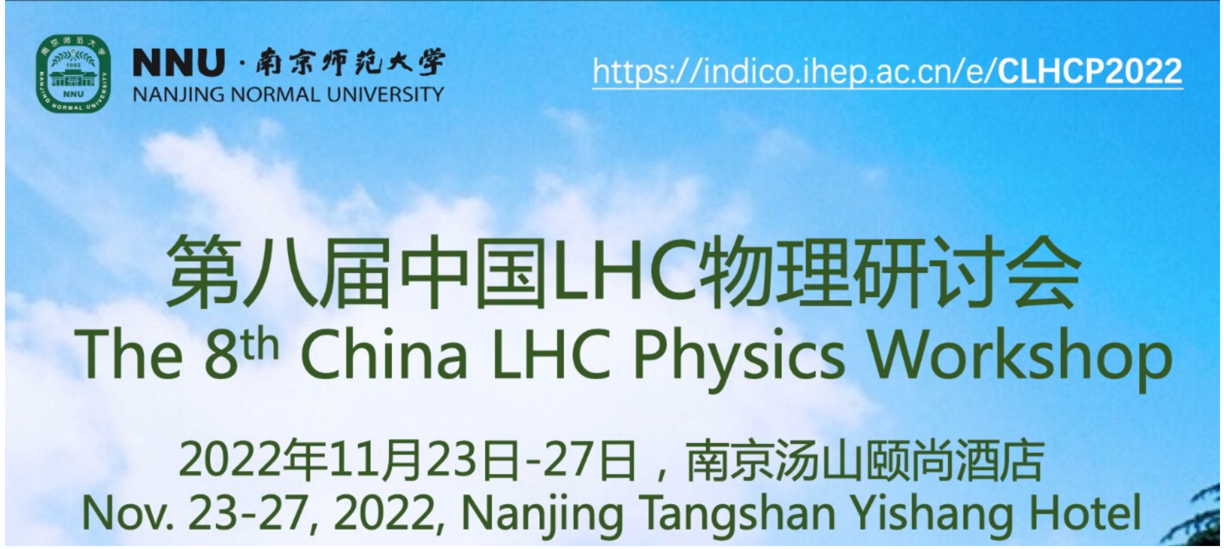


Exotic hadrons at LHCb

Xiao-Rui Lyu (吕晓睿)

University of Chinese Academy Sciences

(on behalf of the LHCb collaboration)

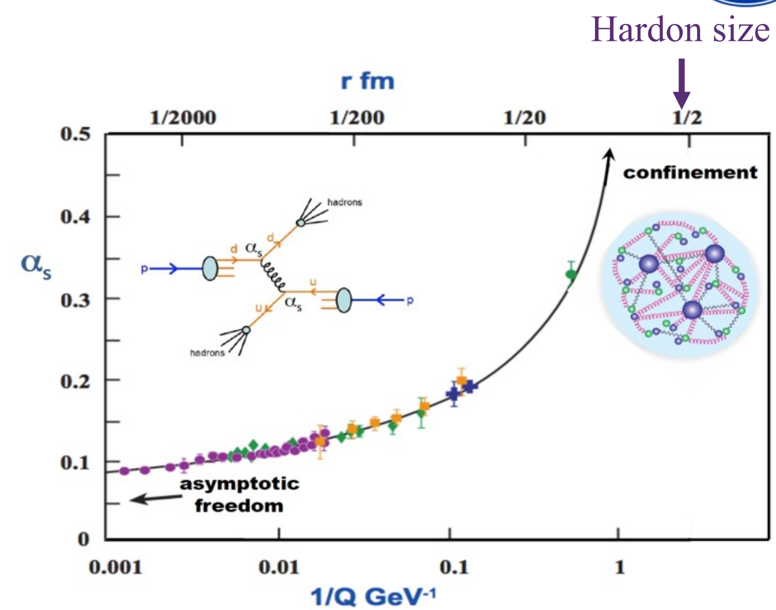
Outline

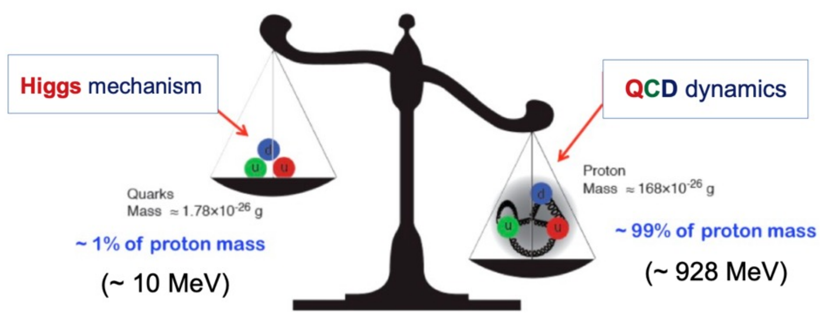
- Introduction
- $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$
- Open-charm tetraquark $T^a_{c\bar{s}0}(2900)$ in $B \to D D_s \pi$
- $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$
- Neutral $Z_{cs}(4000)/T^{\theta}_{\phi s1}(4000)$ in $B^0 \to J/\psi \phi K_S$
- Searches for exotics in
  - ✓ $B^- \to \Lambda_c^+ \Lambda_c^- K^-$
  - ✓ $B^+ \to K^+ \eta J/\psi$
- Pentaquark $P^{\Lambda}_{\psi s}(4338)$ in $B^- \to J/\psi \Lambda \bar{p}$
- Summary

more details, see talks by:
Shuangli Yang and Zhihong Shen today afternoon;
Quan Zou yesterday afternoon

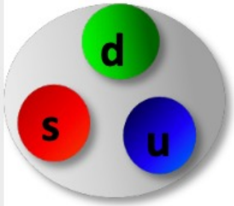
Introduction

- Quarks and gluons not isolated in nature.
  - Formation of colorless bound states: "**Hadrons**"
  - **1-fm scale** size of hadrons?
- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence





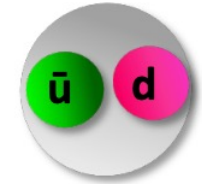
Different types of hadrons to be explored



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

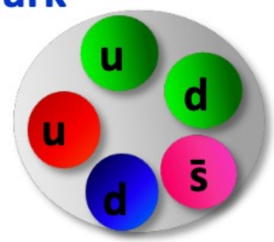


π=ūd

Other possible combinations of quarks and gluons :

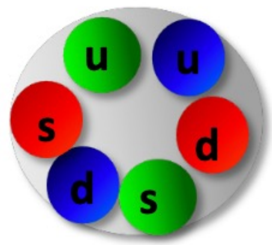
Pentaquark

S= +1 Baryon



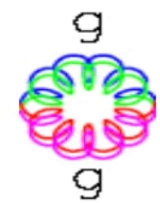
H di-Baryon

Tightly bound 6 quark state



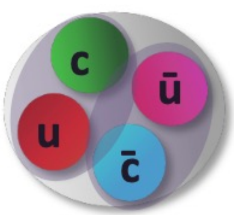
Glueball

Color-singlet multi-gluon bound state



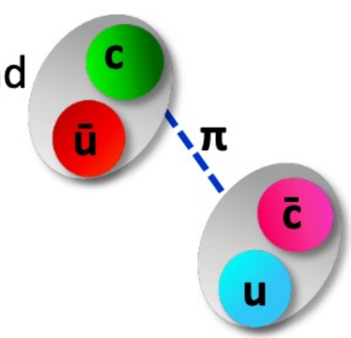
Tetraquark

Tightly bound diquark & anti-diquark

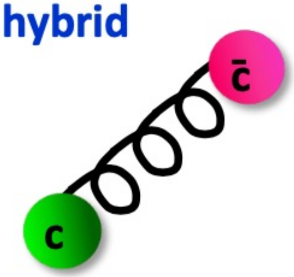


Molecule

loosely bound meson-antimeson "molecule"

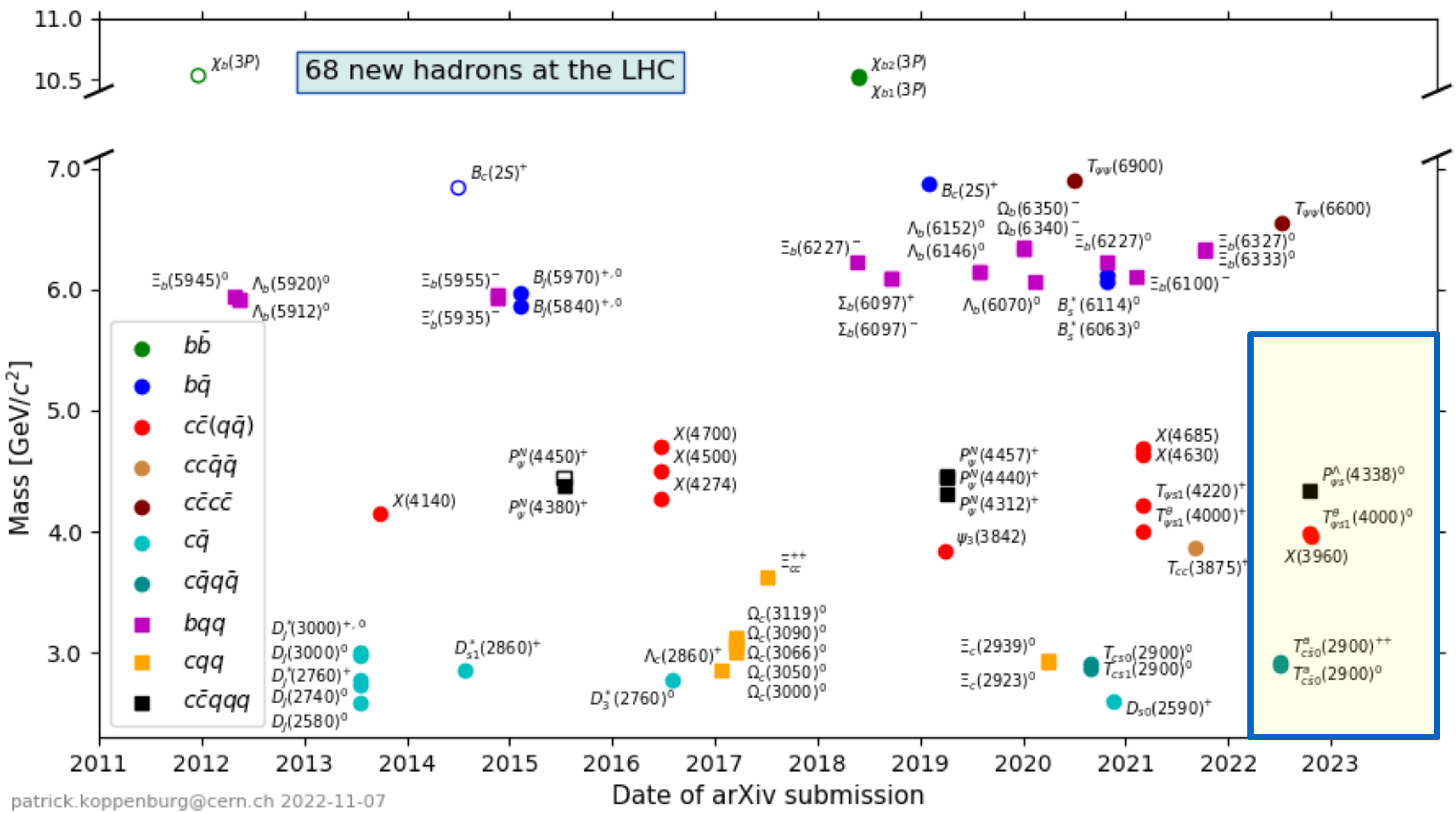


qq̄ -gluon hybrid mesons



Heavy hadron Spectroscopy

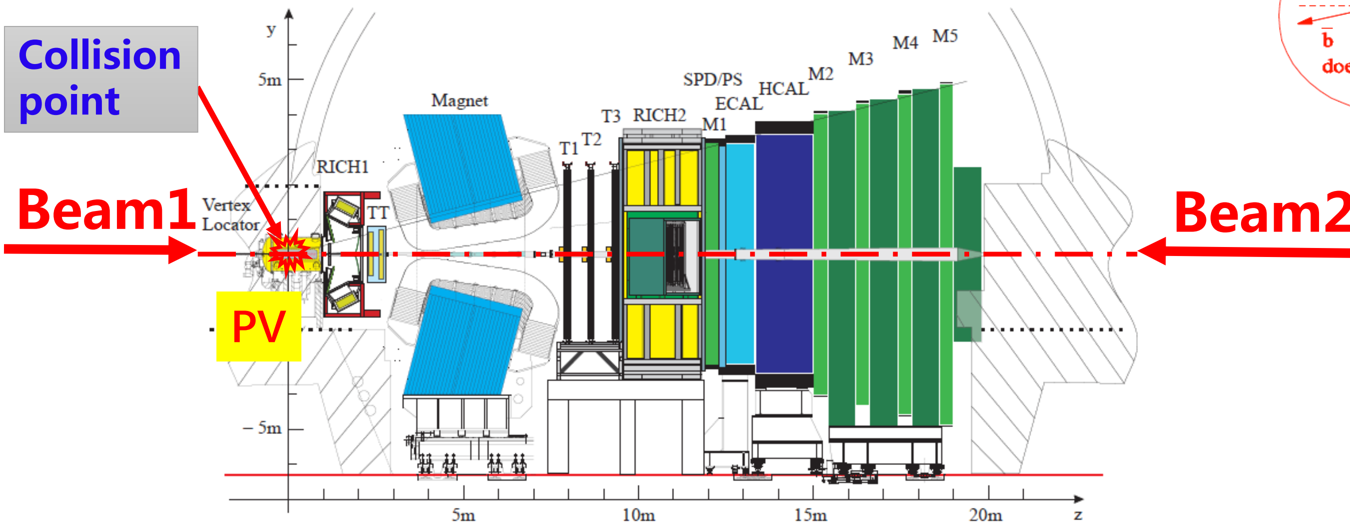
an example: LHC as a Large Hadron Discovery Factory

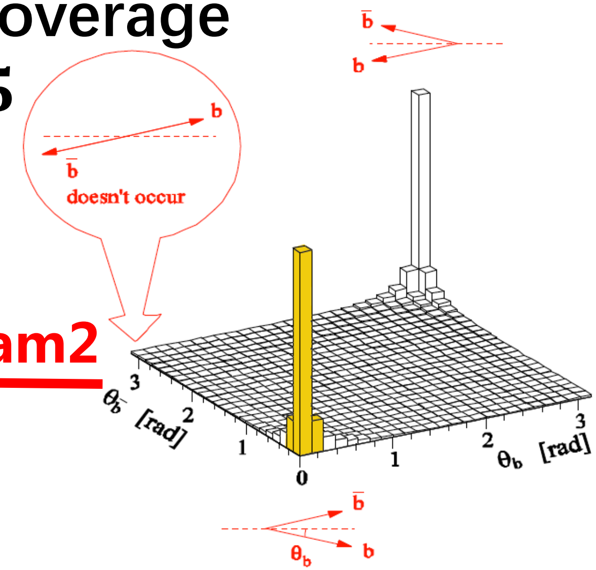


The LHCb detector and physics

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30 (2015) 1530022

Pseudorapidity coverage
$2 < \eta < 5$





Excellent vertex and IP, decay time resolution:

- $\sigma(\text{IP}) \approx 20$ μm for high-p_T tracks
- $\sigma(\tau) \approx 45$ fs for $B_s^0 \to J/\psi\phi$ and $B_s^0 \to D_s^-\pi^+$ decays

Very good momentum resolution:

- $\delta p/p \approx 0.5\% - 1\%$ for $p \in (0,200)$ GeV
- $\sigma(m_B) \approx 24$ MeV for two-body decays

Hadron and Muon identification

- $\epsilon_{K\to K} \approx 95\%$ for $\epsilon_{\pi\to K} \approx 5\%$ up to 100 GeV
- $\epsilon_{\mu\to\mu} \approx 97\%$ for $\epsilon_{\pi\to\mu} \approx 1-3\%$

Data good for analyses

- $> 99\%$

Designed for CP violation and heavy flavor studies

X(3872) before LHC

$\chi_{c1}(3872)$: B factory era

X(3872) $I^G(J^P) = ?^?(?^?)$ **PDG2004**

OMITTED FROM SUMMARY TABLE

Seen by CHOI 03 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state, but not seen in the $\gamma\chi_{c1}$ final state of these decays. Possibly absent in the invariant mass spectrum of the final state $\pi^+\pi^- J/\psi(1S)$ in e^+e^- collisions. Interpretation as a 1^{--} charmonium state not favored.

Quantum numbers are not established.

X(3872) MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3872.0±0.6±0.5	36	CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

X(3872) WIDTH

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
<2.3	90	36	CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

X(3872) DECAY MODES

	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	
Γ_2	$\pi^+\pi^- J/\psi(1S)$	seen
Γ_3	$\gamma\chi_{c1}$	

X(3872) $I^G(J^{PC}) = 0^?(?^{?+})$ **PDG2012**

Seen by CHOI 03 in $B \to K\pi^+\pi^- J/\psi(1S)$ decays as a narrow peak in the invariant mass distribution of the $\pi^+\pi^- J/\psi(1S)$ final state, but not seen in the $\gamma\chi_{c1}$ final state of these decays. Possibly absent in the invariant mass spectrum of the final state $\pi^+\pi^- J/\psi(1S)$ in e^+e^- collisions. Interpretation as a 1^{--} charmonium state not favored. Isovector hypothesis excluded by AUBERT 05B and CHOI 11. A helicity amplitude analysis of the $X(3872) \to J/\psi\pi^+\pi^-$ decay gives two possible J^{PC} assignments: $J^{PC} = 1^{++}$ and 2^{-+} (ABULENCIA 07E and CHOI 11). A study of the 3π invariant mass distribution in $J/\psi\omega$ decays slightly favors $J^P = 2^-$ (DEL-AMO-SANCHEZ 10B).

See our note on "Developments in Heavy Quarkonium Spectroscopy".

X(3872) MASS FROM $J/\psi X$ MODE

LHCb measured its mass using 2010 data ($34.7\ \mathrm{pb}^{-1}$)

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3871.68± 0.17 OUR AVERAGE					
3871.95± 0.48±0.12	0.6k	AAIJ	12H	LHCB	$pp \to J/\psi\pi^+\pi^- X$
3871.85± 0.27±0.19	~ 170	[1] CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27 ± 8	[2] DEL-AMO-SA.	10B	BABR	$B \to \omega J/\psi K$
3871.61± 0.16±0.19	6k	[2,3] AALTONEN	09AU	CDF2	$p\bar{p} \to J/\psi\pi^+\pi^- X$
3871.4 ± 0.6 ±0.1	93.4	AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
3868.7 ± 1.5 ±0.4	9.4	AUBERT	08Y	BABR	$B^0 \to K^0_S J/\psi\pi^+\pi^-$
3871.8 ± 3.1 ±3.0	522	[2,4] ABAZOV	04F	D0	$p\bar{p} \to J/\psi\pi^+\pi^- X$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3868.6					
3871.3					
3873.4					
3871.3					
3872.0					
3836					

Mass: close to the $\bar{D}^{*0}D^0$ threshold
Width: narrow
C parity: +
Isospin: 0

X(3872) during LHC Era

Produced in b-hadron decays: B, Bs, Λ_b, … and prompt production in $e^+e^-/pp/p\bar{p}$ and heavy ion collision;

PDG2022

$\chi_{c1}(3872)$ $\quad I^G(J^{PC}) = 0^+(1^{++})$

also known as $X(3872)$

This state shows properties different from a conventional $q\bar{q}$ state. A candidate for an exotic structure. See the review on non-$q\bar{q}$ states.

$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE

Mass resolution: $0.06\ \mathrm{MeV}/c^2$

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
3871.65 ± 0.06 OUR AVERAGE					
3871.64 ± 0.06 ±0.01	19.8k	[1] AAIJ	20S	LHCB	$B^+ \to J/\psi\pi^+\pi^-K^+$
3871.9 ± 0.7 ±0.2	20	ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
3871.95 ± 0.48 ±0.12	0.6k	AAIJ	12H	LHCB	$pp \to J/\psi\pi^+\pi^- X$
3871.85 ± 0.27 ±0.19	170	[2] CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
3873 $^{+1.8}_{-1.6}$ ±1.3	27	[3] DEL-AMO-SA...	10B	BABR	$B \to \omega J/\psi K$
3871.61 ± 0.16 ±0.19	6k	[3,4] AALTONEN	09AU	CDF2	$p\bar{p} \to J/\psi\pi^+\pi^- X$
3871.4 ± 0.6 ±0.1	93.4	AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$

$\chi_{c1}(3872)$ WIDTH

Width: $1.19 \pm 0.21\ \mathrm{MeV}/c^2$

VALUE (MeV)	CL%	EVTS	DOCUMENT ID		TECN	COMMENT
1.19±0.21 OUR AVERAGE			Error includes scale factor of 1.1.			
1.39±0.24±0.10		15.6k	[1] AAIJ	20AD	LHCB	$pp \to J/\psi\pi^+\pi^- X$
$0.96^{+0.19}_{-0.18}$±0.21		4.2k	[2] AAIJ	20S	LHCB	$B^+ \to J/\psi\pi^+\pi^-K^+$
• • • We do not use the following data for averages, fits, limits, etc. • • •						
<2.4	90		ABLIKIM	14	BES3	$e^+e^- \to J/\psi\pi^+\pi^-\gamma$
<1.2	90		CHOI	11	BELL	$B \to K\pi^+\pi^- J/\psi$
<3.3	90		AUBERT	08Y	BABR	$B^+ \to K^+ J/\psi\pi^+\pi^-$
<4.1	90	69	AUBERT	06	BABR	$B \to K\pi^+\pi^- J/\psi$
<2.3	90	36	[3] CHOI	03	BELL	$B \to K\pi^+\pi^- J/\psi$

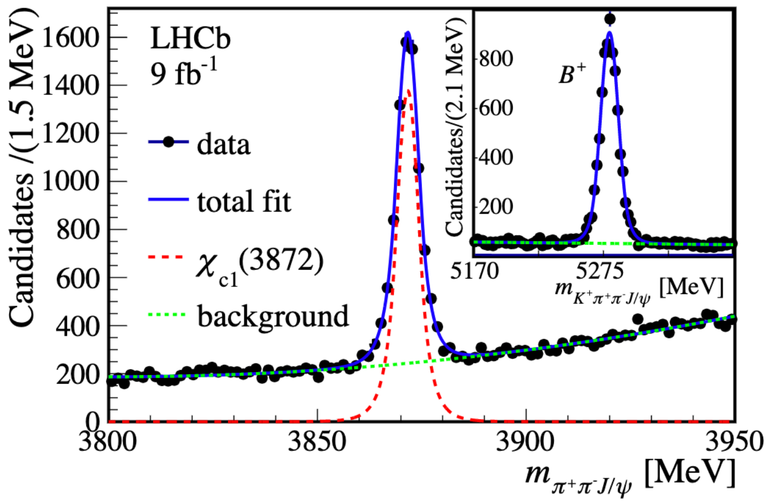
[1] Using $\chi_{c1}(3872)$ produced in inclusive b-hadron decays. Breit-Wigner parametrization.
[2] Using Breit-Wigner parametrization. Partially overlapping dataset with that of AAIJ 20AD.
[3] Superseded by CHOI 11.

- **Loosely $D^0\bar{D}^{0*}$ bound state?**
- **Mixture of $\chi_{c1}(2P)$ and $D^0\bar{D}^{0*}$?**

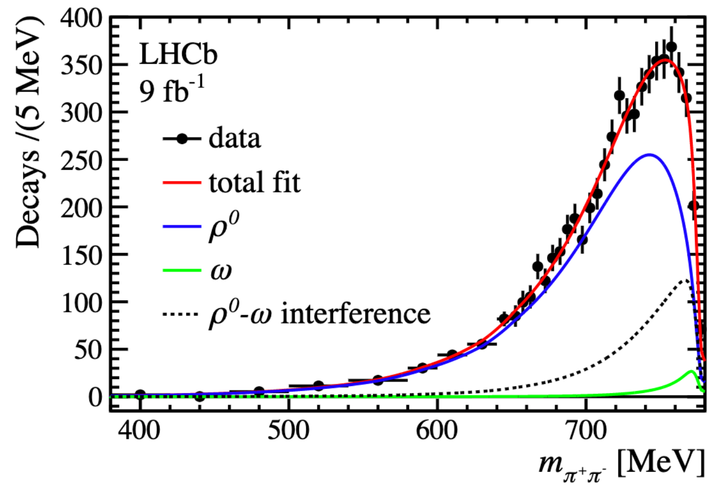
	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	$< 2.8 \times 10^{-6}$
Γ_2	$\pi^+\pi^- J/\psi(1S)$	$(3.8 \pm 1.2)\%$
Γ_3	$\pi^+\pi^-\pi^0 J/\psi(1S)$	not seen
Γ_4	$\omega\eta_c(1S)$	$< 33\%$
Γ_5	$\omega J/\psi(1S)$	$(4.3 \pm 2.1)\%$
Γ_6	$\phi\phi$	not seen
Γ_7	$D^0\bar{D}^0\pi^0$	$(49^{+18}_{-20})\%$
Γ_8	$\bar{D}^{*0}D^0$	$(37 \pm 9)\%$
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}	$\gamma\psi(2S)$	$(4.5 \pm 2.0)\%$

Observation of sizeable ω contribution in $X(3872) \to \pi^+\pi^- J/\psi$

arXiv:2204.12597

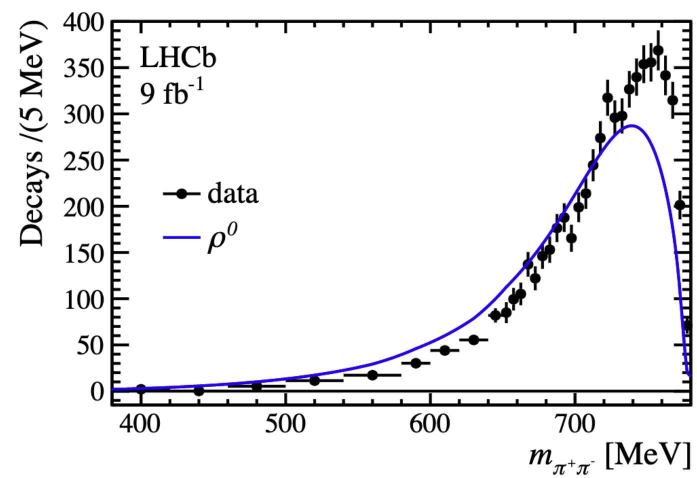


$B^+ \to K^+ X(3872)$ studied with RUN 1+2 data



$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = \sqrt{\frac{\mathcal{B}(\omega\to\pi^+\pi^-)}{\mathcal{R}^{0\,\prime}_{\omega/\rho}}} = 0.29 \pm 0.04.$$

$$\frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = \sqrt{\frac{\mathcal{B}(\psi(2S)\to\pi^0 J/\psi)}{\mathcal{B}(\psi(2S)\to\eta J/\psi)}\,\frac{p_\eta{}^3}{p_{\pi^0}{}^3}} = 0.045 \pm 0.001$$



The isospin violating ρ^0 contribution, quantified for the first time with proper subtraction of the ω contribution, is an order of magnitude too large for X(3872) to be a pure charmonium state.

Open flavor tetraquark

- The $D_{s0}^{*}(2317)^{+}$ ($D_s^+\pi^0$) state was **observed in 2003.**
- It is argued to contain some **tetraquark component** in several theoretical descriptions whose $I=1$ partners can exist in the $D_s^+\pi^\pm$ **final states.**
- *Cheng & Hou:* It would be astonishing if a doubly charged resonance is found. [PLB 566, 193 (2003)]

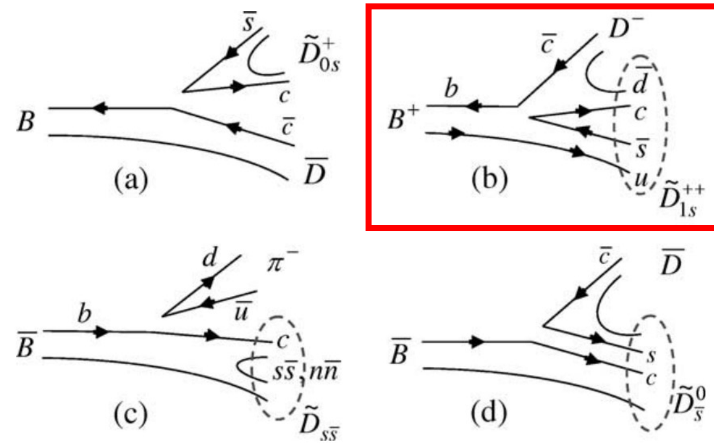
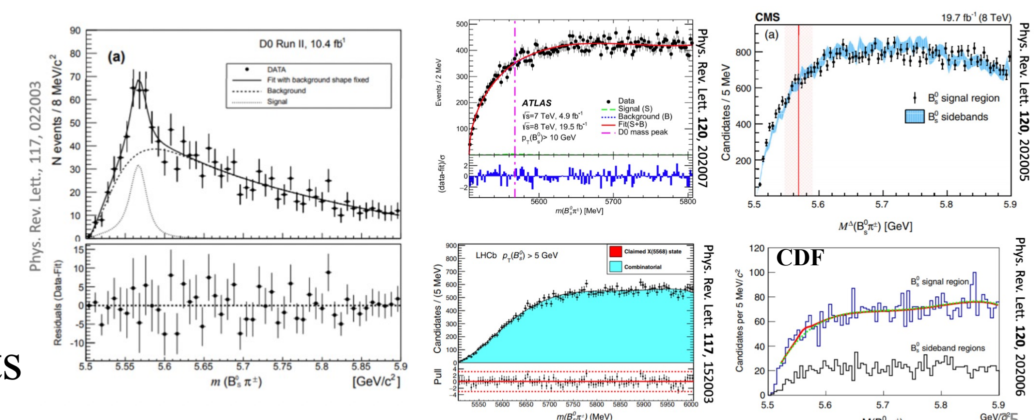


Fig. 2. Diagrams for (a) $B\to\bar{D}\tilde{D}_{0s}^{+}$, (b) $B^+\to D^-\tilde{D}_{1s}^{++}$ $(B\to\bar{D}\tilde{D}_{Is})$, (c) $\bar{B}\to\pi^-\tilde{D}_{s\bar{s}}, \pi^-\tilde{D}$, (d) $B\to\bar{D}\tilde{D}_{\bar{s}}^{0}$.

- D0 claimed evidence for the X(5568) in decaying to $B_s\pi^+$, interpreted as tetraquark state $[bs\bar{u}\bar{d}]$
- But not seen in other experiments



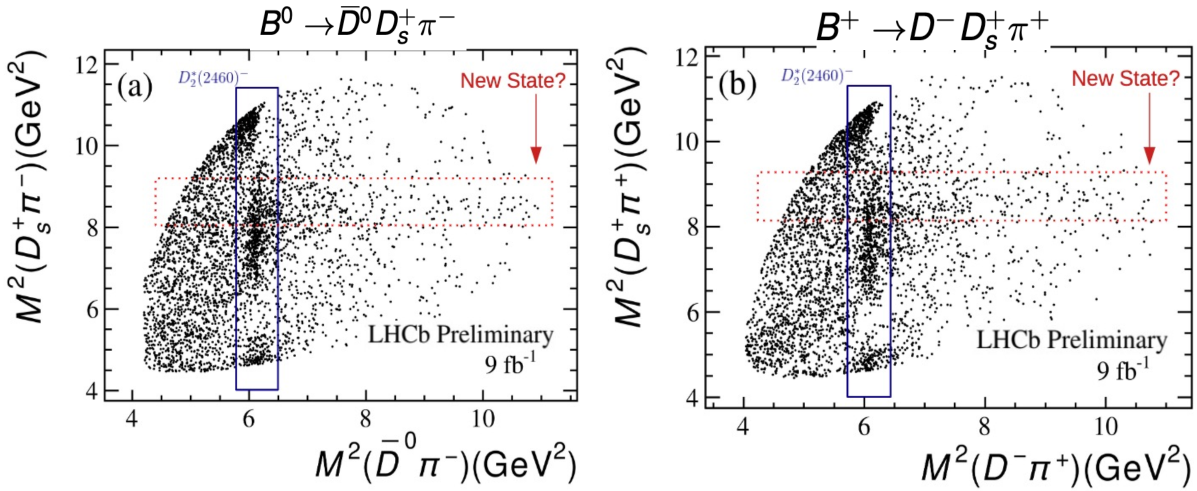
Observation of a doubly charged tetraquark $T_{c\bar{s}0}(2900)^{++}$ [$c\bar{s}u\bar{d}$] and its neutral partner $T_{c\bar{s}0}(2900)^{0}$ [$c\bar{s}\bar{u}d$]

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027

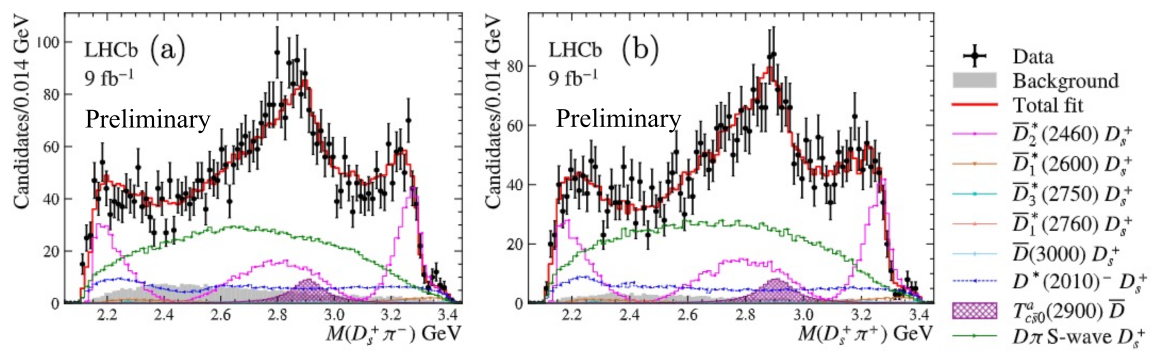
- First simultaneous amplitude analysis of $B^+ \to D^- \boldsymbol{D_s^+\pi^+}$ & $B^0 \to \bar{D}^0 \boldsymbol{D_s^+\pi^-}$ with RUN 1+2 9 fb^{-1} data

- $D_s\pi$ mass spectra well described by adding $J^P = 0^+$ (> **7.5 σ**) $T^a_{c\bar{s}0}(2900)$ > **9 σ**

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

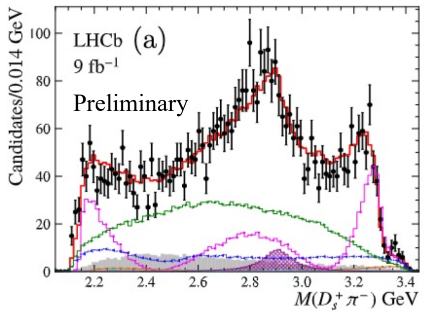


- Separate resonance fits:
  - $T^{a0}_{c\bar{s}}$: $m = 2892 \pm 14 \pm 15$ MeV, $\Gamma = 119 \pm 26 \pm 12$ MeV;
  - $T^{a++}_{c\bar{s}}$: $m = 2921 \pm 17 \pm 19$ MeV, $\Gamma = 137 \pm 32 \pm 14$ MeV

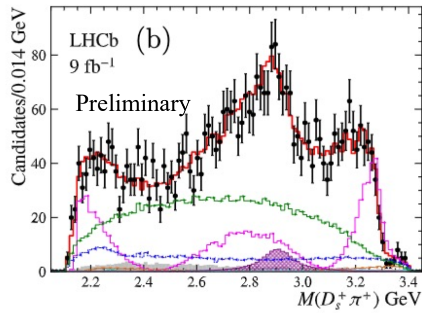


$T^{a}_{c\bar{s}0}(2900)$ and $X_{0,1}(2900)$

LHCb-PAPER-2022-026 ; LHCb-PAPER-2022-027



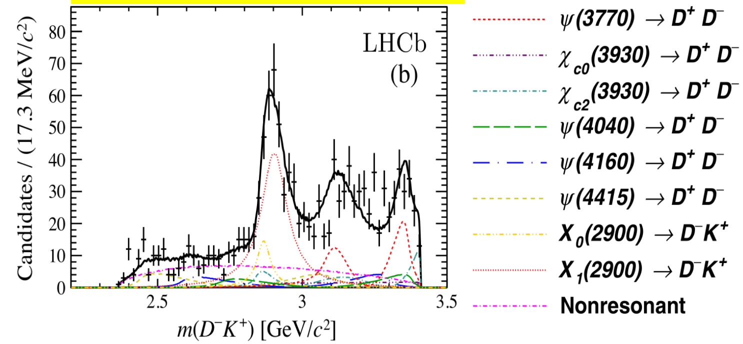
$T^{a}_{c\bar{s}0}(2900)^0[c\bar{s}\bar{u}d]$



$T^{a}_{c\bar{s}0}(2900)^{++}[c\bar{s}u\bar{d}]$

PRD 102, 112003 (2020)

$B^+ \to D^+ D^- K^+$



$X_0(2900), X_1(2900)[cs\bar{u}\bar{d}]$

	Mass (GeV)	Width (GeV)	J^P
$T^{a}_{c\bar{s}0}(2900)^0$ & $T^{a}_{c\bar{s}0}(2900)^{++}$	$2.908 \pm 0.011 \pm 0.020$	$0.136 \pm 0.023 \pm 0.020$	0^+
$X_0(2900)/T_{cs0}(2900)$	$2.866 \pm 0.007 \pm 0.002$	$0.057 \pm 0.012 \pm 0.004$	0^+
$X_1(2900)/T_{cs1}(2900)$	$2.904 \pm 0.005 \pm 0.001$	$0.110 \pm 0.011 \pm 0.004$	1^-

- **$T^{a}_{c\bar{s}0}(2900)$ v.s. $X_0(2900)$**
  - ✓ Similar mass, but width and flavor contents are different.
  - ✓ $T^{a}_{c\bar{s}1}(2900)$?
  - ✓ $T^{a}_{c\bar{s}0}(2900)^{++} \to D^+K^+$?
  - ✓ $T^{a}_{c\bar{s}0}(2900)^{+} \to D_s^+\pi^0, D_s^+\pi^+\pi^-$?

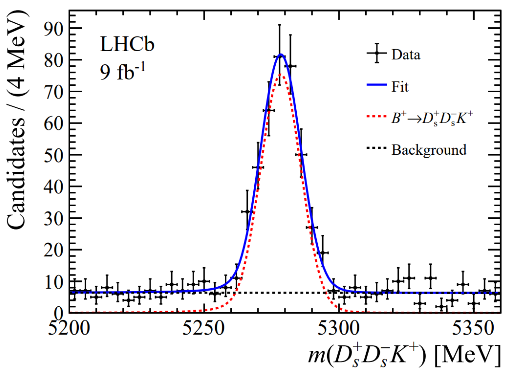
- **no isospin relation: $[c\bar{s}u\bar{d}]$ v.s. $[cs\bar{u}\bar{d}]$**
- **U-spin relation: $[c\bar{s}\bar{u}d]$ v.s. $[c\bar{d}\bar{u}s]$**
- $T^{a}_{c\bar{s}0}(2900)$ mass and width larger than $T_{cs0}(2900)$

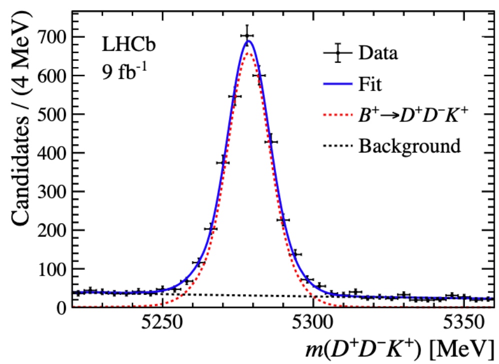
Study on $B^+ \to D_s^+ D_s^- K^+$

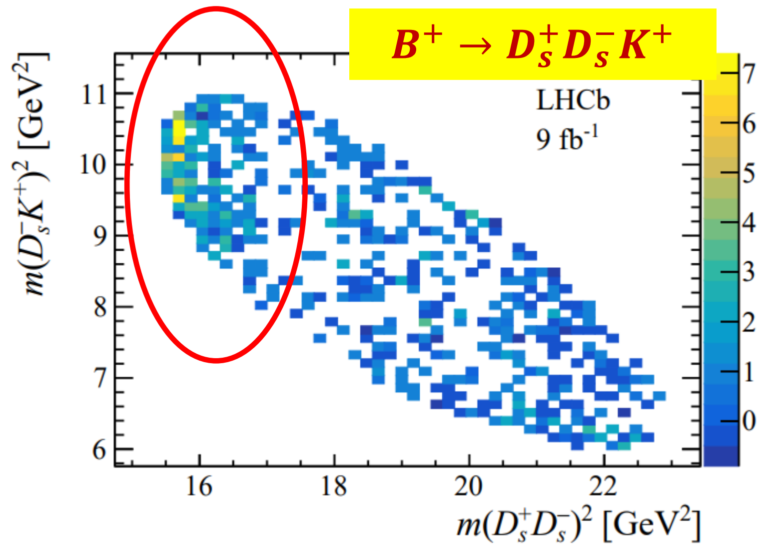
arXiv:2211.05034
arXiv:2210.15153

- Relative measurement of branching fractions :

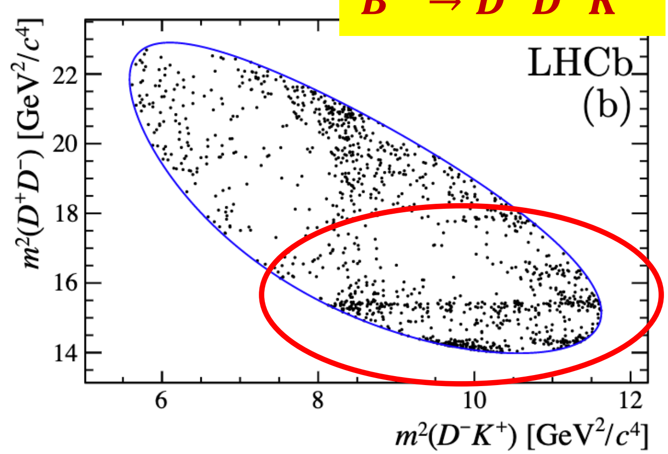
$$\frac{\mathcal{B}(B^+ \to D_s^+ D_s^- K^+)}{\mathcal{B}(B^+ \to D^+ D^- K^+)} = 0.525 \pm 0.033 \pm 0.027 \pm 0.034$$







- $D_s^+ D_s^-$ near-threshold enhancement is seen
- Similar to the $\chi_{c0,2}(3930)$ observed in $B^+ \to D^+ D^- K^+$?



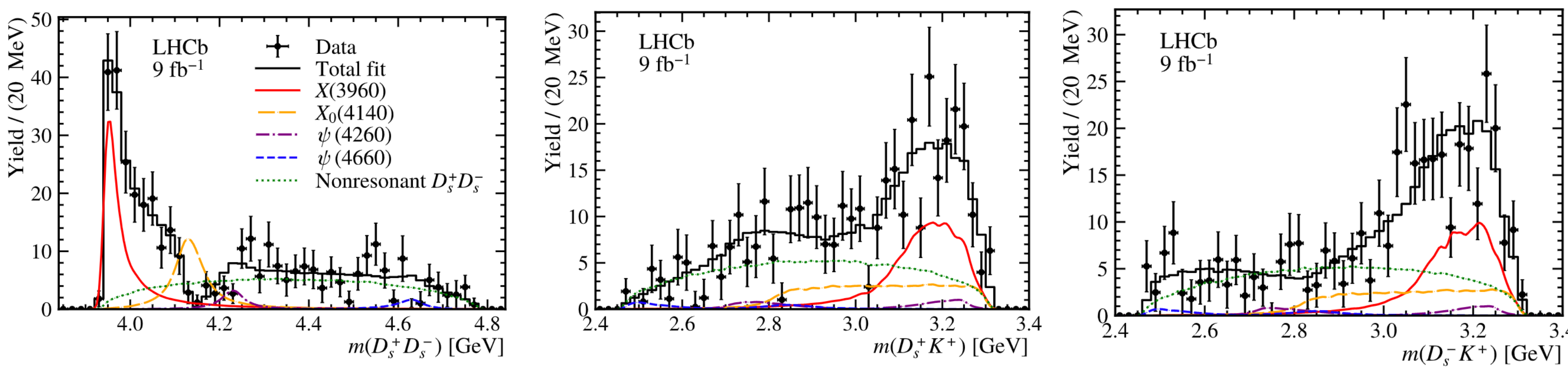
PRL125, 242001 (2020)

Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

New $[c\bar{c}s\bar{s}]$ state in $D_s^+ D_s^-$

arXiv:2211.05034
arXiv:2210.15153

- Near threshold structure $X(3960)$: **12σ**, $J^P = 0^{++}$
- $X_0(4140)$ accounts for the dip around 4.14 GeV



Components	J^{PC}	Mass (MeV)	Width (MeV)	Fit fraction (%)	Significance (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 (fixed)	55 (fixed)	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 (fixed)	64 (fixed)	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	S-wave	–	–	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

dip at 4.14 GeV via interference

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

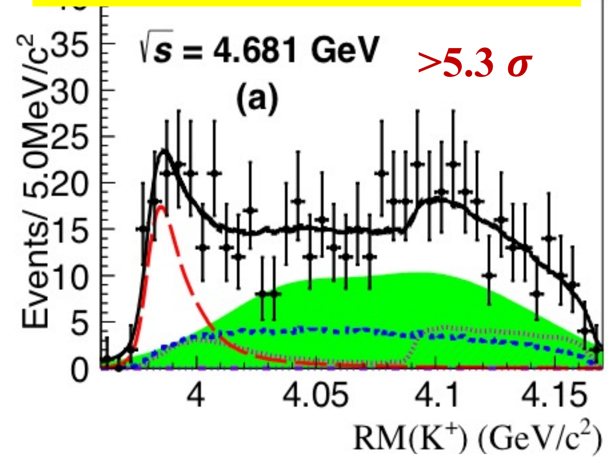
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$

If $X(3960)$ and $\chi_{c0}(3930)$ the same particle, the ratio (<1) indicates intrinsic $[s\bar{s}]$ components. Hence, they could be exotic $[c\bar{c}s\bar{s}]$ tetraquark state.

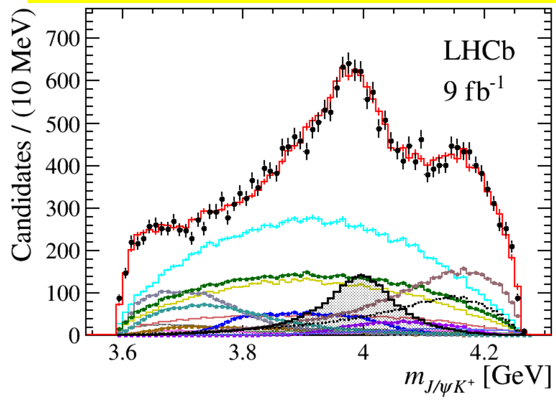
Zcs $[c\bar{c}u\bar{s}]$ states

- Charged Zcs states are observed at BESIII and LHCb: $Z_{cs}(3985)$, $Z_{cs}(4000)$, $Z_{cs}(4220)$
- It is natural to search for the neutral isospin partners

BESIII, PRL 126, 102001 (2021)

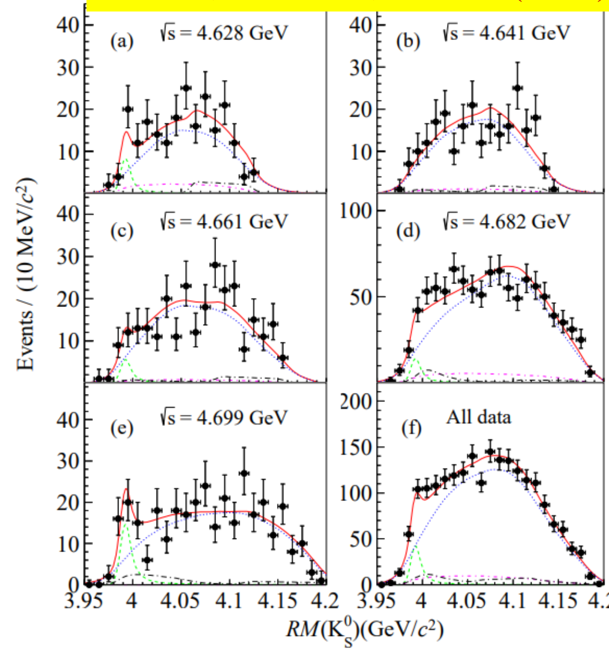


LHCb, PRL127, 082001 (2021)



$e^+e^- \to K_S^0(D_s^- D^{*+} + D_s^{*-} D^+)$

BESIII, PRL 129 , 112003 (2022)



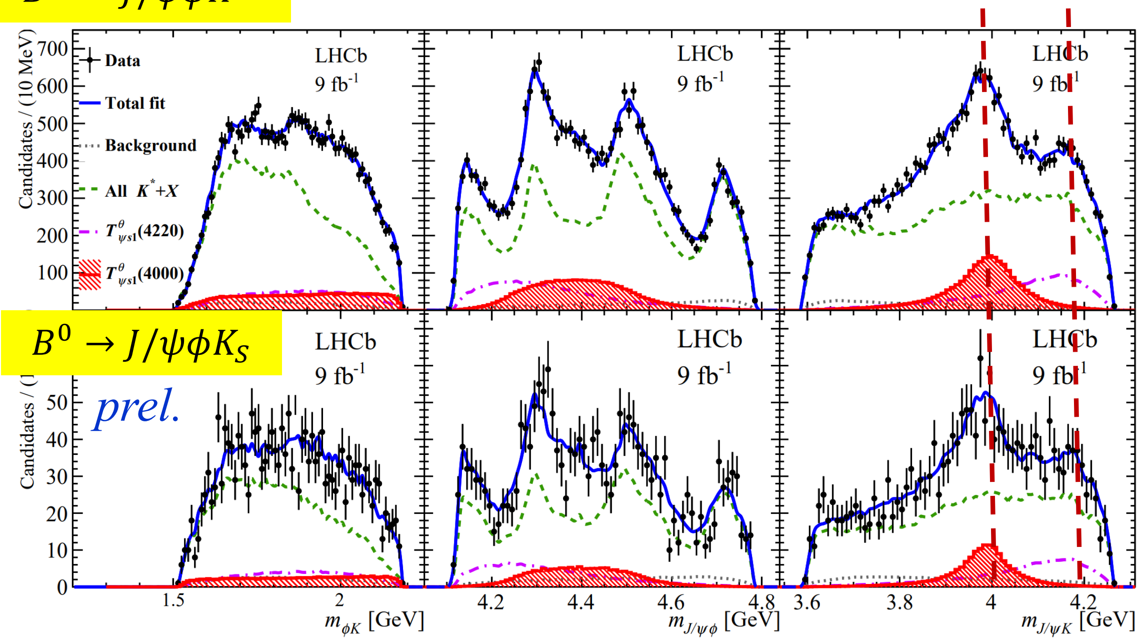
All $Z_{cs}(1^+)$				$25 \pm 5^{+11}_{-12}$
$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

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

$T^{\theta}_{\psi s1}(4000)^0$ in $B^0 \to J/\psi\phi K^0_S$

LHCb−PAPER−2022−040

preliminary results



simultaneous fits to $B^0 \to J/\psi\phi K_S$ and $B^+ \to J/\psi\phi K^+$, assuming isospin symmetry for all the intermediate states, except for the charged and neutral $T^{\theta}_{\psi s1}(4000)$ states.

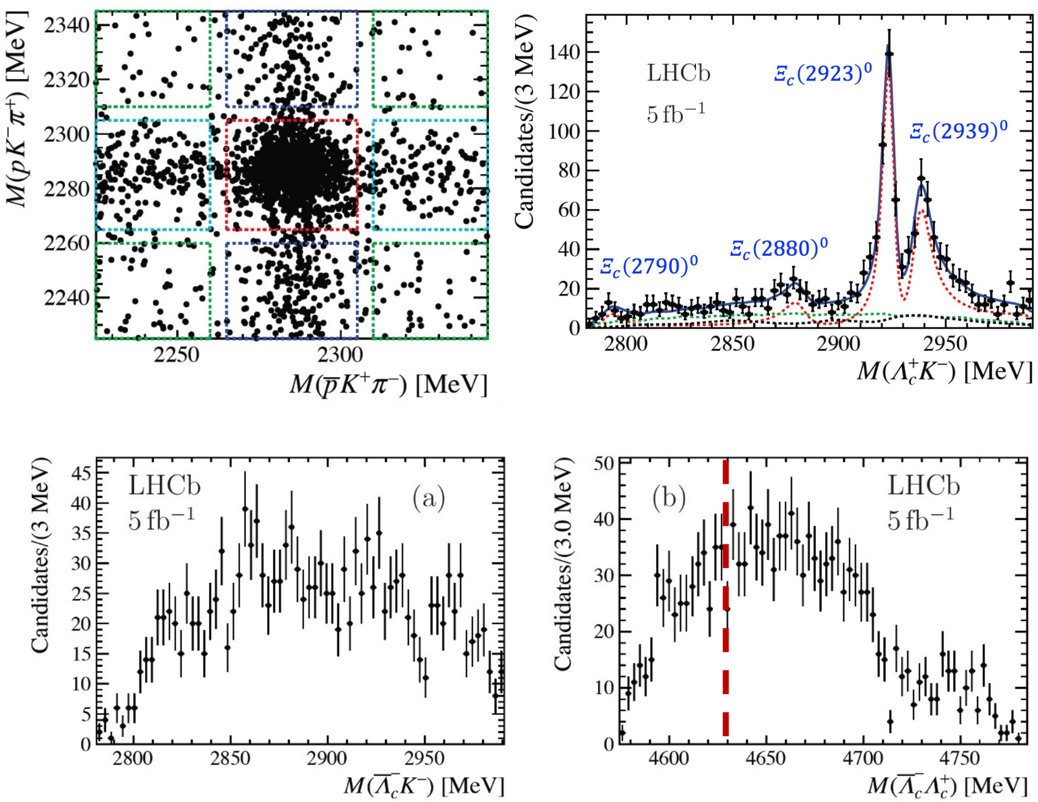
- Consistent with being isospin partners: $\Delta m = -12.1^{+11.1+6.0}_{-10.2-4.2}$ MeV/c^2
- Significance is. 4.0σ without isospin symmetry for $T^{\theta}_{\psi s1}(4000)$, while 5.4$\sigma$ with isospin symmetry constrains

	J^P	Mass (MeV/c^2)	Width (MeV)	Fit fraction
prel. $T^{\theta}_{\psi s1}(4000)^0 \to J/\psi K^0_S$	1^+	$3991.3^{+11.7+8.5}_{-10.4-16.7}$	$104.8^{+29.3+17.1}_{-25.3-23.3}$	$7.9 \pm 2.5^{+3.0}_{-2.8}$
Z^+_{cs} /$T^{\theta}_{\psi s1}(4000)^+ \to J/\psi K^+$	1^+	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$

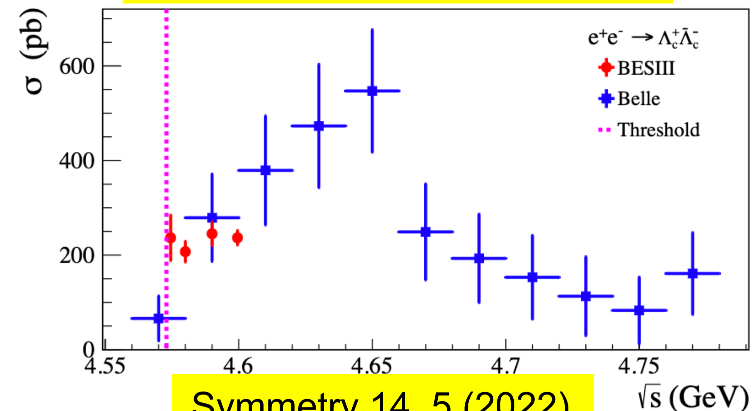
Search for exotics in $B^- \to \Lambda_c^+ \bar{\Lambda}_c^- K^-$

arXiv:2211.00812

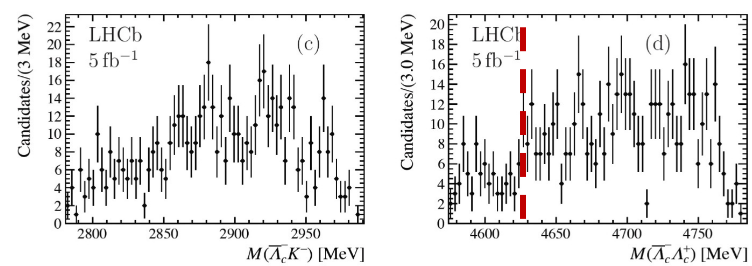
- $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\Lambda_c^- K^-$ systems are good places to search for exotics
- Near threshold enhancment of $Y(4630) \to \Lambda_c^+ \bar{\Lambda}_c^-$ is observed at Belle. However, the Breit-Wigner line shape is not supported by BESIII



Belle: PRL101, 172001 (2008)
BESIII: PRL120,132001(2018)



Symmetry 14, 5 (2022)



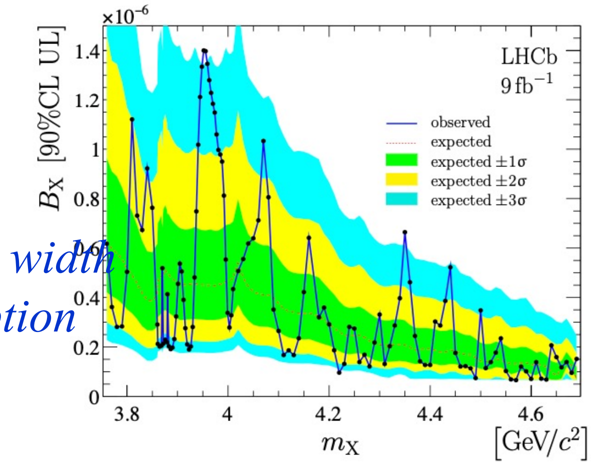
vetoing 2.90 GeV $< M(\Lambda_c^+ K^-) <$ 2.97 GeV

No obvious structures are seen in $\Lambda_c^+ \bar{\Lambda}_c^-$ and $\Lambda_c^- K^-$ systems

Charmonium(-like) states in $B^+ \to K^+ \eta J/\psi$

JHEP 22, 046 (2022)

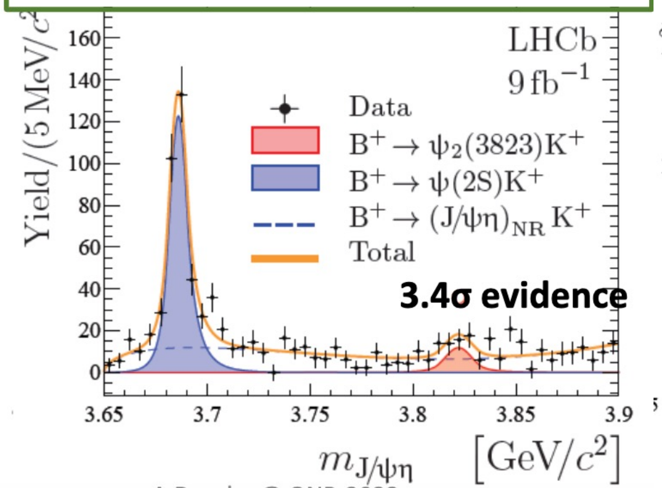
- With RUN 1+2 LHCb data, evidence is found for $\psi_2(3823) \to \eta J/\psi$ and $\psi(4040) \to \eta J/\psi$
- Searches for the known XYZ states and provides UL on BF in $B^+ \to K^+ X$

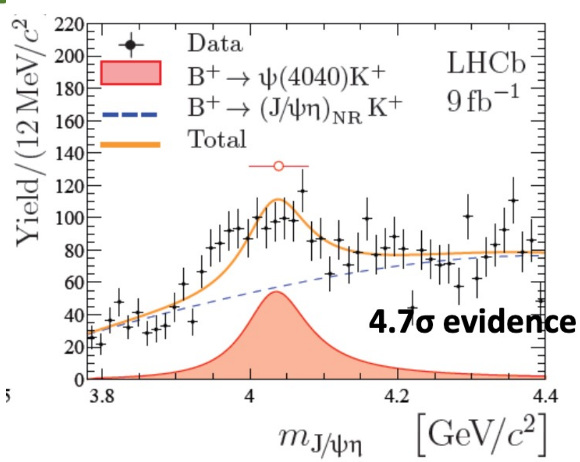


narrow width assumption

$$F_X \equiv \frac{\mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)}{\mathcal{B}(B^+ \to \psi(2S)K^+) \times \mathcal{B}(\psi(2S) \to J/\psi\eta)},$$

$$B_X \equiv \mathcal{B}(B^+ \to XK^+) \times \mathcal{B}(X \to J/\psi\eta)$$



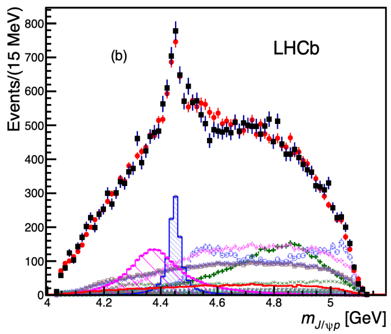


	Upper limit at 90% CL	
	F_X [10^{-2}]	B_X [10^{-7}]
ψ(3770)	2.2	4.6
$\psi_3(3842)$	2.9	6.1
ψ(4160)	4.2	8.7
ψ(4415)	4.6	9.6
R(3760)	2.0	4.1
R(3790)	3.2	6.7
$Z_c(3900)^0$	2.1	4.3
ψ(4230)	1.9	3.9
ψ(4360)	6.0	12.4
ψ(4390)	11.6	24.1
$Z_c(4430)^0$	6.1	12.7
X_C'	1.9	3.9

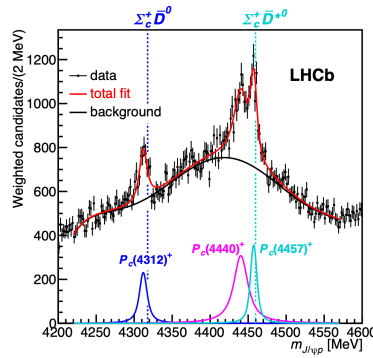
$$F_{\psi_2(3823)} = (5.95\,^{+3.38}_{-2.55}) \times 10^{-2}, \quad B_{\psi_2(3823)} = (1.25\,^{+0.71}_{-0.53} \pm 0.04) \times 10^{-6},$$
$$F_{\psi(4040)} = (40.6 \pm 11.2) \times 10^{-2}. \quad B_{\psi(4040)} = (8.53 \pm 2.35 \pm 0.30) \times 10^{-6}$$

Pentaquark states at LHCb

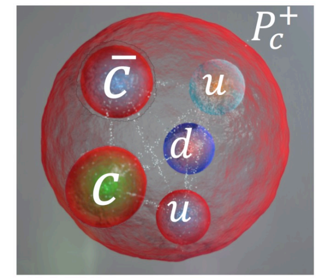
- **Observation of $[c\bar{c}uud]$ pentaquarks:** $P_\psi^N(4312)^+$, $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$ in $\Lambda_b^0 \to J/\psi p K^-$ decays; near thresholds of $\Sigma_c^+\overline{D}^0$, $\Sigma_c^+\overline{D}^{*0}$, J^P not determined



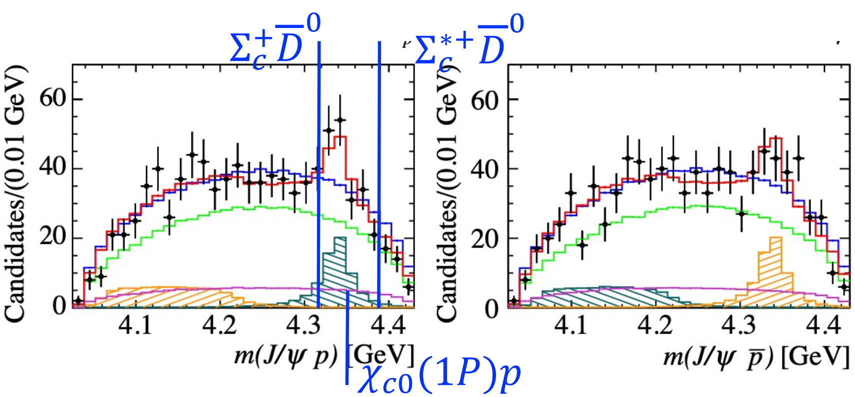
PRL115, 072001(2015)



PRL122, 222001(2019)

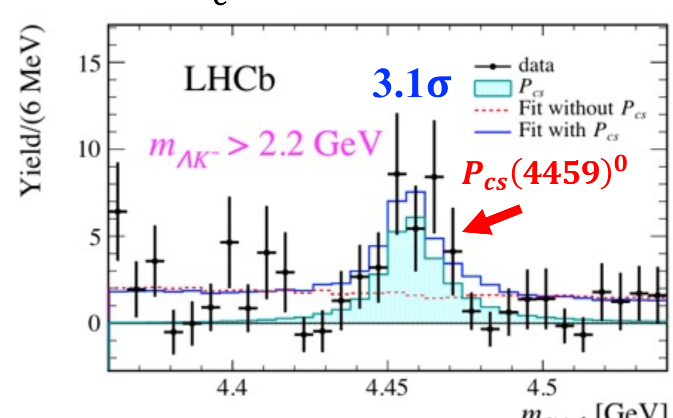


- **Evidence of $[c\bar{c}uud]$ pentaquark:** $P_\psi^N(4337)^+$ in $B_s^0 \to J/\psi p\bar{p}$ decays



PRL128, 062001(2022)

- **Evidence for $[c\bar{c}uds]$ pentaquark candidate with strangeness:** $P_{\psi s}^{\Lambda}(4459)^0$ in $\Xi_b^- \to J/\psi \Lambda K^-$ decays, near threshold of $\Xi_c^0\overline{D}^{*0}$



Sci.Bull.66, 1278(2021)

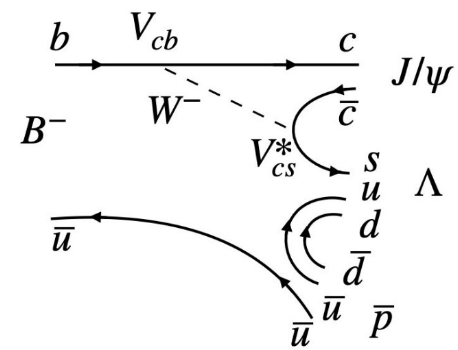
Observation of the hidden-charm strange pentaquark [$c\bar{c}uds$]

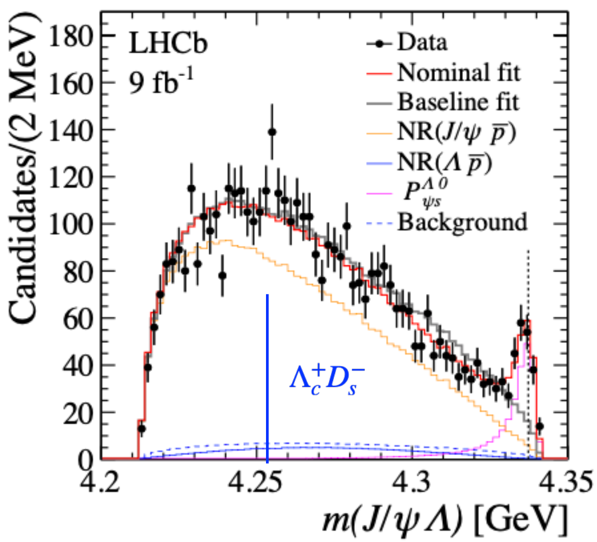
arXiv:2210.10346

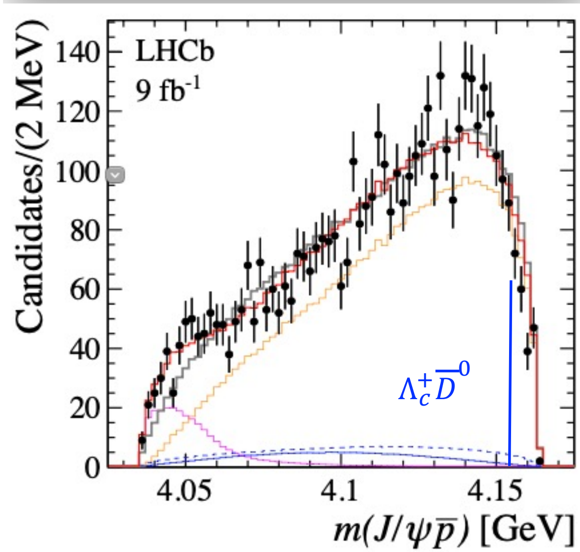
- narrow structure in $J/\psi\Lambda$ in $B^- \to J/\psi\Lambda\bar{p}$, with 9 fb^{-1} LHCb data
- amplitude analysis is performed
- $P^{\Lambda}_{\psi s}(4338)^0 \to J/\psi\Lambda$ observed with significance larger than 10σ
- $J^P = \frac{1}{2}^-$ preferred and close to $\Xi_c^+ D^-$ threshold
  -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

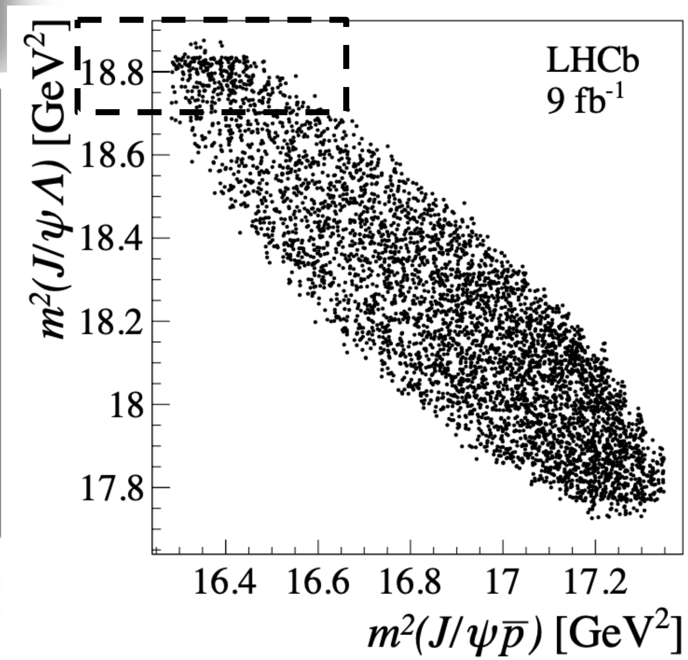
$M_{P_{cs}} = 4338.2 \pm 0.7 \pm 0.4$ MeV

$\Gamma_{P_{cs}} = 7.0 \pm 1.2 \pm 1.3$ MeV









no evidence for $P^{\Lambda}_{\psi s}(4255)^0$ and $P^{N}_{\psi}(4152)^+$

Summary

- 3 tetraquark states and 1 pentaquark state observed at LHCb in 2022
  - $T^{a}_{c\bar{s}0}(2900)^{0,++}$ $[c\bar{s}u\bar{d}]$ in $B \to DD_s\pi$
    - first doubly charged tetraquark candidate
  - $X(3960)$ $[c\bar{c}s\bar{s}]$ in $B^+ \to D_s^+ D_s^- K^+$
  - $T^{\theta}_{\psi s1}(4000)^0$ $[c\bar{c}d\bar{s}]$ in $B^0 \to J/\psi\phi K_S^0$
    - isospin partner of $Z_{cs}(4000)$
  - Observation of new pentaquark state $P^{\Lambda}_{\psi s}(4338)$ $[c\bar{c}uds]$
    - first open-strange pentaquark candidate
- Observation of $\chi_{c1}(3872) \to \omega J/\psi$ in $\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$
- More data in Run 3 are desired for further improvement on understanding their natures

Thank you!

谢谢！

Exotic hadron naming convention

LHCb-PUB-2022-013, arXiv:2206.15233

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(3872)$
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(3900)^+$
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\psi 1}(4430)^+$
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+$, $J^{PC} = 1^{++}$	$\chi_{c1}(4140)$
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}$, $J^P = 1^+$	$T^\theta_{\psi s1}(4000)^+$
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}$, $J^P = 1^?$	$T_{\psi s1}(4220)^+$
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+$, $J^{PC} = ?^{?+}$	$T_{\psi\psi}(6900)$
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+$, $J^P = 1^+$	$T^b_{\Upsilon 1}(10610)^+$
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P^N_\psi(4312)^+$
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P^\Lambda_{\psi s}(4459)^0$

- P for pentaquarks, T for tetraquarks
- P states: i.e. $P^N_\psi(4312)^+$, $P^\Lambda_{\psi s}(4459)^0$

  Superscript: denotes isospin: Λ,N,Σ,Δ for I= 0,1/2,1,3/2

  Subscript: Υ,ψ,ϕ for hidden beauty, charm, strangeness; b,c,s for open flavor quantum numbers