Spectroscopy results from the LHC

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FPCP 2020
Opportunities to test QCD and its effective models

- Various theoretical models probing QCD make predictions on the heavy hadron production and properties
- New states/decays provide inputs to theory
- Understanding the structure and properties of hadrons from QCD remains a challenge due to non-perturbative long distance effects involved
- Many observed states which are not fitting the standard picture still lack of interpretation (e.g. exotic states)

But also to be able to fully understand processes which are the Standard Model background in the search for new physics
LHCb, ATLAS and CMS experiments

- LHCb, ATLAS and CMS are complementary in heavy flavour spectroscopy studies
  - ATLAS and CMS cover high $p_T$ and low rapidity range
  - LHCb covers low $p_T$ and higher rapidity region
  - In addition LHCb has an excellent vertexing and particle identification capabilities: dedicated to heavy flavour physics

[arXiv: 0708.0551]
Charmed baryons
Excited $\Xi^0_c$ states at LHCb [arXiv:2003.13649]

- Investigate a different charm spectrum to understand the nature of the excited $\Omega_c$ states decaying to $\Xi^+_c K^-$ [LHCb PRL118 (2017) 182001, Belle PRD97(2018) 051102]

- Search for analogous excited $\Xi^0_c$ resonances in the $\Lambda^+_c K^-$ spectrum with $\Lambda^+_c \rightarrow p K^- \pi^+$

- Data sample: 5.6 fb$^{-1}$ in 2016-2018 at $\sqrt{s} = 13$ TeV

- Mass spectrum already studied by Belle [EPJC78(2018)252] and BaBar [PRD77 (2018) 031101, PRD77 (2008) 012002]: peaking structure interpreted as the $\Xi_c(2930)^0$

  - $\sim 125$M $\Lambda_c$ signal, purity: 93%

  - $\Xi^0_c$ reconstructed combining $\Lambda_c$ selected candidates with a $K^-$ candidate from primary vertex (PV)

  - Combinatorial background due to the large number of $K^-$ candidates: optimizing selection on particle identification response/$p_T$


Shown only 20% of the full selected candidates
Three new peaks are observed for the first time

Relativistic BW convolved with mass-resolution function for signals

Several feed-down decays considered

Background modelled by empirical function
Three new peaks are observed

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$\Xi_c(2923)^0$</td>
<td>$142.91 \pm 0.25 \pm 0.20$</td>
<td>$2923.04 \pm 0.25 \pm 0.20 \pm 0.14$</td>
<td>$7.1 \pm 0.8 \pm 1.8$</td>
</tr>
<tr>
<td>$\Xi_c(2939)^0$</td>
<td>$158.45 \pm 0.21 \pm 0.17$</td>
<td>$2938.55 \pm 0.21 \pm 0.17 \pm 0.14$</td>
<td>$10.2 \pm 0.8 \pm 1.1$</td>
</tr>
<tr>
<td>$\Xi_c(2965)^0$</td>
<td>$184.75 \pm 0.26 \pm 0.14$</td>
<td>$2964.88 \pm 0.26 \pm 0.14 \pm 0.14$</td>
<td>$14.1 \pm 0.9 \pm 1.3$</td>
</tr>
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</table>

Two structures observed in the vicinity of the previously observed $\Xi_c(2930)^0$: $\Xi_c(2923)^0$ and $\Xi_c(2939)^0$

- broad $\Xi_c(2930)^0$ could be the overlap of these two narrower states?

$\Xi_c(2965)^0$ is close in mass to the $\Xi_c(2970)^0$

- Mass and width are lower for $\Xi_c(2965)^0$ wrt $\Xi_c(2970)^0$
- $\Xi_c(2970)^0$ observed in different decay modes (not in $\Lambda_c^+ K^-$) by Belle [EPJC78(2018)252] and BaBar [PRD77 (2018) 031101, PRD77 (2008) 012002]
- Different baryons?

More studies required...

Equal spacing rule [Phys.Rev.125 (1962) 1067, Prog.Theor.Phys,27 (1962) 949] seems to work for the new states: relation to the excited $\Omega_c^0$ baryons observed in the $\Xi_c^+ K^-$ spectrum
Beauty baryons
Excited $\Omega_b^-$ resonances at LHCb \cite{PRL124 (2020) 082002}

- Several theoretical models aiming to describe observed $\Omega_c$ peaks: predictions also on $\Omega_b$ states

- Search for analogous excited $\Omega_b$ states in the $\Xi_b^0 K^-$ spectrum using full Run 1 + 2 data sample (9 fb$^{-1}$)

- $\Xi_b$ candidate is reconstructed pairing a $\Xi_c$ (reconstructed in $\rightarrow pK^-\pi^+$ final state) with a $\pi^-$ candidate: selection based on topology of the decays and particle identification requirements

- $\Xi_b$ candidate is combined then with a $K^-$ candidate from PV: large combinatorial background suppressed using particle identification requirement on the bachelor kaon
Simultaneous fit to right-sign (RS) and wrong-sign (WS) spectra

Four peaks modeled with a relativistic BW convolved with a Gaussian resolution function in the RS spectrum
Excited $\Omega_b^-$ resonances: results  

<table>
<thead>
<tr>
<th>$\Omega_b(n)$</th>
<th>$\delta M_{\text{peak}}$ [MeV]</th>
<th>Mass [MeV]</th>
<th>Width [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b(6316)^-$</td>
<td>523.74 ± 0.31 ± 0.07</td>
<td>6315.64 ± 0.31 ± 0.07 ± 0.50</td>
<td>&lt;2.8(4.2) 2.1 $\sigma$</td>
</tr>
<tr>
<td>$\Omega_b(6330)^-$</td>
<td>538.40 ± 0.28 ± 0.07</td>
<td>6330.30 ± 0.28 ± 0.07 ± 0.50</td>
<td>&lt;3.1(4.7) 2.6 $\sigma$</td>
</tr>
<tr>
<td>$\Omega_b(6340)^-$</td>
<td>547.81 ± 0.26 ± 0.05</td>
<td>6339.71 ± 0.26 ± 0.05 ± 0.50</td>
<td>&lt;1.5(1.8) 6.7 $\sigma$</td>
</tr>
<tr>
<td>$\Omega_b(6350)^-$</td>
<td>557.98 ± 0.35 ± 0.05</td>
<td>6349.88 ± 0.35 ± 0.05 ± 0.50</td>
<td>&lt;2.8(3.2) 6.2 $\sigma$</td>
</tr>
</tbody>
</table>

Global significances taking into account look-elsewhere effect

- Possible interpretations
  - Excited $\Omega_b^-$ states ($L = 1$ angular momentum excitations or $n = 2$ radial excitations)
  - Decay of higher-mass excited $\Omega_b^-$ state: $\Omega_b^{**-} \rightarrow \Xi_b' ^0 (\rightarrow \Xi_b ^0 \pi^0)K^-$ where $\pi^0$ is undetected and assuming $m_{\Xi_b'} > m_{\Xi_b^0} + m_{\pi^0}$
  - Spectra observed in $\Xi_b^0 K^-$ and $\Xi_c^0 K^-$ are similar as expected from heavy quark symmetry
A number of excited $\Lambda_b$ baryon states are predicted with masses in the range 5.9-6.4 GeV

$\Lambda_b^0 \pi^+ \pi^-$ mass spectrum extensively studied

Low mass region (near threshold) studied by LHCb with $1 \text{ fb}^{-1}$: two narrow $\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$ states [PRL109 (2012) 172003], heavier state confirmed by CDF [PRD88 (2013) 071101]

Recently high mass $\Lambda_b^0 \pi^+ \pi^-$ spectrum (6.10-6.25 GeV) with Run1+Run2 data sample ($9 \text{ fb}^{-1}$) studied by LHCb [PRL123 (2019) 152001]

Intermediate mass region studied by CMS [PLB803(2020)135345] with 2016-2018 data corresponding to $140 \text{ fb}^{-1}$ and LHCb [2002.05112] with Run1+Run2 data sample ($9 \text{ fb}^{-1}$)
Excited $Λ_b^0$ baryons

  - $Λ_b^0$ candidates are reconstructed in $Λ_c^+π^−$ and $J/ψpK^−$ final states
  - Yield for $Λ_b^0 → J/ψpK^−$ is smaller: used as cross-check

- CMS [PLB803 (2020) 135345]:
  - $Λ_b^0$ candidates reconstructed in $J/ψΛ$ and $ψ(2S)Λ$ final states
  - Add then two prompt pions
Observed clear excess: $\sim 6.15$ GeV

Treated at the beginning as a single broad state

Above $\Sigma_b^{*\pm}\pi^\pm$ threshold: investigate spectrum in three nonoverlapping $\Lambda_b^0\pi^\pm$ regions

- $\Sigma_b^{\pm}$
- $\Sigma_b^{*\pm}$
- Non resonant

Simultaneous fit in the three regions

Two signal hypothesis favored at $7\sigma$ significance

Consistent with a $\Lambda_b(1D)^0$ doublet with $J^P = \frac{3}{2}^+ / \frac{5}{2}^+$

Interpretation as excited $\Sigma_b$ cannot be excluded

$m_{\Lambda_b(6152)^0} = 6146.17 \pm 0.33 \pm 0.22 \pm 0.16$ MeV

$m_{\Lambda_b(6146)^0} = 6152.51 \pm 0.26 \pm 0.22 \pm 0.16$ MeV

$\Gamma_{\Lambda_b(6146)^0} = 2.9 \pm 1.3 \pm 0.3$ MeV

$\Gamma_{\Lambda_b(6152)^0} = 2.1 \pm 0.8 \pm 0.3$ MeV
Narrow peak at $\sim 6500$ GeV consistent with the overlap of the $\Lambda_b(6146)^0$ and $\Lambda_b(6150)^0$ signal

Broad enhancement in the region below 6100 MeV

Fit using three signal functions (BW convolved with a double-Gaussian resolution function) and a smooth background

$M_{\Lambda_b(6146)^0} = 6146.5 \pm 1.9 \pm 0.8 \pm 0.2$ MeV

$M_{\Lambda_b(6152)^0} = 6152.7 \pm 1.1 \pm 0.4 \pm 0.2$ MeV

In good agreement with the LHCb measurements

Broad excess: $M = 6073 \pm 5$ MeV and $\Gamma = 55 \pm 11$ MeV

- It seems to be related to the intermediate $\Sigma_b^{\pm}$ and $\Sigma_b^{*\pm}$ baryon states
- It could be a superposition of several narrow states
$\Lambda_b^\ast 0 \pi^+ \pi^-$ at LHCb

- Simultaneous binned maximum-likelihood fit (200 keV bin width) to the six distributions

\[ m_{\Lambda_b^\ast 0} = 6072.3 \pm 2.9 \pm 0.6 \pm 0.2 \text{ MeV} \]
\[ \Lambda_{\Lambda_b^\ast 0} = 72 \pm 11 \pm 2 \text{ MeV} \]

- Consistent with the CMS broad excess
- Agreement with expectations for the $\Lambda_b(2S)^0$ state
- It could be a superposition of more than one narrow states
- Interpretation of these states as excited $\Sigma_b$ resonances disfavoured

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$\Lambda_b(5912)^0$ and $\Lambda_b(5920)^0$

**LHCb** [arXiv:2002.05112]

- $\Lambda_b(5912)^0$:
  - $M_{\Lambda_b(5912)^0} = 5912.21 \pm 0.03 \pm 0.01 \pm 0.21$ MeV
  - $\Gamma(\Lambda_b(5912)^0) < 0.28$ MeV

- $\Lambda_b(5920)^0$:
  - $M_{\Lambda_b(5920)^0} = 5920.11 \pm 0.02 \pm 0.01 \pm 0.21$ MeV
  - $\Gamma(\Lambda_b(5920)^0) < 0.20$ MeV

**CMS** [PLB803(2020)135345]

- $M_{\Lambda_b(5912)^0} = 5912.32 \pm 0.12 \pm 0.01 \pm 0.17$ MeV
- $M_{\Lambda_b(5920)^0} = 5920.16 \pm 0.07 \pm 0.01 \pm 0.17$ MeV
Exotic states
Exotic spectroscopy

The observation of states with properties inconsistent with pure $c\bar{c}$ and $b\bar{b}$ states raised the interest of the so-called exotic (non-standard) quarkonium states from both the theoretical and experimental point of view starting from the discovery of the $X(3872)$ state.

Then, a plethora of unexpected neutral ($X$, $Y$) and charged ($Z^+$, $P_c^+$) states have been discovered.

The nature and the internal structure of these states are still unclear (molecular/tightly bound): many efforts needed to uncover their nature.

[Rev.Mod.Phys 90 (2018) 015003]

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Pentaquarks
Investigate $J/\psi p$ invariant mass using $\Lambda_b \to J/\psi pK^-$ decays

Update of Run1 analysis

Using Run1+Run2 data (3 + 6 fb$^{-1}$): order of magnitude increase in signal yield

More $J/\psi p$ structures (not significant in the Run1 analysis): $P_c^+ (uudc\bar{c})$ states

- Narrow peak at 4312 MeV with a width comparable to the mass resolution ($\sim 2 \div 3$ MeV)
- The structure at 4450 MeV: resolved into two narrow peaks at 4440 MeV and 4457 MeV

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>(95% CL)</th>
<th>$R$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4312)^+$</td>
<td>4311.9$^{+6.8}_{-0.6}$</td>
<td>$9.8 \pm 2.7^{+3.7}_{-4.5}$</td>
<td>(&lt; 27)</td>
<td>0.30$^{+0.34}_{-0.09}$</td>
</tr>
<tr>
<td>$P_c(4440)^+$</td>
<td>4440.3$^{+4.1}_{-4.7}$</td>
<td>$20.6 \pm 4.9^{+8.7}_{-10.1}$</td>
<td>(&lt; 49)</td>
<td>1.11$^{+0.22}_{-0.10}$</td>
</tr>
<tr>
<td>$P_c(4457)^+$</td>
<td>4457.3$^{+4.1}_{-1.7}$</td>
<td>$6.4 \pm 2.0^{+5.7}_{-1.9}$</td>
<td>(&lt; 20)</td>
<td>0.53$^{+0.15}_{-0.13}$</td>
</tr>
</tbody>
</table>
Motivated by the LHCb observation of $P_c^+(uudcc)$ states

- Run 1 data corresponding to 4.9 and 20.6 fb$^{-1}$ at $\sqrt{s} = 7$ and 8 TeV
- No particle identification: background dominated by $H_b \rightarrow J/\psi h_1 h_2$ where $h_{1,2} = p, K, \pi$ are coming from light neutral mesons ($\Lambda^*, K^*, \phi, f_2$)
- Remove events with $M(\pi K/K\pi) < 1.55$ GeV
- Same-sign two-hadron background is subtracted

N($\Lambda_b^0 \rightarrow J/\psi pK^-$) = 1010 ± 140 in the signal region
Data prefer two or more $P_c^+$'s model

Model with no pentaquarks not excluded: p-value = 0.91%

Two pentaquarks fit: masses and widths compatible with LHCb

<table>
<thead>
<tr>
<th>$P_c^+$</th>
<th>$P_c$</th>
</tr>
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<tbody>
<tr>
<td>$m(P_{c1})$</td>
<td>$4282^{+33}<em>{-26}^{(stat)}^{+28}</em>{-7}^{(syst)}$ MeV</td>
</tr>
<tr>
<td>$\Gamma(P_{c1})$</td>
<td>$140^{+77}<em>{-50}^{(stat)}^{+41}</em>{-33}^{(syst)}$ MeV</td>
</tr>
<tr>
<td>$m(P_{c2})$</td>
<td>$4449^{+93}<em>{-50}^{(stat)}^{+10}</em>{-10}^{(syst)}$ MeV</td>
</tr>
<tr>
<td>$\Gamma(P_{c2})$</td>
<td>$51^{+59}<em>{-48}^{(stat)}^{+14}</em>{-46}^{(syst)}$ MeV</td>
</tr>
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</table>

2-$P_c$ p-value = 55.7%

4-$P_c$ p-value = 68.6%
Searches of new exotic resonances at CMS: $B^+ \rightarrow J/\psi \bar{\Lambda}p$ [JHEP 12 (2019) 100]

- Using 2012 $\sqrt{s} = 8$ TeV (19.6 fb$^{-1}$) data sample
- Possibility to study both near-threshold $J/\psi p$ and $J/\psi \bar{\Lambda}$ systems
- Spectra consistent with $K^* \rightarrow \bar{\Lambda}p$ contributions

$$\mathcal{B}(B^+ \rightarrow J/\psi \bar{\Lambda}p)/\mathcal{B}(B^+ \rightarrow J/\psi K^{*+}) = (1.054 \pm 0.057 \pm 0.028 \pm 0.011) \times 10^{-2}$$
Searches of new exotic resonances at CMS: 
$\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ observation

[PLB802(2020)135203]

- using a data sample corresponding to $60 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$
- Observation of $\Lambda_b^0 \rightarrow J/\psi \Lambda \phi$ with $286 \pm 29$ events
- $\mathcal{B}(\Lambda_b^0 \rightarrow J/\psi \Lambda \phi)/\mathcal{B}(\Lambda_b^0 \rightarrow \psi(2S)\Lambda \phi) = (8.26 \pm 0.90 \pm 0.68 \pm 0.11) \times 10^{-2}$
- Opportunity to further explore $J/\psi \phi$ and $J/\psi \Lambda$ systems
Tetraquarks
Search for $X_{bb\bar{b}\bar{b}}$ at CMS

- Using data corresponding to $35.9 \text{ fb}^{-1}$ at $\sqrt{s} = 13 \text{ TeV}$

- Search for heavy bottom tetraquark in the $\Upsilon(1S)\mu^+\mu^-$ final state in $[17.5, 19.5]\text{ GeV}$

- LHCb: no hint of signal [JHEP10(2018)086]

- Probe of a kinematical region not accessible at LHCb

- In addition generic search for narrow resonances in an extended mass window $[16.5, 27]\text{ GeV}$

- No significant excess is observed

- Largest excess: $m = 25.1 \text{ GeV}$ with a local significance of $2.4\sigma$

Example with $m = 19 \text{ GeV}$ with $\sim 1\sigma$
ULs set on $\sigma(X_{bb\bar{b}\bar{b}}) \times B(X_{bb\bar{b}\bar{b}} \rightarrow \Upsilon(1S)\mu^+\mu^-)$ using different signal models

ULs between 5 and 380 pb depending on the mass and signal model.
Observed for the first time in 2003 by the Belle collaboration [JHEP09(2019)028]

First observation of an unexpected charmonium candidate: resurrection of the interest in the non-conventional states spectroscopy

Nature of \(X(3872)\) still unclear: suggested several exotic interpretations (tetraquark, molecule, mixture ...)

More measurements of \(b\) hadron decays involving \(X(3872)\) production would provide important inputs for understanding its internal structure and creation dynamics

In addition lineshape studies can shed a light on the nature of this state
$\Lambda_b^0 \rightarrow X(3872)pK^-$ at LHCb

- Using data corresponding to 1.0, 2.0 and 1.9 fb$^{-1}$ at 7, 8 and 13 TeV

- First observation $\Lambda_b^0 \rightarrow X(3872)pK^-$ with $X(3872) \rightarrow J/\psi\pi^+\pi^-$

- Signal yield determined from a 2D fit to $(M_{J/\psi\pi^+\pi^-} - pK^-, m_{J/\psi\pi^+\pi^-})$

(58 ± 15)$\%$ proceed via $\Lambda_b^0 \rightarrow X(3872)\Lambda(1520)$

$$\frac{B(\Lambda_b^0 \rightarrow X(3872)pK^-)}{B(\Lambda_b^0 \rightarrow \psi(2S)pK^-)} \times \frac{B(X(3872) \rightarrow J/\psi\pi^+\pi^-)}{B(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)} = (5.4 \pm 1.1 \pm 0.2) \times 10^{-2}$$

$N = 55 \pm 11$ with $7\sigma$
$B^0_s \rightarrow X(3872)\phi$ at CMS

- Using data corresponding to 140 fb$^{-1}$ at $\sqrt{s} = 13$ TeV
- Observation of $B^0_s \rightarrow X(3872)\phi$ with $X(3872) \rightarrow J/\psi\pi^+\pi^-$ and $\phi \rightarrow K^+K^-$
- Signal yield determined from a 2D fit to $(M_{J/\psi\pi^+\pi^-}, m_{K^+K^-})$
- $N(B^0_s \rightarrow X(3872)\phi) = 299 \pm 39$ with $> 6\sigma$

\[
\frac{\mathcal{B}(B^0_s \rightarrow X(3872)\phi)}{\mathcal{B}(B^0_s \rightarrow \psi(2S)\phi)} \times \frac{\mathcal{B}(X(3872) \rightarrow J/\psi\pi^+\pi^-)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi\pi^+\pi^-)} = (2.21 \pm 0.29 \pm 0.17)\% 
\]

- Significant difference in branching fraction ratio compared to $\psi(2S)$ modes
  \[
  \frac{\mathcal{B}(B^0_s \rightarrow X(3872)\phi)}{\mathcal{B}(B^+ \rightarrow X(3872)K^+)} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070 
  \]
  \[
  \frac{\mathcal{B}(B^0_s \rightarrow \psi(2S)\phi)}{\mathcal{B}(B^+ \rightarrow \psi(2S)K^+)} = 0.87 \pm 0.10 
  \]
- $X(3872)$ formation in $B$ meson decays is different from $\psi(2S)$ formation: $X(3872)$ is not a pure charmonium state

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Using data corresponding to $9 \text{fb}^{-1}$ at $\sqrt{s} = 7$, 8 and 13 TeV

First observation of $B^+ \rightarrow (\psi_2(3823) \rightarrow J/\psi \pi^+ \pi^-)K^+$ with $5\sigma$ ($N = 137 \pm 26$)

$$\frac{\mathcal{B}(B^+ \rightarrow \psi_2(3823)K^+) \times \mathcal{B}(\psi_2(3823) \rightarrow J/\psi(2S)\pi^+\pi^-)}{\mathcal{B}(B^+ \rightarrow \psi(2S)K^+) \times \mathcal{B}(\psi(2S) \rightarrow J/\psi(2S)\pi^+\pi^-)} = (1.31 \pm 0.25 \pm 0.04) \times 10^{-3}$$

Using a BW parametrisation masses and widths are measured

$$m_{\psi_2(3823)} = 3824.08 \pm 0.53 \pm 0.14 \pm 0.01 \text{ MeV}$$

$$m_{\chi_{c1}(3872)} = 3871.59 \pm 0.06 \pm 0.03 \pm 0.01 \text{ MeV}$$

$$\Gamma_{\psi_2(3823)} < 5.2(6.6) \text{ MeV at } 90(95)\%$$

$$\Gamma_{\chi_{c1}(3872)} = 0.96^{+0.19}_{-0.18} \pm 0.21 \text{ MeV}$$
**X(3872) lineshape at LHCb**

- Run1 data (3 fb$^{-1}$ at $\sqrt{s} = 7, 8$ TeV)
- $X(3872) \rightarrow J/\psi\pi^+\pi^-$ from b-hadron decays
- Mass resolution is studied using simulation samples and the large sample of $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$ decays
- Analysis is performed in $p_\pi^+\pi^-$ bins to consider resolution dependence

**Breit-Wigner fit**

$m_{X(3872)} - m_{\psi(2S)} = 185.598 \pm 0.067 \pm 0.068$ MeV  
$m_{X(3872)} = 3871.695 \pm 0.067 \pm 0.068 \pm 0.010$ MeV  
$\Gamma_{BW} = 1.39 \pm 0.24 \pm 0.10$ MeV  
$\delta E = m_{D^0} + m_{\bar{D}^*0} - m_{X(3872)} = 0.01 \pm 0.14$ MeV

**Flatté lineshape accounts for the opening up of $D^0\bar{D}^*$ threshold**

**Flattè fit:**  
Mode = $3871.69^{+0.00+0.05}_{-0.04-0.13}$ MeV (in agreement with the mean of the BW lineshape)  
FWHM = $0.22^{+0.06+0.25}_{-0.08-0.17}$

**FWHM $\ll \Gamma_{BW}$: importance of a physically well-motivated lineshape parameterization**

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To investigate the nature: analytic structure of the amplitude examined in the vicinity of the $D^0 \bar{D}^0$ threshold

Two poles are found: one pole appears on the physical sheet; the other on the unphysical sheet $\Rightarrow$ quasi-bound $D^0 \bar{D}^0$ state (with $E_b < 100$ keV)

First pole allowed on the unphysical sheet at the $2\sigma$ level: quasi-virtual state assignment cannot be excluded.

Asymmetry of the locations of the two poles: information on the composition of the $X(3872)$ state: molecular or compact state

Relative fraction of compact component is 15% and can reach a maximum of 33%
Conclusions

- After the discovery of the five excited $\Omega_c$ states, observation of the analogous $\Omega_{b}^{*-}$ and $\Xi_{c}^{0}$ resonances!
- Observed now five excited $\Lambda_{b}^{0}$
- Possibility for discovering new exotic states is opening up
  - New channels with potential for discovery of exotic states are under study
  - Search for fully heavy tetraquark states started
- Knowledge of the $X(3872)$ is constantly improving
  - Non-pure charmonium state is suggested from the study of $b$-decays
  - Improvement in the mass and width measurements
  - Study of the Flatté lineshape
- Continuing to exploit LHC experiment potential adding Run2 data
- Long Shutdown 2 started, the detectors are going to be upgraded: collect a larger data sample with high efficiency starting in 2021!
Spare slides
Nominal fit model does not accurately describe the data in the mass region close to the kinematic threshold: additional component due to the partial reconstruction of the state that peaks around $\Delta M \simeq 140$ MeV when it decays directly to the $\Lambda_c^+ K^- \pi^+$ final state without any intermediate resonance.