Exotic hadrons at LHCb

Daria Savrina (ITEP & SINP MSU) on behalf of the LHCb collaboration
Outline

- Why exotic hadrons?
- The LHCb experiment
- Exotic mesons
  - study of the $B^+ \rightarrow J/\psi \phi K^+$ decay
  - search for $X(5568)$
- Exotic baryons
  - search in $\Lambda_b \rightarrow J/\psi \rho \pi$
  - steps towards future studies
**Exotic hadrons**

Exotic hadrons – everything beyond qq-meson and qqq-baryon scheme

Could be various multiquark states, hadron molecules, glueballs, hybrids...

First predicted in 1964 the original papers by M.Gell-Mann and G.Zweig

[CERN-TH-412, Phys.Lett. 8 (1964) 214]

First seen by Belle in 2003


**A SCHEMATIC MODEL OF BARYONS AND MESONS**

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

antitriplet as antiquarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(qqq)$, $(qqqqq)$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q})$, etc. It is assuming that the lowest

**Observation of a Narrow Charmoniumlike State in Exclusive $B^+ \to K^+\pi^+\pi^- J/\psi$ Decays**

$B^+ \to X(3872)K^+$

$X(3872) \to J/\psi \pi^+\pi^-$

Expected quark content [ccuu]

Internal structure is still under discussion
Exotic zoo

Not a very strict naming scheme

X – neutral, first seen in B-mesons decays, positive parity

Y – neutral, first seen in ee annihilation with initial state radiation, negative parity

Z – charged (and their isospin partners)

P – pentaquarks

No clear pattern seen yet

Lots of predictions within different theoretical models

Tightly bound tetraquarks

Diquark-onium

Meson molecules

Hadroquarkonium

Quarkonium adjoint meson

Would like not only to find new exotic hadrons, but also determine their quantum numbers
Exotics in beauty decays

Most of them are not narrow
Need amplitude analysis
Use Argand diagram to prove their resonance nature

Decay quite fast
Pentaquark lifetime $\sim 10^{-23}\text{s}$

Decays of $b$-hadrons is a convenient tool
Inclusive decays: good understanding of the initial state
Relatively long lifetime
Decays with charmonium provide a clear signature
The LHCb experiment

LHC:
Cross-sections in the LHCb acceptance:
\[ \sigma_{pp\rightarrow b\bar{b}} = 72.0\pm0.3\pm6.8 \, \mu b \quad @ \sqrt{s} = 7\,\text{TeV} \]
\[ \sigma_{pp\rightarrow b\bar{b}} = 144 \pm1 \pm21 \, \mu b \quad @ \sqrt{s} = 13\,\text{TeV} \]

Access to all possible b-hadrons
\[ B^0:\Lambda^0_b:B^0_s \sim 4:2:1 \]
[JHEP08 (2014) 143]

Fully instrumented rapidity range \(2 < \eta < 5\): \(\sim 40\%\) of b quarks produced hit the detector acceptance

VELO:
Decay time resolution \(\sim 45\,\text{fs}\)
Impact parameter resolution: \((15 + 29/pT[\text{GeV}]) \, \mu m\)
Relative track momentum resolution: 0.5\% at low momentum 1.0\% at 200 \(\text{GeV/c}\)

Particle identification:
Kaon ID \(\sim 95\%\) for \(\sim 5\%\) \(\pi \rightarrow K\) mis-id probability
Muon ID \(\sim 97\%\) for 1-3 \% \(\pi \rightarrow \mu\) mis-id probability

Muon system: \(\sim 90\%\) trigger efficiency for dimuon channels
The LHCb experiment

This talk – Run 1
3 fb⁻¹ of pp data

Run 2 - work in progress

6 fb⁻¹ of data collected so far

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2017

Integrated Recorded Luminosity (1/fb)

Year


2010 (3.5 TeV): 0.04 /fb
2011 (3.5 TeV): 1.11 /fb
2012 (4.0 TeV): 2.08 /fb
2015 (6.5 TeV): 0.33 /fb
2016 (6.5 TeV): 1.67 /fb
2017 (6.5 TeV): 0.90 /fb
Exotic mesons
Study of the $B^+ \to J/\psi \phi K^+$ decay

First observed by CDF in $J/\psi \phi$ system, then confirmed by CMS and D0

$X(4140)$ Exotic candidate, containing no u- or d-quarks

World average:

\[
m = 4147.1 \pm 2.4 \text{ MeV/c}^2 \\
\Gamma = 15.7 \pm 6.3 \text{ MeV/c}^2
\]

Not included in the average


Study of the $B^+ \to J/\psi \phi K^+$ decay

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X(4274)

Seen by CDF and CMS

CDF: \[ M = 4274.4^{+8.4}_{-6.7} \pm 1.9 \text{ MeV/c}^2 \]
\[ \Gamma = 32.0^{+22}_{-15} \pm 8 \text{ MeV/c}^2 \]

CMS: \[ M = 4313.8 \pm 5.3 \pm 7.3 \text{ MeV/c}^2 \]
\[ \Gamma = 38.0^{+30}_{-15} \pm 16 \text{ MeV/c}^2 \]
Study of the $B^+ \rightarrow J/\psi \phi K^+$ decay

First observed by CDF in $J/\psi \phi$ system, not confirmed by Belle, BaBar and LHCb

$X(4140)$


[Phys. Rev. D85, 091103(R) (2012)]

0.37 fb$^{-1}$
Given more data the first full amplitude analysis of this channel has been performed. The signal is 4289 ± 51 with only 23% background. The study of the $B^+ \rightarrow J/\psi \phi K^+$ decay is presented, with a focus on the first fit under the $K^*$ hypothesis and a second fit including exotic states: $X \rightarrow J/\psi \phi$ and $Z \rightarrow J/\psi K$. The analysis involves 6D amplitude analysis with:

- 1 mass: $m_{\phi K}$
- 3 helicity angles: $\theta_{K^*}$, $\theta_{J/\psi}$, $\theta_{\phi}$
- 2 angles between decay planes: $\Delta \phi_{J/\psi}$, $\Delta \phi_{\phi}$
Study of the $B^+ \rightarrow J/\psi \phi K^+$ decay

Not many $K^*$ states decaying to $K\phi$ are well established by now

Use theoretical predictions by Godfrey-Isgur

Forbidden

$p$-value below $10^{-7}$

$J/\psi K$ and $\phi K$ are well described by the model
Study of the $B^+ \rightarrow J/\psi \phi K^+$ decay

After inclusion of 4 additional X-states

Adding more X-states or $Z \rightarrow J/\psi K$ contributions does not improve the fit any more.

$p$-value 22%
Study of the $B^+ \to J/\psi \phi K^+$ decay

$\chi(4140)$

$M = 4146.5 \pm 4.5 \, ^{+4.6}_{-2.8} \, \text{MeV}/c^2$
$\Gamma = 83 \pm 21 \, ^{+21}_{-14} \, \text{MeV}/c^2$ – wider than world average

$J^{PC} = 1^{++}$ with $5.7\sigma$

Rules out $0^{++}$ ro $2^{++} D^{**}_s D^{*-}_s$ molecular models

$\chi(4274)$

$m = 4273.3 \pm 8.3 \, ^{+17.2}_{-3.6} \, \text{MeV}/c^2$

$\Gamma = 56.2 \pm 10.9 \, ^{+8.4}_{-11.1} \, \text{MeV}/c^2$

$J^{PC} = 1^{++}$ with $5.8\sigma$

Not a molecular bound state or cusp

Hybrid charmonium state would have $1^{-+}$

Tetraquarks?

Lebed-Polosa: $1^{++} \chi(4140)$, but $0^{+} \chi(4274)$ [Phys. Rev. D93 (2016) 094024]

Anisovich et al: only one $1^{++}$ state [Int. J. Mod. Phys. A30 (2015) 1550186]

Stancu model: $1^{++} \chi(4140)$ and $1^{++}$ state slightly higher than $\chi(4274)$ [J. Phys.G37 075017]

$\chi(4500)$

$M = 4506 \pm 11 \, ^{+12}_{-15} \, \text{MeV}/c^2$

$\Gamma = 92 \pm 21 \, ^{+21}_{-20} \, \text{MeV}/c^2$

$J^{PC} = 0^{++}$ with $4.0\sigma$

Wang et al predicted virtual $0^{++} D^{**}_s D^{*-}_s$ state at $4.48 \pm 0.17 \, \text{GeV}$


[LHCb, [PRL 118 (2017) 022003] ]

$\chi(4700)$

$M = 4704 \pm 10 \, ^{+14}_{-24} \, \text{MeV}/c^2$

$\Gamma = 120 \pm 31 \, ^{+42}_{-33} \, \text{MeV}/c^2$

$J^{PC} = 0^{++}$ with $4.5\sigma$
**Search for X(5568)**

Exotic candidate, consisting of four quarks of different flavours: b, s, u, d

Seen by D0 in $B^0_s\pi^\pm$ system, not confirmed by CMS

D0 measurement:

- $M_X = 5567.8 \pm 2.9\ (stat) \begin{pmatrix} +0.9 \\ -1.9 \end{pmatrix}\ (syst)\ MeV/c^2$
- $\Gamma_X = 21.9 \pm 6.4\ (stat) \begin{pmatrix} +5.0 \\ -2.5 \end{pmatrix}\ (syst)\ MeV/c^2$

Mass 200 MeV below $B^0K^\pm$ threshold or $\Xi_{bc}\ (ubs)$ mass

**X(5568)**

Expected $J^P$:

- $0^+$, if the $B^0_s\pi^\pm$ is produced in an S-wave
- $1^+$, if the decay proceeds via the chain $X(5568)^\pm \rightarrow B^{*0}_s\pi^\pm$, $B^{*0}_s \rightarrow B^0_s\gamma$
Two reconstructed decay modes: $B^0_s \rightarrow D_s^- \pi^+$ and $B^0_s \rightarrow J/\psi \phi$

~20 times higher event yield than the one used by the D0 collaboration

Measurements for three different $B^0_s$ transverse momentum regions

$p_T(B^0_s) > 5$ GeV/c, $p_T(B^0_s) > 10$ GeV/c, $p_T(B^0_s) > 15$ GeV/c

To account for possibility of the production in hard processes

Scan over wide mass range and various width hypotheses
Search for $X(5568)$


Fit to the data with mass and width fixed to the values claimed by D0

No clear signal seen

Upper limits set on the $B^0_s$ production from $X(5568)$ @90% (95%) CL:

$\rho_X^{LHCb}(p_T(B^0_s) > 5\,\text{GeV}) < 0.011 (0.012)$
$\rho_X^{LHCb}(p_T(B^0_s) > 10\,\text{GeV}) < 0.021 (0.024)$
$\rho_X^{LHCb}(p_T(B^0_s) > 15\,\text{GeV}) < 0.018 (0.020)$

D0: $(8.6 \pm 1.4 \pm 1.9)\%$

CMS (preliminary): $< 3.9\%$ @95% CL

Scan over the wide mass range

Any excesses are consistent with being statistical fluctuations

Applies also to $X(5568)^\pm \rightarrow B^{*0}_s \pi^\pm$,

$B^{*0}_s \rightarrow B^0_s \gamma$
Exotic baryons
**Pentaquarks**

2015 – first observation of resonances consistent with pentaquark states

![Diagram showing pentaquark states](image)

- **Pc(4380)**: @ 9σ significance
  - $M = 4380 \pm 8 \pm 29$ MeV/c$^2$
  - $\Gamma = 205 \pm 18 \pm 86$ MeV/c$^2$

- **Pc(4450)**: @ 12σ significance
  - $M = 4450 \pm 2 \pm 3$ MeV/c$^2$
  - $\Gamma = 39 \pm 5 \pm 19$ MeV/c$^2$

Possible $J^P$ combinations:
- Best fit ($3/2^-$, $5/2^+$)
- Satisfactory fits ($3/2^+$, $5/2^+$) or ($5/2^+$, $3/2^+$)

Check their resonance nature with Argand diagram

Cross-check with the help of model-independent analysis – supports the observation

**Study of the $\Lambda_b \rightarrow J/\psi p\pi$ decay**

Need confirmations in other decays


Similar strategy:
6D amplitude fit to the data

$\Lambda_b \rightarrow J/\psi p\pi$ Cabbibo-suppressed analog of $\Lambda_b \rightarrow J/\psi pK$

Expect $N^*$ states in $m(p\pi)$
Expect $P^+_c$ in $m(J/\psi p)$
Expect $Z_c(4200)^-$ in $m(J/\psi\pi)$

[PRD90 (2014) 112009]

**LHCb**

1885 ± 50 signal events
Conventional states and non-resonant background:

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR $p\pi$</td>
<td>$1/2^-$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$N(1440)$</td>
<td>$1/2^+$</td>
<td>1430</td>
<td>350</td>
</tr>
<tr>
<td>$N(1520)$</td>
<td>$3/2^-$</td>
<td>1515</td>
<td>115</td>
</tr>
<tr>
<td>$N(1535)$</td>
<td>$1/2^-$</td>
<td>1535</td>
<td>150</td>
</tr>
<tr>
<td>$N(1650)$</td>
<td>$1/2^-$</td>
<td>1655</td>
<td>140</td>
</tr>
<tr>
<td>$N(1675)$</td>
<td>$5/2^-$</td>
<td>1675</td>
<td>150</td>
</tr>
<tr>
<td>$N(1680)$</td>
<td>$5/2^+$</td>
<td>1685</td>
<td>130</td>
</tr>
<tr>
<td>$N(1700)$</td>
<td>$3/2^-$</td>
<td>1700</td>
<td>150</td>
</tr>
<tr>
<td>$N(1710)$</td>
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<td>$N(1720)$</td>
<td>$3/2^+$</td>
<td>1720</td>
<td>250</td>
</tr>
<tr>
<td>$N(1875)$</td>
<td>$3/2^-$</td>
<td>1875</td>
<td>250</td>
</tr>
<tr>
<td>$N(1900)$</td>
<td>$3/2^+$</td>
<td>1900</td>
<td>200</td>
</tr>
<tr>
<td>$N(2190)$</td>
<td>$7/2^-$</td>
<td>2190</td>
<td>500</td>
</tr>
<tr>
<td>$N(2300)$</td>
<td>$1/2^+$</td>
<td>2300</td>
<td>340</td>
</tr>
<tr>
<td>$N(2570)$</td>
<td>$5/2^-$</td>
<td>2570</td>
<td>250</td>
</tr>
</tbody>
</table>

Exotic states:
$P_c(4380)^+$, $P_c(4450)^+$ with masses and widths fixed to the previously measured values $J^P$ fixed to the previously measured „best fit“ $(3/2^-, 5/2^+)$

$Z_c(4200)^-$ with $J^P = 1^+$
Combined statistical significance of 3 states 3.1σ
Individual significance of each contribution is low, if others are included

\[ \frac{\text{Br}(\Lambda_b \to P_c(4380)^+K)}{\text{Br}(\Lambda_b \to P_c(4380)^+\pi)} = 0.050 \pm 0.016^{+0.016}_{-0.014} \pm 0.025 \]

\[ \frac{\text{Br}(\Lambda_b \to P_c(4450)^+K)}{\text{Br}(\Lambda_b \to P_c(4450)^+\pi)} = 0.033^{+0.016}_{-0.014}^{+0.011}_{-0.010} \pm 0.009 \]

**Rules out:**
\[ R_{K/\pi} \sim 0.58 \pm 0.05 \]
Interpretations
Need to have interpretations

Tightly bound state?
[PLB 749 289 (2015)]

Hadronic molecule?
[PRL 115 122001 (2015)]

Rescattering effect?
\( \chi_{c1}p \rightarrow J/\psi p \)
Can explain the phase motion
\( P^+_c \) won't be seen in the \( \chi_{c1}p \) final state
[PRD 92 071502 (2015)]
Search for 2 decays together: $\Lambda^0_b \rightarrow \chi_{c1,2} pK$

Normalize by $\Lambda^0_b \rightarrow J/\psi pK$

$\chi_{c1,2} \rightarrow J/\psi \gamma$ decays reconstructed

Mass constrained to $\chi_{c1}$ mode

$\chi_{c1}$ mode shifted to lower mass values

$\Lambda^0_b \rightarrow \chi_{c1} pK$: 453 ± 25 signal events  
29σ significance

$\Lambda^0_b \rightarrow \chi_{c2} pK$: 285 ± 23 signal events  
17σ significance

To few for the amplitude analysis yet
Can measure the branching fractions:

$$B(\Lambda^0_b \rightarrow \chi_{c1} pK^-) = (7.3 \pm 0.4 \pm 0.4 \pm 0.6^{+1.0}_{-0.6}) \times 10^{-5}$$

$$B(\Lambda^0_b \rightarrow \chi_{c2} pK^-) = (7.5 \pm 0.6 \pm 0.4 \pm 0.6^{+1.1}_{-0.6}) \times 10^{-5}$$
$\Xi_b \rightarrow J/\psi pK$ decay

Need to see other pentaquarks


Decay similar to $\Lambda_b \rightarrow J/\psi pK$

Just replace u-quark with s-quark

One may expect appearance of a hidden-charm pentaquark with open strangeness: $[sc\bar{c}ud]$,

First observation!

By the end of Run 2 there should be enough data for an amplitude analysis

Total signal yield ~300 events

Signal significance $21\sigma$

Branching fraction is measured through normalization by $\Lambda_b \rightarrow J/\psi \Lambda$ channel

$$\frac{f_{\Xi_b^-} B(\Xi_b^- \rightarrow J/\psi \Lambda K^-)}{f_{\Lambda_b^0} B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = (4.19 \pm 0.29\text{(stat)} \pm 0.15\text{(syst)}) \times 10^{-2},$$
Conclusions

The exotic studies sector is rapidly developing
   Many new states confirmed/unconfirmed/waiting for confirmation
   Still a large area for studies
      both from experimental and theoretical sides

The LHCb Run 2 data is being analysed
   Many prospects and ideas

Looking forward to new exciting exotic results!