonic (baryonic) molecule

- 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

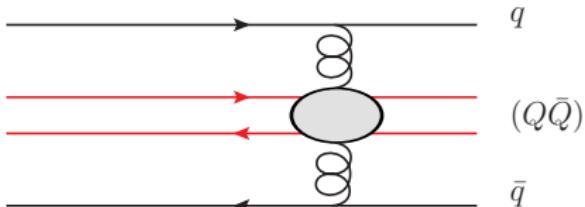


[arXiv:1905.13156], [Phys. Rep. 668, 1-97 (2017)]

Models for multiquark states

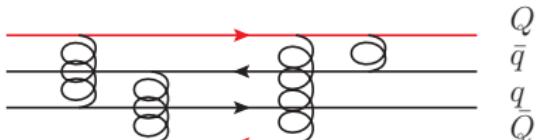
Hadroquarkonium

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



A mess

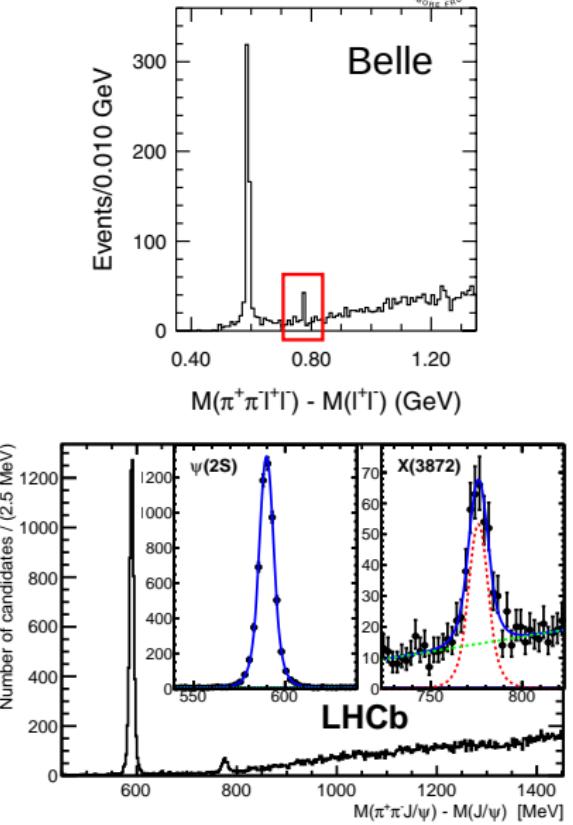
- ?????
- ?????
- ?????
- You have made poor life choices



HIDDEN TETRAQUARKS

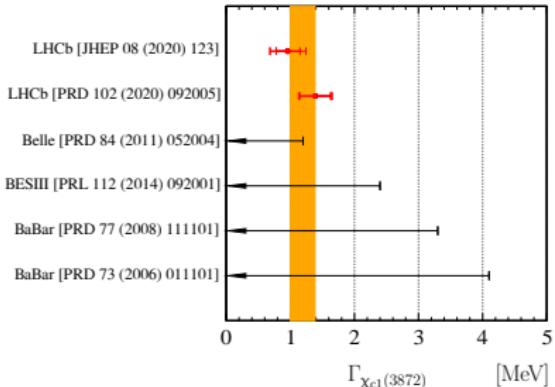
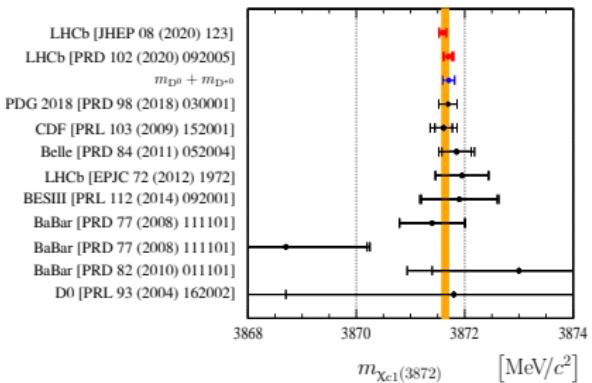
A brief history of $\chi_{c1}(3872)$

- $X(3872)$ 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 $B^+ \rightarrow K^+ J/\psi\pi^+\pi^-$ decays
- Observed in the following years by many other experiments
- $m_{\chi_{c1}} - m_{\bar{D}^0} - m_{D^{*0}} = 0.01 \pm 0.18$ 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



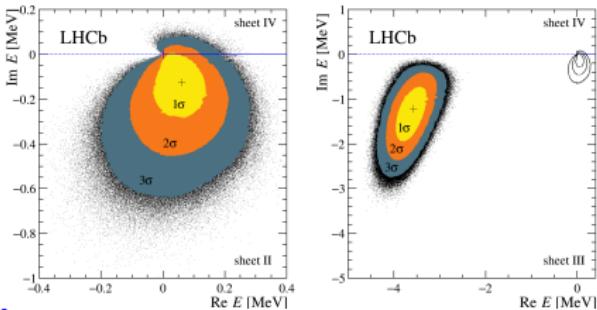
[PRL 91, 262001 (2003)], [PRL 110, 222001 (2013)], [PRD 92, 011102 (2015)]

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



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

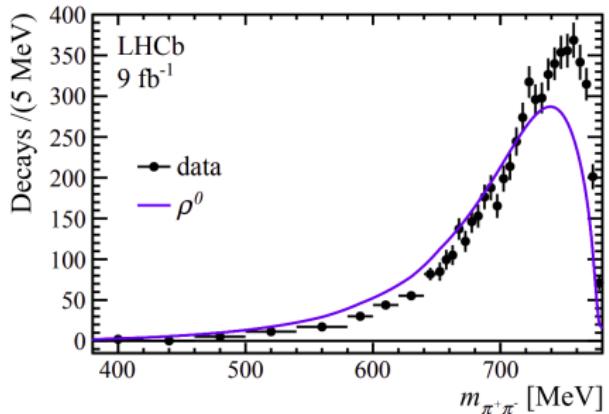
- Lineshape study finds 2 poles in the Riemann surface of the decay amplitude
- Only $\bar{D}^0 D^{*0}$ channel considered
- **Bound state preferred**, virtual assignment cannot be ruled out



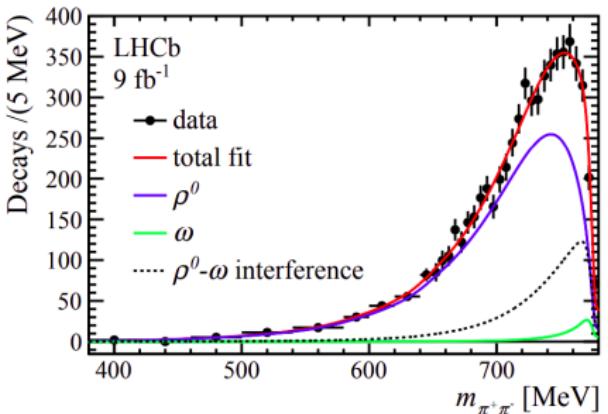
[JHEP 08 (2020) 123], [PRD 102 (2020) 092005]

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

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

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

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

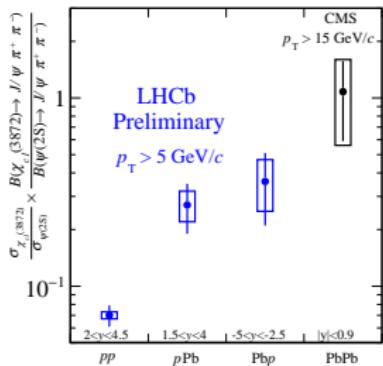
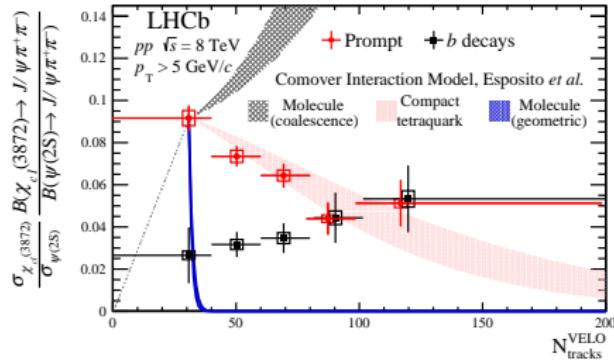
$\chi_{c1}(3872)$ production in pp and $p\text{Pb}$

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

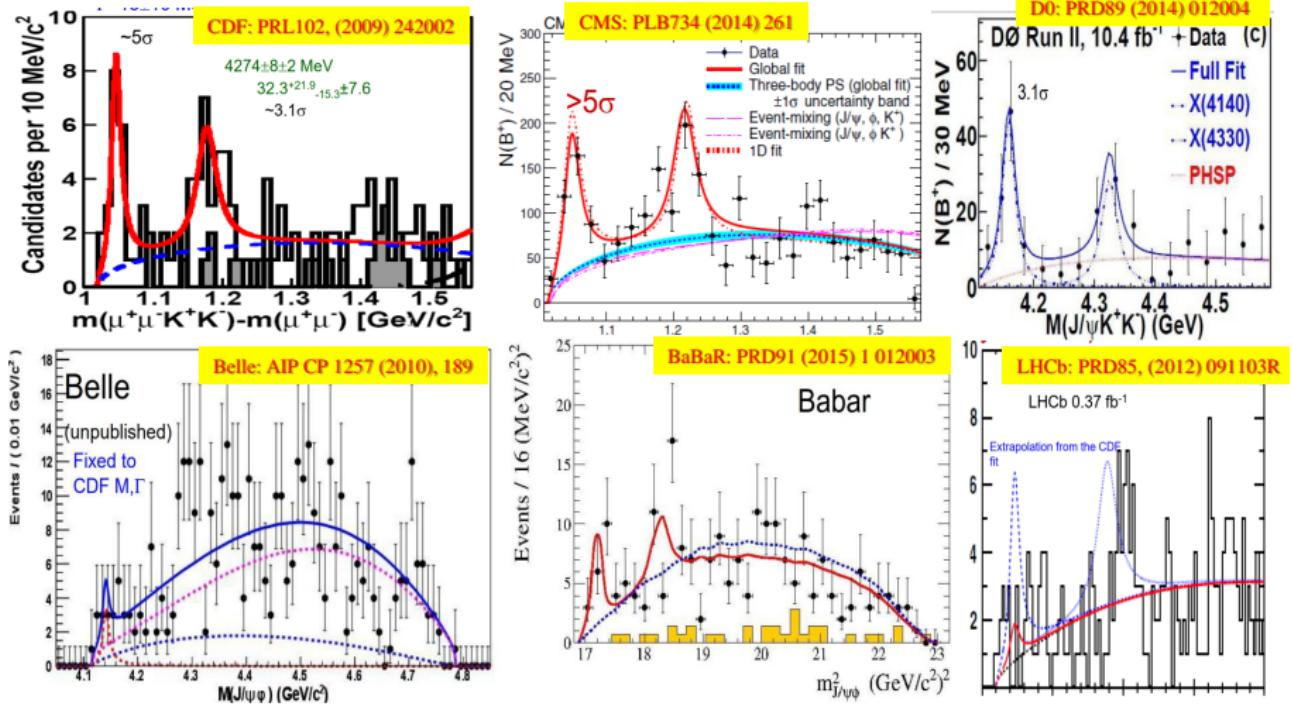
Furthermore, increased cross-section ratio from pp to $p\text{Pb}$ collisions

- Different dynamics in the nuclear medium than conventional charmonia?



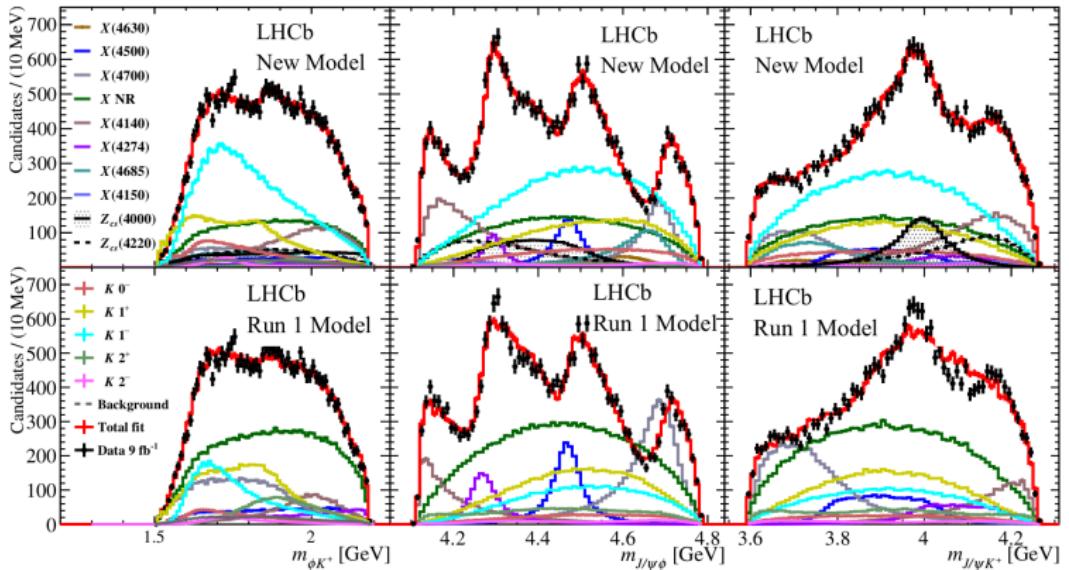
[PRL 126 (2021) 092001], [LHCb-CONF-2022-001]

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



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



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

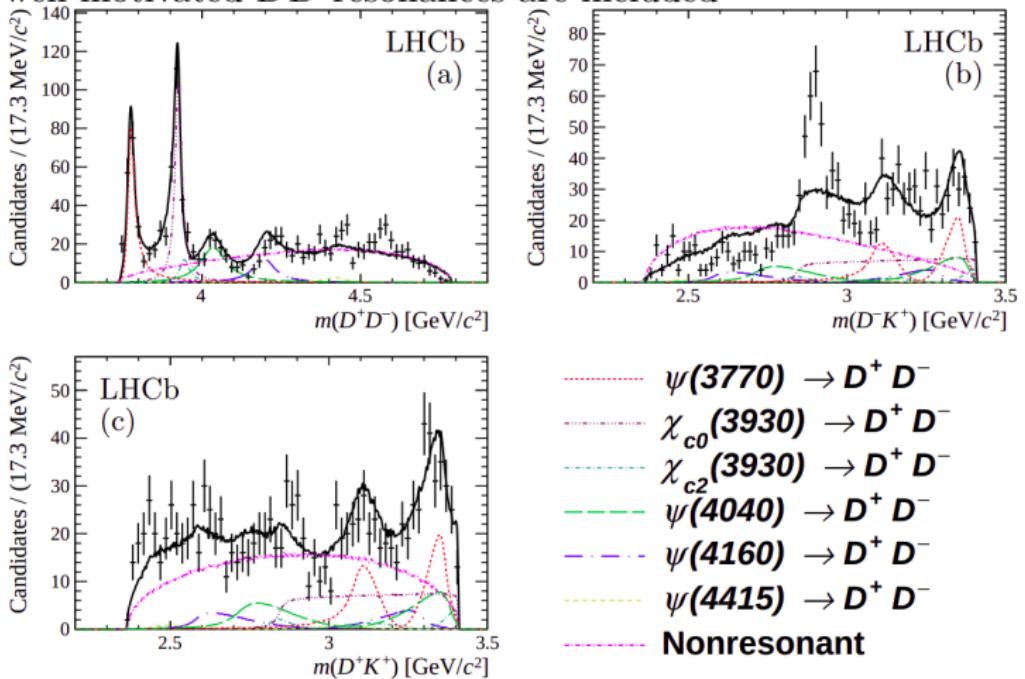
Run 2 analysis: $X(4630)$, $X(4685)$, $Z_{cs}(4000)^+$, $Z_{cs}(4220)^+$

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

CHARGED AND OPEN-FLAVOUR TETRAQUARKS

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

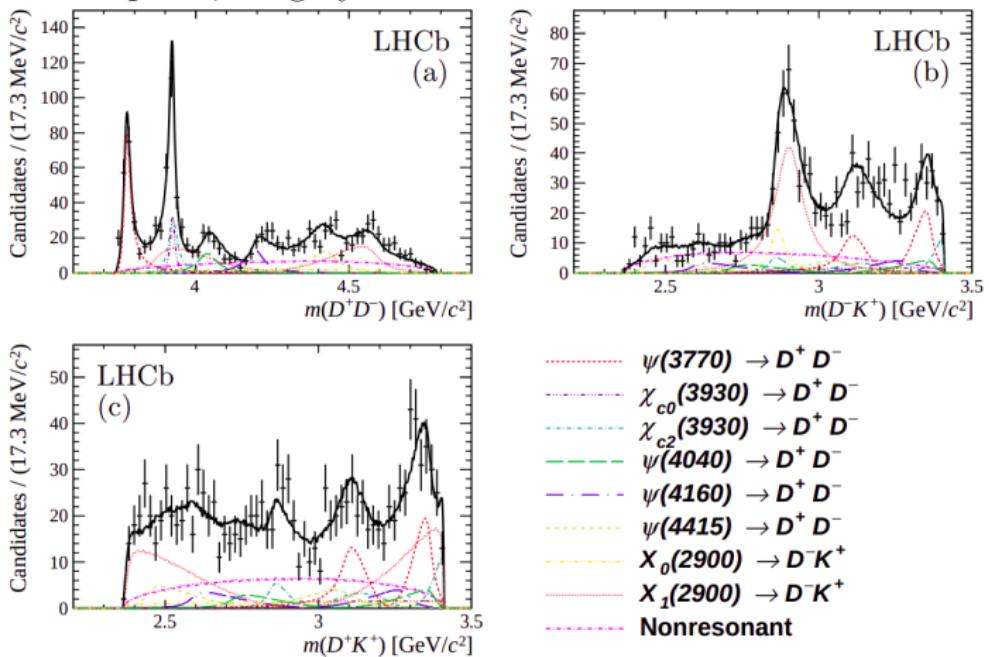
- Amplitude model constructed with the isobar formalism
- Total amplitude dominated by coherent sum of subsequent 2-body decays
- All well-motivated DD resonances are included



[arXiv:2009.00026]

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

- 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



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

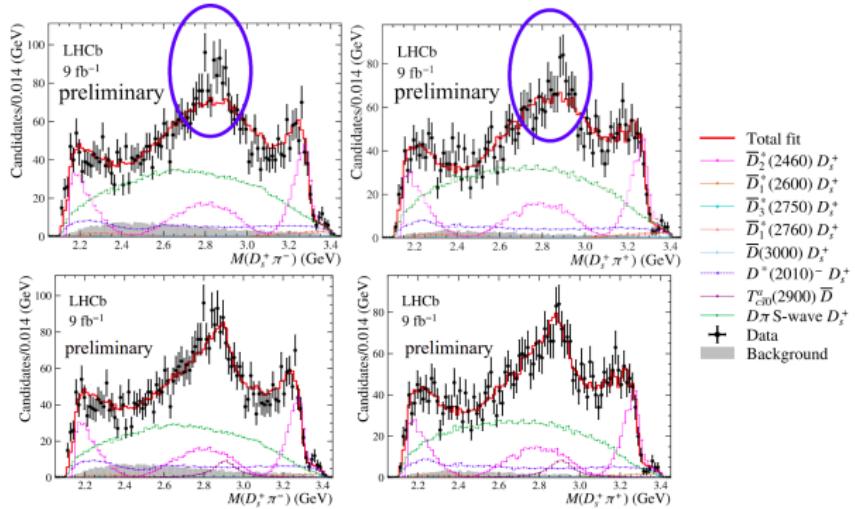
- No evidence for the $\chi_{c0}(3860) \rightarrow D^+ D^-$ state reported by Belle
- $\chi_{c2}(3930)$ contribution better described by 2 states: $\chi_{c0}(3930)$, $\chi_{c2}(3930)$
- Reasonable agreement with data when including 2 $D^- K^+$ Breit-Wigners
- $m_{X_0(2900)} = 2886 \pm 7 \pm 2$ MeV, $\Gamma_{X_0(2900)}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

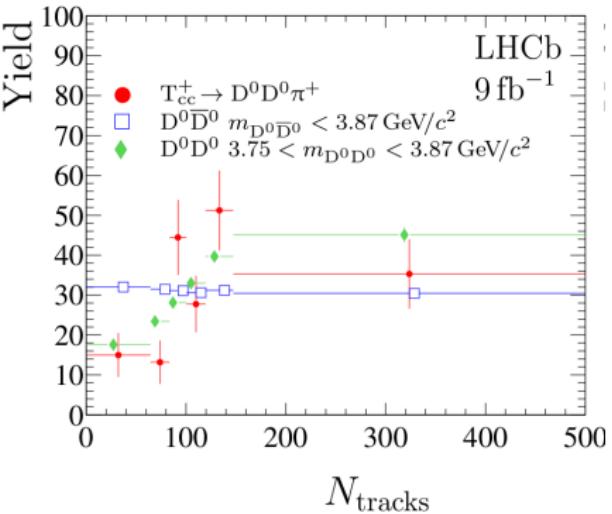
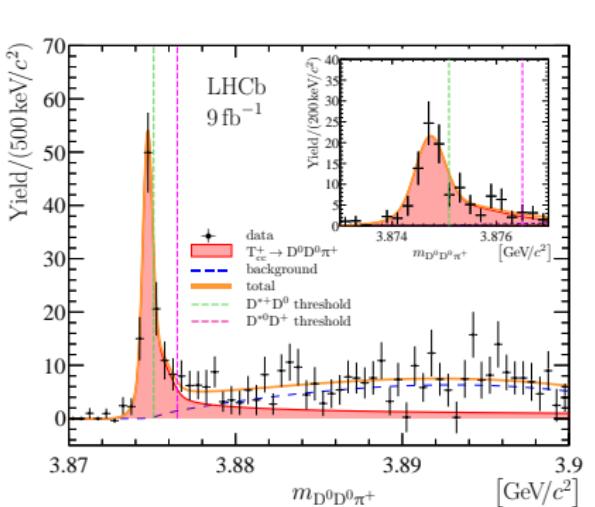
Study of the $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ and $B^+ \rightarrow D^- D_s^+ \pi^+$ channels



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

[PRL 125 (2020) 242001], [PRD 102 (2020) 112003], [arXiv:2212.02716]

Observation of a doubly-charmed tetraquark



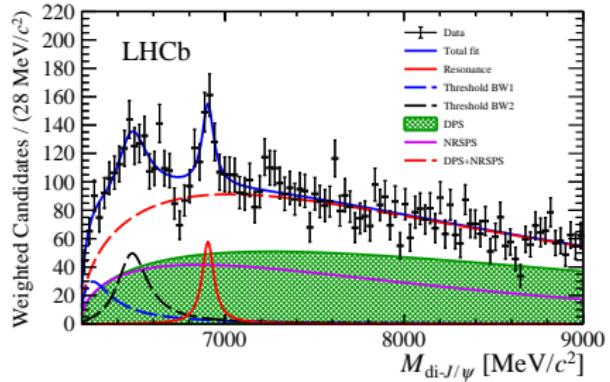
Narrow peak in the $D^0 D^0 \pi^+$ spectrum just below the $D^{*+} D^0$ threshold
 Consistent with the ground isoscalar T_{cc}^+ tetraquark with quark content $cc\bar{u}\bar{d}$

- 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 $\chi_{c1}(3872)$

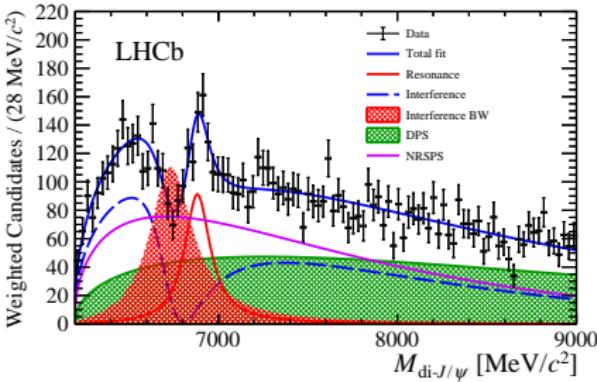
[Nature Physics 18 (2022) 751–754], [Nature Comm. 13 (2022) 3351]

Structure in J/ψ -pair mass spectrum

No interference



SPS-BW interference



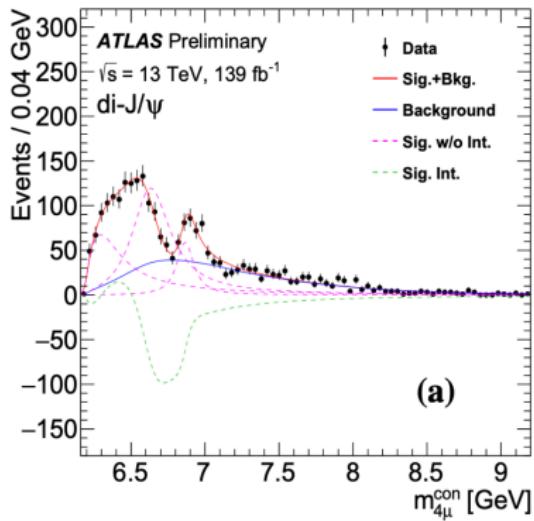
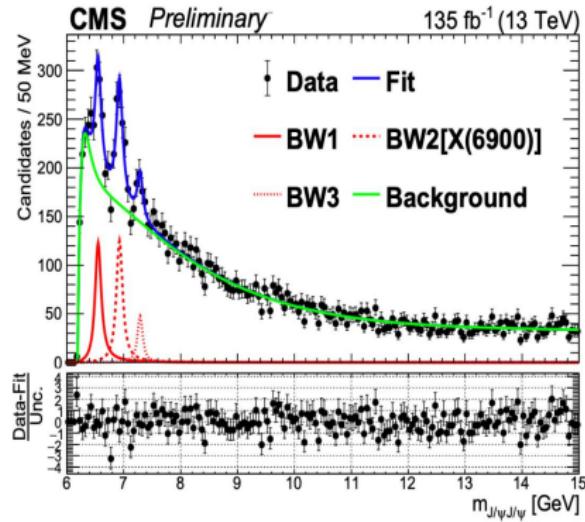
- Threshold enhancement described by two resonances
- S -wave BW \times 2-body phase space
- $m_{X(6900)} = 6905 \pm 11 \pm 7 \text{ MeV}$
- $\Gamma_{X(6900)} = 80 \pm 19 \pm 33 \text{ MeV}$
- Significance $>5\sigma$

- Threshold enhancement described by interference
- One BW, interference with SPS
- $m_{X(6900)} = 6886 \pm 11 \pm 11 \text{ MeV}$
- $\Gamma_{X(6900)} = 168 \pm 33 \pm 69 \text{ MeV}$
- Significance $>5\sigma$

Structure in J/ψ -pair mass spectrum

Observation confirmed and extended to two peaks + evidence for a third peak by both ATLAS and CMS

- Feasibility for a joint analysis?
- Will we be able to see also peaks in Υ -pair mass spectrum?

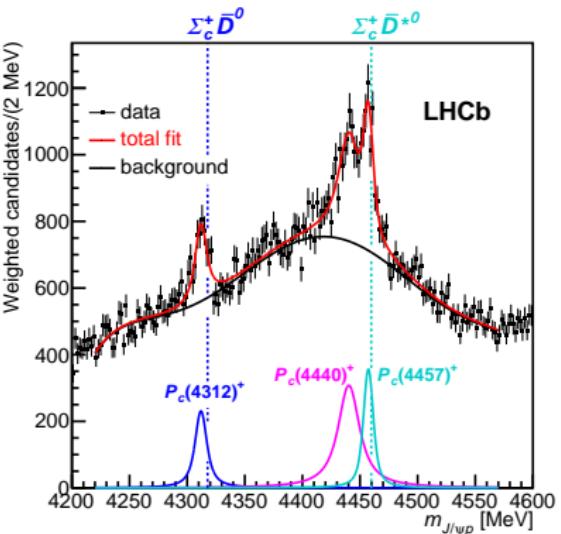
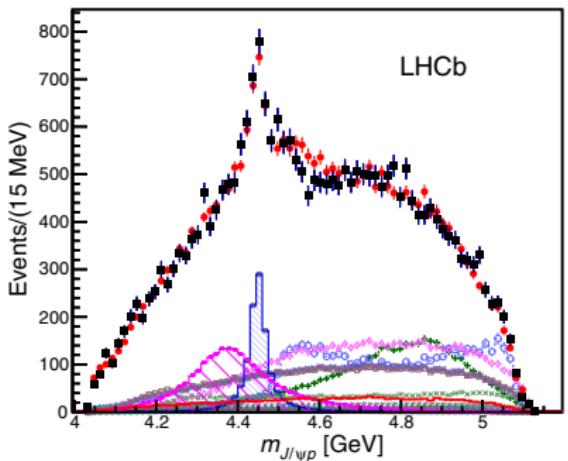


[CMS-PAS-BPH-21-003], [ATLAS-CONF-2022-040]

PENTAQUARKS

Pentaquarks: the origins

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

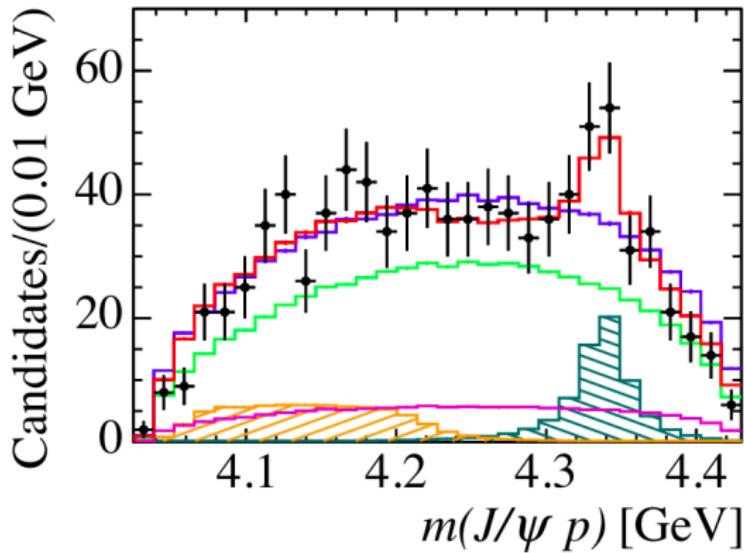


- 14 well established $\Lambda^* \rightarrow pK^-$ resonances in the amplitude model
- The large $P_c(4450)^+$ contribution is resolved into two separate peaks
- All states lie just below some mass threshold - **molecules?**
- Confirmed also with Legendre polynomial expansion

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

New pentaquarks: $P_c(4337)^+$

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



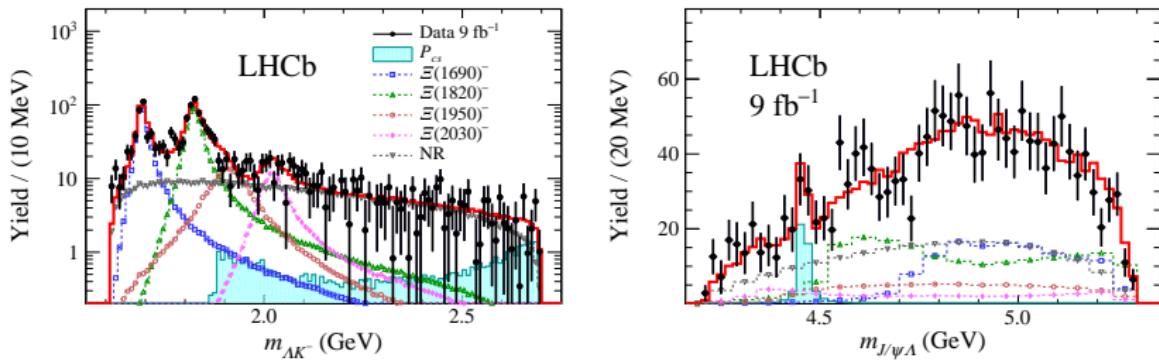
Evidence for a structure in $J/\psi p$ and $J/\psi p\bar{p}$

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

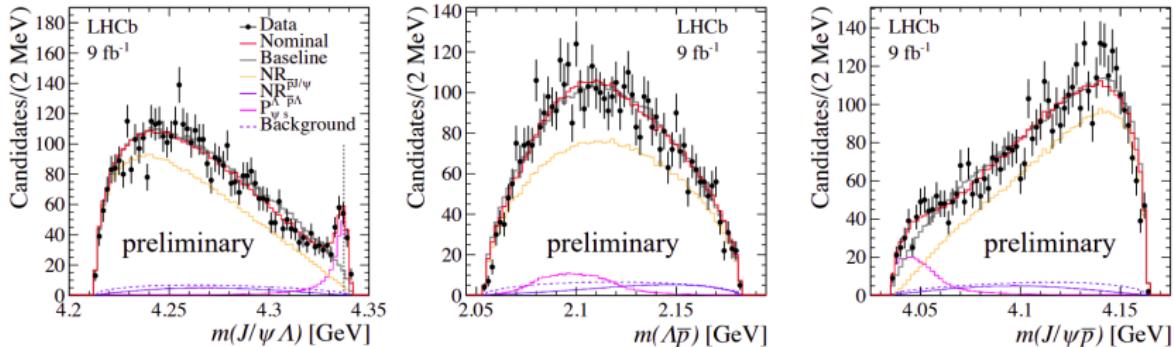
Amplitude analysis of $\Xi_b^0 \rightarrow J/\psi \Lambda K^-$ decays



- 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

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

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



- 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

[arXiv:2210.10346], submitted to PRL

LOOKING INTO THE FUTURE

Prospects for the future: T_{cc} , T_{bc} and T_{bb}

T_{cc} : multiplicity dependence unexpected, what is the production mechanism?

- Study production in pA and AA collisions

T_{bc} and T_{bb} : stable and weakly-decaying states?

- 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

Prospects for the future: $X(6900)$

Double J/ψ final state is perfectly suitable for all LHC experiments

- How about other charmonia? $J/\psi\psi'$, $J/\psi\chi_c$...
- It would be interesting also to check production in pA and AA environments

Prospects: open-charm and pentaquarks



- Many new states are expected to exist
- With LHC Run 3 and beyond, many new channels will be available for analysis
- Mass resolution and PID are essential especially for pentaquarks
- Prompt production still unobserved
- Amplitude analysis is challenging now and it will get worse!

Conclusions

- 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