Structure of Hadrons

static quark model of hadrons

pseudoscalar mesons

$$\vec{J} = \vec{\ell} + \vec{S}, \quad \vec{S} = \vec{s}_q + \vec{s}_{\bar{q}}$$

$\vec{J}$ total angular momentum

$\vec{\ell}$ orbital angular momentum

$\vec{S}$ total spin

S can be either 0 or 1. The mesons with the relative zero orbital angular momentum are lower in energy. For the pion, S=0, hence J=0. Consequently, pions are "scalar" particles. But what about their parity? The parity of the pion is a product of intrinsic parities of the quark (+1), antiquark (-1) and the parity of the spatial wave function $(-1)^l=+1$. Hance the pion has negative parity. It is a **pseudoscalar meson.**

With (u,d,s) quarks, one can construct 9 pseudoscalar mesons:

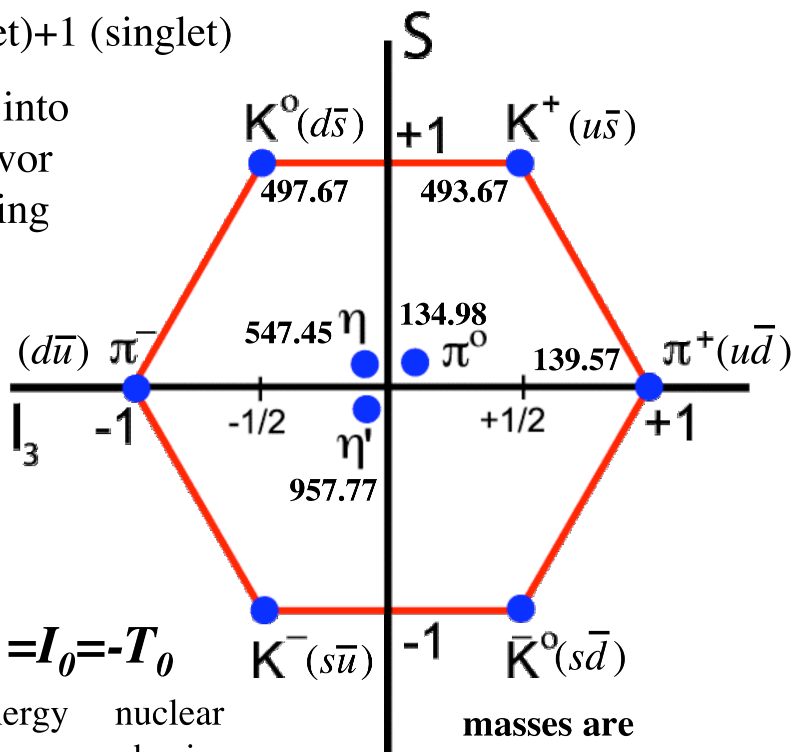
9=8 (octet)+1 (singlet)

Members of the octet transform into each other under rotations in flavor space (SU_3 group!). The remaining meson, η_0, forms a 1-dim irrep.

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle - |d\bar{d}\rangle\right)$$

$$|\eta_8\rangle = \frac{1}{\sqrt{6}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle - 2|s\bar{s}\rangle\right)$$

$$|\eta_0\rangle = \frac{1}{\sqrt{3}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle + |s\bar{s}\rangle\right)$$



$I_3 = I_0 = -T_0$

High-energy physics | nuclear physics

masses are given in MeV/c²

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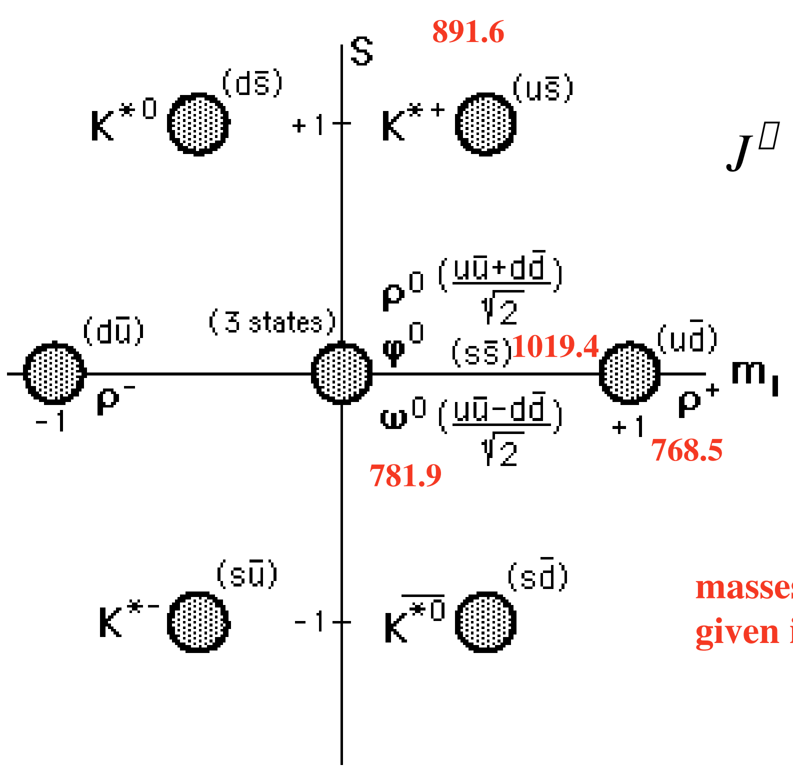
In reality, since the SU_3 (flavor) symmetry is not exact one, the observed mesons are:

$$\eta = \eta_8 \cos\theta + \eta_0 \sin\theta \qquad \eta' = -\eta_8 \sin\theta + \eta_0 \cos\theta$$

θ – Cabibbo angle, ~10° for pseudoscalar mesons

vector mesons

Here S=1, hence J=1. This implies negative parity. The vector mesons are more massive than their pseudoscalar counterparts, reflecting the differences in the interaction between a quark and an antiquark in the S=0 and S=1 states.



$$J^P = 1^-$$

masses are given in MeV/c²

Structure of Hadrons

static quark model of hadrons

baryons

With three flavors, one can construct a total of 3x3x3=27 baryons for a given set of *(l,S)*-values.

27=10+8+8+1

baryon singlet

$$J^{\pi} = \frac{1}{2}^{+},\ t = 0$$

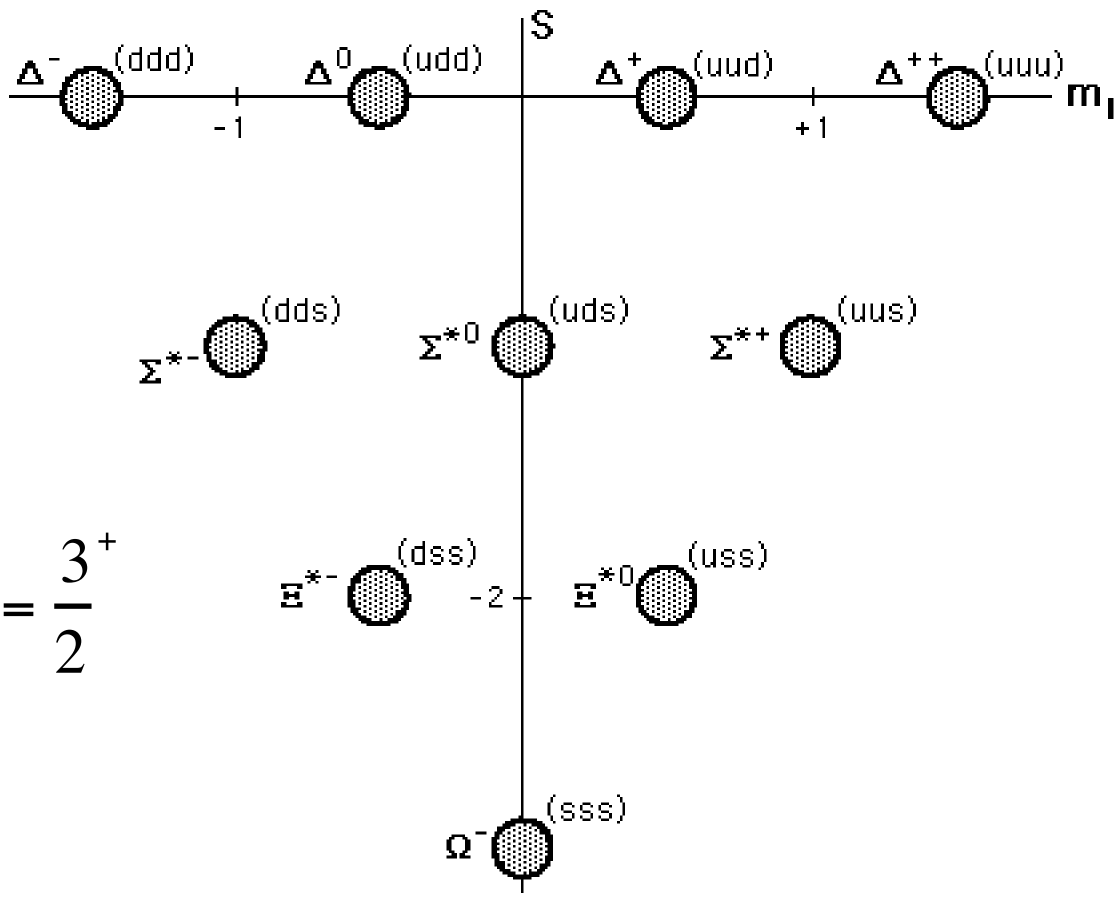
Completely asymmetric under a transformation in flavor

$$|\Lambda_1\rangle = \frac{1}{\sqrt{6}}\left\{|uds\rangle + |dsu\rangle + |sud\rangle - |dus\rangle - |usd\rangle - |sdu\rangle\right\}$$

baryon decuplet

Completely symmetric under a transformation in flavor

$$J^{\pi} = \frac{3}{2}^{+}$$



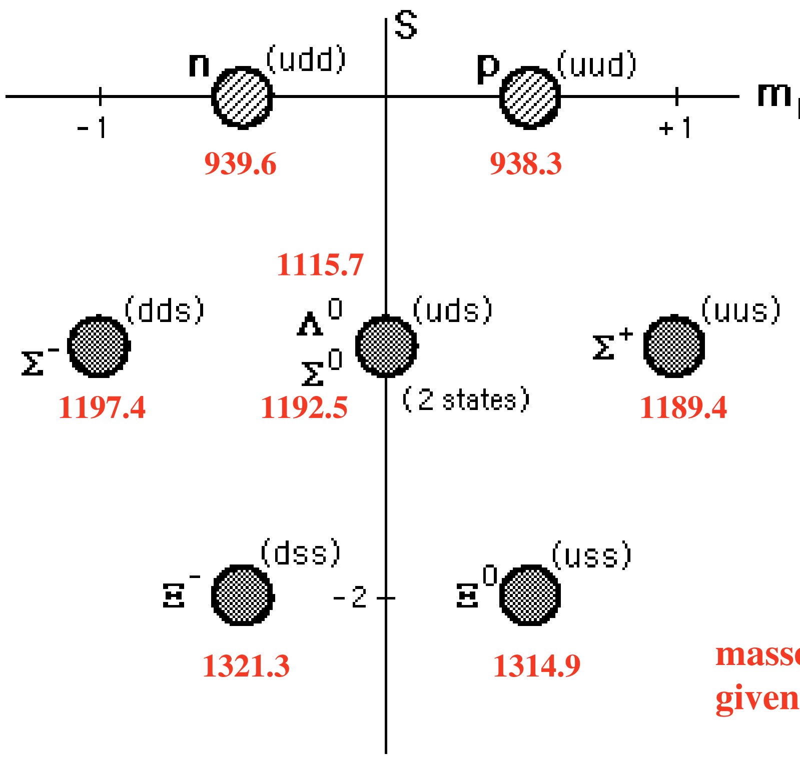
Structure of Hadrons

static quark model of hadrons

baryon octet

The remaining 16 members of the 27 possible baryons constructed from u-, s-, and d-quarks have mixed symmetry in flavor. The lower energy octet contains protons and neutrons as its members. The wave functions for each member in the group is symmetric under the combined exchange of flavor and intrinsic spin (the quarks are antisymmetric in color!)

$$J^{P} = \frac{1}{2}^{+}$$



masses are given in MeV/c²

example: proton wave function

$$
\begin{aligned}
|p\rangle = \frac{1}{\sqrt{18}}\Big\{ & 2\big(|u\uparrow u\uparrow d\downarrow\rangle + |u\uparrow d\downarrow u\uparrow\rangle + |d\downarrow u\uparrow u\uparrow\rangle\big) \\
& - \big(|u\uparrow u\downarrow d\uparrow\rangle + |u\uparrow d\uparrow u\downarrow\rangle + |d\uparrow u\uparrow u\downarrow\rangle\big) \\
& + \big(|u\downarrow u\uparrow d\uparrow\rangle + |u\downarrow d\uparrow u\uparrow\rangle + |d\uparrow u\downarrow u\uparrow\rangle\big)\Big\}
\end{aligned}
$$

In order to get the neutron wave function, one has to substitute all the u-quarks by d-quarks and vice versa.

Structure of Hadrons

magnetic dipole moments of the baryon octet

The magnetic dipole moment of a baryon comes from two sources: the intrinsic dipole moment of the constituent quarks and the orbital motion of the quarks. For the baryon octet, l=0.

$$\vec{\mu} = g\vec{s}\mu_D, \quad \mu_D = \frac{q\hbar}{2m_q c}$$

For Dirac particles (I.e., particles devoid of internal structure), $g=2$ *for* $s=1/2$. Unfortunately, we do not know quark masses. Assuming that the masses of u- and d-quarks are equal, one obtains:

$$\mu_u = -2\mu_d$$

Consider the proton wave function written in terms of u- and d-quarks. The net contribution from u-quarks is 4/3 and that from d-quarks is -1/3. Hence

$$\mu_p = \frac{4}{3}\mu_u - \frac{1}{3}\mu_d$$

By the same token

$$\mu_n = \frac{4}{3}\mu_d - \frac{1}{3}\mu_u$$

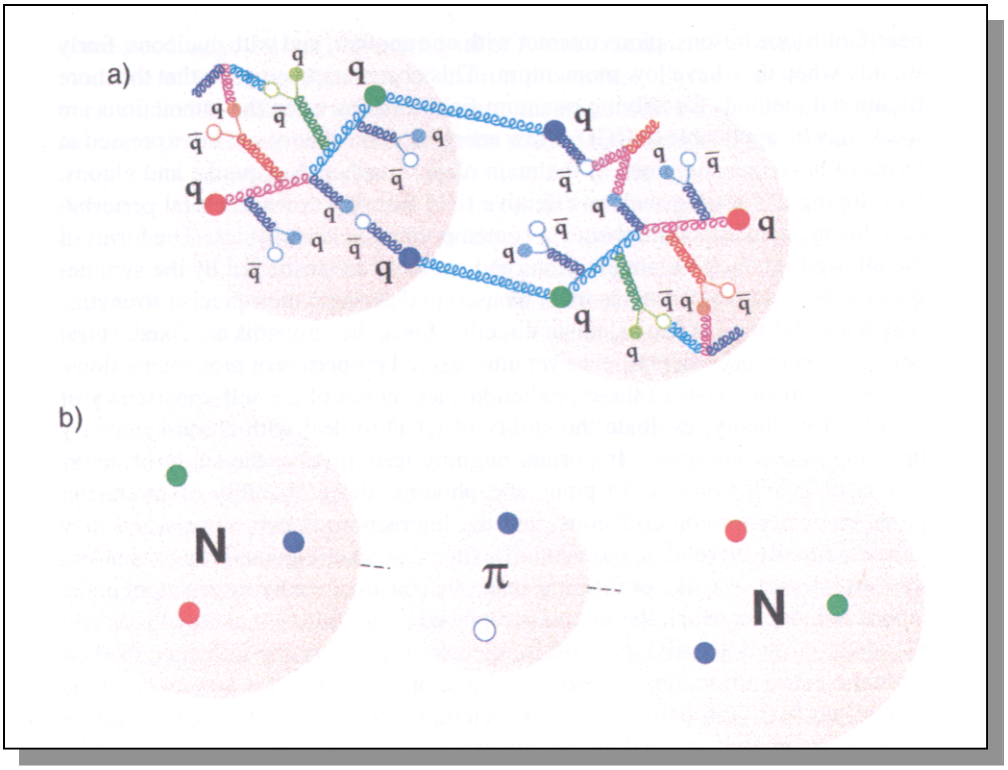
This gives $$\frac{\mu_n}{\mu_p} = -\frac{2}{3}$$ **(=−0.685 experimentally)**

Octet member	Quark content u	d	s	Best fit μ_N	Observed μ_N
p	$\frac{4}{3}$	$-\frac{1}{3}$	0	2.793	2.792847386(63)
n	$-\frac{1}{3}$	$\frac{4}{3}$	0	−1.913	−1.91304275(45)
Λ	0	0	1	−0.613	−0.613(4)
Σ^+	$\frac{4}{3}$	0	$-\frac{1}{3}$	2.674	2.458(10)
Σ^-	0	$\frac{4}{3}$	$-\frac{1}{3}$	−1.092	−1.160(25)
Ξ^0	$-\frac{1}{3}$	0	$\frac{4}{3}$	−1.435	−1.250(14)
Ξ^-	0	$-\frac{1}{3}$	$\frac{4}{3}$	−0.493	−0.6507(25)
$\Sigma^0 \to \Lambda$	$-\sqrt{\frac{1}{3}}$	$\sqrt{\frac{1}{3}}$	0	−1.630	−1.61(8)
Ω^-			3	−1.839	−2.02(5)
u	1			1.852	
d		1		−0.972	
s			1	−0.613	

quark magnetic moments

Structure of Hadrons

Origin of the nucleon-nucleon force



The simplest contributions to the force between nucleons, as viewed from (a) QCD and (b) conventional nuclear theory. In (a), the exchange of two colored gluons causes two quarks in each nucleon to change their colors (blue changes to green and vice versa in the case illustrated). This process produces a force without violating the overall color neutrality of the nucleons. The strength of the force depends on the separation of the different quark colors within each nucleon. On the other hand, low-energy nuclear physics measurements show clearly that the longest-range part of the force arises from the exchange of a single pi meson between two nucleons, as in (b). In this low-energy view, the internal structure of each nucleon is generally attributed to three pseudo-quarks, which somehow combine the properties of the valence quarks, sea quarks, and gluons predicted by QCD.

"Naïve" physically allowed hadrons (<u>color singlets</u>)

$q\bar{q}$ q^3

Conventional quark model
mesons and baryons.

100s of e.g.s

"exotica" :

$g^2, g^3, \ldots$

glueballs

maybe 1 e.g.

$q\underline{q}g,\ q^3g, \ldots$

hybrids

maybe 1-3 e.g.s

$q^2\underline{q}^2,\ q^4\underline{q}, \ldots$

multiquarks

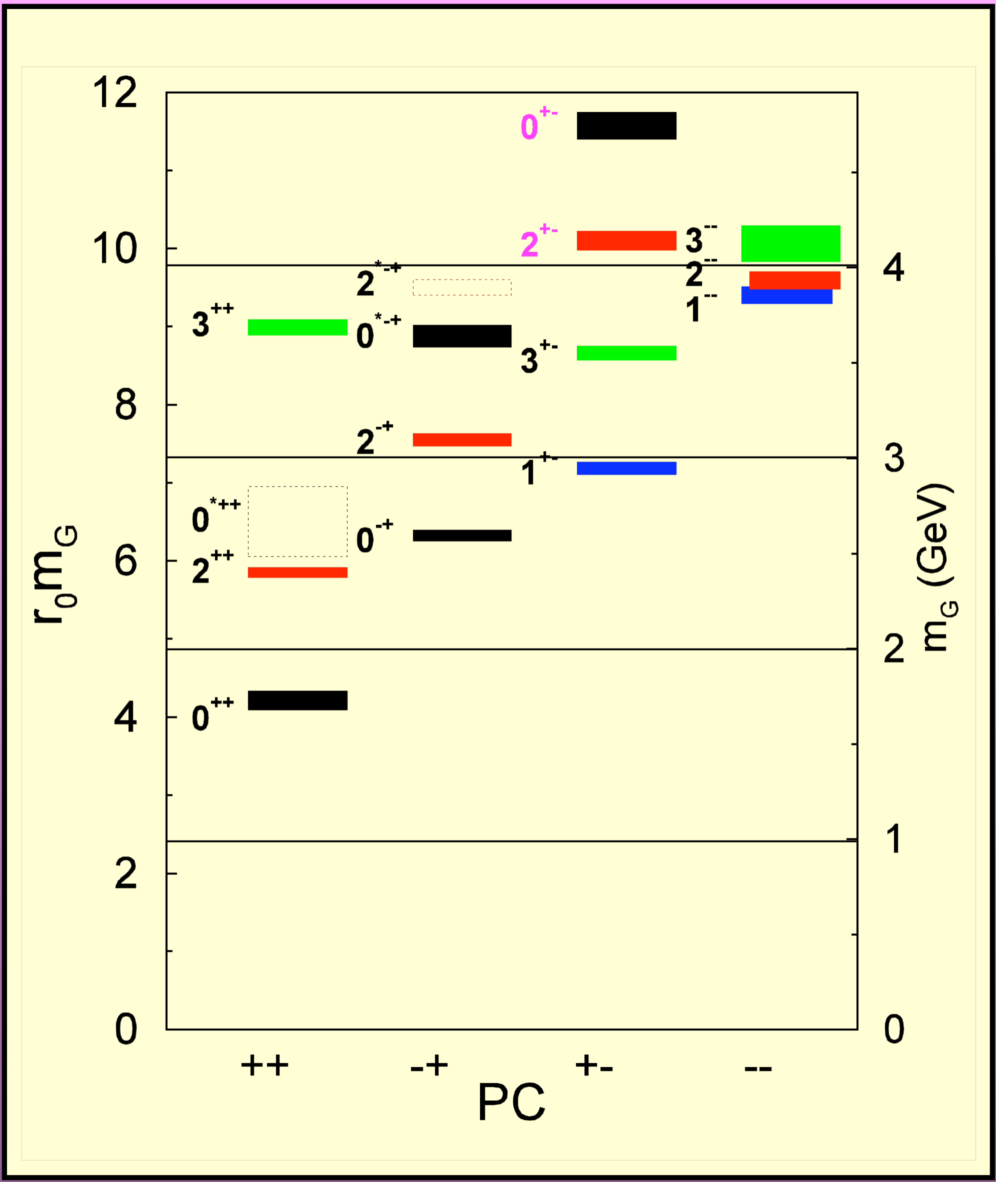
Glueballs:

Theor. masses (LGT)

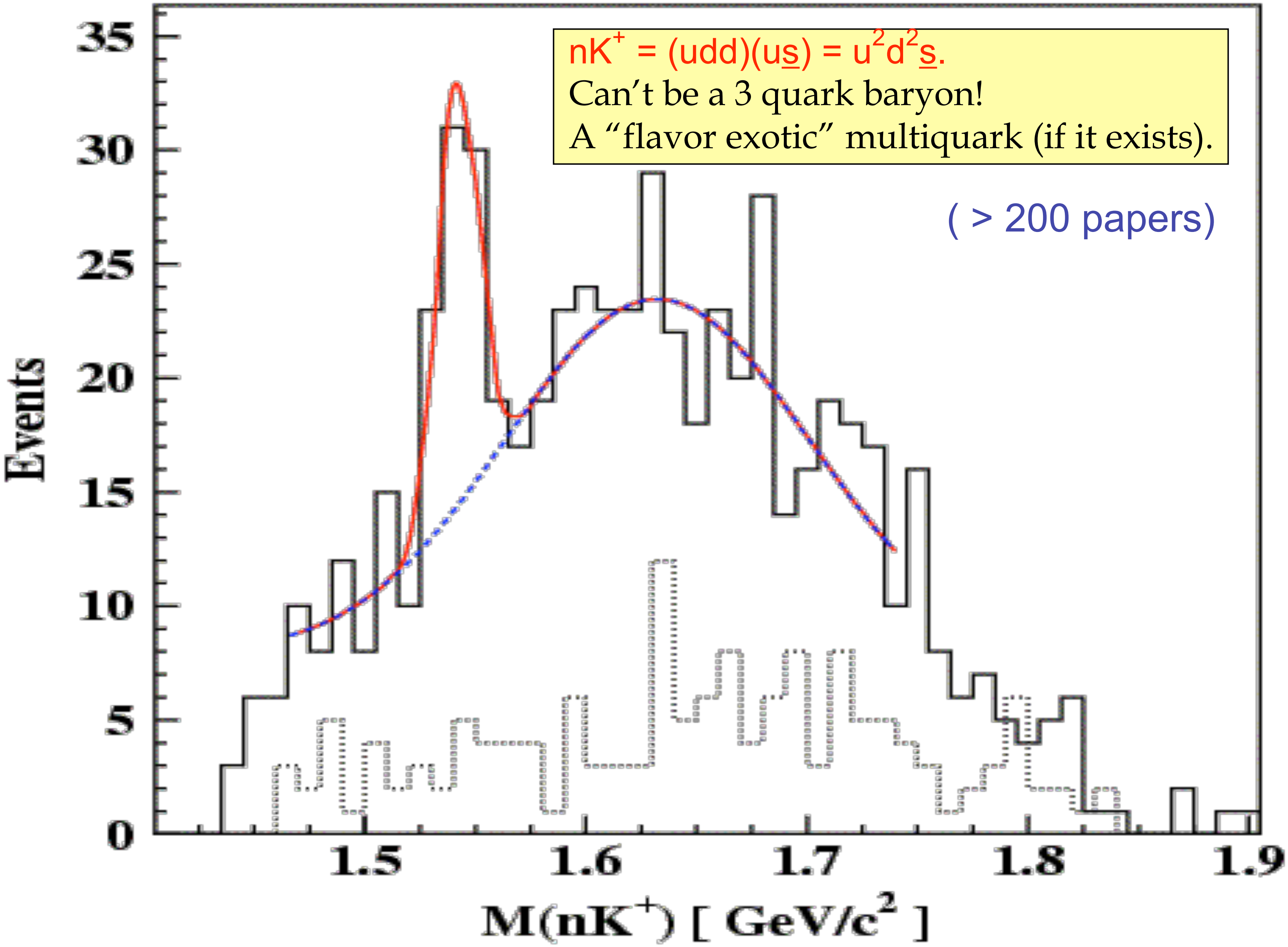
The glueball spectrum from an anisotropic lattice study

Colin Morningstar, Mike Peardon
Phys. Rev. D60 (1999) 034509

The spectrum of glueballs below 4 GeV in the SU(3) pure-gauge theory is investigated using Monte Carlo simulations of gluons on several anisotropic lattices with spatial grid separations ranging from 0.1 to 0.4 fm.



Sometimes the news is too exciting: the pentaquark at CLAS (CEBAF).



An experiment expressly designed to detect “pentaquarks” confirms the existence of these exotic physics particles, researchers reported Sunday. […]

Physicists are cautious about leaping onto the pentaquark bandwagon because of past bad experiences […]

USA Today
3 May 2004

The multiquark fiasco

"These are very serious charges you're making, and all the more painful to us, your elders, because we still have nightmares from five times before."

– village elder, "*Young Frankenstein*"

The dangerous 1970s multiquark logic:

(which led to the multiquark fiasco)

The known hadron resonances, $\mathbf{q\underline{q}}$ and **qqq** (and $\mathbf{\underline{qqq}}$) exist because they are color singlets.

Therefore all higher Fock space “multiquark” color singlet sectors will also possess hadron resonances.

$\mathbf{q^2\underline{q}^2}$ “baryonia”

$\mathbf{q^6}$ “dibaryons”

$\mathbf{q^4\underline{q}}$ “Z*” for $\underline{q}$ = $\underline{s}$ …
now “pentaquarks”

MANY theoretical predictions of a **very rich spectrum** of multiquark resonances followed in the 1970s/early 1980s.

(Bag model, potential models, QCD_SRs, color chemistry,…)

Post-fiasco physically allowed hadrons (color singlets)

“Naive” physically allowed hadrons (color singlets)

$q\bar{q}$ $\quad$ q^3

Conventional quark model mesons and baryons.

100s of e.g.s

$(q^3)^n$, $(q\bar{q})(q\bar{q})$, $(q\bar{q})(q^3)$, …

nuclei / molecules

ca. 10^6 e.g.s of $(q^3)^n$, maybe 1-3 others

Basis state mixing may be very important in some sectors.

”exotica” :

g^2, g^3, …

glueballs

maybe 1 e.g.

$q\bar{q}g$, q^3g, …

hybrids

maybe 1-3 e.g.s

$(q^2\bar{q}^2)$, $(q^4\bar{q})$, …

$q^2\bar{q}^2$, $q^4\bar{q}$, …

multiquark clusters ???

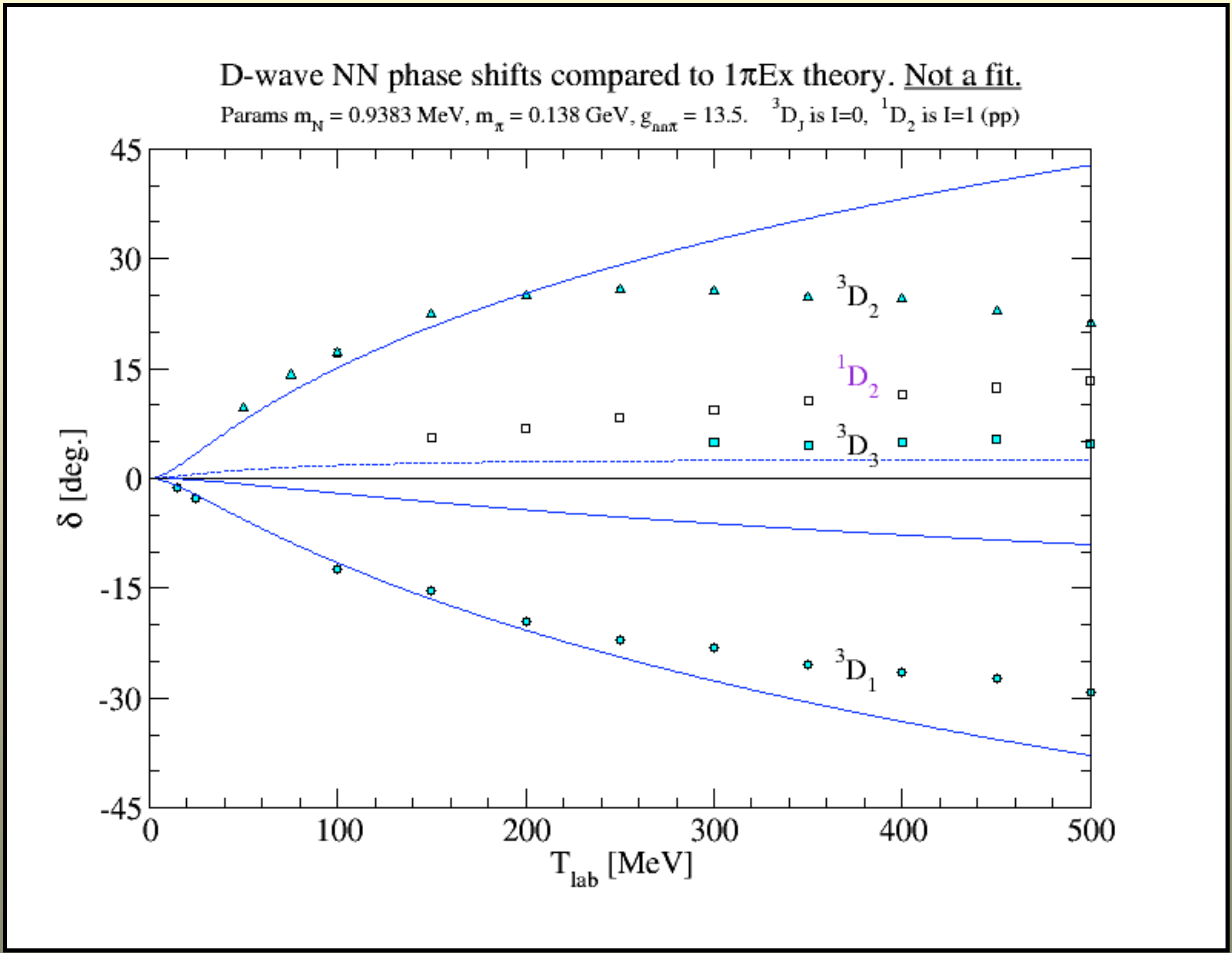
multiquarks

controversial

e.g. $\Theta(1542)$?

An example of an NN force model.

One pion exchange (lines) versus L=2 NN scattering phase shifts.



Summary and conclusions:

The strong interaction is described by QCD, a gauge theory of quarks and gluons. Recent developments in hadron spectroscopy have been concerned with the possible existence of "exotica" - glueballs, hybrids and multiquarks, and charmed mesons much at lower masses than expected.

The derivation of nuclear forces (e.g. NN) from QCD remains an interesting and open topic.

Future experimental facilities (not discussed):
BESIII in Beijing ($e^+e^- \to c\underline{c}$), 2007;
PANDA in Darmstadt ($p\underline{p} \to c\underline{c}$), 2012;
GlueX at JLab, Va, USA, ($\gamma \to$ exotic mesons) 2012.