Exotic Spectroscopy at LHCb

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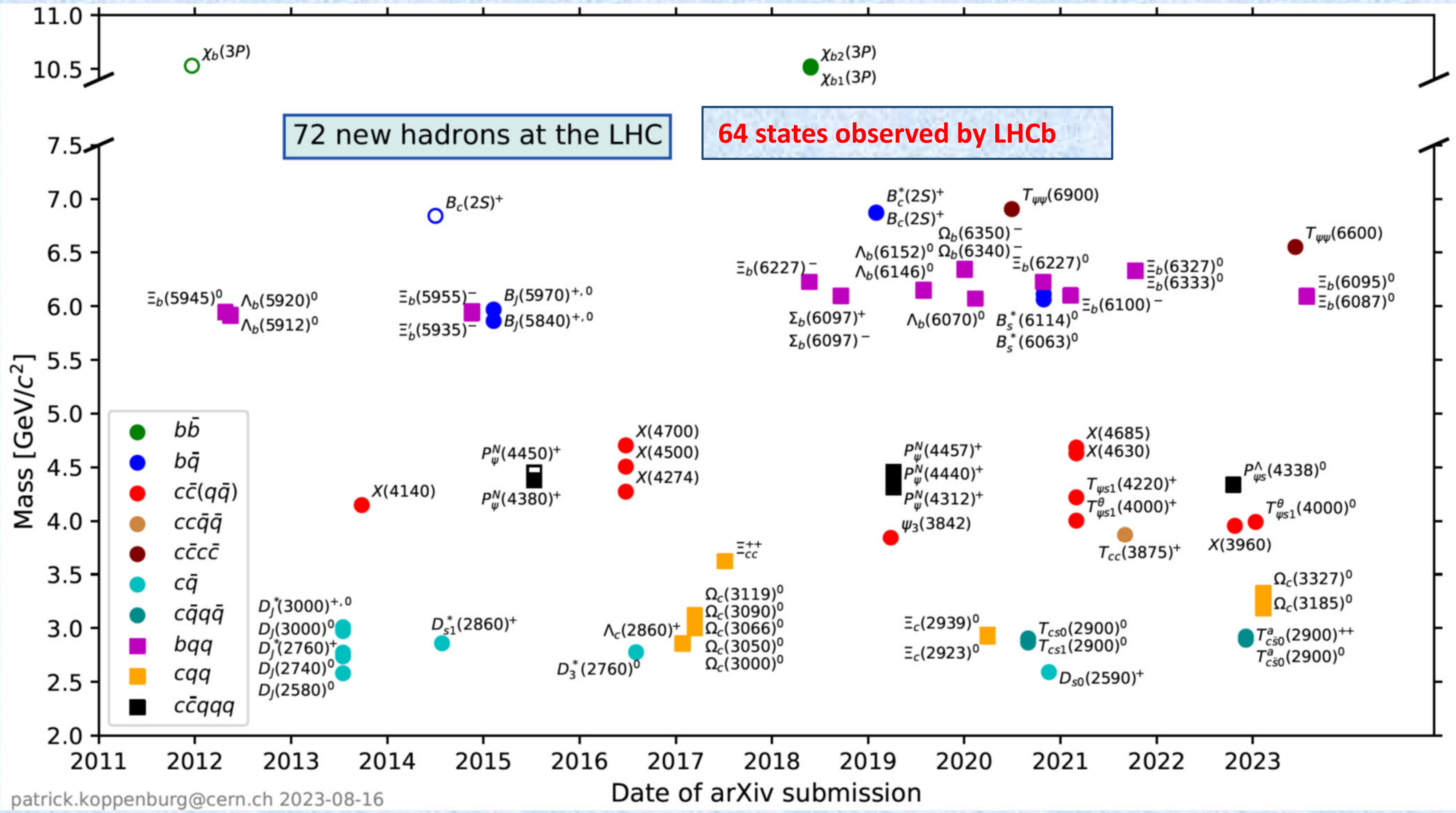
1. (Very brief) introduction to the spectroscopy of hadron states
2. LHCb spectrometer - an excellent tool for heavy hadron spectroscopy
3. $\chi_{c1}(3872)$ (X(3872)) state
4. Candidates for pentaquarks
5. Candidates for tetraquarks

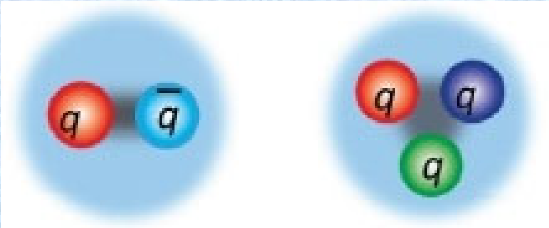
Hadron Spectroscopy at LHC(b)



➢ **At least 25 states (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

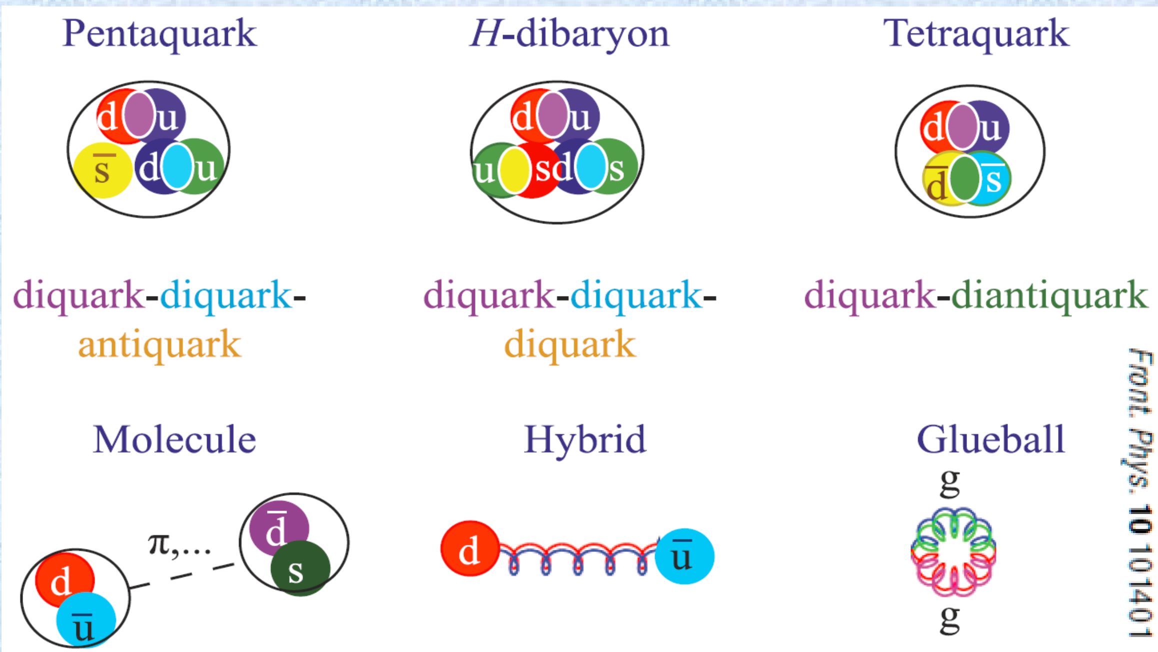
M. GELL-MANN

California Institute of Technology, Pasadena, California

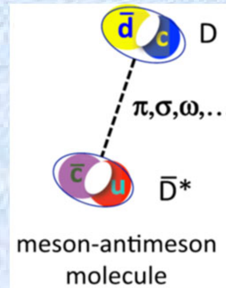
anti-triplet as anti-quarks q̄. Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q q̄), etc., while mesons are made out of (q q̄), (q q q̄ q̄), etc. It is assuming that the lowest

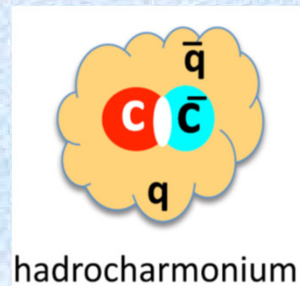
Phys. Lett. 8 (1964) 214-215

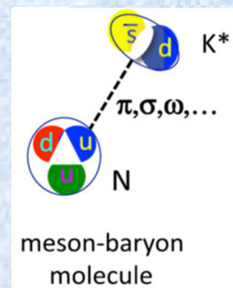
➢ **Exotic states:**

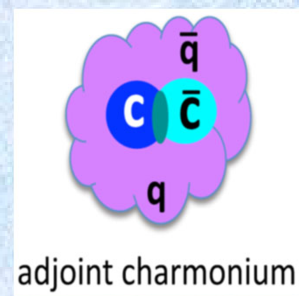


but also:









Rev. Mod. Phys. 90 (2018) 015003

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

Exotic Hadron Naming Convention

➢ **New taxonomy, as proposed by the LHCb**

arXiv:2206.15233

T is for tetraquarks, **P** is for pentaquarks

Subscript(s) - heavy quark content

Superscript – indicates isospin, parity and G-parity:

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

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

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

➢ **Tools of exotic spectroscopy:**

angular distributions, amplitude analysis, model independent approach, Dalitz and Argand plots, …

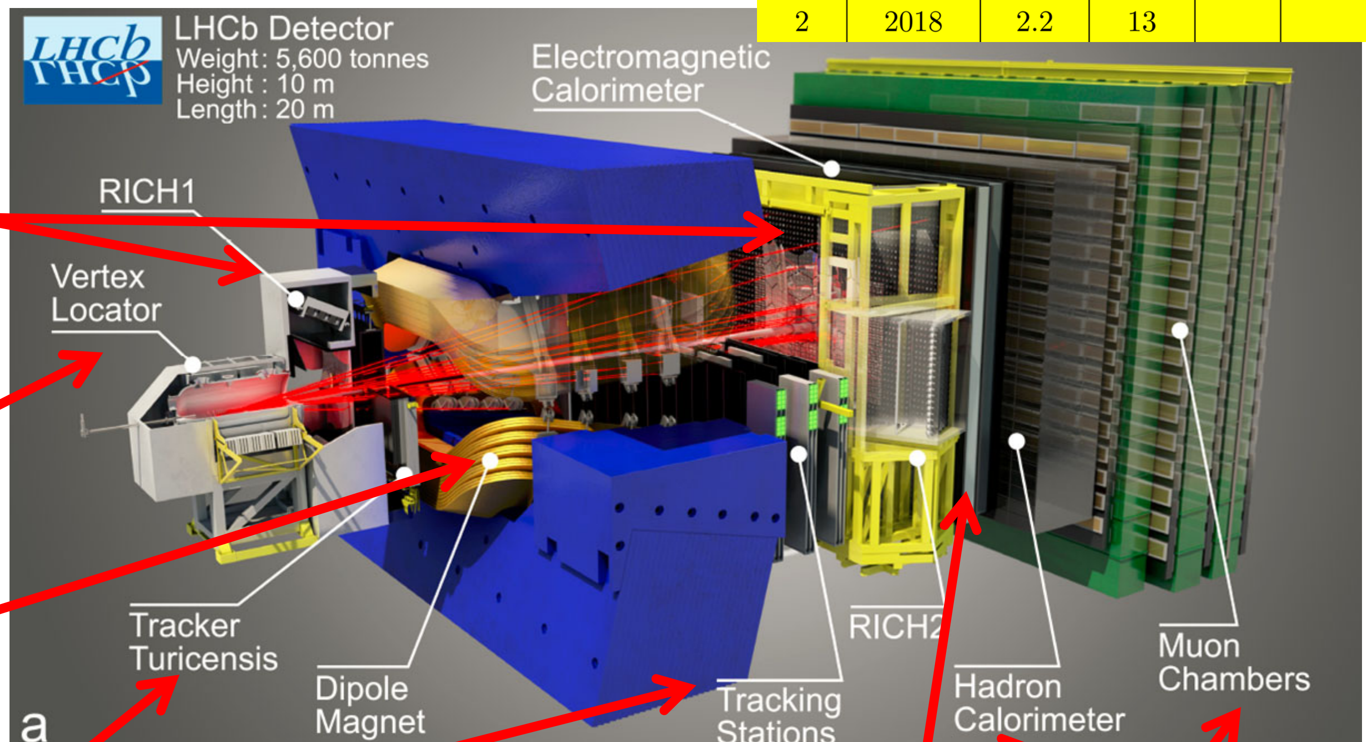
LHCb: Spectrometer and Data Sample

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

Run 1 & Run 2: 9 fb^{-1}

Run	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

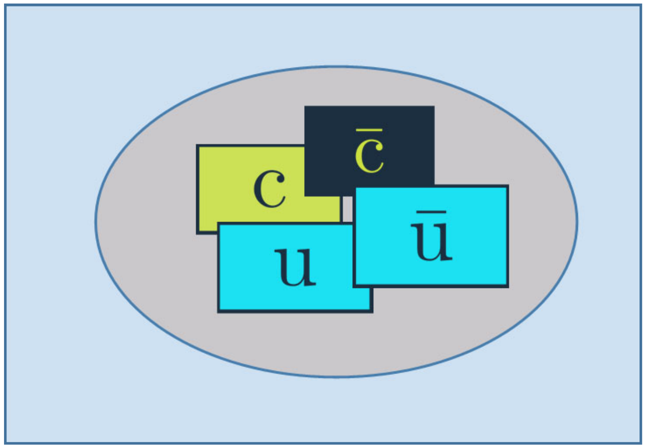
Electromagnetic and hadronic calorimeters
ECAL: $\frac{\sigma_E}{E} = 1\ \% \oplus \frac{10\ \%}{\sqrt{E[\mathrm{GeV}]}}$

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"

$\chi_{c1}(3872)$



$\chi_{c1}(3872)$: Past and Latest Measurements

- **X(3872) - the trigger of exotic revolution**
  - Belle (2003): observation of narrow state X in $B \to [\pi^+\pi^- J/\psi]\, K$ decay
  - The current nomenclature of the PDG: $X(3872) \equiv \chi_{c1}(3872)$

PRL 91 (2003) 262001

- **The (striking) properties of χ_{c1}(3872):**

$\mathbf{M(D^0 + \bar{D}^{0*}) = (3871.68 \pm 0.10)\ MeV/c^2}$

Mass consistent with the $D^0\bar{D}^{0*}$ threshold: $\mathbf{M(\chi_{c1}(3872)) = (3871.65 \pm 0.06)\ MeV/c^2\ (PDG)}$

Surprisingly narrow width $\mathbf{\Gamma = (1.19 \pm 0.21)\ MeV/c^2\ (PDG)}$ Spin-parity $\mathbf{J^{PC} = 1^{++}}$

- **The interpretation of χ_{c1}(3872) (2^3P_1) – most probably a mixture of conventional P-wave $[c\bar{c}]$ meson with a DD* molecule, but also options for tetraquark, hybrid meson, glueball etc.**

- **LHCb studies:**

Mass: JHEP 08 (2020) 123

Lineshape: PRD 102 (2020) 092005

Spin-parity: PRL 110 (2013) 222001; PRD 92 (2015) 011102(R)

Production:

Inclusive production	JHEP 01 (2022) 131
Multiplicity dependence	PRL 126 (2021) 092001
$\Lambda_b \to \chi_{c1}(3872) p K^-$	JHEP 09 (2019) 028
$\Lambda_b \to \chi_{c1}(3872) p \pi^-$	JHEP 05 (2021) 095
$B_s^0 \to \chi_{c1}(3872)\phi$	JHEP 02 (2021) 024
$B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$	JHEP 07 (2023) 084

Decay:

$\chi_{c1}(3872) \to p\bar{p}$ — PLB 769 (2017) 305

$\chi_{c1}(3872) \to \psi(2S)\gamma$ — Nucl. Phys. B886 (2014) 665

$\chi_{c1}(3872) \to \pi^+\pi^- J/\psi$ — PRD 108 (2023) L011103

$\chi_{c1}(3872)$: Selected Latest LHCb Results

- $\chi_{c1}(3872)$ **- the most precise mass measurement** (in $B^+ \to (J/\psi\pi^+\pi^-)K^+$ decays)

The measurements of mass differences:

$m_{\chi_{c1}(3872)} - m_{\psi_2(3823)} = (47.50 \pm 0.53 \pm 0.13)\ \mathrm{MeV/c^2}$

$m_{\psi_2(3823)} - m_{\psi(2S)} = (137.98 \pm 0.53 \pm 0.14)\ \mathrm{MeV/c^2}$

$m_{\chi_{c1}(3872)} - m_{\psi(2S)} = (185.49 \pm 0.06 \pm 0.03)\ \mathrm{MeV/c^2}$

$\delta m(\psi(2S))$

$\mathbf{m_{\chi_{c1}(3872)} = (3871.59 \pm 0.06 \pm 0.03 \pm 0.01)}\ \mathrm{MeV/c^2}$

$\mathbf{m_{\psi_2}(3823) = (3824.08 \pm 0.53 \pm 0.14 \pm 0.01)}\ \mathrm{MeV/c^2}$

JHEP 08 (2020) 123

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

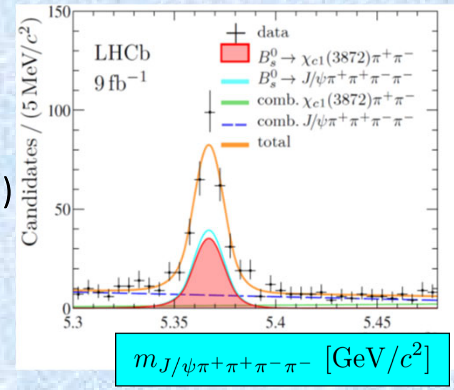
$B_s^0 \to \chi_{c1}(3872)\pi^+\pi^-$: 155 ± 23 events (7.3σ)

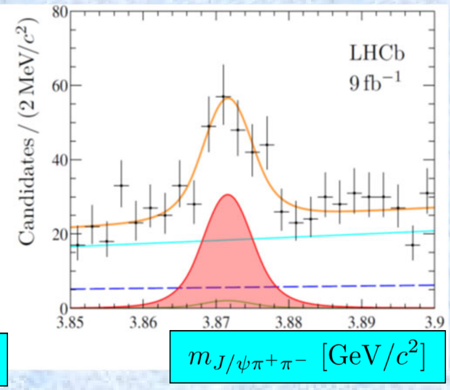
$B_s^0 \to \psi(2S)\pi^+\pi^-$: 1301 ± 47 events (normalization channel)

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

$= (1.6 \pm 0.3 \pm 0.1 \pm 0.3) \times 10^{-6}$

JHEP 07 (2023) 084





- **Study of ω contribution in $\chi_{c1}(3872) \to J/\psi\pi\pi$**

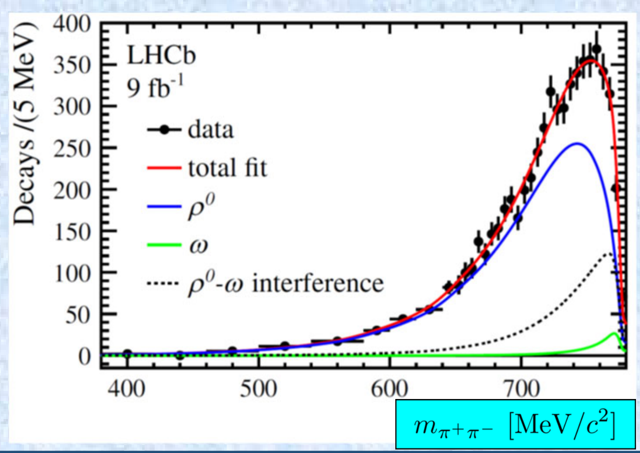
$\chi_{c1}(3872) \to J/\psi\rho$ – violation of isospin symmetry

$\chi_{c1}(3872) \to J/\psi\omega$ – isospin conserving

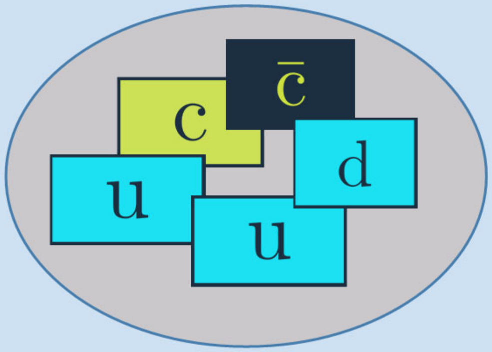
PRD 108 (2023) L011103

LHCb: **The first observation of a sizeable contribution from** $\chi_{c1}(3872) \to J/\psi\omega$ **:** $(21.4 \pm 2.3 \pm 2.0)\%$ 7.1σ (through ρ^0- ω interference)

Ratio of isospin violating to isospin conserving couplings (6x $c\bar{c}$ expectation): $\frac{g_{\chi_{c1}(3872)\to\rho J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04$



Pentaquarks



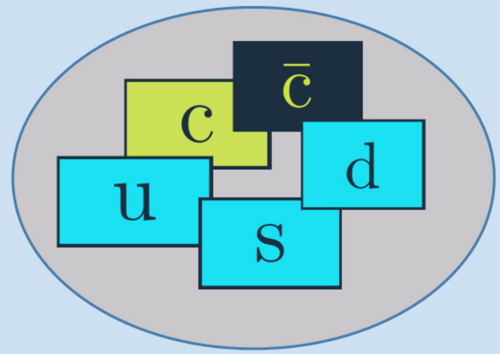
$[J/\psi p]$

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

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

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

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



$[J/\psi \Lambda]$

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

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

Pentaquarks: the First Observations in $J/\psi p$

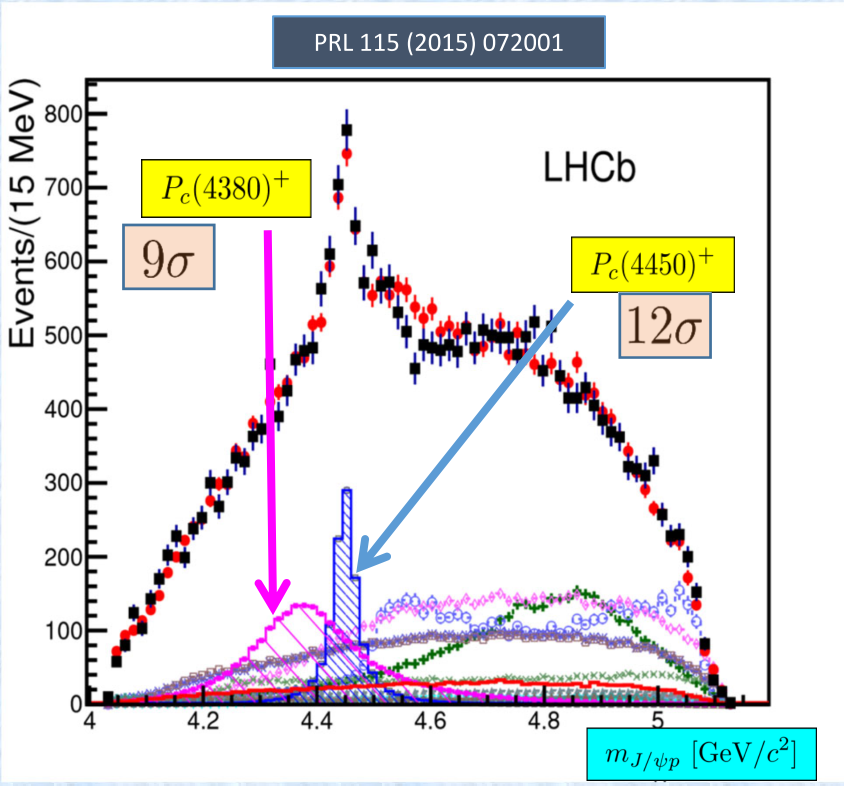
LHCb (2015):

Amplitude analysis of $\Lambda_b \to J/\psi p K$ (Run1 data)

- structures close to the thresholds: $\Sigma_c^+ \bar{D}^0$, $\Sigma_c^+ \bar{D}^{*0}$

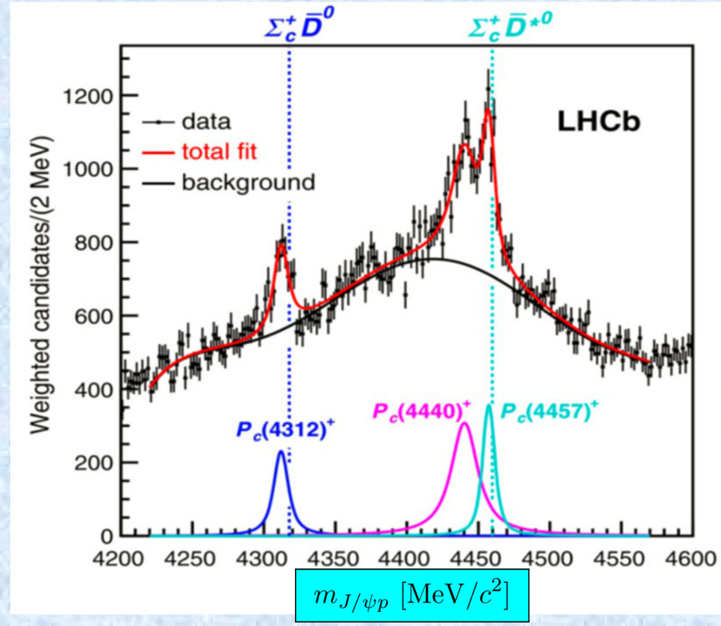
Two narrow states in $[J/\psi p]$: $P_c(4380)$ and $P_c(4450)$

PRL 115 (2015) 072001



Results confirmed with the Legendre polynomial expansion approach

LHCb: repeated study with Run1 + Run2 data



- **New state $P_\psi^N(4312)^+$:** $\mathbf{m}[\mathbf{P}_\psi^\mathbf{N}(\mathbf{4312})^+] = (4311.9 \pm 0.7^{+6.8}_{-0.6})\ \mathrm{MeV}/c^2$; $\mathbf{\Gamma}[\mathbf{P}_\psi^\mathbf{N}(\mathbf{4337})^+] = (9.8 \pm 2.7^{+3.7}_{-4.5})\ \mathrm{MeV}/c^2$ — 7.3σ
- **$P_c(4450)^+$ resolved into two separate peaks: $P_\psi^N(4440)^+$ and $P_\psi^N(4457)^+$** PRL 122 (2019) 222001

State	Mass [MeV/c^2]	Width [MeV/c^2]
$P_\psi^N(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$
$P_\psi^N(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$

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

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

Amplitude analysis of $B_s^0 \to J/\psi p\bar{p}$

797 ± 31 events

PRL. 128 (2022) 062001

PRL. 122 (2019) 191804

Evidence for a structure in $[J/\psi p]$ and $[J/\psi\bar{p}]$

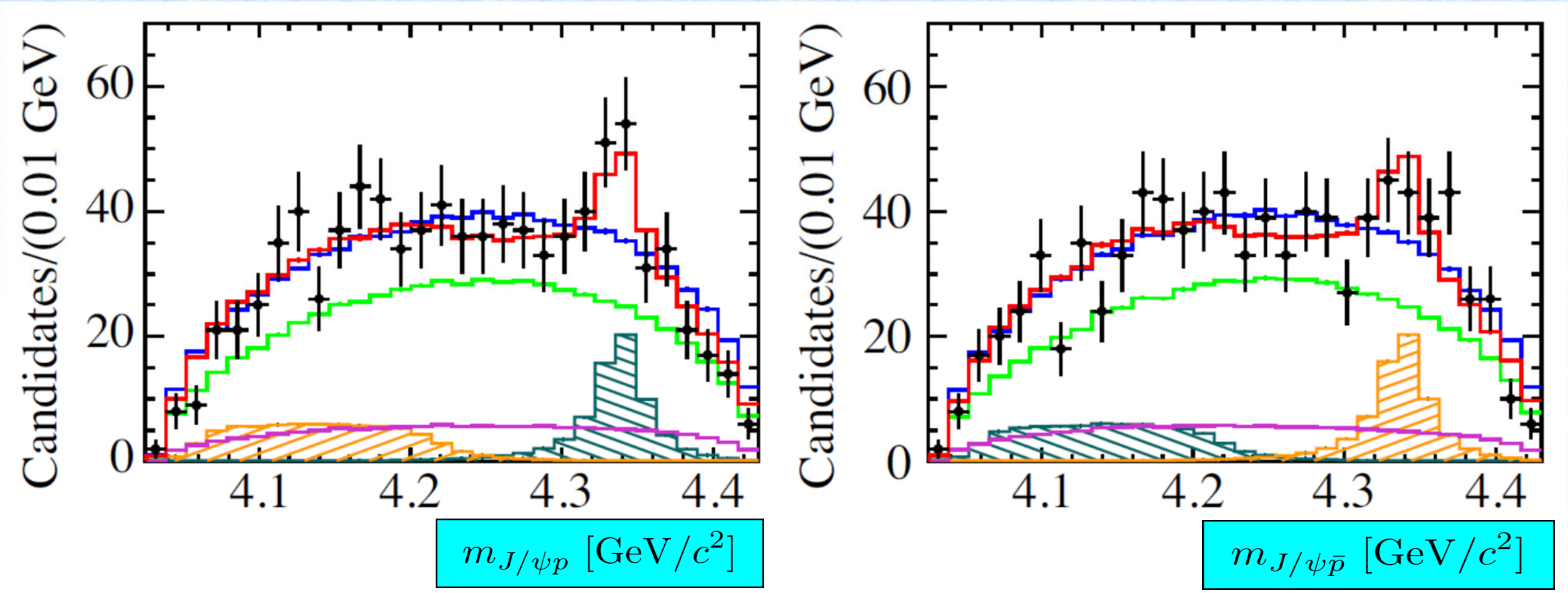
$\mathrm{m}[\mathrm{P}_{\psi}^{\mathrm{N}}(4337)^{+}] = (4337^{+7+2}_{-4-2})\ \mathrm{MeV/c^2}$

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

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

Very close to the $(\Xi_c^+ D^-)$ threshold

No evidence for $P_{\psi}^{N}(4312)$, nor for $f_J(2200)$ (glueball)



Quark content [$c\bar{c}uud$] → look for strange counterparts [$c\bar{c}uds$]

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

Amplitude analysis of $\Xi_b^- \to J/\psi\Lambda K^-$ decays 1750 ± 50 events

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

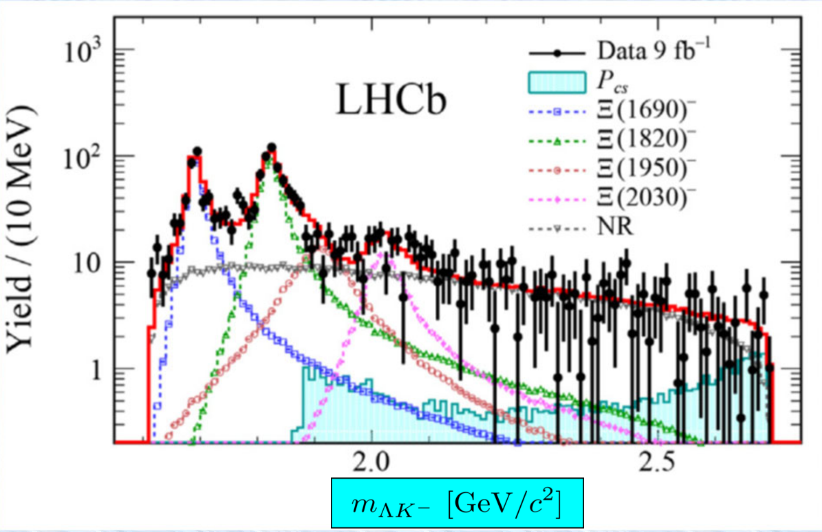
Evidence for a new pentaquark with strangeness in $[J/\psi\Lambda]$ – 19 MeV/c² below the $(\Xi_c^0 D^{*0})$ threshold

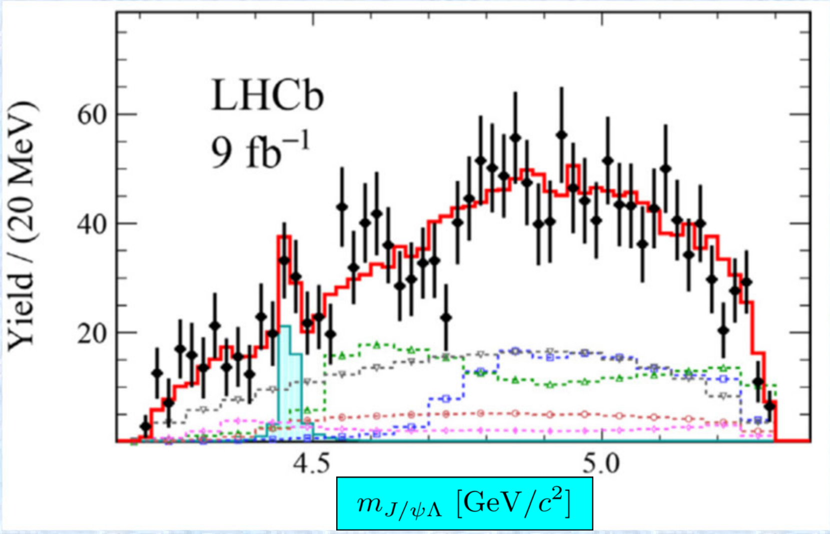
$\mathbf{m[P^{\Lambda}_{\psi s}(4459)^0]} = (4458.8 \pm 2.9^{+4.7}_{-1.1})\ \mathrm{MeV/c^2}$

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

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

J^P not yet determined





Theoretical expectation: two states with $J^P = 1/2^-$ and $3/2^-$ and mass difference of 6 MeV/c²
Current study cannot confirm or refute the two peak hypothesis

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

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

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

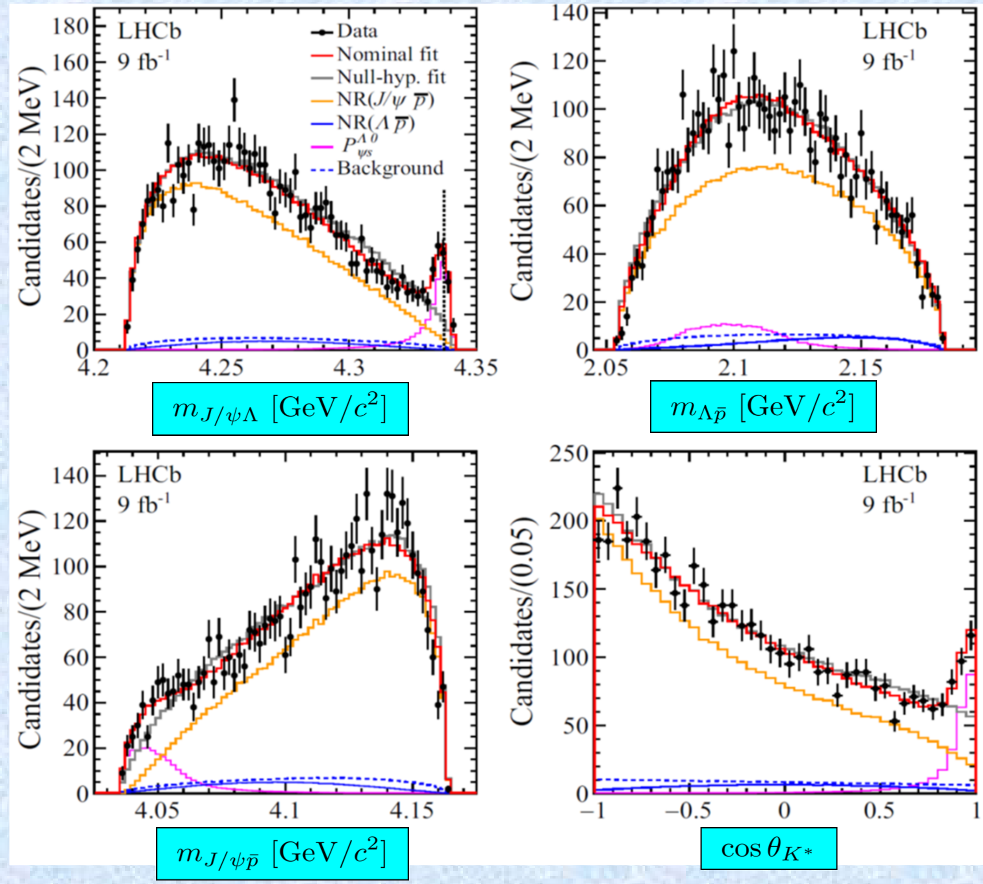
4620 ± 70 events

PRL 131 (2023) 031901

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

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

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

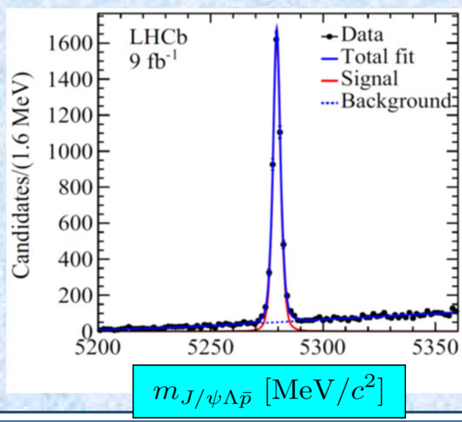


Very close to the $(\Xi_c^+ D^-)$ threshold

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

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

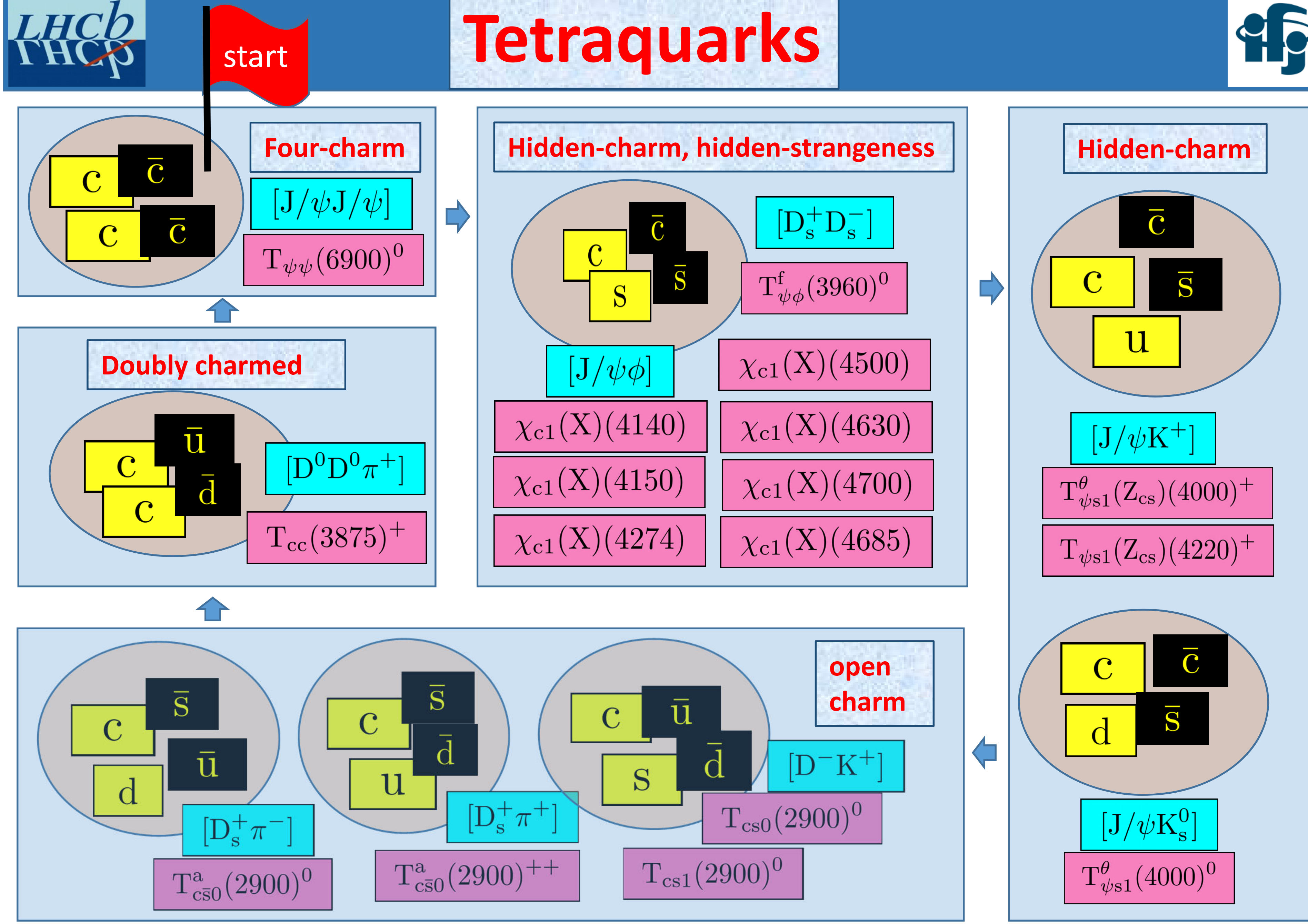
J = $\frac{1}{2}^+$ – excluded at 90% C. L.



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

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

Tetraquarks



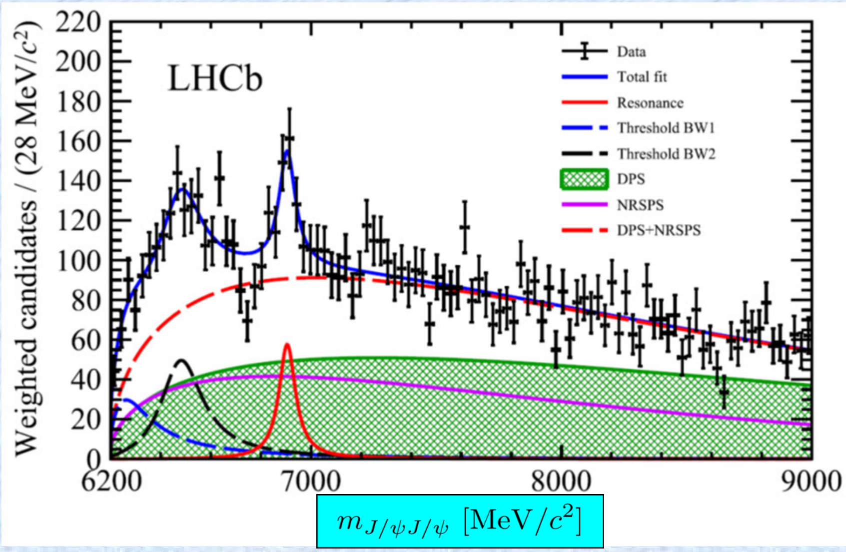
Four-charm Tetraquark $T_{\psi\psi}(6900)^0$

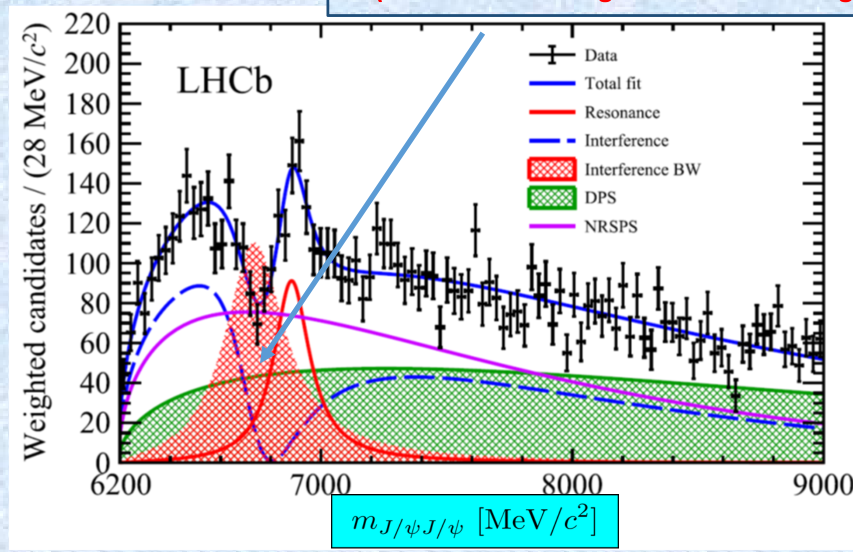
Two structures observed in di-J/ψ mass spectrum:

Science Bulletin 65 (2020) 1983

- Broad maximum close to the $J/\psi J/\psi$ mass threshold
- Narrow structure around 6900 MeV/c² - quark content $[cc\bar{c}\bar{c}]$

Interference (destructive) - between the threshold maximum and continuum NRSPS (Non Resonant Single Parton Scattering)





➢ **Model I (no interference)** 252 ± 63 events

$\mathbf{m}[\mathbf{T}_{\psi\psi}(\mathbf{6900})^\mathbf{0}] = (6905 \pm 11 \pm 7)\ \mathrm{MeV/c^2}$

$p = 4.6\%$

$\mathbf{\Gamma}[\mathbf{T}_{\psi\psi}(\mathbf{6900})^\mathbf{0}] = (80 \pm 19 \pm 33)\ \mathrm{MeV/c^2}$

Model II (with interference) 784 ± 148 events

$\mathbf{m}[\mathbf{T}_{\psi\psi}(\mathbf{6900})^\mathbf{0}] = (6886 \pm 11 \pm 11)\ \mathrm{MeV/c^2}$

$p = 15.5\%$

$\mathbf{\Gamma}[\mathbf{T}_{\psi\psi}(\mathbf{6900})^\mathbf{0}] = (168 \pm 33 \pm 69)\ \mathrm{MeV/c^2}$

➢ $T_{\psi\psi}$ structures recently seen by CMS arXiv 2306.07164 and ATLAS arXiv 2304.08962 :
  - ➢ Confirmation of $T_{\psi\psi(}6900)^0$ state
  - ➢ Confirmation of hints seen by LHCb at 6600 and 7200 MeV/c²

Hidden-charm, Hidden-strangeness Tetraquark X(3960)

➢ Amplitude analysis of $B^+ \to D_s^+ D_s^- K^+$ $(D_s^+ \to K^+ K^- \pi^+)$ 360 events

PRL 131 (2023) 071901

- A near-threshold peaking structure $X(3960) \to D_s^+ D_s^-$

$\mathbf{M[X(3960)] = (3956 \pm 5 \pm 10)\ MeV/c^2}$ $> 12\sigma$ $J^{PC} = 0^{++}$ $> 9\sigma$

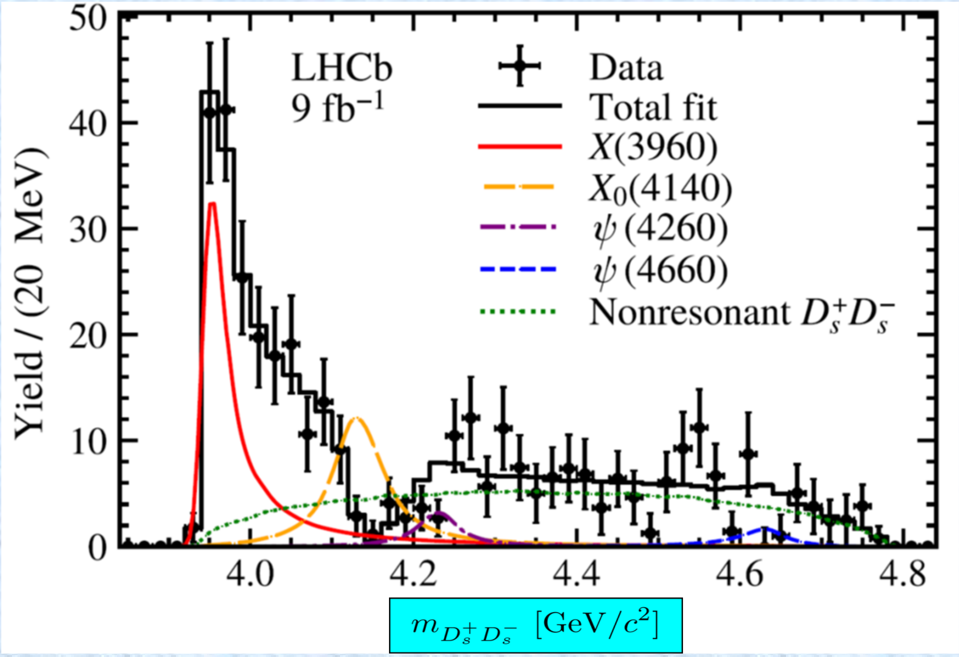
$\mathbf{\Gamma[X(3960)] = (43 \pm 13 \pm 8)\ MeV/c^2}$

- Additional structure, $X_0(4140)$, in the $D_s^+ D_s^-$ mass spectrum – accounting for the dip at 4.14 GeV/c² via interference

$\mathbf{M[X_0(4140)] = (4133 \pm 6 \pm 6)\ MeV/c^2}$

$\mathbf{\Gamma[X_0(4140)] = (67 \pm 17 \pm 7)\ MeV/c^2}$ 3.5σ

- Two known conventional states $\psi(4260)$ and $\psi(4660)$



- X(3960) – a candidate for $[cs\bar{c}\bar{s}]$ state → $T^f_{\psi\varphi}(3960)$
- Dip at 4.14 GeV/c²: either a destructive interference with the $X_0(4140)$ 0^{++} resonance, or the coupled-channel effect of the $J/\psi\phi \leftrightarrow D_s^+ D_s^-$

Hidden-charm, Hidden-strangeness $[cs\bar{c}\bar{s}]$ and Hidden-charm $[cu\bar{c}\bar{s}]$ Tetraquarks

- **LHCb (2017, 3fb^{-1}):** the 1st amplitude analysis of the $B^+ \to J/\psi\varphi K^+$ — 4289 ± 151 events
  - observation of four states in $J/\psi\varphi$ mass:
  - 1^+: **X(4140), X(4274)** 0^+: **X(4500), X(4700)** - quark content $[cs\bar{c}\bar{s}]$

PRL 118 (2017) 02203
PR D95 (2017) 012002

- **LHCb (2021, 9fb^{-1}) : 6x larger signal yield** — 24220 ± 170 events

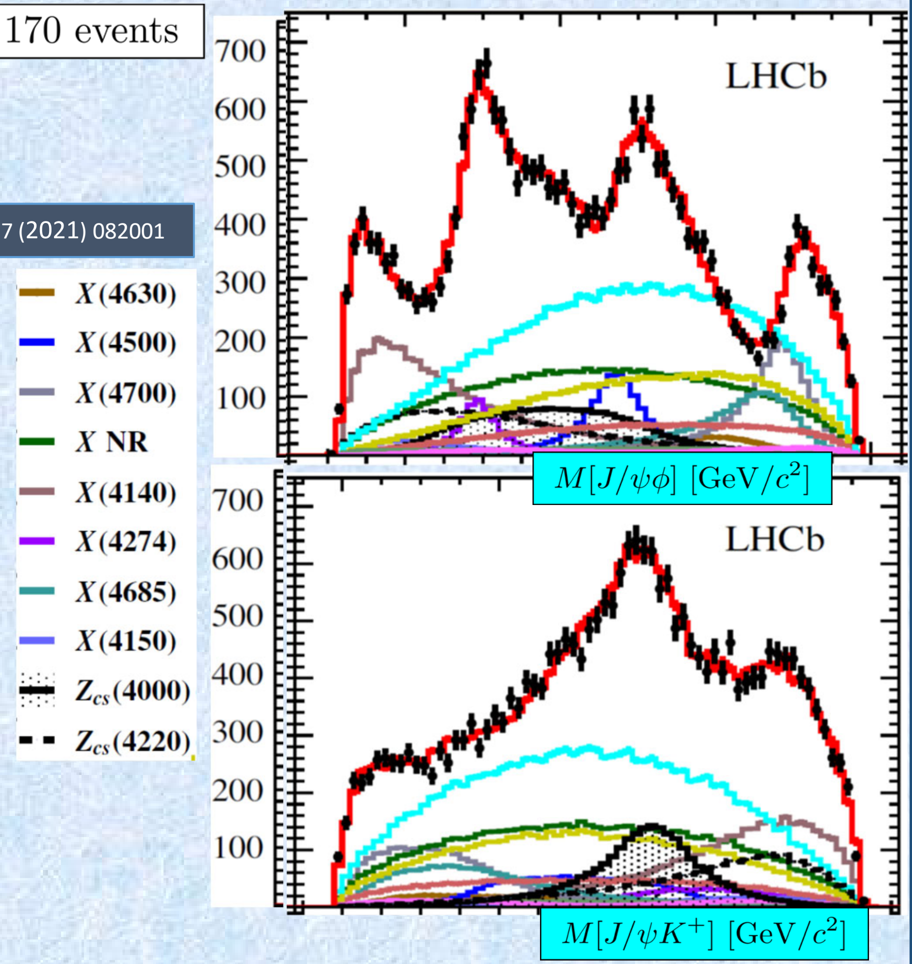
seven $X \to J/\psi\varphi$ states and two $Z_{cs} \to J/\psi K^+$

χ_{c1} - quark content $[cs\bar{c}\bar{s}]$

PRL 127 (2021) 082001

State	Mass [MeV/c^2]	Width [MeV/c^2]	J^P	Signif. [σ]
$X(4140)^0$	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	1^+	13
$X(4150)^0$	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	2^-	4.8
$X(4274)^0$	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	1^+	18
$X(4500)^0$	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	0^+	20
$X(4630)^0$	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	1^-	5.5
$X(4685)^0$	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	1^+	15
$X(4700)^0$	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	0^+	17
$Z_{cs}(4000)^+$	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	1^+	15
$Z_{cs}(4220)^+$	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$1^+(1^-)$	5.9

$T_{\psi s1}$ $T^{\theta}_{\psi s1}$ - quark content $[cu\bar{c}\bar{s}]$



Hidden-charm Tetraquark $T^{\theta}_{\psi s1}(4000)^0$

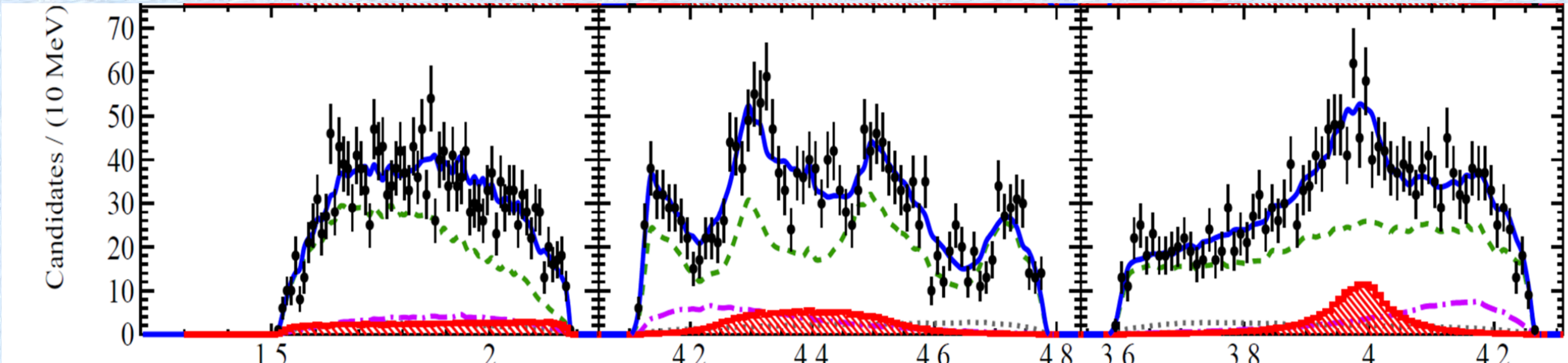
- **LHCb (2023):**

PRL 131 (2023) 131901

Amplitude analysis of the $B^0 \to J/\psi\varphi K^0_s$

1866 ± 47 events

- evidence for a structure in $[J/\psi K^0_s]$ system:



$m_{\phi K}$ [GeV/c^2]

$m_{J/\psi\phi}$ [GeV/c^2]

$m_{J/\psi K}$ [GeV/c^2]

4σ

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

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

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

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

$Z_{cs}(4000)$

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

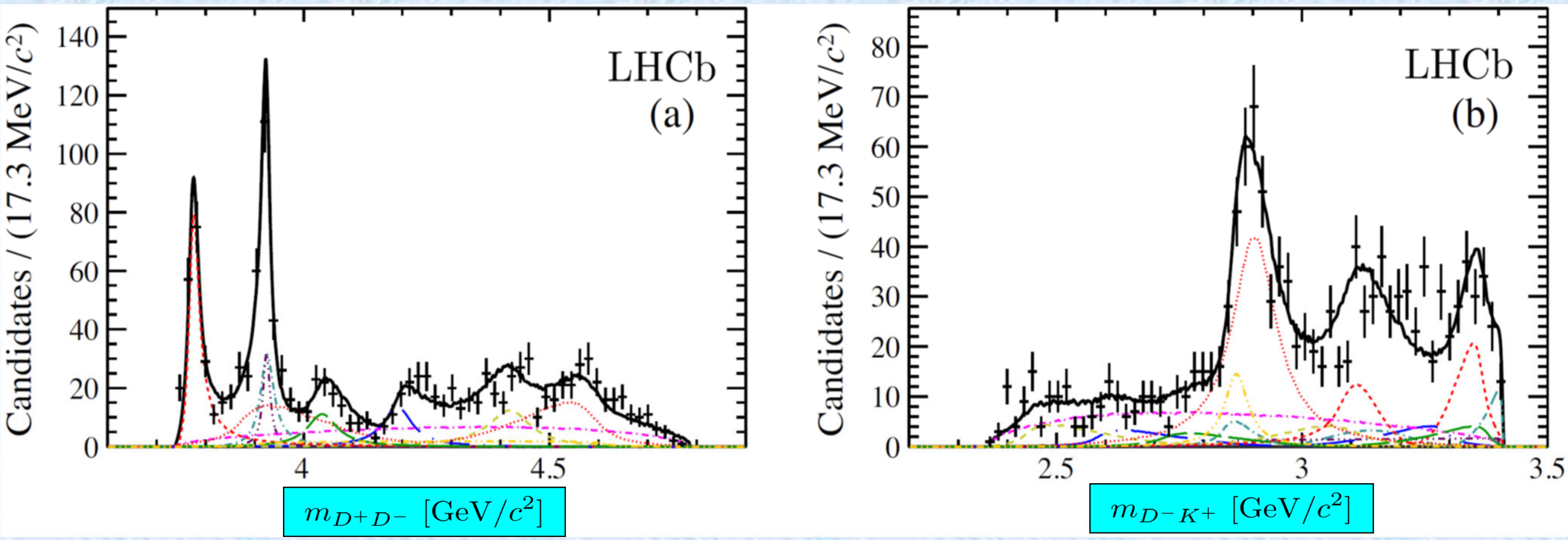
Open-Charm Tetraquarks $T_{cs0,1}(2900)^0$

➢ **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



- $\psi(3770) \to D^+ D^-$
- $\chi_{c0}(3930) \to D^+ D^-$
- $\chi_{c2}(3930) \to D^+ D^-$
- $\psi(4040) \to D^+ D^-$
- $\psi(4160) \to D^+ D^-$
- $\psi(4415) \to D^+ D^-$
- $X_0(2900) \to D^- K^+$
- $X_1(2900) \to D^- K^+$
- Nonresonant

Evidence for two new states:

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

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

$J^P = 0^+$

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

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

$J^P = 1^-$

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

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

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

Evidence for two new states in $[D_s \pi]$:

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

$\mathrm{M}[\mathrm{T}^{a}_{c\bar{s}0}(2900)^0] = (2879 \pm 17 \pm 18)\ \mathrm{MeV/c^2}$

$\Gamma[\mathrm{T}^{a}_{c\bar{s}0}(2900)^0] = (57 \pm 12 \pm 4)\ \mathrm{MeV/c^2}$

6.6σ $J^P = 0^+$

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

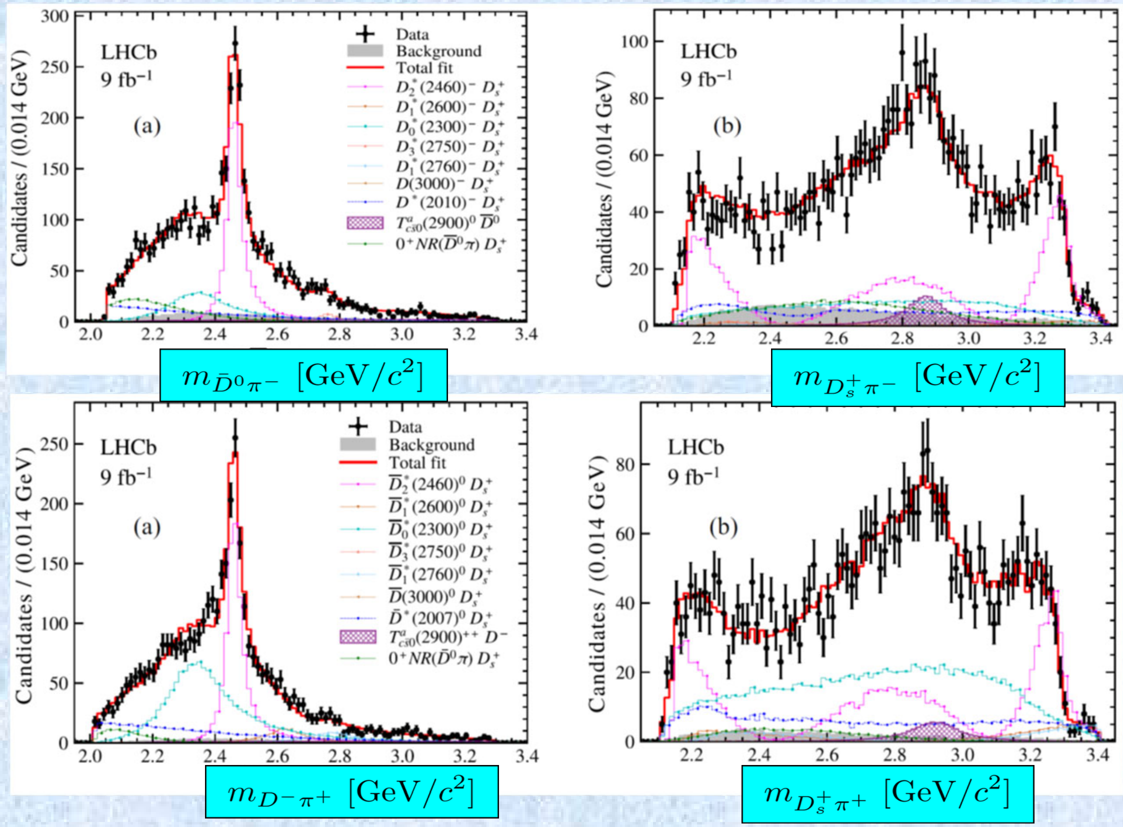
$B^+ \to D^- D_s^+ \pi^+$ — 3870 ± 64 events

$\mathrm{M}(\mathrm{T}^{a}_{c\bar{s}0}(2900)^{++}) = (2935 \pm 21 \pm 13)\ \mathrm{MeV/c^2}$

$\Gamma(\mathrm{T}^{a}_{c\bar{s}0}(2900)^{++}) = (143 \pm 38 \pm 25)\ \mathrm{MeV/c^2}$

4.8σ $J^P = 0^+$

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



Mass splitting

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

No hint for DD_s structures

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

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:

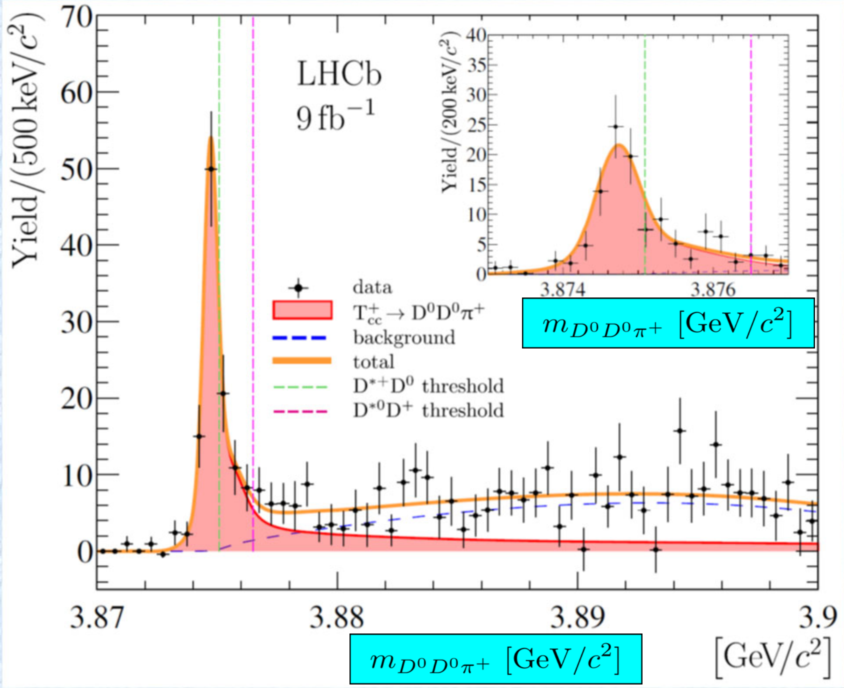
$$\delta m = m[T_{cc}(3875)^+] - (m[D^{*+}] + m[D^0]) = (-273 \pm 61 \pm 5^{+11}_{-14}(\text{model}))\ \text{keV}/c^2$$

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)

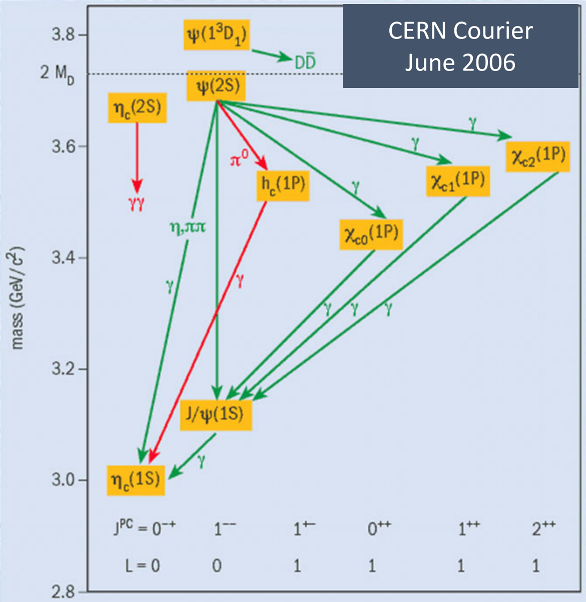
Observation of $T_{cc}(3875)^+$ strongly supports the existence of

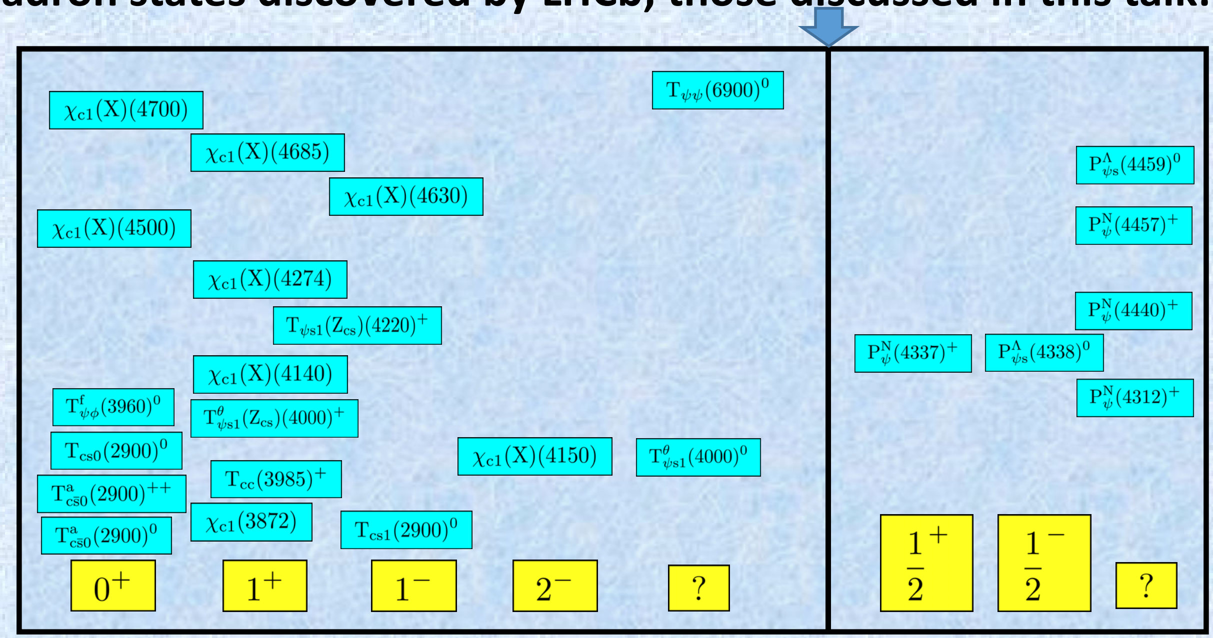
- **$[bb\bar{u}\bar{d}]$ tetraquark that is stable w.r.t. the strong and electromagnetic interactions**
- **$[bc\bar{u}\bar{d}]$ tetraquark state about 10 MeV below $\bar{B}D$ threshold**

Karliner, Rosner ArXiv 1707.07666

Summary

- A plethora of new (exotic) hadron states discovered by LHCb; those discussed in this talk:





- 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 (2x) and Run 4 (7x) data

BACKUP

Hidden and explicit exotics

Hidden exotics

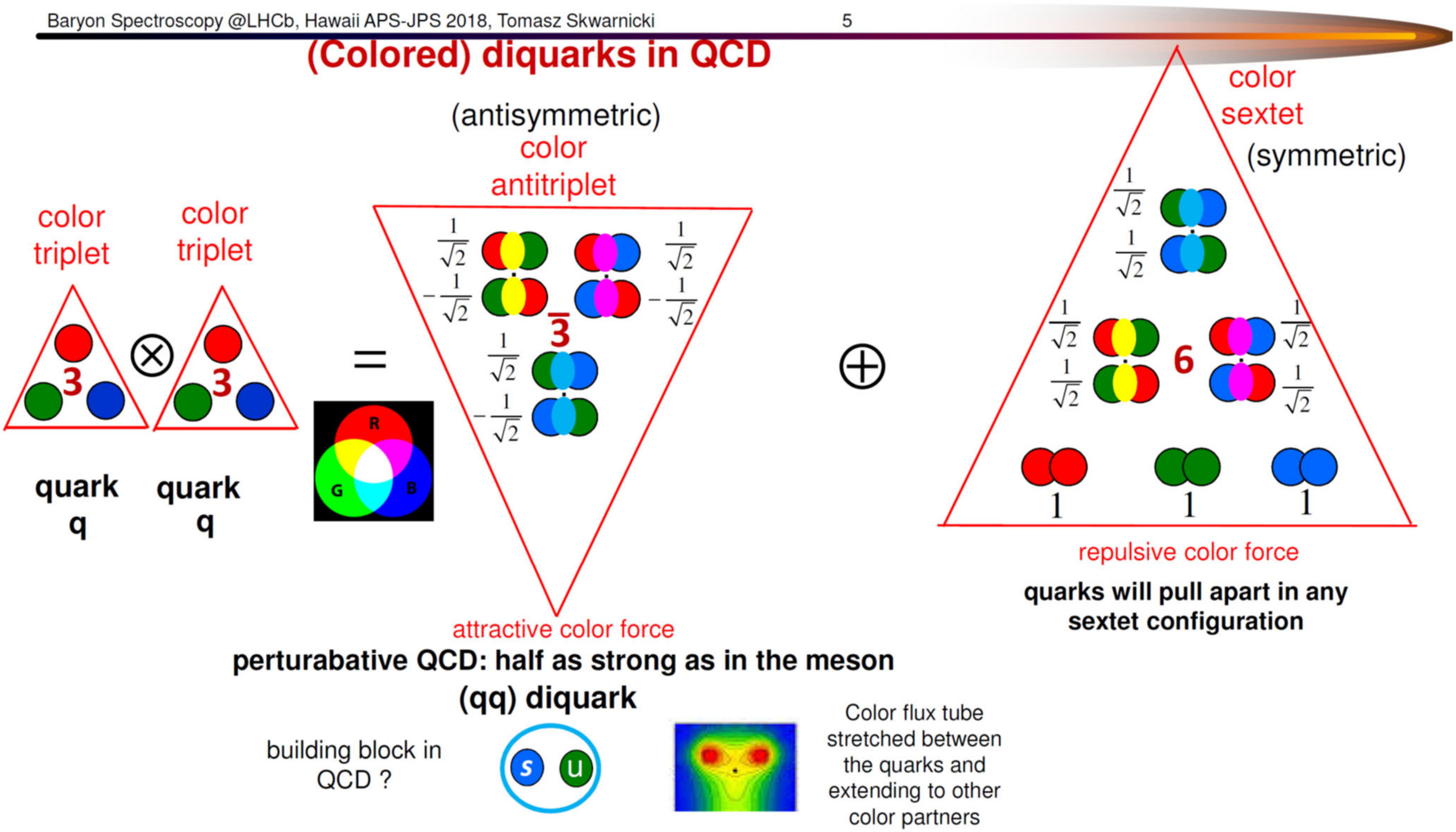
- Minimal quark content "mimics" regular hadrons structure
- $[c\bar{c}u\bar{u}]$, $[c\bar{c}d\bar{d}]$...
- Careful study needed
- Quantum numbers
- Production cross-section
- Unusual mass and/or width
- Unusual decay pattern

Explicit exotics

- Minimal quark content manifestly exotic
- "Charged quarkonia" such as Z_c^+, Z_b^+ with $[c\bar{c}u\bar{d}]$ or $[b\bar{b}u\bar{d}]$
- Open-flavour tetraquarks: $[cs\bar{u}\bar{d}]$
- Doubly charm tetraquarks: $[cc\bar{u}\bar{d}]$
- Fully charm tetraquarks: $[cc\bar{c}\bar{c}]$
- Pentaquarks: $[c\bar{c}uud]$, $[c\bar{c}uds]$

Studied by many different experiments: LHCb, BESIII, ATLAS, CMS, Belle, Belle II, BaBar, CDF, D0, ALICE...

Heavy Hadrons in Quark Model



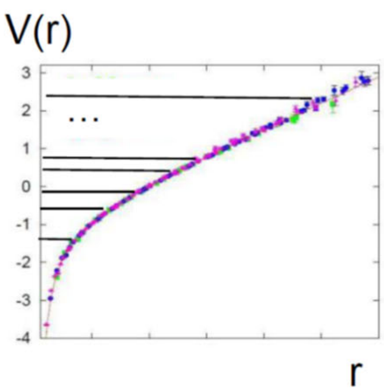
Compact tetraquarks (pentaquarks) vs meson-meson (meson-baryon) molecules

- The same quark content can, in principle, create a **compact tetra- or penta-quark with direct color couplings** or create **a loosely bound hadron-hadron "molecule" via nuclear-type couplings**
- However, mass spectrum ("spectroscopy") from these two types of bindings are very different

compact tetraquark

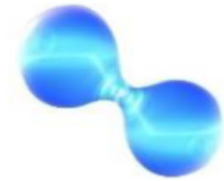
$((\bar{q}\bar{q})(qq))$

Very rich mass and J^P spectrum expected (all n, L, S)!

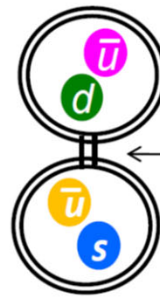


No obvious mechanism to suppress fall-apart to simpler hadrons – **wider states expected** (except if near/below strong decays thresholds)

meson-meson molecule

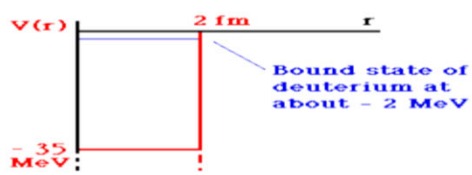


$(q\bar{q})$-$(q\bar{q})$



Usual phenomenology describes binding forces here via exchange of light mesons:

$\pi, \varrho, \omega, \eta, \ldots$



Typically expect only **one-two states** $n=1, L=0, S=S_1 \otimes S_2$

Mass and **J^P fairly constrained** from the constituents.

Fall-apart prevented by spatial separation – **narrow states** if below the related threshold.

Summary

Two nearly separate confining volumes.

One confinement volume.

By now overwhelming evidence for hadron-hadron interactions playing an important role in creating narrow mass structures near the corresponding thresholds in meson-meson
[$Z_b(10510)^{\pm,0}$, $Z_b(10560)^{\pm,0}$, $Z_c(3900)^{\pm,0}$, $Z_c(4020)^{\pm,0}$, $Z_{cs}(3985)^{\pm,0}$] ⟷ *Other production mechanism?*
and meson-baryon
[$P_c(4312)^{\pm}$, $P_c(4440)^{\pm}$, $P_c(4457)^{\pm}$, $P_{cs}(4438)^0$, $P_{cs}(4456)^0$?, $P_{cs}(4468)^0$?] ⟷ *Isospin partners? Other decay modes? Other production mechanism?*
interactions

Don't trust the extracted spectrum details since the amplitude models are missing coupled-channel effects. ⟷

Best evidence for compact tetraquarks is a rich spectrum of broader charmonium-like states [Z_c, Z_{cs}] seen in B decays
[$J/\psi\pi^{\pm}, J/\psi K^{\pm}, J/\psi K_S^0$, $\psi(2S)\pi^{\pm}, \psi(2S)K^{\pm}?, J/\psi\phi, \chi_{c1}\pi^{\pm}$]
as well as existence of $J/\psi\, J/\psi$, $\psi(2S)\, J/\psi$?, $T_{c\bar{s}0}(2900)^0, T_{c\bar{s}0}(2900)^{++}$, $T_{cc}(3875)^{\pm}$ states ⤡

Isospin partners for some of them
Other decay modes?
Other production mechanism?

Compact pentaquarks? [$P_c(4337)^{\pm}$?]

Not clear if well formed bound-states ("molecules") or other forms (e.g. virtual states)

Various color binding schemes possible (e.g. "good" and "bad" diquarks?)

Many states can mix more than one dynamics; the two above if narrow and near thresholds [e.g. $T_{cc}(3875)^{\pm}, X(3872)$], with ordinary mesons [e.g. $X(3872)$, some $J/\psi\phi$ states, Y states] and with hybrid states [e.g. $Y(4220), Y(4660), Y(...)$]

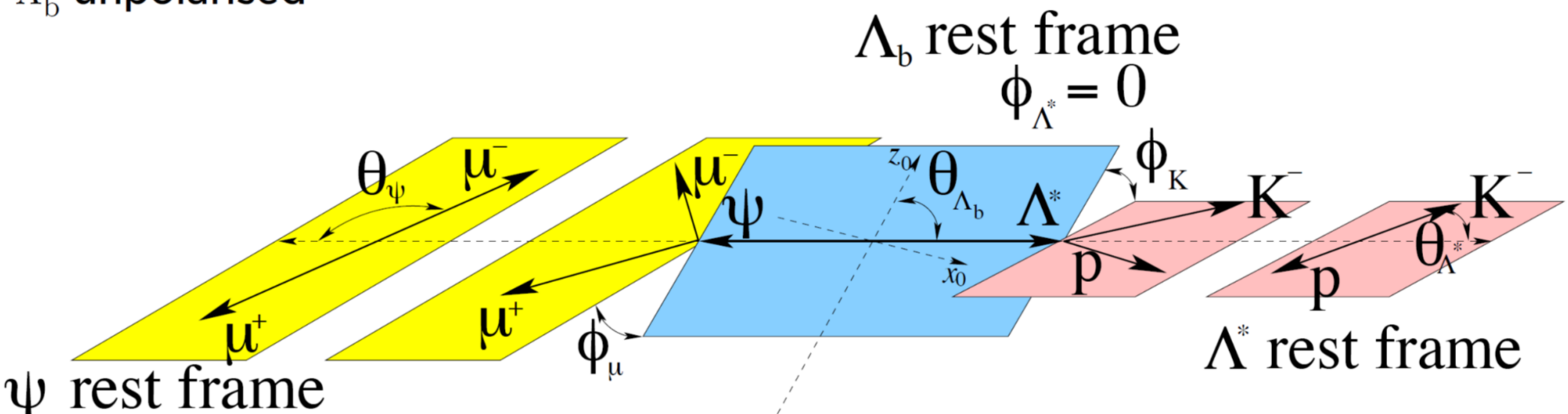
The systematic multiquark spectroscopy explaining unambiguously all states will be difficult. The best we can probably hope for, is demonstrating presence of various binding mechanisms on systems in which they dominate.

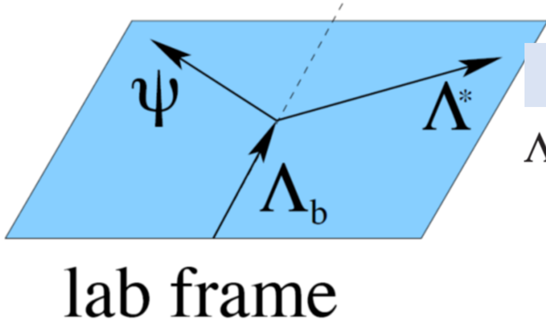
Amplitude analysis

Isobar Model Helicity Amplitudes for $\Lambda_b \to J/\psi \Lambda^*$

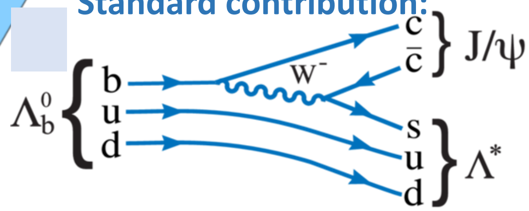
Matrix Element $\mathcal{M}^{\Lambda^*}$ parametrized as a function of 5 angles and one mass m^2_{pK}

Λ_b unpolarised





Standard contribution:



$J/\psi \to \mu^+\mu^-$

$\Lambda^* \to K^- p$

[PRL115(2015)072001]

Isobar Model Helicity Amplitudes for $\Lambda_b \to J/\psi \Lambda^*$

- **Angular structures** (no free parameters)
- **Helicity couplings** $\leftarrow$ complex numbers, floating in fit
- Λ^* **partial waves** variety of possible parametrizations (Breit-Wigner, Flatté, Polynomials, Splines)

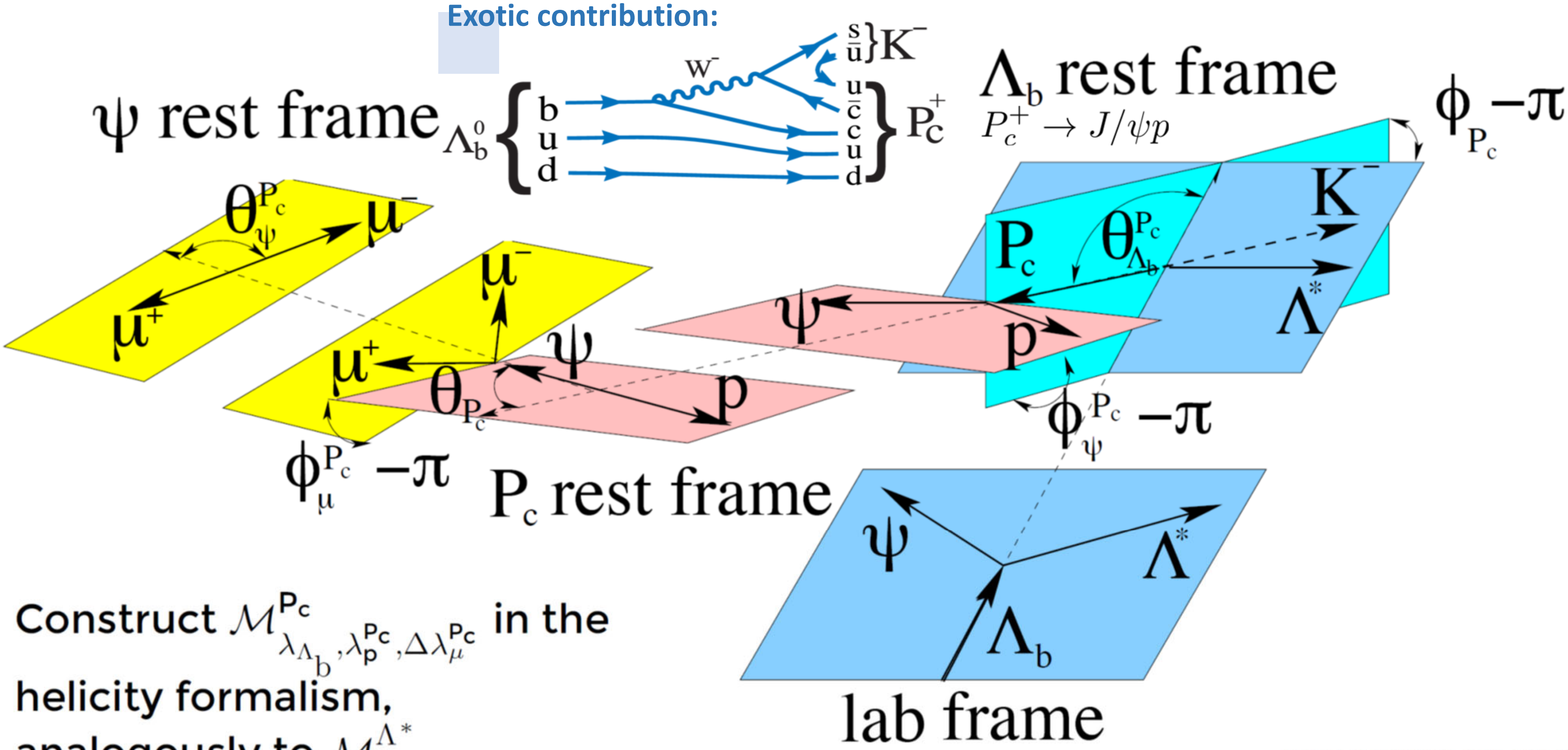
$$\mathcal{M}^{\Lambda^*} = \sum_n R_n(m_{Kp}) \; \Lambda_n^* \to Kp_{\lambda_p} \; \sum_{\lambda_\psi} e^{i\,\lambda_\psi \phi_\mu} \, d^{1}_{\lambda_\psi, \Delta\lambda_\mu}(\theta_\psi) \times$$

$$\sum_{\lambda_{\Lambda^*}} \Lambda_b \to \Lambda_n^* \psi_{\lambda_{\Lambda^*}, \lambda_\psi} \; e^{i\,\lambda_{\Lambda^*} \phi_K} \; d^{\frac{1}{2}}_{\lambda_{\Lambda_b}, \lambda_{\Lambda^*} - \lambda_\psi}(\theta_{\Lambda_b}) \; d^{J_{\Lambda_n^*}}_{\lambda_{\Lambda^*}, \lambda_p}(\theta_{\Lambda^*})$$

Amplitude analysis

Adding Helicity Amplitudes for $\Lambda_b \to P_c K$

Exotic contribution:



Construct $\mathcal{M}^{P_c}_{\lambda_{\Lambda_b}, \lambda_p^{P_c}, \Delta\lambda_\mu^{P_c}}$ in the helicity formalism, analogously to $\mathcal{M}^{\Lambda^*}_{\lambda_{\Lambda_b}, \lambda_p, \Delta\lambda_\mu}$

[PRL115(2015)072001]

Amplitude analysis

Resonance parametrisation

Dynamical Terms $R_n(m_{Kp})$ given by

- Relativistiv, single-channel Breit-Wigner amplitudes $BW(M_{Kp}|M_0^{\Lambda_n^*}, \Gamma_0^{\Lambda_n^*})$

$$BW(M|M_0, \Gamma_0) = \frac{1}{M_0^2 - M^2 - iM_0\Gamma(M)},$$

where

$$\Gamma(M) = \Gamma_0 \left(\frac{q}{q_0}\right)^{2\ell_{\Lambda^*}+1} \frac{M_0}{M} B'_{\ell_{\Lambda^*}}(q, q_0, d)^2 .$$

- Angular-momentum barrier factors $B'_\ell(p, p_0, d)$

$$R_n(m_{Kp}) = B'_{\ell_{\Lambda_b}} \left(\frac{p}{M_{\Lambda_b}}\right)^{\ell_{\Lambda_b}} \times BW(M_{Kp}) \times B'_{\ell_{\Lambda_n^*}} \left(\frac{q}{M_{\Lambda_n^*}}\right)^{\ell_{\Lambda_n^*}} .$$

- special case $\Lambda(1405)$ is subthreshold: Flatté ($K\,p$ and $\Sigma\,\pi$ channels)

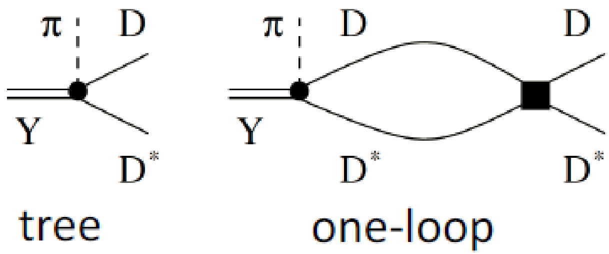
$p(q)$ are momenta of the daughter particles in the rest-frame of the decaying particle.

$p_0(q_0)$ calculated on the nominal resonance mass

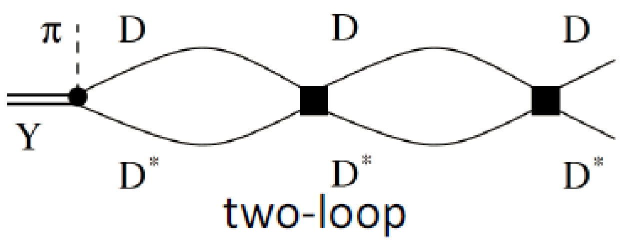
Threshold „cusps”

Threshold cusps are „resonances created kinematically by rapid opening of meson-meson threshold

Example: $Y \to \pi D\bar{D}^*$ **the lowest order diagrams:**



D and Dbar* rescatter elastically **ONCE**



D and Dbar* rescatter elastically **TWICE**

If D and Dbar* are in an S-wave, **the imaginary part of the scattering amplitude** is **zero** for

$$M(B\bar{D}^*) < (m_D + m_{\bar{D}^*})$$

And abruptly rises at threshold as: $\Im T(s) \propto g^2 \rho(s)$

(g – coupling constant, ρ(s) – phase space factor)

Threshold „cusps”

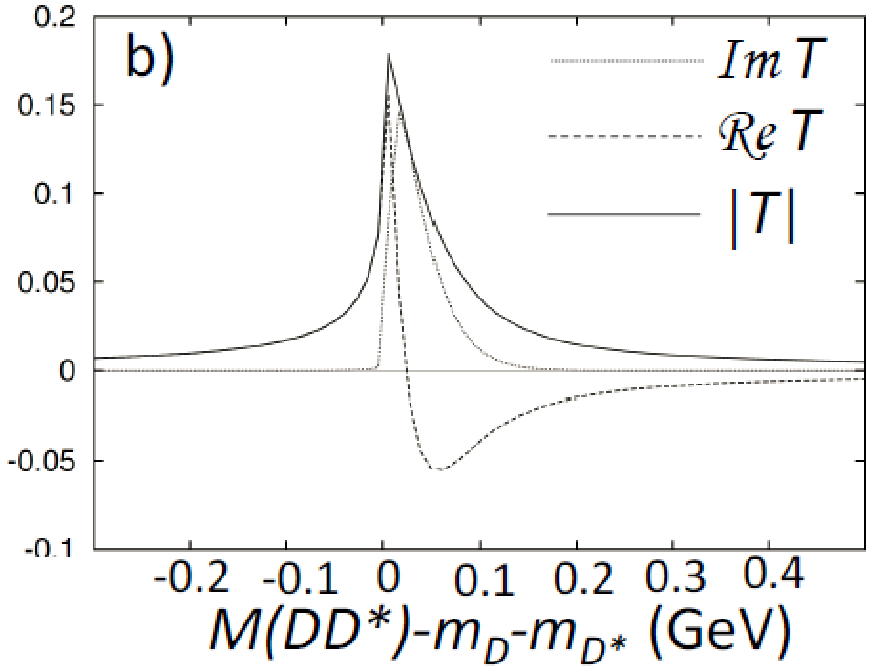
To prevent the increase to an unphysically large value, it has to be attenuated by a hadronic form-factor F(s):

$$\rho(s) = \frac{2k}{\sqrt{s}} F(s)$$

For T(s) to be analytic, it must have a real part of the form:

$$\Re T(s) = \frac{1}{\pi} P \int_{s_{thresh}}^{\infty} \frac{ds' g^2(s') \rho(s')}{s' - s}$$

(P – principal value integral
s_{thresh} – mass squared at threshold

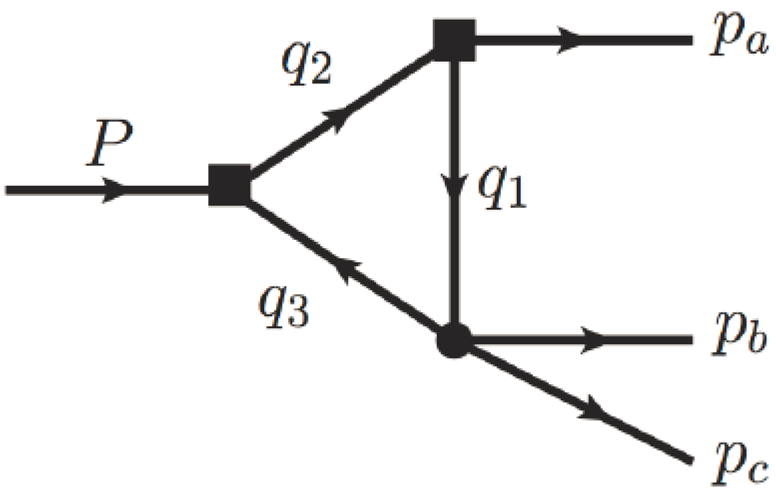


The resulting |T(s)| has a very sharp, cusp-like structure that peaks slightly above the threshold at $M = \sqrt{s_{thresh}}$

That peak originates from kinematics and has nothing common with any resonant structure in the D-Dbar* two-body system.

Anomalous Triangle Singularities (ATS)

ATS – such diagrams become singular when the three virtual particles that form the triangle are all simultaneously on the mass shell



In kinematic regions where the conditions for this singularity are satisfied, resonance-like peaking structures that have nothing to do with true particle resonances can be produced

If the rescattering is purely elastic, the effect of the ATS integrates to zero in the Dalitz plot projections.

However, in case of many coupled channels , the above applies to the sum of intensities of all of them, thus the Dalitz plot projections to individual channels can produce mass peaks

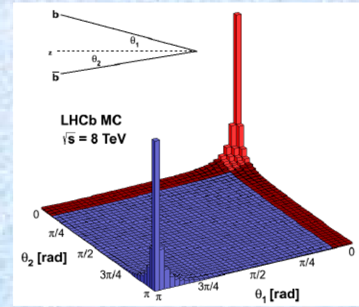
LHCb Data Sample

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

Goal for Run3 and Run4: 50 fb^{-1}

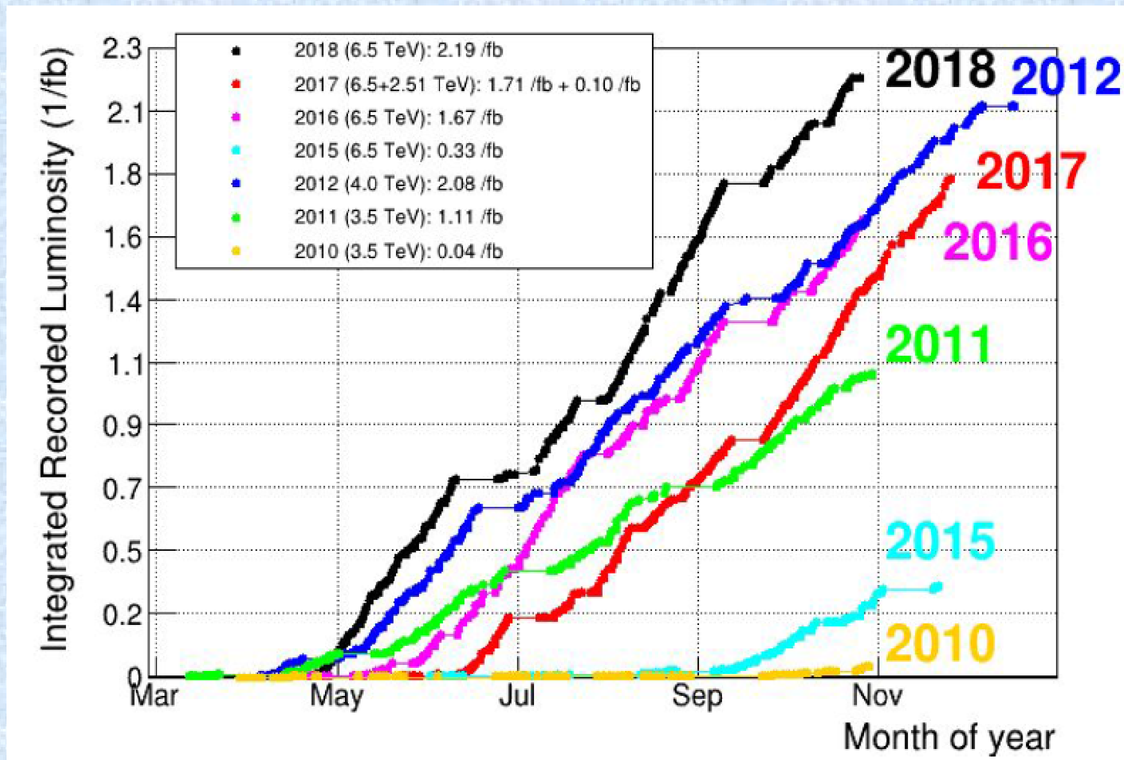
$$2 < \eta < 4.5$$

Nucl. Phys. B871 (2013) 1
JHEP 03 (2016) 159
JHEP 09 (2016) 013
JHEP 03 (2017) 074
PRL 118 (2017) 052002

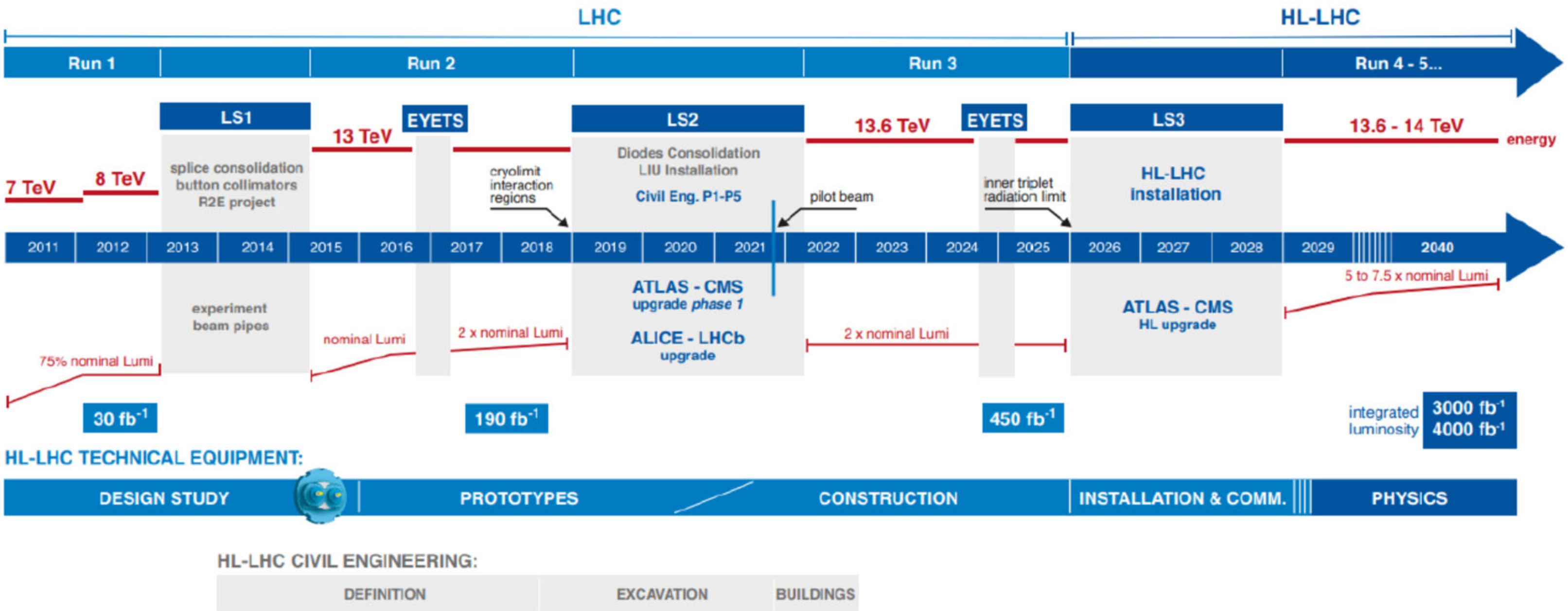


- **All results presented here correspond to Run 1 data:**
  3 fb^{-1}
  4 x 10^{12} b-hadrons produced

- **Run 2 vs Run 1:**
  - more abundant production of b-hadrons
  - improvements in trigger and selection efficiencies



LHC timeline



- LHC Run 2 finished in 2018
  - LHCb: $\int \mathcal{L}dt = 9\,\text{fb}^{-1}$ collected in 2010-2018
- Long shutdown until 2022: upgrade of the machine and detectors
  - LHCb Upgrade I: major upgrade/replacement of the subsystems and readout
- Run 3 until 2026 $\rightarrow$ HL-LHC upgrade $\rightarrow$ Run 4 ...
  - LHCb goal: $50\,\text{fb}^{-1}$ by the end of Run 4 $\rightarrow$ Upgrade II

LHCb Spectrometer

- **General advantages (pp interaction):**

+

- **High production cross-sections for HF** (2x10^4 bbar pairs/s i.e.10^3 larger than at the e^+e^- B factories)
- **Simultaneous accumulation of huge B_d , B_s and b-baryons data samples** (composition 4:1:2)
- **The decay vertices are well separated from the production point** (high boost of heavy hadrons)

- **LHCb specific advantages** (single arm forward spectrometer: $0.8^o < \Theta < 15.4^o$) :

+

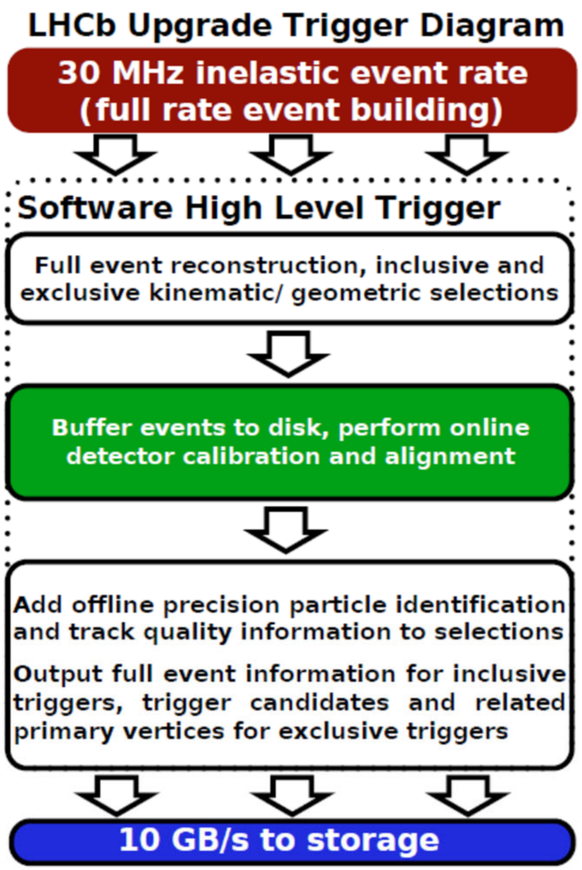
- **LHCb captures a HF production cross-section, comparable to that of ATLAS and CMS (high-p_T range) in MUCH SMALLER SOLID ANGLE** → smaller number of electronic channels → smaller event size → larger trigger bandwith to store (dominated by b and c physics)
- LHCb – forward detector ($p >> p_T$): **efficient muon identification for lower P_T values**
- **Space to accommodate excellent RICH detectors** (flavour tagging, background suppression)

- **General drawbacks:**

-

- **The instantaneous luminosity is limited by the detector readout capabilities** ($4x10^{32}$ $cm^{-2}s^{-1}$)
- **The efficiencies of γ, π^0 and η reconstruction are much lower,** compared with the e^+e^-

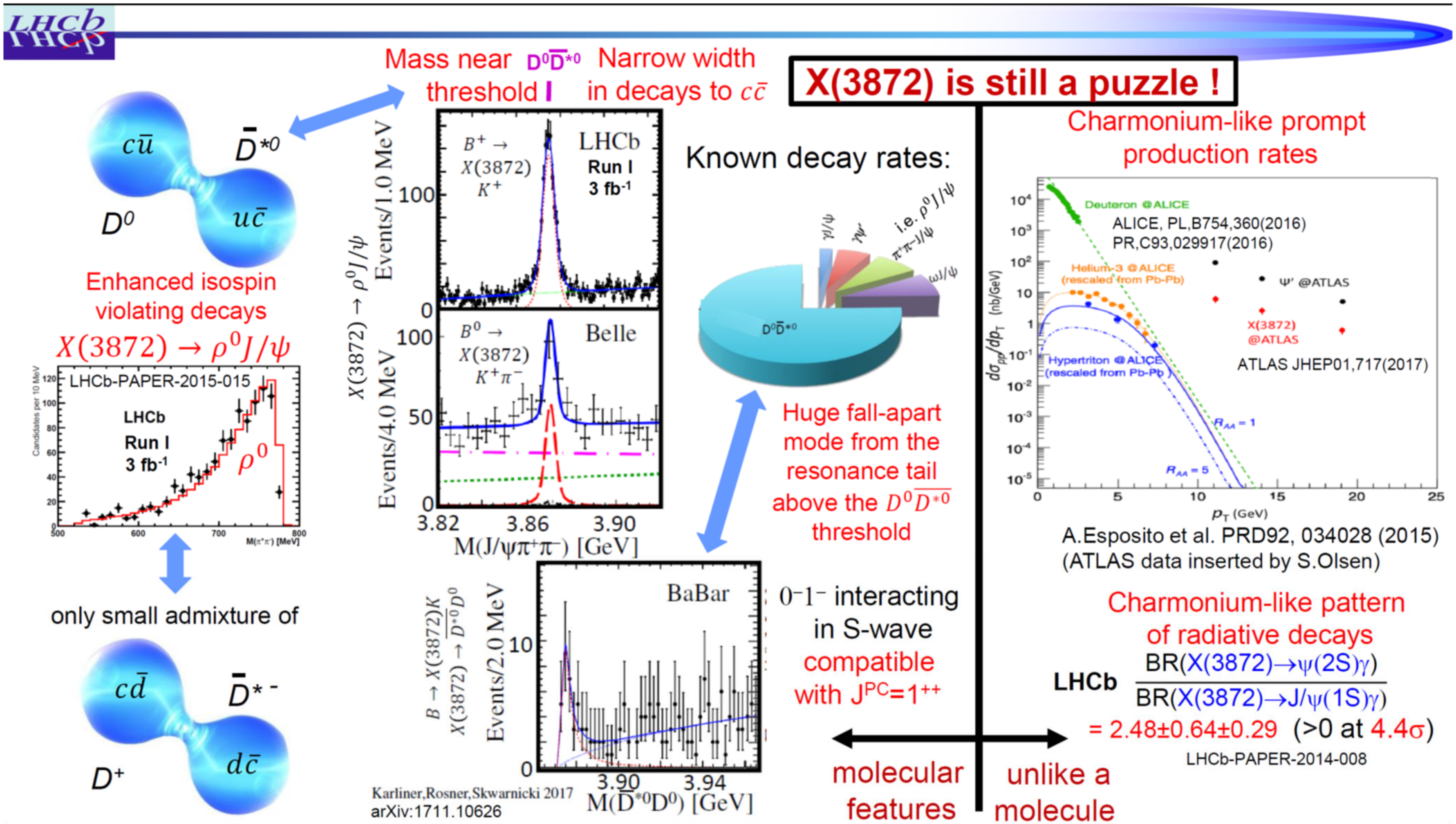
Upgraded LHCb trigger



HLT1: [LHCb upgrade computing TDR]

- Subdetector reconstruction:
  - VELO: clustering, tracking, vertex reconstruction
  - UT, SciFi: tracking
  - Muon: Hit-track matching
- Global event reconstruction:
  - Track fit (Kalman filter)
  - Reconstruction of secondary vertices
- Selections: [LHCb-PUB-2019-013]
  - Single displaced tracks
  - Two-track displaced vertices
  - Single displaced muons
  - Low-mass displaced two-muon vertices
  - High-mass dimuons

X(3872)



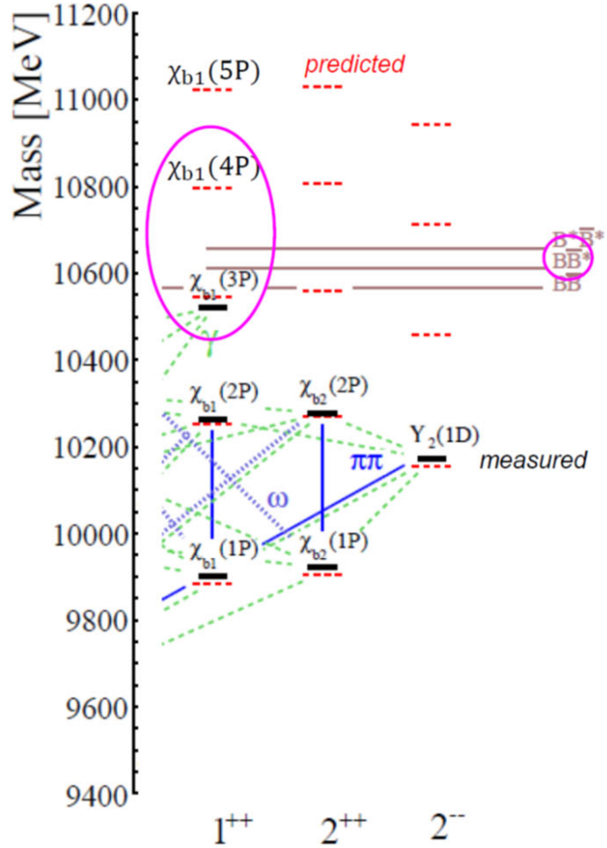
Mass near D⁰D̄*⁰ threshold !
Narrow width in decays to cc̄
X(3872) is still a puzzle !
cū
D̄*0
D0
uc̄
Enhanced isospin violating decays
X(3872) → ρ⁰J/ψ
LHCb-PAPER-2015-015
LHCb
Run I
3 fb-1
ρ0
only small admixture of
cd̄
D̄* -
D+
dc̄
B+ → X(3872) K+
LHCb
Run I
3 fb-1
Belle
B0 → X(3872) K+π−
X(3872) → ρ0J/ψ Events/1.0 MeV
Events/4.0 MeV
M(J/ψπ+π−) [GeV]
BaBar
Events/2.0 MeV
M(D̄*0D0) [GeV]
Karliner,Rosner,Skwarnicki 2017
arXiv:1711.10626
Known decay rates:
D⁰D̄*⁰
Huge fall-apart mode from the resonance tail above the D⁰D̄*⁰ threshold
0−1− interacting in S-wave compatible with JPC=1++
molecular features
unlike a molecule
Charmonium-like prompt production rates
Deuteron @ALICE
ALICE, PL,B754,360(2016)
PR,C93,029917(2016)
Helium-3 @ALICE (rescaled from Pb-Pb)
Ψ' @ATLAS
X(3872) @ATLAS
Hypertriton @ALICE (rescaled from Pb-Pb)
ATLAS JHEP01,717(2017)
pT (GeV)
A.Esposito et al. PRD92, 034028 (2015)
(ATLAS data inserted by S.Olsen)
Charmonium-like pattern of radiative decays
LHCb
BR(X(3872)→ψ(2S)γ) / BR(X(3872)→J/ψ(1S)γ)
= 2.48±0.64±0.29 (>0 at 4.4σ)
LHCb-PAPER-2014-008

Dual nature of X(3872)?

- X(3872) mixes features expected for a loosely bound **molecular** state (mass coincidence with the $D^0\bar{D}^{0*}$ threshold, "right" J^P=1^+, narrow width, large fall-apart rate to $D^0\bar{D}^{0*}$, large isospin violation in decays) with features expected for a tightly bound quark state i.e. **P-wave $c\bar{c}$** (production in many different reactions, pattern of radiative decays?)

- If coincidence of $\chi_{c1}(2^3P_1)$ with the $D^0\bar{D}^{0*}$ threshold is responsible for it, then there is no narrow analog of it in bottomonium

- **P-wave $c\bar{s}$** states, $D_{s0}^*(2317)^-$ and $D_{s1}(2460)^-$ also believed to be predominantly D^0K^-, D^0K^{*-} molecules



Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi\, p\, K^-$ Decays

- **LHCb: fortification of the P_c states observation: Model independent approach**

PRL 117 (2016) 082002

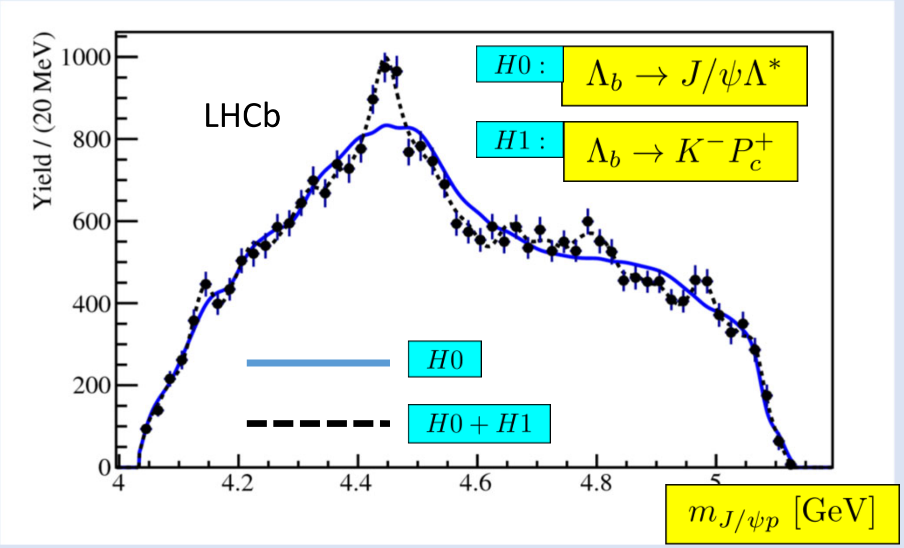
- 👍 - no need for the Λ* model; 👎 - can only indicate the presence of exotic states
- **2D analysis in terms of** $(m(Kp),\ \cos\theta_{\Lambda^*})$ (θ_{Λ^*}- helicity angle of the K-p system)
- The $\cos\theta_{\Lambda^*}$ ang. Distribution is expanded in Legendre polynomials (in bins of m(Kp)):

$$\frac{dN}{d\cos\theta_{\Lambda^*}} = \sum_{l=0}^{l_{max}} \langle P_l^U \rangle P_l(\cos\theta_{\Lambda^*})$$

Λ^* resonances can contribute only to low order moments up to $l_{max} = 2J_{max}$

J_{max} – the highest spin of any Kp contribution at the given m_{kp} bin

- $< P_l^U >$ - **Legendre moments:** contain all the information of the angular structure of the system as well as the spin of Λ* resonances



- The [Kp] mass and angular distributions are projected as reflection into the J/ψ p system

- **9σ discrepancy with data, assuming only Λ^* contributions (H0 hypothesis)**

- **The discrepancy concentrated in the region of mass corresponding to the P_c states** (best seen on the m(J/ψ p) distribution)

Search for b-flavoured Pentaquarks

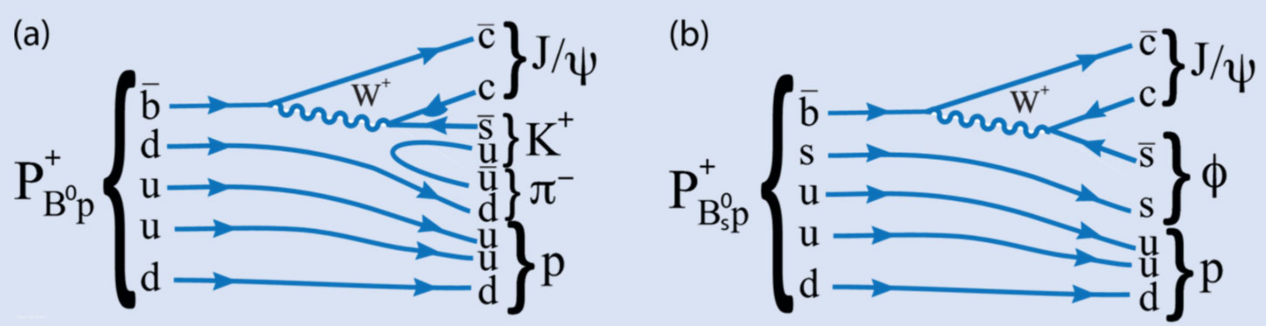
- The (uudc$\bar{c}$) states observed (decaying strongly)
- **The Skyrme model:** Proc. Roy. Soc. London A 260 (1961) 127
  expectation of b-flavoured pentaquarks P_b($b\bar{q}qqq$/$\bar{b}qqqq$), that decay via the weak interaction and are
  - **tightly bound** (Skyrme model: the binding grows with the mass of the constituent quarks)
  - **narrow** ($\Gamma \approx 6$ MeV, to compare with (40-200) MeV for P_cs)

- **LHCb:** the search for four types of P_b states PRD 97 (2018) 032010 Run 1 data, 3fb^{-1}

new

Mode	Quark content	Decay mode	Search window
I	$\bar{b}duud$	$P^+_{B^0 p} \to J/\psi K^+\pi^- p$	4668–6220 MeV
II	$b\bar{u}udd$	$P^-_{\Lambda^0_b\pi^-} \to J/\psi K^-\pi^- p$	4668–5760 MeV
III	$b\bar{d}uud$	$P^+_{\Lambda^0_b\pi^+} \to J/\psi K^-\pi^+ p$	4668–5760 MeV
IV	$\bar{b}suud$	$P^+_{B^0_s p} \to J/\psi \phi p$	5055–6305 MeV

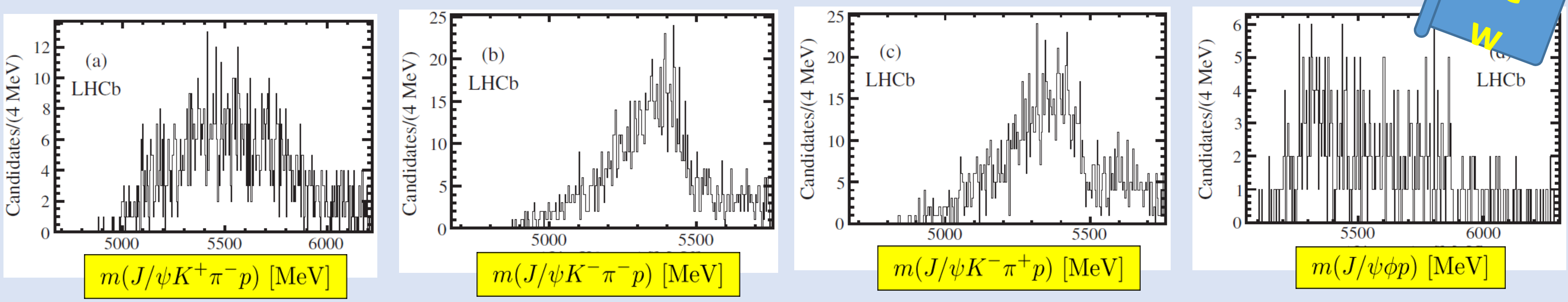
below the threshold for strong decays



Search for b-flavoured Pentaquarks

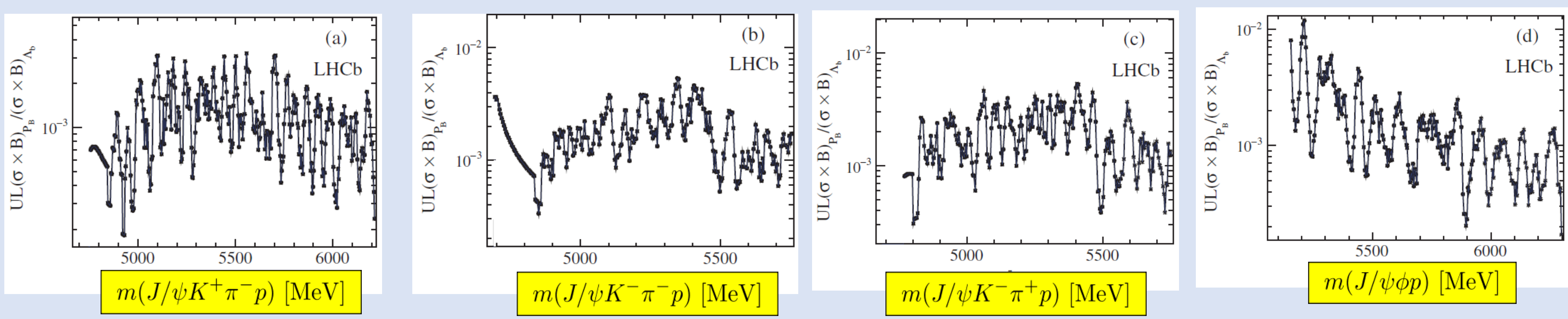
- No signal observed

PRD 97 (2018) 032010



- Upper limits on the P_b production ratio w.r.t. $\Lambda_b^- \rightarrow J/\psi K^- p$

$$R = \frac{\sigma(pp \rightarrow P_b X) \cdot \mathcal{B}(P_b \rightarrow J/\psi X)}{\sigma(pp \rightarrow \Lambda_b^0 X) \cdot \mathcal{B}(\Lambda_b \rightarrow J/\psi p K^-)}$$



- The limits (90% CL) on R are at the level 10^{-2} - 10^{-3}

Search for Beautiful Tetraquarks

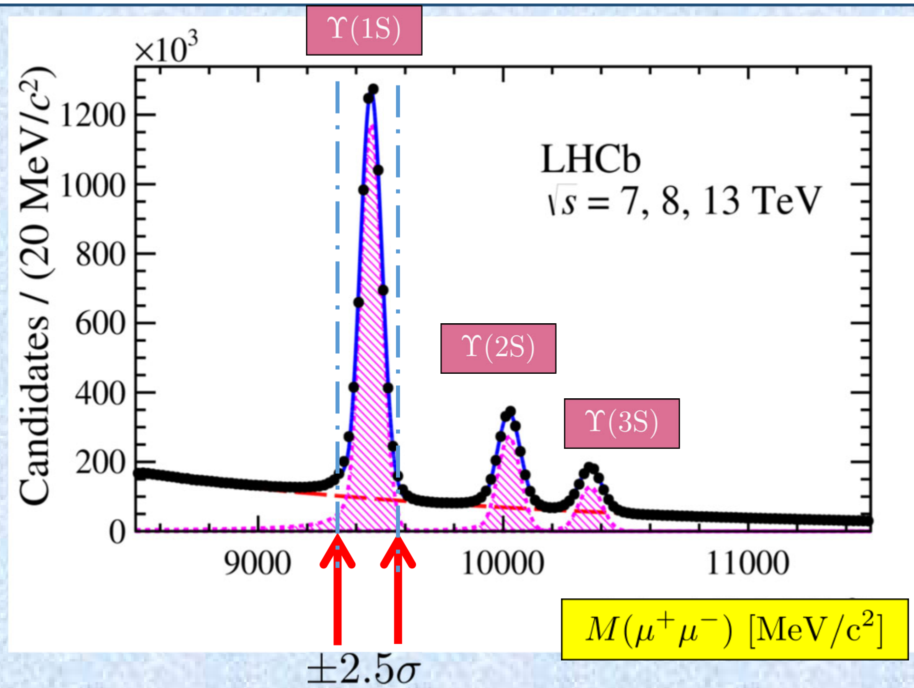
- No exotic hadron, composed of more than two heavy quarks has been observed so far
- Several theoretical predictions for the existence of an exotic state $X_{b\bar{b}b\bar{b}}$
  - Mass in the range [18.4, 18.8] GeV/c^2, close but below the $\eta_b\eta_b$ threshold (18.798±0.005) GeV/c^2
  - → The expected, experimentally favorable, decay mode: $X_{b\bar{b}b\bar{b}} \to \Upsilon(1S)l^+l^-, \quad (l = e, \mu)$
  - Lattice QCD calculations: no indication for the X state in the hadron spectrum

- **LHCb(2018)**:

JHEP 10 (2018) 086

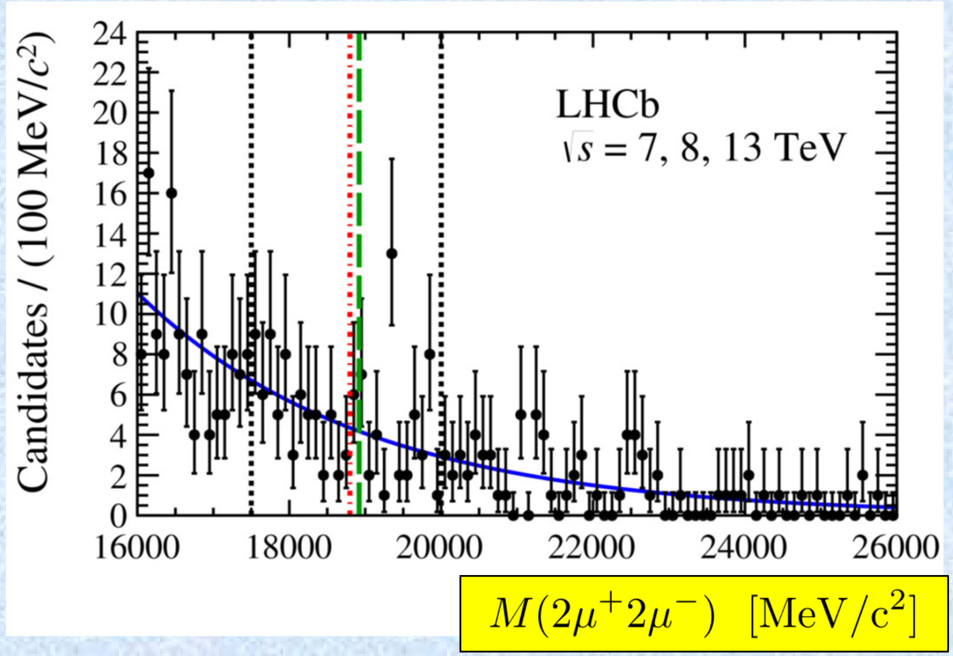
- 6.3 fb^{-1} of data recorded between 2011 and 2017
- the search for the X state decaying to $\Upsilon(1S)(\to \mu^+\mu^-)\mu^+\mu^-$
- the normalization decay channel: $\Upsilon(1S) \to \mu^+\mu^-$

$$N(\Upsilon(1S) \to \mu^+\mu^-) = (6.37 \pm 0.12) \times 10^6$$

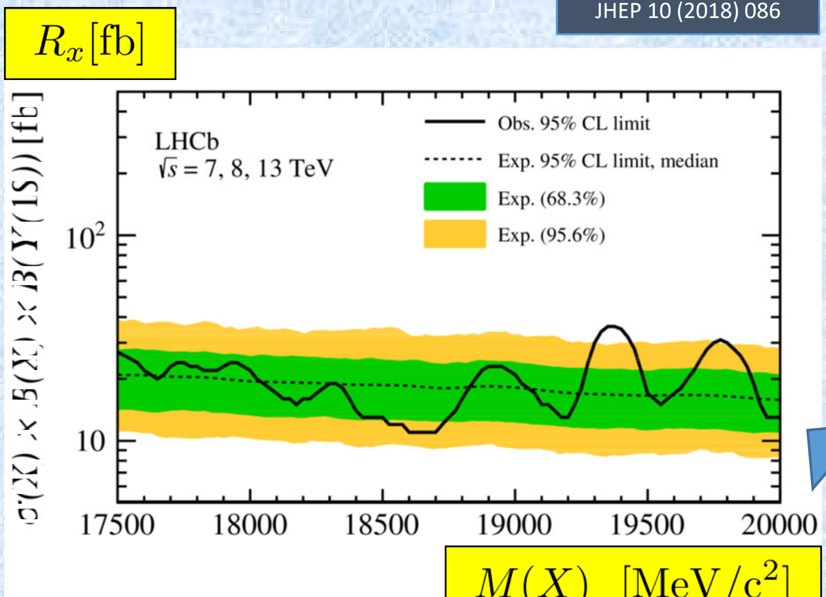


Search for Beautiful Tetraquarks

- The search for an excess in the $M(2\mu^+2\mu^-)$ in the mass range [17.5, 20] GeV/c^2
- Cut based selection
- J/ψ mass veto applied: $M(\mu^+\mu^-) \notin [3050, 3150]\ \mathrm{MeV/c^2}$



JHEP 10 (2018) 086



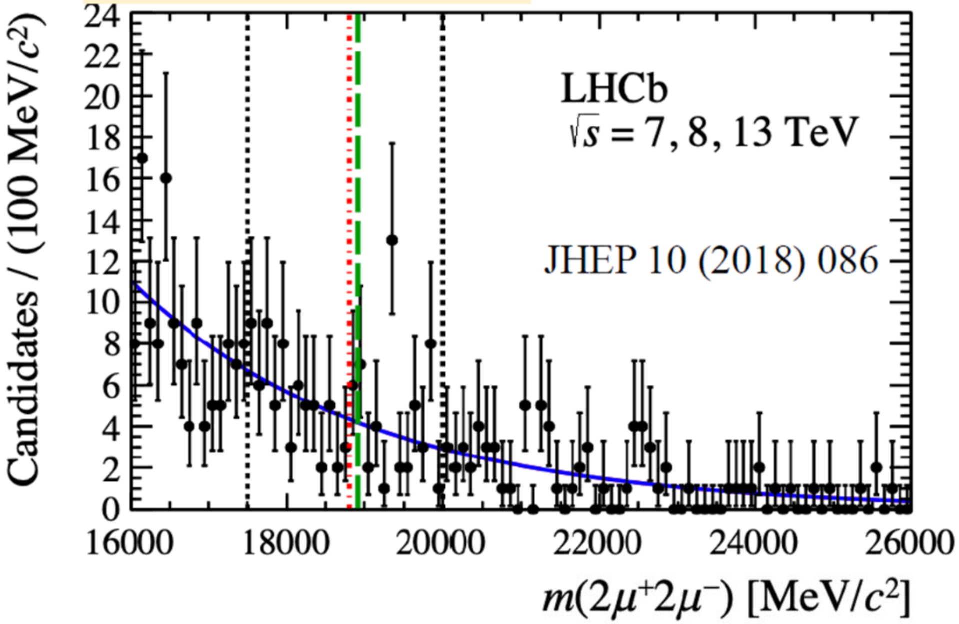
- **No significant excess is observed in data in the mass range [17.5, 20] GeV/c^2**
- **An upper limit is set for**

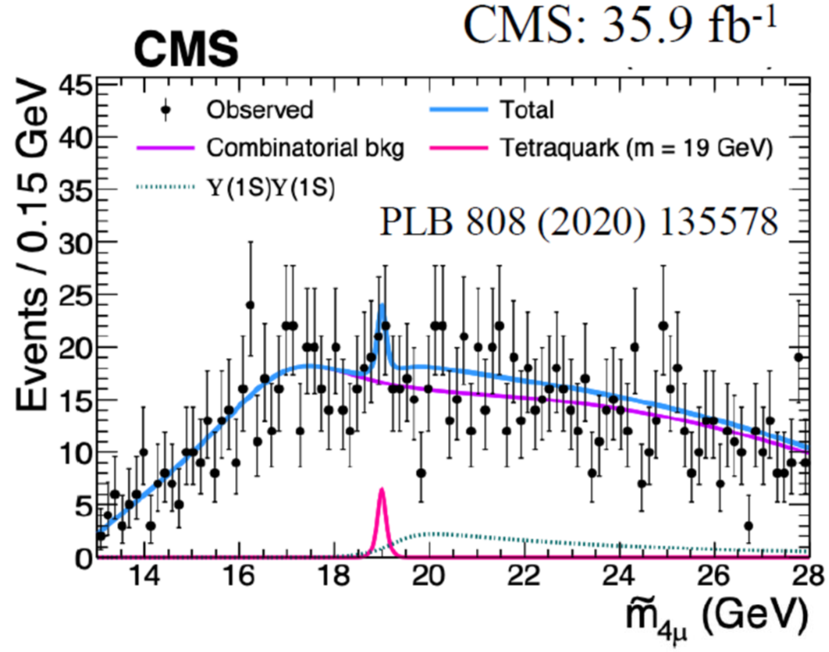
$$R_X = \sigma(pp \to X)\times$$
$$\times\mathcal{B}(X \to \Upsilon(1S)\mu^+\mu^-) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-)$$

Search for $T_{bb\bar{b}\bar{b}}$ state

- Studied in $\Upsilon\mu^+\mu^-$ final state by LHCb and CMS

Di-$b\bar{b}$ thresholds





No obvious signals, eager to see full data analysis at CMS/ATLAS

Search for $T_{bc\bar{b}\bar{c}}$ state

LHCb-PAPER-2022-047
arXiv:2305.15580

- Statistics too low to seen any structure in $J/\psi - \Upsilon$ mass spectrum
- Data consistent with DPS dominating production