Exotic hadron spectroscopy at LHCb

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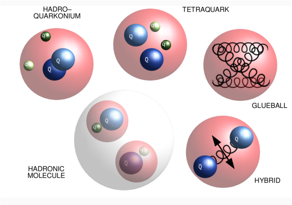
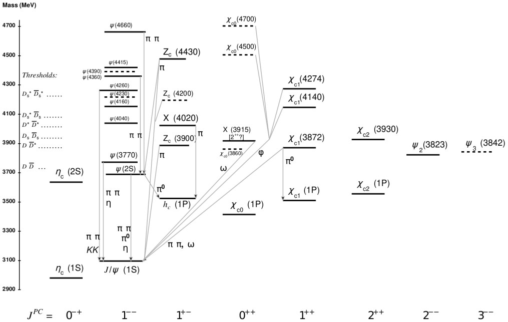
Introduction to exotic hadron spectroscopy

- Exotic hadrons predicted since proposal of quark model [PL 8 (1964) 214-215]
    - Tetraquarks ($q\bar{q}q\bar{q}$)
    - Pentaquarks ($qqqq\bar{q}$)
    - Glueballs, hybrids….
- Decades-long hunt for such states
- Several charmonium tetraquark candidates since 2003 [PRL 91 262001 etc…]
- Bottomonium tetraquark candidates seen by Belle in 2012 [PRL 108 122001]
- Charmonium pentaquark candidates seen by LHCb in 2015/2019 [PRL 115 072001, PRL 112 222001]
- This year: four-charm and open charm tetraquark candates seen by LHCb



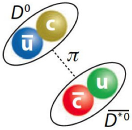
Graphics: C. Hanhart

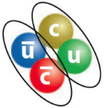


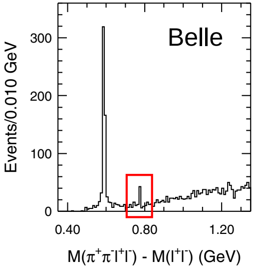
- $c\bar{c}u\bar{u}$ Study of the $\chi_{c1}(3872)$ lineshape
- $c\bar{c}c\bar{c}$ Structure in J/ψ-pair mass spectrum
- $cs\bar{d}\bar{u}$ Observation of exotic structure in $B^+ \to D^+ D^- K^+$
- $c\bar{c}uud$ Search for $P_c(4312)^+ \to \eta_c(1S)p$

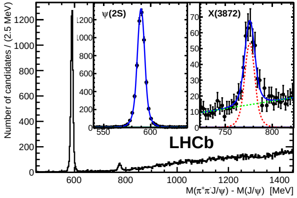
$c\bar{c}u\bar{u}$

- First well-established exotic hadron candidate
- Observed by Belle in 2003 as a narrow peak in $m_{J/\psi\pi\pi}$ from $B^+ \to K^+ J/\psi \pi^+\pi^-$ decays [PRL 91, 262001 (2003)]
- Confirmed by many other experiments
- Breit–Wigner mass right on $D^{*0}\bar{D}^0$ threshold: $m_{\chi_{c1}} - m_{\bar{D}^0} - m_{D^{*0}} = 0.01 \pm 0.18$ MeV
- Narrow width $\Gamma < 1.2$ MeV$/c^2$
- $J^{PC} = 1^{++}$ measured by LHCb [PRL 110, 222001 (2013), PRD 92, 011102 (2015)]
- No unambiguous interpretation yet: compact tetraquark, mesonic molecule, admixture...









Study of the $\chi_{c1}(3872)$ lineshape

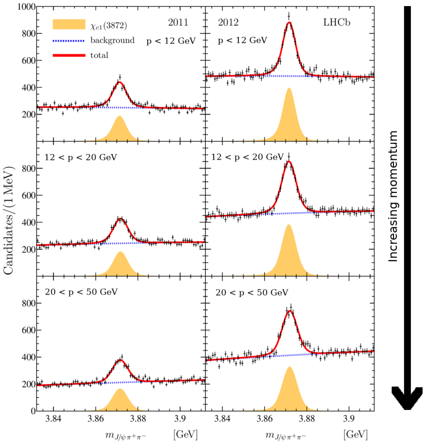
[arXiv:2005.13419, accepted by PRD]

- $b \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)X$ inclusive decays, full Run 1 dataset
- Simultaneous fit to 6 data samples (2 years and 3 di-pion momentum bins)
- Signal: lineshape convoluted with resolution
- Either Breit-Wigner (BW) or a Flatté-inspired model to account for the $\bar{D}^0 D^{*0}$ threshold
  - Indistinguishable after resolution ($\sigma < 100\,\text{keV}$)

$$m^{BW}_{\chi_{c1}(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010 \text{ MeV}$$

$$\Gamma^{BW}_{\chi_{c1}(3872)} = 1.39 \pm 0.24 \pm 0.10 \text{ MeV}$$

- Non-zero BW width



(Bonn-LHCb analysis)

Study of the $\chi_{c1}(3872)$ lineshape

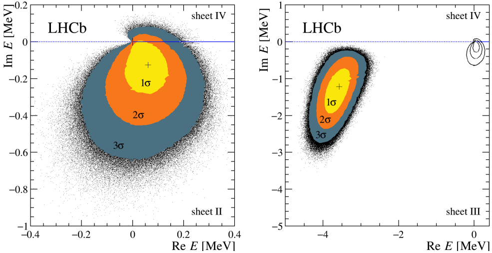
Since

[arXiv:2005.13419, accepted by PRD]

1. $\chi_{c1}(3872) \to D^{*0}\bar{D}^0$ observed
2. $D^{*0}\bar{D}^0$ threshold is within the natural width of the $\chi_{c1}(3872)$ lineshape

$\Rightarrow$ Breit–Wigner description not usable: use Flatté to account for opening of $D^{*0}\bar{D}^0$ channel

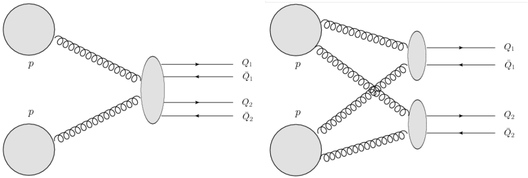
- No longer straightforward to read off mass and width. Instead look for poles
  - Two poles found (as expected)
- Pole positions shed light on how to interpret the state
  - Bound state preferred with binding energy $< 100\,\text{keV}$
  - Virtual assignment not excluded



$$c\bar{c}c\bar{c}$$

Structure in J/ψ-pair mass spectrum

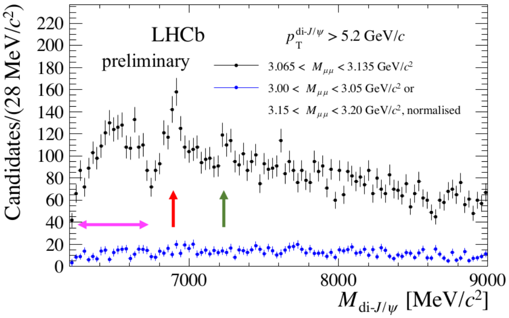
- Predictions for the masses of a 4-charm state: 5.8-7.4 GeV
- Clean experimental environment for J/ψ-pair analysis
- J/ψ pairs from double-parton scattering (DPS) or single-parton scattering (SPS)

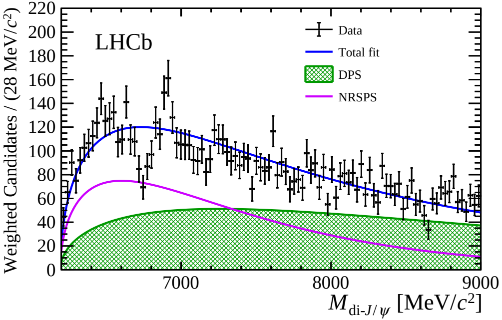


Structure in J/ψ-pair mass spectrum

[arXiv:2006.16597, accepted by Science Bulletin]

- Visible structure in the di-J/ψ mass spectrum
  - Threshold enhancement
  - Dip below 6.9 GeV
  - Narrow peak at 6.9 GeV
  - Hint of something at 7.15 GeV
- Background-subtracted data not well described by DPS + NR SPS



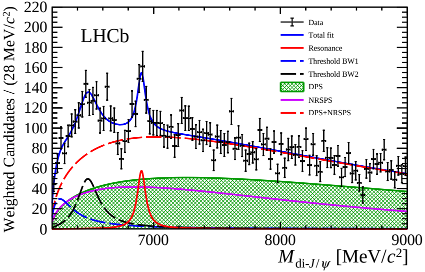


Structure in J/ψ-pair mass spectrum

[arXiv:2006.16597, accepted by Science Bulletin]

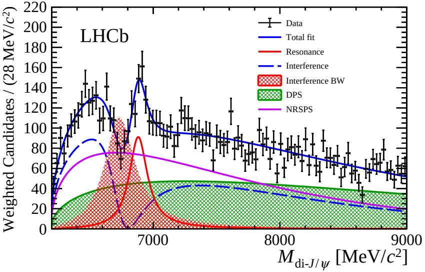
Structure not well decribed by single resonance. Many models tried, here are two:

No interference



- Three non-interfering BW peaks
- $m_{X(6900)} = 6905 \pm 11 \pm 7$ MeV
- $\Gamma_{X(6900)} = 80 \pm 19 \pm 33$ MeV

SPS-BW interference

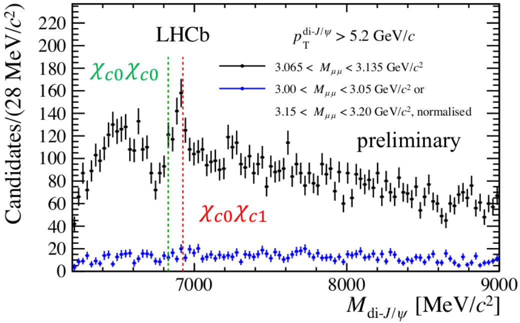


- Two BW peaks: one interferes with NR SPS
- $m_{X(6900)} = 6886 \pm 11 \pm 11$ MeV
- $\Gamma_{X(6900)} = 168 \pm 33 \pm 69$ MeV

If confirmed $\Longrightarrow$ first observation of an exotic hadron entirely composed of heavy quarks.

Structure in J/ψ-pair mass spectrum

- $\chi_c - \chi_c$ thresholds may play a role

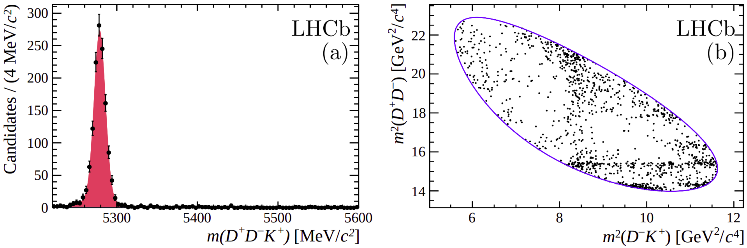


$$cs\bar{d}\bar{u}$$

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

[arXiv:2009.00025]

- ✓ D^+D^- resonance $\Rightarrow c\bar{c}$
- ! D^-K^+ resonance $\Rightarrow \overline{c}\overline{s}ud$
- ✗ D^+K^+ resonance $\Rightarrow$ doubly charged

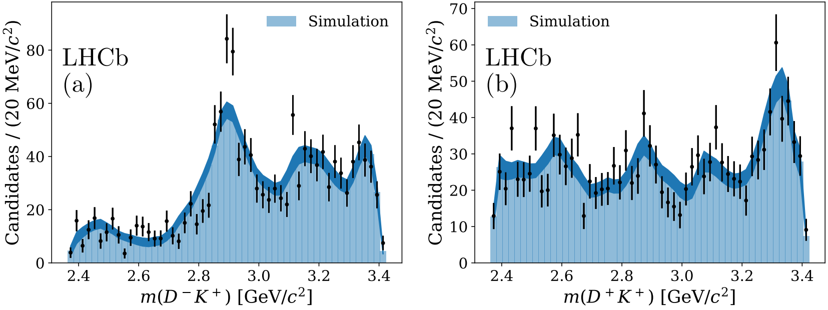


Check $c\bar{c}$-only hypothesis using Legendre expansion in $\cos\theta_{DD}$ up to order 4 (allowing $L \leq 2$)

$$\frac{dN^k}{d(\cos\theta_{DD})} = \sum_{l=0}^{l_{max}} a_l^k P_l(\cos\theta_{DD}), \text{ where } a_l^k = \frac{2}{N_{MC}^k} \sum_{i=1}^{N_{data}^k} P_l(\cos\theta_{DD}^i)$$

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

[[arXiv:2009.00025]]

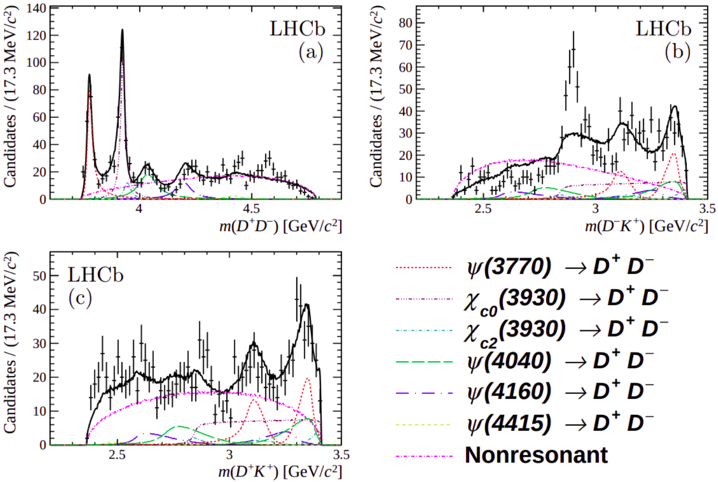


- Data not well described by Legendre moments from resonances up to $J = 2$
- Higher-spin resonances are suppressed
- The $D^+ K^+$ spectrum does not present any unexplained structure
- The hypothesis of only $D^+ D^-$ resonances up to spin 2 are present is rejected with a significance of 3.9σ
- Amplitude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

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

[arXiv:2009.00026]

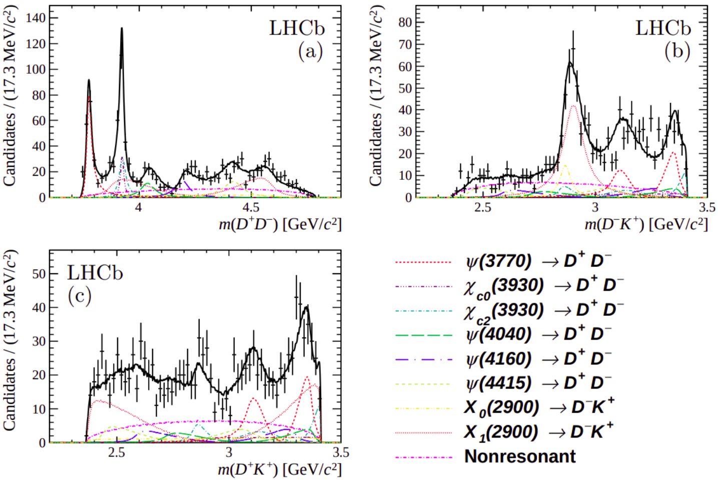
- All well-motivated *DD* resonances are included
  - $\chi_{c0}(3930)$ and $\chi_{c2}(3930)$ are seen
- Data not well described by considering only *DD* resonances



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

[arXiv:2009.00026]

- Two $D^- K^+$ Breit-Wigners added to improve significantly the fit
  - Spin-0 and spin-1 with roughly the same mass



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

[arXiv:2009.00026]

- No evidence for the $\chi_{c0}(3860) \to D^+ D^-$ state reported by Belle

- The $\chi_{c2}(3930)$ contribution is better described by two states
- $m_{\chi_{c0}(3930)} = 3923.8 \pm 1.5 \pm 0.4$ MeV, $\Gamma_{\chi_{c0}(3930)} = 17.4 \pm 5.1 \pm 0.8$ MeV
- $m_{\chi_{c2}(3930)} = 3926.8 \pm 2.4 \pm 0.8$ MeV, $\Gamma_{\chi_{c2}(3930)} = 34.2 \pm 6.6 \pm 1.1$ MeV

- 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

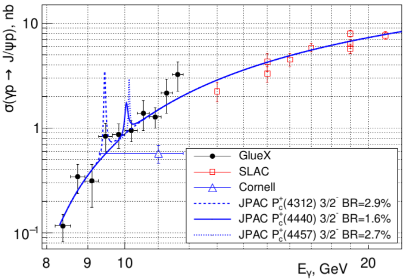
Minimal quark content: $[cs\bar{d}\bar{u}]$

- Each quark has a different flavour!

$c\bar{c}uud$

Where do pentaquarks get their width?

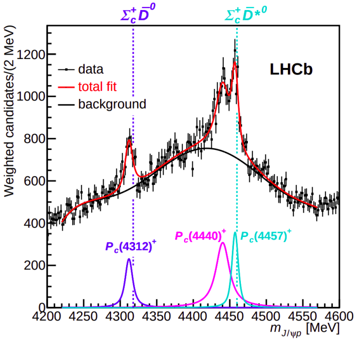
- Charmonium-pentaquarks (P_c) states seen by LHCb in 2015 and 2019 [PRL 115 072001, PRL 112 222001]
- Photoproduction experiments put upper limit on partial width $\Gamma(P_c \to J/\psi\, p) < 2 \sim 5\%$ [PRL 123 7, 072001]



- Expect to see P_c in other channels with larger branching fractions
  - If molecules, should couple strongly to channels with open charm, *e.g.* $\Lambda_c^+\bar{D}^0, \Sigma_c^+\bar{D}^0, \Lambda_c^+\bar{D}^{*0}$
- Focus of analysis topics in the Bonn LHCb group

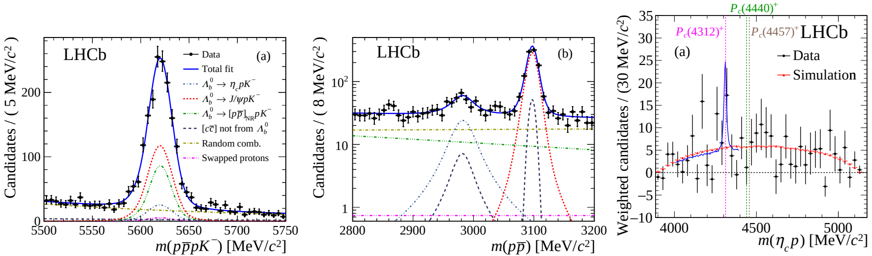
Search for $P_c(4312)^+ \to \eta_c(1S)p$

- $P_c(4312)^+ \to J/\psi p$ observed in $\Lambda_b^0 \to J/\psi p K^-$
- Mass slighly below $\Sigma_c^+ \overline{D}^0$ threshold, expected for a molecular state
- If a $\Sigma_c^+ \overline{D}^0$ molecule, branching fraction to $\eta_c(1S)p$ should be $\sim 3\times$ than to $J/\psi\, p$



Search for $P_c(4312)^+ \to \eta_c(1S)p$

- Dataset: 5.5 fb^{-1} collected at $\sqrt{s} = 13$ TeV
- Both η_c and J/ψ (normalisation) reconstructed as pp
- No evidence of pentaquark contributions, limit set at 90% CL (mystery deepens...)
- $\mathscr{R}_{\eta_c p} = \dfrac{\mathscr{B}(\Lambda_b^0 \to P_c(4312)^+ K^-) \times \mathscr{B}(P_c(4312)^+ \to \eta_c(1S)p)}{\mathscr{B}(\Lambda_b^0 \to \eta_c p K^-)} < 24\%$



First observation of the decay $\Lambda_b^0 \to \eta_c p K^-$ with significance of 7.7σ

$\mathscr{B}(\Lambda_b^0 \to \eta_c p K^-) = (1.06 \pm 0.16 \pm 0.06^{+0.22}_{-0.19}(\mathscr{B})) \times 10^{-4}$

Conclusions

- Explosion of exotic hadron candidates in the last decades shows no sign of slowing down
- LHCb has established itself as a major contributor
- Precision studies of the $\chi_{c1}(3872)$ bring us closer to understanding its nature
- New exotic quark contents ($cc\overline{c}\overline{c}$, $cs\overline{u}\overline{d}$) found this year
- Run 3 of LHC will see a much larger dataset for LHCb to explore

Thanks for listening