Exotic Spectroscopy at LHCb

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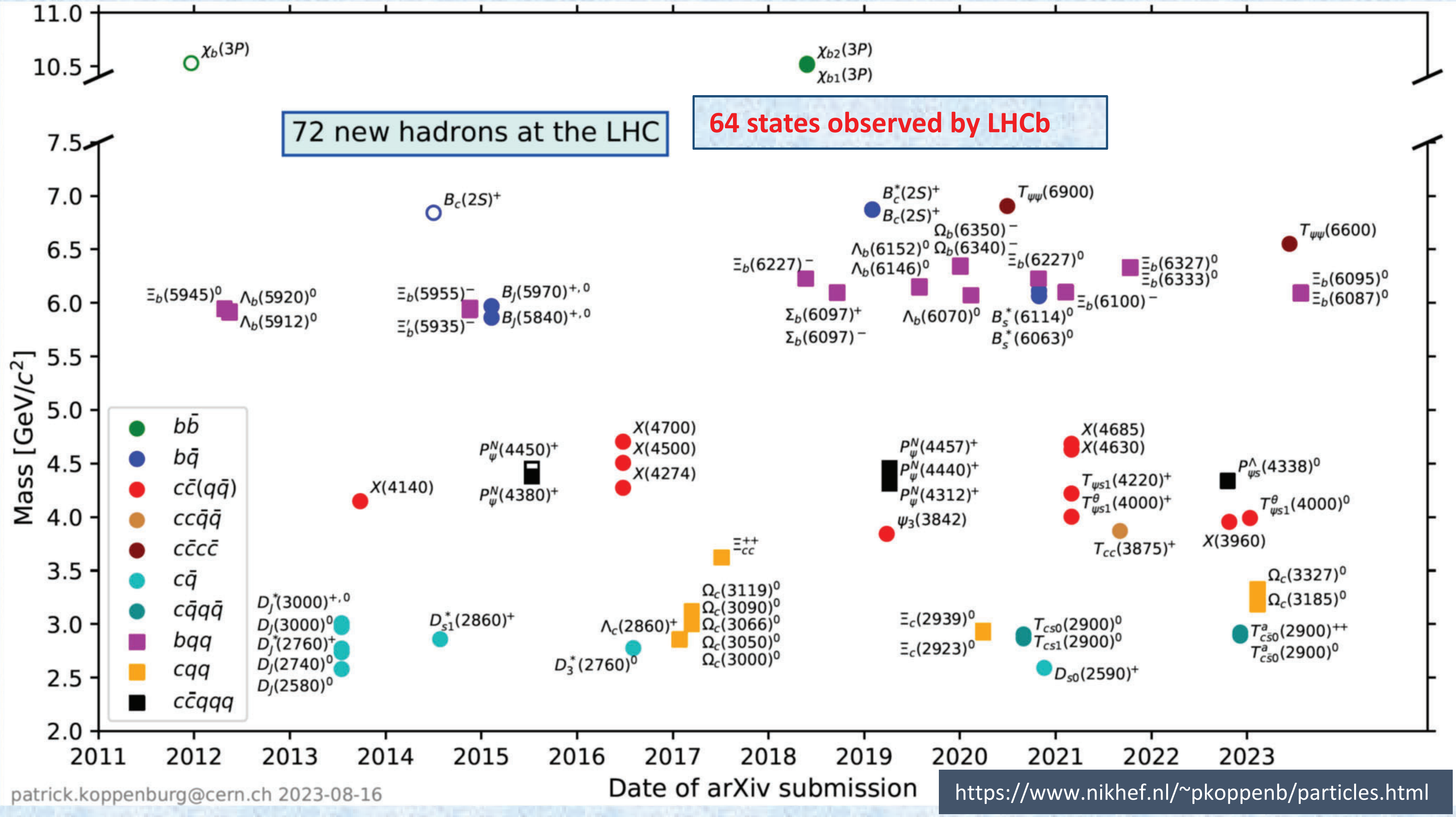
1. (Very brief) introduction to the spectroscopy of hadron states
2. LHCb spectrometer -an excellent tool for heavy hadron spectroscopy
3. Candidates for pentaquarks
4. Candidates for tetraquarks

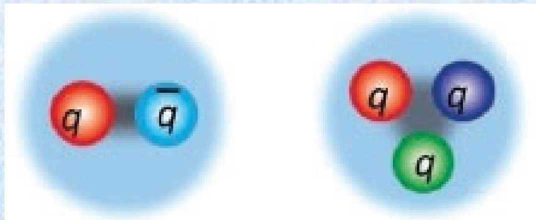
Hadron Spectroscopy at LHC(b)



- At least 23 states (most of them discussed in this talk) do not fit into the convention of baryons and mesons

Standard vs Exotic States

➢ **Standard states:**



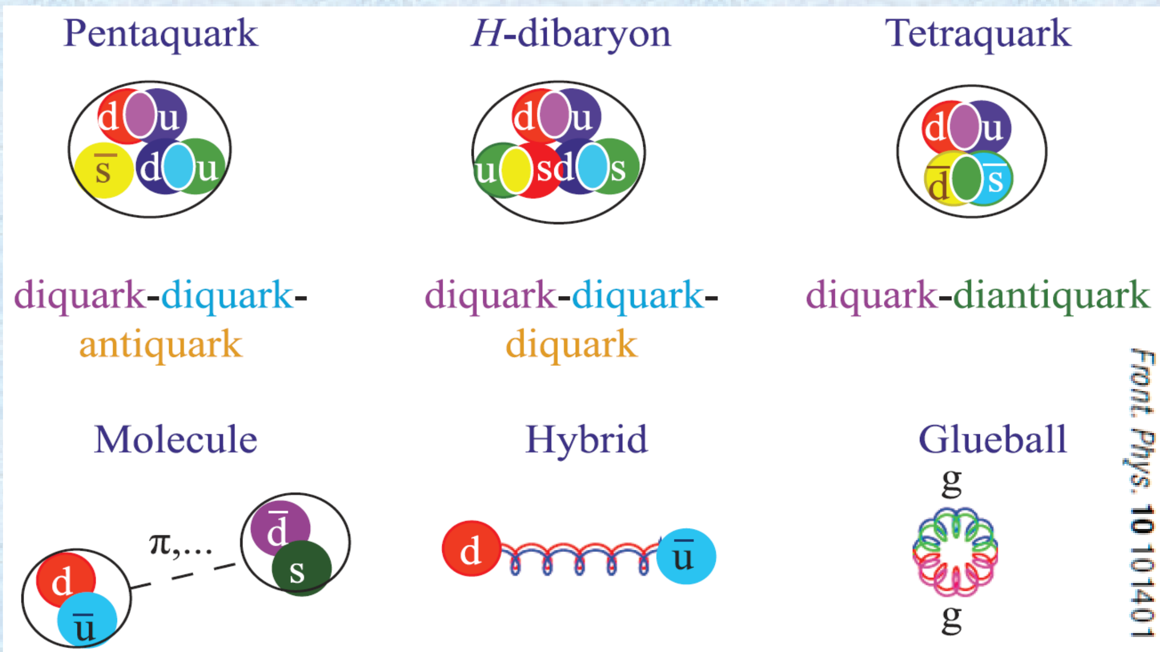
A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN
California Institute of Technology, Pasadena, California

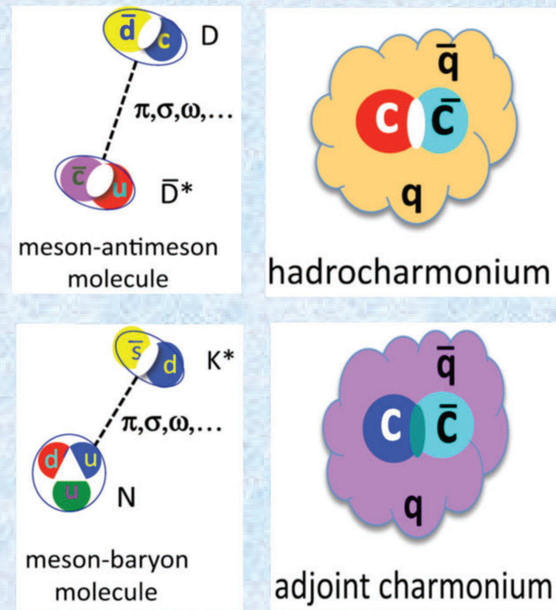
anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc. It is assuming that the lowest

Phys. Lett. 8 (1964) 214-215

➢ **Exotic states:**



but also:



Rev. Mod. Phys. 90 (2018) 015003

and near threshold kinematical effects: cusps, anomalous triangular singularities (ATS)…

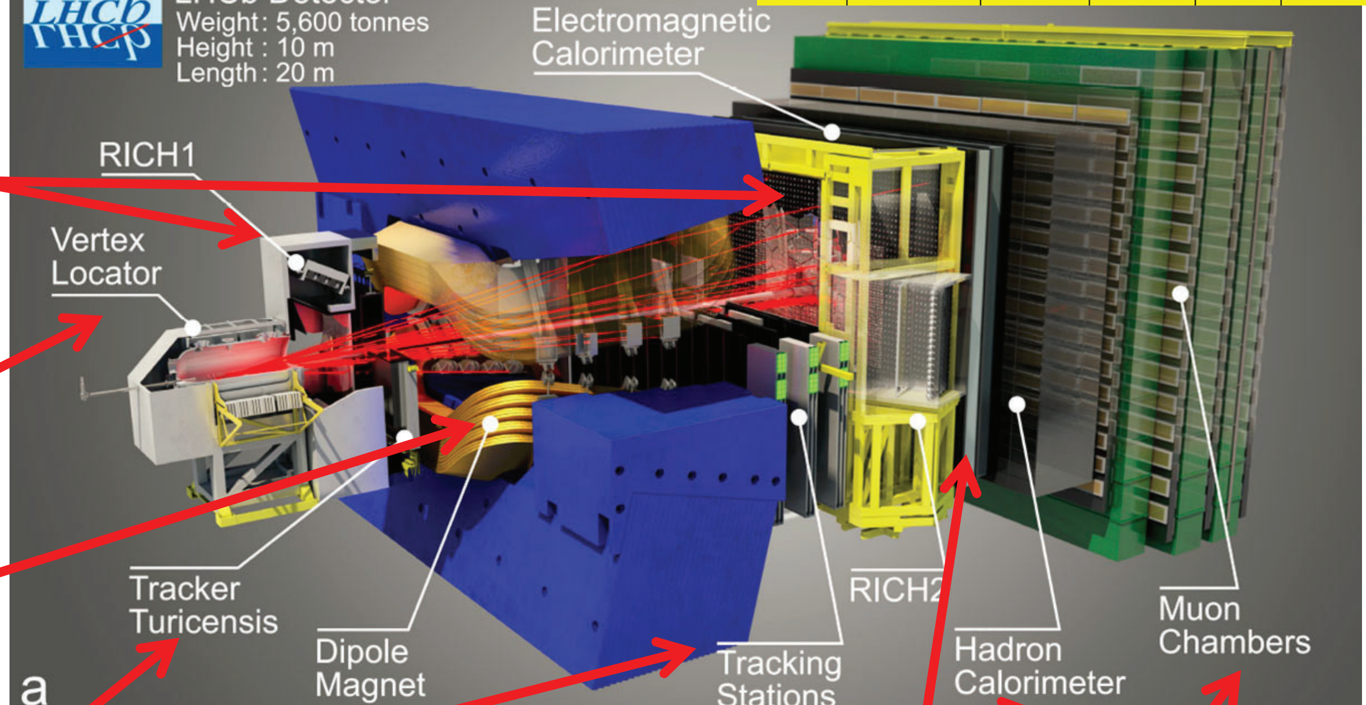
LHCb: Spectrometer and Data Sample

The first hadron-collider experiment that is dedicated to heavy flavour (HF) physics

Run 1 & Run 2: 9 fb^{-1}
Run 3 started in 2023

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		

The geometry of forward spectrometer $2 < \eta < 5$



RICH:
Separation of K, p from π:
ε(K→K) ≈ 95 %   ε(π →K) ≈ 5 %
ε(p→p) ≈ 95 %   ε(π →p) ≈ 5 %

Vertex Detector:
Impact parameter resolution:
$\sigma_{IP} \approx 20\ \mu\mathrm{m}$
Decay time resolution:
heavy hadrons: ≈50 fs

Dipole magnet:
Bending power: 4 Tm

Precise tracking system:
ε(trk) ≈ 96 %
Momentum resolution:
$\frac{\Delta p}{p} = 0.5\ \%\quad p = 5\ \mathrm{GeV}/c$
$1.0\ \%\quad p = 200\ \mathrm{GeV}/c$

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

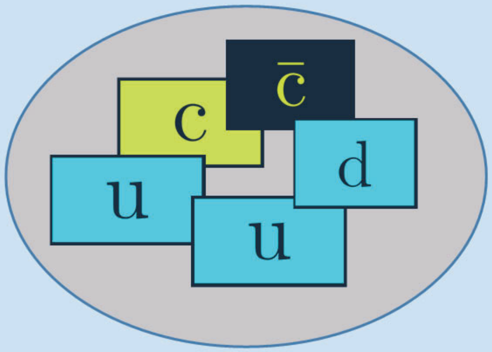
Electromagnetic and hadronic calorimeters
ECAL: $\frac{\sigma_E}{E} = 1\ \% \oplus \frac{10\ \%}{\sqrt{E[\mathrm{GeV}]}}$

Muon system:
ε(μ → μ) ≈ 97 %
ε(π → μ) ≈ (1-3) %

Spectrometer:
very good mass resolution $\sigma(m_{B\to hh}) \approx 22\ \mathrm{MeV}$

Trigger:
Highly flexible, currently have “offline quality”

Pentaquarks



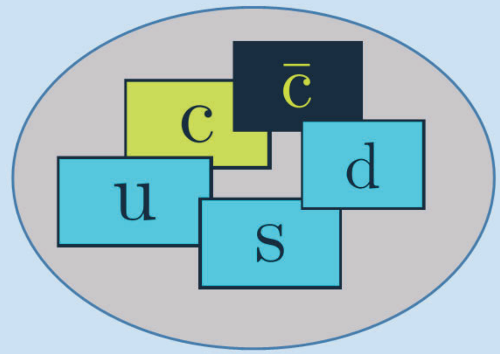
$[J/\psi p]$

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

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

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

$P_{\psi}^{N}(4337)^{+}$



$[J/\psi \Lambda]$

$P_{\psi s}^{\Lambda}(4459)^{0}$

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

Pentaquarks in the $J/\psi p$ and $J/\psi\bar{p}$ Systems

LHCb (2015-19): Study of the decay $\Lambda_b \to J/\psi pK$

246000 events

- Observation of three narrow states in m($J/\psi p$) close to the thresholds: $[\Sigma_c^+\bar{D}^0]$, $[\Sigma_c^+\bar{D}^{*0}]$

State	Mass [MeV/c²]	Width [MeV/c²]	Signif [σ]
$P_\psi^N(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	5.4
$P_\psi^N(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	5.4
$P_\psi^N(4312)$	$4311.9 \pm 0.7^{+6.8}_{-0.8}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	7.3

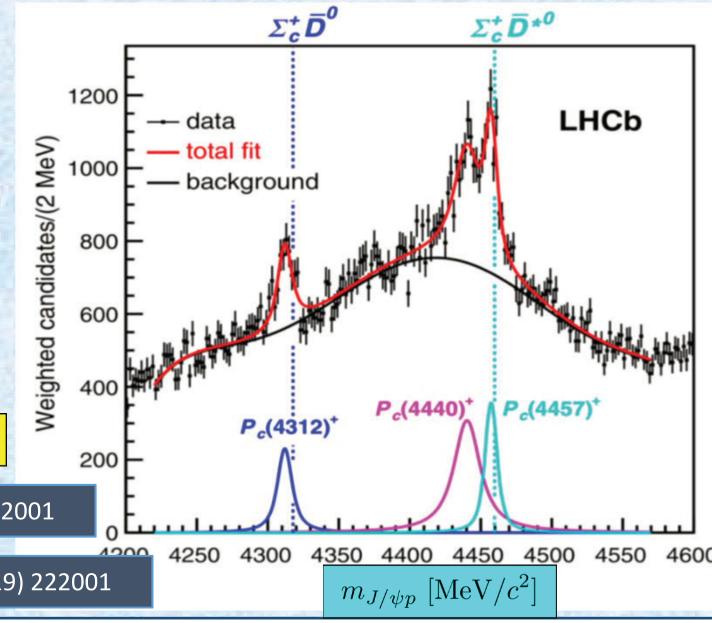
J^P not yet determined

- Amplitude analysis confirmed with the Legendre polynomial expansion approach
- Quark content [$c\bar{c}uud$] - $P_\psi^{N\,+}$

PRL 115 (2015) 072001

PRL 117 (2016) 082002

PRL 122 (2019) 222001



LHCb (2019-22): Study of the Decay $B_s^0 \to J/\psi p\bar{p}$

797 ± 31 events

- Evidence for a structure in $[J/\psi p]$ and $[J/\psi\bar{p}]$
- Very close to the $[\Xi_c^+ D^-]$ threshold

$$\mathbf{m[P_\psi^N(4337)^+]} = (4337^{+7+2}_{-4-2})\ \mathrm{MeV/c^2}$$

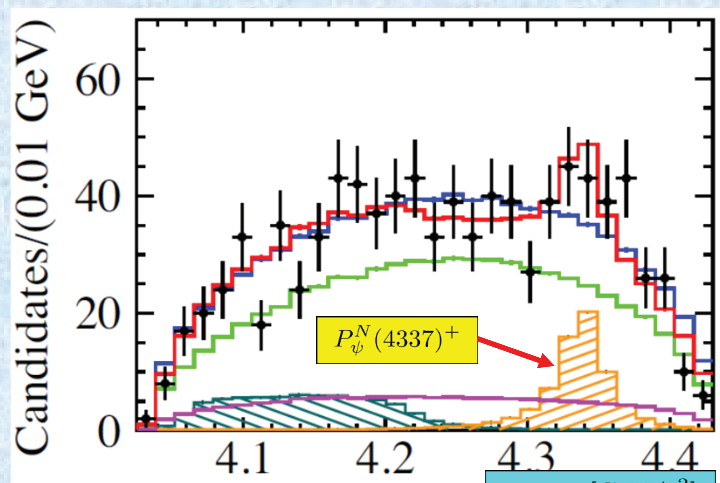
$$\mathbf{\Gamma[P_\psi^N(4337)^+]} = (29^{+26+14}_{-12-14})\ \mathrm{MeV/c^2}$$

$$J^P = \frac{1}{2}^+ \quad (3.7\sigma)$$

PRL. 122 (2019) 191804

PRL. 128 (2022) 062001

- Quark content [$c\bar{c}uud$] - $P_\psi^{N\,+}$



Search for Prompt Production of $[J/\psi p]$ Pentaquarks in Charm Hadron Final States

- **LHCb 2024:** Search for $[J/\psi p]$ pentaquark decays into a wide range of Σ_c, Λ_c^+, and D combinations
- Out of 42 different modes; 32 modes tested

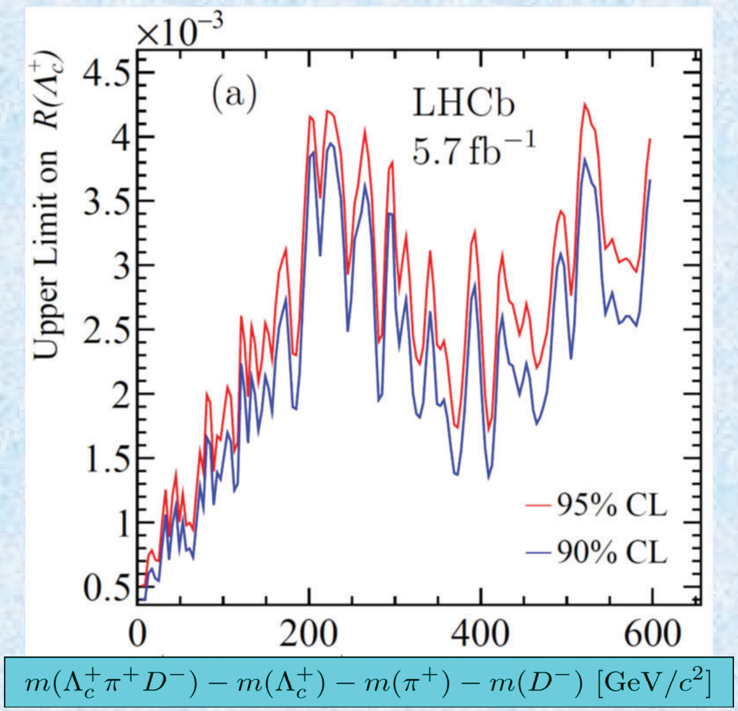
(10 modes – insufficient statistics)

$\Sigma_c^{++}\bar{D}^0$	~~$\Sigma_c^{++}D^0$~~	$\Sigma_c^{++}D^-$	~~$\Sigma_c^{++}D^+$~~	~~$\Sigma_c^{++}D^{*-}$~~	~~$\Sigma_c^{++}D^{*+}$~~
$\Sigma_c^{0}\bar{D}^0$	~~$\Sigma_c^{0}D^0$~~	$\Sigma_c^{0}D^-$	~~$\Sigma_c^{0}D^+$~~	~~$\Sigma_c^{0}D^{*-}$~~	~~$\Sigma_c^{0}D^{*+}$~~
$\Sigma_c^{*++}\bar{D}^0$	$\Sigma_c^{*++}D^0$	$\Sigma_c^{*++}D^-$	$\Sigma_c^{*++}D^+$	$\Sigma_c^{*++}D^{*-}$	~~$\Sigma_c^{*++}D^{*+}$~~
$\Sigma_c^{*0}\bar{D}^0$	$\Sigma_c^{*0}D^0$	$\Sigma_c^{*0}D^-$	$\Sigma_c^{*0}D^+$	$\Sigma_c^{*0}D^{*-}$	~~$\Sigma_c^{*0}D^{*+}$~~
$\Lambda_c^+\bar{D}^0$	$\Lambda_c^+D^0$	$\Lambda_c^+D^-$	$\Lambda_c^+D^+$	$\Lambda_c^+D^{*-}$	$\Lambda_c^+D^{*+}$
$\Lambda_c^+\bar{D}^0\pi^+$	$\Lambda_c^+D^0\pi^+$	$\Lambda_c^+D^-\pi^+$	$\Lambda_c^+D^+\pi^+$	$\Lambda_c^+D^{*-}\pi^+$	$\Lambda_c^+D^{*+}\pi^+$
$\Lambda_c^+\bar{D}^0\pi^-$	$\Lambda_c^+D^0\pi^-$	$\Lambda_c^+D^-\pi^-$	$\Lambda_c^+D^+\pi^-$	$\Lambda_c^+D^{*-}\pi^-$	$\Lambda_c^+D^{*+}\pi^-$

arXiv:2404.0713[hep-ex]

- Simultaneous fit to Σ_c/Λ_c^+, and D signal and sidebands regions
- Scan of the mass in 4 MeV/c^2 steps in search for peaks
- Calculation of p-value
- No clear signal observed → mass dependent upper limits set w.r.t. the $\Lambda_c^+ \to p K^- \pi^+$ decay

$$R(\Lambda_c^+) = \frac{N_P}{N_{\Lambda_c^+}} \times \frac{\epsilon_{\Lambda_c^+}}{\epsilon_P}, \quad (P - \text{pentaquark})$$



- The upper limits at the level of 10^{-3}

$P^{\Lambda}_{\psi s}(4459)^0$

LHCb 2017-21: Amplitude analysis of $\Xi_b^- \to J/\psi\Lambda K^-$ decays

1750 ± 50 events

Sci. Bull. 66(13) (2021) 1278
PLB 772 (2017) 265

Evidence for a new pentaquark with strangeness in $[J/\psi\Lambda]$ – 19 MeV/c^2 below the $[\Xi_c^0 D^{*0}]$ threshold

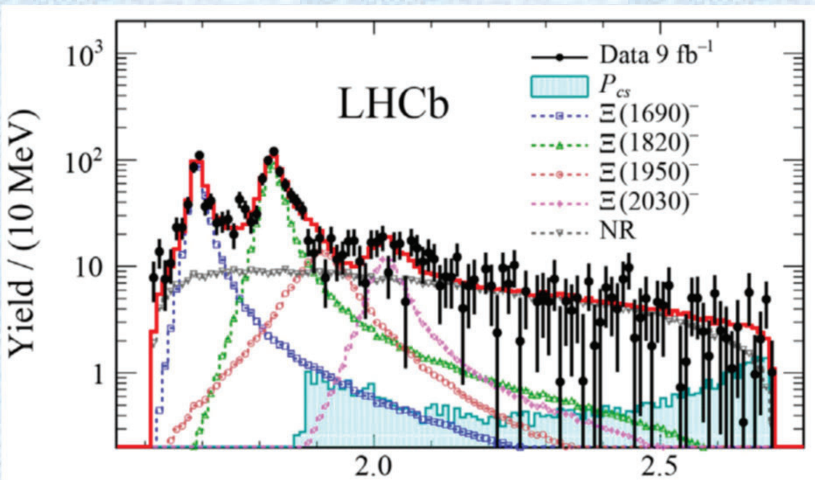
$\mathrm{m}[\mathbf{P}^{\Lambda}_{\psi s}(\mathbf{4459})^{\mathbf{0}}] = (4458.8 \pm 2.9^{+4.7}_{-1.1})\ \mathrm{MeV/c^2}$

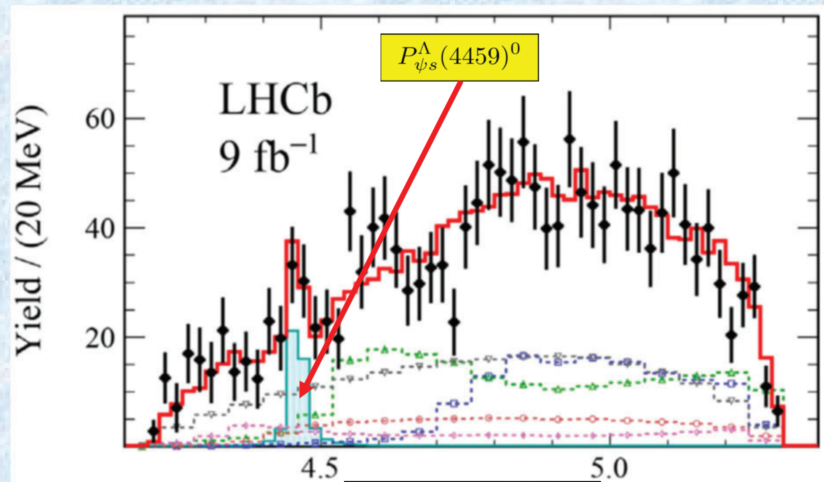
$\Gamma[\mathbf{P}^{\Lambda}_{\psi s}(\mathbf{4459})^{\mathbf{0}}] = (17.3 \pm 6.5^{+8.0}_{-5.7})\ \mathrm{MeV/c^2}$

3.1σ

Quark content [$c\bar{c}uds$]

$\mathrm{J^P}$ not yet determined





Theoretical expectation: two states with $J^P = 1/2^-$ and $3/2^-$ and mass difference of 6 MeV/c^2
Current study cannot confirm or refute the two peak hypothesis

Two new Ξ^{*-} states observed: $\Xi(1690)^-$ and $\Xi(1820)^-$

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

LHCb 2023: Amplitude analysis of $B^- \to J/\psi\Lambda\bar{p}$ decays

4620 ± 70 events

PRL 131 (2023) 031901

Observation of a narrow pentaquark state in $[J/\psi\Lambda]$:

$> 15\sigma$

$\mathbf{m}[\mathbf{P}_{\psi s}^{\Lambda}(4338)^0] = (4338.2 \pm 0.7 \pm 0.4)\ \mathrm{MeV/c^2}$

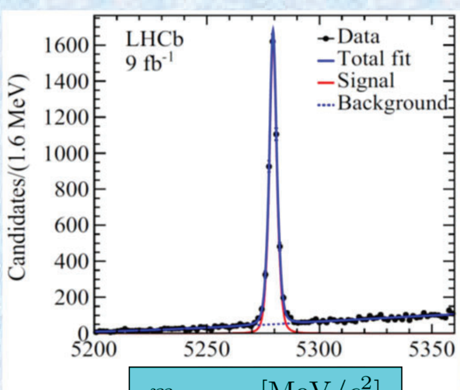
$\mathbf{\Gamma}[\mathbf{P}_{\psi s}^{\Lambda}(4338)^0] = (7.0 \pm 1.2 \pm 1.3)\ \mathrm{MeV/c^2}$

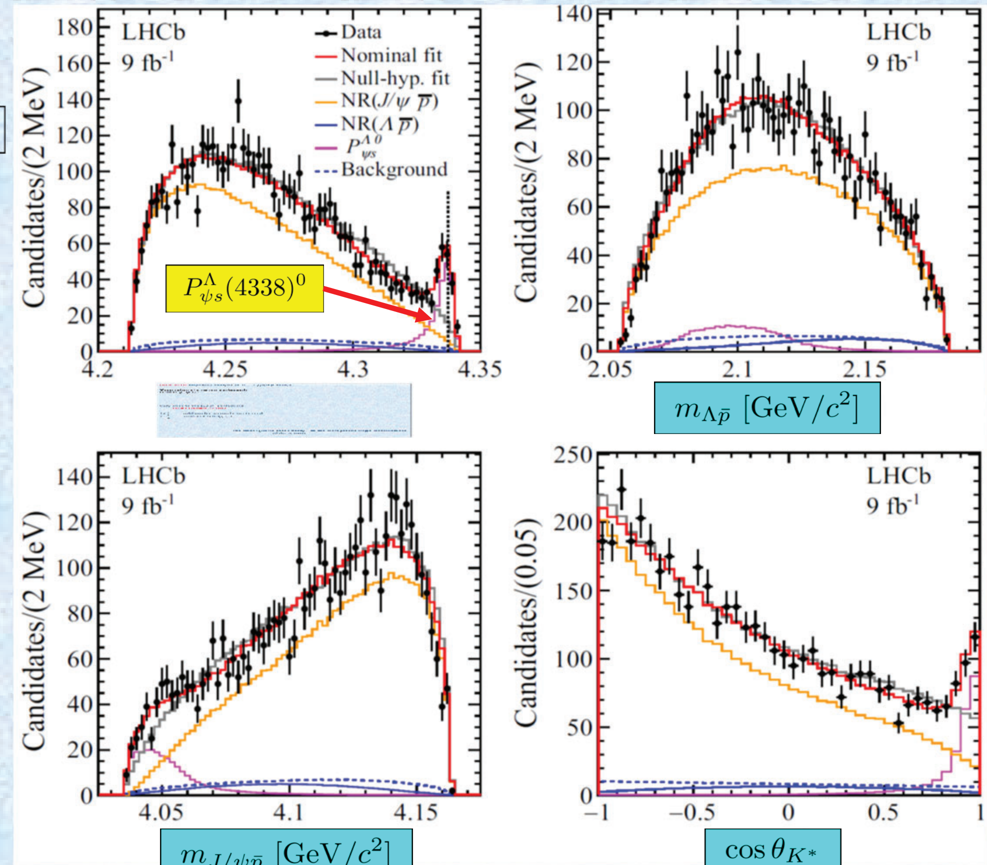
Very close to the $[\Xi_c^+ D^-]$ threshold

Quark content [$c\bar{c}uds$]

J = $\frac{1}{2}^-$ – **odd parity strongly preferred**

J = $\frac{1}{2}^+$ – excluded at 90% C. L.

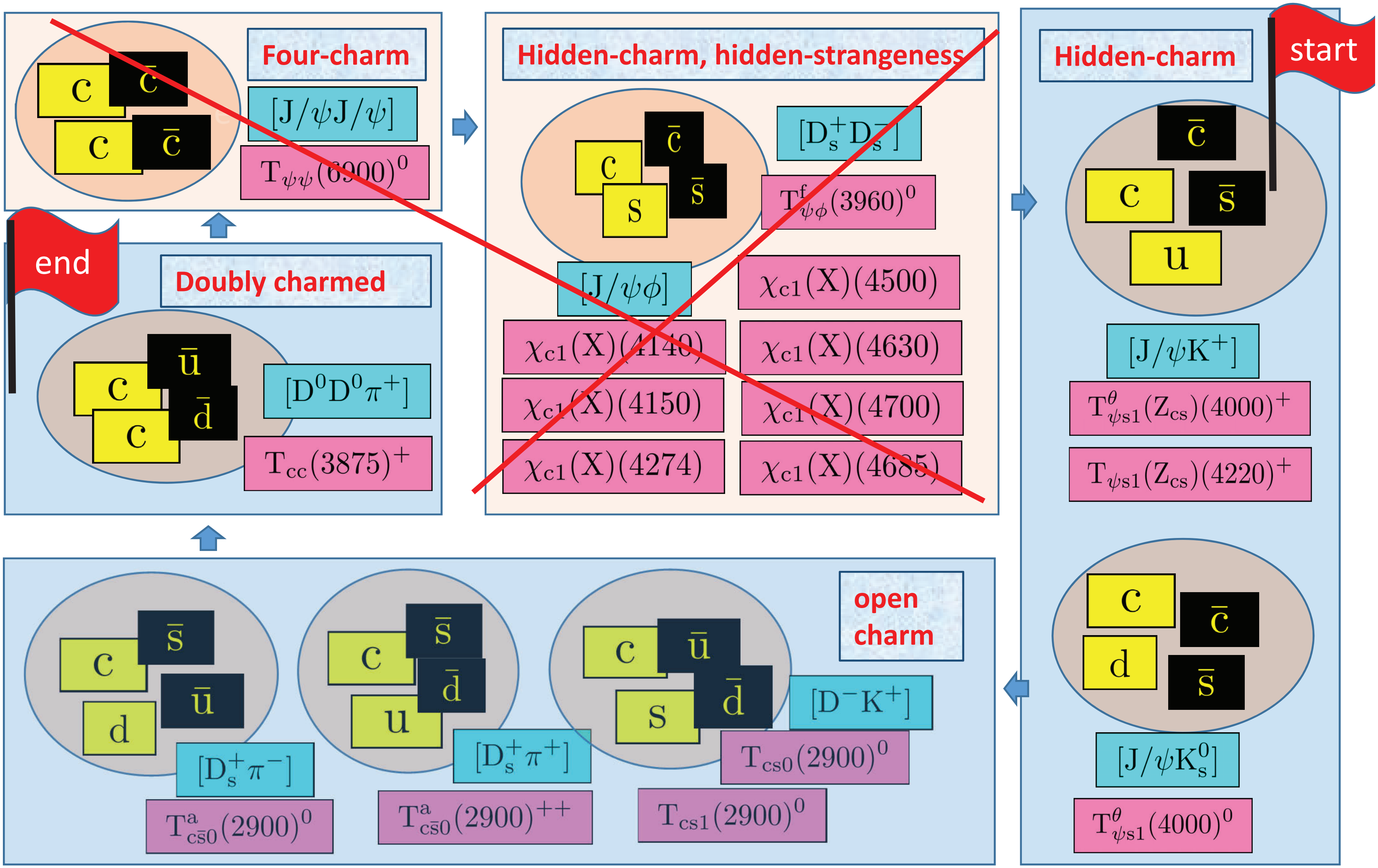




The small Q value of the decay ➔ the most precise single measurement of the B⁻ mass:

$\mathbf{m}[\mathbf{B}^-] = (5279.44 \pm 0.05 \pm 0.07)\ \mathrm{MeV/c^2}$

Tetraquarks



Hidden-charm Tetraquarks $T^{\theta}_{\psi s1}$

LHCb (2021): Amplitude analysis of the $B^+ \to J/\psi\varphi K^+$

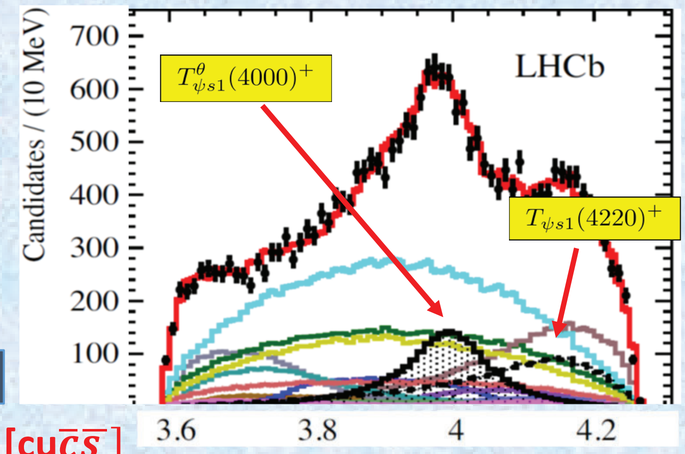
24220 ± 170 events

in particular discovery of two states in $[J/\psi K^+]$ system:

State	Mass [MeV/c^2]	Width [MeV/c^2]	J^P	Signif. [σ]
$T^{\theta}_{\psi s1}(4000)^+$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	1^+	15
$T_{\psi s1}(4220)^+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$1^+(1^-)$	5.9

PRL 127 (2021) 082001

- quark content [$cu\bar{c}\bar{s}$]



LHCb (2023): Amplitude analysis of the $B^0 \to J/\psi\varphi K^0_s$

1866 ± 47 events

discovery of a structure in $[J/\psi K^0_s]$ system:

4σ

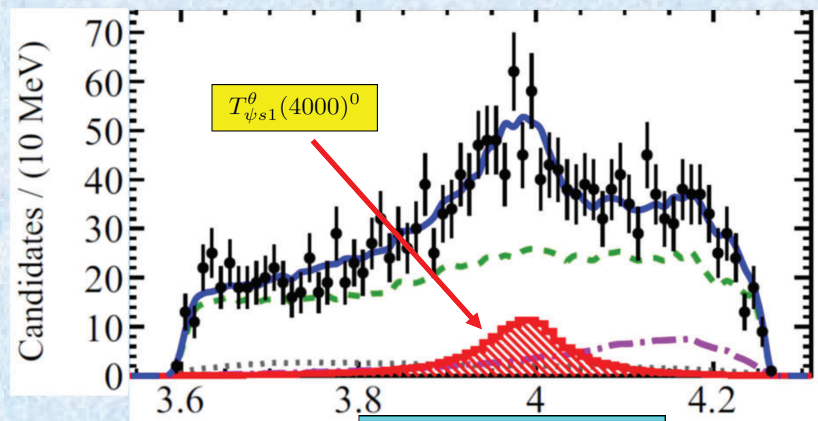
$$M[T^{\theta}_{\psi s1}(4000)^0] = (3991^{+12+9}_{-10-17})\ \text{MeV}/c^2$$

$$\Gamma[T^{\theta}_{\psi s1}(4000)^0] = (105^{+29+17}_{-25-23})\ \text{MeV}/c^2$$

PRL 131 (2023) 131901

5.4σ - assuming isospin symmetry (total likelihood of the B^+ and B^0 decays)

- quark content [$cd\bar{c}\bar{s}$]



The mass splitting: $\Delta M = M[T^{\theta}_{\psi s1}(4000)^0] - M[T^{\theta}_{\psi s1}(4000)^+] = (-12^{+11+6}_{-10-4})\ \text{MeV}/c^2$

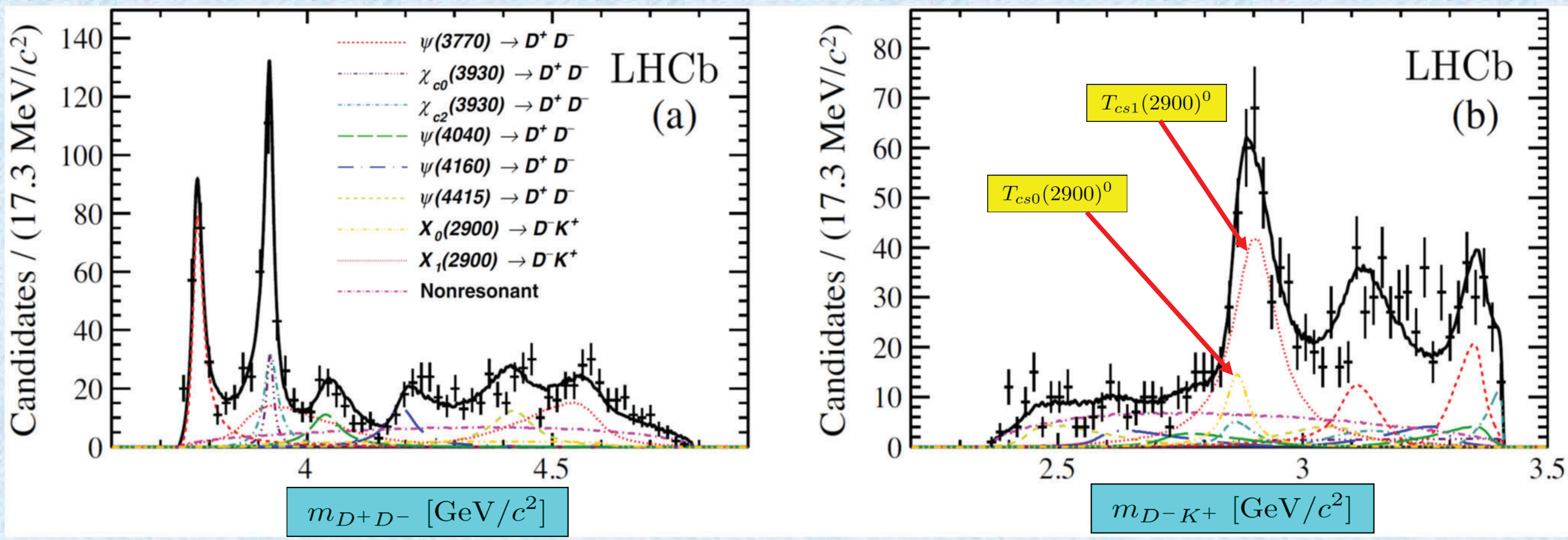
Open-Charm Tetraquarks $T_{cs0,1}(2900)^0$

LHCb (2020):

The first amplitude analysis of the $B^+ \to D^+ D^- K^+$ with the inclusion of known charmonium and $[D^- K^+]$ resonances

PRD 102 (2020) 112003

1260 events



Evidence for two new states in the $[D^- K^+]$ system:

quark content [$ud\bar{c}\bar{s}$]

No evidence for $[D^+ K^+]$ structures

$\mathrm{M}[\mathrm{T_{cs0}}(2900)^0] = (\mathbf{2886 \pm 7 \pm 2})\ \mathrm{MeV/c^2}$

$\Gamma[\mathrm{T_{cs0}}(2900)^0] = (\mathbf{57 \pm 12 \pm 4})\ \mathrm{MeV/c^2}$

$J^P = 0^+$

$\mathrm{M}[\mathrm{T_{cs1}}(2900)^0] = (\mathbf{2904 \pm 5 \pm 1})\ \mathrm{MeV/c^2}$

$\Gamma[\mathrm{T_{cs1}}(2900)^0] = (\mathbf{110 \pm 11 \pm 4})\ \mathrm{MeV/c^2}$

$J^P = 1^-$

The first clear observation of exotic hadrons with open heavy flavor

The first observation of an exotic state that do not contain a heavy quark-antiquark pair

Open-Charm Tetraquarks $T^{0,++}_{c\bar{s}0}(2900)^0$

LHCb (2020):

The first amplitude analysis of the $B^0 \to \bar{D}^0 D_s^+ \pi^-$ & $B^+ \to D^- D_s^+ \pi^+$ (with the inclusion of known $[D^- K^+]$ resonances)

PRD 108 (2023) 012017

Discovery of two new states in $[D_s \pi]$:

$B^0 \to \bar{D}^0 D_s^+ \pi^-$ — 4009 ± 70 events

$\mathrm{M}[\mathrm{T}^{\mathrm{a}}_{c\bar{s}0}(2900)^0] = (\mathbf{2892 \pm 14 \pm 15})\ \mathrm{MeV/c^2}$

$\Gamma[\mathrm{T}^{\mathrm{a}}_{c\bar{s}0}(2900)^0] = (\mathbf{119 \pm 26 \pm 13})\ \mathrm{MeV/c^2}$

8.0σ $J^P = 0^+$

quark content $[cd\bar{s}\bar{u}]$

$B^+ \to D^- D_s^+ \pi^+$ — 3870 ± 64 events

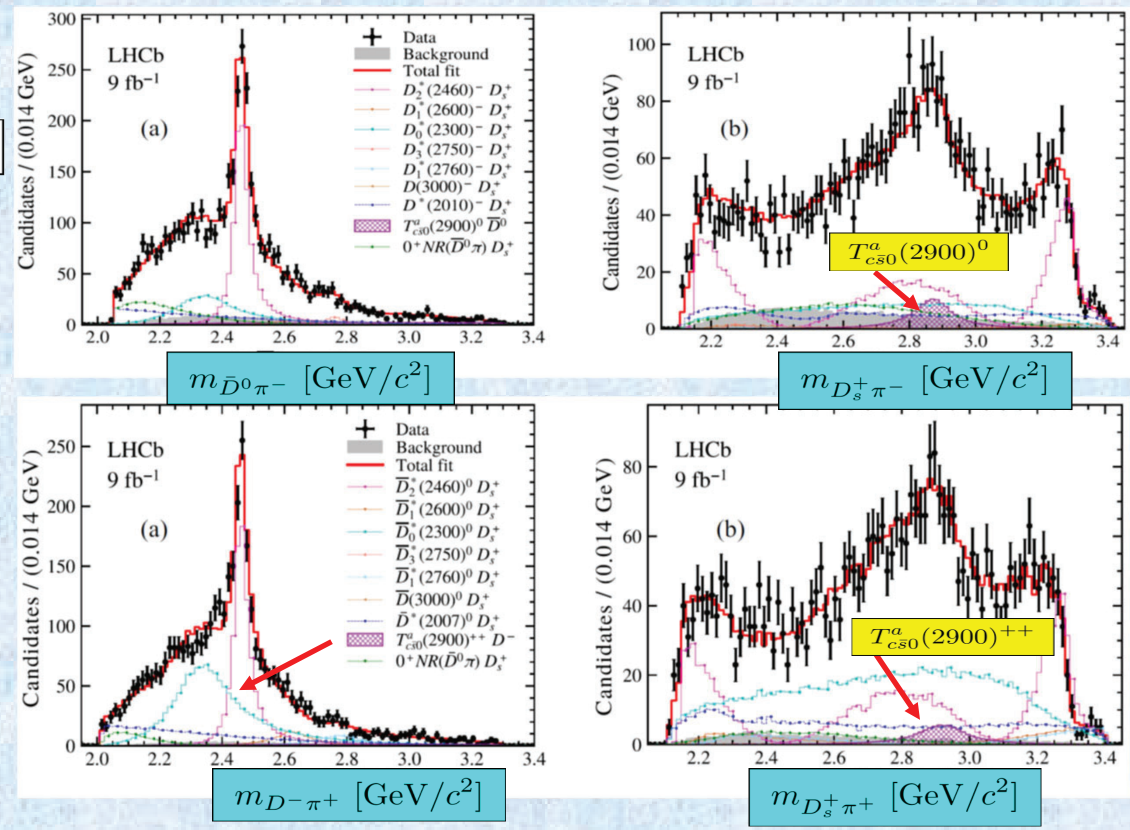
$\mathrm{M}(\mathrm{T}^{\mathrm{a}}_{c\bar{s}0}(2900)^{++}) = (\mathbf{2921 \pm 17 \pm 20})\ \mathrm{MeV/c^2}$

$\Gamma(\mathrm{T}^{\mathrm{a}}_{c\bar{s}0}(2900)^{++}) = (\mathbf{137 \pm 32 \pm 17})\ \mathrm{MeV/c^2}$

6.5σ $J^P = 0^+$

quark content $[cu\bar{s}\bar{d}]$

No hint for $[DD_s]$ structures



Mass splitting

$\Delta\mathrm{M} = \mathrm{M}[\mathrm{T}^{\mathrm{a}}_{c\bar{s}0}(2900)^{++}] - \mathrm{M}[\mathrm{T}^{\mathrm{a}}_{c\bar{s}0}(2900)^0] = (\mathbf{28 \pm 20 \pm 12})\ \mathrm{MeV/c^2}$

The Doubly Charmed Tetraquark $T_{cc}(3875)^+$

LHCb (2022):
The first observation of double-charmed tetraquark with the quark content $[cc\bar{u}\bar{d}]$ in its decay to $D^0D^0\pi^+$ - manifestly exotic

Nature Physics 18 (2022) 751 | Nature Commun 13 (2022) 3351

Mass of $T_{cc}(3875)^+$ very close and slightly below to the $D^{*+}D^0$ threshold:

$$\delta m = m[T_{cc}(3875)^+] - (m[D^{*+}] + m[D^0]) = (-273 \pm 61 \pm 5^{+11}_{-14}(\text{model}))\ \text{keV}/c^2$$

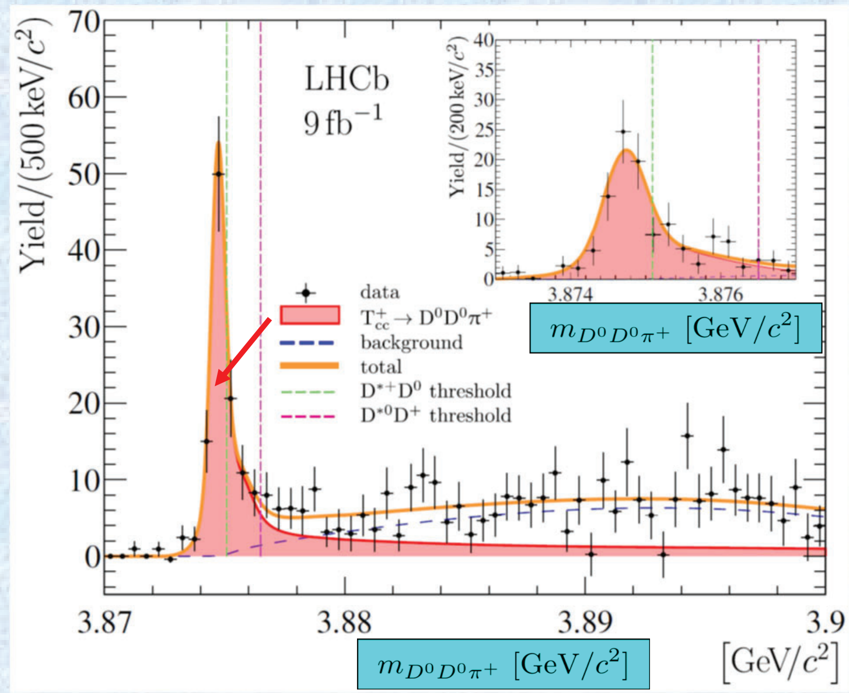
117 ± 16 events | 22σ

Extremely narrow
(the narrowest exotic state observed to date):

$$\Gamma[T_{cc}(3875)^+] = (410 \pm 65 \pm 43^{+18}_{-38}(\text{model}))\ \text{keV}/c^2$$

Consistent with the isoscalar $J^P = 1^+$ hypothesis

$T_{cc}(3875)^+$ is the first manifestation of the family of the [QQ'qq'] hadrons, which are expected to be almost stable against strong interaction ($\tau \sim 10^{-20}$ s)



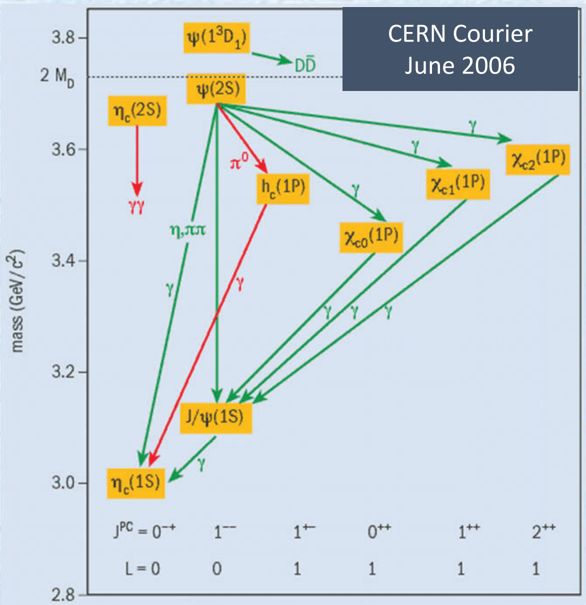
Observation of $T_{cc}(3875)^+$ strongly supports existence of

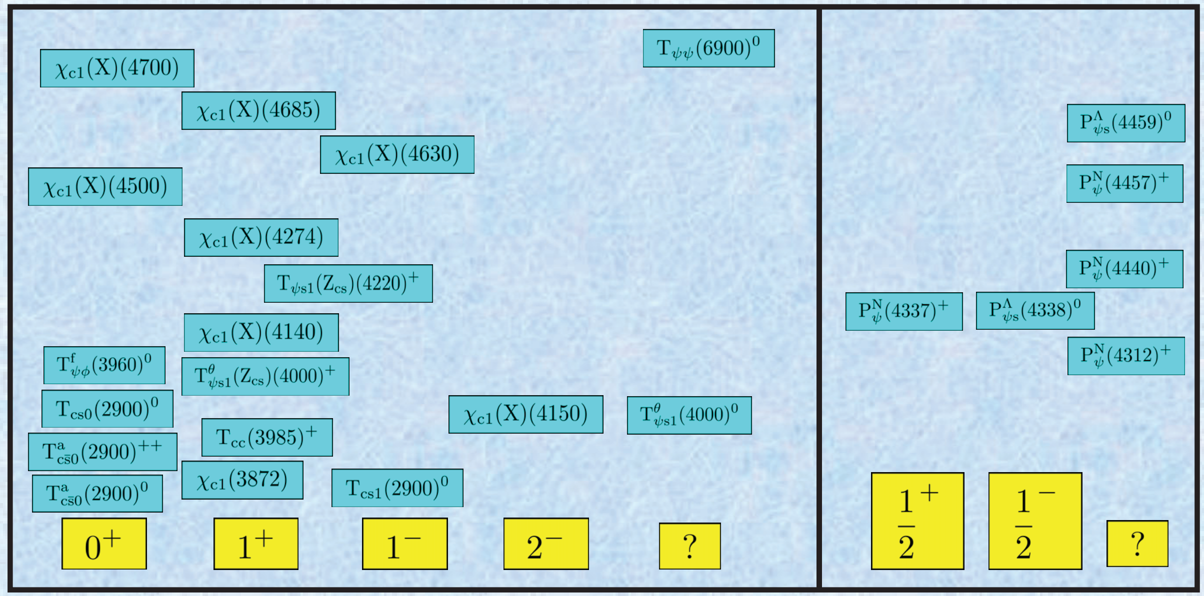
- **$[bb\bar{u}\bar{d}]$ tetraquark that is stable w.r.t. the strong and electromagnetic interactions**
- **$[bc\bar{u}\bar{d}]$ tetraquark state about 10 MeV below $\bar{B}D$ threshold**

Karliner, Rosner ArXiv 1707.07666

Summary

- A plethora of new (exotic) hadron states discovered by LHCb:





- The systematic explanation of the current picture of exotic spectroscopy will be troublesome (and equally exciting)

- In the recent period, LHCb has been one of crucial players in heavy flavour spectroscopy of exotic states

- More precise spectroscopic measurements from the LHCb experiment and, hopefully, some new observations should follow with the analysis of Run 3 and Run 4 data