New relatives of the proton

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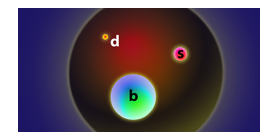

BARYONS WITH LOWEST SPIN (J = ½)
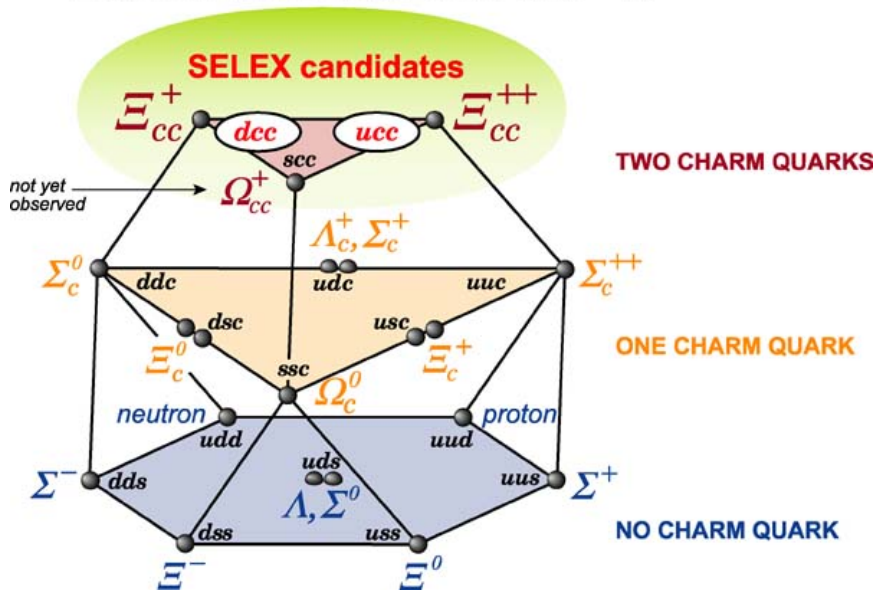
BARYONS WITH HIGHEST SPIN (J = ³⁄₂)
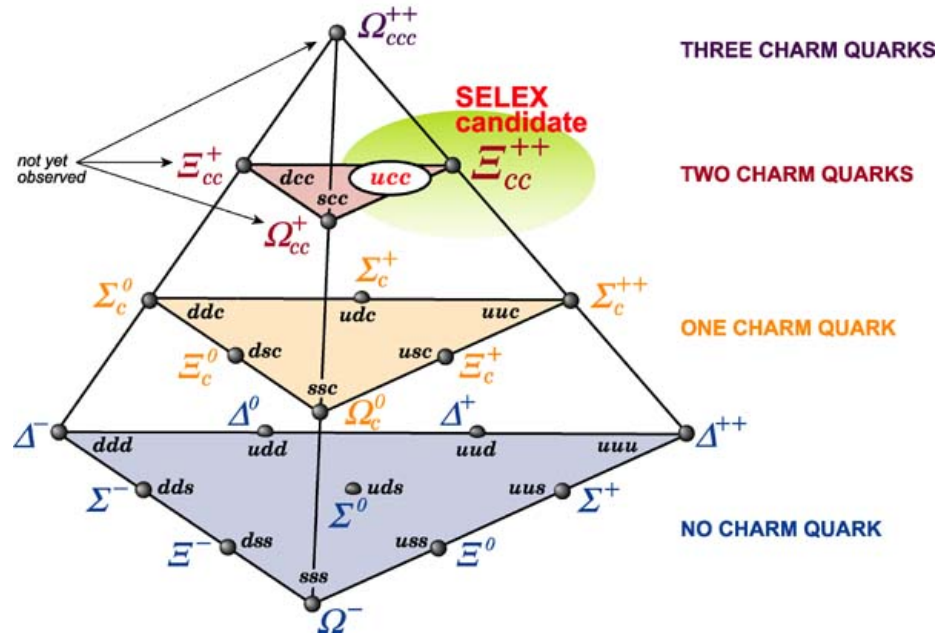
Baryon Supermultiplet using four-quark models and half spin

Two New Particles Enter the Fold
http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.114.062004

$$\Xi'^{-}_{b} \text{ and } \Xi^{*-}_{b}$$

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.

$N(1440)$ $1/2^+$

$$I(J^P) = \tfrac{1}{2}(\tfrac{1}{2}^+)$$

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

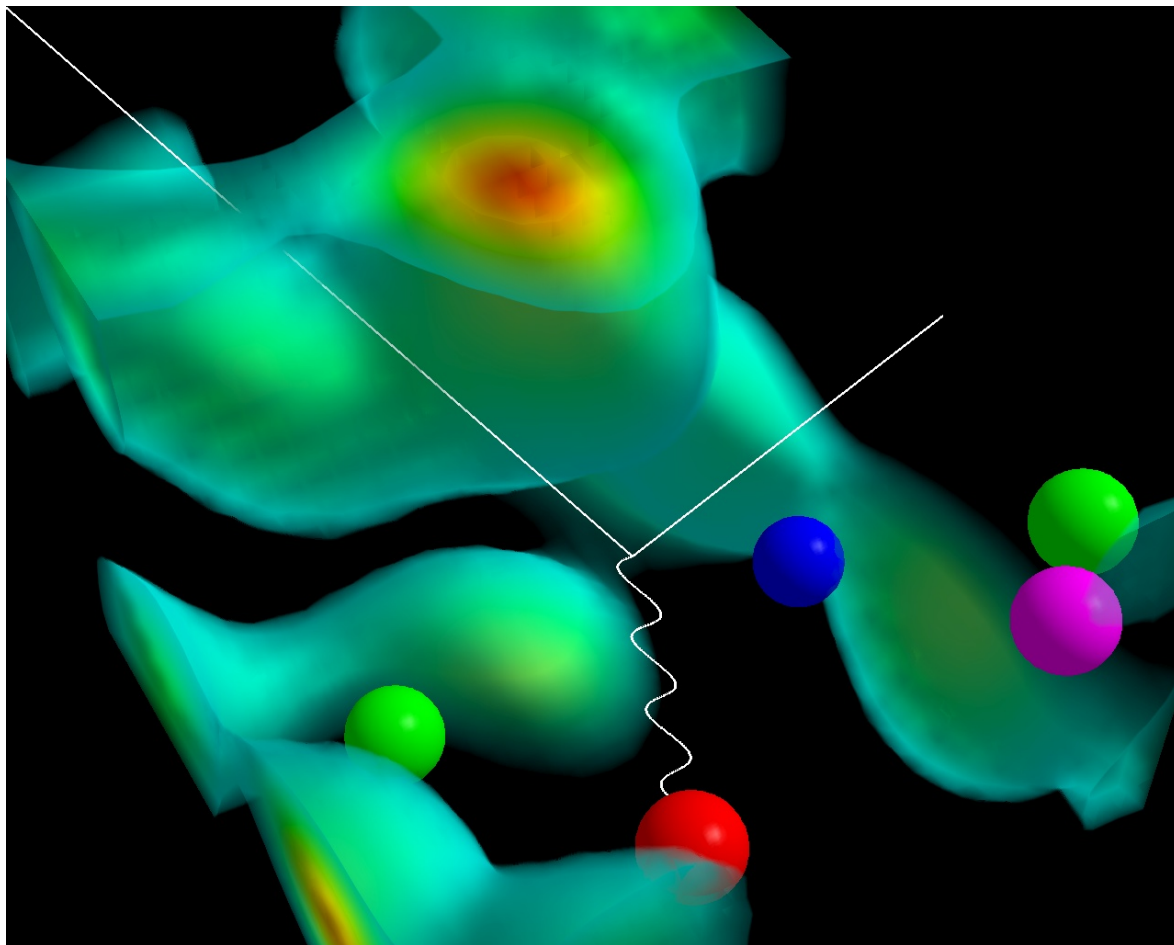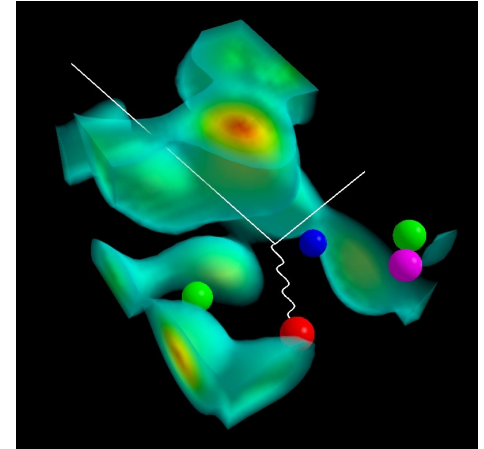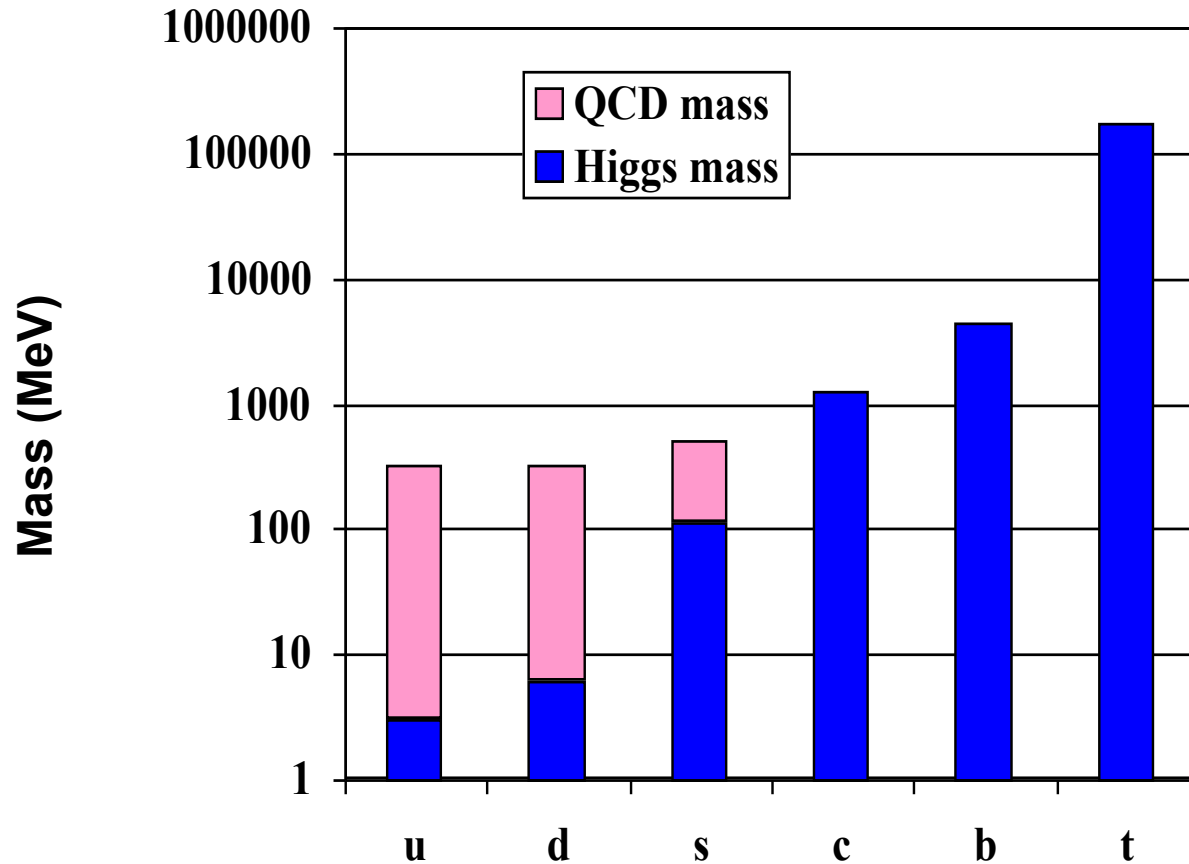N experimental and model states below 2200 MeV
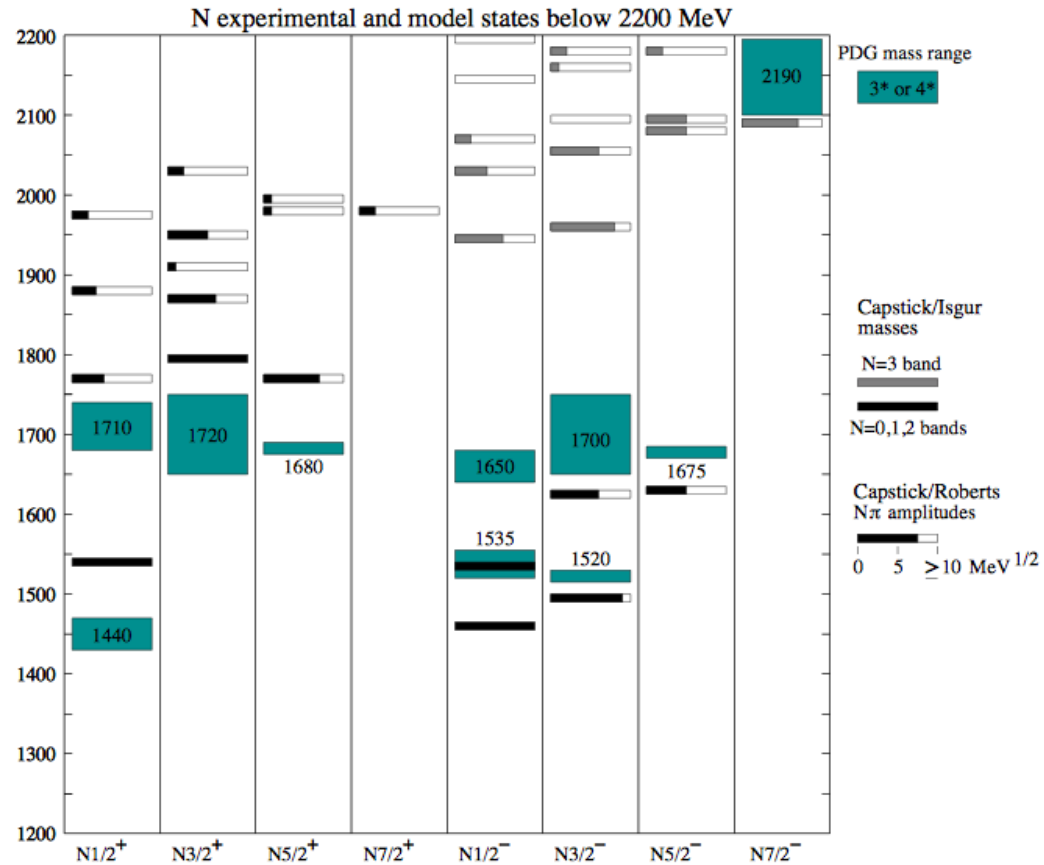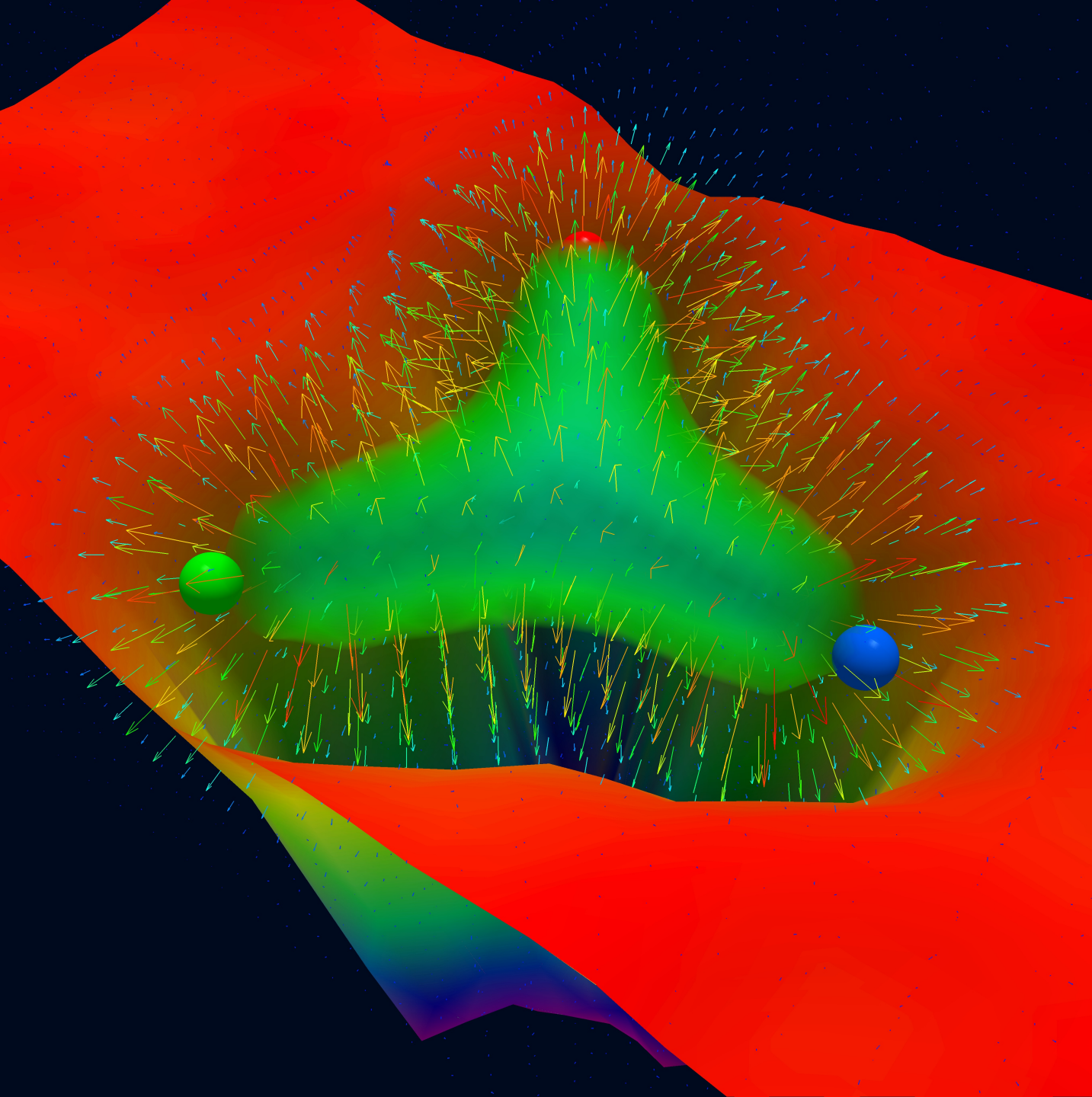
The positions of the three quarks composing the proton are illustrated by the colored spheres. The surface plot illustrates the reduction of the vacuum action density in a plane passing through the centers of the quarks. The vector field illustrates the gradient of this reduction. The positions in space 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
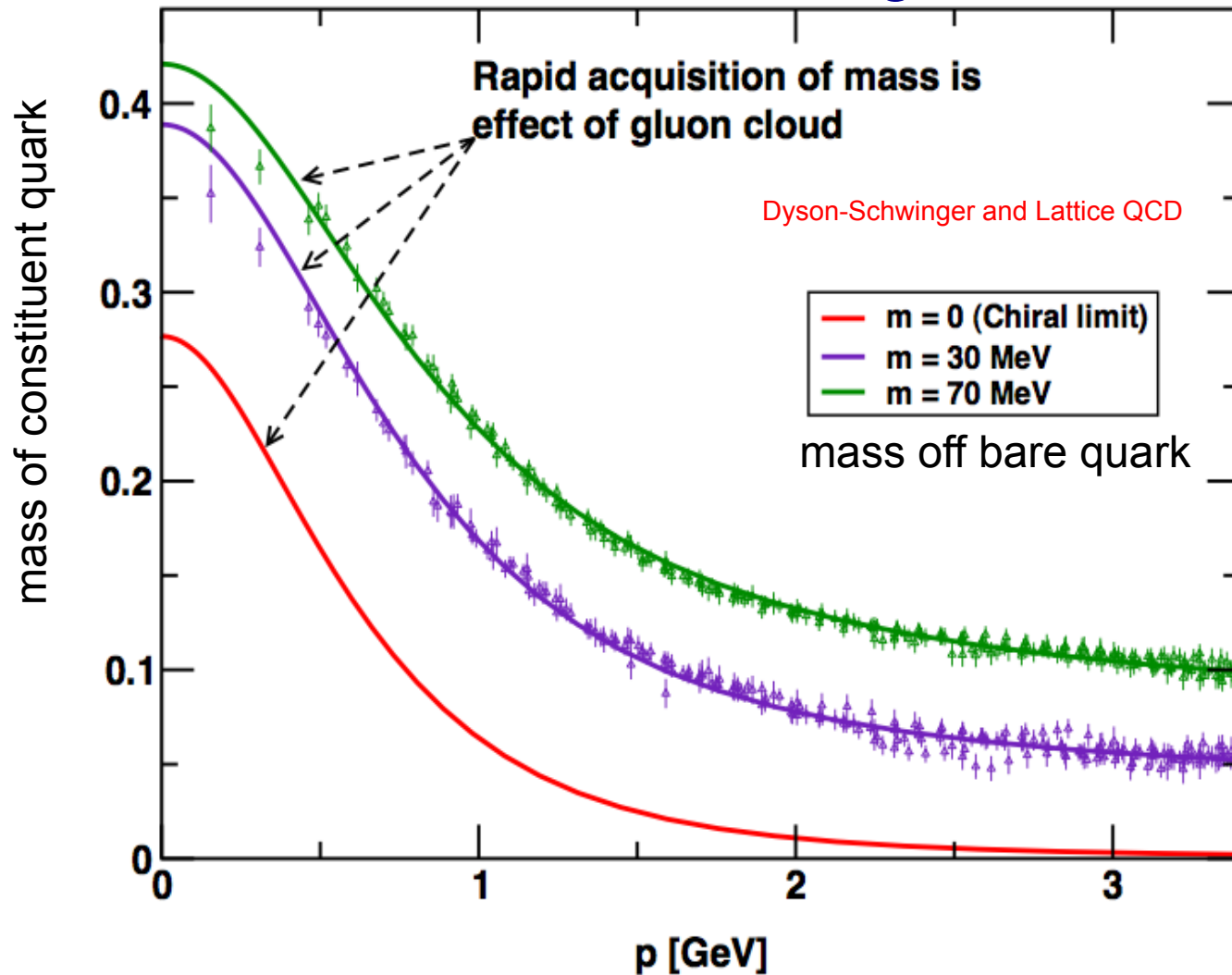
Nucl. Phys. A750, 84 (2005)

$$u + u + d = \text{proton}$$

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.

Low-lying Hadron Spectrum

Dürr, Fodor, Lippert et al., BMW Collaboration

More than 99% of the mass of the visible universe is made up of protons and neutrons. Both particles are much heavier than their quark and gluon constituents, and the Standard Model of particle physics should explain this difference. We present a full ab initio calculation of the masses of protons, neutrons, and other light hadrons, using lattice quantum chromodynamics. Pion masses down to 190 mega–electron volts are used to extrapolate to the physical point, with lattice sizes of approximately four times the inverse pion mass. Three lattice spacings are used for a continuum extrapolation. Our results completely agree with experimental observations and represent a quantitative confirmation of this aspect of the Standard Model with fully controlled uncertainties
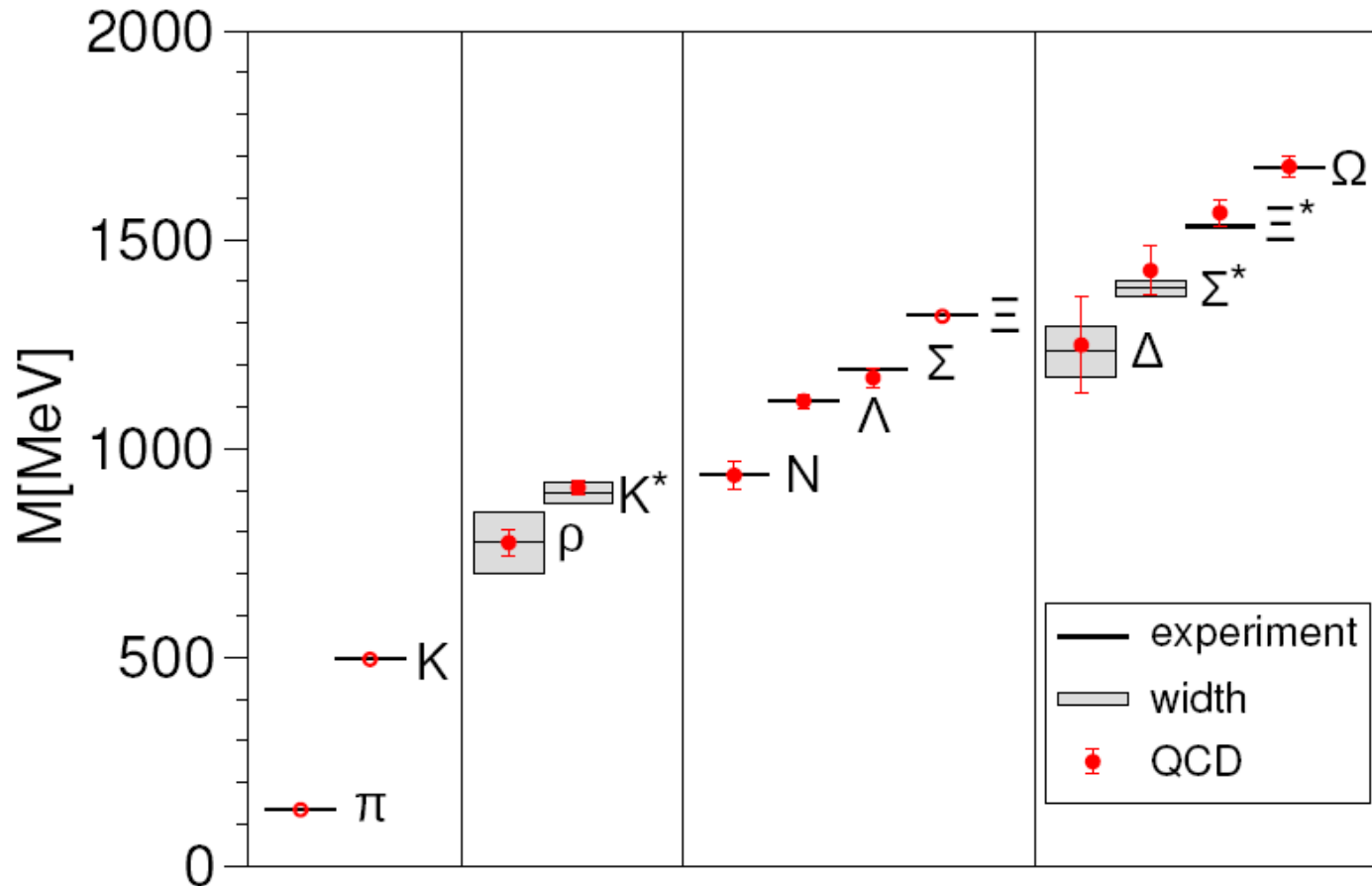
Isospin Splittings in the Light-Baryon Octet from Lattice QCD and QED
(ab initio calculation of the neutron-proton mass difference)

Neutron = 939.56563 MeV
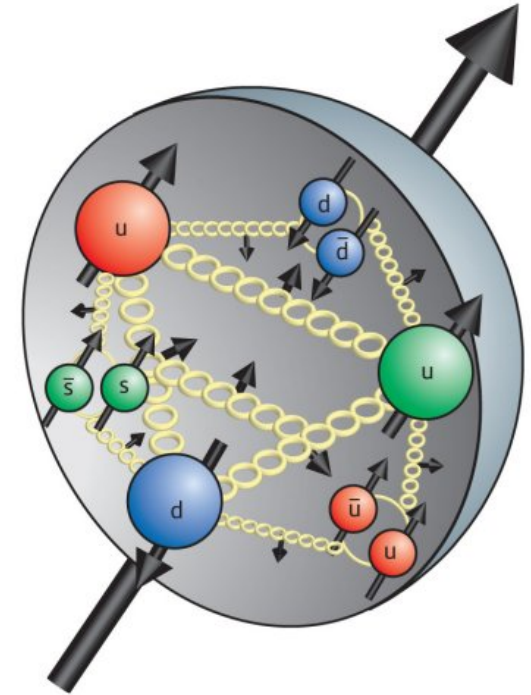Proton = 938.27231 MeV
Electron = 0.51099906 MeV

Science 347, 1452 (2015)
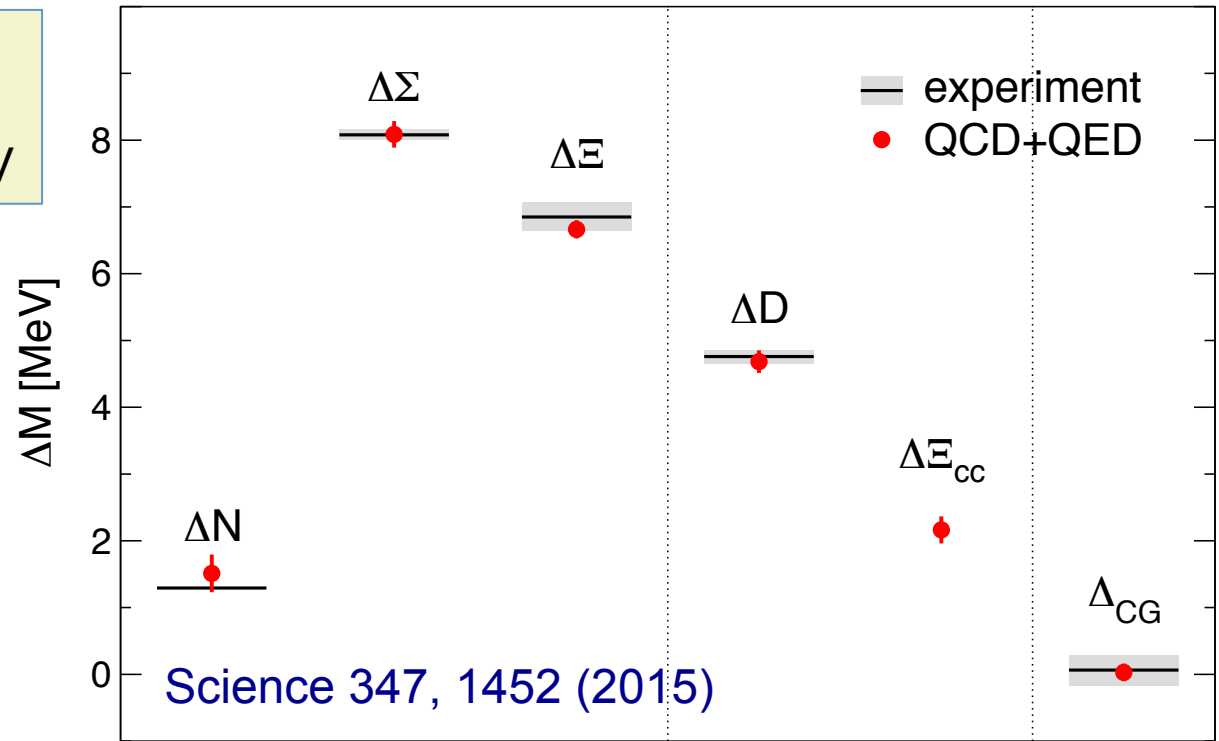
	mass splitting [MeV]	QCD [MeV]	QED [MeV]
$\Delta N = n - p$	1.51(16)(23)	2.52(17)(24)	-1.00(07)(14)
$\Delta\Sigma = \Sigma^- - \Sigma^+$	8.09(16)(11)	8.09(16)(11)	0
$\Delta\Xi = \Xi^- - \Xi^0$	6.66(11)(09)	5.53(17)(17)	1.14(16)(09)

"The neutron–proton mass difference, one of the most consequential parameters of physics, has now been calculated from fundamental theories. This landmark calculation portends revolutionary progress in nuclear physics." Wilczek, Nature 520, 303 (2015)

The spin structure of the nucleon

Rev. Mod. Phys. 85, 655 (2013)

The Past

Naïve parton model:

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta d_v)$$

1989 EMC (CERN):
$\Delta\Sigma = 0.12 \pm 0.09 \pm 0.14$

$\Delta\Sigma = \Delta u + \Delta d + \Delta s + \Delta\bar{u} + \Delta\bar{d} + \Delta\bar{s}$

⇒ Spin Crisis

The Present (and near future)

⇒ Gluons are polarized (ΔG)
⇒ Sea quarks are polarized:

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta\bar{q}) + \Delta G$$

The Future

For complete description include parton orbital angular momentum L_z:

$$\frac{1}{2} = \frac{1}{2}(\Delta q + \Delta\bar{q}) + \Delta G + L_z$$
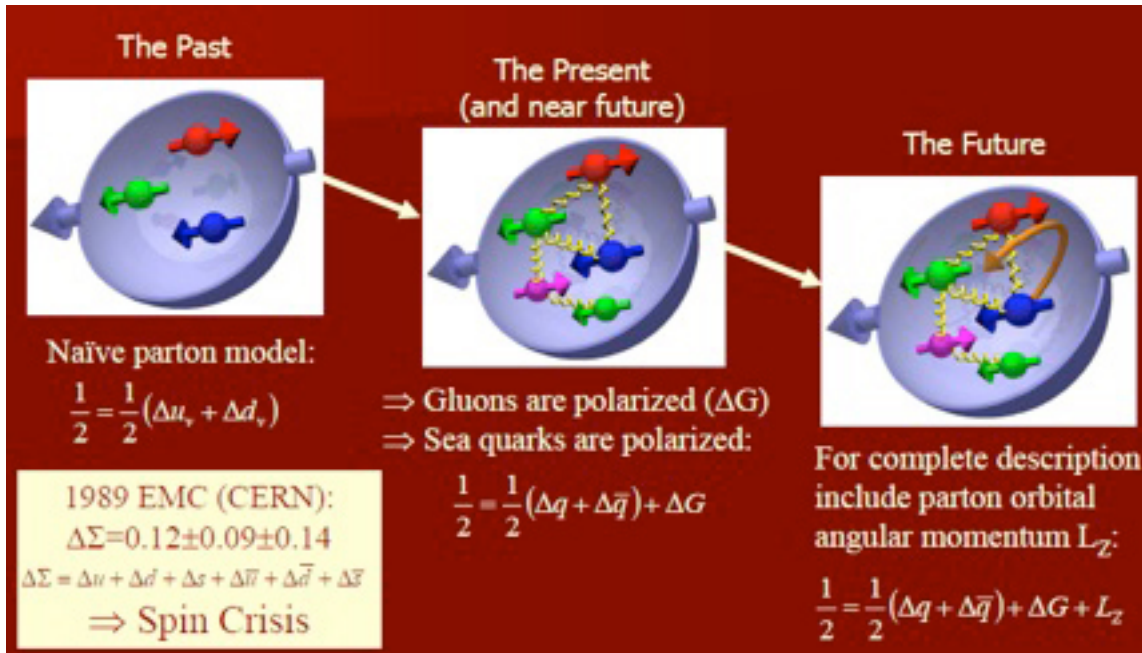
How do the proton's various constituents contribute to its overall spin? As illustrated by the diagram, the quarks, antiquarks, and gluons are all believed to have their own intrinsic spins, and these must contribute. But so also must the relative orbital motions of the quarks and gluons inside the proton. The first measurements of the proton's spin substructure have been made recently, employing the technique of deep inelastic scattering with spin-polarized beams bombarding spin-polarized targets. By combining these measurements with constraints from other data, one can infer the fraction of the proton's spin carried by the intrinsic spin of quarks (and antiquarks) of different flavors. The results of experiments performed at CERN, SLAC, and DESY, summarized in the graph, point to an unexpected outcome: all the quarks and antiquarks together account for **no more than one-third of the total spin**. More direct probes of the spin alignment of different flavors of quarks, separation of the contributions from quarks and antiquarks, and extraction of information on the gluon spin contributions are goals of ongoing and planned second-generation experiments.

http://physicsworld.com/cws/article/news/2014/jul/11/gluons-get-in-on-proton-spin
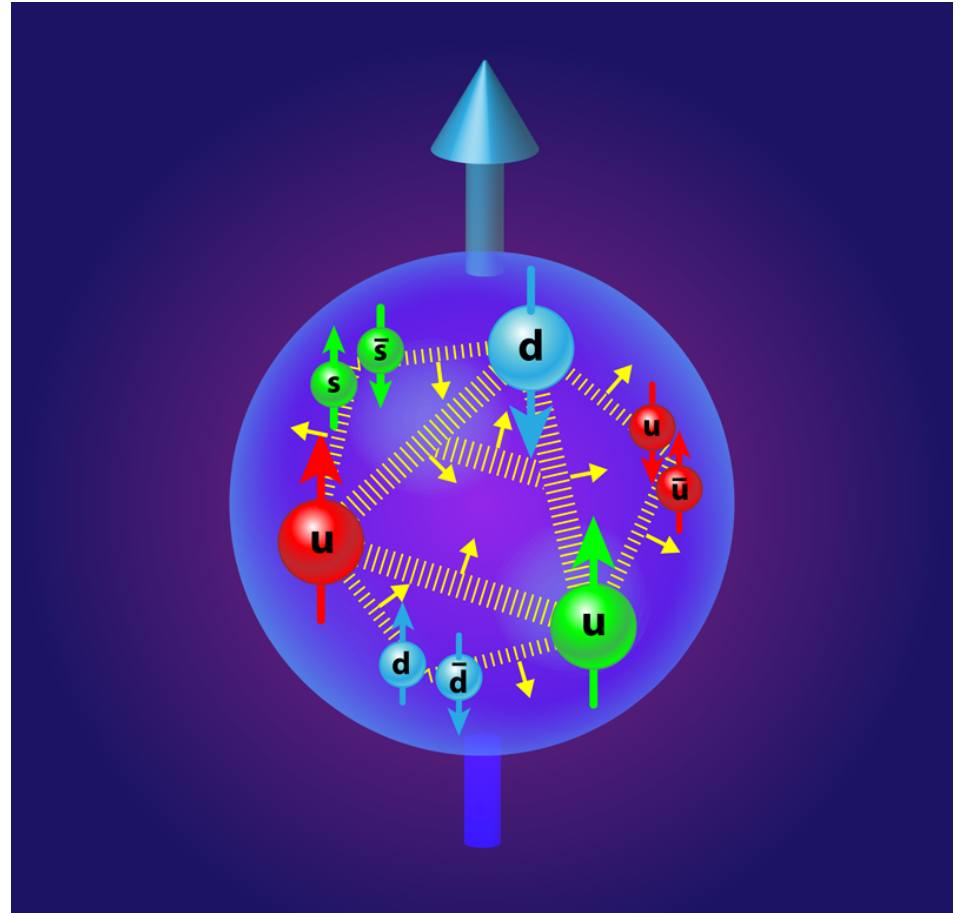http://www.scientificamerican.com/article/proton-spin-mystery-gains-a-new-clue1/

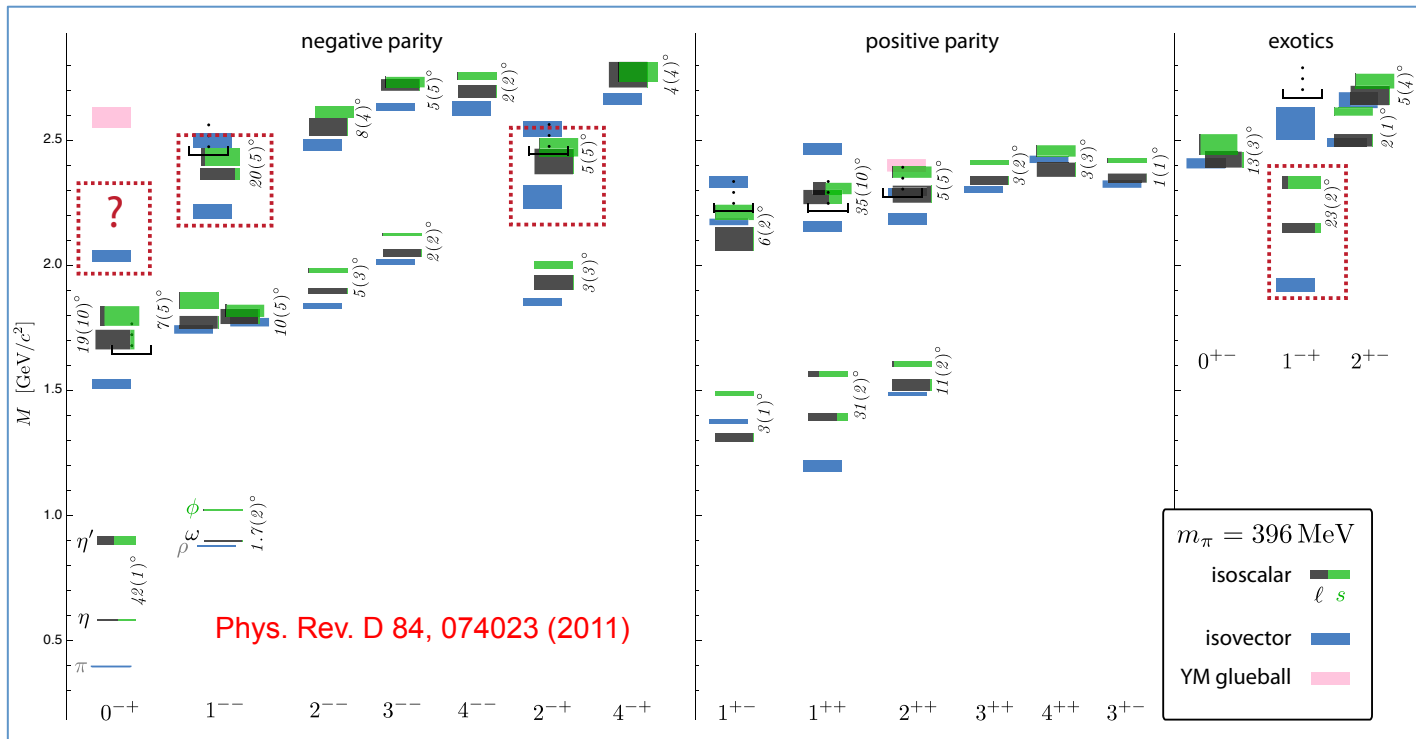# Viewpoint: Spinning Gluons in the Proton

Computer simulations indicate that about 50% of the proton's spin comes from the spin of the gluons that bind its quark constituents
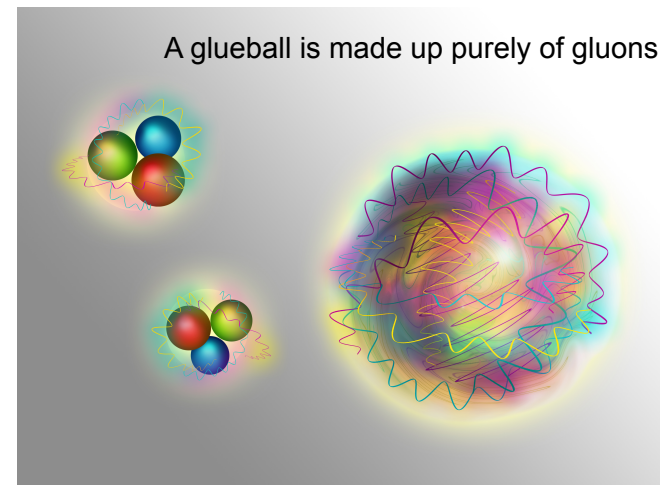Phys. Rev. Lett. 118, 102001 (2017)

Where is the glue? Search for exotic particle

Phys. Rev. D 84, 074023 (2011)

$m_\pi = 396 \, \text{MeV}$

http://www.gluex.org

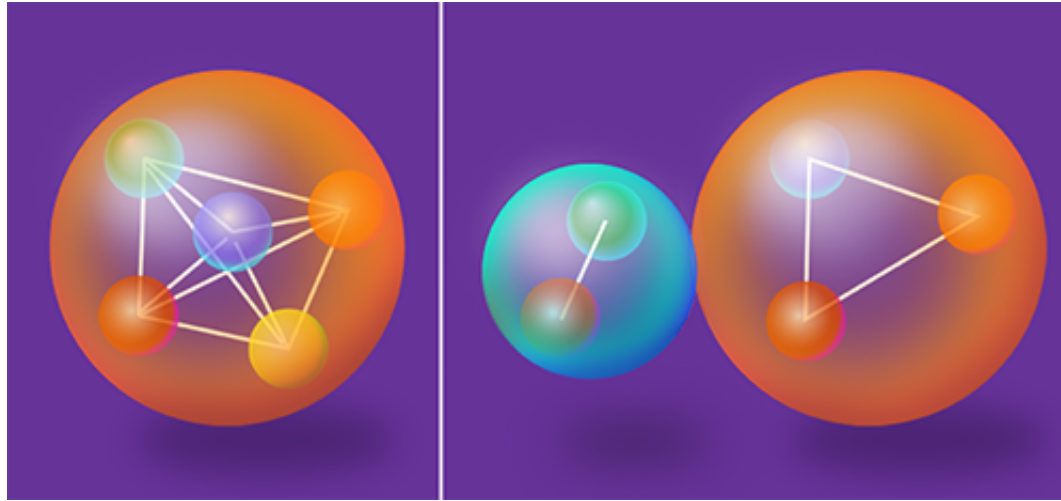A glueball is made up purely of gluons

- Non-quark model mesons include exotic mesons, which have quantum numbers not possible for mesons in the quark model;
- glueballs or gluonium, which have no valence quarks at all;
- tetraquarks, which have two valence quark-antiquark pairs;
- hybrid mesons, which contain a valence quark-antiquark pair and one or more gluons.

http://phys.org/news/2015-10-particle-purely-nuclear.html

The rise and fall (and rise) of the pentaquark

http://www.symmetrymagazine.org/article/september-2006/the-rise-and-fall-of-the-pentaquark

http://physics.aps.org/articles/v8/77

LHCb produces charmonium pentaquarks: Phys. Rev. Lett. 115, 072001 (2015)

http://physics.aps.org/articles/v8/77
http://phys.org/news/2015-07-cern-lhcb-exotic-pentaquark-particles.html
http://www.sciencedaily.com/releases/2015/07/150714082858.htm

http://physicsworld.com/cws/article/news/2016/feb/29/fermilab-bags-a-tetraquark
http://physicsworld.com/cws/article/news/2016/mar/21/cern-fails-to-confirm-fermilab-tetraquark-discovery

http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.117.082003   Confirmed!

The Structure
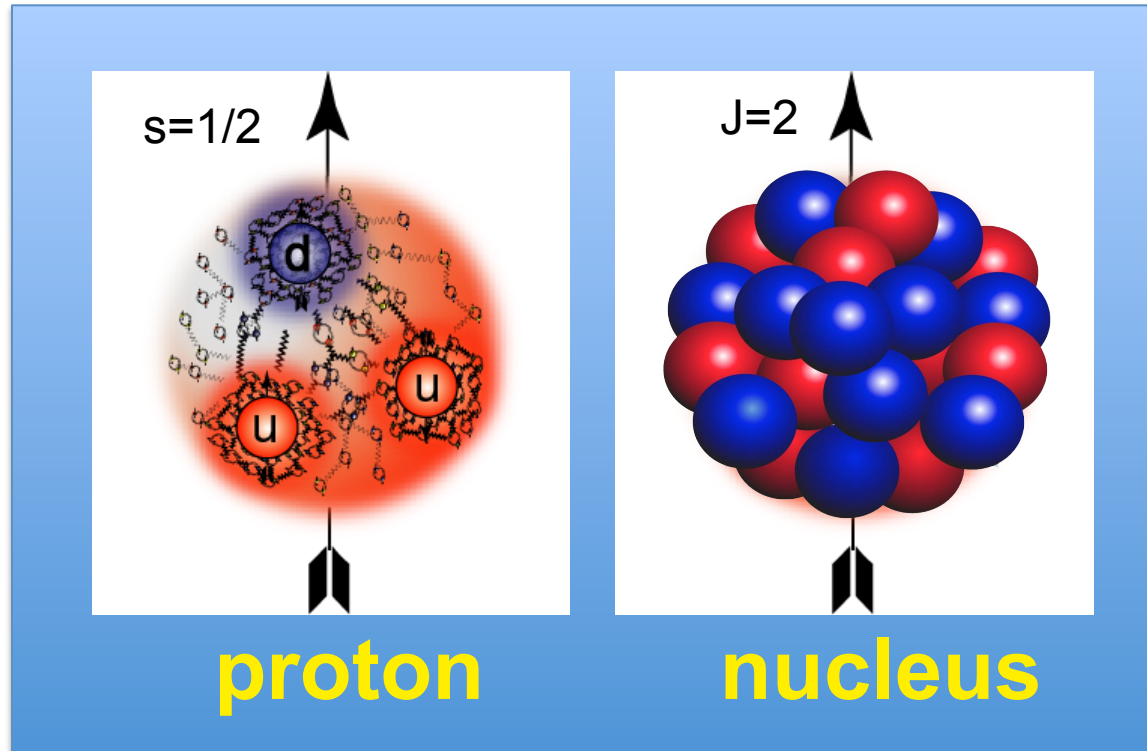
hadron spectroscopy

The origin of confinement
The origin of mass, spin
Quantum numbers and symmetries

nuclear spectroscopy

The origin of nuclear force
The origin of binding, spin
Quantum numbers and symmetries