Experimental Road to a Charming Family of Tetraquarks...and Beyond

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Based on Chin. Phys. Lett. 41 111201

The 10th China LHC Physics Conference

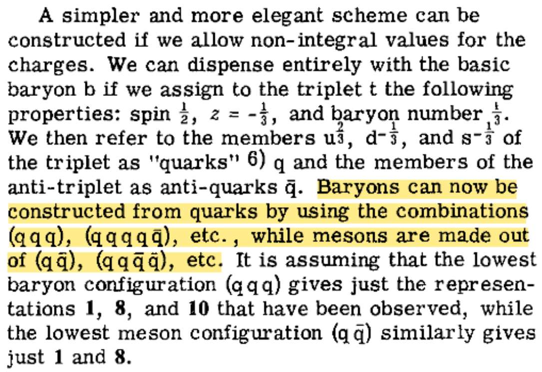
2024.11.14 Qingdao

Outline

- Step to All-Heavy Exotic Mesons
  - Discovery of the X(3872) meson and charged charmonium-like states
  - $J/\psi\phi$ mass spectrum
  - Di-Charmonium Channel
- m^2 vs resonance index (Regge trajectory)
- Summary and Ongoing

Discovery of the X(3872) meson

Phys.Lett. 8 (1964) 214-215



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**.

Fig1: four-quark and five-quark states were theorized as exotic hadrons.

Phys.Rev.Lett. 91 (2003) 262001 · *Phys.Rev.Lett.* 93 (2004) 072001 · *Phys.Rev.Lett.* 93 (2004) 162002 · *Phys.Rev.D* 71 (2005) 071103

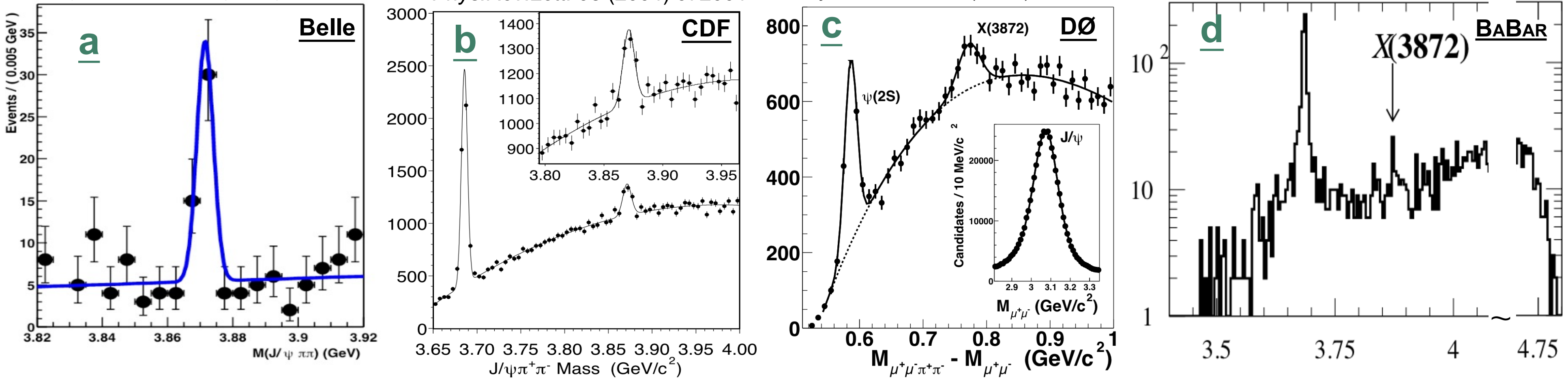
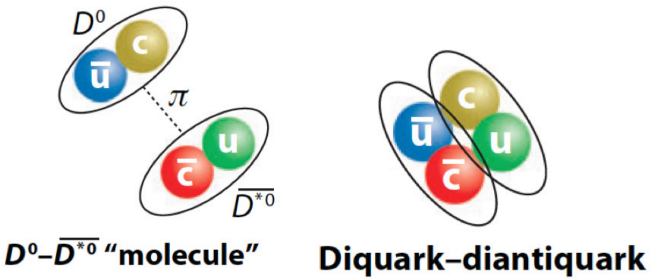


Fig2: X(3872) has been observed by Belle in the J/ψπ⁺π⁻ channel (a), and then confirmed by CDF (b), DØ (c) and BaBar (d).

- In 2003, Belle reported a peak in the $J/\psi\pi^+\pi^-$ channel, which confirmed by CDF, DØ and BaBar.
- However, its mass differs from traditional hadron model predictions, sparking debate over the internal structure of X(3872).



Discovery of charged charmonium-like states

Phys.Rev.Lett. 100 (2008) 142001

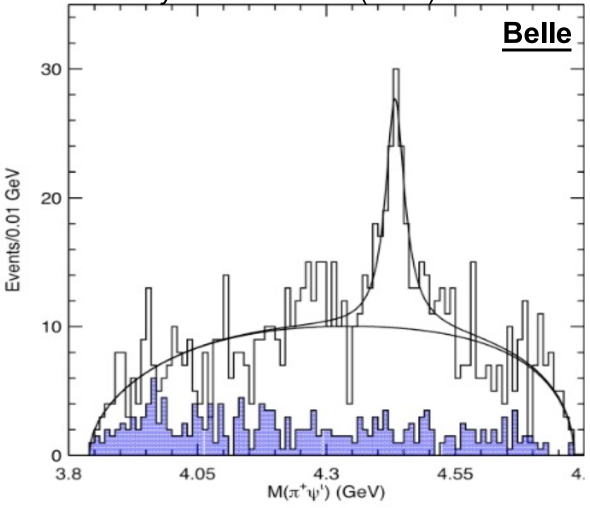


Fig1: The $Z_c(4430)^+$ in the M [$\psi(2S)\pi^+$] distribution from Belle.

Phys.Rev.Lett. 95 (2005) 142001 | *Phys.Rev.Lett.* 110 (2013) 252001 | *Phys.Rev.Lett.* 110 (2013) 252002

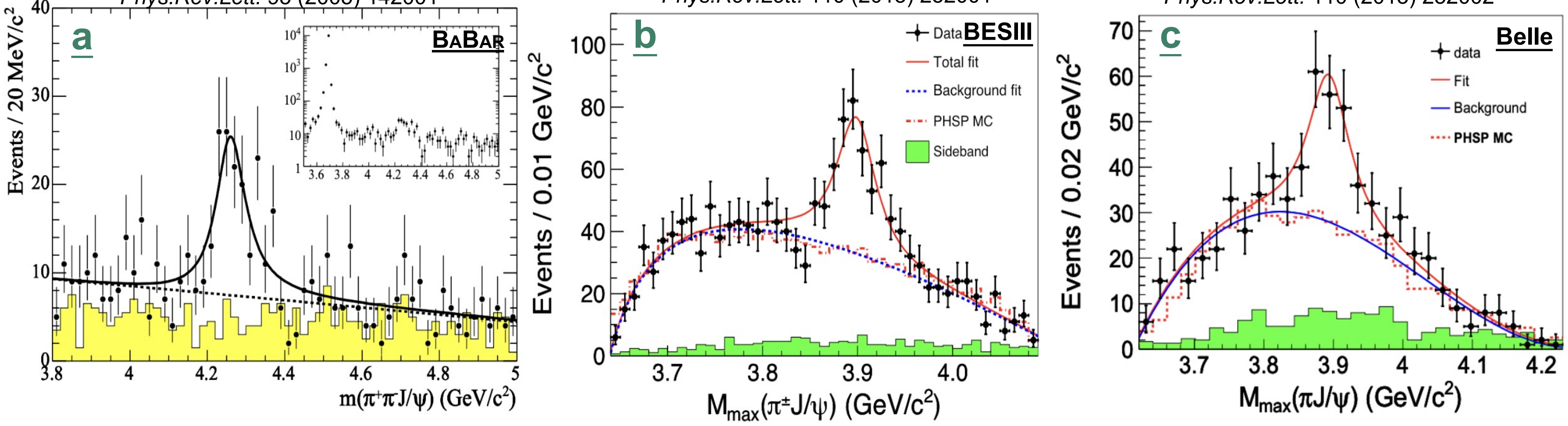
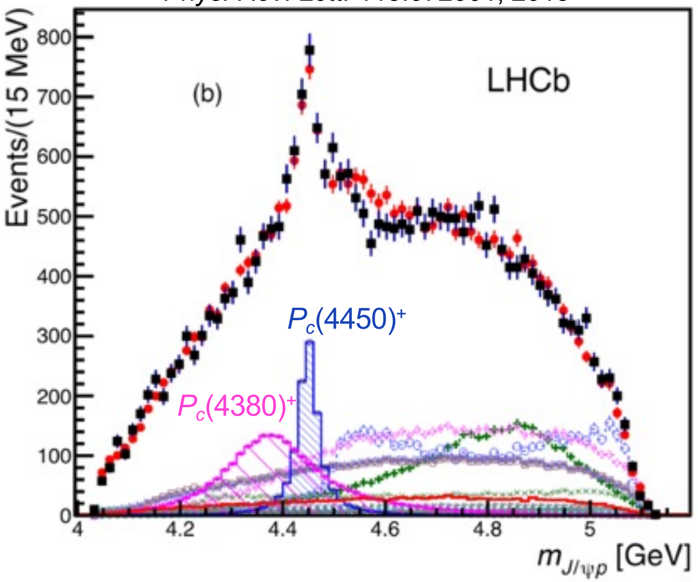


Fig2: The $J/\psi\pi^+\pi^-$ spectrum from BABAR showing the charmonium-like Y(4260) (a). The $J/\psi\pi^\pm$ spectrum from BESIII (b), and Belle (c), showing the $Z_c(3900)^+$ peaks.

- Charmonium-like states must be neutral, so a charged charmonium-like states must be exotic, but it is not easy to find it.
- Belle first observed the charged $Z_c(4430)^+$ in 2008, later confirmed by LHCb in 2014 with precise measurements.
- In 2013, BESIII and Belle detected the $Z_c(3900)^+$ in $e^+ e^- \rightarrow J/\psi\pi^+\pi^-$ data at the Y(4260) mass.

Pentaquarks

Phys. Rev. Lett. 115:072001, 2015



Phys. Rev. Lett. 122(22):222001, 2019

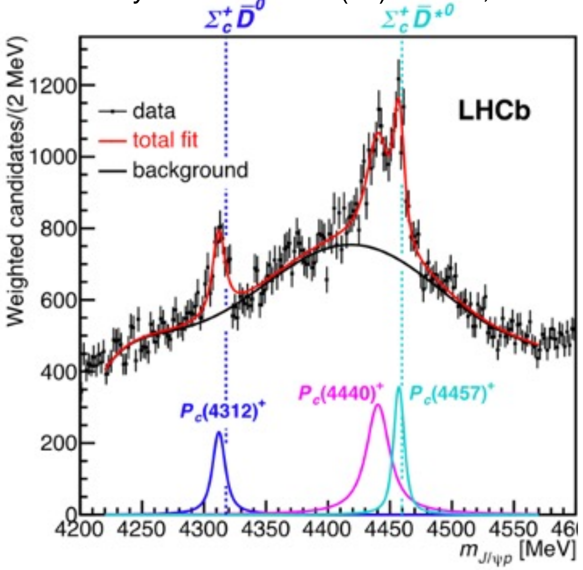
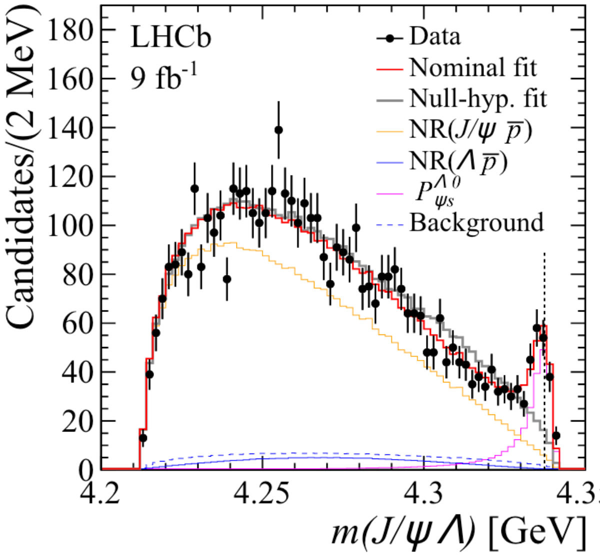


Fig1: In 2015 analysis with 3 fb⁻¹ (left), two structures were observed. In 2019 analysis with 6 fb⁻¹ (right), the $P_c(4450)$+ was actually resolved into two overlapping narrow peaks and a new narrow state was also seen.

Phys. Rev. Lett. 131 (2023) 3, 031901



Sci. Bull. 66 (2021) 1278-1287

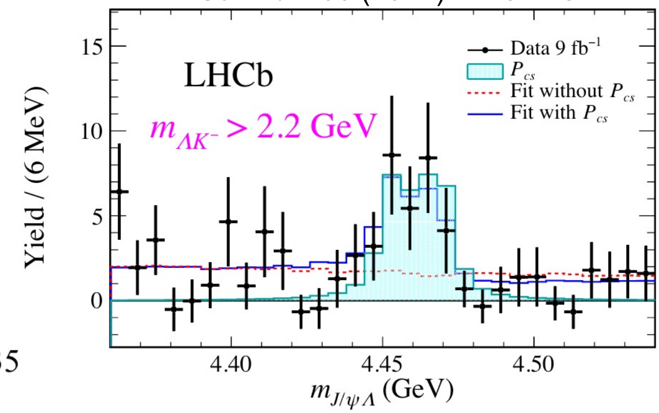
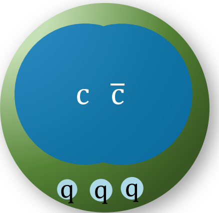
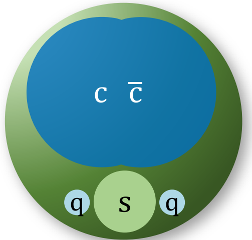


Fig2: Two pentaquark candidates containing a strange quark.





An Intermediate Step to All-Heavy Exotic Mesons

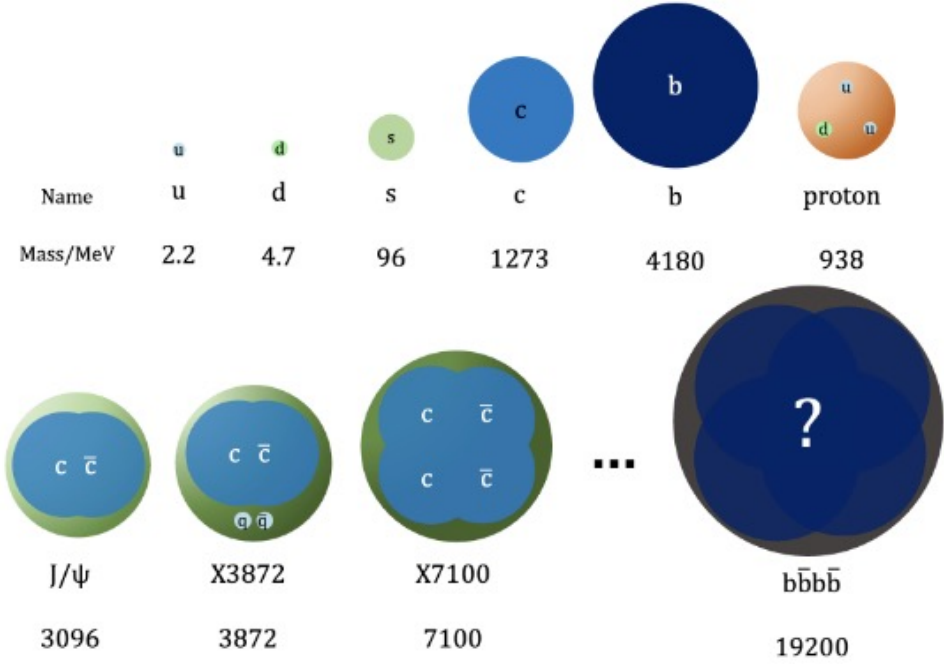
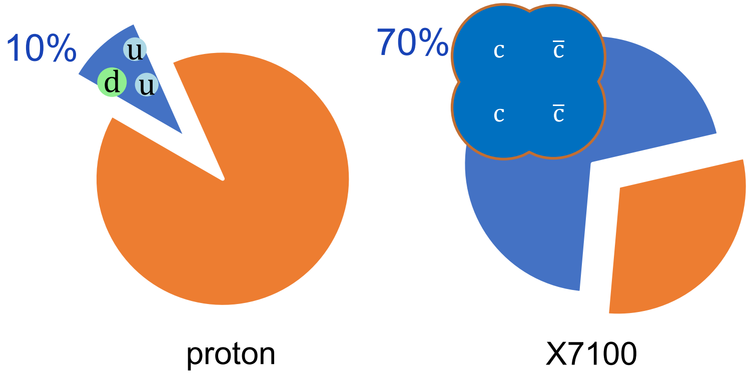


Fig1: Illustration of the scale of particle masses. The hadrons are shown with volumes proportional to their masses

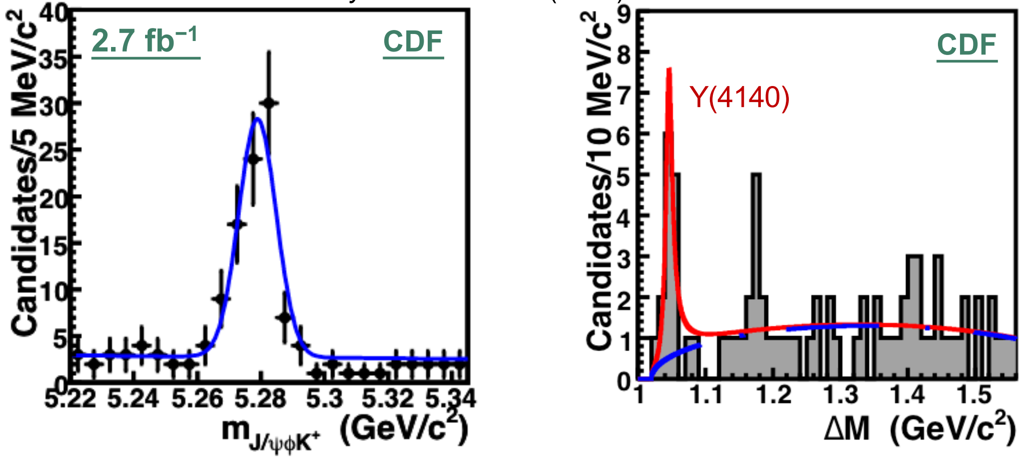


Year Experiment	Luminosity	Process and yield $B \to J/\psi\phi K$	Mass (MeV)	Width (MeV)	Signf.[$*\sigma$]
2009 CDF [114]	$2.7\,\text{fb}^{-1}$	58 ± 10	$4143.0 \pm 2.9 \pm 1.2$	$11.7^{+8.3}_{-5.0} \pm 3.7$	3.8
2011 CDF [115,116]	$6.0\,\text{fb}^{-1}$	115 ± 12	$4143.4^{+2.9}_{-3.0} \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	5.0
			$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$	3.1
2012 LHCb [117]	$0.37\,\text{fb}^{-1}$	346 ± 20	4143.0 fixed	15.3 fixed	
2013 CMS [118]	$5.2\,\text{fb}^{-1}$	2480 ± 160	$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	5.0
2013 D0 [119]	$10.4\,\text{fb}^{-1}$	215 ± 37	$4159.0 \pm 4.3 \pm 6.6$	$19.9 \pm 12.6^{+1.0}_{-8.0}$	3.1
2014 BaBar [120]	$422.5\,\text{fb}^{-1}$	189 ± 14	4143.4 fixed	15.3 fixed	1.6
2014 BESIII [121]		$e^+e^- \to \gamma\phi J/\psi$			
2015 D0 [122]	$10.4\,\text{fb}^{-1}$	$p\bar{p} \to J/\psi\phi + anything$	$4152.5 \pm 1.7^{+6.2}_{-5.4}$	$16.3 \pm 5.6 \pm 11.4$	4.7 (5.7)
2016 LHCb [123]	$3\,\text{fb}^{-1}$	4289 ± 151	$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4
			$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56 \pm 11^{+8}_{-11}$	6.0
			$4506 \pm 11^{+12}_{-15}$	$92 \pm ^{+21}_{-20}$	6.1
			$4704 \pm 10^{+14}_{-2}$	$120 \pm 31^{+42}_{-33}$	5.6
2021 LHCb [124]	$9\,\text{fb}^{-1}$	24220 ± 170	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	13 (16)
			$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	4.8 (8.7)
			$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	18 (18)
			$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	20 (20)
			$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	5.5 (5.7)
			$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+36}_{-41}$	15 (15)
			$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	17 (18)

Fig2: Summary of structures reported in the J/ψφ mass spectrum. The significances are evaluated accounting for total (statistical-only) uncertainties.

J/ψϕ mass spectrum

Phys.Rev.Lett. 102 (2009) 242002



Phys.Lett.A 32 (2017) 26, 1750139

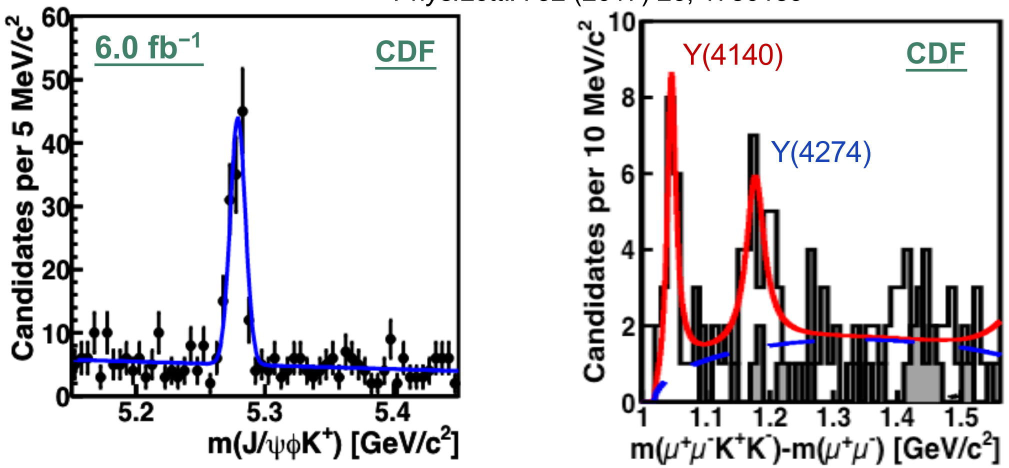


Fig1: In 2009, the CDF experiment initially reported evidence for a J/ψφ structure (top). By 2011, with 6.0 fb^{-1} of data, CDF confirmed the existence of the Y(4140) and identified a new structure Y(4274) (down).

Phys. Lett. B 734 (2014) 261-281

Phys. Rev. D 89 (2014) 1, 012004

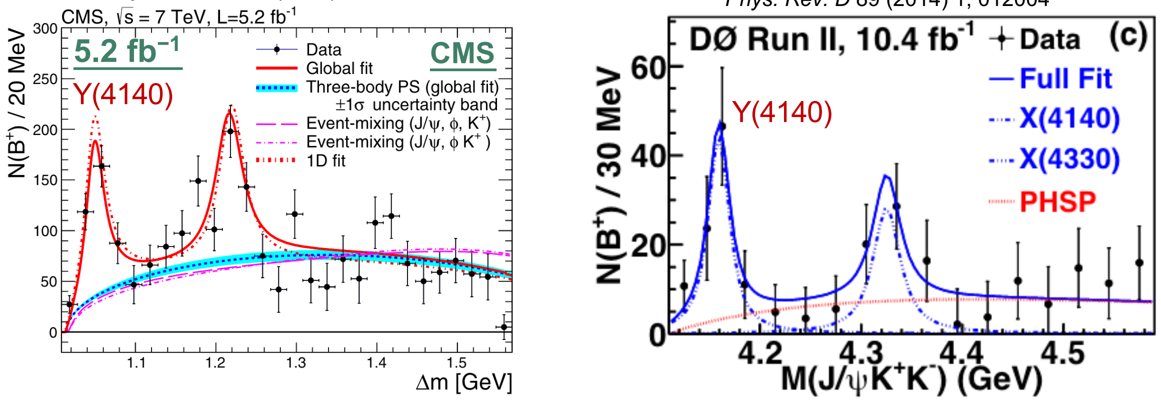


Fig2: CMS confirmed CDF 's results using 5.2 fb^{-1} (left). DØ searched for the inclusive production of the Y (4140) in hadronic collisions and found strong evidence (right).

Phys. Rev. D 95 (2017) 1, 012002

Phys. Rev. Lett. 127 (2021) 082001

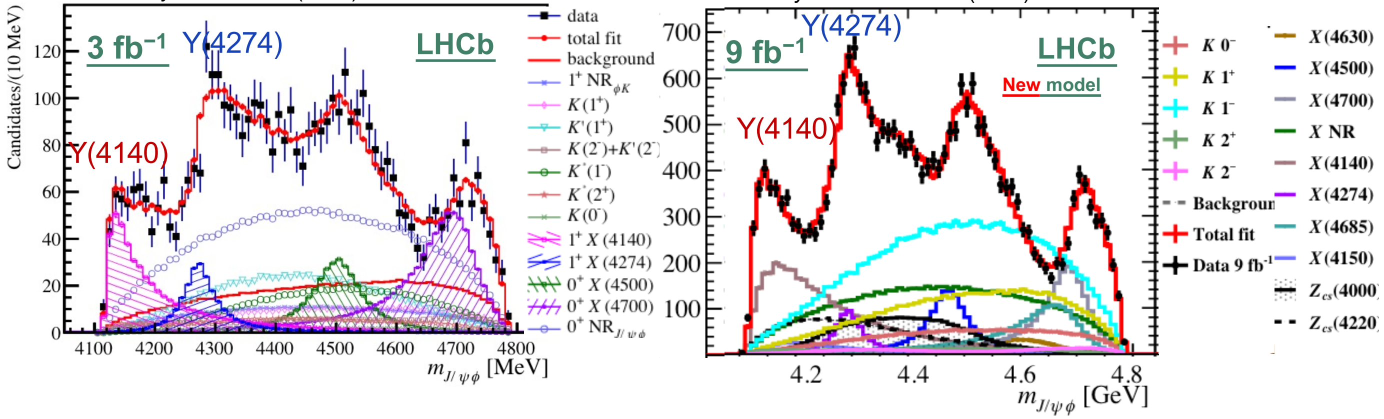


Fig3: LHCb performed an amplitude analysis in 2016 (left) and 2021 (right) established the Y(4140) and Y(4274), and enriched the list of exotic heavy-quark states.

Structures in the Di-Charmonium Channel

Phys. Lett. B 158 (1985) 85

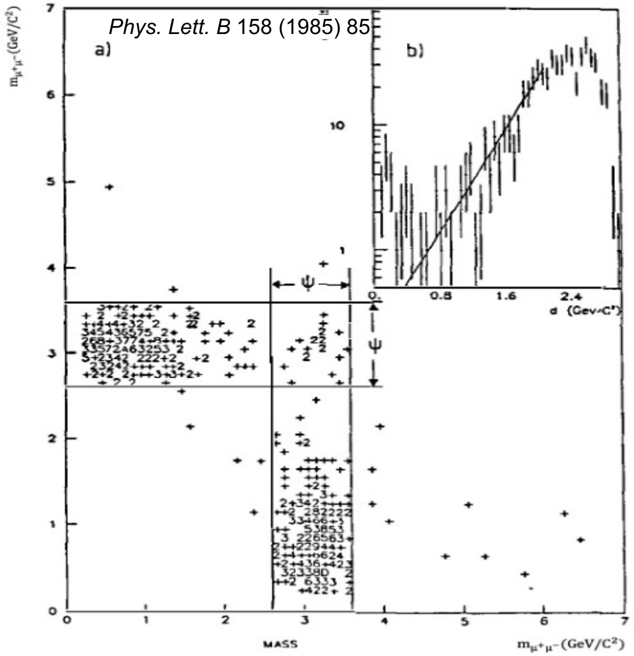
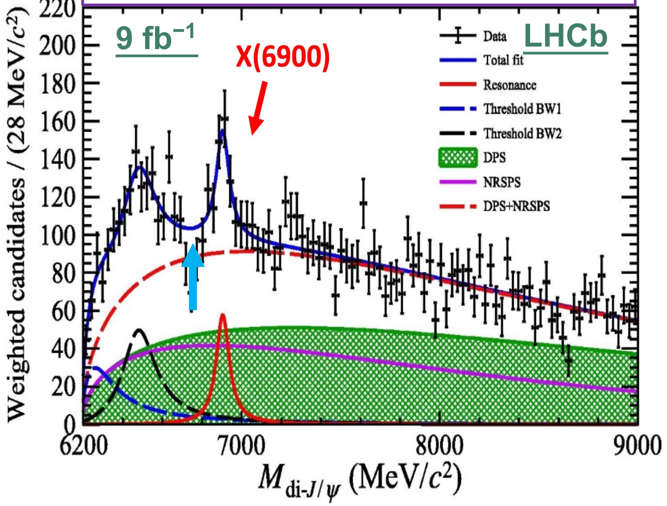
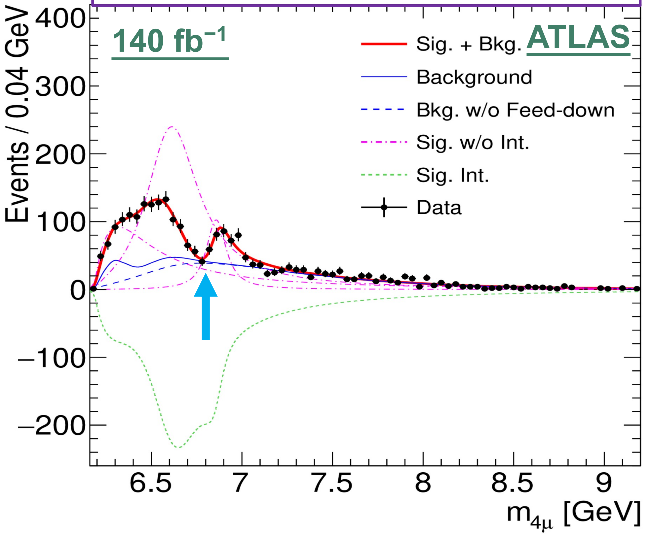


Fig1: In 1985, NA3 experiment pioneered the exploration of this channel and reported 13 $J/\psi\ J/\psi$ events.

Sci.Bull. 65 (2020) 23, 1983-1993



Phys.Rev.Lett. 131 (2023) 15, 151902



Phys.Rev.Lett. 132 (2024) 11, 111901

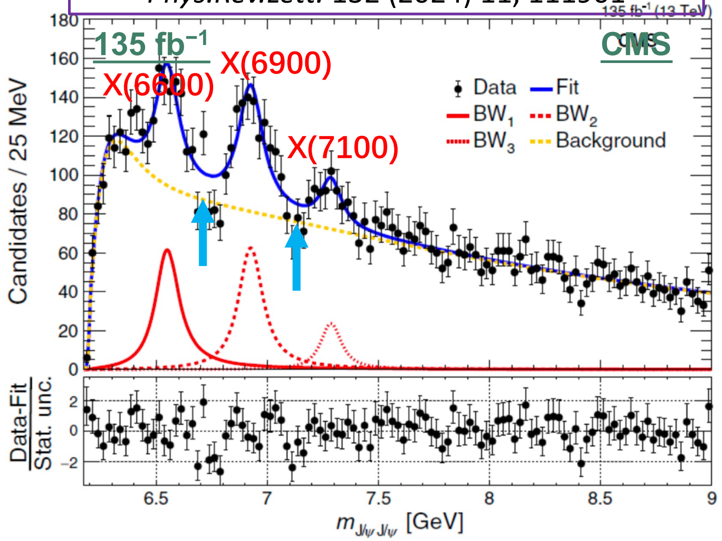
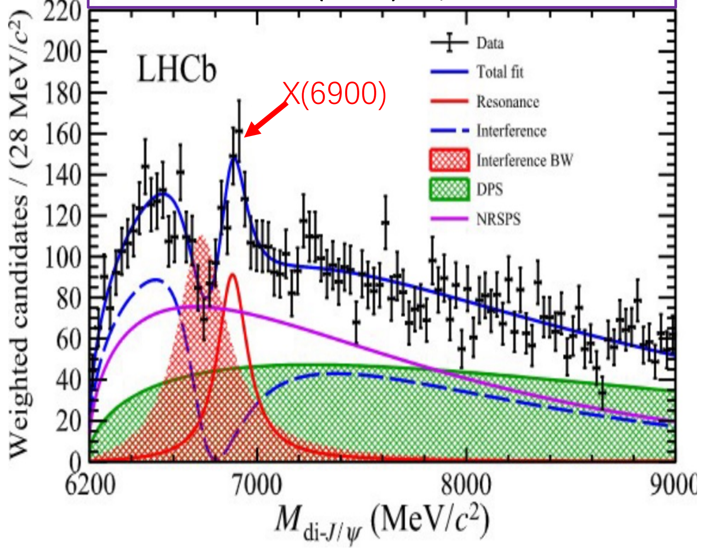
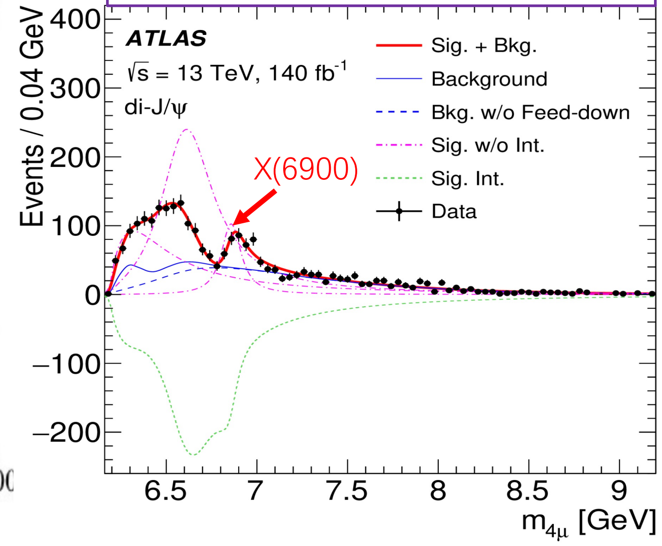


Fig2: The J/ψ J/ψ mass spectra from LHCb's model I fit (top left) and CMS no-interference fit (top right).

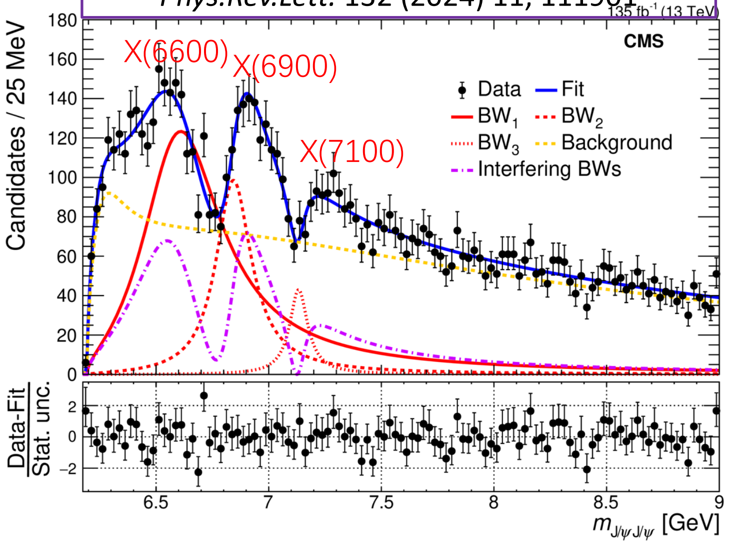
Sci.Bull. 65 (2020) 23, 1983-1993



Phys.Rev.Lett. 131 (2023) 15, 151902

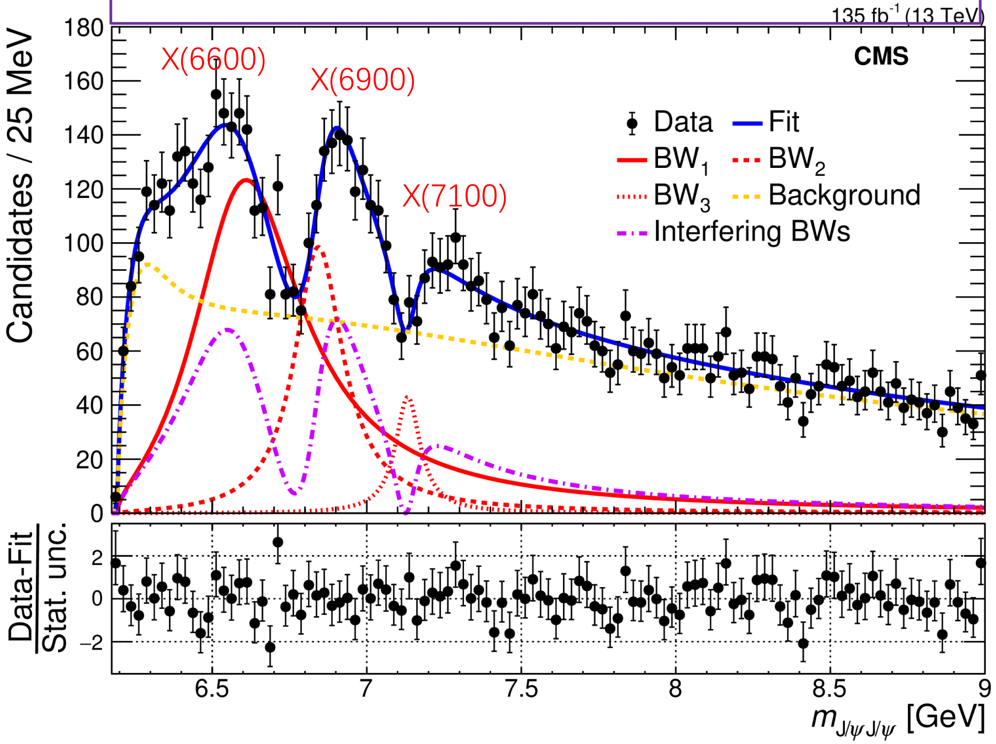


Phys.Rev.Lett. 132 (2024) 11, 111901



- LHCb model
  - Model I: background+2 auxiliary BWs+ X(6900) → poor description of 'dip' around 6.7 GeV
  - Model II: a “virtual” X(6700) to interfere with NRSPS background
- ATLAS model
  - Model A: interference among three resonances, two for the threshold hump and one for the X(6900).
  - Model B: a “virtual” X(6700) to interfere with NRSPS background
- CMS model
  - No-interference model: background + BW1 BW2 BW3
  - Interference model : background + BW1 BW2 BW3 + interference between BWs

Phys.Rev.Lett. 132 (2024) 11, 111901



7.9σ 4.7σ

- X(6600) X(7100) We provisionally adopt them as two physical structures.
- All exp see X(6900) and interference dip
  → have the same J^{PC}
  → X triplet to be a "family"

Are there systematic patterns among the triplet's parameters?

- **Shift attention from individual states to relationships among states**

Di-Charmonia: Inferences, Speculations, and Explanations?

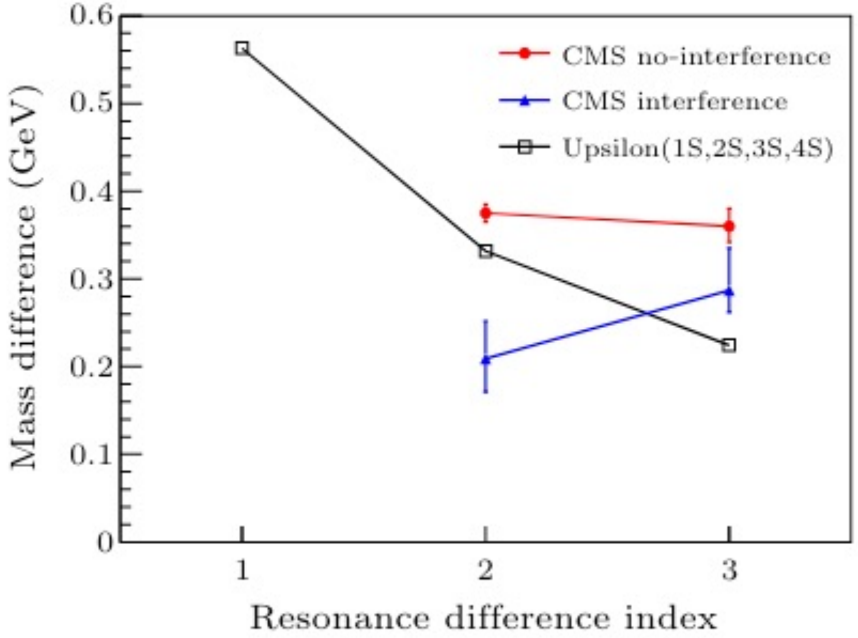


Fig1: The mass differences between neighboring states as a function of state index.

	$X(6600)$	$X(6900)$	$X(7100)$
non-Interf. [MeV]	M(BW1)	M(BW2)	M(BW3)
	6652 ± 10	6927 ± 9	7287^{+20}_{-18}

Interf. [MeV]	M(BW1)	M(BW2)	M(BW3)
	6638^{+43}_{-38}	6847^{+44}_{-28}	7134^{+48}_{-25}

$$\Delta m_i(\Upsilon) = m[\Upsilon(\{i+1\}S)] - m[\Upsilon(iS)],$$

$$\Delta m_i = m_{i+1} - m_i$$

$$m_i = 2, 3, 4 \ \ for\ X(6600), X(6900), and\ X(7100)$$

- **Mass differences are relatively large**
  - Larger than is generally characteristic of spin or orbital mass splittings
- **X mass splittings are roughly similar to those for 2S–4S Y's.** (≈ linear regime of confining potential)

X triplet to be a family of radial excitations

Di-Charmonia: Inferences, Speculations, and Explanations?

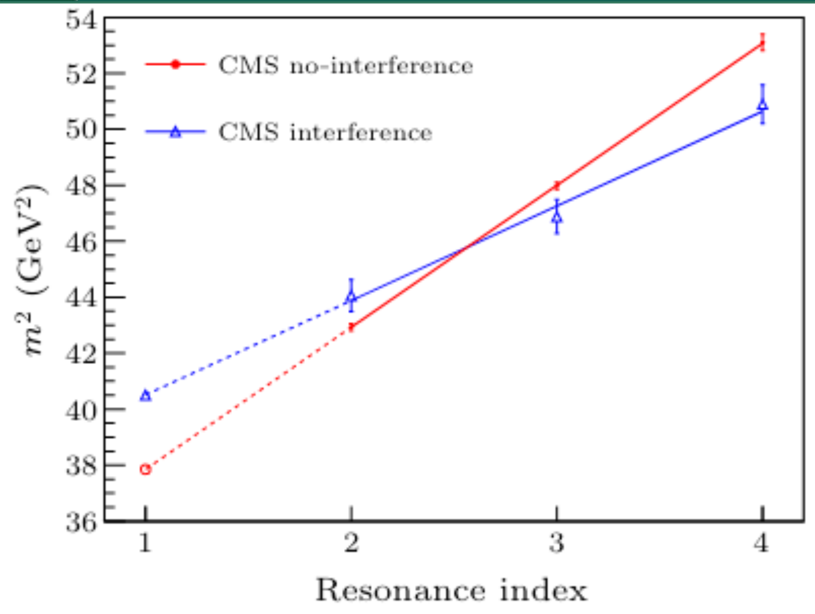


Fig1: A Regge-like plot of the square of the CMS X(6600), X(6900), and X(7100) masses as a function of their index i = 2, 3, and 4.

Nucl. Phys. B. 966:115393, 2021

- Based on Regge trajectory:

$$J = \alpha m^2 + \alpha_0 \cdots\cdots ①$$

J : spin or angular momentum of hadron

Or

$$n_r = \beta m^2 + \beta_0 \cdots\cdots ②$$

n_r : radial quantum number

Projected Mass (GeV)		
	No-interf	Interf
n_r = 1	6.152 ± 0.020	6.359 ± 0.058
n_r = 5	7.951 ± 0.028	7.598 ± 0.057

- Origin of threshold excess is unknown: tetraquark? feeddown? threshold enhancement?...other potential complications
- IF a family member : predict mass based on interference model Regge

- Can predict mass of hypothetical next family member
- n=5 state above $\Xi_{cc}\Xi_{cc}$threshold(~7240 MeV): X(7100) may be last member of **J/ψ J/ψ** family

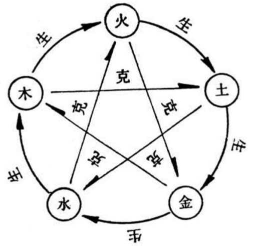
Summary and ongoing

- From X(3872) meson to all-heavy tetraquark states
- Three new structures observed in J/ψJ/ψ spectrum—by CMS, LHCb, ATLAS
- X mass confirm to Regge trajectory
- Everything seems to point to family of all-heavy tetraquark (candidates)
- More data also means all-heavy tetraquarks contain bottom quarks···

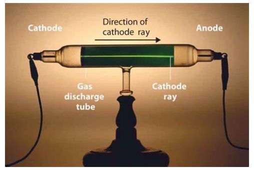
Thanks!

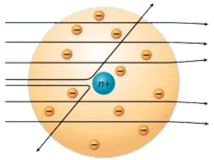
Back up

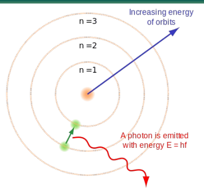
The History of the Atom

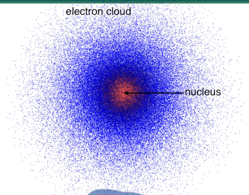


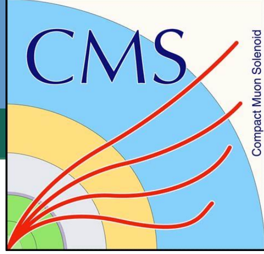
Five Elements

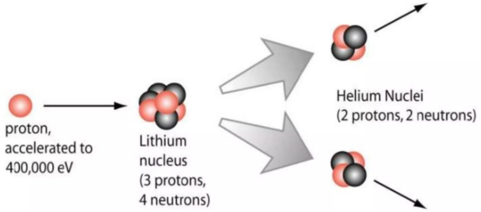
















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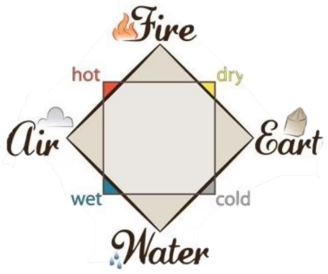


The four element theory

1803
John Dalton
Solid sphere model

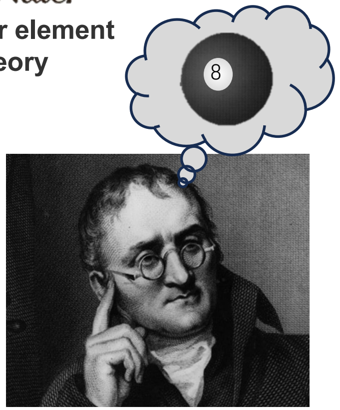
1904
JJ Thomson
Plum pudding model

1911
Ernest Rutherford
Nuclear model

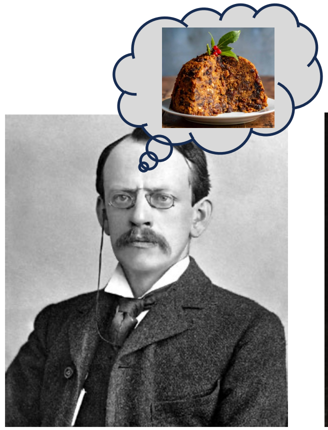
1913
Niels Bohr
Planetary model

1926
Erwin Schrödinger
Quantum model

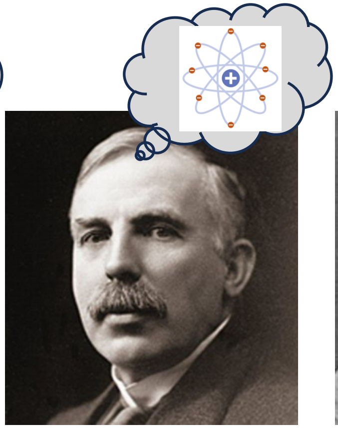
1932
Cockcroft and Walton
Splitting the atom



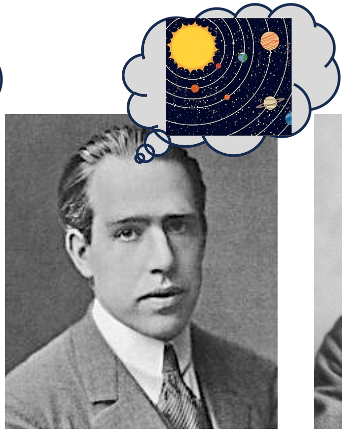
John Dalton
Atoms are indivisible spheres unique to each element, combining to form compounds.



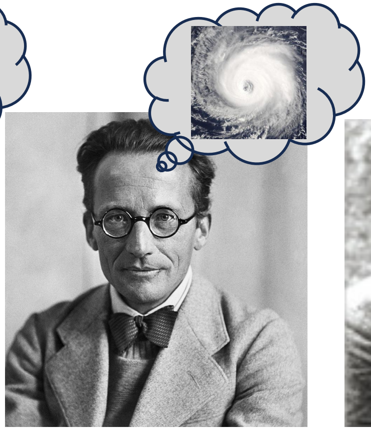
JJ Thomson
Atoms have negatively charged electrons within a positive "plum pudding."



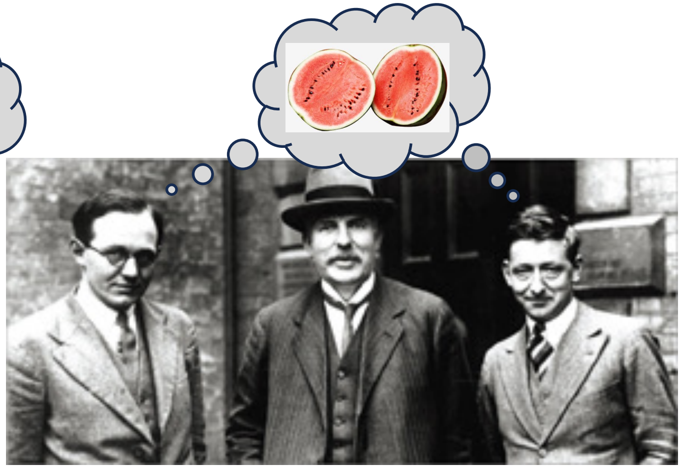
Ernest Rutherford
Atoms have a dense nucleus with electrons in surrounding space.



Niels Bohr
Electrons occupy specific energy levels around the nucleus.

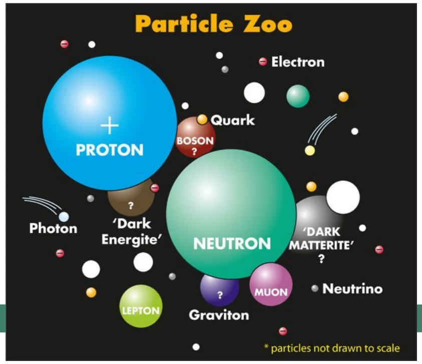


Erwin Schrödinger
Electrons exist in probability-based clouds, not fixed orbits.



Ernest Rutherford **(center)** encouraged **Ernest Walton** **(left)** and **John Cockcroft** **(right)** to build a high-voltage accelerator to split the atom.

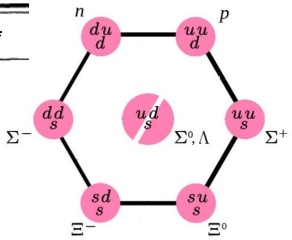
The History of the Quark Model

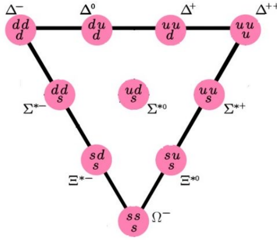


Particle Zoo need an administrator!!

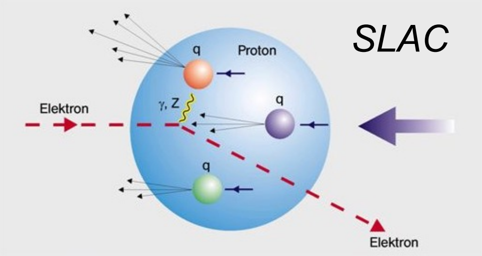
Name	Model **
π	$\mathfrak{N}+\bar{\mathfrak{N}}$
$\theta(\tau)$	$\mathfrak{N}+\bar{\Lambda}$
$\bar{\theta}(\bar{\tau})$	$\bar{\mathfrak{N}}+\Lambda$
Σ	$\mathfrak{N}+\bar{\mathfrak{N}}+\Lambda$
Ξ	$\bar{\mathfrak{N}}+\Lambda+\Lambda$

1956
Shoichi Sakata
p, n, Λ^0 model

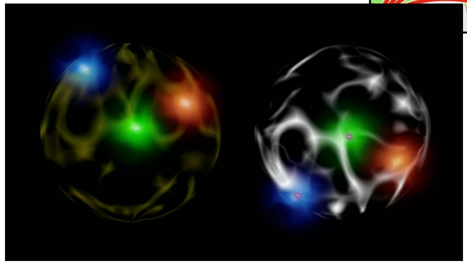




1964
Murray Gell-Mann
George Zweig
u, d, s model

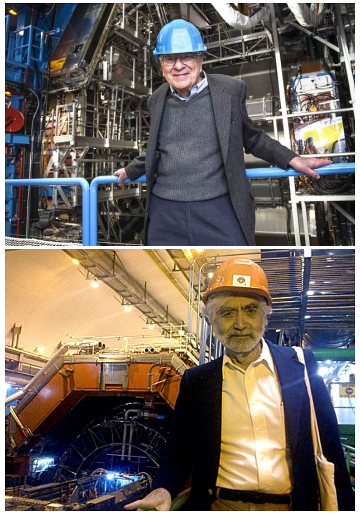


1969
deep-inelastic e-p scattering



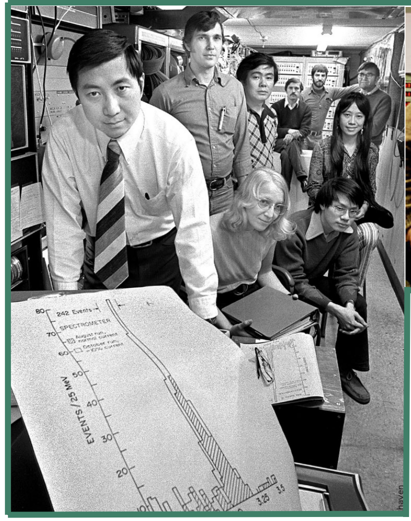
1973
quantum chromodynamics (QCD)
Phys. Lett. B 47 (1973) 365-368

Shoichi Sakata



Murray Gell-Mann (top)
George Zweig (bottom) at CERN

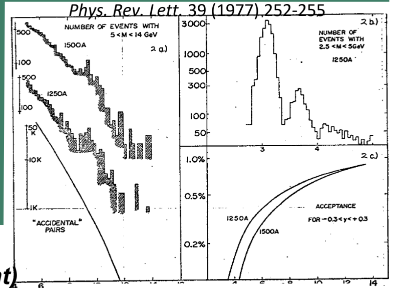
Phys. Rev. Lett., 33:1404, 1974



Phys. Rev. Lett. 33:1406, 2 1974

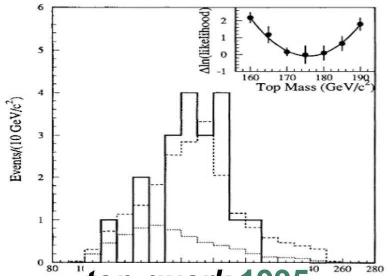
Samuel Ting and his group (left)
Burton Richter and his group (right)
***J/ψ* 1974**

Phys. Rev. Lett. 39 (1977) 252-255



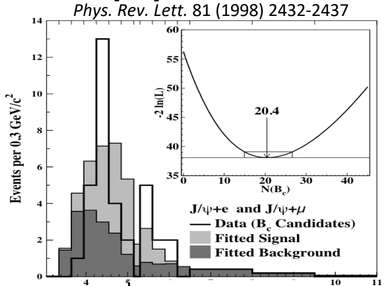
***ϒ*, bottom quark 1977**

Phys. Rev. Lett. 74 (1995) 2626-2631

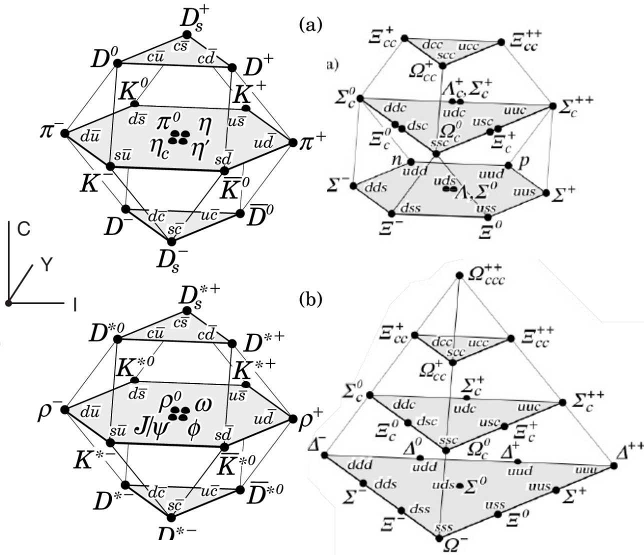


***top quark* 1995**

Phys. Rev. Lett. 81 (1998) 2432-2437



***B_c^+ meson* 1998**



Quark model of hadrons was utterly triumphant