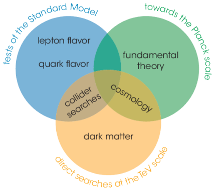
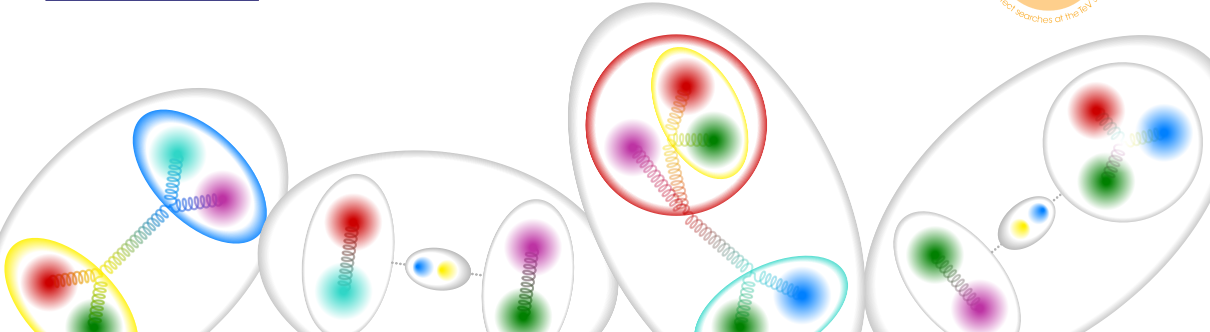
RTG students lecture

I - QCD Exotica: Introduction and brief overview

Marian Stahl

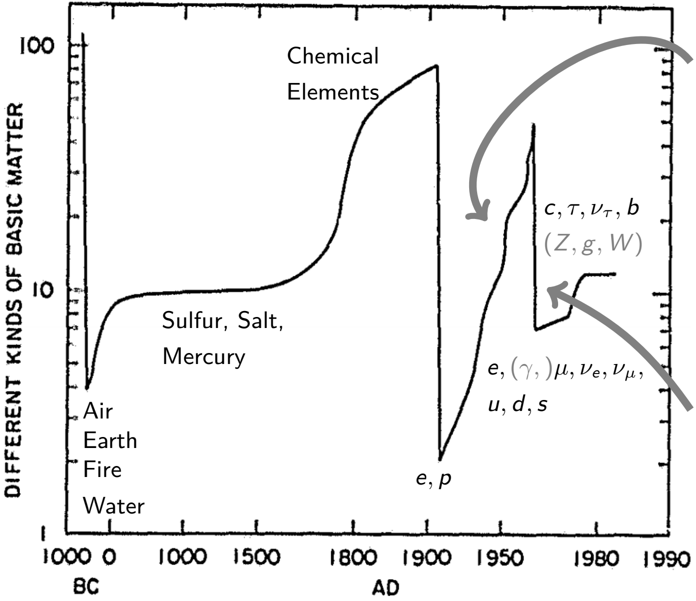
November 28th, 2016

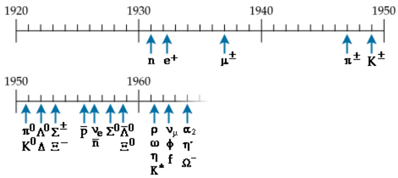




History of Elementary Particles

[ISBN: 978-0-309-03576-7]





"eightfold way" $SU(3)_{\text{flavor}}$

$\rightsquigarrow$ color doF in QCD $SU(3)_{\text{color}}$

- In 1961 Gell-Mann and independently Ne'eman proposed mesons and baryons as resonances of fundamental fields obeying symmetry relations
  - $\rightsquigarrow$ Realized later that the fundamental fields are what we know as **quarks** today
  - QCD emerged from **need to find scheme ($\mathbf{SU(3)_{flavor}}$) for observations**

- In 1961 Gell-Mann and independently Ne'eman proposed mesons and baryons as resonsances of fundamental fields obeying symmetry relations
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  - QCD emerged from **need to find scheme ($SU(3)_{flavor}$) for observations**

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

8419/TH.412
21 February 1964

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

II *)

G. Zweig
CERN---Geneva

*) 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".

- QCD exotics (tetra-, penta-quarks, glueballs etc.) potentially provide key insights to relate basic concepts of QCD to observed phenomena
  - Hadronization, binding mechanism, color structure ...

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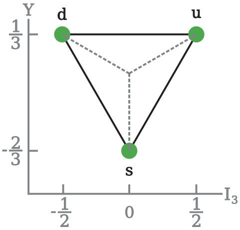
N.B.: all ground state mesons $q_1\bar{q}_2$ with $q_{1,2} = u, d, s, c, b$ have been observed!



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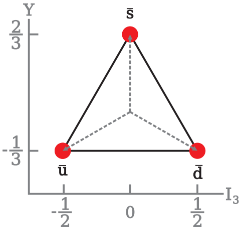

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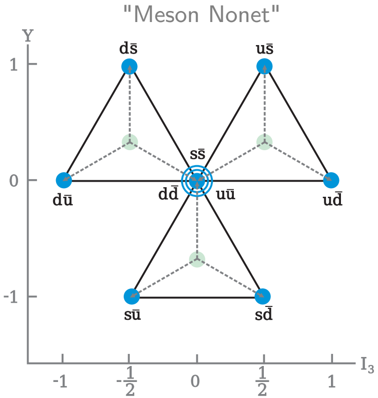

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

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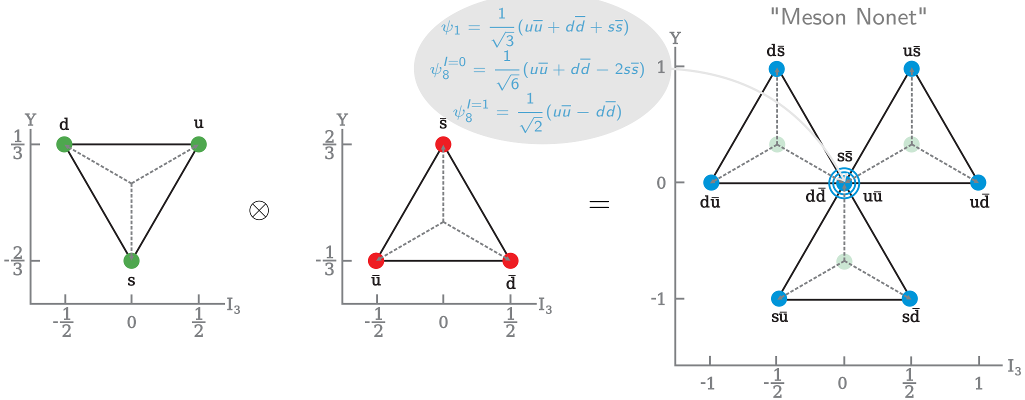
$$\psi_1 = \frac{1}{\sqrt{3}}(u\bar{u} + d\bar{d} + s\bar{s})$$

$$\psi_8^{I=0} = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$$

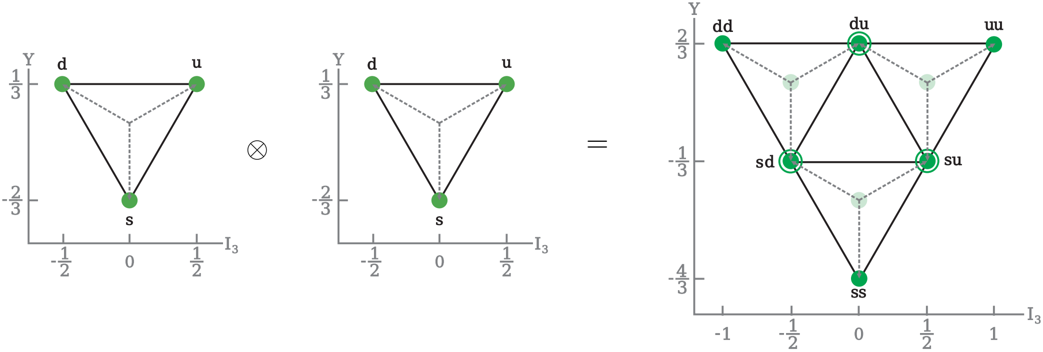
$$\psi_8^{I=1} = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$



$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

- Hadrons are physical observable color singlet bound states of quarks
- They can be labelled by their minimum (valence) quark content
- For $SU(3)_{flavor}$ baryon multiplets, take a detour via *diquarks*:

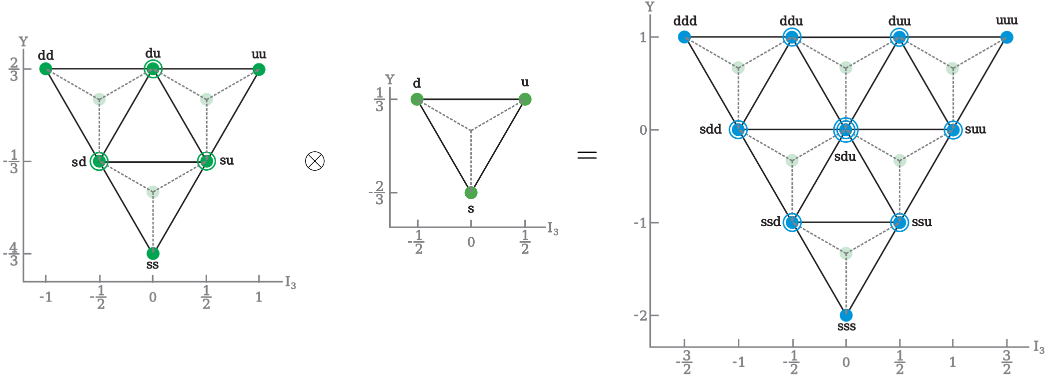
Diquarks are a hypothesized substructure in baryons and exotics. More details later



$$\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \bar{\mathbf{3}}$$

- Hadrons are physical observable color singlet bound states of quarks
- They can be labelled by their minimum (valence) quark content
- Now the SU(3)$_{\text{flavor}}$ baryon multiplets:

All ground state baryons except from those containing two or more heavy quarks (c,b) have been observed

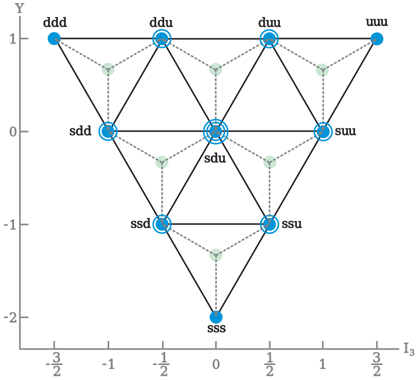


$$(\mathbf{6} \oplus \bar{\mathbf{3}}) \quad \otimes \quad \mathbf{3} \quad = \quad \mathbf{10}_S \oplus \mathbf{8}_M \oplus \mathbf{8}_M \oplus \mathbf{1}_A$$

- Hadrons are physical observable color singlet bound states of quarks
- They can be labelled by their minimum (valence) quark content
- Now the $SU(3)_{flavor}$ baryon multiplets:

$\Psi_{total} = \xi_{space} \cdot \zeta_{flavor} \cdot \chi_{spin} \cdot \phi_{color}$

Octet baryon	mass [MeV]	Decuplet baryon	mass [MeV]
n,p	940	$\Delta^{0,\pm,++}$	1230
$\Lambda/\Sigma^{0,\pm}$	1116/1190	$\Sigma(1385)^{0,\pm}$	1385
$\Xi^{0,-}$	1320	$\Xi(1530)^{0,-}$	1530
		Ω^{-}	1672



Gell-Mann – Okubo mass formula:

$$M = a_0 + a_1 S + a_2 \left[I(I+1) - \frac{1}{4} S^2 \right]$$

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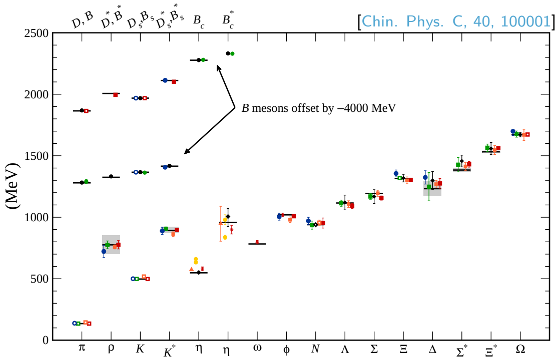
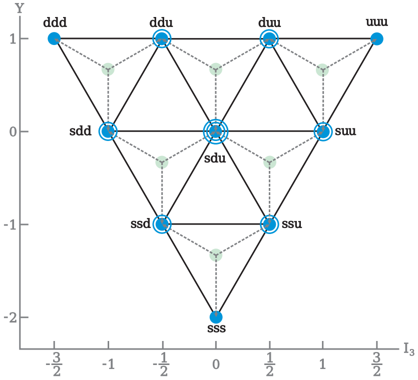
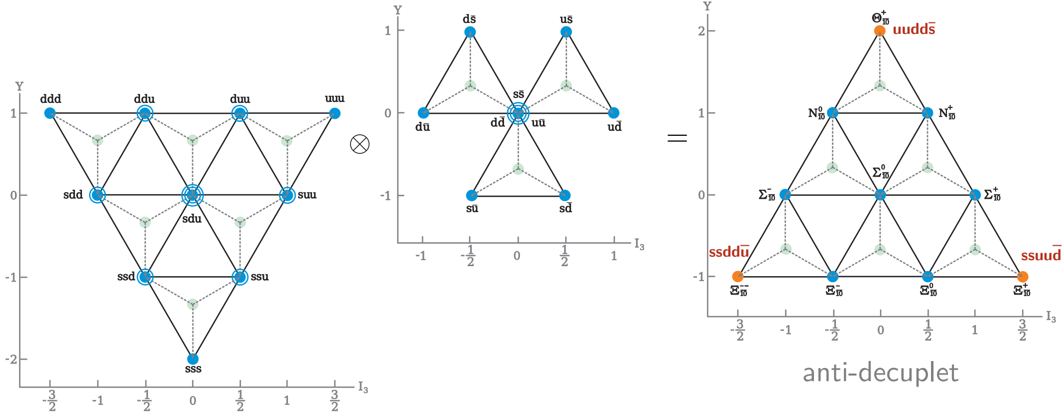




- Hadrons are physical observable color singlet bound states of quarks
- They can be labelled by their minimum (valence) quark content
- Take Gell-Mann's and Zweig's recipe at face value and build $qqqq\bar{q}$:



$$(\ldots \oplus \mathbf{8} \oplus \ldots) \quad \otimes \quad (\mathbf{8} \oplus \ldots) = \ldots \oplus \mathbf{27} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1} \oplus \ldots$$

- Broad exotic KN resonances predicted 1976 [SLAC-PUB-1774]
- Resonant partial waves claimed in 70's and early 80's [PDG, RPP 1992]

Z BARYONS
$(S = +1)$

... 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.

- Broad exotic KN resonances predicted 1976 [SLAC-PUB-1774]
- Resonant partial waves claimed in 70's and early 80's [PDG, RPP 1992]
- Light, narrow $\Theta^+(uudd\bar{s})$ predicted in 1997 [Z. Phys. A 359 305]

  narrow resonances are easy to see in 1D mass spectra

- Seen by some experiments since 2003; "Undiscovered" subsequently [PDG, RPP 2008]

Z BARYONS
($S = +1$)

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EXOTIC BARYONS

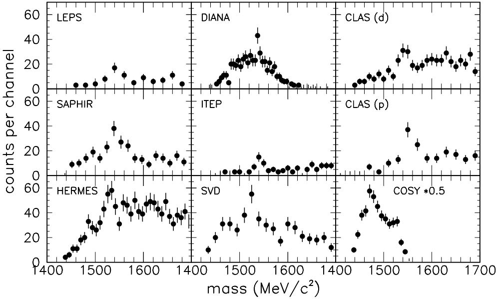
There are two or three recent experiments that find weak evidence for signals near the nominal masses, but there is simply no point in tabulating them in view of the overwhelming evidence that the claimed pentaquarks do not exist. The only advance in particle physics thought worthy of mention in the American Institute of Physics "Physics News in 2003" was a false alarm. The whole story—the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual "undiscovery" —is a curious episode in the history of science.

[DESY-2014-00703]

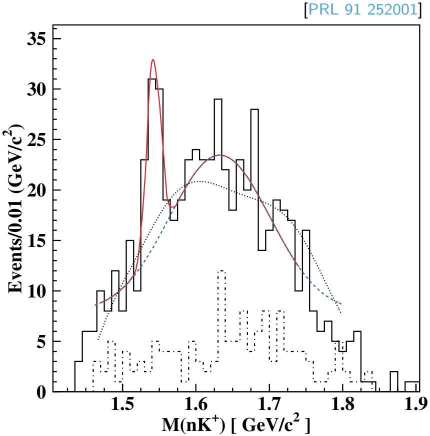
Original measurement			Repeated measurement			
Group	**Reaction**	**Z**	**Group**	**Reaction**	**Stat.**	**Result**
LEPS [74]	$\gamma\mathrm{C} \to (nK^+)K^-X$	$\sim 4\sigma$	LEPS [85]	$\gamma d \to (nK^+)K^-X$	$\times 8$	$Z \sim 5\sigma$
			LEPS [86]	$\gamma d \to (nK^+)K^-X$	$\times 20$	Θ^+ seen
DIANA [77]	$K^+\mathrm{Xe} \to (pK^0)\mathrm{Xe}'$	$\sim 4\sigma$	Belle [87]	$K^+\mathrm{Si} \to (pK^0)X$	$\times 10$	$\Gamma_{\Theta^+} < 1$ MeV
			DIANA [88]	$K^+\mathrm{Xe} \to (pK^0)\mathrm{Xe}'$	$\times 2$	$Z \sim 5\sigma$
			DIANA [89]	$K^+\mathrm{Xe} \to (pK^0)\mathrm{Xe}'$	$\times 2.2$	$Z \sim 6\sigma$
			DIANA [90]	$K^+\mathrm{Xe} \to (pK^0)\mathrm{Xe}'$	$\times 2.5$	$Z \sim 6\sigma$
CLAS [78]	$\gamma d \to (nK^+)K^-p$	$\sim 5\sigma$	CLAS [91]	$\gamma d \to (nK^+)K^-p$	$\times 30$	$\sigma_{\mathrm{tot}} < 0.3$ nb
			CLAS [92]	$\gamma d \to (nK^+)\Lambda$	$\times 30$	$\sigma_{\mathrm{tot}} < 25$ nb
ITEP [79]	$\nu A \to (pK^0)X$	$\sim 7\sigma$	NOMAD [93]	$\nu A \to (pK^0)X$	$\times 12$	$< 2.13 \cdot 10^{-3}$/evt
SAPHIR [80]	$\gamma p \to (nK^+)K^0$	$\sim 5\sigma$	CLAS [94]	$\gamma p \to (nK^+)\pi^+K^-$	$\times 5$	$Z \sim 8\sigma$
			CLAS [95]	$\gamma p \to (nK^+)K^0$	$\times 50$	$\sigma_{\mathrm{tot}} < 0.8$ nb
			CLAS [96]	$\gamma p \to (nK^+/pK^0)K^0$	$\times 50$	$\sigma_{\mathrm{tot}} < 0.7$ nb
			CLAS [97]	$\gamma p \to (pK^0)K^0$	$\times 50$	$Z \sim 5\sigma^1$
HERMES [81]	$e^+d \to (pK^0)X$	$\sim 4\sigma$	BaBar [99]	$e^+\mathrm{Be} \to (pK^0)X$	$\times 190$	no Θ^+ seen
COSY [82]	$pp \to (pK^0)\Sigma^+$	$\sim 5\sigma$	COSY [100]	$pp \to (pK^0)\Sigma^+$	$\times 12$	$\sigma_{\mathrm{tot}} < 0.15\ \mu$b
ZEUS [83]	$ep \to (p/\bar{p}K^0)e'X$	$\sim 4\sigma$	H1 [101]	$ep \to (p/\bar{p}K^0)e'X$	$\times 0.6$	$\sigma_{\mathrm{tot}} < 90$ pb
SVD [84]	$pA \to (pK^0)X$	$\sim 6\sigma$	SPHINX [102]	$p\mathrm{C} \to (pK^0)K^0\mathrm{C}$	$\times 12$	$\frac{\sigma(\Theta^+\bar{K}^0)}{\sigma(\Lambda(1520)K^+)} < 0.02$
			HERA-B [103]	$pA \to (pK^0)X$	$\times 4$	$\frac{\sigma(\Theta^+)}{\sigma(\Lambda(1520))} < 0.12$
			HyperCP [104]	$p/\pi^+/K^+W \to (pK^0)X$	$\times 40$	$\frac{\sigma(\Theta^+)}{\sigma(pK^0_{S\,\mathrm{bkg}})} < 0.003$
			SVD [105]	$pA \to (pK^0)X$	$\times 1.5$	$Z \sim 6$–9σ

Table 2.1: Summary of positive results in searches for the Θ^+ and repeated experiments from the same group or from another group with a similar measurement. If a group revised their initial finding, no more experiments of the same type are listed. If the situation is controversial, all similar experiments are listed. The measurements are chronologically ordered by submission to the publisher. Due to inconsistencies in the calculation of the significance Z, only a rounded value is given. Details are described in the text.

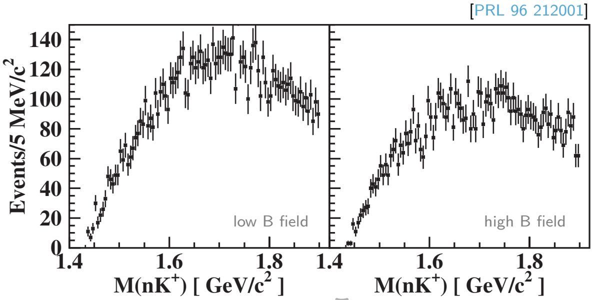
[arXiv:hep-ex/0406077]



- Current consensus: Θ^+ signals were statsitical fluctuations, faked by kinematic cuts, reflections or experimental artefacts
- My opinion: amplitude analysis needed to settle the Θ^+ issue for good
  - either with exclusive decay chain (e.g. $\Lambda_b^0 \to (pK_S^0)K^-$ at LHCb)
    K_S^0 is self tagging, i.e. pure $d\bar{s}$ state
  - or a fully exclusive reaction (e.g. $\gamma d \to (nK^+)pK^-$ at LEPSII)

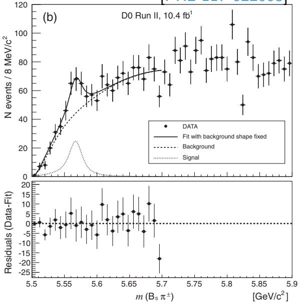


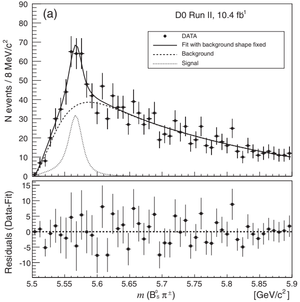
reaction: $\gamma d \to pK^-(K^+n)$

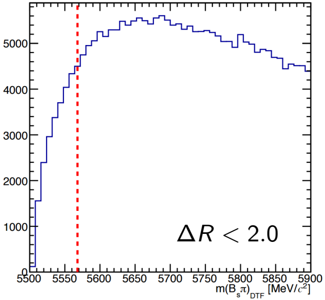


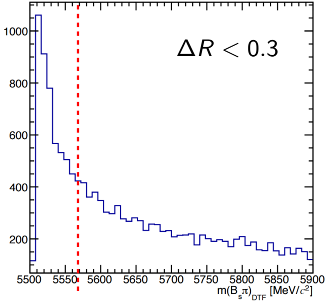
same experiment,
30-fold statistics

[PRL 117 022003]









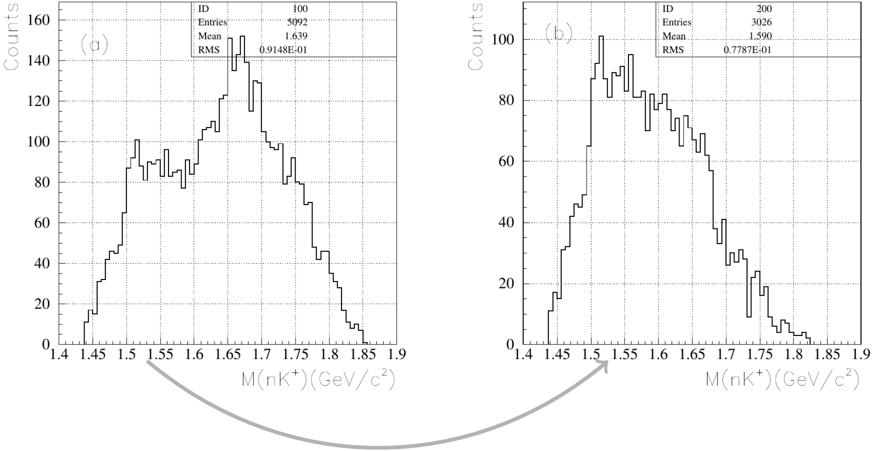
"cone cut" between B_s and π

$$\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} < 0.3$$

- Enhancement certainly not due to cone cut, but background shape changes drastically $\rightsquigarrow Z_{\text{w/o cut}} = 3.9\,\sigma \to Z_{\text{w/ cut}} = 5.1\,\sigma$

reaction: $\gamma d \to pK^-(K^+n)$

[Thesis Y. Kato (LEPS)]



$\Lambda(1520)$ cut in K^-p system

- Amplitude analysis of full exclusive reaction needed

- Hunting narrow peaks in mass spectra is tempting but error-prone
- One sentence-summary about exotic mesons in the light-quark sector:
  - No sign of exotics, only candidates for cryptoexotic states (e.g. $d\bar{u}u\bar{u}$) or states with gluonic degrees of freedom
- **Absence of exotics** seems to be **obvious** feature of QCD!

- Hunting narrow peaks in mass spectra is tempting but error-prone
- One sentence-summary about exotic mesons in the light-quark sector:
  - No sign of exotics, only candidates for cryptoexotic states (e.g. $d\bar{u}u\bar{u}$) or states with gluonic degrees of freedom
- Absence of exotics seems to be obvious feature of QCD
- Until the charmonium and bottomonium sector was studied in greater detail
  - Up to now, evidence for about 30 tetraquark candidates was found
  - In 2015 two pentaquark candidates have been observed by LHCb
- Can we make sense of the observations?
  - Next: Discussion of promising models
  - After that: Overview of experimental observations

- No single model fits all observed states
- States might be a quantum-mechanical mixture
- Distinction between models can blur
- Can only give very rough picture here.
  More on QCD exotica in recent (2016) reviews : [arXiv:1610.04528], [Phys. Rept. 639 1]

- Bind color-neutral objects with color-neutral residual QCD force
- Prime reference: deuteron, a stable proton + neutron bound state
  - $m_d = 1875.6$ MeV, $m_p + m_n = 1877.8$ MeV $\Rightarrow E_b = 2.2$ MeV

Table 1. The quantum numbers of the lowest spin states of NN, and their relative coupling numbers γ_{SI}^{NN}

J^P	S	I	Spin orbital	γ_{SI}^{NN}
0^+	0	0	$^1S_0$	$+25/3$
0^-	1	1	$^3P_0$	$-25/9$
1^-	0	1	$^1P_1$	-25
1^+	1	0	$^3S_1$, $^3D_1$,	$+25/3$, the deuteron

Notation: $^{(2S+1)}L_J$

- Quantum numbers (from experiment): $I(J^P) = 0(1^+) \xrightarrow[|L-S|\leq J\leq L+S]{P=(-1)^L} L = 0, 2$
- Wave-function: $|\psi_d\rangle = u(r)|^3S_1\rangle + w(r)|^3D_1\rangle$ with $\langle w(r)\rangle \approx \sqrt{0.04}$

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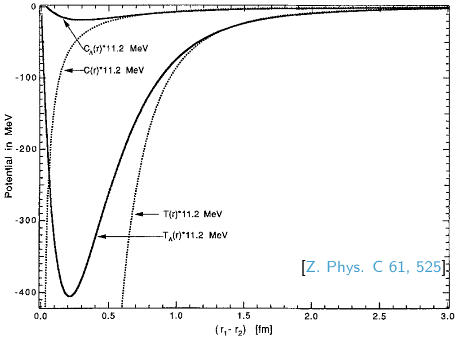
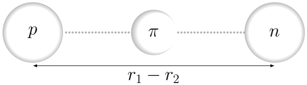
$\langle ^3S_1|S_{12}|^3S_1\rangle$ $\langle ^3S_1|S_{12}|^3D_1\rangle$

  - Potential: $V_d(r) = -\frac{25}{3}V_0\left[\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix}C(r) + \begin{pmatrix}0 & \sqrt{8}\\ \sqrt{8} & -2\end{pmatrix}T(r)\right]$

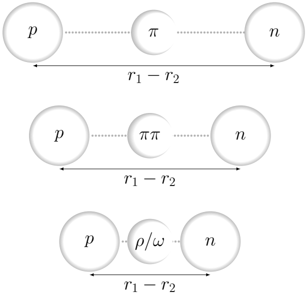
S_{12} $\langle ^3D_1|S_{12}|^3D_1\rangle$





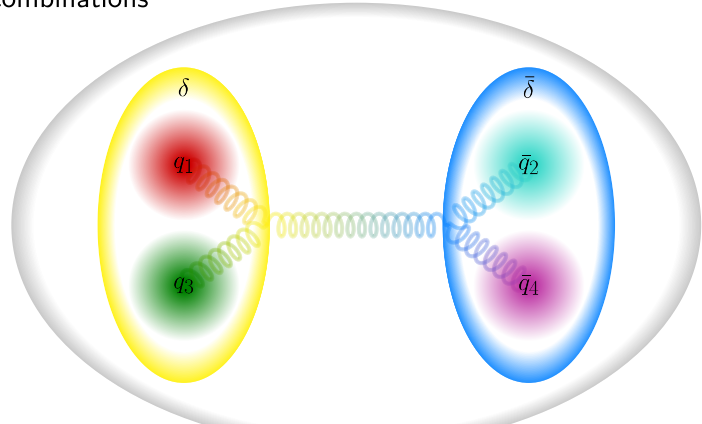
- $C(r)$ insufficient for binding, otherwise $|^1S_0\rangle$ would be bound as well. Tensor force in $|^3S_1\rangle \leftrightarrow |^3D_1\rangle$ transition lowers energy sufficiently for binding

- Bind color-neutral objects with color-neutral residual QCD force
- Prime reference: deuteron, a stable proton + neutron bound state
  - $m_d = 1875.6$ MeV, $m_p + m_n = 1877.8$ MeV $\Rightarrow E_b = 2.2$ MeV
  - Wave-function: $|\psi_d\rangle = u(r)|^3S_1\rangle + w(r)|^3D_1\rangle$ with $\langle w(r)\rangle \approx \sqrt{0.04}$
  - Potential: $V_d(r) = -\frac{25}{3} V_0 \left[\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} C(r) + \underset{S_{12}}{\begin{pmatrix} \overset{\langle{}^3S_1|S_{12}|{}^3S_1\rangle}{0} & \overset{\langle{}^3S_1|S_{12}|{}^3D_1\rangle}{\sqrt{8}} \\ \sqrt{8} & \underset{\langle{}^3D_1|S_{12}|{}^3D_1\rangle}{-2} \end{pmatrix}} T(r) \right]$
  - Binding energy small net effect since other exchanges and scales are involved $\rightsquigarrow$ mechanism qualitatively understood $\Rightarrow$ can QCD exotica help to resolve details?



- For QCD exotica: tensor potential assumed to be crucial in all mesonic molecules
- Quark exchange and other binding mechanisms for exotic molecules under investigation

- Diquarks have long history as proposed constituents of baryons.
  Evidence from lattice-QCD [PRL 97 222002]
- Quarks couple as $\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \bar{\mathbf{3}}$ to diquarks (δ) in color-space.
  $\bar{\mathbf{3}}$ is attractive color-channel (coupling half as strong as color-singlet!)
- System bound by fundamental QDC forces $\rightsquigarrow$ expect states for all spin and isospin combinations

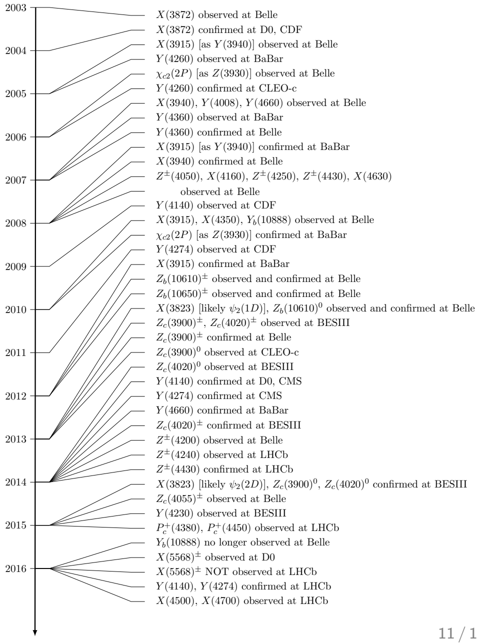


- Diquarks have long history as proposed constituents of baryons. Evidence from lattice-QCD [PRL 97 222002]
- Quarks couple as $\mathbf{3} \otimes \mathbf{3} = \mathbf{6} \oplus \bar{\mathbf{3}}$ to diquarks (δ) in color-space. $\bar{\mathbf{3}}$ is attractive color-channel (coupling half as strong as color-singlet!)
- System bound by fundamental QDC forces $\rightsquigarrow$ expect states for all spin and isospin combinations
- Constrain this large number of states by e.g. dynamical diquarks [PRL 113 112001]
  - $\delta_{\bar{\mathbf{3}}}\bar{\delta}_{\mathbf{3}}$ pair produced at high relative momentum
  - kinetic energy between δ and $\bar{\delta}$ not sufficient to create $q\bar{q}$ from vacuum, but gradually converted in potential energy of color flux tube due to confinement
  - hadronization via large r tails of mesonic wave functions $\rightsquigarrow$ smaller decay widths
- Other proposed mechanisms with special focus on proximity to open channel thresholds: hybrid tetraquarks [PLB 758, 292], tetraquark cusps [PRD 91, 094025]

Experiments: Overview

[arXiv:1610.04528 [hep-ph]]

Particle	$I^G J^{PC}$	Mass [MeV]	Width [MeV]	Production and Decay
$X(3823)$ $(\psi_2(1D))$	(0^-2^{--})	3822.2 ± 1.2 [170]	< 16	$B \to KX;\ X \to \gamma\chi_{c1}$ $e^+e^- \to \pi^+\pi^- X;\ X \to \gamma\chi_{c1}$
$X(3872)$	0^+1^{++}	3871.69 ± 0.17 [170]	< 1.2	$B \to KX;\ X \to \pi^+\pi^- J/\psi$ $B \to KX;\ X \to D^{*0}\bar{D}^0$ $B \to KX;\ X \to \gamma J/\psi, \gamma\psi(2S)$ $B \to KX;\ X \to \omega J/\psi$ $B \to K\pi X;\ X \to \pi^+\pi^- J/\psi$ $e^+e^- \to \gamma X;\ X \to \pi^+\pi^- J/\psi$ pp or $p\bar{p} \to X$ + any.; $X \to \pi^+\pi^- J/\psi$
$Z_c(3900)$	1^+1^{+-}	3886.6 ± 2.4 [170]	28.1 ± 2.6	$e^+e^- \to \pi Z;\ Z \to \pi J/\psi$ $e^+e^- \to \pi Z;\ Z \to D^*\bar{D}$
$X(3915)$	0^+0^{++}	3918.4 ± 1.9 [170]	20 ± 5	$\gamma\gamma \to X;\ X \to \omega J/\psi$
$Y(3940)$				$B \to KX;\ X \to \omega J/\psi$
$Z(3930)$ $(\chi_{c2}(2P))$	0^+2^{++}	3927.2 ± 2.6 [170]	24 ± 6	$\gamma\gamma \to Z;\ Z \to D\bar{D}$
$X(3940)$		$3942^{+7}_{-6} \pm 6$ [38]	$37^{+26}_{-15} \pm 8$	$e^+e^- \to J/\psi + X;\ X \to D\bar{D}^*$
$Y(4008)$	1^{--}	$3891 \pm 41 \pm 12$ [22]	$255 \pm 40 \pm 14$	$e^+e^- \to Y;\ Y \to \pi^+\pi^- J/\psi$
$Z_c(4020)$	$1^+?^{?-}$	4024.1 ± 1.9 [170]	13 ± 5	$e^+e^- \to \pi Z;\ Z \to \pi h_c$ $e^+e^- \to \pi Z;\ Z \to D^*\bar{D}^*$
$Z_1(4050)$	$1^-?^{?+}$	$4051 \pm 14^{+20}_{-41}$ [128]	82^{+21+47}_{-17-22}	$B \to KZ;\ Z \to \pi^\pm\chi_{c1}$
$Z_c(4055)$	$1^+?^{?-}$	$4054 \pm 3 \pm 1$ [142]	$45 \pm 11 \pm 6$	$e^+e^- \to \pi^\mp Z;\ Z \to \pi^\pm\psi(2S)$
$Y(4140)$	0^+1^{++}	$4146.5 \pm 4.5^{+4.6}_{-2.8}$ [120]	$83 \pm 21^{+21}_{-14}$	$B \to KY;\ Y \to \phi J/\psi$ pp or $p\bar{p} \to Y$ + any.; $Y \to \phi J/\psi$
$X(4160)$		$4156^{+25}_{-20} \pm 15$ [38]	$139^{+111}_{-61} \pm 21$	$e^+e^- \to J/\psi + X;\ X \to D^*\bar{D}^*$
$Z_c(4200)$	1^+1^{+-}	4196^{+31+17}_{-29-13} [43]	$370^{+70+70}_{-70-132}$	$B \to KZ;\ Z \to \pi^\pm J/\psi$
$Y(4230)$	0^-1^{--}	$4230 \pm 8 \pm 6$ [143]	$38 \pm 12 \pm 2$	$e^+e^- \to Y;\ Y \to \omega\chi_{c0}$
$Z_c(4240)$	1^+0^{--}	$4239 \pm 18^{+45}_{-10}$ [133]	$220 \pm 47^{+108}_{-74}$	$B \to KZ;\ Z \to \pi^\pm\psi(2S)$
$Z_2(4250)$	$1^-?^{?+}$	$4248^{+44+180}_{-29-35}$ [128]	$177^{+54+316}_{-39-61}$	$B \to KZ;\ Z \to \pi^\pm\chi_{c1}$
$Y(4260)$	0^-1^{--}	4251 ± 9 [170]	120 ± 12	$e^+e^- \to Y;\ Y \to \pi\pi J/\psi$
$Y(4274)$	0^+1^{++}	$4273.3 \pm 8.3^{+17.2}_{-3.6}$ [120]	$52 \pm 11^{+8}_{-11}$	$B \to KY;\ Y \to \phi J/\psi$
$X(4350)$	$0^+?^{?+}$	$4350.6^{+4.6}_{-5.1} \pm 0.7$ [164]	$13^{+18}_{-9} \pm 4$	$\gamma\gamma \to X;\ X \to \phi J/\psi$
$Y(4360)$	1^{--}	4346 ± 6 [170]	102 ± 10	$e^+e^- \to Y;\ Y \to \pi^+\pi^-\psi(2S)$
$Z(4430)$	1^+1^{+-}	4478^{+15}_{-18} [170]	181 ± 31	$B \to KZ;\ Z \to \pi^\pm J/\psi$ $B \to KZ;\ Z \to \pi^\pm\psi(2S)$
$X(4500)$	0^+0^{++}	$4506 \pm 11^{+12}_{-15}$ [120]	$92 \pm 21^{+21}_{-20}$	$B \to KX;\ X \to \phi J/\psi$
$X(4630)$	1^{--}	4634^{+8+5}_{-7-8} [144]	92^{+40+10}_{-24-21}	$e^+e^- \to X;\ X \to \Lambda_c\bar{\Lambda}_c$
$Y(4660)$	1^{--}	4643 ± 9 [170]	72 ± 11	$e^+e^- \to Y;\ Y \to \pi^+\pi^-\psi(2S)$
$X(4700)$	0^+0^{++}	$4704 \pm 10^{+14}_{-24}$ [120]	$120 \pm 31^{+42}_{-33}$	$B \to KX;\ X \to \phi J/\psi$
$P_c(4380)$		$4380 \pm 8 \pm 29$ [34]	$205 \pm 18 \pm 86$	$\Lambda_b \to KP_c;\ P_c \to pJ/\psi$
$P_c(4450)$		$4449.8 \pm 1.7 \pm 2.5$ [34]	$39 \pm 5 \pm 19$	$\Lambda_b \to KP_c;\ P_c \to pJ/\psi$
$X(5568)$		$5567.8 \pm 2.9^{+0.9}_{-1.9}$ [169]	$21.9 \pm 6.4^{+5.0}_{-2.5}$	$p\bar{p} \to X$ + anything; $X \to B_s\pi^\pm$
$Z_b(10610)$	1^+1^{+-}	10607.2 ± 2.0 [170]	18.4 ± 2.4	$e^+e^- \to \pi Z;\ Z \to \pi\Upsilon(1S,2S,3S)$ $e^+e^- \to \pi Z;\ Z \to \pi h_b(1P,2P)$ $e^+e^- \to \pi Z;\ Z \to B\bar{B}^*$
$Z_b(10650)$	1^+1^{+-}	10652.2 ± 1.5 [170]	11.5 ± 2.2	$e^+e^- \to \pi Z;\ Z \to \pi\Upsilon(1S,2S,3S)$ $e^+e^- \to \pi Z;\ Z \to \pi h_b(1P,2P)$ $e^+e^- \to \pi Z;\ Z \to B^*\bar{B}^*$
$Y_b(10888)$	0^-1^{--}	10891 ± 4 [170]	54 ± 7	$e^+e^- \to Y;\ Y \to \pi\pi\Upsilon(1S,2S,3S)$ $e^+e^- \to Y;\ Y \to \pi\pi h_b(1P,2P)$



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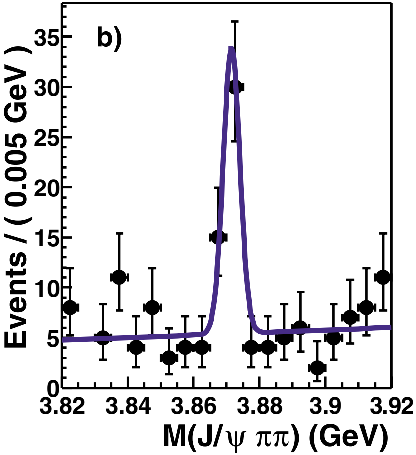
[PRL 91 262001]



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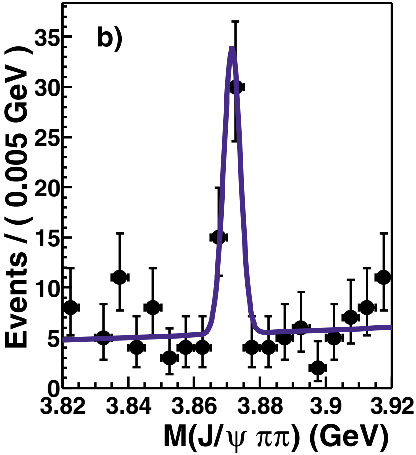
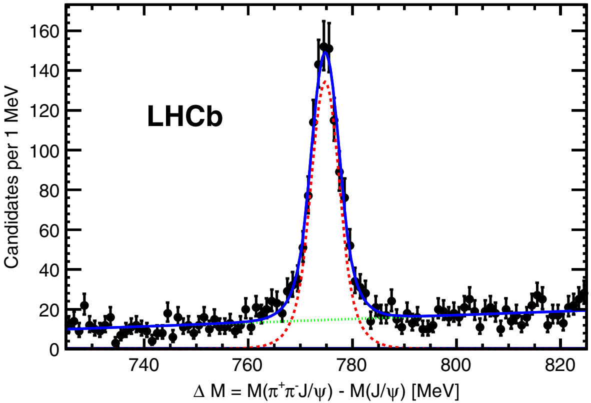


[PRD 92 011102]



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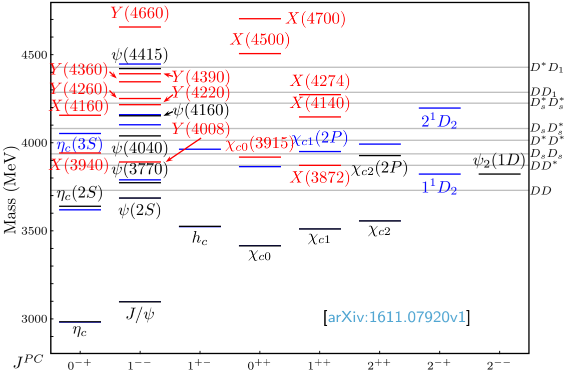
- Width < 1.2 MeV @ 90% CL despite being above open charm threshold



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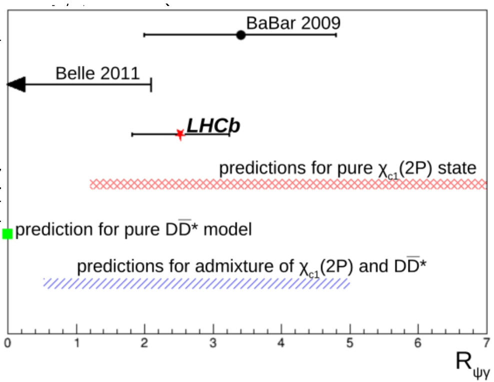
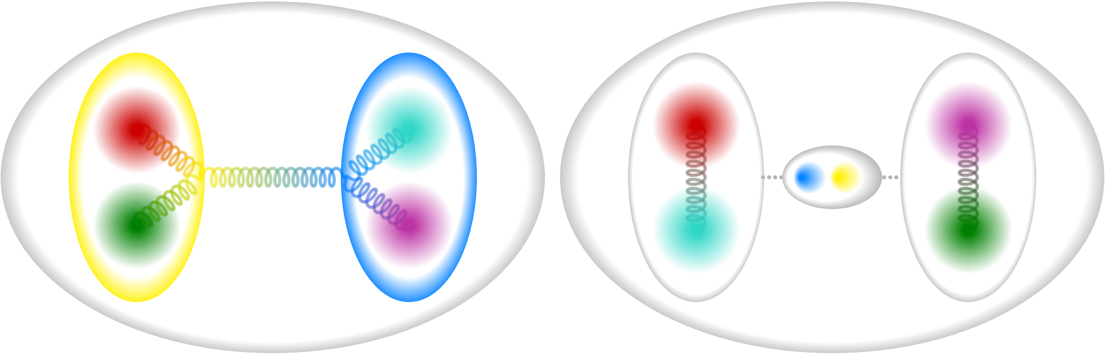
- $\frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 2.6 \pm 0.6$



- **Pure charmonium** ruled out by mass, width, isospin violation
- Production in hadron collisions and radiative decays difficult to explain in **molecular models**
- Absence of charged modes problematic for **diquark picture**.
  How to take $D^0 \overline{D}^{*0}$ threshold into account?



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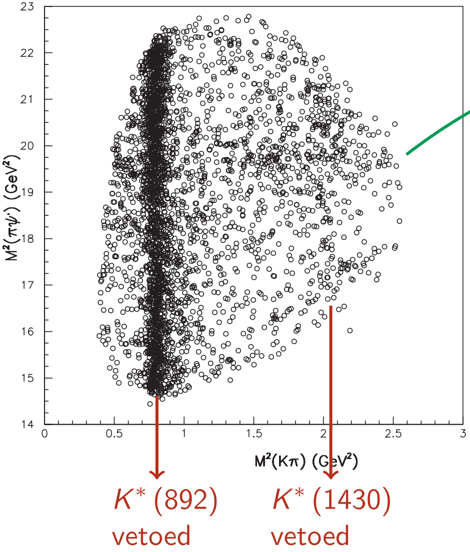
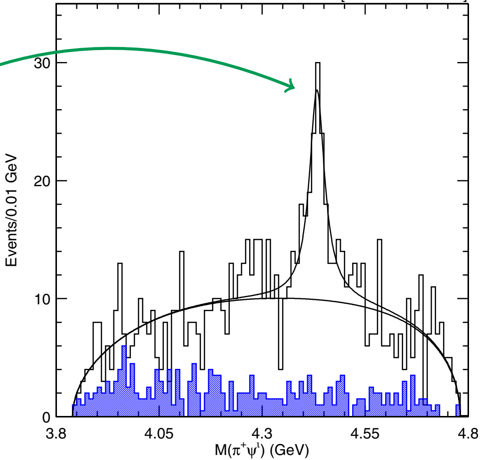
- Absence of charged modes problematic for **diquark picture**.
  How to take $D^0\bar{D}^{*0}$ threshold into account?
- Most attractive solution currently is a $c\bar{c}$-$D\bar{D}^*$ hybrid
  - Small ($\mathcal{O}(5\,\%)$) χ'_{c1} and $D^{\pm}D^{*\mp}$ components, large $D^0\bar{D}^{*0} + c.c.$ component
  - Binding from $c\bar{c}$-$D\bar{D}^*$ couplings rather than molecular D-$\bar{D}^*$ attraction
  - Production via χ'_{c1} component
  - Isospin naturally "violated"

- Discovered by Belle in 2007 in $B \to [\psi(2S)\pi^{\pm}]_{Z(4430)^{\pm}} K$
  $\Rightarrow$ minimal quark content $c\bar{c}u\bar{d}$ + $c.c.$

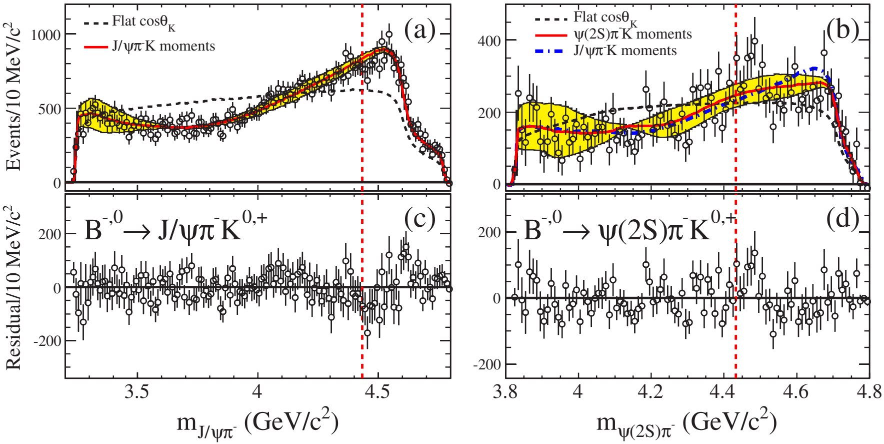


[PRL 100 142001]



- Discovered by Belle in 2007 in $B \to [\psi(2S)\pi^{\pm}]_{Z(4430)^{\pm}} K$
  $\Rightarrow$ content $c\bar{c}u\bar{d} + c.c.$
- Not confirmed by BaBar in 2008 due to dominant $K\pi$ reflections in an extensive model-independent analysis

[PRD 79 112001]



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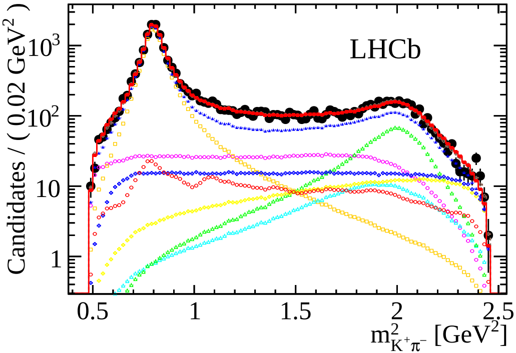
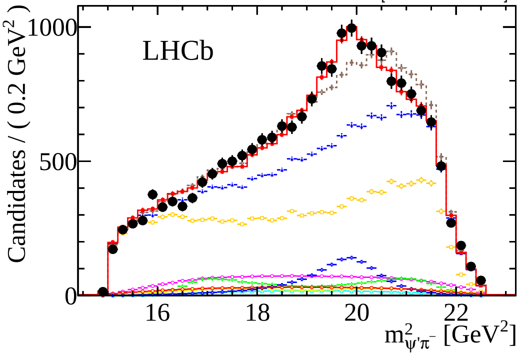
[PRL 112 222002]





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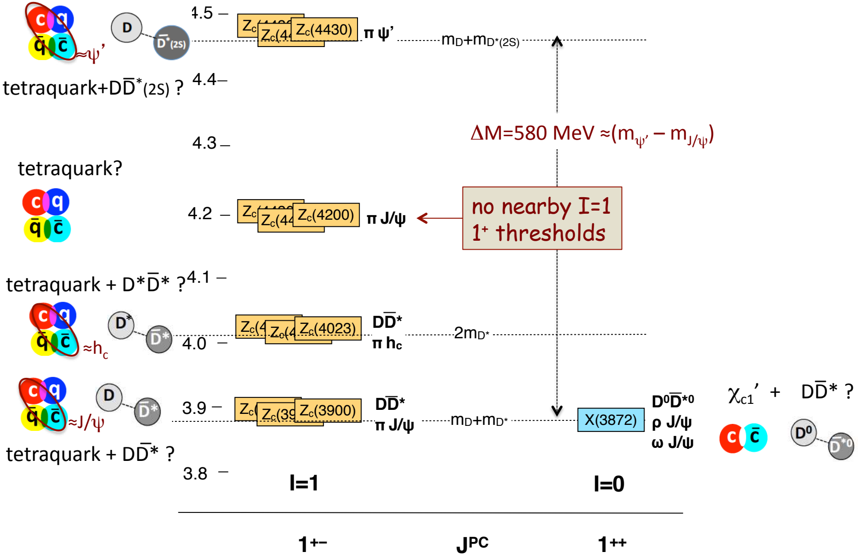
- Not confirmed by BaBar in 2008 due to dominant $K\pi$ reflections in an extensive model-independent analysis
- Confirmed by LHCb with 4D amplitude analysis in 2014 at higher mass and larger width
- Quantum numbers are $J^P = 1^+$, $\dfrac{\mathcal{B}(Z(4430)^{\pm} \to \psi(2S)\pi^{\pm})}{\mathcal{B}(Z(4430)^{\pm} \to J/\psi\pi^{\pm})} \approx 10$
- Currently most attractive interpretations:
  - $\bar{D}D^*(2S)$ molecule $(D^*(2S) \equiv D_J^*(2600))$ [PRD 90 074020]
  - Radially excited, dynamical tetraquark [PRL 113 112001]
- Need to search for further decay modes of $Z(4430)^{\pm}$

Interpretation of $J^P = 1^+$ States

[S. L. Olsen, Blois 2015]



- Absence of exotica in the light quark sector
  - No compelling manifestly exotic candidate has been found by experiments
  - Picturesque view: light quarks more easily "rearrangeable" into conventional hadrons than the rather static b and c quarks
  - But, there are lessons to learn from the charmonium and bottomonium sector which will help to understand the puzzling spectrum of light states
- Large number of Tetraquark candidates in the charmonium region
  - Highly active experimental and theoretical community
  - There are a huge amount of theoretical predictions waiting to be tested
  - No model naturally explains all observations $\rightsquigarrow$ mixing of models likely
  - All observed exotic states contain $c\bar{c}$ or $b\bar{b}$. Are there open charm/beauty exotica?
  - Most states observed near thresholds
- Exotica are excellent laboratory to study the poorly understood dynamics and binding mechanisms of QCD

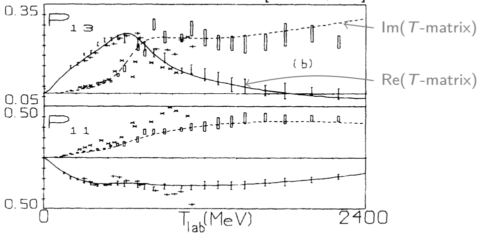
Backup slides start here

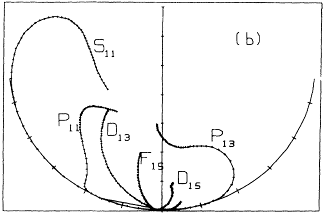
- Broad exotic KN resonances predicted 1976 [SLAC-PUB-1774]
- Resonant partial waves claimed in 70's and early 80's [PDG, RPP 1992]

Z BARYONS
($S = +1$)

... 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.

[PRD 46, 961]





here: $L_{I2J} \Rightarrow P_{13}$:

$I(J^P) = 1 \left(\frac{3}{2}^+\right)$

Argand Plot

Breit-Wigner resonances make full circular counter-clockwise motion

- Light quarks as cloud around core made of heavy quarks
- Motivated by decay of some states to hidden rather than open charm
- Constituents do not need to be color neutral
- Spin and wave functions of core are conserved
- Binding dynamics:
  - color van der Waals attraction mainly through chromoelectric dipole
  - repulsion from Fermi motion $\Rightarrow$ large effective mass of light constituents to suppress Fermi motion
  - wavefunction of light cloud overlaps core entirely contrary to molecular model
- Coexistence of molecular and hadrocharmonium in different regimes possible

- Hybrids are hadrons with explicit gluonic degree of freedom
- Mostly thought of as quasiparticle "flux tube", but also modelled as non-local effective constituent
- Lattice QCD finds evidence for both pictures, with a $J^{PC} = 1^{+-}$ quasiparticle at 1 GeV excitation energy in the former
- Hybrids may have manifestly exotic quantum numbers ($J^{PC} = 0^{+-}, 1^{-+}$)
- States consisting of just gluons ("glueballs") are hypothesised as well
- No postdiction from hybrids for LHCb's pentaquark candidates (that i know of)