New exotics from B-decay

On behalf of LHCb Collaboration

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16TH INTERNATIONAL WORKSHOP ON HEAVY QUARKONIUM (QWG 2024)

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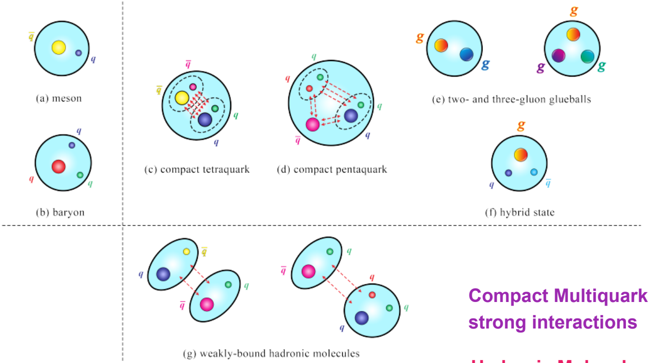
Hadrons

1. **Conventional States** : states well understood phenomenologically in the Quark Model i.e. $q\bar{q}$ and qqq.
2. **Exotics** : $qq\overline{qq}$, $qq\bar{q}qq$, unconventional J^{PC}, glue balls...

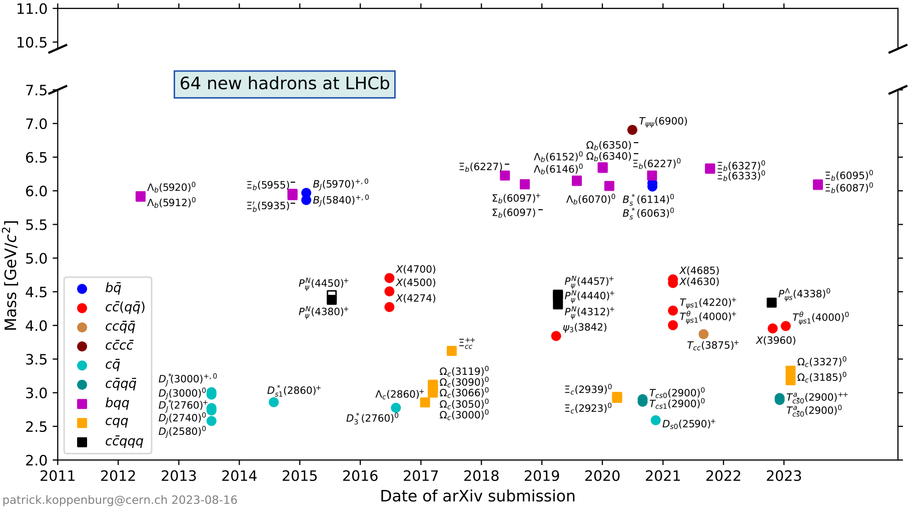


Compact Multiquark : Tightly bound directly by strong interactions

Hadronic Molecular : Weakly bound by residual strong interaction

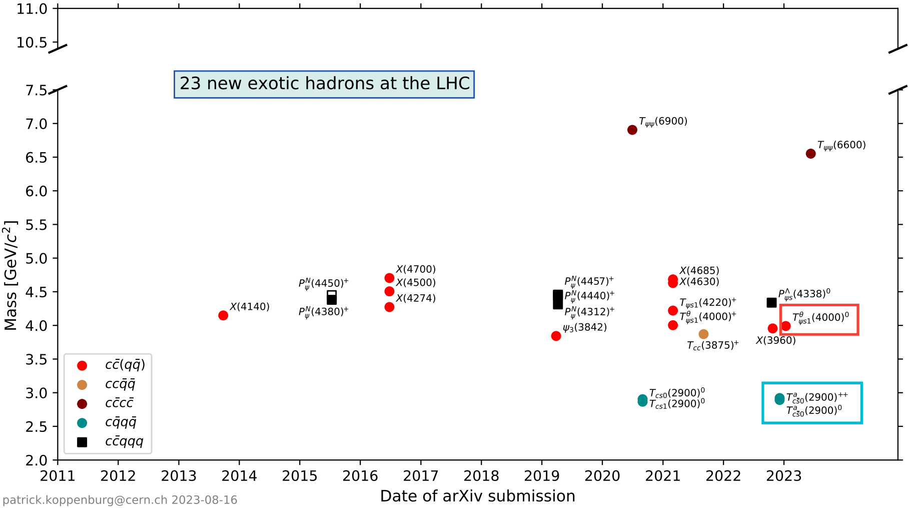
[Rep. Prog. Phys. 86 026201(2023)]

Hadron Spectroscopy at LHCb



https://www.nikhef.nl/~pkoppenb/particles.html

Exotics at LHCb



https://www.nikhef.nl/~pkoppenb/particles.html

Improved Naming Convention

[arXiv:2205.15233]

- T for tetra-quark : Mesons
- P for penta-quark : Baryons
- Superscript: isospin, parity and G-parity
- Subscript : Heavy quark content
  - b, c, s : open flavours
  - $c\bar{c}$, $b\bar{b}$: hidden beauty, charm strange
- No change in name if not unambiguously declared exotic.

2024 Name	minimal quark content	$I^{(G)}(J^{P(C)})$	2022 Name
$T^*_{cs0}(2870)^0$	$cs\bar{u}\bar{d}$	$?(0^+)$	$X_0(2900)$
$T^*_{cs1}(2900)^0$	$cs\bar{u}\bar{d}$	$?(1^-)$	$X_1(2900)$
$T^*_{c\bar{s}0}(2900)^{++}$	$c\bar{s}u\bar{d}$	$1(0^+)$	
$T_{cc}(3875)^+$	$cc\bar{u}\bar{d}$	$?(?^?)$	
$T_{c\bar{c}1}(3900)^+$	$c\bar{c}u\bar{d}$	$1^+(1^{+-})$	$Z_c(3900)^+$
$T_{c\bar{c}}(4020)^+$	$c\bar{c}u\bar{d}$	$1^+(?^{?-})$	$X(4020)^+$
$T_{c\bar{c}}(4050)^+$	$c\bar{c}u\bar{d}$	$1^-(?^{?+})$	$X(4050)^+$
$T_{c\bar{c}}(4055)^+$	$c\bar{c}u\bar{d}$	$1^+(?^{?-})$	$X(4055)^+$
$T_{c\bar{c}}(4100)^+$	$c\bar{c}u\bar{d}$	$1^-(?^{?+})$	$X(4100)^+$
$T_{c\bar{c}1}(4200)^+$	$c\bar{c}u\bar{d}$	$1^+(1^{+-})$	$Z_c(4200)^+$
$T_{c\bar{c}0}(4240)^+$	$c\bar{c}u\bar{d}$	$1^+(0^{--})$	$R_{c0}(4240)^+$
$T_{c\bar{c}}(4250)^+$	$c\bar{c}u\bar{d}$	$1^-(?^{?+})$	$X(4250)^+$

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

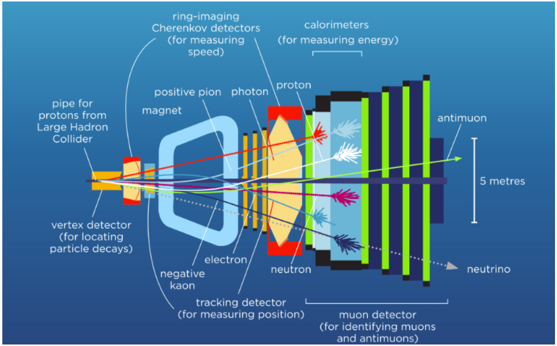
$I=0$	$I=\frac{1}{2}$	$I=1$	$I=\frac{3}{2}$
Λ	N	Σ	Δ

LHCb Spectrometer

- **The first hadron-collider experiment that is dedicated to heavy flavour physics**
- **CP violation, rare decays of beauty and charm meson, exotics....**

- Single arm forward spectrometer : $2 < \eta < 5$
- Impact parameter resolution: $\sigma_{IP} \approx 20\mu m$
- Momentum resolution:
  - $\frac{\Delta P}{P} \backsim 0.5 - 1\%$
- Efficient hadronic identification.
- PID separation K , p from π:
  - $\epsilon(K \to K) \approx 95\%$ and $\epsilon(\pi \to K) \approx 5\%$
  - $\epsilon(p \to p) \approx 95\%$ and $\epsilon(\pi \to p) \approx 5\%$

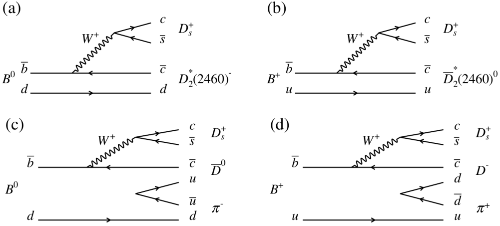
Run	Years	Lum. [fb^{-1}]	$\sqrt{s}$ [TeV]	$\sigma_{b\bar{b}}$ [μb]	$\sigma_{c\bar{c}}$ [μb]
1	2011-12	3.0	7,8	70	1400
2	2015-17	3.8	13	150	2400
2	2018	2.2	13		



[JINST 3 (2008) S08005];
[IJMPA 30 (2015) 1530022]

Open charm

1. Either only c or only $\bar{c}$, non zero net charm
2. D0 : $X(5568)$ - Not confirmed
3. $T^*_{cs0}(2870)^0, T^*_{cs1}(2900)^0$
4. $T^+_{cc}(3875)$: $cc\bar{u}\bar{d}$



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

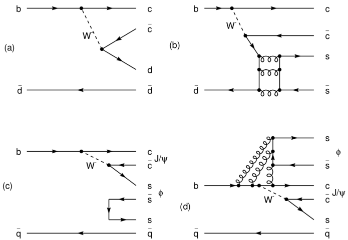
$B^+ \to D^- D_s^+ \pi^+$

[Phys. Rev. D 108, 012017]

Hidden charm

1. $c\bar{c}$ pairs, zero net charm
2. Fully charm $T_{\psi\psi}(6900)^+$: $c\bar{c}c\bar{c}$
3. $P^{\Lambda}_{\psi s}(4459)^0$, $T^{\theta}_{\psi s1}(4000)^+$,....

[Phys. Rev. D 95, 012002 (2017)]



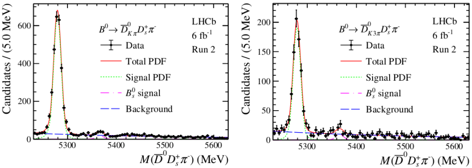
$B^+ \to J/\psi \phi K^+$

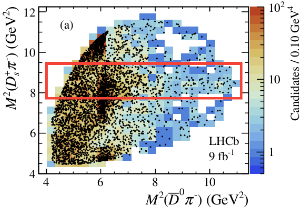
$B^0 \to \overline{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

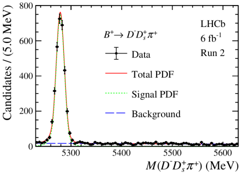
[Phys. Rev. Lett. 131, 041902]

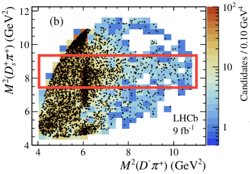
- 2 decays related by isospin symmetry.
- Reconstruction :
  - $\overline{D}^0 \to K^+\pi^-,\ K^+\pi^-\pi^+\pi^-$
  - $D^- \to K^+\pi^-\pi^-$
  - $D_s^+ \to K^+K^-\pi^+$
- Veto : $D^*(2010)^-$ from $B^0 \to D^{*-} D_s^+$
- Mis-ID : $B_s^0 \to \overline{D}^0 D_s^+ K^-$, $\Lambda_b^0 \to \overline{D}^0 D_s^+ \overline{p}$
- Mis-ID : $e^+ - \pi^+$, $D^{*-} \to \overline{D}^0 \pi^-$
- Non - double charm backgrounds
- BDT classifier implemented.

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









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

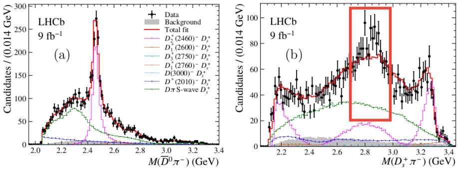
- Signal Yields :
  - $B^0 \to \overline{D}^0 D_s^+ \pi^-$: 4000 with 90% purity.
  - $B^+ \to D^- D_s^+ \pi^+$: 3750 with 95% purity.

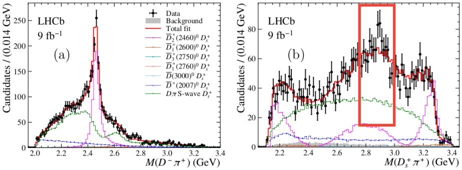
Amplitude Analysis

- Isobar Formalism : Coherent sum of quasi 2-body amplitude either resonant or non-resonant

- RBW : default resonance line shape; Expo : NR contribution
- All D^{**} with natural spin parity.
- qMI description for $D\pi$ S-wave
- $\overline{D}^*_J(3000)$: different J^P tested

Resonance	J^P	Mass (GeV)	Width (GeV)	Comments
$\overline{D}^*(2007)^0$	1^-	2.00685 ± 0.00005	$< 2.1 \times 10^{-3}$	Width set to be 0.1 MeV
$D^*(2010)^-$	1^-	2.01026 ± 0.00005	$(8.34 \pm 0.18) \times 10^{-5}$	
$\overline{D}^*_0(2300)$	0^+	2.343 ± 0.010	0.229 ± 0.016	#
$\overline{D}^*_2(2460)$	2^+	2.4611 ± 0.0007	0.0473 ± 0.0008	#
$\overline{D}^*_1(2600)^0$	1^-	2.627 ± 0.010	0.141 ± 0.023	#
$\overline{D}^*_3(2750)$	3^-	2.7631 ± 0.0032	0.066 ± 0.005	#
$\overline{D}^*_1(2760)^0$	1^-	2.781 ± 0.022	0.177 ± 0.040	#
$\overline{D}^*_J(3000)^0$	??	3.214 ± 0.060	0.186 ± 0.080	# $J^P = 4^+$ is assumed





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

$\chi^2/ndf = 2.23$

Model Including only Dπ

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

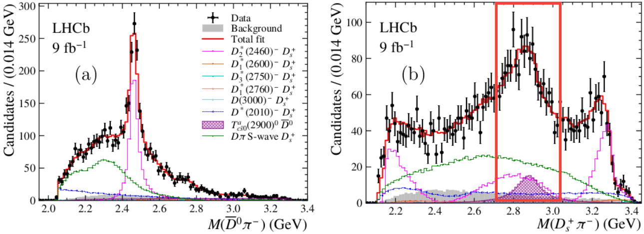
$\chi^2/ndf = 2.14$

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

[Phys. Rev. D 108, 012017]

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

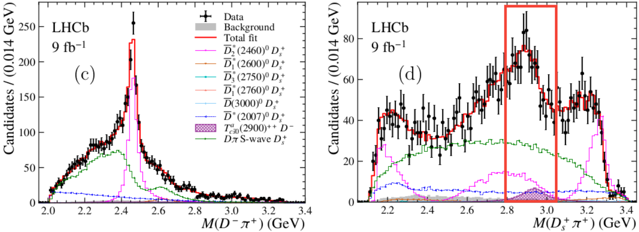
$\chi^2/ndf = 1.39$



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

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

$\chi^2/ndf = 2.03$



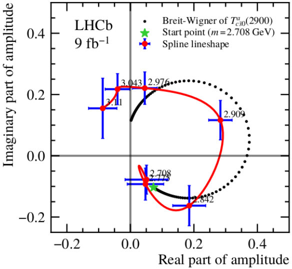
$T^a_{c\bar{s}0}(2900)^{++}$

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

[Phys. Rev. D 108, 012017]

First Observation of doubly charged tetraquark and its neutral partner !

- Exotic $D_s^+ \pi$ states observed near 2.9 GeV :
  - $T^a_{c\bar{s}0}(2900)^0$
  - $T^a_{c\bar{s}0}(2900)^{++}$
- Tested against spin 0 and 1 : 0^+ is favoured.
- Significance of $T^a_{c\bar{s}0}(2900)$: 9σ
- $J^P = 1^-$ leads to 6.3σ; Simultaneous $= 1.3\sigma$
- Spin parity tested upto 4^+ : $0^+ > 5\sigma$
- Argand plot : spline and BW models go anticlockwise - support the resonant structure of $T^a_{c\bar{s}0}(2900)$.



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

$$
\begin{aligned}
T^a_{c\bar{s}0}(2900)^0 : M &= 2.892 \pm 0.014 \pm 0.015\,\text{GeV}, \\
\Gamma &= 0.119 \pm 0.026 \pm 0.013\,\text{GeV}, \\
T^a_{c\bar{s}0}(2900)^{++} : M &= 2.921 \pm 0.017 \pm 0.020\,\text{GeV}, \\
\Gamma &= 0.137 \pm 0.032 \pm 0.017\,\text{GeV},
\end{aligned}
$$

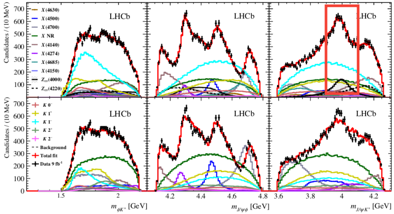
Isospin triplet of exotic mesons with four different quark flavors : $T^a_{c\bar{s}0}(2900)^{++}$ $[c\bar{s}u\bar{d}]$

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

$B^0 \to J/\psi\phi K^0_S$

[Phys. Rev. Lett. 131, 131901]

- $T^{\theta}_{\psi s1}(4000)^+$ $[c\bar{c}u\bar{s}]$ in m($J/\psi K^+$) in $B^+ \to J/\psi\phi K^+$ (PRL127, 082001 (2021))
- Prediction : neutral partner based on isospin symmetry of the strong interaction
- Candidate : $B^0 \to J/\psi\ \phi\ K^0_S$ for $T^0_{\psi s}$
- Reconstruction :
  - $J/\psi \to \mu^+\mu^-$
  - $\phi \to K^+K^-$
  - $K^0_S \to \pi^+\pi^-$
- B^0 : 1866 $\pm$ 47 with 94% purity.

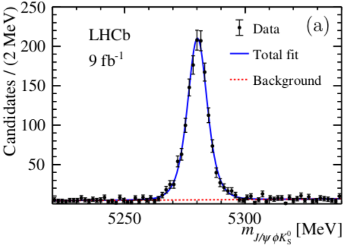


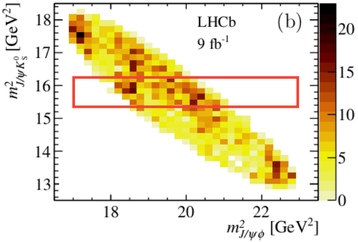
$T^{\theta}_{\psi s1}(4000)^+$

RUN I Model

$B^0 \to J/\psi\phi K^0_S$

$B^+ \to J/\psi\phi K^+$





RUN I and II

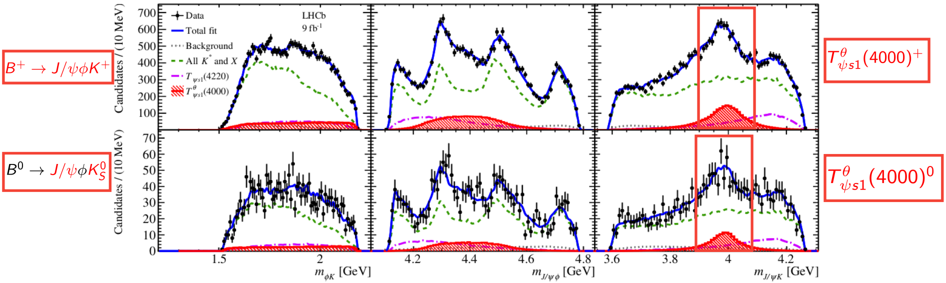
$B^0 \to J/\psi\phi K_s^0$

[Phys. Rev. Lett. 131, 131901]

- Small Sample size : simultaneous fit is performed to $B^0 \to J/\psi\phi K_S^0$ and $B^+ \to J/\psi\phi K^+$
- The default model same as $B^+ \to J/\psi\phi K^+$
- Decay sequences :
  - $B^0 \to J/\psi(K^* \to \phi K_s^0)$: 9 K^*
  - $B^0 \to (X \to J/\psi\phi)K_s^0$: 7 X's (4150, 4630, 4500,...
  - $B^0 \to (T_{\psi s1} \to J/\psi K_s^0)\phi$: (4000, 4220)
  - 1 non-resonant $J\psi\phi$
- Line shapes : RBW
- Significance: 4 σ (5.4 σ when iso-spin symmetry is assumed)
- $\Delta M = M_{T^{\theta}_{\psi s1}(4000)^0} - M_{T^{\theta}_{\psi s1}(4000)^+} = 12^{+11+6}_{-10-4}$ MeV

Quark Content : $[c\bar{c}d\bar{s}]$

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



Theoretical Models

- Z_S^{++} and Z_V^{++} : **Diquark-anitdiquark** model [Phys.Lett.B 820 (2021)]
- **Prediction** : $B^+ \to D^- D_s^+ \pi^+$ for quark content $[cu][\bar{s}\bar{d}]$
- **Observation** : $T^a_{c\bar{s}0}(2900)^0$ and $T^a_{c\bar{s}0}(2900)^{++}$ in disagreement with predicted parameters
- **Hadronic molecule** : $D_s^{*+}\rho^+$ and $D^{*+}K^{*+}$ [J.Phys.G: Nucl.Part.Phys.50 055002]
- Mass close to D^*K^* threshold → **isovector molecular** state in One-Boson exchange model.[arXiv:2208.10196]
- **Threshold effects** : Triangular singularity(TS) peak around D^*K^* threshold in decay via $\chi_{c1}K^*D^*$ explains $T_{c\bar{s}}(2900)$ in $D_S^+\pi$. [Eur. Phys. J. C 82, 955 (2022)]
- Interesting implication : nn equivalence to $\bar{n}$ in color space suggests $c\bar{s}nnn$ in B^+ and Λ_b^0 decays. [Phys. Rev. D 106, L111501]

No definite conclusions on Model

- For Isospin partners of $T^\theta_{\psi s1}(4000)^0$ $[c\bar{c}d\bar{s}]$:
  - ***HadronicMolecules*** : [Phys.Rev.D102(2020)111502]
  - ***Compact − tetraquarks*** : [Science Bulletin 66(2021)1616]
  - ***Thresholdeffects*** : [Phys.Rev.D105 (2022)014012]

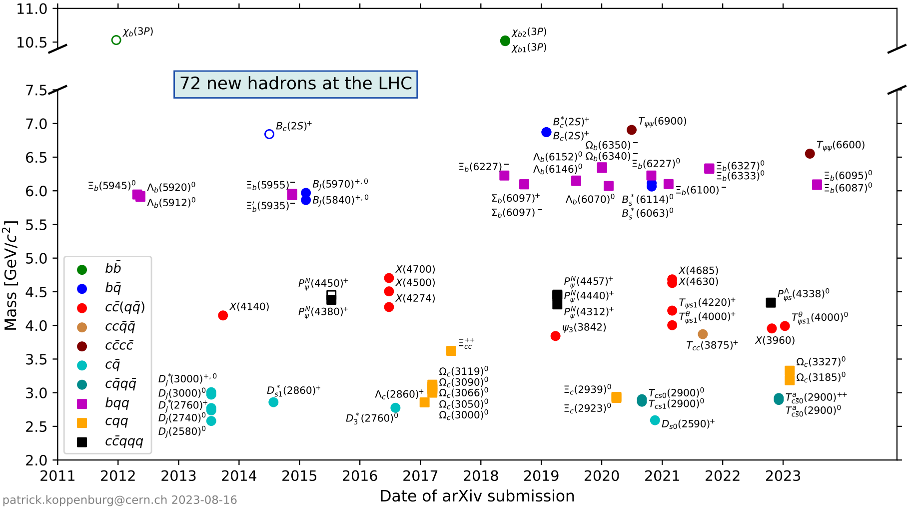
3 Meson weak B-decays : good source of rare fully open tetraquark states!

Summary and Outlook

- LHCb year 2023 :
  - First Observation of a doubly charged tetraquark and its neutral partner i.e. $T^{a}_{c\bar{s}0}(2900)^{++}$ and $T^{a}_{c\bar{s}0}(2900)^{0}$: (PRL131, 041902)
  - Evidence of a $J/\psi K^0_S$ structure i.e. $T^{\theta}_{\psi s1}(4000)^0$ in $B^0 \to J/\psi \phi K^0_S$ (PRL131, 131901)
- New exotic hadrons and decay channels of B mesons being discovered, open new possibilities in hidden as well as open sector.
- Significantly larger data samples will be collected by the upgraded LHCb detector in the coming years, enabling further deeper explorations.

Back up

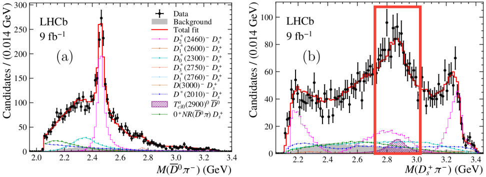
Hadrons at LHC



Model-dependent results : $D_s^+\pi$

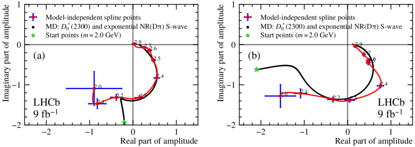
Model	ΔLL	Mass (GeV)	Width (GeV)	Fraction (%)
$T^a_{c\bar{s}0}(2900)^0$	70.1	2.871 ± 0.012	0.135 ± 0.025	3.0 ± 0.5
$T^a_{c\bar{s}0}(2900)^{++}$	33.2	2.922 ± 0.014	0.161 ± 0.033	2.0 ± 0.5

1. $D_0^*(2300)$: 0^+ qMI model replaced by RBW
2. 0^+ non resonant component.
3. Consistent with qMI model
4. Validates the default fit.

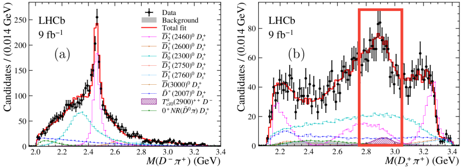


$B^0 \to \overline{D}^0 D_s^+ \pi^-$

Argand plot : qMI and MD Dπ in agreement after 2.2 GeV



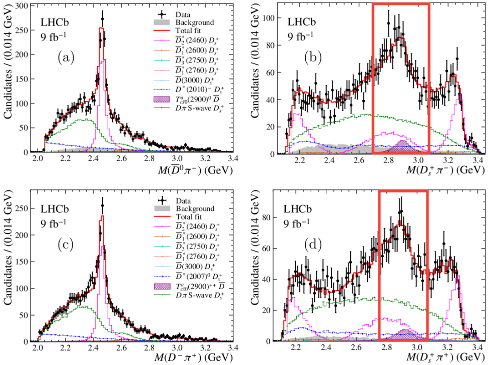
$B^0 \to \overline{D}^0 D_s^+ \pi^-$ $\quad$ $B^+ \to D^- D_s^+ \pi^+$



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

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

1. Improve precision and stability of fit results.
2. All complex parameters of D^{**} state are shared except $\overline{D}^*(2700)^0$ and $D^*(2010)^-$
3. Small isospin symmetry breaking effects near $D\pi$ mass threshold.
4. Consistent with separate fit and leads to higher significance.



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

Additional investigations : $D_s^+\pi$ [Phys. Rev. D 108, 012017] ex

- Exotic $D_s^+\pi$ tested with other spin-parity : 0^+ favoured but spin-1 reasonably good.
- Tested extra $D\pi$,$D_s^+\pi$ and DD_s^+ with natural spin-parity upto 3^- with varying mass and widths when including 0^+ $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$.
- Changes in NLL are insignificant (stat. sig. $< 2\sigma$)
- No extra $D\pi$ state expected to be observed.
- Excited D states :
  - $D_2^*(2460)^-$: $m_0 = (2465.2 \pm 1.0)$ MeV, $\Gamma_0 = (38.7 \pm 2.5)$ MeV.
  - $D_2^*(2460)^0$: $m_0 = (2464.4 \pm 1.2)$ MeV, $\Gamma_0 = (44.6 \pm 2.8)$ MeV.
  - Charged isospin partners of $D_1^*(2600)^0$ and $D_j^*(3000)^0$ significance in $B^0 \to \overline{D}_0 D_s^+ \pi^-$ with known masses and widths is estimated as 4.8σ and 2.2σ respectively.
  - $D_{s0}^*(2317)$ and $D_{s0}^*(2317)^{++}$: free variation of mass and width under different spin-parity : insignificant.
  - Upper limits on the fit fractions of neutral and doubly charged $D_{s0}^*(2317)$ under 3 different hypothesis at 90% C.L. are less and 1%

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

[Phys. Rev. D 95, 012002 (2017)]

TABLE I. Fit results from the default amplitude model. The significances are evaluated accounting for total (statistical) uncertainties. The listed masses and widths without uncertainties are taken from PDG [14] and are fixed in the fit. The listed world averages of the two K_2 and $K^*(1680)$ resonances do not contain the contributions from the previous LHCb run 1 results.

J^P		Contribution	Significance (σ)	M_0 (MeV)	Γ_0 (MeV)	FF (%)
1^+	2^1P_1	$K(1^+)$	4.5 (4.5)	$1861 \pm 10^{+16}_{-46}$	$149 \pm 41^{+231}_{-23}$	
	2^3P_1	$K'(1^+)$	4.5 (4.5)	$1911 \pm 37^{+124}_{-48}$	$276 \pm 50^{+319}_{-159}$	
	1^3P_1	$K_1(1400)$	9.2 (11)	1403	174	$15 \pm 3^{+3}_{-11}$
2^-	1^1D_2	$K_2(1770)$	7.9 (8.0)	1773	186	
	1^3D_2	$K_2(1820)$	5.8 (5.8)	1816	276	
1^-	1^3D_1	$K^*(1680)$	4.7 (13)	1717	322	$14 \pm 2^{+35}_{-8}$
	2^3S_1	$K^*(1410)$	7.7 (15)	1414	232	$38 \pm 5^{+11}_{-17}$
2^-	2^3P_2	$K_2^*(1980)$	1.6 (7.4)	$1988 \pm 22^{+194}_{-31}$	$318 \pm 82^{+481}_{-101}$	$2.3 \pm 0.5 \pm 0.7$
0^-	2^1S_0	$K(1460)$	12 (13)	1483	336	$10.2 \pm 1.2^{+1.0}_{-3.8}$
2^-		$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
1^-		$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
0^+		$X(4500)$	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)			$28 \pm 8^{+19}_{-11}$
1^+		$X(4140)$	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)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
1^+		$Z_{cs}(4000)$	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)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$