Hadron Spectroscopy

Part II: Exotic Hadrons

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National Nuclear Physics Summer School
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INSTITUTE for NUCLEAR THEORY

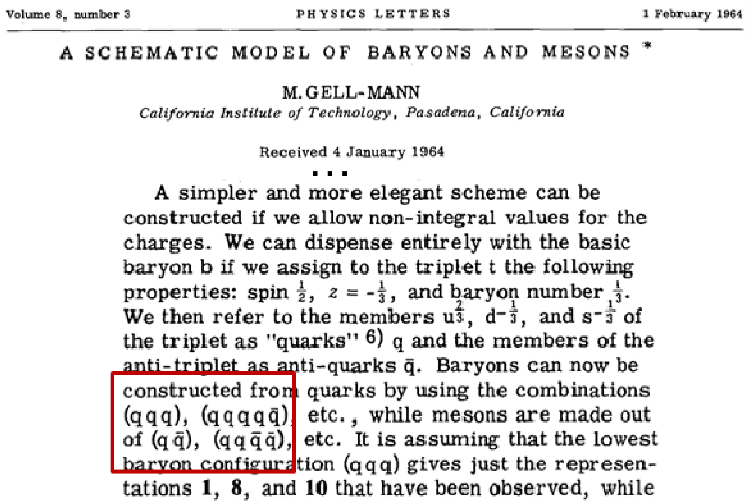
Comments on exotic hadron spectroscopy

- Lots of experimental and theoretical activity in recent years, especially for heavy quarkonium-like exotic state candidates (“XYZ states”)
- Many interesting effects beyond conventional hadrons are now well established experimentally, but their theoretical interpretation are subject of hot disputes
- You may be led to diametrically opposite points of view about what is being observed, depending whom you invite to speak. No generally accepted consensus.
- I will present most, but not all, of existing experimental evidence for hadron exotics
- I will also give you my own point of view at the present situation

Nomenclature

- "Exotic hadrons" means different thing to different people
- I use a broad definition of this term:
  - Any strongly interacting particle with substructure not yet experimentally proven to create a well distinguishable family of states
  - In practice, any hadron which is not a $q\bar{q}$ meson, a qqq baryon or a nucleus
- Such possible exotic hadrons can be:
  - **Explicitly exotic** by having quantum numbers not encountered in simple quark model. Examples:
    - Mesons with $J^{PC}=0^{--}$, 0^{+-},1^{-+},2^{+-} ($q\bar{q}$ can create only $P=(-1)^{l+1}$,$C=(-1)^{l+S}$ with $|l-S| \leq J \leq l+S$)
    - Baryon with anti-strangeness or anti-baryon with strangeness
    - Some communities reserve "exotic hadrons" term to mean "explicitly exotic hadrons"
  - **Crypto exotic** states i.e. with properties found among conventional hadrons but nevertheless not with a $q\bar{q}$ or qqq substructure
- Be also aware that "exotic hadron" is (usually) not an "exotic particle".
  - The latter term is reserved for particles not made out of fundamental fermions or bosons found in Standard Model, e.g. squark.
  - "Exotica at LHC" is not going to have a session/chapter on "exotic hadrons". It will be about searches for physics beyond SM at LHC.
- Tetra- and penta-quarks usually mean tightly bound systems, with just one color confining volume. Yet, some people use it more broadly and include molecular systems in it.

“Exotic” multiquark states conceived already at the birth of Quark Model



Volume 8, number 3 PHYSICS LETTERS 1 February 1964

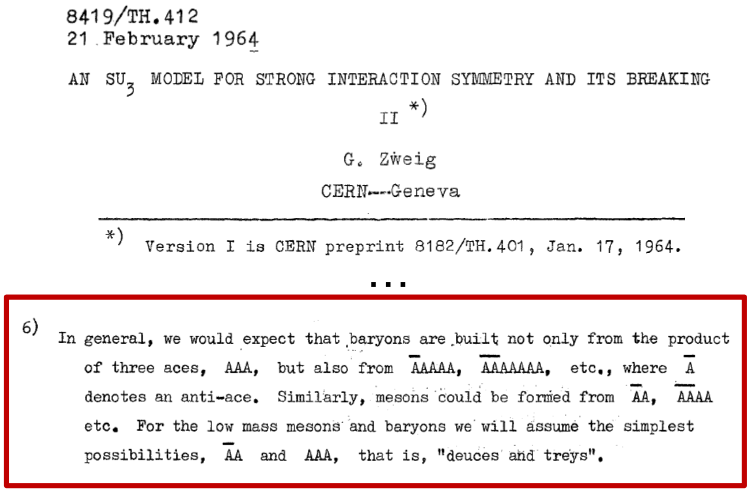
A SCHEMATIC MODEL OF BARYONS AND MESONS *

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 (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 baryon configuration (qqq) gives just the representations **1**, **8**, and **10** that have been observed, while



8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING
II *)

G. Zweig
CERN---Geneva

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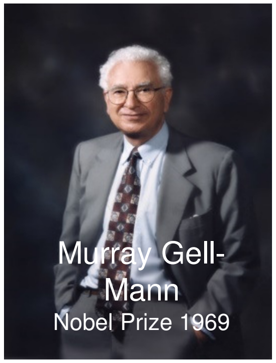
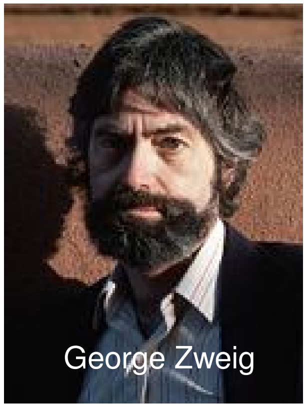
*) Version I is CERN preprint 8182/TH.401, Jan. 17, 1964.

...

6) In general, we would expect that baryons are built not only from the product of three aces, AAA, but also from $\bar{A}AAAA$, $\bar{A}\bar{A}AAAAA$, etc., where $\bar{A}$ denotes an anti-ace. Similarly, mesons could be formed from $\bar{A}A$, $\bar{A}\bar{A}AA$ etc. For the low mass mesons and baryons we will assume the simplest possibilities, $\bar{A}A$ and AAA, that is, "deuces and treys".



Murray Gell-Mann
Nobel Prize 1969

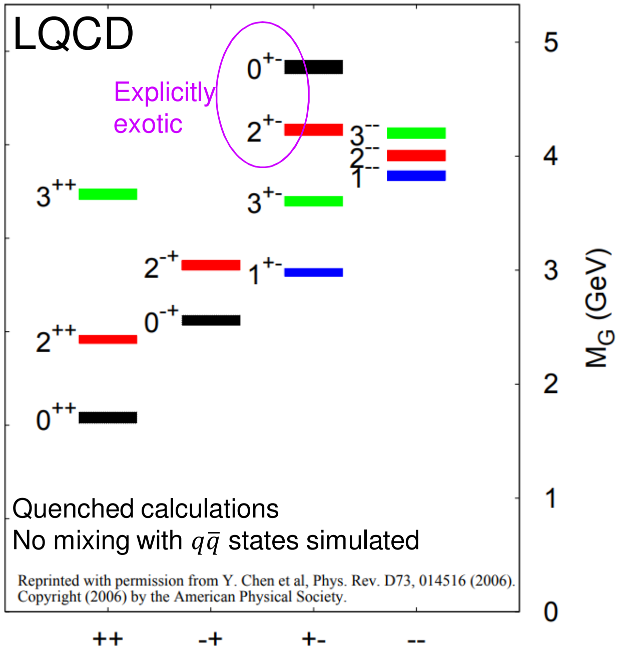


George Zweig

Diaquarks motivated by QCD, provide additional inspiration for tetra- and penta-quarks (discuss this later)

QCD predicts existence of exotic hadrons with gluon as a constituent

- Gluons ($J^{PC}=1^{--}$) carry color charge! (more exactly color-anticolor)
- Glueballs:
  - Two gluons in color singlet and color neutral configuration. Can have its own excitations.
  - No constituent quarks inside, only fluctuating virtual $q\bar{q}$ pairs, i.e. “sea” quarks (necessarily isoscalars!).



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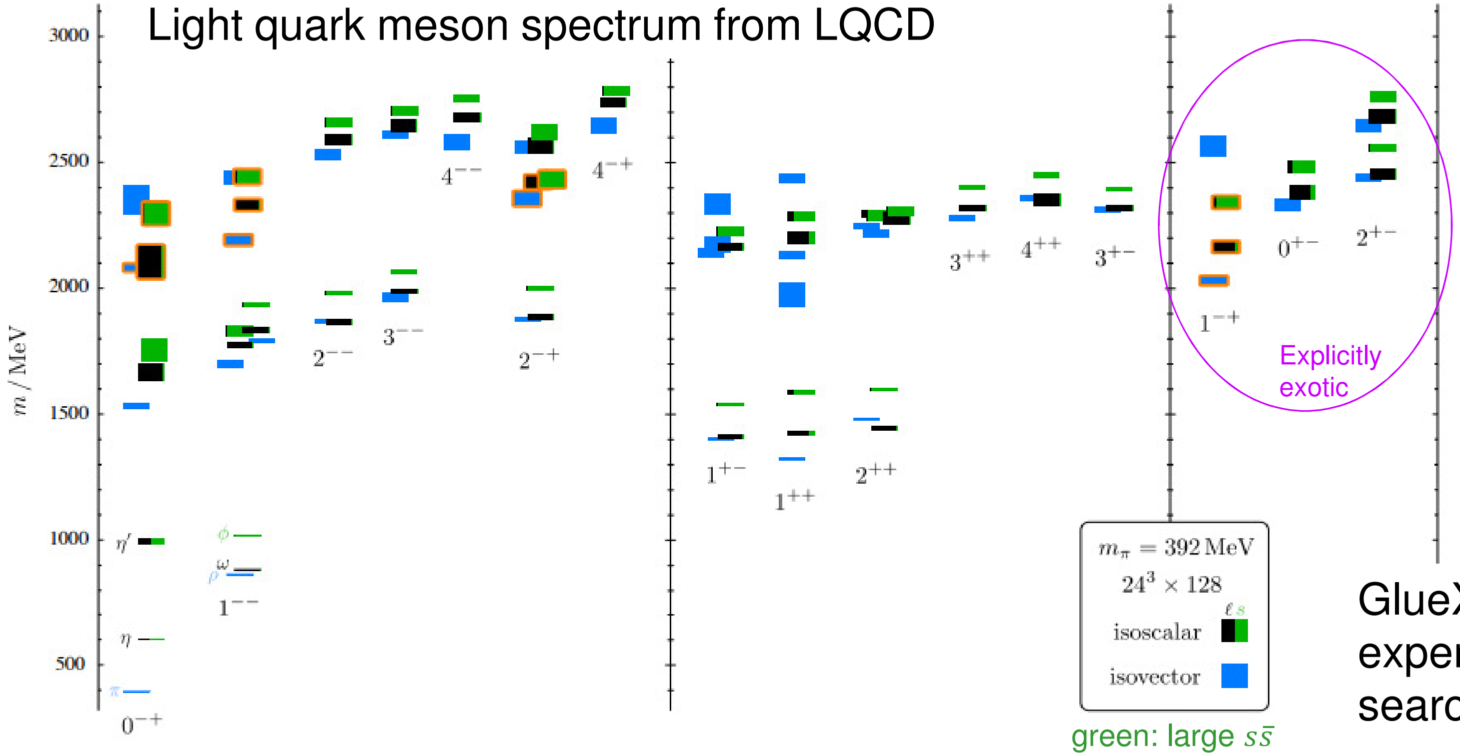
Crypto-exotic glueballs are likely to mix with nearby $q\bar{q}$ states (which are often broad).

Production and decay pattern of glueballs different that of $q\bar{q}$ states, e.g. small coupling to $\gamma\gamma$, large to gg. Mixing with $q\bar{q}$ states can obscure these characteristics.

No clear cut candidates have been found in the data so far. Detailed discussion can be found e.g. among the review notes published by PDG (see 2016 edition notes on “Quark Model”, “Non $q\bar{q}$ candidates”, “Note on scalar mesons below 2 GeV”).

Hybrids

- Excitations of color fields stretched between constituent quarks (can happen in both mesons and baryons)
- Expected at higher masses than quark states they excite



Light quark meson spectrum from LQCD

Explicitly exotic

green: large $s\bar{s}$

orange: large gluon contribution

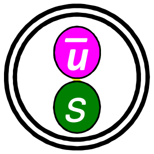
Hadron Spectrum Collaboration, PRD88, 094505 (2013)

GlueX at JLab is one of the experiments dedicated to their searches

Conventional and exotic hadrons

Conventional

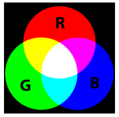
Strong binding.
Compact systems.



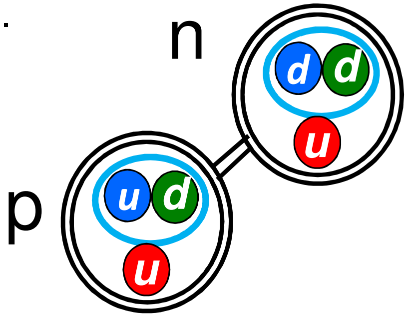
(s$\bar{q}$)
K meson

((sd)u)
Λ baryon

Meson and baryons motivated Quark Model and QCD

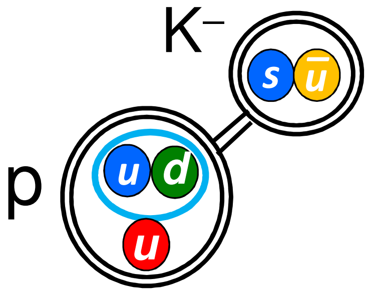


Weak binding. Large systems.

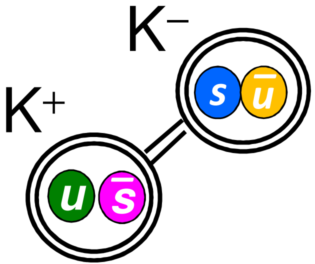


(u(ud)) (u(dd))
deutron

Baryonic molecules exists!



(u(ud)) (s$\bar{u}$))
KN **molecule**

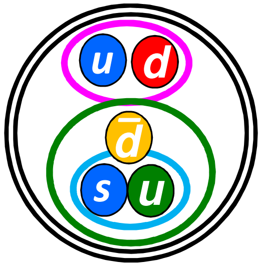


(s$\bar{q}$) (s$\bar{q}$)
$\bar{K}$K **molecule**

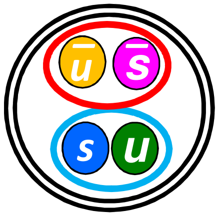
Are molecular forces in such systems strong enough to create bound states, or pronounced effects?

Exotic

Strong binding. Compact systems.

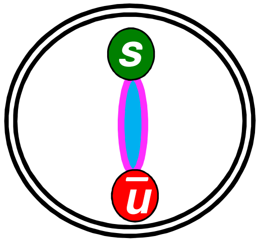


(($\bar{q}$(sq))(qq))
pentaquark

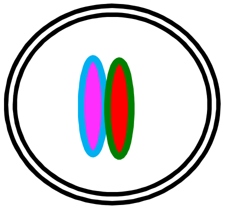


(($\bar{s}\bar{q}$)(sq))
tetraquark

QCD predicts attractive forces in some of such configurations.
Do they live long enough to produce observable states/effects ?



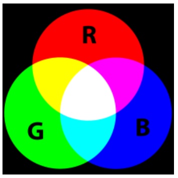
(s$\bar{q}$g)
Hybrid meson



(gg)
Glueball

Firmly expected in QCD

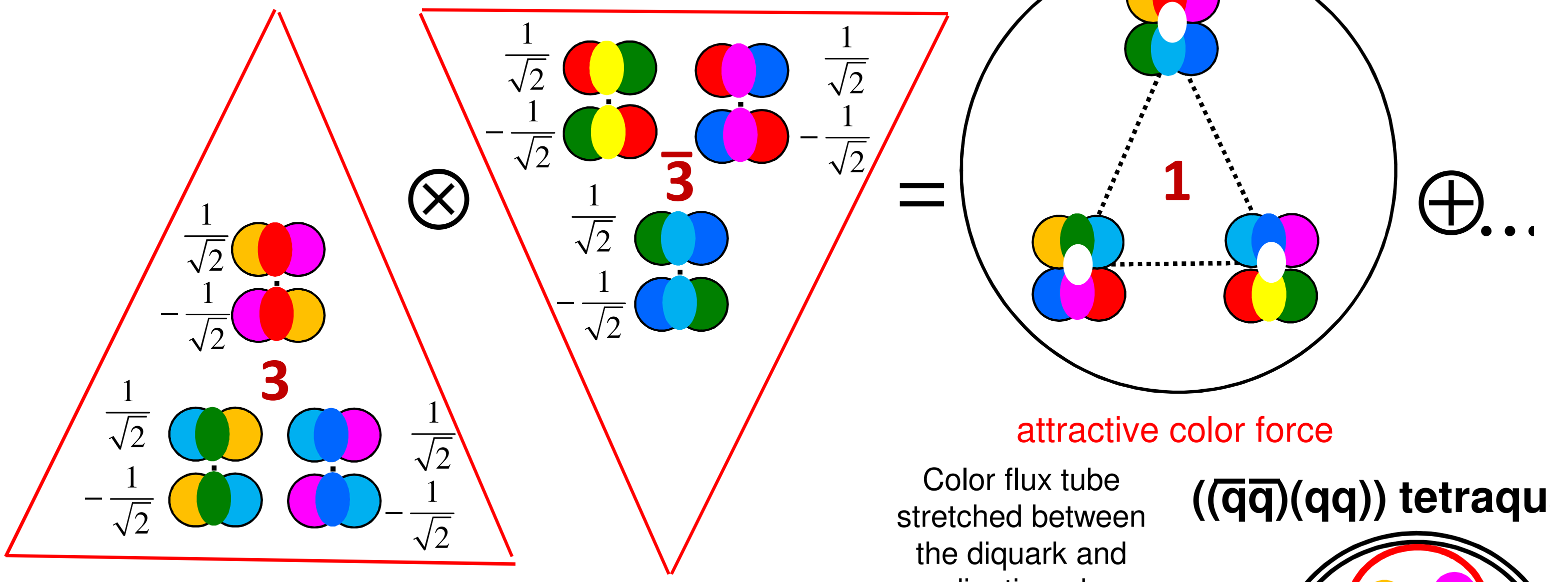
Diaquarks can make tetraquarks!



color triplet

color antitriplet

color singlet



attractive color force

Tetraquarks from diquarks and diantiquarks

However, it is not clear if an efficient mechanisms to suppress the fall-apart mode to two mesons exists, especially when all quarks are light.

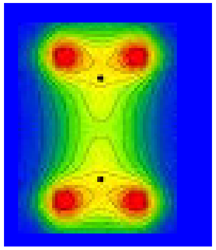
attractive color force

$(\overline{qq})$ diantiquark

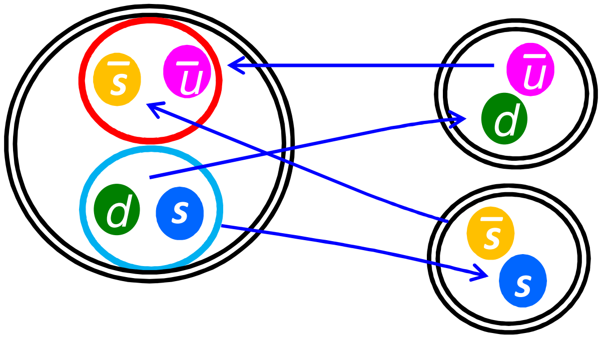
attractive color force

(qq) diquark

Color flux tube stretched between the diquark and diantiquark



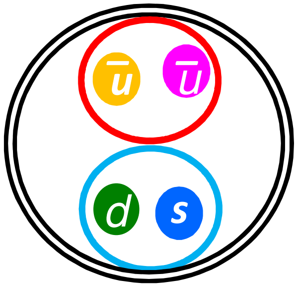
$((\overline{qq})(qq))$ tetraquark



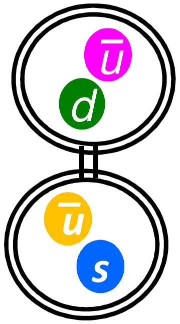
Tetraquarks vs meson-meson molecules

- Additional complication arises for experimental tetraquark candidates, since the same quark content can, in principle, create a molecular meson-meson molecule
- However, mass spectrum from these two types of binding are very different

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



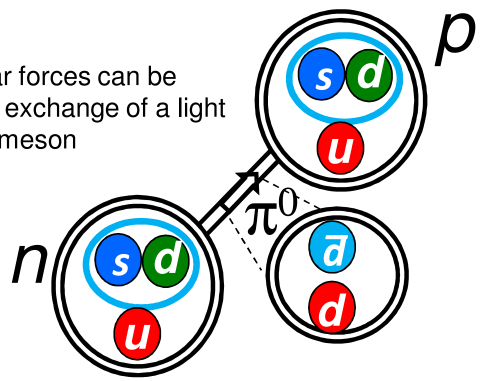
$(q\bar{q})$-$(q\bar{q})$
meson-meson molecule



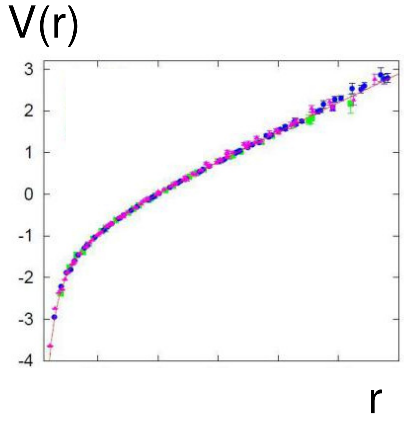
We don't know if either one exist (“exotic hadron”)

(qqq)- (qqq)
baryon-baryon molecule
e.g. deuteron

Molecular forces can be described as exchange of a light meson

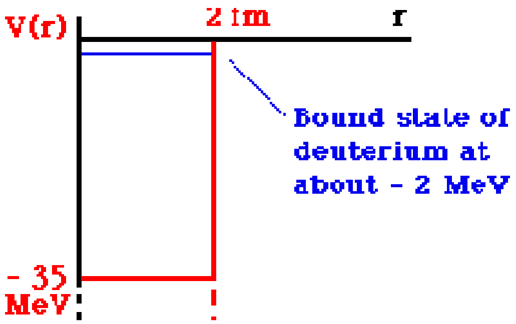


We exist thanks to these structures!



Very rich mass spectrum expected!

However, states can be undetectable if extremely broad.



Bound state of deuterium at about - 2 MeV

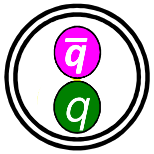
Typically expect only **one state**
$n=1$, $L=0$.

Fall apart prevented by spatial separation – long-lived states.

Mass and J^P fairly constrained from the constituents.

Puzzles of isosinglet light unflavored scalars

Unflavored

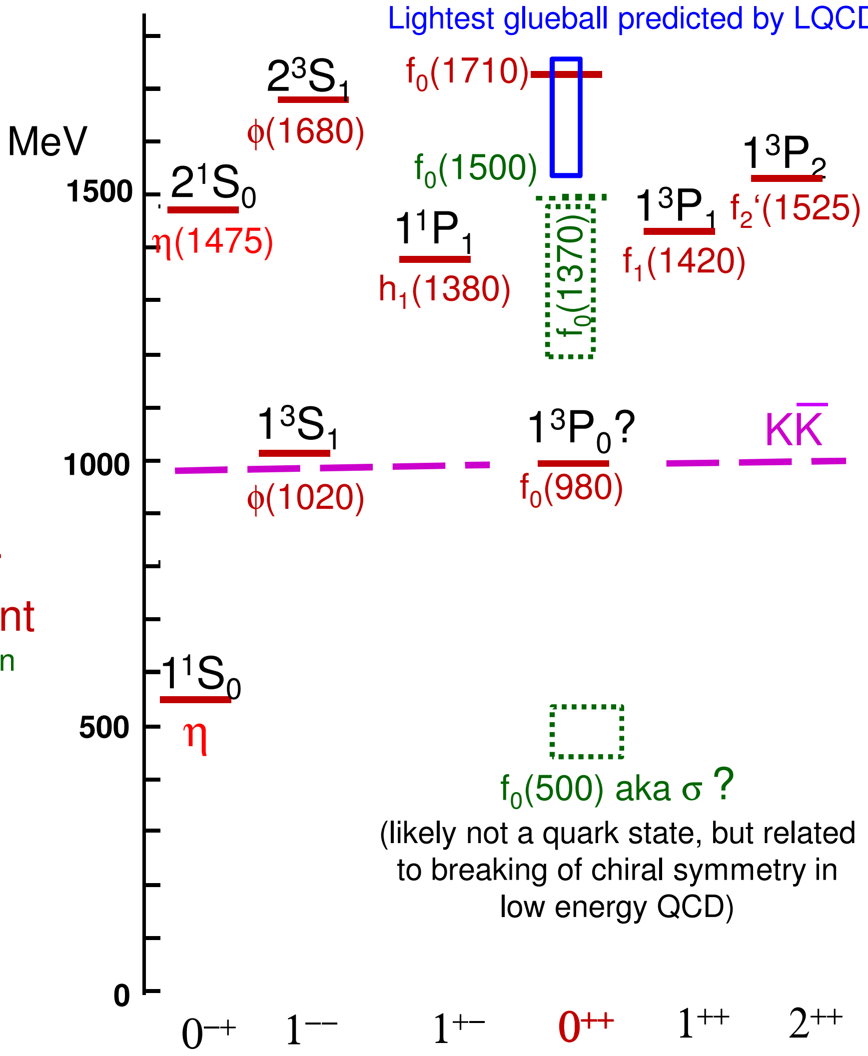


q=u,d,s

I=0

with larger $s\bar{s}$ component

(except for green colored states)



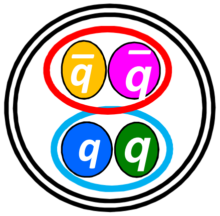
Experimental difficulties of distinguishing broad 0^{++} resonances from smooth backgrounds may be partially to blame for too many candidate states.

Lightest glueball could be mixing with n^3P_0 (n=1,2?) $q\bar{q}$ states in 1500-1700 region.

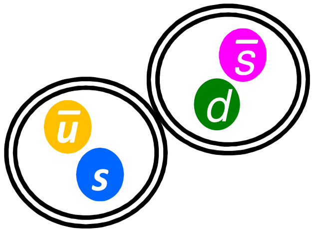
$f_0(1500)$ is the best candidate for large glueball component.

$f_0(980)$ mass is too low for "normal" 1^3P_0 state, which should lie above 1^3S_1.

Popular explanations for the $f_0(980)$ anomaly:



Tetraquark



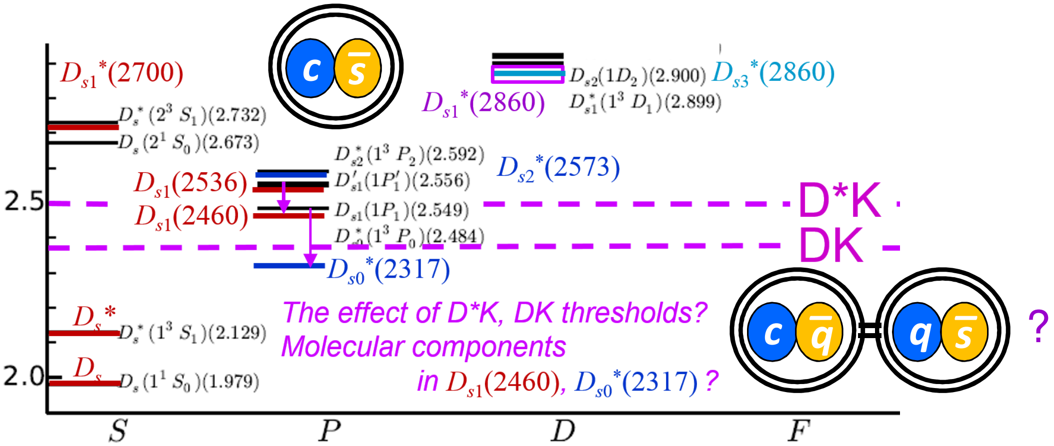
$K\bar{K}$ molecule

Mixed with the 1^3P_0 $q\bar{q}$ state?

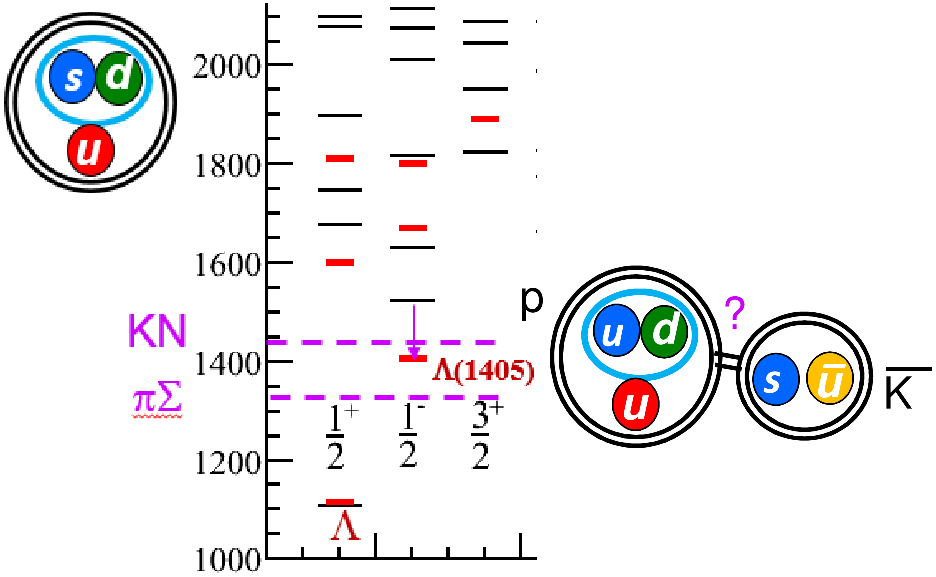
Motivated by coincidence with the $K\bar{K}$ threshold

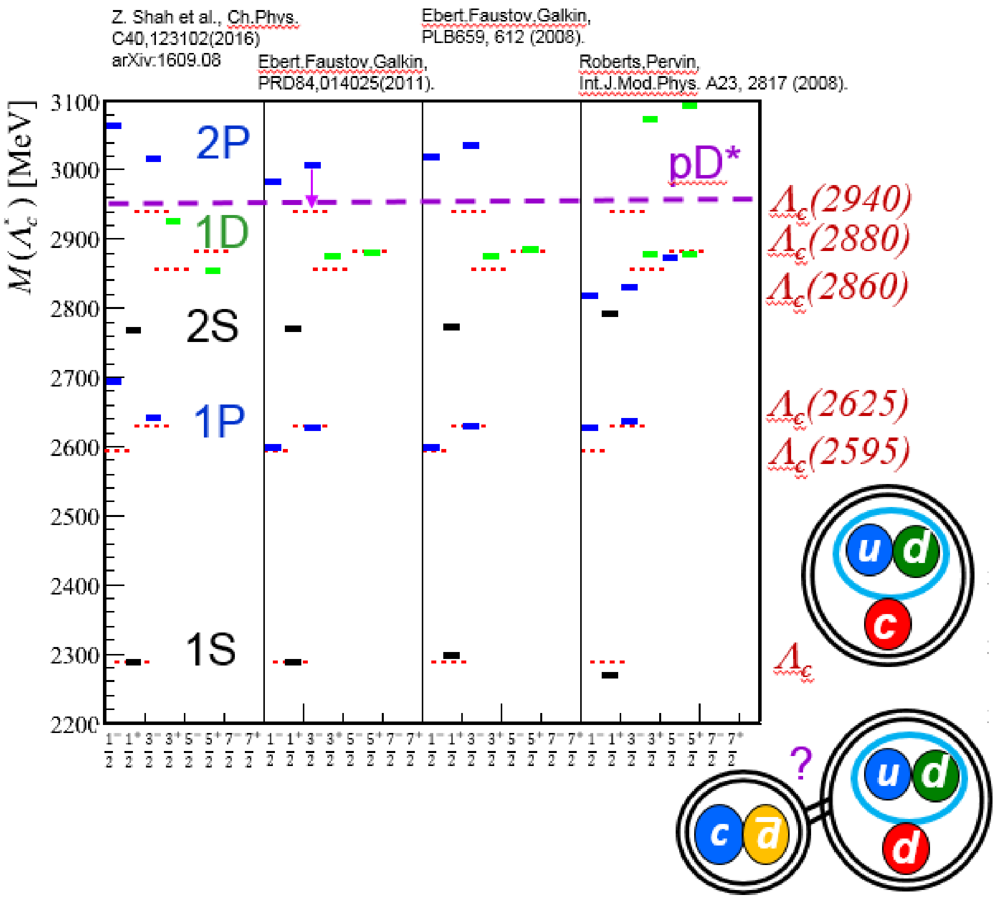
Other "non-exotic" explanations exist.

Other near-threshold anomalies mentioned yesterday



The effect of D*K, DK thresholds?
Molecular components
in $D_{s1}(2460)$, $D_{s0}^*(2317)$?

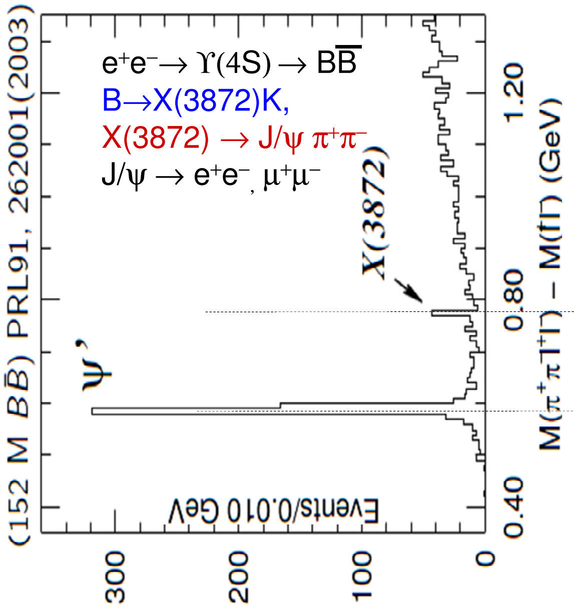




Discovery of X(3872)

2nd charmonium revolution, June 2003

Belle PRL 91, 262001 (2003)
(1261 citations)



seen in B-decays by Belle, BaBar, LHCb (later also in other production and decay modes)

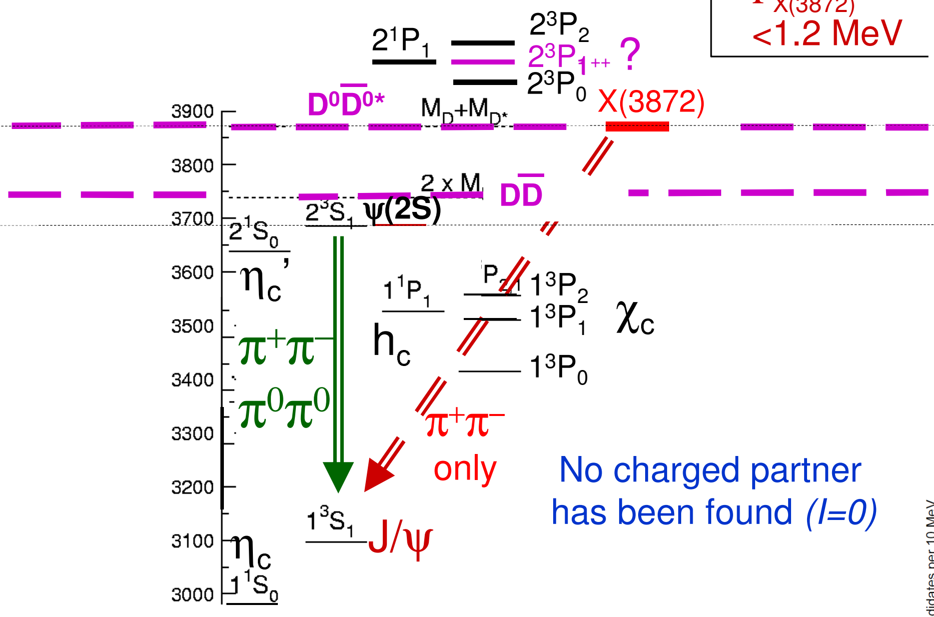
$J^{PC}=1^{++}$ established

by LHCb from studies of angular correlation in the B-decay chain **PRL 110, 222001 (2013), PR D92, 011102 (2015).**

Mass indistinguishable from $D^0\overline{D}^{0*}$ threshold:

$$\Delta M_{th} = M_{X(3872)} - M_{D^0\overline{D}^{0*}} = 0.0 \pm 0.2 \text{ MeV}$$

very narrow
$\Gamma_{X(3872)} < 1.2$ MeV



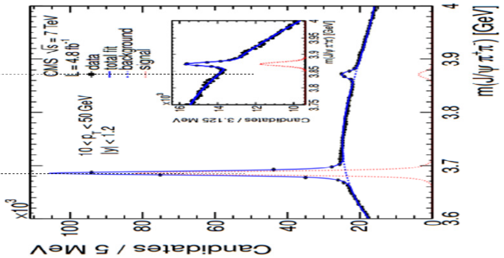
No charged partner has been found *(I=0)*

$2^3P_1 \to \pi\pi\ 1^3S_1$ expected to have tiny rates,
In fact not observed in $b\bar{b}$ system.

- *Unexpected discovery, but not to all …*

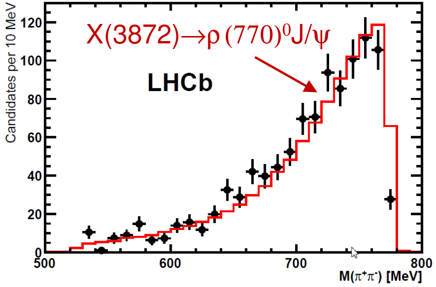
$pp \to X(3872) + \ldots$,
$X(3872) \to J/\psi\, \pi^+\pi^-$
$J/\psi \to \mu^+\mu^-$

CMS JHEP 04, 154 (2013)



seen in prompt production at Tevatron (CDF,D0) and LHC (LHCb, CMS, ATLAS)

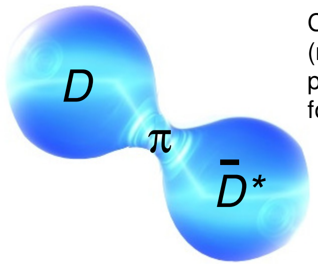
LHCb PR D92 (2015) 011102



Isospin violation in the decay!

Is X(3872) a $D\overline{D^*}$ molecule?

- **Molecular charmonium first discussed by Voloshin & Okun in 1976 JETP Lett. 23 (1976) 333, Pisma Zh.Eksp.Teor.Fiz. 23 (1976) 369.**
- **Numerical predictions** of N. Tornqvist **Z. Phys. C61 (1994) 525.**



Calculations based on the model of deuteron (np molecule) with scalar and tensor potentials representing single pion exchange forces.

$$V_\pi(r) = -\gamma V_0\,[D\cdot C(r) + S_{12}(\hat{r})\cdot T(r)]\,,$$
$$C(r) = \frac{\mu^2}{m_\pi^2}\frac{e^{-\mu r}}{m_\pi r}\,,$$
$$T(r) = C(r)[1 + \frac{3}{\mu r} + \frac{3}{(\mu r)^2}]\,,$$
$$\mu^2 = m_\pi^2 - (M_V - M_P)^2$$

Predicted a decade before the X(3872) discovery by Belle!

The role of pion exchange force in binding such molecule is hotly disputed see e.g. V.Baru et al PR D91, 034002 (2015) , but qualitative expectations are generic.

Generic prediction

Predicted the mass and J^{PC}

J of a molecule
=
$J_1 \otimes J_2$
of constituents
(S-wave interactions)

Composite	J^{PC}	Deuson
$D\bar{D}^*$	0^{-+}	$\eta_c(\approx 3870)$
$D\bar{D}^*$	1^{++} ✓	$\chi_{c1}(\approx 3870)$
D^*D^*	0^{++}	$\chi_{c0}(\approx 4015)$
$D^*\bar{D}^*$	0^{-+}	$\eta_c(\approx 4015)$
$D^*\bar{D}^*$	1^{+-}	$h_{c0}(\approx 4015)$
$D^*\bar{D}^*$	2^{++}	$\chi_{c2}(\approx 4015)$
$B\bar{B}^*$	0^{-+}	$\eta_b(\approx 10545)$
$B\bar{B}^*$	1^{++}	$\chi_{b1}(\approx 10562)$
$B^*\bar{B}^*$	0^{++}	$\chi_{b0}(\approx 10582)$
$B^*\bar{B}^*$	0^{-+}	$\eta_b(\approx 10590)$
$B^*\bar{B}^*$	1^{+-}	$h_b(\approx 10608)$

✓

X(3872) MASS

VALUE (MeV)
3871.69± 0.17

Mass of a molecule
=
mass of
constituents
–
“nuclear binding“
O(10^{0-1}) MeV

+
a few MeV
for virtual states

- Decays to charmonium suppressed via spatial separation of c and $\overline{c}$
- The observed X(3872) mass:
  - Consistent with the $D^0\overline{D^{*0}}$ threshold
  - 8MeV below the $D^+\overline{D^{*-}}$ threshold
- As a consequence the molecular model predicts a large isospin violation in its decays:
- The molecular model also predicts a large rate to fall-apart modes

Generic prediction

Explains narrow width

X(3872) WIDTH

VALUE (MeV)	CL%
<1.2	90

✓

N.Tornqvist PL, B590, 209 (2004).
Prediction specific to this molecule
(large isopin violation in D meson masses)

Explains Isospin violation

Generic prediction

Predicted large fall apart rates

X(3872) DECAY MODES

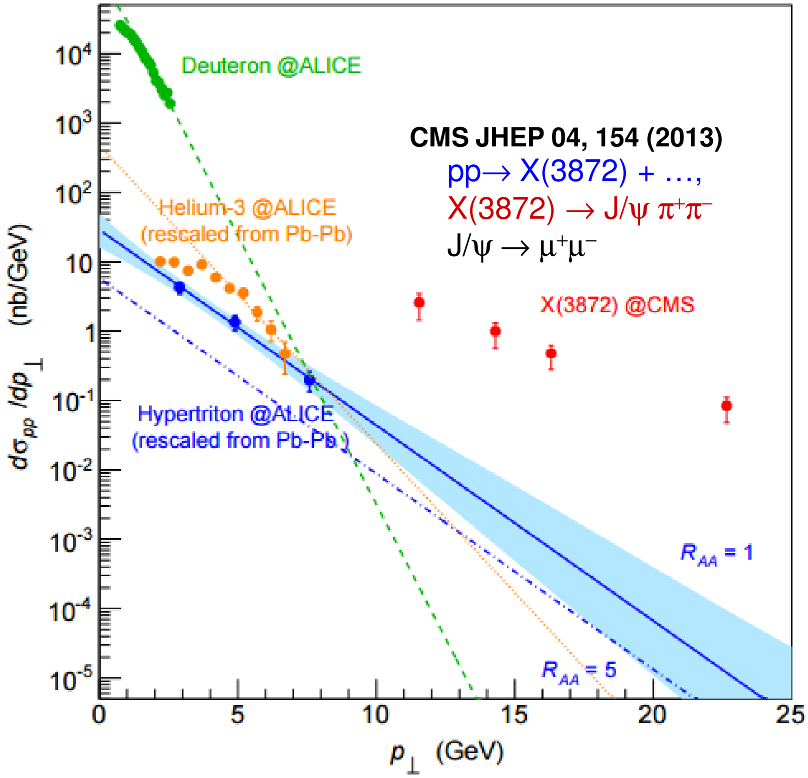
	Mode	Fraction (Γ_i/Γ)
Γ_1	e^+e^-	
Γ_2	$\pi^+\pi^- J/\psi(1S)$	> 2.6 %
Γ_3	$\rho^0 J/\psi(1S)$	
Γ_4	$\omega J/\psi(1S)$	> 1.9 %
Γ_5	$D^0\overline{D}{}^0\pi^0$	>32 %
Γ_6	$\overline{D}{}^{*0}D^0$	>24 %

I=1
I=0
✓

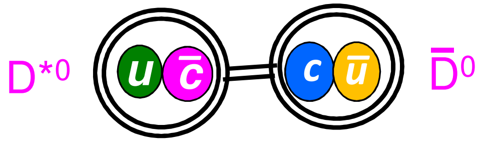
✓
tail of X(3872)

X(3872) is not a molecule?

Esposito, Guerrieri, Maiani, Piccinini, Pilloni, Polosa, Riquer PRD 92, 034028 (2015)

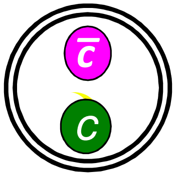


- prompt production rate at LHC (and Tevatron) way too large for a loosely-bound molecular object



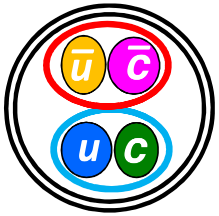
☐

- at par with prompt production rates for ordinary charmonium states



☑

- or expectations for tightly-bound tetraquark states



☑

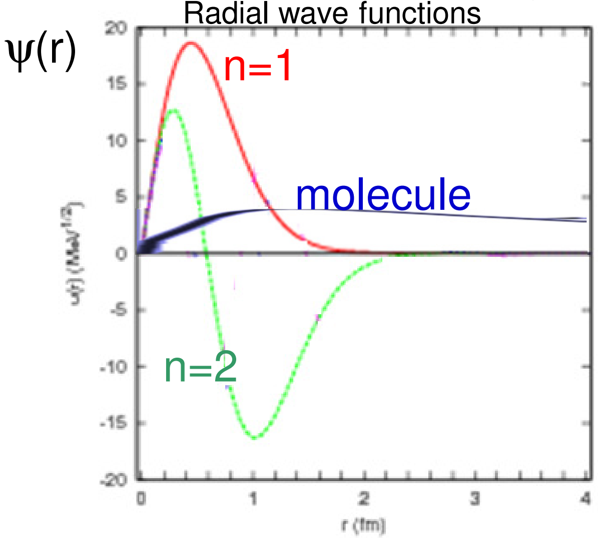
Radiative decays of X(3872) in LHCb

LHCb NP B886 (2014) 665

$BR(X(3872)\to\psi(2S)\gamma)/BR(X(3872)\to J/\psi(1S))$

$= 2.48 \pm 0.64 \pm 0.29$ (>0 at 4.4σ)

$BR \sim |\langle\psi_f|\, r\, |\psi_i\rangle|^2\, E_\gamma^3$



$|\langle 2S|\, r\, |2P\rangle|^2 \gg |\langle 1S|\, r\, |2P\rangle|^2$

$\chi_{c1}(2^3P_{1++})$ $\boxed{\gamma}$

$|\langle 2S|\, r\, |\text{mole.}\rangle|^2 \ll |\langle 1S|\, r\, |\text{mole.}\rangle|^2$

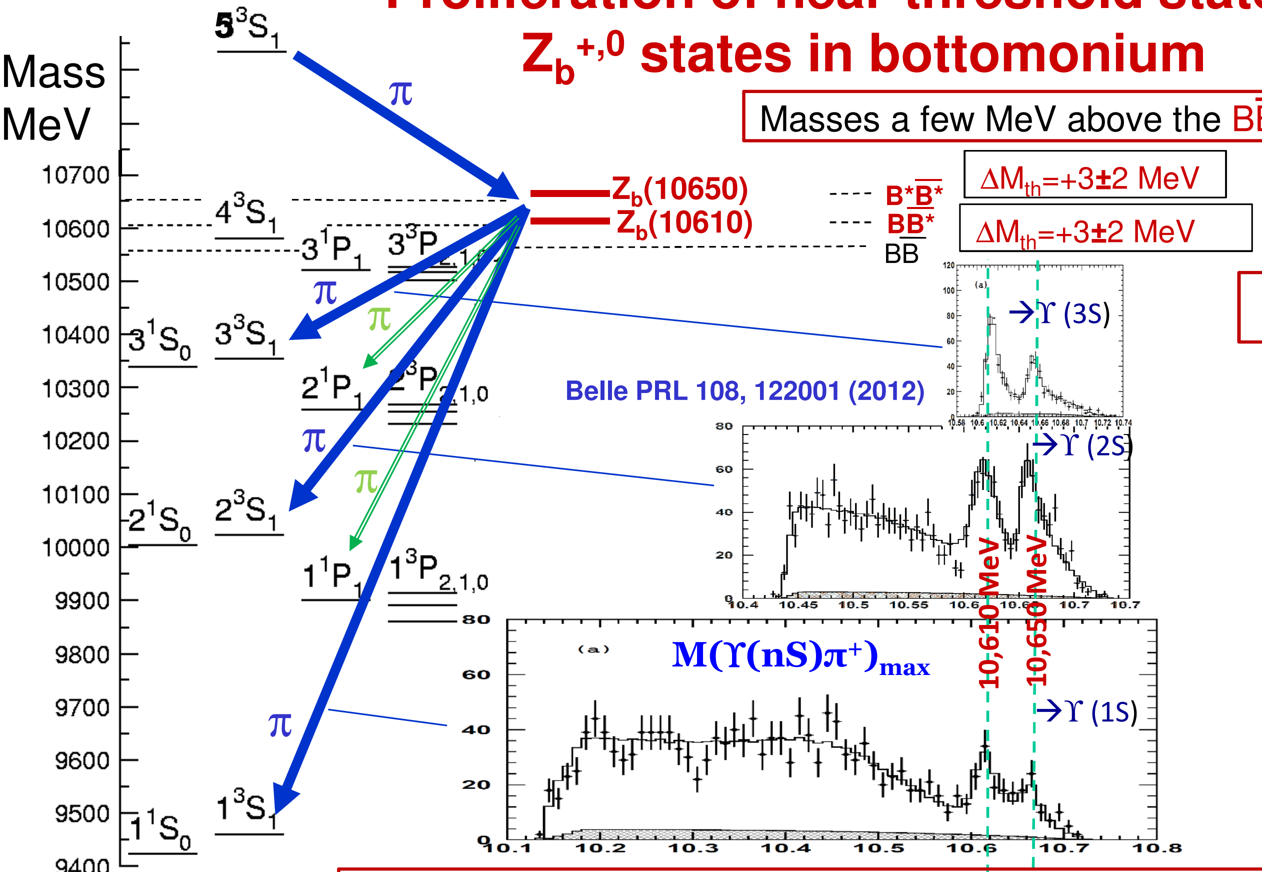
molecule ☐

- X(3872) is likely a mixture of a $\chi_{c1}(2^3P_{1++})$ charmonium state and of $D\overline{D}^*$ molecule

see e.g. C. Hanhart et al. Eur.Phys.J. A47,101 (2011)
Interplay of quark and meson degrees of freedom in a near-threshold resonance: multi-channel case

Mixing more than one dynamics in one physical state is an important lesson from X(3872) !

Proliferation of near-threshold states: $Z_b^{+,0}$ states in bottomonium



Masses a few MeV above the $B\bar{B}^*$, $B^*\bar{B}^*$ thresholds ✓

ΔM_{th}=+3±2 MeV

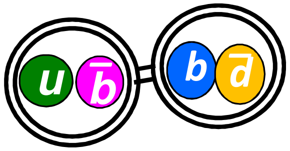
ΔM_{th}=+3±2 MeV

Γ 11.5± 2.2 / 18.4± 2.4 MeV ✓

Both $J^{P(C)}=1^{+(-)}$ ✓

F.-K.Guo, C.Hanhart, et al
PRD 93, 074031 (2016),
arXiv:1602.00940
The most sophisticated data analysis to date
$Z_b(10610)$ virtual state
$Z_b(10650)$ resonance

Charged and **neutral** versions detected $I^G=1^+$



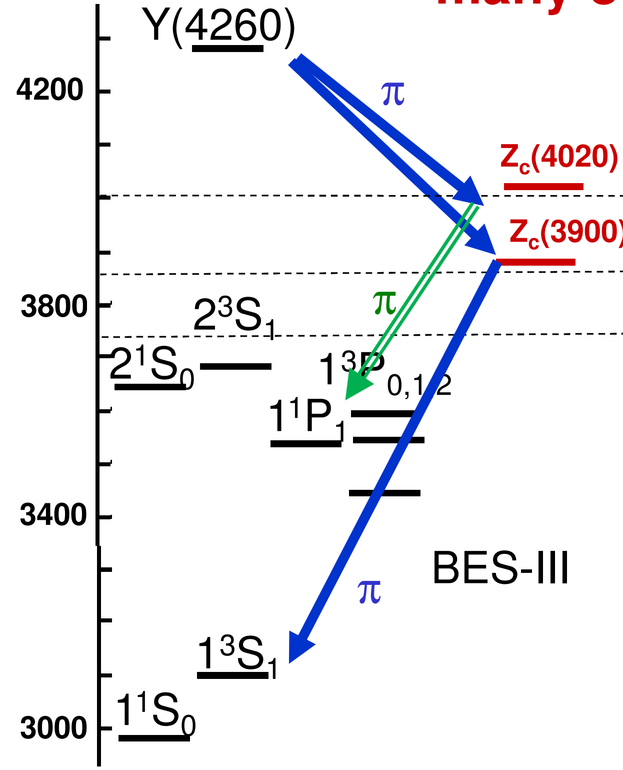
Charged Z_b^+ states cannot mix with $b\bar{b}$ states: "smoking gun" for 4-quark effects!

Large rate to fall-apart modes observed: **Belle PRL116, 212001 (2016)** ✓

- Molecular states of $B\bar{B}^*$, $B^*\bar{B}^*$ (very weakly bound or slightly virtual) or their coupled-channel cusps [DY.Chen,X.Liu,, PR D84, 094003 (2011), E. Swanson PD D91, 034009 (2015)]
- Alternative viewpoint: **tightly bound diquark tetraquarks**: A. Ali, L. Maiani, A. Polosa, V. Riquer, PRD91, 017502 (2015)

More near-threshold states: many of $Z_c^{+,0}$ charmonium states

- Expected from Z_b states and Heavy Quark Symmetry



$D^*\bar{D}^*$ ΔM_{th}=+7±2 MeV

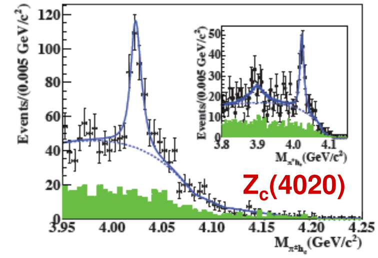
$D\bar{D}^*$ ΔM_{th}=+11±3 MeV

$D\bar{D}$

Masses a few MeV above the $D\bar{D}^*$, $D^*\bar{D}^*$ thresholds ✓

Γ 13 ±5 MeV
28.1± 2.6 ✓

$J^{P(C)}=1^{+(-)}$
(established only for $Z_c(3900)$) ✓

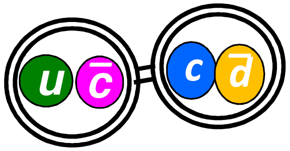


Large rate to fall-apart modes

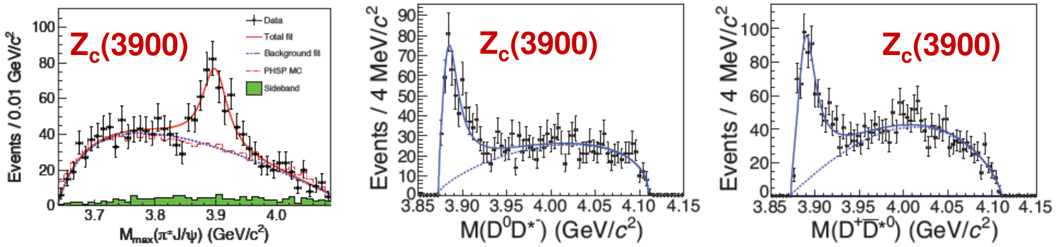
$$\frac{\Gamma[Z_c(4025)\to D^*D^*]}{\Gamma[Z_c(4020)\to\pi h_c]}\sim 9.$$

$$\frac{\Gamma[Z_c(3900)\to DD^*]}{\Gamma[Z_c(3900)\to\pi J/\psi]}=6.2\pm1.1_{\mathrm{stat}}\pm2.7_{\mathrm{sys}}$$

✓



Charged and **neutral** versions detected $I^G=1^+$



(also seen be Belle)

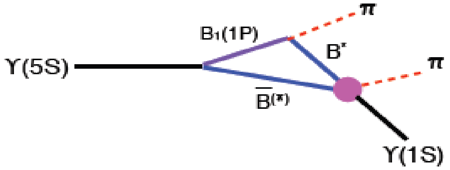
Recent results:
BESIII PRL 115, 112003, 182002, 222002 (2015),
BESIII PRD92, 092006, 012008, 032009 (2015),
Belle JHEP, 1506, 132 (2015).

➡ Molecular states of $D\bar{D}^*$, $D^*\bar{D}^*$ (very weakly bound or slightly virtual states, or cusps)

Anomalous 1^{--} states above open beauty threshold ?

- Rates for $e^+e^- \to \Upsilon(5S) \to \pi\pi\Upsilon(nS)$ are 100 times larger than for $e^+e^- \to \Upsilon(2,3,4S) \to \pi\pi\Upsilon(nS)$
- Previously it was speculated that there is an exotic 1^{--} state [“$Y_b(10890)$”] underneath $\Upsilon(5S)$
- Recent scans by Belle: $\sigma(e^+e^- \to \pi\pi\Upsilon(nS))$ and $\sigma(e^+e^- \to \pi\pi h_b(nP))$ follow $\sigma(e^+e^- \to \text{hadrons})$ i.e. are consistent with the $\Upsilon(5S)$ and $\Upsilon(6S)$. Thus, **there is no evidence for unexpected states.**
- Still the anomalously large decay rates to $\pi\pi\Upsilon(nS)$ and $\pi\pi h_b(nP)$ (via Z_b states) are not understood:
  - Admixture of tightly bound tetraquarks? Hybrids?
  - Rescattering of excited B meson pairs offers a “non-exotic” mechanism?

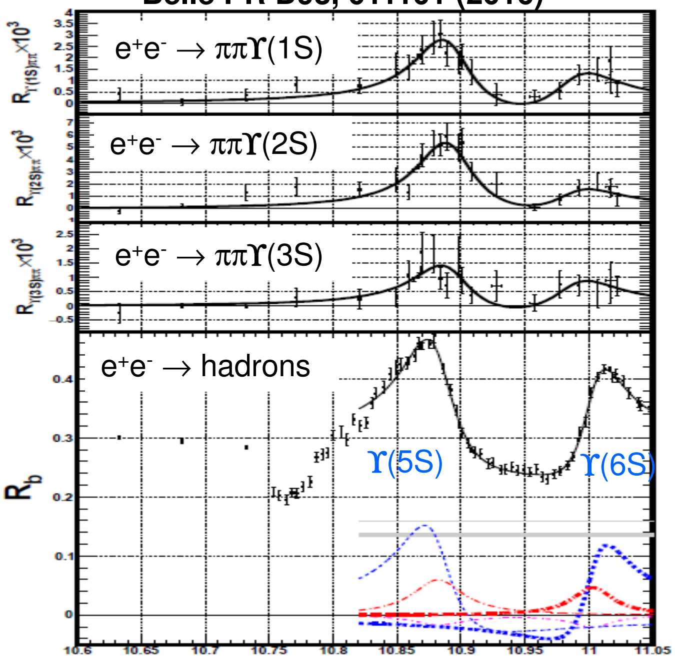
E. Eichten, QWG Workshop
https://indico.hep.pnnl.gov/event/0/session/11/contribution/40/material/slides/0.pdf



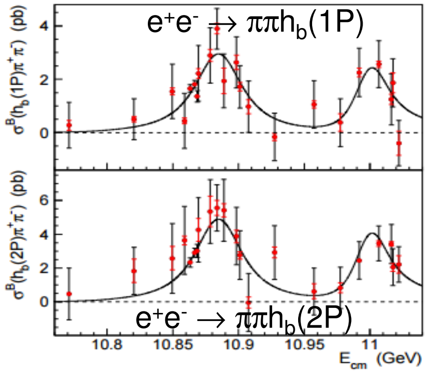
See also A.E.Bondar,M.B.Voloshin
PR D93, 094008 (2016)

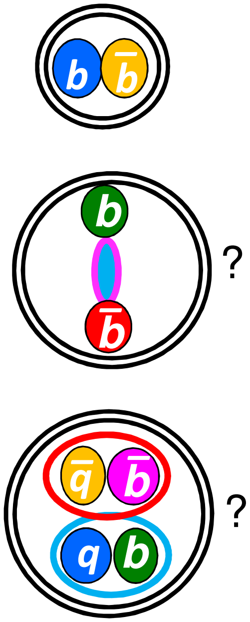
More scan data (Belle II) with investigation of all possible decay modes will be useful to sort this out

Belle PR D93, 011101 (2016)



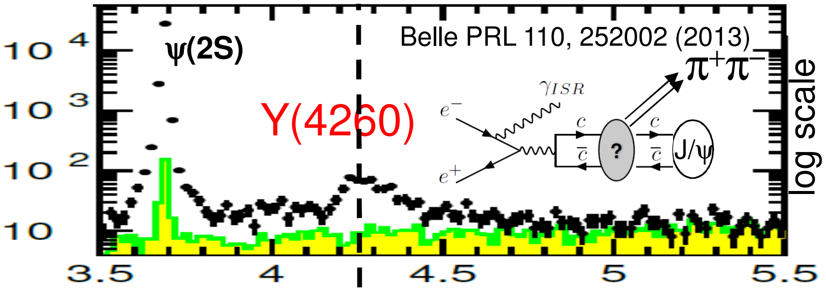
Belle PRL 117, 142001 (2016)

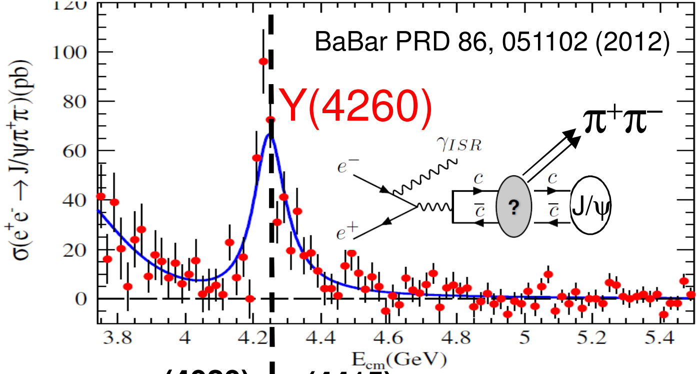


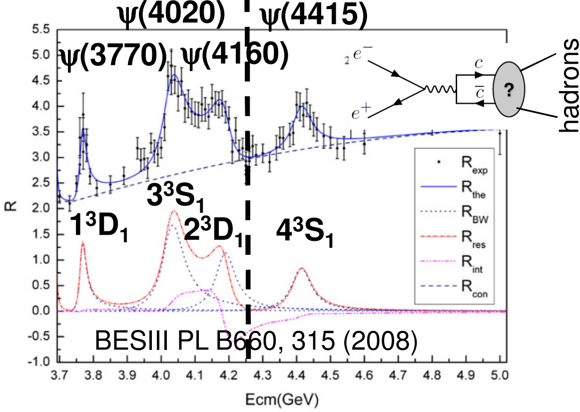


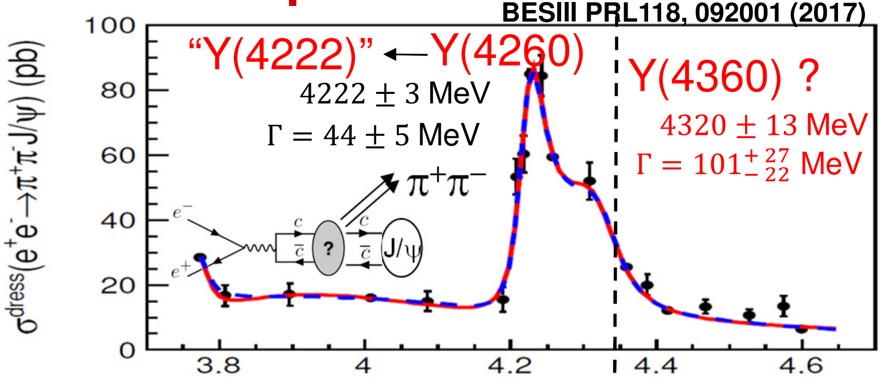
First observed by BaBar in 2005

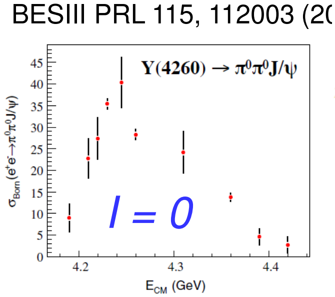
Anomalous 1^{--} states above open charm threshold

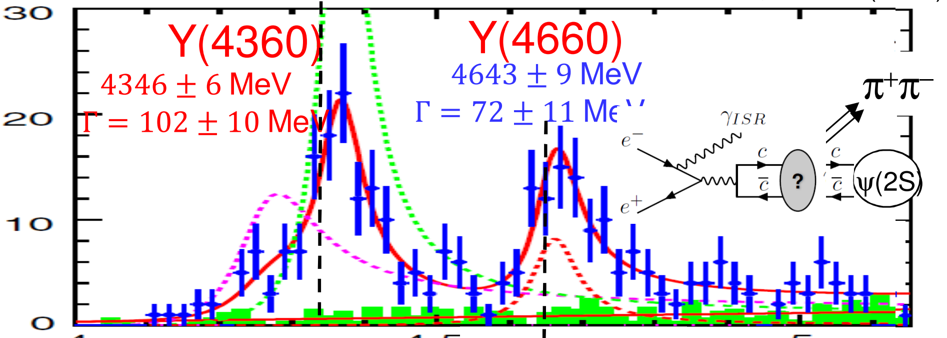

Belle PRL 110, 252002 (2013)

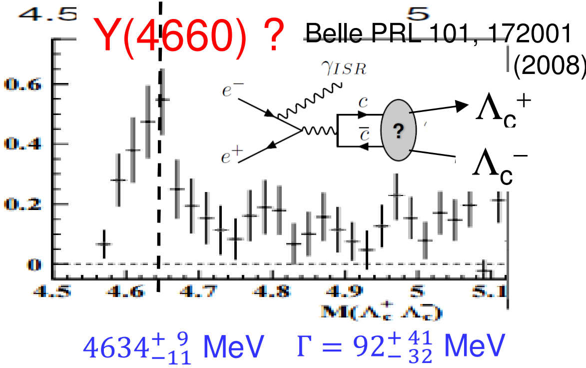

BaBar PRD 86, 051102 (2012)


BESIII PL B660, 315 (2008)


BESIII PRL118, 092001 (2017)


BESIII PRL 115, 112003 (20


Belle PRD 91, 112007 (2015)


Belle PRL 101, 172001 (2008)

4634^{+9}_{-11} MeV $\Gamma = 92^{+41}_{-32}$ MeV

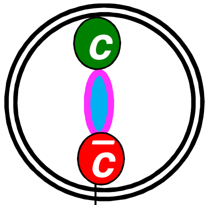
- Y(4260) and Y(4360) do not align with $c\bar{c}$ states
- Γ_{ee} widths suppressed by $10^{2\text{-}3}$
- $\Gamma_{\pi\pi\psi}$ widths huge
- Is Y(4660) a 5^3S_1 $c\bar{c}$ state, baryononium, hexaquark, two different states?

Interpretations of Y(4260), Y(4360)

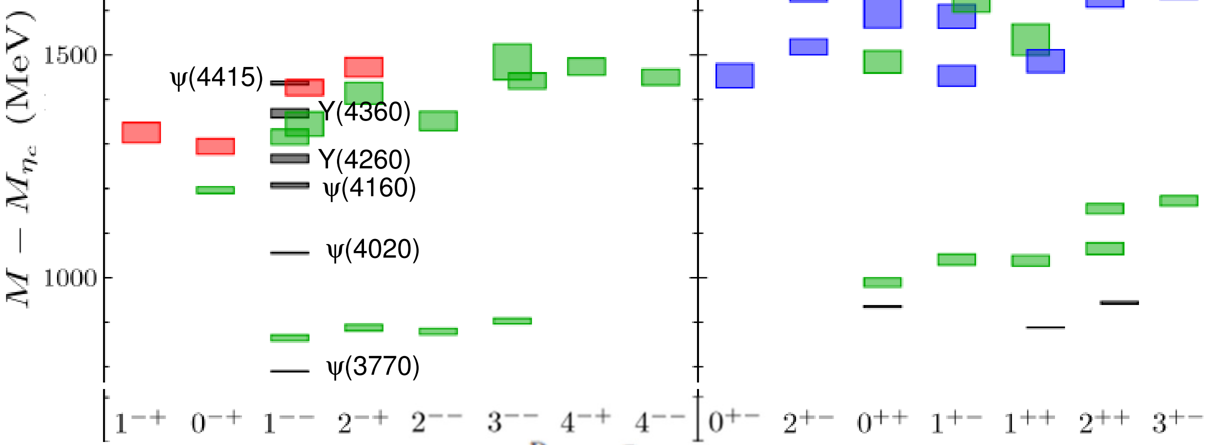
- **Hybrid-charmonium:**
  - Masses not too far from the predicted 1^{--} hybrid by the lattice QCD:
    - Only one 1^{--} hybrid expected in this mass range
    - ψ(4020),ψ(4160),ψ(4415) not well reproduced by lattice

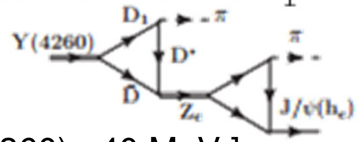
F.Close, P.Page PL B628, 215 (2005)
E.Kou, O.Pene, PL B631, 164 (2005)
S-L. Zhu, PL B625, 212 (2005)

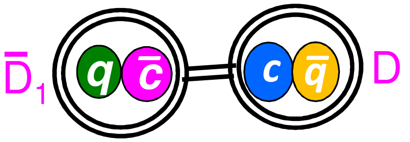
  - Γ_{ee} suppressed by a spin-flip needed to produce $c\bar{c}$ in S=0 configuration
  - ππψ can proceed via $D\bar{D}^{**}$ rescattering
  - However, expected to decay to $D\bar{D}^{(*)}\pi$, but not observed [CLEO-c PR D80, 072001(2009)]



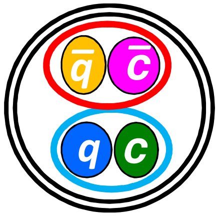
Hadron Spectrum Collaboration (LQCD m_π=240 MeV)
JHEP 1612, 089 (2016)







- **$\bar{D}D_1$(2420) molecule** Q.Wang, C.Hanhart, Q.Zhao, PRL 111, 132003 (2013)
  - The latest mass determination makes it unlikely: ~ -60 MeV binding? [Y(4360) +40 MeV]
- **Tetraquark (diaquarkonium)** L.Maiani, F. Piccinini, A. Polosa, V. Riquer, PR D89, 114010 (2014):
  - Tetraquark→tetraquark transitions: Y(4260)→Z_c(3900)π, Y(4260)→X(3872)γ (possibly observed by BESIII).



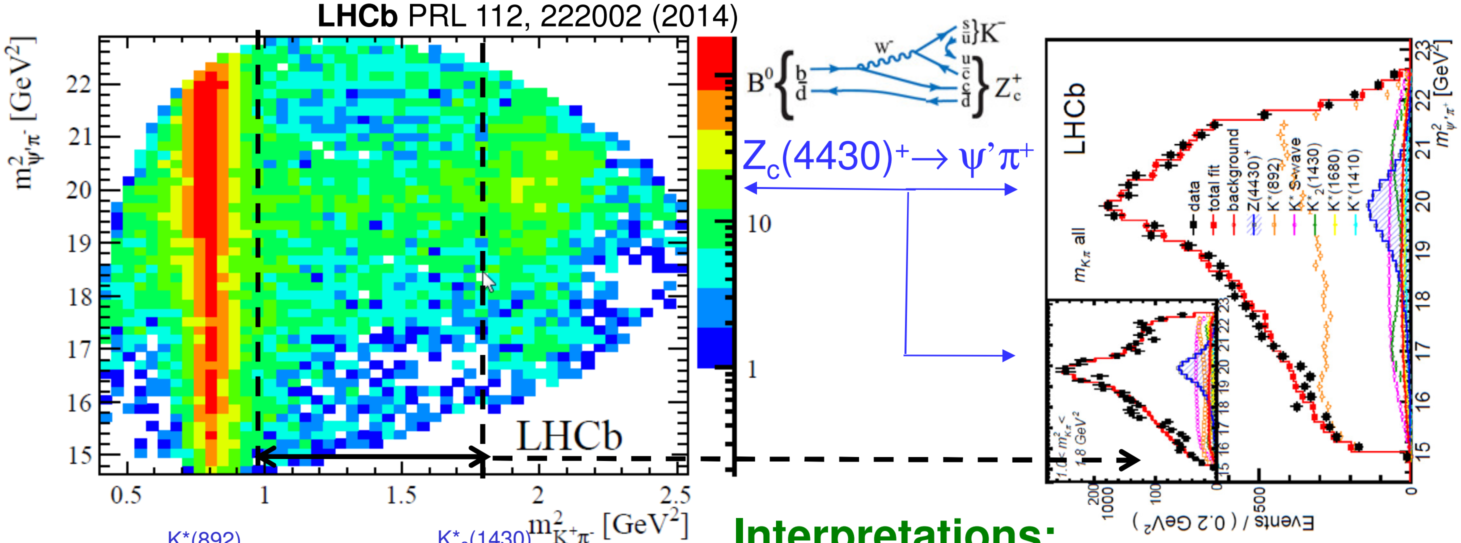
LHCb PRL 112, 222002 (2014).

First observed by Belle
PRL 100, 142001 (2008)

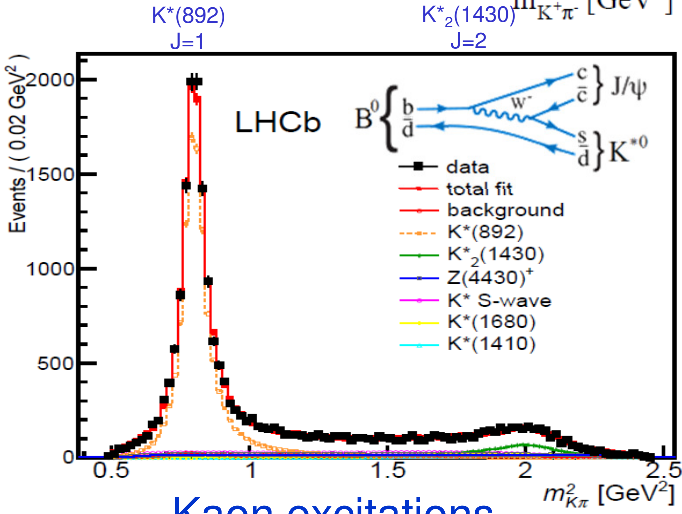
$B^0 \to \psi' \pi^+ K^-$

4D amplitude analysis of masses & decay angles

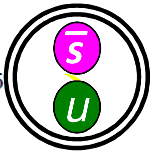
LHCb PRL 112, 222002 (2014)



Tetraquark or meson-meson molecule



Kaon excitations



Interpretations:

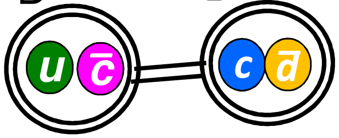
L. Ma et al PRD 90, 037502 (2014)
T. Barnes et al, PRD 91, 014004 (2015)

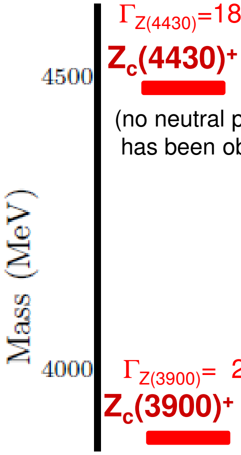
$\Gamma_{D(2600)}$=104±20 MeV

$\bar{D}$ 1^1S_0 D*(2600) 2^3S_1

Radial excitation of the $^3S_1$ meson inside meson molecule

$\bar{D}$ 1^1S_0 D* 1^3S_1





$\Gamma_{Z(4430)}$=181±31 MeV

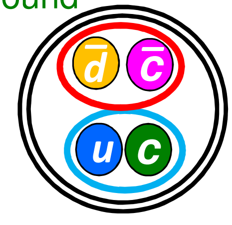
$Z_c(4430)^+$ 1^+

(no neutral partner has been observed yet)

$\Gamma_{Z(3900)}$= 28± 3 MeV

$Z_c(3900)^+$ 1^+

Radial excitation of tightly bound tetraquark



L. Maiani et al PR D**89,** 114010 (2014)

$[cu]_{S=1} [\bar{c}\bar{d}]_{S=0} - [\bar{c}\bar{u}]_{S=0} [cd]_{S=1}$

Mechanical resonance

- Forced harmonic oscillator:

Restoring force (spring)

Damping force:

Driving force

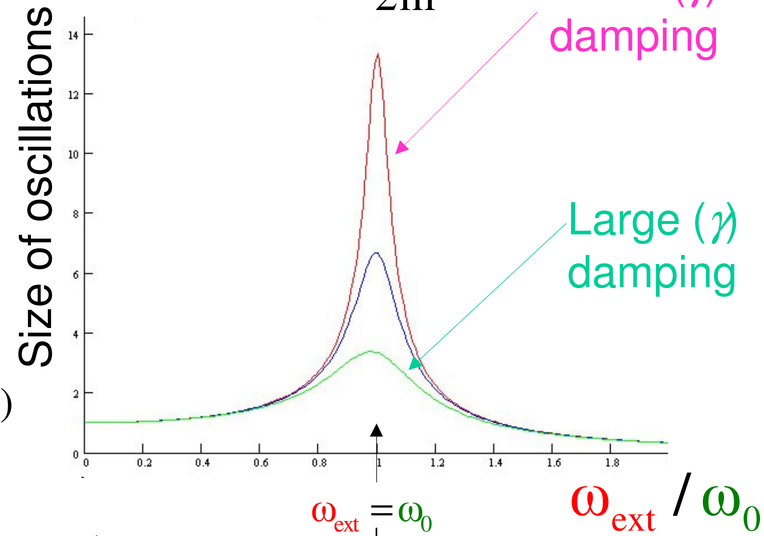
Differential equation for x(t)

(Newton's law)

$$m \frac{d}{dt}\left(\frac{dx}{dt}\right) = -\,k\,x \quad -b\frac{dx}{dt} \quad -F_0\cos(\omega_{ext}t)$$

natural frequency: $\omega_0 = \sqrt{\frac{k}{m}}$

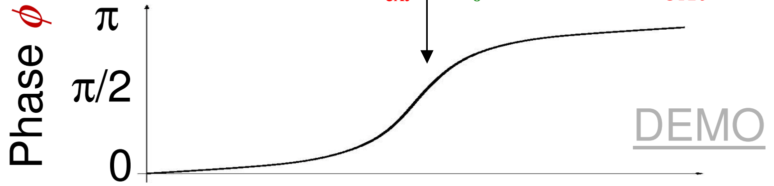
dumping factor: $\gamma = \frac{b}{2m}$



Solution (forced oscillatons):

$$x(t) \overset{t\to\infty}{\to} \frac{\frac{F_0}{m}}{\sqrt{(\omega_{ext}{}^2 - \omega_0{}^2)^2 + (2\gamma\omega_{ext})^2}}\cos(\omega_{ext}t + \phi)$$

$$\tan\phi = \frac{2\gamma\omega_{ext}}{\omega_{ext}{}^2 - \omega_0{}^2}$$



DEMO

Hadronic vs mechanical resonance

Expect the same behavior for hadronic resonances!

- Produced $m_{\psi'\pi}$ mass plays a role of the driving frequency:
  - $m_{\psi'\pi} \sim E_{\psi'\pi} \sim \omega_{ext}$ (Einstein: $E=mc^2$; $E \sim p = \hbar\omega$ de Broglie matter waves 1924)
- Mass of the resonant pole is the resonance frequency:
  - $M_{Z(4430)} \sim \omega_0$
- Decays obstruct creation of the resonance and play a role of the dumping factor:
  - $\Gamma_{Z(4430)} \sim \gamma$
  - Quick decay (short lifetime), large uncertainty in its mass:

Heisenberg's uncertainty principle:

$$\Delta E \, \Delta t \sim \hbar$$

$$\Gamma \, \tau \sim \hbar$$

Hadronic resonance in quantum mechanics

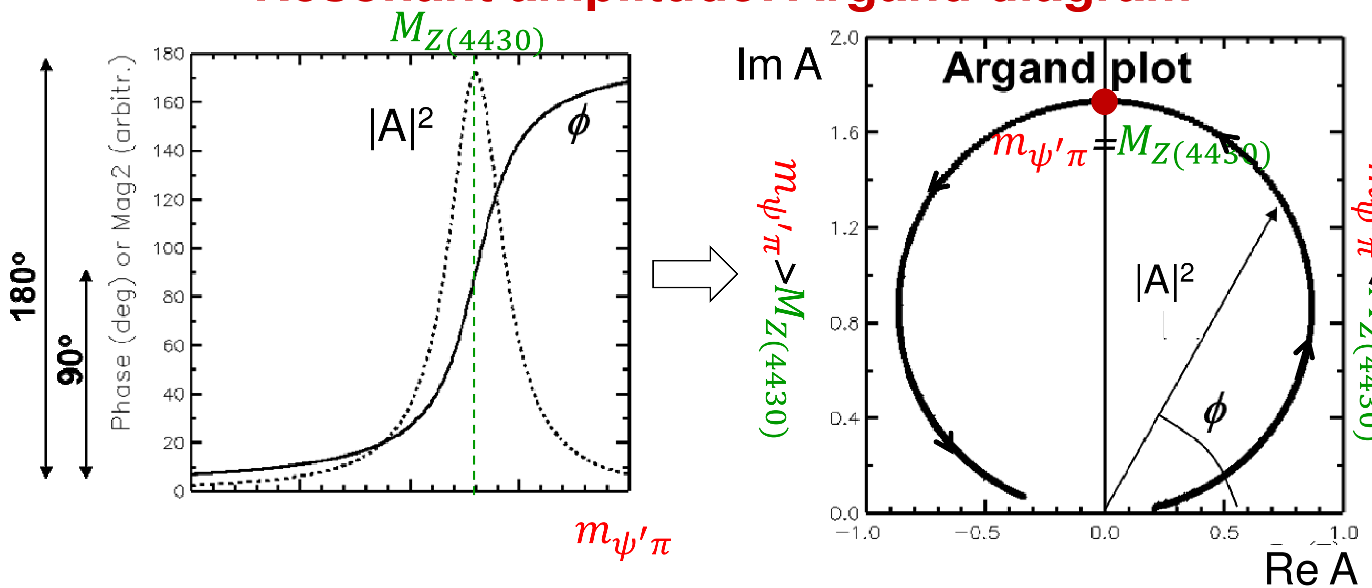
- In quantum mechanics probability for particle production and decay is represented by a complex amplitude $A(m_{\psi'\pi})$ ("matrix element")
- Probability ~ | $A(m_{\psi'\pi})$ $|^2$
- Resonance is a complex pole in the amplitude:

$$A(m_{\psi'\pi}) \sim \frac{1}{{M_{Z(4430)}}^2 - {m_{\psi'\pi}}^2 - iM_{Z(4430)}\Gamma_{Z(4430)}}$$

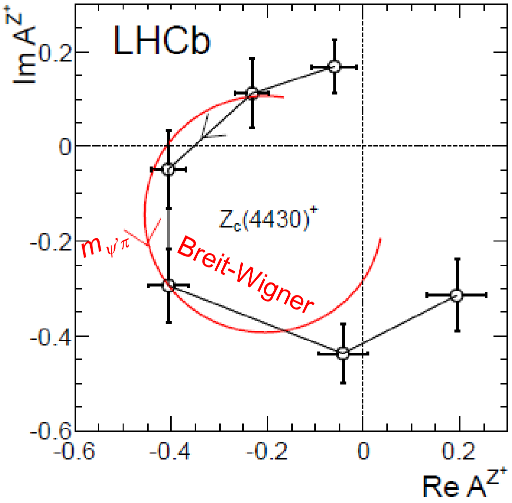
Breit-Wigner amplitude

- If more than one amplitude (here K*s and Z(4430)) in the matrix element, then get experimental sensitivity to the complex phase difference between the amplitudes

Resonant amplitude: Argand diagram



Argand diagram



It is rotated because of choice of reference phase in the analysis.

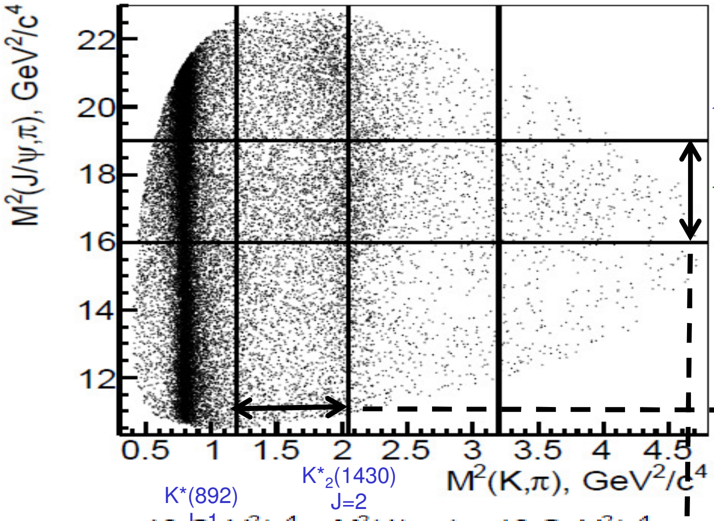
Circle with counter-clockwise evolution of the complex resonant amplitude with the mass
The fastest change of phase at the peak of the intensity.

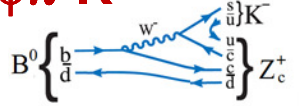
- A peak in probability at certain mass can occur for other reasons than presence of a resonant amplitude
- Extremely useful to get sensitivity to the evolution of the phase of the amplitude with the mass: can check for the resonant behavior

Good evidence for resonant character of Z(4430) !

$B^0 \to J/\psi\pi^+K^-$ 4D amplitude analysis

Belle PR D90, 112009 (2014)



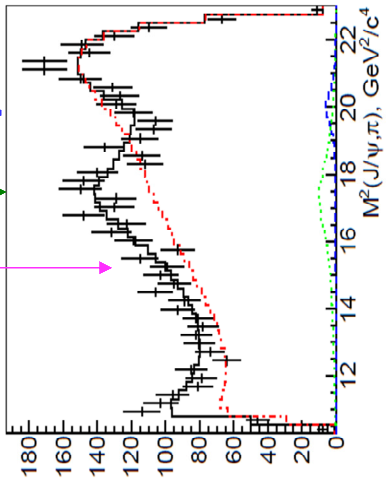


$Z_c(4430)^+ \to J/\psi\pi^+$

$Z_c(4200)^+ \to J/\psi\pi^+$

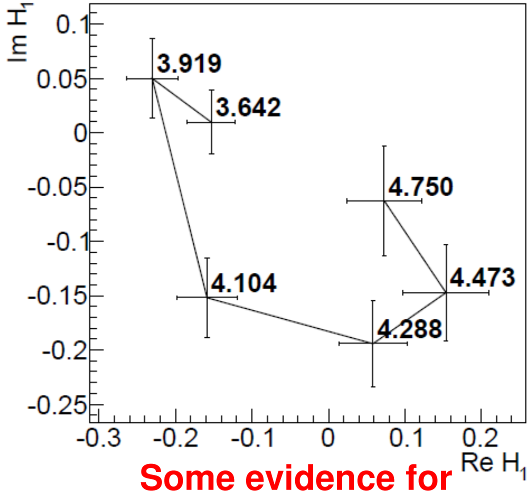
4196^{+31+17}_{-29-13} MeV

No $Z_c(3900)^+$



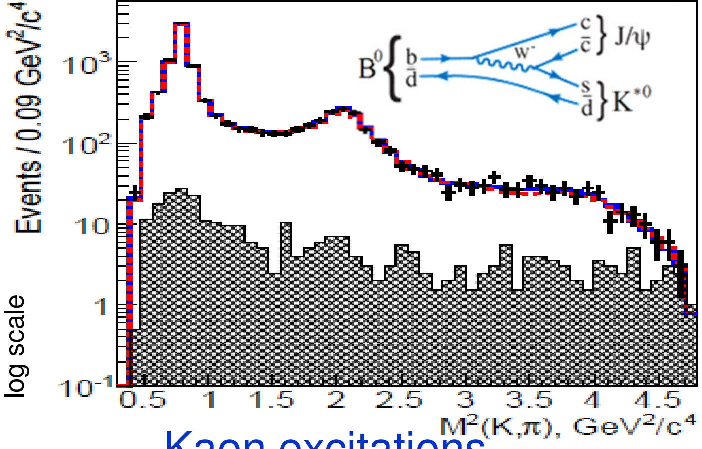
Tetraquark or meson-meson molecule

Argand diagram



Some evidence for resonant character

16 GeV²/c⁴ < M²(J/ψ,π) < 19 GeV²/c⁴



Kaon excitations

$$\mathcal{B}(\bar{B}^0 \to Z_c(4430)^+K^-) \times \mathcal{B}(Z_c(4430)^+ \to J/\psi\pi^+) = (5.4^{+4.0+1.1}_{-1.0-0.9}) \times 10^{-6},$$

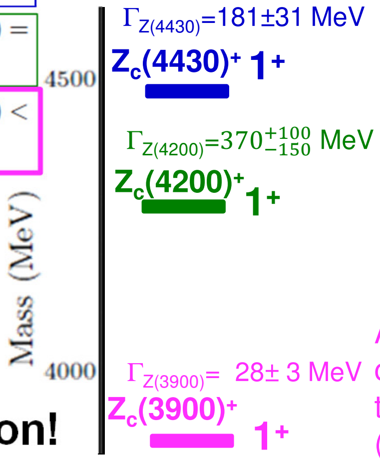
$$\mathcal{B}(\bar{B}^0 \to Z_c(4200)^+K^-) \times \mathcal{B}(Z_c(4200)^+ \to J/\psi\pi^+) = (2.2^{+0.7+1.1}_{-0.5-0.6}) \times 10^{-5},$$

$$\mathcal{B}(\bar{B}^0 \to Z_c(3900)^+K^-) \times \mathcal{B}(Z_c(3900)^+ \to J/\psi\pi^+) < 9 \times 10^{-7}\ (90\%\ \mathrm{CL}).$$

No molecular thresholds can explain $Z_c(4200)^+$

With such a large width less likely to be a resonance

$Z_c(4200)^+$ needs confirmation!



While it has been suggested $Z_c(4200)^+$ is a tetraquark, no tetraquark model can accommodate it together with $Z_c(4430)^+$

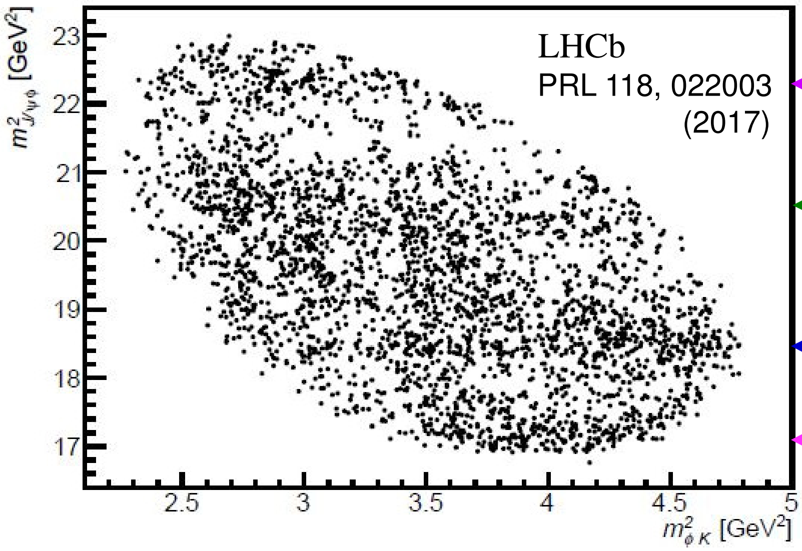
C.Deng et al PR D92, 034027 (2015)

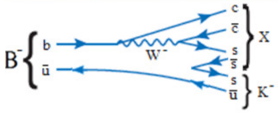
Absence of $Z_c(3900)^+$ in this channel makes it questionable to pair it up with $Z_c(4430)^+$ (see the previous slide)

LHCb PRL118, 022003 (2017)

X(4140) first observed by CDF
PRL 102, 242002 (2009)

$B^- \to J/\psi\, \phi\, K^-$





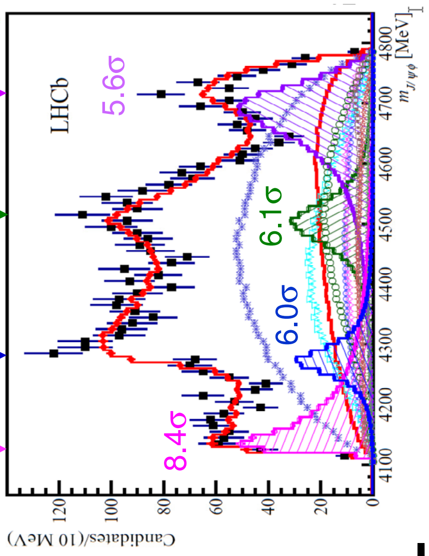
6D amplitude analysis

X(4700)→ J/ψφ

X(4500)→ J/ψφ

X(4274)→ J/ψφ

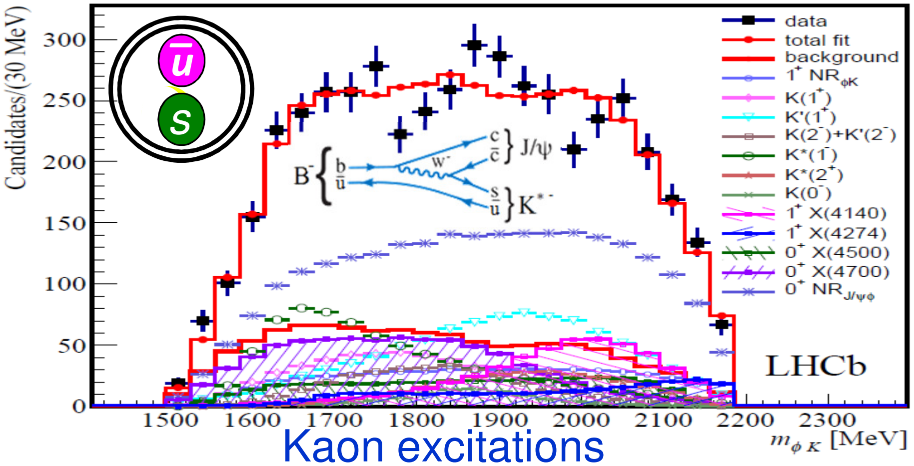
X(4140)→ J/ψφ



Tetraquarks or $D_s\overline{D_s}$ molecules

Not enough data to test resonant amplitudes on Argand diagrams.

X(4140) was previously observed by CDF,CMS,D0. Hints of X(4274) in CDF data.

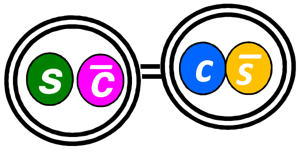


Kaon excitations

No η-exchange

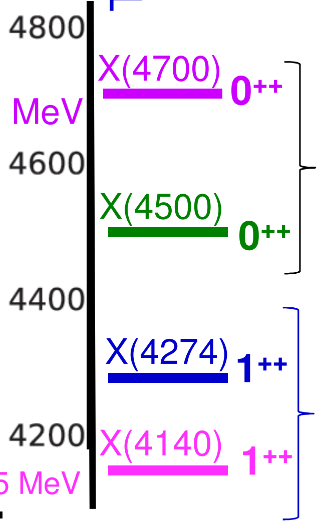
~~$D_{s0}^{+}D_{s0}^{*-}$~~ +69±26 MeV

Plenty of other thresholds, but no matching J^{PC} numbers



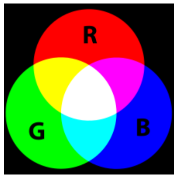
No π-exchange forces!

η-exchange OK $D_s^{+}D_s^{*-}$ +66±5 MeV



Postdiction by L.Maiani, A.D.Polosa, V. Riquer PRD94, 054026 (2016)
Possibly radially excited 0^{++} tetraquarks. However, only one 1^{++} state with color triplet diquarks.

F. Stancu, J.Phys. G37, 075017 (2010)
Predicted two 1^{++} tetraquarks in this mass range (S=0,1 diquarks in color triplet and sextet)



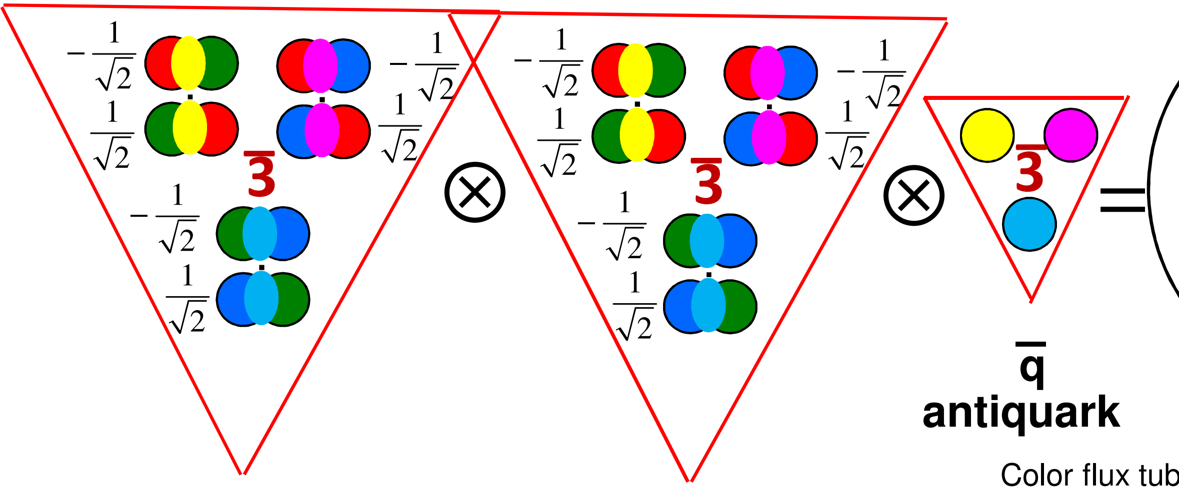
Pentaquark directly from two diquarks and antiquark

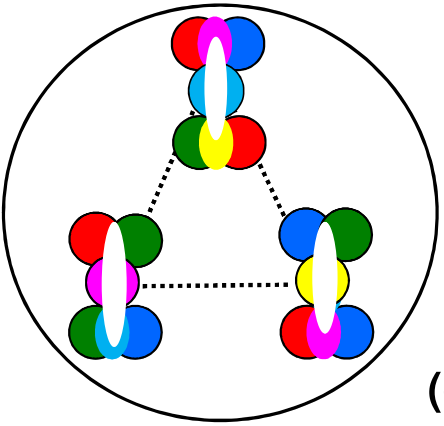
color antitriplet

color antitriplet

color antitriplet

color singlet





Again, not clear if efficient mechanism to suppress fast fall apart decay exist

$\bar{q}$ antiquark

attractive color force

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

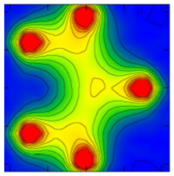
attractive color force

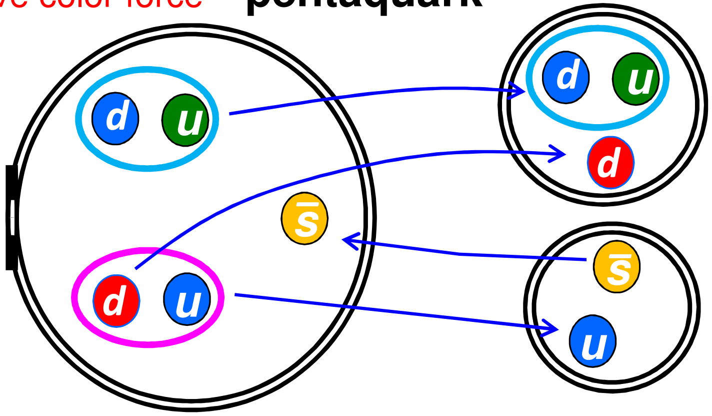
(qq) diquark

attractive color force

(qq) diquark

Color flux tube stretched between the diquarks and antiquark



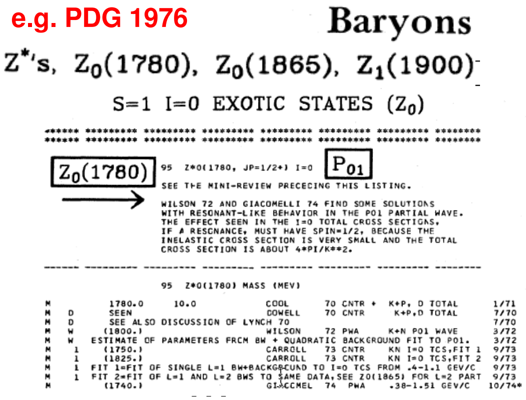


Different forms of quark configurations in a pentaquark can coexist. Modeling of pentaquarks is complicated.

R. L. Jaffe and F. Wilczek, PRL 91, 232003 (2003)

Two waves of past pentaquark claims (with s)

e.g. PDG 1976



Baryons

Z*'s, $Z_0(1780)$, $Z_0(1865)$, $Z_1(1900)$

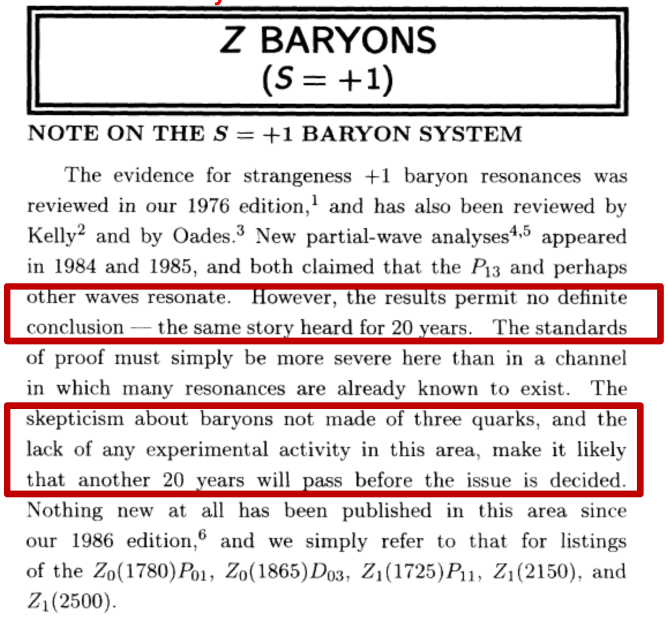
S=1 I=0 EXOTIC STATES (Z_0)

$\boxed{Z_0(1780)}$ →

$\boxed{P_{01}}$

```
****** ********* ********* ********* ********* ********* ********* ********
****** ********* ********* ********* ********* ********* ********* ********

95  Z*0(1780, JP=1/2+) I=0

SEE THE MINI-REVIEW PRECEDING THIS LISTING.

WILSON 72 AND GIACOMELLI 74 FIND SOME SOLUTIONS
WITH RESONANT-LIKE BEHAVIOR IN THE P01 PARTIAL WAVE.
THE EFFECT SEEN IN THE I=0 TOTAL CROSS SECTIONS,
IF A RESONANCE, MUST HAVE SPIN=1/2, BECAUSE THE
INELASTIC CROSS SECTION IS VERY SMALL AND THE TOTAL
CROSS SECTION IS ABOUT 4*PI/K**2.

------ --------- --------- --------- --------- --------- --------- --------

95  Z*0(1780) MASS (MEV)

M       1780.0     10.0           COOL      70 CNTR +  K+P, D TOTAL      1/71
M   D    SEEN                     DOWELL    70 CNTR     K+P,D TOTAL      7/70
M   D    SEE ALSO DISCUSSION OF LYNCH 70                                 7/70
M   W    (1800.)                  WILSON    72 PWA     K+N P01 WAVE      3/72
M   W  ESTIMATE OF PARAMETERS FROM BW + QUADRATIC BACKGROUND FIT TO P01.  3/72
M    1   (1750.)                  CARROLL   73 CNTR    KN I=0 TCS,FIT 1  9/73
M    1   (1825.)                  CARROLL   73 CNTR    KN I=0 TCS,FIT 2  9/73
M    1 FIT 1=FIT OF SINGLE L=1 BW+BACKGROUND TO I=0 TCS FROM .4-1.1 GEV/C  9/73
M    1 FIT 2=FIT OF L=1 AND L=2 BWS TO SAME DATA,SEE Z0(1865) FOR L=2 PART 9/73
M        (1740.)                  GIACOMEL  74  PWA    .38-1.51 GEV/C   10/74*
                         - - -
```

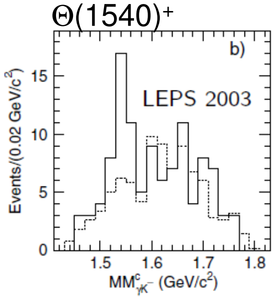
Last mention of baryonic Z*'s PDG 1992



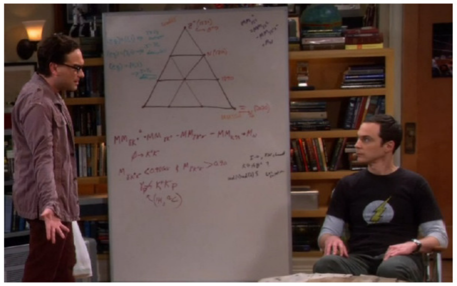
Z BARYONS
($S = +1$)

NOTE ON THE $S = +1$ BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition,[1] and has also been reviewed by Kelly[2] and by Oades.[3] New partial-wave analyses[4,5] appeared in 1984 and 1985, and both claimed that the P_{13} and perhaps other waves resonate. However, the results permit no definite conclusion — the same story heard for 20 years. The standards of proof must simply be more severe here than in a channel in which many resonances are already known to exist. The skepticism about baryons not made of three quarks, and the lack of any experimental activity in this area, make it likely that another 20 years will pass before the issue is decided. Nothing new at all has been published in this area since our 1986 edition,[6] and we simply refer to that for listings of the $Z_0(1780)P_{01}$, $Z_0(1865)D_{03}$, $Z_1(1725)P_{11}$, $Z_1(2150)$, and $Z_1(2500)$.

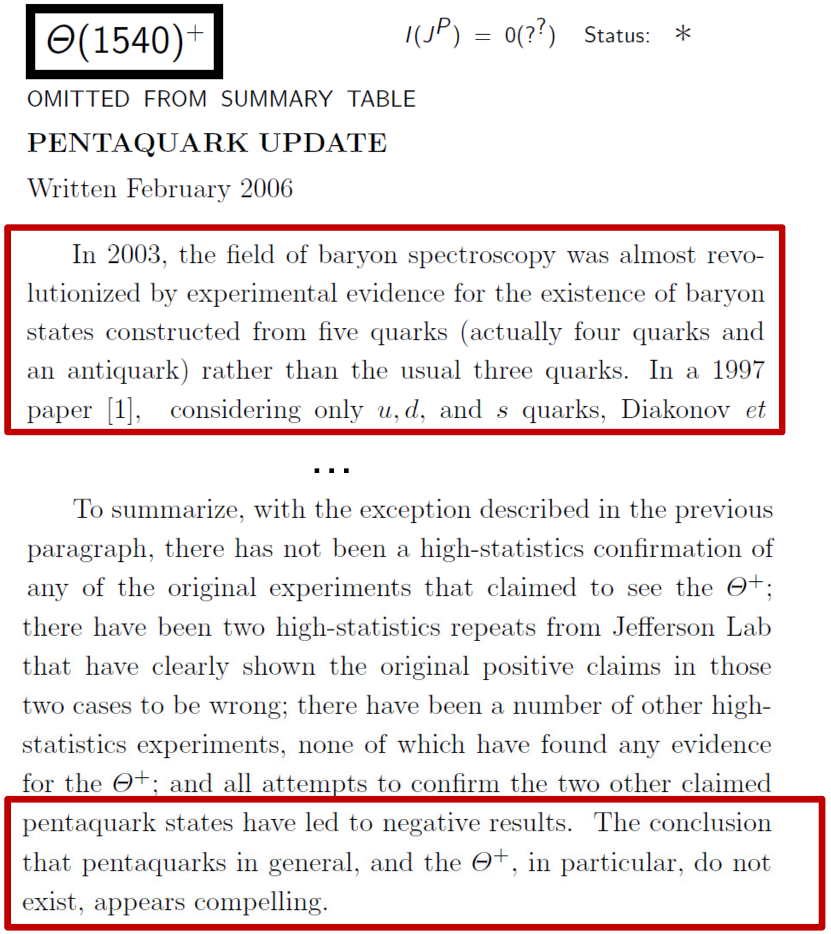


K. Hicks, Eur. Phys. J. H 37, 1 (2012)
T. Liu *et al.*, Int. J. Mod. Phys. A 29, 1430020 (2014)



Last mention of 2nd pentaquark wave: PDG 2006

Found/debunked by looking for "bumps" in mass spectra



$\boxed{\Theta(1540)^+}$ $I(J^P) = 0(?^?)$ Status: $*$

OMITTED FROM SUMMARY TABLE

PENTAQUARK UPDATE

Written February 2006

In 2003, the field of baryon spectroscopy was almost revolutionized by experimental evidence for the existence of baryon states constructed from five quarks (actually four quarks and an antiquark) rather than the usual three quarks. In a 1997 paper [1], considering only u, d, and s quarks, Diakonov *et*

…

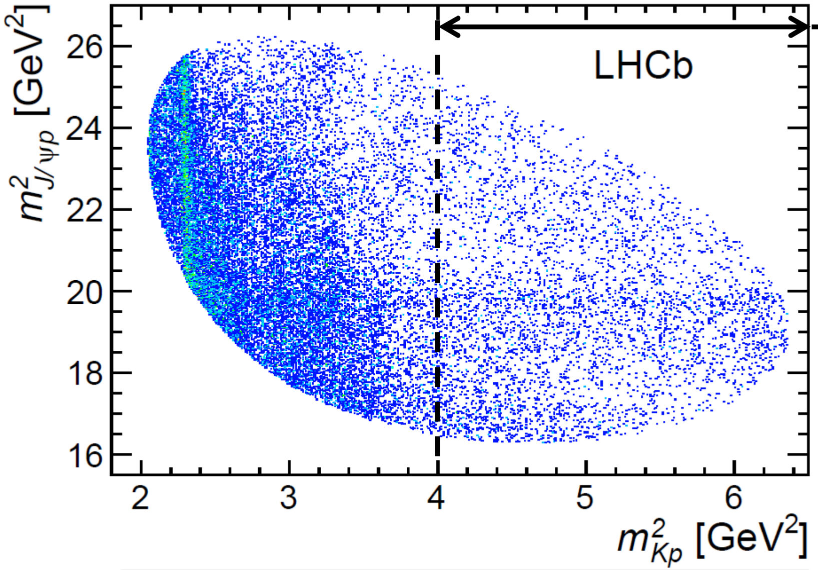
To summarize, with the exception described in the previous paragraph, there has not been a high-statistics confirmation of any of the original experiments that claimed to see the Θ^+; there have been two high-statistics repeats from Jefferson Lab that have clearly shown the original positive claims in those two cases to be wrong; there have been a number of other high-statistics experiments, none of which have found any evidence for the Θ^+; and all attempts to confirm the two other claimed pentaquark states have led to negative results. The conclusion that pentaquarks in general, and the Θ^+, in particular, do not exist, appears compelling.

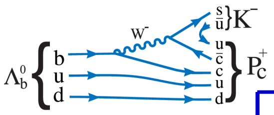
LHCb 115, 07201 (2015)

PRL 115, 07201 (2015)

$\Lambda_b^0 \to J/\psi p K^-$

5D amplitude analysis





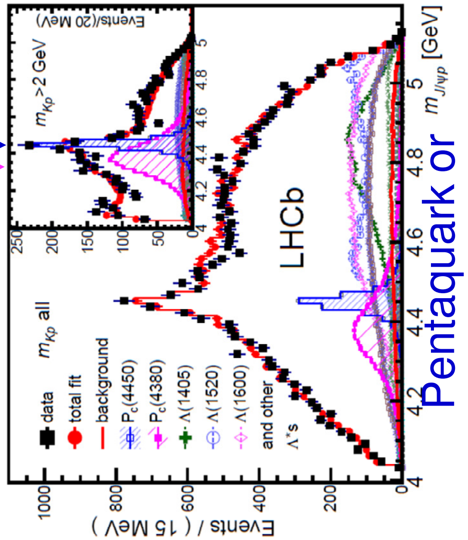
$\Gamma = 39 \pm 20$ MeV

$P_c(4450)^+ \to J/\psi\, p$

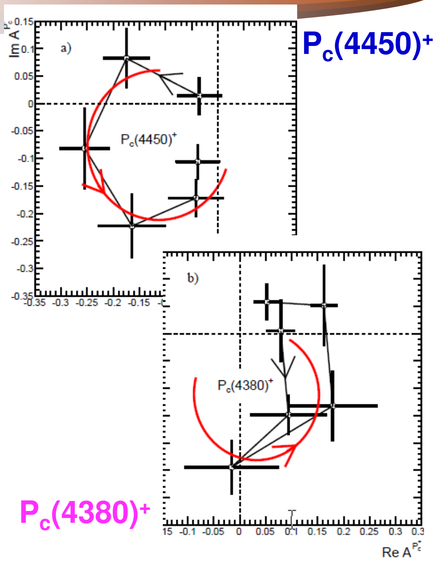
$P_c(4380)^+ \to J/\psi\, p$

$\Gamma = 205 \pm 88$ MeV

No $\frac{5}{2}^{\pm}$ molecules in this mass range



Pentaquark or baryon-meson molecule



Can accommodate $\frac{5}{2}^{\pm}$ when at least one diquark in $S=1$ state

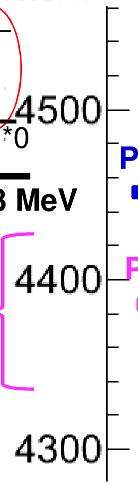
Maiani et al PLB749, 289 (2015) and many others

Karliner,Rosner PRL115, 122001(2015) and others

No π-exchange

$\frac{1}{2}^{+}, \frac{3}{2}^{+}$ $p\,\chi_{c1}$ +1±3 MeV

$\frac{1}{2}^{-}, \frac{3}{2}^{-}$ $\Sigma_c^+ \overline{D}^{*0}$ - 10±3 MeV



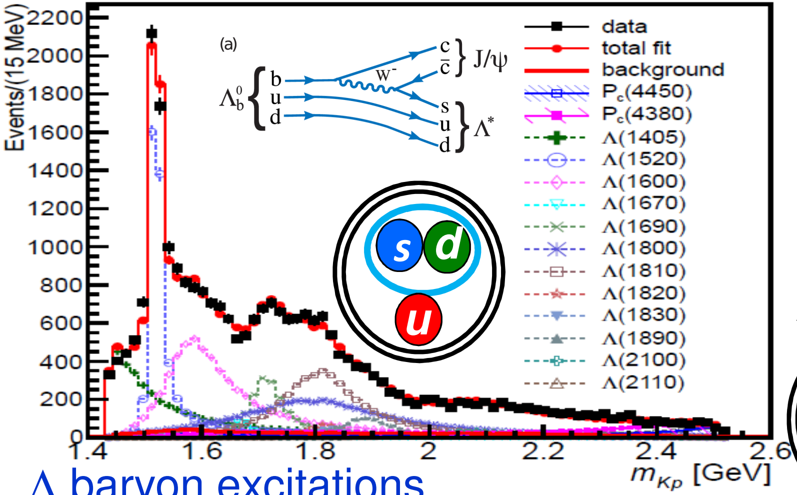
$P_c(4450)^+$ $\frac{5}{2}^{\mp}$ or $\frac{3}{2}^{\mp}$

$P_c(4380)^+$ $\frac{3}{2}^{\mp}$ or $\frac{5}{2}^{\mp}$

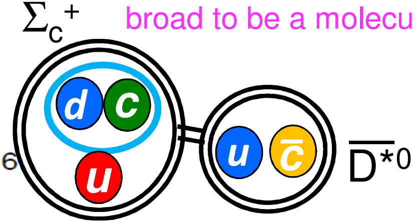
J^P "preferred" rather than definitely determined

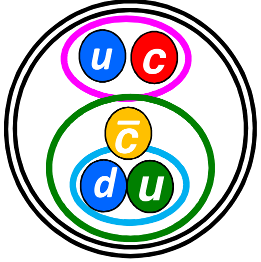
$P_c(4380)^+$ is too broad to be a molecule

Such mass difference and the opposite parity can be explained by $\Delta L=1$

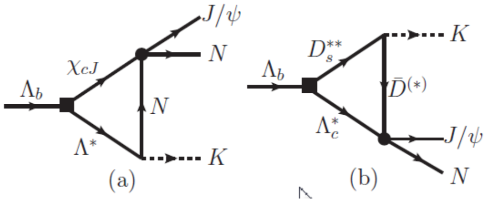


Λ baryon excitations

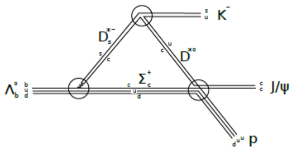




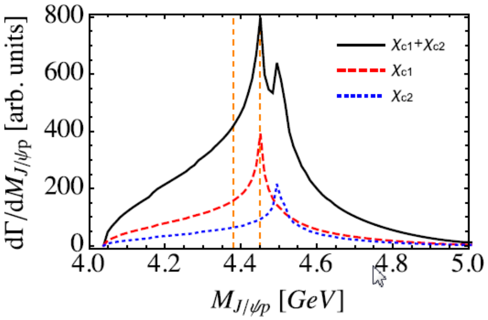
Triangle singularities

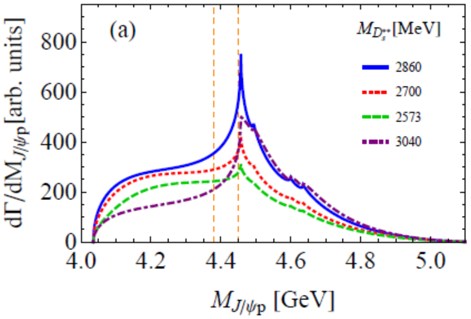


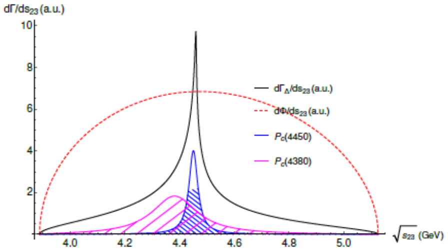
When all particles in the triangle loop are near their mass shell, the amplitude peaks



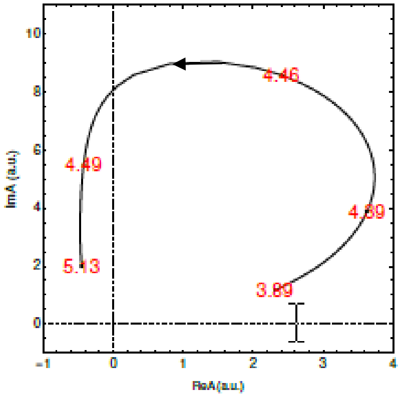
Z.-H.Liu,Q.Wang,Q.Zhao [arXiv:1507.05359],
M. Mikhashenko [arXiv:1507.06552],
A. Szczepaniak [arXiv:1510.01789], …
See also R.F.Lebed et al arXiv:1610.04528







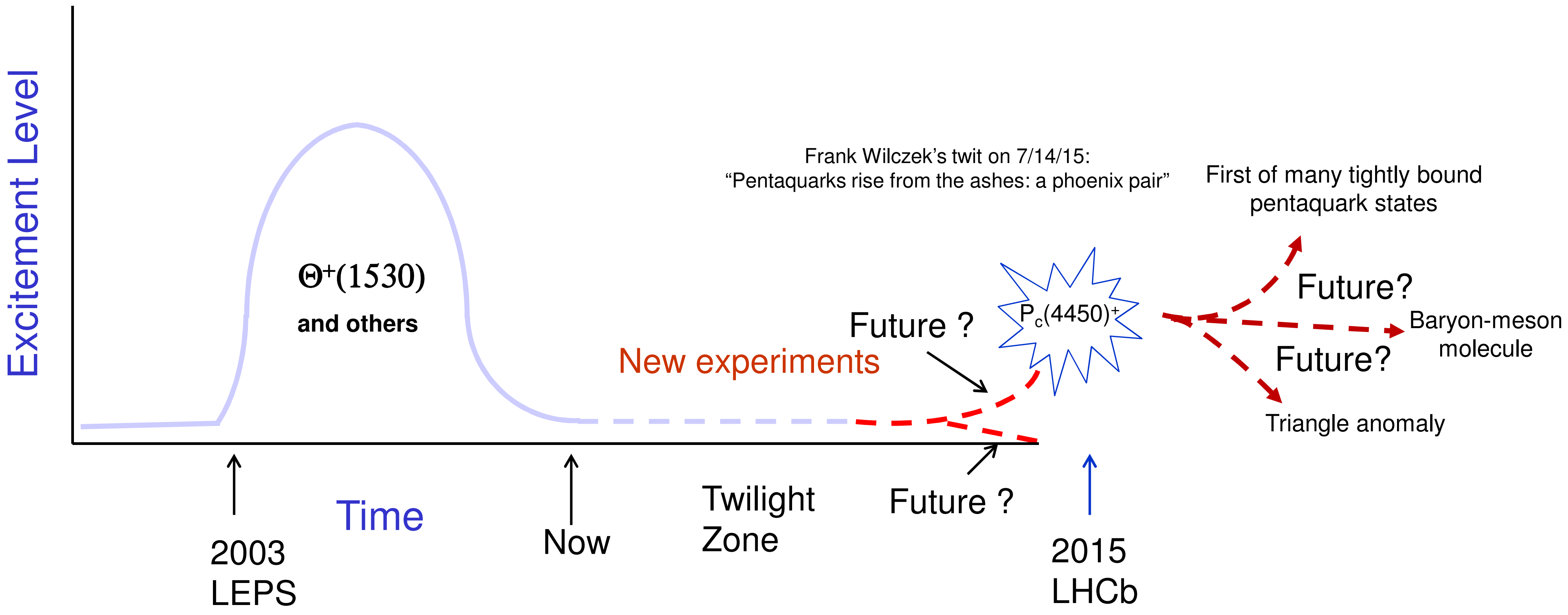
Argand diagram



- Conventional hadrons produced and then rescatter (rearrange quarks) to produce a peak in the exotic channel.
- **Peaking structures related to the same mass thresholds as discussed already for molecules, but can occur above them.**
- Effective J^P like for molecules (L=0). Cannot accommodate $\frac{5}{2}^{\pm}$.
- Ad hoc parameter values to generate desired structures (lack of predictive power).
- Can sometimes arrange for counter-clockwise phase running, but not exactly the same as in the resonance (large statistics data would be able to distinguish them).
- Given proliferation of thresholds, why aren't they everywhere?

Wolfgang Lorenzon's slide from his talk "Pentaquarks" on Oct 2005:

Pentaquark Vital Signs



More LHCb data, other experiments (photo-production at JLab) will show the path

Conclusions

- **Four-quark and five-quark effects in quarkonium-like systems above the open flavor threshold established beyond any doubt.**
- The only clear “exotic spectroscopy” which has emerged so far are molecular $J^P=1^+$ structures at every Pseudoscalar-Vector and Vector-Vector isospin-½ meson thresholds. The narrow pentaquark candidate has a plausible molecular explanation too. **Evidence for molecular effects also from light hadron spectroscopy.**
  - However, molecular models remain qualitative. Many other hadron-hadron thresholds do not show molecular effects and not clear why.
- Yet, we are finding structures, like newly observed $J/\psi\phi$ states, which do not fit molecular hypothesis:
  - Tetra- and penta-quark effects, binding all quarks in the same confining volume may play a role! However, no experimental evidence for rich spectroscopy of such states, at least not yet. Models get tweaked to each system separately. No clear theoretical mechanisms to prevent fast fall apart.
- More data (LHCb upgrade program, Belle II, BES III, photoproduction at JLab, …) will help to clarify the nature of the established effects, and hopefully give us some new surprises.

END