New discoveries of the exotic states at LHCb

Misha Mikhasenko
on behalf of LHCb

ORIGINS Excellence Cluster

September 6th, 2022
QNP2022
Two ways of building complexity

### Hadron variety

- $3S$ y $3S$?
- $2P$ y $2P$(0,1,2)$^+$, $1^+$
- $1P$ y $1P$(0,1,2)$^+$, $1^+$
- $1S$ y $1S$(0,1,2)$^+$, $1^+$

### Atomic variety

- $2D$ y $2D$(1,2,3)$^+$, $3^+$
- $1G$ y $1G$(1,2,3)$^+$, $3^+$
- $1F$ y $1F$(0,1,2)$^+$, $1^+$
- $[1^+]S$ y $[1^+]S$(0,1,2)$^+$, $1^+$

\[
\vec{J} = \vec{L} + \vec{S} \quad J = \vec{L} + \vec{S} \]
\[
\vec{S} = \vec{s}_1 + \vec{s}_2
\]

Deuteron

- Type of Decay
  - $\beta^+$
  - $\beta^-$
  - $\alpha$
  - Fission
  - Proton
  - Neutron
  - Stable Nuclide
  - Unknown

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**Hadron variety**

- $3S$ ?
  - $6^{-}, 1^{-}$
- $2P$
  - $(0, 1, 2)^{++}, 1^{-}$
- $1F$
  - $(2, 3, 4)^{++}, 3^{+}$
- $1D$
  - $(0, 1, 2)^{--}, 2^{--}$
- $1S$
  - $0^{--}, 1^{--}$

**Atomic variety**

\[
\vec{J} = \vec{L} + \vec{S} \quad J = s_1 + s_2
\]

See [the talk] on conventional states at LHCb by Aleksei Dzyuba on Thursday.
Example: innerworking of $T_{cc}^+$

**Molecular configuration:**
- two mesons are well separated,
- bound by forces similarly to el.mag. van der Waals,
- entirely coupled to $D^{*+}D^0$,
- lifetime is limited by $D^{*+}$,
- ? spatially-extended object.

**Compact configuration:**
- genuine QCD state,
- compact (cc) core,
- there is no limit on lifetime, depends on how much it couples to continuum,
- ? typical hadronic size of 1 fm.
Summary of Pentaquarks studies

(*) will be discussed today

\[ X_b \rightarrow (J/\psi p) \ldots \]

\[ \Lambda_b^0 \rightarrow (J/\psi p)K^- \quad (*) \]
\[ \Lambda_b^0 \rightarrow (J/\psi p)\pi^- \]
\[ B_s^0 \rightarrow (J/\psi p)\bar{p} \]

Thresholds: \( \Sigma_c^{(*)} + D^{(*)0} / \Sigma_c^{(*)} + D^{(*)-} \)

\[ \Xi_b^- \rightarrow (J/\psi \Lambda)K^- \quad (*) \]
\[ B^- \rightarrow (J/\psi \Lambda)\bar{p} \quad (*) \]

\[ P^N \psi : \]
\[ P^\Lambda \psi_s : \]

LHCb proposal for the new name convention of exotic hadrons [arXiv:2206.15233]
$\Lambda_b^0 \rightarrow J/\psi p K^-$
The first pentaquarks

- Close to the $\Sigma_c \bar{D}^{(*)}$ threshold,
- Multiplicity matches spin combination: $1/2 \otimes 1 = 1/2 \oplus 3/2$
- Narrow(!): 10, 20, and 5 MeV for $\Gamma_{BW}$

@9 fb$^{-1}$

LHCb

$\Sigma_c^+ \bar{D}^0$

$\Sigma_c^+ \bar{D}^{*0}$

Candidates/(0.105 $\text{GeV}^2$

$P_c^{N}(4440)$

$P_c^{N}(4312)$

$P_c(4410)^+$

$P_c(4440)^+$

$P_c(4457)^+$

$m_{J/\psi} [\text{MeV}]$

$m_{\psi(4410)} [\text{MeV}]$

$m_{\psi(4440)} [\text{MeV}]$

$m_{\psi(4457)} [\text{MeV}]$

$m_{\psi}(4312)$

$m_{\psi}(4440)$

$m_{\psi}(4457)$

Weighted candidates/(0.105 $\text{GeV}^2$

$m_{K_P} [\text{GeV}]$

$m_{\psi}(4312)$

$m_{\psi}(4440)$

$m_{\psi}(4457)$

$m_{J/\psi} [\text{MeV}]$

$m_{\psi} [\text{MeV}]$

$m_{\psi}(4410)^+$

$m_{\psi}(4440)^+$

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$m_{J/\psi} [\text{MeV}]$

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LHCb
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$p_N \psi$, $p_N \psi (4440)$, $p_N \psi (4312)$

@9 fb$^{-1}$ LHCb

$P_c (4312)^+$, $P_c (4440)^+$, $P_c (4457)^+$

$\Sigma_c^+ \bar{D}^0$, $\Sigma_c^{**} \bar{D}^0$, $\Sigma_c^{**} \bar{D}^{*0}$

LHCb

$M_{J/\psi}$

$4440$, $4312$, $4457$
$\Xi_b^- \rightarrow J/\psi \Lambda K^-$
Hint for the strange partners

$\Xi_c^- \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Lambda(\rightarrow p\pi^-)K^- \text{ data sample} \ [\text{Sci.Bull. 66 (2021) 1278-1287}]$

- Full data sample 1750 signals with purity 80%.
- The decay is dominated by the $\Xi$ resonances
- $P_{\psi_s}^\Lambda(4459)$: $m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV with $4.3\sigma$ significance
Hint for the strange partners

$$\Xi_b^- \to J/\psi (\to \mu^+ \mu^-) \Lambda (\to p \pi^-) K^-$$ data sample [Sci.Bull. 66 (2021) 1278-1287]

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$B^− \rightarrow J/ψΛ\bar{p}$

$P^Λ_{ψs}$
$B^- \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\Lambda(\rightarrow p\pi)\bar{p}$

- Amplitudes:
  - NR$(J/\psi p)$, 84.0 ± 2.2%
  - NR$(\Lambda\bar{p})$, 11.3 ± 1.3%
  - New $P^{\Lambda}_{\psi s}$, 12.5 ± 0.7%
  - with parameters:
    - $m(P^{\Lambda}_{\psi s}) = 4338.2 \pm 0.7$ MeV
    - $\Gamma(P^{\Lambda}_{\psi s}) = 7.0 \pm 1.2$ MeV

- $J^P = 1/2^-$ is preferred
- BW mass is close to $\Xi_c \bar{D}$ thresholds:
  - 0.8 MeV above $\Xi_c^+ D^-$
  - 2.9 MeV above $\Xi_c^0 D^0$
Tetraquarks candidates

(*) will be discussed today

\( J/\psi \pi^+ \)  
\( \psi (Z_c) \)  
3900, 4430, \ldots

\( J/\psi K^+ \)  
\( \psi_s (Z_{cs}) \)  
4000, 4220

\( J/\psi \phi \)  
\( \psi \psi (T_{cc\bar{c}\bar{c}}) \)  
4140, 4274, 4500, \ldots

\( J/\psi J/\psi \)  
\( \psi \psi (T_{cc\bar{c}\bar{c}}) \)  
6900, \ldots(!)

\( D^0 D^0 \pi^+ \)  
\( T_{cc} \)  
3874

\( D^+ K^- \)  
\( T_{cs} (X) \)  
2900

\( D_s^\pm \pi^+ \)  
\( T_{c\bar{s}} (X) \)  
2900
$B^+ \rightarrow D^+ D^- K^+ \quad \underbrace{\quad T_{CS} \quad}$
Dalitz plot for $B^+ \rightarrow D^+ D^- K^+$

- Horizontal bands are resonances in $D^+ D^-$
- Hint for a vertical band around 8.5 GeV$^2$ in $m^2(D^- K^+)$
- Exotic candidate $T_{cs}(2900)$: $[\bar{c}\bar{s}ud]$
- Both quantum numbers $J^P = 0^+$ and $1^-$ are required in the fit
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\[ B^+ \rightarrow D_s^+ D_s^- K^+ \]

\[ \chi_{c0}/T_{\psi\phi} \]
Threshold enhancement at $D_s^+D_s^-$ in $B^+ \to D_s^+D_s^-K^+$ decays

[LHCb-PAPER-2022-018, 019 (in preparation)]

![Graph showing the mass distribution of $D_s^+D_s^-$ and $K^+K^-$ pairs with indicated signal candidates and purity.]
**B^+ \rightarrow D_s^+ D_s^- K^+** amplitude analysis

Main features of the data:
- Enhancement at the $D_s^+ D_s^-$ threshold
- Followed by a dip at 4.15 GeV.

Baseline model: $D_s^+ D_s^-$ resonances
- $1^{--}$: $\psi(4260) \sim 4\%$, $\psi(4660) \sim 2\%$
- $0^{++}$: $X(3960) \sim 24\%$, $X(4140) \sim 18\%$, NR$\sim 50\%$
Alternative model using \textit{K}-matrix \cite{LHCb-PAPER-2022-018, 019 (in preparation)}

Three interfering components in $0^{++}$ are replaced by the \textit{K}-matrix.

Mass parameters:

- $3960$: $m = 3956 \pm 5 \pm 11 \text{ MeV}$, $\Gamma = 43 \pm 13 \pm 8 \text{ MeV}$
- $4140$: $m = 4133 \pm 6 \pm 11 \text{ MeV}$, $\Gamma = 67 \pm 17 \pm 7 \text{ MeV}$

- Coupled channels $D_s^+ D_s^- / \psi(4460) / \psi(4660)$
- One \textit{K}-matrix pole + bgd term

Gives equally good fit
Is $X(3960)$ the same as $\chi_{c0}(3930)$ from $D^+D^-$?

Assuming to be the same, $\mathcal{B}(\chi_{c0} \to D^+D^-)/\mathcal{B}(\chi_{c0} \to D_s^+D_s^- P) \sim 0.3$

- large molecular component, or large tetraquark component, $T_{\psi\phi}$
- [JHEP 06 (2021) 035] finds a state coupled to $D_s^+D_s^-$ on the lattice
Is $X(3960)$ the same as $\chi_{c0}(3915)$?

$B^+ \rightarrow (D_s^+ D_s^-) K^+$ by LHCb:

$\gamma \gamma \rightarrow J/\psi \omega$ by Belle:

- Belle sees a clean state in $J/\psi \omega$ with $J^P = 0^+$
- The $D_s^+ D_s^-$ signal might be a tail of the $\chi_{c0}(3915)$ state
\[ B^+ \rightarrow D^- D_s^+ \pi^+ \]

\[ B^0 \rightarrow \bar{D}^0 D_s^+ \pi^- \]
$T_{cs}^a(2900)$ in the $D_s^{\pm}\pi^+$ system

[ LHCb-PAPER-2022-026 (in preparation) ]

- 4420 $B^0$ decays and 3940 $B^-$ decays, including charge-conjugated reactions
- Simultaneous fit using the isospin symmetry
- Main components in $B^0/B^+$ model:
  - $D^* \sim 17/14\%$
  - $D_2^* \sim 22/23\%$
  - $D\pi$ S-wave $\sim 45/48\%$.
- $T_{cs}^a \sim 2\%$ needed ($> 5\sigma$), $J^P = 0^+$ is favored ($7.5\sigma$)
- Mass and width are close to those of $T_{cs}^a(2900)$
  - $T_{cs}^{a0}$: $m = 2892 \pm 14 \pm 15$ MeV, $\Gamma = 119 \pm 26 \pm 12$ MeV;
  - $T_{cs}^{a++}$: $m = 2921 \pm 17 \pm 19$ MeV, $\Gamma = 137 \pm 32 \pm 14$ MeV
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![Graphs and plots](image)
Summary and conclusion

- With excellent performance of LHCb, we are exploring the uncharted waters
- This summer, more puzzle pieces for the quest of understanding nature complexity

Hints for the bigger picture:

- New $P_{\psi_s}^\Lambda$ in $B$ decays are close to $\Xi_c D$ threshold $\leftrightarrow$ $P_{\psi}^N$ are connected to $\Sigma_c \bar{D}(*)$
  Note, not the SU(3) flavour symmetry(!). Check $\Lambda_c \bar{D}(*)$ and $\Xi'_c \bar{D}(*)$ thresholds

- New $T_{c\bar{s}}^a$ appear to be similar to $T_{cs}$
  HQSS is in action? Where is the good/bad diquark mass difference?

- New $\chi_{c0}/T_{\psi\phi}$ close to the $D_s^+D_s^-$ threshold.
  A hadronic molecule or the scalar charmonium?
LHCb:

- ramping up after major Upgrade I
- ×5 statistics in Run 3(2023-2025) @13.6 TeV + Run 4(2029-2032) @14 TeV
Thank you for your attention
CMS confirms $T_{\psi\psi}$ structures

CMS Preliminary

135 fb$^{-1}$ (13 TeV)

Data Fit

BW1 BW2[X(6900)]

BW3 Background

[CMS-PAS-BPH-21-003]

- Clear dips is present that makes the incoherent fit struggles
- Third state is significant

CMS confirms $T_{\psi\psi}$ structures

[CMS-PAS-BPH-21-003]

- Clear dips is present that makes the incoherent fit struggles
- Third state is significant

ATLAS also finds structures in $J/\psi J/\psi$
ATLAS also finds structures in $J/\psi J/\psi$ and $\psi' J/\psi$

- Hints for the near-threshold structure
- Resonances in $\psi' J/\psi$ might produce structures in $J/\psi J/\psi$ as partial-reconstructed decays, $\psi' \rightarrow J/\psi +$ neutrals
Four-body decay angles

\[ \theta \] is the polar angle of \((J/\psi)_1\) with respect to the polarization direction

\((\theta_1, \phi_1)\) are the spherical angles of \(\mu^+\) in the \((J/\psi)_1\) helicity frame

\((\theta_2, \phi_2)\) are the spherical angles of \(\mu^+\) in the \((J/\psi)_2\) helicity frame

No polarization \(\Rightarrow\) no \(z\) \(\Rightarrow\) no decay plane (pink) \(\Rightarrow\) only \(\phi = \phi_1 + \phi_2\) matters.
Matrix of helicity couplings

\[ H_{\lambda_1, \lambda_2} = \begin{pmatrix} h_{1,1} & h_{1,0} & h_{1,-1} \\ h_{0,1} & h_{0,0} & h_{0,-1} \\ h_{-1,1} & h_{-1,0} & h_{-1,-1} \end{pmatrix} \]

The same-color elements are connected by symmetries.

The symmetry relates the couplings

\[ H_{\lambda_1, \lambda_2} = (-1)^J \eta X H_{-\lambda_1, -\lambda_2}, \]
\[ H_{\lambda_1, \lambda_2} = (-1)^J H_{\lambda_2, \lambda_1}. \]
Four categories of possible helicity matrices

<table>
<thead>
<tr>
<th>group</th>
<th>$\eta_x(-1)^J, (-1)^J$</th>
<th>$J^P$</th>
<th>symmetry</th>
</tr>
</thead>
<tbody>
<tr>
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<td>+, +</td>
<td>0+, 2+, 4+, 6+</td>
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</tr>
<tr>
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<tr>
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<td>1−, 3−, 5−, 7−</td>
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$b, a, c, d$ are still unknown coefficients, complex in general.
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</table>

\[
\begin{pmatrix}
    b & a \\
    d & a \\
\end{pmatrix}_S \quad \begin{pmatrix}
    b & a \\
    -b & a \\
\end{pmatrix}_S \quad \begin{pmatrix}
    -a & a \\
    -a & a \\
\end{pmatrix}_A
\]

$a, b, c, d$ are still unknown coefficients, complex in general.
Rederivation of the Landau-Yang theorem

"A massive particle with spin 1 cannot decay into two photons", wikipedia

Photons do not carry the longitudinal polarization \( \Rightarrow H_{0,i} = H_{i,0} = 0 \)

\[
\begin{align*}
H^{(I)} & : 
\begin{pmatrix}
  b & a & c \\
  a & d & -a \\
  c & a & b \\
  b & d & b \\
\end{pmatrix}_S \\
H^{(II)} & : 
\begin{pmatrix}
  b & a \\
  a & -a \\
  b & -b \\
\end{pmatrix}_S \\
H^{(III)} & : 
\begin{pmatrix}
  a & -a \\
  a & a \\
\end{pmatrix}_A \\
H^{(IV)} & : 
\begin{pmatrix}
  a & c \\
  -c & a \\
  -a & a \\
\end{pmatrix}_A \\
\end{align*}
\]

No decay to two photons for \( 1^+ \), and group-\( III \): \( 1^-, 3^-, 5^-, \ldots \)
Natural parity chanmonia above $D^+D^-$ threshold:

- $\psi(3770)$, $\chi_{c0}(3930)$, $\chi_{c2}(3930)$,
- $\psi(4040)$, $\psi(4160)$, $\psi(4415)$
Dalitz Plot Decomposition (DPD)

Update to the angular analysis formalism

Spin in 3-body decays

[MM et al. PRD (2019)]
[Mengzhen Wang et al., 2012.03699 (2020)]

\[ A_{\lambda_0,\lambda_1,\lambda_2} = \sum_{\text{spin align.}} O^{(12)}_{\nu,\lambda_1,\lambda_2}(m_{12}^2, m_{23}^2) \times O^{(23)}_{\nu,\lambda_1,\lambda_2}(m_{12}^2, m_{23}^2) \times O^{(31)}_{\nu,\lambda_1,\lambda_2}(m_{12}^2, m_{23}^2) \]

Used in the past

- unphysical inhomogeneity
- spin 1/2: \( A(\pi) \neq A(-\pi) \)
- range of \( \phi \) matters \([-\pi, \pi]\) vs \([0, 2\pi]\)

Proposed in DPD

- correct \( \phi \) dependence by construction