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

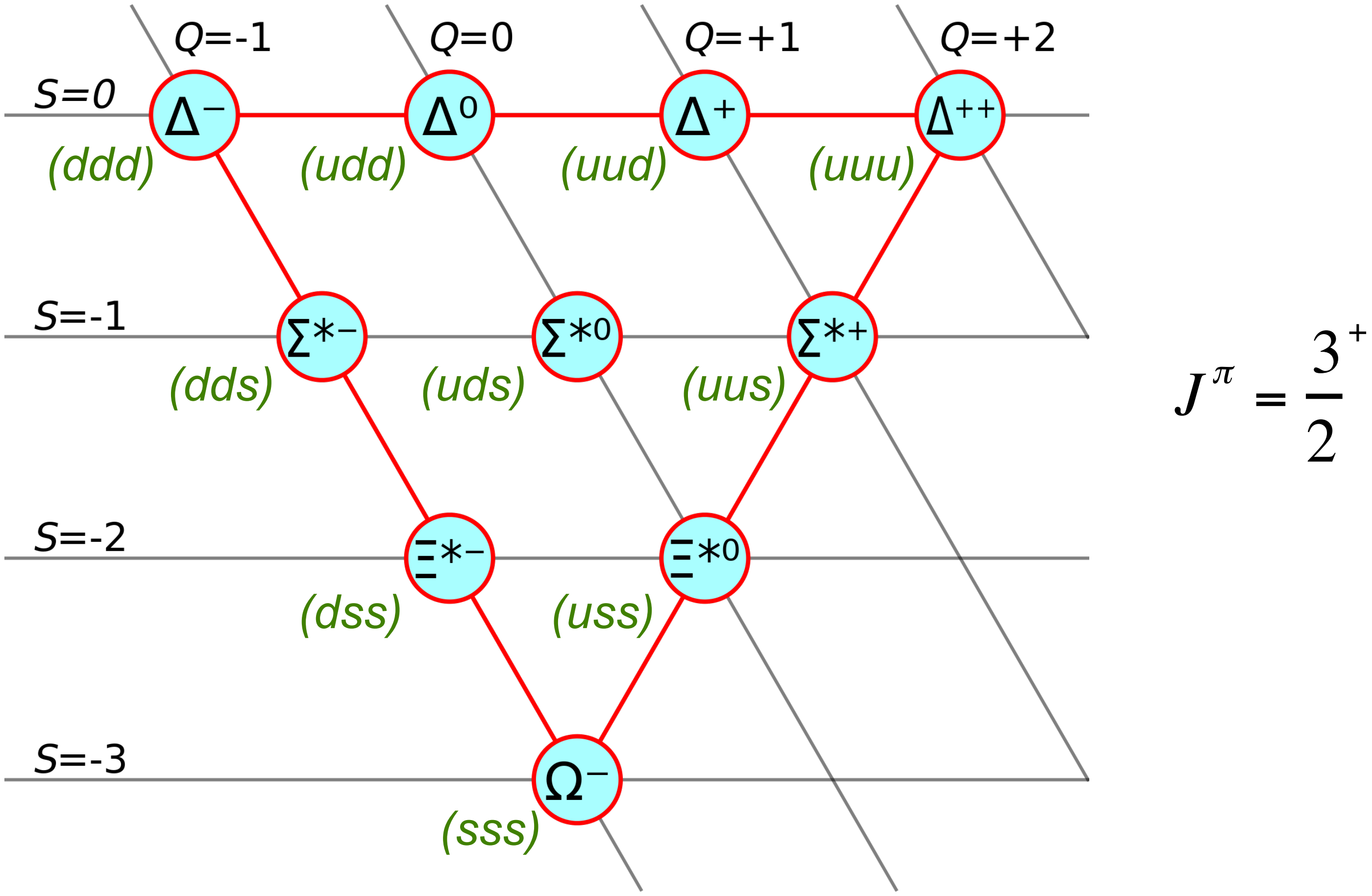
$t = 0$

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

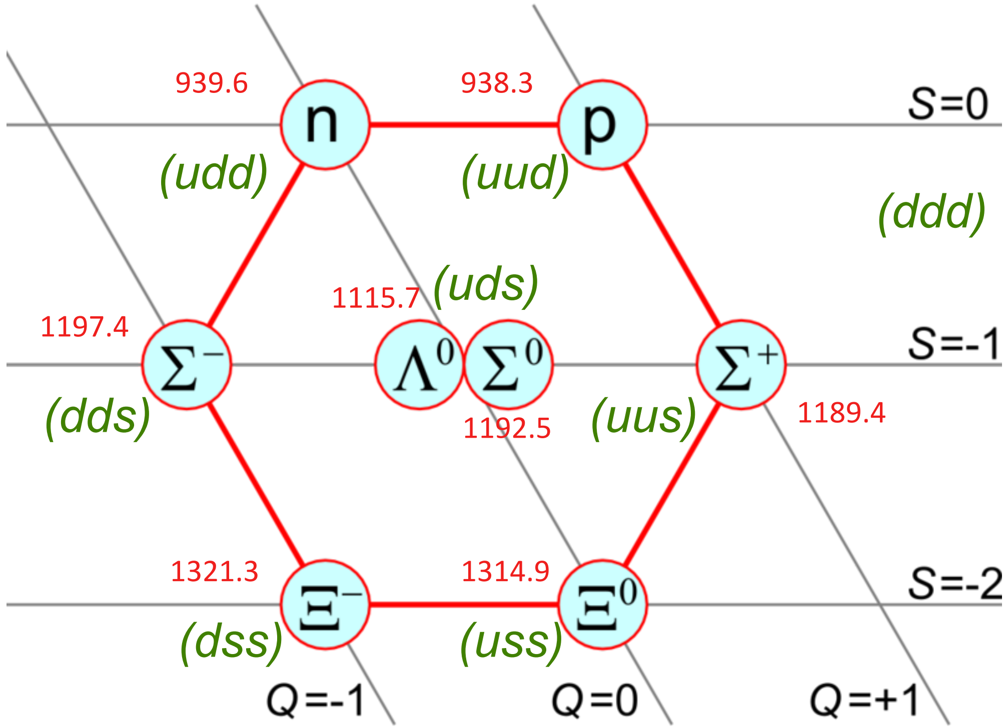


The discovery of the omega baryon was a great triumph for the quark model of baryons since it was found only after its existence, mass, and decay products had been predicted by Murray Gell-Mann in 1962. It was discovered at Brookhaven in 1964.

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

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

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 $\frac{\mu_n}{\mu_p} = -\frac{2}{3}$

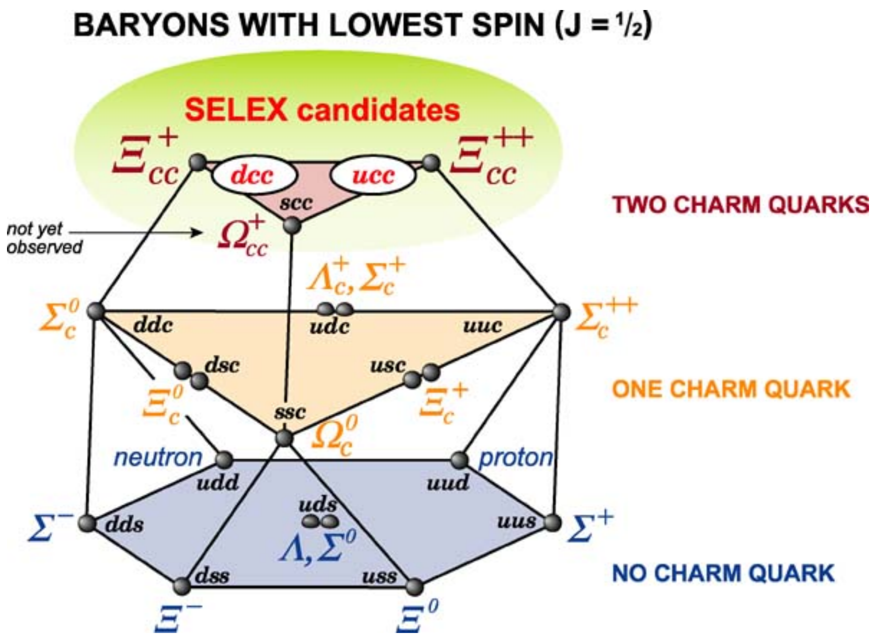
(=-0.685 experimentally)

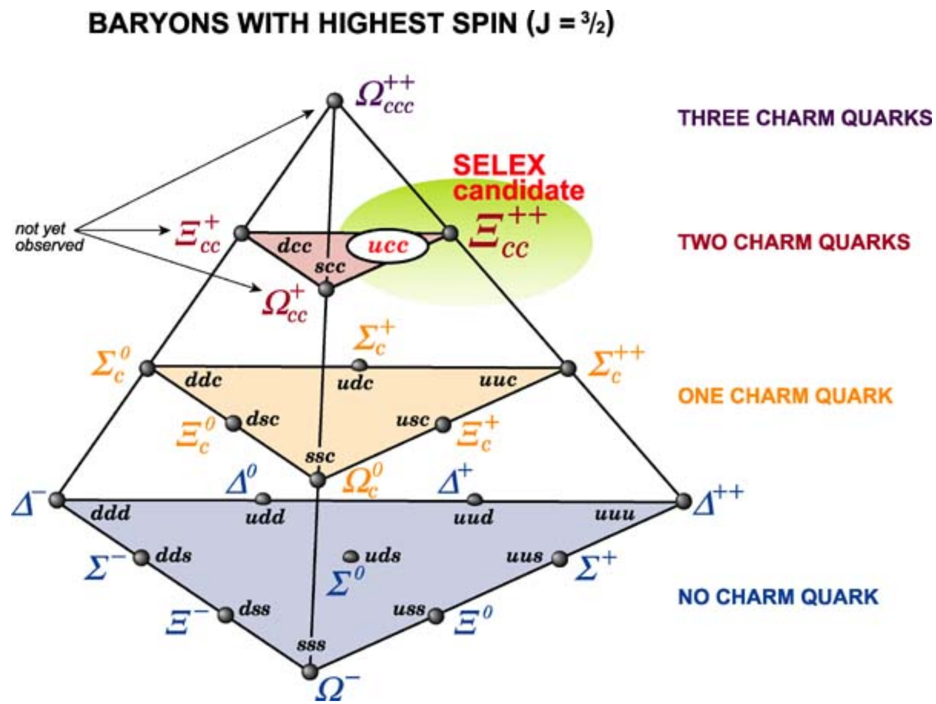
Octet member	Quark content u	d	s	Best fit μ_N	Observed μ_N
p	$\frac{4}{3}$	$-\frac{1}{3}$	0	2.793	2.792847386(63)
n	$-\frac{1}{3}$	$\frac{4}{3}$	0	−1.913	−1.91304275(45)
Λ	0	0	1	−0.613	−0.613(4)
Σ^+	$\frac{4}{3}$	0	$-\frac{1}{3}$	2.674	2.458(10)
Σ^-	0	$\frac{4}{3}$	$-\frac{1}{3}$	−1.092	−1.160(25)
Ξ^0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

New relatives of the proton

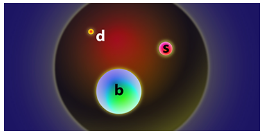
http://www.fnal.gov/pub/ferminews/ferminews02-06-14/selex.html





Two New Particles Enter the Fold

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



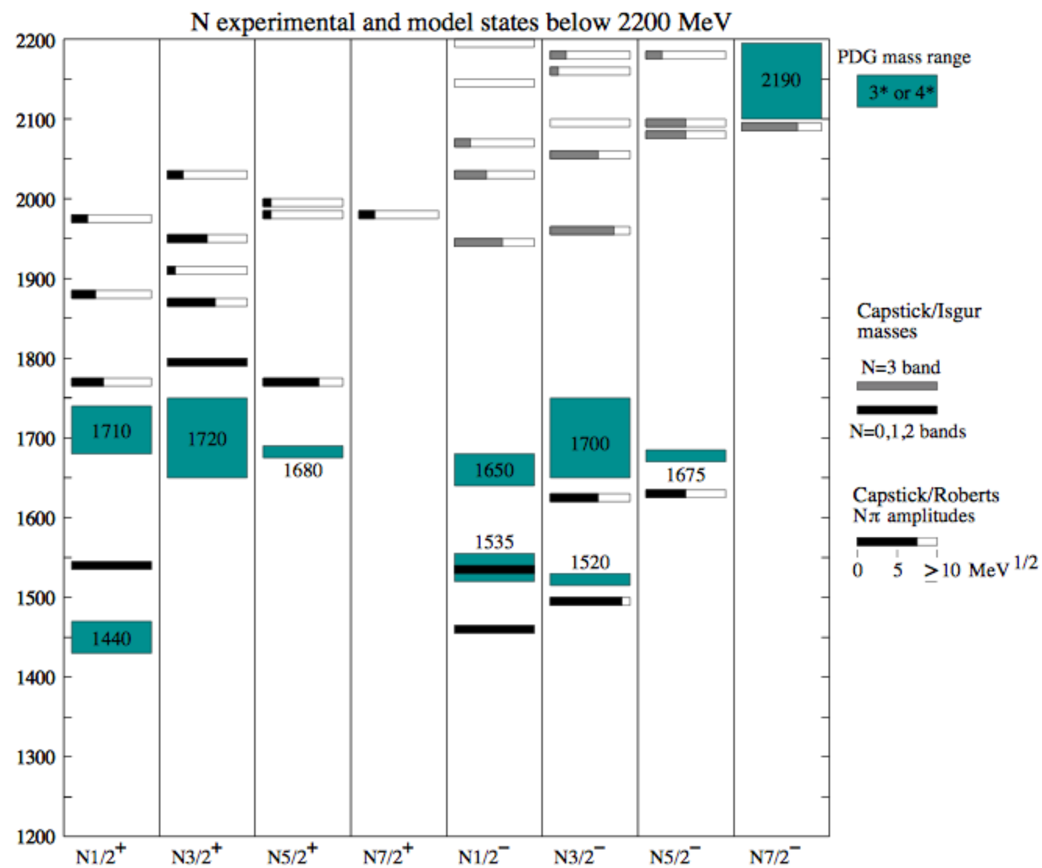
$\Xi_b'^{-}$ and Ξ_b^{*-}

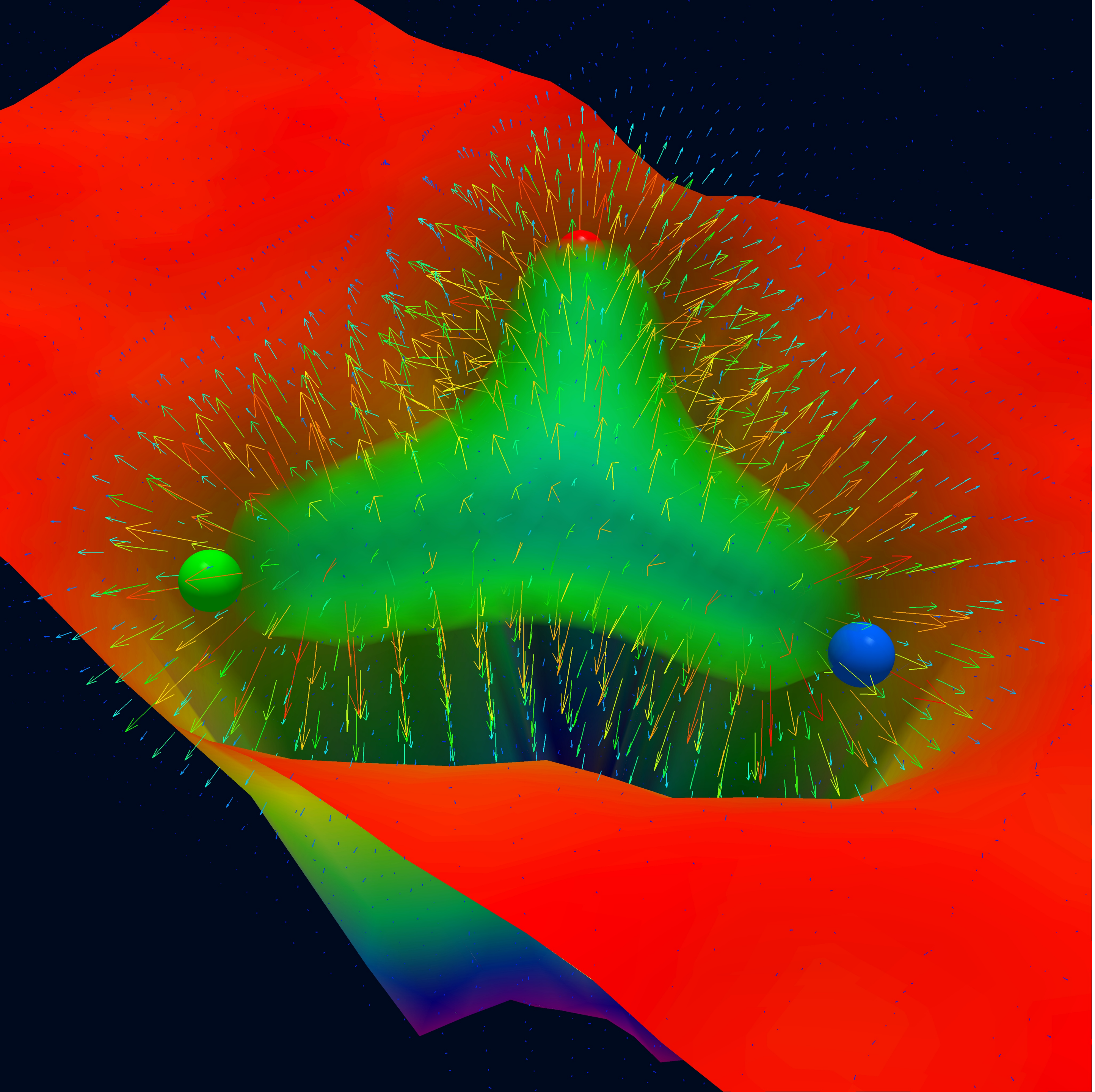
The Roper resonance [$N(1440)P_{11}$] is the proton's first radial excitation. Its lower-than-expected mass owes to a dressed-quark core shielded by a dense cloud of pions and other mesons.

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

Breit-Wigner mass = 1420 to 1470 (≈ 1440) MeV
Breit-Wigner full width = 200 to 450 (≈ 300) MeV
$p_{beam} = 0.61$ GeV/c $4\pi\bar{\lambda}^2 = 31.0$ 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

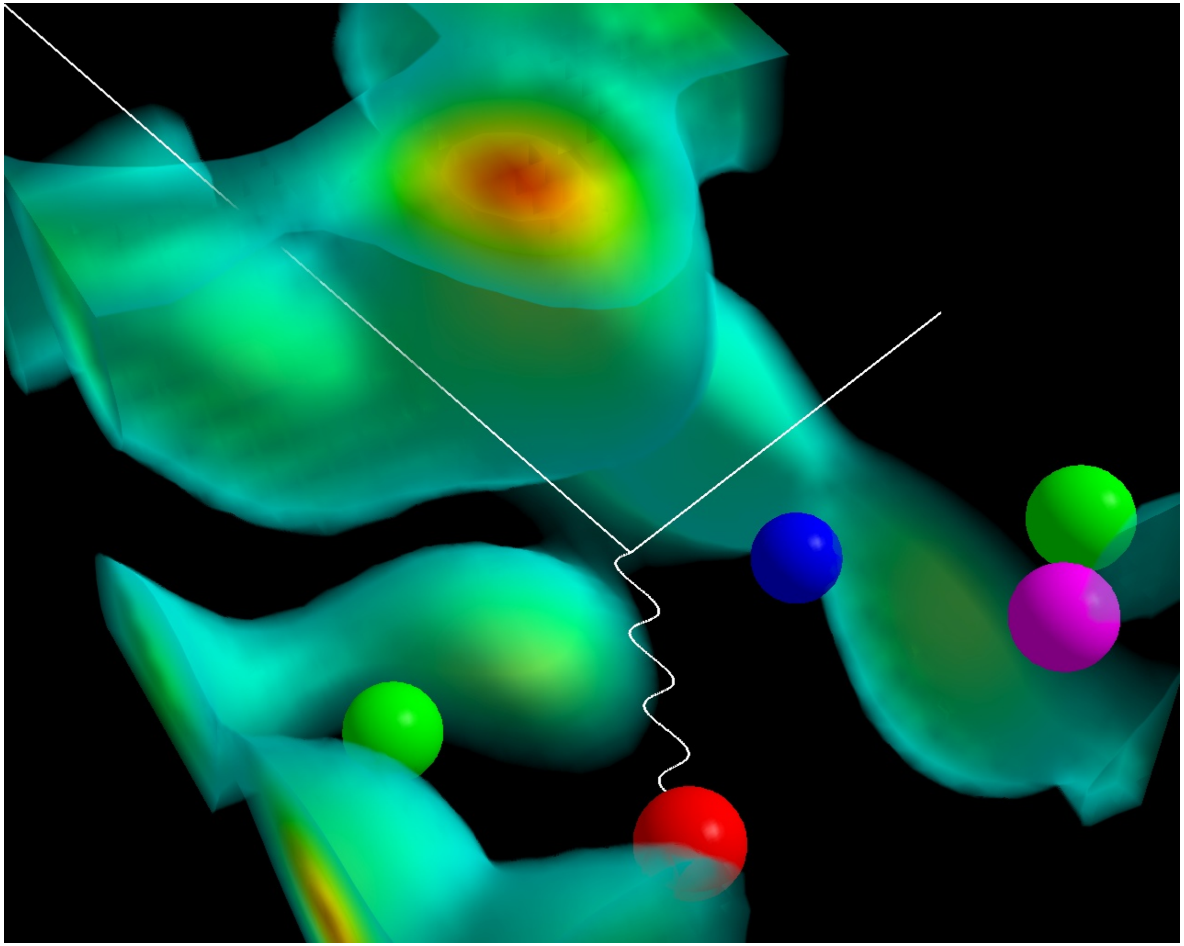




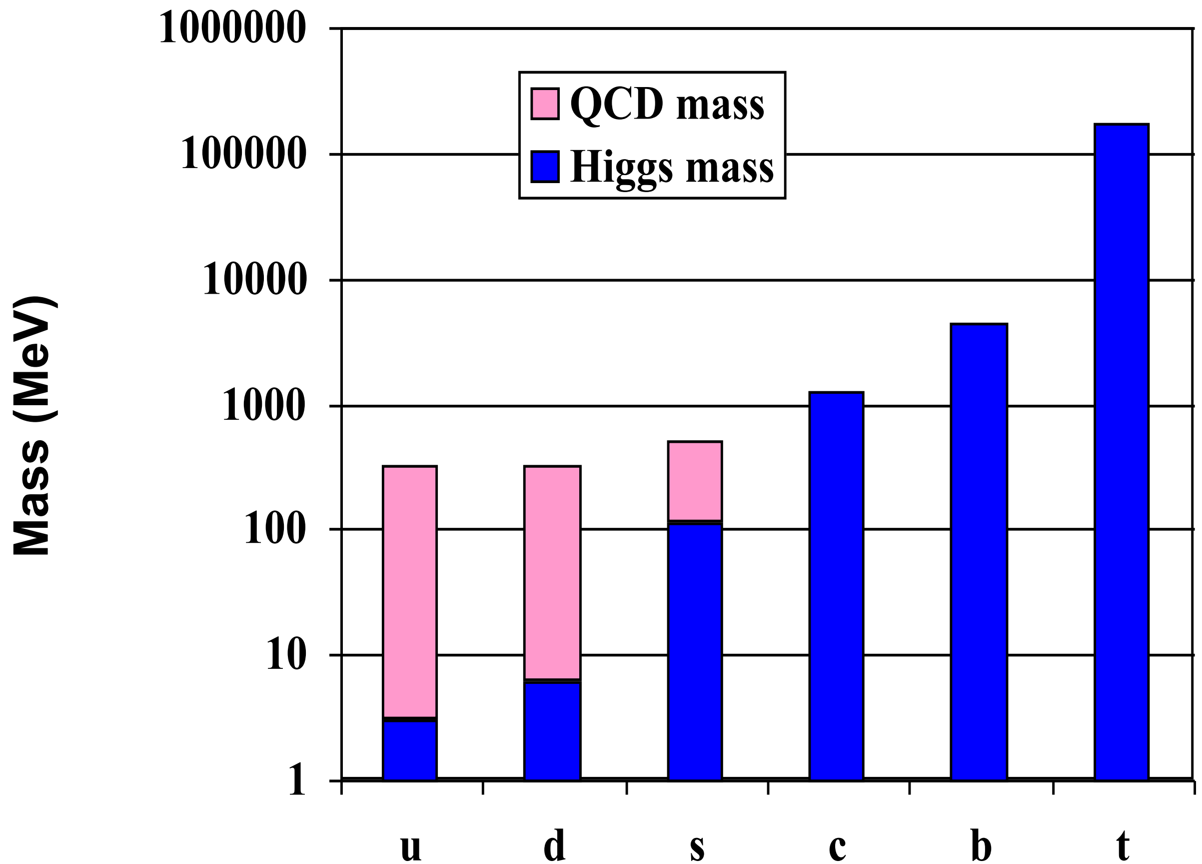
The positions of the three quarks composing the proton are illustrated by the colored spheres. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quarks. The vector field illustrates the gradient of this reduction. The positions in space 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.

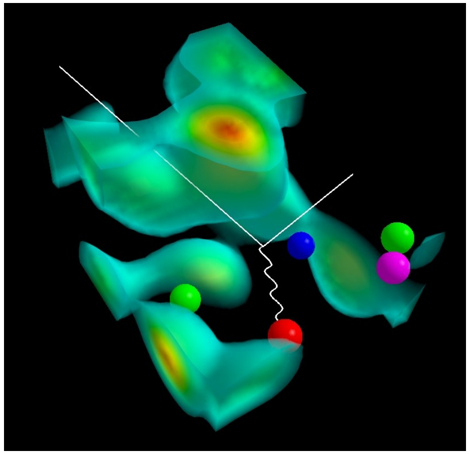
- Three quarks indicated by red, green and blue spheres (lower left) are localized by the gluon field.
- A quark-antiquark pair created from the gluon field is illustrated by the green-antigreen (magenta) quark pair on the right. These quark pairs give rise to a meson cloud around the proton.

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



Nucl. Phys. A750, 84 (2005)





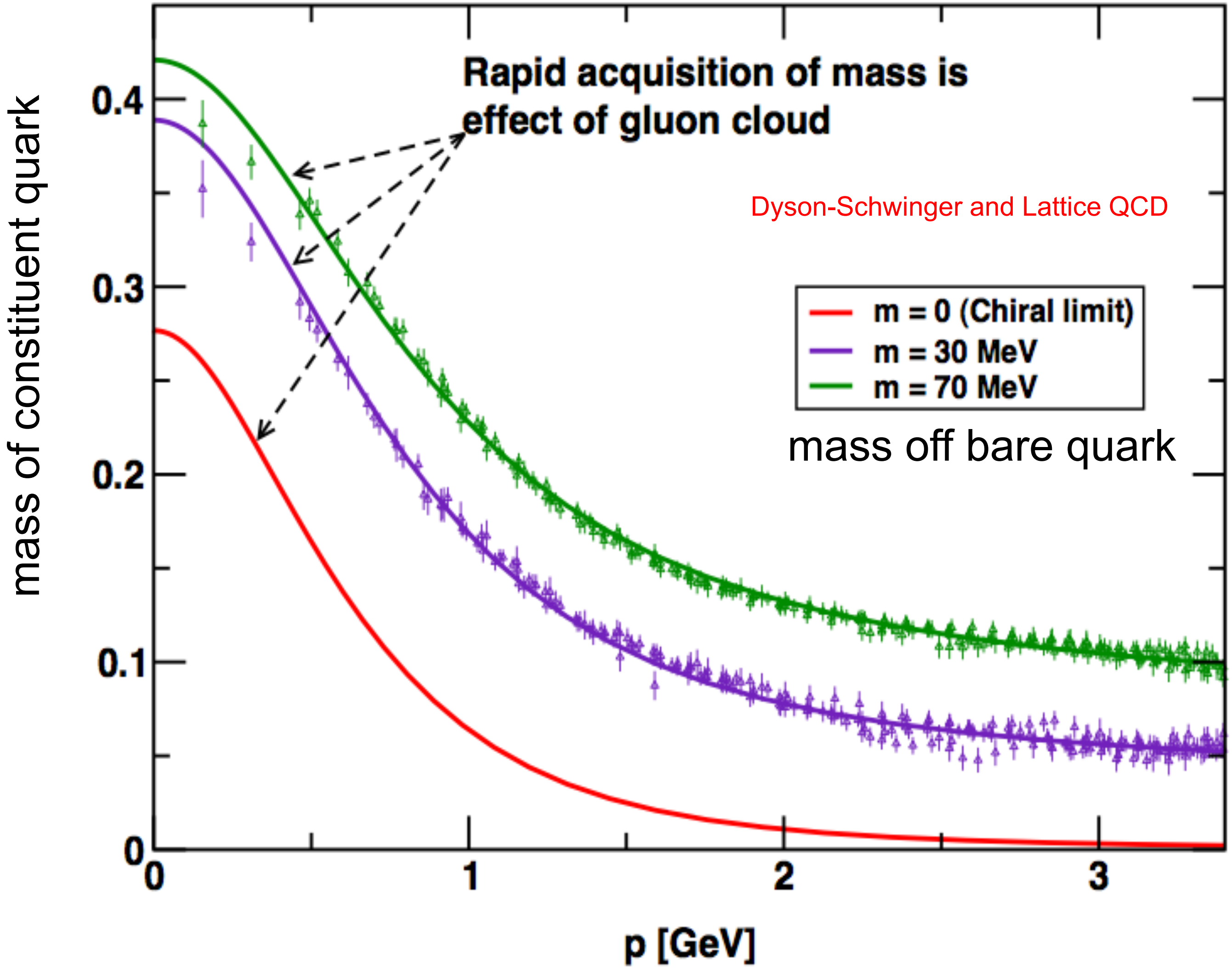
u + u + d = proton

mass: 0.003 + 0.003 + 0.006 ≠ 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.