Discovery of $T_{cc}^+$, new species of hadronic matter

[LHCb, arXiv:2109.01038]

[LHCb, arXiv:2109.01056]

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October 7$^{th}$, 2021
RU-A Day of ORIGINS
Standard model of particle physics
One of the most beautiful and elegant(!) theory in physics
Standard model of particle physics

One of the most beautiful and elegant(!) theory in physics

\[ \mathcal{L}_{\text{SM}} = -\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - g_s f^{abc} f_{abc} \phi g^a g^b g^c - \frac{1}{4} f^{abc} f_{abc} \phi g^a g^b g^c - \partial_\mu W^a_+ \partial^\mu W^a_+ - M^2 W^a_+ W^a_- - \frac{1}{2} \partial_\mu Z^0 \partial^\mu Z^0 - \frac{1}{4} Z^0 F^a Z^0 F^a - \frac{1}{2} \partial_\mu A_\mu A_\mu - \frac{1}{2} \partial_\mu A_\mu \partial^\mu A_\mu - W^a_+ W^a_- - W^a_- W^a_+ \] - \mathcal{L}_{\text{Higgs}} - QCD: Self-couplings of gluons, color confinement

Hadronic matter

Conscious life

\[ M_{\text{phys}} \]

Misha Mikhasenko (ORIGINS Cluster)

Discovery of $T_{cc}^+$

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Standard model of particle physics

One of the most beautiful and elegant(!) theory in physics

\[ L_{\text{SM}} = -\frac{1}{2} \partial_{\mu} q^{a} \partial^{\mu} q^{a} - g_{s} f^{abc} q^{a} \partial_{\nu} q^{b} g^{c} \partial_{\nu} g^{c} - \frac{1}{2} M_{W}^{2} W_{\mu}^{+} W_{\mu}^{-} - \frac{1}{2} Z_{0}^{2} Z_{0}^{-2} - \frac{1}{2} g_{s} A_{\mu} A_{\mu} - i g_{W} (\partial_{\mu} Z_{0}^{\mu} W_{\nu}^{-} - W_{\nu}^{-} \partial_{\mu} W_{\nu}^{-}) - Z_{0}^{0} (\partial_{\mu} A_{\mu} W_{\nu}^{\pm} - W_{\nu}^{\pm} \partial_{\mu} A_{\mu}) \]

QCD: Self-couplings of gluons, — color confinement
Standard model of particle physics

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\[ \mathcal{L}_{\text{SM}} = -\frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi - g_{s} f^{abc} \phi \theta_{a} g_{b} \phi \theta_{c} \phi' - \frac{1}{2} M^{2} \phi^{2} - \frac{1}{2} \partial_{\mu} \phi^{a} \partial^{\mu} \phi^{a} - \lambda_{\phi} \phi^{4} - \lambda_{\phi^2} \phi^{2} - \frac{1}{2} \lambda_{\phi^3} \phi^{3} - \frac{1}{2} \lambda_{\phi^4} \phi^{4} - \frac{1}{2} \lambda_{\phi^5} \phi^{5} - \frac{1}{2} \lambda_{\phi^6} \phi^{6} \]

\[ \text{SM: Electroweak-Higgs & QCD} \]

\[ \downarrow \]

\[ \text{QCD: Self-couplings of gluons,} \quad \text{— color confinement} \]

\[ \downarrow \]

\[ \text{Hadronic matter} \]
Standard model of particle physics

One of the most beautiful and elegant(!) theory in physics

\[ \mathcal{L}_{SM} = -\frac{1}{2} \partial_\mu \partial_\nu \phi \phi - g_s f_{abc} q^a g_s q^b g_s q^c - \frac{1}{2} M^2 \phi^2 - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \partial_\nu \phi^T \phi^T - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{2} \partial_\mu \phi^T \partial^\mu \phi - \frac{1}{
Conventional hadrons

Meson: \( q \bar{q} \)

Baryon: \( q q' q'' \)

\[ \Rightarrow \sim 10 \text{ classes of mesons and} \]
\[ \sim 20 \text{ classes of baryons} \]
Growing evidence of exotic states

- All but one with hidden flavor: \((c\bar{c})\) or \((b\bar{b})\)
- Complex discovery, controversial interpretation

<table>
<thead>
<tr>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>(X_0(2900), X_1(2900))  [22,23]</td>
</tr>
<tr>
<td>(\chi_{c1}(3872))       [7]</td>
</tr>
<tr>
<td>(Z_c(3900)) [24], (Z_c(4020)) [25,26], (Z_c(4050)) [27], (X(4100)) [28], (Z_c(4200)) [29], (Z_c(4430)) [30,31,32,33], (R_{c0}(4240)) [32]</td>
</tr>
<tr>
<td>(Z_{cs}(3985)) [34], (Z_{cs}(4000)), (Z_{cs}(4220)) [35]</td>
</tr>
<tr>
<td>(\chi_{c1}(4140)) [36,37,38,39], (\chi_{c1}(4274)), (\chi_{c0}(4500)), (\chi_{c0}(4700)) [39], (X(4630)), (X(4685)) [35], (X(4740)) [40]</td>
</tr>
<tr>
<td>(X(6900)) [15]</td>
</tr>
<tr>
<td>(Z_b(10610), Z_b(10650)) [41]</td>
</tr>
<tr>
<td>(P_{c}(4312)) [42], (P_{c}(4380)) [43], (P_{c}(4440)), (P_{c}(4457)) [42], (P_{c}(4357)) [44]</td>
</tr>
<tr>
<td>(P_{cs}(4459)) [45]</td>
</tr>
</tbody>
</table>
Meet $T_{QQ'}$

Anticipated open-flavor exotic hadron

- Ground state: $(QQ' \bar{u} \bar{d})$, $J^P = 1^+$, isospin 0
- Exists?
  - $T_{bb}$: most theorists believe that it exists.
  - $T_{cc}$: no consensus
- Exp: “does not exist before observed”

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

- J. Carlson et al. 1987
- B. Silvestre-Brac and C. Semay 1993
- C. Semay and B. Silvestre-Brac 1994
- M. A. Moinester 1995
- S. Pepin et al. 1996
- B. A. Gelman and S. Nussinov 2003
- J. Vijande et al. 2003
- D. Jane and M. Rosina 2004
- F. Navarra et al. 2007
- J. Vijande et al. 2007
- D. Ebert et al. 2007
- S. H. Lee and S. Yasui 2009
- Y. Yang et al. 2009
- N. Li et al. 2012
- G.-Q. Feng et al. 2013
- S.-Q. Luo et al. 2017
- M. Karliner and J. Rosner 2017
- E. J. Eichten and C. Quigg 2017
- Z. G. Wang 2017
- W. Park et al. 2018
- P. Junnarkar et al. 2018
- C. Deng et al. 2018
- M.-Z. Liu et al. 2019
- L. Maiani et al. 2019
- G. Yang et al. 2019
- Y. Tan et al. 2020
- Q.-F. Lü et al. 2020
- E. Braaten et al. 2020
- D. Gao et al. 2020
- J.-B. Cheng et al. 2020
- S. Noh et al. 2021
- R. N. Faustov et al. 2021
Selected theory approaches

- Phenomenological approach for compact hadrons
- Non-relativistic constituent quark model [more on the next slide]
- Molecule models
- Hydrogen bond in QCD
- Lattice QCD [more on the next slide]
- ...
Non-relativistic quark model. $T_{cc}^+$ wave function

- Solve Heisenberg equation. Interaction between every pair of quarks

$$H = \sum_i (m_i + \frac{p^2}{2m_i}) - \frac{3}{16} \sum_{i<j} v_{ij}(r_{ij}), \text{ with } r_{ij} = |\vec{r}_i - \vec{r}_j|$$

- Different variants for potential are used (“Bhaduri” and “Grenoble”)

$$v_{ij}^{(Bhaduri)}(r_{ij}) = \lambda_i \lambda_j \left[ \Lambda - \frac{\kappa}{r} + \lambda r \frac{\exp(\frac{-r}{r_0})}{r_0^2} \sigma_i \sigma_j \right]$$

with parameters adjusted by fit to conv. states.

- $T_{bb}$ is bound and rather compact:
  (bb) in triplet, $J_{(bb)} = 1$.

- $T_{cc}^+$ is near binding and looks like $D^* D$:
  (cc) in (sixt.), $J_{(cc)} = 0, 1$.

  $\delta m \in \{-1, 0, 11, 13\}$ MeV [Semay, Silvestre-Brac (1993)]

  $\delta m \in \{-2.7, -0.6\}$ MeV [Janc, Rosina (2004)]
Non-relativistic quark model. $T_{cc}^+$ wave function

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- Different variants for potential are used ("Bhaduri" and "Grenoble")

\[ v_{ij}^{(Bhaduri)}(r_{ij}) = \tilde{\lambda}_i \tilde{\lambda}_j \left[ \Lambda - \frac{\kappa}{r} + \lambda r \right] + \frac{\kappa}{m_i m_j} \frac{\exp(-r/r_0)}{r_0^2} \sigma_i \sigma_j, \]

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Lattice QCD

First-principles theoretical (numerical) approach to QCD.

Several calculations are done. The situation is puzzling

- HAL QCD Collaboration (2014): attraction but **no binding**
- Hadron Spectrum Collaboration (2017): **no binding**
- Junnarkar et al. (2018): $-23 \pm 11$ MeV **binding**

![Graph showing energy levels for different states with no extra level indicated](image)

**[Junnarkar et al. (2018)]**
**[Cheung et al., (2017)]**

**Discovery of $T_{cc}^+$**

Misha Mikhasenko (ORIGINS Cluster)

October 7th, 2021
Observation of $T_{cc}^+$
LHCb

Muon Stations
- Muon ID ~ 97%
- pi/mu mis ID ~ 1-3%

R_{ing} Imaging CH_{erenkov}
- Kaon ID ~ 95%
- pi/K mis ID ~ 5%

Dipole Magnet

V_{ertex} LO_{cator}
- IP res ~ 20 um

dp / p = 0.5-1.0\%

Tracking stations

Electromagnetic CAL_{orimeter}

pp collider (7+7 TeV)
Selection of $D^0 D^0 \pi^+$

- Select $D^0 D^0 \pi^+$ candidates from primary vertex with detached $D^0 \rightarrow K^- \pi^+$
- Require detached $K^- \pi^+$ with high $p_T$
- Require good quality of tracks, vertexes, and particle ids.
- Ensure no $K/\pi$ candidates belong to one track (clones)
- Ensure no reflections via mis-ID
- Subtract fake-D background using 2d fit to $(m_{K\pi} \times m_{K\pi})$
The first hint of the signal: $D^0D^0\pi^+$ and $D^0\bar{D}^0\pi^+$

A narrow peak near $D^{*0}D^0$ threshold!
Cross-checks

- Different years (2011-2018)
- Different data-taking conditions (magnet polarity)
- No signal when using fake $D^0$

![Graphs showing yield vs. mass for different conditions](image-url)
Spectrum fit and significance
Breit-Wigner model

Too naive model

BW signal $[(DD)_S \pi P\text{-wave}]$ + ph.sp. background
- significance $> 10\sigma$
- peak below $(4.3\sigma)$

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

Fundamental properties? Need better model ($D^* D$ threshold)
Extracting $T_{cc}^{+}$ parameters
$T_{cc}^+$ decay amplitude

Model assumptions:

- $J^P = 1^+$: $S$-wave decay to $D^* D$
- $T_{cc}^+$ is an isoscalar: $|T_{cc}^+\rangle_{I=0} = \{ |D^{*0}D^+\rangle - |D^{*+}D^0\rangle \} / \sqrt{2}$
- No isospin violation in couplings to $D^{*+}D^0$ and $D^{*0}D^+$

$T_{cc}^+$

- $D^{*0}D^+$
- $\pi^0 D^0 D^+$
- $\gamma D^0 D^+$
- $\pi^+ D^0 D^0$
- $\gamma D^+$
- $\pi^0 D^+$
- $\pi^+ D^0$
The self-energy function $A(s)$ counts for all decay channels.

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

The real part is

$$\text{Im} \left[ \text{diagram} \right] = \rho_{\text{tot}}.$$
Fit to the spectrum

Unitarized model

- The signal shape does not depend on $|g|$ for $|g| \to \infty$.
- The lower limit: $|g| > 7.7(6.2)$ GeV at 90(95)% CL
- $\delta m_0$ is the only parameter

<table>
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<tr>
<td>$N$</td>
<td>186 ± 24</td>
</tr>
<tr>
<td>$\delta m_U$</td>
<td>$-359 \pm 40$ keV/c$^2$</td>
</tr>
<tr>
<td>$</td>
<td>g</td>
</tr>
</tbody>
</table>

Excellent agreement with the data. Reaction amplitude is fully fixed.
Predicted mass spectrum
resolution removed

Visible characteristics:
- Peak position: $-359 \pm 40$ keV
- FWHM: $47.8 \pm 1.9$ keV,
- Lifetime: $\tau \approx 10^{-20}$ s.

- Nearly-isolated resonance below $D^{*+}D^0$ threshold
- Long tail with cusps on $D^{*+}D^0$ and $D^{*0}D^+$ thresholds
Fundamental resonance parameters

Mass and width – position of the complex pole of the reaction amplitude

- Analytic continuation is non-trivial due to three-body decays [MM et al. (JPAC), PRD 98 (2018) 096021]

The pole parameters:

\[ \delta m_{\text{pole}} = -360 \pm 40^{+4}_{-0} \text{ keV}, \]
\[ \Gamma_{\text{pole}} = 48 \pm 2^{+0}_{-14} \text{ keV}. \]
The $D^*$ width gives the limit to $T_{cc}^+$ width, $< \Gamma_{T_{cc}^+}^{(\text{max})}$

- Parameter $|g|$ sets the value in the range $[0, \Gamma_{T_{cc}^+}^{(\text{max})}]$
- The fit prefers the limit value
Testing model predictions/
Validating model assumptions
Does $T_{cc}^+$ decay via off-shell $D^*$?

- Peak at high mass requires $D^*$ propagator
- $P$-wave behavior on the left limit
- $S$-wave behavior on the right limit
Partially-reconstructed decays

Independent selection of the prompt $D^0 D^0$ and $D^+ D^0$ events.

- Lineshape of $D^0 D^0$ and $D^+ D^0$ spectra are predicted well by the model.
- Relative yields of $D^0 D^0$ and $D^0 D^+$ is in good agreement with the model predictions.
Isospin partners?

What if the $T_{cc}^+$ is a part of the isospin-1 triplet

$$
\begin{align*}
T_{cc}^0 : & \quad cc\bar{d}\bar{d} \\
T_{cc}^+ : & \quad cc\bar{u}\bar{d} \\
T_{cc}^{++} : & \quad cc\bar{u}\bar{u} \quad \rightarrow D^+ D^{*+}
\end{align*}
$$

The partners should be roughly of the same mass, more precise

$$m_{T_{cc}^{++}} - (m_{D^+} + m_{D^{*+}}) = 2.7 \pm 1.3 \text{ MeV}(\text{using mass of } \Sigma^0_c, \Sigma^+_c, \Sigma^+_{c^+})$$

No indication of $I = 1$ family.
Testing model assumptions

Two extreme spatial configurations

“Molecule” 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.

“Atomic” 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.
Effective range and Weinberg compositeness

Non-relativistic expansion near the threshold:

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

<table>
<thead>
<tr>
<th>Scattering length, ( a )</th>
</tr>
</thead>
<tbody>
<tr>
<td>a characteristic size of the state</td>
</tr>
<tr>
<td>( a &gt; 0 ): moderate interaction</td>
</tr>
<tr>
<td>( a &lt; 0 ): strong attraction forming a bound state</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effective range, ( r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>is the second order correction</td>
</tr>
<tr>
<td>( r ) is always positive in potential scattering</td>
</tr>
</tbody>
</table>

Weinberg compositeness:
\[ 1 - Z = \sqrt{\frac{1}{1 - |r/a|}} \]

\( 1 - Z = 1 \) : composite (molecule) \quad \( 1 - Z = 0 \) elementary

\[ T_{cc}^+ : a = (-7.16 \pm 0.51) + i(1.85 \pm 0.28) \text{ fm} \]
\[ T_{cc}^+ : r \text{ is negative in the model: } 0 < -r < 11.9(16.9) \text{ fm at } 90(95) \% \text{ CL} \]
\[ T_{cc}^+ : 1 - Z > 0.48(0.42) : \text{ not-entirely elementary, well} \]
Do other hadrons of the \((QQ'qq')\) family exist?

- Exists? Now, we are sure they do, all of them.
- Can be observed? Certainly some. Some might be too broad.

- \(T_{bb}^+(bb\bar{u}\bar{d})\) are likely stable wrt QCD
- \(T_{cb}^+(cb\bar{u}\bar{d})\) is either stable or almost as \(T_{cc}^+\)
- Radial and orbital excitations of isoscalar \(T_{QQ}^*\)
- Isovector \(T_{QQ}\) and its family

[Karliner, Rosner (2017)]
Summary

- $T_{cc}^+$ is the first representee of $(QQ'\bar{q}\bar{q}')$ hadrons
- Undoubted proof of hadrons beyond conventional $(q\bar{q})$ and $(qqq)$ scheme
- Almost stable with respect to the strong interaction
Summary

- $T_{cc}^+$ is the first representee of $(QQ'\bar{q}\bar{q}')$ hadrons
- Undoubted proof of hadrons beyond conventional $(q\bar{q})$ and $(qqq)$ scheme
- Almost stable with respect to the strong interaction

Outlook

- Model assumption are consistent with the data, but need to be proven:
  - Accurate accounting for three-body effects
  - Dalitz-plot analysis and test of $J^P$
- Analysis of the production cross sections

[I’m looking for good Bachelor/Master students]
Remarks

- Papers are submitted to Nature
- Wide interest in media
  - > 150 media citations in Russian
  - > 20 in English
  - 1 in German
  - Brazilian, Hebrew, ...
- Publicly available code to build the model in Julia

[QuantaMagazine [link]]

[Haaretz]
Testing model assumptions

New hadrons observed at LHCb

55 new hadrons at LHCb

Date of arXiv submission

Mass [MeV/c²]


October 7th, 2021

Misha Mikhasenko (ORIGINS Cluster)
Thank you for the attention
Two models

Naive model as similar quality but yeilds incorrect parameters

Naive model \((\Gamma_{BW} = 410 \pm 165 \text{ MeV})\)

Complete model
\((\Gamma_{pole} = 48 \pm 2^{+9}_{-14} \text{ MeV})\)

The reason: background and resolution. Confirmed by MC studies.