Experimental hadron spectroscopy

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SFB 1044
THE LOW-ENERGY FRONTIER
OF THE STANDARD MODEL

JG|U
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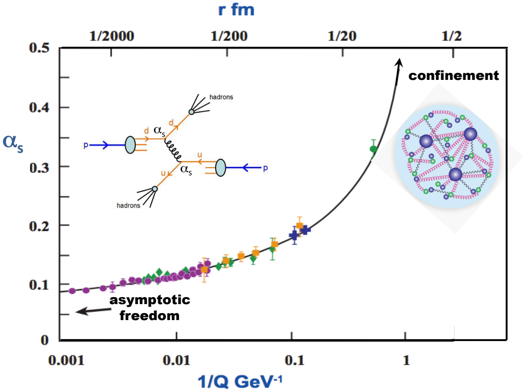
PRISMA+

Goal: better understanding of QCD

Quantum Chromodynamics (QCD): strong force, describes interaction of quarks

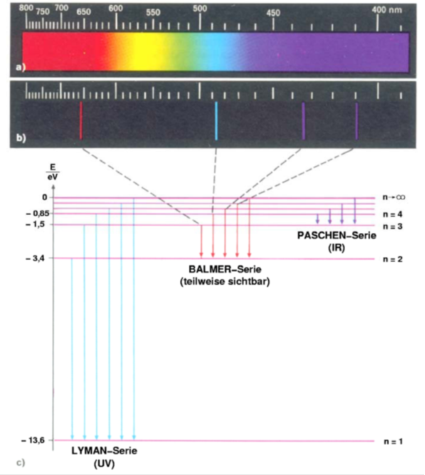
Study QCD in the regime where non-perturbative effects are important or dominant



RMP 90, 15003 (2018)

Confinement:
observable objects are $SU(3)_C$ singlets,
i.e. colour-neutral bound states

Analogy: atomic spectroscopy



Information on bound systems by observing

- Energy levels
- Transitions between levels

Discovery of discrete spectral lines

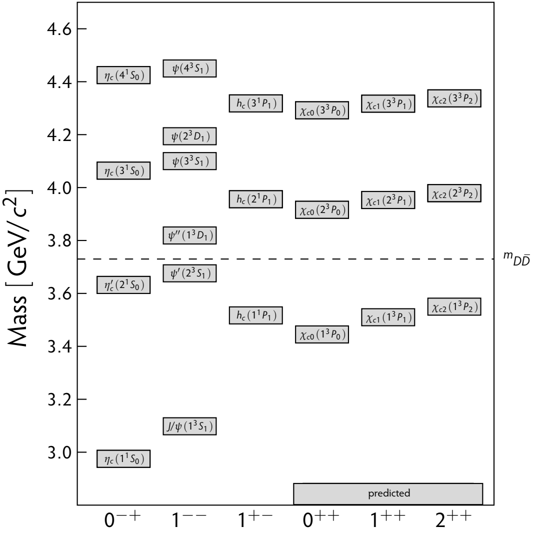
➡ Discrete energy levels in atoms

$$E_{nm} = R\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

➡ Precision measurements lead to discovery of fine structure, Lamb shift …

predictions made using QED potential

Example: charmonium spectrum []



Potential:

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

$+$ relativistic corrections

Godfrey & Isgur, PRD 32, 189 (1985);
Barnes, Godfrey & Swanson, PRD 72, 054026 (2005)

Use a few well-established states to fix parameters, then predict remainder of spectrum, and transitions

➡ refine model

The naming of states

spectroscopic notation:

$$n^{2S+1}L_J$$

n	radial quantum number
S	total spin of quarks
L	orbital angular momentum $(S, P, D, \ldots)$
J	total angular momentum: $J = \lvert L - S \rvert, \ldots, L + S$

Low-lying states historically carry their own names (e.g. J/ψ (1^3S_1), η_c (1^1S_0), ...), indicating quantum numbers and flavour contents

States with the same quantum numbers (and net flavour) can mix

Mixing more pronounced for broad, overlapping states
$\Rightarrow$ light hadron spectroscopy much more complicated

Properties to determine experimentally

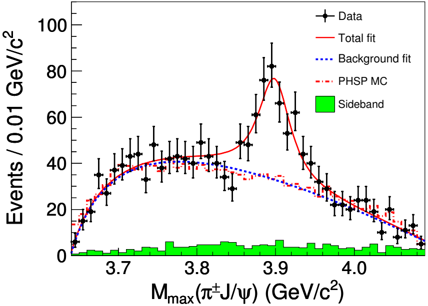
Mass and width (or, more advanced: pole position $M + \frac{i}{2}\Gamma$)

Quantum numbers: spin J, P, C

Quark / flavour composition

Production channels

Decay modes

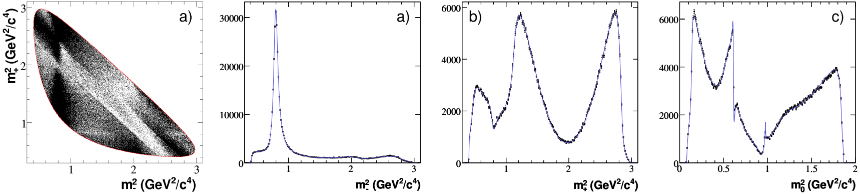


Determine *J*, *P*, *C*

Easy: if state is directly and copiously produced in e^+e^-: $J^{PC} = 1^{--}$

Sometimes, decay modes can provide clues (e.g., $\pi^0\pi^0$ is only possible for $J =$ even)

Multi-body decays: interference with cross-channels provides access to J and P
requires Dalitz plot, partial wave, amplitude analysis



$D^0 \to K_S^0\pi^+\pi^-$
Coherent sum of 10 resonant amplitudes to describe data

BABAR, PRD78 (2008) 034023

Kinematic reflections

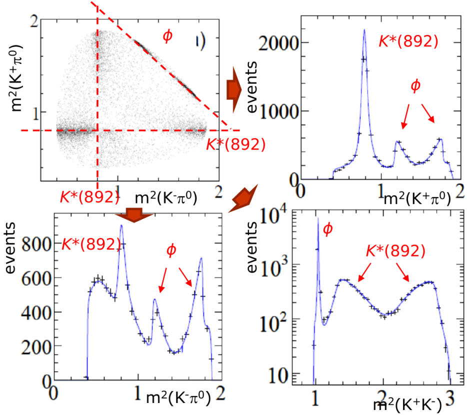
In multi-body decays, resonance in one subchannel can produce peaks in other mass projections (reflections)

Not every peak in a mass distribution is a new state!

For example $D^0 \to K^+K^-\pi^0$:

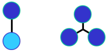
relatively easy to understand

decay dominated by $\phi\pi^0$ and $K^{*\pm}K^{\mp}$



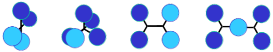
‘Exotic’ hadrons

Well-known classes of hadrons: mesons ($q\bar{q}$) and baryons (qqq)



Already on page 1 of the quark model: other colour-neutral combinations possible

multi-quark states (tetraquark, pentaquark, …)



hybrids (excitation in gluonic degrees of freedom)

glueballs

Manifestly exotic

- Quark contents requires more than $q\bar{q}$ or qqq
- Quantum numbers J^{PC} not reachable for ordinary mesons or baryons

‘Cryptoexotic’

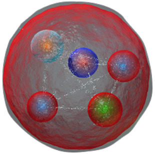
- mass / width not fitting in spectra
- overpopulation of states
- production and/or decay patterns incompatible with standard mesons/baryons

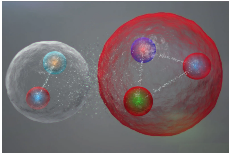
Multiquark states

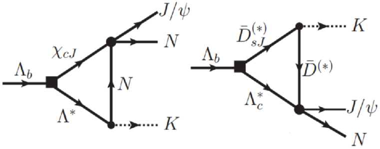
Search for 'exotics' long-standing motivation for hadron spectroscopy

Now: compelling evidence for multiquark states found in data

What are they? compact objects, (meson) molecules, triangular singularities?



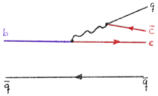




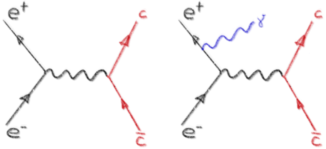
More experimental information needed — other states, line shapes, transitions …

Exotic hadrons …and where to find them

- Decays of hadrons with heavy quarks

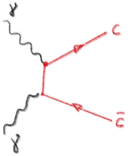


- e^+e^- direct, or via ISR

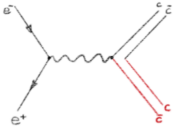


- pp, $p\bar{p}$ inclusive
- photo- / electroproduction

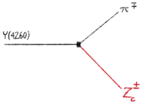
- photon–photon fusion



- double charmonium production



- decays of higher charmonia



Exotic hadrons ...and where to find them

e^+e^-

B factories (*BABAR*, *Belle*, Belle II)
τ-charm factory (BESIII)

Direct production of 1^{--} states (or via ISR)

$\gamma\gamma$ interactions: $C = +1$, L even states

Clean environment, but low cross sections

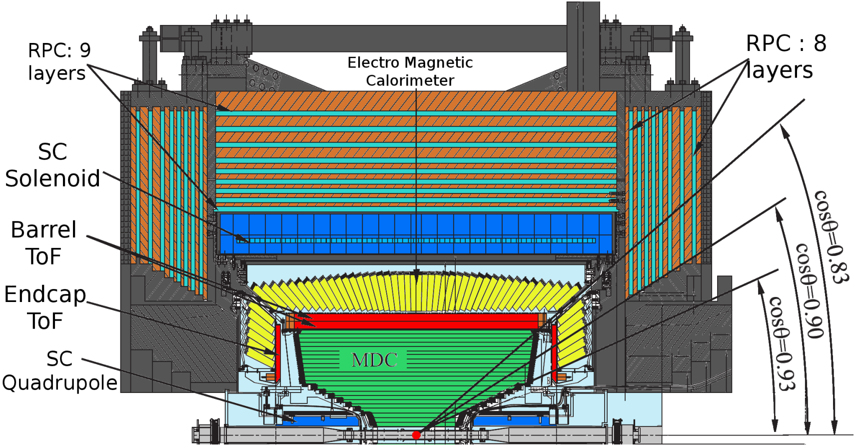
pp

Production of heavy quarks in initial hard scattering

subsequent hadronisation can produce all sorts of hadrons

At LHC energies: huge production cross sections

BESIII

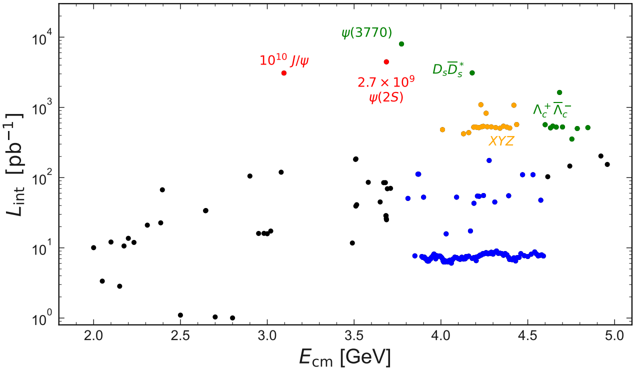


At BEPCII in Beijing: e^+e^- collisions at $\sqrt{s}$ between 2 and 5 GeV

12 years data taking at BESIII

Data sets collected so far include

- 10×10^9 J/ψ events
- 2.7×10^9 ψ' events
- $8\,\mathrm{fb}^{-1}$ on $\psi(3770)$
- scan data between
  2.0 and 3.08 GeV,
  and above 3.735 GeV
- large datasets for *XYZ* studies:
  scan with $> 500\,\mathrm{pb}^{-1}$ per energy point
  spaced 10 – 20 MeV apart



Recent results from BESIII at ISMD2022:

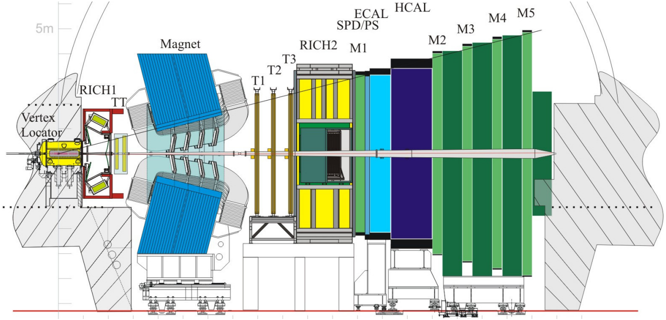
- **Hadron spectroscopy**: Song Weimin, later this session
- **R-value measurement**: Christoph Redmer, Tuesday
- **Light-flavour vector mesons**: Zhang Hao (poster)
- **Hyperon physics**: Viktor Thorén, Friday

LHCb

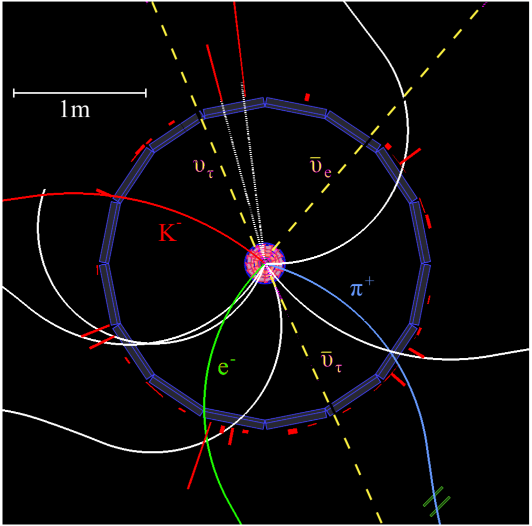
Forward, single-arm spectrometer, *pp* collisions

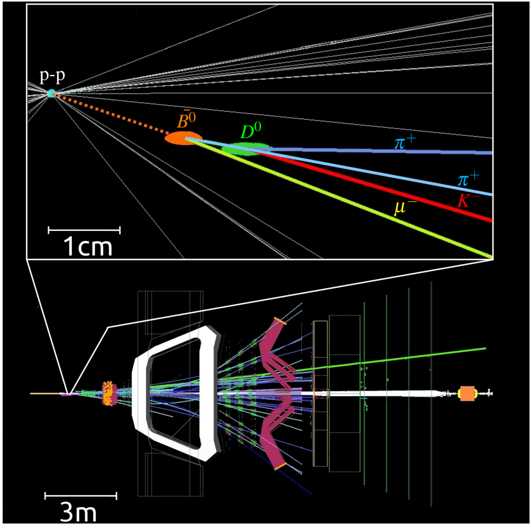
Huge production cross sections in fiducial volume: $\sim$ 2.4 mb for $c\bar{c}$, $\sim$ 0.14 mb for $b\bar{b}$ at 13 TeV

Fantastic vertex resolution + large Lorentz boost: decay time resolution 45 fs



e^+e^- vs. pp at LHC energies





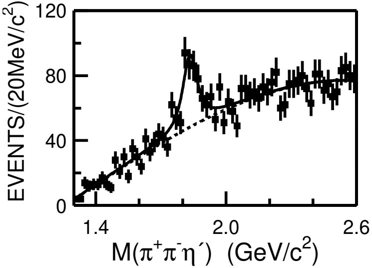
from Ciezarek *et al.*, Nature 546, 227 (2017)

Significant experimental progress in the past several years

For this talk:

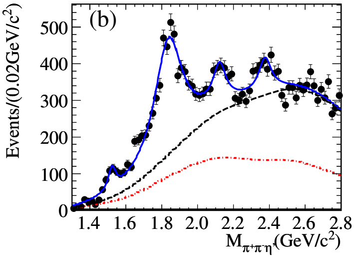
- Light hadron spectroscopy: $X(1835), X(2600) \to \eta'\pi^+\pi^-$
  and why taking 10^{10} J/ψ events was not a bad idea
- Charmonium-like states in e^+e^- collisions:
  the story of $Y(4260)$
- exotic states at LHCb:
  the power of ultra-high statistics

$J/\psi \to \gamma\eta'\pi^+\pi^-$



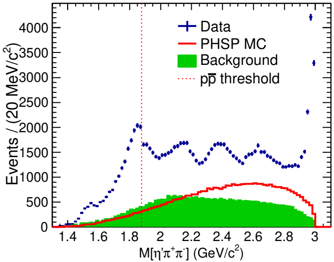
58×10^6 J/ψ events

BES, PRL 95 (2005) 262001



225.2×10^6 J/ψ events

BESIII, PRL 106 (2011) 072002



1090×10^6 J/ψ events

BESIII, PRL 117 (2016) 042002

Structure just at or below $p\bar{p}$ threshold: $X(1835)$

Non-trivial lineshape: try to fit with Flatté or sum of interfering Breit-Wigners

Additional structures: $X(2120)$, $X(2370)$, ??

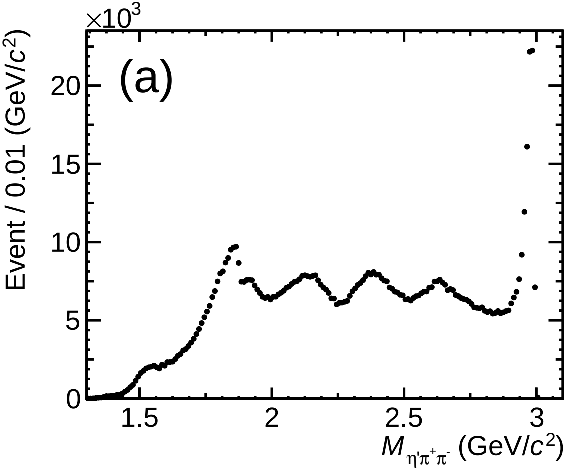
$J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII, PRL 129 (2022) 042001

$10\,087 \times 10^6$ J/ψ events

Confirmation of $X(1835)$, $X(2120)$, and $X(2370)$

New structure $X(2600)$
J^{PC} to be determined



$J/\psi \to \gamma\eta'\pi^+\pi^-$

BESIII, PRL 129 (2022) 042001

$10\,087 \times 10^6$ J/ψ events

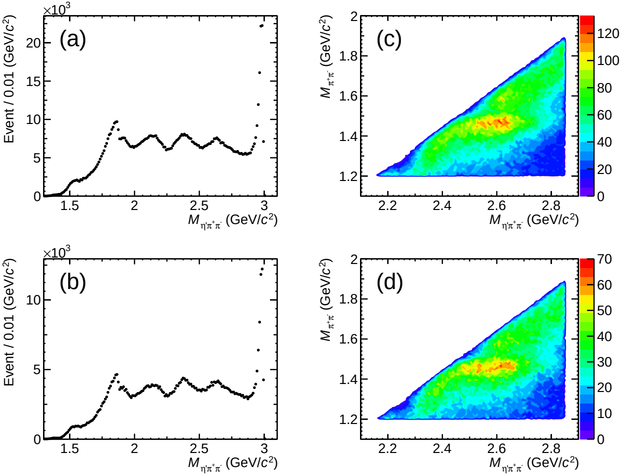
Confirmation of $X(1835)$, $X(2120)$, and $X(2370)$

New structure $X(2600)$

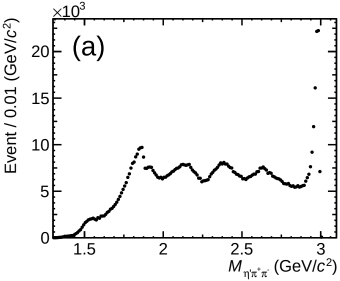
J^{PC} to be determined

connected to complicated structure in $m_{\pi^+\pi^-}$ around 1.5 GeV

more studies needed!



$X(1835)$



Seen in radiative J/ψ decays to $\eta'\pi^+\pi^-$
and in Dalitz decays $J/\psi \to e^+e^-\eta'\pi^+\pi^-$

Threshold enhancement in $J/\psi \to \gamma p\bar{p}$

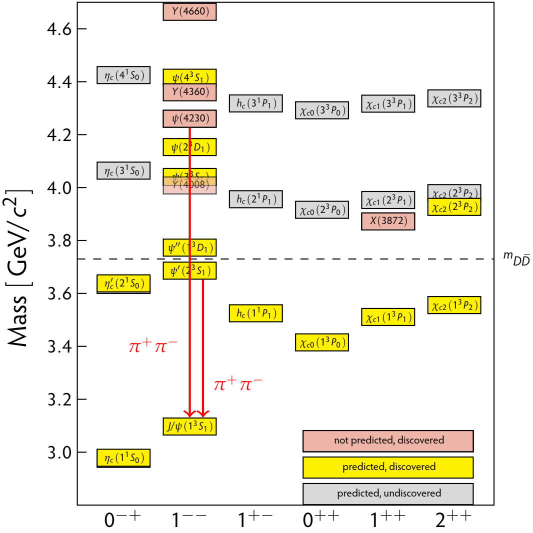
$X(1835)$ seen in other decay modes:

- $J/\psi \to \gamma 3(\pi^+\pi^-)$ [225M J/ψ, BESIII, PRD 88 (2013) 091502(R)]
- $J/\psi \to \eta K_S^0 K_S^0$ [1.3B J/ψ, BESIII, PRL 115 (2015) 091803]
- $J/\psi \to \gamma\gamma\phi$ [1.3B J/ψ, BESIII, PRD 97 (2018) 051101(R)]

$K_S^0 K_S^0$ and $\gamma\phi$ decays seem to indicate non-negligible $s\bar{s}$ component
➡ second radial excitation of η'?

Connection to threshold enhancement seen in $J/\psi \to \gamma p\bar{p}$? Two close-by states?

$\psi(4230) \to J/\psi\,\pi^+\pi^-$



e^+e^- collisions near $\Upsilon(4S)$

in ISR production, $e^+e^- \to \gamma_{\text{ISR}} J/\psi\,\pi^+\pi^-$

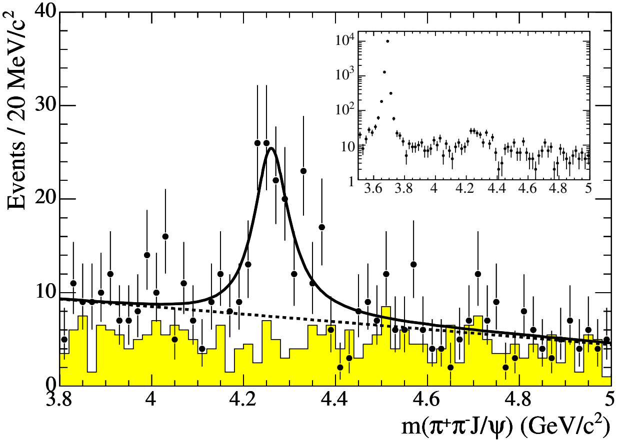
$\Rightarrow J^{PC} = 1^{--}$

Supernumerary vector state:
all 'ordinary' $c\bar{c}$ vector states already seen

$\psi(4230) \to J/\psi\, \pi^+\pi^-$

BABAR, 211 fb^{-1}, PRL 95 (2005) 142001

Discovered by *BABAR* in $e^+e^- \to \gamma_{\text{ISR}} J/\psi\, \pi^+\pi^-$



Fit with single Breit-Wigner

$$M = 4259 \pm 8^{+2}_{-6}\,\text{MeV}$$

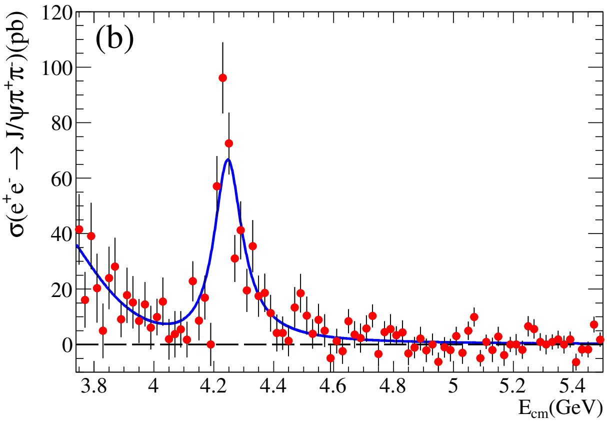
$$\Gamma = 88 \pm 23^{+6}_{-4}\,\text{MeV}$$

Call this structure $Y(4260)$

$\psi(4230) \to J/\psi\, \pi^+ \pi^-$

BABAR, 454 fb^{-1}, PRD 86 (2012) 051102

BABAR update with double the data set



Fit with single Breit-Wigner

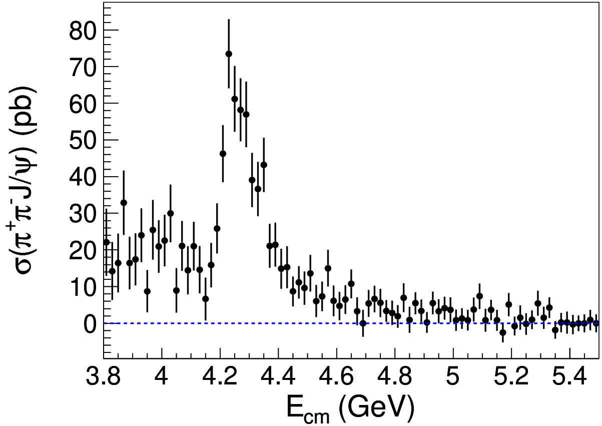
$$M = 4244 \pm 5 \pm 4\,\text{MeV}$$

$$\Gamma = 114^{+16}_{-15} \pm 7\,\text{MeV}$$

$\psi(4230) \to J/\psi\, \pi^+ \pi^-$

Belle, 967 fb^{-1}, PRL 110 (2013) 252002

Belle measurement, using ISR, 2×



Single Breit-Wigner fit to line shape still satisfactory

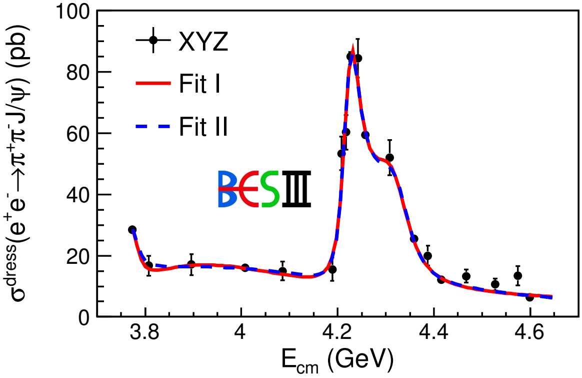
$$M = 4248.6 \pm 8.3 \pm 12.1\,\text{MeV}$$

$$\Gamma = 134.1 \pm 16.4 \pm 5.5\,\text{MeV}$$

$\psi(4230) \to J/\psi\,\pi^+\pi^-$

BESIII, PRL 118, 092001 (2017)

BESIII: make use of first batch of *XYZ* scan data set



Single Breit-Wigner not appropriate to fit line shape

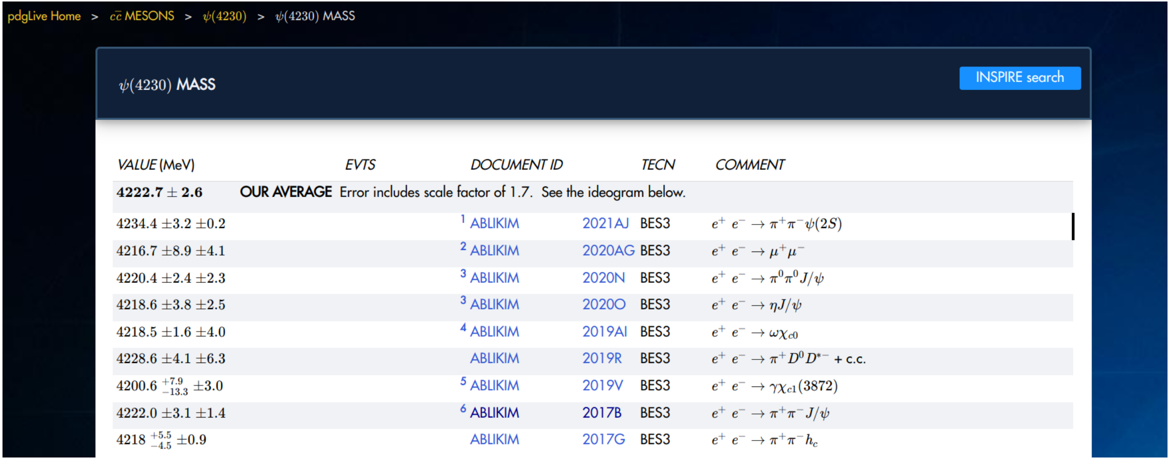
Two-resonance fit:

Parameter	Fit 1 / MeV	Fit 2 / MeV
$M(R_1)$	$3812.6^{+61.9}_{-96.6}$	$\cdots$
$\Gamma_{tot}(R_1)$	$476.9^{+78.4}_{-64.8}$	$\cdots$
$M(R_2)$	4222.0 ± 3.1	4220.9 ± 2.9
$\Gamma_{tot}(R_2)$	44.1 ± 4.3	44.1 ± 3.8
$M(R_3)$	4320.0 ± 10.4	4326.8 ± 10.0
$\Gamma_{tot}(R_3)$	$101.4^{+25.3}_{-19.7}$	$98.2^{+25.4}_{-19.6}$

Fit 1, Fit 2: different treatment of non-resonant contribution

➡ high-statistics datasets essential to resolve finer structure of line shape

$\psi(4230)$ in different decay channels

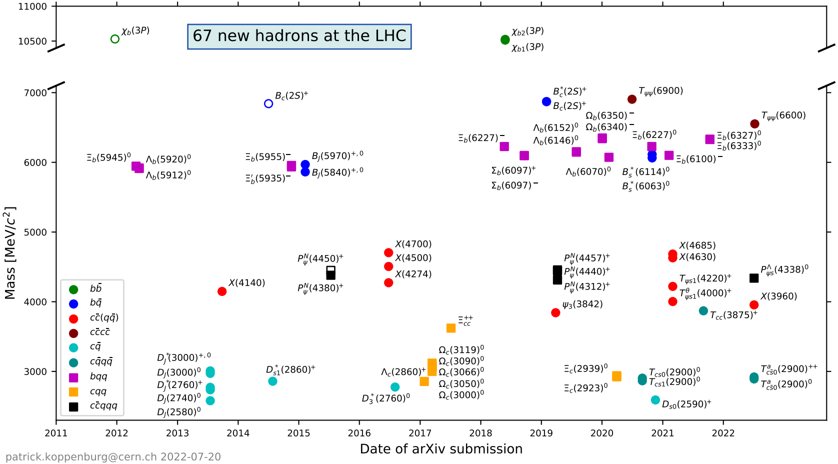


$\psi(4230)$ **MASS**

VALUE (MeV)	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
$\mathbf{4222.7 \pm 2.6}$	**OUR AVERAGE** Error includes scale factor of 1.7. See the ideogram below.			
$4234.4 \pm 3.2 \pm 0.2$		[1] ABLIKIM 2021AJ	BES3	$e^+ e^- \to \pi^+\pi^-\psi(2S)$
$4216.7 \pm 8.9 \pm 4.1$		[2] ABLIKIM 2020AG	BES3	$e^+ e^- \to \mu^+\mu^-$
$4220.4 \pm 2.4 \pm 2.3$		[3] ABLIKIM 2020N	BES3	$e^+ e^- \to \pi^0\pi^0 J/\psi$
$4218.6 \pm 3.8 \pm 2.5$		[3] ABLIKIM 2020O	BES3	$e^+ e^- \to \eta J/\psi$
$4218.5 \pm 1.6 \pm 4.0$		[4] ABLIKIM 2019AI	BES3	$e^+ e^- \to \omega\chi_{c0}$
$4228.6 \pm 4.1 \pm 6.3$		ABLIKIM 2019R	BES3	$e^+ e^- \to \pi^+ D^0 D^{*-}$ + c.c.
$4200.6 ^{+7.9}_{-13.3} \pm 3.0$		[5] ABLIKIM 2019V	BES3	$e^+ e^- \to \gamma\chi_{c1}(3872)$
$4222.0 \pm 3.1 \pm 1.4$		[6] ABLIKIM 2017B	BES3	$e^+ e^- \to \pi^+\pi^- J/\psi$
$4218 ^{+5.5}_{-4.5} \pm 0.9$		ABLIKIM 2017G	BES3	$e^+ e^- \to \pi^+\pi^- h_c$

PDG now calls the narrow structure $\psi(4230)$ — seen in many different decay modes, mainly charmonium + light meson(s)

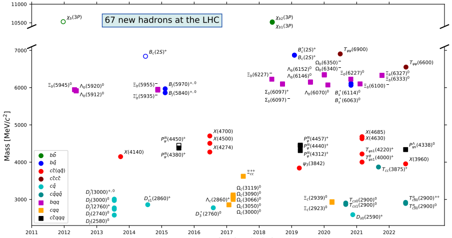
New hadrons discovered at the LHC



patrick.koppenburg@cern.ch 2022-07-20

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

New hadrons discovered at the LHC



patrick.koppenburg@cern.ch 2022-07-20

59 of these seen at LHCb

- Conventional hadrons with heavy flavour (c, b) excited open-charm mesons, doubly-charmed baryons Ξ_{cc}, …
- Hidden-charm pentaquarks P_ψ^N
- Hidden-charm tetraquark candidates
- Tetraquarks with double-charm contents

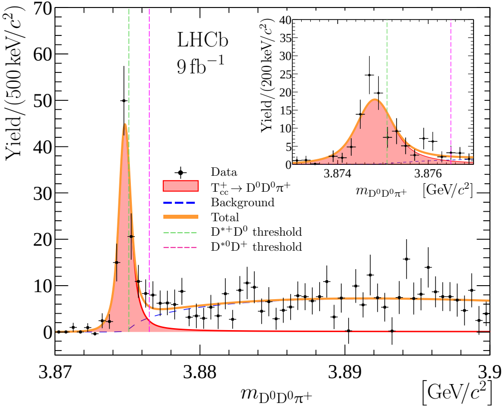
Far too many to cover in one talk …

pick out two striking, recent examples:

- ➡ $T_{cc}(3875)^+$
- ➡ $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$

Doubly-charmed tetraquark $T_{cc}(3875)^+$

LHCb, Nat. Phys. 18, 751 (2022)



Background-subtracted $D^0D^0\pi^+$ mass spectrum

Select two D^0 candidates from same primary vertex, combine with π^+

Clear peak just below D^*D thresholds;
decay proceeds likely via off-shell D^{*+}

LHCb, Nat Commun 13, 3351 (2022)

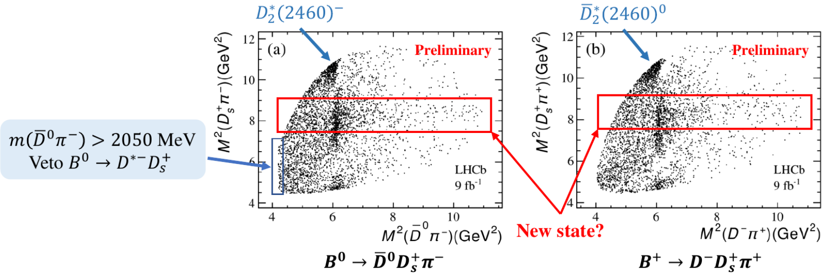
Extremely narrow!

Minimal quark contents: $cc\bar{u}\bar{d}$

- manifestly exotic
- prompt production in pp collisions strongly suggests that this is a bound state

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

Study $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$; perform simultaneous amplitude analysis



$m(\bar{D}^0\pi^-) > 2050$ MeV
Veto $B^0 \to D^{*-}D_s^+$

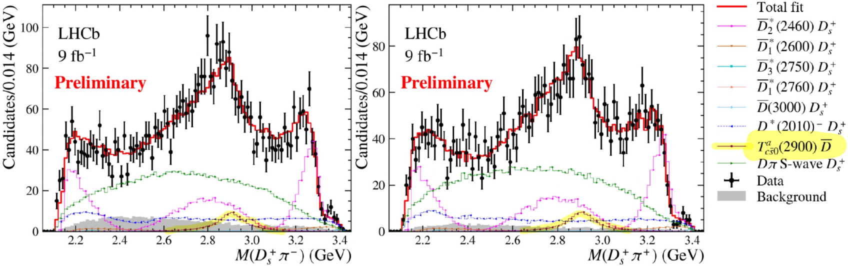
$B^0 \to \bar{D}^0 D_s^+ \pi^-$

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

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

LHCb preliminary, Ma Ruiting at ICHEP '22

Study $B^0 \to \bar{D}^0 D_s^+ \pi^-$ and $B^+ \to D^- D_s^+ \pi^+$; perform simultaneous amplitude analysis



Doubly-charged tetraquark $T^a_{c\bar{s}0}(2900)^{++} \to D_s^+ \pi^+$ and neutral partner $T^a_{c\bar{s}0}(2900)^0 \to D_s^+ \pi^-$
$J^P = 0^+$ favoured

Four quark flavours: $c\bar{s}u\bar{d}$ and $c\bar{s}d\bar{u}$

Summary

- Compelling evidence for multi-quark states seen by various experiments
  not only 'charged charmonium-like states' such as $Z_c(3900)^+$ a.k.a. $T_\psi^b(3900)^+ \to J/\psi\,\pi^+$, but
    doubly-charmed $T_{cc}(3875)^+$
    doubly-charged $T_{c\bar{s}0}^a(2900)^{++}$ + spin-exotic candidates
- Begin to see whole families of such states in data
  Large, clean datasets required
  Sophisticated amplitude analyses needed to measure quantum numbers
- Connection between these states?
  Can we identify the same state in different datasets, with different production mechanisms?
- So, question shifts from "where are they?" to "what are they?"
  Experimental input essential