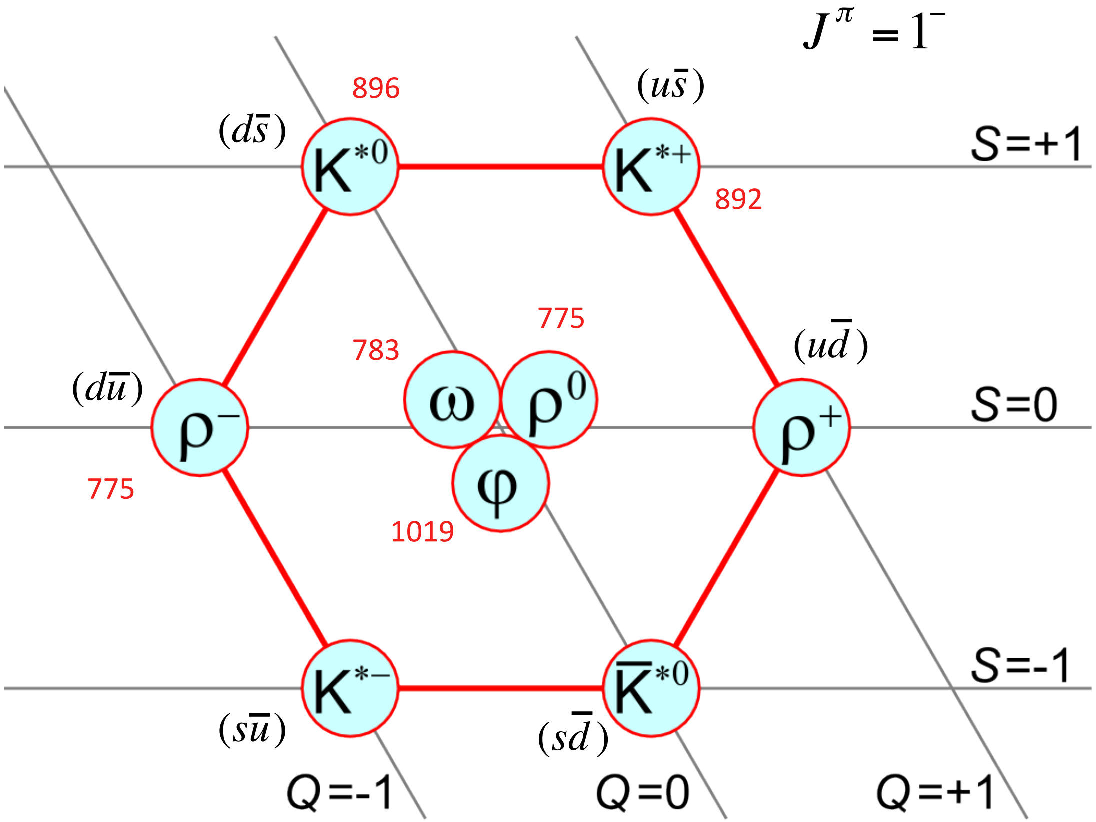
Vector mesons

Here *S*=1, hence *J*=1. They have 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.

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

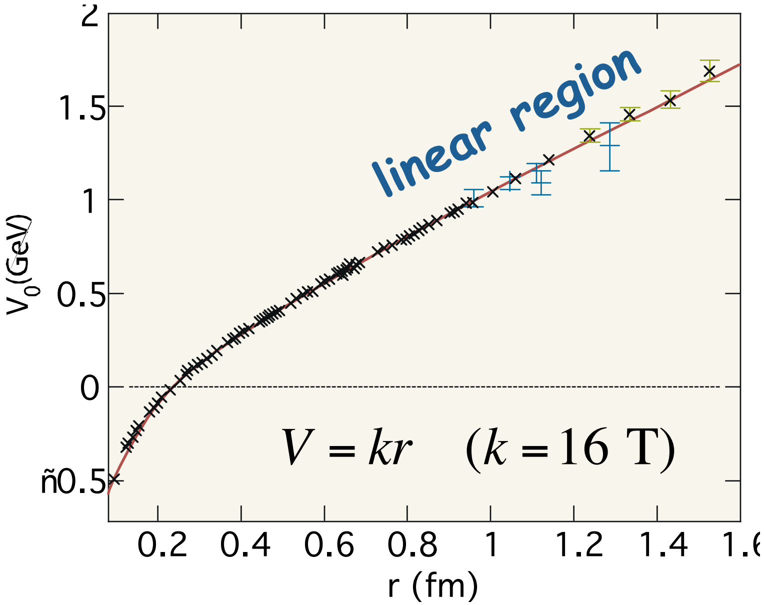
$$|\omega\rangle = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$$

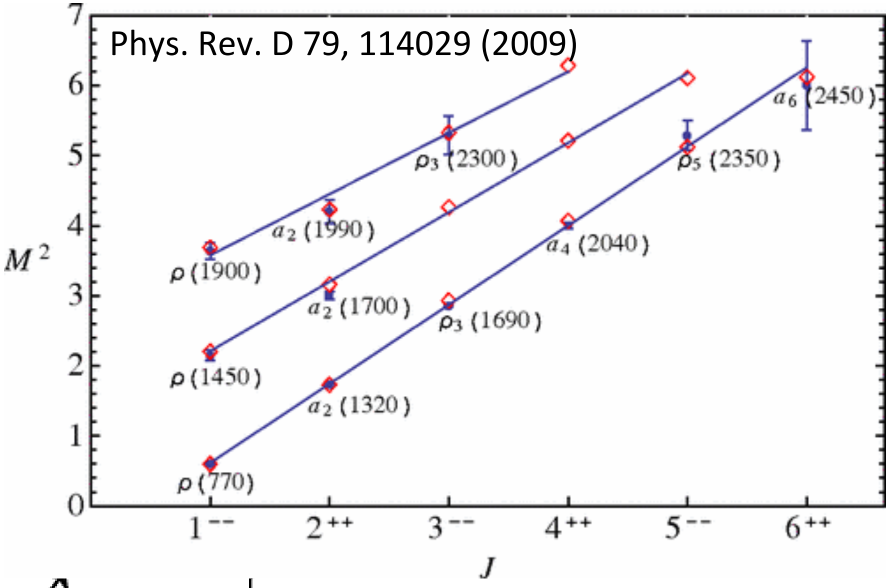
$$|\varphi\rangle = |s\bar{s}\rangle$$

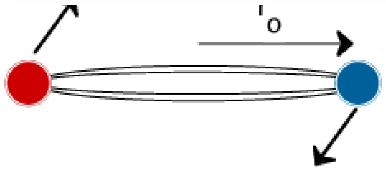


Flux tubes and confinement

Lattice “measurement” of the quenched static potential

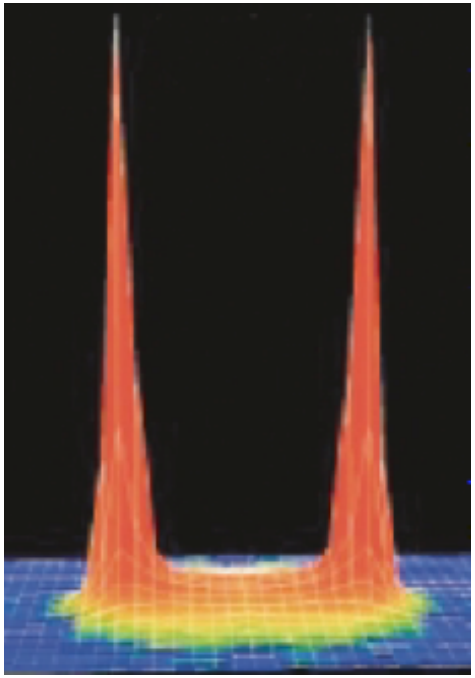



Phys. Rev. D 79, 114029 (2009)

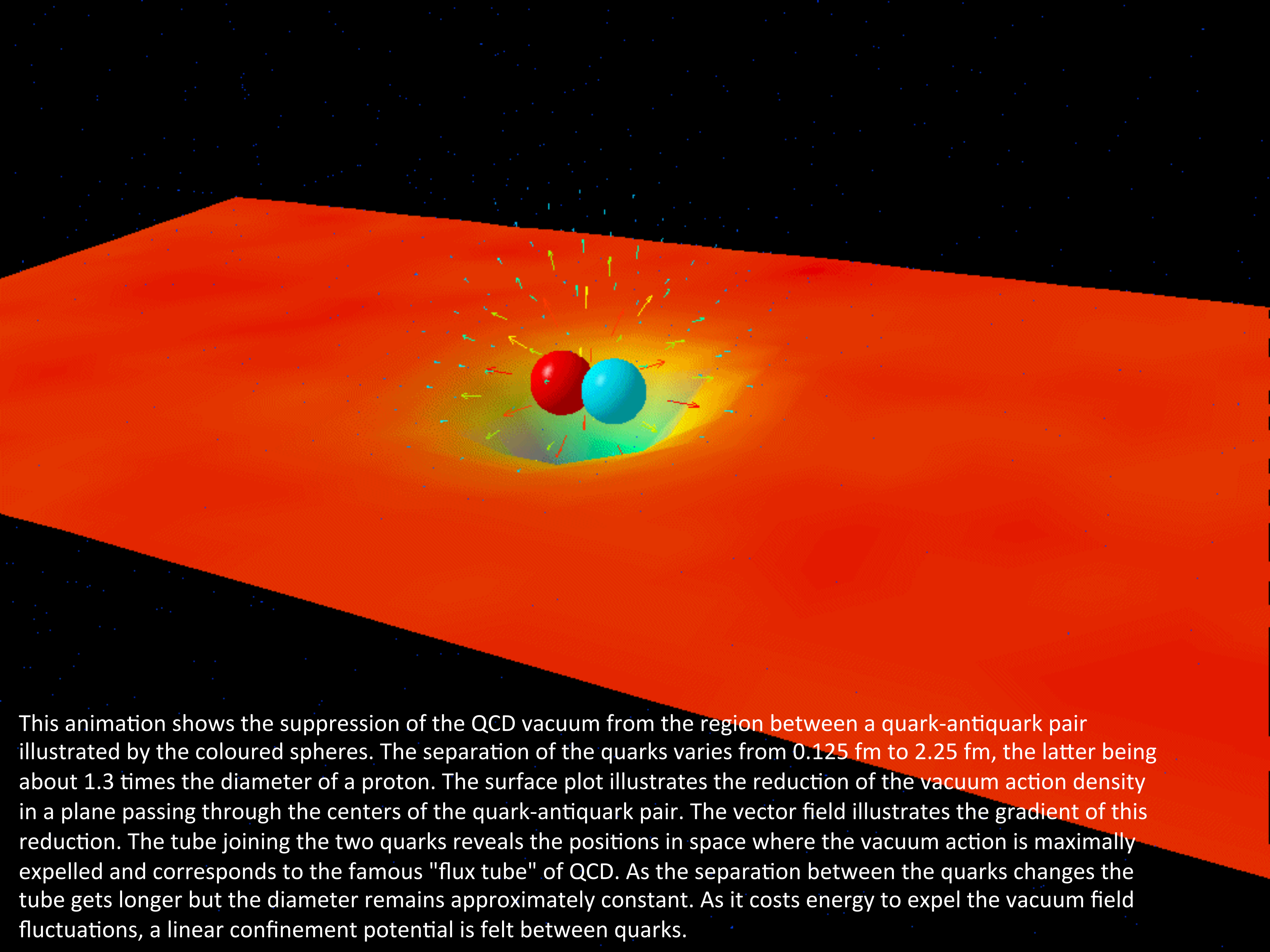


Regge trajectories
(Nambu 1970)

Phys. Rev. D 51, 5165 (1995)

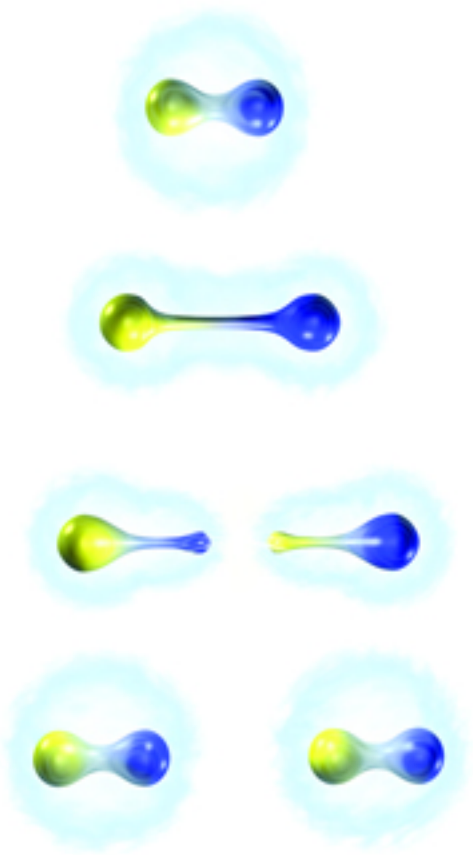


The origin of the linear potential between quarks may be traced to the flux tube: a string of gluon energy density between the quark pair. The QCD vacuum acts like a *dual superconductor*, which squeezes the color electric field to a minimal geometrical configuration, a narrow tube. It costs energy for the flux to spread out in space. The tube roughly has a constant cross section and with constant energy density. Because of this, the energy stored in the flux increases linearly with the length of the flux.



This animation shows the suppression of the QCD vacuum from the region between a quark-antiquark pair illustrated by the coloured spheres. The separation of the quarks varies from 0.125 fm to 2.25 fm, the latter being about 1.3 times the diameter of a proton. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quark-antiquark pair. The vector field illustrates the gradient of this reduction. The tube joining the two quarks reveals the positions in space where the vacuum action is maximally expelled and corresponds to the famous "flux tube" of QCD. As the separation between the quarks changes the tube gets longer but the diameter remains approximately constant. As it costs energy to expel the vacuum field fluctuations, a linear confinement potential is felt between quarks.

http://www.fair-center.eu



Quarks do not exist in isolation. Attempts to separate quarks from one another require huge amounts of energy and results in the production of new quark-antiquark pairs.

The theory of the strong interaction predicts the existence of glueballs-particles that consist only of gluons (above), and so-called hybrids composed of two quarks and a gluon (below).

Baryons (qqq)

With three flavors, one can construct a total of 3×3×3=27 baryons

$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

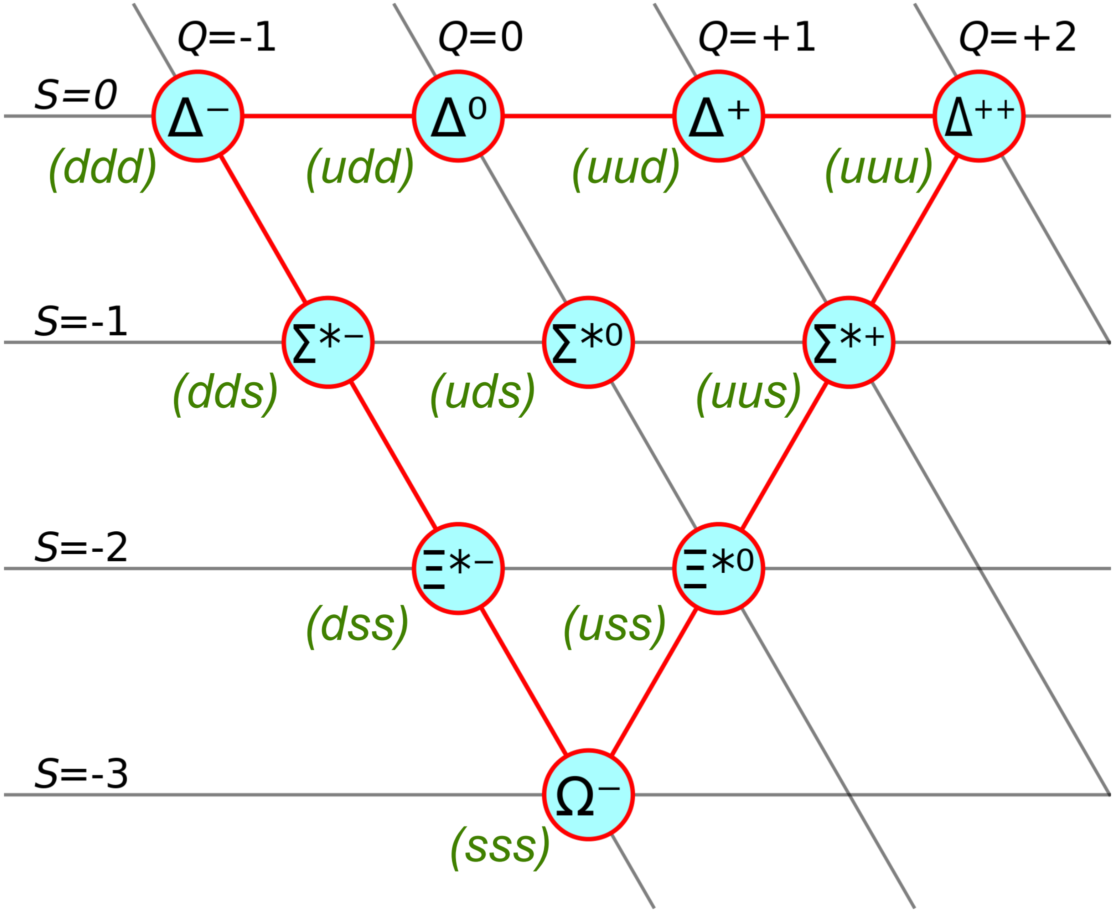
baryon singlet $t = 0$

Completely asymmetric under flavor rotations

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

The color and flavor wave-functions should be antisymmetric and thus zero orbital angular momentum and spin-1/2 are not possible if the wave-functions is to be overall antisymmetric as required by Fermi–Dirac statistics. Hence, *L*=1 $J^{\pi} = \frac{1}{2}^{-}$ Λ (1405)

baryon decuplet



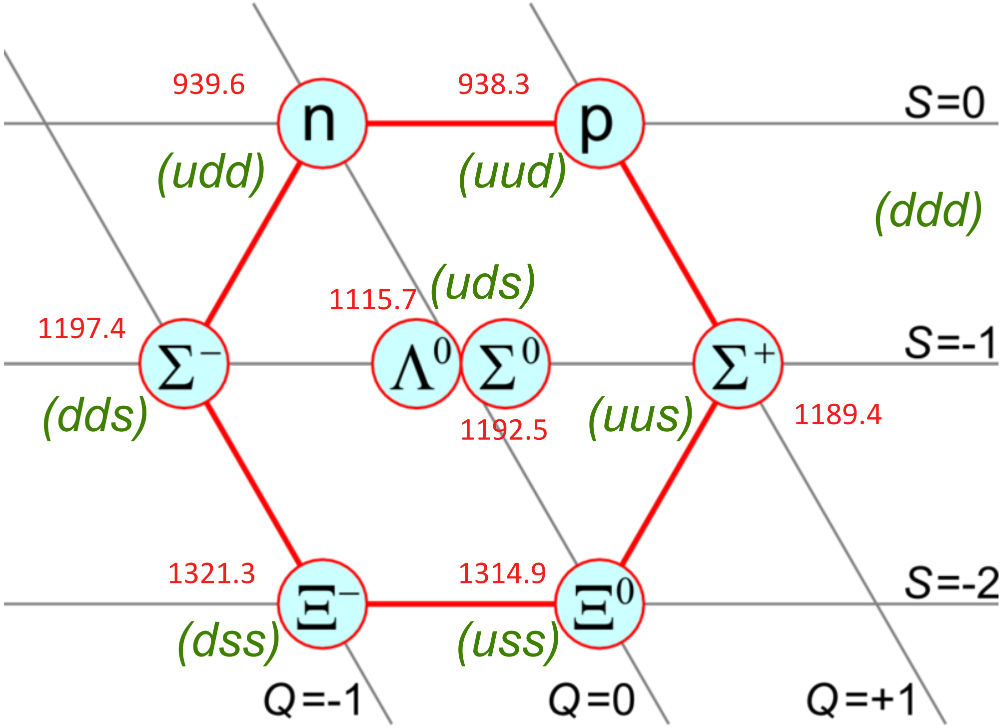
$$J^{\pi} = \frac{3}{2}^{+}$$

The discovery of the omega baryon was a great triumph for the quark model of baryons since it was found only after its existence, mass, and decay products had been predicted by Murray Gell-Mann in 1962. It was discovered at Brookhaven in 1964.

baryon octet

The remaining 16 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!)

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



example: proton wave function

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

Which of the following reactions is allowed, and what are the forces (strong, electro weak) that govern them? Which conservation laws prevent the reactions that are not allowed? Remember that weak interaction can mix quark flavors.

1) $p + \bar{p} \rightarrow \pi^+ + \pi^-$

2) $\pi^0 \rightarrow \gamma + \gamma$

3) $p + \pi^0 \rightarrow \Delta^+$

4) $K^- \rightarrow \pi^+ + \pi^0$

5) $\Sigma^0 \rightarrow \Lambda^0 + \pi^0$

6) $\mu^- \rightarrow e^- + \bar{\nu}_e$

7) $n + \bar{n} \rightarrow \pi^+ + \pi^- + \pi^0$

8) $e^+ + e^- \rightarrow \mu^+ + \mu^-$

9) $p \rightarrow e^+ + \gamma$

10) $\Sigma^+ \rightarrow p + \gamma$

Magnetic dipole moments of the nucleon

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 precisely. Assuming that the masses of *u*- and *d*-quarks are equal, one obtains:

$$\mu_u = -2\mu_d$$

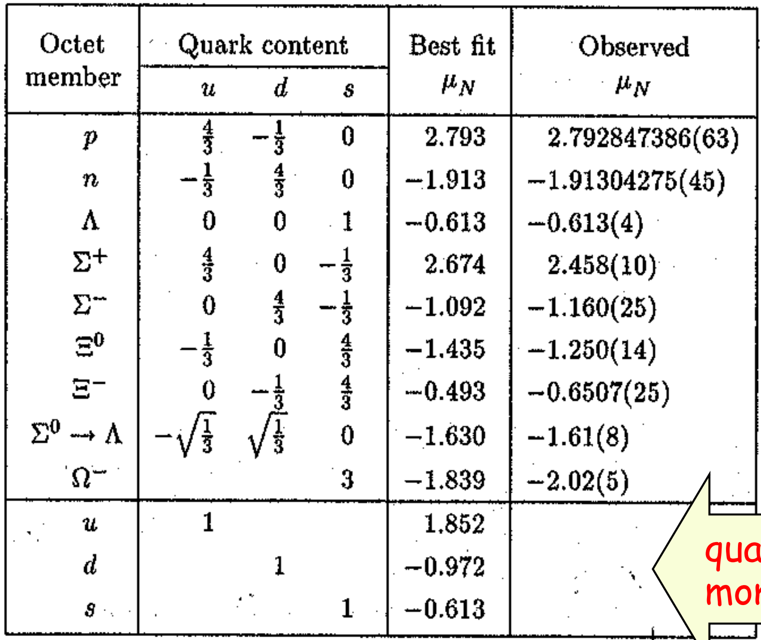
Consider the proton wave function written in terms of *u*- and d-quarks. The net contribution from *u*-quarks is 4/3 and that from *d*-quarks is -1/3. Hence

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

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)

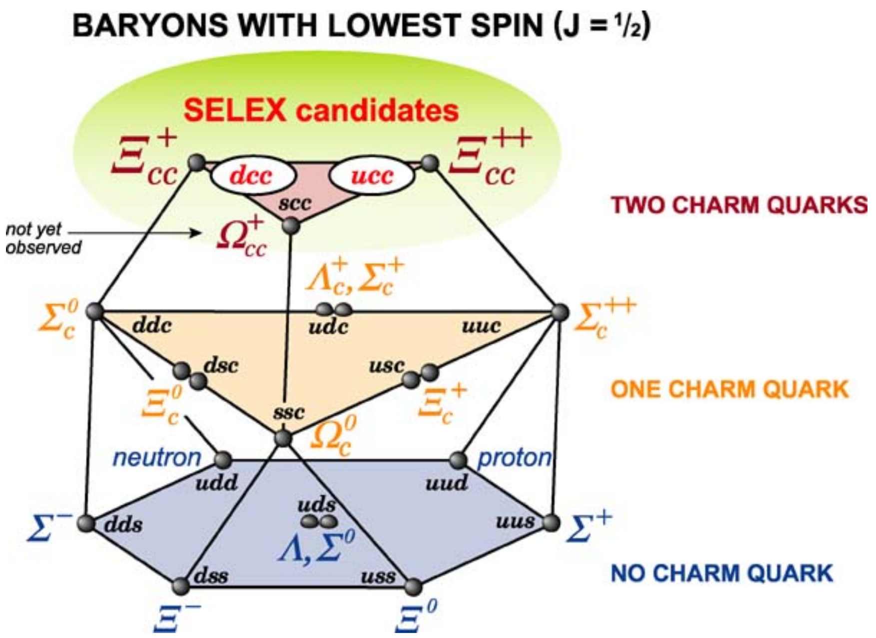


Octet member	Quark content			Best fit μ_N	Observed μ_N
	u	d	s		
p	$\frac{4}{3}$	$-\frac{1}{3}$	0	2.793	2.792847386(63)
n	$-\frac{1}{3}$	$\frac{4}{3}$	0	−1.913	−1.91304275(45)
Λ	0	0	1	−0.613	−0.613(4)
Σ^+	$\frac{4}{3}$	0	$-\frac{1}{3}$	2.674	2.458(10)
Σ^-	0	$\frac{4}{3}$	$-\frac{1}{3}$	−1.092	−1.160(25)
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	

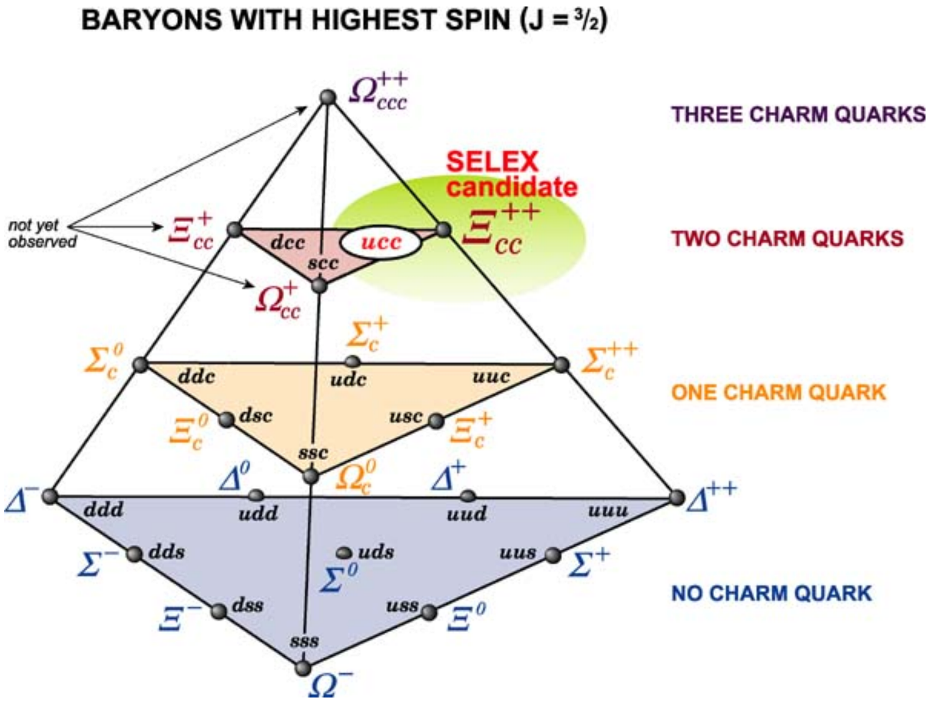
quark magnetic moments

New relatives of the proton

http://www.fnal.gov/pub/ferminews/ferminews02-06-14/selex.html



BARYONS WITH LOWEST SPIN (J = ½)

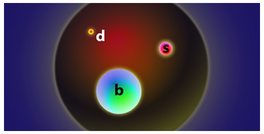


BARYONS WITH HIGHEST SPIN (J = 3/2)

Baryon Supermultiplet using four-quark models and half spin

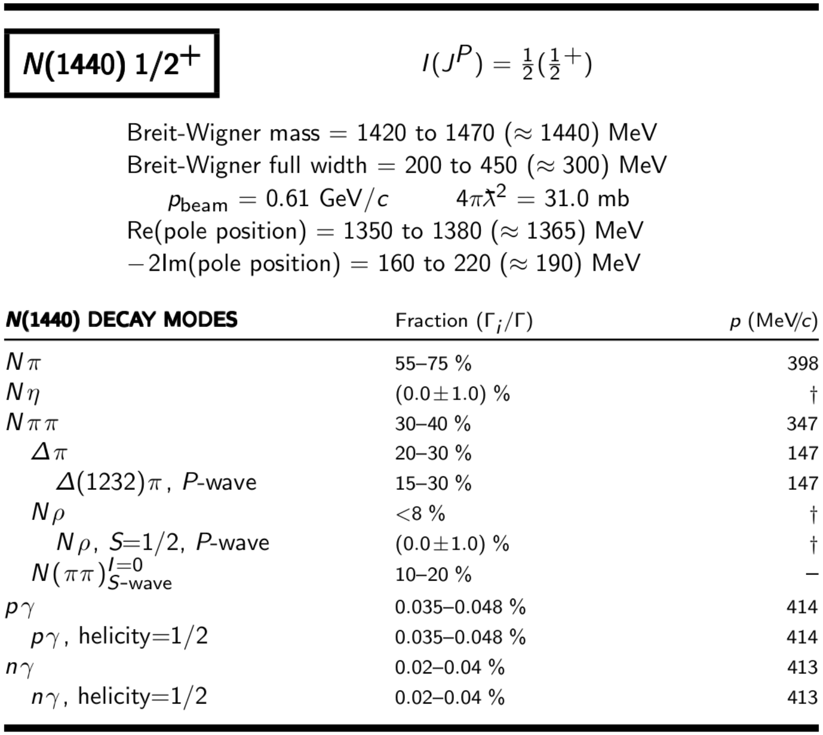
Two New Particles Enter the Fold

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.114.062004



$\Xi_b'^{-}$ and Ξ_b^{*-}

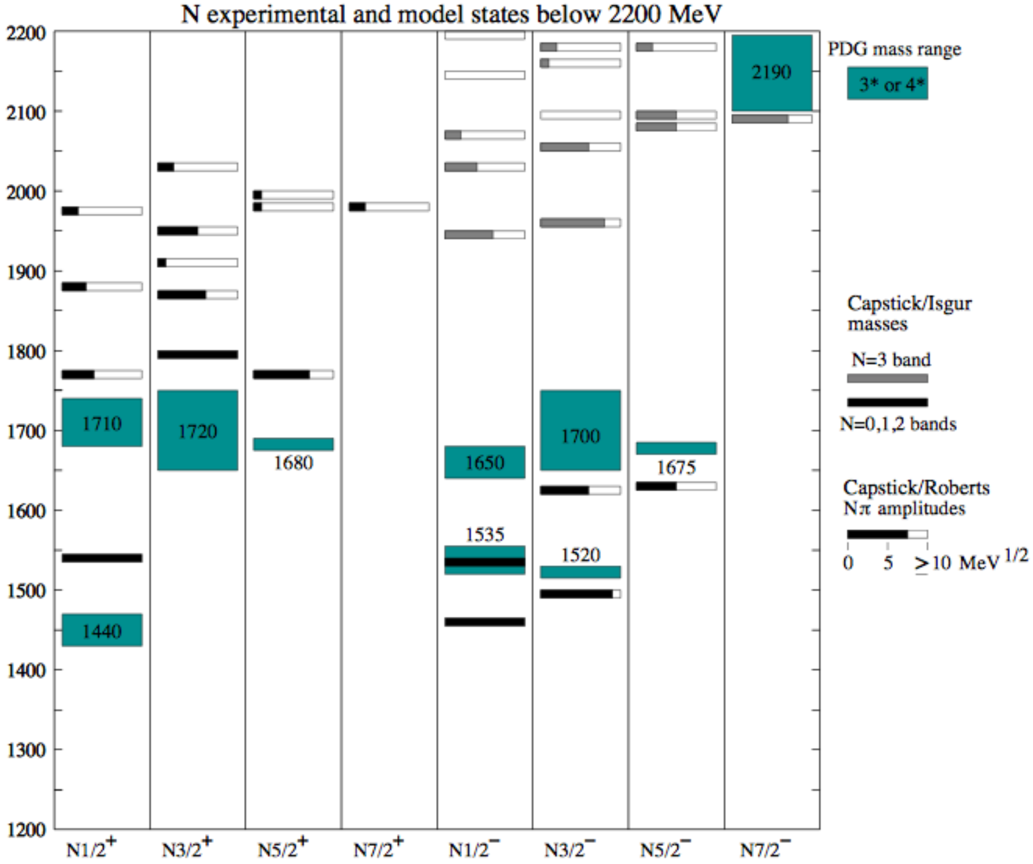
The Roper resonance $[N(1440)P_{11}]$ is the proton's first radial excitation. Its lower-than-expected mass owes to a dressed-quark core shielded by a dense cloud of pions and other mesons.

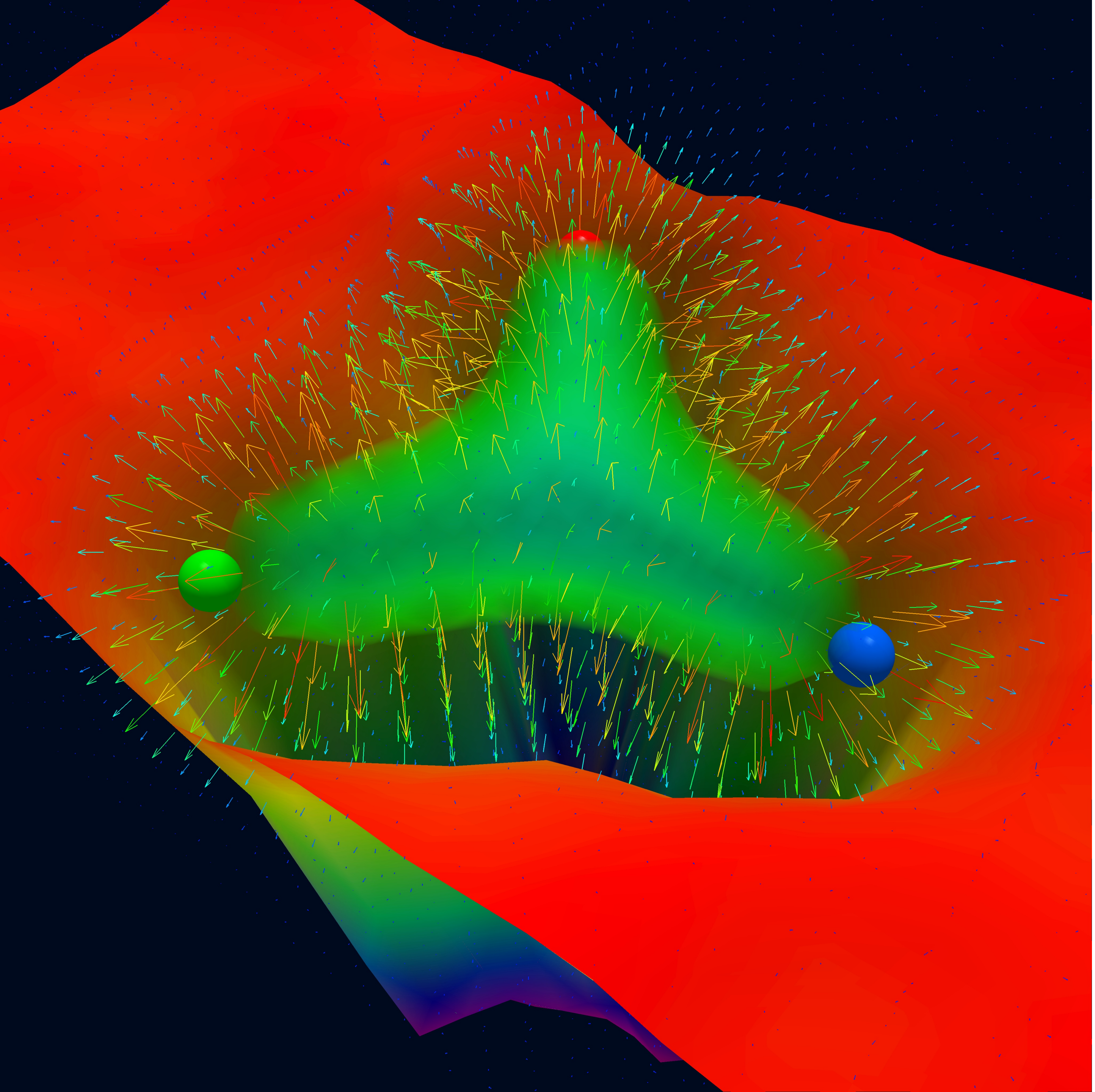


N(1440) 1/2$^+$ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$

Breit-Wigner mass = 1420 to 1470 (≈ 1440) MeV
Breit-Wigner full width = 200 to 450 (≈ 300) MeV
$p_{\text{beam}} = 0.61$ GeV/c $4\pi\lambdabar^2 = 31.0$ mb
Re(pole position) = 1350 to 1380 (≈ 1365) MeV
−2Im(pole position) = 160 to 220 (≈ 190) MeV

N(1440) DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$N\pi$	55–75 %	398
$N\eta$	(0.0±1.0) %	†
$N\pi\pi$	30–40 %	347
$\Delta\pi$	20–30 %	147
$\Delta(1232)\pi$, P-wave	15–30 %	147
$N\rho$	<8 %	†
$N\rho$, S=1/2, P-wave	(0.0±1.0) %	†
$N(\pi\pi)^{I=0}_{S\text{-wave}}$	10–20 %	–
$p\gamma$	0.035–0.048 %	414
$p\gamma$, helicity=1/2	0.035–0.048 %	414
$n\gamma$	0.02–0.04 %	413
$n\gamma$, helicity=1/2	0.02–0.04 %	413

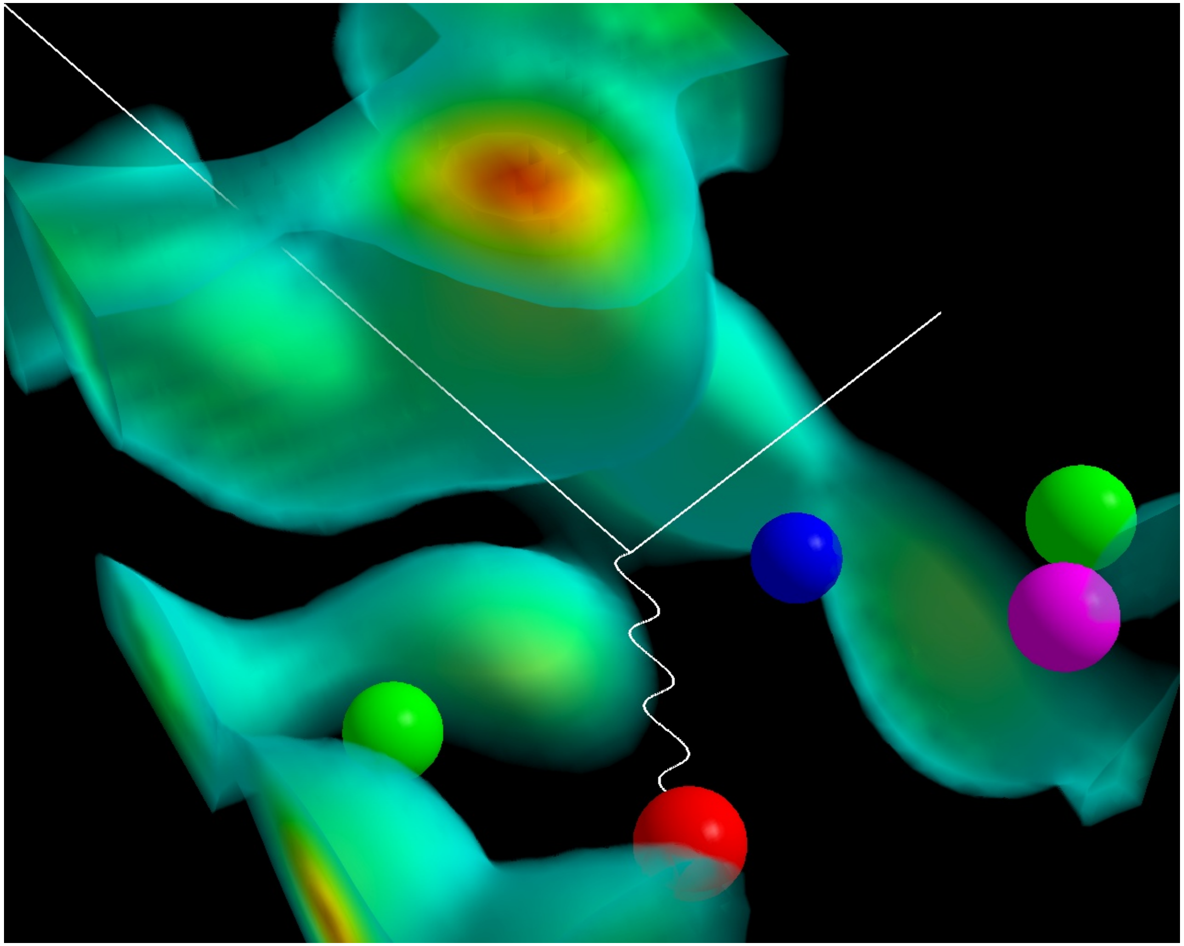




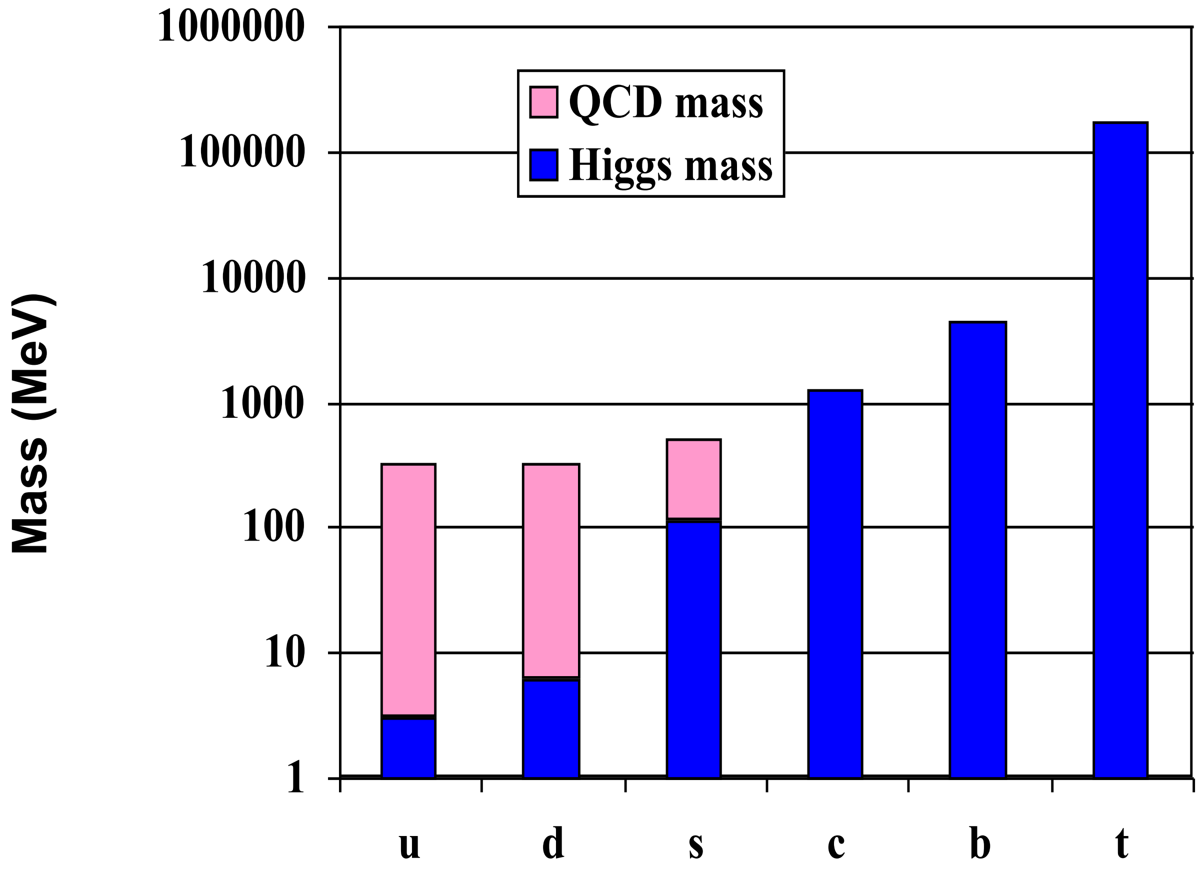
The positions of the three quarks composing the proton are illustrated by the colored spheres. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quarks. The vector field illustrates the gradient of this reduction. The positions in space where the vacuum action is maximally expelled from the interior of the proton are also illustrated by the tube-like structures, exposing the presence of flux tubes. A key point of interest is the distance at which the flux-tube formation occurs. The animation indicates that the transition to flux-tube formation occurs when the distance of the quarks from the center of the triangle is greater than 0.5 fm. Again, the diameter of the flux tubes remains approximately constant as the quarks move to large separations.

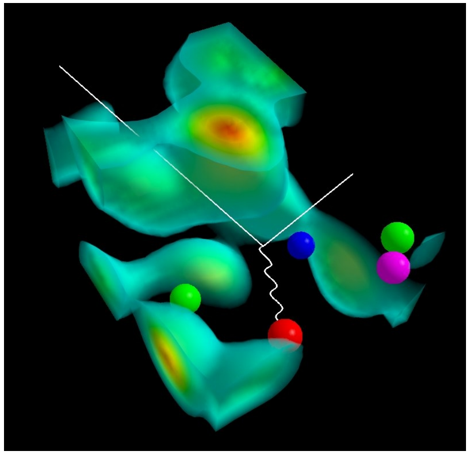
- Three quarks indicated by red, green and blue spheres (lower left) are localized by the gluon field.
- A quark-antiquark pair created from the gluon field is illustrated by the green-antigreen (magenta) quark pair on the right. These quark pairs give rise to a meson cloud around the proton.

http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/Nobel/index.html



Nucl. Phys. A750, 84 (2005)





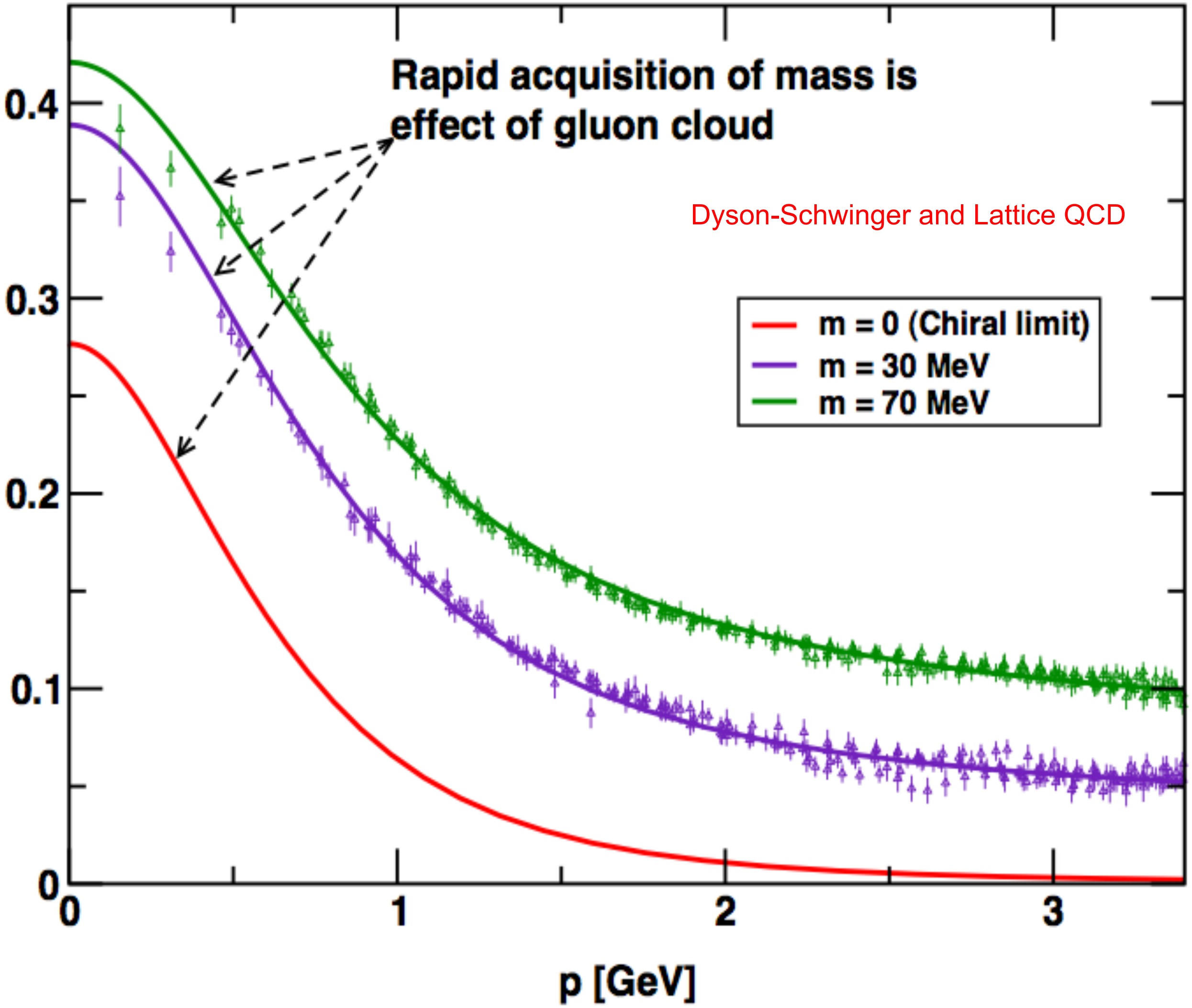
u + u + d = proton

mass: 0.003 + 0.003 + 0.006 $\neq$ 0.938 GeV

HOW does the rest of the proton mass arise?

HOW does the rest of the proton spin (magnetic moment,…), arise?

Mass from nothing



It is known that the dynamical chiral symmetry breaking; namely, the generation of mass *from nothing,* does take place in QCD. It arises primarily because a dense cloud of gluons comes to clothe a low- momentum quark. The vast bulk of the constituent-mass of a light quark is contained in a cloud of gluons, which are dragged along by the quark as it propagates. In this way, a quark that appears to be absolutely massless at high energies acquires a large constituent mass at low energies.