Recent studies of tetraquark states at LHCb

The 23rd International Conference on Few-Body Problems in Physics
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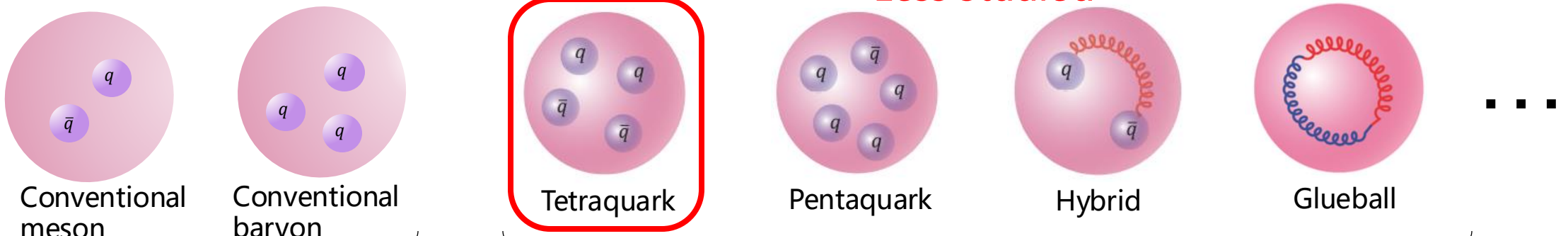
Zhihong Shen
Peking University
On behalf of the LHCb collaboration

Exotic hadrons

- Hadrons

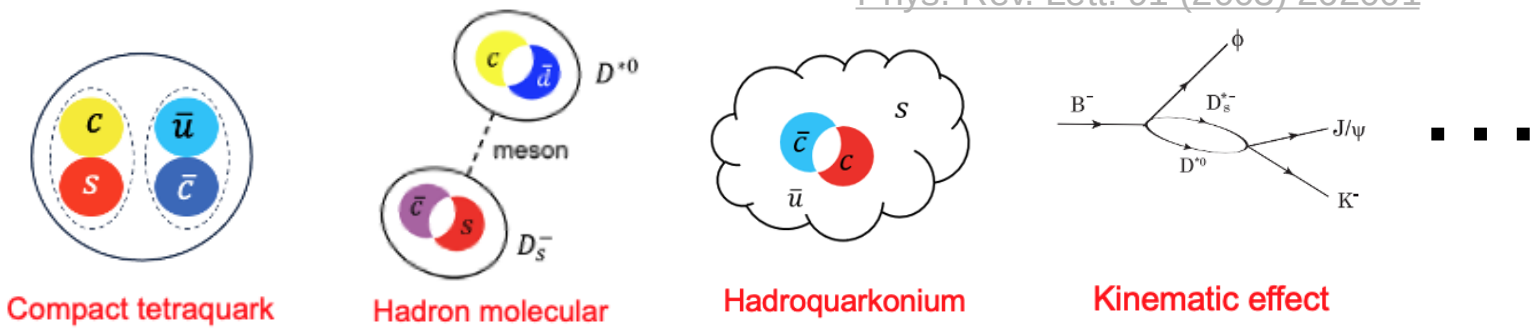
More complex inner structure
Less studied



- Since discovery of $\chi_{c1}(3872)$ aka $X(3872)$ in 2003, dozens of more exotic candidate observed

Phys. Rev. Lett. 91 (2003) 262001

- Theoretic explanations



- Exotic hadrons studies help to further understand non-perturbative QCD at low energies

The LHCb detector

- A single-arm forward spectrometer covering $2<\eta<5$
- Designed for heavy flavour physics

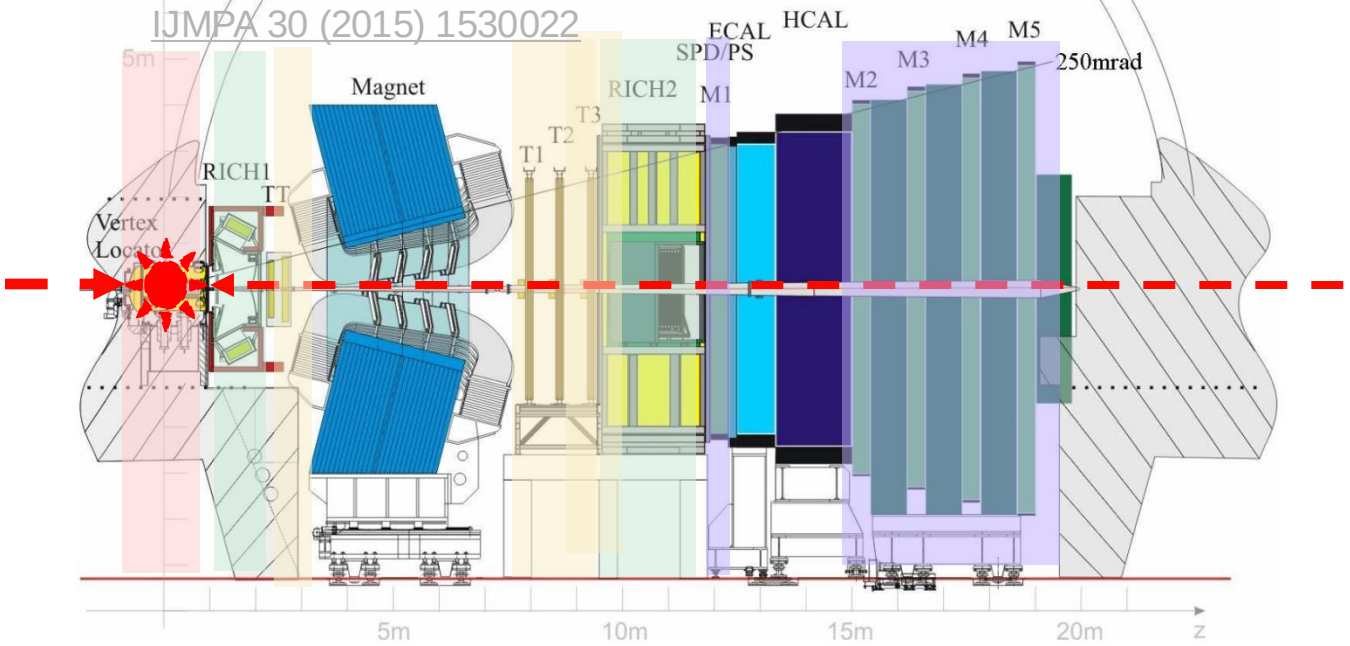
Vertex Locator
$\sigma_{\mathrm{IP}}\sim 20\ \mu\mathrm{m}$
$\sigma_{\tau}\sim 45$ fs

Tracking system
$\epsilon_{\mathrm{tracking}}\sim 96\%$
$\sigma_p/p\sim 0.5\% - 1\%\ (5 - 200\ \mathrm{GeV})$

RICHs
$\epsilon(K \to K) \sim 95\%$
mis-ID $\epsilon(\pi \to K) \sim 5\%$

Muon system
$\epsilon(\mu \to \mu) \sim 97\%$
mis-ID $\epsilon(\pi \to \mu) \sim 1 - 3\%$

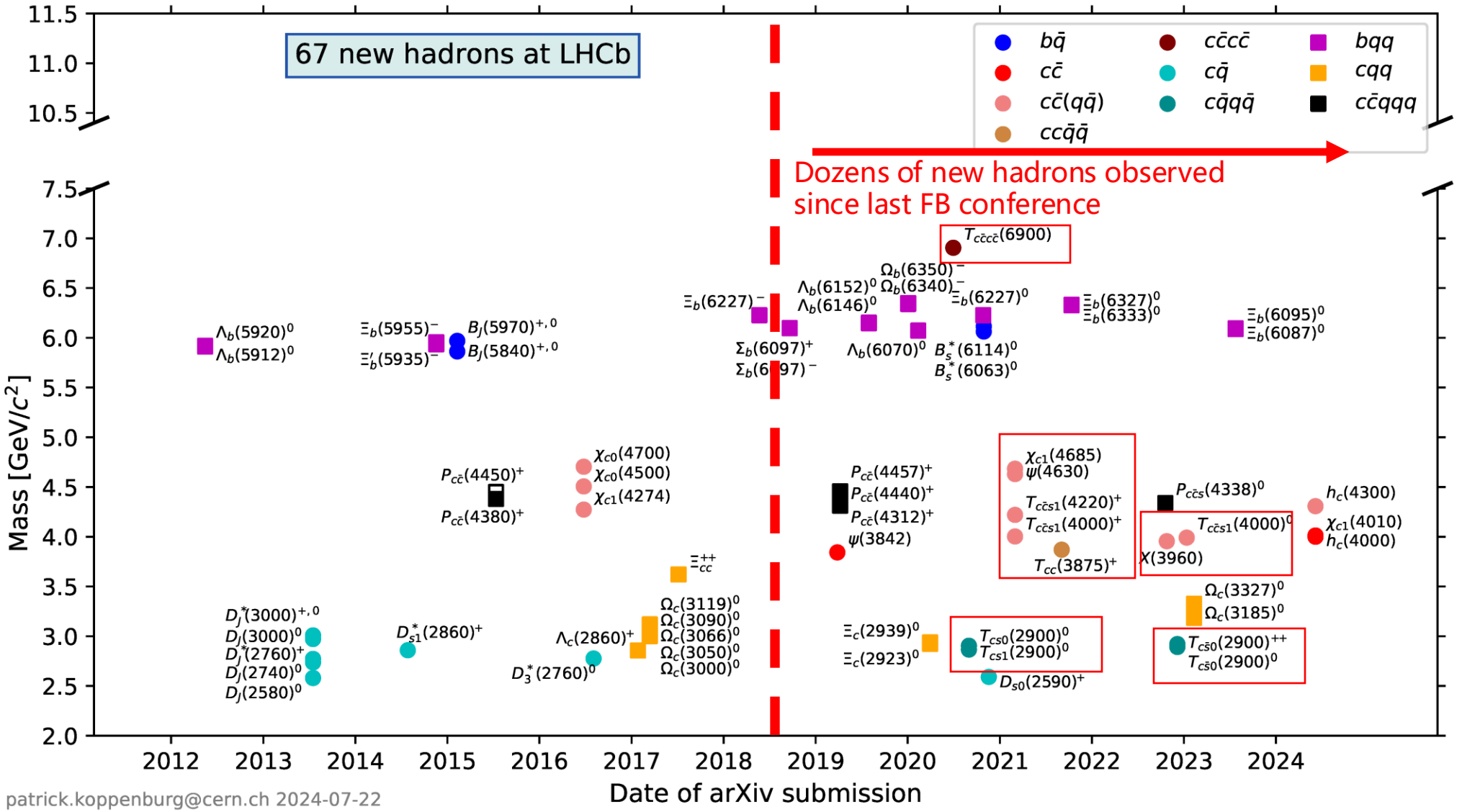
JINST 3 (2008) S08005
IJMPA 30 (2015) 1530022



LHC: heavy hadron states factory
LHCb:
- precise vertex resolution
- good momentum resolution
- powerful particle identification

Competitive in heavy hadron spectroscopy studies

New hadrons at LHCb



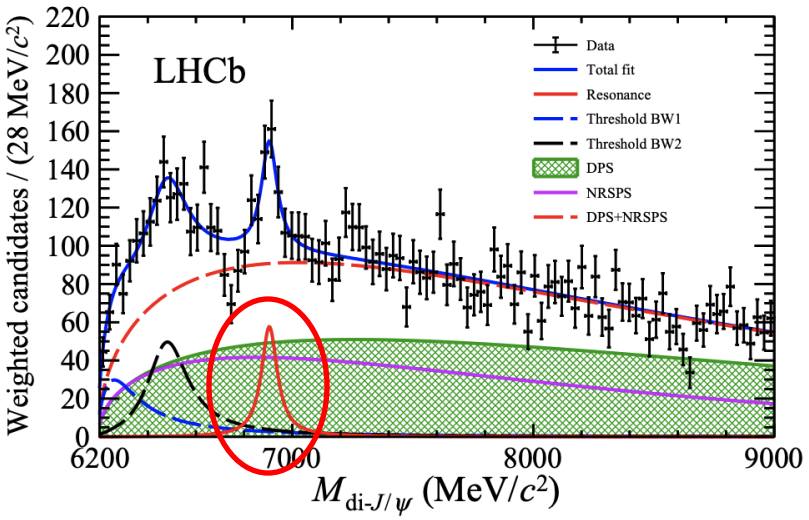
https://www.nikhef.nl/~pkoppenb/hadrons//Masses_LHCb.pdf

Results not detailed in this talk

… but important

Fully-charmed tetraquark

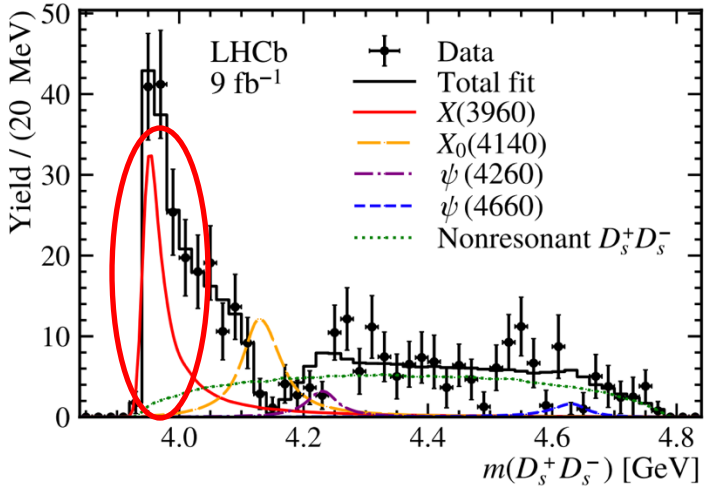
- $T_{c\bar{c}c\bar{c}}(6900)$ in J/ψ pair mass spectrum



Science Bulletin 65 (2020) 1983

Candidate for $[c\bar{c}s\bar{s}]$

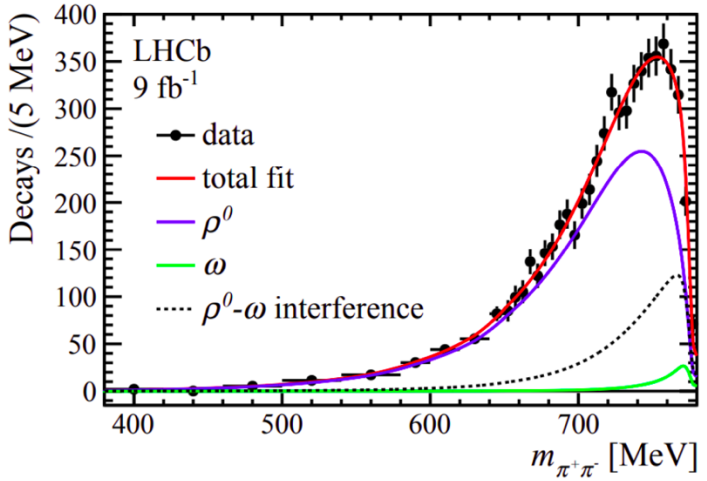
- $X(3960)$ in $B^+ \to D_s^+ D_s^- K^+$



Phys. Rev. Lett. 131, (2023) 071901

$\chi_{c1}(3872)$ properties

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



Phys. Rev. D 131 (2023) L011103

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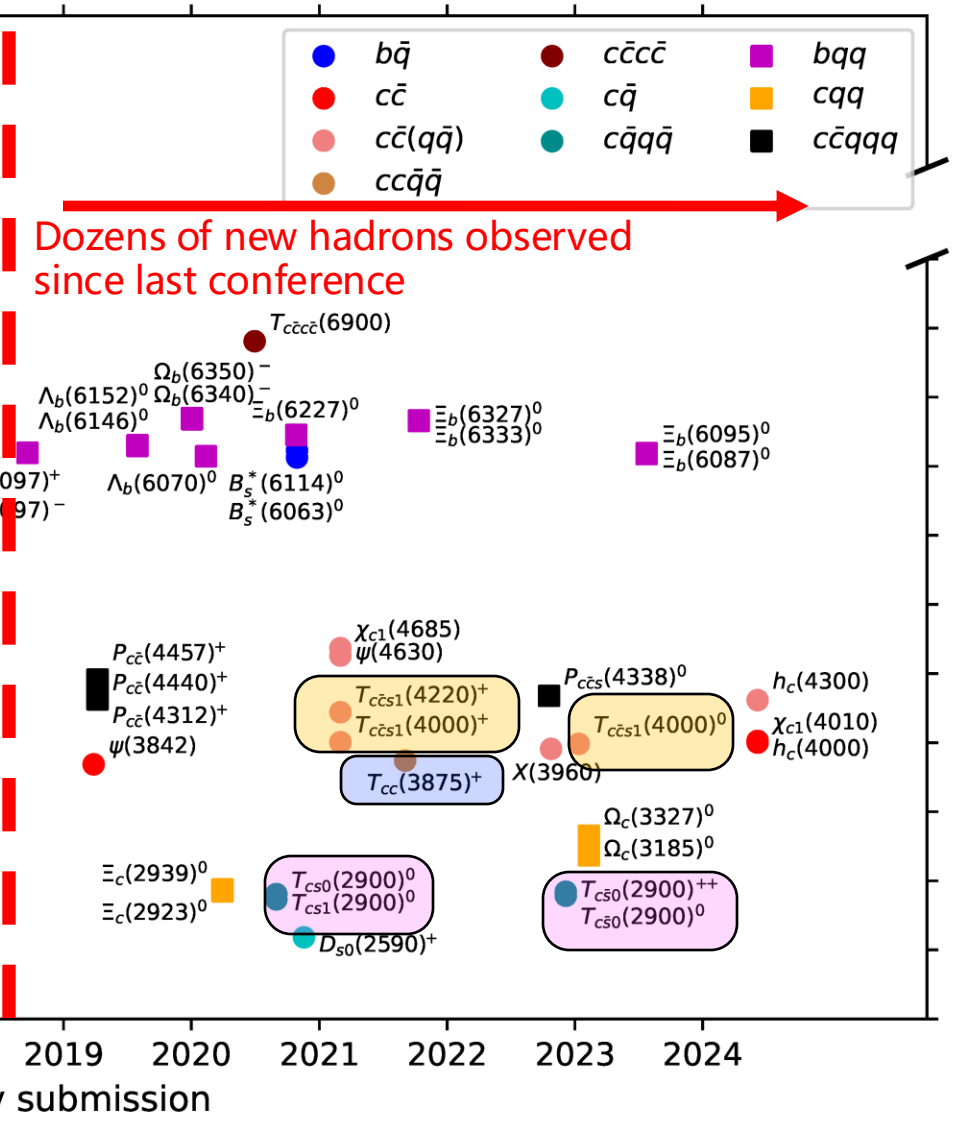
Results shown in this talk



- **Hidden exotics:**

  Minimal quark content "mimics" regular hadronic structure

  - Radiative decay of $\chi_{c1}(3872)$

- **Manifestly exotics**

  Minimal quark content shows up as explicitly exotic

  - Hidden-charm tetraquarks with strangeness
    - Charged: $T_{c\bar{c}s1}(4000)^+$ and $T_{c\bar{c}s1}(4220)^+$
    - Neutral: $T_{c\bar{c}s1}(4000)^0$
  - Doubly-charmed tetraquarks
    - $T_{cc}(3875)^+$
  - Open-charmed tetraquarks
    - $T_{cs0}(2900)^0$ and $T_{cs1}(2900)^0$
    - $T_{c\bar{s}0}(2900)^{++}$ and $T_{c\bar{s}0}(2900)^0$

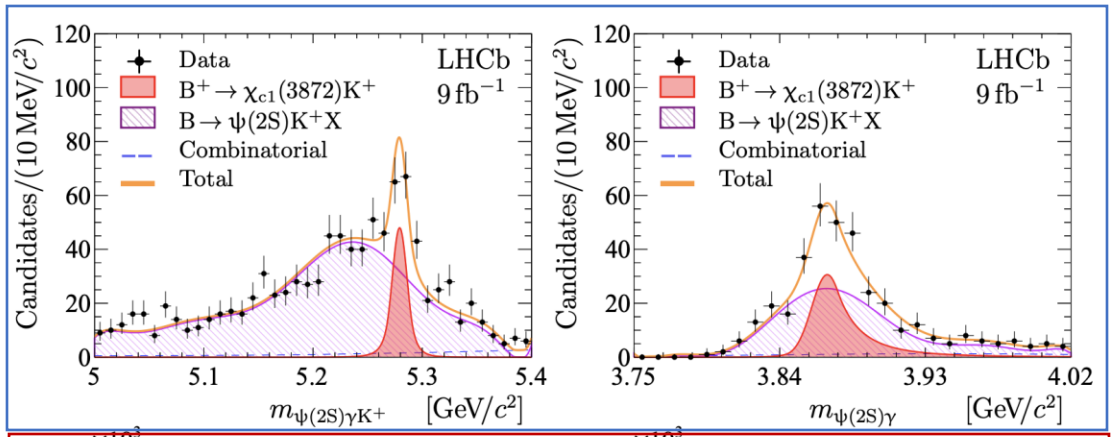
PART 01

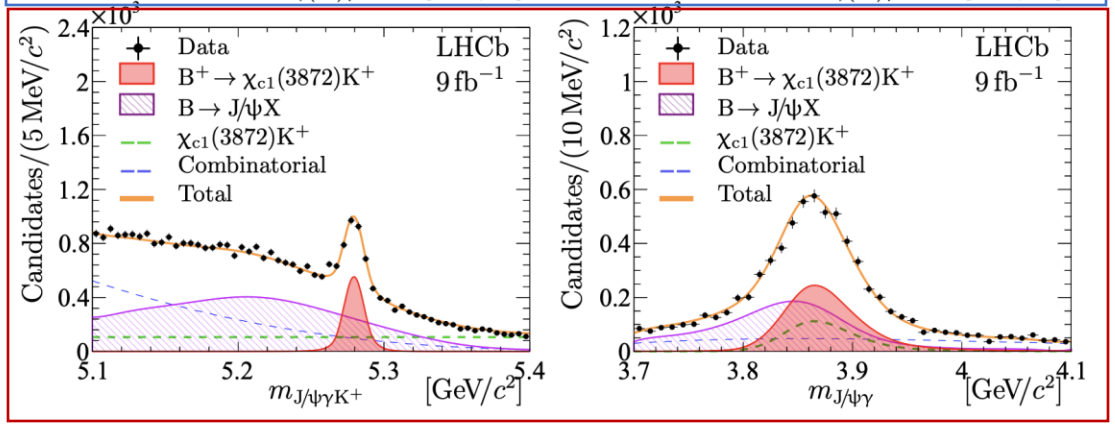
Hidden exotics

Radiative decays of $\chi_{c1}(3872)$

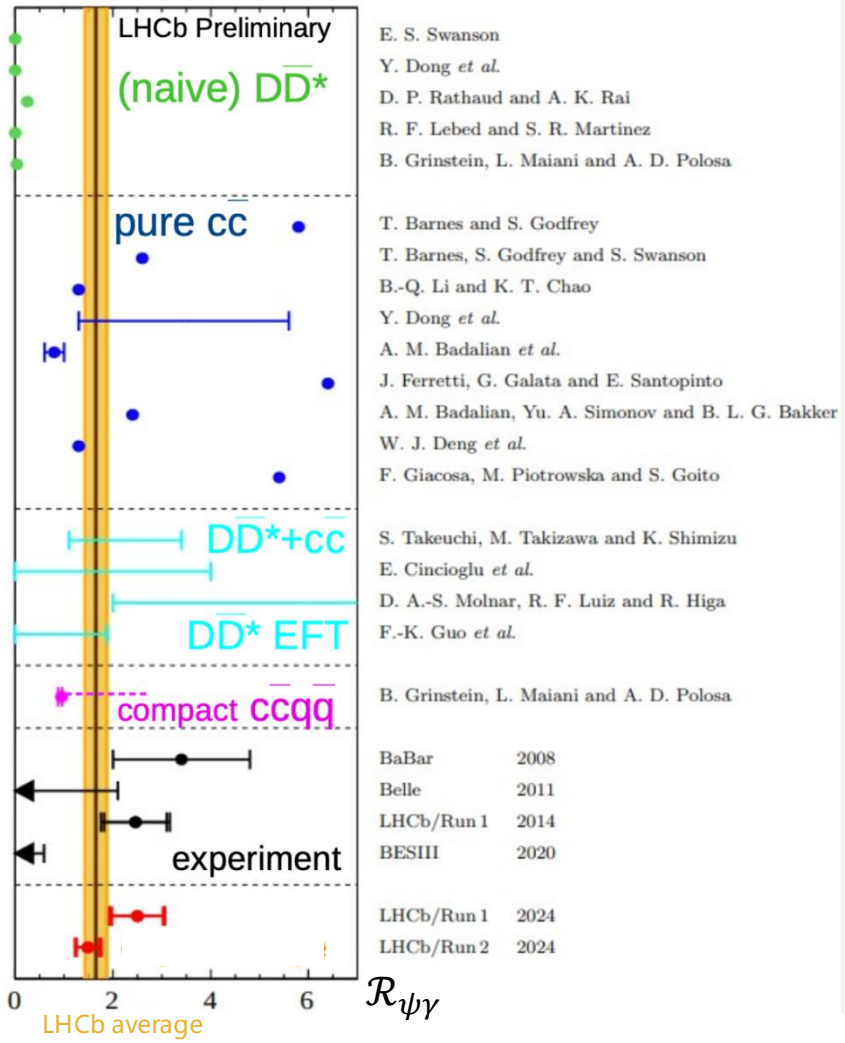
- First observation of $\chi_{c1}(3872) \to \psi(2S)\gamma$, 6σ

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





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



$$\mathcal{R}_{\psi\gamma} = \frac{\mathcal{B}(B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+)}{\mathcal{B}(B^+ \to (\chi_{c1}(3872) \to J/\psi)K^+)}$$

Radiative decays of $\chi_{c1}(3872)$

- First observation of $\chi_{c1}(3872) \to \psi(2S)\gamma$, 6σ

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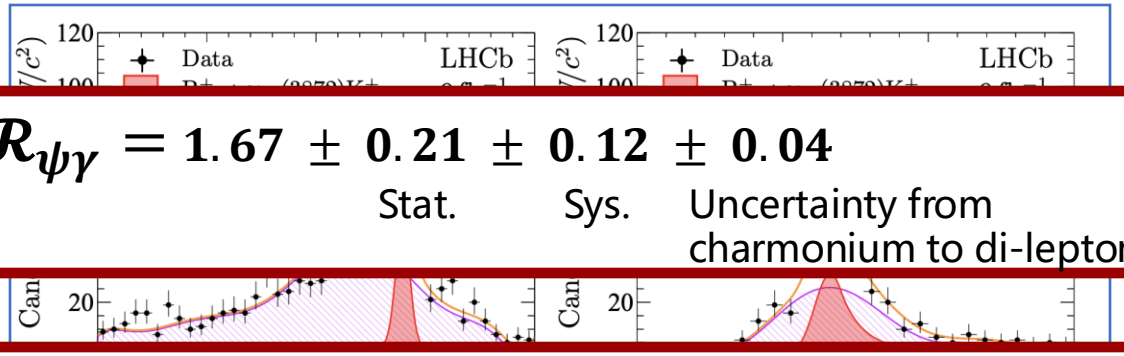
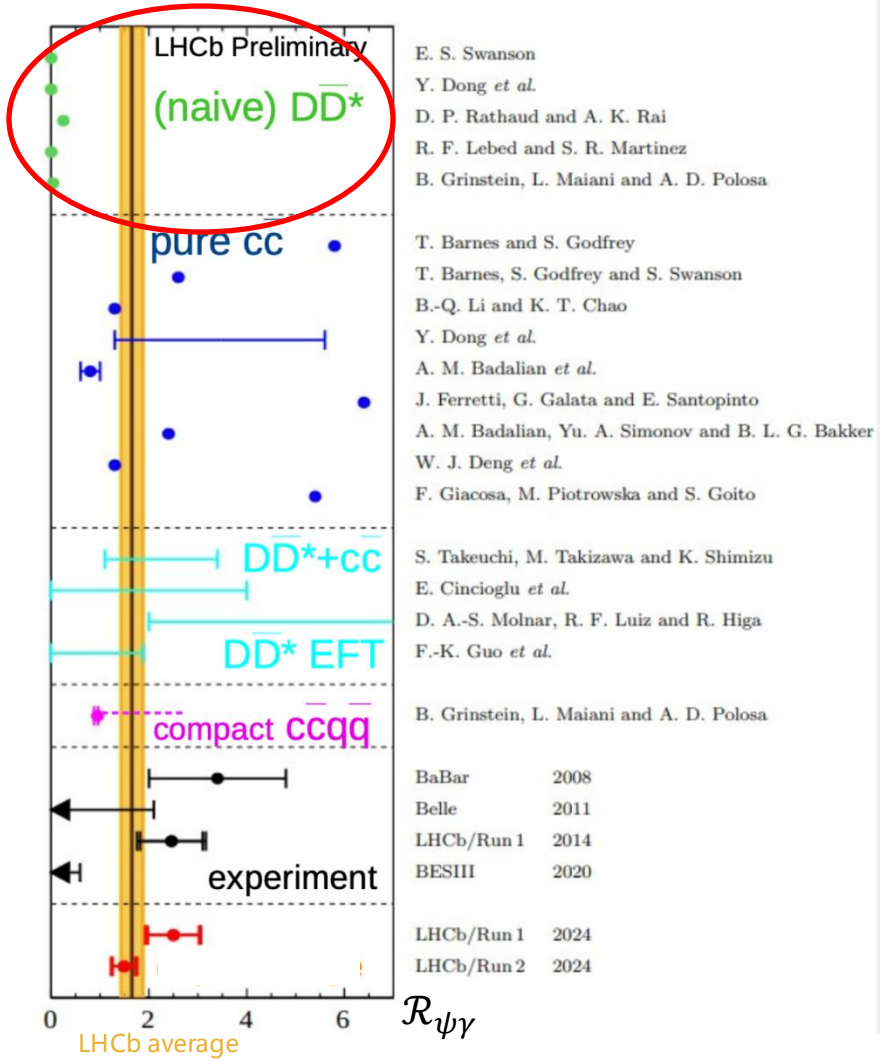


$$\mathcal{R}_{\psi\gamma} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

Stat. Sys. Uncertainty from charmonium to di-lepton

- Pure molecule model questionable
- Strong indication of a sizeable compact component

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



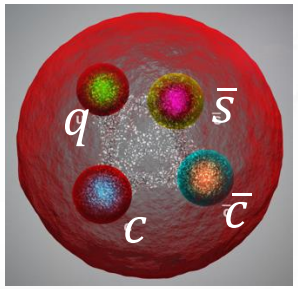
$$\mathcal{R}_{\psi\gamma} = \frac{\mathcal{B}(B^+ \to (\chi_{c1}(3872) \to \psi(2S)\gamma)K^+)}{\mathcal{B}(B^+ \to (\chi_{c1}(3872) \to J/\psi)K^+)}$$

arXiv:2406.17006, submitted to JHEP

PART 02

Manifestly exotics

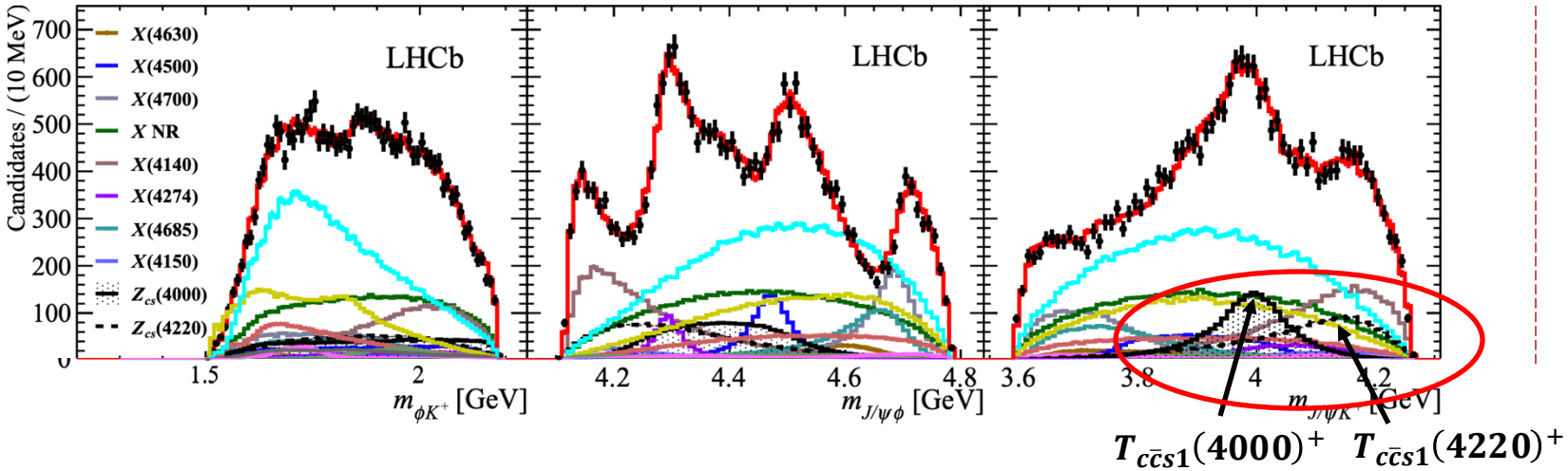
Hidden-charm tetraquarks with strangeness



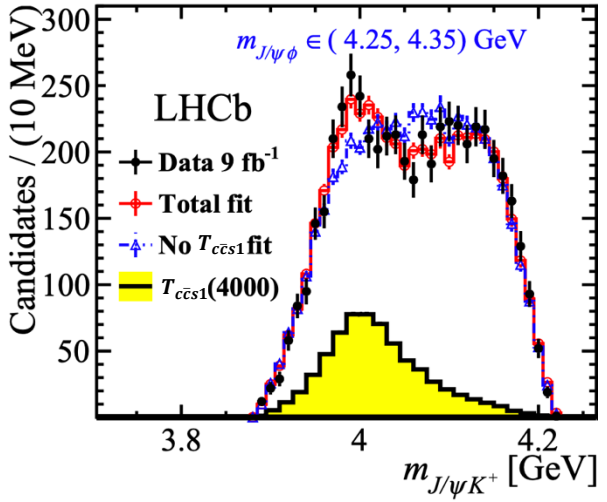
Observation of $T_{c\bar{c}s1}(4000)^+$ and $T_{c\bar{c}s1}(4220)^+$

- Amplitude analysis on $B^+ \to J/\psi K^+ \phi$ decays

Phys. Rev. Lett. 127 (2021) 082001

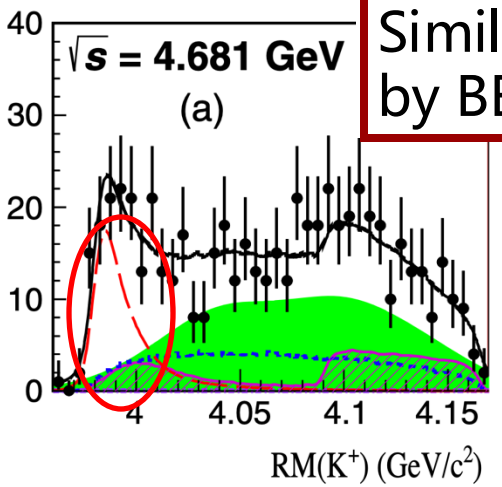


Obvious $T^+_{c\bar{c}s1}$ contributions



States	Contents	Mass [MeV]	Width [MeV]	Significance [σ]	J^P
$\chi_{c1}(4685)$	$c\bar{c}s\bar{s}$?	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-15}$	15	1^+
$X(4630)$	$c\bar{c}s\bar{s}$	$4626 \pm 16^{+13}_{-16}$	$174 \pm 27^{+134}_{-73}$	5.5	1^-
$T_{c\bar{c}s1}(4000)^+$	$c\bar{c}u\bar{s}$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	15	1^+
$T_{c\bar{c}s1}(4220)^+$	$c\bar{c}u\bar{s}$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	5.9	$1^+/1^-$

Similar results by BESIII



$e^+e^- \to K^+ D_s^- D^{*0}$ and $K^+ D_s^{*-} D^0$

Phys. Rev. Lett. 126 (2021)102001

Two hidden-charm tetraquark with strangeness

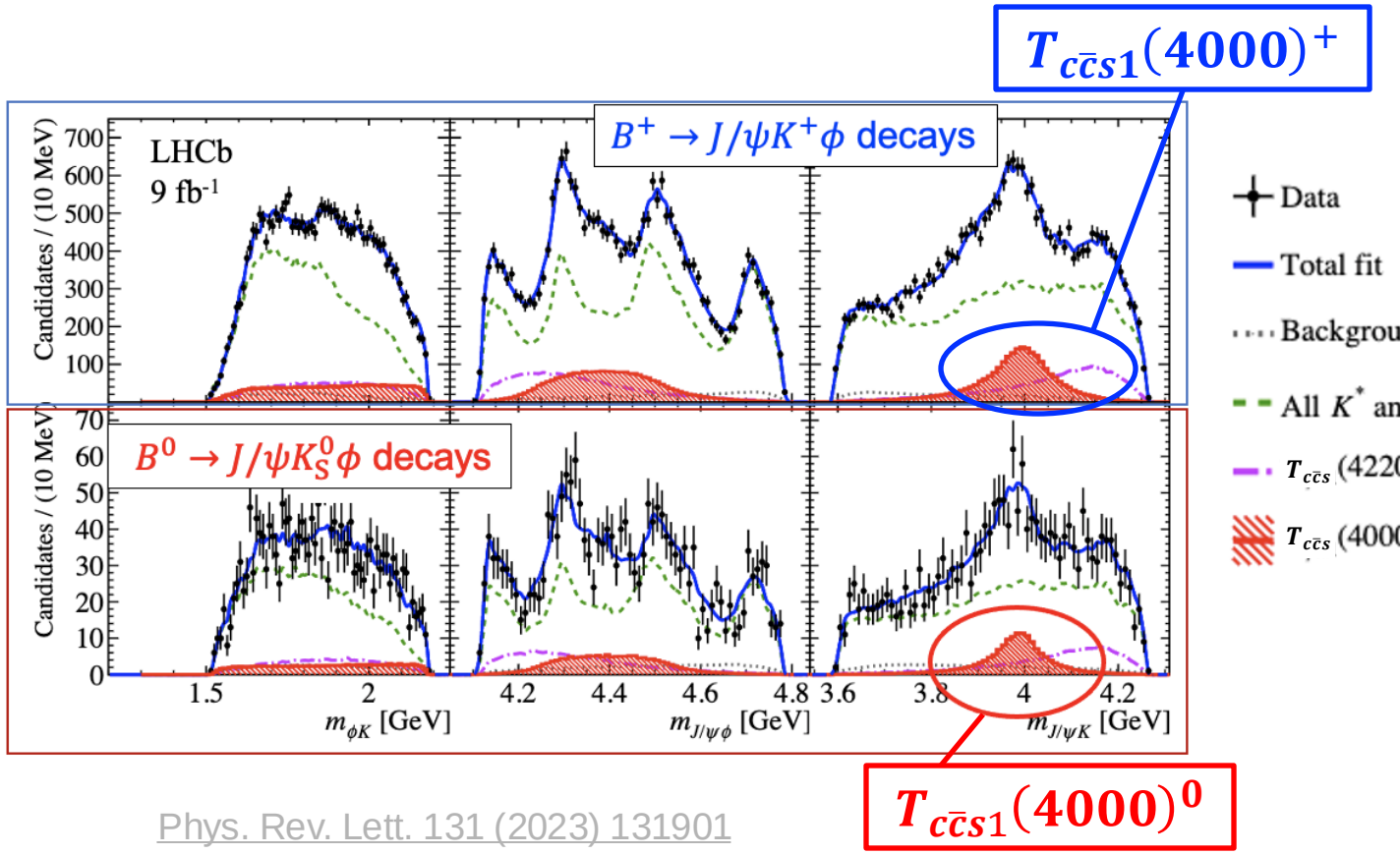
Isospin partner of $T_{c\bar{c}s1}(4000)^+$: $T_{c\bar{c}s1}(4000)^0$

- Search for $T_{c\bar{c}s1}(4000)^0$ in $B^0 \to J/\psi K_S^0 \phi$
- Simultaneous amplitude analysis of $B^+ \to J/\psi K^+ \phi$ and $B^0 \to J/\psi K_S^0 \phi$
- Evidence for $T_{c\bar{c}s1}(4000)^0$ with a significance of $4.0\,\sigma$
- Mass, width of $T^{+,0}_{c\bar{c}s1}$

	State	Mass (MeV)	Width (MeV)
$[c\bar{c}d\bar{s}]$	$T_{c\bar{c}s1}(4000)^0$	$3991\,^{+12}_{-10}\,^{+9}_{-17}$	$105\,^{+29}_{-25}\,^{+17}_{-23}$
$[c\bar{c}u\bar{s}]$	$T_{c\bar{c}s1}(4000)^+$	$4003 \pm 6\,^{+4}_{-14}$	$131 \pm 15 \pm 26$

$$\Delta M \equiv M_{T_{c\bar{c}s1}(4000)^0} - M_{T_{c\bar{c}s1}(4000)^+} = -12^{+11}_{-10}\,^{+6}_{-4}\ \text{MeV}$$

Consistent with $T_{c\bar{c}s1}(4000)^0$ and $T_{c\bar{c}s1}(4000)^+$ being isospin partners



Phys. Rev. Lett. 131 (2023) 131901

Isospin partner of $T_{c\bar{c}s1}(4000)^+$: $T_{c\bar{c}s1}(4000)^0$

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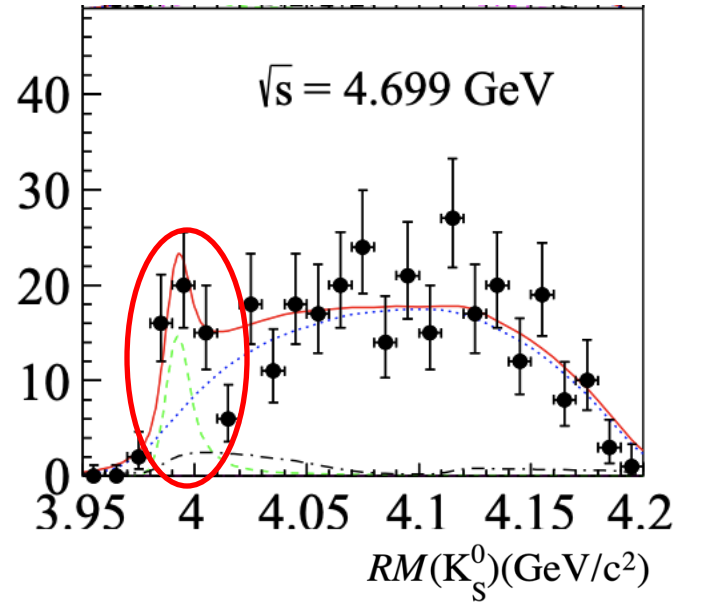
- Simultaneous amplitude analysis of $B^+ \to J/\psi K^+ \phi$ and $B^0 \to J/\psi K_S^0 \phi$
- Ev
  w
- M

$[c\bar{c}d\bar{s}]$

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

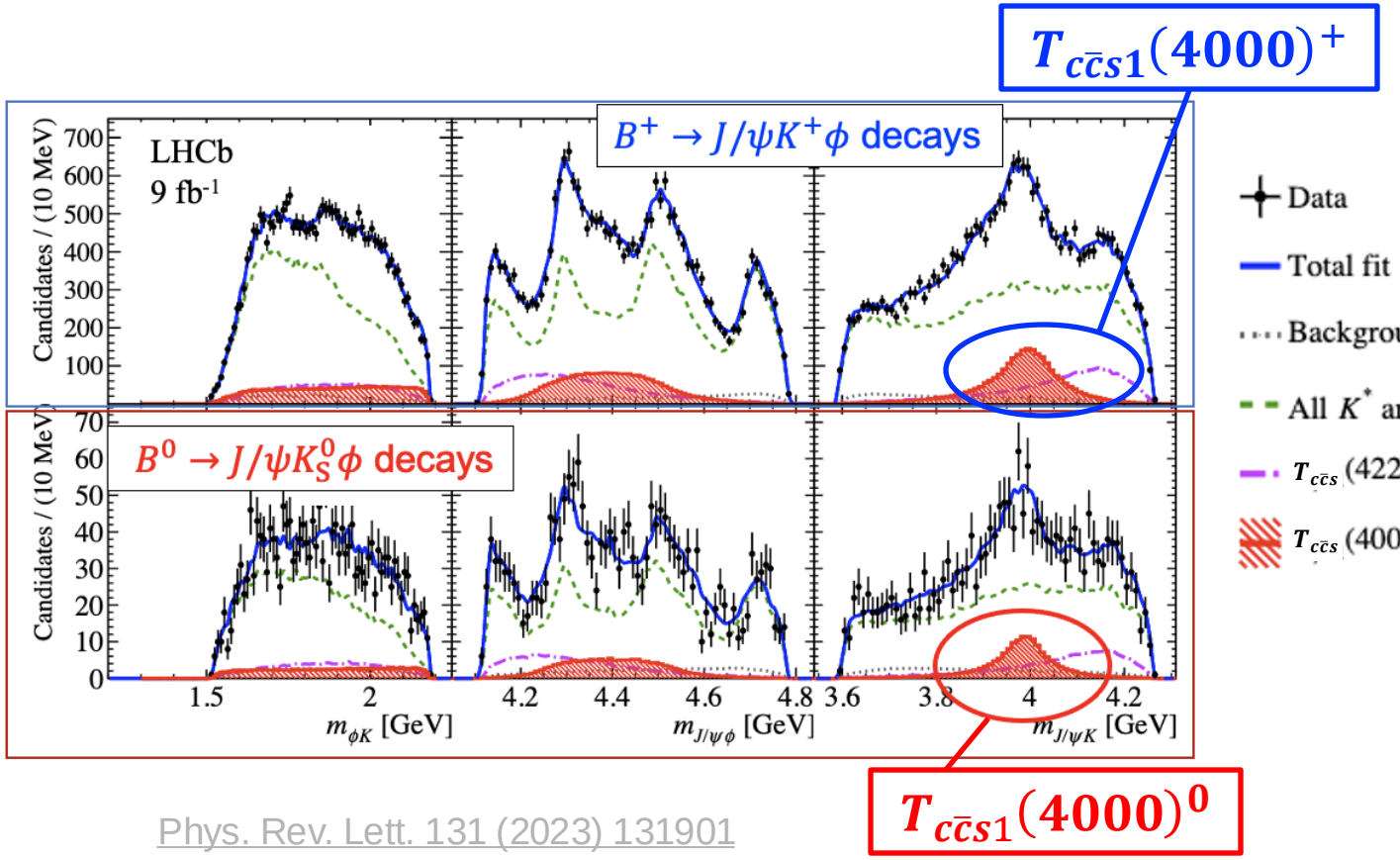
$\Delta M \equiv$

Similar results by BESIII



Phys. Rev. Lett. 129, (2022) 112003

Consistent with $T_{ccs1}(4000)^+$ and $T_{c\bar{c}s1}(4000)^+$ being isospin partners



$T_{c\bar{c}s1}(4000)^+$

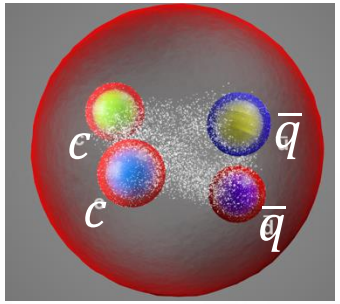
$T_{c\bar{c}s1}(4000)^0$

Phys. Rev. Lett. 131 (2023) 131901

PART 03

Manifestly exotics

Doubly-charmed tetraquarks

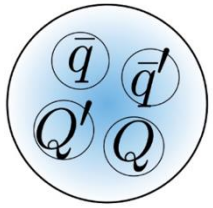


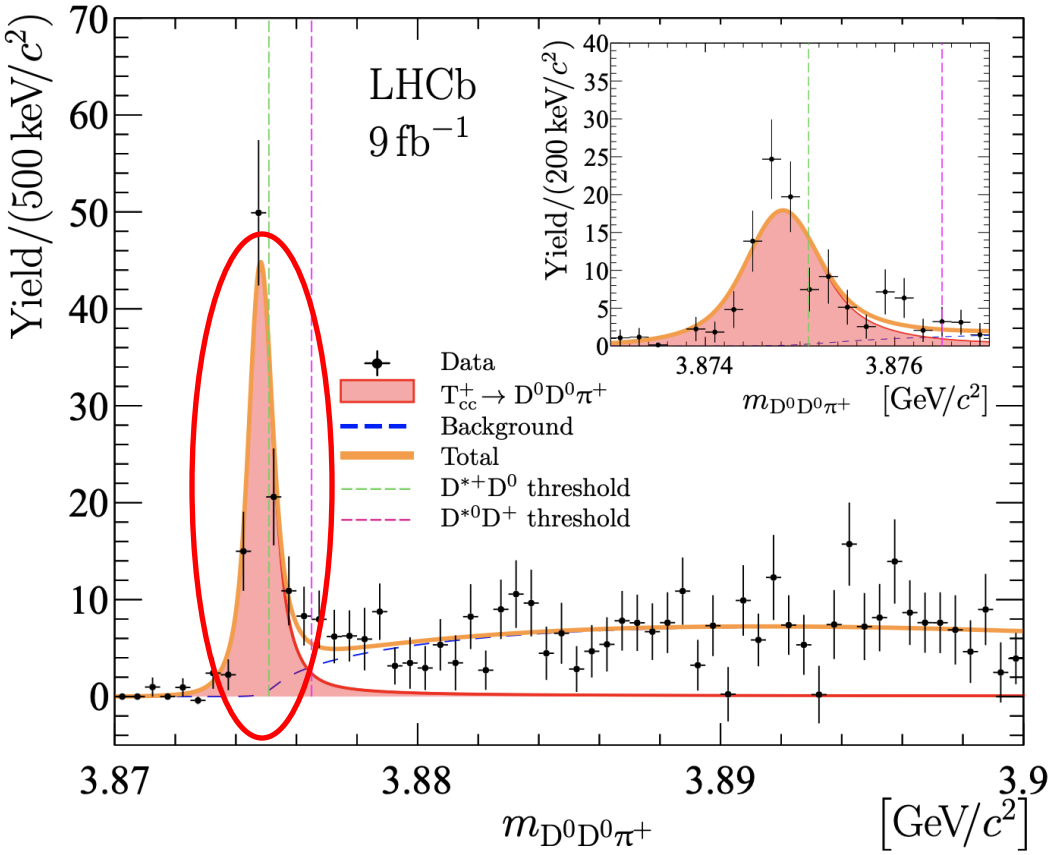
Doubly-charmed tetraquarks: $T_{cc}(3875)^+$

- Frist observation of $T_{cc}(3875)^+ \to D^0 D^0 \pi^+$
  - Exotic quark content $[cc\bar{u}\bar{d}]$
- Close to $D^{*+}D^0$ mass threshold, narrow

$$\delta m_{\mathrm{BW}} \equiv m_{\mathrm{BW}} - (m_{D^{*+}} + m_{D^0})$$
$$= -273 \pm 61(\mathrm{stat}) \pm 5(\mathrm{syst})^{+11}_{-14}(\mathrm{model})\ \mathrm{KeV}$$
$$\Gamma = 410 \pm 65(\mathrm{stat}) \pm 43(\mathrm{syst})^{+18}_{-38}(\mathrm{model})\ \mathrm{KeV}$$

- Consistent with isoscalar, $J^P = 1^+$
- First representative of $QQ'\bar{q}\bar{q}'$
  - Almost stable against strong interaction $\tau \sim 10^{-20}$ s
  - Support existence of T^-_{bb} $[bb\bar{u}\bar{d}]$ and T^0_{bc} $[bc\bar{u}\bar{d}]$ might be found in the future





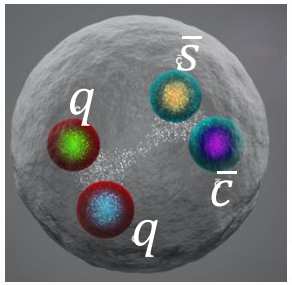
Nature Physics 18 (2022) 751–754

Nature Communicatitions, 13 (2022) 3351

PART 04

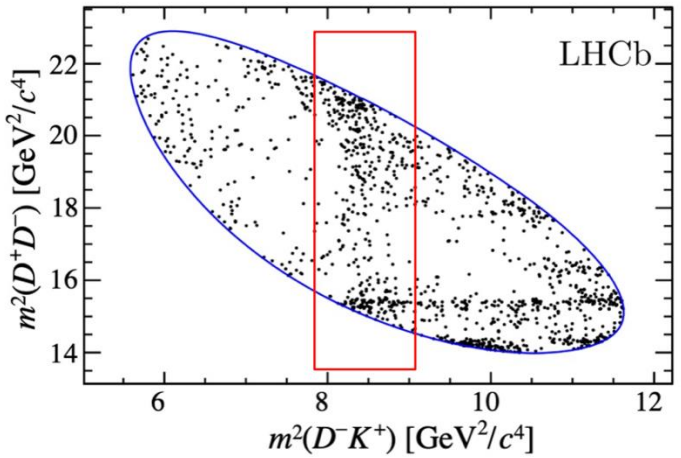
Manifestly exotics

Open-charmed tetraquarks

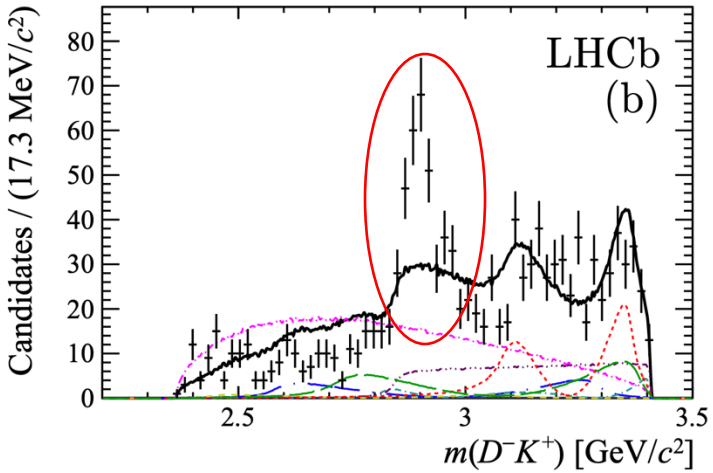


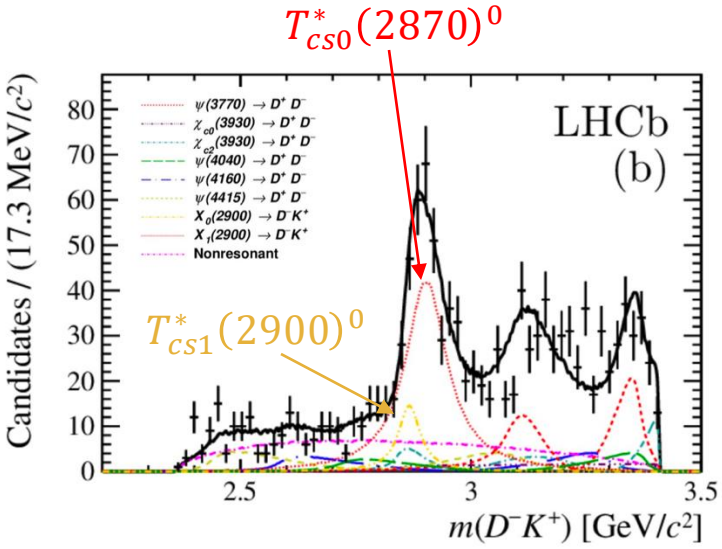
Open-charm tetraquarks: $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$

- Amplitude analysis on $B^+ \to D^+ D^- K^+$ decay



Without $T^*_{cs0}(2870)^0$ and $T_{cs1}(2900)^0$





- Model with only charmonia cannot describe data well
- Two new states needed to describe data

Phys. Rev. D 102, 112003 (2020)

Resonance	Mass (GeV/c^2)		Width (MeV)	
$T^*_{cs0}(2870)^0$	2.866 ± 0.007	± 0.002	57 ± 12	± 4
$T^*_{cs1}(2900)^0$	2.904 ± 0.005	± 0.001	110 ± 11	± 4
	stat	syst		

Strong candidate for tetraquark states with quark content $\bar{c}\bar{s}du$

Amplitude analysis of $B^+ \to D^{*\pm}D^{\mp}K^+$

- Confirmation of $T^*_{cs0}(2870)^0$ and $T^*_{cs1}(2900)^0$ in $B^+ \to D^+D^-K^+$

Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12

- No structure found in $D^{*-}K^+$ spectrum
- Three new states in $D^{*\pm}D^{\mp}$ spectrum observed

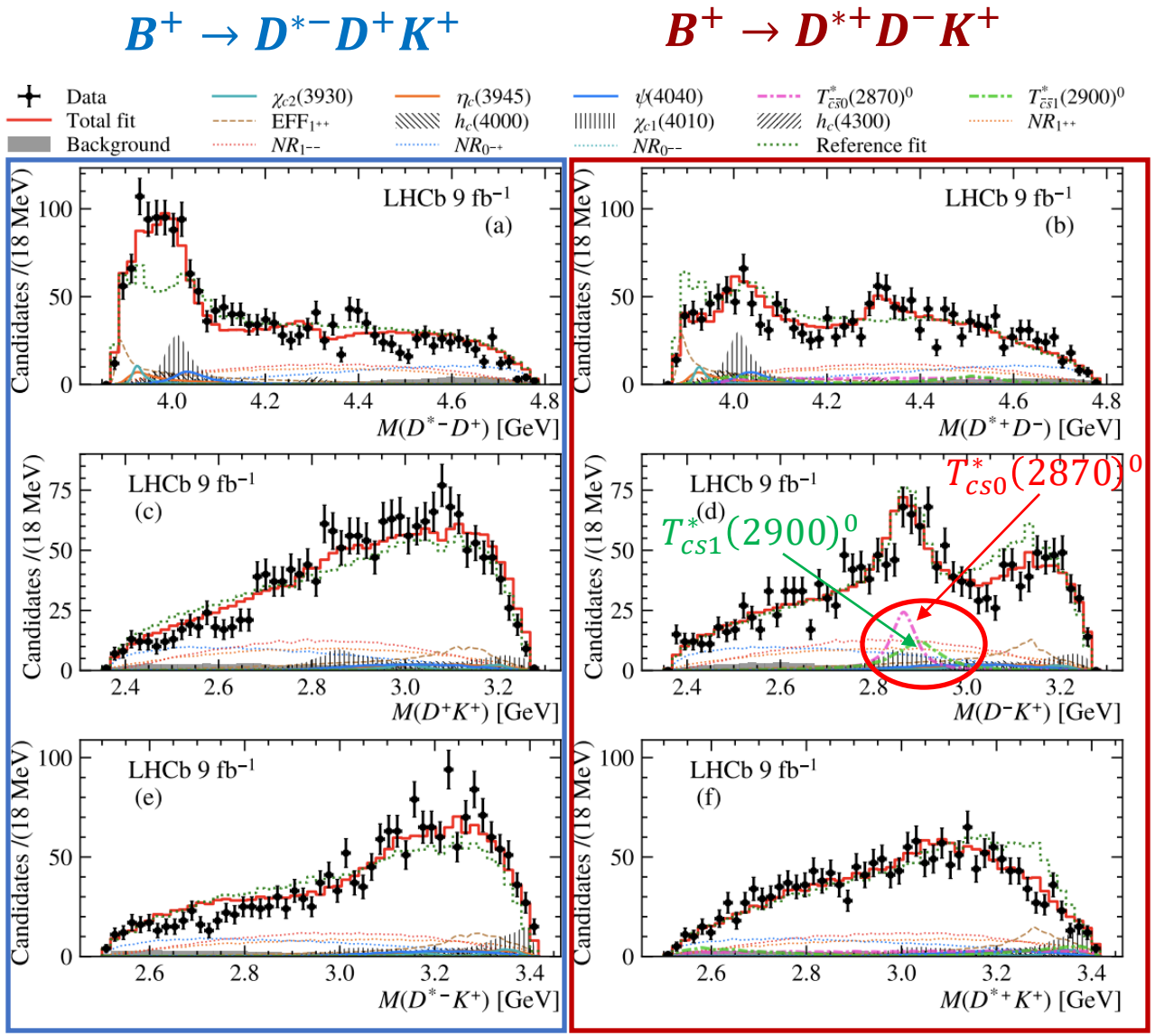
Unit: MeV

$h_c(4000)$	$J^{PC} = 1^{+-}$
$m_0 = 4000\,^{+17\,+29}_{-14\,-22}$	$\Gamma_0 = 184\,^{+71\,+97}_{-45\,-61}$
$\chi_{c1}(4010)$	$J^{PC} = 1^{++}$
$m_0 = 4012.5\,^{+3.6\,+4.1}_{-3.9\,-3.7}$	$\Gamma_0 = 62.7\,^{+7.0\,+6.4}_{-6.4\,-6.6}$
$h_c(4300)$	$J^{PC} = 1^{+-}$
$m_0 = 4307.3\,^{+6.4\,+3.3}_{-6.6\,-4.1}$	$\Gamma_0 = 58\,^{+28\,+28}_{-16\,-25}$

$h_c(2P)$?

$\chi_{c1}(2P)$?

$h_c(3P)$?



Amplitude analysis of $B \to DD_s\pi$

- Joint amplitude analysis linked through isospin symmetry
  - $B^0 \to \bar{D}^0 D_s^+ \pi^-$
  - $B^+ \to D^- D_s^+ \pi^+$
- Two exotic states observed

$$T^*_{c\bar{s}0}(2900)^0 : M = 2.892 \pm 0.014 \pm 0.015\,\text{GeV}, \quad J^P = 0^+$$
$$\Gamma = 0.119 \pm 0.026 \pm 0.013\,\text{GeV},$$
$$T^*_{c\bar{s}0}(2900)^{++} : M = 2.921 \pm 0.017 \pm 0.020\,\text{GeV}, \quad J^P = 0^+$$
$$\Gamma = 0.137 \pm 0.032 \pm 0.017\,\text{GeV},$$

Not the same as $T^*_{cs0}(2870)^0$ $[\bar{c}\bar{s}du]$ observed in $B^+ \to D^+ D^- K^+$

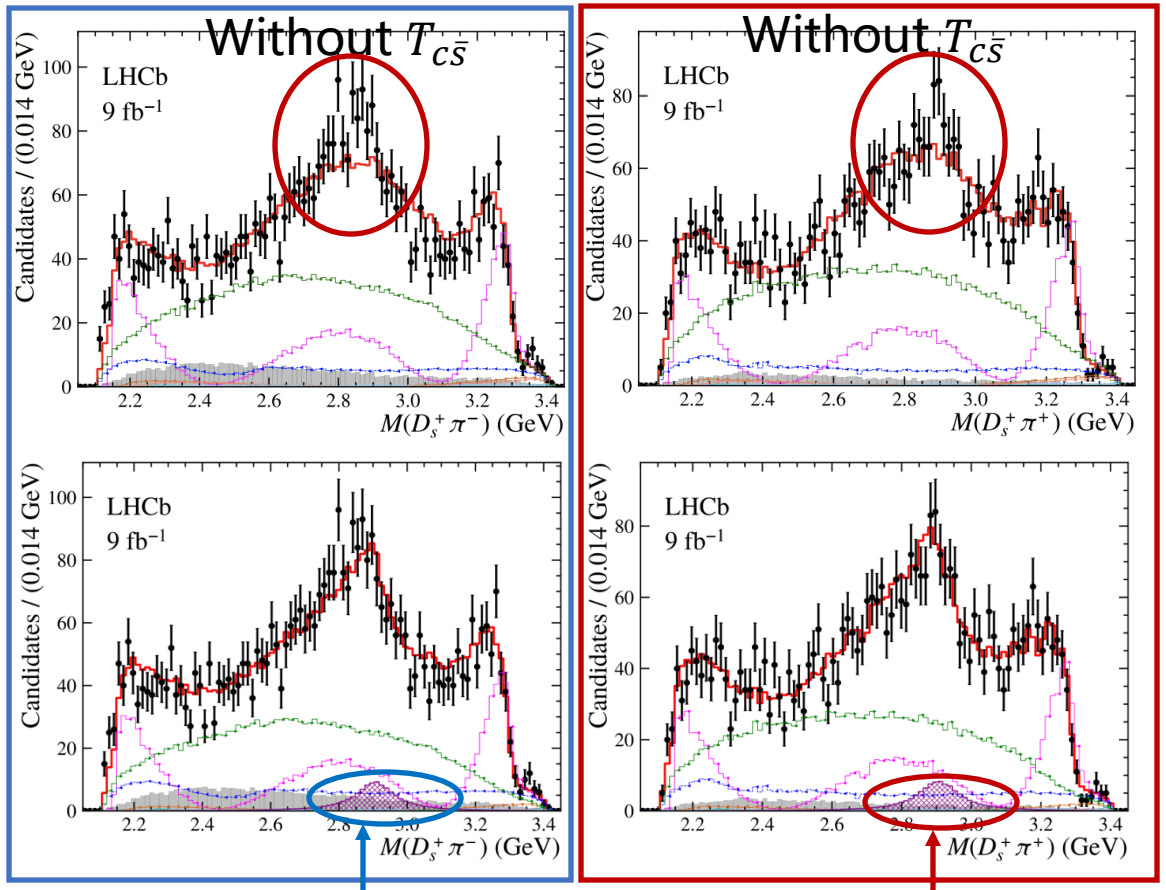
- Isospin triplet?

$T^*_{c\bar{s}0}(2900)^0 \to D_s^+\pi^-$

? $T^*_{c\bar{s}0}(2900)^+ \to D_s^+\pi^0$ to be searched

$T^*_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$

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



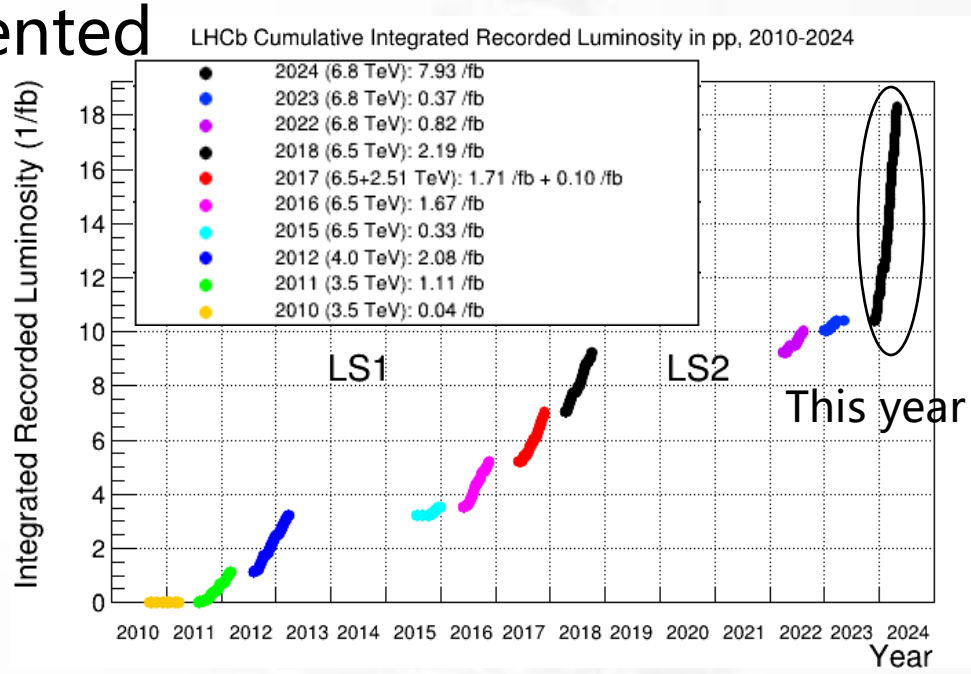
$[c\bar{s}d\bar{u}]$ $T^*_{c\bar{s}0}(2900)^0$ $T^*_{c\bar{s}0}(2900)^{++}$ $[c\bar{s}u\bar{d}]$

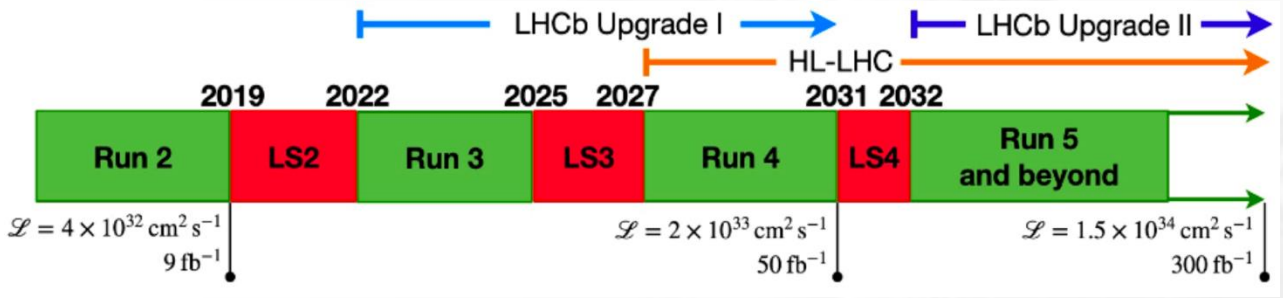
Phys. Rev. Lett. 131 (2023) 041902

Phys. Rev. D 108 (2023) 012017

Summary and outlook

- Some recent results on tetraquark states presented
  - Hidden exotics: radiative decay of $\chi_{c1}(3872)$
  - Manifestly exotics:
    - $[c\bar{c}q\bar{s}]$: $T_{c\bar{c}s1}(4000)^+$, $T_{c\bar{c}s1}(4220)^+$, $T_{c\bar{c}s1}(4000)^0$
    - $[cc\bar{q}\bar{q}]$: $T_{cc}(3875)^+$
    - $[c\bar{s}qq]$: $T_{cs0}(2900)^0$, $T_{cs1}(2900)^0$, $T_{c\bar{s}0}(2900)^{++}$, $T_{c\bar{s}0}(2900)^0$
- LHCb upgrade
  - Larger data sample will help tetraquark studies
    - Properties of observed tetraquarks
    - Likely to observe more tetraquarks
    - ...





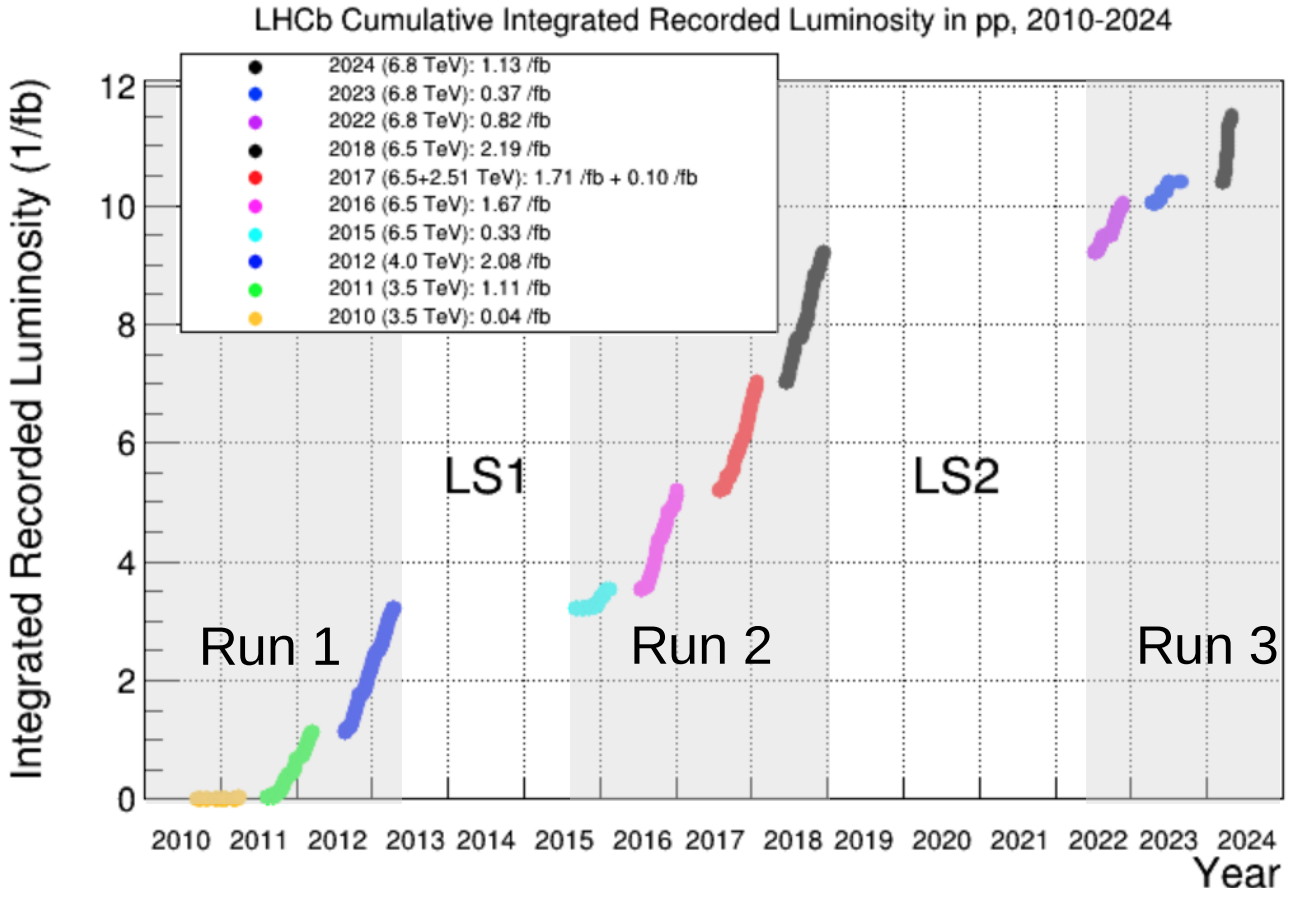
Thanks for your attention!

北京大学
PEKING UNIVERSITY

Back up

LHCb dataset

- Run 1:
  $3\ \mathrm{fb}^{-1}$ pp collision @ $7, 8\ \mathrm{TeV}$
- Run 2:
  $6\ \mathrm{fb}^{-1}$ pp collision @ $13\ \mathrm{TeV}$



Details of $B^0 \to J/\psi K_S^0 \phi$

- Relativistic Breit-Wigner to describe lineshape
- Floating parameters
  - Mass, width, helicity couplings
- Parameters configuration
  - Isospin symmetry for all resonances except for $T^{\theta}_{\psi s1}(4000)$ in B^+ and B^0 decay
    - Corresponding parameters **shared**
  - Not assuming isospin symmetry for $T^{\theta}_{\psi s1}(4000)^0$ and $T^{\theta}_{\psi s1}(4000)^+$
    - Corresponding parameters **vary independently**

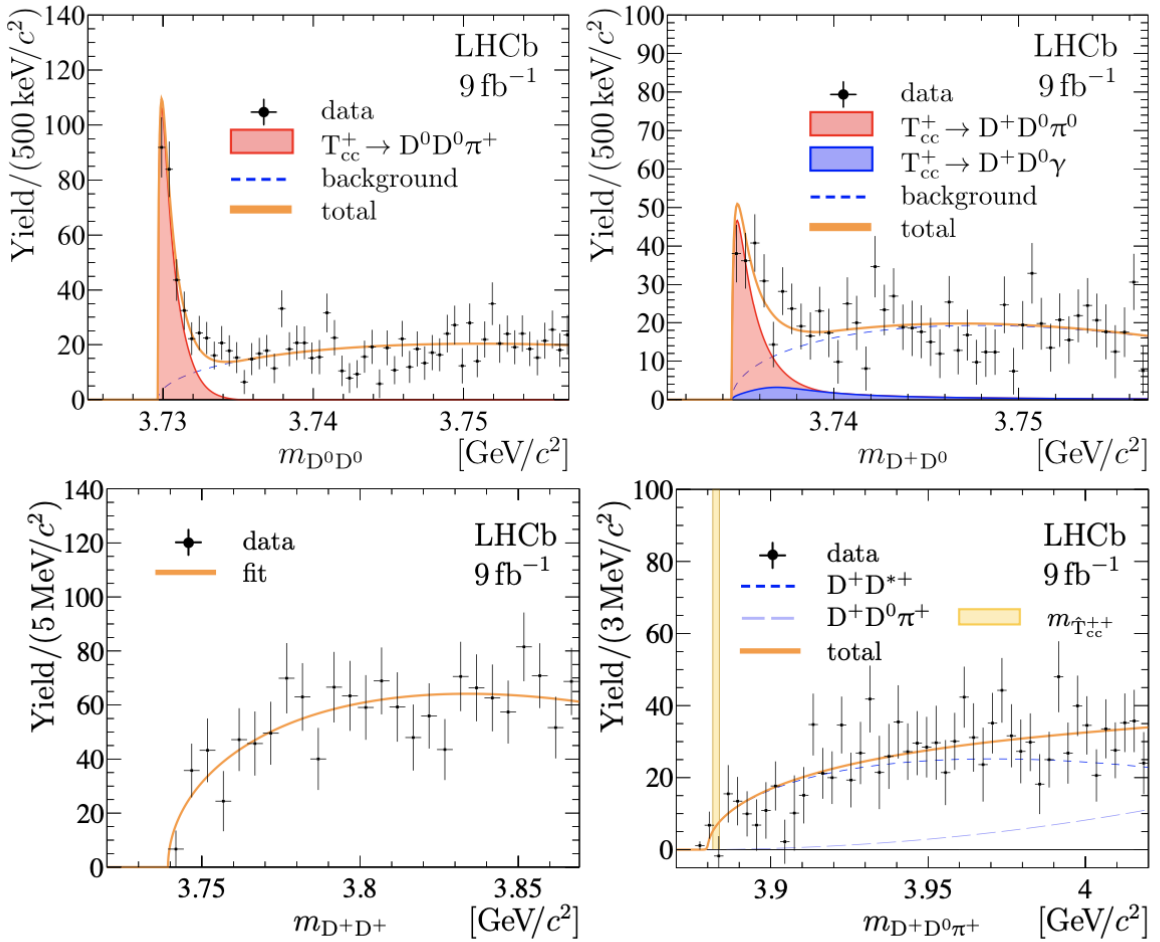
K^* chain: $B \to J/\psi\ K^*$; $J/\psi \to \mu^+\mu^-$; $K^* \to \phi K$; $\phi \to K^+K^-$

X chain $[c\bar{c}s\bar{s}]$: $B \to X\ K$; $X \to J/\psi\ \phi$; $J/\psi \to \mu^+\mu^-$; $\phi \to K^+K^-$

$T_{\psi s}$ chain: $[c\bar{c}d\bar{s}]$ $[c\bar{c}u\bar{s}]$: $B \to \phi\ T_{\psi s}$; $\phi \to K^+K^-$; $T_{\psi s} \to J/\psi K$; $J/\psi \to \mu^+\mu^-$

2^1P_1	$K(1^+)$	$\eta_{c2}(4150)$	$T^{\theta}_{\psi s1}(4000)$
$2^1P_1^3$	$K'(1^+)$	$T^{\eta}_{\psi\phi 1}(4630)$	$T_{\psi s1}(4220)$
1^3P_1	$K_1(1400)$	$\chi_{c0}(4500)$	
1^1D_2	$K_2(1770)$	$\chi_{c0}(4700)$	
1^3D_2	$K_2(1820)$	$NR_{J/\psi\phi}$	
1^3D_1	$K^*(1680)$	$\chi_{c1}(4140)$	
2^3S_1	$K^*(1410)$	$\chi_{c1}(4274)$	
2^3P_2	$K_2^*(1980)$	$\chi_{c1}(4685)$	
2^1S_0	$K(1460)$		

Details of $T_{cc}(3872)^+$



Nature Communicatitions, 13, 3351 (2022)

Reflections from T_{cc}^+ in $m(D^0D^0)$ and $m(D^+D^0)$ spectra consistent with isoscalar hypothesis

Isovector components T_{cc}^0 and T_{cc}^{++} would show up in $m(D^+D^+)$ and $m(D^+D^0\pi^+)$ spectra
$\to$ not observed

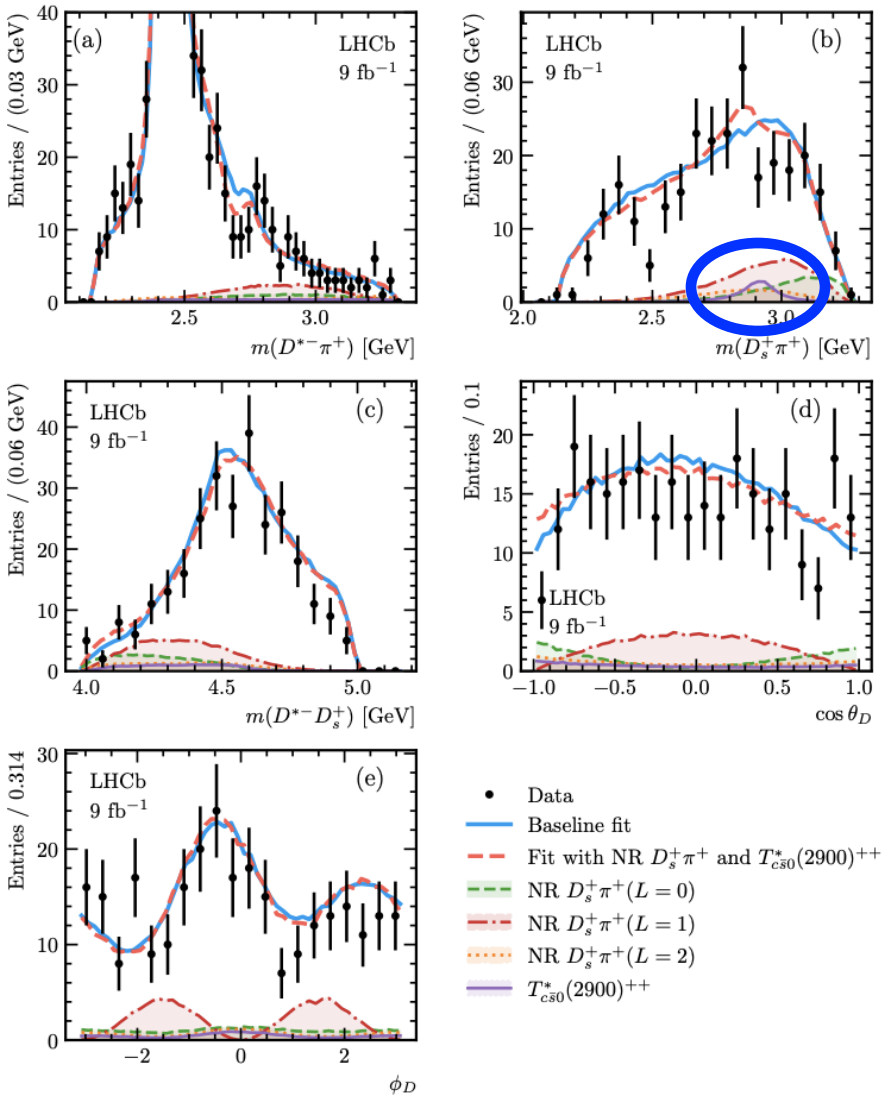
Unitarised 3-body BW model, assuming $I = 0$ and $J^P = 1^+$:

Characteristic size estimates
$R_{\Delta E} = 7.49 \pm 0.42\,\text{fm}$
$R_a \quad = 7.16 \pm 0.51\,\text{fm}$
(molecular-like)

Unlike $\chi_{c1}(3872)$, no T_{cc}^+ suppression for high multiplicity (wrt. $D^0\bar{D}^0$)

Amplitude analysis of $B^+ \to D^{*-} D_s^+ \pi^+$

- $T^*_{c\bar{s}0}(2900)^{++}$ has been searched in $D_s^+\pi^+$ spectrum
- No strong evidence of tetraquarks contributing to the total decay amplitude
- Fit fraction of $T^*_{c\bar{s}0}(2900)^{++} \to D_s^+\pi^+$ is found to be less than 2.3% at 90% CL



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