多夸克强子态的实验研究进展

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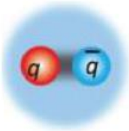
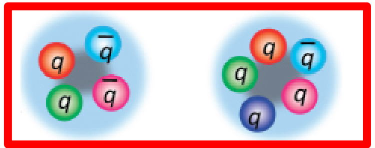
第十六届粒子物理、核物理和宇宙学交叉学科前沿问题研讨会

Outline

- Introduction
- Selected experimental results of exotic hadrons in heavy quark sector
- Summary

描述强子的理论：夸克模型

强子的夸克成分：

普通夸克模型的 常规强子		超出普通夸克模型的 新型强子
介子	重子	多夸克结构
价夸克数=2 （正反夸克对）	价夸克数=3	价夸克数>＝4 存在？
		

近年来，实验上发现了一系列被认为是4夸克或5夸克的候选粒子

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 lowest

[Rev. Mod. Phys. 90, 15003 (2018)]

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)
CERN - Geneva

In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $AAAA\bar{A}$, $AAAAA\bar{A}\bar{A}$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $A\bar{A}$, $AA\bar{A}\bar{A}$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $A\bar{A}$ and AAA, that is, "deuces and treys".

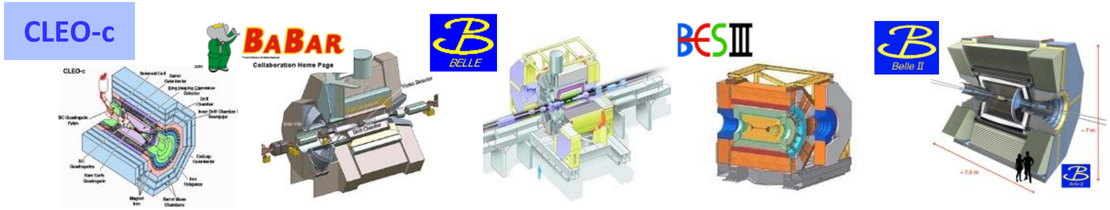
Hidden-charm sector is ideal for exotic searches

- **Theoretical models** well-established for conventional
- **Experimentally** easy to measure
  - Narrow and non-overlapping
  - Agreement below DD threshold

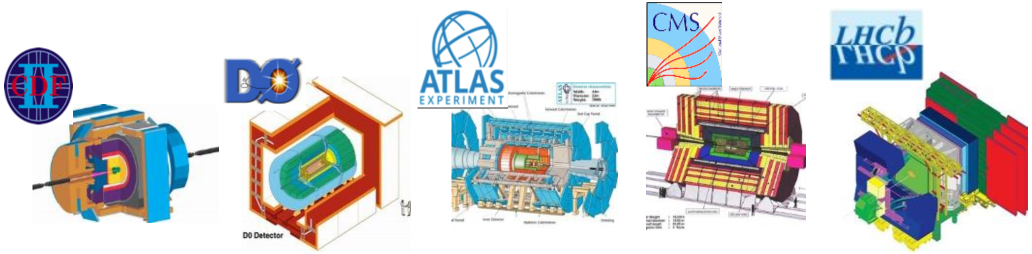
⇒ Exotics easier to identify respect to light and heavy-light sector

Main contributors worldwide

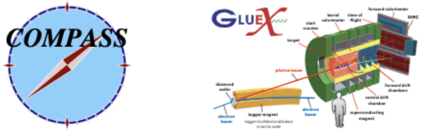
- e^+e^- collider



- Hadron collider



- Fixed-target experiments



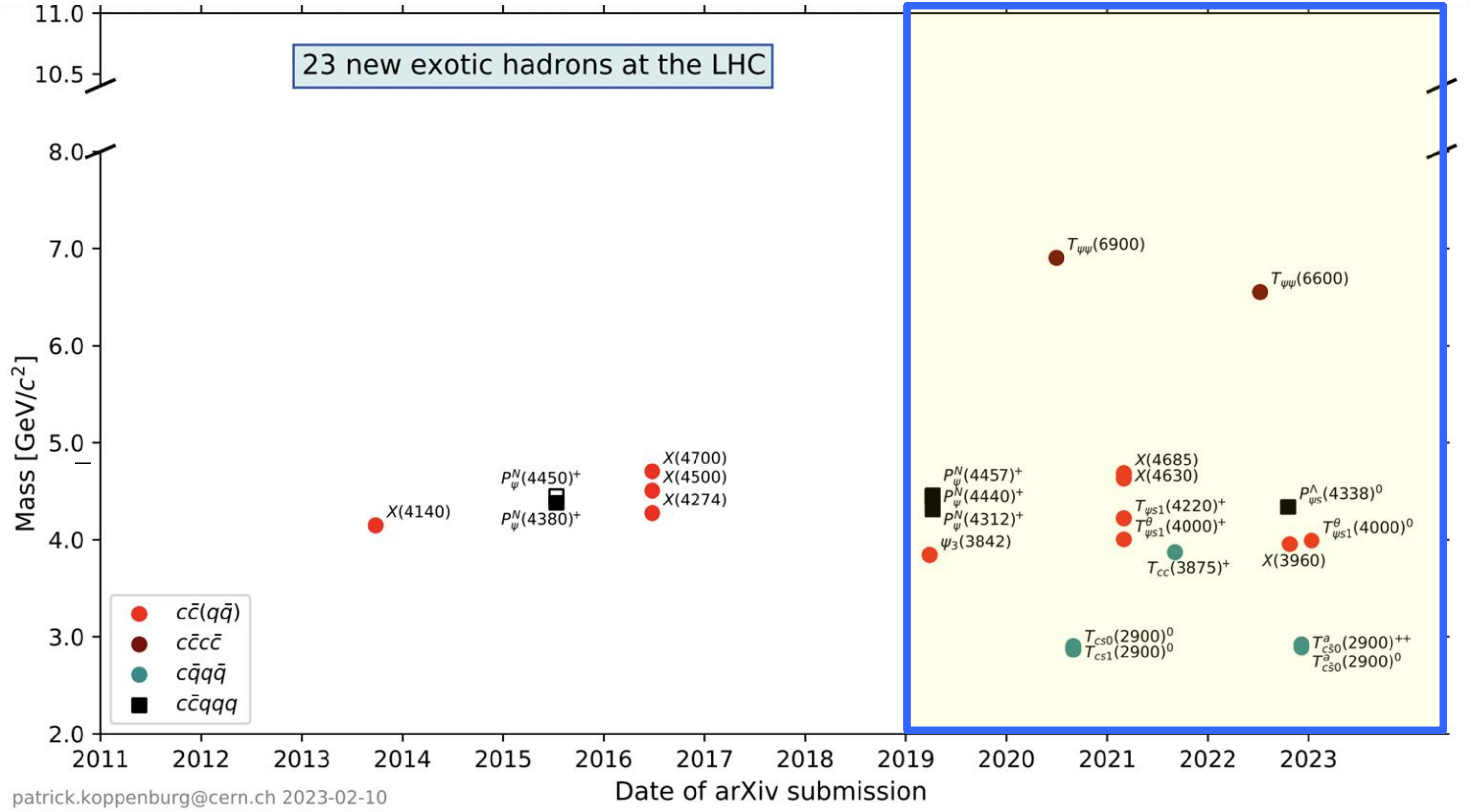
基础软件工具：TF-PWA的开发

https://tf-pwa.readthedocs.io/en/latest/

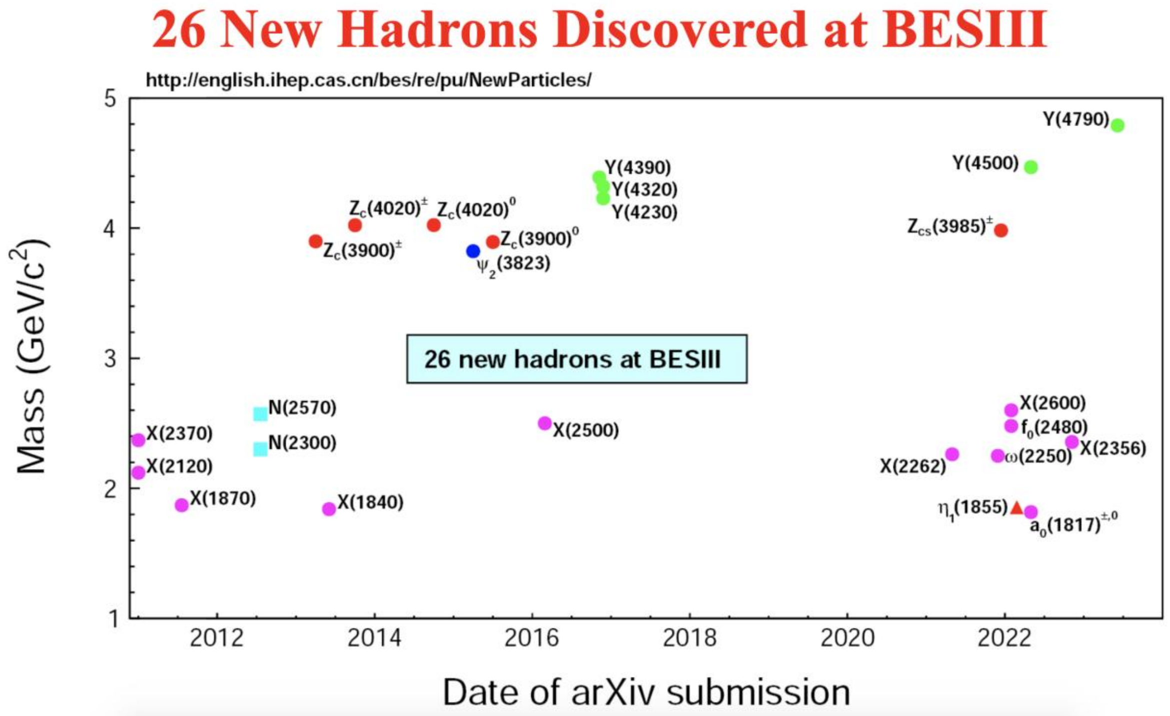
- 研究强子态和CP破缺的基础软件工具
  - 分波分析：在多体（≥三体）末态衰变中，通过对末态粒子的排列组合，寻找并测量共振态及其量子数。
- 基于TensorFlow软件库 + GPU，用于分波分析
- 极大的简化了分波分析，加快了分析速度
- 简单易用的界面

易用性 ⇒ BESIII实验与LHCb实验上的分波分析工具之一

An example: Spectroscopy at LHC



New Hadrons Discovered at BESIII



内部夸克分布?

Compact tetra/pentaquark

Color Forces

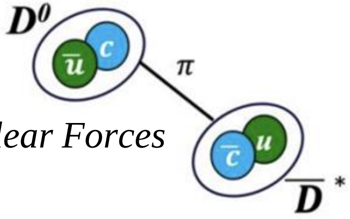
Diquark-antidiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)

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



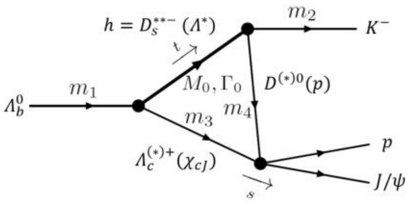
\+ $q\bar{q}g$ hybrid, glueball or mixture

- ✦ 阈效应、散射共振或末态相互作用贡献并未厘清
- ✦ QCD理论目前无法给出非常可靠的判据

States could also be mimic by

Rescattering effects

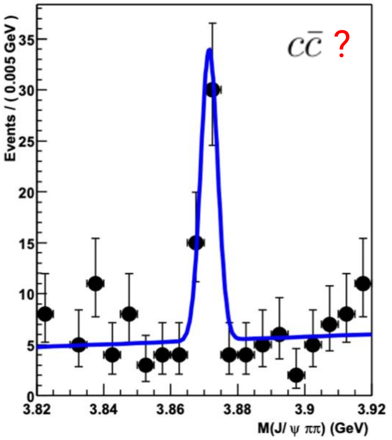
PRD 92 (2015) 071502
PLB 757 (2016) 231
PLB 757 (2016) 61
and others



One of the first exotic candidates: X(3872)

X(3872)

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



PRL **91**, 262001 (2003)

$\Rightarrow$ $J^{PC}=1^{++}$ by LHCb

PRL. 110 (2013) 222001

- **$X(3872)$ nature is still uncertain, although many studies are performed since 2003**
  - **$J^{PC} = 1^{++}$**
  - **Mass = 3871.69 $\pm$ 0.17 MeV**
  - **Width < 1.2 MeV @90% CL**

  $\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = 0.01 \pm 0.20$ MeV
- **Production**
  - **In e^+e^- collision, see strong connection of Y(4260) resonance decays**
    [BESIII, PRL 112. 092001 (2014); 122, 202001 (2019)]
  - **In b-hadron decays: B, Bs, Λ_b, …**
  - **Prompt production in $pp/p\bar{p}$ and heavy ion collision**
- **What is it?**
  - **Loosely $D^0\bar{D}^{0*}$ bound state?**
  - **Mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{0*}$?**
- **Important to fully explore its production and decay properties**

Mode		Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$< 2.8 \times 10^{-6}$
Γ_2	$\pi^+\pi^- J/\psi(1S)$	$(3.8 \pm 1.2)\%$
Γ_3	$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen
Γ_4	$\omega\eta_c(1S)$	$< 33\%$
Γ_5	$\omega J/\psi(1S)$	$(4.3 \pm 2.1)\%$
Γ_6	$\phi\phi$	not seen
Γ_7	$D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$
Γ_8	$\bar{D}^{*0}D^0$	$(37 \pm 9)\%$
Γ_9	$\gamma\gamma$	$< 11\%$
Γ_{10}	$D^0\bar{D}^0$	$< 29\%$
Γ_{11}	D^+D^-	$< 19\%$
Γ_{12}	$\pi^0\chi_{c2}$	$< 4\%$
Γ_{13}	$\pi^0\chi_{c1}$	$(3.4 \pm 1.6)\%$
Γ_{14}	$\pi^0\chi_{c0}$	$< 70\%$
Γ_{15}	$\pi^+\pi^-\eta_c(1S)$	$< 14\%$
Γ_{16}	$\pi^+\pi^-\chi_{c1}$	$< 7 \times 10^{-3}$
Γ_{17}	$p\bar{p}$	$< 2.4 \times 10^{-5}$
Radiative decays		
Γ_{18}	γD^+D^-	$< 4\%$
Γ_{19}	$\gamma\bar{D}^0D^0$	$< 6\%$
Γ_{20}	$\gamma J/\psi$	$(8 \pm 4) \times 10^{-3}$
Γ_{21}	$\gamma\chi_{c1}$	$< 9 \times 10^{-3}$
Γ_{22}	$\gamma\chi_{c2}$	$< 3.2\%$
Γ_{23}	$\gamma\psi(2S)$	$(4.5 \pm 2.0)\%$

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

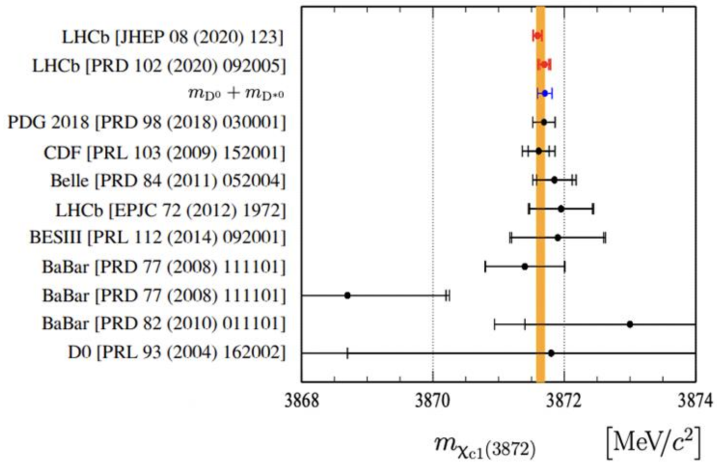
Many experiments contribute to it:

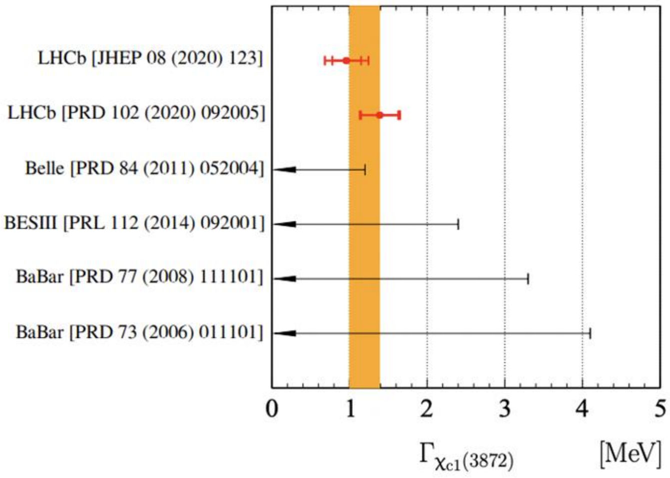
- Spin assignment: $J^{PC} = 1^{++}$ [1]
- Mass is consistent with **$m(D^0) + m(D^{*0})$**
- Width is surprisingly narrow

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



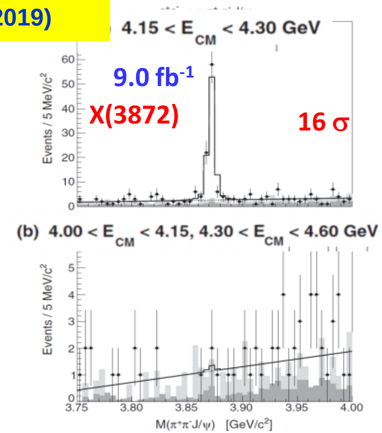


[1] PRL. 110 (2013) 222001, PRD 92 (2015) 011102(R)

$X(3872)$ production (1)

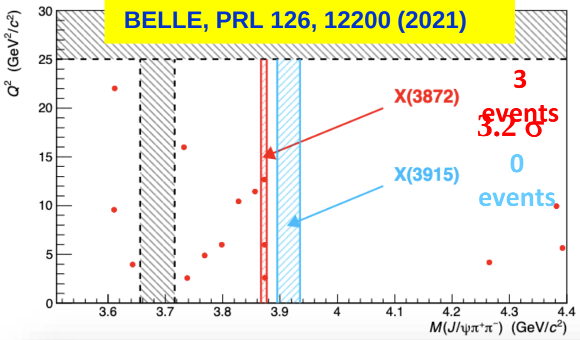
- Radiative production in $e^+e^- \to \gamma\, X(3872)$

BESIII, PRL122, 202001 (2019)



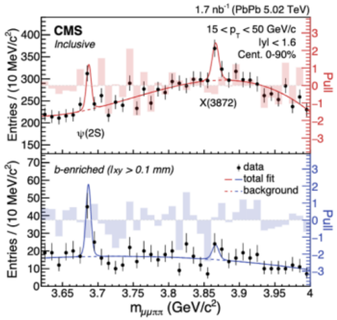
- From two-photon process:
evidence of $\gamma\gamma^* \to X(3872) \to \pi^+\pi^- J/\psi$

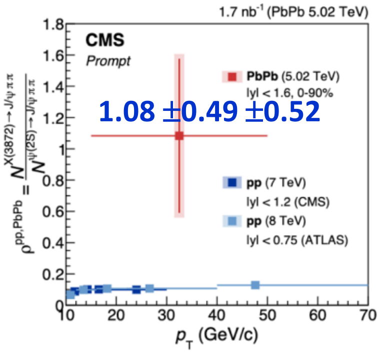
BELLE, PRL 126, 12200 (2021)



$$\tilde{\Gamma}_{\gamma\gamma}\mathcal{B}(X \to J/\psi\pi^+\pi^-) = 5.5^{+4.1}_{-3.8}\,(\text{stat.}) \pm 0.7\,(\text{syst.})\ \text{eV}$$

- Evidence in heavy ion collision: P_bP_b collision at $\sqrt{S_{NN}}$ = 5.02 TeV per nucleon pair





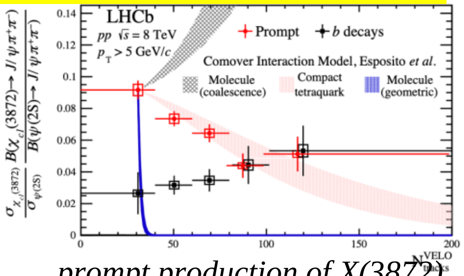
CMS, PRL128, 032001 (2022)

An indication of large R in P_bP_b collisions with respect to the pp collisions.

$X(3872)$ production (2)

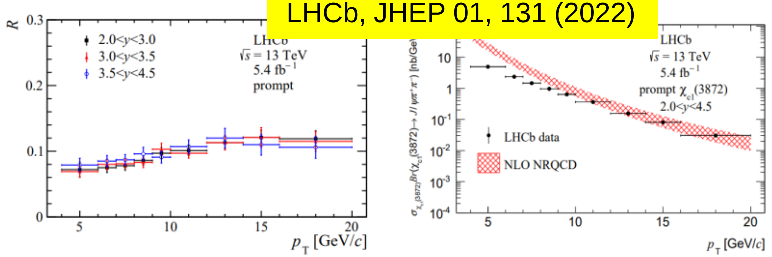
- Observation of prompt X(3872) relative to $\psi(2S)$ in pp collisions

LHCb, PRL126, 092001 (2021)



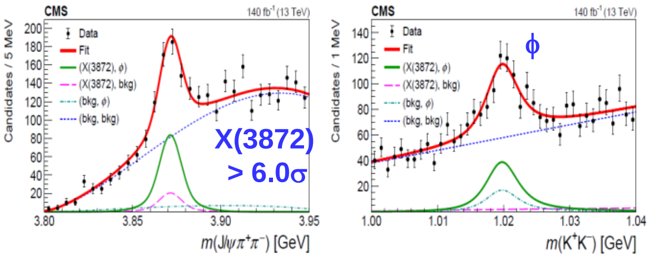
prompt production of X(3872) suppressed relative to prompt $\psi(2S)$ production as multiplicity increases.

LHCb, JHEP 01, 131 (2022)



- From B_s decays:
  $B_s \to X(3872)\,\phi$ at CMS and LHCb

CMS, PRL125, 152001 (2020)



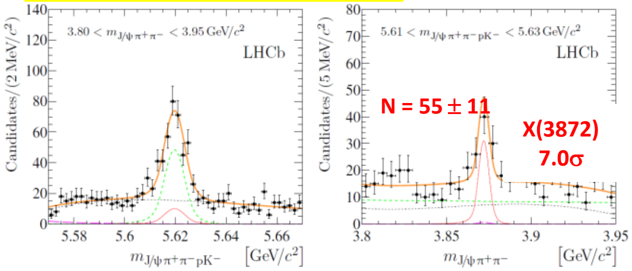
$$\frac{Br(B_s^0 \to X(3872)\phi)}{Br(B^+ \to X(3872)K^+)} = 0.482 \pm 0.063 \pm 0.037 \pm 0.070\,(Br)$$

about two times smaller than the ratio for $\psi(2S)$

Also observe $B_s \to X(3872)\,K^+K^-$ at LHCb (in later slides)

- From Λ_b^0 decays: $\Lambda_b^0 \to pK^- X(3872)$

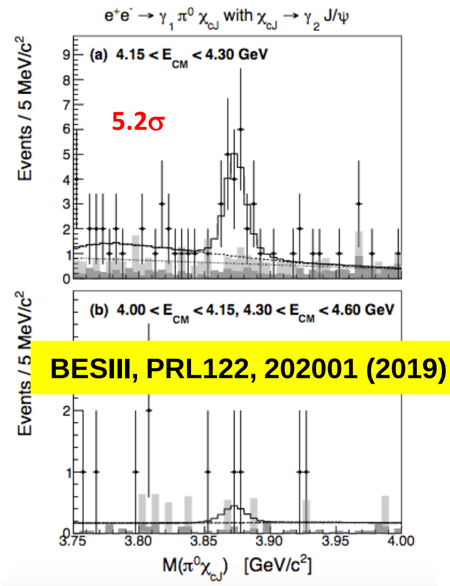
LHCb, JHEP 09, 028



half of pK^- from $\Lambda(1520)$

More X(3872) decay information

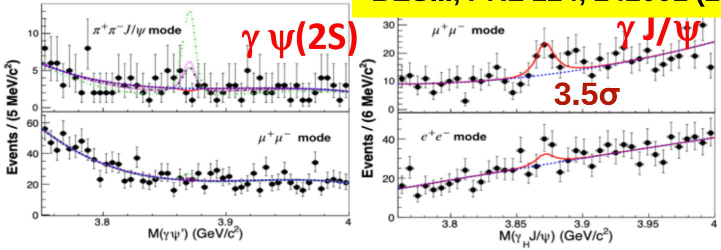
- Observation of X(3872) →$\pi^0\chi_{c1}$



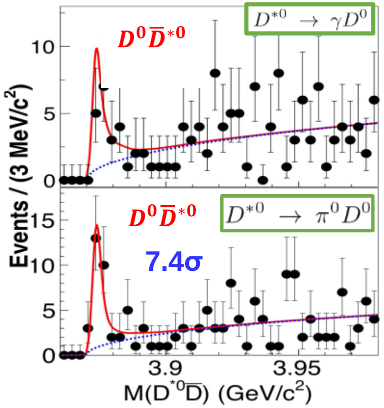
BESIII, PRL122, 202001 (2019)

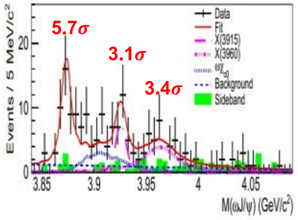
- Transition of $X(3872) \to \gamma J/\psi$, $\gamma\psi(2S)$

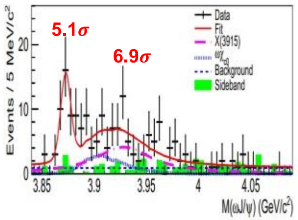
BESIII, PRL 124, 242001 (2020)



$R = \frac{BF(X(3872)\to\gamma\psi(2S))}{BF(X(3872)\to\gamma J/\psi)} < 0.59$ at 90% C.L. , agrees with Belle(<2.1), while challenges Babar(3.4±1.1) and LHCb results (2.46± 0.70)







- Observation of X(3872) → ωJ/ψ

BESIII, PRL 122, 232002 (2019)

- Observation of X(3872) →$D^0\bar{D}^{*0}$

BESIII, PRL 124, 242001 (2020)

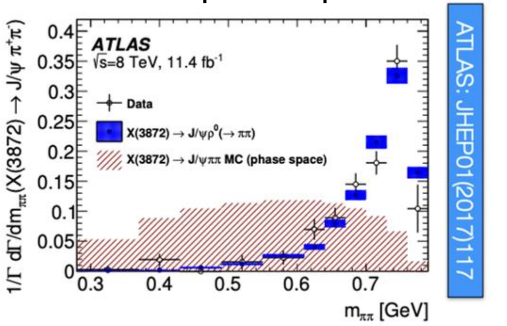
ω contribution in $\chi_{c1}(3872) \to J/\psi\pi\pi$

arXiv:2204.12597v1

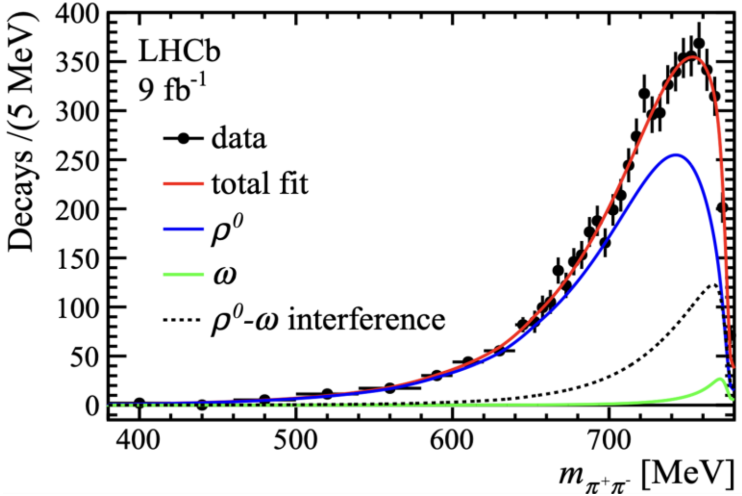
Studying **decay processes** can help understand its nature:

- Measure the isospin violating $\chi_{c1}(3872) \to J/\psi\rho$

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



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



Ratio of isospin violating to isospin conserving couplings is much larger than expected for a charmonium

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04.$$

$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

⇒ $\chi_{c1}(3872)$ cannot be a pure charmonium state

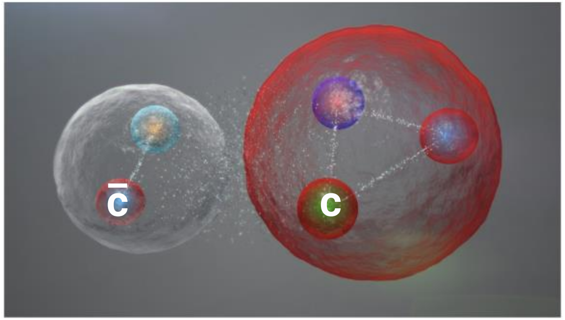
Exotics : Hidden-charm pentaquark

$P_{\psi}^{N}(4457)^{+}$
$P_{\psi}^{N}(4440)^{+}$
$P_{\psi}^{N}(4312)^{+}$

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

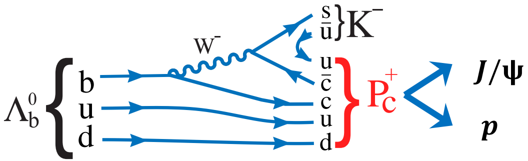
arxiv:2210.10346

$P_{\psi s}^{\Lambda}(4338)^{0}$



Pentaquarks in $\Lambda_b^0 \to J/\psi p K^-$ decays

- Pentaquarks [$c\bar{c}uud$] were first observed in 2015 by LHCb in $\Lambda_b^0 \to J/\psi p K^-$ decays

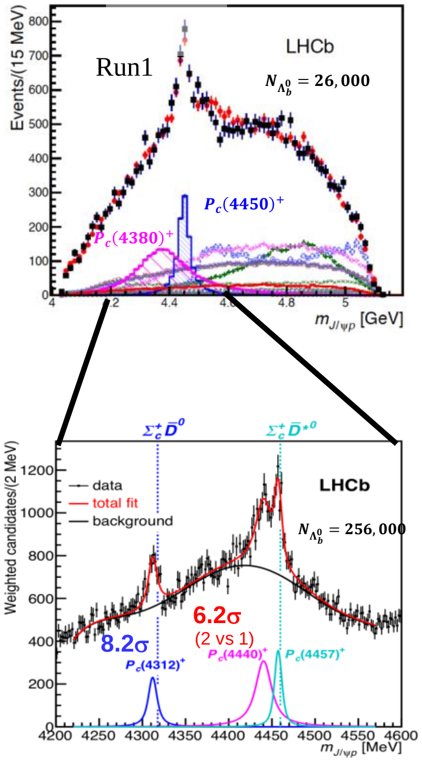


- New pentaquark and fine structure were discovered in 2019 with x10 signals
  - Three narrow pentaquarks just below $\Sigma_c^+ D^{(*)0}$ thresholds, favors molecular picture

State	M [MeV]	Γ [MeV] (95% CL)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+\ 3.7}_{-\ 4.5}$ (< 27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+\ 8.7}_{-10.1}$ (< 49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+\ 5.7}_{-\ 1.9}$ (< 20)

- A lot of open questions:
  - J^P, more decay modes,…?
  - SU(3) partners, hidden-bottom pentaquarks?

PRL115, 072001(2015)



RUN 1

RUN 1+2

PRL122, 222001(2019)

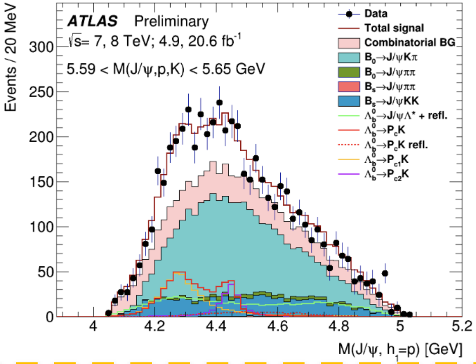
Pc confirmations in *b* decays at ATLAS and D0

- ATLAS studied ~1K $\Lambda_b^0 \to J/\psi p K^-$ using RUN1 data
- **Pc states are needed to describe data**: two Pc's fit (left) and four Pc's fit (right)

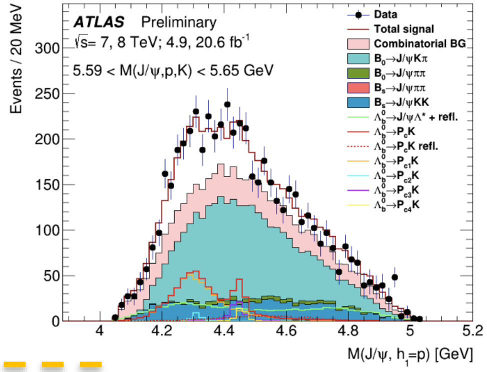
ATLAS-CONF-2019-048

Fitted Pc parameters consistent with LHCb's

Parameter	Value	LHCb value [5]
$N(P_{c1})$	400^{+130}_{-140}(stat)$^{+110}_{-100}$(syst)	–
$N(P_{c2})$	150^{+170}_{-100}(stat)$^{+50}_{-90}$(syst)	–
$N(P_{c1}+P_{c2})$	540^{+80}_{-70}(stat)$^{+70}_{-80}$(syst)	–
$\Delta\phi$	$2.8^{+1.0}_{-1.6}$(stat)$^{+0.2}_{-0.1}$(syst) rad	–
$m(P_{c1})$	4282^{+33}_{-26}(stat)$^{+28}_{-7}$(syst) MeV	$4380 \pm 8 \pm 29$ MeV
$\Gamma(P_{c1})$	140^{+77}_{-50} (stat)$^{+41}_{-33}$ (syst) MeV	$205 \pm 18 \pm 86$ MeV
$m(P_{c2})$	4449^{+20}_{-29} (stat)$^{+18}_{-10}$ (syst) MeV	$4449.8 \pm 1.7 \pm 2.5$ MeV
$\Gamma(P_{c2})$	51^{+59}_{-48} (stat)$^{+14}_{-46}$ (syst) MeV	$39 \pm 5 \pm 19$ MeV

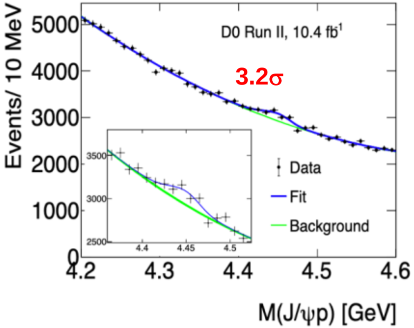


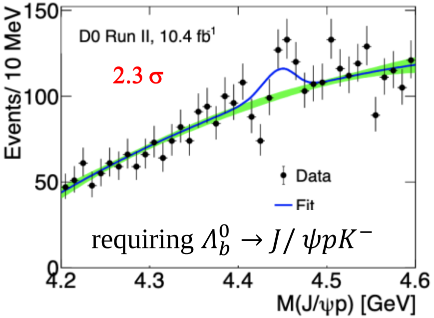
Pc parameters fixed to LHCb's results



- **D0 studied $J/\psi p$ in *b*-decays with displaced vertex**
- **A sum of Pc(4440) and Pc(4457) confirmed in b-decays: major contributions from b SL decays**

D0, arXiv:1910.11767



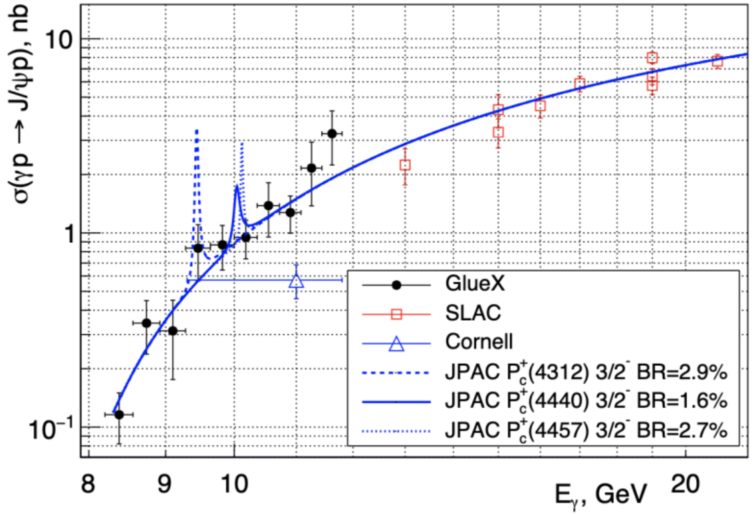


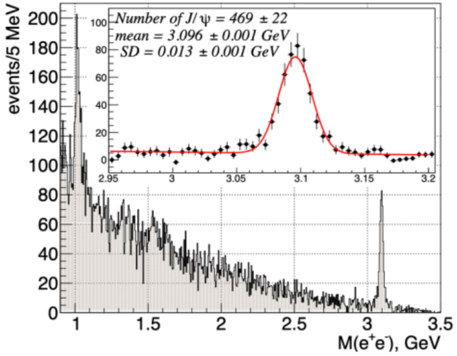
- **Pc(4312) is not evident**
- **No Pc states seen in prompt production**

Pentaquark photoproduction at GlueX

PRL123, 072001 (2019)

- Photoproduction: $\gamma p \rightarrow P_c \rightarrow J/\psi p$ studied with GlueX data in 2016 and 2017
- Combined data from SLAC and Cornell





The results do not exclude the molecular model, but are an order of magnitude lower than the predictions in the hadrocharmonium scenario.

Model-dependent upper limits at the 90% C.L. are et for cross section times branching fraction for the Pc states:

4.6 nb for $P_c(4312)$
1.8 nb for $P_c(4440)$
3.9 nb for $P_c(4457)$

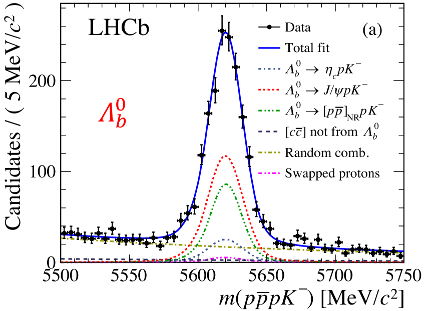
Search for Pc in $\Lambda_b^0 \to \eta_c p K^-$

PRD102, 112012 (2020)

- Same quark contents as $\Lambda_b^0 \to J/\psi p K^-$
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule,

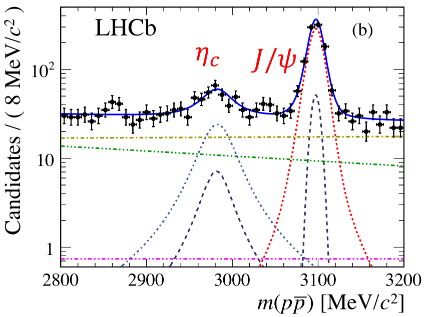
  $R(P_c(4312)^+) = \frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$ is predicted

  [PRD 100, 034020 (2019); 100, 074007 (2019); 102, 036012 (2020)]

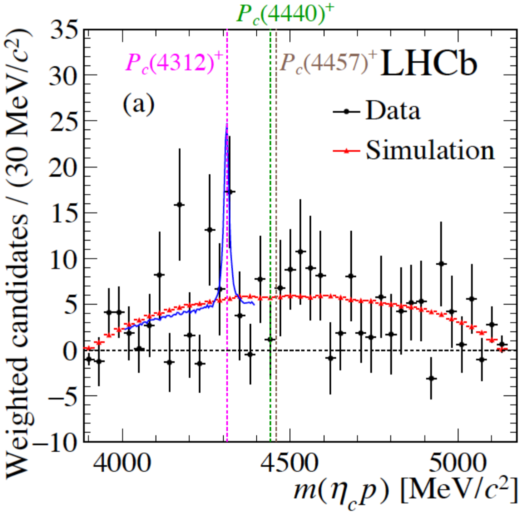


- LHCb run2 data (5.5 fb^{-1}): η_c reconstructed using $\eta_c \to p\bar{p}$
- Study background-subtracted $\eta_c p$ mass spectrum

~170 $\Lambda_b^0 \to \eta_c p K^-$ signals



No significant $P_c(4312)^+$ contribution (~2σ)



$R(P_c(4312)^+) < 0.24$ @ 95% C.L.

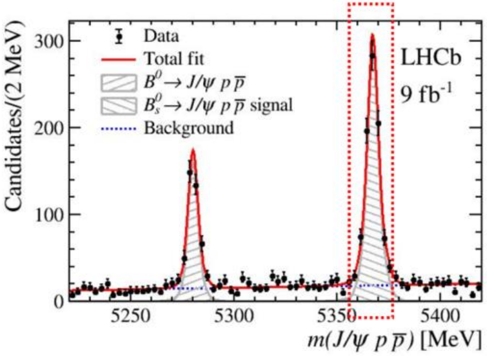
Pc state in $B_s^0 \to J/\psi p\bar{p}$

PRL 128, 062001 (2022)

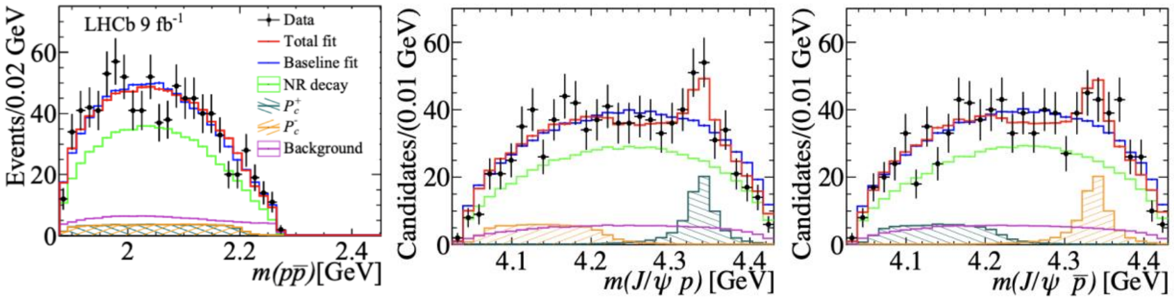
- ✦ **RUN 1+2 data, untagged B decay, with CP conservation, ~800 signals**
- ✦ **4D amplitude analysis implemented**
- ✦ **Evidence for a new pentaquark-like state Pc:**

$$M_{P_c} = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})\ \text{MeV}$$

$$\Gamma_{P_c} = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})\ \text{MeV}$$



- **3.1~3.7σ for $(\frac{1}{2}^{\pm}, \frac{3}{2}^{\pm})$ hypothesis; statistics not sufficient for determining the spin-parity**



- No evidence for $P_c(4312)$, glueball $f_J(2220)$, $p\bar{p}$ enhancement

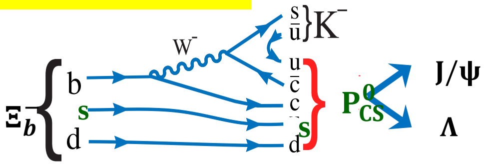
Evidence for the hidden-charm strange pentaquark P_{cs} $[c\bar{c}uds]$

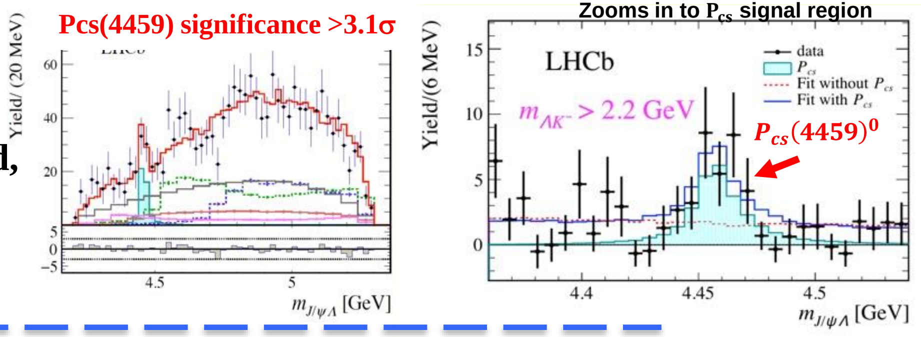
Sci. Bull. 66, 1278(2021)

- Aim to search for P_{cs}, a SU(3) partner of P_c state
- RUN 1+2 data: detect ~1750 $\Xi_b^- \to J/\psi \Lambda K^-$ signals
- 6D amplitude analysis is performed
- Statistics not enough for J^P determination

$m(P_{cs}^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV

$\Gamma(P_{cs}^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

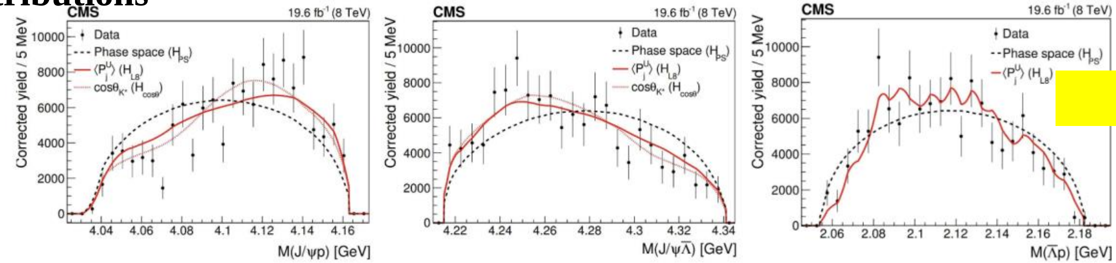




- $P_{cs}(4459)^0$ mass close to $\Xi_c \bar{D}^*$ threshold, two $I = 0$ states with $\frac{1}{2}^-$ or $\frac{3}{2}^-$

  More data needed to resolve

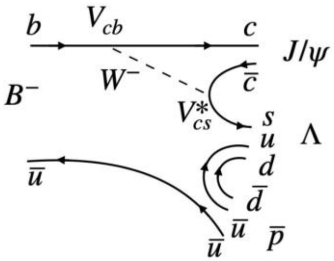
- $B^- \to J/\psi \Lambda \bar{p}$ decays with 19.6 fb^{-1} CMS data
- It finds that data is inconsistent with purely phase space distributions, but consistent with model-independent K* contributions



JHEP12, 100(2019)

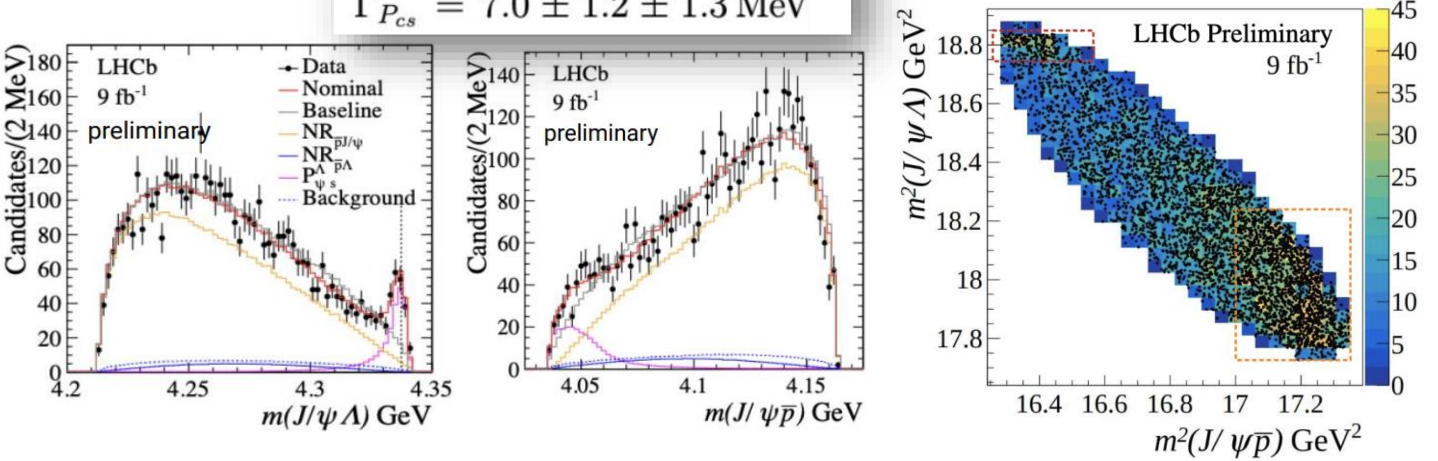
Observation of the hidden-charm strange pentaquark

- narrow structure in $J/\psi\Lambda$ in $B^- \to J/\psi\Lambda\bar{p}$ decays, with 9 fb^{-1} LHCb data
- amplitude analysis is performed
- $P_{\psi s}^{\Lambda}(4338) \to J/\psi\Lambda$ observed with significance larger than 10σ
- $J^P = \frac{1}{2}^-$ preferred and close to $\Xi_c^+ D^-$ threshold
  - 0.8 MeV above $\Xi_c^+ D^-$;
  - 2.9 MeV above $\Xi_c^0 \bar{D}^0$



$$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4\,\text{MeV}$$
$$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3\,\text{MeV}$$

arxiv:2210.10346

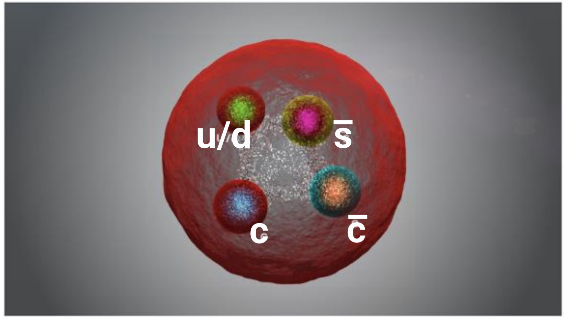


Hidden-charm tetraquarks with strange quark

Z_{cs}^{+} ($\rightarrow T^{\theta}_{\psi s1}$)

PRL 127, 082001 (2021)

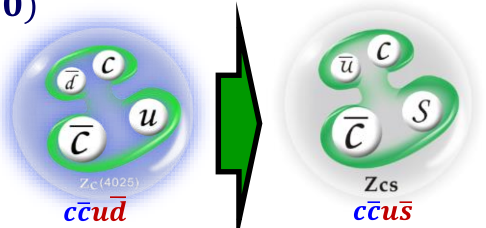
LHCb-PAPER-2022-040



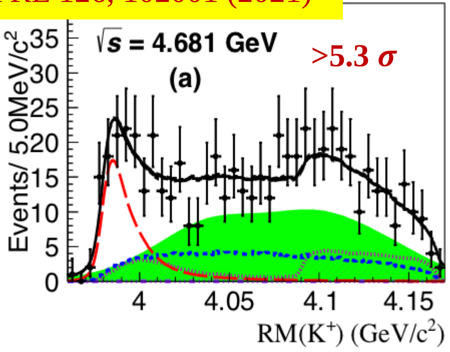
Zcs [$c\bar{c}u\bar{s}$]: SU(3) partner of Zc state

✦ **Important to look for Z_{cs}, the SU(3) partners of $X(3872)$/ $Z_c(3900)$**

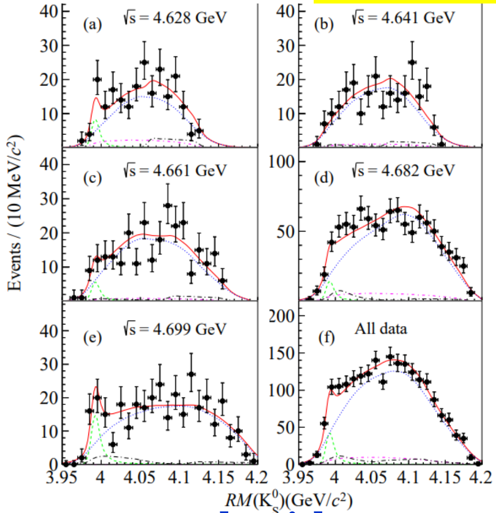
- **BESIII analyzes the process of $e^+e^- \to K^+(D_s^- D^{*0} + D_s^{*-} D^0)$ with 3.7fb^{-1} data at energies between 4.628 and 4.698GeV**



PRL 126, 102001 (2021)



$e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$ PRL 129, 112003 (2022)



- **A fit of J^P=1$^+$ S-wave Breit-Wigner with mass dependent width returns:**

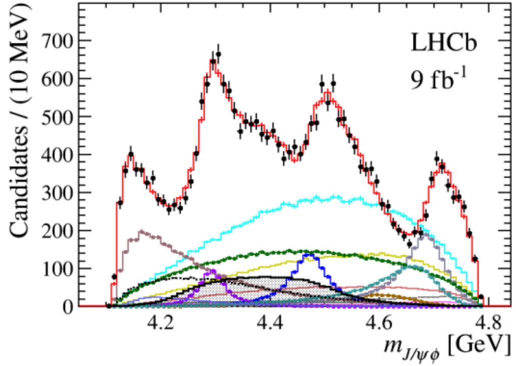
	Mass (MeV/c^2)	Width (MeV)
$Z_{cs}(3985)^0$	$3992.2 \pm 1.7 \pm 1.6$	$7.7^{+4.1}_{-3.8} \pm 4.3$
$Z_{cs}(3985)^+$	$3985.2^{+2.1}_{-2.0} \pm 1.7$	$13.8^{+8.1}_{-5.2} \pm 4.9$

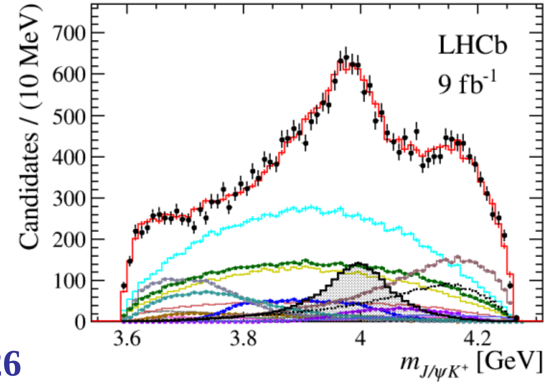
First candidate of the hidden-charm tetraquark with strangeness, and isospin triplet confirmed!

Amplitude analysis of $B^+ \to J/\psi\phi K^+$

- With Run 1 $B^+ \to J/\psi\phi K^+$ data, LHCb performed 1st amplitude fit and **observed** the $X(4140)$, $X(4274)$, $X(4500)$ and $X(4700)$ ➔ $[c\bar{c}s\bar{s}]$ tetraquark?
- LHCb RUN 1+2: 24K signals, about 6× larger than RUN 1

PRL127, 082001 (2021)





- **New states:**
  $Z_{cs}(4000)$, $X(4685)$ > 15σ
  $Z_{cs}(4220)$, $X(4630)$ > 5σ
  $X(4150)$ < 5σ
- $Z_{cs}(4000)$ & $X(4685)$: 1^+
- $Z_{cs}(4220)$ can be 1^+ or 1^-
- **Confirmed states:**
  $X(4140)$, $X(4274)$,
  $X(4500)$, $X(4700)$

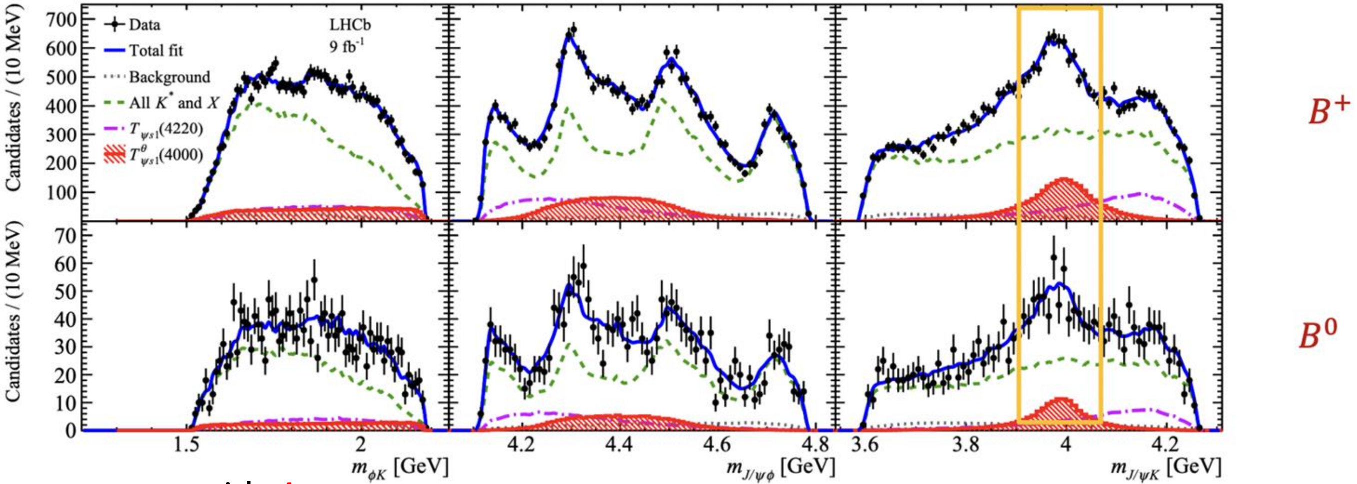
Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$	Syst. included(Stat.)			
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5^{+14}_{-7}$
$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3^{+8}_{-10}$
$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

$B^0 \to J/\psi \Phi K_s$ decays

arxiv:2301.04899

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

- All components except $\boldsymbol{T^{\theta}_{\psi s1}(4000)}$ in B^0 decay are constrained by those in B^+ decay

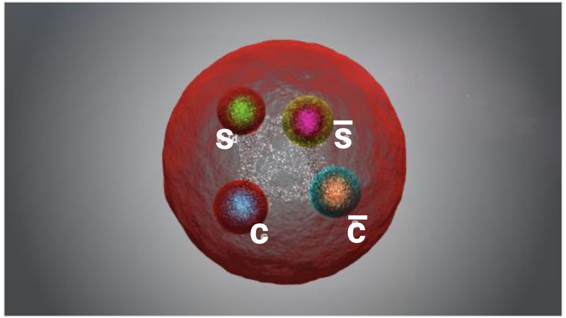


Evidence for a new state with 4σ

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

⇒ $\boldsymbol{T^{\theta}_{\psi s1}(4000)^0}$ & $\boldsymbol{T^{\theta}_{\psi s1}(4000)^+}$: consistent with being isospin partners, $\Delta M = 12^{+11}_{-10}{}^{+6}_{-4}$ MeV

Hidden-charm tetraquarks & hidden-strange



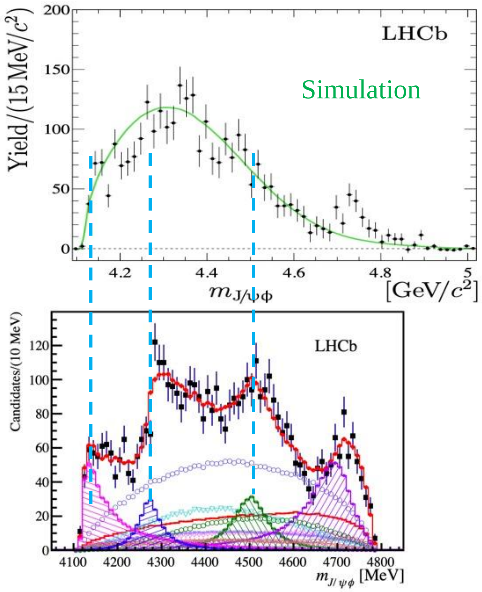
arXiv:2211.05034,
arXiv:2210.15153

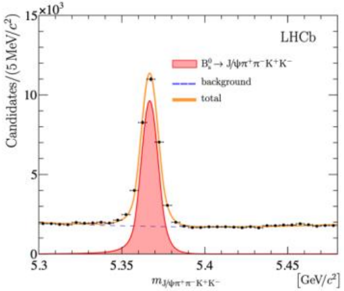
$X(4740)$ structure with $[c\bar{c}s\bar{s}]$

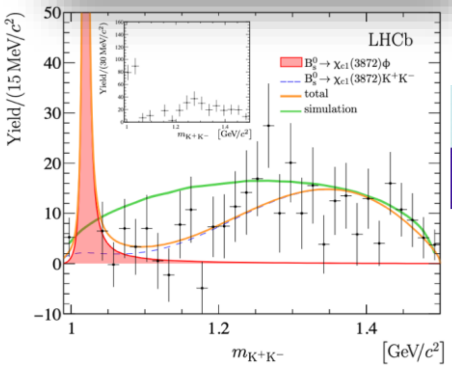
JHEP02, 024 (2021)

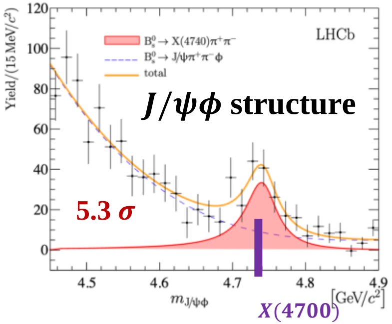
- Study of $B_S^0 \to J/\psi\pi^+\pi^-K^+K^-$ using LHCb RUN 1+2 data: 26.5K signals
- Observations of $B_S^0 \to X(3872)K^+K^-$ and $X(3872)\phi$

$$\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2},$$
$$\mathcal{R}_{K^+K^-} = 1.57 \pm 0.32 \pm 0.12,$$









1D fit using S-wave Breit-Wigner

$m_{X(4740)} = 4741 \pm 6 \pm 6$ MeV

$\Gamma_{X(4740)} = 53 \pm 15 \pm 11$ MeV

Systematic uncertainties:
- Shape of underlying non-X
- Alternative P-wave or D-wave BW
- Inteferenc $\mathcal{F}_S(m_{J/\psi\phi}) \propto |\mathcal{A}(m_{J/\psi\phi}) + b(m_{J/\psi\phi})e^{i\varphi}|^2$

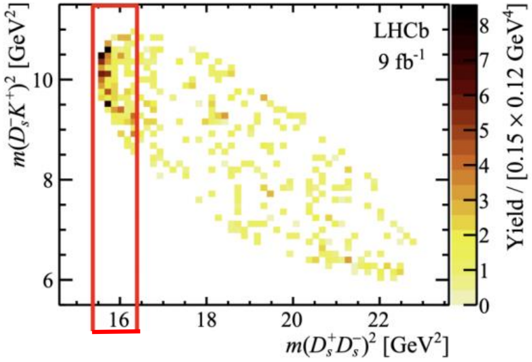
$X(4740)$: could be the $X(4700)$ in $B^+ \to J/\psi\phi K^+$

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

arXiv:2211.05034, arXiv:2210.15153

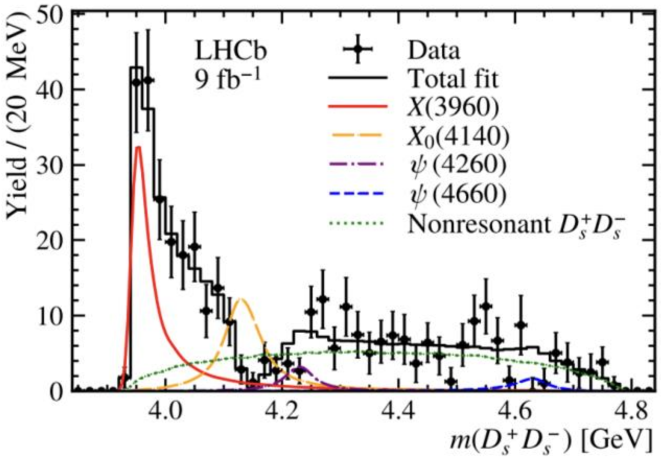
Signal yield: 360 events with 9 fb^{-1}

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 $J/\psi\varphi \to D_s D_s$ rescattering



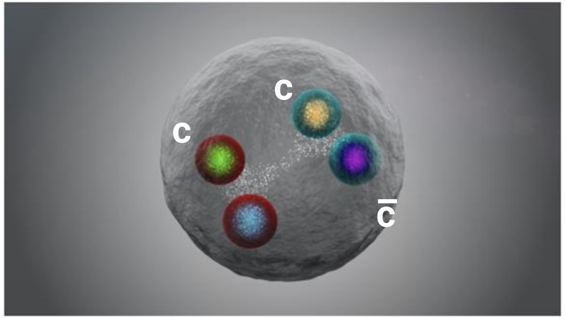
Same state as $\chi_{c0}(3930)$?

Exotic $c\bar{c}s\bar{s}$ or conventional state?

- conventional charmonium predominantly decay to $D^{(*)}D^{(*)}$, while:

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

Hidden-charm tetraquarks : Di-ψ resonance

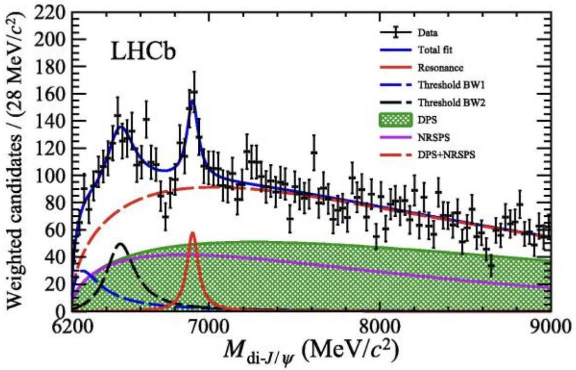


Sci.Bull. 65 (2020), 23

CMS-PAS-BPH-21-003

$T_{\psi\psi}$ resonances

Sci.Bull. 65 (2020), 23



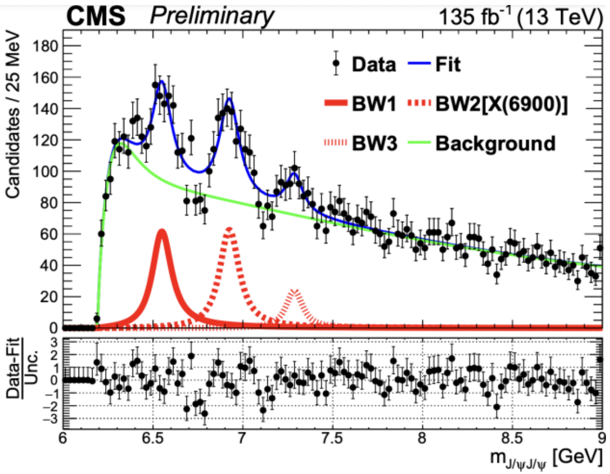
Narrow structure at 6.9 GeV

→ $T_{\psi\psi}(6900)$

Broad structure just above double-J/ψ threshold

→ **5σ deviation** from NR

CMS-PAS-BPH-21-003

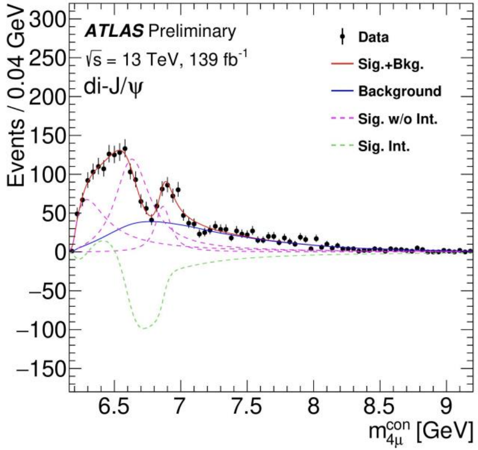


$T_{\psi\psi}(6900)$ consistent with LHCb

\+ New peak at 6600 with ~10σ

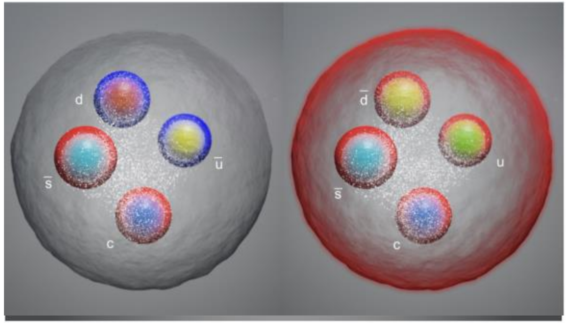
3rd peak seen with 4σ

arXiv:2304.08962



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

Open-charm tetraquarks



$T_{cs0}(2900)^0$
$T_{cs1}(2900)^0$

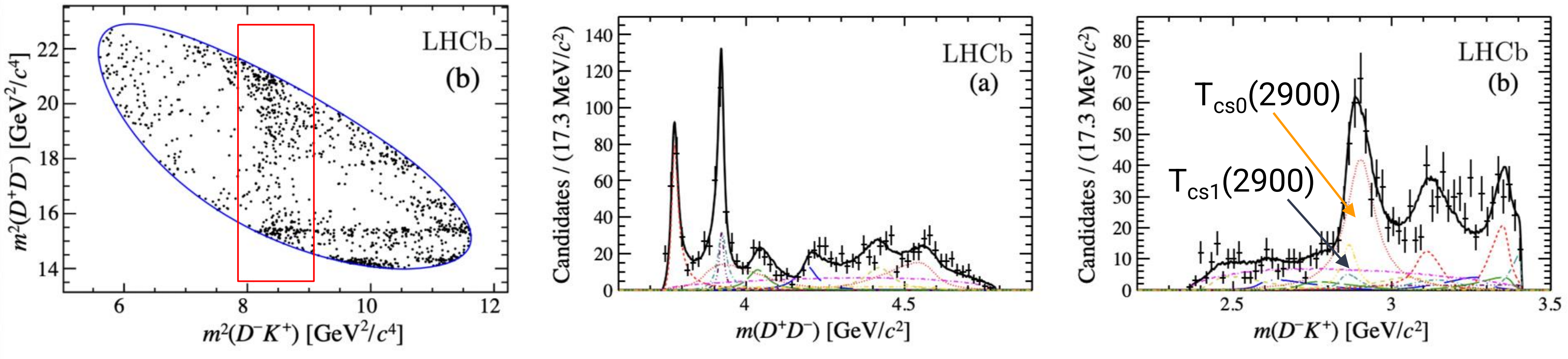
PRD, 2005, 72: 054026

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

arXiv:2212.02716

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

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



$T_{cs0,1}(2900) \to D^-K^+$: 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 $\boldsymbol{B \to DD_s\pi}$ decays

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

arXiv:2212.02716, arxiv:2212.02717

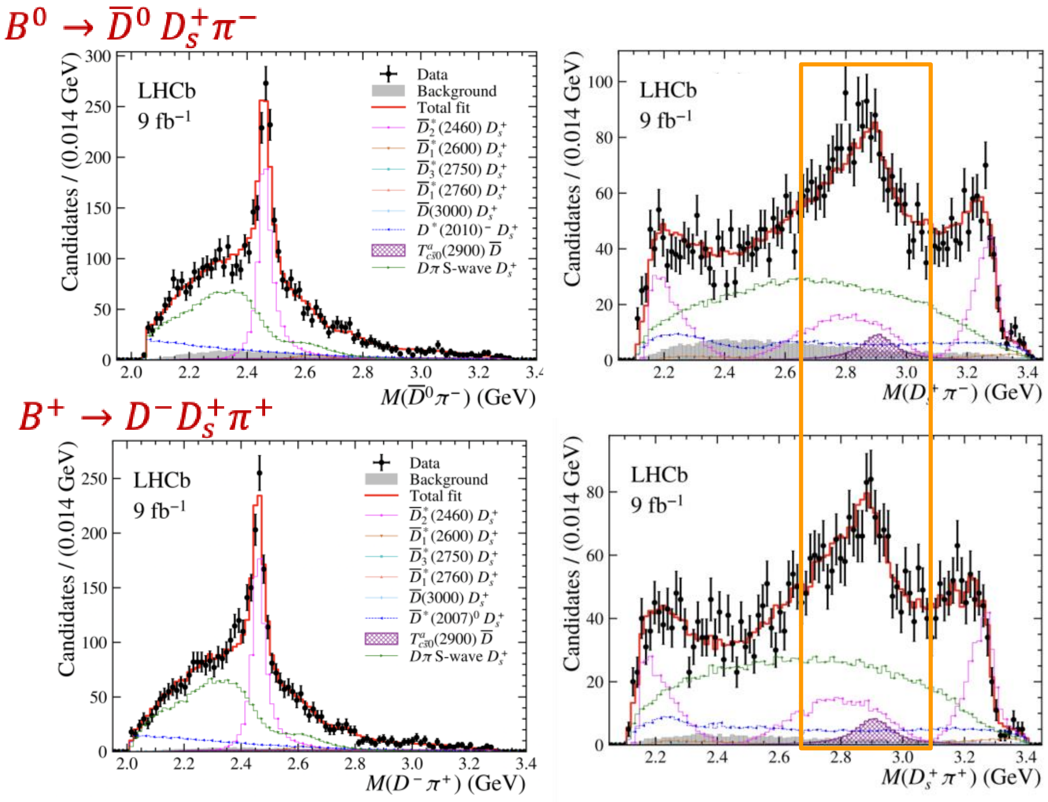
Isospin symmetry
→ combined amplitude
analysis of the 2 channels

$T^a_{c\bar{s}0}(2900)^{0/++}$ **> 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)



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

arXiv:2212.02716, arxiv:2212.02717

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

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

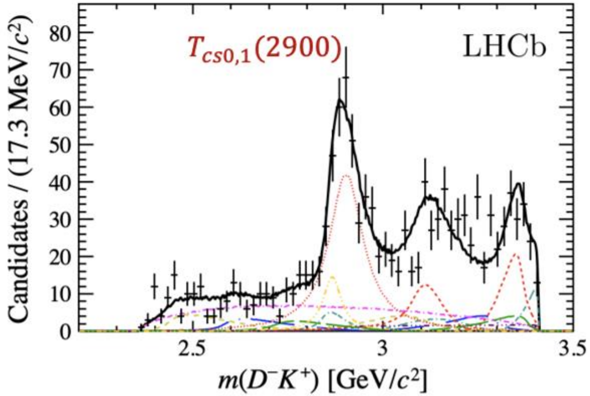
- Isospin triplet?

$T^a_{c\bar{s}0}(2900)^0$
$T^a_{c\bar{s}0}(2900)^+$? ⇒ to be searched for in $D_s^+\pi^0$
$T^a_{c\bar{s}0}(2900)^{++}$

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

$T_{cs0}(2900)$ $cs\bar{u}\bar{d}$
$T_{c\bar{s}0}(2900)$ $c\bar{s}\bar{u}d$
⇒ SU(3) flavour partners?

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

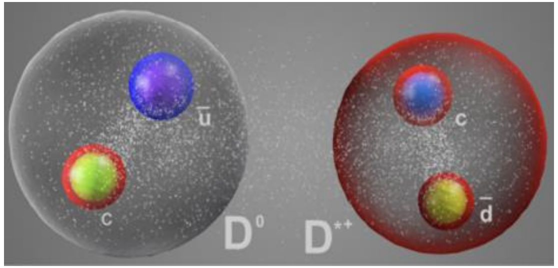


Doubly-charm tetraquark

$T_{cc}(3875)^+$

Nature Physics (2022);

Nat. Comm. 13, 3351 (2022)



Observation of doubly charm tetraquark

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

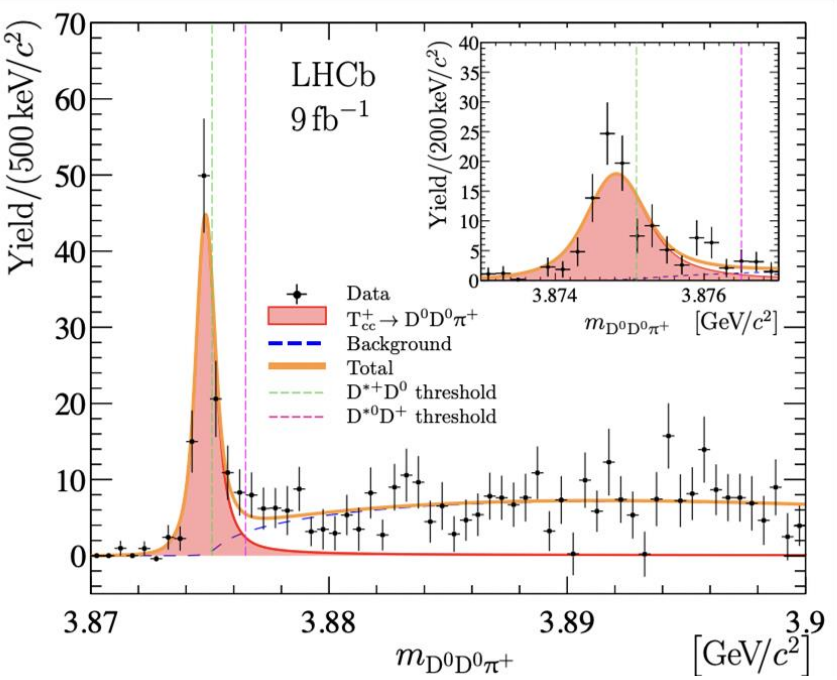
First observation of same-sign
double charmed tetraquark, $T_{cc}^{+}(3875) \rightarrow D^0 D^0 \pi^+$

$\Rightarrow$ exotic quark content $cc\bar{u}\bar{d}$

Mass close to $D^{*+}D^0$ threshold and very narrow

$$\delta m_{\rm BW} = -273 \pm 61({\rm stat}) \pm 5({\rm syst})^{+11}_{-14}({\rm model})\ {\rm keV}$$
$$\Gamma = 410 \pm 65({\rm stat}) \pm 43({\rm syst})^{+18}_{-38}({\rm model})\ {\rm keV}$$

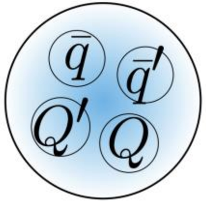
Consistent with **isoscalar** with **J^P=1$^+$**



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

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

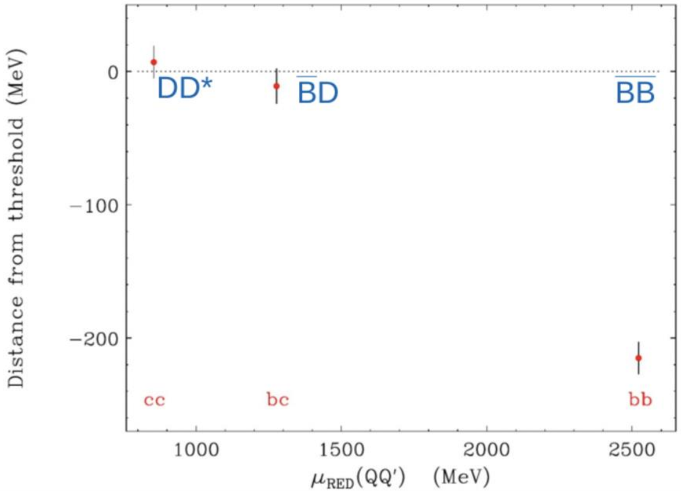
→ almost stable against strong interaction: $\tau \sim 10^{-20}$ s



⇒ It supports existence of:

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

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



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Summary

- **An exciting period of finding new (heavy) hadrons**
- **Many new hadrons are observed at different experiments**
  - **hidden-charm tetraquark states:**
    Zcs(3985), Zcs(4000) and Zcs(4220) [$c\bar{c}u\bar{s}$];
    X(6900), X(6600) [$c\bar{c}c\bar{c}$];
    X(4630), X(4685), $X(4740)$, X(3960) [$c\bar{c}s\bar{s}$];
  - **singly charmed tetraquark states:**
    X(2900) [$\bar{c}\bar{s}ud$]; $T_{c\bar{s}0}(2900)^{++}$ [$c\bar{s}u\bar{d}$]; $T_{c\bar{s}0}(2900)^{0}$ [$c\bar{s}\bar{u}d$]
  - **doubly charmed tetraquark state: T_{cc}^{+} [$cc\bar{u}\bar{d}$]**
  - **observation/evidence of new pentaquark states: Pc(4312), Pc(4440), Pc(4457) and Pc(4337) [$c\bar{c}uud$]; $P_{cs}(4338)$, $P_{cs}(4459)$ [$c\bar{c}uds$]**
- **More data are desired for marginal evidence or observation, determination of spin-parity**
  - **new results based on higher statistics data can be expected**

Backup

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