Latest exotic spectroscopy results from LHCb

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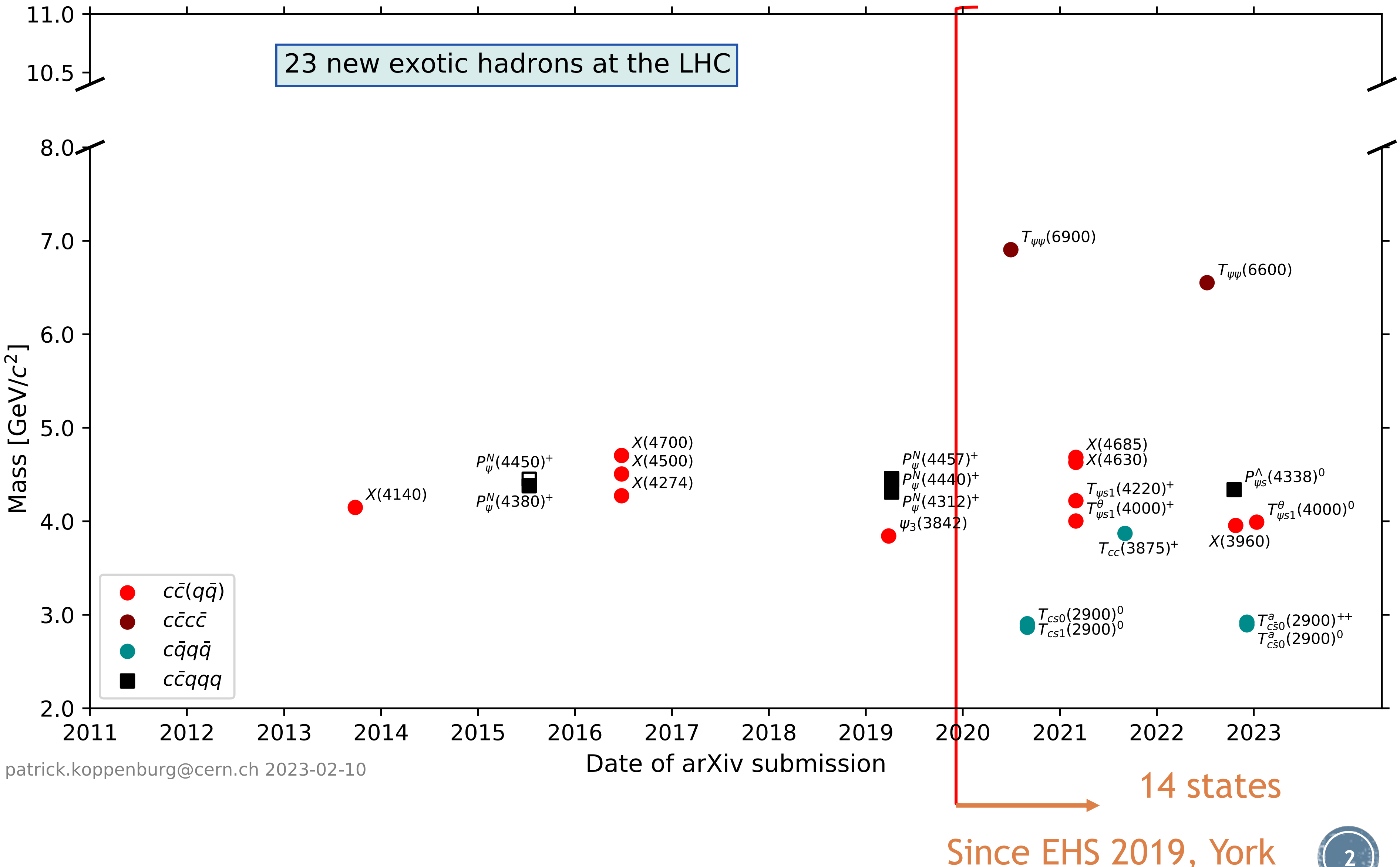
Exotic Hardon Spectroscopy 2023

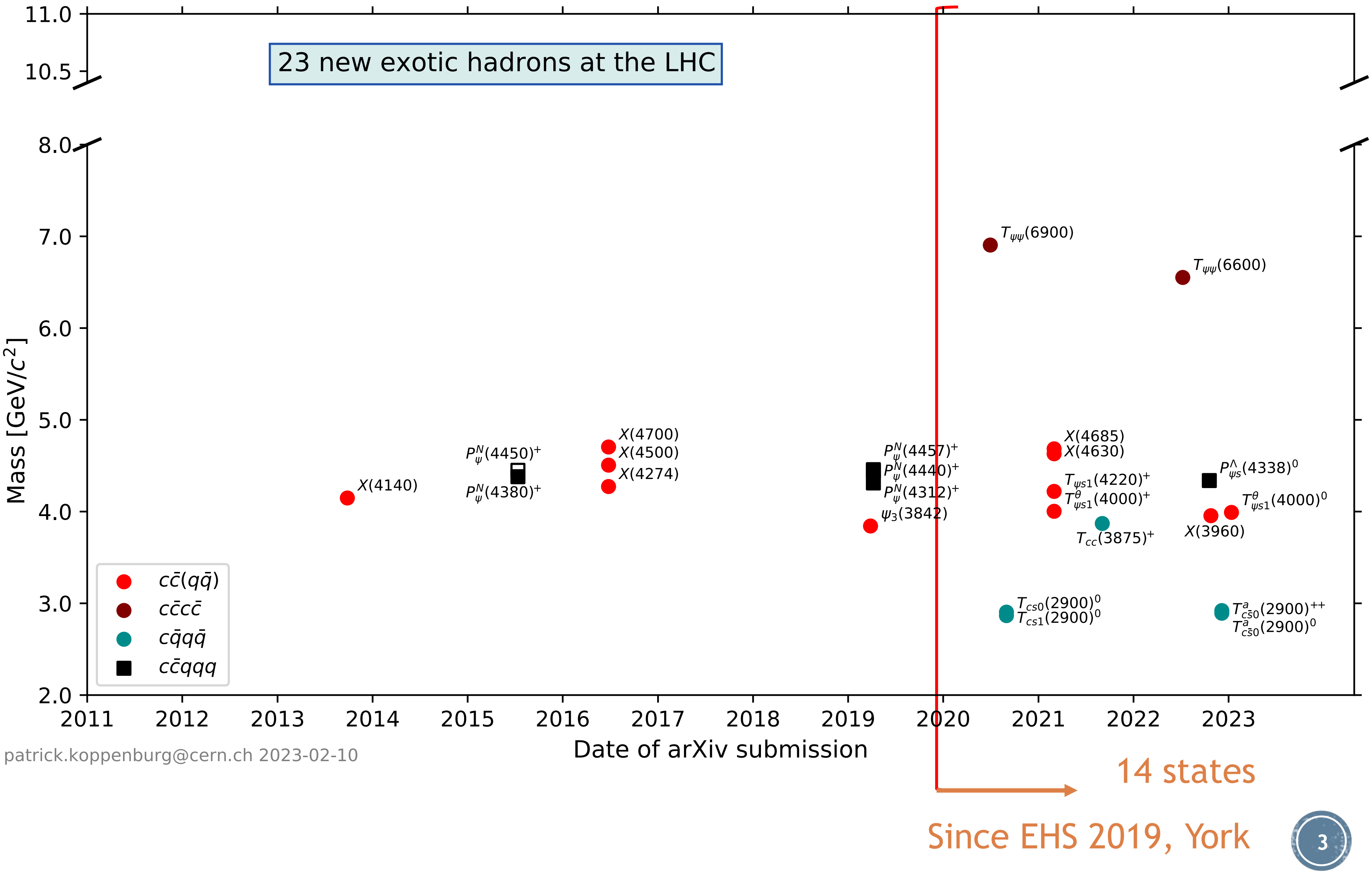
20 Apr. 2023, Durham

Exotic hadrons at LHC

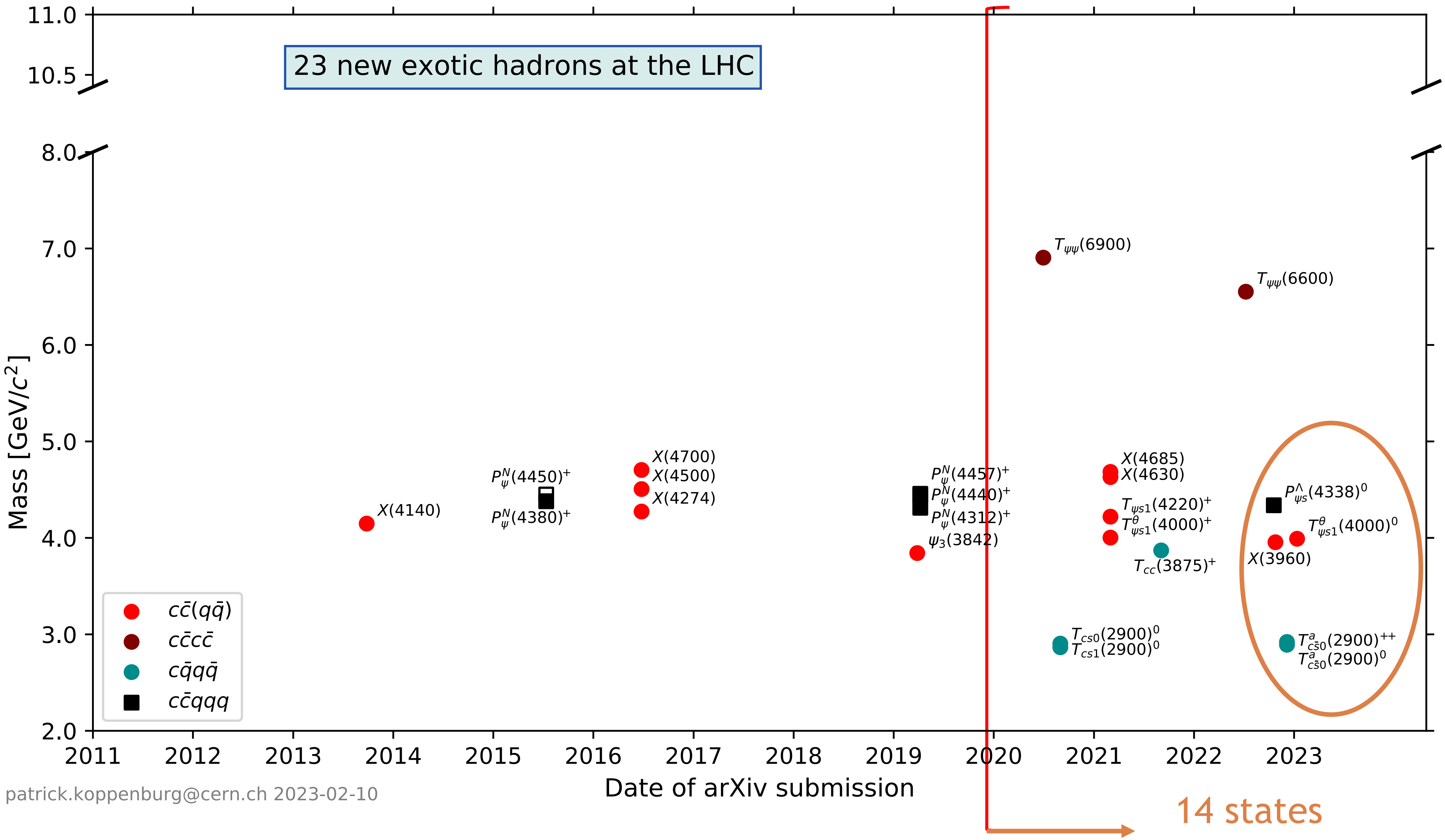


Exotic hadrons at LHC

I'd like to cover all the 14 states, which this talk is too short to contain



Exotic hadrons at LHC



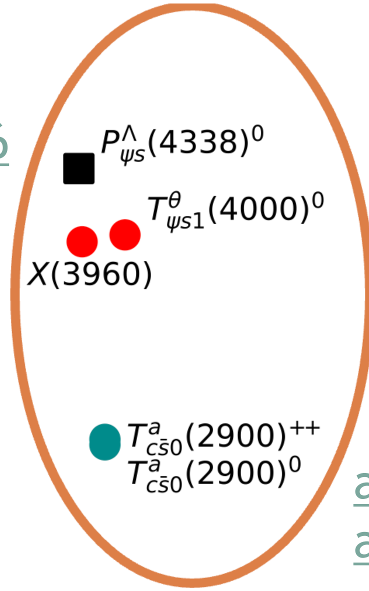
14 states

Since EHS 2019, York

LHCb results in this talk

- New exotic hadrons

arXiv:2210.10346



arXiv:2301.04899

arXiv:2210.15153
arXiv:2211.05034

arXiv:2212.02717
arXiv:2212.02716

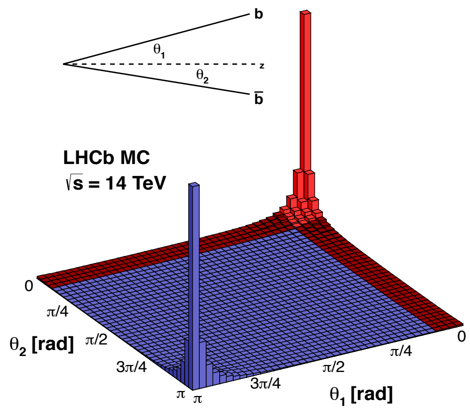
- Observations of new decays
  - $B^+ \to J/\psi \eta' K^+$ [arXiv:2303.09443]
  - $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$ [arXiv:2302.10629]

LHCb experiment

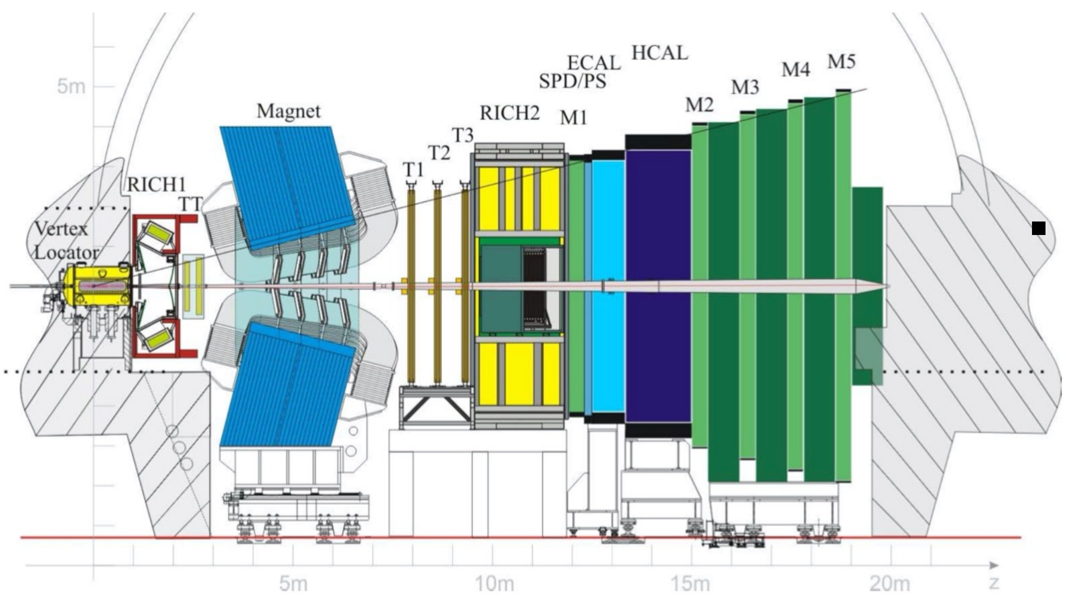
JINST 3 (2008) S08005, Int.J.Mod.Phys. A30 (2015) 1530022

- Dedicated for precise and efficient heavy-hadron reconstruction
  - Single-arm and forward design

$2 < \eta < 5$ range: ~25% $b\bar{b}$ pairs in LHCb acceptance



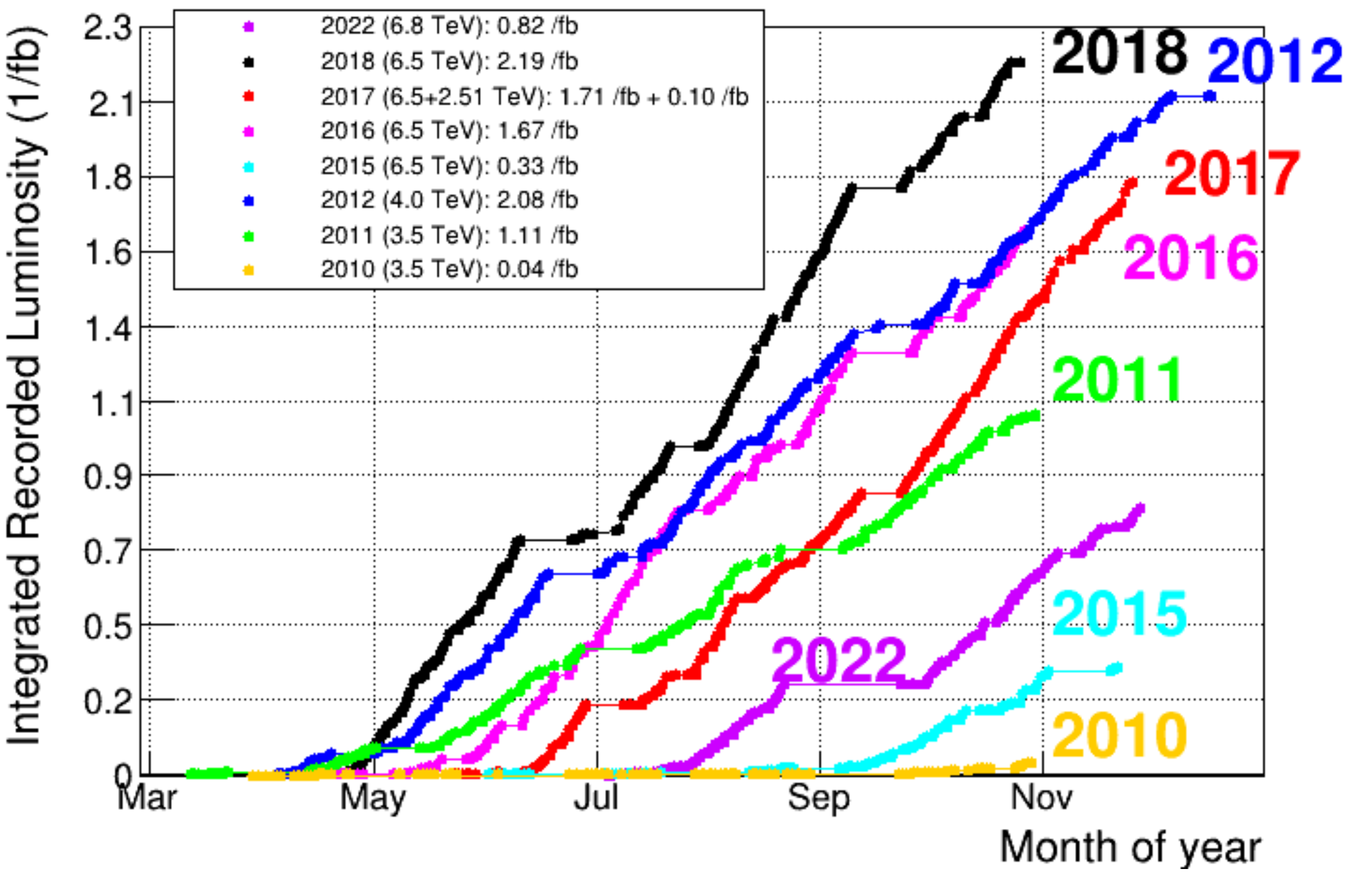
- Powerful particle identification
  - $\epsilon(K \to K) \sim 95\%$ with $\epsilon(\pi \to K) \sim 5\%$
  - $\epsilon(\mu \to \mu) \sim 97\%$ with $\epsilon(\pi \to \mu) \sim 1 - 3\%$
- High momentum resolution
  - $\Delta p/p = 0.4 \sim 0.6\%$ $(5 - 100\text{GeV}/c)$
  - σ_{m_B}~10MeV for $B \to D\bar{D}K$
- High spatial resolution
  - σ_{IP}~20μm; $\sigma_{\text{PV},x/y}$~10μm; $\sigma_{\text{PV},z}$~60μm



LHCb dataset

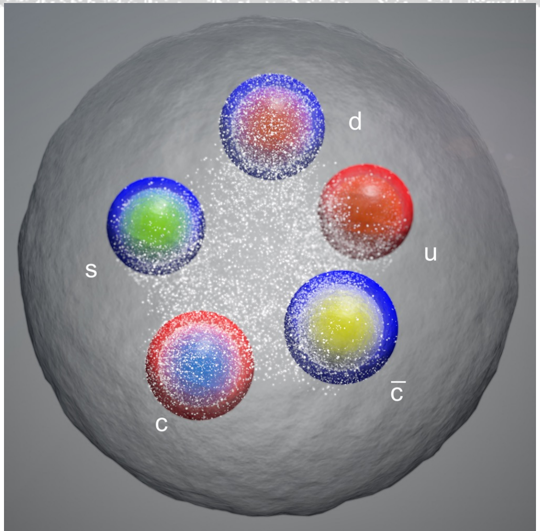
- Run1: 3 fb^{-1} pp collision @ 7, 8 TeV
- Run2: 6 fb^{-1} pp collision @ 13 TeV
- Run3: started in 2022

All analyses in this talk used the Run1 + Run2 dataset



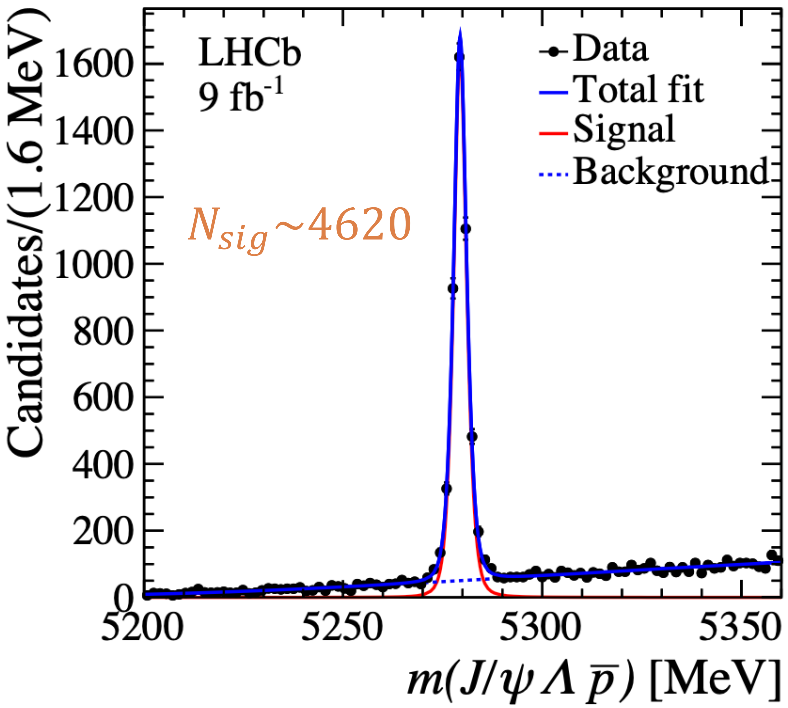
Observation of pentaquark $P_{\psi s}^{\Lambda}(4338)$ in $B^- \to J/\psi\Lambda\bar{p}$

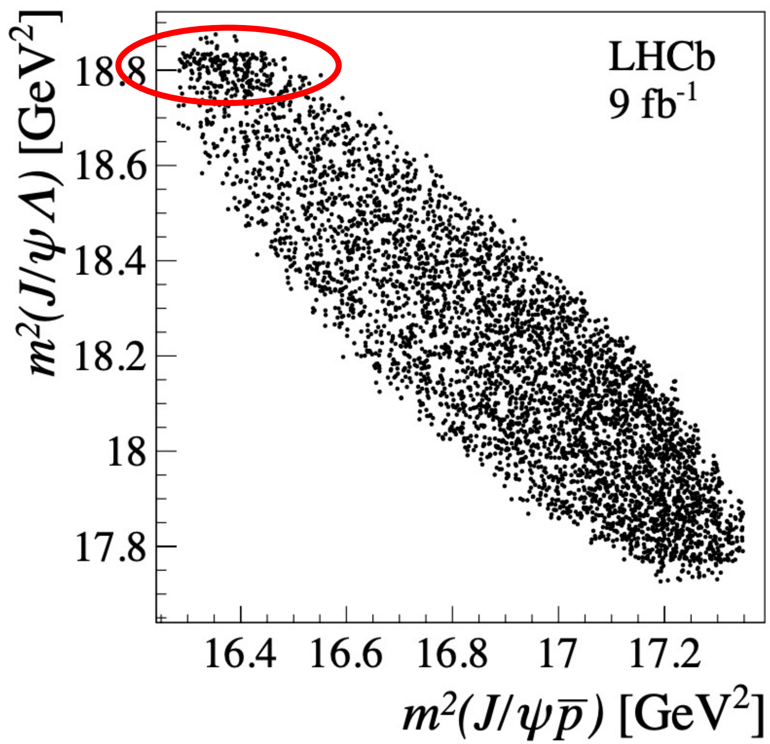
arXiv:2210.10346



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

- $J/\psi \to \mu^+\mu^-$, $\Lambda \to p\pi^-$



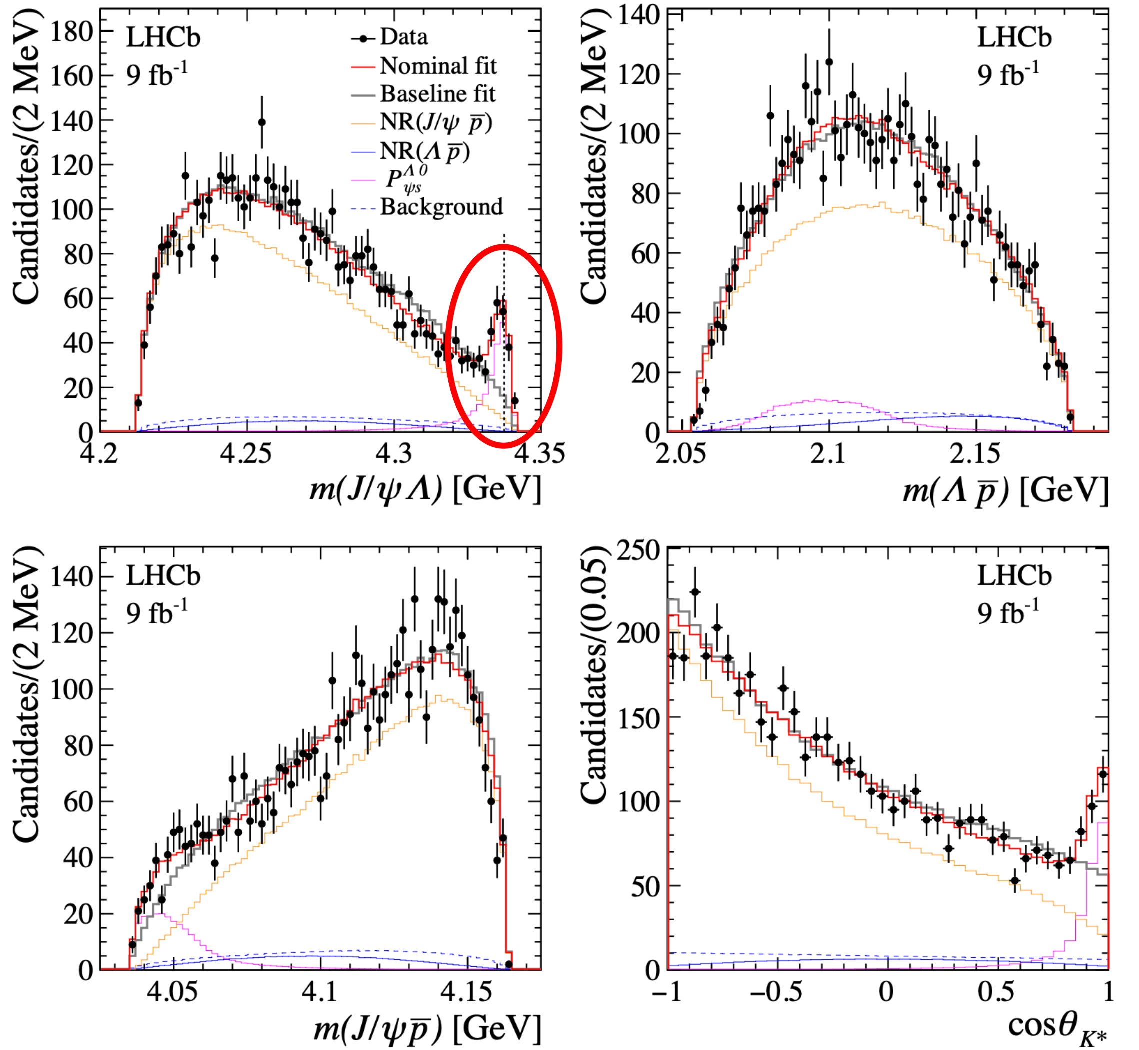


arXiv:2210.10346

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

- $P_{\psi s}^{\Lambda}(4338)^0$: $> 10\sigma$
  - $M_0 = 4338.2 \pm 0.7 \pm 0.4$ MeV
  - $\Gamma_0 = 7.0 \pm 1.2 \pm 1.3$ MeV
  - $J = \frac{1}{2}$
  - $P = -1$ is favored (+1 excluded at 90% CL)

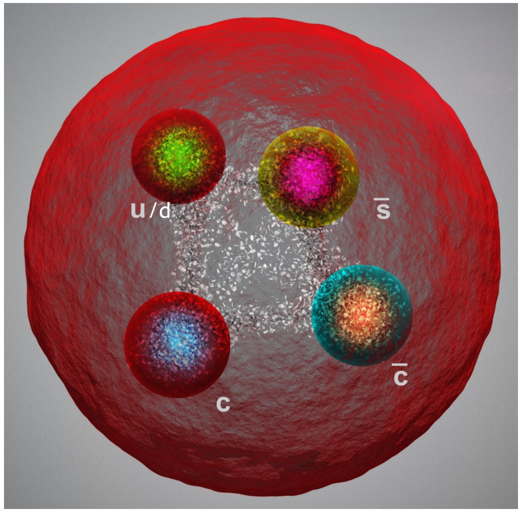
- Interesting facts:
  - Mass close to $\Xi_c^+ D^-$ threshold and in S-wave
  - Mass similar to $P_{\psi}^{N}(4337)$
    - Same pattern as $P_{\psi s}^{\Lambda}(4459)$ & $P_{\psi}^{N}(4457)$



Can fit in SU(3) flavor multiplets or are more likely a molecular state?

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

arXiv:2301.04899



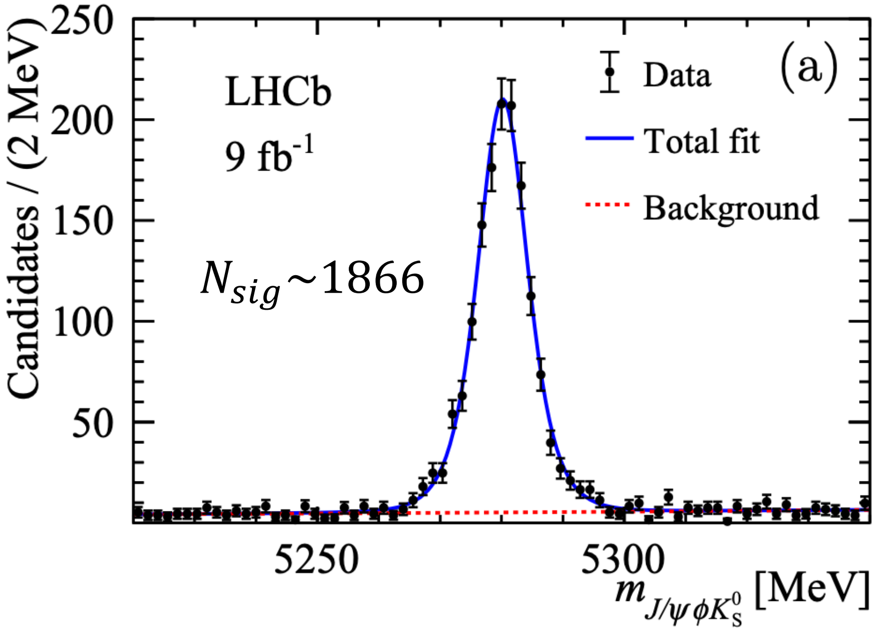
Isospin extention of $B^+ \to J/\psi K^+ \phi$ analysis where $c\bar{c}u\bar{s}$ tetraquarks $T^{\theta}_{\psi s1}(4000)^+$ and $T_{\psi s1}(4220)^+$ were observed

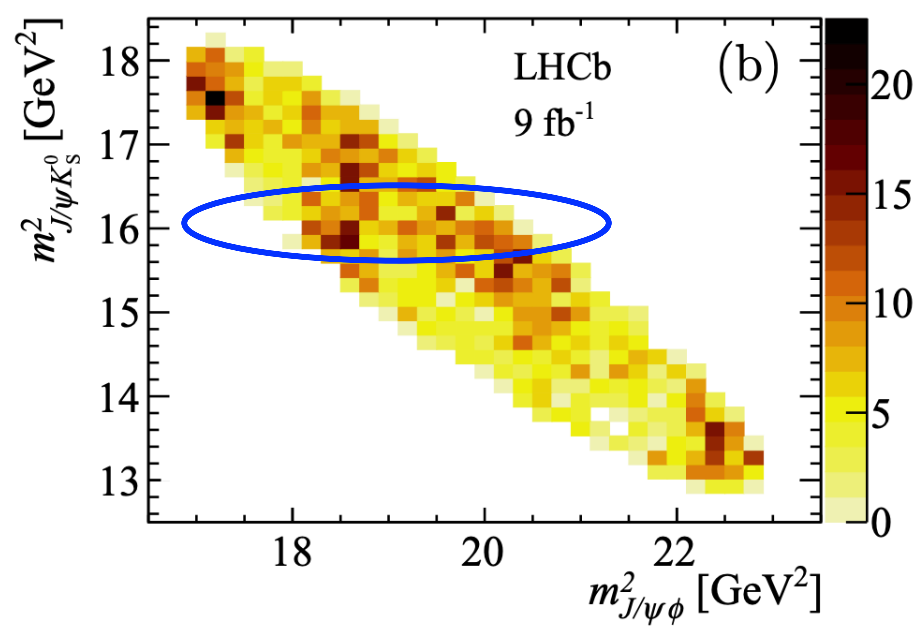
Phys. Rev. Lett. 127 (2021) 082001

arXiv:2301.04899

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

- $J/\psi \to \mu^+\mu^-;\ \phi \to K^+K^-;\ K_S^0 \to \pi^+\pi^-$

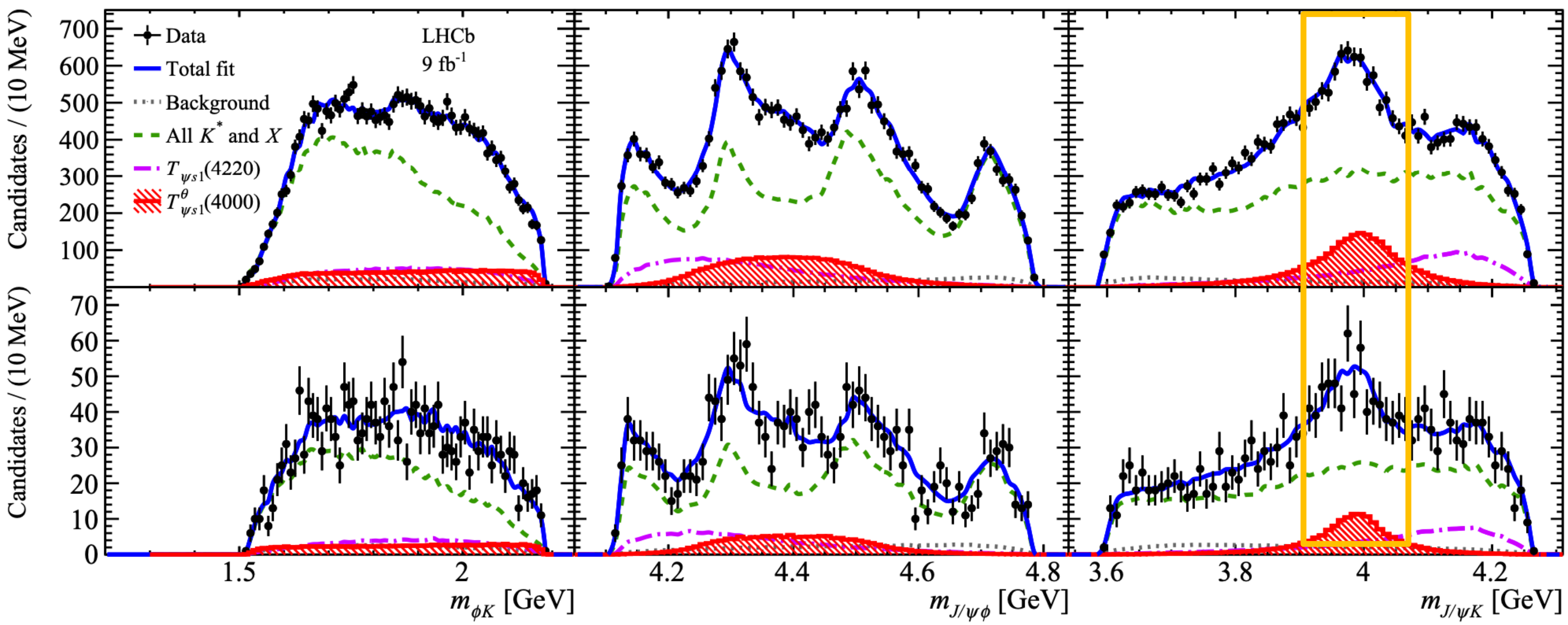




arXiv:2301.04899

Amplitude analysis

- $B^0 \to J/\psi K_S^0 \phi$ & $B^+ \to J/\psi K^+ \phi$ connected by isospin symmetry
- Combined fit to B^+ & B^0 decays
  - All components except $T_{\psi s1}^{\theta}(4000)^0$ in B^0 decay are constrained by those in B^+ decay



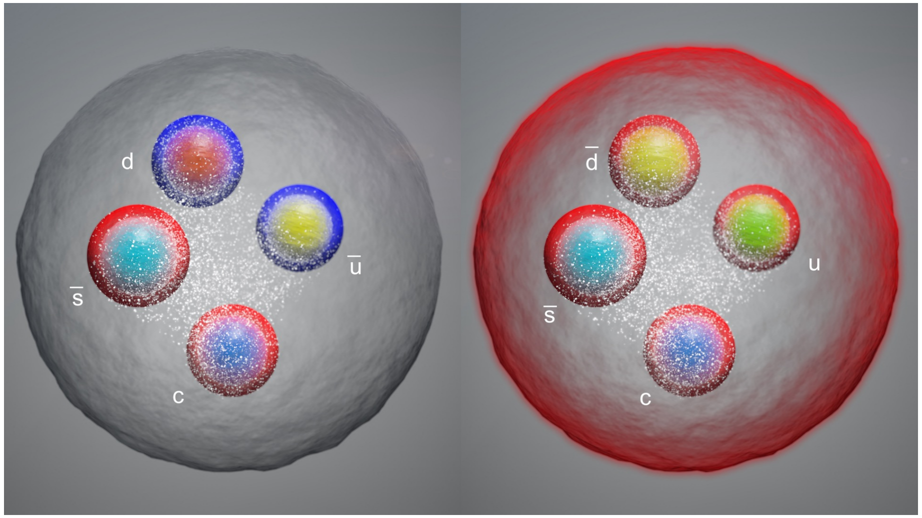
$$M(T_{\psi s1}^{\theta}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\,\mathrm{MeV}$$
$$\Gamma(T_{\psi s1}^{\theta}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}\,\mathrm{MeV}$$

Significance: 4σ

(would be 5.4σ if assuming isospin symmetry for $T_{\psi s1}^{\theta}(4000)^0$)

Observation of tetraquarks $T^{a}_{c\bar{s}0}(2900)^{++/0}$ in $B \to \bar{D} D_s^{+} \pi^{+/-}$

arXiv:2212.02717
arXiv:2212.02716

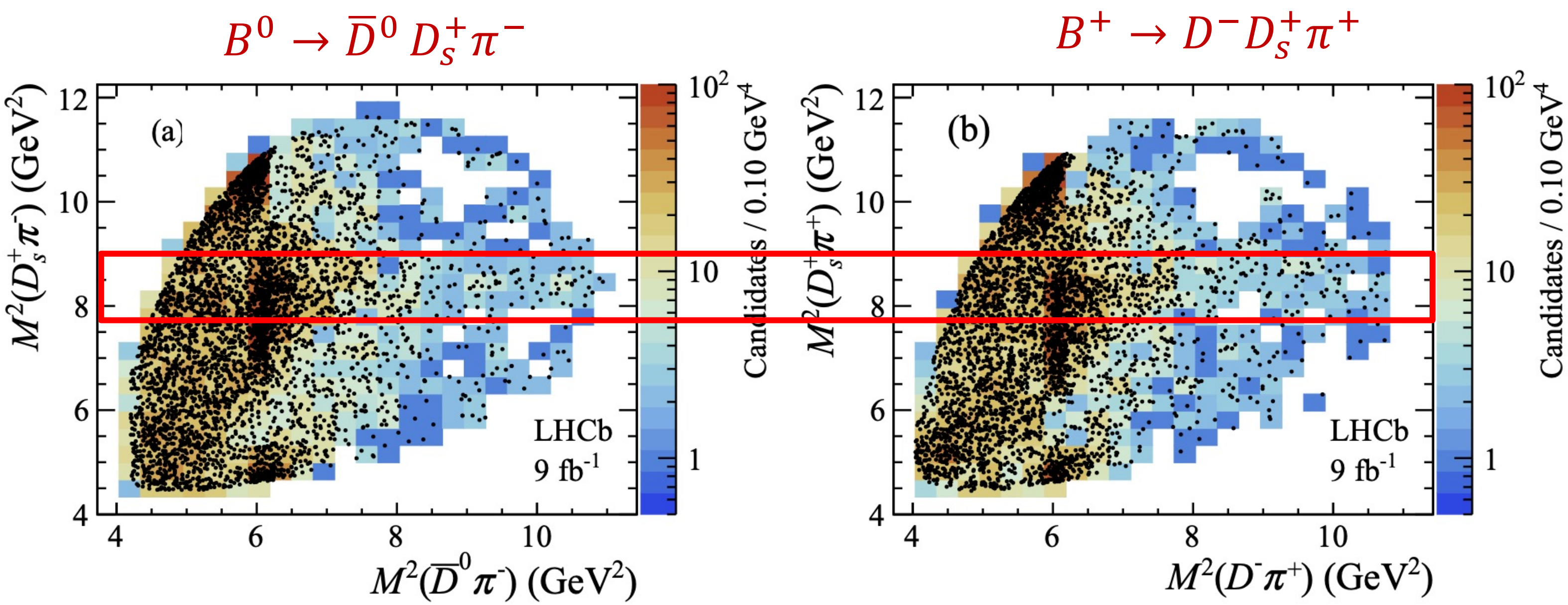


$B \to \bar{D} D_s^+ \pi^{+/-}$ dataset

arXiv:2212.02717
arXiv:2212.02716

- $D^- \to K^+\pi^-\pi^-$;   - $\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^+\pi^-$;   - $D_s^+ \to K^+K^-\pi^+$

- Signal yields:
  - $B^+ \to D^- D_s^+ \pi^+$: ~3751
  - $B^0 \to \bar{D}^0 D_s^+ \pi^-$: ~4008



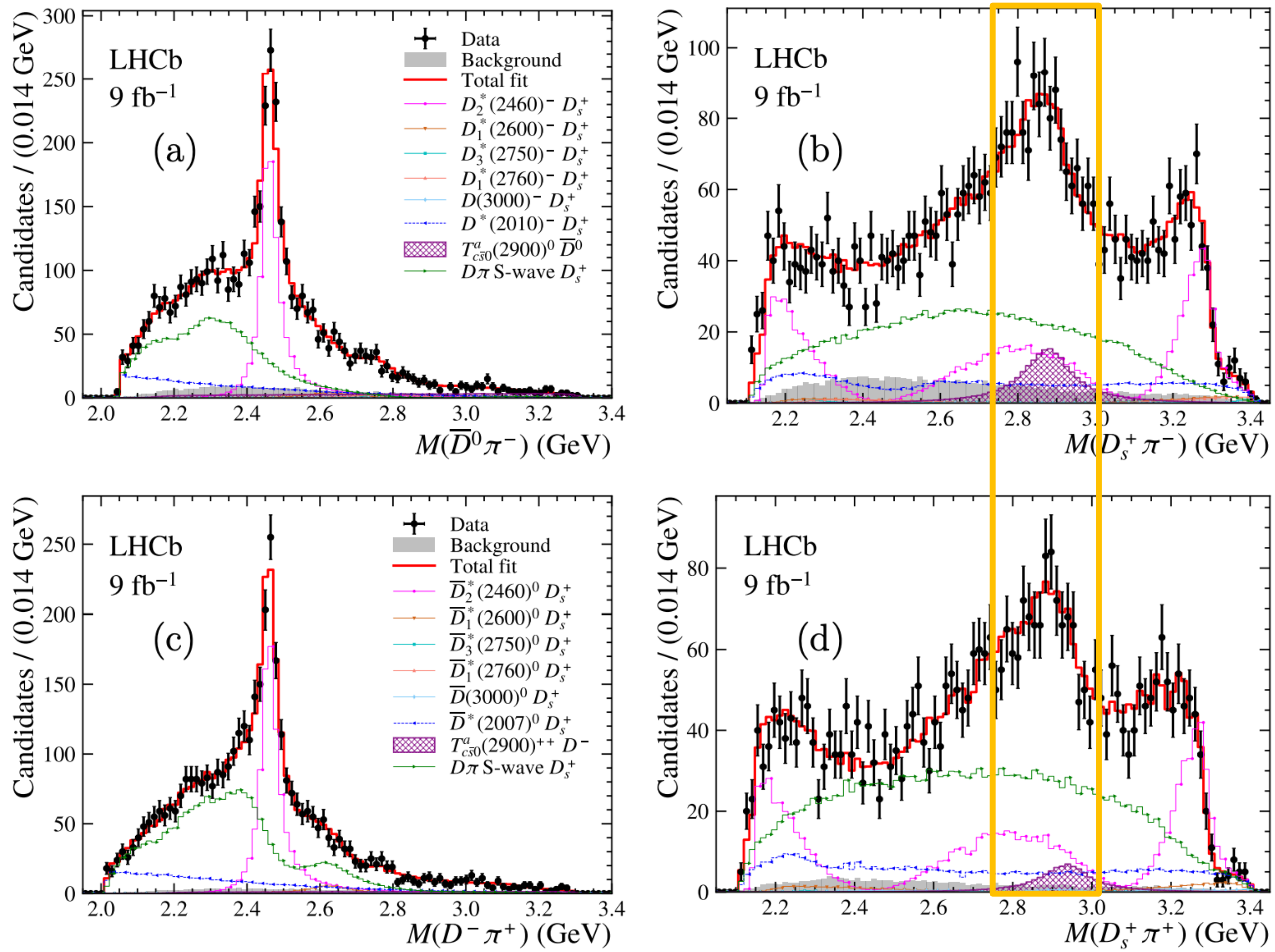
- Clear vertical band at $M^2(\bar{D}\pi)$~6 GeV^2 : $D_2^*(2460)$
- Faint horizonal band at $M^2(D_s\pi)$~8.5 GeV^2: new tetraquark candidates

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

arXiv:2212.02717
arXiv:2212.02716

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

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



- Isospin symmetry -> combined amplitude analysis to the two channels
  - $T^a_{c\bar{s}0}(2900)^{++/0}$: $> 9\sigma$; $J^P = 0^+$ $M = 2.908 \pm 0.011 \pm 0.020\,\mathrm{GeV}$

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

Discussions on $T^{a}_{c\bar{s}0}(2900)^{++/0}$

arXiv:2212.02717
arXiv:2212.02716

- $T^{a}_{c\bar{s}0}(2900)^{++}$ & $T^{a}_{c\bar{s}0}(2900)^{0}$ in isospin triplet
  - Where is $T^{a}_{c\bar{s}0}(2900)^{+}$? -> be searched for in $D_s^+\pi^0$

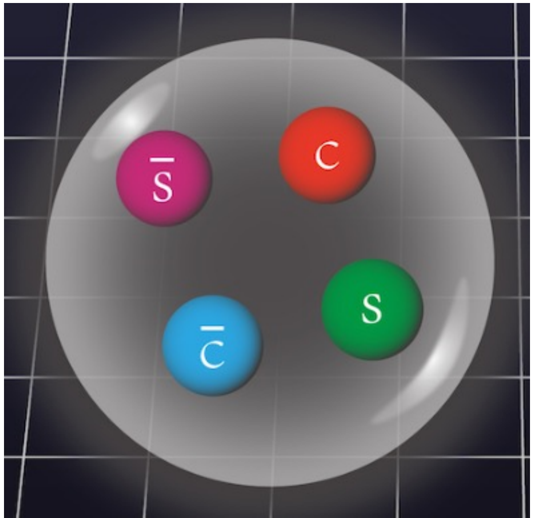
$T_{cs0}(2900) \equiv X_0(2900)$

- $T^{a}_{c\bar{s}0}(2900)$ & $T_{cs0}(2900)$ have similar masses
  - Are they SU(3) flavor partners?
  - Where are other states in the SU(3) multiplets?

Remain to be revealed in future studies

A near-threshold $D_s^+ D_s^-$ structure in $B^+ \to D_s^+ D_s^- K^+$

arXiv:2210.15153
arXiv:2211.05034

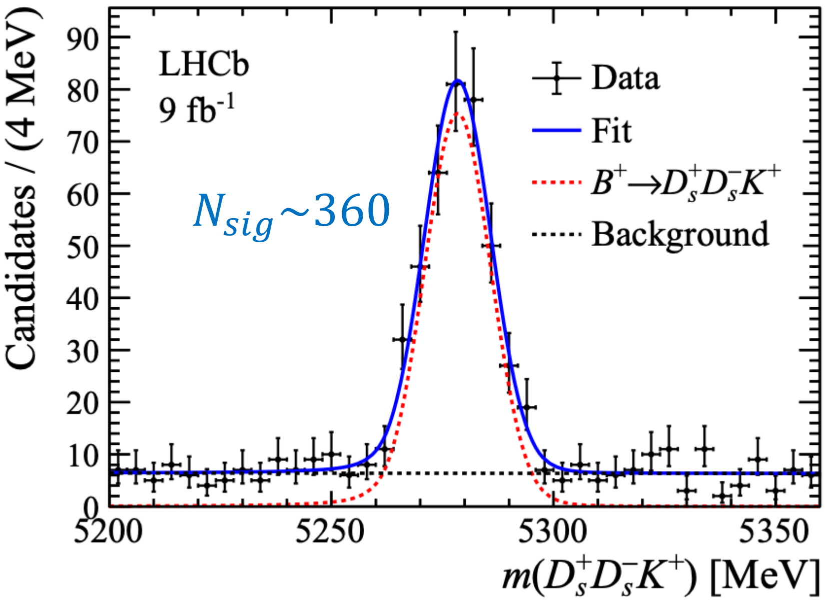


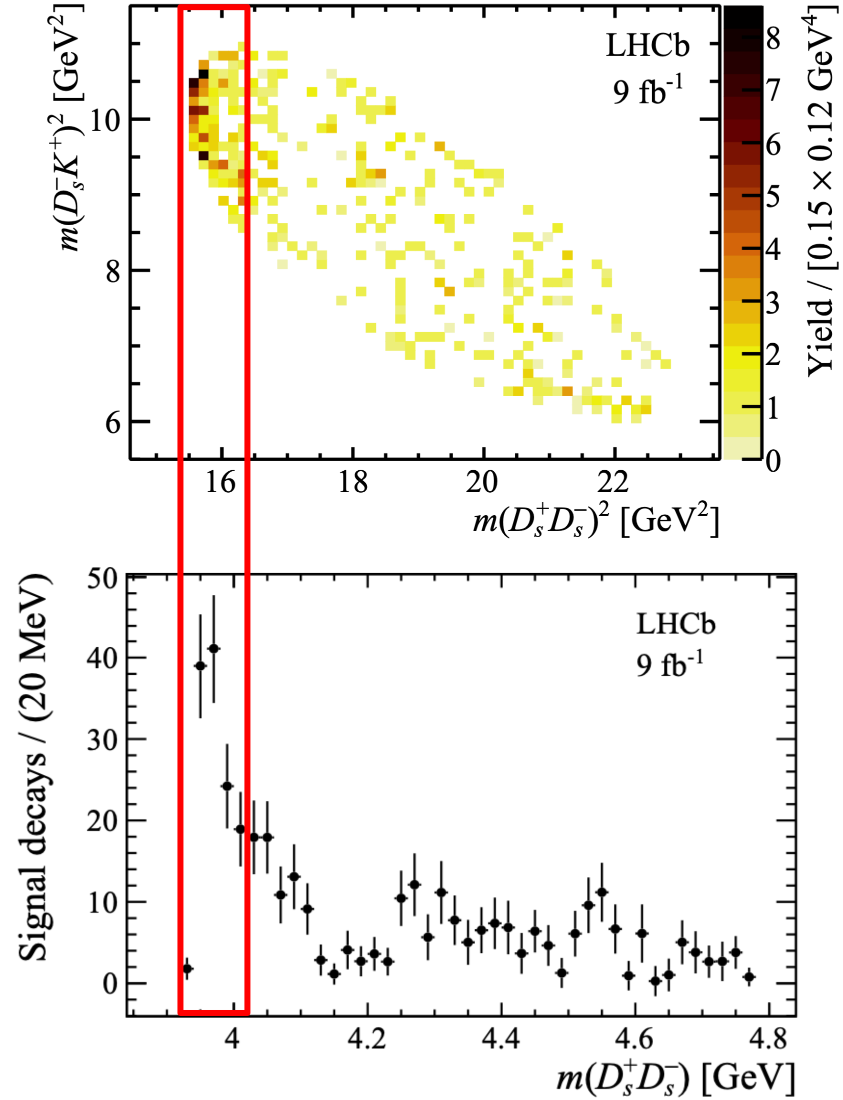
?

Observation of $B^+ \to D_s^+ D_s^- K^+$

arXiv:2210.15153
arXiv:2211.05034

$D_s^\pm \to K^\mp K^\pm \pi^\pm$



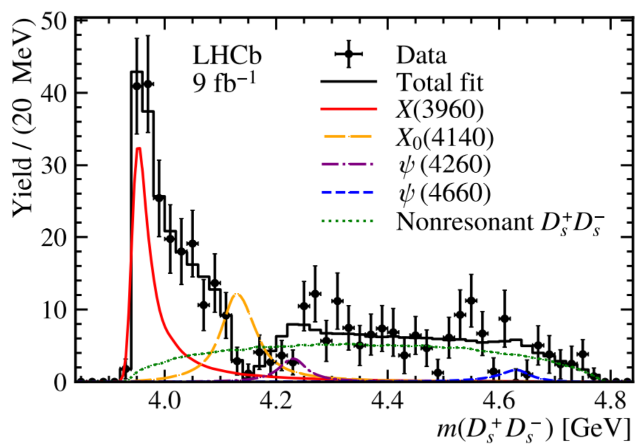


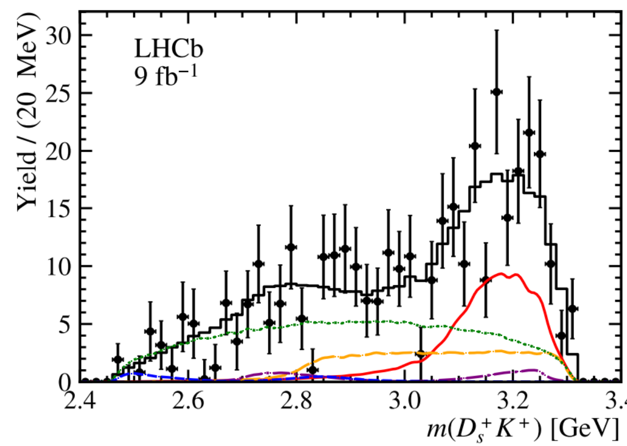
$$\mathcal{B}(B^+ \to D_s^+ D_s^- K^+) = (1.15 \pm 0.07 \pm 0.06 \pm 0.38) \times 10^{-4}$$

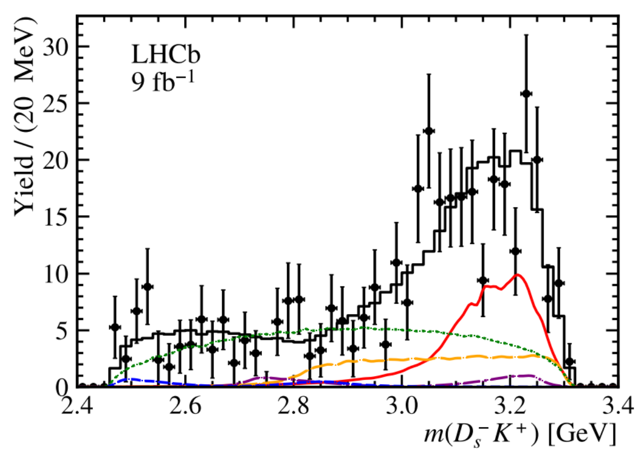
Observation of $X(3960)$ in $D_s^+ D_s^-$

arXiv:2210.15153
arXiv:2211.05034

- Two new states with $J^{PC} = 0^{++}$:
  - $X(3960)$: to describe the near-threshold peak $> 12\sigma$
  - $X_0(4140)$: to account for the dip at ~ 4.14 GeV via interference $> 3\sigma$







Background subtracted

RBW mass lineshape for all resonances

$X(3960)$ vs $\chi_{c0}(3930)$

arXiv:2210.15153
arXiv:2211.05034

- $X(3960)$: $M_0 = 3955 \pm 6 \pm 11$ MeV; $\Gamma_0 = 48 \pm 17 \pm 10$ MeV; $J^{PC} = 0^{++}$
- $\chi_{c0}(3930)$: $M_0 = 3924 \pm 2$ MeV; $\Gamma_0 = 17 \pm 5$ MeV; $J^{PC} = 0^{++}$

Phys.Rev.D102(2020) 112003, Phys. Rev. Lett. 125 (2020) 242001

- Are they the same particle? If yes

$$\frac{\Gamma(X \to D^+D^-)}{\Gamma(X \to D_s^+D_s^-)} = \frac{\mathcal{B}(B^+ \to D^+D^-K^+)\,\mathcal{FF}^X_{B^+ \to D^+D^-K^+}}{\mathcal{B}(B^+ \to D_s^+D_s^-K^+)\,\mathcal{FF}^X_{B^+ \to D_s^+D_s^-K^+}}$$

$$= 0.29 \pm 0.09\,(\text{stat}) \pm 0.10\,(\text{syst}) \pm 0.08\,(\text{ext})$$

$\mathcal{FF}$: Fit fractions in the two B^+ decays

- $\Gamma(X \to D^+D^-) < \Gamma(X \to D_s^+D_s^-)$ -> exotic $\quad T^f_{\psi\phi 0}(39xx)$
  - Conventional charmonium predominantly decays into $D^{(*)}\bar{D}^{(*)}$
    - It is harder to excite an $s\bar{s}$ pair from vacuum compared with $u\bar{u}(d\bar{d})$

- What can we do in the future?

- Precision measurements of $X(3960)/\chi_{c0}(3930)$ properties -> to see if they are really the same particle

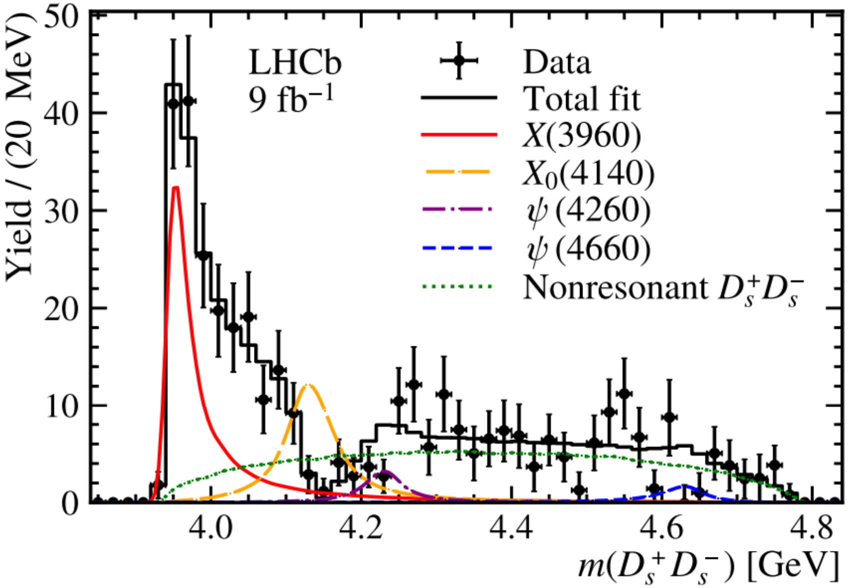
- $X(3960)/\chi_{c0}(3930)/\chi_{c0}(3915) \to J/\psi\omega$ -> more input to help reveal the nature of this state

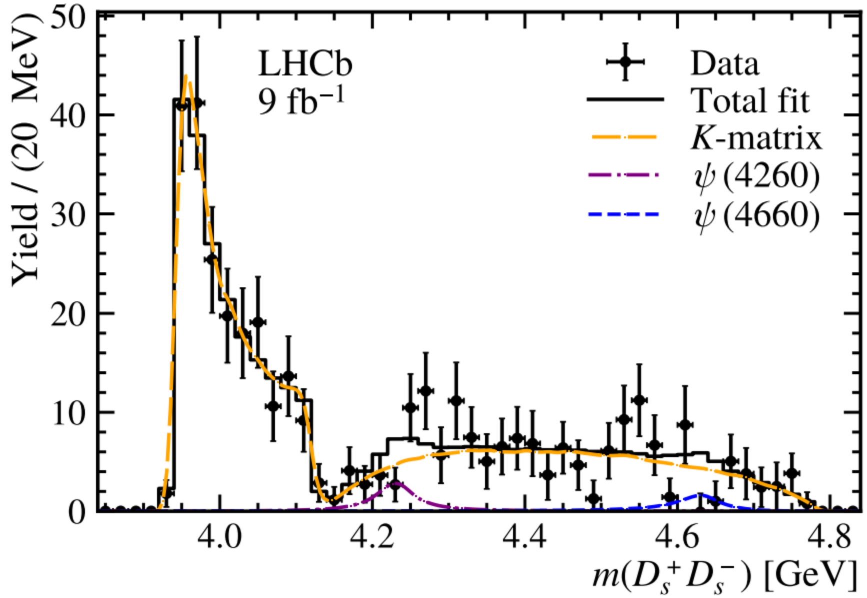
- E.g. $B \to J/\psi\omega K$

Look again at $X_0(4140)$

arXiv:2210.15153
arXiv:2211.05034

Background subtracted





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 $X_0(4140)$

Observation of $B^+ \to J/\psi\eta' K^+$

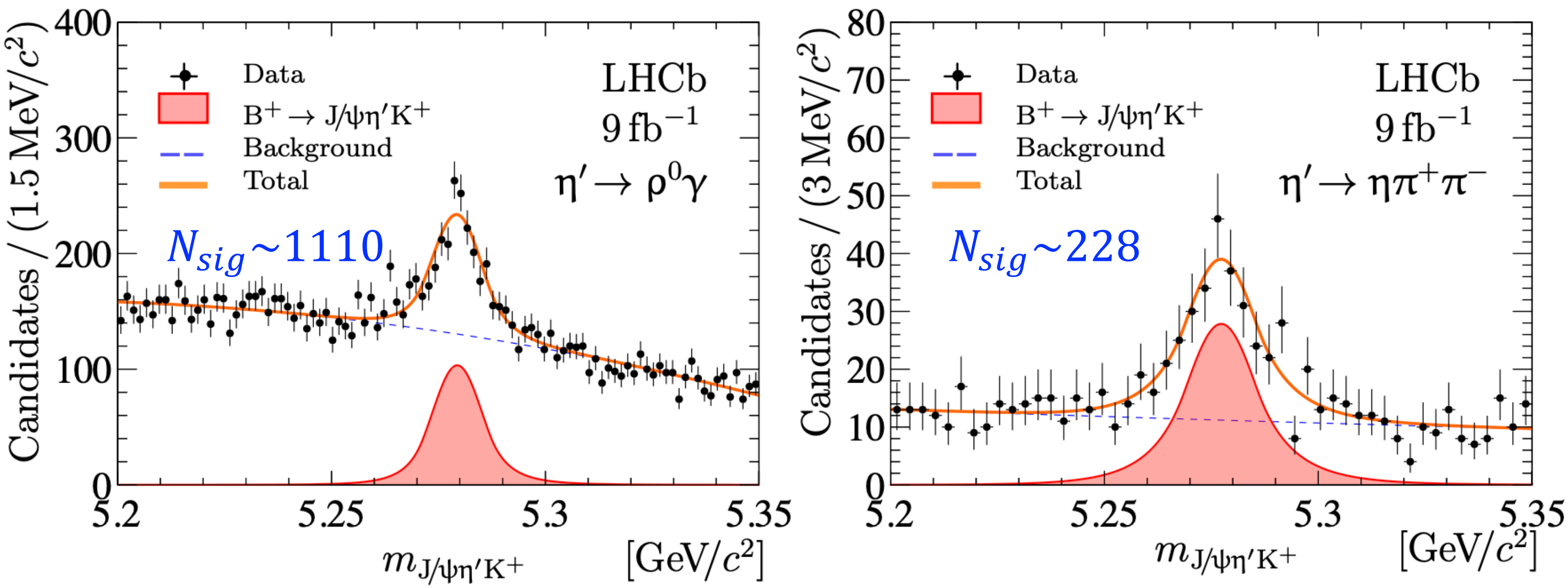
arXiv:2303.09443

Opportunity to investigate exotic resonances in $J/\psi\eta'$ and $J/\psi K^+$ systems

arXiv:2303.09443

Observation of $B^+ \to J/\psi\eta' K^+$

- $B^+ \to J/\psi\eta' K^+,\ \ J/\psi \to \mu^+\mu^-$
  - $\eta' \to \rho^0(\to \pi^+\pi^-)\gamma$
  - $\eta' \to \eta(\to 2\gamma)\pi^+\pi^-$

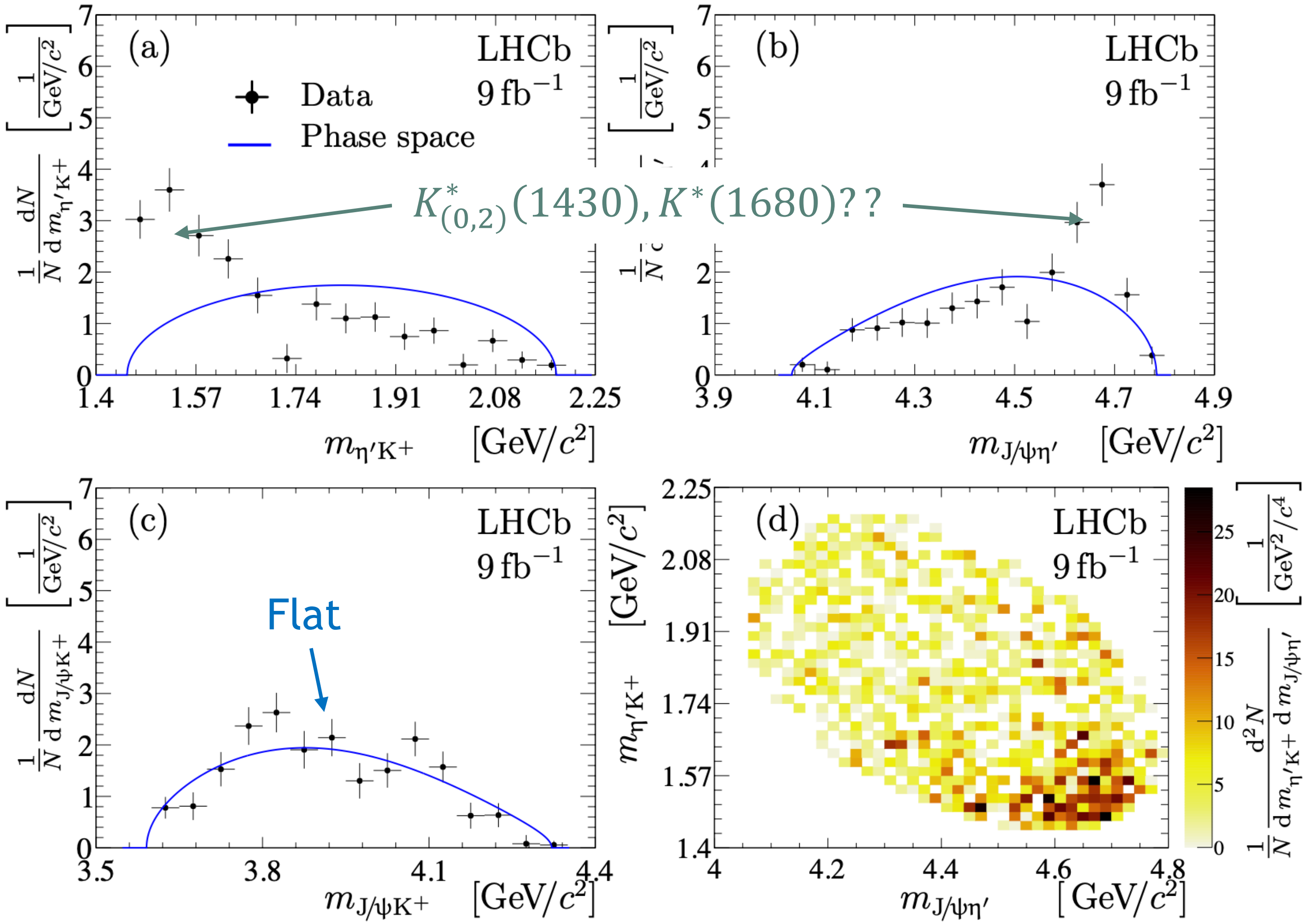


$$\mathcal{B}(B^+ \to J/\psi\eta' K^+) = (3.06 \pm 0.29 \pm 0.18 \pm 0.04) \times 10^{-5}$$

Investigation of phase space

arXiv:2303.09443

Background subtracted



No hint of exotic in $m(J/\psi\eta')$ or $m(J/\psi K^+)$

But let's wait for more data !!

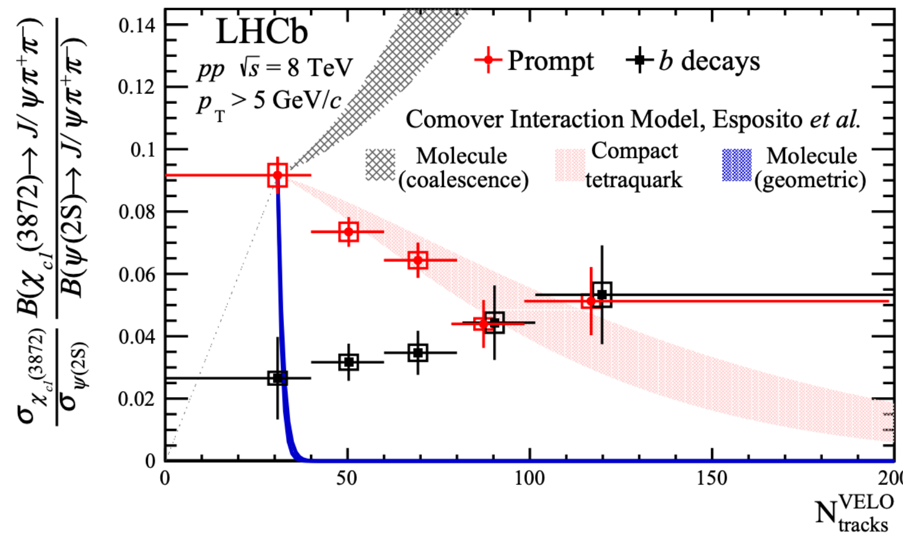
Observation of $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$

arXiv:2302.10629

Probing $\chi_{c1}(3872)$ nature via production

- Prompt: multiplicity dependence
  - Compact scheme is favored by the $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ trend

Phys. Rev. Lett. 126 (2021) 092001



- B decays:
  - Puzzling difference in $\mathcal{B}(B^+ \to \chi_{c1}(3872)K^+)$ [$(2.1 \pm 0.7)\times10^{-4}$] and $\mathcal{B}(B^0 \to \chi_{c1}(3872)K^0)$ [$(1.1 \pm 0.4)\times10^{-4}$]

PDG2022

  - But similar $\mathcal{B}(B^0 \to \chi_{c1}(3872)K^0)$ [$(1.1 \pm 0.4)\times10^{-4}$] and $\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\phi)$
  - The above two phenomena could be explained by a compact-tetraquark interpretation

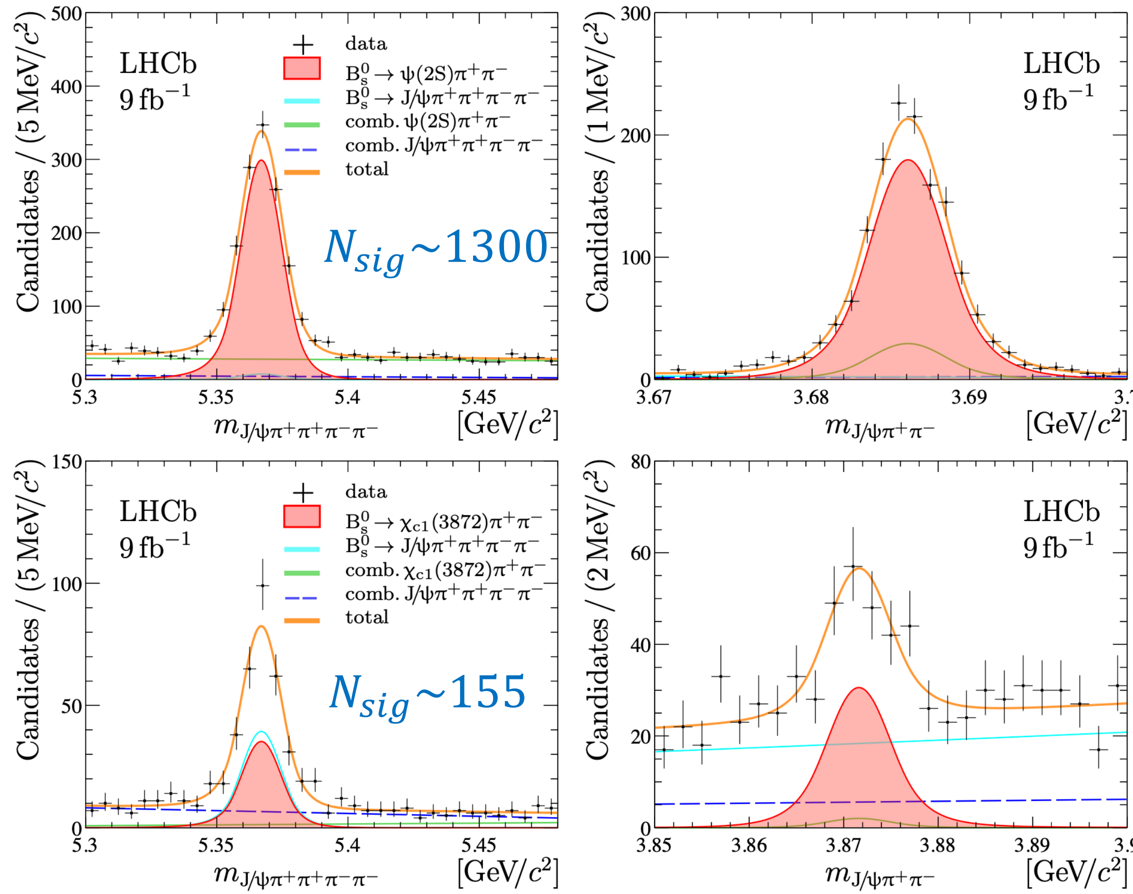
Phys. Rev. D102 (2020) 034017

Let's investigate more B-hadron decays!

arXiv:2302.10629

$B_s^0 \to \chi_{c1}(3872)(\to J/\psi\pi^+\pi^-)\pi^+\pi^-$

- Signal yield determined from 2D mass fit



$$\frac{\mathcal{B}(B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-)}{\mathcal{B}(B_s^0 \to \psi(2S)\pi^+\pi^-) \times \mathcal{B}(\psi(2S) \to J/\psi\pi^+\pi^-)} = (6.8 \pm 1.1 \pm 0.2) \times 10^{-2}$$

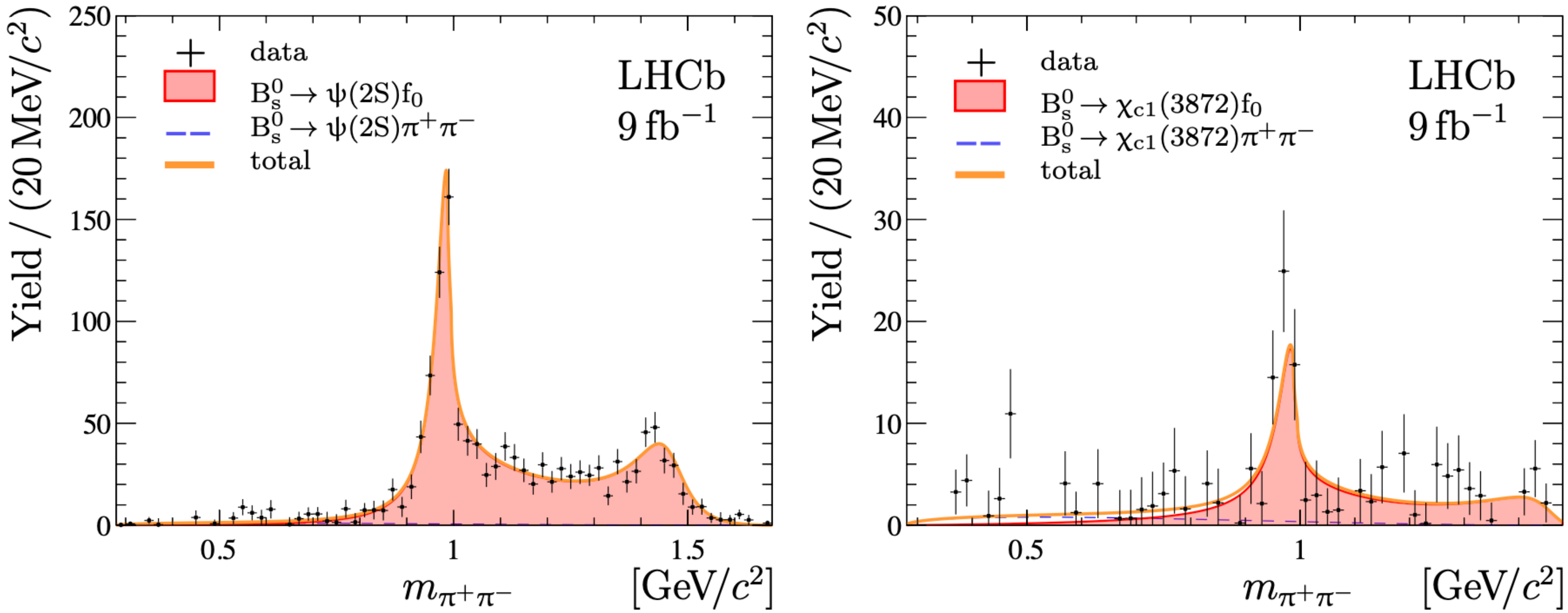
Three times of the ratio: $\mathcal{R}^{\chi_{c1}(3872)\phi}_{\psi(2S)\phi} = (2.42 \pm 0.23 \pm 0.07) \times 10^{-2}$

JHEP 02 (2021) 024

arXiv:2302.10629

The recoiled $\pi^+\pi^-$ mass

Background subtracted



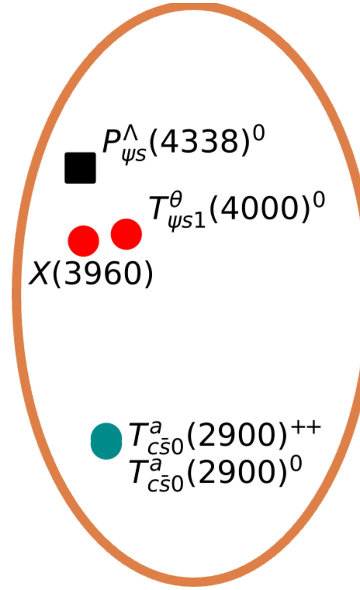
$$F(m) \propto mqp^3 \left| f \mathcal{A}_{f_0(980)}(m) + e^{i\varphi} \mathcal{A}_{f_0(1500)}(m) \right|^2$$ + Phase space contribution

- Similar to $B_s^0 \to J/\psi\pi^+\pi^-$ and $B_s^0 \to \psi(2S)\pi^+\pi^-$

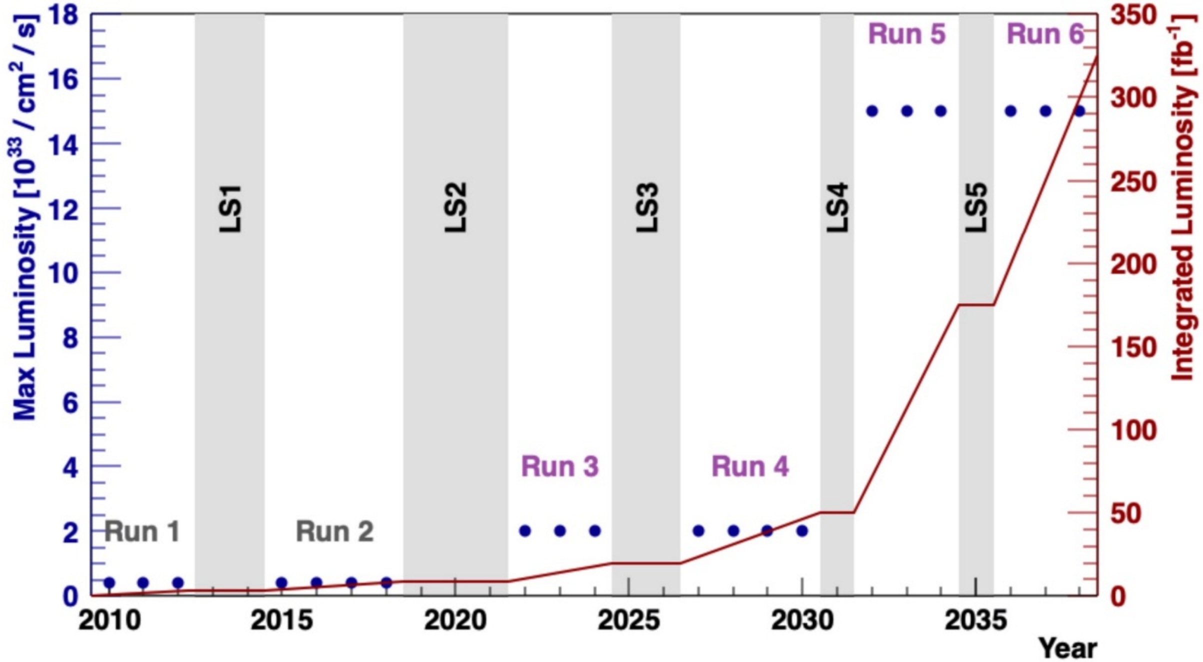
- Observation of $B_s^0 \to \chi_{c1}(3872) f_0(980)$: $> 7\sigma$

Amplitude measurement urges for more data !!

Summary and prospects



- Recent exotic candidates at LHCb
- Observations of new B decays show potential for future exotic studies
  - $B^+ \to J/\psi \eta' K^+$
  - $B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$
- More LHCb data will provide new opportunities



Thank you for your attention!

Backup slides

New exotic naming scheme

arXiv:2206.15233

- T for tetraquark
- P for pentaquark
- **superscript**: based on existing symbols, to indicate isospin, parity and G-parity
- **subscript**: heavy quark content

T states
zero net S, C, B

(P,G)	$I=0$	$I=1$
$(-,-)$	ω	π
$(-,+)$	η	ρ
$(+,+)$	f	b
$(+,-)$	h	a

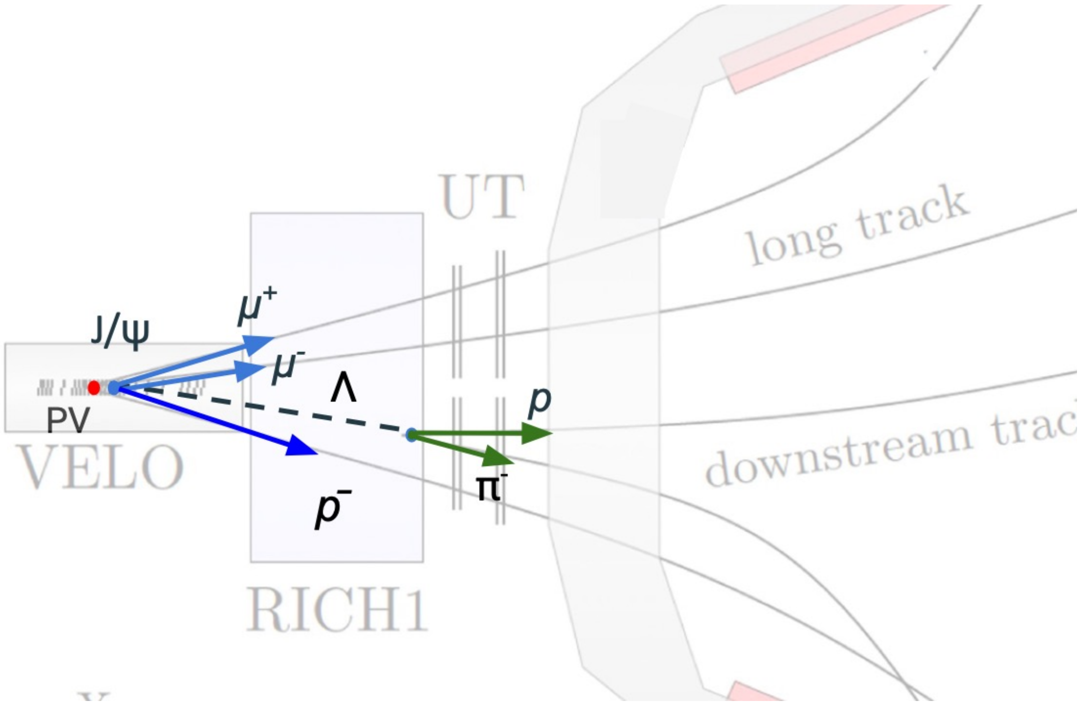
T states
non-zero net S, C, B

(P)	$I=0$	$I=\frac{1}{2}$	$I=1$
$(-)$	η	τ	π
$(+)$	f	θ	a

P states

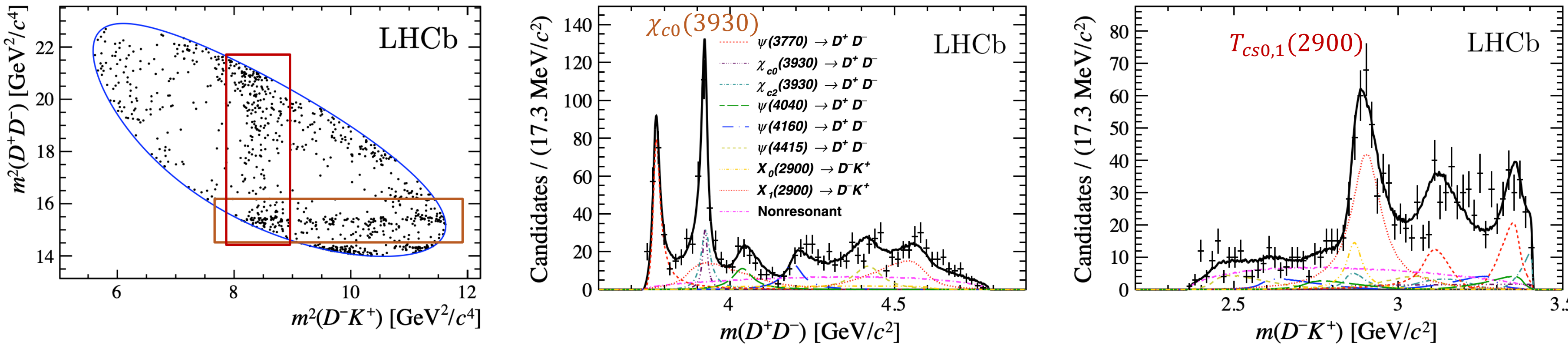
$I=0$	$I=\frac{1}{2}$	$I=1$	$I=\frac{3}{2}$
Λ	N	Σ	Δ

Minimal quark content	Current name	$I^{(G)}$, $J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G=0^+$, $J^{PC}=1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi1}(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G=1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\psi1}(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G=0^+, J^{PC}=1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I=\frac{1}{2}$, $J^P=1^+$	$T^\theta_{\psi s1}(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I=\frac{1}{2}$, $J^P=1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G=0^+$, $J^{PC}=?^{?+}$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P=0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P=1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G=1^+$, $J^P=1^+$	$T^b_{\Upsilon1}(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I=\frac{1}{2}$	$P^N_\psi(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I=0$	$P^\Lambda_{\psi s}(4459)^0$	[20]


UT
long track
J/ψ
μ+
μ-
Λ
p
PV
VELO
p̄
π-
downstream trac
RICH1

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

Phys.Rev.D102(2020) 112003
Phys. Rev. Lett. 125 (2020) 242001



$T_{cs0,1}(2900) \to D^- K^+$: first $cs\bar{u}\bar{d}$ tetraquarks arXiv:2204.02649

- Some models predict its SU(3) flavour partners, e.g. $T_{c\bar{s}} \to D_s \pi$?

Searched for in $B \to \bar{D} D_s \pi$

$\chi_{c0}(3930) \to D^+ D^-$:

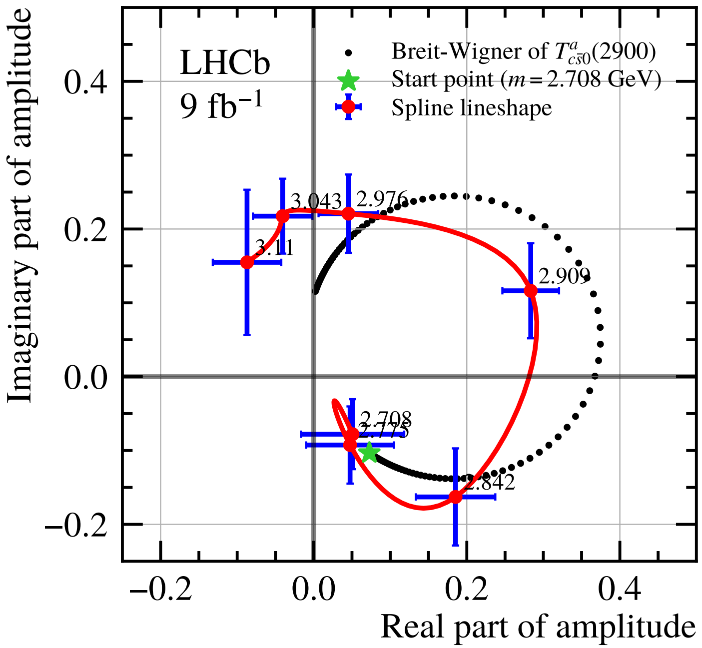
- It is suggested to be the same particle as $\chi_{c0}(3915) \to J/\psi\omega$ PDG 2020
- Some theories suggest that it is a $c\bar{c}s\bar{s}$ tetraquark candidate

JHEP 06 (2021) 035
Sci. Bull., 2021, 66: 1413

Search for $\chi_{c0}(3930) \to D_s^+ D_s^-$ in $B^+ \to D_s^+ D_s^- K^+$

$T^{a}_{c\bar{s}0}(2900)$ Argand plot

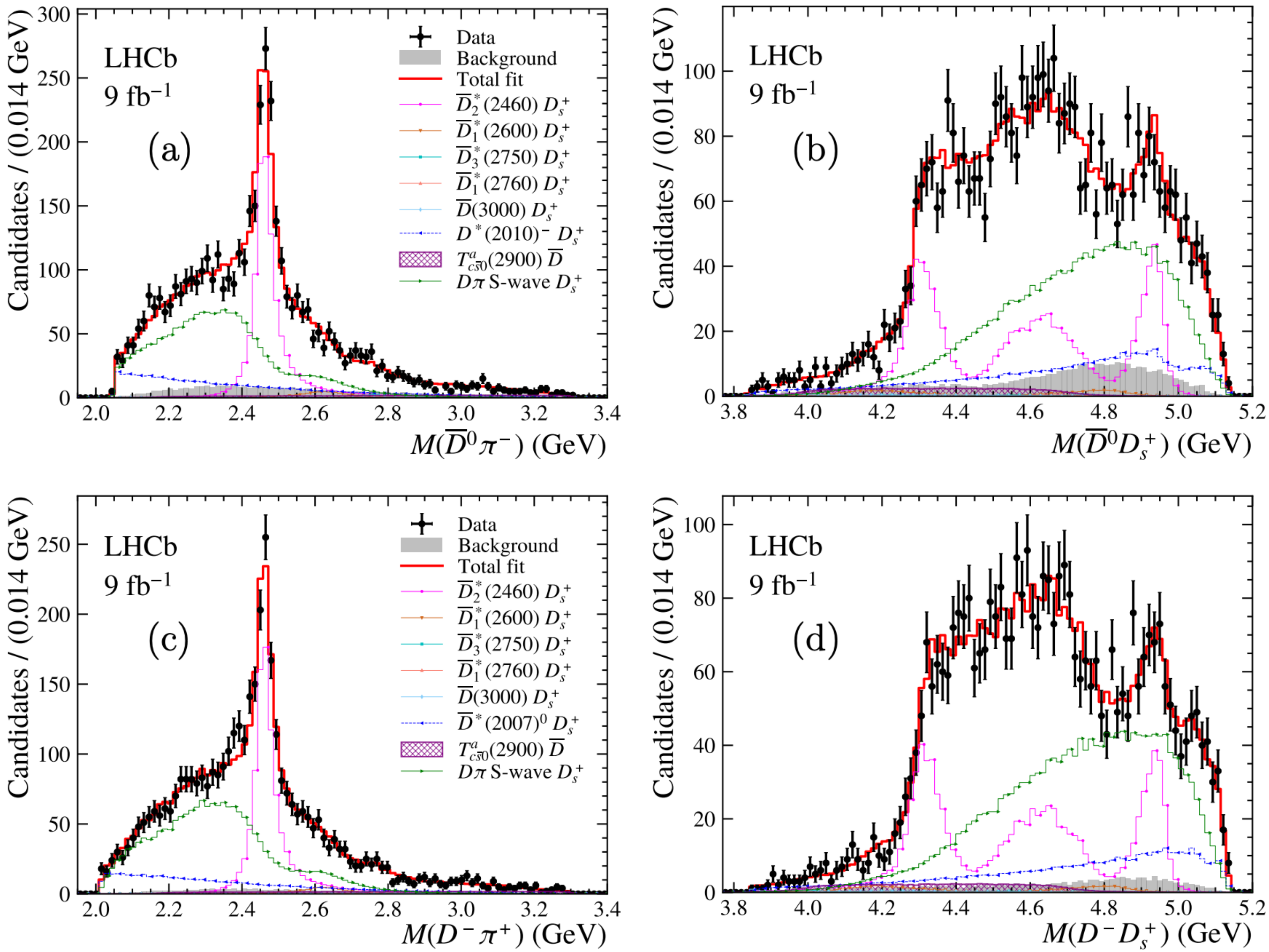
arXiv:2212.02717
arXiv:2212.02716



Spline and BW models both go anticlockwise
->
Support the resonant nature of $T^{a}_{c\bar{s}0}(2900)$

Other projections

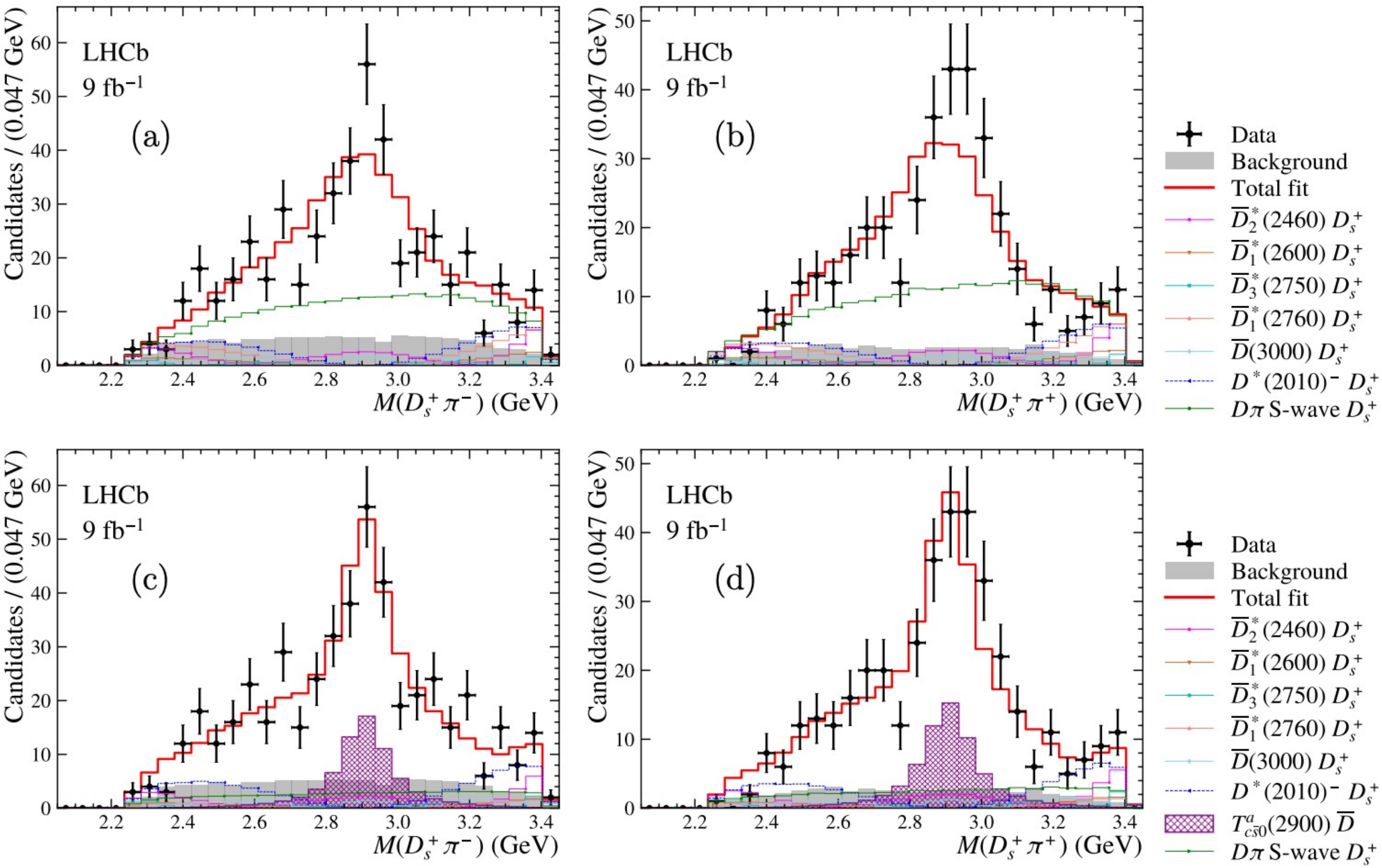
arXiv:2212.02717
arXiv:2212.02716



Other projections

arXiv:2212.02717
arXiv:2212.02716

$m(\overline{D}\pi) > 2.7$ GeV



$B^+ \to D_s^+ D_s^- K^+$ fit results

arXiv:2210.15153
arXiv:2211.05034

- $\mathcal{F}$: fit fraction
- $\mathcal{S}$: significance

(numbers in brackets don not include systematic effect)

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (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	55	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633	64	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

- Fixed parameters taken from PDG 2018/2020 ($\psi(4260)$ is $\psi(4230)$ in PDG2022)

- Spin-parity tests:
  - $X(3960)$: 0^{++} favored; 1^{--} and 2^{++} rejected by at least 9σ
  - $X_0(4140)$: 0^{++} favored; 1^{--} and 2^{++} rejected by at least 3.5σ

K-matrix model for $X(3960)$

arXiv:2210.15153
arXiv:2211.05034

$$\begin{pmatrix} \mathcal{M}_{D_s^+D_s^-\to D_s^+D_s^-} & \mathcal{M}_{D_s^+D_s^-\to J/\psi\phi} \\ \mathcal{M}_{J/\psi\phi\to D_s^+D_s^-} & \mathcal{M}_{J/\psi\phi\to J/\psi\phi} \end{pmatrix} \equiv \begin{pmatrix} \mathcal{K}_{11} & \mathcal{K}_{12} \\ \mathcal{K}_{21} & \mathcal{K}_{22} \end{pmatrix}$$

$$\mathcal{K}_{ab}(m) = \sum_R \frac{g_b^R g_a^R}{M_R^2 - m^2} + f_{ab}$$

$$\mathcal{P}_b(m) = \sum_R \frac{\beta_R g_b^R}{M_R^2 - m^2} + \beta_b$$

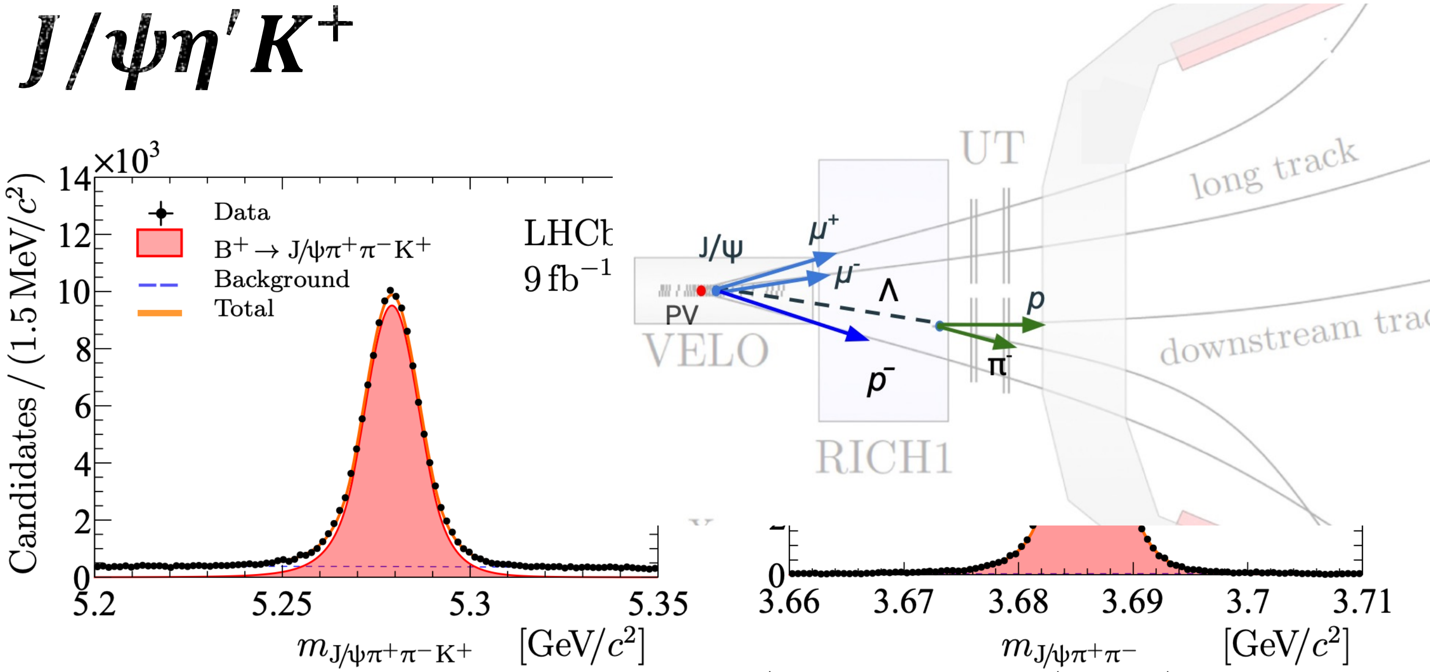
$$\mathcal{M}_a = \sum_b (I - i\rho\mathcal{K})^{-1}_{ab}\mathcal{P}_b$$

Contribution	J^{PC}	M_R (MeV)	g_1^R (MeV)	Γ_ψ (MeV)	$\mathcal{F}$ (%)
$\lvert\mathcal{M}_1\rvert^2$	0^{++}	3957 ± 14	1350 ± 344		94.7 ± 0.4
$\psi(4260)$	1^{--}	4230 [59]		55 [59]	3.2 ± 0.5
$\psi(4660)$	1^{--}	4633 [31]		64 [31]	2.1 ± 0.2

β_R	$(1, 0i)$	β_1	$(-1.2, 2.5i) \pm (4.5, 3.1i)$
β_2	$(-137.2, -1.5i) \pm (2.7, 218.6i)$	f_{11}	0.8 ± 1.2
$f_{12} = f_{21}$	0.1 ± 0.1	f_{22}	8.0 ± 5.1

Large uncertainties. Larger data sample is needed

$B^+ \to J/\psi \eta' K^+$



$$\frac{\mathcal{B}(B^+ \to J/\psi\eta' K^+)}{\mathcal{B}(B^+ \to \psi(2S)K^+)} = (4.91 \pm 0.47 \pm 0.29 \pm 0.07) \times 10^{-2}$$

Source	Value [%]
B^+ kinematics	0.1
B^+ decay model	1.1
Tracking efficiency correction	0.7
Photon reconstruction correction	3.6
Kaon identification	2.8
Trigger efficiency	1.1
Data-simulation agreement	3.0
Fit model	1.6
Simulation sample size	0.9
Total	6.0