

Supplementary information

Observation of an exotic narrow doubly charmed tetraquark

In the format provided by the authors and unedited

Contents of this report

1. [Manuscript details](#): overview of your manuscript and the editorial team.
2. [Review synthesis](#): summary of the reviewer reports provided by the editors.
3. [Editorial evaluations](#): personalized evaluation and recommendation from all 3 journals.
4. [Annotated reviewer comments](#): the referee reports with comments from the editors.
5. [Open research evaluation](#): advice for adhering to best reproducibility practices.

About the editorial process

Because you selected the **Nature Portfolio Guided Open Access** option, your manuscript was assessed for suitability in three of our titles publishing high-quality work across the spectrum of physics research: ***Nature Physics***, ***Nature Communications***, and ***Communications Physics***. More information about Guided Open Access can be found [here](#).

Collaborative editorial assessment



Your editorial team discussed the manuscript to determine its suitability for the Nature Portfolio Guided OA pilot. Our assessment of your manuscript takes into account several factors, including whether the work meets the **technical standard** of the Nature Portfolio and whether the findings are of **immediate significance** to the readership of at least one of the participating journals in the Nature Portfolio Guided Open Access physics cluster.

Peer review

Experts were asked to evaluate the following aspects of your manuscript:



- **Novelty** in comparison to prior publications;
- **Likely audience** of researchers in terms of broad fields of study and size;
- **Potential impact** of the study on the immediate or wider research field;
- **Evidence** for the claims and whether additional experiments or analyses could feasibly strengthen the evidence;
- **Methodological detail** and whether the manuscript is reproducible as written;
- Appropriateness of the **literature review**.

Editorial evaluation of reviews



Your editorial team discussed the potential suitability of your manuscript for each of the participating journals. They then discussed the revisions necessary in order for the work to be published, keeping each journal's specific editorial criteria in mind.

Journals in the Nature portfolio will support authors wishing to transfer their reviews and (where reviewers agree) the reviewers' identities to journals outside of Springer Nature. If you have any questions about review portability, please contact our editorial office at guidedoa@nature.com.

Manuscript details

Tracking number	Submission date	Decision date	Peer review type
GUIDEDOA-21-00251	Sep 7, 2021	Oct 20, 2021	Single-blind
Manuscript title Observation of an exotic narrow doubly charmed tetraquark Preprint: https://arxiv.org/abs/2109.01038		Author details Ivan Belyaev <i>et al.</i> (LHCb Collaboration) Affiliation: Institute For Theoretical and Experimental Physics/ITEP NRC (complete author list in manuscript)	

Editorial assessment team

Primary editor	Stefanie Reichert Home journal: <i>Nature Physics</i> Email: stefanie.reichert@nature.com
Other editors consulted	Marco Bentivegna Home journal: <i>Nature Communications</i> ORCID: orcid.org/0000-0002-3986-5760 Elena Belsole Home journal: <i>Communications Physics</i> ORCID: orcid.org/0000-0001-6196-5277
About your primary editor	Stefanie joined <i>Nature Physics</i> in 2018. She obtained her PhD from the University of Manchester, where she studied transitions between particles and their respective anti-particles at the LHCb experiment at the Large Hadron Collider at CERN. She then joined the LHCb group at the Technical University Dortmund as post-doc, where she worked on several decay channels on the quest for finding new physics. Stefanie is based in our Berlin office.

Editorial assessment and review synthesis

Editor's summary and assessment

The LHCb Collaboration reports the observation of a new tetraquark state based on 9/fb of proton–proton collision data. The minimal quark content of this state is two charm, an anti-up and an anti-down quark. The combination of the near-threshold mass, narrow decay width and its appearance in prompt hadroproduction demonstrates that the state observed here has a genuine resonance character, which is consistent with it being a T_{cc}^+ .

Although this is not the first observation of a tetraquark, it's a truly exotic state because its minimal quark content consists of two charm quarks besides an anti-up and an anti-down quark.

Editorial synthesis of reviewer reports

All three reviewers agree that the observation of the T_{cc}^+ state is both novel and important. They expect that this work will have a significant impact and will also raise an interest beyond the particle physics community. Although an independent confirmation of the observation would be desirable, the statistical significance of over 22 standard deviations is compelling.

Reviewer #2 raises a number of technical concerns, and reviewer #3 believes that the manuscript would benefit from additional clarifications.

Editorial evaluations

<i>Nature Physics</i> Minor revisions	The novelty and significance of this work make it suitable for <i>Nature Physics</i> after a minor revision. This revision should address the comments from reviewers #2 and #3.
<i>Nature Communications</i> Minor revisions	Similar to <i>Nature Physics</i> , we would be happy to consider a revision of this manuscript at <i>Nature Communications</i> .
<i>Communications Physics</i> Minor revisions	Similar to <i>Nature Physics</i> and <i>Nature Communications</i> , we would be happy to consider a revision of this manuscript at <i>Communications Physics</i> .

Next steps

Editorial recommendation:

Our recommendation is to revise and resubmit your manuscript to *Nature Physics*. We feel the requests from our reviewers are reasonable and fair, and can be addressed by the authors.

Revision

To follow our recommendation, please upload the revised manuscript files using **the link provided in the decision letter**.

Revision checklist

- Cover letter, stating to which journal you are submitting
- Revised manuscript
- Point-by-point response to reviews
- Updated Reporting Summary and Editorial Policy Checklist
- Supplementary materials (if applicable)

Submission elsewhere

If you choose not to follow our recommendations, you can still take the reviewer reports with you.

Option 1: Transfer to another Nature Portfolio journal

Springer Nature provides authors with the ability to transfer a manuscript within the Nature Portfolio, without the author having to upload the manuscript data again. To use this service, **please follow the transfer link provided in the decision letter**. If no link was provided, please contact guidedOA@nature.com.

Note that any decision to opt in to In Review at the original journal is not sent to the receiving journal on transfer. You can opt in to In Review at receiving journals that support this service by choosing to modify your manuscript on transfer.

Option 2: Portable Peer Review option for submission to a journal outside of Nature Portfolio

If you choose to submit your revised manuscript to a journal at another publisher, we can share the reviews with another journal outside of the Nature Portfolio if requested. You will need to request that the receiving journal office contacts us at guidedOA@nature.com. We have included editorial guidance below in the reviewer reports and open research evaluation to aid in revising the manuscript for publication elsewhere.

Annotated reviewer reports

The editors have included some additional comments on specific points raised by the reviewers below, to clarify requirements for publication in the recommended journal(s). However, please note that all points should be addressed in a revision, even if an editor has not specifically commented on them.

Reviewer #1 information	
Expertise	Theoretical particle and nuclear physics, XYZ states
Editor's comments	The reviewer recommends publication.
Reviewer #1 comments	
Section	Annotated Reviewer Comments
Remarks to the Author: Overall significance	<p>The significance of this paper is not in question: it is reporting the discovery of a new exotic state of a type never observed before, composed by two heavy charm quark and two light quarks, with an unprecedented long lifetime among exotics. The result is therefore certainly original and significant, previous work has been credited appropriately as well the main literature.</p> <p>Since this is a discovery of a new type of exotic state it has the potential to be interesting also to other communities and the wider fields.</p> <p>For all these reasons I believe that the paper deserves publication on Nature. Please note that we believe that the reviewer means Nature Physics here.</p>
Remarks to the Author: Impact	<p>This paper will definitely influence thinking in the field: it is an important discovery with great implications in the field of strong interactions and in general in the field of strongly correlated systems.</p>
Remarks to the Author: Strength of the claims	<p>The work is convincing, the method used is explained and it is appropriate. The discovery plot seems to be extremely convincing and the observation seems to be away from any artefact for many standard deviations.</p> <p>It would be nice if other experiments like CMS or ATLAS could set up to confirm this result, even if they are less suitable to the aim. Although we agree with the reviewer, we do not believe that an independent confirmation is feasible or required for publication at this stage.</p>
Remarks to	The statistical analysis seems to be appropriate and all the details of how the results

the Author: Reproducibility	have been achieved have been given.
------------------------------------	-------------------------------------

Reviewer #2 information

Expertise	Experimental particle physics, XYZ states with a focus on tetraquarks
Editor's comments	The reviewer raises some points that would strengthen the manuscript.

Reviewer #2 comments

Section	Annotated Reviewer Comments
Remarks to the Author: Overall significance	This manuscript describes an observation of a new type hadron containing four quarks, namely $c\bar{c}u\bar{d}$, which is beyond the conventional quark model telling us only baryons and mesons. The results are original and has great impact to the particle physics field usually studying sub-atom particles. It helps complete the exotic hadron picture, which is popular and of interest in a wide community over the last two decades. Within my knowledge, I think the authors credited previous work properly, except for the tetraquark candidate observed by Belle in 2013 (Phys. Rev. Lett. 110, 252002), which should be added in the reference as well.
Remarks to the Author: Impact	I believe the results present in the current manuscript will influence peoples' thinking in the field, and refresh our knowledge about sub-atom physics. I recommend its publication in nature physics.
Remarks to the Author: Strength of the claims	<p>The observed resonance has a statistical significance of over 22 standard deviation, which is convincing and the probability to be due to fluctuation is negligible. However, before the publication, I have quite a few questions and comments, which might help strength the claims present in the current manuscript if addressed properly.</p> <p>Below I list the detailed questions/comments. I know there is an accompanied paper submitted to Nature communication, however, a paper published in Nature Physics journal should stand on its own.</p> <p>1. P1, 2nd para, L1: I think here it's difficult to claim "all exotic hadrons decay</p>

- via strong interaction". A quick example will be $X(3872) \rightarrow \gamma J/\psi$, which is radiative transition. Also, the decay width is from "keV to a few hundred MeV" is more precise
2. P1, 2nd para, L7: should be bound -> could be bound
 3. P1, 2nd para, L9: it's better to write out which pseudoscalar and vector beauty meson here.
 4. P2, 2nd para: although the authors mentioned "charged conjugate decays are implied", is the $\bar{D}^0 \pi^+$ mass distribution agree with the $D^0 \pi^+$ and also shows a same narrow peak? This should be mentioned explicitly in the text.
 5. P2, 2nd para: In my understanding, the $D^0 \pi^+$ events was obtained in each $M(D^0 \pi^+)$ mass bin, by a 2-dimensional fit to the $D^0 D^0$ mass distribution. Then in this case, you can only perform a binned maximum likelihood fit to the $M(D^0 \pi^+)$ distribution. Please make it clear how a unbinned fit ongoing here.
 6. P2, 3rd para, L6: In the fit to the signal, the author use a P-wave resonance, and treat other options as systematic. However, in my opinion, the $D^0 \pi^+$ system is very likely to be a virtue D^{*+} (which is a vector), as indicated also by $D^0 \pi^+$ events in the higher mass region. Thus, it seems S-wave resonance is the most natural parameterization method, still within the $J^P=1^+$ assumption.
 7. P2, 3rd para, L15-16: I am not sure root mean square is equivalent to standard deviation here. Usually we model detector resolution with a Gaussian.
 8. P2, 3rd para, last three lines: For the background term, it seems no background contribution below the $D^{*+} D^0$ mass threshold, due to the product of phase space with polynomial. Why? There could be 3-body phase space events near $D^0 \pi^+$ threshold.
 9. P2, 3rd para: the authors seem never discuss possible interference between T_{cc} and phase space $D^0 \pi^+$ events. Potential phase space background will significantly affect your signal significance.
 10. P3, last line: how to avoid D^0 - \bar{D}^0 mixing here? It's interesting to see it in the Method chapter.
 11. P5, last three lines: "The observation... further support..." seems not make sense to me. Before we found the T_{bb} state, we can say nothing about it.
 12. P6, Selection, L8: The mass window of D^0 is 130 MeV, what's the D^0 mass resolution here? In page 2, the authors mention the resolution is 400 keV.
 13. P7, 1st para, L3-4: it's not clear to me what's the aim of these requirements.
 14. P7, 1st para: The misidentification of the bachelor pion was not mentioned in the text.
 15. P7, 2nd para: the non- D^0 background level for D^0 reconstruction was not mentioned in the text. Is it high, or only a small fraction? Should the reader worry about the background level, and therein the $D^0 D^0$ signal extraction with sPlot technique?
 16. P8, item 1, L1: is "imperfect modelling" means the difference between data and MC simulation, and then a correction factor is applied? If so, please write it

	<p>our more explicitly.</p> <p>17. P8, item 2, last line: is it possible to parameterize the background component as the sum of phase space (2-body or 3-body) and polynomial?</p> <p>18. P8, 4th para: For the T_{cc} mass measurement, with D_0 candidate constrain to its nominal mass, the most relevant momentum scale is the pion track, which should be mentioned more explicitly about its quality.</p> <p>19. P8, 4th & 5th para: here half of the difference is taken as systematic uncertainty, and I am wondering why should only take half. Usually the full difference with ± 1 standard deviation of the source to the nominal approach should be considered as systematic uncertainty.</p> <p>20. P8, last para, L1: mases -> masses</p>
<p>Remarks to the Author: Reproducibility</p>	<p>Usually a confirmation of an observation in particle physics by a second independent experiment is important. However, for such a large international research infrastructure like LHCb, I am afraid there is no chance to find a second experiment to reproduce the work in a short time. Consider the signal significance is high, maybe it is not necessary to reproduce. The quality of the LHCb data is good, and the presentation is clear.</p> <p>We agree with the reviewer that an independent confirmation is neither feasible nor required for publication at this stage.</p>

Reviewer #3 information

<p>Expertise</p>	<p>Experimental particle physics; broader but also tetraquarks</p>
<p>Editor's comments</p>	<p>The reviewer suggests some improvements and clarifications.</p>

Reviewer #3 comments

<p>Section</p>	<p>Annotated Reviewer Comments</p>
<p>Remarks to the Author: Overall significance</p>	<p>The main result, the observation of an exotic doubly charmed tetraquark, is of appropriate importance and significance to be published.</p> <p>The result is novel and has not been made prior to this measurement and all appropriate previous measurements have been cited.</p> <p>The claims are supported and well motivated as well as being based on the measurements made in this paper.</p>
<p>Remarks to the</p>	<p>N/A</p>

<p>Author: Impact</p>	
<p>Remarks to the Author: Strength of the claims</p>	<p>The claims are well supported in the paper.</p> <p>The main issue is with some of the ways the work is presented that could be clarified as described below.</p> <ol style="list-style-type: none"> 1. The first paragraph could do with being rewritten to improve the clarity of the arguments. It is hard to follow and make out the major points. 2. Is a definition of pseudo rapidity required. 3. At the end of page 3 "statistically subtracting" 4. The final sentence of the main part of the paper "The observation of this ccud tetraquark candidate close to the D^*+D_0 threshold further supports the existence of a bbud tetraquark that is stable with respect to the strong and electromagnetic interactions" is not required and not really supported by the work in the paper. I would just drop it. 5. Page 7 " all track pairs of the same charge are required to have opening angle" - define what this requirement is?
<p>Remarks to the Author: Reproducibility</p>	<p>The data and methods used in this analysis are presented so that an accomplished particle physics researcher could reproduce the results (in conjunction with the companion paper).</p> <p>After a minor revision following the comments raised by all reviewers, the level of detail in this and the accompanying manuscript should be sufficient to follow the analysis procedure in detail.</p>

Open research evaluation

Data availability

Data availability statement

Thank you for including a Data Availability statement. However, we noted that you have only indicated that data are available upon request. The data availability statement must make the conditions of access to the “minimum dataset” that are necessary to interpret, verify and extend the research in the article, transparent to readers.

In addition, Nature Portfolio policies include a strong preference for research data to be archived in public repositories. For data types without specific repositories, we recommend that data are deposited in a generalist repository such as figshare or Dryad. More information about our data availability policy can be found [here](#).

See [here](#) for more information about formatting your Data Availability Statement.

Code availability statement

For all studies using custom code or mathematical algorithm that is deemed central to the conclusions, a statement must also be included under the heading "Code availability", indicating whether and how the code or algorithm can be accessed, including any restrictions to access. Code availability statements should be provided as a separate section after the data availability statement but before the References.

In the Reporting Summary, you included a link to <https://gitlab.cern.ch/lhcb-bandq/X2DDstar>. As this link is not publicly accessible, please clarify the limitations of access in the Code Availability Statement.

Other data requests

Springer Nature strongly supports data sharing and believes that all datasets on which the conclusions of the paper rely should be available to readers. We encourage authors to ensure that their datasets are either deposited in publicly available repositories (where available and appropriate) or presented in the main manuscript or additional supporting files whenever possible.

Please see Springer Nature’s information on recommended repositories [here](#).

In the Editorial Policy Checklist, you have confirmed that all relevant accession codes are provided; however, we observed that no data requiring mandated deposition was generated in the study. Further, the ‘data’ section of the reporting summary declares that ‘LHCb has an open data policy, see document LHCb-PUB-2013-003, <http://cdsweb.cern.ch/record/1543410?ln=en>. Subject to the resources being identified, LHCb will endeavor to provide open access to some reconstructed level data on disk at

CERN.' This link directs to the data access policy of LHCb, which provides information on restrictions on data availability. Further, a link to access the data is not provided in the manuscript or in the reporting summary.

Please make the limitations of access more explicit in the Data Availability Statement.

All source data underlying the graphs and charts presented in the main figures must be made available as Supplementary Data (in Excel or text format) or via a generalist repository (eg, Figshare or Dryad). This is mandatory for publication in a Nature Portfolio journal, but is also best practice for publication in any venue. In the present paper, Figure 1 requires associated source data.

Please provide a 'Competing interests' statement using one of the following standard sentences:

1. The authors declare the following competing interests: [specify competing interests]
2. The authors declare no competing interests.

See our [competing interests policy](#) for further information.

Reporting & reproducibility

Nature Portfolio journals allow unlimited space for Methods. The Methods must contain sufficient detail such that the work could be repeated. It is preferable that all key methods be included in the main manuscript, rather than in the Supplementary Information. Please avoid use of “as described previously” or similar, and instead detail the specific methods used with appropriate attribution.

Statistics and data presentation

The meaning of all error bars/bands and how they were calculated should be described within the captions of all figures in which they occur. If they represent standard deviations (or absolute minima and maxima) then this can be simply stated as such, but if not, more detail is required.

Other notes

We have included as an attachment to the decision letter a version of your Reporting Summary with a few notes. This is mainly for your information, but we hope it is helpful when preparing your revised manuscript. If you decide to resubmit the manuscript for further consideration, please be sure to include an updated Reporting Summary.