LHCb: exotic spectroscopy

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on behalf of the LHCb collaboration

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(virtual)
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Summary of the talk

$\chi_{c1}(3872)$

- Study of the lineshape of the $\chi_{c1}(3872)$ state
- Study of the $\psi_2(3823)$ and $\chi_{c1}(3872)$ states in $B^+ \to (J/\psi\ \pi^+\pi^-)K^+$ decays

$X(6900)$

- Observation of structure in the J/ψ-pair mass spectrum

$X(2900)$

- A model-independent study of resonant structure in $B^+ \to D^+D^-K^+$ decays
- Amplitude analysis of the $B^+ \to D^+D^-K^+$ decay

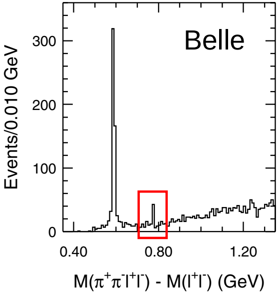
Pentaquarks searches

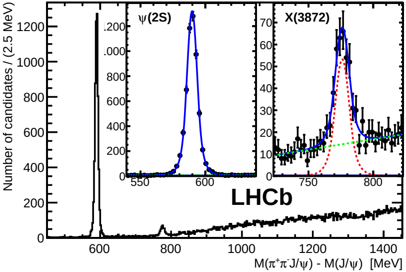
- First observation of the decay $\Lambda_b^0 \to \eta_c(1S)pK^-$
- Observation of the $\Lambda_b^0 \to \Lambda_c^+K^+K^-\pi^-$ decay

STUDY OF $\chi_{c1}(3872)$ PROPERTIES

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

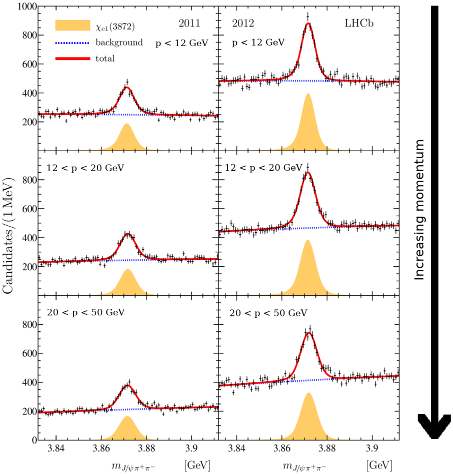




[PRL 91, 262001 (2003)], [PRL 110, 222001 (2013)], [PRD 92, 011102 (2015)]

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

- $b \to (\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)X$ inclusive decays, full Run 1 dataset
- Measure the mass difference $\Delta m = m_{\chi_{c1}(3872)} - m_{\psi(2S)}$
- Simultaneous fit to 6 data samples (2 years and 3 momentum bins)
- Signal: lineshape convoluted with resolution
- Either Breit-Wigner (BW) or a Flatté-inspired model to account for the $\overline{D}^0 D^{*0}$ threshold
- Indistinguishable after resolution
- Non-zero BW width



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

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

[arXiv:2005.13419], accepted for publication on Physical Review D

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

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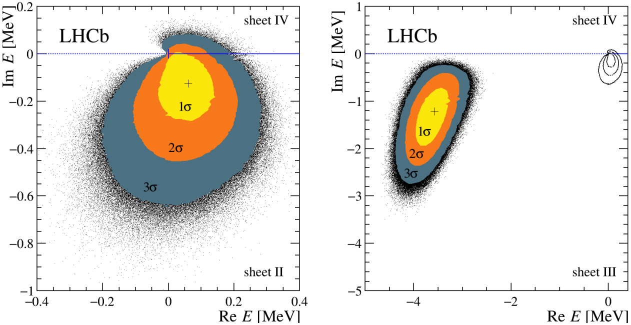
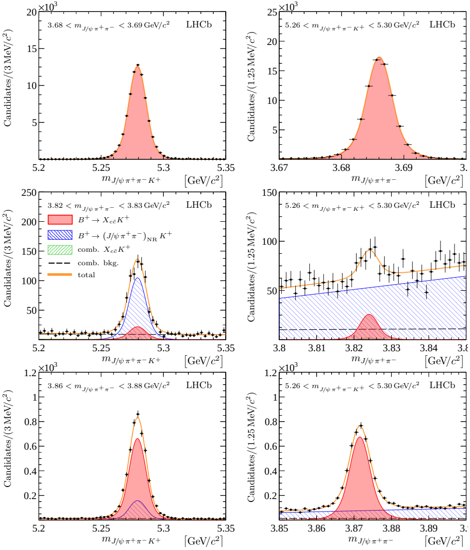
Study of the analytic structure of the amplitude near $\overline{D}^0 D^{*0}$ threshold

- Complex amplitude is a function of $\sqrt{E} \Longrightarrow$ two-sheeted Riemann surface
- Two poles are found using the Flatté amplitude for the $\overline{D}^0 D^{*0}$ channel
- One (left) on the physical sheet, the other (right) on the unphysical sheet
- Bound state preferred, virtual assignment cannot be ruled out
- Binding energy $E_b < 100$ keV, $Prob$(compact component) $< 33\%$



$\psi_2(3823)$ and $\chi_{c1}(3872)$ in $B \to J/\psi\pi^+\pi^- K^+$

- $\psi_2(3823) \to \chi_{c1}\gamma$ only final state observed with more than 5σ (BESIII)
- Full Run 1 + Run 2 dataset
- Using both $\psi(2S) \to J/\psi\pi\pi$ and $\chi_{c1}(3872) \to J/\psi\pi\pi$ as normalisation channels
- This allows to measure $\chi_{c1}(3872)$ properties as well
- 2D fit to m_{B+} and $m_{J/\psi\pi^+\pi^-}$
- $\psi_2(3823)$ significance: 5.1σ
- $\chi_{c1}(3872)$ is described by a Breit-Wigner convoluted with a resolution function



[PRL 115, 011803 (2015)], [JHEP 08 (2020) 123]

$\psi_2(3823)$ and $\chi_{c1}(3872)$ in $B^+ \to J/\psi\pi^+\pi^- K^+$

Calculation of branching fractions ratios, where $\mathcal{R}_Y^X = \frac{\mathcal{B}(B^+ \to X K^+) \times \mathcal{B}(X \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B^+ \to Y K^+) \times \mathcal{B}(Y \to J/\psi\pi^+\pi^-)}$:

- $\mathcal{R}_{\chi_{c1}(3872)}^{\psi_2(3823)} = (3.56 \pm 0.67 \pm 0.11) \times 10^{-2}$ **First measurement**
- $\mathcal{R}_{\psi(2S)}^{\psi_2(3823)} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3}$ **First measurement**
- $\mathcal{R}_{\psi(2S)}^{\chi_{c1}(3872)} = (3.69 \pm 0.07 \pm 0.06) \times 10^{-3}$ **Most precise**

Mass and width of the $\psi_2(3823)$ state:

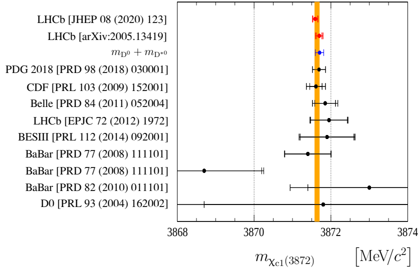
- $m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01(m_{\psi(2S)})$ MeV **Most precise**
- $\Gamma_{\psi_2(3823)} < 5.2$ MeV at 90% CL **World best limit**

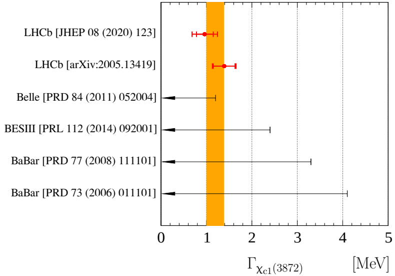
Mass, binding energy and width of $\chi_{c1}(3872)$:

- $m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01(m_{\psi(2S)})$ MeV **Most precise**
- $\Delta m_{\chi_{c1}(3872)} = m_{\overline{D}^0} + m_{D^{*0}} - m_{\chi_{c1}(3872)} = 0.12 \pm 0.13$ MeV
- $\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21$ MeV **Non-zero width**

The $\chi_{c1}(3872)$ parameters are in agreement with the ones extracted from the lineshape study

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





Yellow vertical bands correspond to the new world averages:

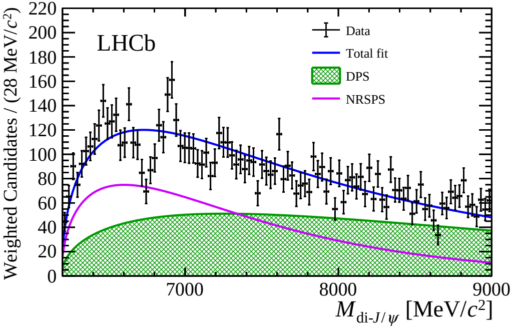
$$m^{BW}_{\chi_{c1}(3872)} = 3871.64 \pm 0.06 \text{ MeV}$$

$$\Gamma^{BW}_{\chi_{c1}(3872)} = 1.19 \pm 0.19 \text{ MeV}$$

OBSERVATION OF $X(6900)$

Structure in J/ψ-pair mass spectrum

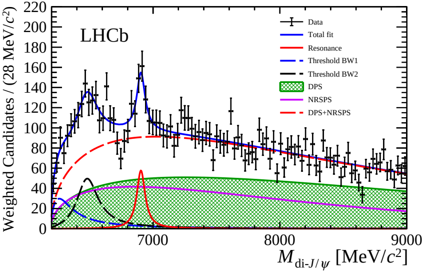
- Predictions for the masses of a 4-charm state: 5.8-7.4 GeV
- Clean experimental environment for J/ψ-pair analysis
- Full Run 1 + Run 2 dataset
- Irreducible backgrounds: double-parton scattering (DPS) + non-resonant single-parton scattering (SPS)
- Background-subtracted data are clearly not well described by DPS+SPS



[arXiv:2006.16597], accepted for publication on Science Bulletin

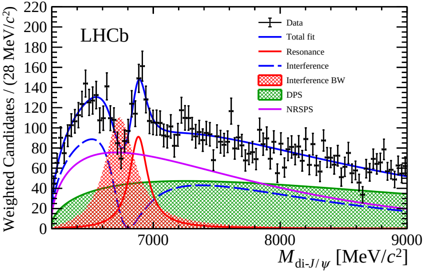
Structure in J/ψ-pair mass spectrum

No interference



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

SPS-BW interference



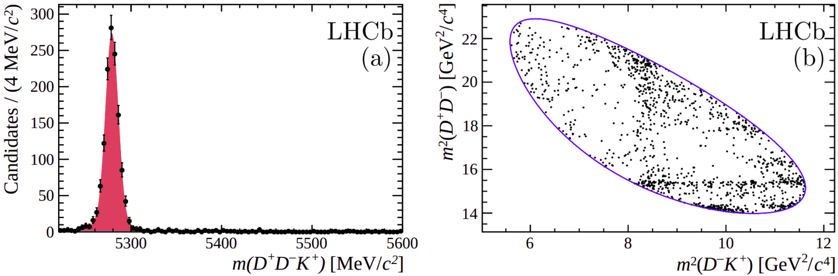
- Threshold enhancement described by interference
- One BW, interference with SPS
- $m_{X(6900)} = 6886 \pm 11 \pm 11$ MeV
- $\Gamma_{X(6900)} = 168 \pm 33 \pm 69$ MeV
- Significance $>5\sigma$

Further studies are required to investigate the nature of X(6900).
If confirmed $\Longrightarrow$ first observation of an exotic hadron entirely composed by heavy quarks of the same flavour

OBSERVATION OF $X(2900)$

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

Study of the resonant structure of $B^+ \to D^+ D^- K^+$, expanding the DD helicity angle in terms of Legendre polynomials



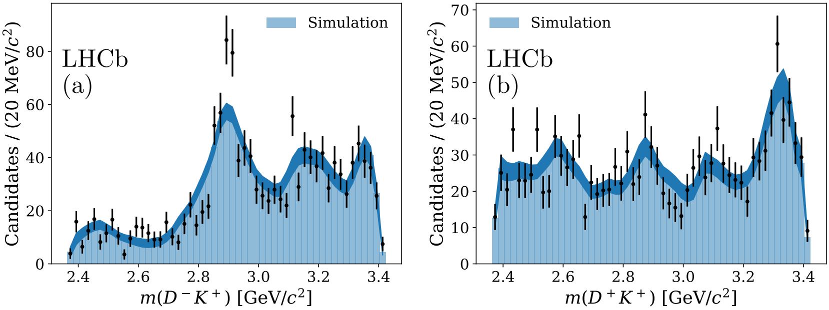
A non-resonant simulated sample is generated and, for the k-th mass bin containing N^k candidates, weighted according to

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

l_{max} is twice the maximum spin allowed for any $D^- K^+$ resonance, set to 4

[arXiv:2009.00025]

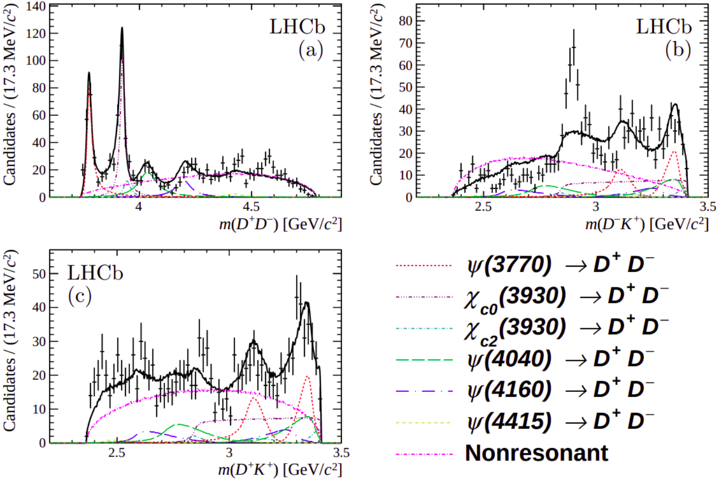
Model-independent study of $B^+ \to D^+D^-K^+$



- Full Run 1 + Run 2 dataset
- 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
- Amplitude analysis is necessary for a more detailed study

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

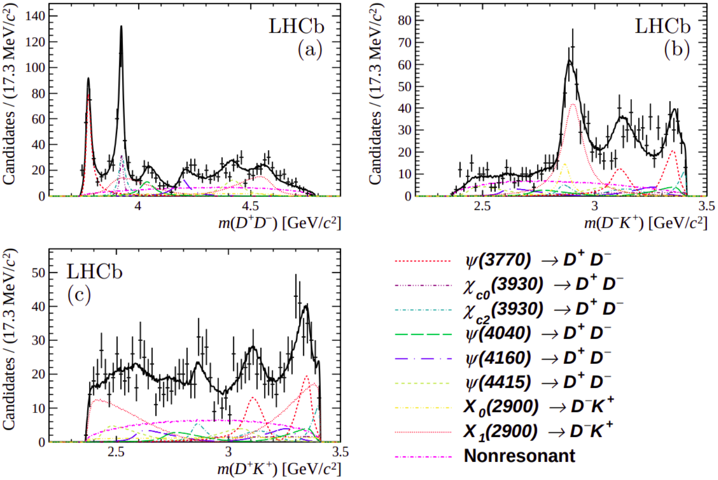
- Amplitude model constructed with the isobar formalism
- Relativistic BW with Zemach tensors and Blatt–Weisskopf barrier factor
- All well-motivated DD resonances are included



[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



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

- 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

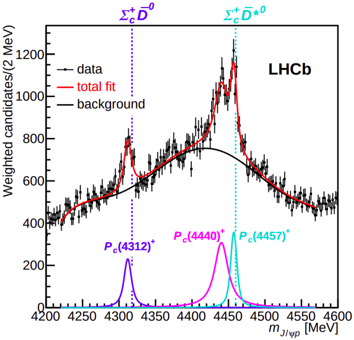
If interpreted as resonances $\Longrightarrow$ first clear observation of exotic hadrons with open flavour, and without a heavy quark-antiquark pair

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

SEARCHES FOR PENTAQUARK STATES

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
- $P_c(4312)^+ \to \eta_c(1S)p$ rate varies with the binding model
- If $P_c(4312)^+$ is a $\Sigma_c^+ \overline{D}^0$ molecule it is predicted to have a larger BR, $\mathcal{B}(P_c(4312)^+ \to \eta_c(1S)p) \sim 3 \times \mathcal{B}(P_c(4312)^+ \to J/\psi p)$



[PRL 112, 222001 (2019)]

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

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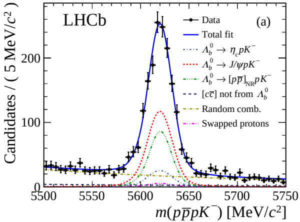
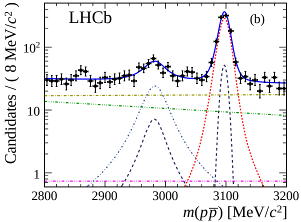
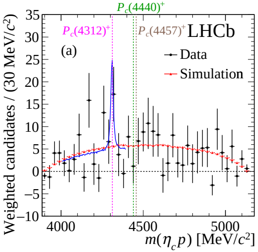
- Dataset: 5.5 fb^{-1} collected at $\sqrt{s} = 13$ TeV
- Both η_c and J/ψ (normalisation) reconstructed as pp
- No evidence of pentaquark contributions, limit set at 90% CL
- $\mathcal{R}_{\eta_c p} = \frac{\mathcal{B}(\Lambda_b^0 \to P_c(4312)^+ K^-) \times \mathcal{B}(P_c(4312)^+ \to \eta_c(1S)p)}{\mathcal{B}(\Lambda_b^0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







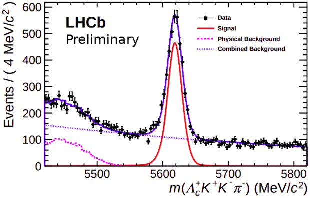
First observation of the decay $\Lambda_b^0 \to \eta_c p K^-$ with significance of 7.7σ
$\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-) = (1.06 \pm 0.16 \pm 0.06^{+0.22}_{-0.19}(\mathcal{B})) \times 10^{-4}$

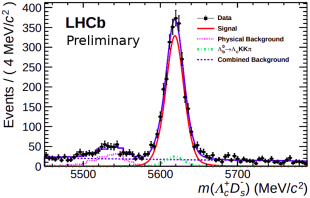
[arXiv:2007.11292]

Search for $P_{cs}^{++} \to \Lambda_c^+ K^+$

$\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decays used to search for possible single-charm pentaquarks as narrow peaks in the $\Lambda_c^+ K^+$ invariant mass

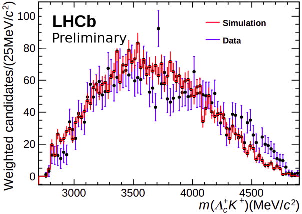
- Run 1 dataset, with $\Lambda_c^+ \to p K^- \pi^+$ and $D_s^- \to K^+ K^- \pi^-$





- First observation of the $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$ decay
- $\dfrac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (9.26 \pm 0.29 \pm 0.46 \pm 0.26(D_s^-)) \times 10^{-2}$

Background-subtracted data show no obvious structure in the $\Lambda_c^+ K^+$ invariant mass



CONCLUSIONS

Conclusions

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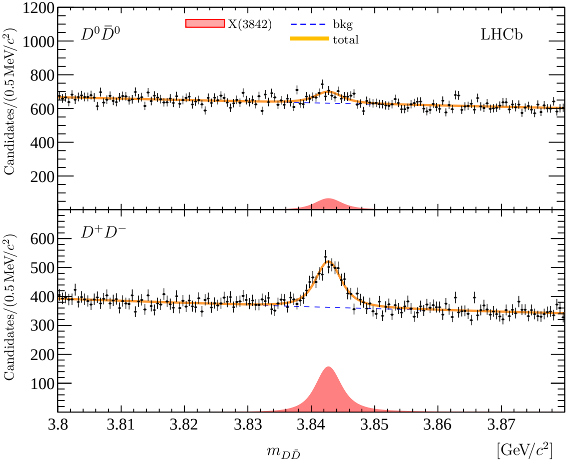
- Exotic spectroscopy is an extremely rich and productive field, and LHCb has established itself to be a major player
- One step closer to finally understanding the $\chi_{c1}(3872)$: the position of the poles indicates a preference towards a $\overline{D}^0 D^{*0}$ bound state
- Precision on the mass measurement has improved by a factor of 6
- Non-zero width measured for the first time with two different methods
- New tetraquark configurations observed: 4-charm and open-charm states
- The search for more pentaquarks continues
- Run 3 will start with an upgraded detector and a software-only trigger
- Many new exciting results awaiting

BACKUP

Near $D\overline{D}$ spectroscopy at LHCb



No evidence of $\chi_{c0}(3860) \to D\overline{D}$ at LHCb

[JHEP 07 (2019) 035]