20 years of exotic hadrons

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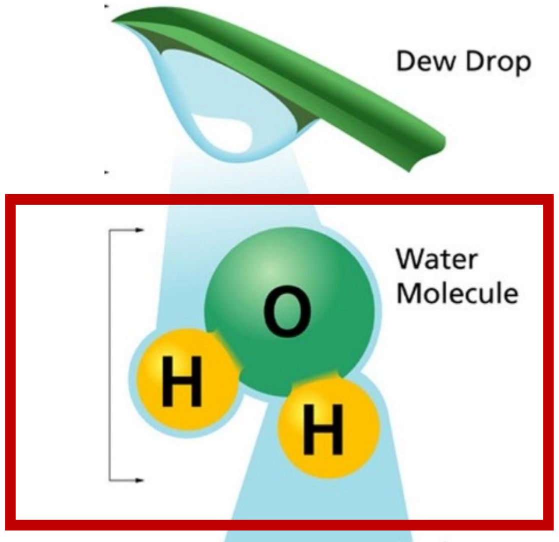
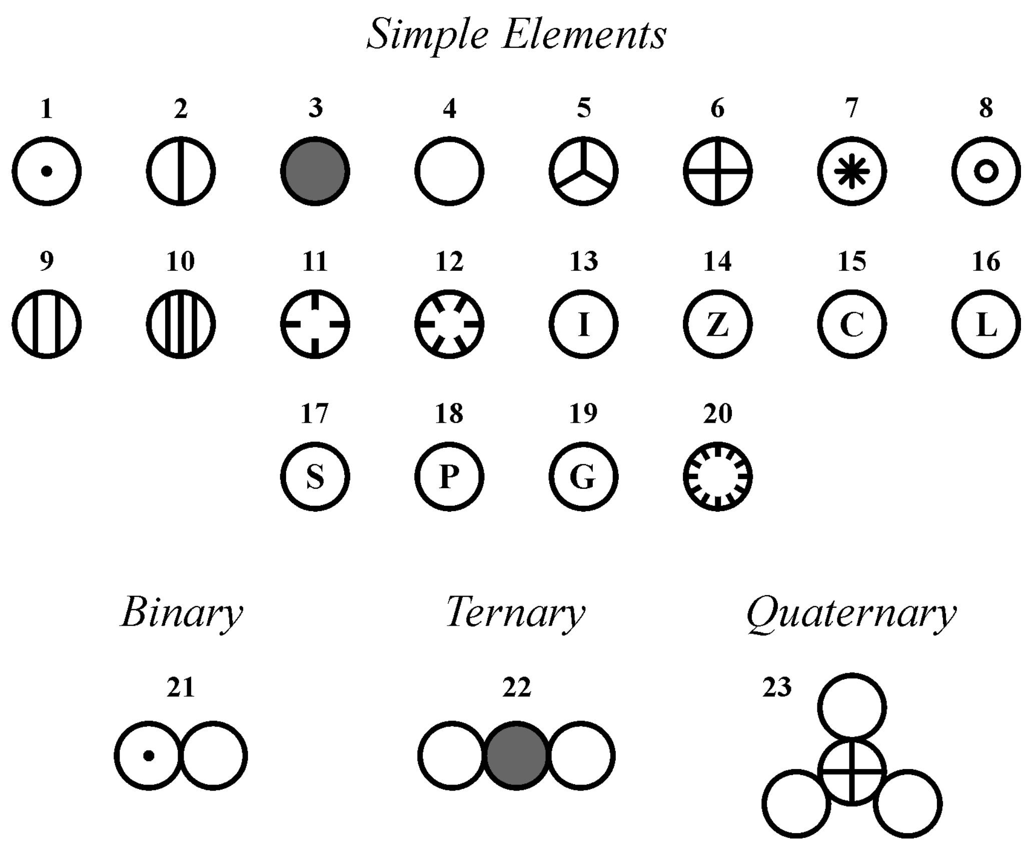
RIKEN, Japan

What is matter made of



Atomic theory of John Daton [~1800]

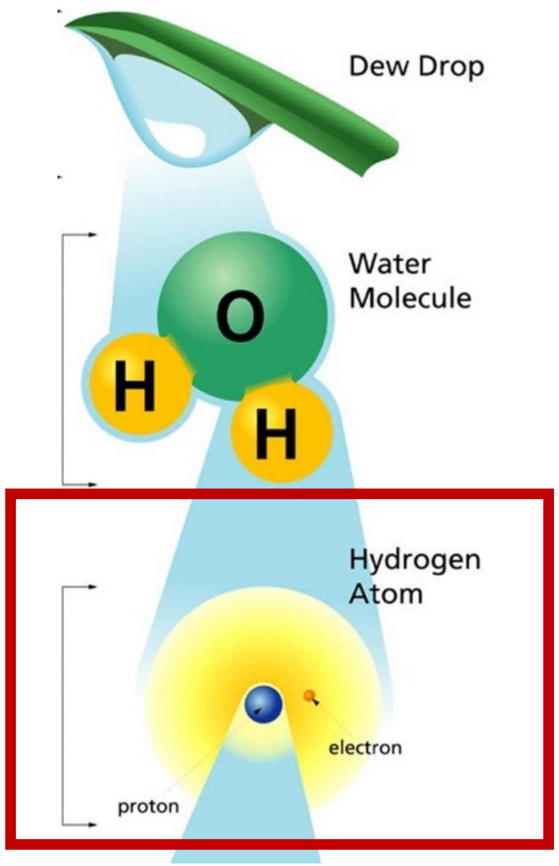
All matter is made of indivisible **atoms/elements**



113
Nh
nihonium

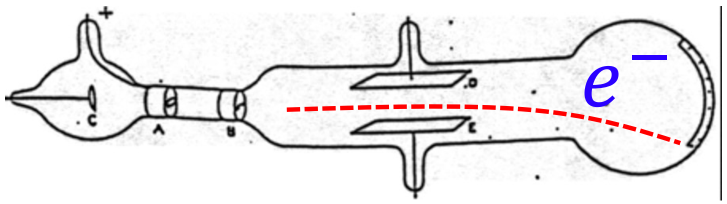
discovered at RIKEN

What is matter made of



Atomic structure [~1900 -1950]

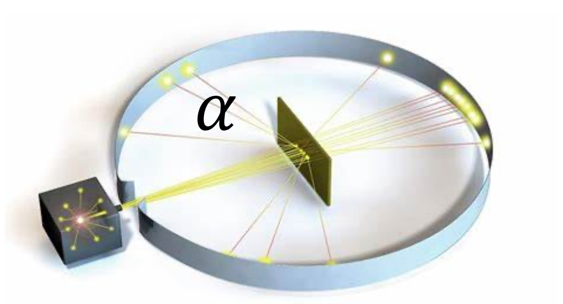
Discovery of **electrons** by Thomson, 1897



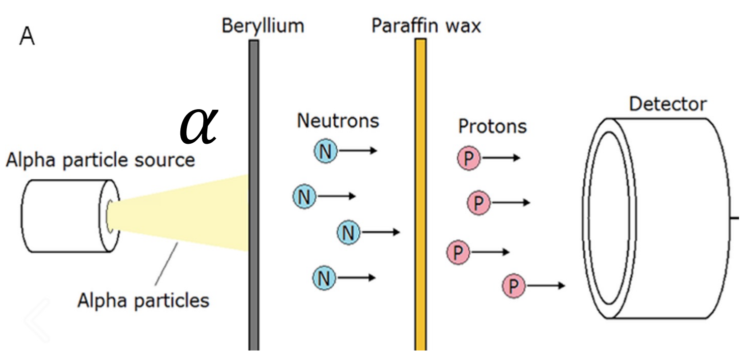
Cathode ray tubes

Discovery of **nuclei and proton** by Rutherford, 1910s

Discovery of **neutron** by Chadwick, 1932

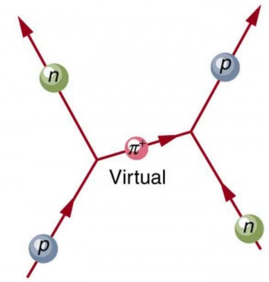


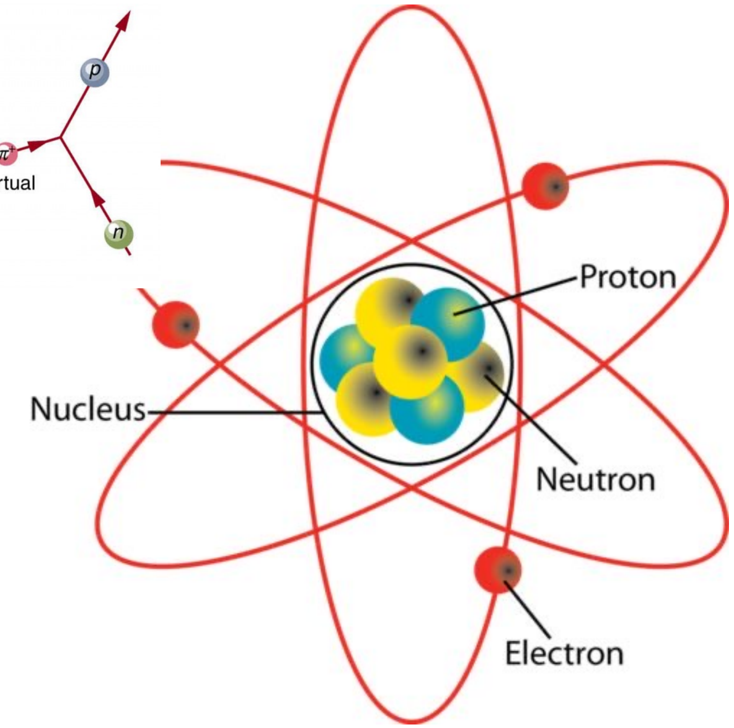
$\alpha + 14\mathrm{N} \rightarrow {}^{17}\mathrm{O} + \mathbf{p}$



$\alpha + 9\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \mathbf{n}$

Nuclear force

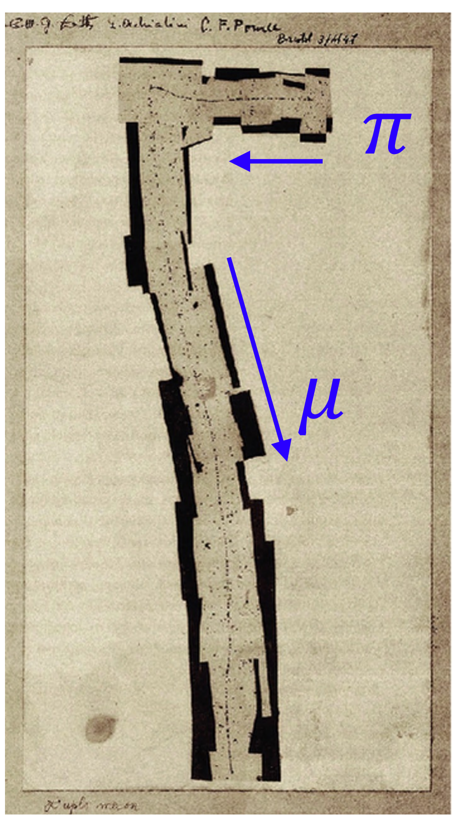




Yukawa interaction between nucleons [1935]

A **strong interaction** mediated by **pions**

Pions discovered by Powell in cosmic rays, 1947



The model of matter up to 1950s

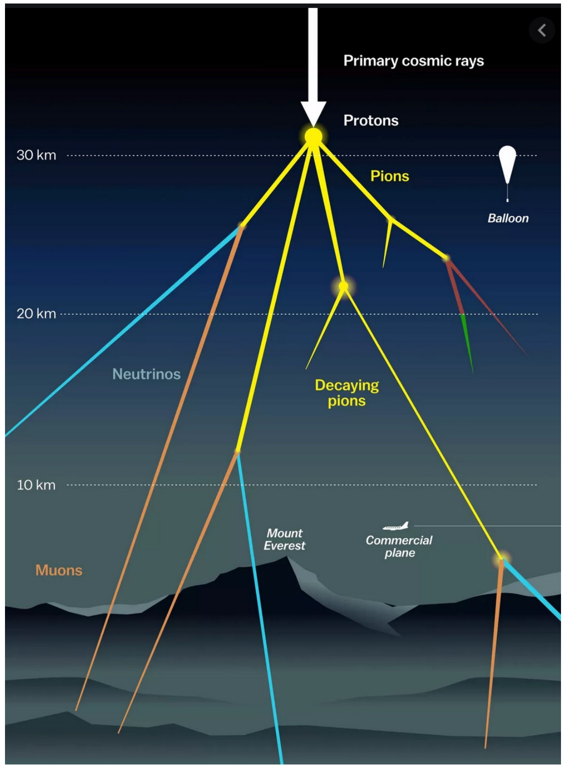
Proton, Neutron $\xrightarrow{\pi}$ Nucleus

Nucleus, Electron $\xrightarrow{\gamma}$ Atom

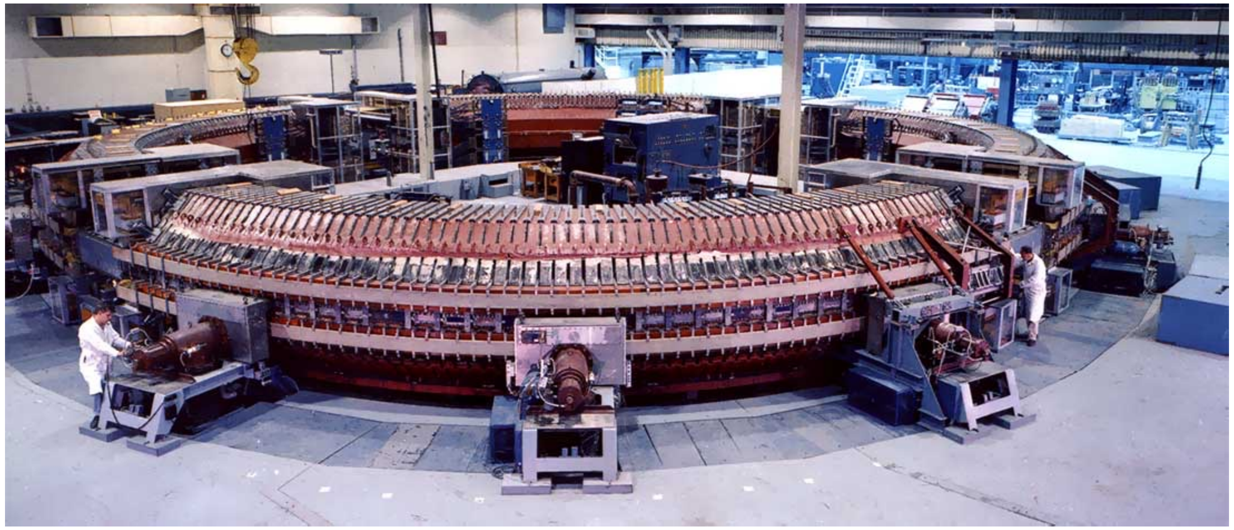
The zoo of hadrons

- Two ways of new particle appearance

Cosmic rays



Accelerators, since 1950s



Eg: Cosmotron (1952-66) at Brookhaven

- New particles discovered

$p, n, \Sigma, \Lambda, \Xi, \Delta, \ldots \ldots$ baryons

$\pi, K, \rho, \omega, \phi, \eta, \ldots \ldots$ mesons

Or hadrons, strongly interacting particles

Wolfgang Pauli:

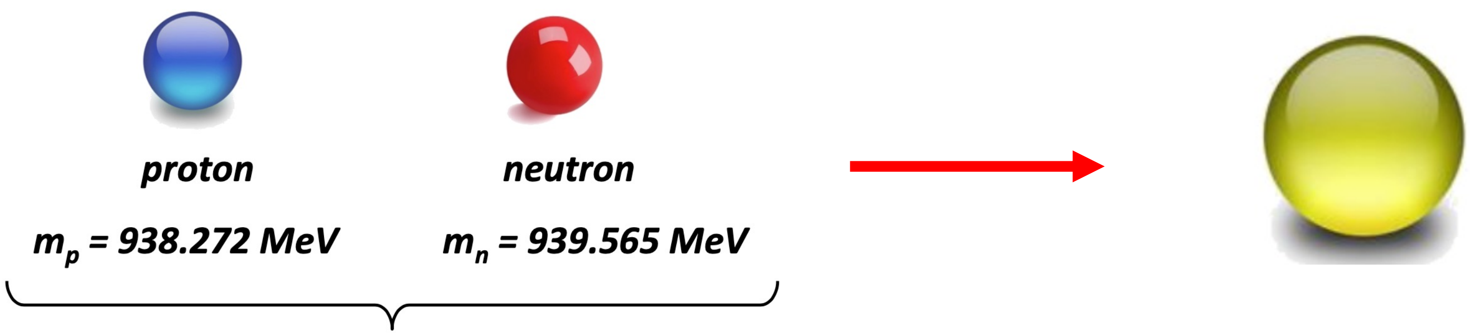
"Had I foreseen that (these particles), I would have gone into botany!", or zoology

All elementary?

Do they exist for any reasons?

Isospin symmetry among hadrons

- Proton and neutron identical under strong interaction



Up and down types of nucleon

Introduce new quantum number: *isospin*

Proton and neutron form isospin doublet (I, I_3): $p = \left|\frac{1}{2}, +\frac{1}{2}\right\rangle$, $n = \left|\frac{1}{2}, -\frac{1}{2}\right\rangle$

Indication of internal degree of freedom

- Other isospin multiplets

$I = 1/2$

K^+ $|\frac{1}{2}, +\frac{1}{2}\rangle$

K^0 $|\frac{1}{2}, -\frac{1}{2}\rangle$

m_K ~ 500 MeV

$I = 1$

π^+ $|1, +1\rangle$

π^0 $|1, 0\rangle$

π^- $|1, -1\rangle$

m_π ~ 140 MeV

$I = 3/2$

Δ^{++} $|\frac{3}{2}, +\frac{3}{2}\rangle$

Δ^+ $|\frac{3}{2}, +\frac{1}{2}\rangle$

Δ^0 $|\frac{3}{2}, -\frac{1}{2}\rangle$

Δ^- $|\frac{3}{2}, -\frac{3}{2}\rangle$

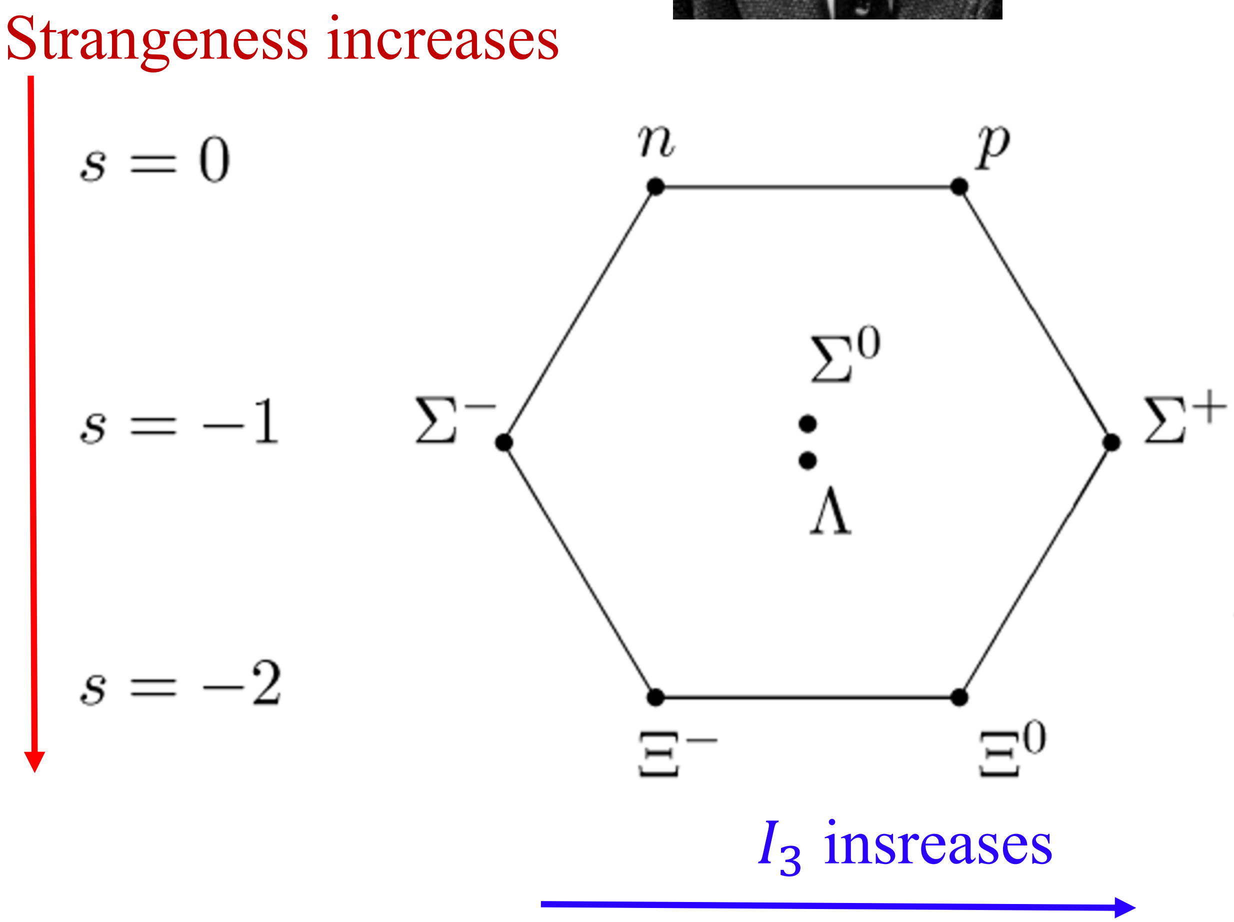
m_Δ ~ 1232 MeV

Extending the symmetry

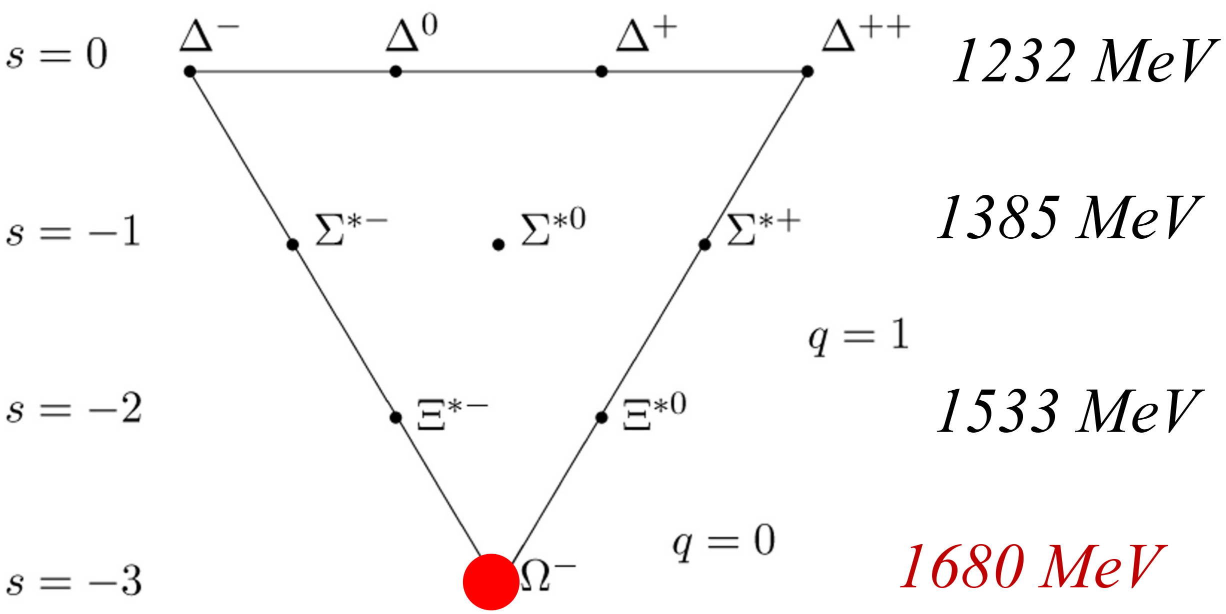
- The eight-fold way by Gell-Mann (1961): hadrons arranged in multiplets according to isospin and strangeness (another internal quantum number)

8 lightest strange baryons: baryon octet

Particle	Mass	S
n	938.3	0
p	939.6	0
Σ^+	1189.4	-1
Σ^0	1192.6	-1
Σ^-	1197.4	-1
Λ^0	1115.6	-1
Ξ^0	1314.9	-2
Ξ^-	1321.3	-2

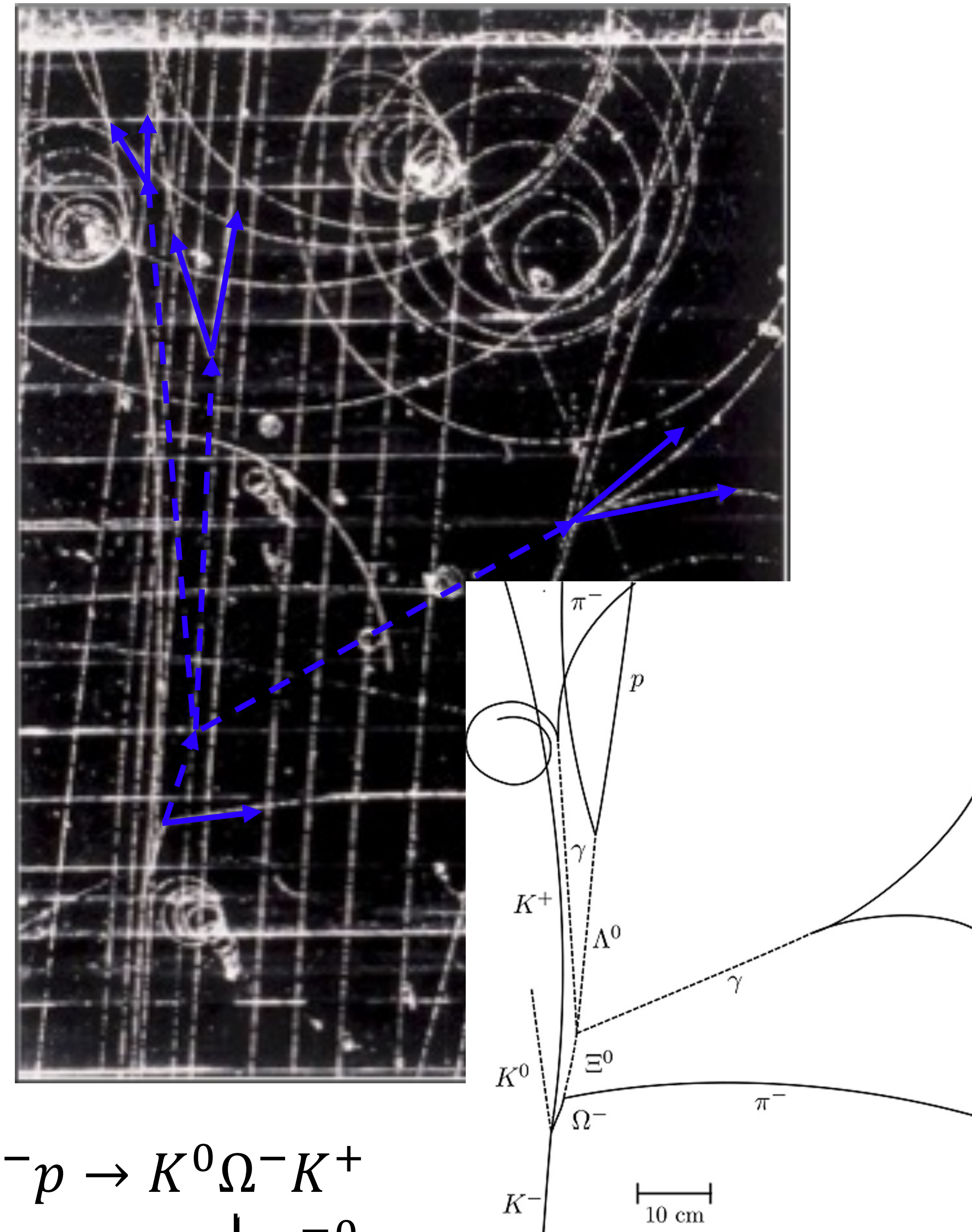


Baryon decuplet



Ω^- baryon not known by then

Eight-fold way predicts Ω^- and its properties. Observed in 1964.



$K^- p \to K^0 \Omega^- K^+$

$\quad \hookrightarrow \Xi^0 \pi^-$

$\qquad \hookrightarrow \Lambda^0 \pi^0$

$\qquad\quad \hookrightarrow p \pi^-$

The quark model

- Gell-Mann and Zweig (1964):

"All multiplet patterns can be explained if you assume hadrons are composite particles built from more elementary constituents: quarks"

A SCHEMATIC MODEL OF BARYONS AND MESONS *

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

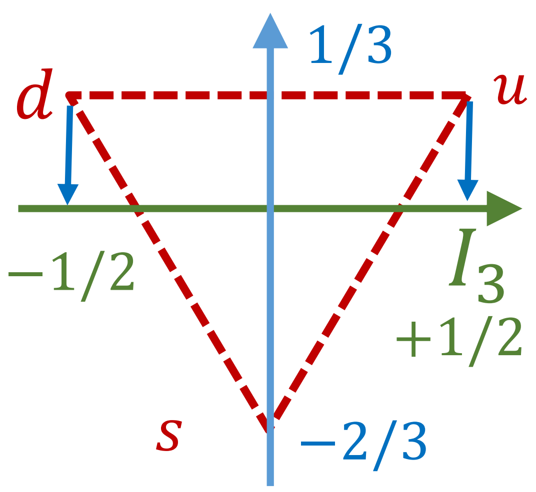
Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks"[6] q and the members of the 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 baryon configuration $(q\,q\,q)$ gives just the representations **1**, **8**, and **10** that have been observed, while the lowest meson configuration $(q\,\bar{q})$ similarly gives just **1** and **8**.

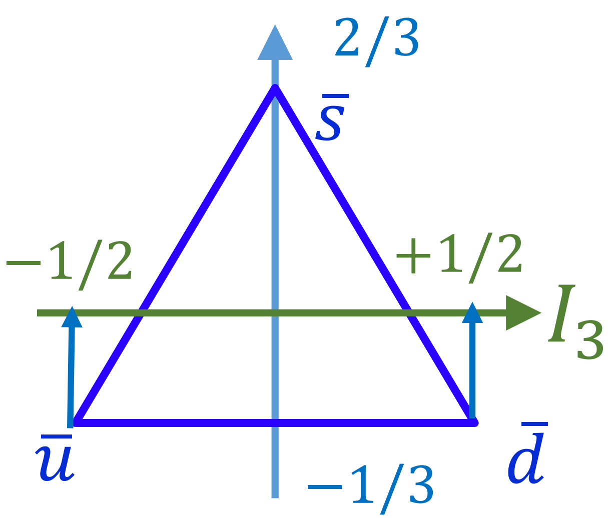
Three quark flavors, SU(3)

- Flavor as a quantum number for quark: take three values u, d, s
  - Strong interaction is blind to flavor, rotations among u, d, s form SU(3) symmetry
  - Isospin: symmetry between $u - d$ flavors (quarks)
  - Symmetry breaking by non-strong interactions
    - Mass difference: large between u/d and s, smaller between u and d
    - Electric charge difference: $Q_u = +2/3$, $Q_{d/s} = -1/3$

- Mesons and baryons built from two basic flavor triplets



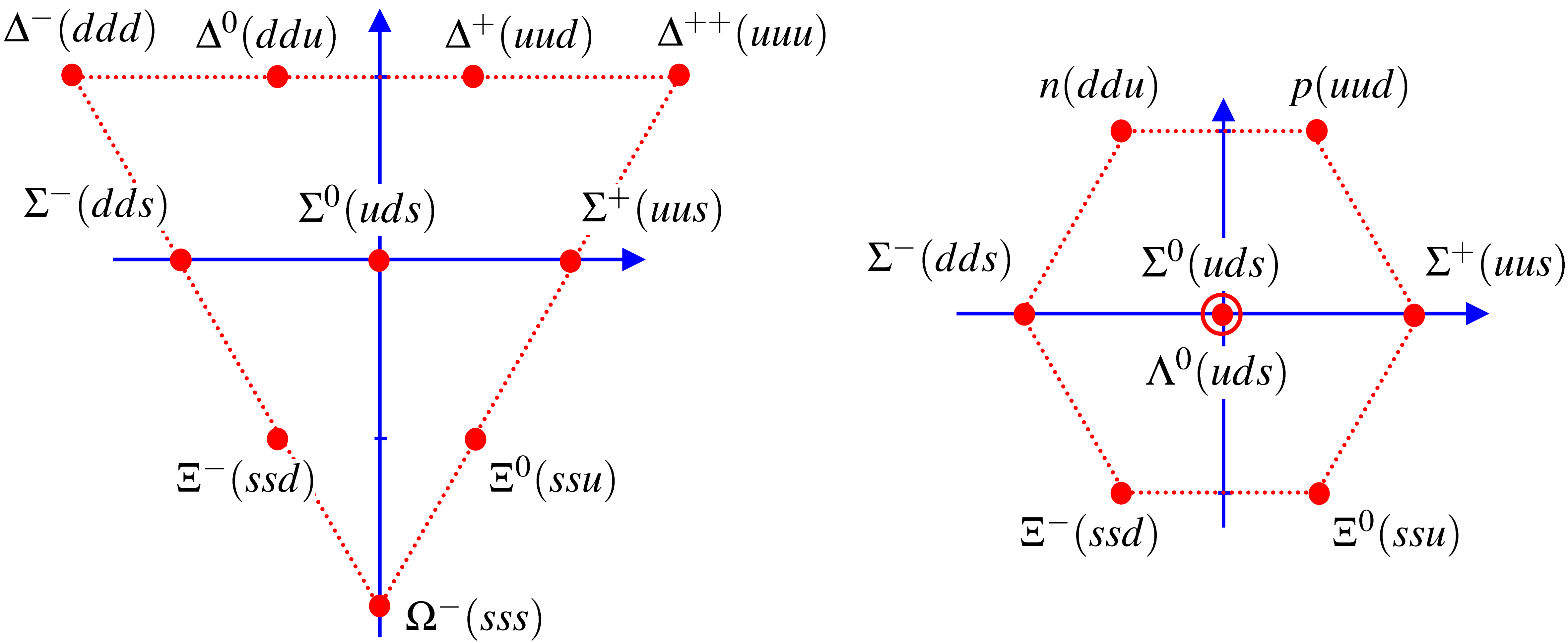
Quark



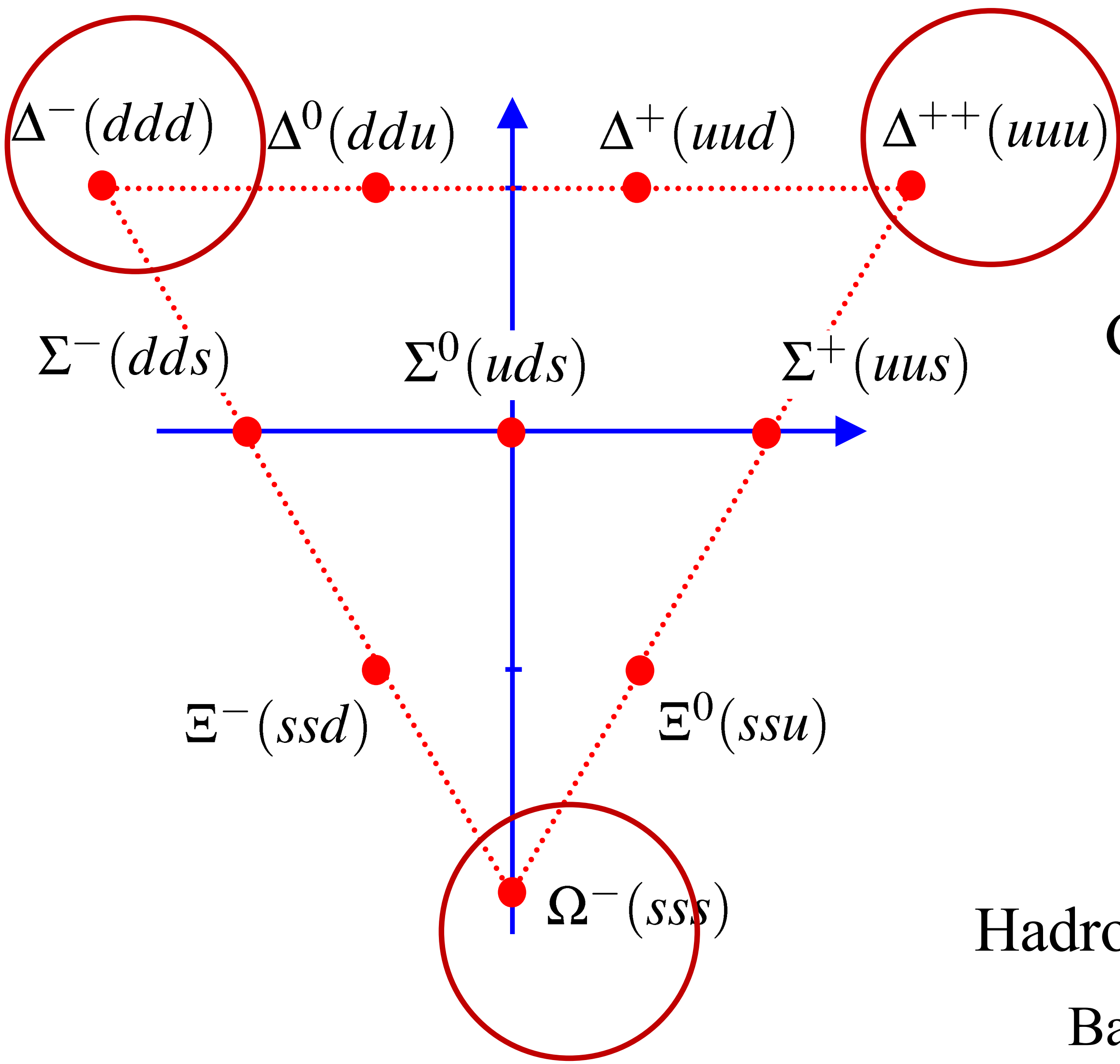
Antiquark

The genes of the particle zoo

Quark configuration of known baryons



The color quantum number



Pauli exclusion principle:
can't be at the same configuration

Greenberg (1964):

Quark carries color quantum number

Red, Green, Blue

Antiquark carries anticolor

anti-Red, anti-Green, anti-Blue

Hadrons are colorless (color singlet) state

Baryons (qqq): RGB
Mesons ($q\bar{q}$): $R\bar{R}$+ $G\bar{G}$ + $B\bar{B}$

Hunting for quarks

It is fun to speculate about the way quarks would behave if they were physical particles of finite mass

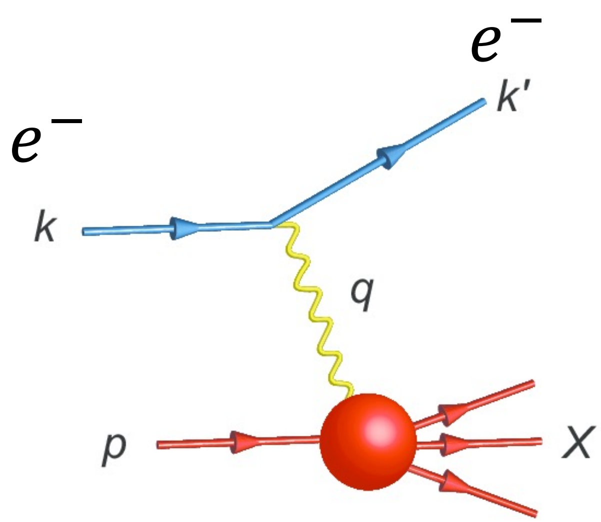
(instead of purely mathematical entities as they would be in the limit of infinite mass). Since charge

that it would never have been detected. A search for stable quarks of charge $-\frac{1}{3}$ or $+\frac{2}{3}$ and/or stable di-quarks of charge $-\frac{2}{3}$ or $+\frac{1}{3}$ or $+\frac{4}{3}$ at the highest energy accelerators would help to reassure us of the non-existence of real quarks.

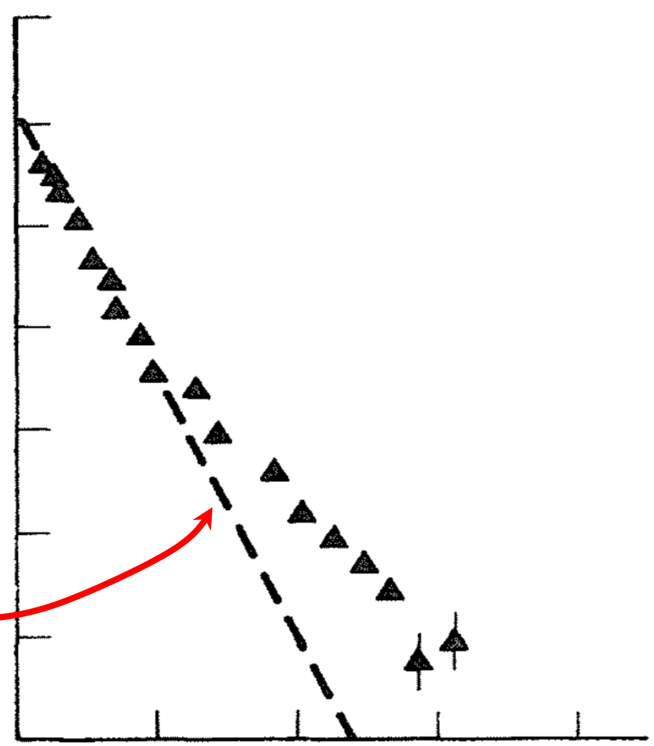
No free quarks ever observed

Deep inelastic scattering

Rutherford scattering of electron on proton



Counts



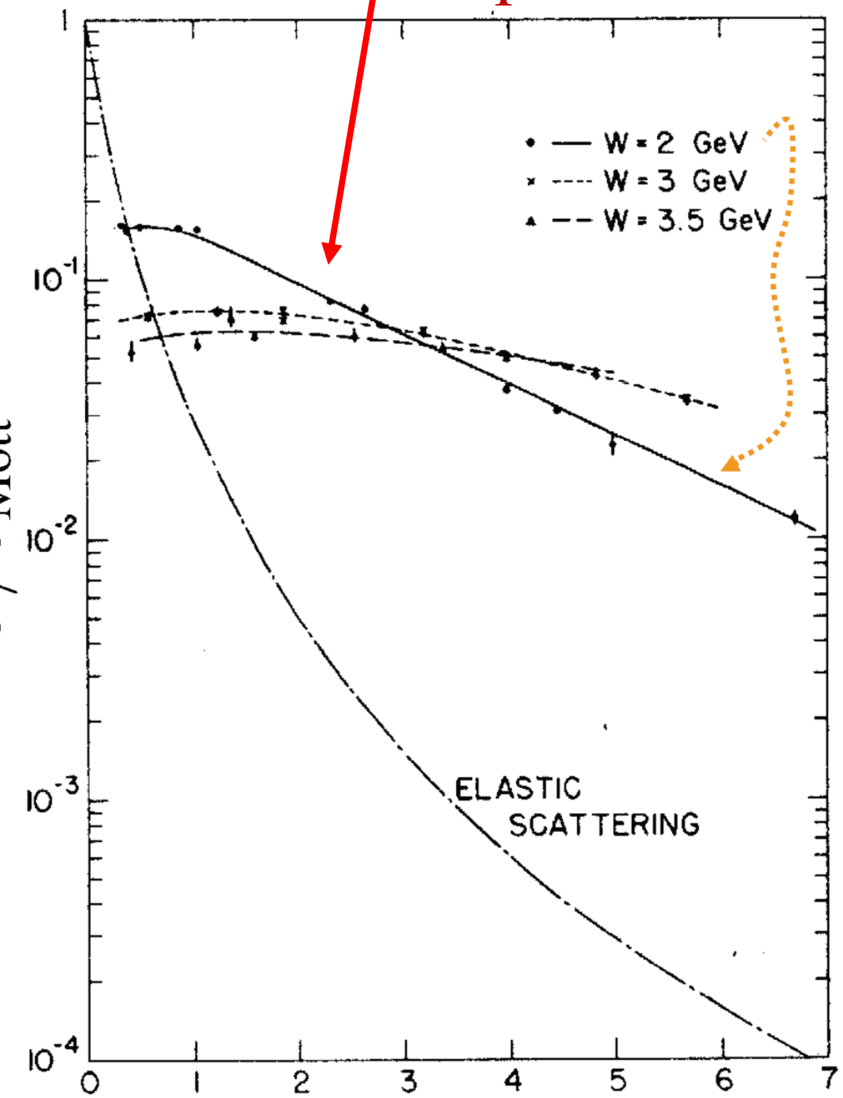
Without internal structure

e^- scattering angle

$e^- p \to e^- X$

Scatter on point-like particles: consistent with quark model

$\sigma / \sigma_{\mathrm{Mott}}$



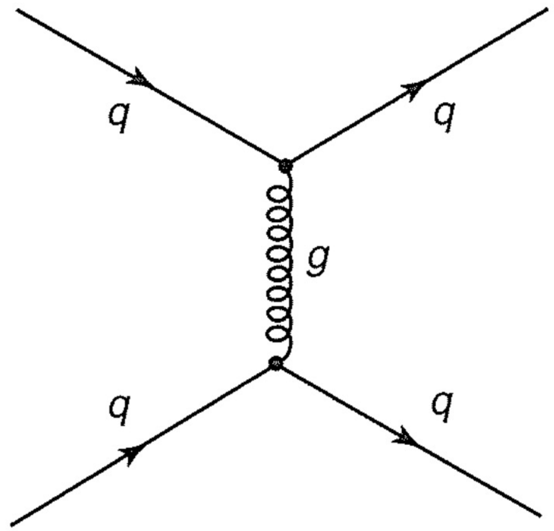
Q^2/GeV^2

$Q^2 = -q^2$

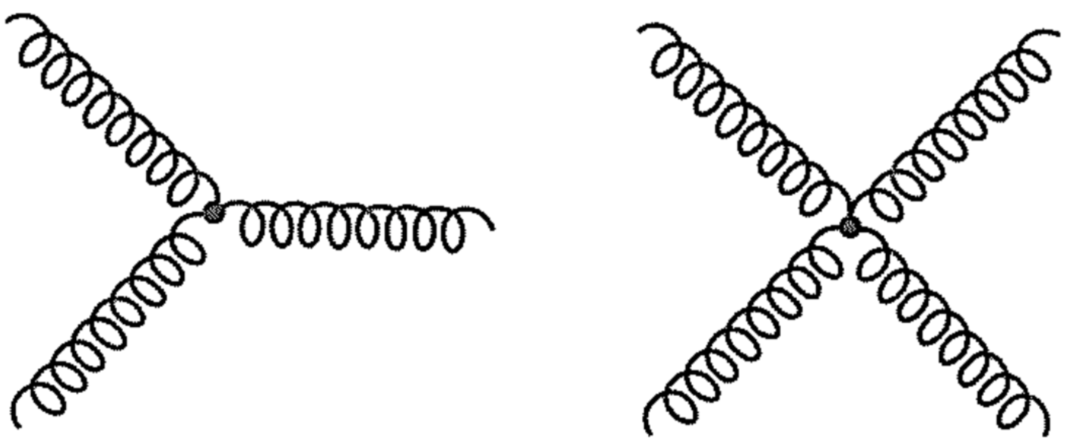
Quantum Chromodynamics

- QCD: theory for strong interaction between colored objects. More fundamental than π-exchange between nucleons

Strong interaction between quarks mediated by gluons

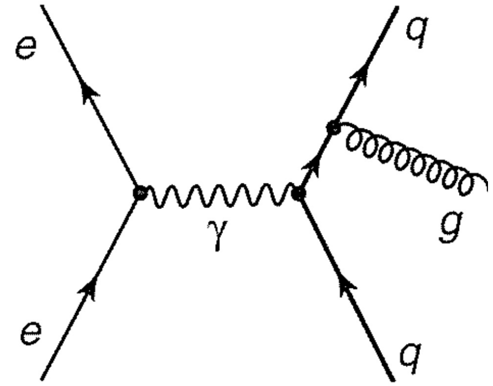


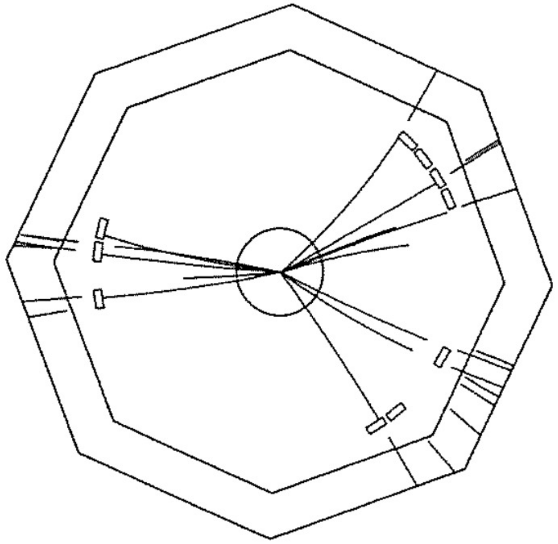
Direct self-interaction between gluons



- Experimental signals of gluons: three-jet events

$$e^+e^- \rightarrow q\bar{q}g$$



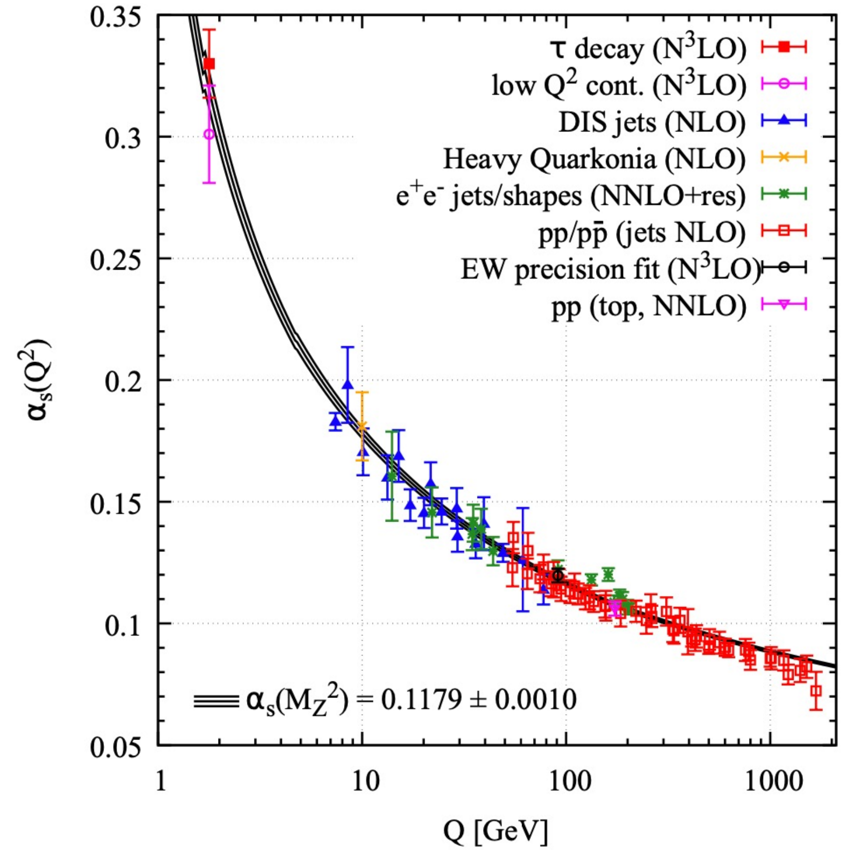


Confinement

- Energy dependent coupling strength

$$\alpha_s(Q^2) \approx \frac{1}{\beta_0 \ln(Q^2/\Lambda^2)}$$

$Q^2 \rightarrow \Lambda^2, \alpha_s \rightarrow \infty$

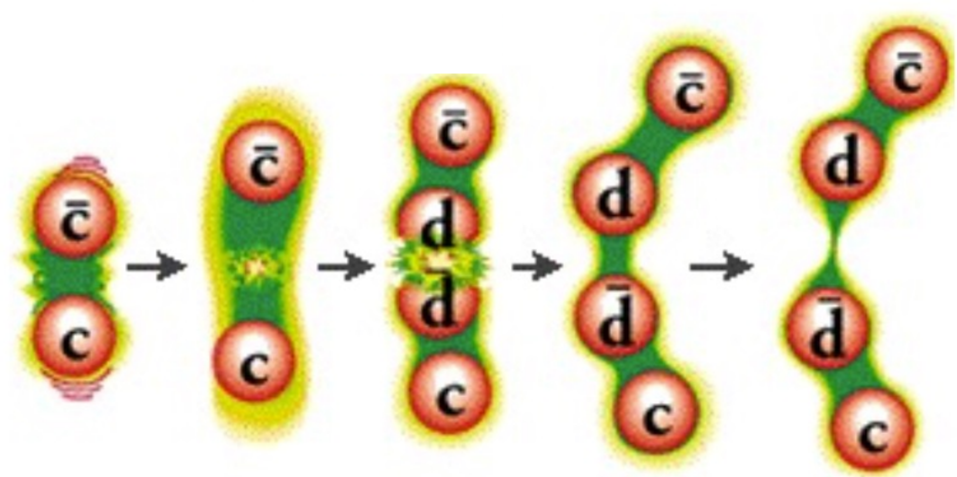


- ➢ Non perturbative in expansions of α_s at low-Q^2
- ➢ Color confinement, no free quarks/gluons

Quarks and gluons contained in colorless hadrons

What happens of one tries to separate two quarks?

ψ



$\overline{D}^0$

D^0

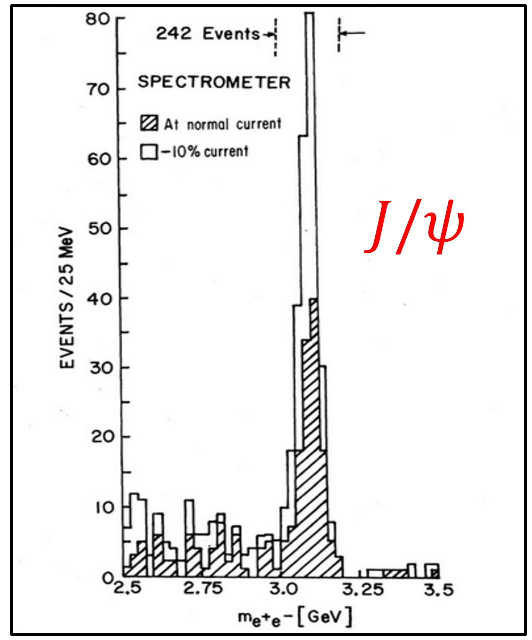
Extensions of quark flavors

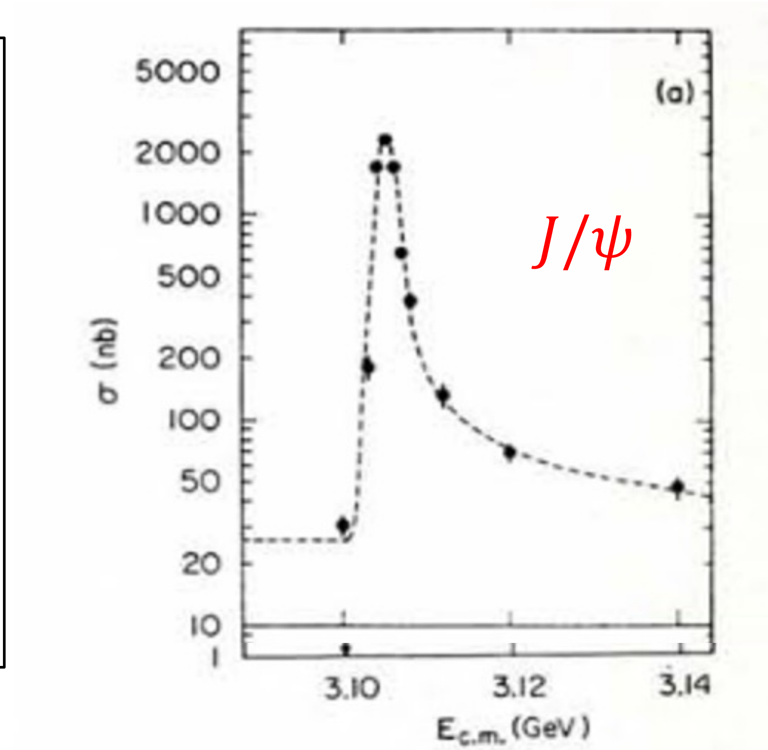
- Discovery of J/ψ in 1974, indication of a new quark flavor (charm quark, c)

Narrow width given being much heavier than known mesons

$m_{J/\psi} \sim 3100$ MeV, $\Gamma_{J/\psi} \sim 0.1$ MeV

Formed by a new type of quark



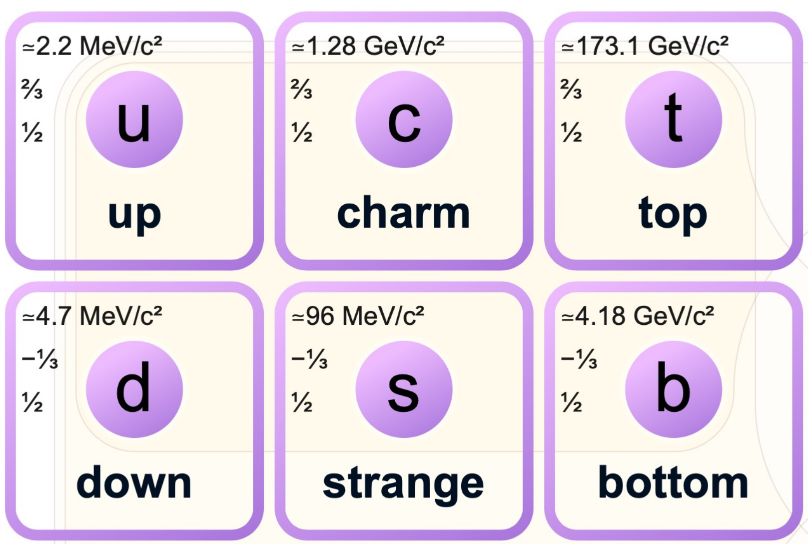


- Discovery of Υ in 1977, indication of another new flavor (bottom quark, b)

$m_{\Upsilon} \sim 9500$ MeV, $\Gamma_{\Upsilon} \sim 0.1$ MeV

- Top quark (t) discovered in 1995, lifetime $\tau \sim 10^{-25} s$, smaller than needed to form hadrons ($\tau \sim 10^{-22} s$)

Six quark flavors observed in total →



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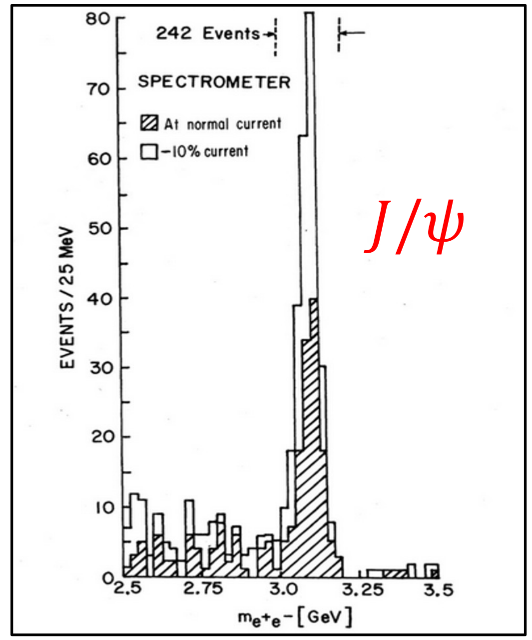

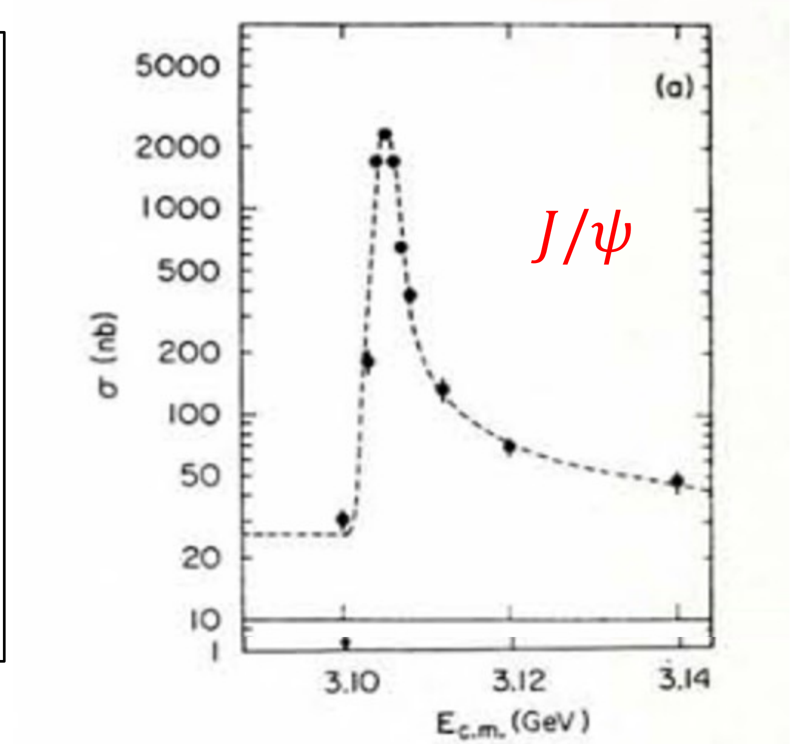

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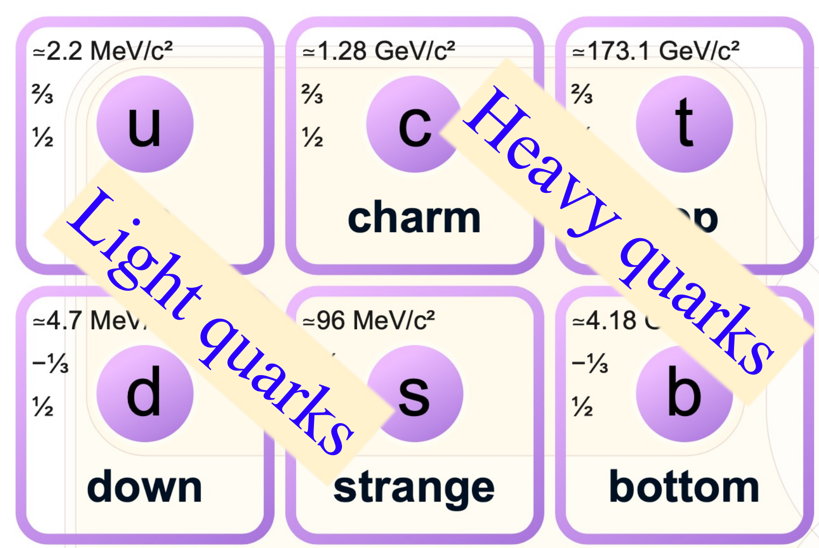
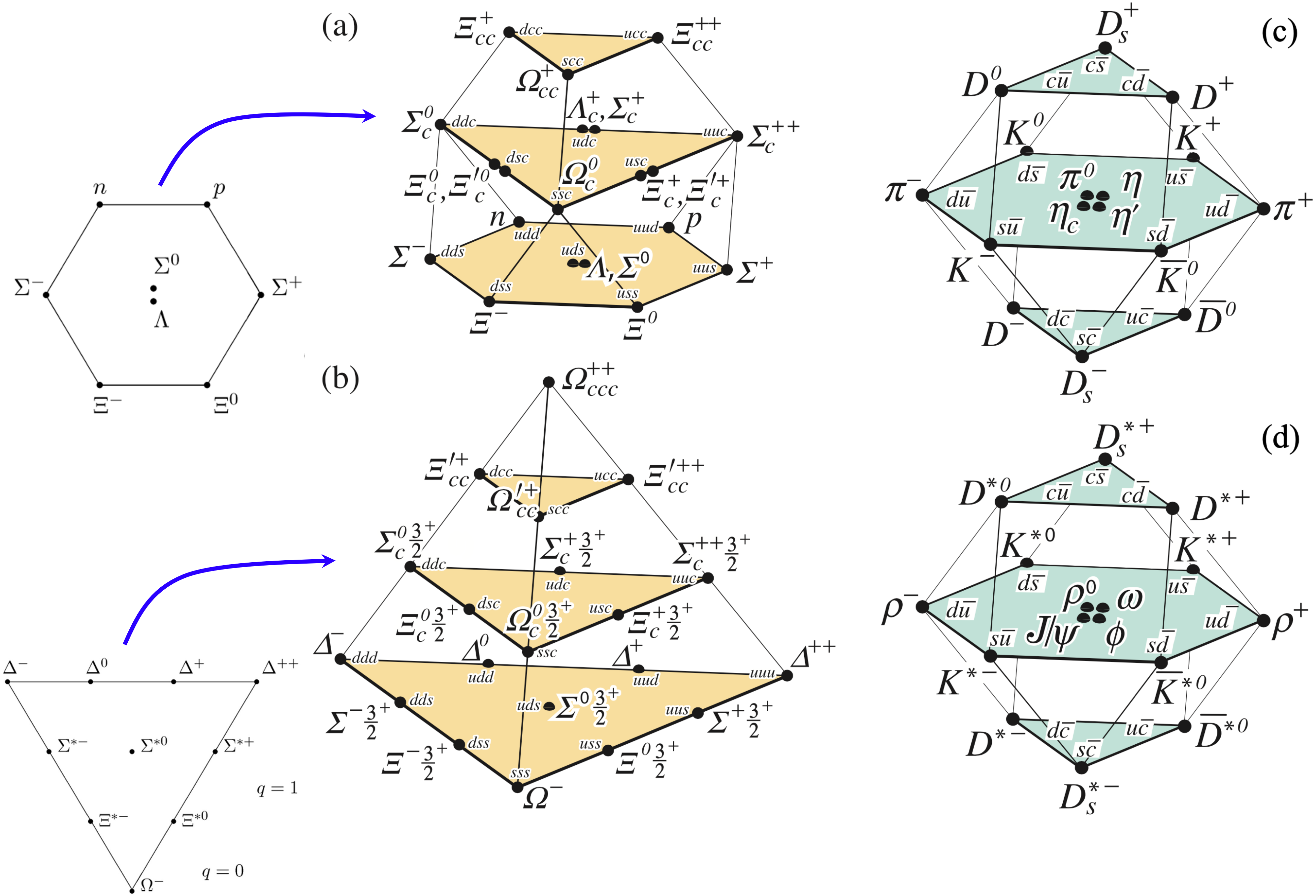


Hadron spectroscopy

- Flavor multiplets with u, d, s, c quarks

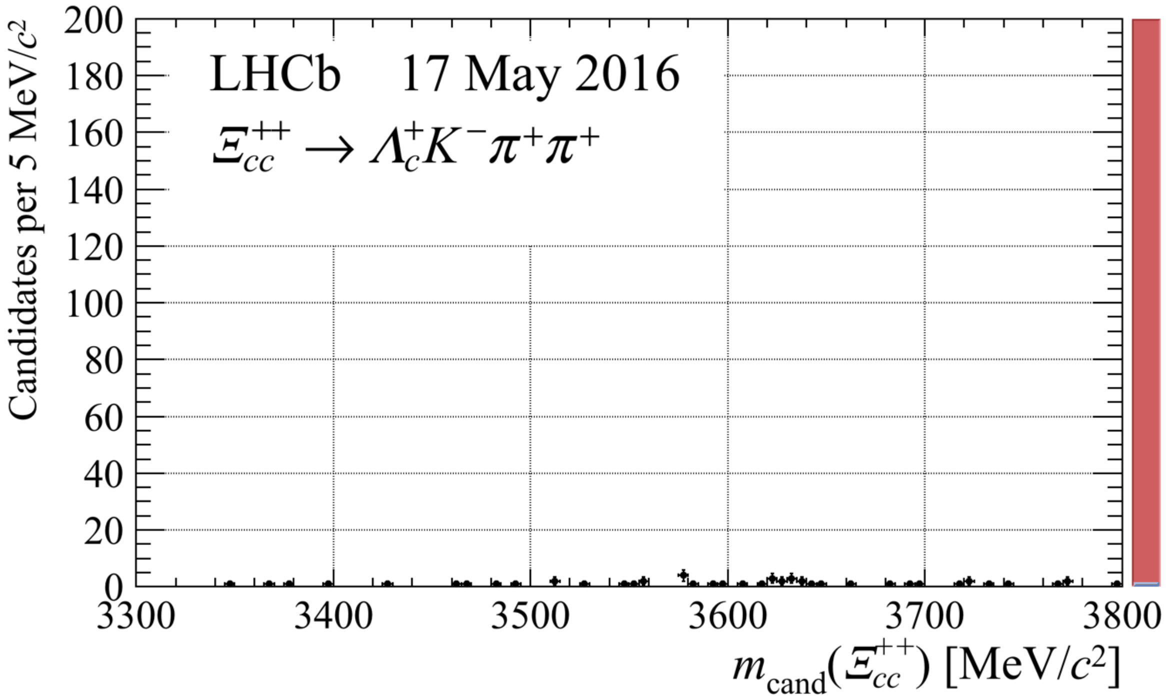
Baryons

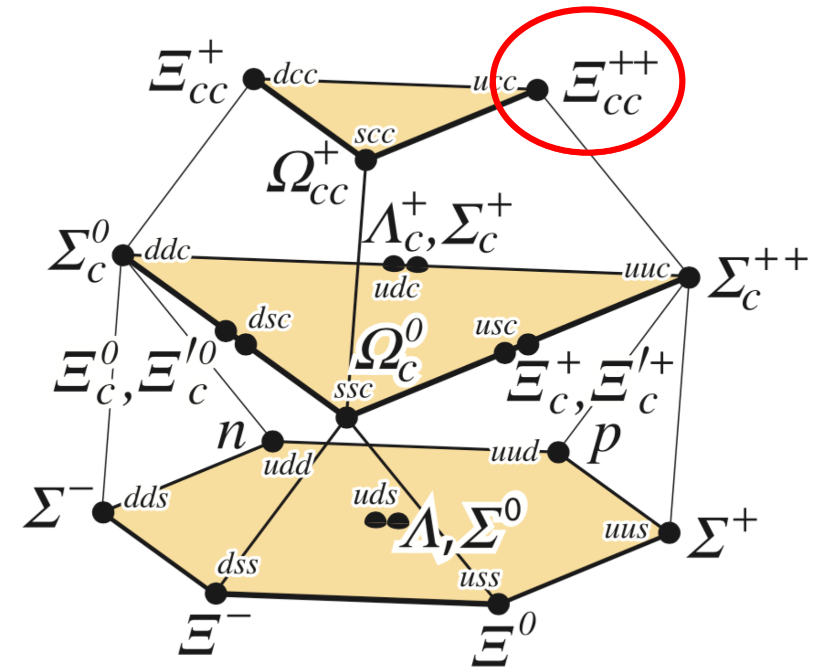
Mesons



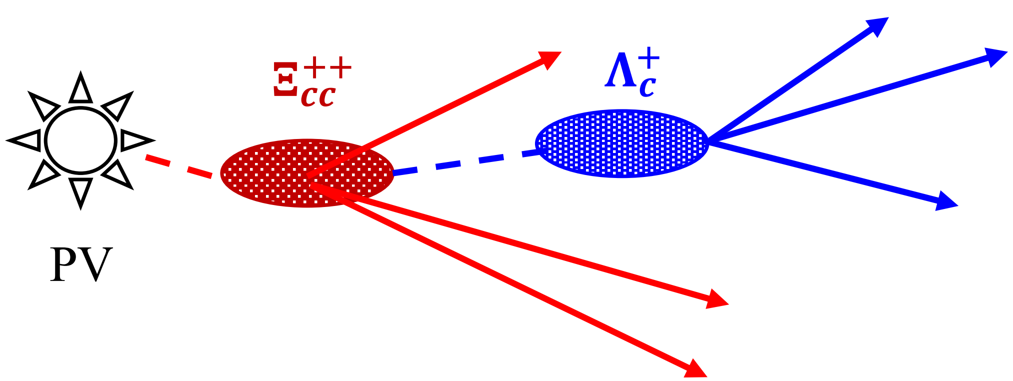
Completing multiplets: observation of Ξ_{cc}^{++} by LHCb

Peaking structure around 3.6 GeV (2016), properties consistent with $\Xi_{cc}^{++}(ccu)$





Discovery decay channel: $\Xi_{cc}^{++} \to K^-\pi^+\pi^+\Lambda_c^+(\to pK^-\pi^+)$

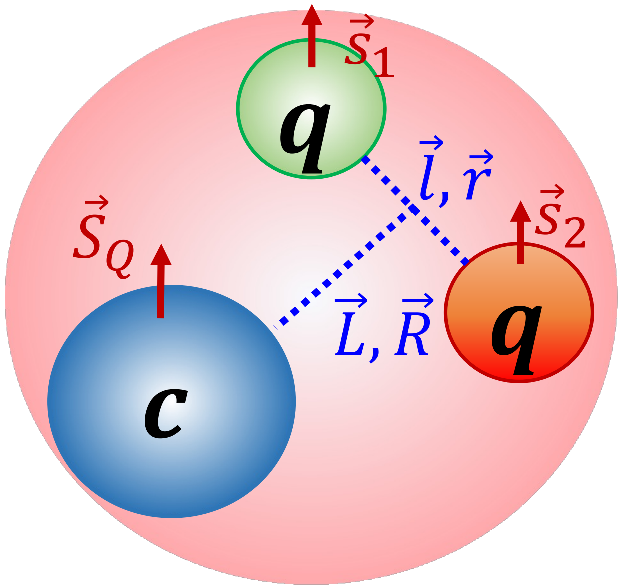


- Rare production and low detection efficiency: large dataset
- Complex topology and background: machine learning

Require well-designed experimental tools

Excitation spectrum (energy levels of the same flavors)

Baryon as example



$\vec{s}_1, \vec{s}_2, \vec{S}_Q$: spin of quarks

$\vec{l}, \vec{L}$: orbital angular momentum

$\vec{s} = \vec{s}_1 + \vec{s}_2 + \vec{l}$: spin of light quark system

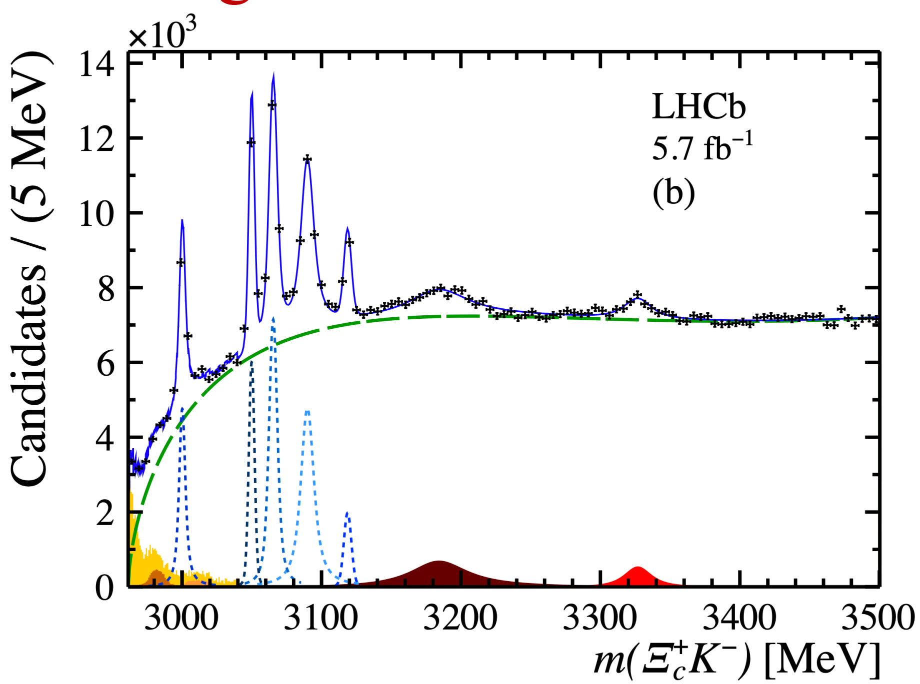
$\vec{j} = \vec{s} + \vec{L}$: total angular momentum of light system

$\vec{J} = \vec{j} + \vec{s}_Q$: total angular momentum of hadron

$\vec{r}, \vec{R}$: radial excitations

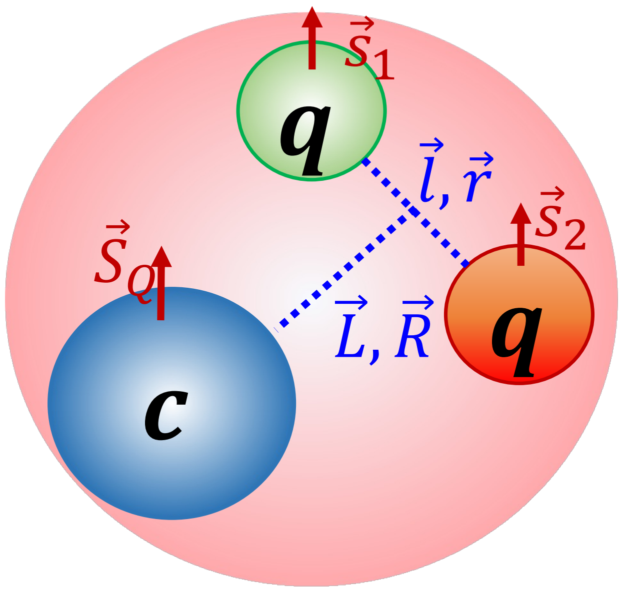
Discovery of 7 narrow $\Omega_c^0(css)$ states in $\Xi_c^+ K^-$ invariant mass spectrum (2023)

Matching to excitation modes difficult, under ongoing study



Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	3000.44 ± 0.07	3.83 ± 0.23
$\Omega_c(3050)^0$	3050.18 ± 0.04	0.67 ± 0.17
$\Omega_c(3065)^0$	3065.63 ± 0.06	3.79 ± 0.20
$\Omega_c(3090)^0$	3090.16 ± 0.11	8.48 ± 0.44
$\Omega_c(3119)^0$	3118.98 ± 0.12	0.60 ± 0.63
$\Omega_c(3185)^0$	3185.1 ± 1.7	50 ± 7
$\Omega_c(3327)^0$	3327.1 ± 1.2	20 ± 5

Excitation spectrum



Baryon as example

$\vec{s}_1, \vec{s}_2, \vec{S}_Q$: spin of quarks

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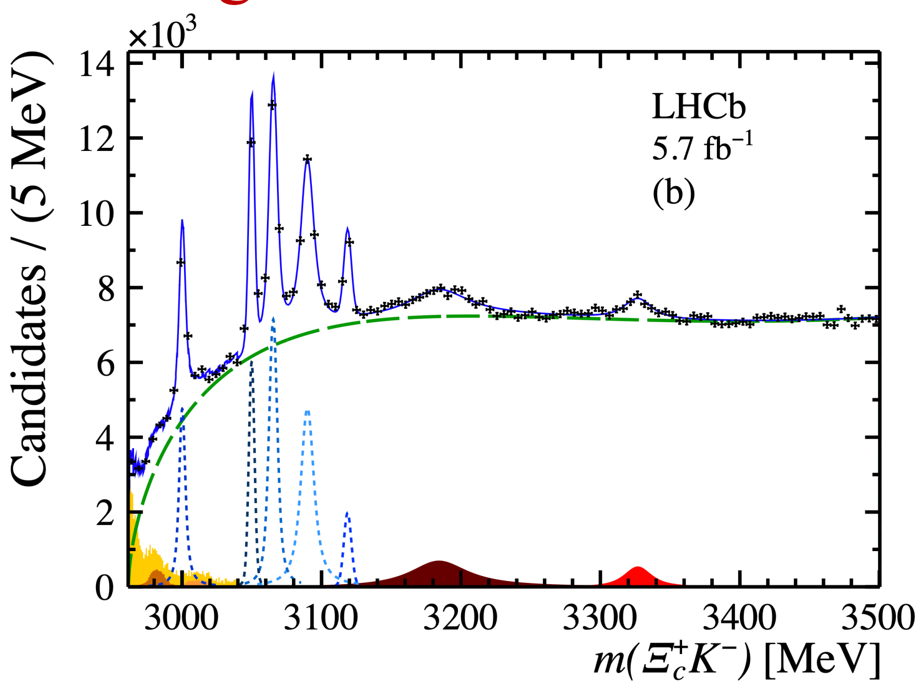
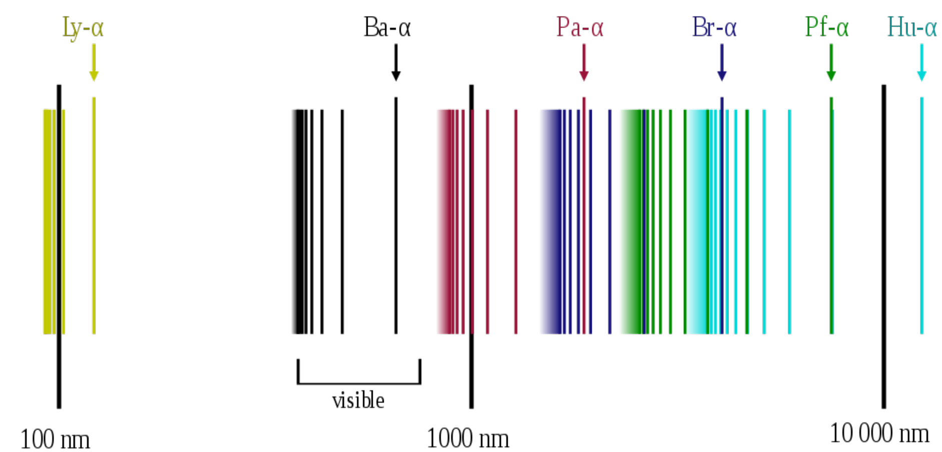


Similarity to light spectrum!



How to study new hadrons 1

- Most hadrons with short lifetimes, $\tau = \text{ps, fs} \ldots 10^{-22}$ s
- **First**, produce them at particle colliders, with a large enough amount

A few active large facilities in the world

Large Hadron Collider @ CERN

pp collisisions
$\sqrt{s} \sim 10$ TeV

$\int \mathcal{L}dt \sim 10$ fb^{-1} (LHCb)

SuperKEK @ Japan

e^+e^- collisisions
$\sqrt{s}{\sim}10$ GeV

$\int \mathcal{L}dt \sim 50$ ab^{-1}

BESIII @ China

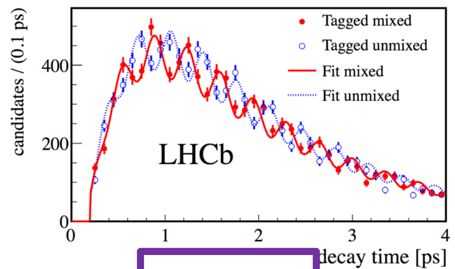
e^+e^- collisisions
$\sqrt{s}{\sim}4$ GeV

$\int \mathcal{L}dt \sim 50$ fb^{-1}

How to study new hadrons 2

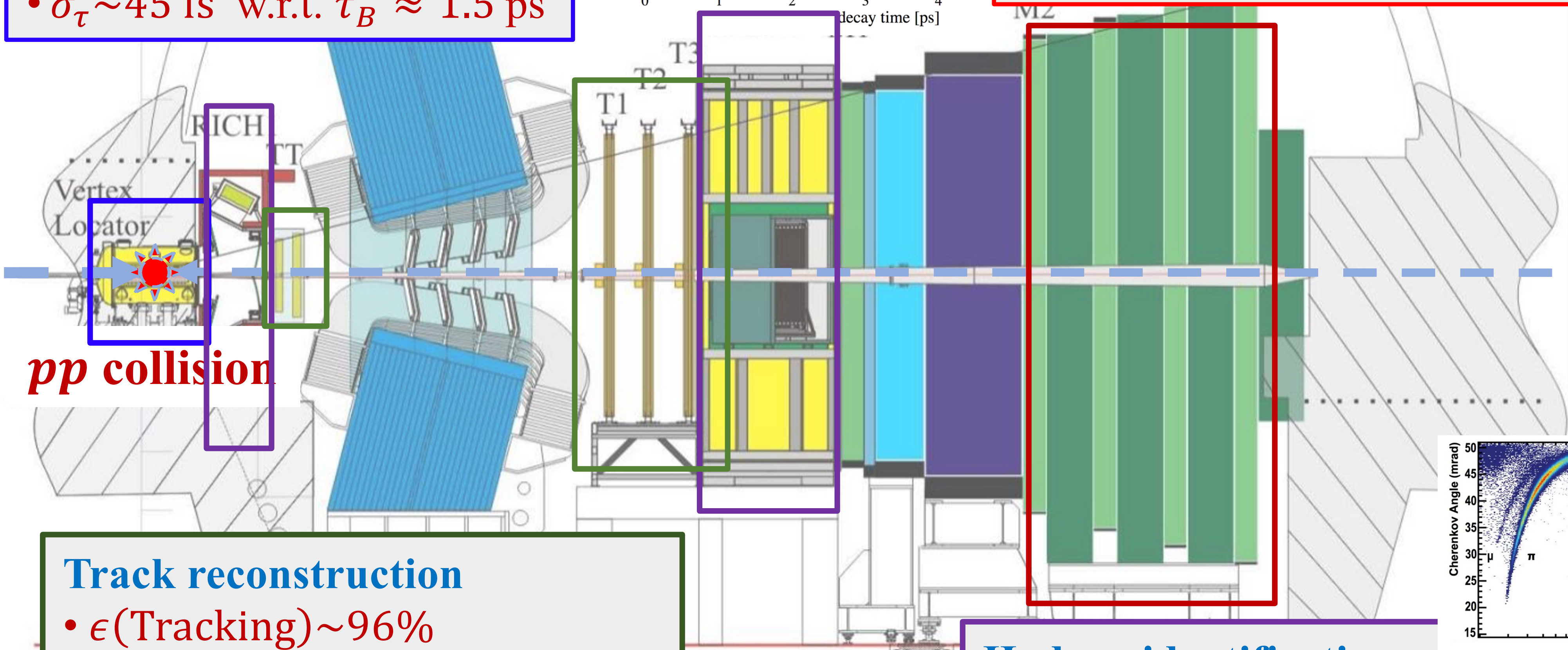
- **Second**, detect their decays into “stable” particles (those leave trajectories or produce particle showers)

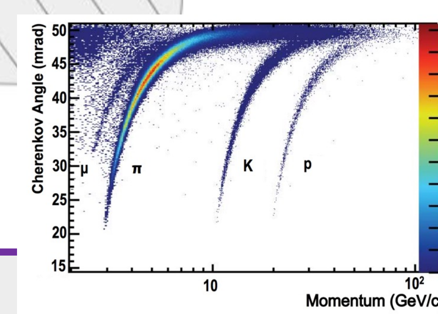
eg: LHCb at LHC, dedicated for measurements of charm and bottom hadrons



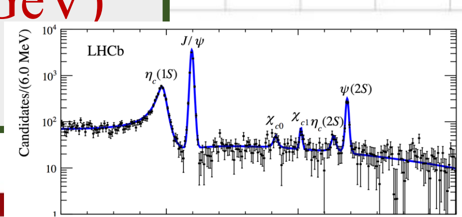
Vertex reconstruction
- $\sigma_{IP}\sim 20\ \mu\text{m}$
- $\sigma_{\tau}\sim 45$ fs w.r.t. $\tau_B \approx 1.5$ ps

Muon identification
- $\epsilon(\mu \to \mu)\sim 97\%$
- MisID rate $(\pi \to \mu)\sim 1-3\%$





Track reconstruction
- $\epsilon(\text{Tracking})\sim 96\%$
- $\delta p/p \sim 0.5\%$-1% (5-200 GeV)
- $\epsilon(m_{J/\psi}) \approx 15$ MeV

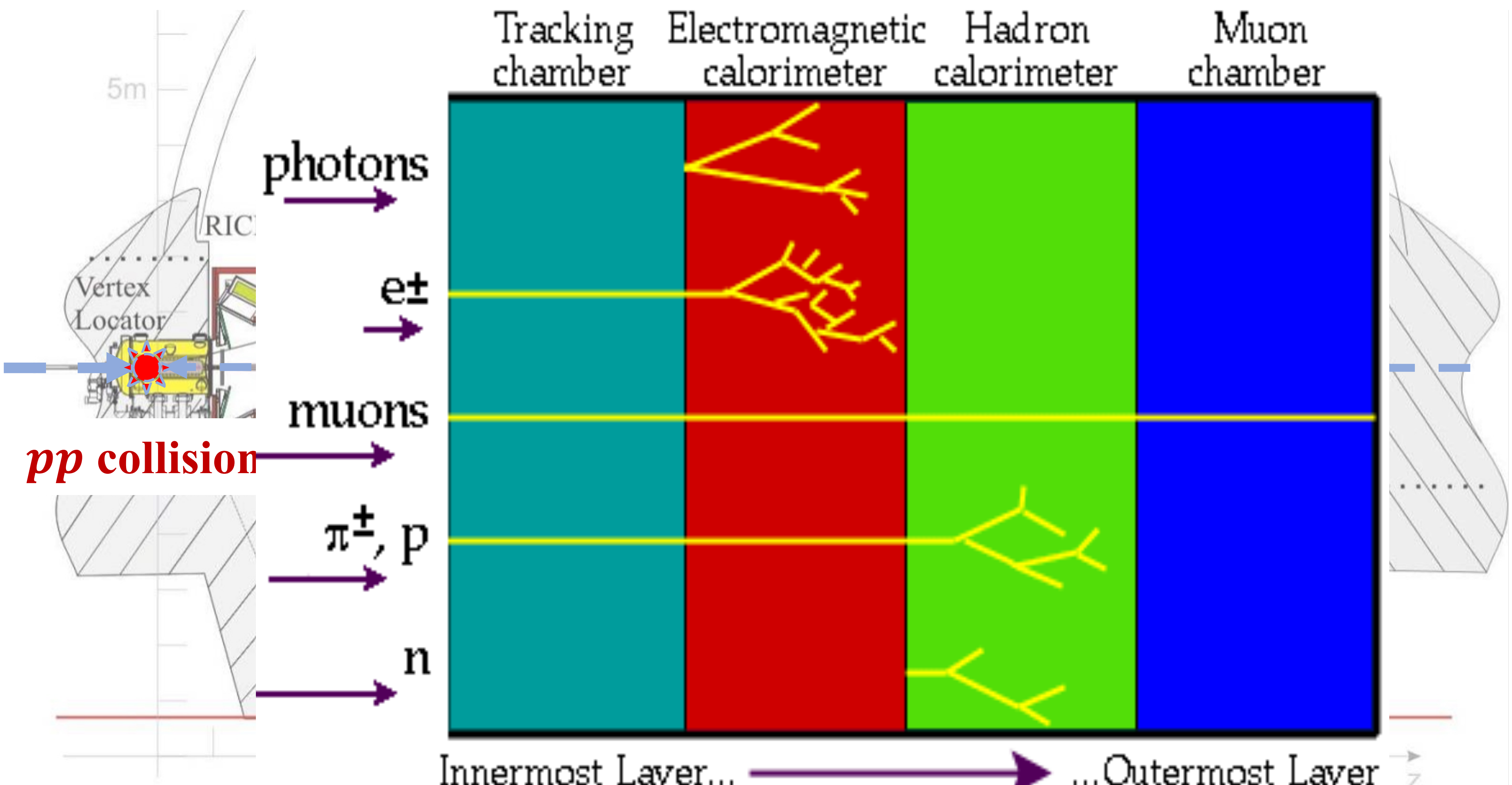


Hadron identification
- $\epsilon(K \to K), \epsilon(p \to p) > 90\%$
- MisID rate $(\pi \to K/p) < 5\%$

How to study new hadrons 2

- **Second**, detect their decays into “stable” particles (those leave trajectories or produce particle showers)

eg: LHCb at LHC, dedicated for measurements of charm and bottom hadrons



How to study new hadrons 3

- **Third**, form experimental quantities to extract signal and measure properties

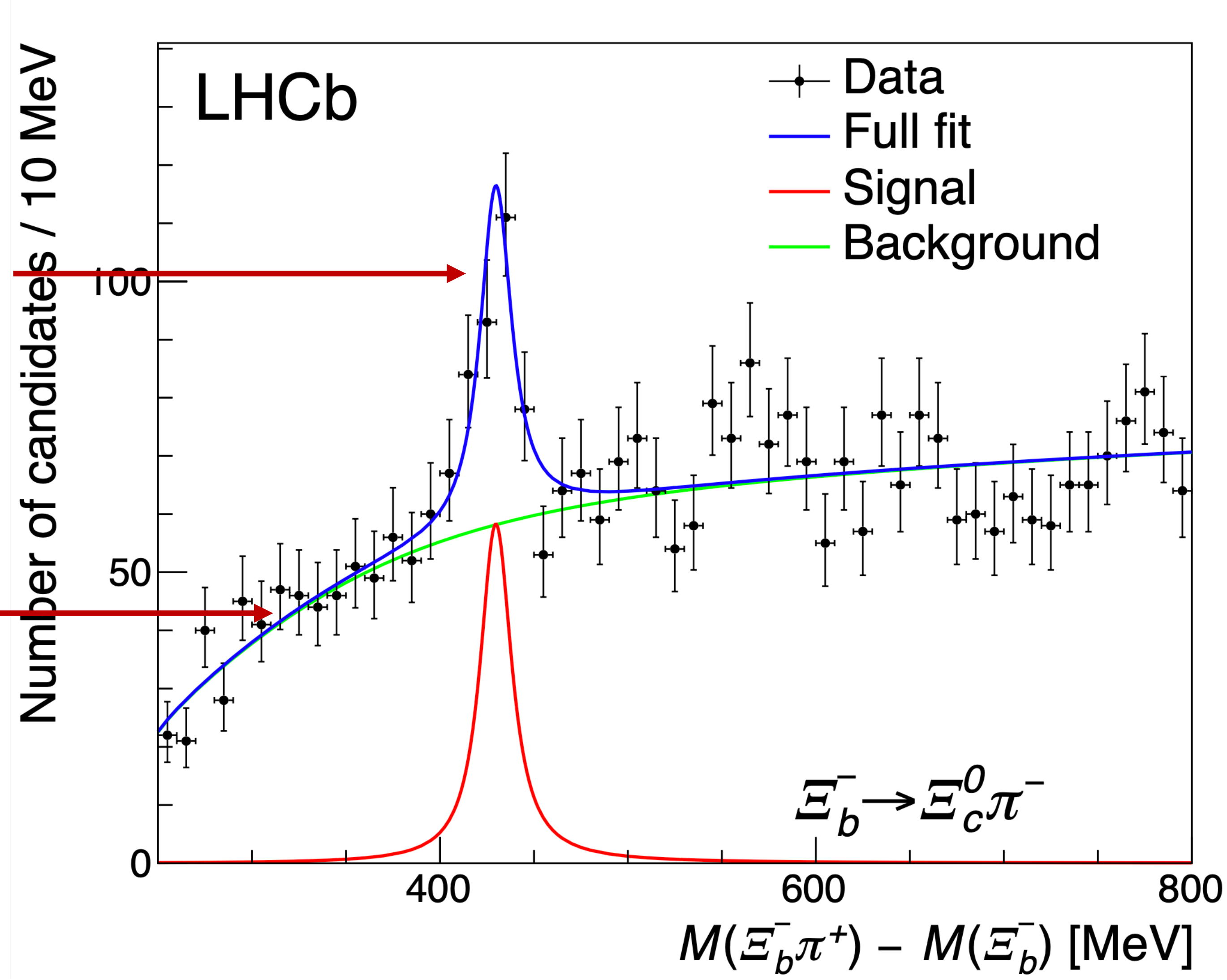
Usually invariant mass

$$X \to a + b \qquad m_{X'} = \sqrt{(E_a + E_b)^2 - (\vec{p}_a + \vec{p}_b)^2}$$

Natural width ⊗ resolution

Resonance

Background



Important: keep low background and high mass resolution!

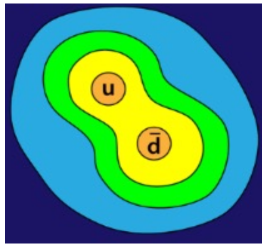
Experimental studies of "exotic" hadrons

- No experimental evidence of hadrons with more than three quarks → Exotic hadrons

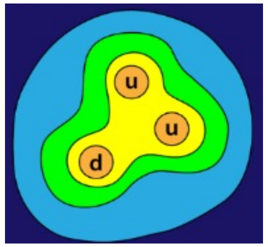
> anti-triplet as anti-quarks q̄. Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q q̄), etc., while mesons are made out of (q q̄), (q q q̄ q̄), etc. It is assuming that the lowest

Conventional: $q\bar{q}$, qqq

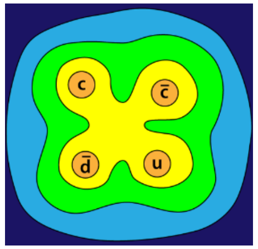
Exotic hadrons: $qq\bar{q}\bar{q}$, $qqqq\bar{q}$, gluons…



$q\bar{q}$



qqq

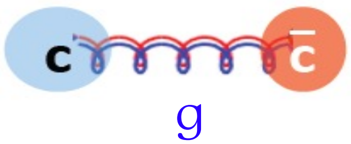


$qq\bar{q}\bar{q}$

Tetraquark

$qqqq\bar{q}$

Pentaquark



Unique color configuration

Baryons: RGB

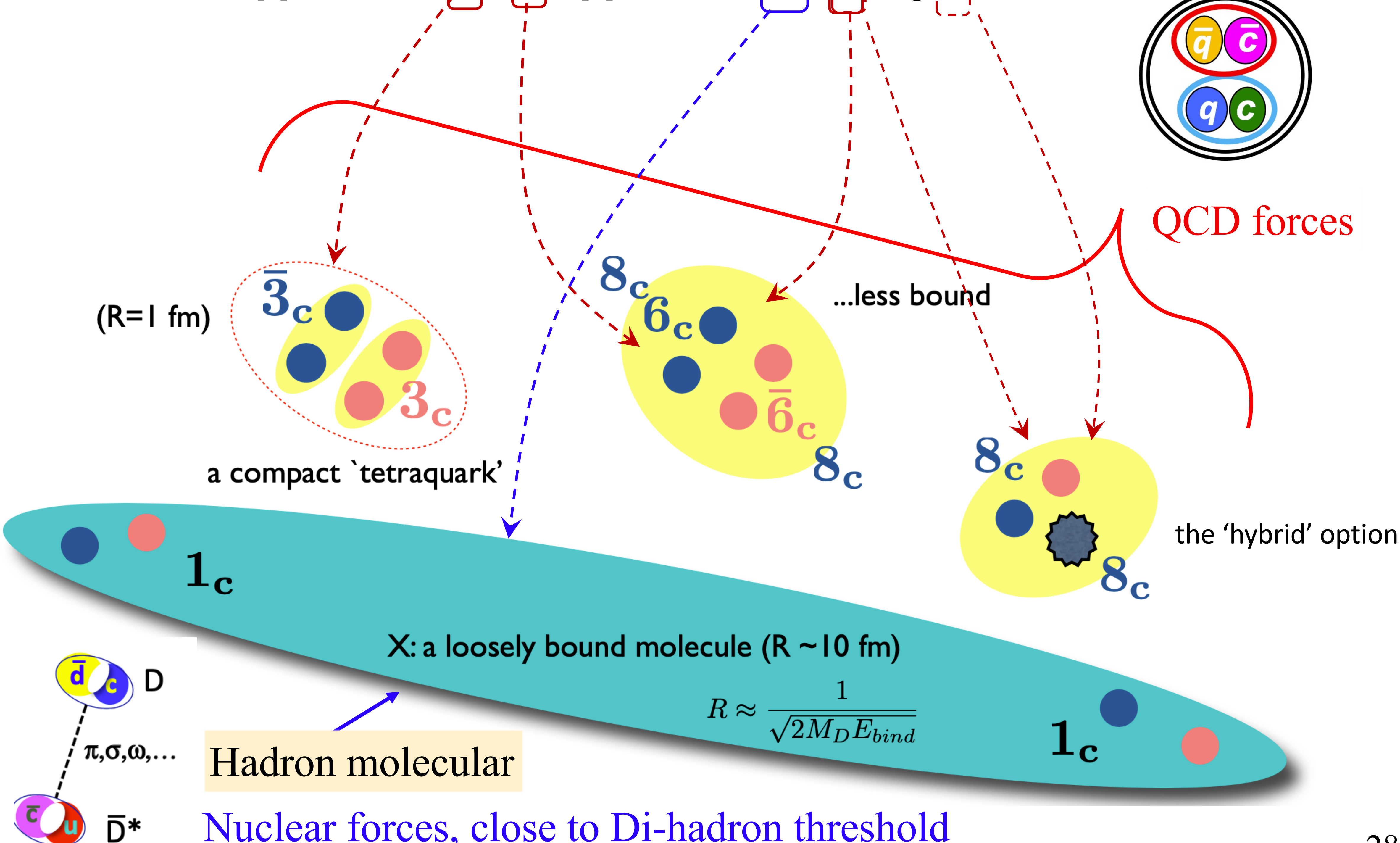
Mesons: $R\bar{R}$ + $G\bar{G}$ + $B\bar{B}$

Exotics: more possibilities to form color singlet

Color structure in exotic states

Rev.Mod.Phys. 90 (2018) 015003

Color: $qq\ 3 \otimes 3 = \bar{3} \oplus 6$; $q\bar{q}\ 3 \otimes \bar{3} = 1 \oplus 8$; $g\ 8$

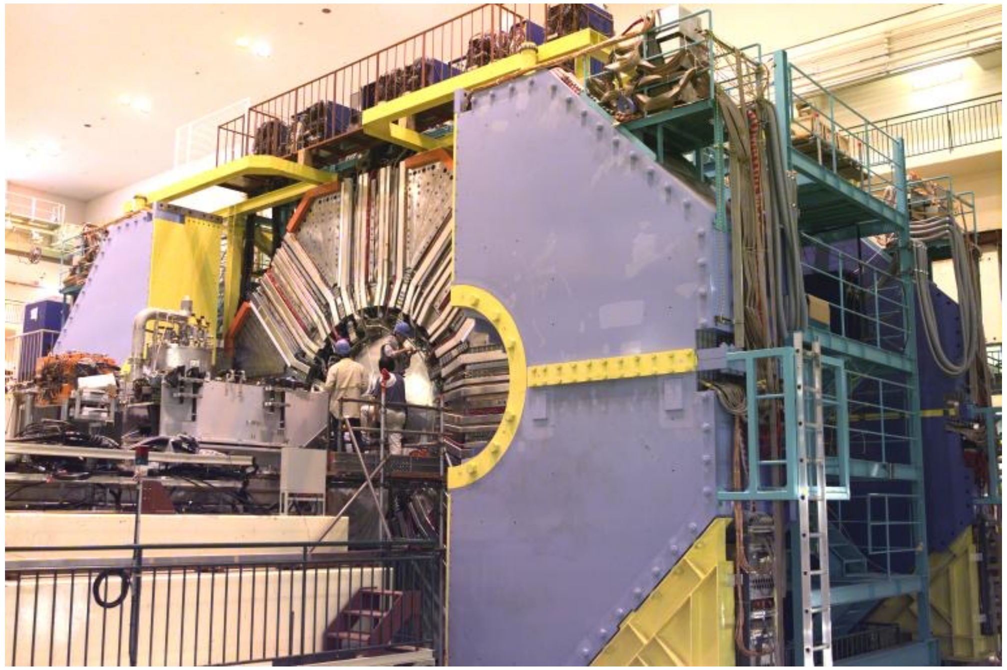


First evidence of exotic

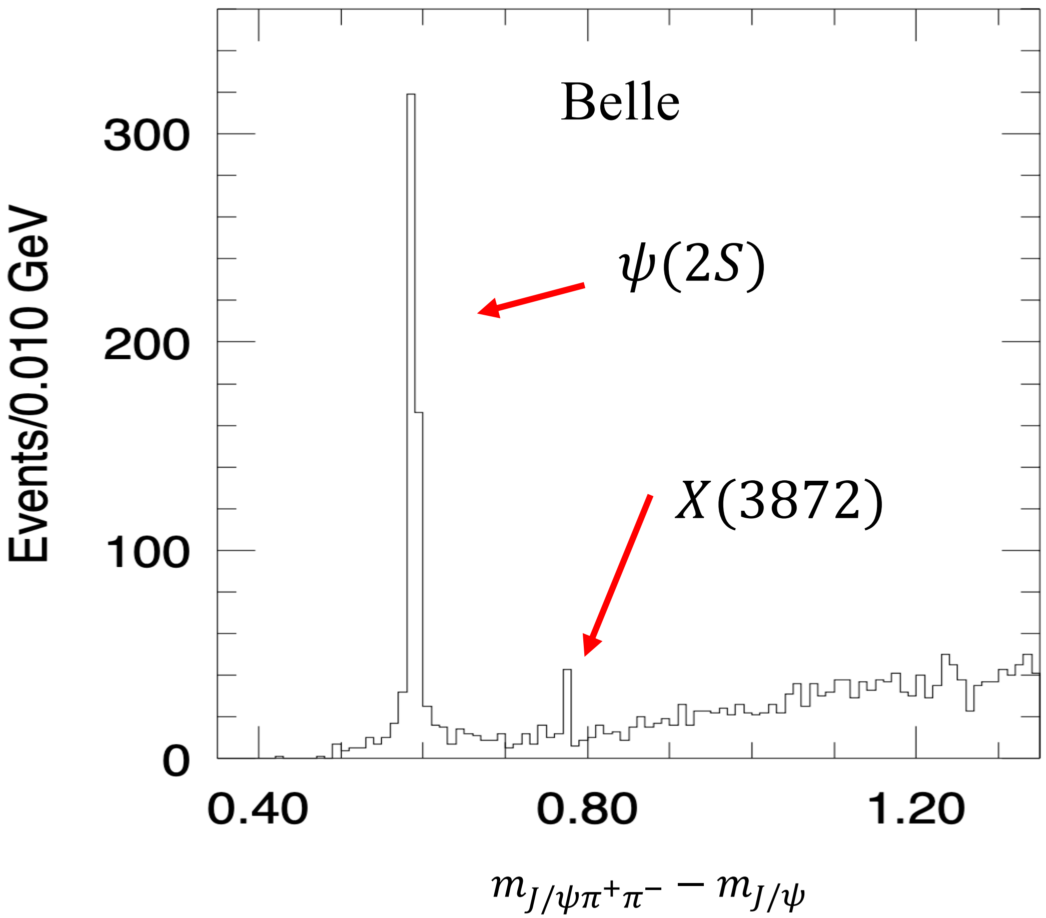
$X(3872)$ discovered at KEK in 2003

$X(3872) \rightarrow J/\psi\pi^+\pi^-$

- Narrow width
- Close to $D^{*0}D^0$ threshold
- Isospin breaking decay …



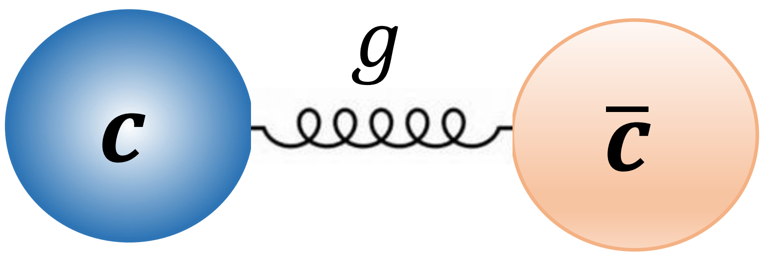
PRL91(2003)262001



$X(3872)$ as an exotic

$X(3872) \to J/\psi\pi^+\pi^-$, $X(3872)$ contains the $c\bar{c}$ component, like a charmonium

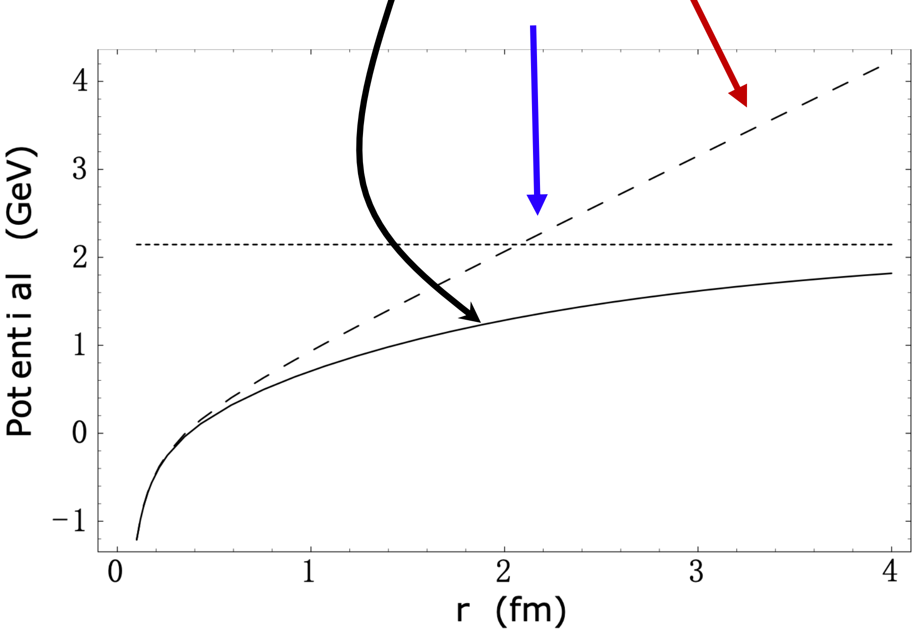
Non-relativistic potential for $\bar{c}c$



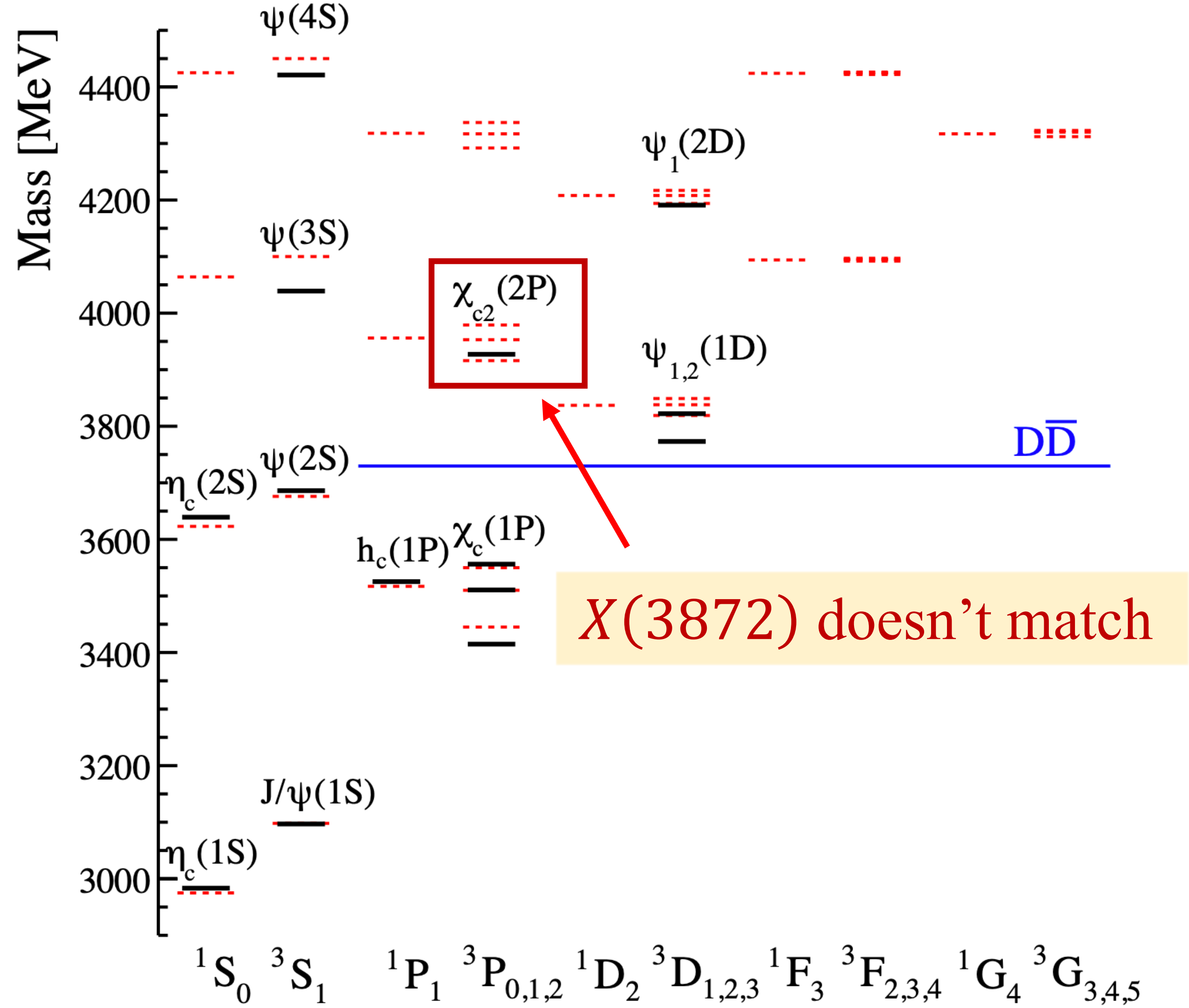
Coulomb

Confinement

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + b\times r$$

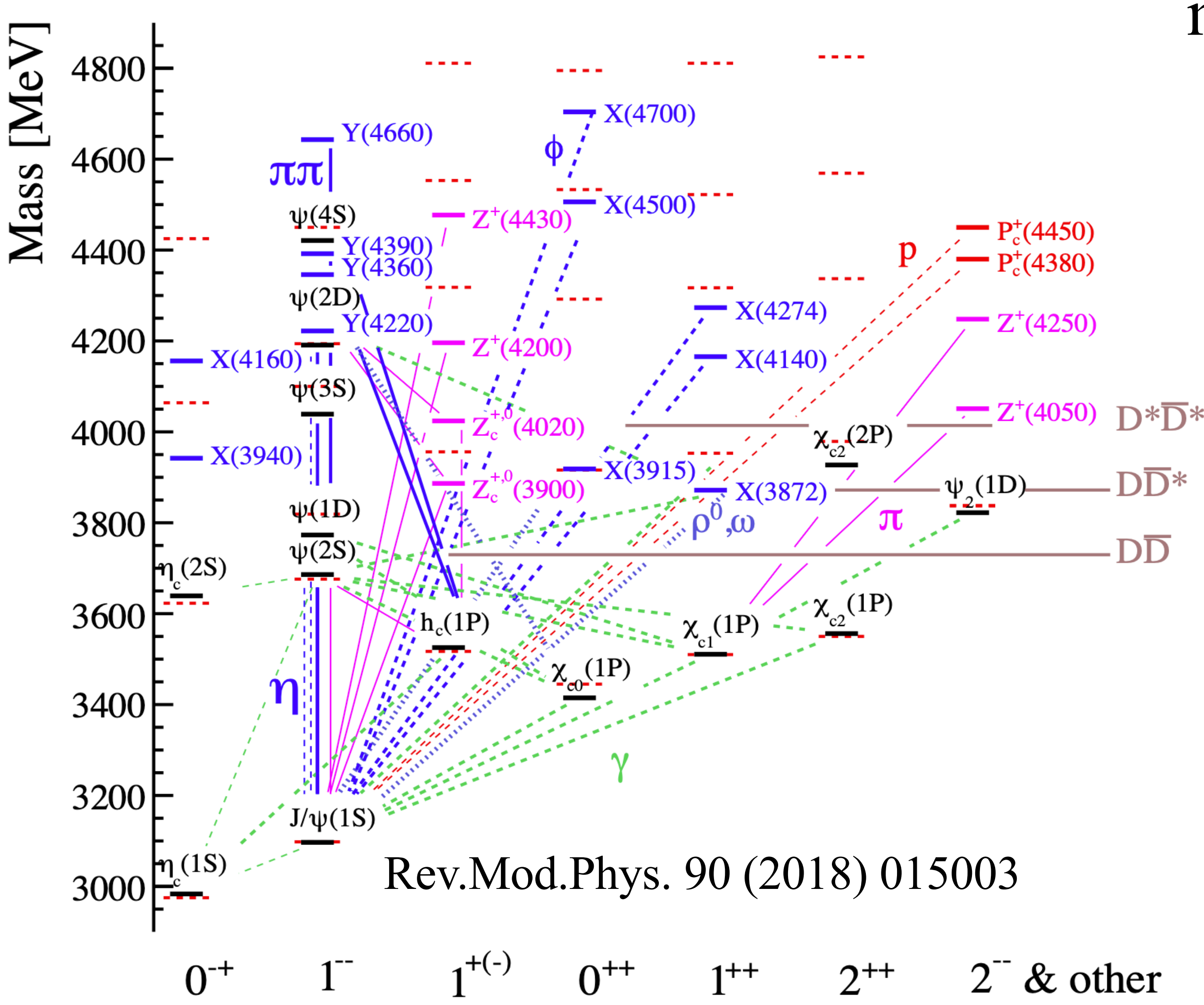


Predicted spectrum v.s. experiment



More charmonium like exotics

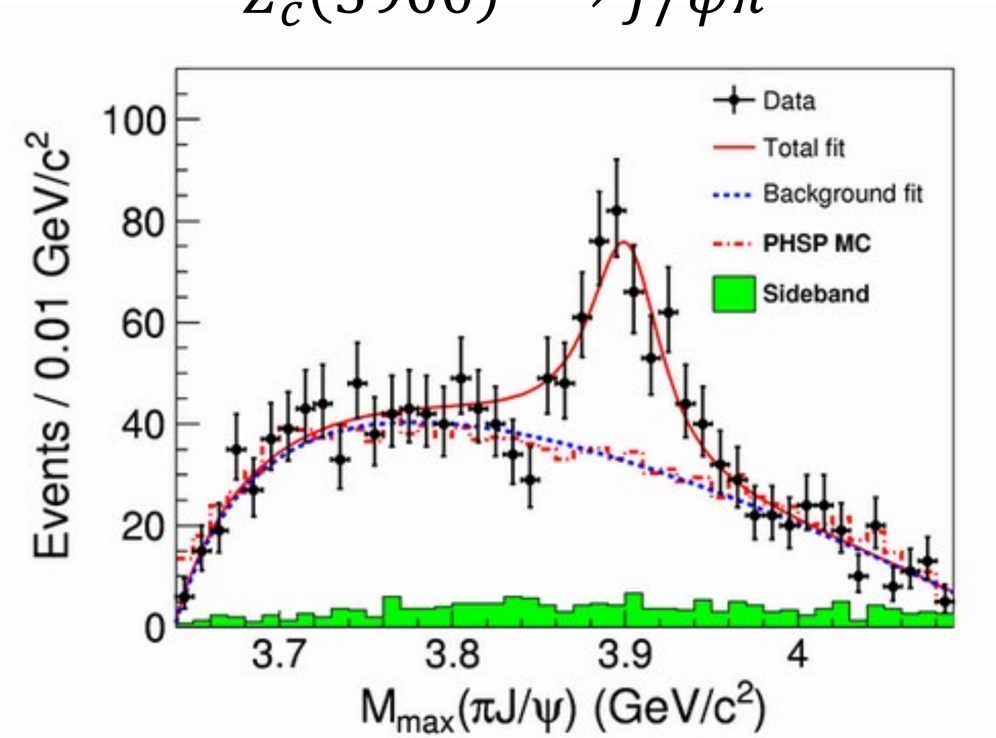
States with $c\bar{c}$ quark contents

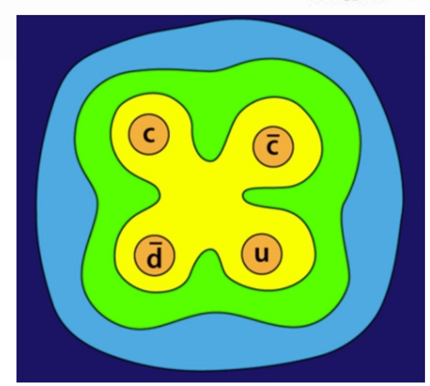


Rev.Mod.Phys. 90 (2018) 015003

Charged $Z_c(3900)^+$ by BESIII (2013) manifestly exotic, $c\bar{c}u\bar{d}$

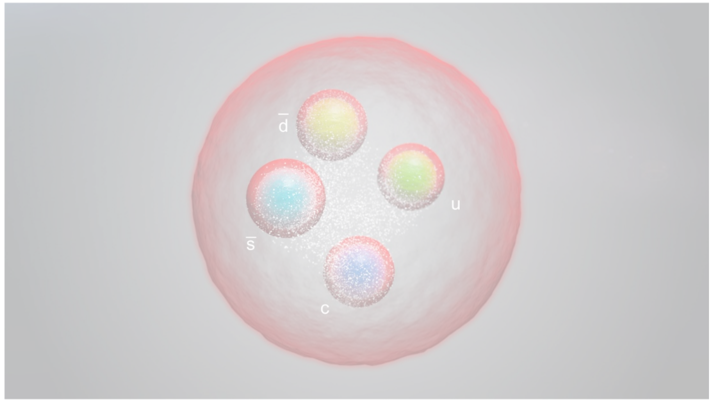
$$Z_c(3900)^+ \to J/\psi\pi^+$$



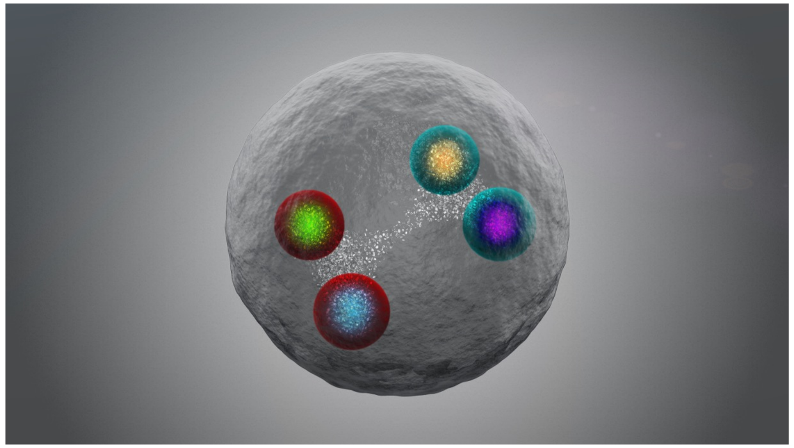


PRL 110 (2013) 252001

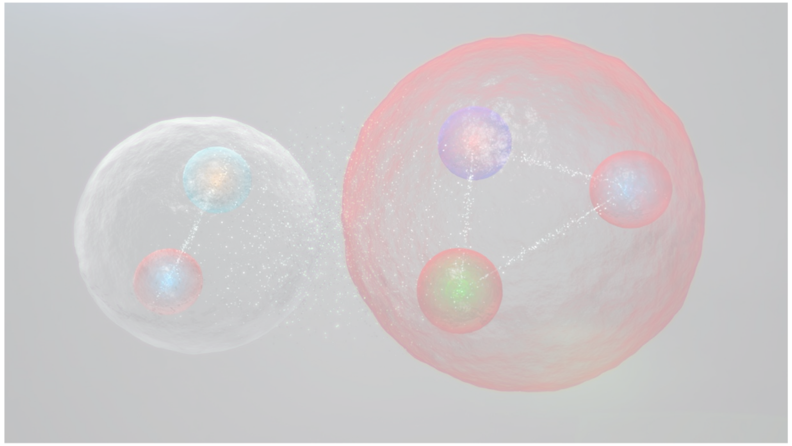
❑ Single-charm tetraquark



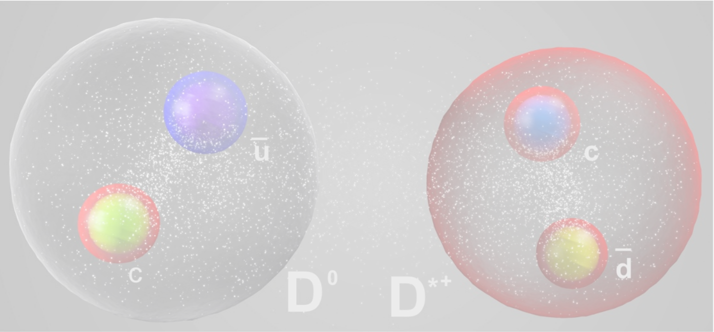
❑ Hidden-charm tetraquark



❑ Hidden-charm pentaquark



❑ Double-charm tetraquark



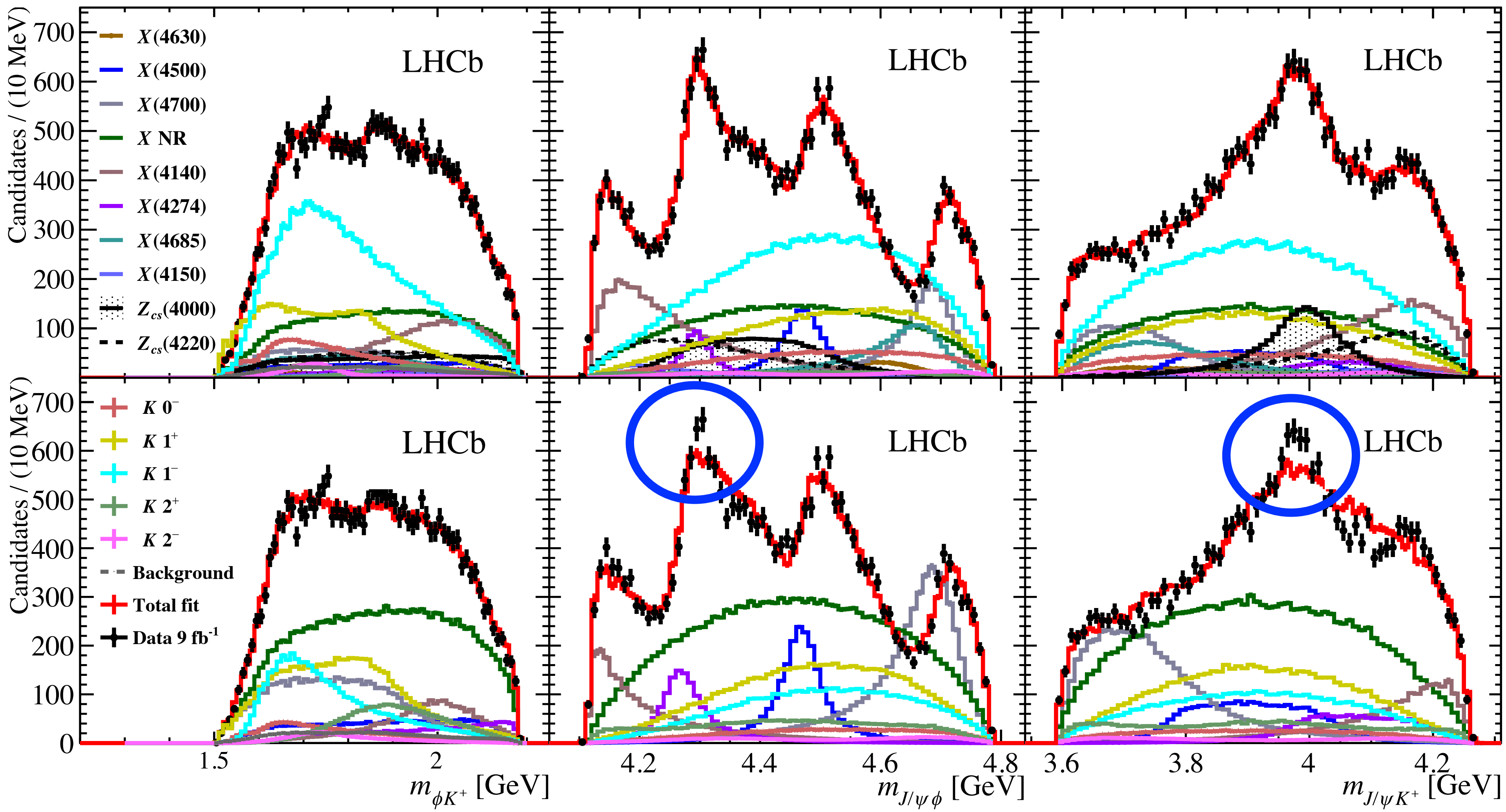
Structures in $B^+ \to J/\psi\phi K^+$ decays

PRL 127 (2021) 082001

- Exotic discovered in $B^+ \to J/\psi\phi K^+$ with amplitude analysis
  - Multiple $X \to J/\psi\phi$ states, $[c\bar{c}s\bar{s}]$ tetraquarks or charmonium
  - Two $Z_{cs}^+ \to J/\psi K^+$ states: $Z_{cs}(4000)^+$ and $Z_{cs}(4200)^+$ with $[c\bar{c}u\bar{s}]$, $J^P = 1^+$

w/ Z_{cs}^+

w/o Z_{cs}^+



Isospin analysis of $B \to J/\psi\phi K$ decays

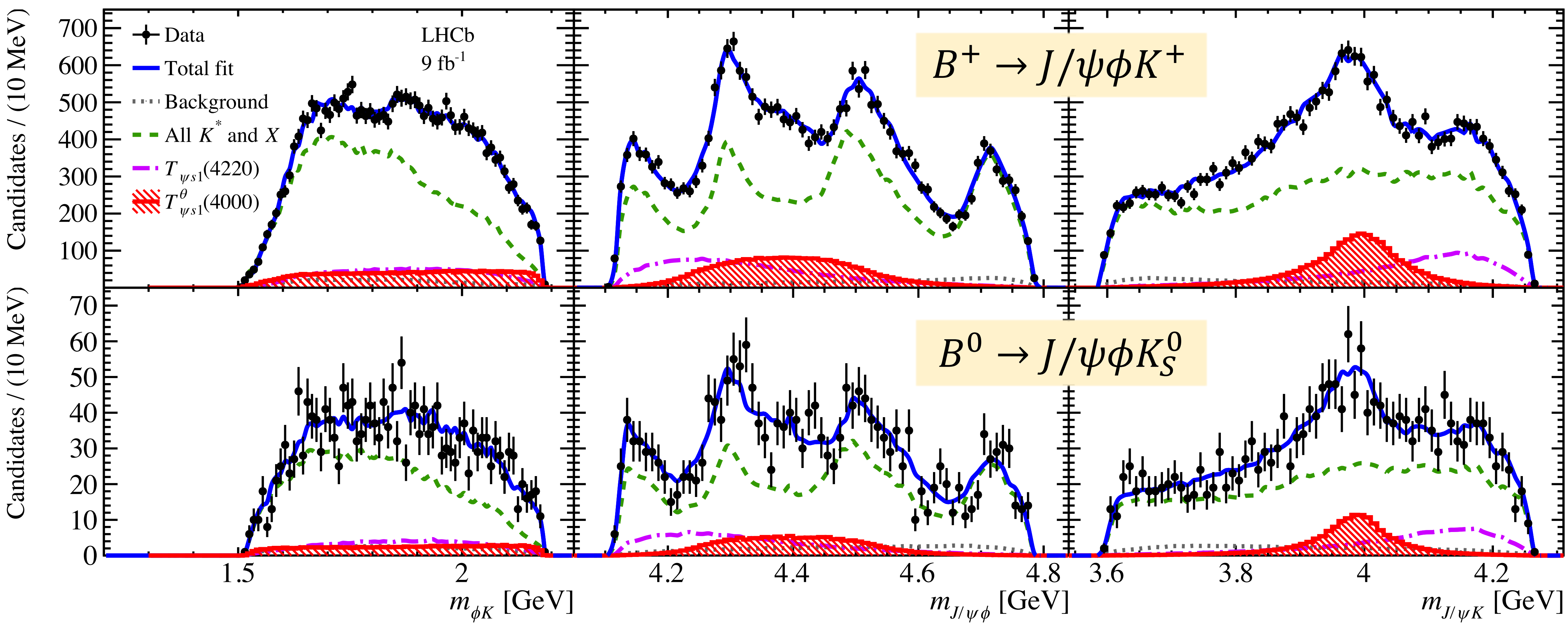
PRL127(2021)082001
LHCb-PAPER-2022-040

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

Evidence of $T_{\psi s1}^{\theta}(4000)^0[c\bar{c}d\bar{s}] \to J/\psi K_S^0$, isospin partners of $T_{\psi s1}^{\theta}(4000)^+$

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

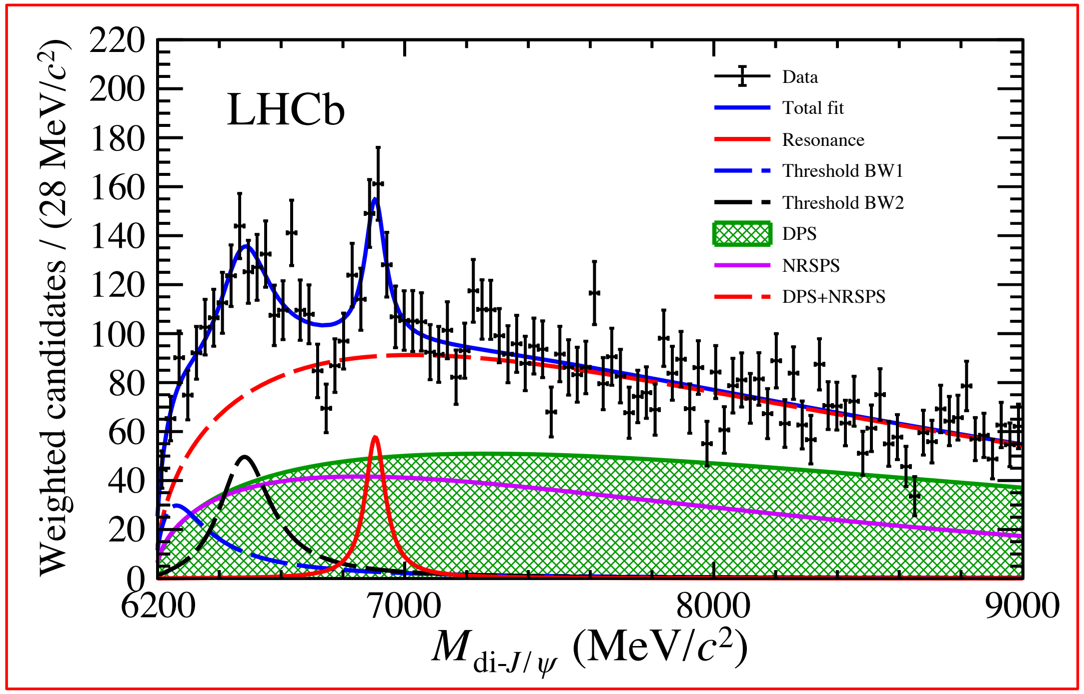
$$\Delta M_{\text{isospin}} = -12^{+11+6}_{-10-4}\ \mathrm{MeV}$$

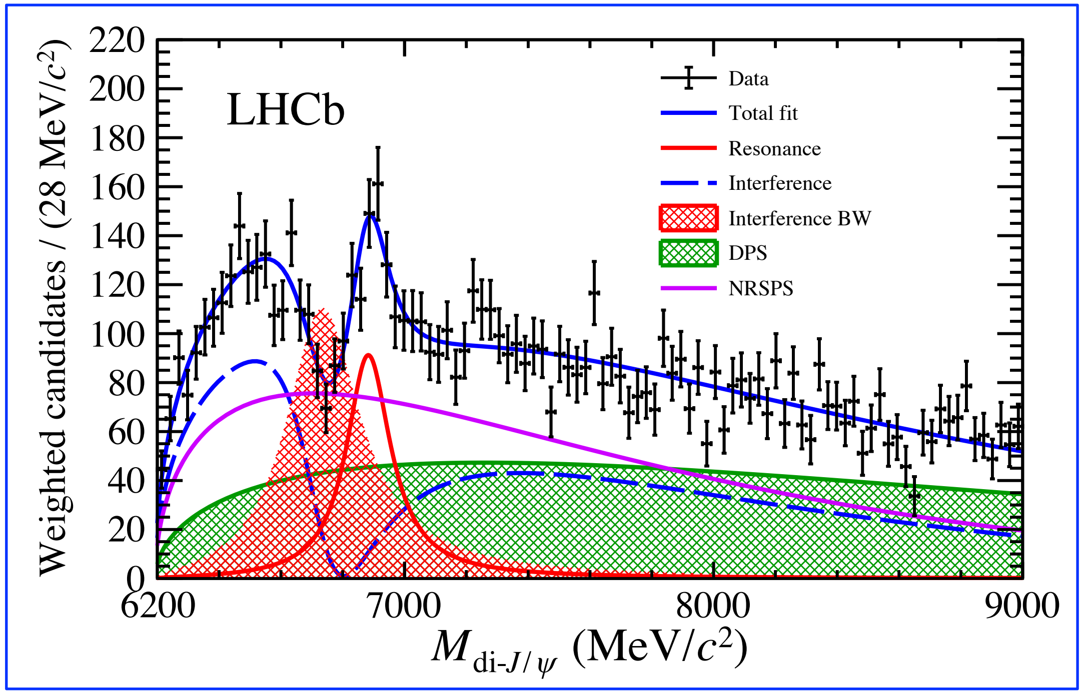


$X(6900)$ in J/ψ-pair spectrum

Science Bulletin 65 (2020) 1983

- Structure in J/ψ-J/ψ final state
  - $X(6900)$ consistent with fully charmed tetraquark $T_{cc\bar{c}\bar{c}}$
  - Structure close to threshold: $T_{cc\bar{c}\bar{c}}$ or feed-down decays
- Two alternative interpretation of data

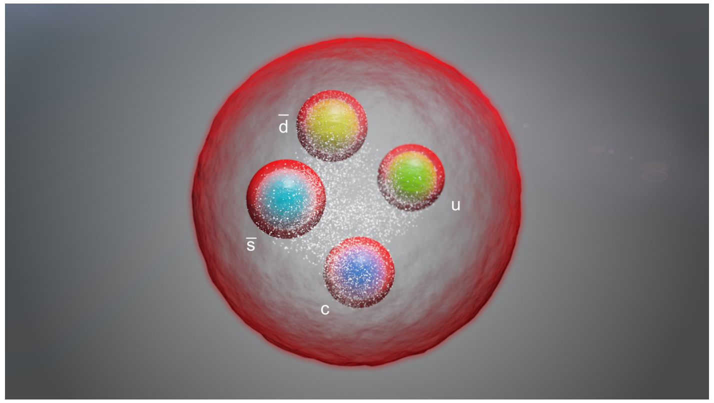




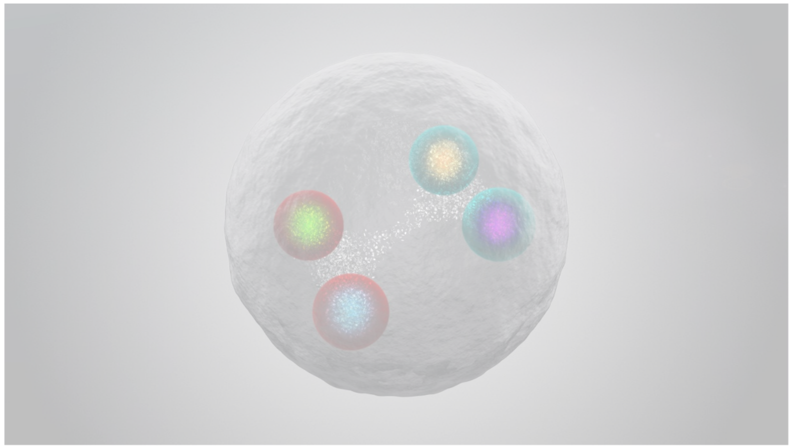
$M(X(6900)) = 6905 \pm 11 \pm 7\ \text{MeV}/c^2$
$\Gamma(X(6900)) = 80 \pm 19 \pm 33\ \text{MeV}/c^2$

$M(X(6900)) = 6886 \pm 11 \pm 11\ \text{MeV}/c^2$
$\Gamma(X(6900)) = 168 \pm 33 \pm 69\ \text{MeV}/c^2$

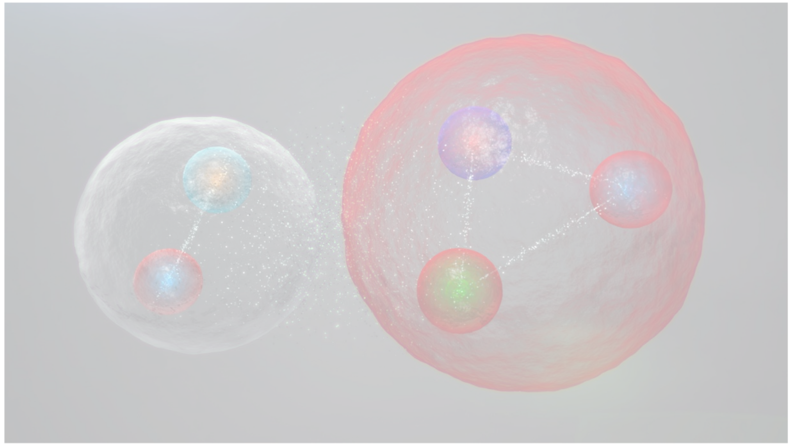
- Single-charm tetraquark



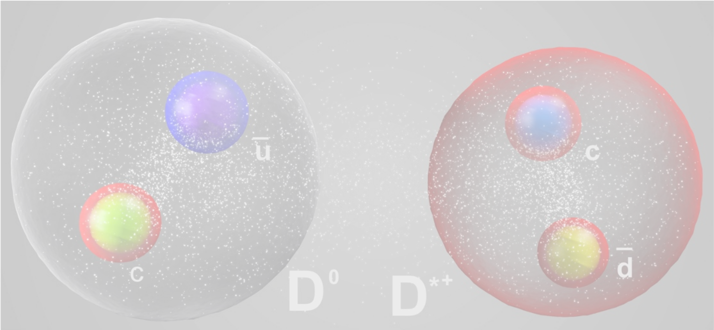
- Hidden-charm tetraquark



- Hidden-charm pentaquark

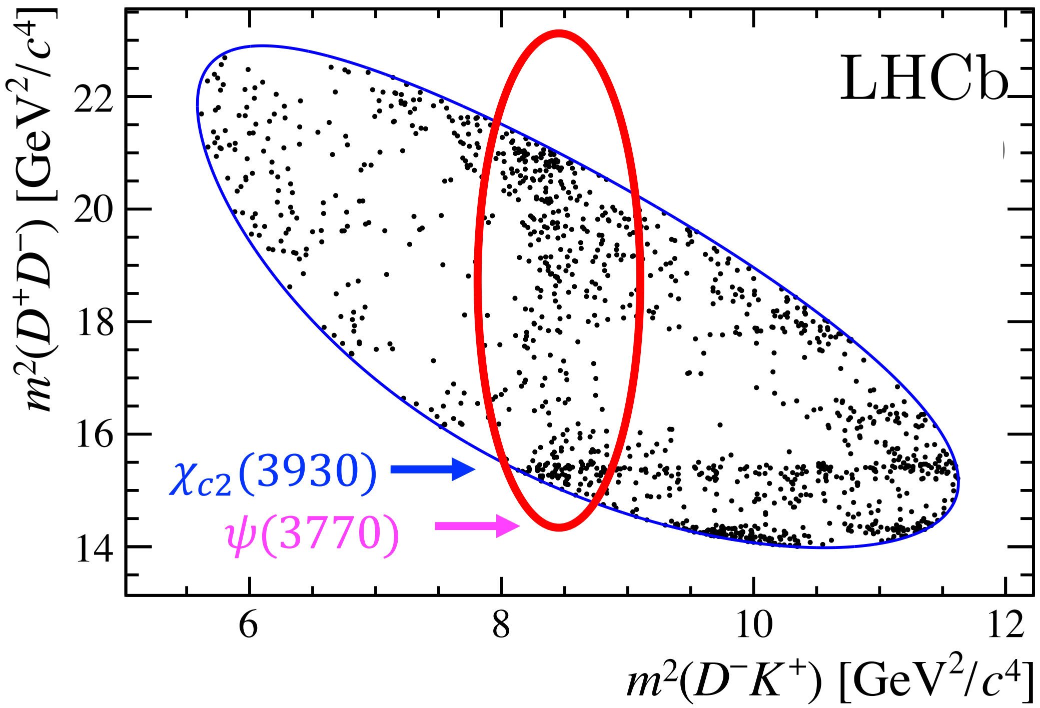


- Double-charm tetraquark

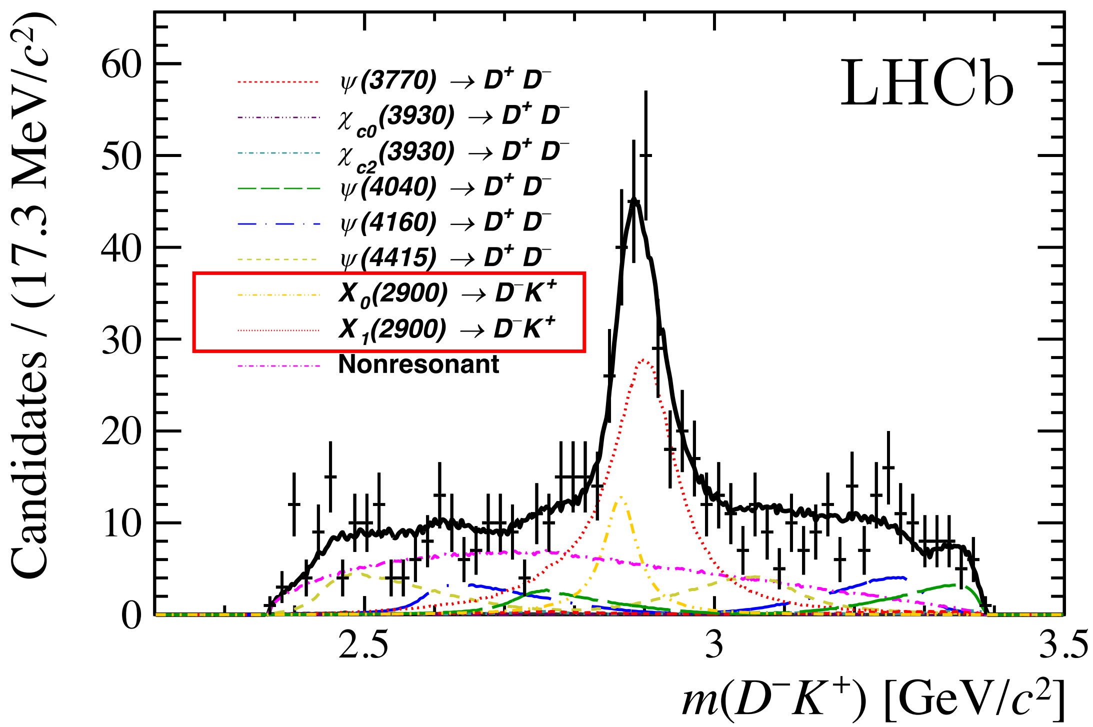


Tetraquarks in $B^+ \to D^+ D^- K^+$

- Structures in $B^+ \to D^+ D^- K^+$: amplitude analysis resolved $X_0(2900)$ and $X_1(2900)$ in $D^- K^+$ final state
- Open charm tetraquarks with four different flavors $[cs\bar{u}\bar{d}]$



$m(D^+D^-) > 4$ GeV$/c^2$



0^+ $\quad X_0(2900): \quad M = 2.866 \pm 0.007 \pm 0.002\,\mathrm{GeV}/c^2, \quad \Gamma = 57 \pm 12 \pm 4\,\mathrm{MeV}$

1^- $\quad X_1(2900): \quad M = 2.904 \pm 0.005 \pm 0.001\,\mathrm{GeV}/c^2, \quad \Gamma = 110 \pm 11 \pm 4\,\mathrm{MeV}$

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

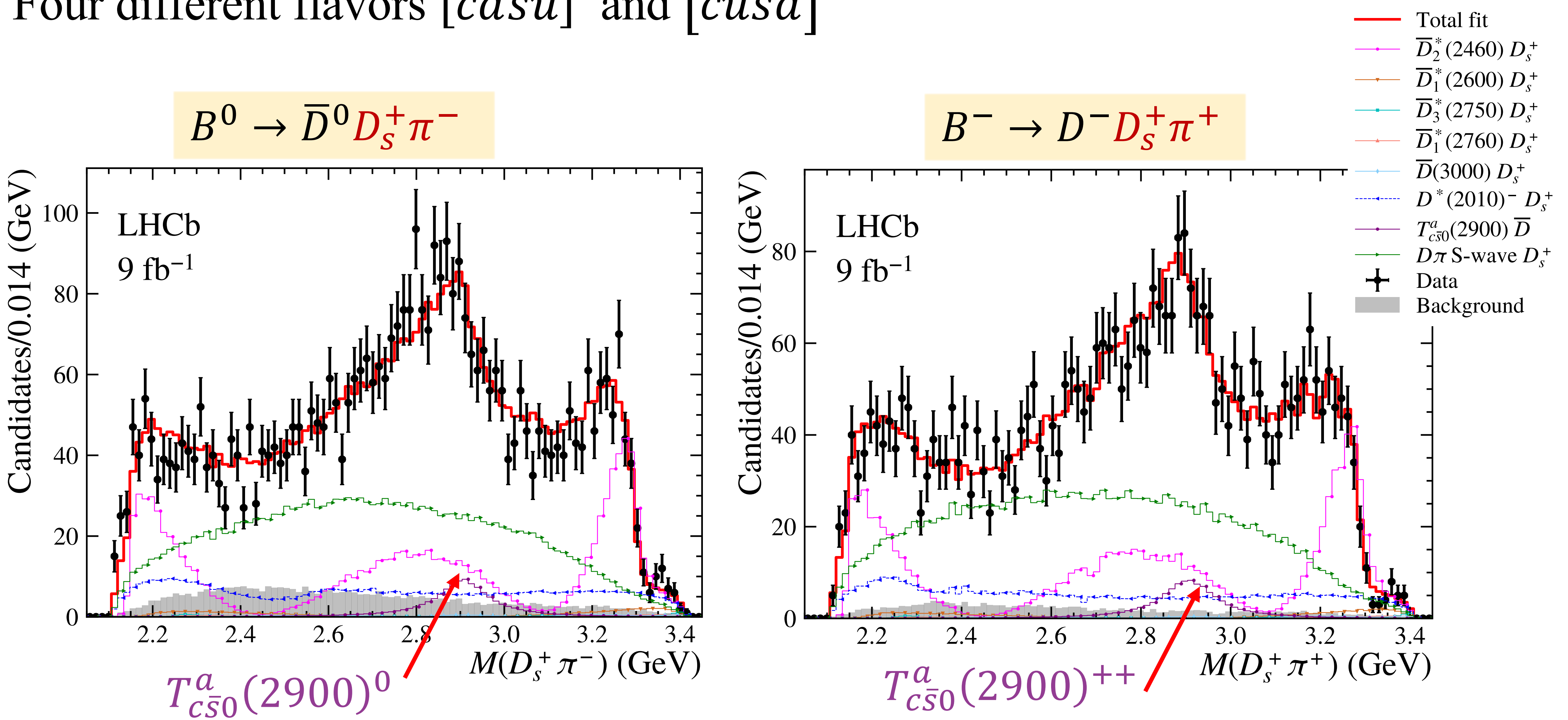
- Two isospin patterners: $T_{c\bar{s}0}^{a}(2900)^0 \to D_s^+ \pi^-$, $T_{c\bar{s}0}^{a}(2900)^{++} \to D_s^+ \pi^+$

Joint amplitude analysis

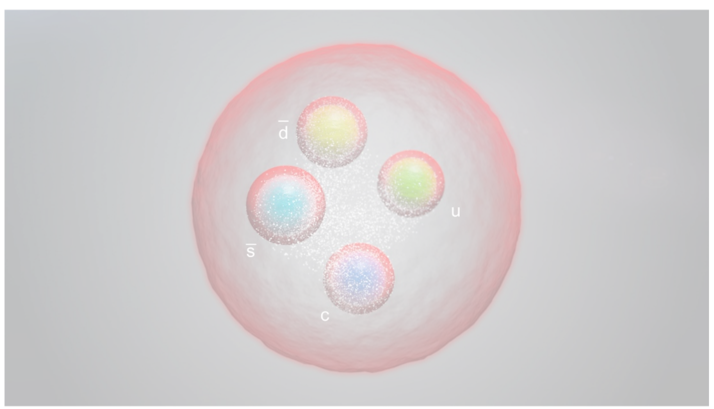
$$M = 2.908 \pm 0.011 \pm 0.020\ \text{GeV}$$
$$\Gamma = 0.136 \pm 0.023 \pm 0.011\ \text{GeV}$$

$J^P = 0^+$

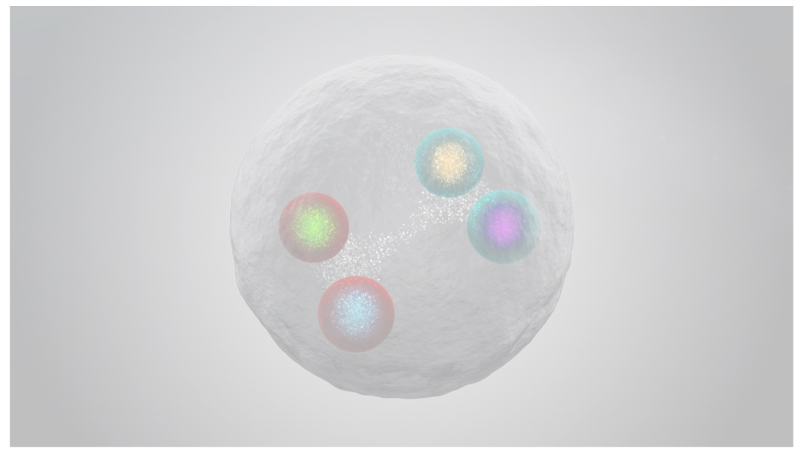
- Four different flavors $[cd\bar{s}\bar{u}]$ and $[cu\bar{s}\bar{d}]$



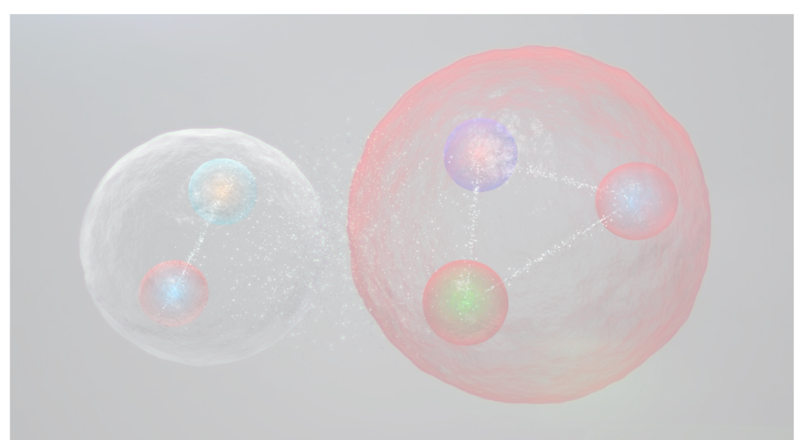
- Single-charm tetraquark



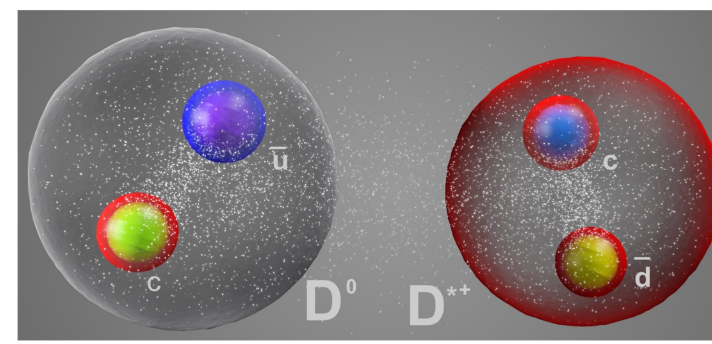
- Hidden-charm tetraquark



- Hidden-charm pentaquark



- Double-charm tetraquark

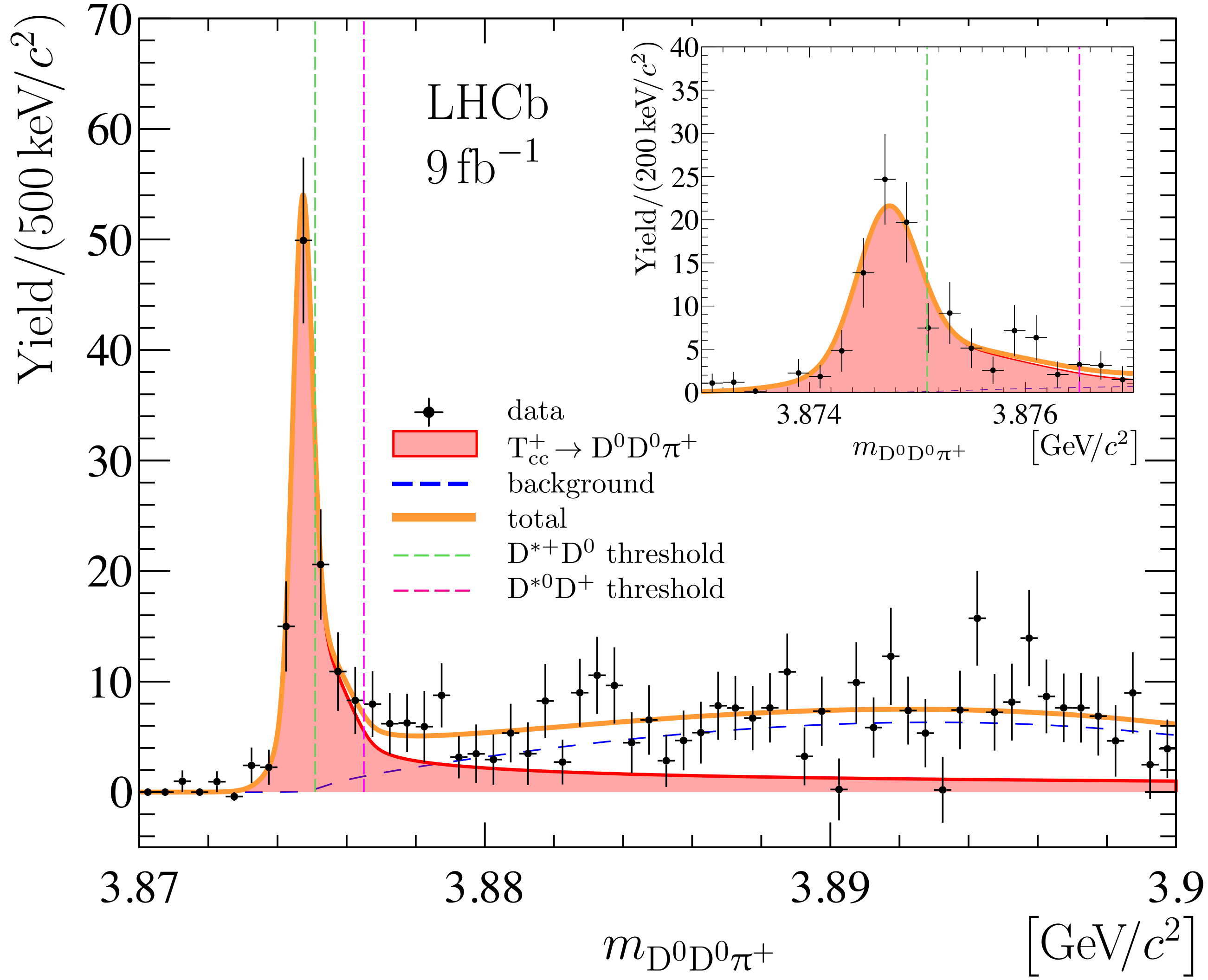


Observation of T_{cc}^{+} in $D^0D^0\pi^+$

[arXiv: 2109.01038] (Nature Physics)
[arXiv: 2109.01056] (Nature Communications)

- Minimum contents $[cc\bar{u}\bar{d}]$, first tetraquark candidate with cc
- Two fit models

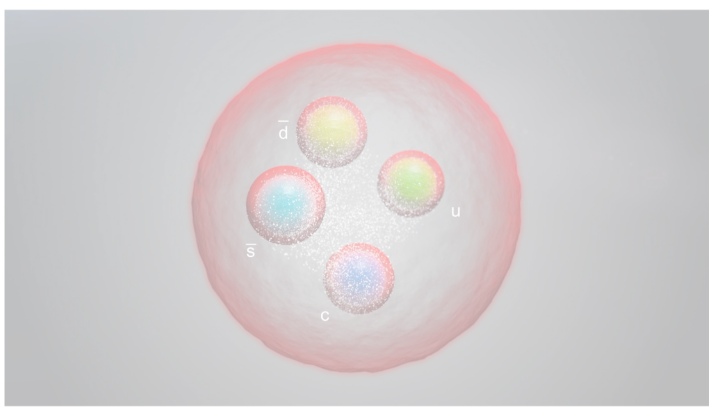
Breit-Wigner resonance



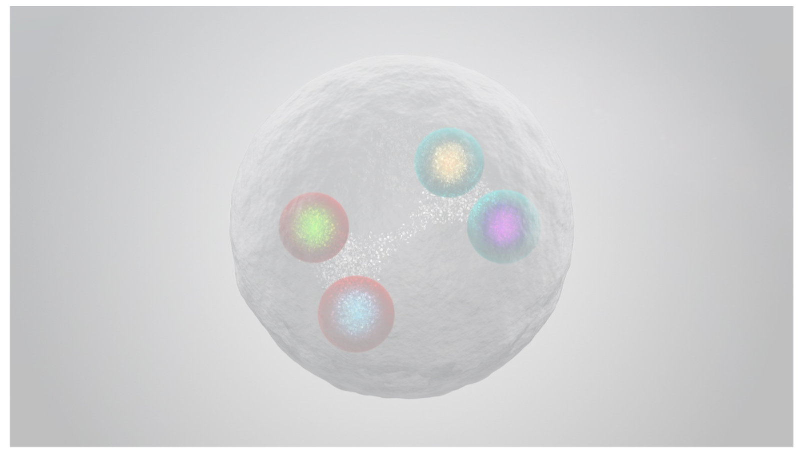
- Mass below D^0D^{*+} threshold

	$\delta\mathfrak{m}$ [keV/c^2]	$\mathfrak{w}$ [keV/c^2]
$\mathfrak{F}^{\mathrm{BW}}$	-279 ± 59	409 ± 163
$\mathfrak{F}^{\mathrm{U}}$	-361 ± 40	47.8 ± 1.9

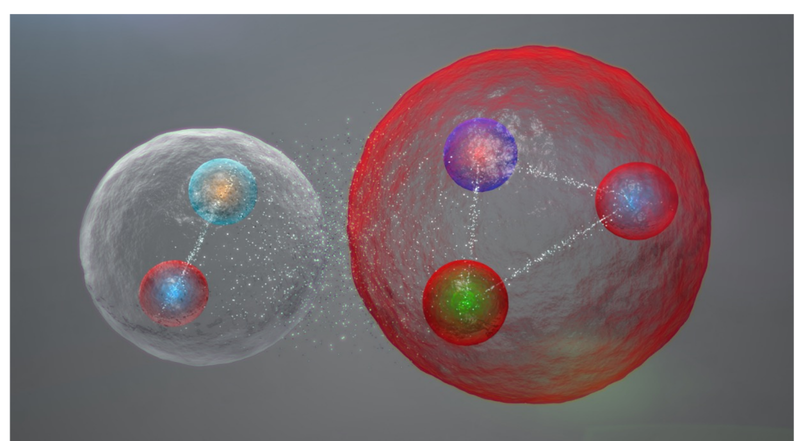
❑ Single-charm tetraquark



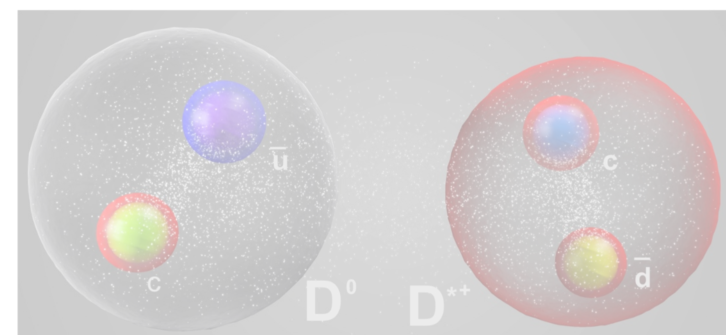
❑ Hidden-charm tetraquark



❑ **Hidden-charm pentaquark**



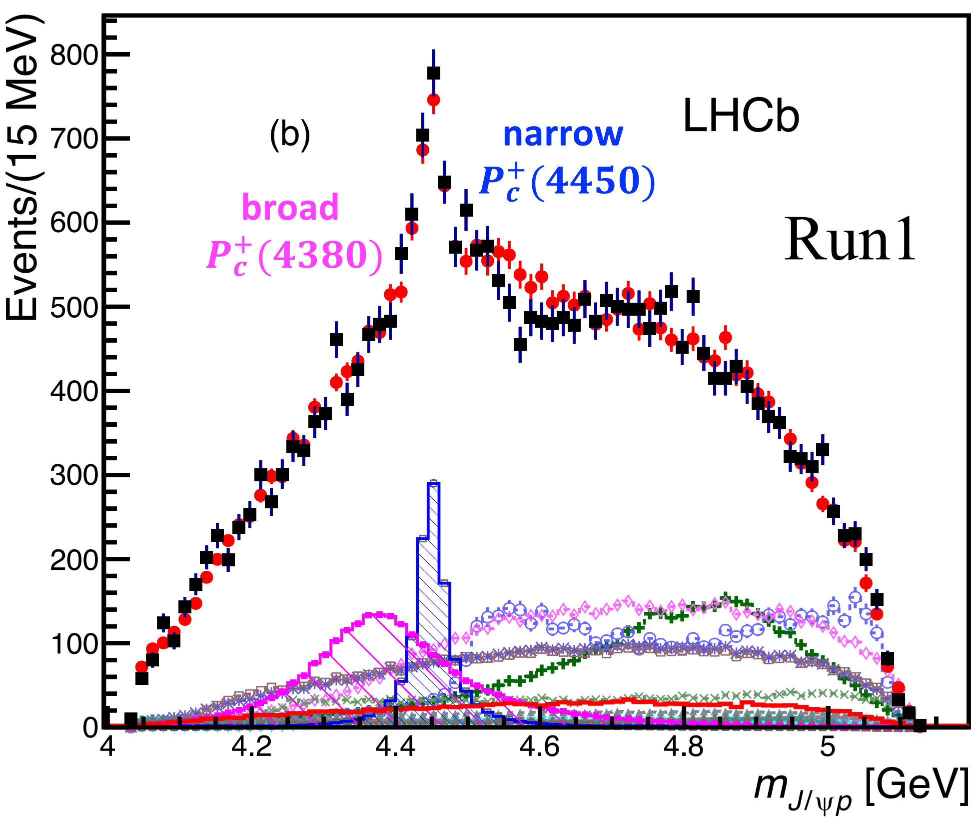
❑ Double-charm tetraquark



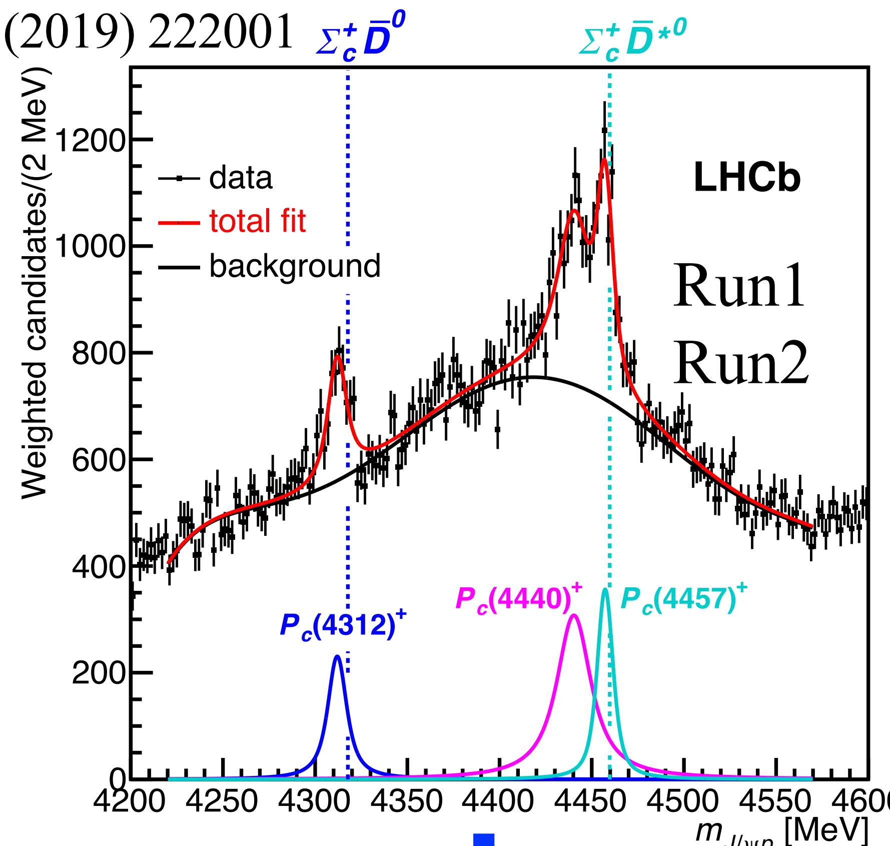
Observation of P_c^+ in $\Lambda_b^0 \to J/\psi p K^-$

- $P_c^+(c\bar{c}uud)$ states were first observed in $\Lambda_b^0 \to J/\psi p K^-$ using Run1 data
- Analysis updated with ×9 more data
  - $P_c^+(4450)$ resolved into two peaks, $P_c^+(4440)$ and $P_c^+(4457)$, fine structure
  - A new state $P_c^+(4312)$ observed

PRL 115 (2015) 072001



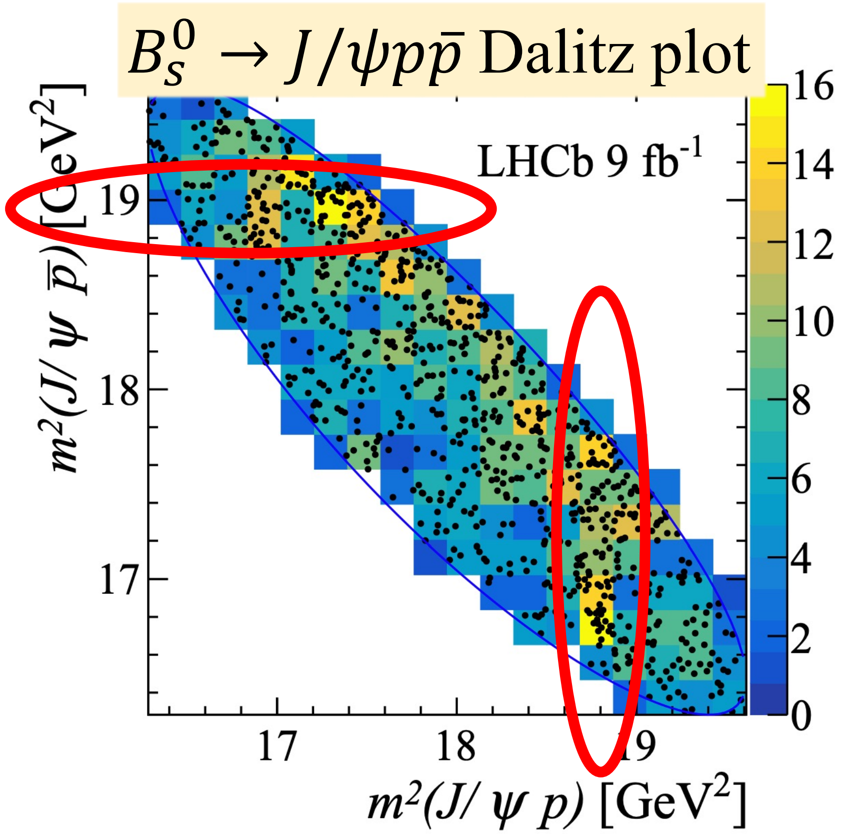
PRL 122 (2019) 222001



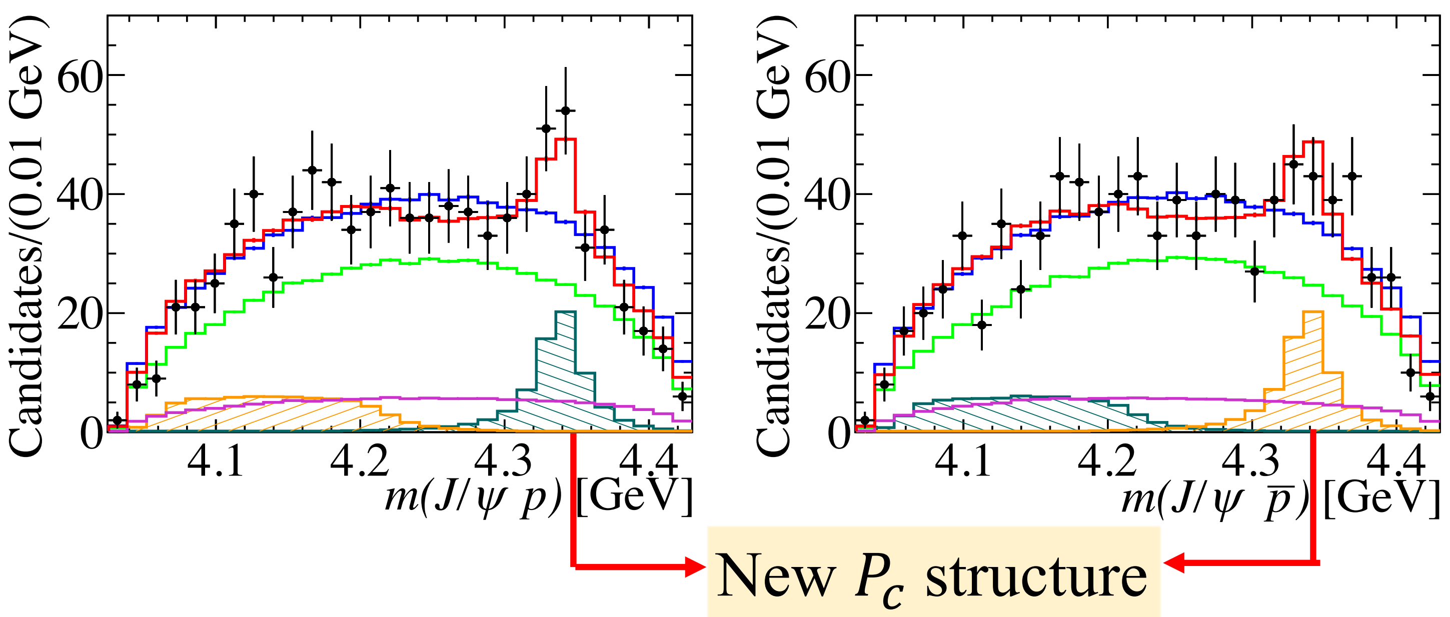
States close to $\Sigma_c^+ \overline{D}^0$ and $\Sigma_c^+ \overline{D}^{*0}$ mass thresholds consistent with molecular interpretation

P_c state in $B_s^0 \to J/\psi p\bar{p}$

PRL 128 (2022) 062001



Amplitude analysis



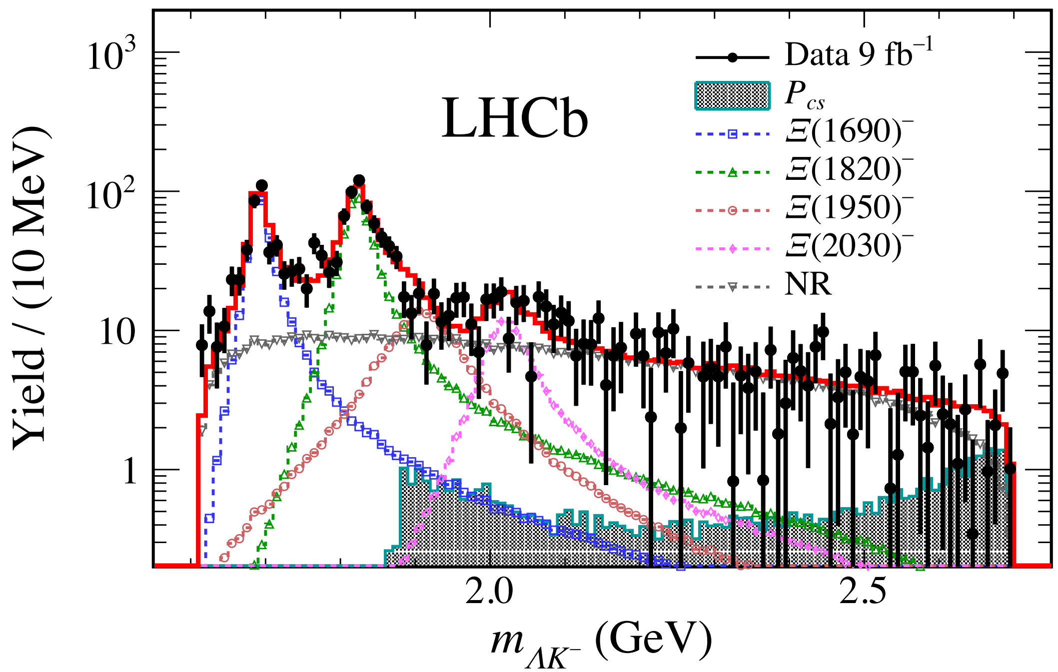
- New pentaquark candidate: $P_c(4337)^+ \to J/\psi p > 3\sigma$ for $J^P = 1/2^\pm, 3/2^\pm$

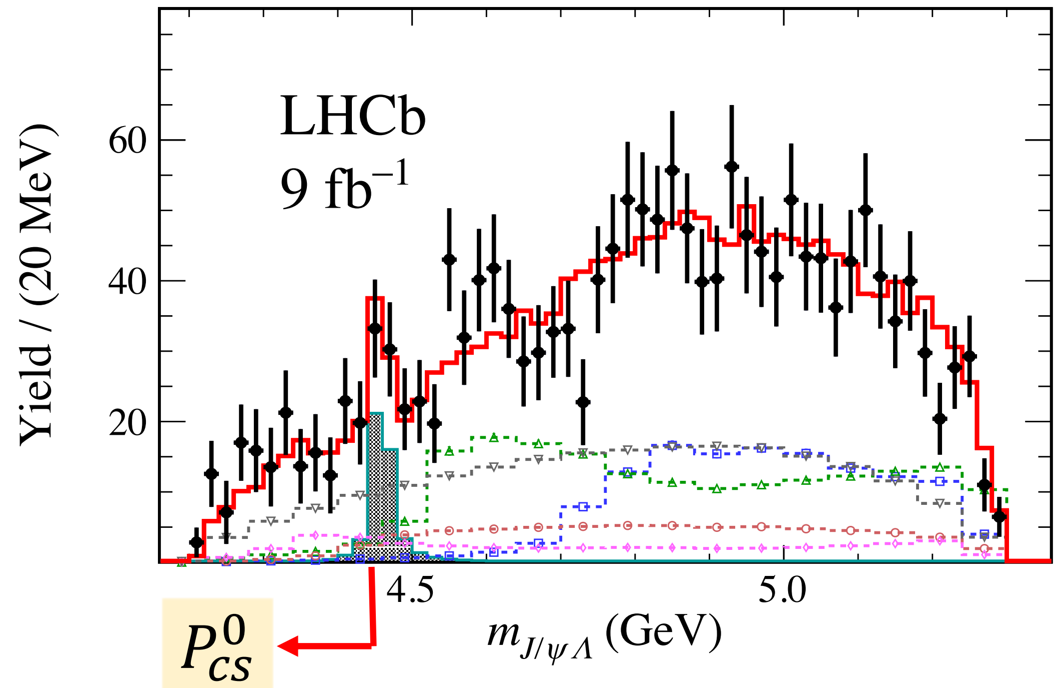
  $M = 4337^{+7}_{-4}(\text{stat})^{+2}_{-2}(\text{syst})$ MeV, $\Gamma = 29^{+26}_{-12}(\text{stat})^{+14}_{-14}(\text{syst})$ MeV

- No evidence of P_c^+ states observed in $\Lambda_b^0 \to J/\psi p K^-$

Evidence of P_{cs}^0 in $\Xi_b^- \to J/\psi\Lambda K^-$ Science Bulletin 66 (2021)1278

- P_{cs}^0 $(c\bar{c}sud)$ observed through amplitude analysis of $\Xi_b^- \to J/\psi\Lambda K^-$ at 3.1σ





$m(P_{cs}^0) = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, $\Gamma(P_{cs}^0) = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV

close to $\Xi_c \overline{D}^*$ threshold, consistent with molecular state

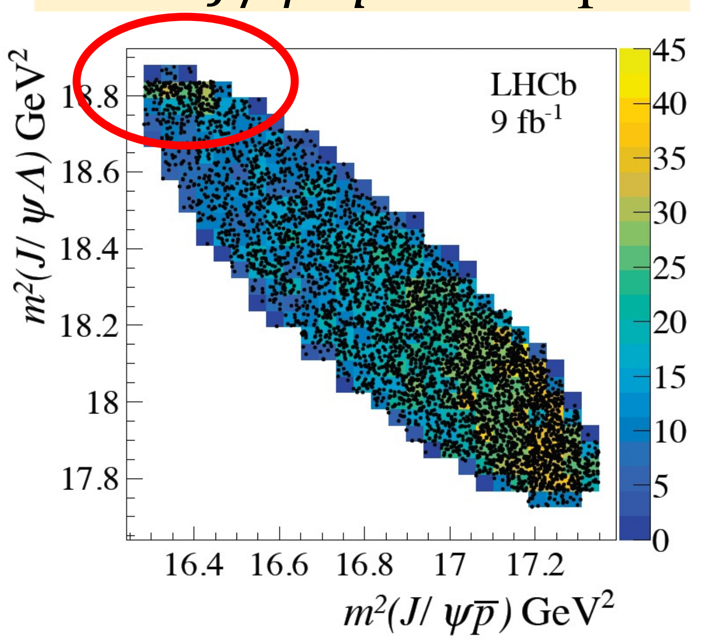
More data to resolve double-peak structure and measure J^P

PRD101(2020)034018

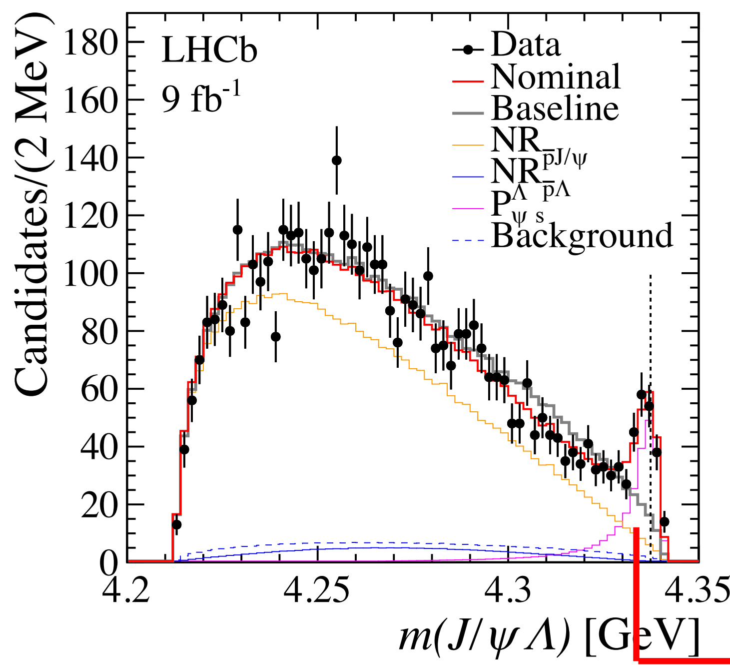
P_{cs} state in $B^- \to J/\psi\Lambda\bar{p}$

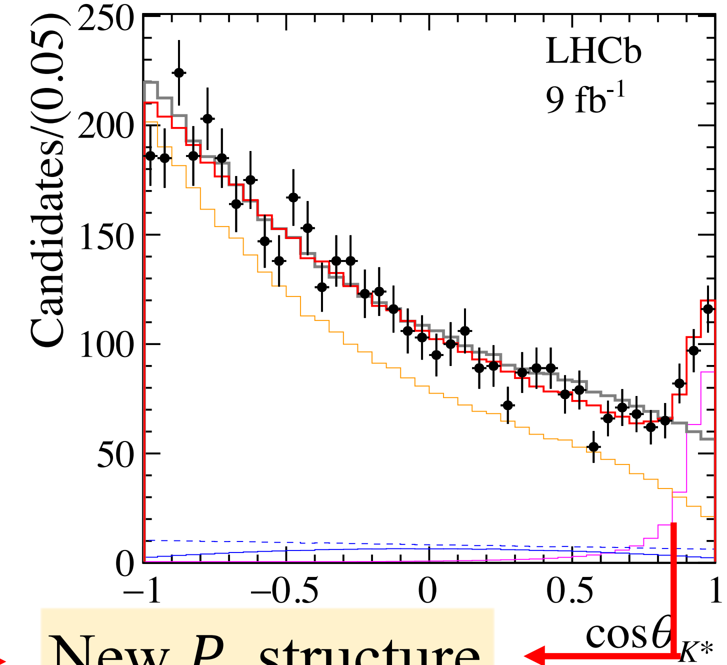
LHCb-PAPER-2022-031

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



Amplitude analysis: NR + P_{cs}





New P_c structure

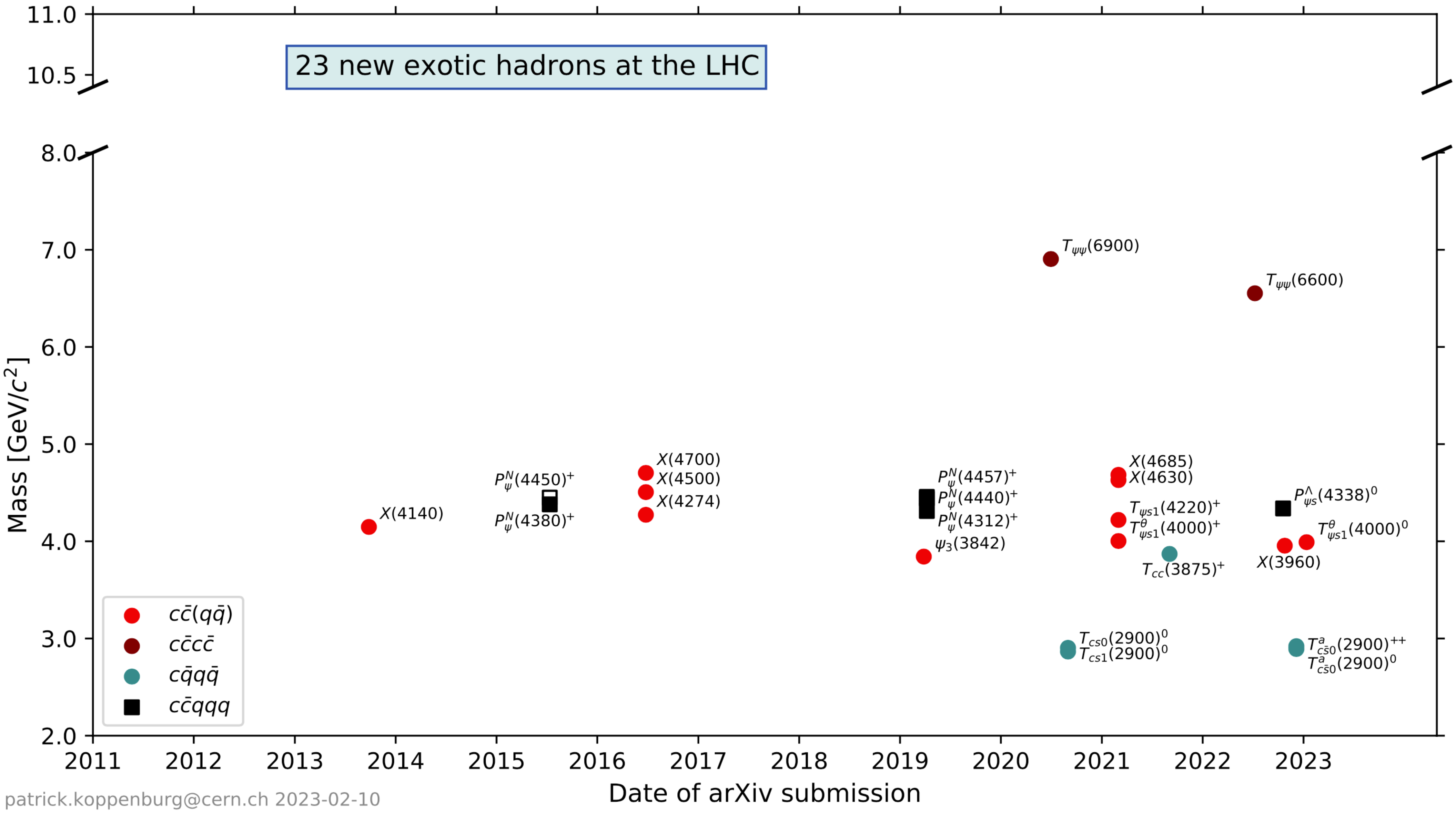
- New pentaquark candidate: $P_{cs}(4338)^+ > 10\sigma, J^P = 1/2^-$

  $M = 4338.2 \pm 0.7 \pm 0.4$ MeV, $\Gamma = 7.0 \pm 1.2 \pm 1.3$ MeV

- First establishment of pentaquark with strangeness $[c\bar{c}uds]$

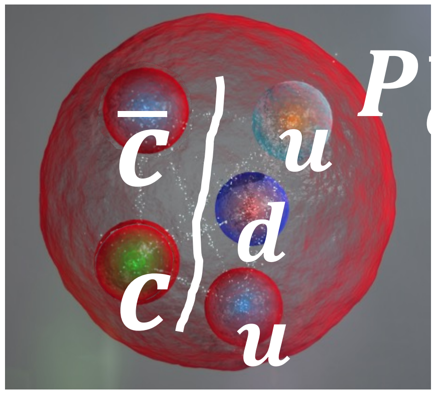
- Close to $\Xi_c^+ D^-$ threshold and in S-wave

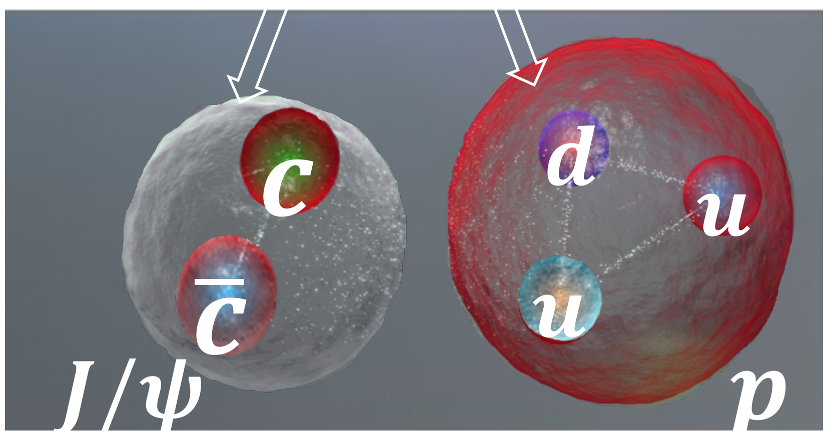
Possible exotic states by LHC



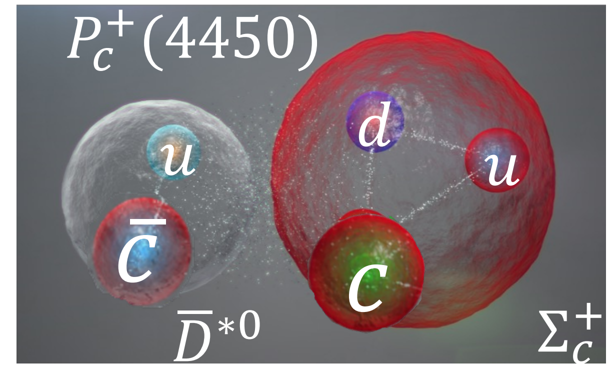
The question: molecule or compact tetraquark

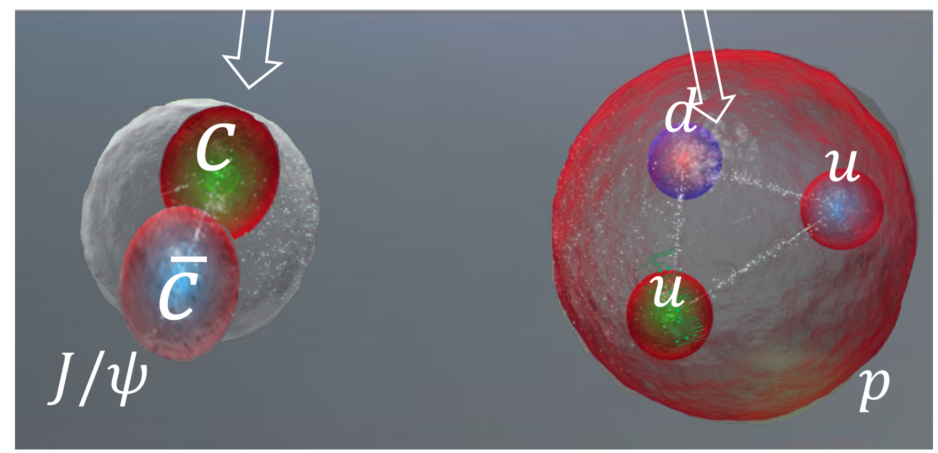
Compact





Molecule

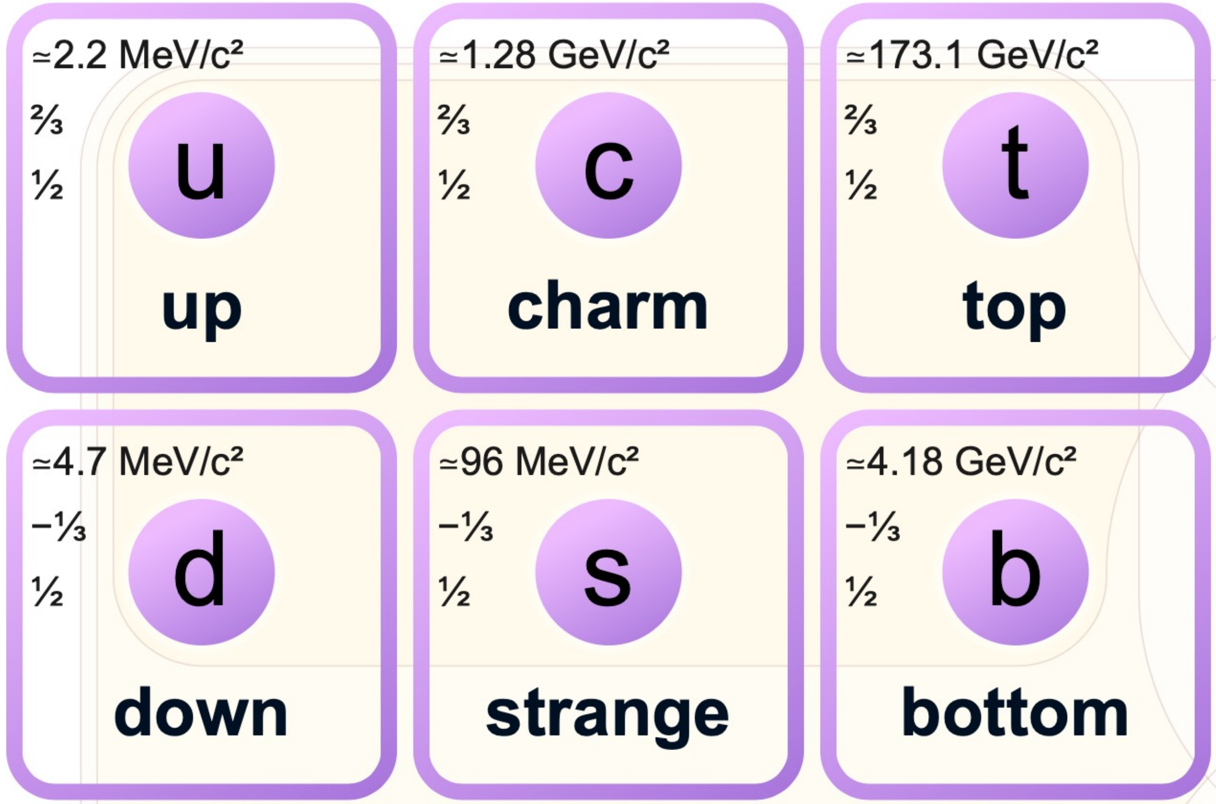




Most exotic states compatible with molecule picture

What those compact states? Unstable?

“Build” your favourable exotic and find them in a zoo/an experiment

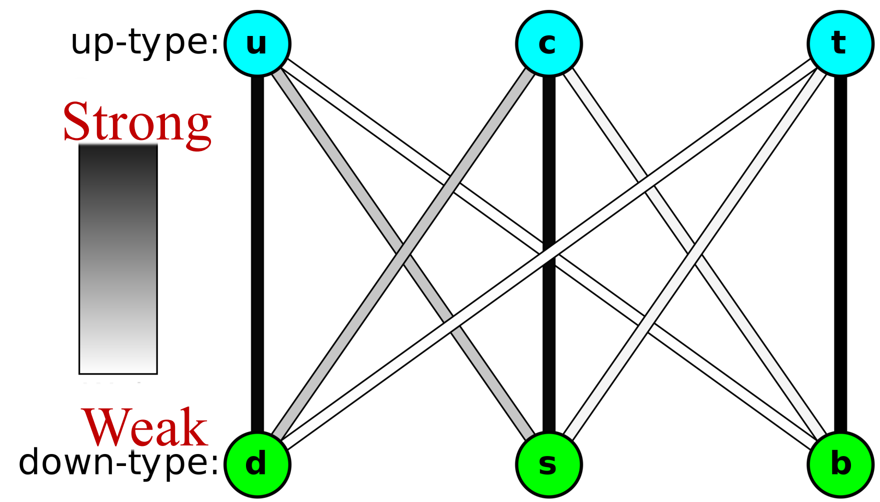


anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), $(qqqq\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest

Why six quarks

Cabibbo-Kobayashi-Maskawa (CKM) matrix (1973)

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

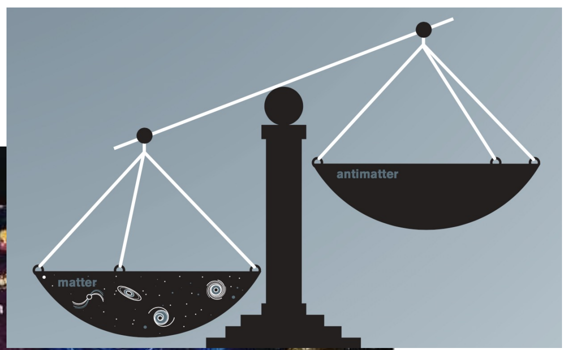



Makoto Kobayashi


Toshihide Maskawa

Origins of matter and anti-matter asymmetry

Matter Anti-matter



Explains violations of CP symmetry

C: charge conjugation

P: parity

ありがとうございました

감사합니다

Thank you

謝謝

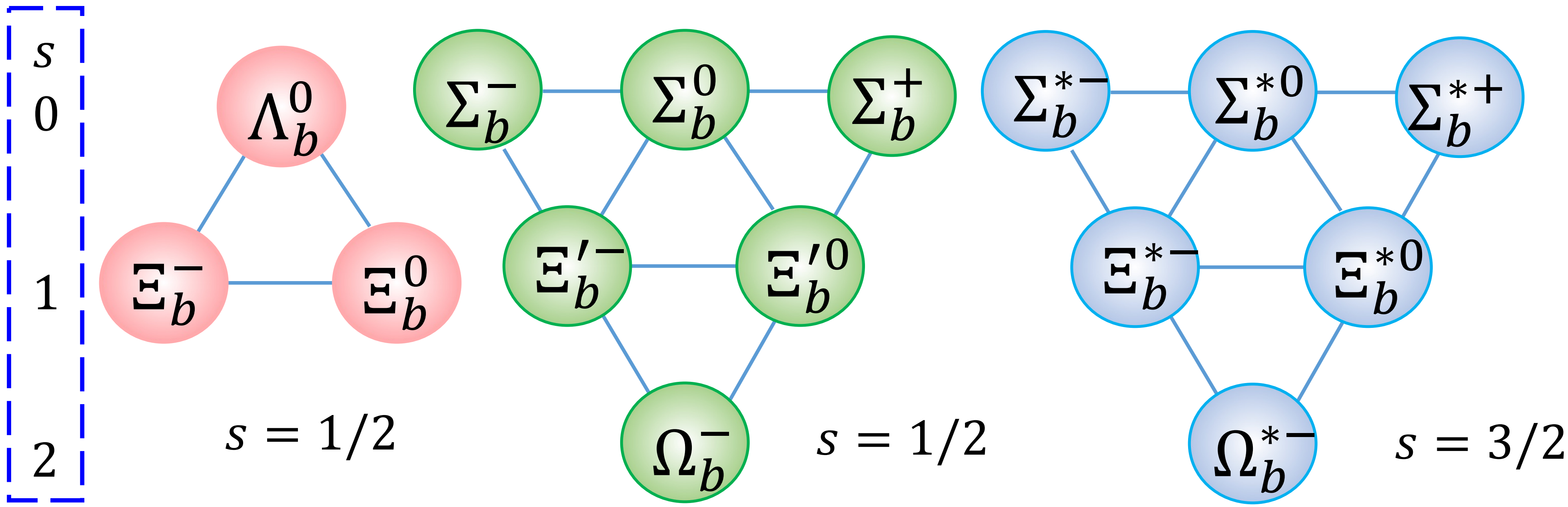
Backup slides

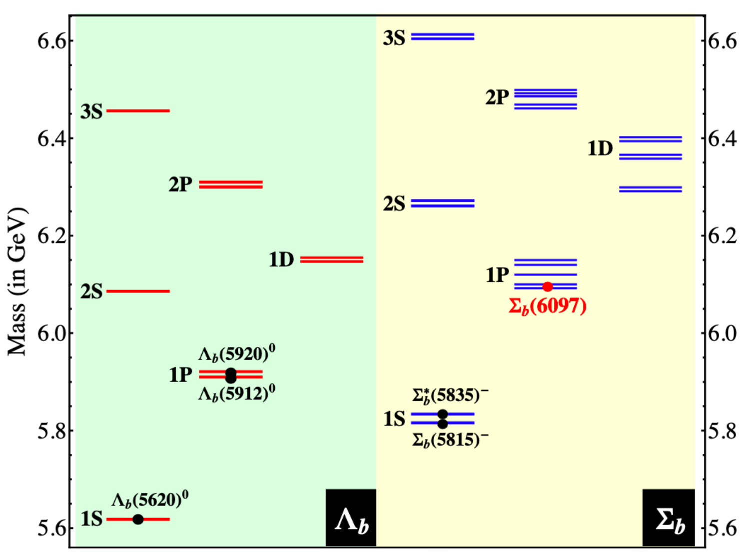
Beauty baryons

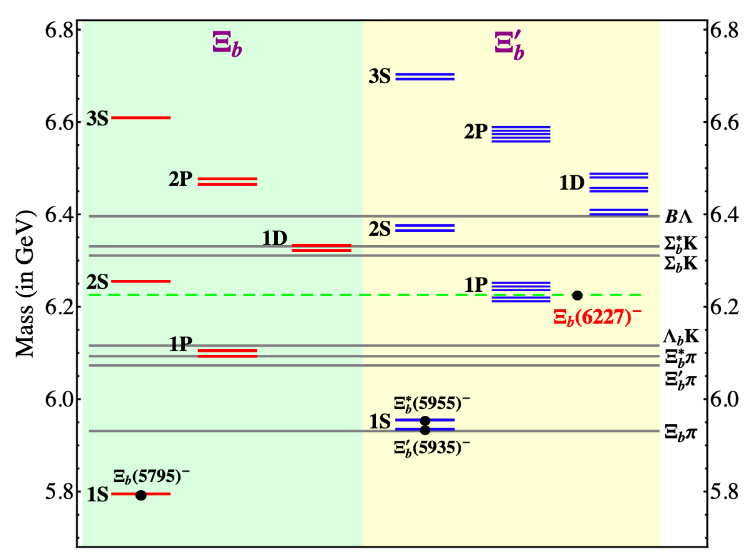
- Ground states

SU(3)$_F$ asymmetric

SU(3)$_F$ symmetric



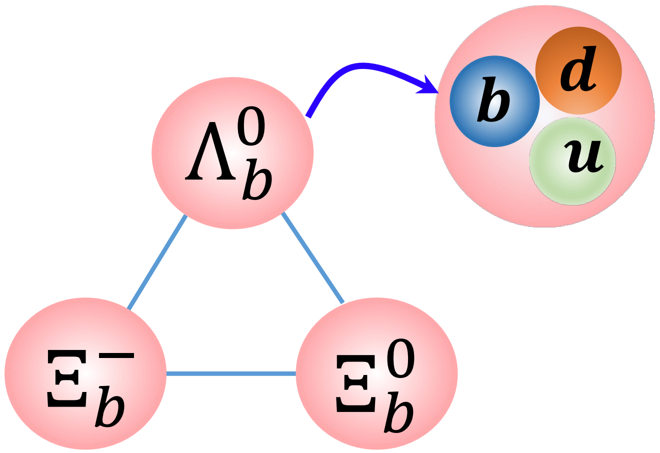




PRD 98 (2018) 031502
PRD 98 (2018) 074032
PRD 100 (2019) 094032

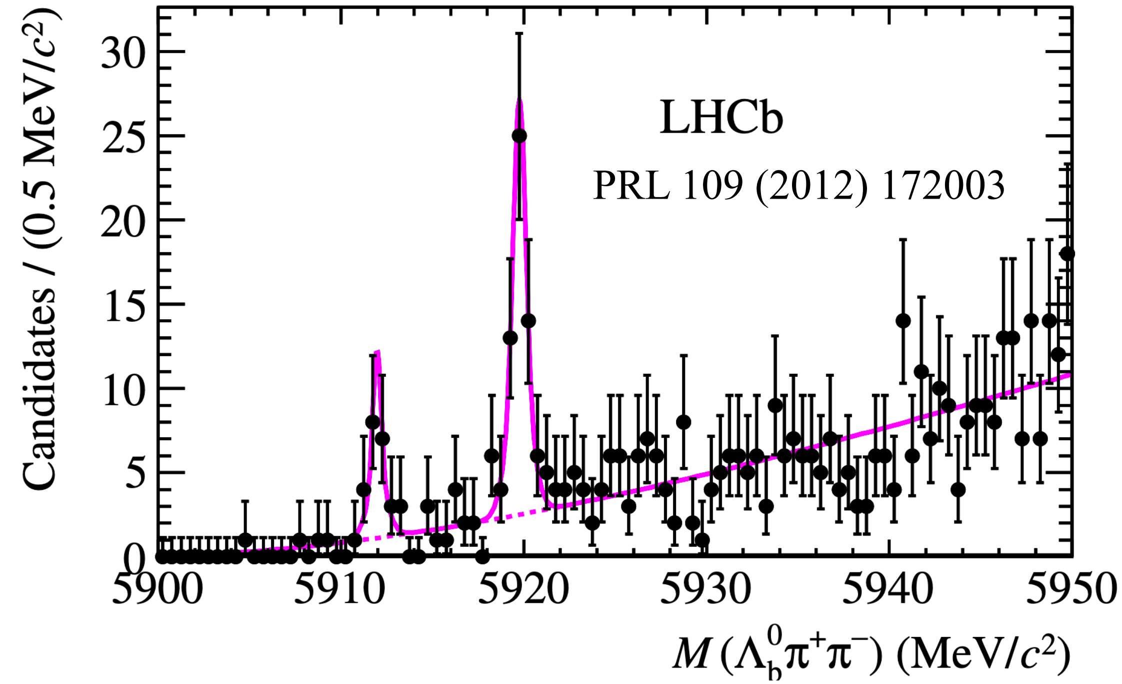
Spectrum poorly established

Excited Λ_b^0 baryons

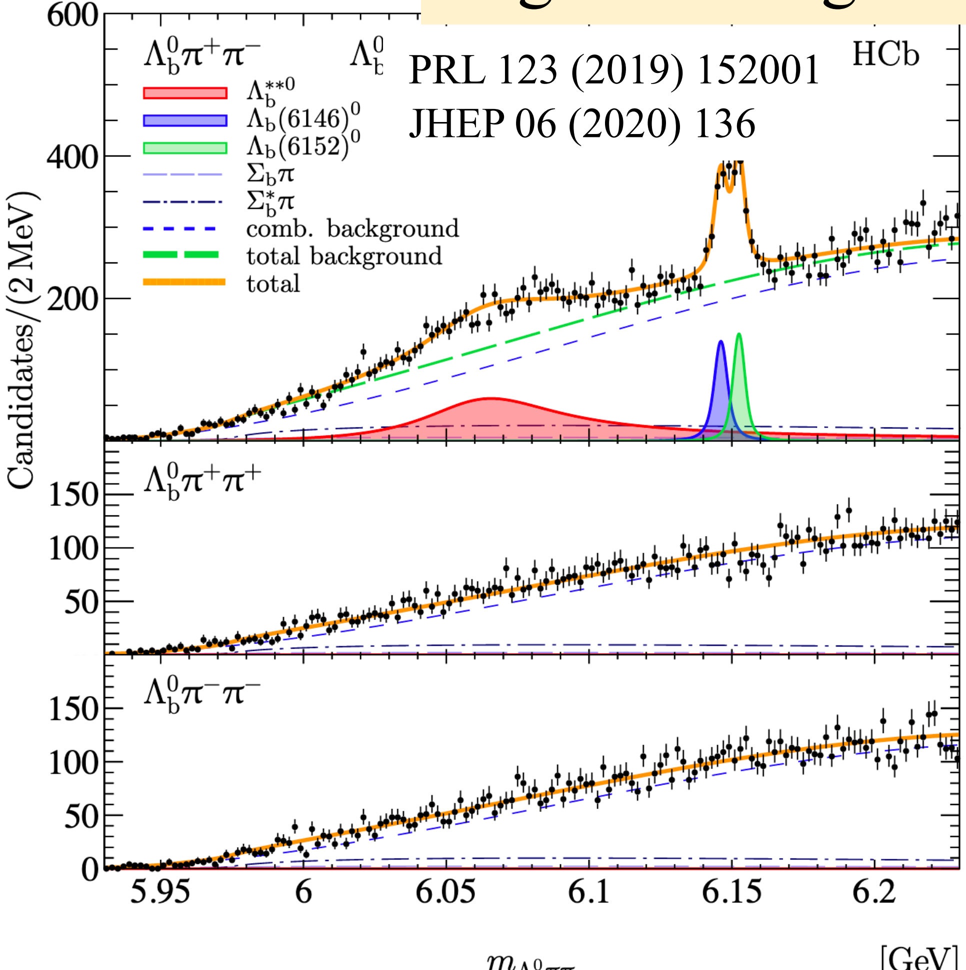


$\Lambda_b^{**0} \to \Lambda_b^0 \pi^+ \pi^-$

Low mass region

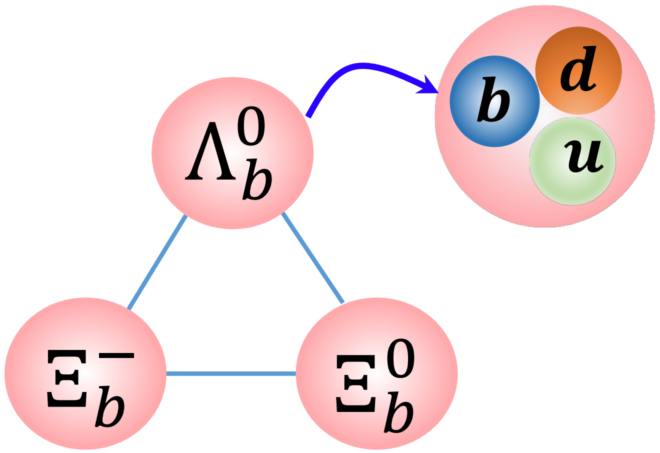


High mass region



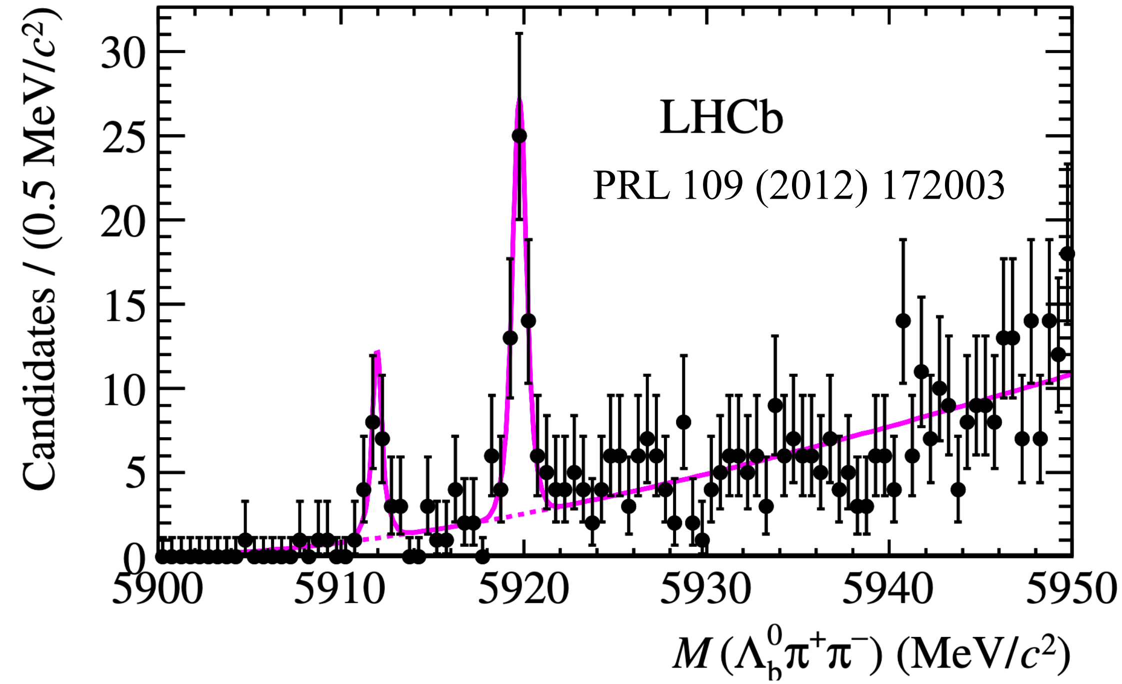
State	Mass (MeV)	Width (MeV)
$\Lambda_b^0(5620)$	5620.60 ± 0.17	−
$\Lambda_b^0(5912)$	5912.20 ± 0.21	< 0.66
$\Lambda_b^0(5920)$	5919.92 ± 0.19	< 0.83
$\Lambda_b^0(6072)$	6072.3 ± 3.0	72 ± 11
$\Lambda_b^0(6146)$	6146.2 ± 0.4	2.9 ± 1.3
$\Lambda_b^0(6152)$	6152.5 ± 0.4	2.1 ± 0.9

Excited Λ_b^0 baryons

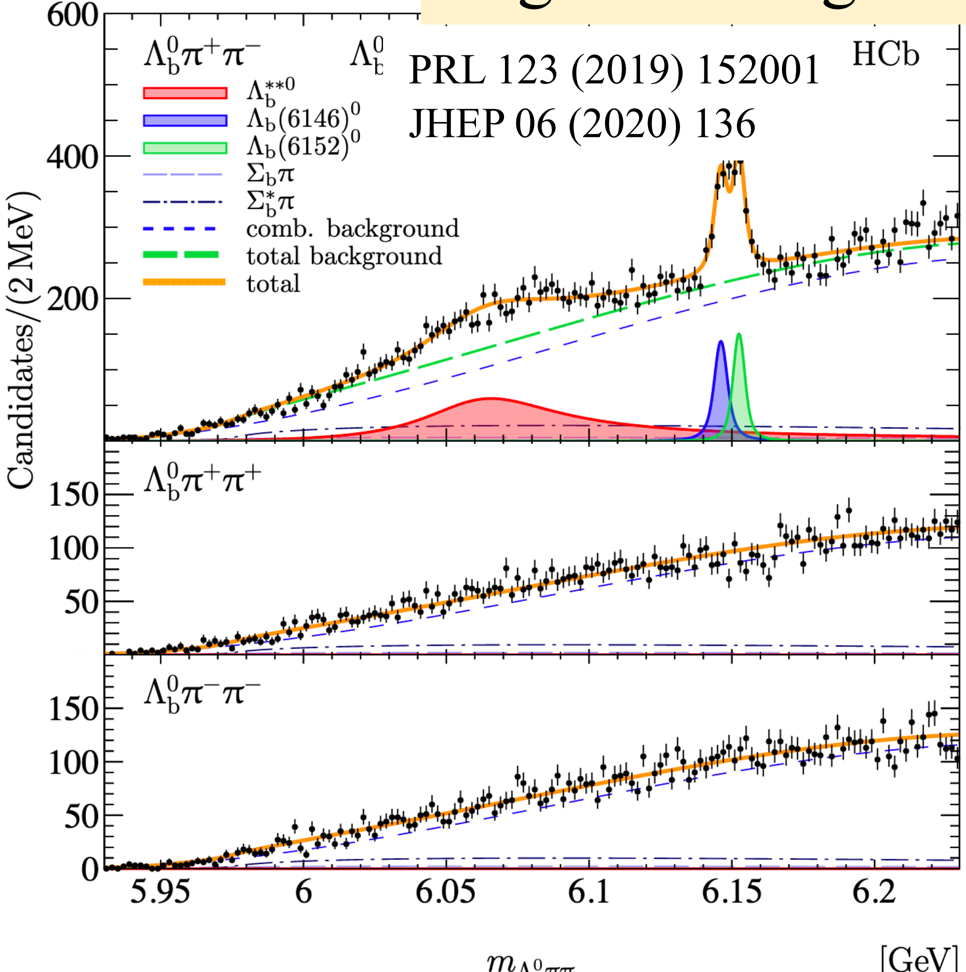


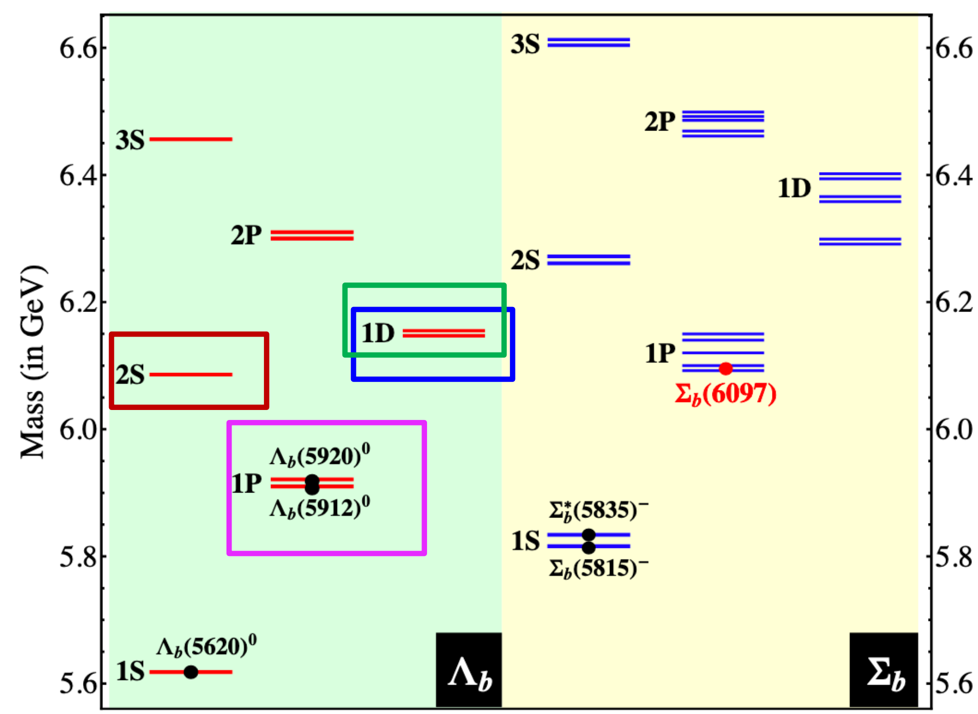
$\Lambda_b^{**0} \to \Lambda_b^0 \pi^+ \pi^-$

Low mass region



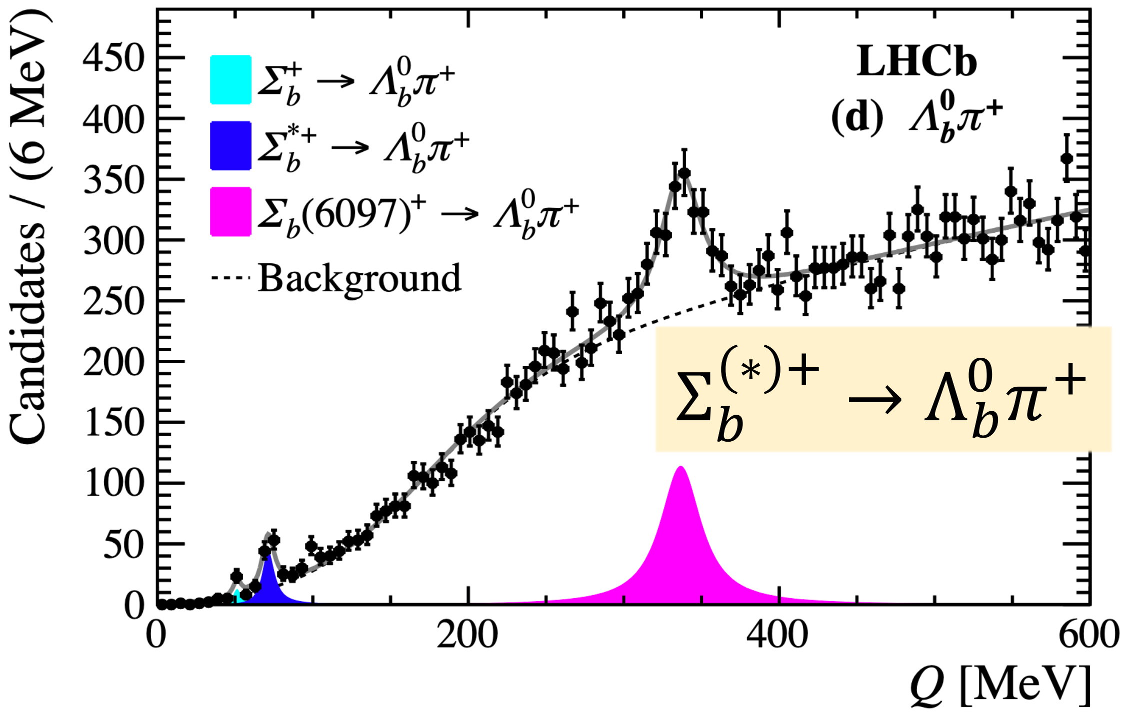
High mass region

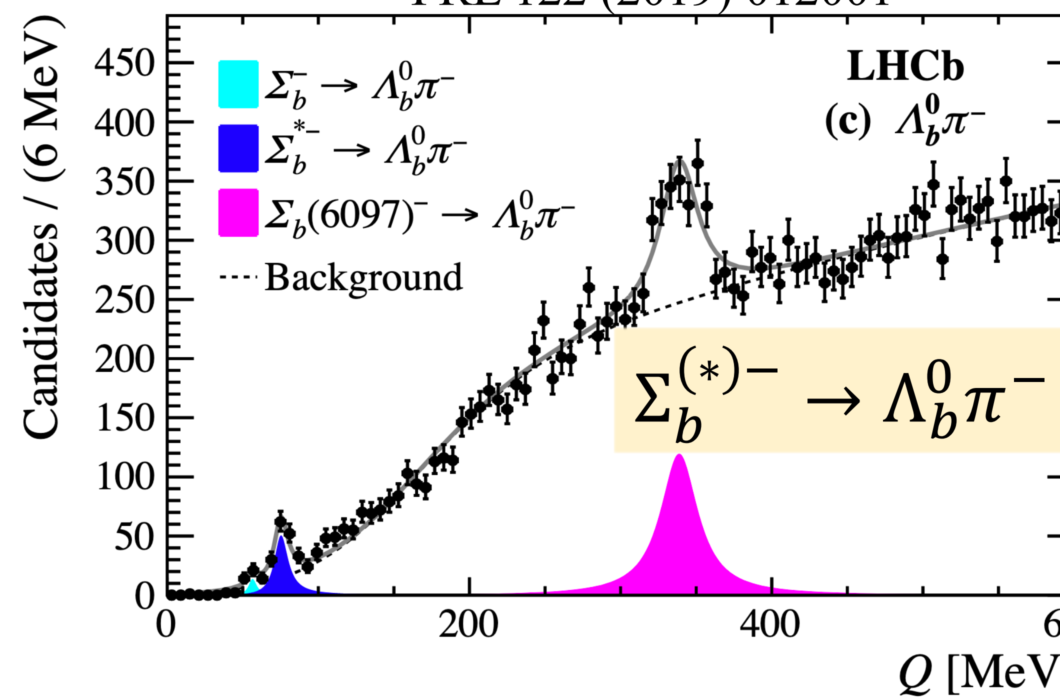


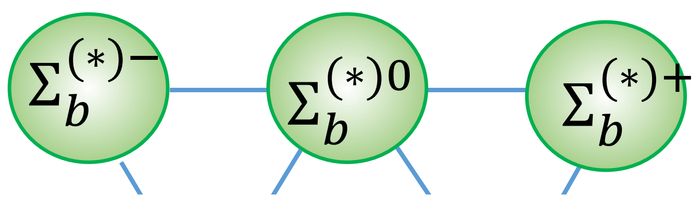


Excited $\Sigma_b^{\pm}$ baryons

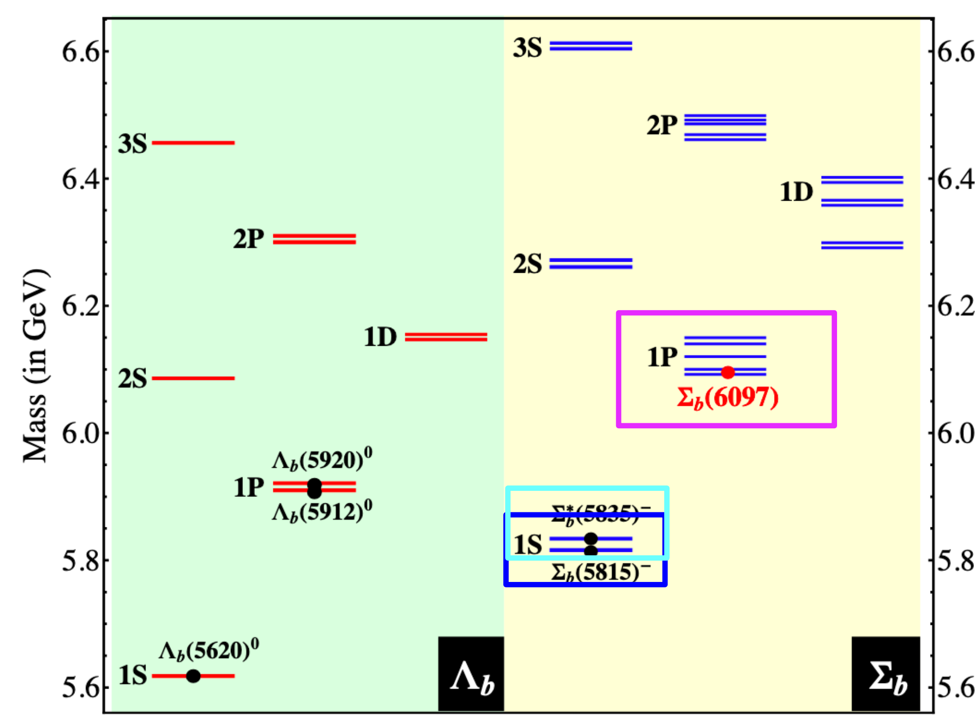
PRL 122 (2019) 012001





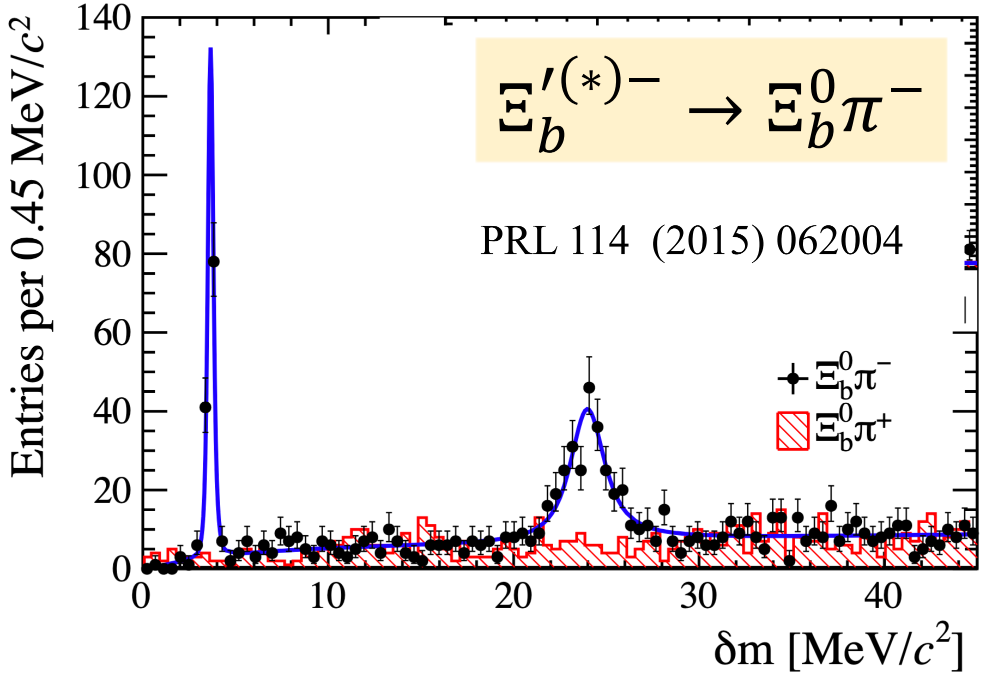


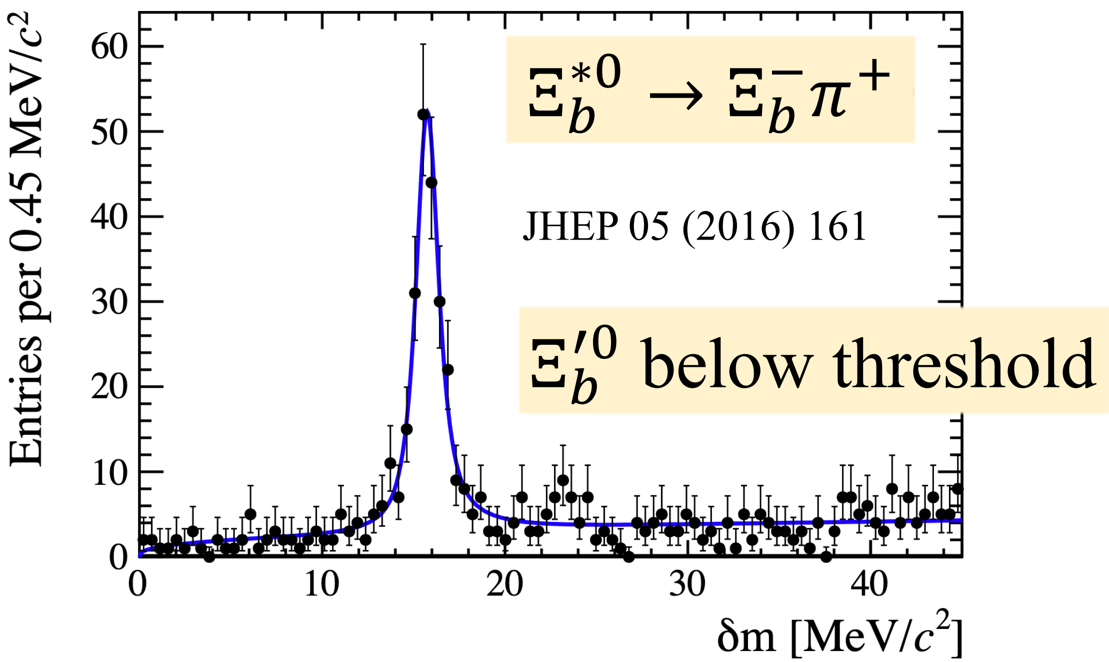
State	Mass (MeV)	Width (MeV)
$\Sigma_b^{+/-}$	5810/5815	5
$\Sigma_b^{*+/-}$	5830/5835	19
$\Sigma_b^{**+/-}$	6098/6096	30

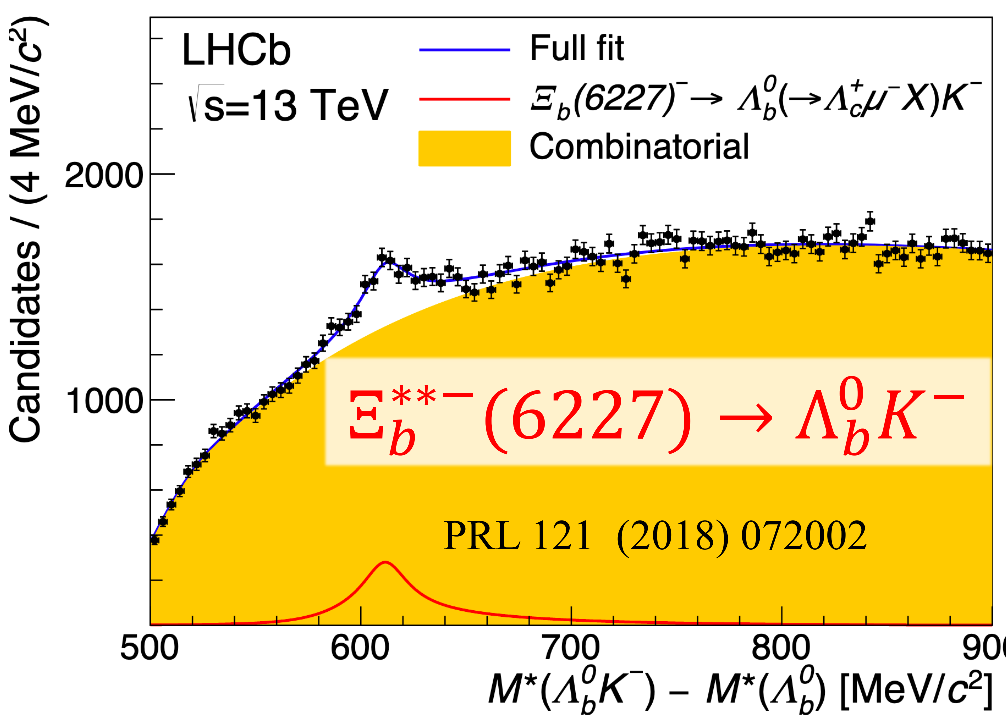


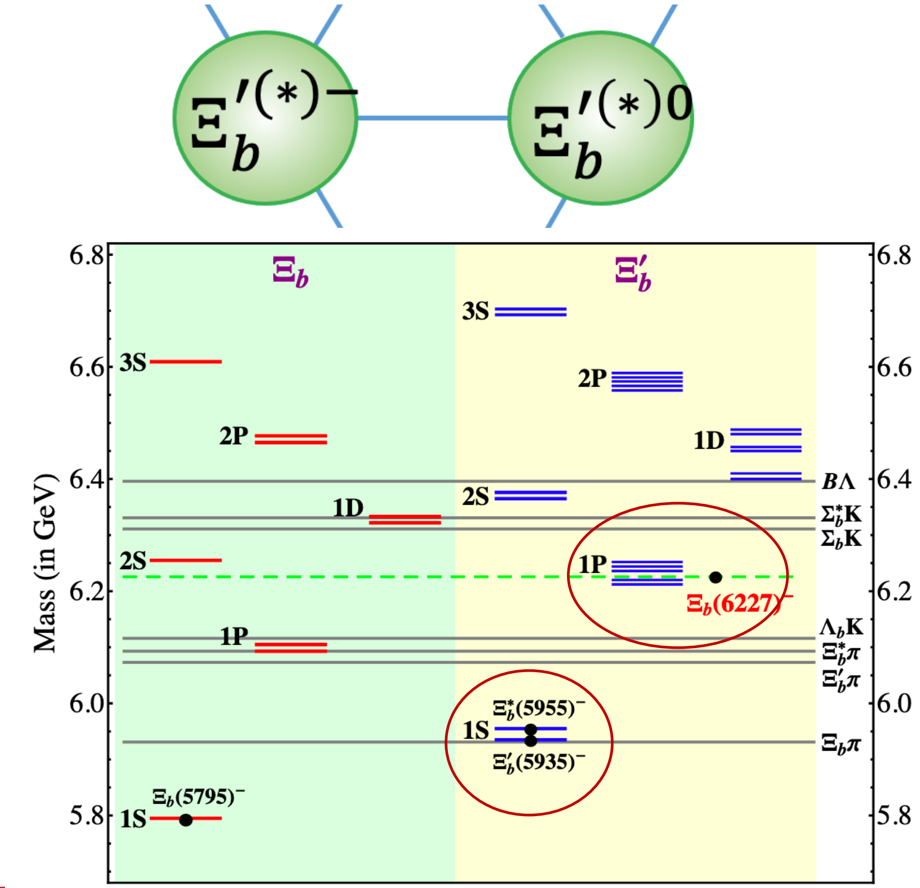
Missing other low-lying P-wave states

Excited Ξ_b baryons





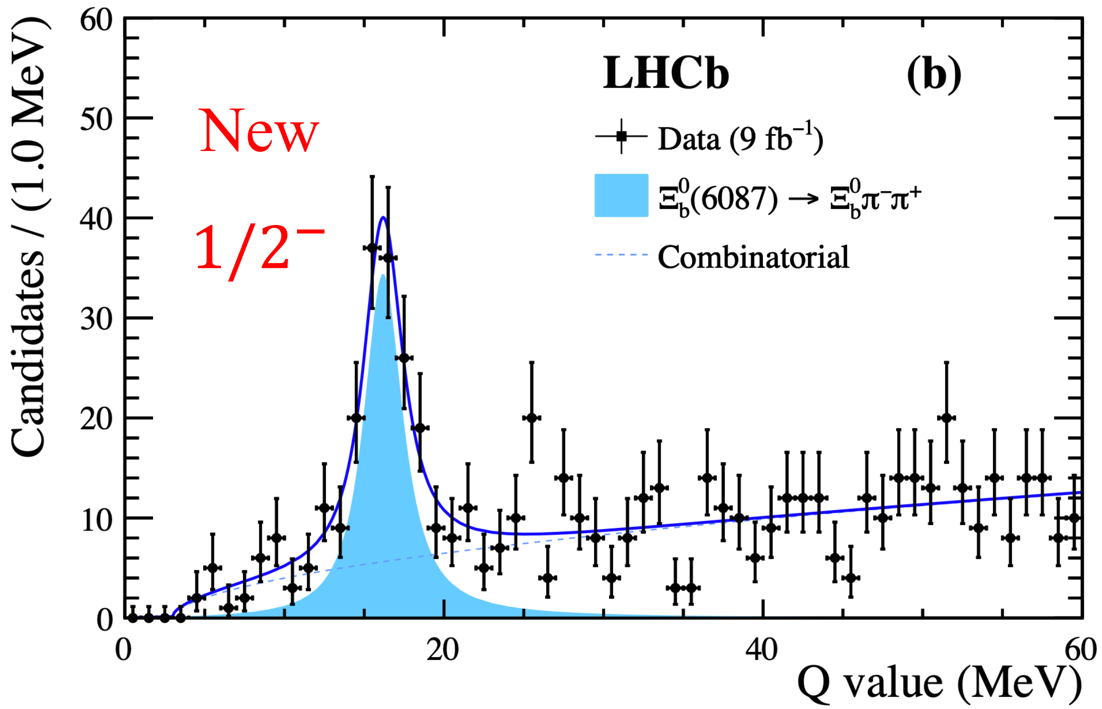




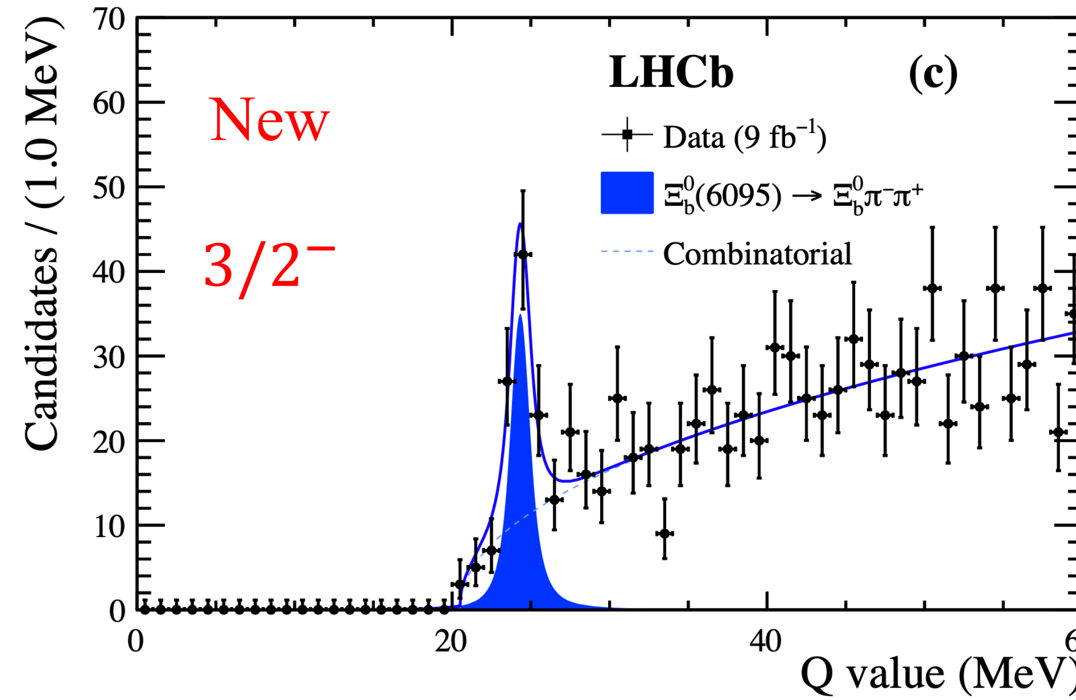
Excited Ξ_b baryons

LHCb-PAPER-2023-008

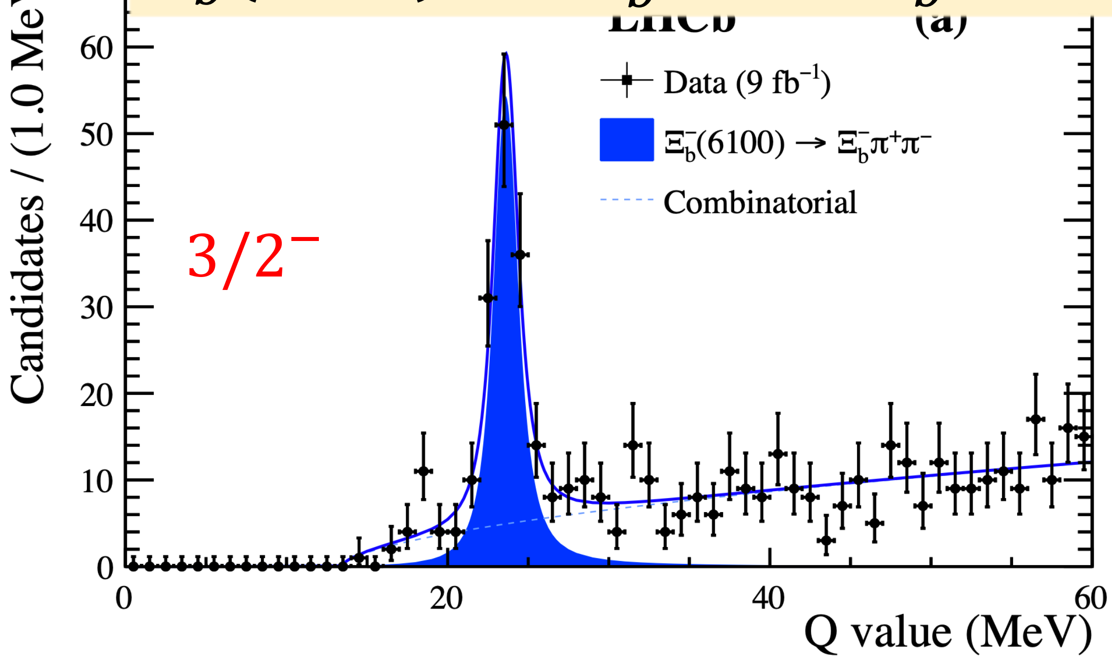
$\Xi_b(6087)^0 \to \Xi_b'^-\pi^+ \to \Xi_b^0\pi^+\pi^-$

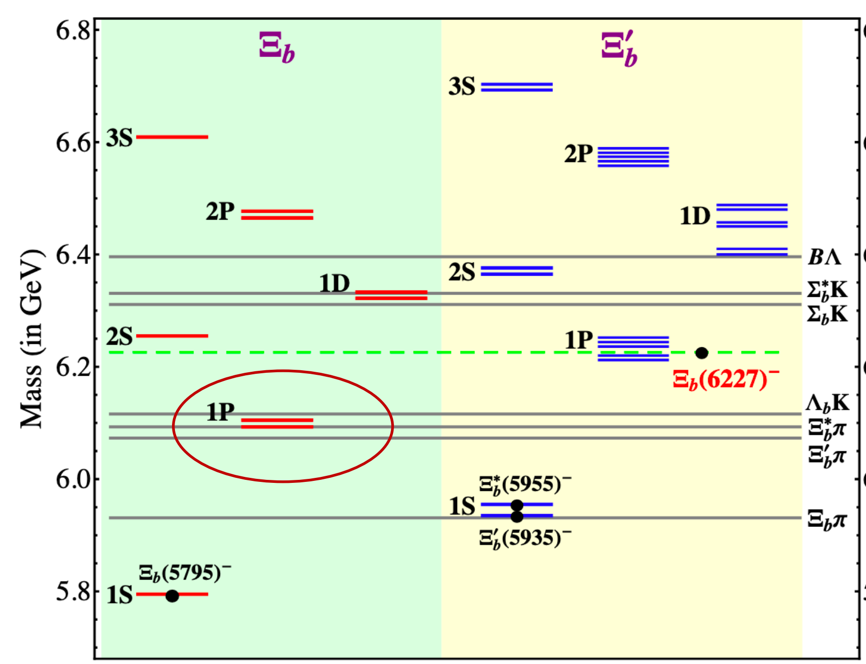


$\Xi_b(6095)^0 \to \Xi_b^{*-}\pi^+ \to \Xi_b^0\pi^+\pi^-$



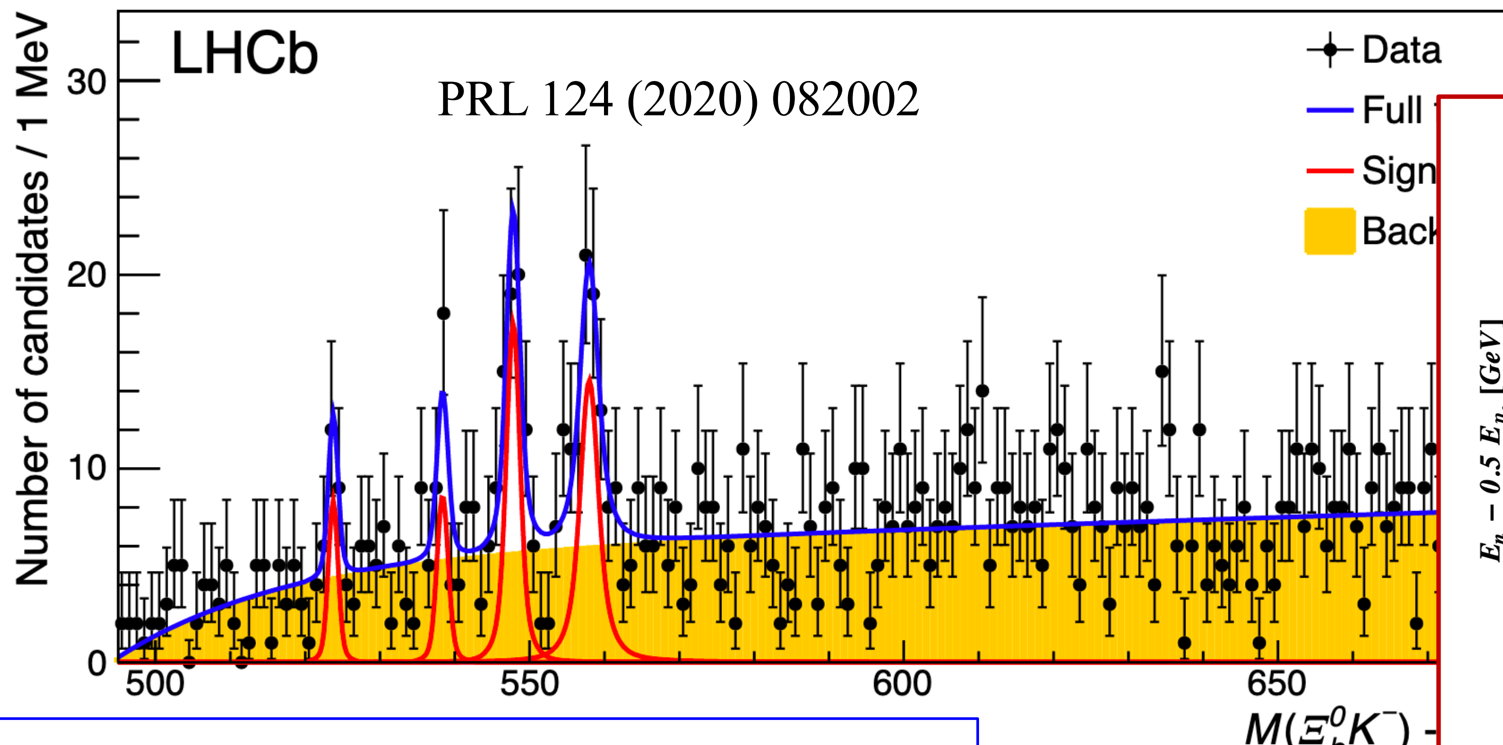
$\Xi_b(6100)^- \to \Xi_b^{*0}\pi^- \to \Xi_b^-\pi^+\pi^-$

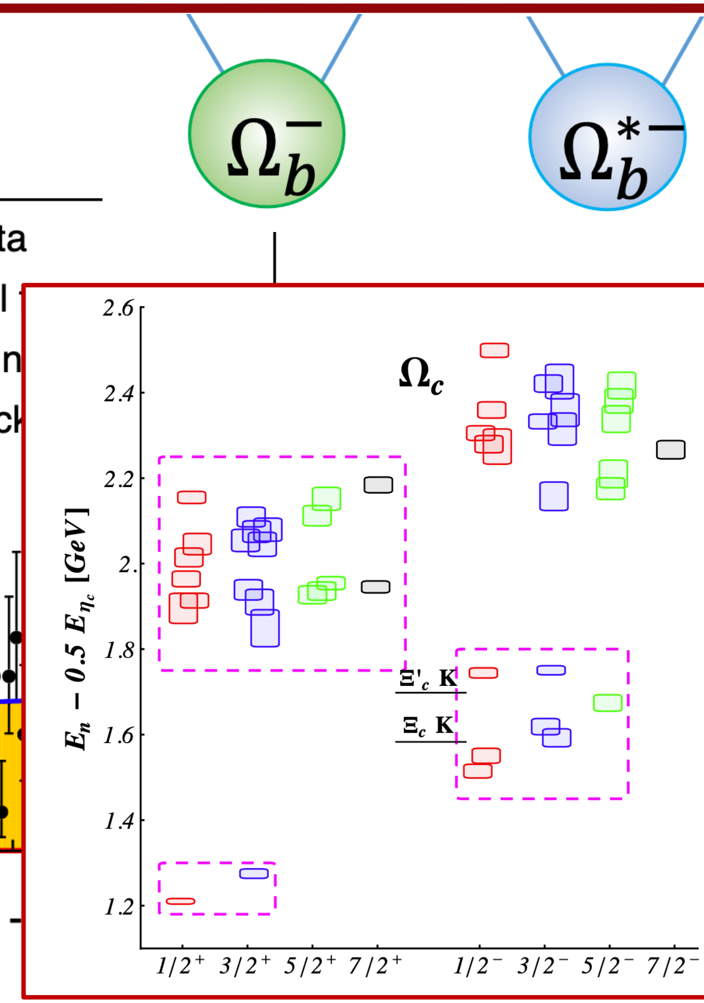




Excited Ω_b^- baryons

- $\Omega_b^{**-} \to \Xi_b^0 K^-$ mass spectrum





Four states separated by about 10 MeV

$m(\Omega_b(6316)^-) = 6315.64 \pm 0.31 \pm 0.07 \pm 0.50\,\text{MeV}$ (2.1σ) $\Gamma < 2.8$ MeV

$m(\Omega_b(6330)^-) = 6330.30 \pm 0.28 \pm 0.07 \pm 0.50\,\text{MeV}$ (2.6σ) $\Gamma < 3.1$ MeV

$m(\Omega_b(6340)^-) = 6339.71 \pm 0.26 \pm 0.05 \pm 0.50\,\text{MeV}$ $(>5\sigma)$ $\Gamma < 1.5$ MeV

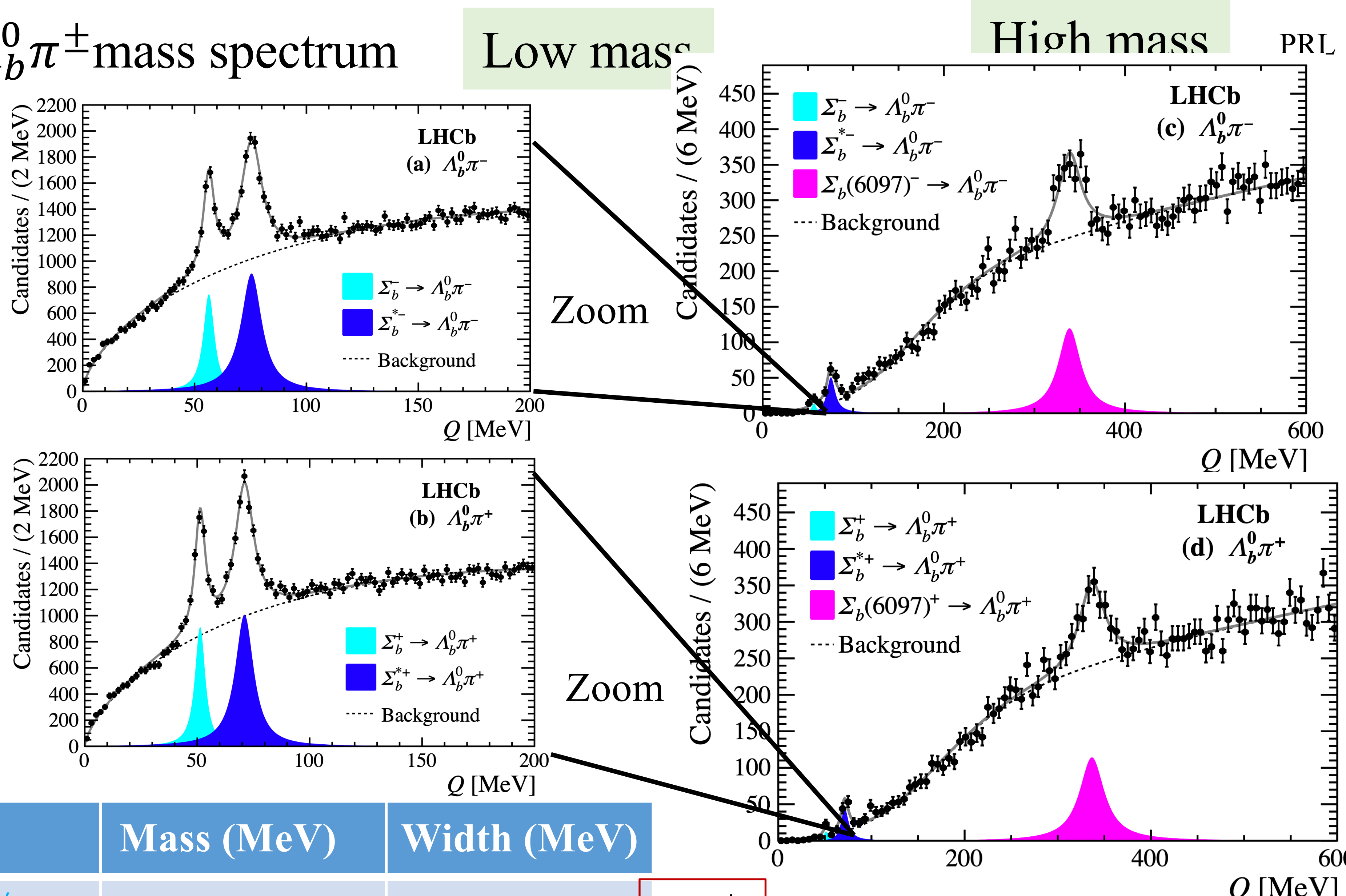
$m(\Omega_b(6350)^-) = 6349.88 \pm 0.35 \pm 0.05 \pm 0.50\,\text{MeV}$ $(>5\sigma)$ $\Gamma = 1.4^{+1.0}_{-0.8} \pm 0.1$ MeV

To compare $m(\Omega_b^-) = 6046.1 \pm 1.7$ MeV

Excited $\Sigma_b^{+/-}$ baryons

- $\Lambda_b^0\pi^\pm$ mass spectrum

PRL 122 (2019) 012001



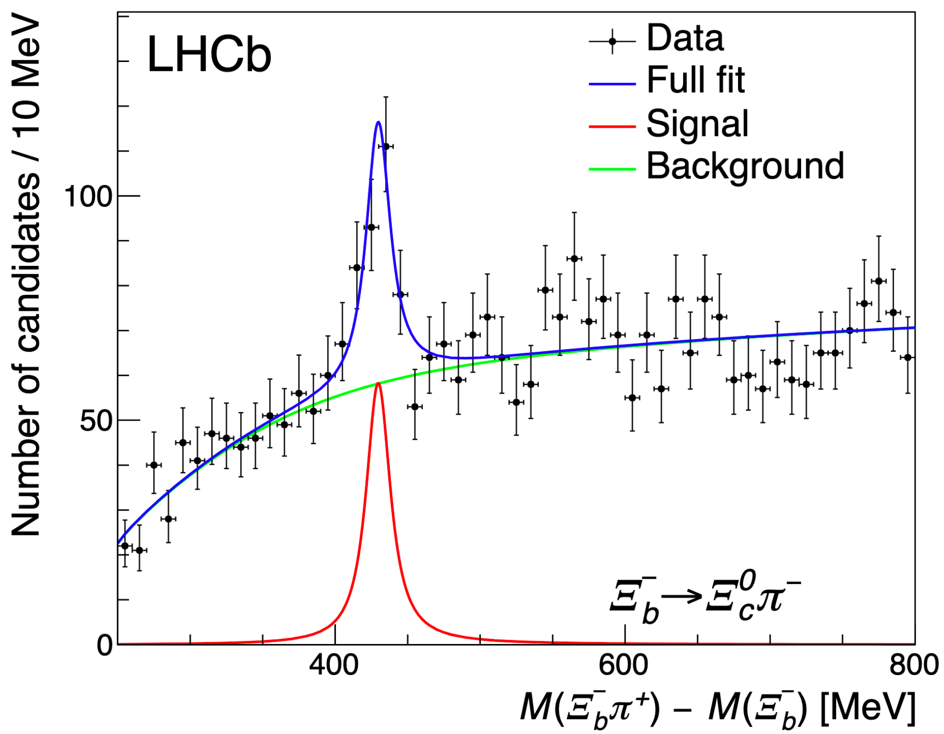
State	Mass (MeV)	Width (MeV)	
$\Sigma_b^{+/-}$	5810/5815	5	$1/2^+$
$\Sigma_b^{*+/-}$	5830/5835	19	$3/2^+$
$\Sigma_b^{**+/-}$	6098/6096	30	

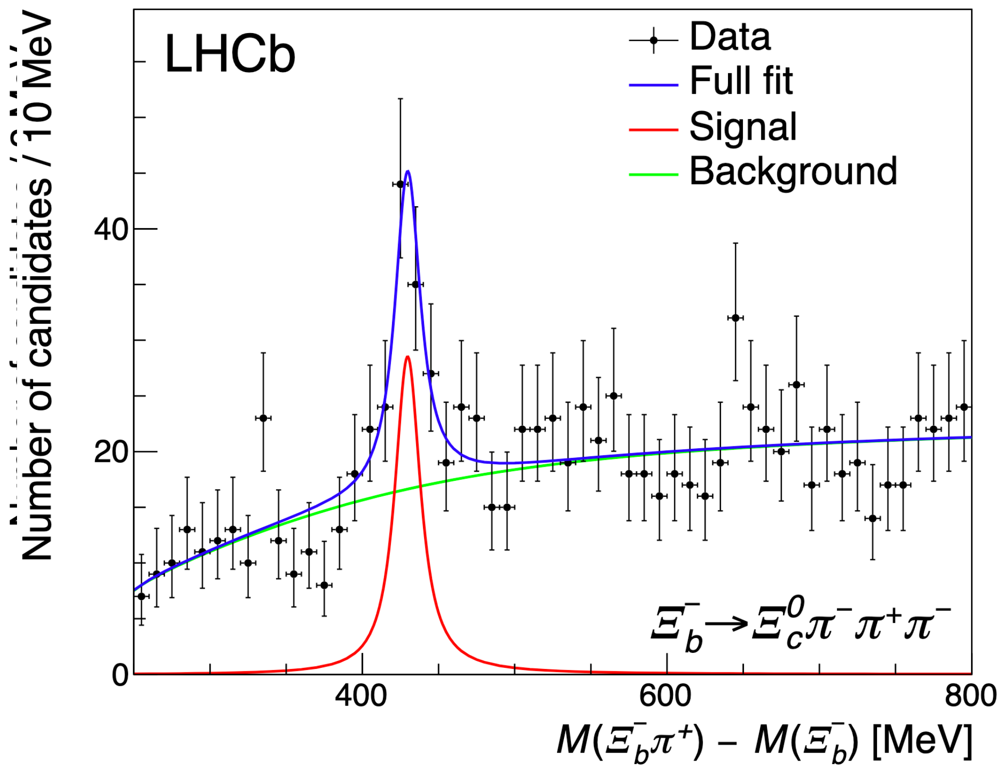
$m(\Sigma_b^{**}) - m(\Sigma_b) \approx m(\Lambda_b(5920)^0) - m(\Lambda_b^0)$

Consistent with P-wave. Five states expected. Many states overlaid?

Excited Ξ_b^0 baryons

- $\Xi_b^-\pi^+$ mass spectrum





A new state $\Xi_b(6227)^0$ observed

State	Mass (MeV)	Width (MeV)
$\Xi_b(6227)^0$	6227.1 ± 1.5	18.6 ± 4.7

$$\frac{f_{\Xi_b(6227)^0}}{f_{\Xi_b^-}}\mathcal{B}(\Xi_b(6227)^0 \to \Xi_b^-\pi^+) = 0.045 \pm 0.008 \pm 0.004$$

Mass and width consistent with $\Xi_b(6227)^-$

Excited Ω_b^- baryons: matching

- Five 1P states with one state not detected $\left(\frac{1}{2}\right)^-, \left(\frac{1}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{3}{2}\right)^-, \left(\frac{5}{2}\right)^-$

States	Ref.1	Ref.2	Ref.3	Ref.4	Ref.5	Ref.6	Ref.7
$\Omega_b(6316)^-$	$\frac{1}{2}-$	$\frac{1}{2}-$ or $\frac{3}{2}-$	$\frac{3}{2}-$	$\frac{1}{2}-$	$\frac{3}{2}-$	$\frac{1}{2}-$	$\frac{1}{2}-$ or $\frac{3}{2}-$
$\Omega_b(6330)^-$	$\frac{1}{2}-$	$\frac{1}{2}-$ or $\frac{3}{2}-$	$\frac{1}{2}-$	$\frac{3}{2}-$	$\frac{1}{2}-$	$\frac{3}{2}-$	$\frac{1}{2}-$
$\Omega_b(6340)^-$	$\frac{3}{2}-$	$\frac{3}{2}-$ or $\frac{5}{2}-$	$\frac{3}{2}-$	$\frac{1}{2}-$	$\frac{5}{2}-$	$\frac{3}{2}-$	$\frac{3}{2}-$
$\Omega_b(6350)^-$	$\frac{3}{2}-$	$\frac{1}{2}-$ or $\frac{5}{2}-$	$\frac{3}{2}-$	$\frac{3}{2}-$	$\frac{3}{2}-$	$\frac{5}{2}-$	$\frac{3}{2}-$

1. PRD 102 (2020) 014207
2. EPJC 80 (2020) 279
3. arXiv:2010.10697
4. J. Phys. Conf. Ser. 1610 (2020) 012011
5. IJMPA 35 (2020) 2050043
6. EPJC 80 (2020) 198
7. PRD 101 (2020) 114013

- Baryon-meson molecule? Thresholds far away.

Main channel	$\Xi_b'\bar{K}$	$\Xi_b^*\bar{K}$	$\Xi\bar{B}$	$\Xi\bar{B}^*$
Threshold mass	6431	6451	6598	6643

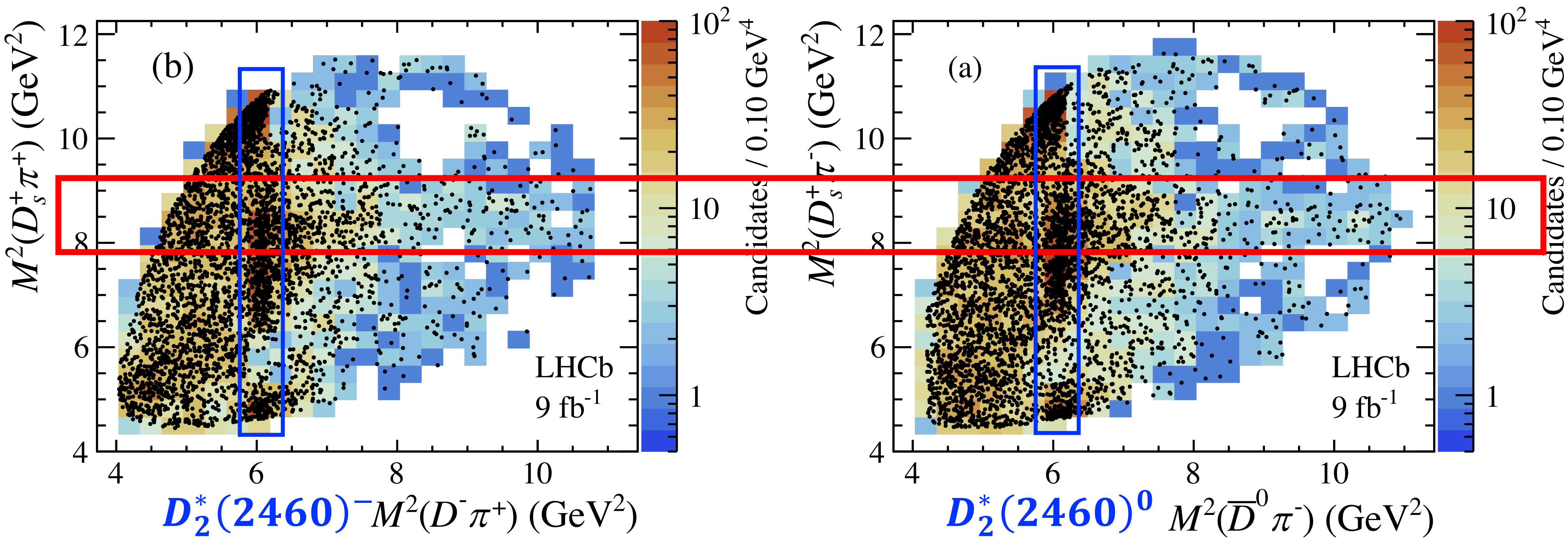
Study of $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$

LHCb-PAPER-2022-026
LHCb-PAPER-2022-027

- Full 9 fb^{-1} Run1+Run2 LHCb data

  $\Rightarrow$ 4420 $B^0 \to \bar{D}^0 D_s^+ \pi^-$ candidates with signal purity of 90.7%

  3940 $B^+ \to D^- D_s^+ \pi^+$ candidates with signal purity of 95.2%



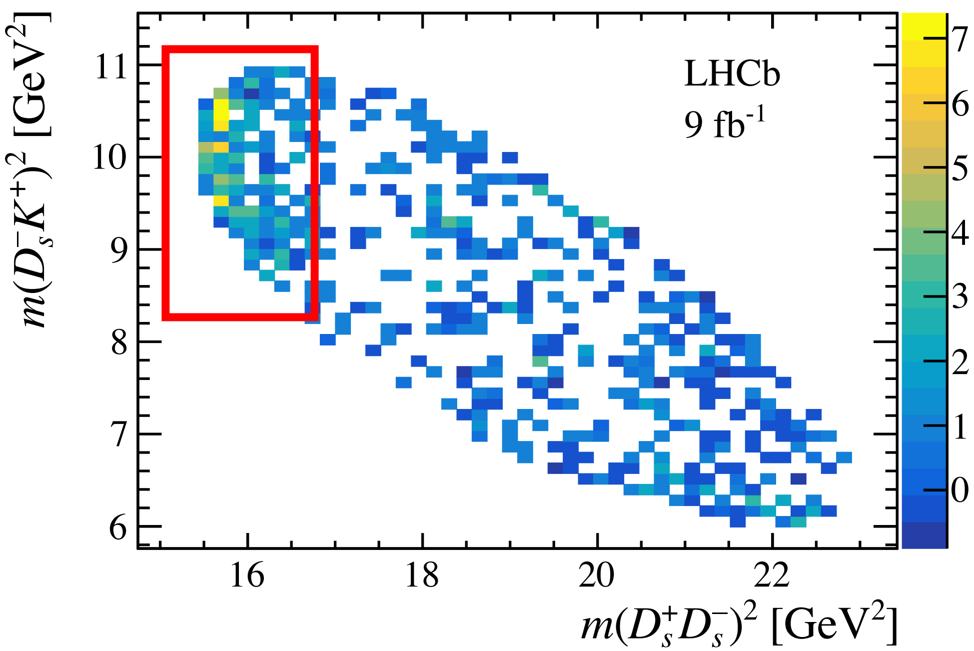
✓Faint horizontal band at $M^2(D_s^+\pi) \approx 8.5\ \text{GeV}^2$ indicating $T_{c\bar{s}}$ candidates

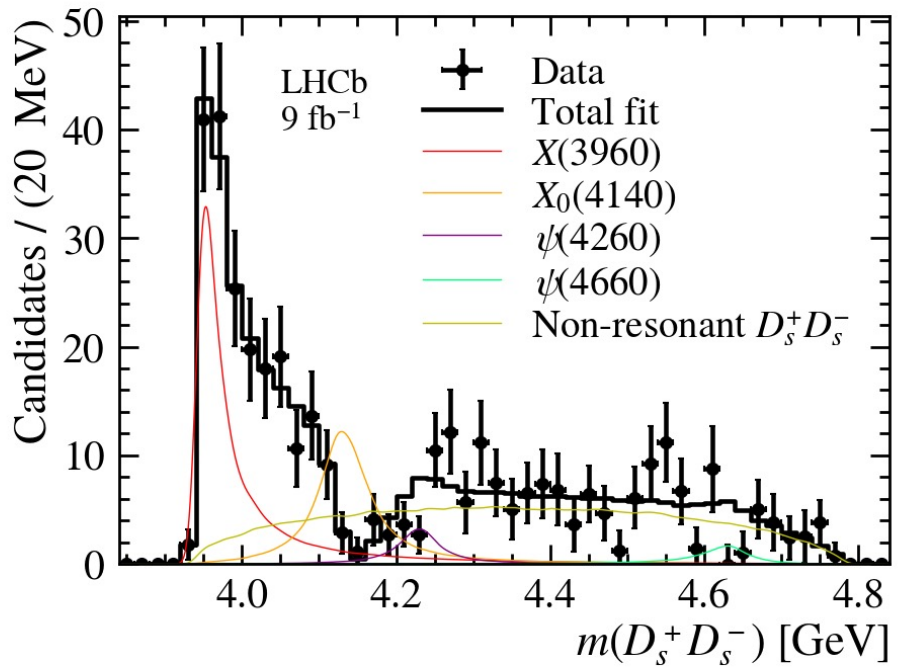
$\Rightarrow$ Joint amplitude analysis where amplitudes of the two decays are related through isospin symmetry

Observation of $X(3960) \to D_s^+ D_s^-$

LHCb-PAPER-2022-018
LHCb-PAPER-2022-019

- Threshold enhancement in $B^+ \to D_s^+ D_s^- K^+$, described by $X(3960) \to D_s^+ D_s^-$
  - $J^{PC} = 0^{++}$ preferred
- Dip at $m(D_s^+ D_s^-) \sim 4.15$ GeV with $X_0(4140)$ or $J/\psi\phi \to D_s^+ D_s^-$ scattering





- $X_0(3930)$ versus $X_0(3960)$

The same state: $\frac{\Gamma(X \to D^+ D^-)}{\Gamma(X \to D_s^+ D_s^-)} = 0.29 \pm 0.16$ prefers genuine $s\bar{s}$ content inside X

Fit parameters

- All states are relatively wide: 50 – 200 MeV

Contribution	Significance $[\times\sigma]$	M_0 [MeV]	Γ_0 [MeV]	FF [%]
$X(2^-)$				
$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28\,^{+59}_{-30}$	$2.0 \pm 0.5\,^{+0.8}_{-1.0}$
$X(1^-)$				
$X(4630)$	5.5 (5.7)	$4626 \pm 16\,^{+18}_{-110}$	$174 \pm 27\,^{+134}_{-73}$	$2.6 \pm 0.5\,^{+2.9}_{-1.5}$
All $X(0^+)$				$20 \pm 5\,^{+14}_{-7}$
$X(4500)$	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)	$4694 \pm 4\,^{+16}_{-3}$	$87 \pm 8\,^{+16}_{-6}$	$8.9 \pm 1.2\,^{+4.9}_{-1.4}$
$\mathrm{NR}_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8\,^{+19}_{-11}$
All $X(1^+)$				$26 \pm 3\,^{+8}_{-10}$
$X(4140)$	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)	$4684 \pm 7\,^{+13}_{-16}$	$126 \pm 15\,^{+37}_{-41}$	$7.2 \pm 1.0\,^{+4.0}_{-2.0}$
All $Z_{cs}(1^+)$				$25 \pm 5\,^{+11}_{-12}$
$Z_{cs}(4000)$	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)	$4216 \pm 24\,^{+43}_{-30}$	$233 \pm 52\,^{+97}_{-73}$	$10 \pm 4\,^{+10}_{-7}$

New $J/\psi\phi$

New $J/\psi\phi$

Large width

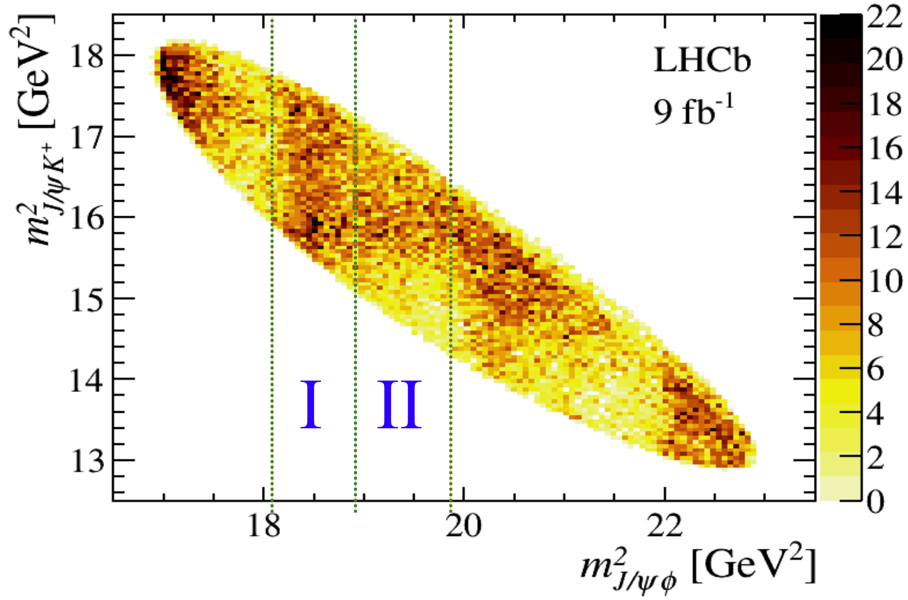
New $J/\psi\phi$

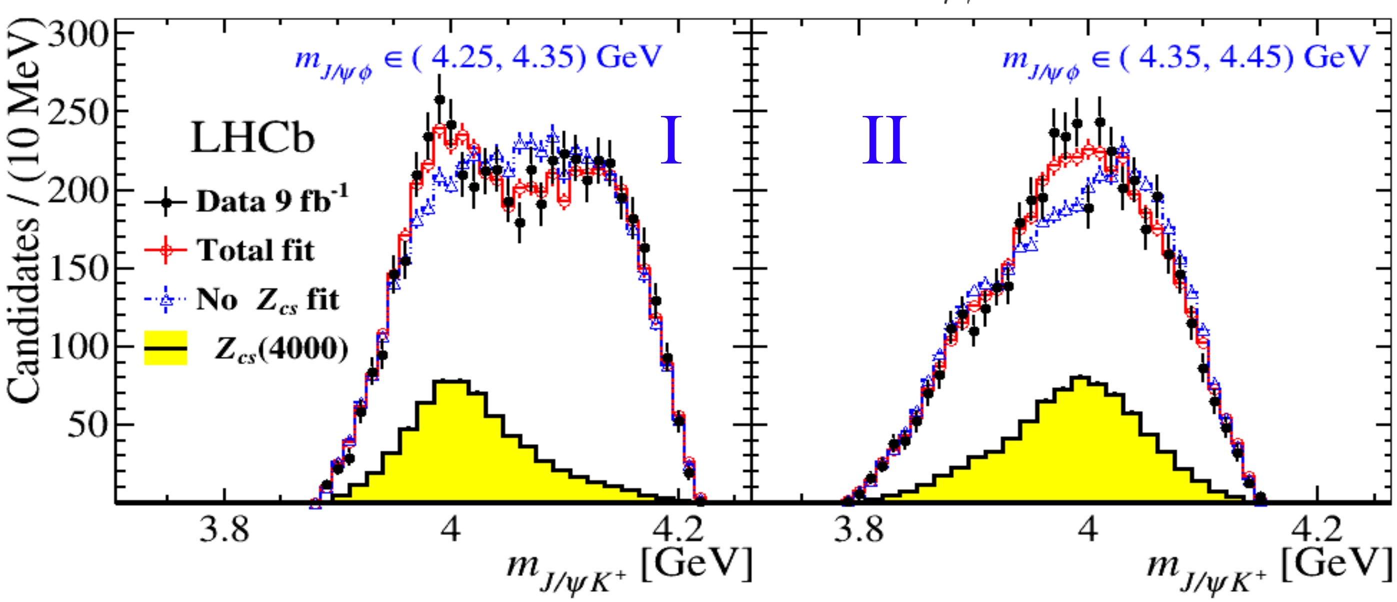
New Z_{cs}^+ states: width inconsistent with $Z_{cs}(3985)^+$ at BESIII. Different state!

Fit projections

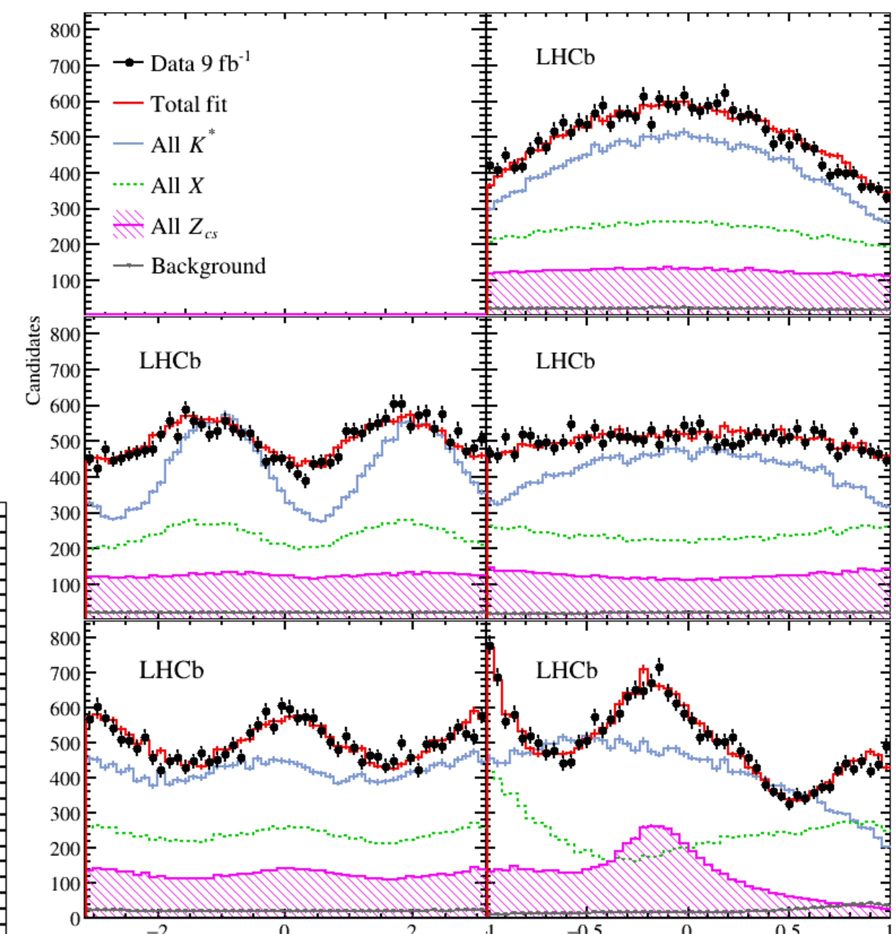
- Z_{cs}^{+} essential to describe data

arXiv:2103.01803





All angular distribution well modelled



Angles in $B^+ \to J/\psi K^*$ chain

J^P analysis

- All X have $C = 1$

$L = 0$ for $J/\psi\phi$ system

Exotic

J^P	$0^{+(+)}$	$0^{-(+)}$	$1^{+(+)}$	$1^{-(+)}$	$2^{+(+)}$	$2^{-(+)}$
$X(4630)$	6.7σ	5.3σ	5.8σ	Prefer	5.9σ	**3.0σ**
$X(4500)$	Prefer	18σ	18σ	18σ	18σ	18σ
$X(4700)$	Prefer	18σ	18σ	18σ	14σ	17σ
$X(4140)$	14σ	15σ	Prefer	14σ	13σ	14σ
$X(4274)$	18σ	18σ	Prefer	18σ	18σ	18σ
$X(4685)$	16σ	16σ	Prefer	15σ	16σ	15σ
$Z_{cs}(4000)$	-	17σ	Prefer	17σ	15σ	16σ
$Z_{cs}(4220)$	-	8.6σ	Prefer	**2.4σ**	4.9σ	5.7σ

Same as $Z_c(4430)^+, Z_c(4200)^+, Z_c(3900)^+$, $L = 0$ for $\psi\pi^+$ system

Interpretations

- Some $X \to J/\psi\phi$ may be $D_s^{(*)}\bar{D}^{(*)}{}_s$ molecular states ?

States	J^{PC}	Mass	Width	Nearest thresholds/MeV	S-wave
$X(4140)$	1^{++}	4118	162	$D_s^+ D_s^{*-}$: 4080	$J^P = 1^+$
$X(4150)$	2^{-+}	4146	135	$D_s^+ D_s^{*-}$: 4080	$J^P = 1^+$
$X(4274)$	1^{++}	4294	53	$D_s^+ D_{s0}^*(2317)^-$: 4286	$J^P = 0^-$
$X(4500)$	0^{++}	4474	77	$D_s^+ D_{s1}^*(2536)^-$: 4503	$J^P = 1^-$
$X(4630)$	1^{-+}	4626	174	$D_s^{*-} D_{s1}^*(2536)^-$: 4636	$J^P = J^-$
$X(4685)$	1^{++}	4684	126	$D_s^{*+} D_{s2}^*(2573)^-$: 4681	$J^P = J^-$
$X(4700)$	0^{++}	4694	87	$D_s^{*+} \bar{D}_{s2}^*(2573)^-$: 4681	$J^P = J^-$

Can't rule out conventional charmonia either, $c\bar{c} \to J/\psi\phi$ not forbidden

- $Z_{cs}(4000)^+$ and $Z_{cs}(4220)^+$:

May be SU(3) flavor partners of $Z_c(3900)^+$ and $Z_c(4020)^+$, molecular sates, $m_{D*} + m_{D_s} \sim 4$ GeV

arXiv:2011.08725

arXiv:2103.08331

Other models

I. One BW for threshold structure + X(6900), w/o interference, $P(\chi^2) = 1.2\%$
II. Only one BW, interfering with SPS, $P(\chi^2) = 2.8\%$
III. Threshold structure due to feed-down decays of excited charmonia (e.g. $\chi_c J/\psi$)
IV. Including a component for 7.2 GeV peak

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