Observation of the doubly charmed tetraquark $T_{cc}^{+}$ in the LHCb experiment

Vanya BELYAEV (NRC Kurchatov Institute/ITEP, Moscow)
Hadrons

• **Mesons:**
  • Quark + antiquark

• **Baryons**
  • Three quarks

• **Everything else, aka “exotics”**
  • Glueballs
  • Hybrids,
  • Pentaquarks,
  • Tetraquarks,
  • Hexaquarks, ...

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**A SCHEMATIC MODEL OF BARYONS AND MESONS**

M. GELL-MANN
California Institute of Technology, Pasadena, California

Received 4 January 1964

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

<table>
<thead>
<tr>
<th>States</th>
<th>Quark content</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_0(2900), X_1(2900)$ [21, 22]</td>
<td>$\bar{c}d u \bar{s}$</td>
</tr>
<tr>
<td>$\chi_{c1}(3872)$ [6]</td>
<td>$c\bar{c}q\bar{q}$</td>
</tr>
<tr>
<td>$Z_c(3900)$ [23], $Z_c(4020)$ [24, 25], $Z_c(4050)$ [26], $X(4100)$ [27], $Z_c(4200)$ [28], $Z_c(4430)$ [29–32], $R_{c0}(4240)$ [31]</td>
<td>$c\bar{c}ud\bar{d}$</td>
</tr>
<tr>
<td>$Z_{cs}(3985)$ [33], $Z_{cs}(4000)$, $Z_{cs}(4220)$ [34]</td>
<td>$c\bar{c}u\bar{s}$</td>
</tr>
<tr>
<td>$\chi_{c1}(4140)$ [35–38], $\chi_{c1}(4274)$, $\chi_{c0}(4500)$, $\chi_{c0}(4700)$ [38], $X(4630)$, $X(4685)$ [34], $X(4740)$ [39]</td>
<td>$c\bar{c}ss\bar{s}$</td>
</tr>
<tr>
<td>$X(6900)$ [14]</td>
<td>$c\bar{c}c\bar{c}$</td>
</tr>
<tr>
<td>$Z_b(10610), Z_b(10650)$ [40]</td>
<td>$b\bar{b}u\bar{d}$</td>
</tr>
<tr>
<td>$P_c(4312)$ [41], $P_c(4380)$ [42], $P_c(4440)$, $P_c(4457)$ [41], $P_c(4357)$ [43]</td>
<td>$c\bar{c}uud\bar{d}$</td>
</tr>
<tr>
<td>$P_{cs}(4459)$ [44]</td>
<td>$c\bar{c}uds$</td>
</tr>
</tbody>
</table>

### Notes

- **24 tetraquark candidates**
- **6 pentaquark candidates**
(24-2) tetraquark candidates

- All are “quarkonium-like”

What is the internal structure?

- Compact tetraquark

- Molecule

- ... something else
• Discussed from the end of 70s
• For large $m_Q$ could be bound and “stable

• $Q\bar{Q}$ attraction in color antitriplet state
  • half of those in $Q\bar{Q}$ in color-singlet state
  • Binding energy: $\alpha_s^2 m_Q$ large for sufficiently heavy $Q$

• Diquark-antidiquark or
diquark + two antiquarks
(“antibaryon”) picture

Jaffe 1977, Jaffe 1978, Lipkin 1987,...

Adler, Richard & Taxil 1982,
Ballot &Richard 1983,
Zouzou, Silvestre-Brac, Gignous&Richard 1986,
Lipkin 1986,
Heller&Tijon 1987,
Manohar & Wise 1993
• $bb\bar{q}q$ : Theory & Lattice QCQ consensus
  - Exists & “stable”
    - mass $<< m(B) + m(B^*)$

• $bc\bar{q}q$ : likely exists and may be almost stable
  - mass close to $m(B) + m(D)$

• $cc\bar{q}q$ : no consensus
color antitriplet

- $S = 1$
- light "good" scalar isoscalar diquark
- $S = 0$
- In S-wave it fixes quantum numbers: $I(J^P) = 0(1^+)$
- Direct relation to $\Xi_{cc}^{++}$ ccu

Karliner&Risner, 2017
$T_{cc}^+$ basic properties

Huge dependency on the mass

\[
\begin{align*}
\Gamma_{D^+D^0} & \quad \Gamma_{D^0D^0\pi^0} \\
\Gamma_{D^*0D^+} & \quad \Gamma_{D^*+D^0}
\end{align*}
\]

\[
\frac{\Gamma_{D^+D^0}}{\Gamma_{D^0D^0\pi^0}}
\]

\[
\frac{\Gamma_{D^*0D^+}}{\Gamma_{D^*+D^0}}
\]

\[
\begin{align*}
\Gamma_{D^+D^0} & \quad \Gamma_{D^0D^0\pi^0} \\
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\end{align*}
\]

\[
\frac{\Gamma_{D^+D^0}}{\Gamma_{D^0D^0\pi^0}}
\]

\[
\frac{\Gamma_{D^*0D^+}}{\Gamma_{D^*+D^0}}
\]
~40% of heavy quarks in <4% of 4π

RICH Detectors:
95% ε(K⁺) @5% π→K misID

Muon:
ε(μ⁺)=97%@1-3% π→μ misID

Tracking:
Δp/p =0.5-0.6% for 5<p<100 GeV/c

The most precise B-masses

pp-interaction point

Vertex Locator
O(50fs) resolution for B

The most precise τ(B)

ECAL: σ_m(π⁰)=7MeV/c²

Muon:
ε(μ⁺)=97%@1-3% π→μ misID
Run I+II

1 fb^{-1}@7 TeV
2 fb^{-1}@8 TeV
8 fb^{-1}@13 TeV

Thanks to LHC accelerator team for the excellent performance of machine

7 Oct 2021/Warwisk

Vanya Belyaev "Doubly charmed tetraquark"
LHCb is very good for DD and D̅D̅

Observation of double charm production involving open charm in pp collisions at $\sqrt{s} = 7$ TeV

Figure 5: Invariant mass distributions for $D^0\bar{D}$ candidates: a) $D^0\bar{D}^0$, b) $D^0D^\pm$, c) $D^0D^\pm_\Sigma$ and d) $D^0\Lambda^\pm_\Sigma$.

Near-threshold D̅D̅ spectroscopy and observation of a new charmonium state $\psi_3(1D)$

Figure 5: Mass spectra of (top) $D^0\bar{D}^0$ and (bottom) $D^+D^-$ candidates in the near-threshold $m_{D\bar{D}} < 3.88$ GeV/$c^2$ region. The result of the simultaneous fit described in the text is superimposed.
$D^0 D^0 \pi^+$: Reconstruction & selection

$D^0 \rightarrow K^- \pi^+$ $(D^0 \rightarrow K^- \pi^+ \pi^+)$

- 5 hadron final state
  - 3 pions + 2 kaons
- PID is important
  (RICH)
- Efficient charm trigger
- Good quality tracks, vertices & PID
- No duplicated tracks
- Finite $D^0$ lifetime
Selected $D^0D^0\pi^+$

Non $D^0$ background is small statistically subtracted using sPlot

Selected $D^0D^0\pi^+$ vs $D^0\bar{D}^0\pi^+$

D$^0$D$^0\pi^+$

**LHCb**
9 fb$^{-1}$

Peak is stable
- Data taking periods
- Data taking conditions
- Dipole magnet polarity
- Charge

**Reflections**
- Fake D$^0$
- Duplicates

**Breit-Wigner fit**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>117 ± 16</td>
</tr>
<tr>
<td>$\delta m_{BW}$</td>
<td>$-273 \pm 61$ keV/c$^2$</td>
</tr>
<tr>
<td>$\Gamma_{BW}$</td>
<td>410 ± 165 keV</td>
</tr>
</tbody>
</table>

- Significance 22$\sigma$
- $m_{BW}$ below D$^*$+D$^0$ threshold 4.3$\sigma$

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Vanya Belyaev "Doubly charmed tetraquark"
**Narrow, just below $D^+D^0$ threshold**
- The most long lived exotics so far
- Very close to threshold like $X(3872)$
  - Is it a coincidence?

**Minimal quark content** $ccu\bar{d}$

**Good match to expected** $T_{cc}^+$

**To get more information a physics motivated model is required instead of Breit-Wigner**
Unitarized 3-body Breit-Wigner

- Build the amplitude $T_{cc}^+ \rightarrow D^*D \rightarrow DD\pi$ or $DD\gamma$
  - $T_{cc}^+ \quad I(J^P) = 0(1^+)$
  - Isospin coupling to $D^*D$ (both $D^*+D^0$ and $D^*0D^+$)
  - In vicinity of threshold keep only $S$-wave
  - $D^* \rightarrow D\pi$ or $D\gamma$

$$|T_{cc}^+\rangle = \frac{1}{\sqrt{2}} (|D^*+D^0\rangle - |D^*0D^+\rangle)$$

$$A_{T_{cc}^+D^*+D^0}^{S-wave} = \frac{g}{\sqrt{2}} \epsilon_{T_{cc}^+} \epsilon^{*\mu}_{D^*}$$

$$A_{T_{cc}^+D^*0D^+}^{S-wave} = -\frac{g}{\sqrt{2}} \epsilon_{T_{cc}^+} \epsilon^{*\mu}_{D^*}$$

- All constants and parameters are taken from $D^*$ decay widths
- Unknowns: the mass and $|g|$

- Calculate $T_{cc}^+ \rightarrow D^*D \rightarrow DD\pi$ or $DD\gamma$ decay widths as functions of mass
- 3-body phase space functions $\rho$
Actual branchings are functions of $T_{cc}^+$ mass (and shape)
Amplitude

\[ \mathcal{F}_f^U(s) = \varrho_f(s) |A_U(s)|^2 , \]

\[ A_U(s) = \frac{1}{m_U^2 - s - i m_U \hat{\Gamma}(s)} , \]

\[ \varrho_f(s) = \frac{1}{(2\pi)^5} \frac{\pi^2}{4s} \int \int ds_{12} ds_{23} \left| \mathcal{M}_f(s, s_{12}, s_{23}) \right|^2 , \]

- Self energy
- Unitarity
- Analiticty
- Causality

\[ \text{2 parameters} \]

\[ \text{mass} \quad m_U \]

\[ \text{coupling} \quad |g| \]

\[ \text{7 Oct 2021/Warwisk} \]

Vanya Belyaev "Doubly charmed tetraquark"
Amplitude

\[ A(s) = \frac{|g|^2}{m^2 - s - i \frac{|g|^2}{2}} \left[ \text{Im} \left( \ldots \right) \right] \]

\[ \text{Im} \left( \ldots \right) = \varrho_{\text{tot}}. \]

Unitarity

\[ \Im \sum(s) \bigg|_{s=0^+} = \frac{1}{2} \varrho_{\text{tot}}(s), \]

\[ \varrho_{\text{tot}}(s) = \sum_f \varrho_f(s). \]

Casuality

\[ \Re \sum(s) \bigg|_{s=0^+} = \xi(s) - \xi(m_U^2), \]

\[ \xi(s) = \frac{s}{2\pi} \text{p.v.} \int_{s_{\text{th}}}^{+\infty} \frac{\varrho_{\text{tot}}(s')}{s'(s' - s)} ds', \]
Fit with advanced model

- Better description
- Asymmetric shape
- Heavy tail

**Significance 22σ**

- \( m_U \) below \( D^{*+}D^0 \) threshold 9σ

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**Parameter** | **Value**
---|---
\( N \) | 186 ± 24
\( \delta m_U \) | \(-359 \pm 40 \text{ keV}/c^2\)
\(|g|\) | \(3 \times 10^{4} \text{ GeV} \text{ (fixed)}\)

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**arXiv:2109:01056**

LHCb
9 fb⁻¹

\( m_{D^0 D^0 \pi^+} \) [GeV/c²]

\( m_{D^0 D^0 \pi^+} \) [GeV/c²]

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What about $|g|$?

Fit claims $|g|$ is not small

$|g| > 7.7 (6.2) \text{ GeV}$

The model exhibits Flatte-like scaling: for large $|g|$ visible widths/FWHM is in saturation

FWHM = 47.8 ± 1.9 keV
Mass shape (remove resolution)

FWHM = 47.8 ± 1.9 keV

arXiv:2109:01056
Systematic for mass parameter

- Vary resolution
- Vary correction factor
- Alternative background
- Coupling constants
  - $D^*$ parameters
- Smaller values of $|g|$
- Momentum scale
- Energy loss
  - Amount of material

\[
\delta m_U = -359 \pm 40^{+9}_{-6} \text{ keV}/c^2
\]

\[|g| > 5.1 (4.3) \text{ GeV at 90 (95) \% CL}\]

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{\delta m_U}$ [keV$/c^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td></td>
</tr>
<tr>
<td>Resolution model</td>
<td>2</td>
</tr>
<tr>
<td>Resolution correction factor</td>
<td>2</td>
</tr>
<tr>
<td>Background model</td>
<td>2</td>
</tr>
<tr>
<td>Coupling constants</td>
<td>1</td>
</tr>
<tr>
<td>Unknown value of $</td>
<td>g</td>
</tr>
<tr>
<td>Momentum scaling</td>
<td>3</td>
</tr>
<tr>
<td>Energy loss</td>
<td>1</td>
</tr>
<tr>
<td>$D^{*+} - D^{0}$ mass difference</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>$^{+9}_{-6}$</td>
</tr>
</tbody>
</table>
What else can we say about $T_{cc}^{+}$?

- Three body final state $D^{0}D^{0}\pi^{+}$

- $l$ and $L$ define $J^{P}$ quantum numbers

- Can we measure them?
**D⁰π⁺ mass spectrum**

### D⁰π⁺ below D⁺D⁰ threshold

D⁰π⁺ mass spectrum depends on the decay dynamic. Perfect agreement with our model

### 3 main features

- D⁺ propagator
- q²+l+1 at left edge
- p²L+1 at right edge
- ... + resolution

---

[Graph showing D⁰π⁺ mass spectrum with data and background compared to total.]

**7 Oct 2021/Warwisk**

*Vanya Belyaev "Doubly charmed tetraquark"*
**D^0\pi^+ mass spectrum: D^*+ and l**

**3 main features**

- **D^*+ propagator**
- q^{2l+1} at left edge
- p^{2L+1} at right edge
- ... + resolution
- ... + interference

---

**Graphical Representation**

- **Yield** in \( (200 \text{ keV}/c^2) \)
- **LHCb** data: \( 9 \text{ fb}^{-1} \)
- **T^{+-}_{cc} \rightarrow D^0D^0\pi^+**
- **Data**
- **Background**
- **Total**

---

\[ \delta m_{D^0D^0\pi^+} < 0 \]

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**Notes**

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Vanya Belyaev "Doubly charmed tetraquark"
3 main features

- $D^{*+}$ propagator
- $q^{2l+1}$ at left edge
- $p^{2L+1}$ at right edge
- $\cdots + \text{resolution}$
- $\cdots + \text{interference}$

$D^{0\pi^+}$ mass spectrum: $L$

$\delta m_{D^0D^0\pi^+} < 0$

$LHCb$

9 fb$^{-1}$

Yield/(200 keV/c$^2$)

$m_{D^0\pi^+}$ [GeV/c$^2$]

$D^{*+}, l=1, L=0$

arXiv:2109:01056
$D^0\pi^+$ mass spectrum: quantum numbers

- $T_{cc}^+$ decays via intermediate off-shell $D^*$ meson
  - $l = 1$
- $L=0$ is largely favored
- $J^P = 1^+$

Spectrum is in perfect agreement with our model for $I(J^P)=0(1^+)$ $T_{cc}^+ \rightarrow D^*D$ decays.
$D^0D^0\pi^+$ Dalitz plot

All quantum numbers can be determined from Dalitz plot analysis
- For future
- Treatment of resolution is not trivial

$\delta m_{D^0D^0\pi^+} = -359$ keV/$c^2$
$\delta m_{D^0D^0\pi^+} = 0$

$LHCb$
$9$ fb$^{-1}$

arXiv:2109:01056
D⁰D⁰π⁺ Dalitz plot

- Complete Dalitz plot analysis for future
- Need more events
- Treatment of resolution is not trivial

- However some variants (including isospin) can be excluded already now

0(1⁺)  I=0,J=1,L=0
1(1⁺)  I=1,J=1,L=0
I=0,J=1,L=1
I=1,J=1,L=1
I=0,J=0,L=1
I=1,J=0,L=1
I=0,J=2,L=1
I=0,J=2,L=1

arXiv:2109:01056
Actual branchings are functions of $T_{cc}^+$ mass (and shape)
Energy release in $D^{*+}\rightarrow D^0\pi^+$ is very small

$D^0D^0$ from $T_{cc}^+\rightarrow D^*D$ form a narrow near-threshold peak

Exact shape depend on the $T_{cc}^+\rightarrow D^*D$ decay dynamics

Select inclusive prompt $D^0D^0$

Excellent agreement with our $O(1+)$ $T_{cc}^+$ decay model
  • in shape
  • in number

Significance $>20\sigma$
Actual branchings are functions of $T_{cc}^+$ mass (and shape)
For $T_{cc}^+ \rightarrow D^*+D^0$ and $T_{cc}^+ \rightarrow D^{*0}D^+$: 3 final states:

1. $T_{cc}^+ \rightarrow D^0D^0\pi^0$
2. $T_{cc}^+ \rightarrow D^+D^0\pi^0$
3. $T_{cc}^+ \rightarrow D^+D^0\gamma$

Select inclusive prompt $D^+D^0$

- Excellent agreement with our $0(1^+)$ $T_{cc}^+$ decay model
  - in shape
  - in number
- Significance $>10\sigma$
I=1 (isovector) nature?

- Many arguments in favor of $I=0$ isocalar, but it could be $I_3=0$ component of $I=1$ isotriplet $T^0_{cc} T^+_{cc} T^{++}_{cc}$
  - Light antiquarks in isovector state, similar to $\Sigma_c, \Sigma_b$ baryons
- Interpreting the observed peak as $I_3=0$ component, from $\Sigma_c$ and $\Sigma_b$ mass splitting the masses of $I_3=\pm 1$ components are
  \[
  m_{T^0_{cc}} - (m_{D^0} + m_{D^{*0}}) = -2.8 \pm 1.5 \text{ MeV}/c^2, \\
  m_{T^{++}_{cc}} - (m_{D^+} + m_{D^{*+}}) = 2.7 \pm 1.3 \text{ MeV}/c^2.
  \]
- $T^0_{cc}$ just below $D^*D^0$ threshold (very narrow)
  - $T^0_{cc} \rightarrow D^*D^0 \rightarrow D^0D^0\pi^0$ and $D^0D^0\gamma$
- $T^{++}_{cc}$ slightly above $D^*D^+$ threshold (can be up to few MeV)
  - $T^{++}_{cc} \rightarrow D^*D^+ \rightarrow D^+D^+\pi^0, D^+D^+\gamma, D^+D^0\pi^+$
- There MUST be signals $D^+D^+$ and $D^+D^0\pi^+$ spectra!
- There MUST be much larger signal in $D^0D^0$ spectrum!
I=1 (isovector) nature?

No sign for $I_3 = \pm 1$ components!

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Expected relative yields *(very approximate)*

<table>
<thead>
<tr>
<th>$I$</th>
<th>$I_3$</th>
<th>$T_{cc}^{++}$</th>
<th>$D^0D^0\pi^+$</th>
<th>$D^0D^0X$</th>
<th>$D^+D^0X$</th>
<th>$D^+D^0\pi^+$</th>
<th>$D^+D^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+1</td>
<td>$T_{cc}^{++}$</td>
<td>-</td>
<td>-</td>
<td>2/3</td>
<td>2/3</td>
<td>1/3</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$T_{cc}^+$</td>
<td>2/3</td>
<td>2/3</td>
<td>1/3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>$T_{cc}^0$</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>$\Sigma$</td>
<td>2/3</td>
<td>5/3</td>
<td>1</td>
<td>2/3</td>
<td>1/3</td>
<td>-</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>$T_{cc}^+$</td>
<td>2/3</td>
<td>2/3</td>
<td>1/3</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

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Vanya Belyaev "Doubly charmed tetraquark"
Amplitude pole

Analytic continuation of the amplitude to the second Riemann sheet

\[ \sqrt{s} \equiv m_{\text{pole}} - \frac{i}{2} \Gamma_{\text{pole}} \]

\[ \delta m_{\text{pole}} = -360 \pm 40 \pm 4 \text{ keV}/c^2 \]
\[ \Gamma_{\text{pole}} = 48 \pm 2 \pm 14 \text{ keV} \]

\[ m_{\text{pole}} \approx m_U \]
\[ \Gamma_{\text{pole}} \approx \text{FWHM} \]
Amplitude pole

\[ \delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV/c}^2 \]

\[ \Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV}, \]

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Vanya Belyaev "Doubly charmed tetraquark"
Amplitude pole

\[
\sqrt{s} \equiv m_{\text{pole}} - \frac{i}{2} \Gamma_{\text{pole}}
\]

\[
\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV}/c^2
\]

\[
\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV},
\]
Low energy scattering parameters

- **Scattering length** $a$
  - $\text{Re } a < 0$: attractive potential
  - $\text{Re } a$: characteristic size

- **Effective range** $r$

\[
A_{NR}^{-1} = \frac{1}{a} + r \frac{k^2}{2} - ik + O(k^4),
\]

\[
\frac{2}{|g|^2} A_{U}^{-1} = - \left[ \xi(s) - \xi(m_U^2) \right] + 2 \frac{m_U^2 - s}{|g|^2} - i \rho_{tot}(s)
\]

$k = 4\pi \sqrt{s} \rho_{tot}(s)$
Low energy scattering parameters

Match to low energy scattering amplitude

\[ A_{NR}^{-1} = \frac{1}{a} + \frac{r k^2}{2} - ik + O(k^4), \]

\[ \frac{2}{|g|^2} A_{U}^{-1} = -\left[\xi(s) - \xi(m_U^2)\right] + 2\frac{m_U^2 - s}{|g|^2} - i\delta \text{tot}(s) \]

Good match for scaled amplitude

\[ \delta \sqrt{s} \lesssim -\Gamma_{D^{*+}} \]
Low energy scattering parameters

\[ A_{NR}^{-1} = \frac{1}{a} + r \frac{k^2}{2} - ik + \mathcal{O}(k^4) \]

- **Scattering length**
  \[ a = \left[ - (7.16 \pm 0.51) + i (1.85 \pm 0.28) \right] \text{ fm} \]

- **Real part is negative**
  \( \rightarrow \) attraction

- **Effective range**
  \[ r = - \frac{1}{w} \frac{16}{|g|^2} \]
  \[ 0 \leq -r < 11.9 (16.9) \text{ fm at } 90 (95)\% \text{ CL} \]

- **Compositness**
  \[ Z \propto |g|^{-2} \]
  \[ Z = 1 - \frac{1}{1 + 2 |r/R a|} \]
  \[ Z < 0.52 (0.58) \text{ at } 90 (95)\% \text{ CL} \]

[Weinberg 1965, Matuschek, Baru, Guo & Hanhart 2021]

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Effective size

- Effective size from the scattering length

\[ R_a \equiv -\delta a = 7.16 \pm 0.51 \text{ fm} \]

- Effective size from the binding energy

\[ \Delta E = -\delta m_U \]
\[ \gamma = \sqrt{2\mu\Delta E} = 26.4 \pm 1.5 \text{ MeV/c} \]
\[ R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4 \text{ fm} \]

- The object is really large
  - ... around Radium or Uranium nuclear
  - Top three: \( X(3872), T_{cc}^+ \) and deuteron (+other nuclei...)

Large size should have effect on production properties
Event activity/Track multiplicity

- Track multiplicity
- low-mass $D\bar{D}$ and $DD$

$p$-value: $T_{cc}^+$ vs $D\bar{D} = 0.1\%$
p-value: $T_{cc}^+$ vs $DD = 12\%$

- Similar to $DD$
  - DPS process
  - ... unexpected
- Different from $D\bar{D}$
  - Expected but totally different!
Track multiplicity for \(X(3872)\)

- Both states are “large”, some similarity could be expected
- \(X(3872)\) clear suppression for large multiplicity
- \(T_{cc}^+\) no suppression!!! One sees enhancement!!!

7 Oct 2021/Warwisk

Vanya Belyaev "Doubly charmed tetraquark"
The pT spectrum for the decay $T_{cc}^+ \rightarrow D^0 D^0 \pi^+$ is shown. The p-value for the comparison of $T_{cc}^+ vs \overline{D} D$ is 1.4%, and the p-value for $T_{cc}^+ vs DD$ is 0.02%. The graph indicates that more data is needed to make a definitive conclusion.

- A bit inconclusive
- More data is needed
**X(3872) → D^0 D^0 \pi^0, D^0\overline{D}^0 \gamma**

- **Huge X(3872) signal**
- Large uncertainty (>30%) due to X(3872) shape and background
- Larger than T_{cc} statistics
- Better understanding of X(3872) is needed

\[ \text{N}(T_{cc}^+) / \text{N}(X(3872)) \sim 1/20 \]

\[ m_{D^0D^0} [\text{GeV}/c^2] \]

**Production estimate**

arXiv:2109:01056

```
X(3872) \rightarrow D^0 \overline{D}^0 \pi^0, D^0\overline{D}^0 \gamma
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Production estimate

arXiv:2109:01056
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\[ m_{D^0D^0} [\text{GeV}/c^2] \]

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\text{LHCb} 9 \text{ fb}^{-1}
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\text{arXiv:2109:01056}
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JHEP 07(2019) 035
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\[ \text{JHEP 07(2019) 035} \]

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N(T_{cc}^+)/N(X(3872)) \sim 1/20
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\[ \text{JHEP 07(2019) 035} \]

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For compact tetraquark interpretation of $X(3872)$ there is charged partner $\bar{X}^+$ close to $D^*+\bar{D}^0$ threshold.

No $\bar{X}^+$ signal is observed

$\bar{X}^+ : T_{cc}^+ : X(3872) < 0.1 : 1 : \sim 20$
• Manifestly exotic state near $D^*+D^0$ threshold is observed with overwhelming significance
  • New class of hadronic matter
  • Narrow
  • Just below threshold
  • Minimal quark content $ccud$
  • Long awaited $T_{cc}^+$
• Breit-Wigner mass and width

$$\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14} \text{ keV}/c^2,$$
$$\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38} \text{ keV},$$
Summary II/V

- Decay proceed via an intermediate off-shell $D^{*+}$
- Strong argument in favor of $J^P=1^+$
- Using dedicated unitarized 3-body model

\[
\delta m_U = -359 \pm 40^{+9}_{-6} \text{ keV}/c^2
\]

\[|g| > 5.1 (4.3) \text{ GeV at 90 (95) \% CL}\]

- Pole position

\[
\delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV}/c^2, \\
\Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV},
\]

- Study of $D^0D^0$ and $D^+D^0$ spectra support isoscalar nature
- Study of $D^+D^+$ and $D^+D^0\pi^+$ spectra rejects isovector nature
Summary III/V

- Scattering length
- Effective range
- Compositness
- Effective size

\[ a = \left[ - (7.16 \pm 0.51) + i (1.85 \pm 0.28) \right] \text{ fm} \]

\[ 0 \leq -r < 11.9 (16.9) \text{ fm at } 90 (95)\% \text{ CL} \]

\[ Z < 0.52 (0.58) \text{ at } 90 (95)\% \text{ CL} \]

\[ R_a \equiv -\Re a = 7.16 \pm 0.51 \text{ fm} \]

\[ R_{\Delta E} \equiv \frac{1}{\gamma} = 7.5 \pm 0.4 \text{ fm} \]

- No suppression of production at large multiplicities
  - Enhancement is seen
- Suprising similarity with \( D^0D^0 \) (DPS) production
• We already know a lot about $T_{cc}^+$ now
  • Is it enough to answer the main questions?
  • What is missing?
• What is the nature of
  • Compact tetraquark? Binding is expected. Closeness to threshold is “accidental”.
  • Molecule? Closeness to threshold is “natural”
• (Nearby) future
  • Amplitude analysis of Dalitz plot
  • Production measurements
    • Relative to $X(3872) \rightarrow D^0 \bar{D}^0 \pi^0, D^0 \bar{D}^0 \gamma, \psi \rightarrow D^0 \bar{D}^0, \Xi_{cc}^{++}$
    • Add new decay channels of $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$
• More data in Run 3
Summary V

- $T_{cc}^+$ is almost stable
- $T_{bc}^0$ can be stable
- $T_{bb}^-$ should be stable
- Theory consensus
- Lattice QCD
- Only weak decays!
- Macroscopic lifetime!

Figure: Karliner & Risner, 2017
Observation of an exotic narrow doubly charmed tetraquark

Abstract

Conventional hadronic matter consists of baryons and quark-antiquark pairs, respectively. The observed narrow resonance, a doubly charmed tetraquark containing an anti-d quark, is reported using data collected at the Large Hadron Collider. This exotic state manifests itself as a narrow peak in the mass spectrum just below the $D^*+D^*$ mass threshold. The near-threshold narrow width reveals the resonance nature of this state.

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Authors are listed at the end of this Letter.

Study of the doubly charmed tetraquark $T_{cc}^+$

Our distinguished colleague, beloved member of LHCb and whole hadron physics community has passed away.

His contribution to the field will have a lasting impact in future generations.

We dedicate the oncoming papers on the observation of the $T_{cc}^+$ to his memory.

Simon Eidelman 1948 - 2021

Vanya Belyaev "Doubly charmed tetraquark"
Mini-workshop on \( T_{cc}^+ \) and beyond, Online

14 September 2021
Europe/Zurich timezone

Overview
Timetable
Contribution List
My Conference
My Contributions
Participant List
Videoconference

The workshop is dedicated to discussion on the recent observation of the exotic doubly charmed tetraquark \( T_{cc}^+ \). The main purpose of the workshop is to summarize our current knowledge, both experimental and theoretical, on double heavy tetraquark system, including the properties of the \( T_{cc}^+ \) tetraquark and discuss the next steps.

1. LHCb-PAPER-2021-031, arXiv:2109.01038
2. LHCb-PAPER-2021-032, arXiv:2109.01056

The workshop is scheduled at the same date after the CERN LHC seminar, where the observation of the \( T_{cc}^+ \) tetraquark and measurement of its properties is reported.

Due to COVID-19, workshop is purely virtual, on-line only.
Thank you!
Extended Data Fig. 2: Mass distributions for $D^0 D^0 \pi^+$ combinations with fake $D^0$ candidates. Mass distributions for $D^0 D^0 \pi^+$ combinations with (a) one true and one fake $D^0$ candidate, (b) two fake $D^0$ candidates and (c) at least one fake $D^0$ candidate. Results of the fits with background-only functions are overlaid.
Extended Data Fig. 4: Mass distributions for $D^0D^+$ and $D^0D^-$ candidates. Background-subtracted $D^0D^+$ and $D^0D^-$ mass distributions.
\[ \mathcal{Q}_f(s) = \frac{1}{(2\pi)^5 \frac{\pi^2}{4s}} \int \int ds_1 ds_2 \frac{|M_f(s, s_{12}, s_{23})|^2}{|g|^2} \]
\[ \xi(s) = \frac{s}{2\pi} \text{p.v.} \int_{s_{\text{th}}^*}^{+\infty} \frac{\rho_{\text{tot}}(s')}{s' (s' - s)} ds' , \]
Mass splitting for isovector:

\[
\begin{align*}
    m_{\Sigma_{c}^{++}} &= m_{\Sigma} + m_{u} + m_{u} - a q_{u} q_{u} - b q_{c} (q_{u} + q_{u}) \\
    m_{\Sigma_{c}^{+}} &= m_{\Sigma} + m_{u} + m_{d} - a q_{u} q_{d} - b q_{c} (q_{u} + q_{d}) \\
    m_{\Sigma_{c}^{0}} &= m_{\Sigma} + m_{d} + m_{d} - a q_{d} q_{d} - b q_{c} (q_{d} + q_{d})
\end{align*}
\]

\[
\begin{align*}
    m_{\hat{T}_{0}^{cc}} &= m_{\hat{T}_{cc}} + m_{u} + m_{u} - a' q_{u} q_{\bar{u}} - b' q_{cc} (q_{\bar{u}} + q_{u}) \\
    m_{\hat{T}_{+}^{cc}} &= m_{\hat{T}_{cc}} + m_{u} + m_{d} - a' q_{u} q_{\bar{d}} - b' q_{cc} (q_{\bar{u}} + q_{d}) \\
    m_{\hat{T}_{++}^{cc}} &= m_{\hat{T}_{cc}} + m_{d} + m_{d} - a' q_{d} q_{\bar{d}} - b' q_{cc} (q_{\bar{d}} + q_{d})
\end{align*}
\]

\[
\begin{align*}
    m_{\hat{T}_{0}^{cc}} - m_{\hat{T}_{+}^{cc}} &= -5.9 \pm 1.5 \text{ MeV}/c^2, \\
    m_{\hat{T}_{++}^{cc}} - m_{\hat{T}_{+}^{cc}} &= 7.9 \pm 1.3 \text{ MeV}/c^2.
\end{align*}
\]
Consistency of two models

Both models describe data well
Resolution background

Cross-check with pseudoexperiments

Parameter | Value
--- | ---
$N$ | $117 \pm 16$
$\delta m_{BW}$ | $-273 \pm 61$ keV/$c^2$
$\Gamma_{BW}$ | $410 \pm 165$ keV

Parameter | Value
--- | ---
$N$ | $186 \pm 24$
$\delta m_U$ | $-359 \pm 40$ keV/$c^2$
$|g|$ | $3 \times 10^4$ GeV (fixed)

mode | [keV/$c^2$] | FWHM | [keV/$c^2$]
--- | --- | --- | ---
$\delta^{BW}$ | $-279 \pm 59$ | $409 \pm 163$
$\delta^{U}$ | $-361 \pm 40$ | $47.8 \pm 1.9$

Parameter | Pseudoexperiments | Data
--- | --- | ---
mean | RMS |
$\delta m_{BW}$ | $-301$ | $-273 \pm 61$
$\Gamma_{BW}$ | $222$ | $410 \pm 165$
$\delta m_U$ | $-378$ | $-359 \pm 40$
Trigger

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu^\pm$
- 150 kHz $e/\gamma$

Defer 20% to disk

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz Rate to storage

Software High Level Trigger

- Partial event reconstruction, select displaced tracks/vertices and dimuons
- Buffer events to disk, perform online detector calibration and alignment
- Full offline-like event selection, mixture of inclusive and exclusive triggers

12.5 kHz Rate to storage