Recent results on Exotic Spectroscopy

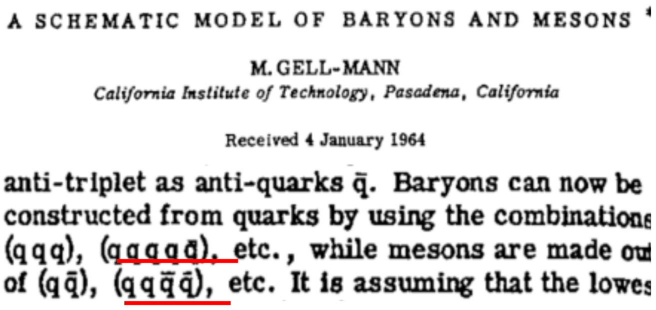
Elisabetta Spadaro Norella

University & INFN Genova

Frontiers in Nuclear and Hadronic Physics 2025, GGI, Firenze

February 27th, 2025

Exotics and heavy quark sector



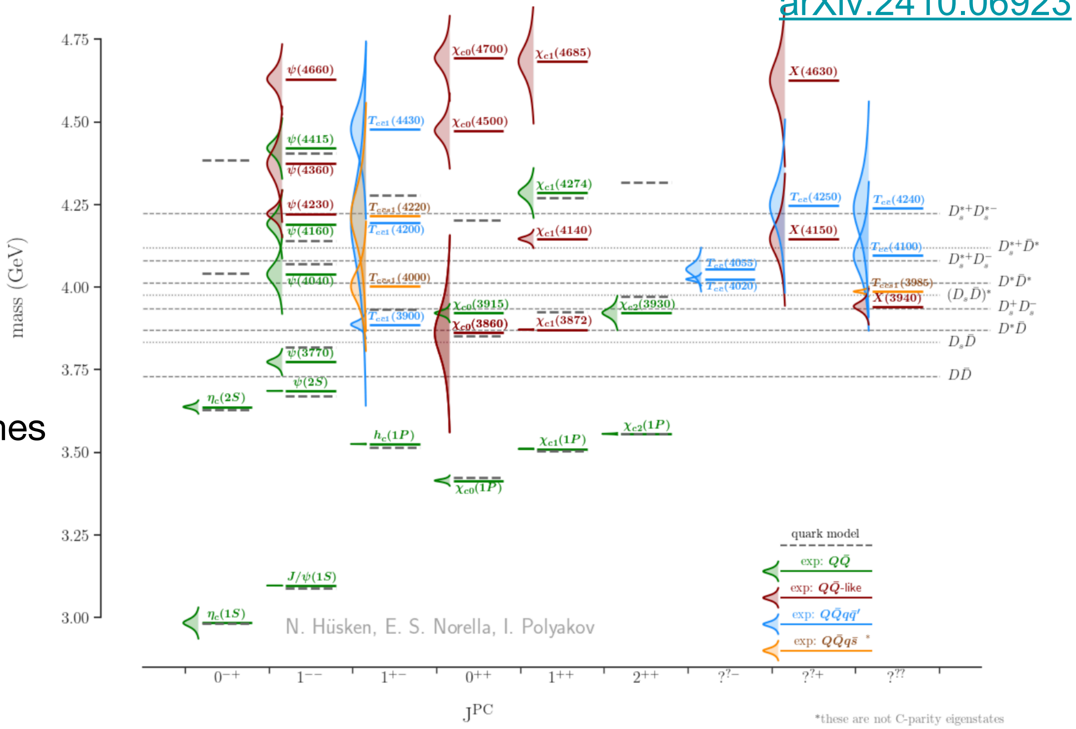
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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 $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowes

[arXiv:2410.06923](https://arxiv.org/abs/2410.06923)



Hidden-charm sector is ideal for exotic searches

- **Theoretical models** well-established for conventional states
- **Experimentally** easy to measure
  - Narrow and non-overlapping
  - Agreement below $D\bar{D}$ threshold

⇒ Exotics easier to identify respect to light and heavy-light sector

The unresolved nature of exotics

Elementary particles

Quarks & gluons

strong interaction (long-distance effects)

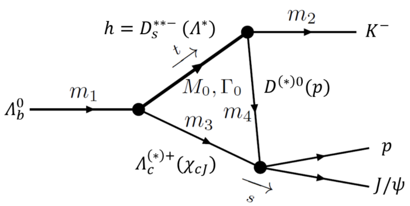
Nature

Color-singlet mesons and baryons

States could also be mimic by

Rescattering effects

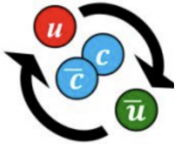
PRD 92 (2015) 071502
PLB 757 (2016) 231
PLB 757 (2016) 61
and others



Compact tetra/pentaquark

Color Forces

Diquark-antidiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)

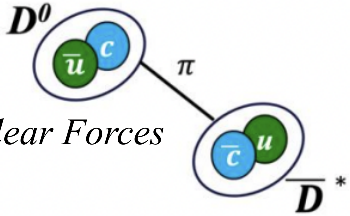


Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic molecules

PRL 105 (2010) 232001,
PRL 115 (2015) 122001
PRD 100 (2019) 011502 (R)
and others

Nuclear Forces



\+ $q\bar{q}g$ hybrid, glueball or mixture

Lattice-QCD is expected to play a leading role in the future
[PRD 10 (1974) 2445, JHEP 07 (2012) 126…]

The unresolved nature of exotics

Elementary particles

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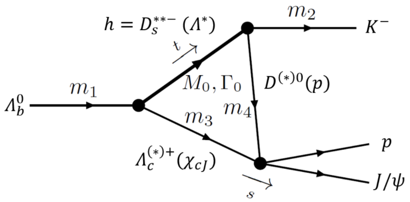

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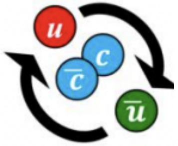

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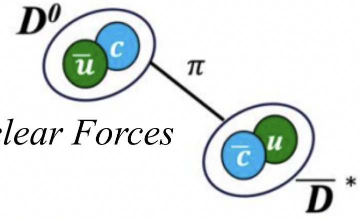


No consensus yet,

What can we do in experiments?

⇒ Different decays and production

⇒ Measure M, Γ, J^P

⇒ Isospin multiplets

How to unravel the New Particle Zoo?

About 50 exotic hadrons with at least one heavy quark (c or b) have been observed so far

arXiv > hep-ph > arXiv:2410.06923

High Energy Physics – Phenomenology

[Submitted on 9 Oct 2024 (v1), last revised 24 Feb 2025 (this version, v2)]

A Brief Guide to Exotic Hadrons

Nils Hüsken, Elisabetta Spadaro Norella, Ivan Polyakov

Accepted by Modern Physics Letters A

Category			States / Candidates
Meson-like (incl. tetraquarks)	Hidden Charm	$I = 0$	$\chi-$like: $\chi_{c1}(3872)$, $\chi_{c0}(3860)$, $\chi_{c0}(3915)$, $\chi_{c2}(3930)$, $X(3940)$
		$I = 0$	$\psi-$like: $\psi(4230)$, $\psi(4360)$, $\psi(4660)$
			with $s\bar{s}$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$, $\chi_{c1}(4500)$, $\chi_{c1}(4700)$ $X(4150)$, $X(4630)$, $X(4740)$
		$I = 1/2$	$T_{c\bar{c}\bar{s}}(3985)^-$, $T_{c\bar{c}\bar{s}1}(4000)^{-/0}$, $T_{c\bar{c}\bar{s}1}(4220)^-$
		$I = 1$	seen in e^+e^-: $T_{c\bar{c}1}(3900)^{+/0}$, $T_{c\bar{c}}(4020)^{+/0}$, $T_{c\bar{c}}(4055)^+$
		$I = 1$	seen in B decays: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}1}(4200)^+$, $T_{c\bar{c}}(4240)^+$, $T_{c\bar{c}}(4250)^+$, $T_{c\bar{c}1}(4430)^+$
	Hidden Bottom	$I = 0$	$\Upsilon(10753)$, $\Upsilon(10860)$, $\Upsilon(11020)$
		$I = 1$	$T_{b\bar{b}1}(10610)^+$, $T_{b\bar{b}1}(10650)^+$
	Hidden Double Charm		$T_{c\bar{c}c\bar{c}}(6550)$, $T_{c\bar{c}c\bar{c}}(6900)$, $T_{c\bar{c}c\bar{c}}(7290)$
	Open Single Charm		D_s^*-like: $D_{s0}^*(2317)^+$, $D_{s1}(2460)^+$
			$T_{cs/c\bar{s}}$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^{0/++}$, $T_{cs1}(2900)^0$
	Open Double Charm		$T_{cc}(3875)^+$
Baryon-like (incl. pentaquarks)	Hidden Charm	$I = 1/2(3/2)$	$P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$ $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$
		$I = 0(1)$	$P_{c\bar{c}s}(4458)^0$, $P_{c\bar{c}s}(4338)^0$

A guide to the new landscape

- **Field guide:** states with similar properties are collected in cards, grouped by the following criteria:

  - number of quarks,
  - flavor content and isospin (I),
  - spin-parity,
  - production and decay channels

4.2 The $\chi_{c1}(3872)$ *(also known as $X(3872)$)*

MESON-LIKE/HIDDEN CHARM/ISOSCALAR

quantum numbers: $I^G(J^{PC}) = 0^+(1^{++})$
minimal quark content: $[c\bar{c}]$, more likely $[c\bar{c}(u\bar{u}+d\bar{d})]$
experiments: Belle, CDF, D0, BaBar, LHCb, CMS, ATLAS, BESIII (and potentially E705, COMPASS)
production: B^+, B^0, B^0_s and Λ^0_b decays, prompt pp, $p\bar{p}$, pPb (Pbp) and PbPb collisions, $e^+e^- \to \gamma\chi_{c1}(3872)$, $\omega\chi_{c1}(3872)$ with the first likely via $\psi(4230)$
decay modes: $\pi^+\pi^- J/\psi$, $\omega J/\psi$, $D^{*0}\bar{D}^0$, $\pi^0\chi_{c1}(1P)$, $\gamma J/\psi$, $\gamma\psi(2S)$
nearby threshold: $D^{*0}\bar{D}^0$
width: 1.19 ± 0.21 MeV (in $\pi^+\pi^- J/\psi$ channel)

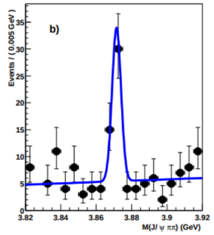


Figure 3: Discovery of the $\chi_{c1}(3872)$ by Belle [71].

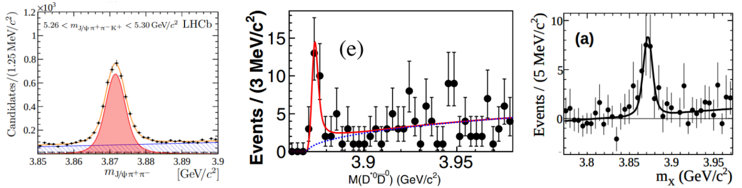
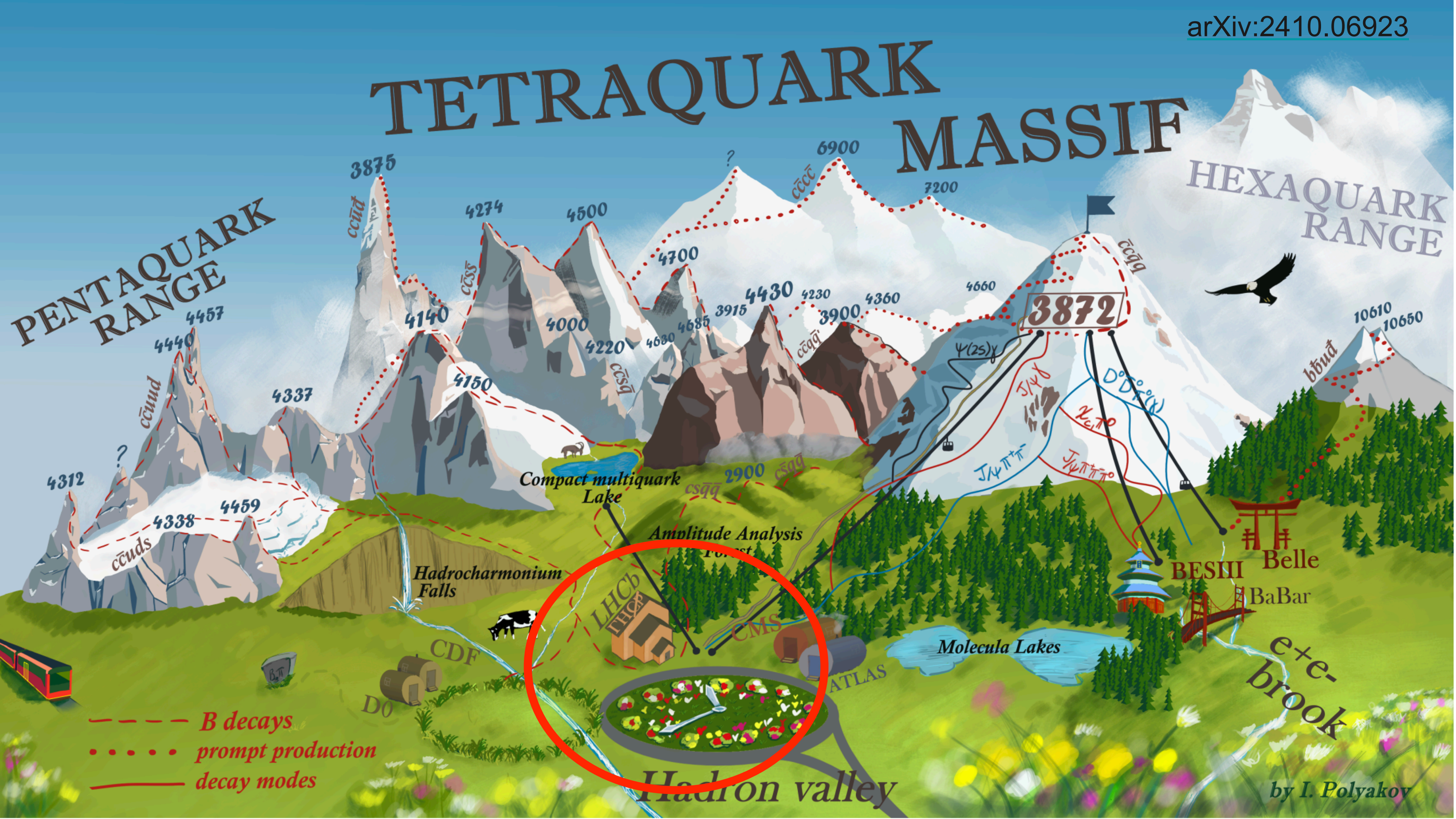


Figure 4: The $\chi_{c1}(3872)$ seen in $J/\psi\pi^+\pi^-$ at LHCb [72] (left), in $D^{*0}[\to D^0\pi^0]\bar{D}^0$ at BESIII [73] (center) and in $J/\psi\gamma$ at BaBar [74] (right).

arXiv:2410.06923


arXiv:2410.06923
TETRAQUARK MASSIF
PENTAQUARK RANGE
HEXAQUARK RANGE
3875
4274
4500
4700
6900
7200
4140
4000
4220
4150
4630
4685
3915
4430
4230
3900
4360
4660
3872
4457
4440
4337
4312
4338
4459
10610
10650
2900
Compact multiquark Lake
Amplitude Analysis Forest
Hadrocharmonium Falls
Molecula Lakes
LHCb
CMS
ATLAS
CDF
D0
BESIII
Belle
BaBar
e+e- brook
Hadron valley
B decays
prompt production
decay modes
by I. Polyakov

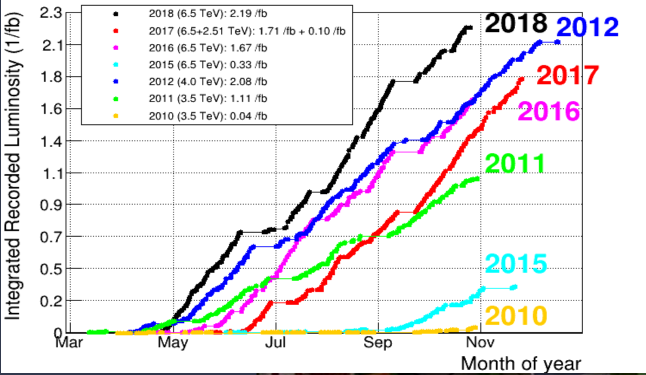
JINST 3 (2008) S08005
IJMP A 30, 1530022 (2015)

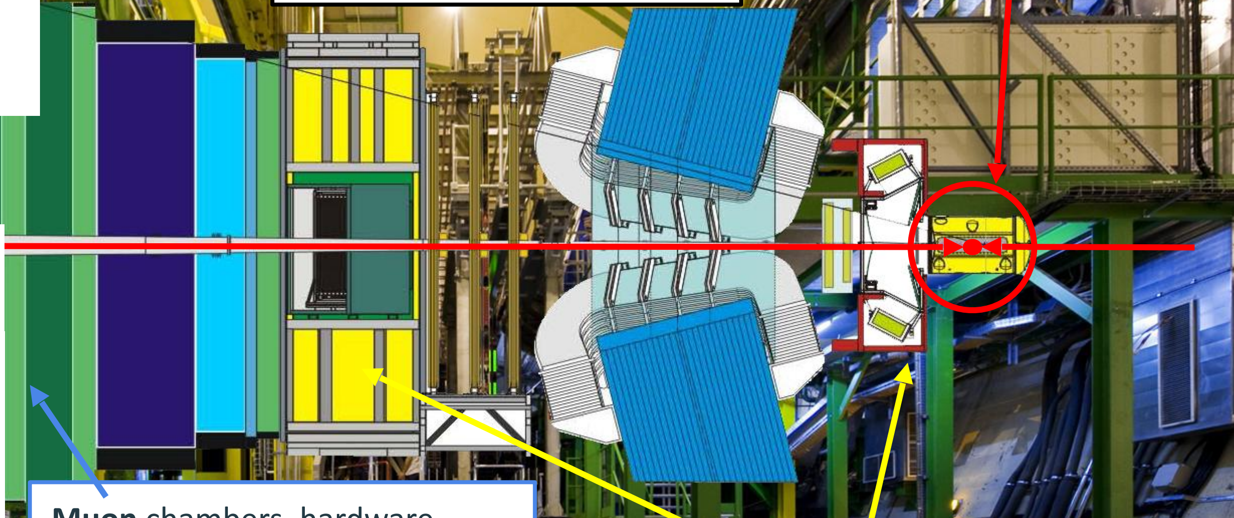
LHCb detector

The major player in spectroscopy thanks to its unique dedicated design

- high invariant mass resolution
- PID for separate K, π, p
- highly performant trigger

Luminosity:
Run 1 and Run 2: 9 fb^{-1}





Tracking: momentum resolution of σ_p / p ~ 0,5 - 1%

VELO: vertex detector
IP resolution: ~25 μm

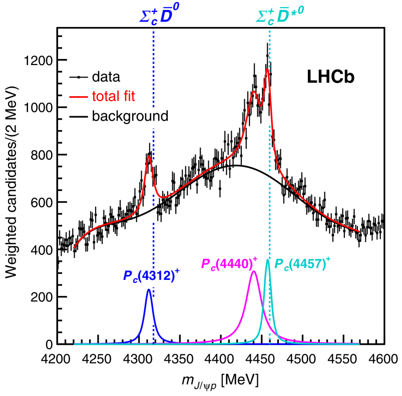
Muon chambers, hardware trigger with ~90% efficiency

Calorimeters, hadron trigger with ~50% efficiency

RICH detectors for particle ID. pid(p - K)~95%

Analysis techniques

Invariant mass fit

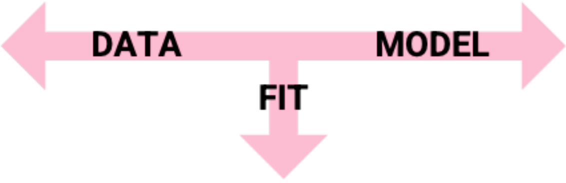


To extract properties of states, M and Γ

BUT cannot measure J^P

Amplitude analysis

Phase space: masses and angles



Helicity/ Tensor formalism + lineshape

Maximum $\mathcal{L}$ fit to extract parameters

To measure J^P, mass and width & account for reflections

⇒ more important for exotic hadron studies

Moment analysis

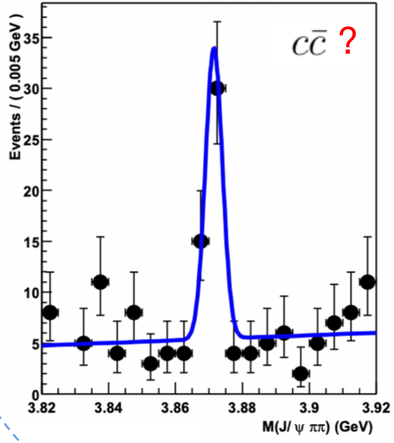
Legendre polynomial expansion

—> Model independent check

First exotic candidates

χ_{c1}(3872)

by Belle in 2003 in
$B^+ \to J/\psi\pi^+\pi^-K^+$ decays



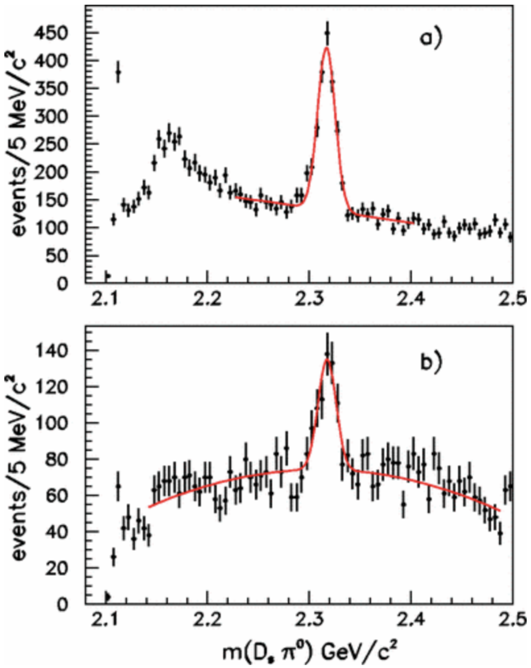
PRL **91**, 262001 (2003)

D^*_{s0}(2317)

by BABAR in 2003
in the isospin violating
$D^+{}_s\pi^0$ decay

PRL 90, 242001 (2003)

$c\bar{s}$?



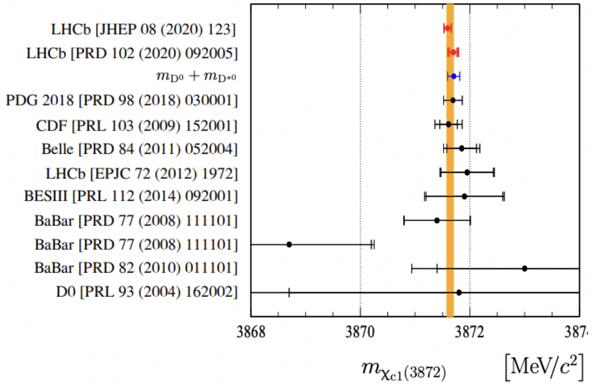
Nature of $\chi_{c1}(3872)$ state

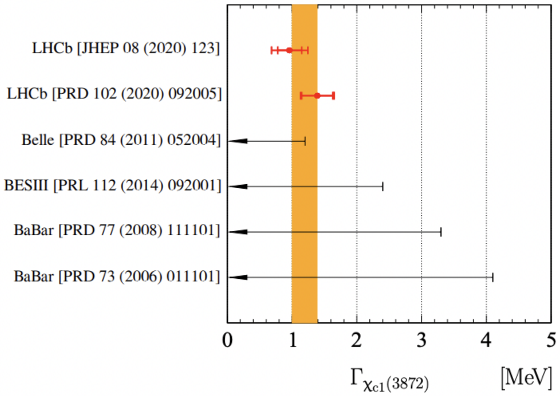
Many experiments contribute to it:

- Spin assignment: $J^{PC} = 1^{++}$ [1] ⇒ consistent with $\chi_{c1}(2P)$
- Mass is consistent with **m(D⁰) + m(D*⁰)** ⇒ disagree with quark model calculation by 100 MeV [2]
- Width is surprisingly narrow

Its nature is still under debate!

→ conventional $\chi_{c1}(2^3P_1)$, DD^* molecular state, tetraquark, hybrid, vector glueball, or mixed?





JHEP 08 (2020) 123

Studying **decay processes** can help understand its nature

[1] PRL. 110 (2013) 222001, PRD 92 (2015) 011102(R)
[2] PhysRevD.69.054008

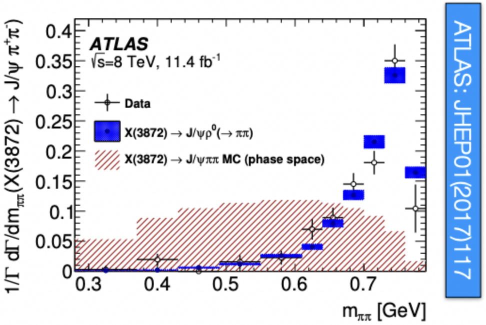
ω contribution in $\chi_{c1}(3872) \to J/\psi\pi\pi$

Phys. Rev. D 108 (2023), no. 1 L011103

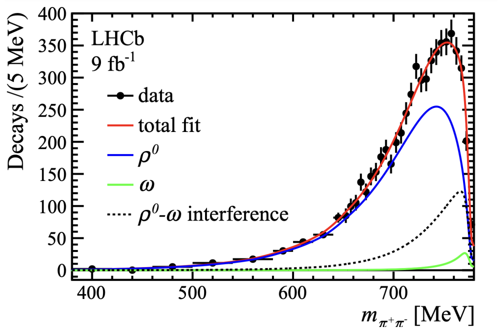
Large isospin violation observed in $\chi_{c1}(3872)$ decays [Belle, BaBar: Phys. Rev. D 82, 011101 (2010)]

→ How large is it in $\chi_{c1} \to J/\psi\pi^+\pi^-$?

Previously only $\chi_{c1}(3872) \to J/\psi\rho$ (isospin violating decay) dominates the phase space



Now with LHCb: ω contribution of 2%, enhanced by ω-ρ interference (~19%)



Isospin violation = ratio of isospin violating to isospin conserving couplings is much larger than expected for a charmonium

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04. \qquad \frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

⇒ $\chi_{c1}(3872)$ is not a pure charmonium state;

Likely related to the ~8 MeV splitting between $\bar{D}^0 D^{*0}$ and $D^{*+}D^-$

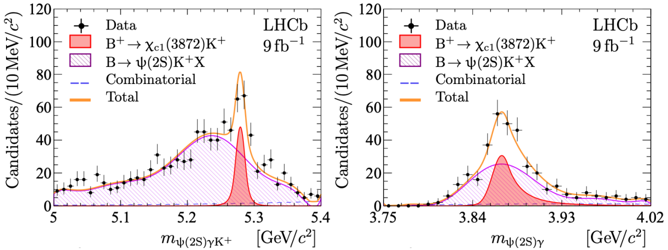
$\chi_{c1}(3872)$ radiative decays

JHEP11(2024)121

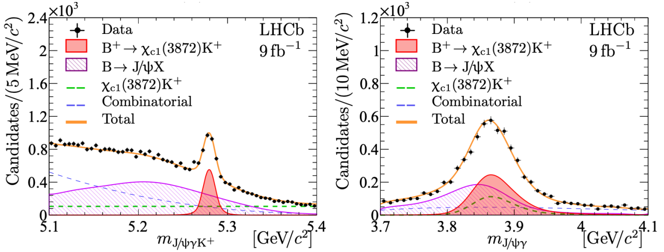
Study of $\chi_{c1}(3872) \to J/\psi\gamma/\psi(2S)\gamma$ in B decays by LHCb

4D fit over:

$B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+$



$B^+ \to (\chi_{c1}(3872) \to J/\psi\gamma)K^+$

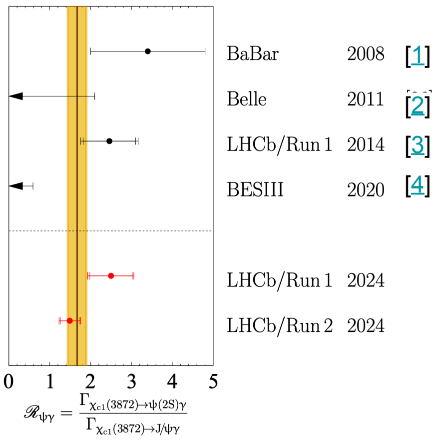


- First observation of $B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+$ at 4.8 (6σ) in Run1 (Run2)
- Ratio measured to be:

$$\frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

=> Large ratio

Previous results



Sizable charmonium or compact tetraquark component are more likely

Pure molecular $D\bar{D}^*$ hypothesis is questionable

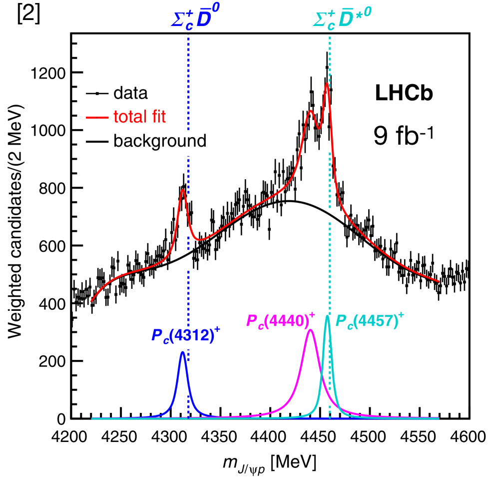
- But small admixture of $c\bar{c}$ component is sufficient to explain the data [PhysLettB 2015 0213]

Manifestly exotic

Pentaquarks $c\bar{c}uud$

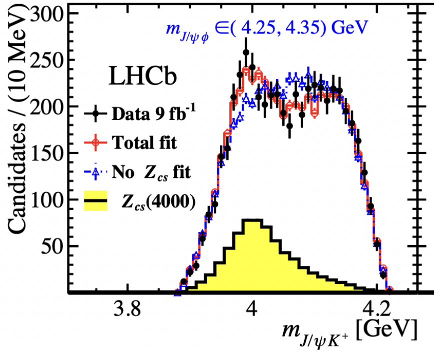
by LHCb in 2015 in $\Lambda_b \to J/\psi p K$[1]

$P_{c\bar{c}}(4312)^{+}$ + 2 peaks at 4450 MeV [2]

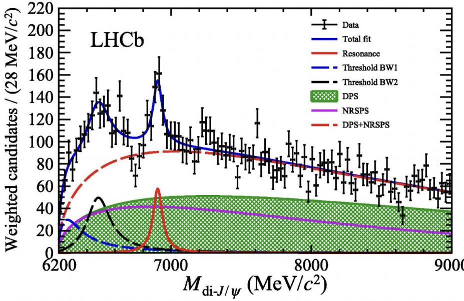


Tetraquarks

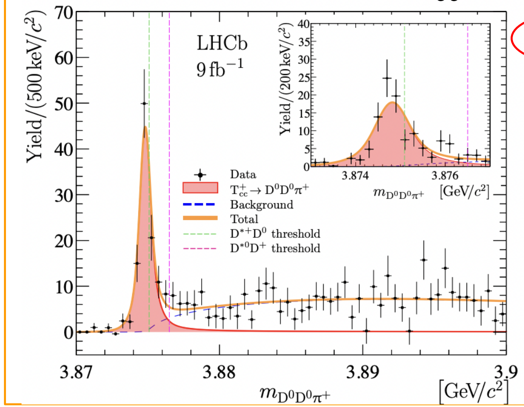
$Z_{cs}(4000)^+$ ($\to T_{cs1}$) [3] $c\bar{c}u\bar{s}$



$T_{c\bar{c}c\bar{c}}(6900)$: di-$\psi$ resonance [4] $c\bar{c}c\bar{c}$

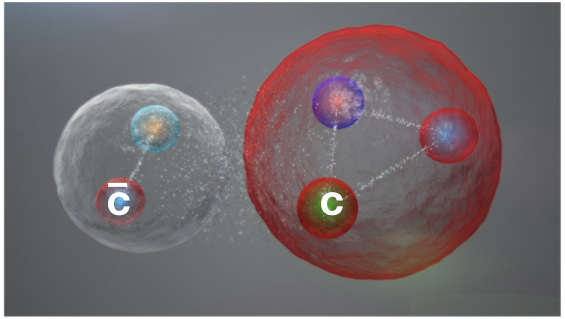


Doubly-charm tetraquark $T_{cc}(3875)^{+}$[5,6] $cc\bar{u}\bar{d}$

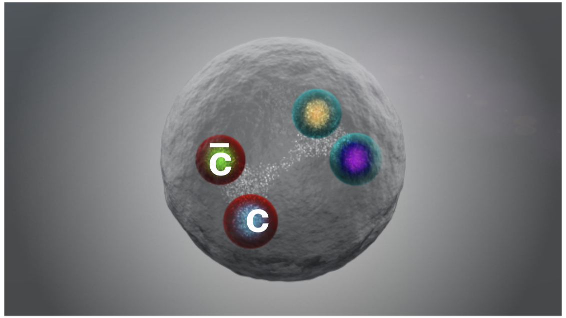


[1] PRL 115, 072001 (2015)
[2] PRL 122, 222001 (2019)
[3] PRL 127, 082001 (2021)
[4] Sc. Bull. 2020 65(23)1983-1993
[5] Nature Physics (2022),
[6] Nature Comm., 13, 3351 (2022)

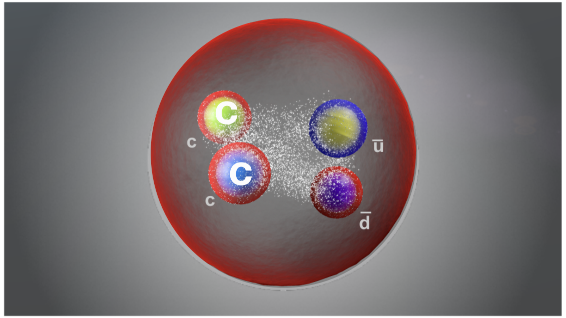
Classifying Exotics...



Hidden-charm pentaquark

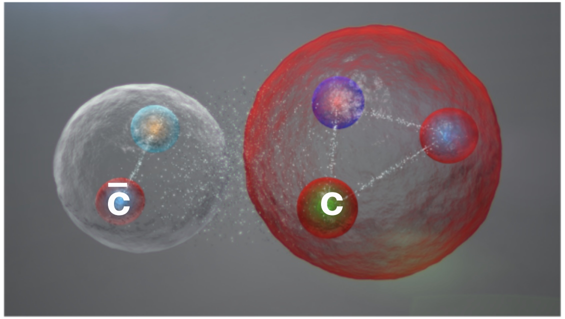


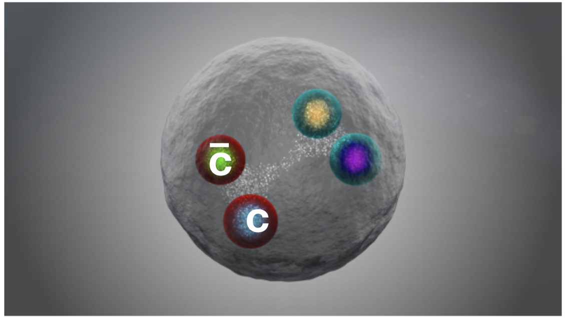
Hidden-charm tetraquarks

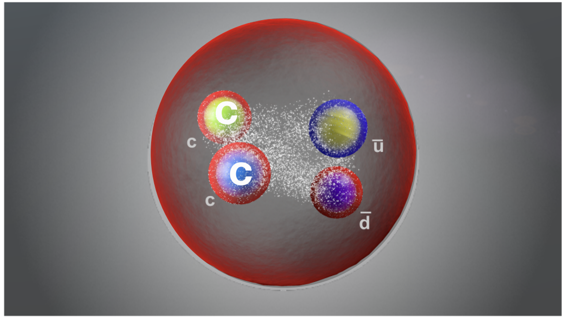


Beyond hidden-charm

Classifying Exotics...







Hidden-charm pentaquark

Hidden-charm tetraquarks

Beyond hidden-charm

$P_{c\bar{c}}$ (also known as P_{ψ}^{N} or P_c)

BARYON-LIKE/HIDDEN CHARM/ISOSPIN=1/2(3/2)

states: $P_{c\bar{c}}(4312)^+$, $P_{c\bar{c}}(4440)^+$, $P_{c\bar{c}}(4457)^+$, $P_{c\bar{c}}(4380)^+$, $P_{c\bar{c}}(4337)^+$

PRL 115, 072001 (2015),
PRL 122, 222001 (2019)

$P_{c\bar{c}s}$ (also known as $P_{\psi s}^{\Lambda}$ or P_{cs})

BARYON-LIKE/HIDDEN CHARM/ISOSPIN=0(1)

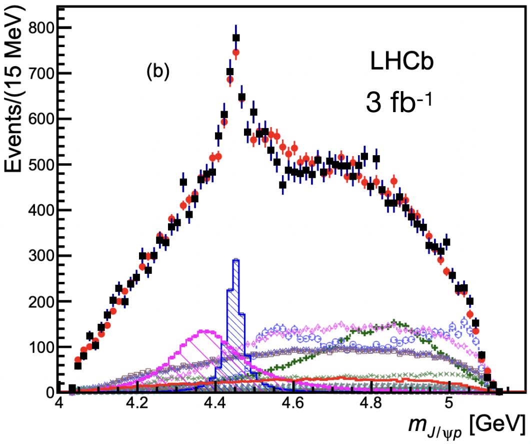
states:

- $I(J^P) = 0(1/2^-)$: $P_{c\bar{c}s}(4338)^0$
- $I(J^P) = 0(?)$: $P_{c\bar{c}s}(4458)^0$

PhysRevLett.131.031901

The observation of P_c states

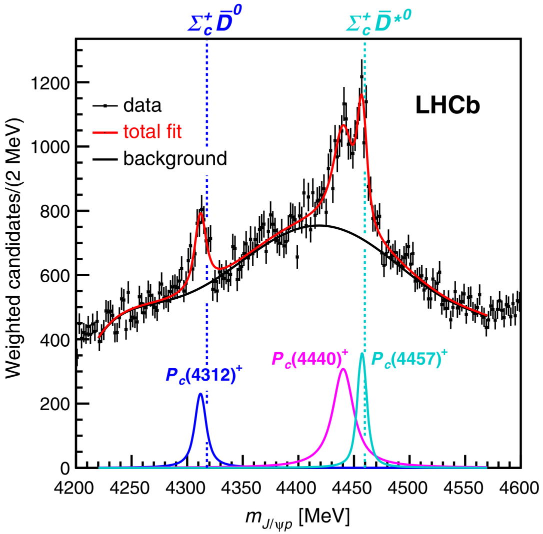
First observation by LHCb in $\Lambda_b \rightarrow J/\psi pK$ with Run1 data [PRL 115, 072001 (2015)]



$P_c(4450)^+$ M = 4450 ± 2 ± 3 MeV
Γ = 39 ± 5 ± 19 MeV
Fit fraction = 4.1 ± 0.5 ± 1.1 %

$P_c(4380)^+$ M = 4380 ± 8 ± 29 MeV
Γ = 205 ± 18 ± 86 MeV
Fit fraction = 8.4 ± 0.7 ± 4.2 %

Run 1 + Run 2 dataset:
new state: $P_\psi(4312)^+$ + 2 peaks at 4450 MeV
[PRL 122, 222001 (2019)]



$B^- \to J/\psi\Lambda\bar{p}$ decays

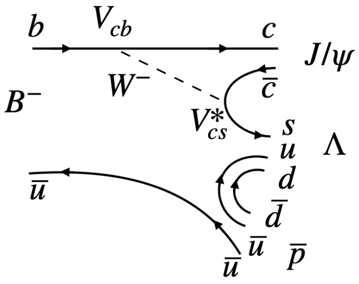
PhysRevLett.131.031901

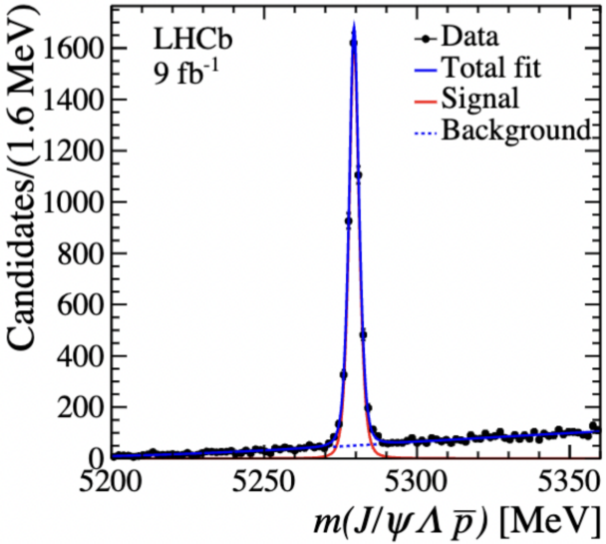
Search for pentaquark candidates in J/ψΛ and J/ψp̄

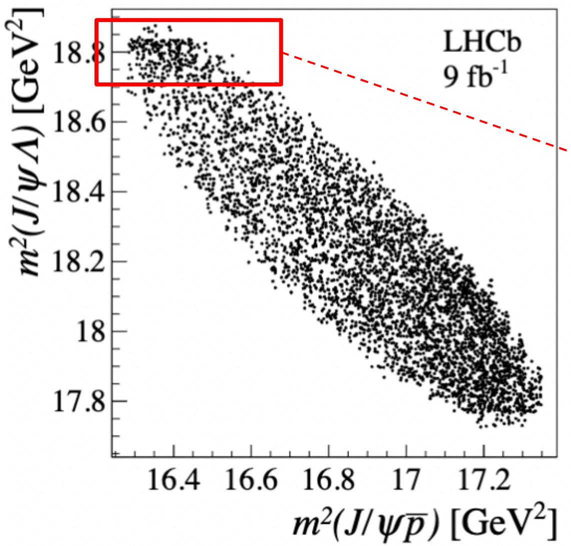
Full LHCb dataset: 9 fb^{-1}

⇒ 4600 candidates in 2.5σ

around peak with 93% of purity







Narrow structure in J/ψΛ

Pentaquark with strangeness in J/ψΛ

PhysRevLett.131.031901

Mass and width (RBW) measured:

$$m(P^{\Lambda}_{\psi s})\ \ 4338.2 \pm 0.7\ MeV$$
$$\Gamma(P^{\Lambda}_{\psi s})\ \ 7.0 \pm 1.2\ MeV$$

Significance larger than 10σ

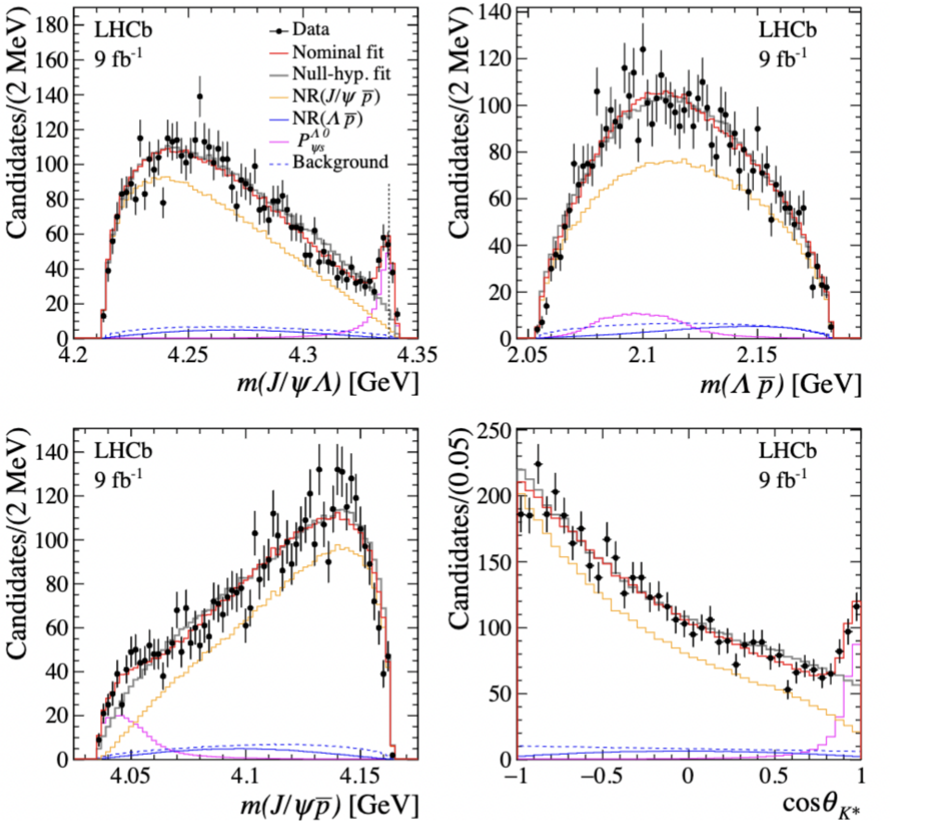
⇒ **Spin-Parity:**

J = ½ determined
P = -1 favored, $½^{+}$ rejected @90% CL

- ✓ Narrow state
- ✓ Close to $\Xi_c^{+} D^{-}$ threshold and in S-wave

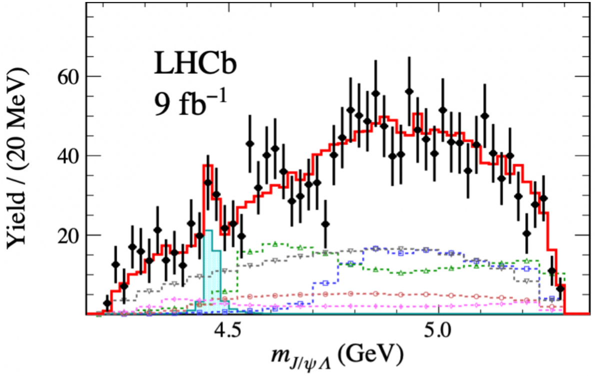
Is it a molecular state [1] or triangle singularities [2]?

[1] PhysRevD.106.036024
[2] PhysLetB.2023.137715



Other pentaquark evidences

Evidence for $P_{c\bar{c}s}(4459)$
in $\Xi_b \to J/\psi\Lambda K$ at 3.1σ $c\bar{c}uds$

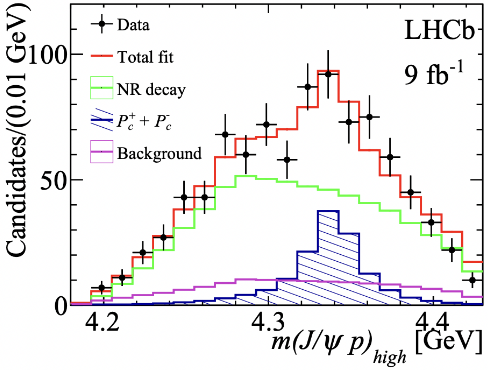


⇒ pentaquark with strangeness

✓ at $\Xi_c^0 D^{*0}$ threshold

Sci.Bull. 66 (2021) 1278-1287
PLB 772 (2017) 265-273

Evidence for $P_{c\bar{c}}(4337)$ in
$B_s \to J/\psi p\bar{p}$ at 3.1σ $c\bar{c}uud$



PRL 122, 191804 (2019)
PRL 128, 062001 (2022)

⇒ $P_{c\bar{c}}$ in B meson decay

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat}) \pm 2(\text{sys})\text{MeV},$$
$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat}) \pm 14(\text{sys})\ \text{MeV}$$

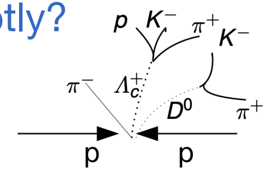
✓ $J^P = 1/2^+$ for $P^+_{c\bar{c}}$ preferred (?)

Prompt pentaquarks in $\Sigma_c D$ or $\Lambda_c D$?

PhysRevD.110.032001

Observed pentaquarks are close to mass threshold of some charm baryon-meson combinations. [PRD (101), 074030]

- Is it coincidental or evidence of bound states?
- Are pentaquarks produced promptly?



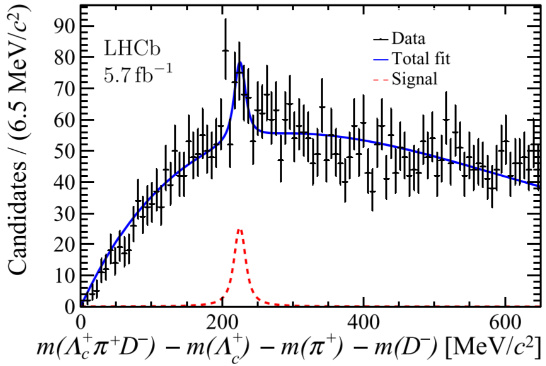
⇒ Inclusive search for pentaquark decays into open-charm Σ_c or Λ_c baryons with D mesons

$\Sigma_c^{++}\bar{D}^0$ $\Sigma_c^{0}\bar{D}^0$	$\cancel{\Sigma_c^{++}D^0}$ $\cancel{\Sigma_c^{0}D^0}$	$\Sigma_c^{++}D^-$ $\Sigma_c^{0}D^-$	$\cancel{\Sigma_c^{++}D^+}$ $\cancel{\Sigma_c^{0}D^+}$	$\cancel{\Sigma_c^{++}D^{*-}}$ $\cancel{\Sigma_c^{0}D^{*-}}$	$\cancel{\Sigma_c^{++}D^{*+}}$ $\cancel{\Sigma_c^{0}D^{*+}}$
$\Sigma_c^{*++}\bar{D}^0$ $\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*++}D^0$ $\Sigma_c^{*0}D^0$	$\Sigma_c^{*++}D^-$ $\Sigma_c^{*0}D^-$	$\Sigma_c^{*++}D^+$ $\Sigma_c^{*0}D^+$	$\Sigma_c^{*++}D^{*-}$ $\Sigma_c^{*0}D^{*-}$	$\cancel{\Sigma_c^{*++}D^{*+}}$ $\cancel{\Sigma_c^{*0}D^{*+}}$
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$ $\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^+$ $\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^+$ $\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^+$ $\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^+$ $\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^+$ $\Lambda_c^+D^{*+}\pi^-$

Crossed combinations are statistically limited

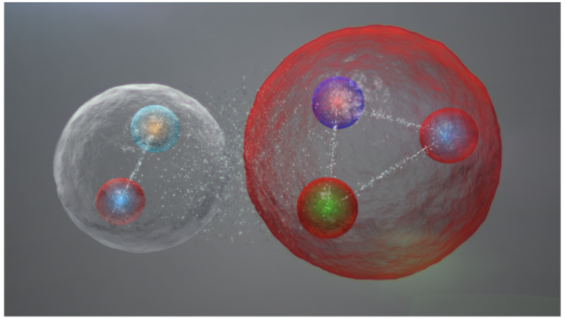
No evidence is found of new or old states & **UL** are set for all modes (32 modes): Scan with width of 5, 10, 15 MeV

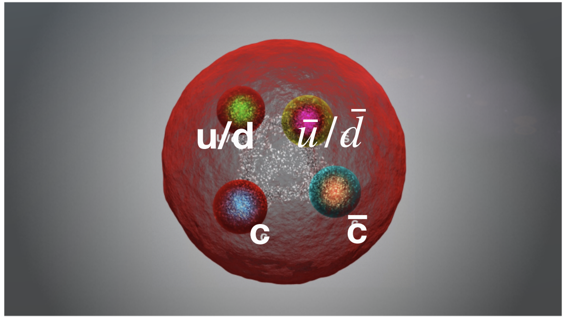
Highest global significance at 3.6σ for $\Lambda_c\pi^+D^-$ mode

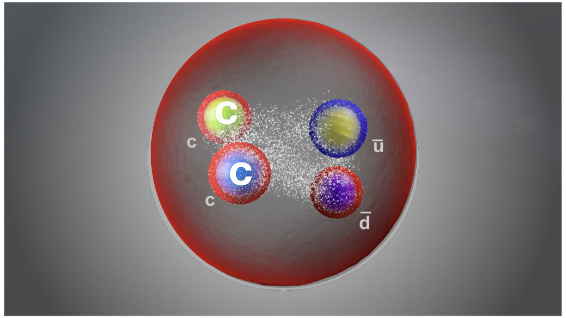


Modes interesting to look at in the future with Run3 data

Classifying Exotics...







Hidden-charm pentaquark

Hidden-charm tetraquarks

χ_c states in $J/\psi\phi$

- $I(J^{PC}) = 0(0^{++})$: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$
- $I(J^{PC}) = 0(1^{++})$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$
  also known as $X(4140)$, $Y(4140)$, ...
- $I(J^{PC}) = 0(?^{?+})$: $X(4150)$, $X(4630)$, $X(4740)$
  also known as $X(4160)$

Beyond hidden-charm

χ_c states in $J/\psi\phi$

MESON-LIKE/HIDDEN CHARM/ISOSCALAR

states:

- $I(J^{PC}) = 0(0^{++})$: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$
- $I(J^{PC}) = 0(1^{++})$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$

  also known as $X(4140)$, $Y(4140)$, ...
- $I(J^{PC}) = 0(?^{?+})$: $X(4150)$, $X(4630)$, $X(4740)$

  also known as $X(4160)$

minimal quark content: $[c\bar{c}]$,
more likely $[c\bar{c}q\bar{q}]$ or $[c\bar{c}s\bar{s}]$

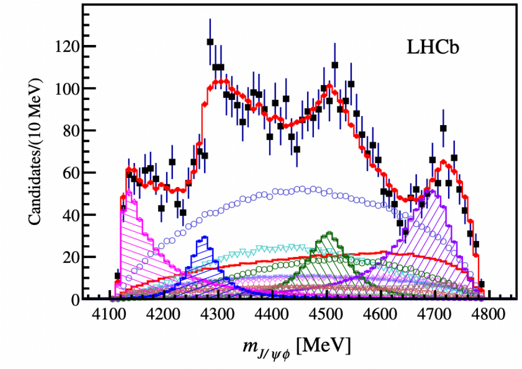
experiments: CDF, CMS, D0, BaBar, LHCb, Belle

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

- First state, $\chi_{c1}(4140)$, seen by CDF
- Amplitude analysis by LHCb with Run1 and later with Run2

LHCb Run 1

Phys. Rev. Lett. 118, 022003



χ_c states in $J/\psi\phi$

MESON-LIKE/HIDDEN CHARM/ISOSCALAR

states:

- $I(J^{PC}) = 0(0^{++})$: $\chi_{c0}(4500)$, $\chi_{c0}(4700)$
- $I(J^{PC}) = 0(1^{++})$: $\chi_{c1}(4140)$, $\chi_{c1}(4274)$, $\chi_{c1}(4685)$

  also known as $X(4140)$, $Y(4140)$, ...
- $I(J^{PC}) = 0(?^{?+})$: $X(4150)$, $X(4630)$, $X(4740)$

  also known as $X(4160)$

minimal quark content: $[c\bar{c}]$,

more likely $[c\bar{c}q\bar{q}]$ or $[c\bar{c}s\bar{s}]$

experiments: CDF, CMS, D0, BaBar, LHCb, Belle

Many states are candidates for conventional charmonium, i.e. $\chi_{c1}(4140)$ for $\chi_{c1}(3P)$; but could also be a $D_s^+ D_s^{*-}$ molecule [1] or cusp [2]

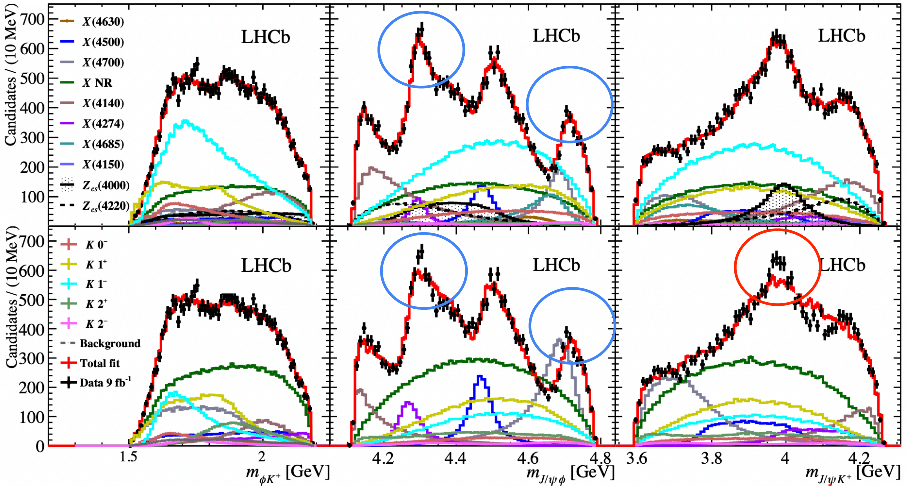
Study of $B^+ \to J/\psi\phi K^+$ decays

- First state, $\chi_{c1}(4140)$, seen by CDF
- Amplitude analysis by LHCb with Run1 and later with Run2

LHCb Run1+2

PhysRevLett.127.082001

Run1 model



Structures in $J/\psi K^+$

[1] Nucl. Phys. A 954 (2016) 365–370

[2] PhysRevD.80.114013

$T^{+}_{c\bar{c}}$ in B meson decays

PhysRevLett.112.222002

MESON-LIKE/HIDDEN CHARM/ISOVECTOR

states:

- $I^G(J^{PC}) = 1^+(1^{+-})$: $T_{c\bar{c}1}(4200)^+$, $\boxed{T_{c\bar{c}1}(4430)^+}$
- $I^G(J^{PC}) = 1^+(?^{?-})$: $T_{c\bar{c}}(4240)^+$
  also known as $R_{c0}(4240)$, $Z_c(4240)$
- $I^G(J^{PC}) = 1^-(?^{?+})$: $T_{c\bar{c}}(4050)^+$, $T_{c\bar{c}}(4100)^+$, $T_{c\bar{c}}(4250)^+$

minimal quark content: $[c\bar{c}q\bar{q}']$
experiments: Belle, LHCb
production: $\bar{B}^0 \to (c\bar{c})\pi^+K^-$, where
$(c\bar{c}) = J/\psi,\ \psi(2S),\ \eta_c,\ \chi_{c1}$
$T_{c\bar{c}}(4200)$ also potentially in $\Lambda_b \to J/\psi\pi^- p$
decay modes: $J/\psi\pi^+$, $\psi(2S)\pi^+$, $\eta_c\pi^+$, $\chi_{c1}\pi^+$
nearby threshold: $D^*\bar{D}^*$
characteristic widths: 82-370 MeV

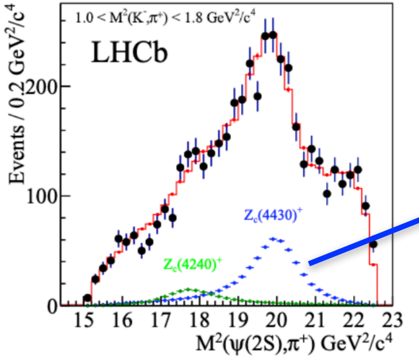


Figure 12: $T_{c\bar{c}1}(4430)^+$ signal at LHCb [164].

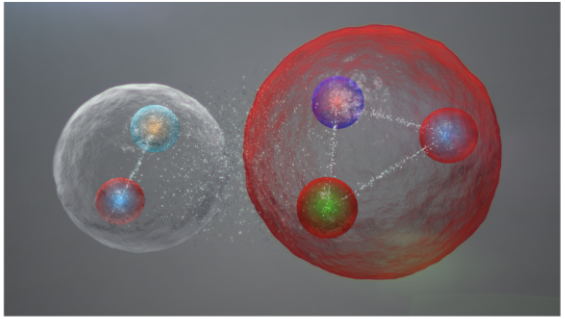
$T_{c\bar{c}}(4430)^+$ in
$B \to \psi(2S)\pi^+K$:

- First charged state seen by Belle in 2007
- Amplitude analysis by LHCb

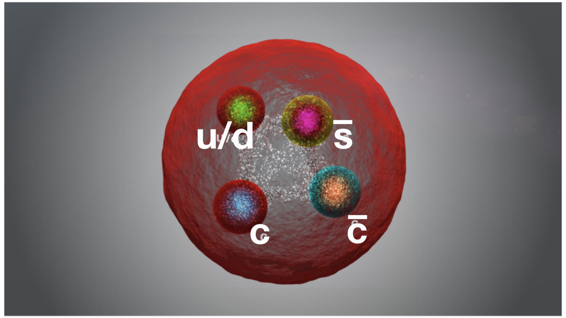
Width of 180 MeV and $J^P = 1^+$

Find out more on the other states in the review!

Classifying Exotics...



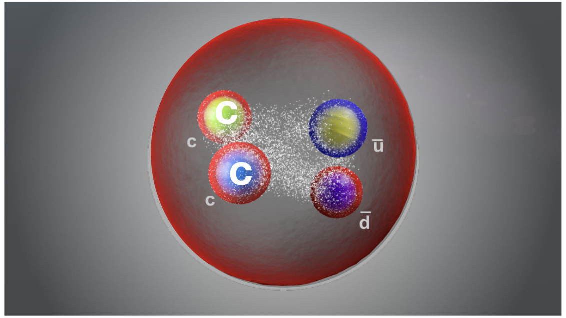
Hidden-charm pentaquark



Hidden-charm tetraquarks

with strange quark content

$T_{c\bar{c}s}$ *(also known as* $T_{\psi s}$ *or* Z_{cs}*)*



Beyond hidden-charm

MESON-LIKE/HIDDEN CHARM/ISOSPIN=1/2

states:

- $I(J^P) = 1/2(?^?)$: $T_{c\bar{c}s}(3985)^{-/0}$
- $I(J^P) = 1/2(1^+)$: $T_{c\bar{c}s1}(4000)^{-/0}$
- $I(J^P) = 1/2(1^?)$: $T_{c\bar{c}s1}(4220)^{-}$

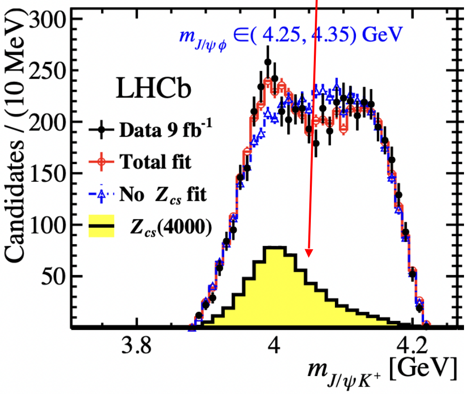
PRL 127, 082001 (2021)

LHCb-PAPER-2022-040

Tetraquark with strangeness

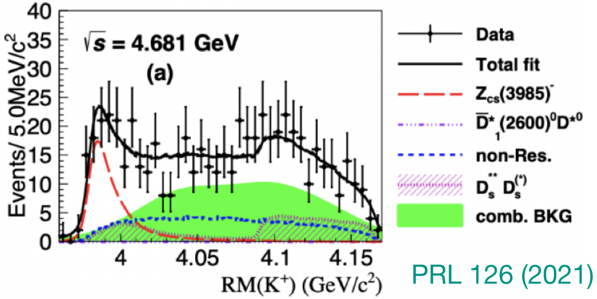
In $B^+ \to J/\psi \phi K^+$ decays, 2 states with strangeness are observed:

$T_{c\bar{c}s}(4420)^+$ *and* $T_{c\bar{c}s}(4000)^+$ state by LHCb



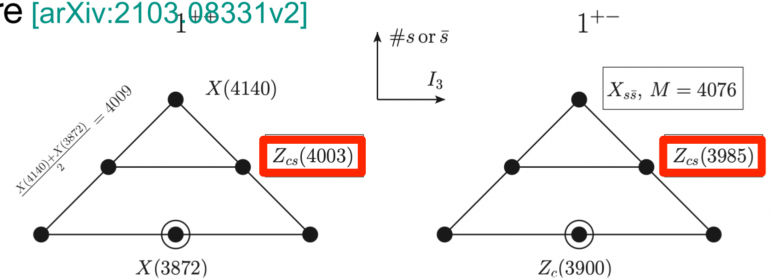
PRL 127, 082001 (2021)

Is it the ***same state*** *as* $T_{c\bar{c}s}(3985)^+$ *in* $D_s^- D^{*0} + D^0 D_s^{*-}$ *by BESIII?*



PRL 126 (2021) 102201

Degeneracy can be explained in compact tetraquark picture [arXiv:2103.08331v2]

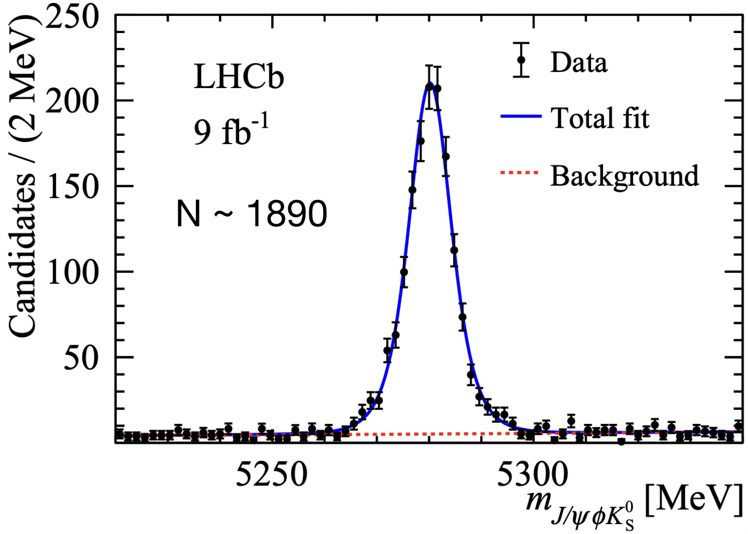


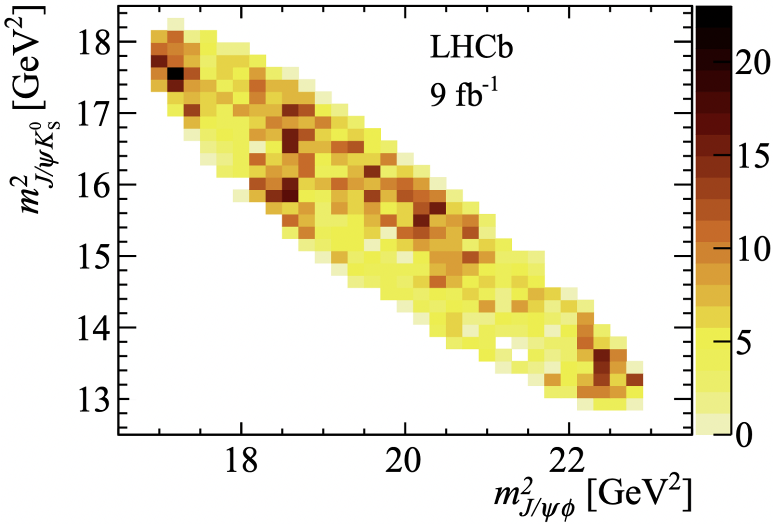
Isospin partners in $B^0 \to J/\psi\phi K^0_S$ decays

PhysRevLett.131.131901

Searching for $T^0_{c\bar{c}s}$ states, isospin partners of $T^+_{c\bar{c}s}$ ***states,*** is crucial for identifying the complete **SU(3) nonet**

Extension of $B^+ \to J/\psi\phi K^+$ with $B^0 \to J/\psi\phi K^0_S$ since the 2 decays are related by isospin symmetry

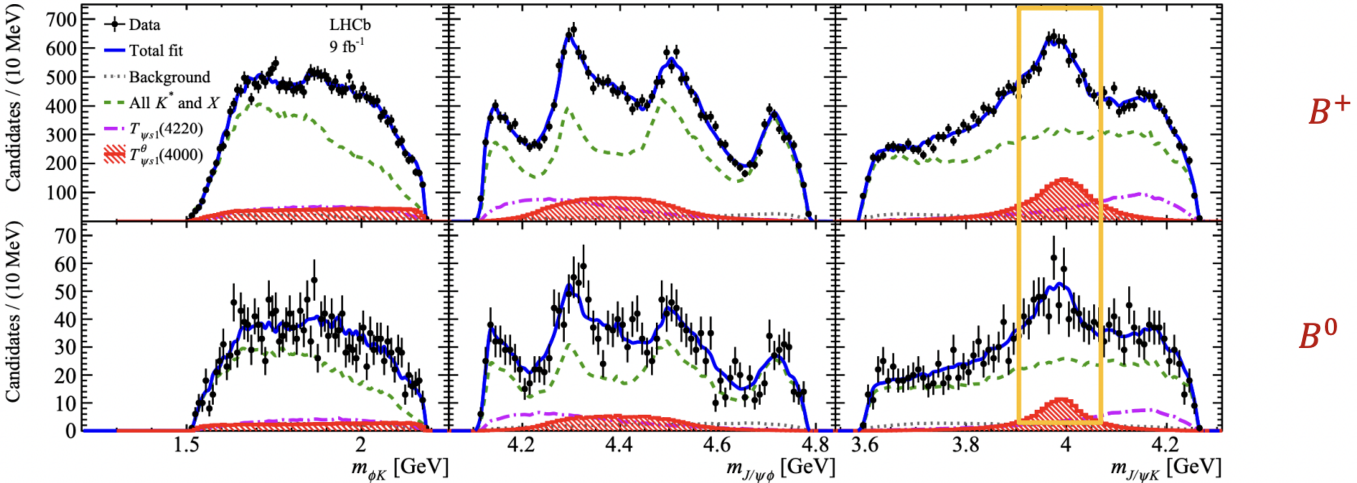




$B^0 \to J/\psi\phi K_S^0$ decays

Combined fit to B^+ and B^0 decays:

- All components except $T_{c\bar{c}s}(4000)^0$ in B^0 decay are constrained by those in B^+ decay

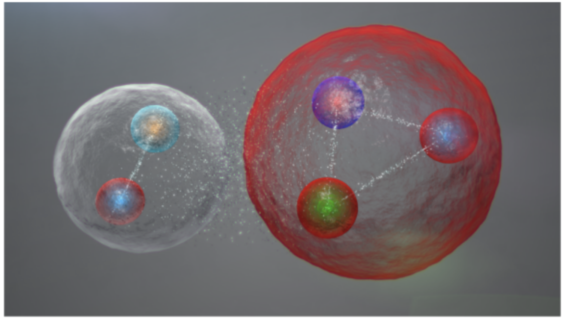


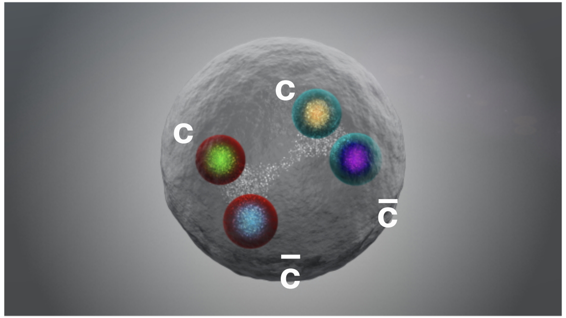
Evidence for a new state with 4σ

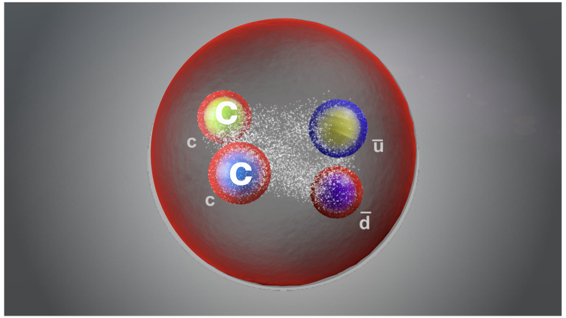
$$M(T^{\theta}_{\psi s1}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\ \mathrm{MeV},$$
$$\Gamma(T^{\theta}_{\psi s1}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}\ \mathrm{MeV},$$

$\Rightarrow$ $T_{c\bar{c}s}(4000)^0$ & $T_{c\bar{c}s}(4000)^+$: consistent with being isospin partners, $\Delta M = 12^{+11+6}_{-10-4}$ MeV

Classifying Exotics...







Hidden-charm pentaquark

Hidden-charm tetraquarks

Beyond hidden-charm

Di-ψ resonance

MESON-LIKE/HIDDEN DOUBLE CHARM

states: $T_{c\bar{c}c\bar{c}}(6550)^0$, $\underline{T_{c\bar{c}c\bar{c}}(6900)^0}$, $T_{c\bar{c}c\bar{c}}(7290)^0$

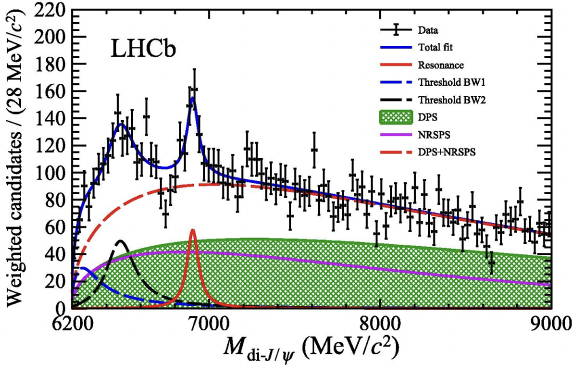
also known as $T_{\psi\psi}(6900)^0$, ... *or* $X(6900)$, ...

Sci.Bull. 65 (2020), 23

CMS-PAS-BPH-21-003

Fully charmed states in prompt production

Sci.Bull. 65 (2020), 23



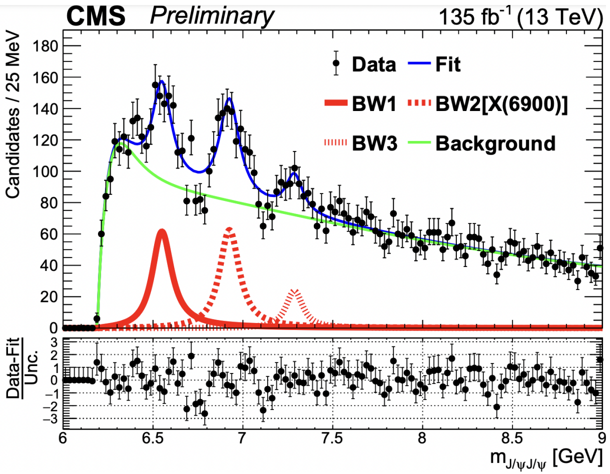
Narrow structure at 6.9 GeV

→ $T_{c\bar{c}c\bar{c}}(6900)$

Broad structure just above double-J/ψ threshold

→ **5σ deviation** from NR

CMS-PAS-BPH-21-003

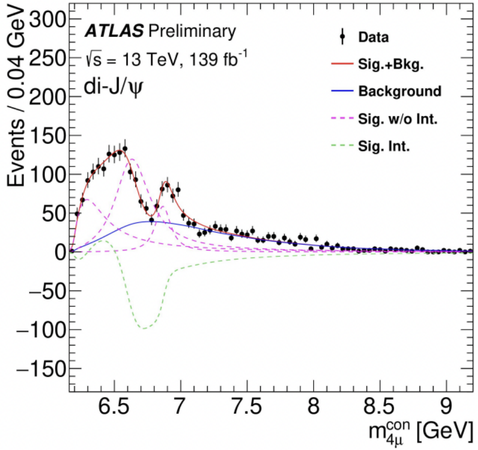


$T_{c\bar{c}c\bar{c}}(6900)$ consistent with LHCb

\+ New peak at 6600 MeV with ~10σ

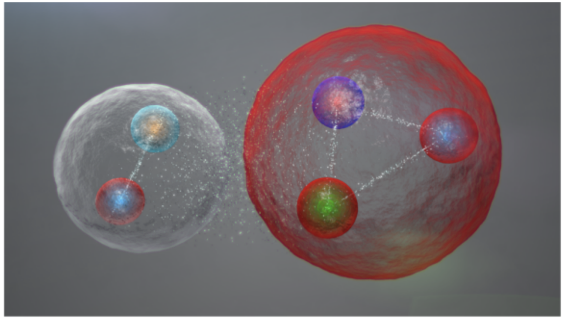
3rd peak seen with 4σ

arXiv:2304.08962

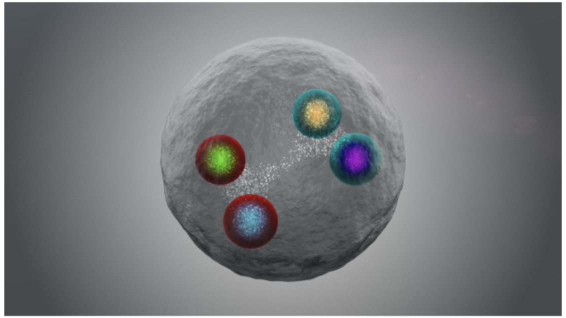


$T_{c\bar{c}c\bar{c}}(6900)$ confirmed & consistent with LHCb

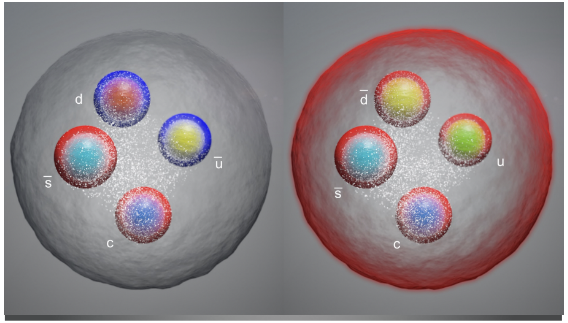
Classifying Exotics...



Hidden-charm pentaquark



Hidden-charm tetraquarks



Beyond hidden-charm

Open-charm tetraquarks

MESON-LIKE/OPEN SINGLE CHARM

states:

- $I(J^P) = ?(0^+)$: $T_{cs0}(2900)^0$, $T_{c\bar{s}0}(2900)^0$, $T_{c\bar{s}0}(2900)^{++}$
- $I(J^P) = ?(1^-)$: $T_{cs1}(2900)^0$

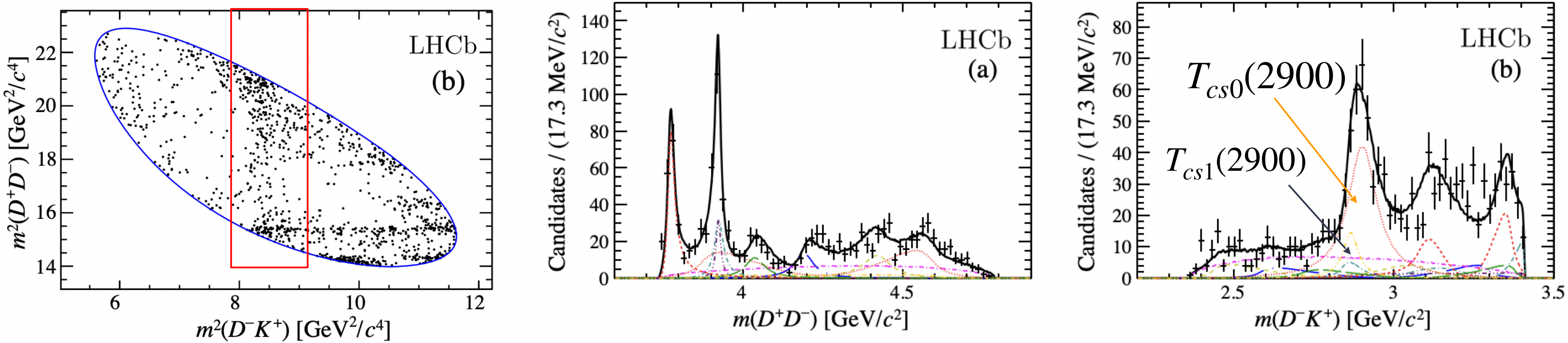
also known as $T^*_{cs0}(2870)^0$, $T^*_{cs1}(2900)^0$, ... *or* $X_0(2900)$,

PRD, 2005, 72: 054026 arXiv:2212.02716

First T_{cs} in $B^+ \to D^+D^-K^+$ decays

[PRD 102 (2020) 112003, PRL 125 (2020) 242001]

T_{cs} states are observed in B decays to D mesons:



$T_{cs0,1}(2900) \to D^-K^+$: first $cs\bar{u}\bar{d}$ tetraquark

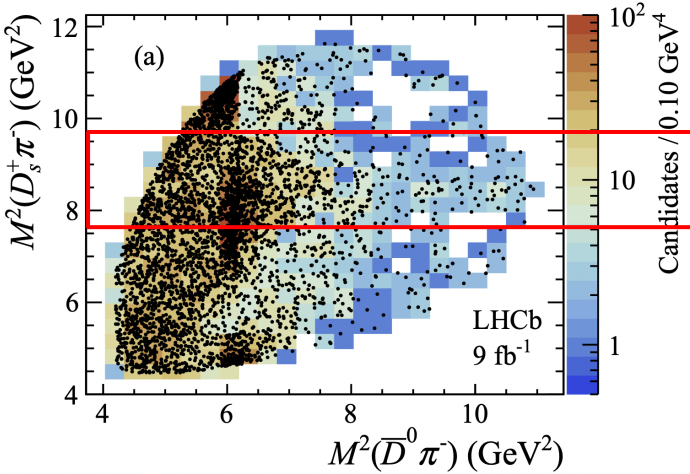
Models predict its SU(3) flavour partner: $T_{c\bar{s}} \to D_s\pi$ $\Rightarrow$ it motivates searches in $B \to DD_s\pi$ decays

$B \to DD_s^+\pi^{-/+}$ decays

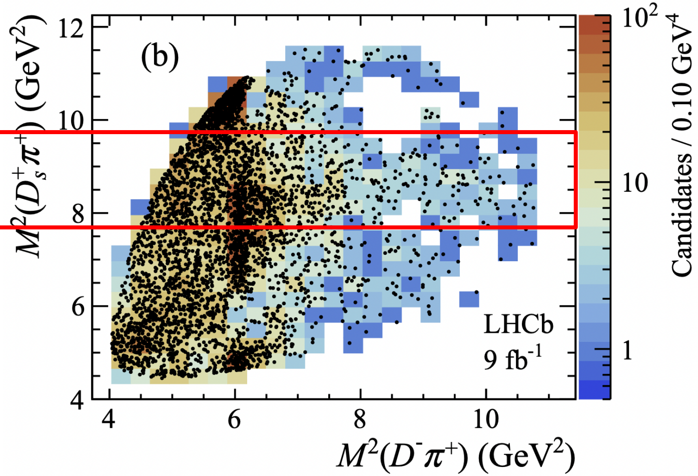
arXiv:2212.02716, arxiv:2212.02717

Signal yields: ~4000 with 90% signal purity 3750 with 95% signal purity

$B^0 \to \bar{D}^0 D_s^+ \pi^-$



$B^+ \to D^- D_s^+ \pi^+$



Horizontal band at $M^2(D_s\pi) \sim 8.5\ GeV^2$

$\Rightarrow$ tetraquark candidates?

$T_{c\bar{s}0}(2900)^{0/++}$ in $D_s^+\pi^{-/+}$

PhysRevLett.131.041902, arxiv:2212.02717

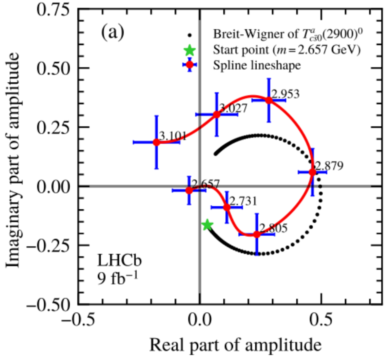
Isospin symmetry → combined amplitude analysis of the 2 channels

$T_{c\bar{s}0}(2900)^{0/++}$ observed with **large significance** (> 9σ) & **J^P= 0+**

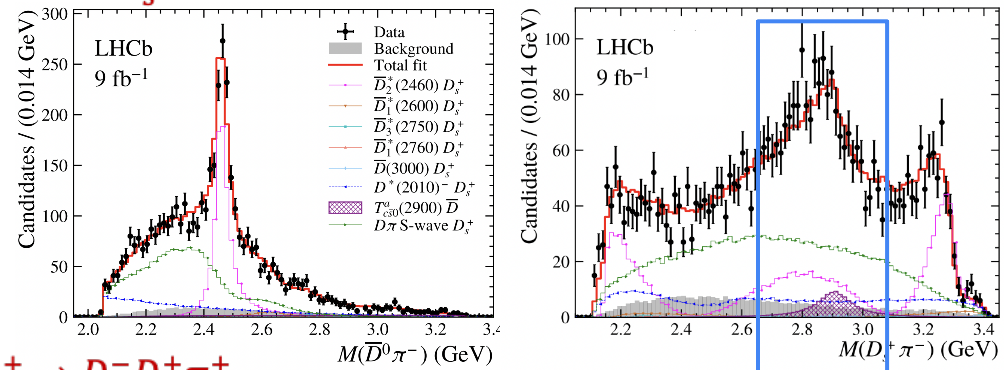
$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV}$$

(RBW)

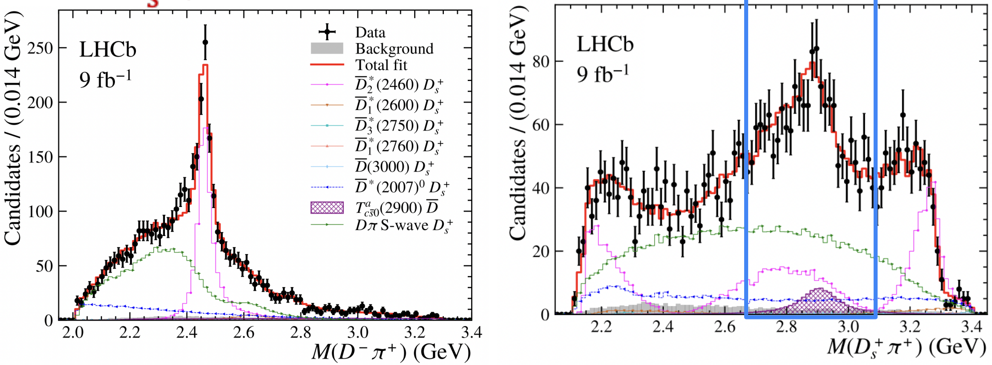
Argand diagrams confirm the resonant nature



$B^0 \to \bar{D}^0 D_s^+ \pi^-$



$B^+ \to D^- D_s^+ \pi^+$



$T_{c\bar{s}0}(2900)^{0/++}$ in $D_s^+\pi^{-/+}$

arXiv:2212.02716, arxiv:2212.02717

First tetraquark candidates composed of $c\bar{s}\bar{u}d$ and $c\bar{s}u\bar{d}$

$T_{c\bar{s}0}(2900)^{++}$ = first doubly-charged tetraquark

- Do they belong to an **isospin triplet**?

$T_{c\bar{s}0}(2900)^{0}$

$T_{c\bar{s}0}(2900)^{+}$? $\Rightarrow$ to be searched for in $D^+\pi^0$

$T_{c\bar{s}0}(2900)^{++}$

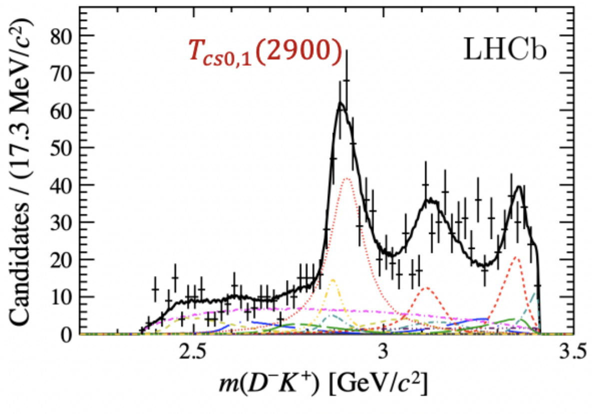
- Same mass of $T_{cs0}(2900)$ observed in $B^+ \to D^+D^-K^+$ [1]

$T_{cs0}(2900)$ $cs\bar{u}\bar{d}$

$T_{c\bar{s}0}(2900)$ $c\bar{s}\bar{u}d$

$\Rightarrow$ SU(3) flavour partners?

[1]PRD 2005, 72: 054026, PRD, 2009, 79: 094004



T_{cs0} in other decays?

NEW

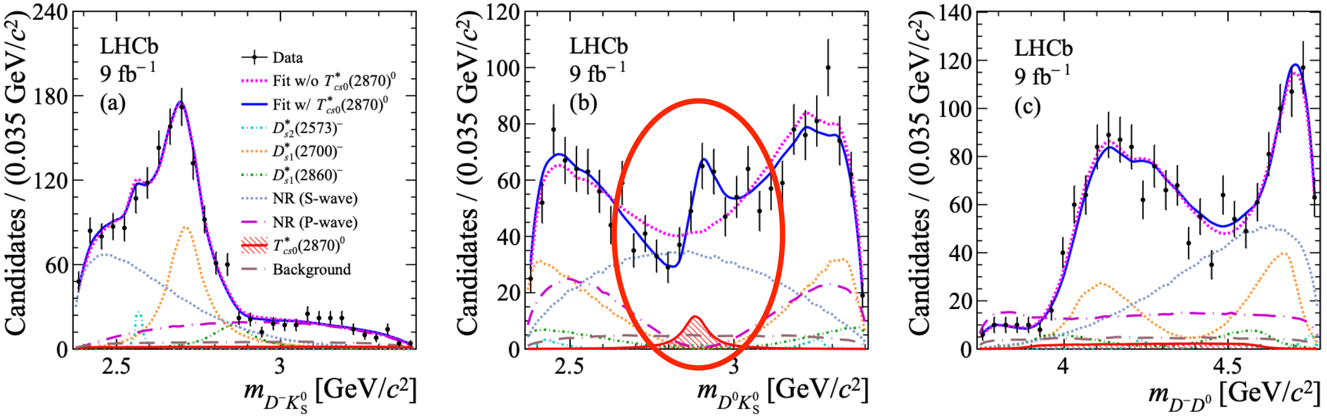
LHCb-PAPER-2024-040

$B^- \to D^- D^0 K^0_s$ decays to search for T_{cs} states (slide 32)

Model includes:

- D^{*-}_{sJ} states in $D^- K^0_S$
- S- and P-wave NR
- State with 5.3σ

$T^*_{cs0}(2880)^0 \to D^0 K^0_S$



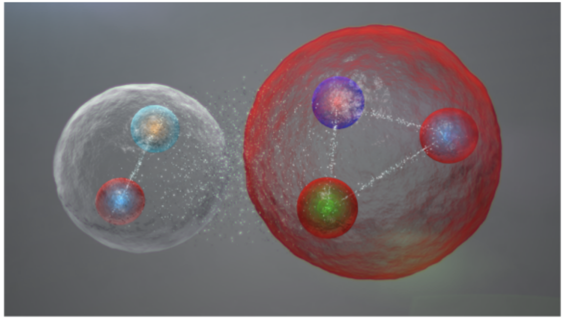
It is consistent with $T^*_{cs0}(2870)^0$ seen in $B \to D^- D^+ K^-$, also known as $T_{cs0}(2900)$ [PRD 102 (2020) 112003]

$$M(T^{*0}_{cs0}) = 2883 \pm 11 \pm 8\,\text{MeV}/c^2,$$
$$\Gamma(T^{*0}_{cs0}) = 87^{+22}_{-47} \pm 17\,\text{MeV},$$
$$\text{FF}(T^{*0}_{cs0} \to D^0 K^0_S) = (2.6 \pm 1.2 \pm 0.4)\%,$$

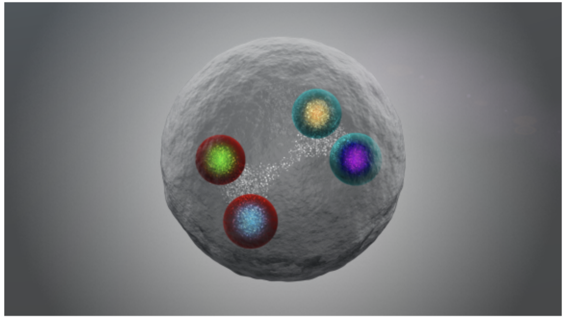
What about the spin-1 state, $T^*_{cs1}(2900)^0$?

- Significance of just 1.8σ
- Ratio of fit fractions in the 2 decays can provide test of isospin symmetry

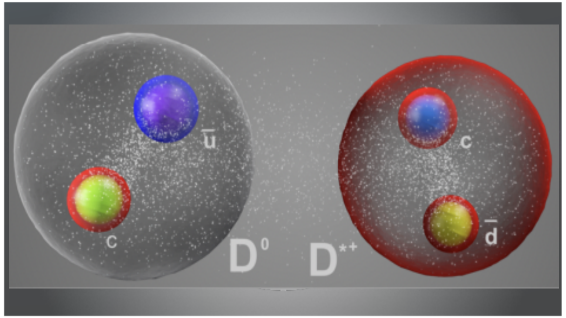
Classifying Exotics…



Hidden-charm pentaquark



Hidden-charm tetraquarks



Beyond hidden charm

Doubly-charm tetraquark

MESON-LIKE/OPEN DOUBLE CHARM
quantum numbers: $I(J^P) = ?(?^?)$, likely $0(1^+)$
minimal quark content: $[cc\bar{u}\bar{d}]$
experiments: LHCb
production: prompt pp collisions

Nature Physics (2022);
Nat. Comm. 13, 3351 (2022)

Observation of doubly charm tetraquark

Nature Physics (2022); *Nature Communications* 13, 3351 (2022)

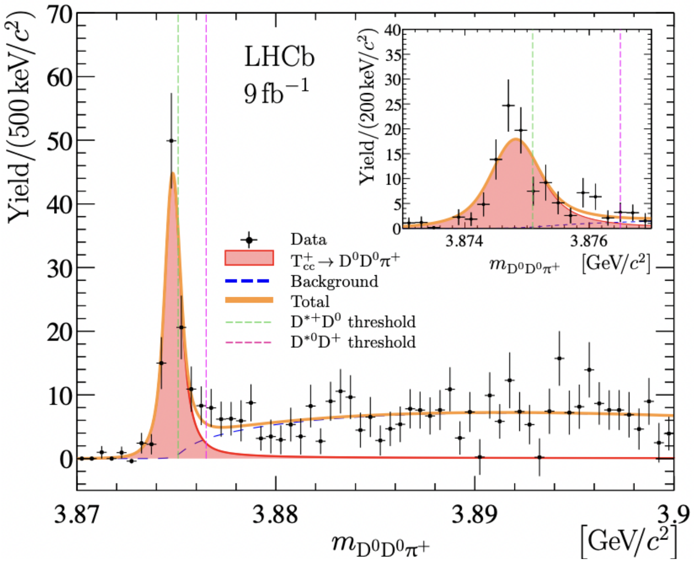
First observation of same-sign
double charmed tetraquark, $T_{cc}^{+}(3875) \rightarrow D^0 D^0 \pi^+$
$\Rightarrow$ exotic quark content $cc\bar{u}\bar{d}$

Mass is below the $D^0 D^{*+}$ threshold and very narrow

$$\delta m = -359 \pm 40^{+9}_{-6}\ keV$$
$$\Gamma = 48 \pm 2^{+0}_{-14}\ keV$$

Consistent with an **isoscalar** with **J^P=1^+**
in accordance with expectation for a $cc\bar{u}\bar{d}$ ground-state

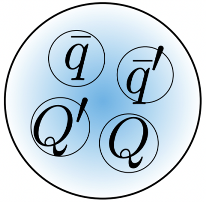
- I=0 is supported by no peaks found in D^+D^+ and $D^+D^0\pi^+$ channels
- Perfect agreement with model considering only decays to DD^* [*Nature Communications* 13, 3351 (2022)]



Likely it is predominately a DD^* molecule, but also a compact component is allowed [1]

[1] arXiv:hep-ph/0405208

$QQ'\bar{q}\bar{q}'$ states



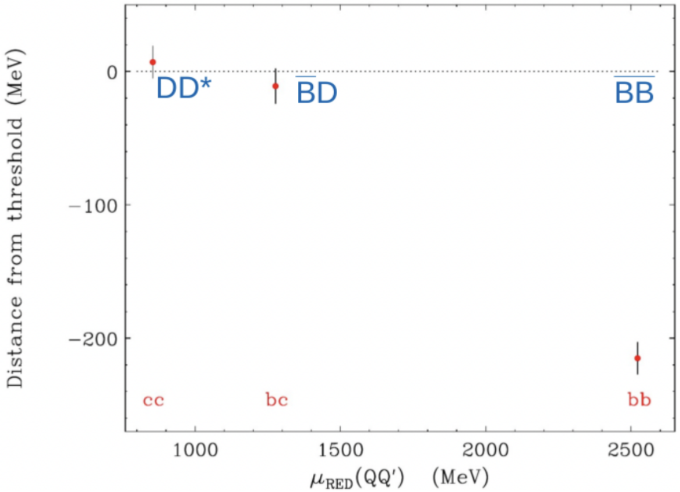
T_{cc}^{+} is the first representee of ($QQ'\bar{q}\bar{q}'$) hadrons

→ almost stable against strong interaction: $\tau \sim 10^{-20} s$

⇒ It supports existence of:

T_{bb}^{-} $(bb\bar{u}\bar{d})$: stable against QCD with binding energy about 215 MeV with respect to BB^{*} threshold

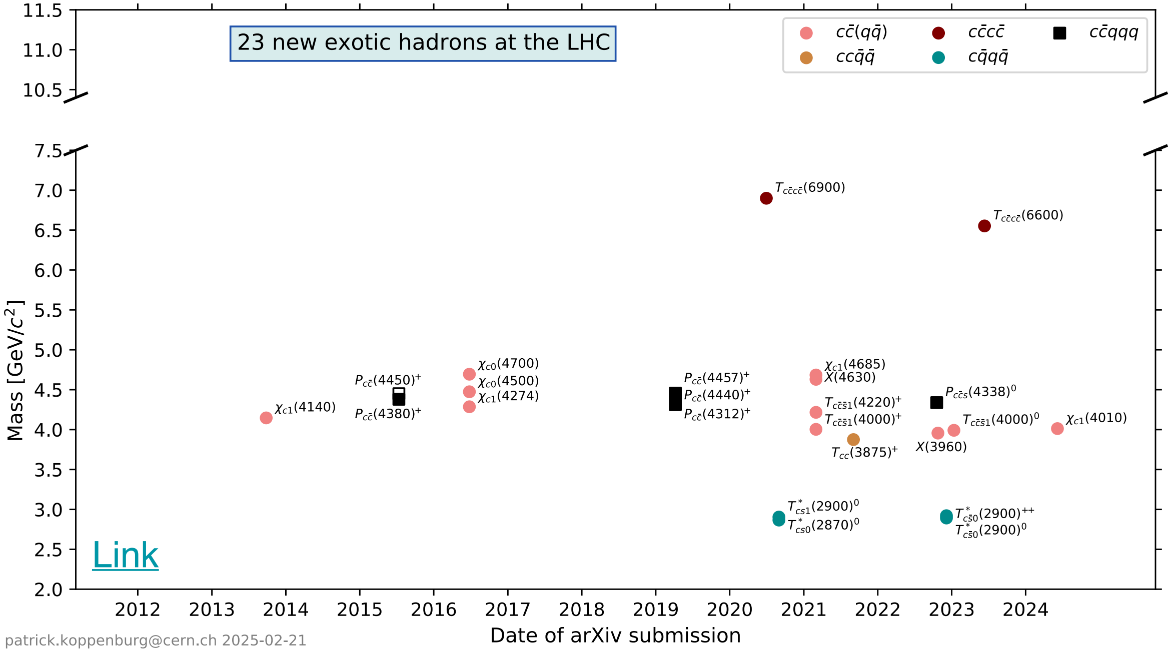
T_{cb}^{0} $(bc\bar{u}\bar{d})$: either stable or almost, like T_{cc}^{+}



Phys. Rev. Lett. 119, 202001 (2017)

Many new exotics at LHC

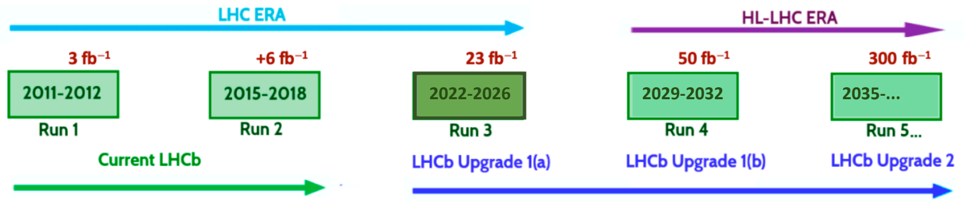
Lots of exotic states discovered in recent years



No coherent theoretical picture to describe all observed exotic hadron candidates

⇒ **call for more experimental studies**

What's next?



LHCb Upgrade I (in Run3 & Run4)

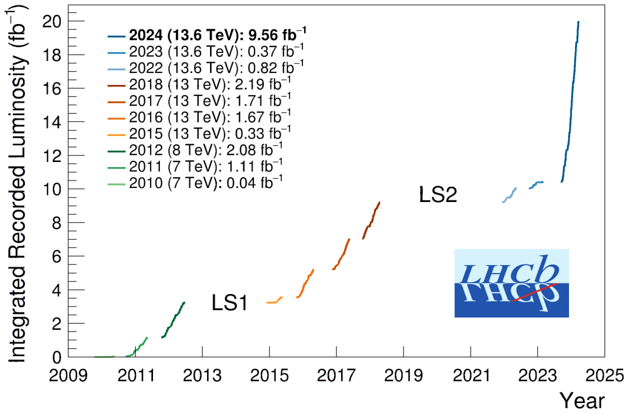
Brand-new detector and fully software-based trigger

- Allows operation at higher luminosity

  ⇒ detector read out at 40 MHz

  ⇒ x5 luminosity increase: $L = 2 \times 10^{33} cm^{-2} s^{-1}$

- Improved efficiency in hadronic modes



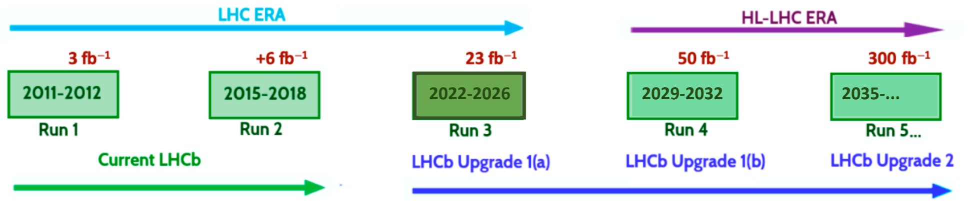
Boosting data to a new level!

- $9\ fb^{-1}$ of collected luminosity so far
- x2 statistics per lumi wrt Run2

  ⇒ Already x4 in statistics

First results to come out soon!

What’s next?

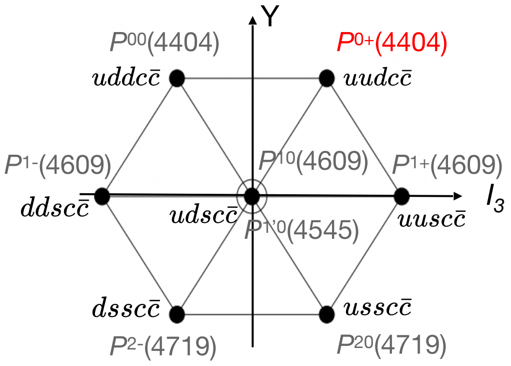


More investigation of the observed states:

- Confirm states in different channels
- Measure J^P, study lineshape and resonance parameters

Many new states to explore:

- Access to *bc* tetraquarks and pentaquark with *beauty*
- Search for exotic flavour multiplets

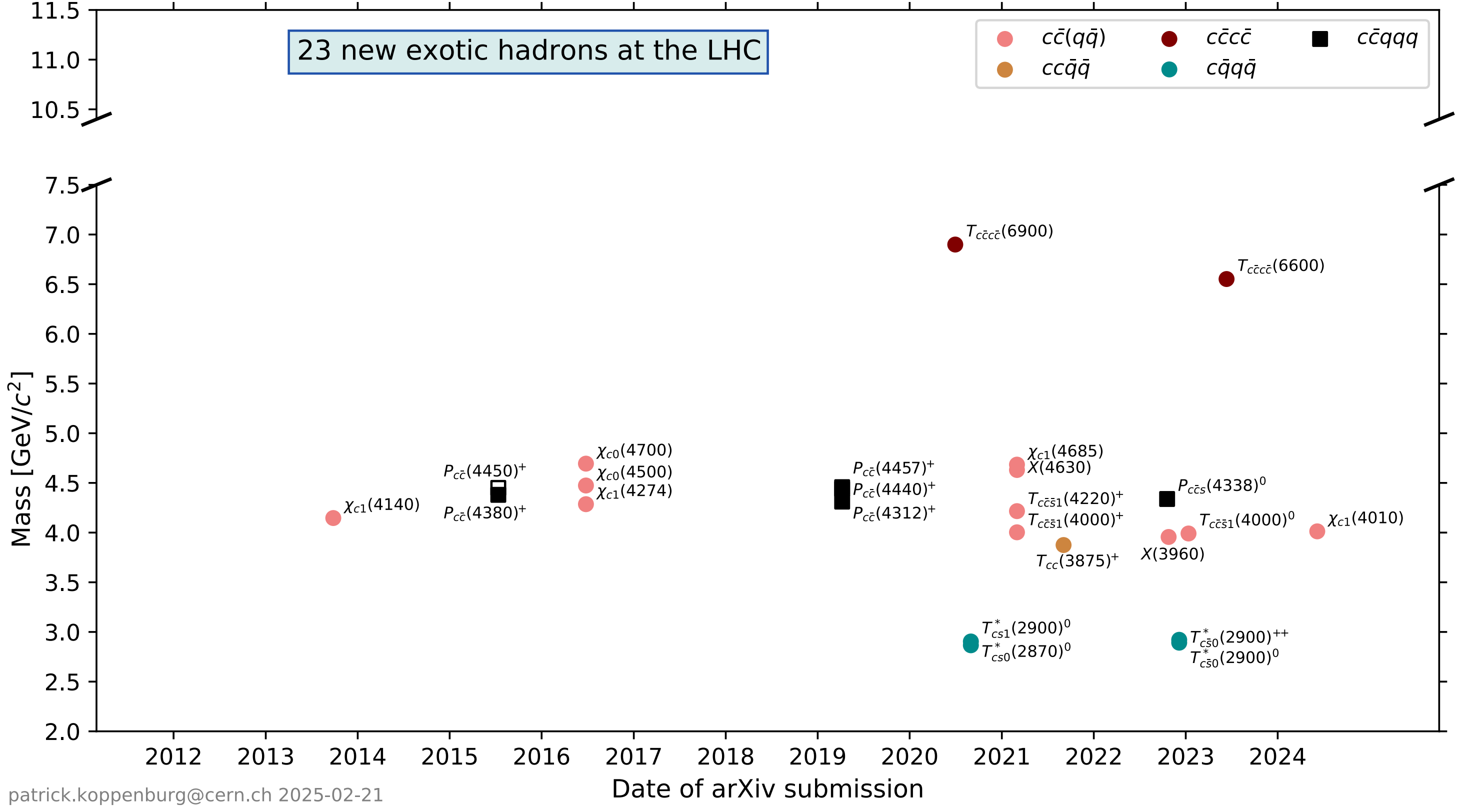


PhysRevD.96.014014

Thank you for the attention!

Backup

Exotic hadrons at LHCb



Link

What about the spin 1 state, $T^*_{cs1}(2900)^0$?

- $T^*_{cs1}(2900)^0$ contribution is not significant
  - $T^{*0}_{cs0}(2870)$ and $T^*_{cs1}(2900)^0$ states are observed with 6.4 σ and 1.8 σ
- **Test of isospin symmetry**: $I(T^{*0}_{cs}) = 0$ or 1
  - Relative width of T^{*0}_{cs0}: $R_I(T^{*0}_{cs0}) \equiv \Gamma(T_{cs} \to D^0\overline{K^0})/\Gamma(T_{cs} \to D^+K^-)$ ≈ 1
  - Ratio, R_{FF}, of $T^{*0}_{cs1}/T^{*0}_{cs0}$ should be equal in $B^- \to D^-D^0K^0_s$ and $B \to D^-D^+K^-$

Observable	Result			
$R_{\rm I}(T^*_{cs0}(2870)^0)$	3.3	± 1.1	± 1.1	± 1.1
$R_{\rm I}(T^*_{cs1}(2900)^0)$	0.15	± 0.15	± 0.05	± 0.05
$R_{\rm FF}(D^0\overline{K}^0)/R_{\rm FF}(D^+K^-)$	$0.044 \pm 0.035 \pm 0.020$			

$$R_{\rm I}(T^{*0}_{cs}) = \frac{\mathcal{B}(B^- \to D^-D^0\overline{K}^0){\rm FF}(T^{*0}_{cs} \to D^0K^0_{\rm S})}{\mathcal{B}(B^- \to D^-D^+K^-){\rm FF}(T^{*0}_{cs} \to D^+K^-)},$$

=> For T_{cs0}: consistent with isospin invariance, although large isospin violation cannot be excluded at current precision

=> For T_{cs1}: much lower than unity which indicates isospin violation

Isospin violation can be explained as state caused by triangle singularity or not definite isospin.

Model with only K*

LHCb-PAPER-2022-031, arxiv:2210.10346

Amplitude contributions:

- NR($\bar{p}\Lambda$)
- $K^{*+}_{2,3,4}$ → peaks out of phsp, no obvious contribution in $\bar{p}\Lambda$ distribution

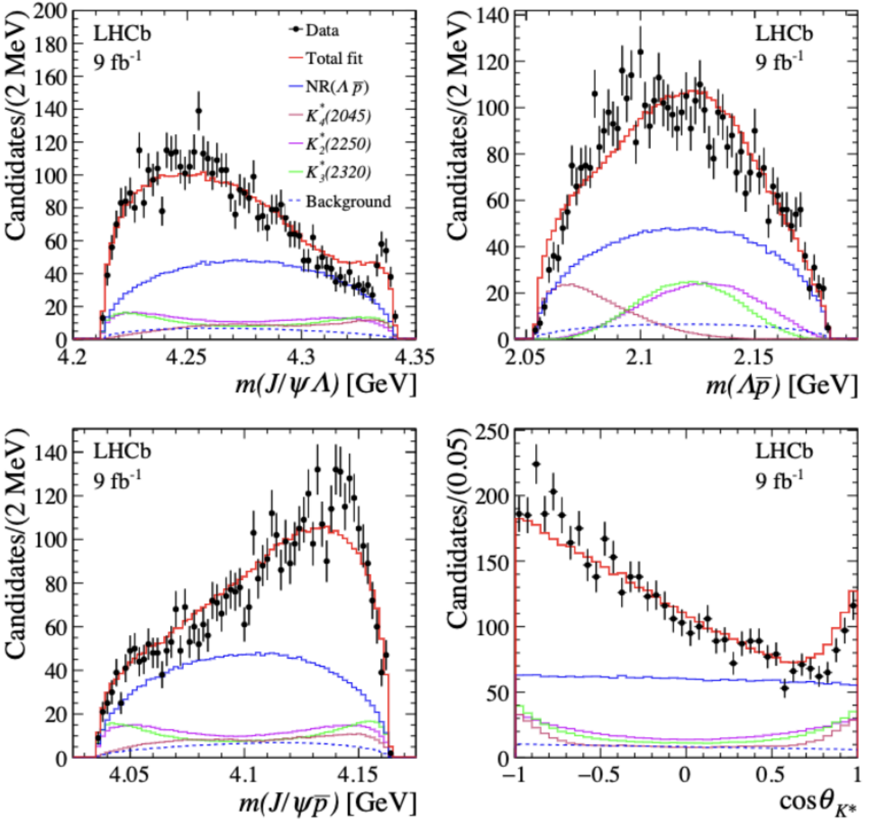
Resonance	Mass (MeV)	Natural width (MeV)	J^P
$K_4^*(2045)^+$	2045 ± 9	198 ± 30	4^+
$K_2^*(2250)^+$	2247 ± 17	180 ± 30	2^-
$K_3^*(2320)^+$	2324 ± 24	150 ± 30	3^+

PDG 2020

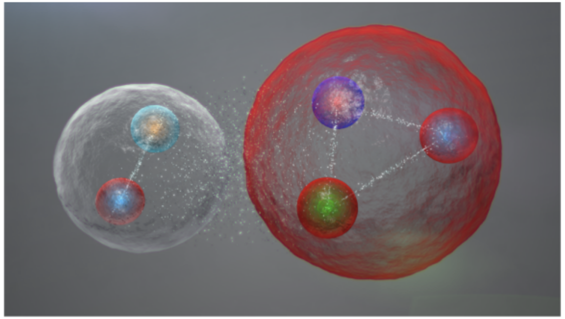
Model with K^* cannot describe data

Goodness-of-fit test

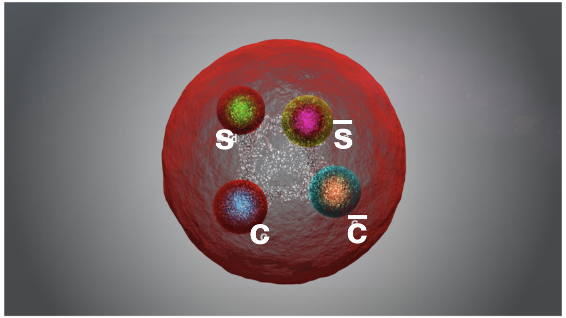
$$\chi^2/ndf = 123/33$$



Exotics

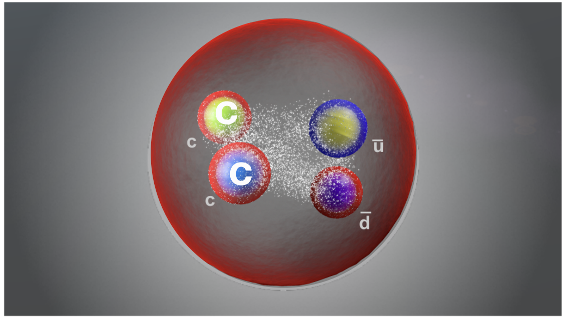


Hidden-charm pentaquark



Hidden-charm tetraquarks

& hidden-strange



Beyond hidden-charm

$c\bar{c}s\bar{s}$?

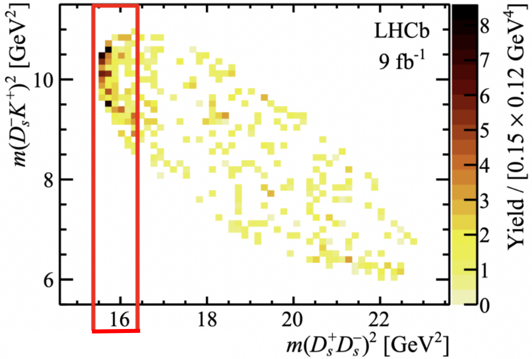
arXiv:2211.05034,
arXiv:2210.15153

$B^+ \to D_s^+ D_s^- K^+$: new $X(3960) \to D_s^+ D_s^-$

arXiv:2211.05034, arXiv:2210.15153

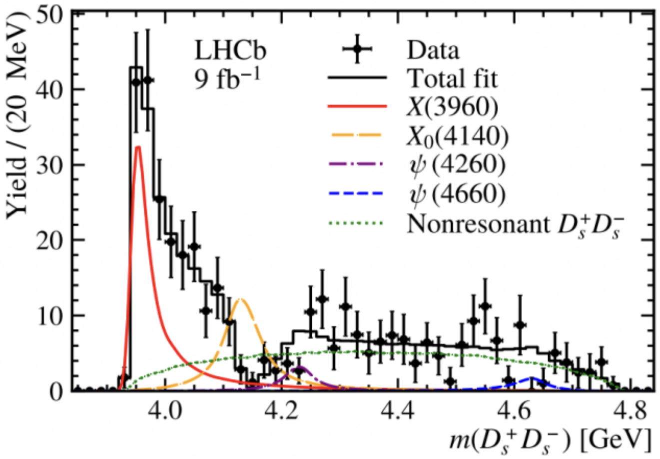
Signal yield: 360 events with 9 fb^{-1}

Near threshold enhancement in $D_s^+ D_s^-$



New states with $J^P=0^{++}$:

- X(3960) to describe the near-threshold enhancement
- X(4140): to describe the deep
  → but also described by $J/\psi\phi \to D_s D_s$ rescattering

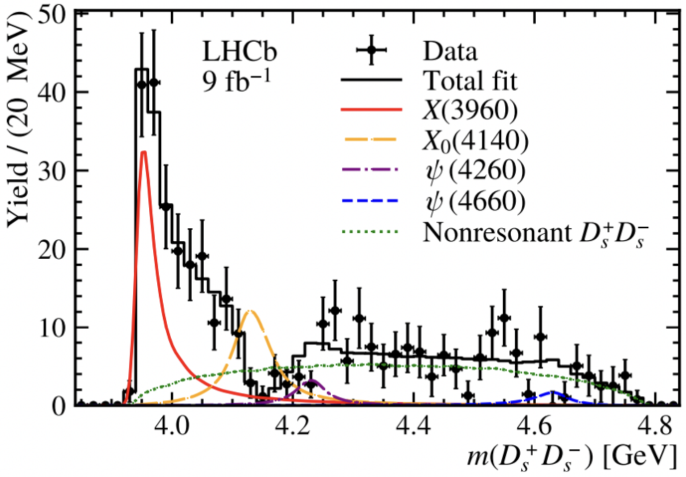


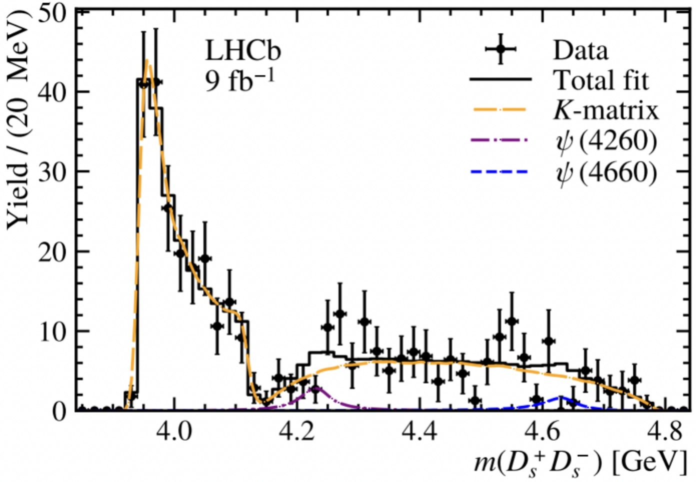
Same state as $\chi_{c0}(3930)$?

Exotic $c\bar{c}s\bar{s}$ or conventional state?
Conventional charmonium predominantly decay to $D^{(*)}D^{(*)}$, while:

$$\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.09 \pm 0.10 \pm 0.08$$

Looking again at X(4140)





The default model: dip@4.14GeV modelled by a new resonance, $X_0(4140)$

Can also be described by considering $J/\psi\phi \to D_s^+D_s^-$ rescattering in the K-matrix formula

No definitive conclusion on existence of $X_0(4140)$

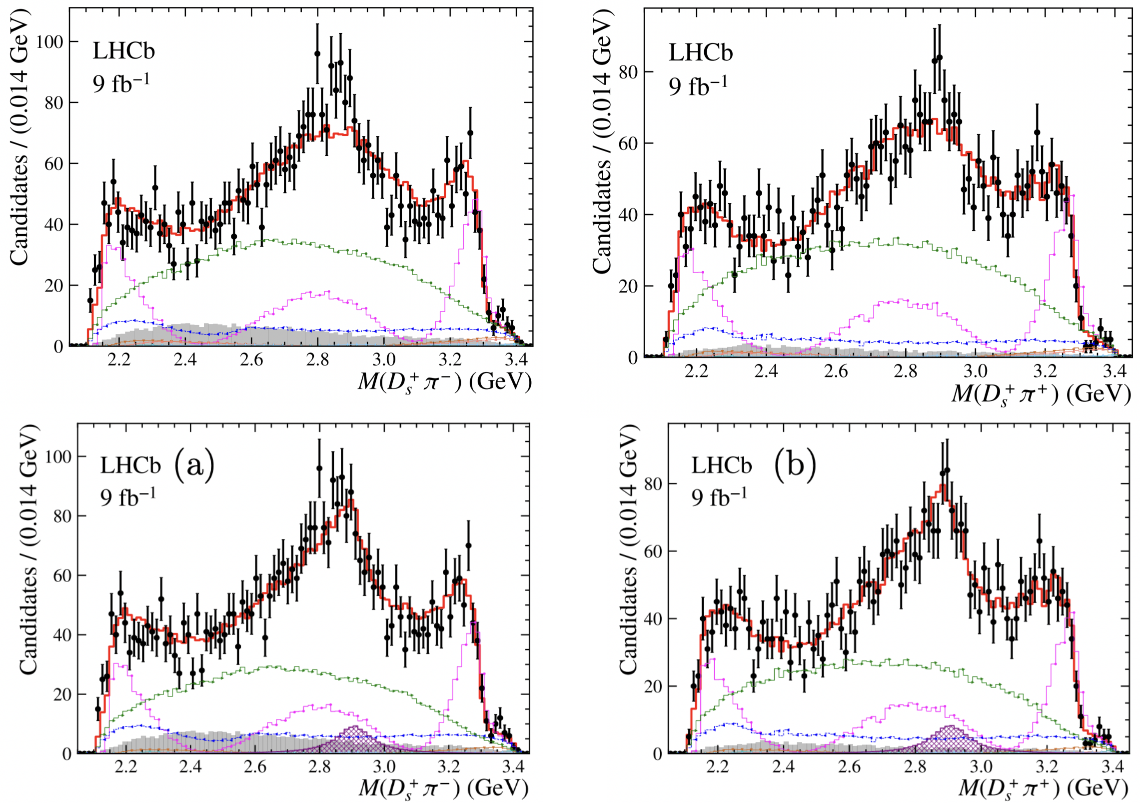
$T^{a}_{c\bar{s}0}(2900)^{0/++}$ in $D_s^{+}\pi^{-/+}$

arXiv:2212.02716, arxiv:2212.02717

$T^{a}_{c\bar{s}0}(2900)^{0/++}$ **> 9σ & J^P= 0$^+$**

$$M = 2.908 \pm 0.011 \pm 0.020\,\text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\,\text{GeV}$$

(RBW)



LHCb naming scheme

LHCb-PUB-2022-013, arxiv2206.15233

No PDG rule for
- exotic mesons with s, c, b quantum numbers
- no extension for pentaquark states

Idea of the proposal
- *T* for tetra, *P* for penta
- **Superscript**: based on existing symbols, to indicate isospin, parity and G-parity
- **Subscript**: heavy quark content

Impact on existing states

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$Z_c(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$