Mapping out symmetry violation in nucleon structure

John Arrington

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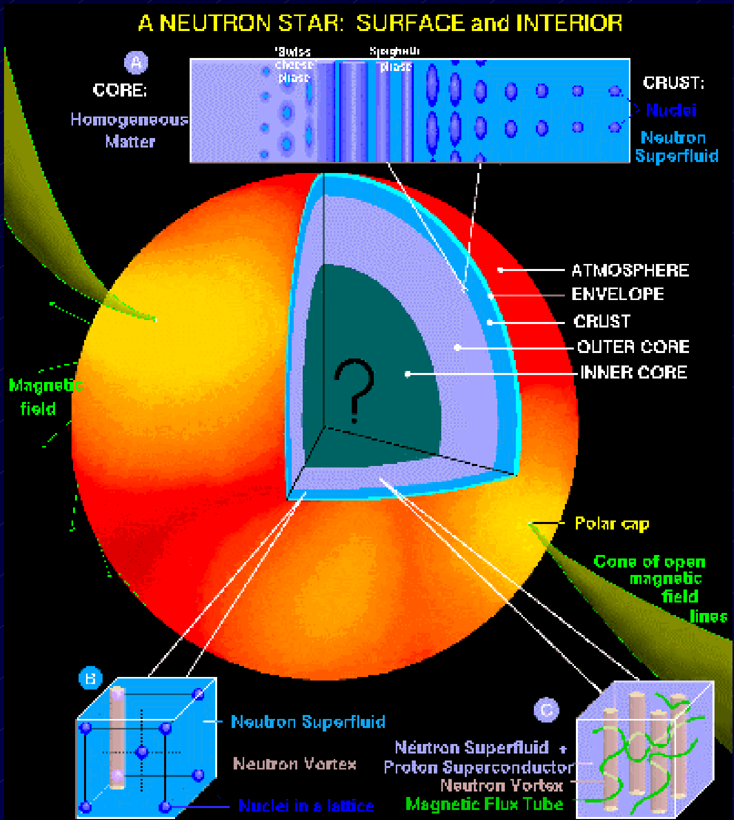
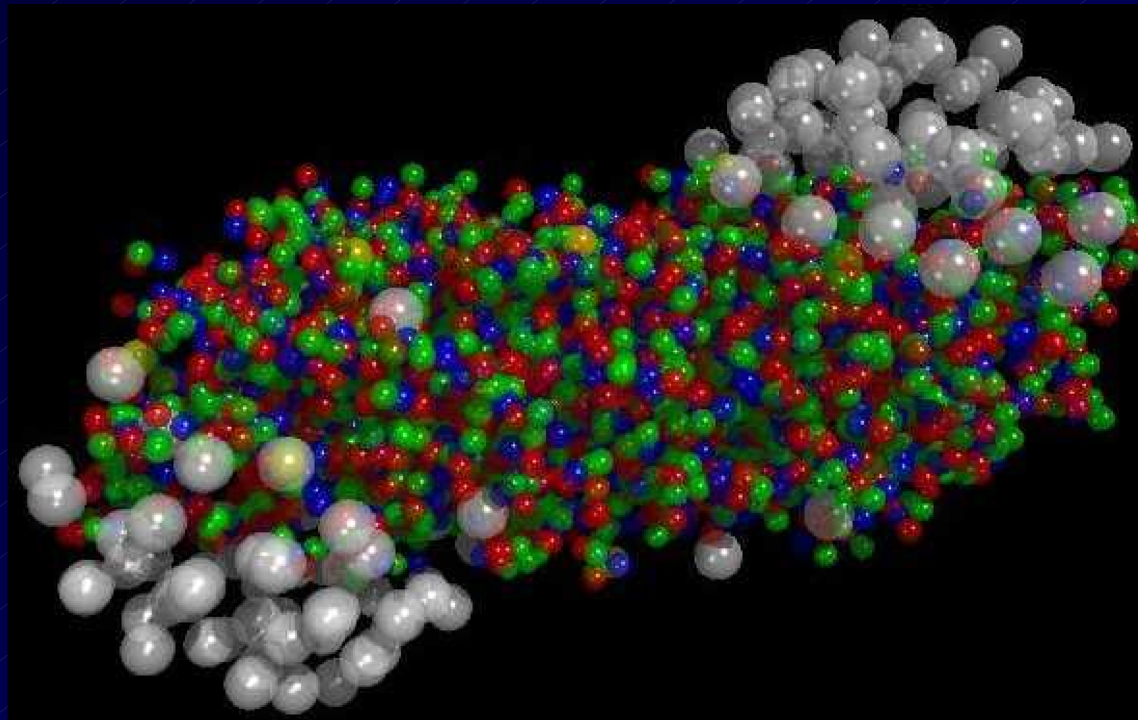
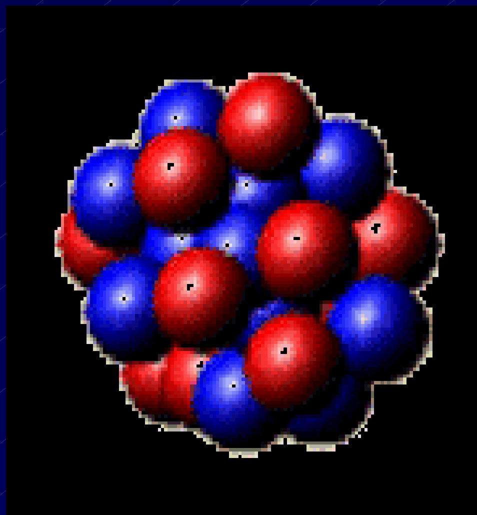
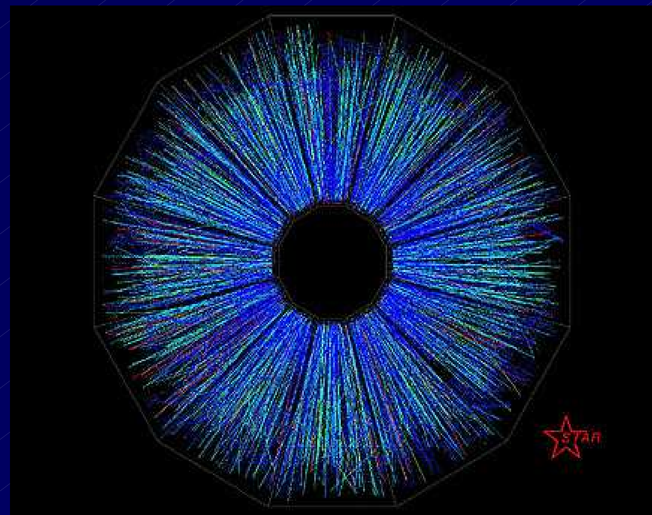








Ecole Joliot-Curie

Oct 1, 2010

QCD: What's up with that?

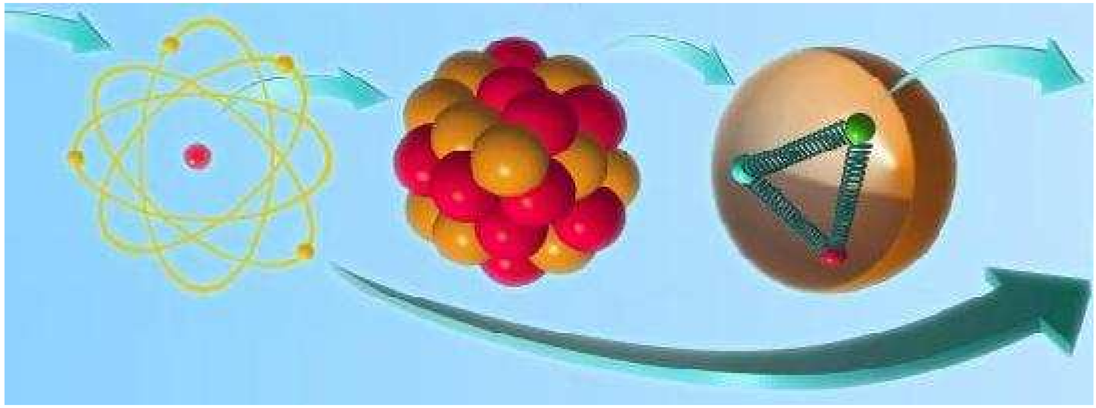
- What's wrong with QCD?
- What does this mean to nuclear physics (and nuclear physicists)?
- How do we deal with the challenges of QCD?

- Guy's talk; some confusion about the starting approach: That's very good, very healthy!
- The approach is extremely reasonable, but QCD *is not reasonable*. Practical approaches to QCD *should* seem odd

Caveats

- All opinions expressed are the responsibility of the speaker; JC2010 does not (and probably should not) endorse these statements
- My goal is to explain and illustrate some key assumptions and issues. Being "correct" is secondary. Being "true" is unnecessary.
- I'll make some strong statements and oversimplificatios which may (but should not) offend people in certain fields. To be safe, I'll try to potentially offend everyone equally.
- Should I happen to describe something as "blisteringly stupid", it should be taken as illustrative, not critical

"Nucleus" means different things to different people



Field of Study	Picture of Nucleus
Chemistry/Atomic Physics	Small, heavy, static, unimportant
Low Energy Nuclear Physics	Point-like protons & neutrons, complicated shell structure, angular momentum,….
Medium Energy Physics (& most neutrino scattering)	Complex protons & neutrons, usually non-interacting
High Energy Physics (& RHIC)	Bag of free quarks (actually, a poor quality quark beam)

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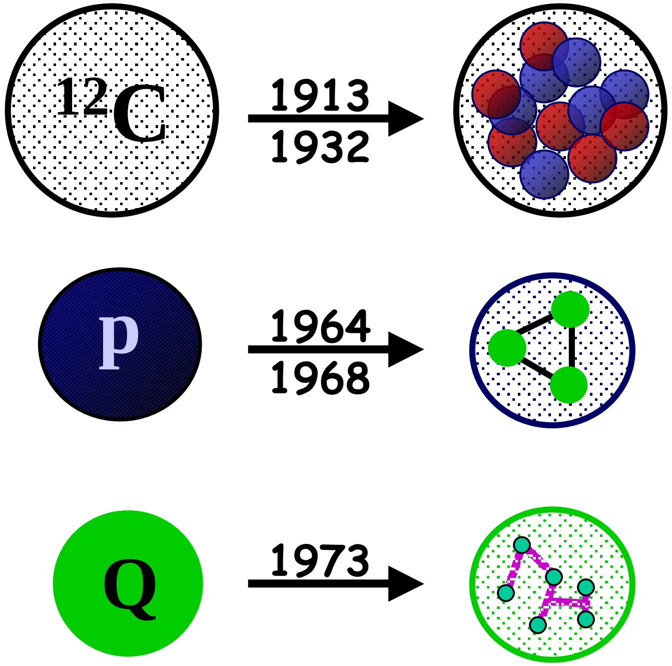
Which of these pictures is correct?

Summary (last 100 years)



Nucleus = protons + neutrons

+ strong interaction of hadrons

proton = Constituent Quarks

+ strong interaction of Quarks

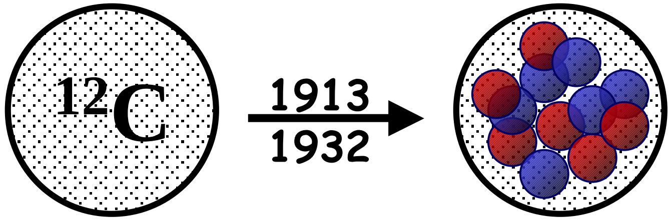
Constituent Quark =

quarks + gluons

+ strong interaction of QCD

Different energy scales mean dealing with
different constituents, different dynamics

Summary (last 100 years)



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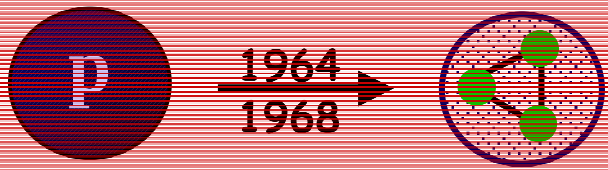
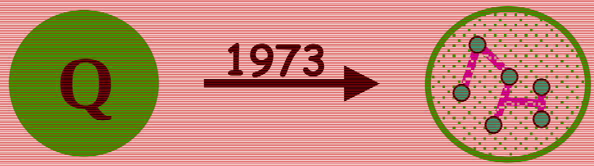


proton = Constituent Quarks

+ strong interaction of Quarks



Constituent Quark =

quarks + gluons

+ strong interaction of QCD

Nearly a century of nuclear physics has shown that a *NUCLEUS* can be extremely well described in terms of protons, neutrons, the strong force, *and nothing else*

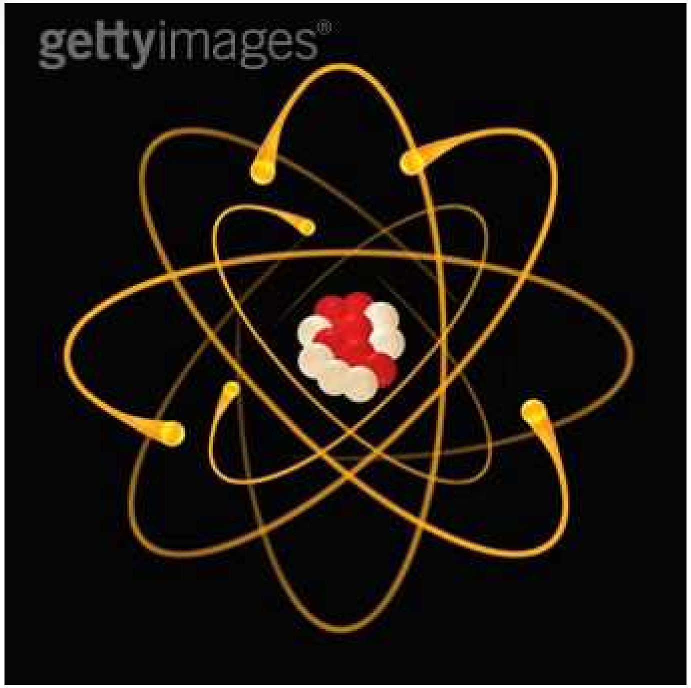
Energy Scales Matter

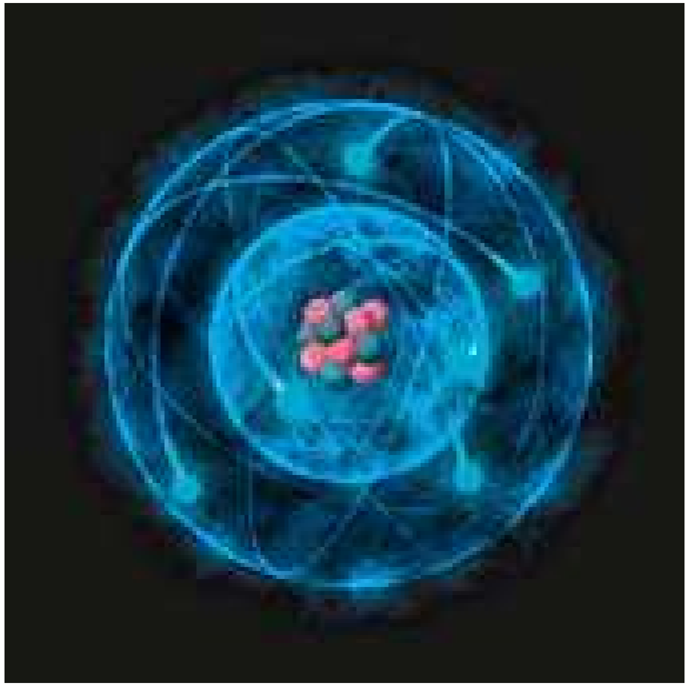
- "Layers" of matter:
  - **Atom as 1 nucleus + Z electrons**
  - **Nucleus as Z protons + N neutrons**
  - **Proton as 3 constituent quarks**
  - **Constituent quarks as complex state of ?? quarks and gluons**
- In each case, treat consistutents as 'fundamental', typically pointlike
- "Truth" and completeness aside, each of these is a perfectly reasonable picture in the region of validity
- Effective Field Theories (EFTs): formal expansion, allowing one to ignore (integrate over) energy scales above the region of interest

At each scale, picture evolves over time

J.J.Thompson's
plum pudding model

Rutherford planetary model



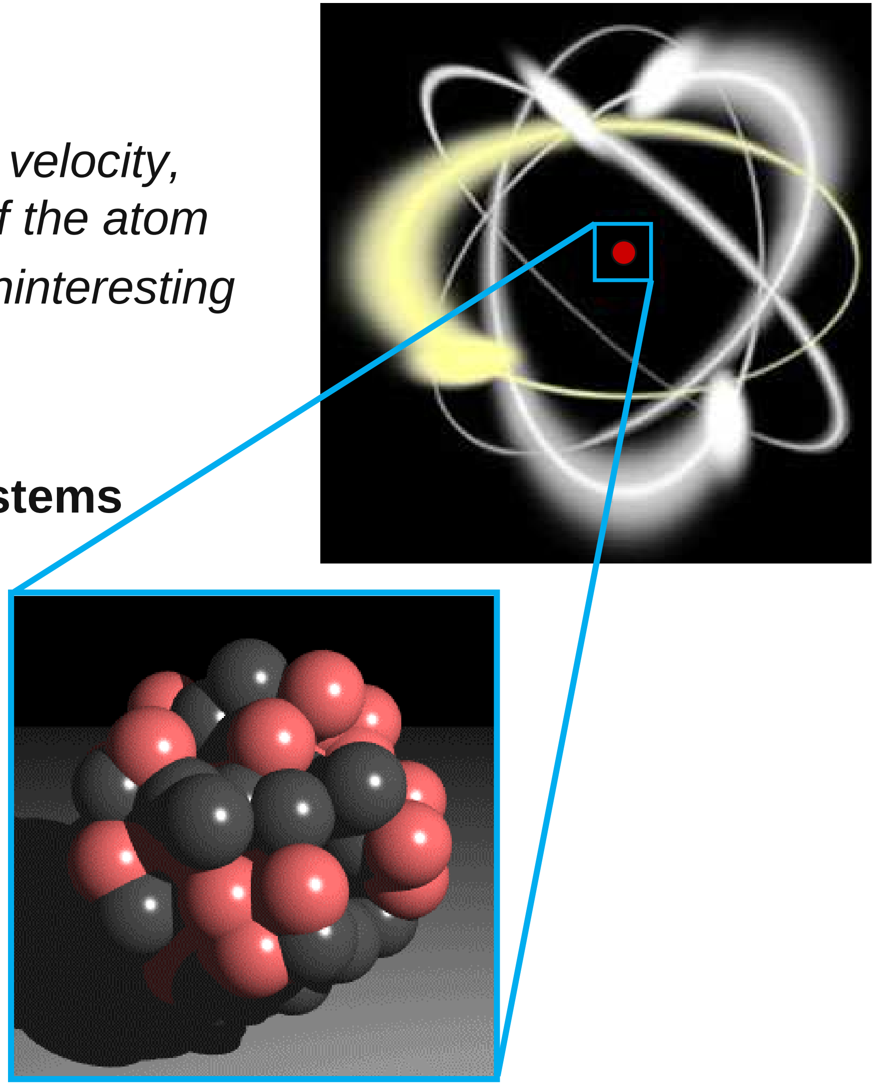


Quantum mechanical models:
Rutherford-Bohr
Schrodinger

The Atom

- **Standard picture of the atom**
  - *Electrons zooming around at high velocity, drive the chemistry, interactions of the atom*
  - *Nuclei are static, point-like, and uninteresting*

- **In reality, nuclei are complex, strongly-interacting many-body systems**



Nuclei: energetic, dense, complex systems

- **Nuclei are incredibly dense**
  - >99.9% of the mass of the atom
  - <1 trillionth of the volume
  - ~10^{14} times denser than normal matter
    (close to neutron star densities)

- **Nuclei are extremely energetic**
  - "Fast" nucleons moving at ~50% the speed of light (electrons at 1-10%)
  - "Slow" nucleons still moving at ~**10^9 cm/s**, in an object ~**10^{-12} cm** in size: 10^{21} orbits/s

The moon at nuclear densities (A_{moon} ≈ 5×10^{49})

Simple picture is totally false, but extremely effective

Nucleus isn't unimportant because it's static, but because atomic interactions happen "slowly", over much larger distance scales

In atomic physics, doing anything other than ignoring this fact would be foolish. What do we need to ignore for nuclei?

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The Standard Model

- We know, and to a large extent understand, the fundamental particles and forces

- The electron is the only fundamental particle that is directly apparent in matter

- Quarks and gluons make up the bulk of the matter, but do not appear as relevant degrees of freedom (nor do other aspects of QCD such as color)

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.4	−1
W$^+$	80.4	+1
Z^0	91.187	0

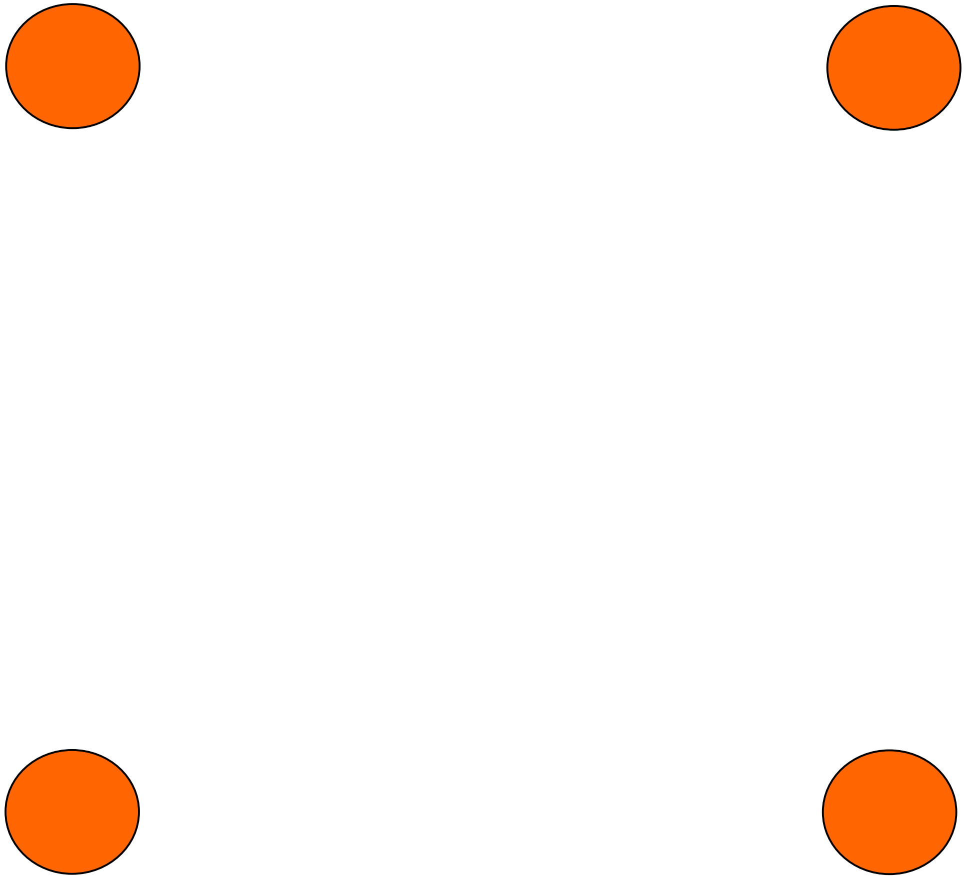
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

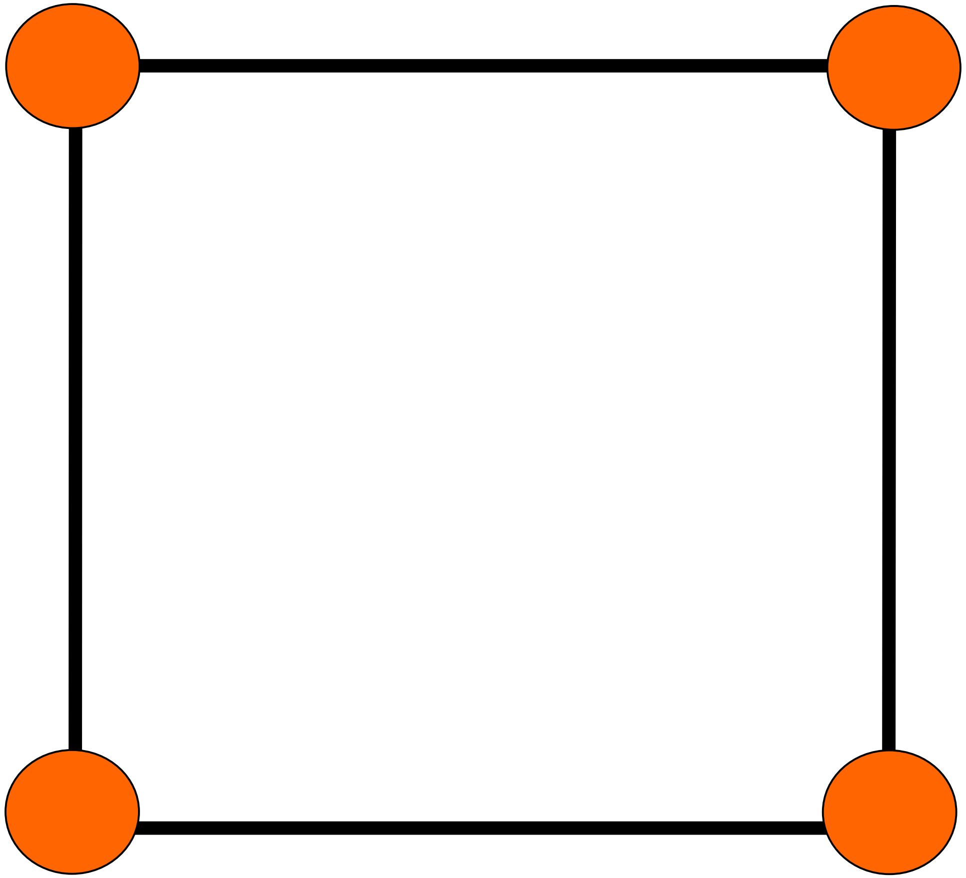
Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Spontaneous Symmetry Breaking



What is the least amount of railroad track needed to connect these 4 cities?

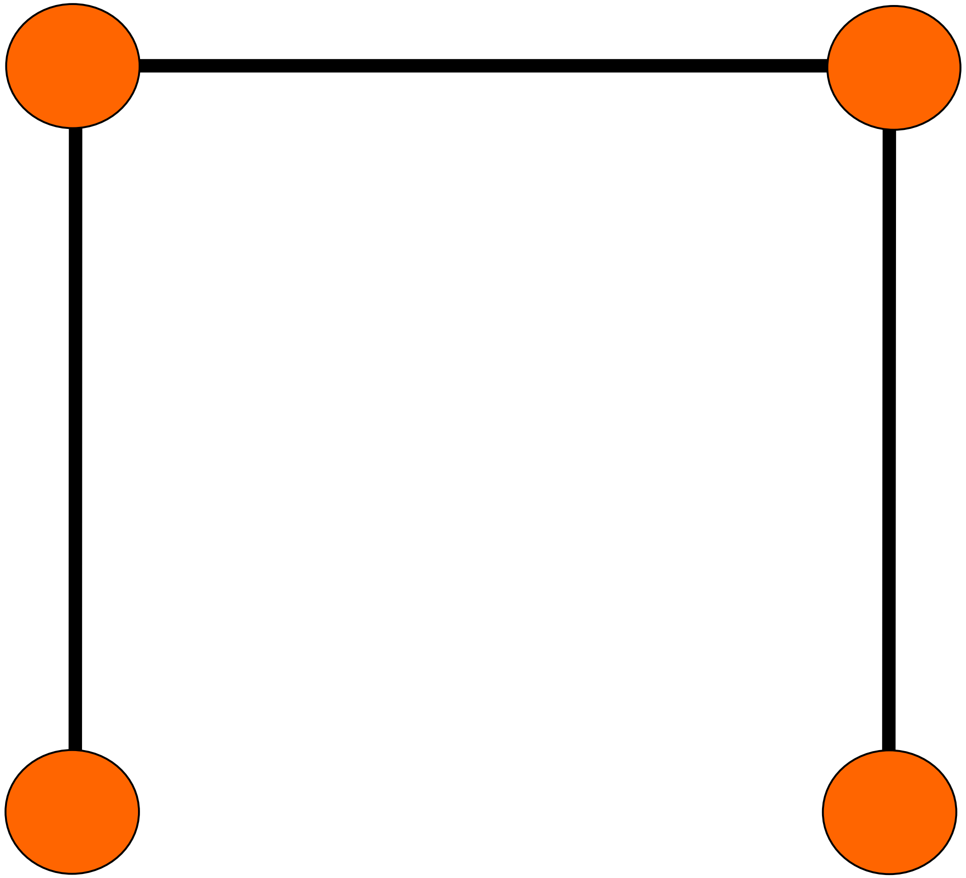
One Option



I can connect them this way at a cost of 4 units.

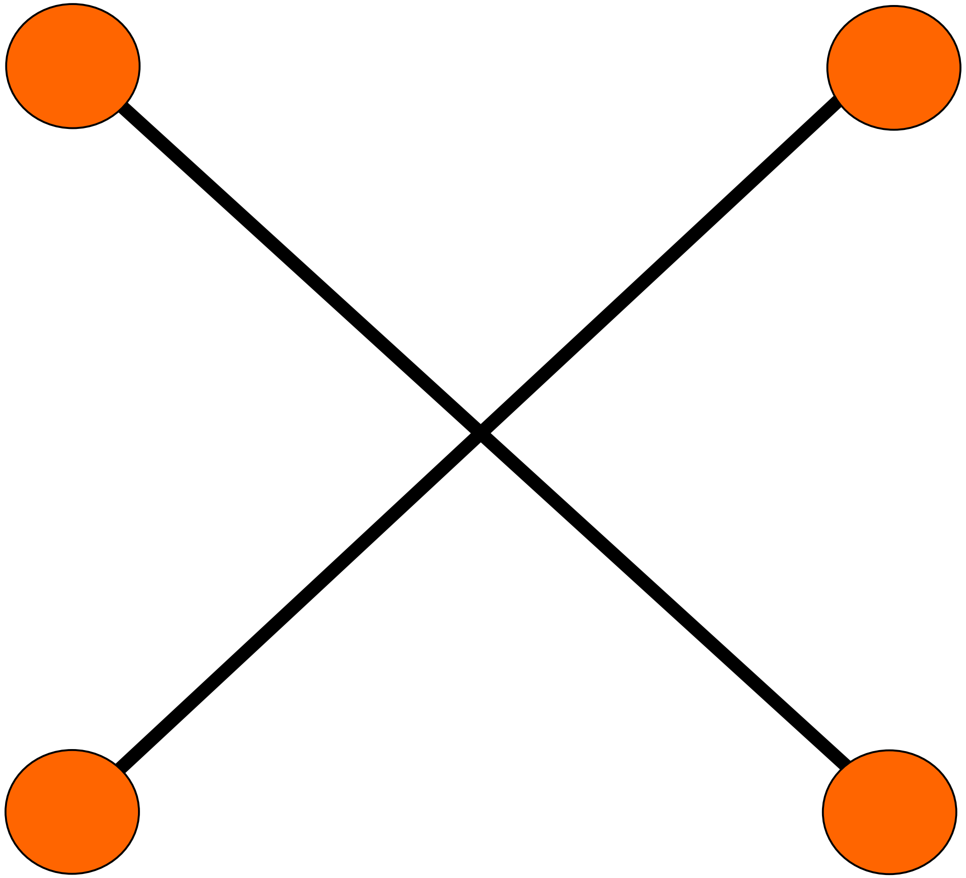
(length of side = 1 unit)

Option Two



I can connect them this way at a cost of only 3 units.

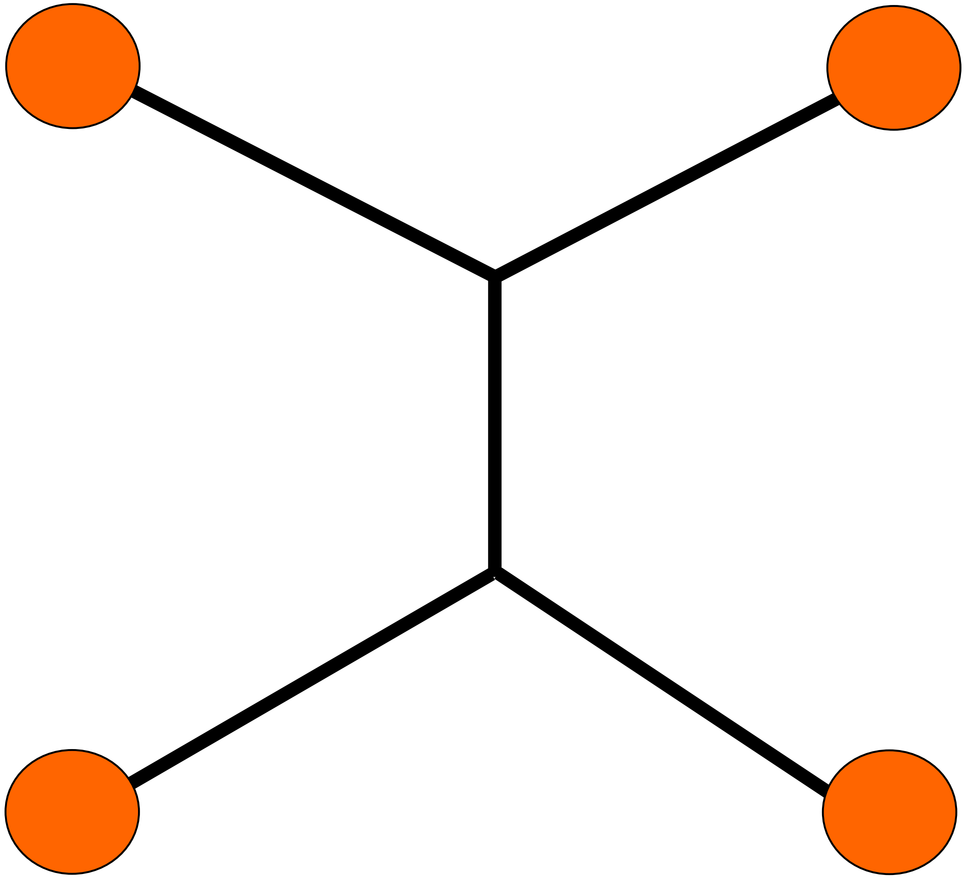
The Solution that Looks Optimal, But Really Isn't



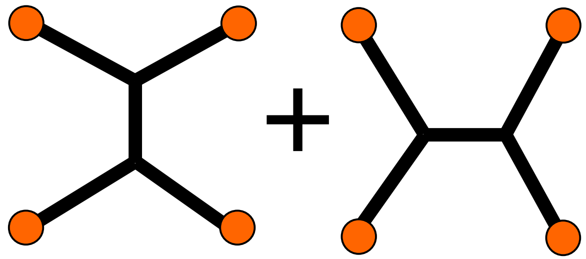
This requires only $2\sqrt{2}$

The Real Optimal Solution

This requires $1+\sqrt{3}$



Note that the symmetry of the solution is lower than the symmetry of the problem: this is the definition of ***Spontaneous Symmetry Breaking***



The sum of the solutions has the same symmetry as the problem

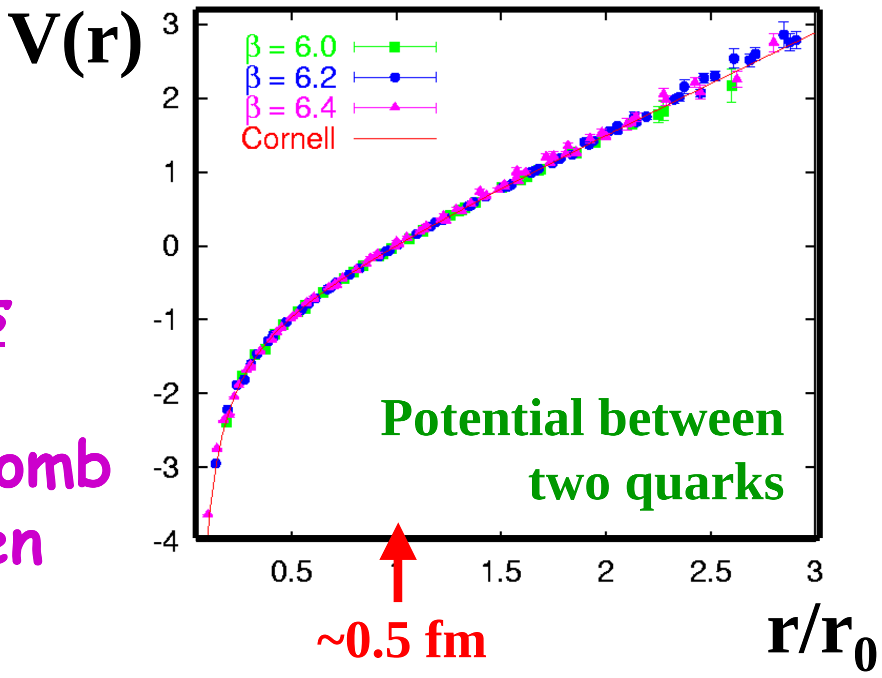
Two Realms of Nuclear Physics

Quantum Chromo Dynamics (QCD): The fundamental theory describing the strong force in terms of **quarks and gluons** carrying **color** charges.

Strongly attractive at all distances.

1 GeV/fm → *18 tons*

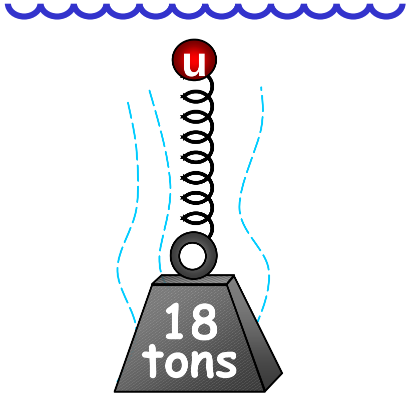
>10^{12} times the Coulomb attraction in hydrogen

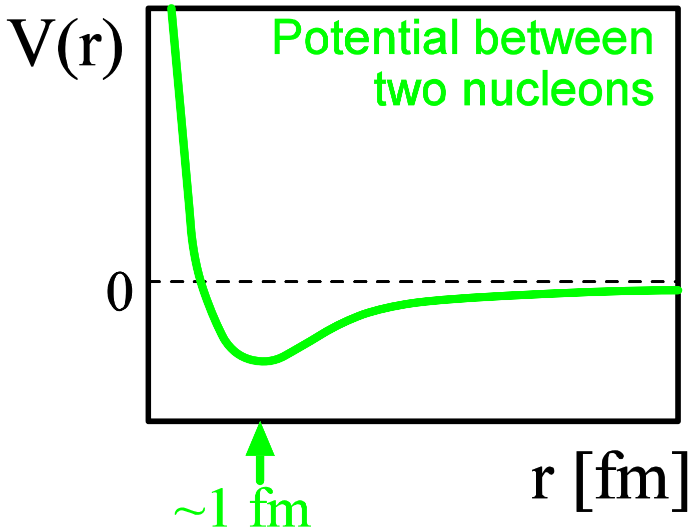


Two Realms of Nuclear Physics

Start in the "Land of QCD": quarks, gluons, and color

- QCD forms *colorless* bound states of quarks
- Quark interactions cancel at large distances → finite range residual strong force
- Nucleons *appear* to be fundamental objects





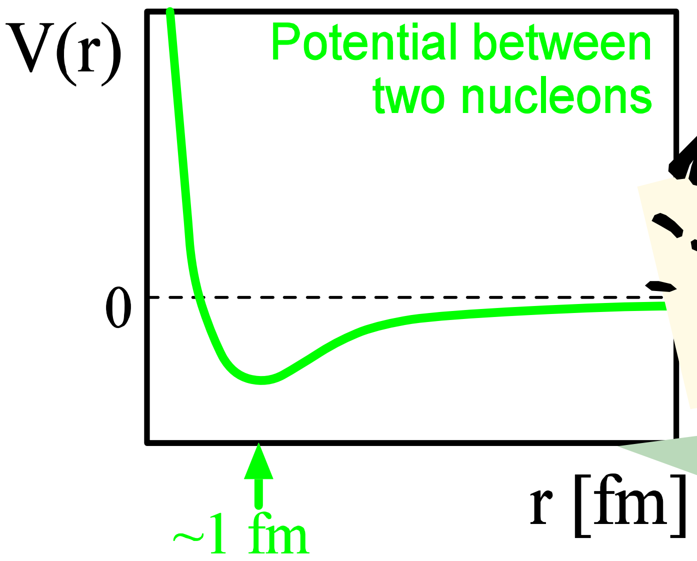
"Real World": Nucleons, mesons, residual strong interaction

Two Realms of Nuclear Physics

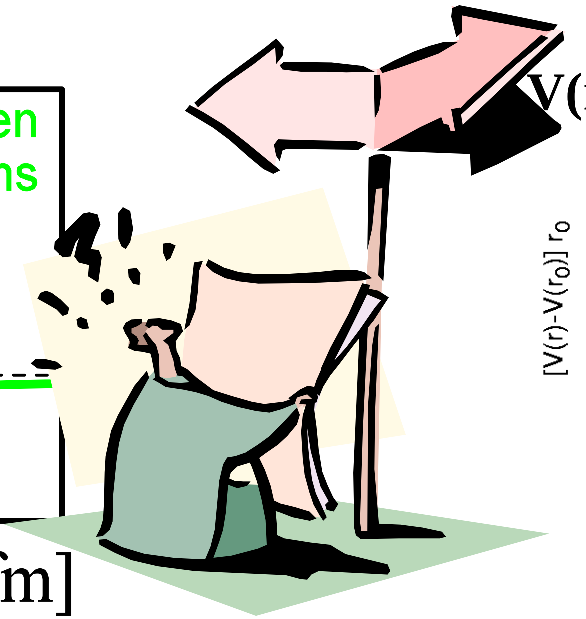
QCD gives the true picture

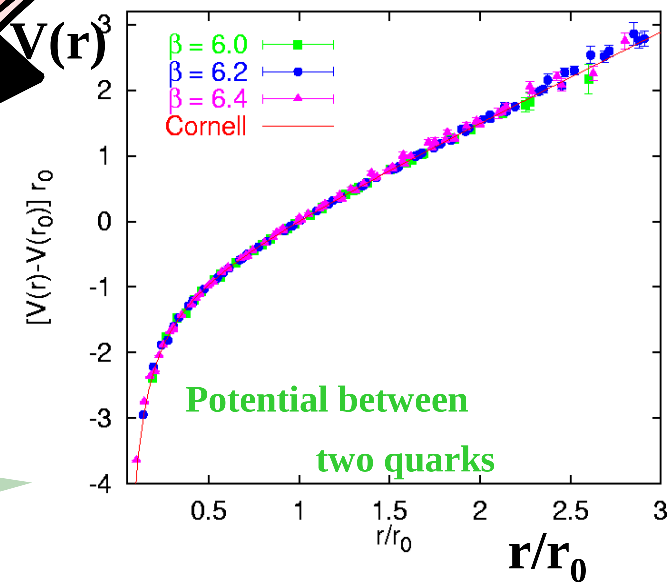
The hadronic picture is the correct picture (i.e. the one that works) for nuclei

No roadmap from land of QCD to the Real world, but it's usually pretty easy to tell where you are



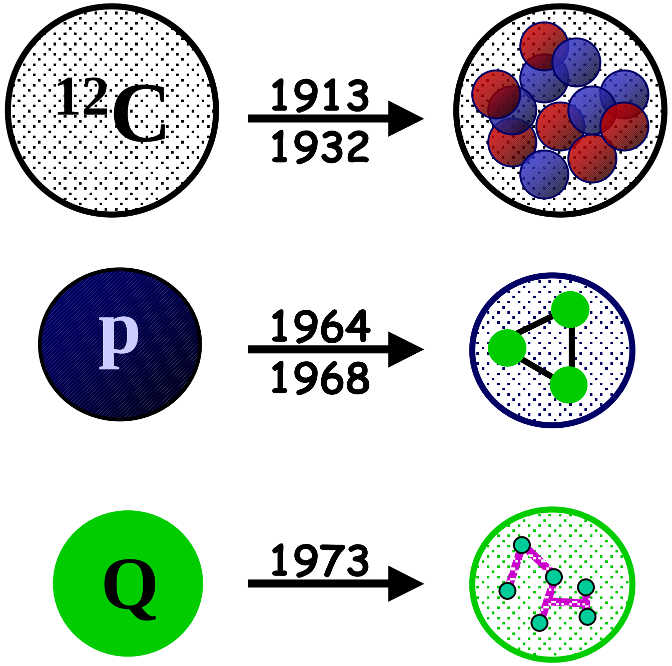
"Real World"





Land of QCD

Summary (last 100 years)



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+ strong interaction of hadrons

proton = Constituent Quarks

+ strong interaction of Quarks

Constituent Quark =

quarks + gluons

+ strong interaction of QCD

Nearly a century of nuclear physics has shown that a ***NUCLEUS*** can be extremely well described in terms of **protons**, **neutrons**, **the strong force**, ***and nothing else***

Don't *need* to know what a proton is, but may still *want* to know!

Why don’t we understand protons structure?

- **Nature of QCD explains why we don’t SEE the proton sub-structure in examining nucleon interactions or nuclear structure**

- **We know that proton is made of quarks and gluons**

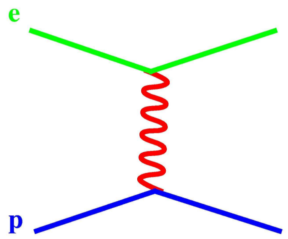
- **QCD is the theory of the strong interaction and describes the interactions of quarks and gluons**

- **Why don’t we already understand the structure of the proton?**

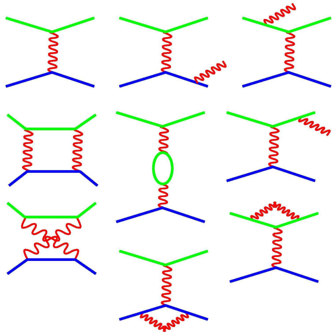
QED: e-p Interactions

- In QED, interaction of electron and proton via exchange of photon is well understood
- Higher order diagrams suppressed by factor α_{EM} (~1/137)
- Precise calculations "straightforward but tedious"

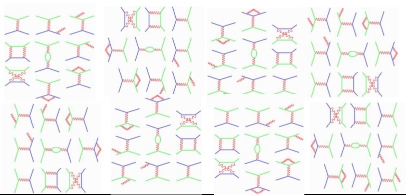
Born diagram: one-photon exchange



Higher order terms: additional photons coupling to electron or proton

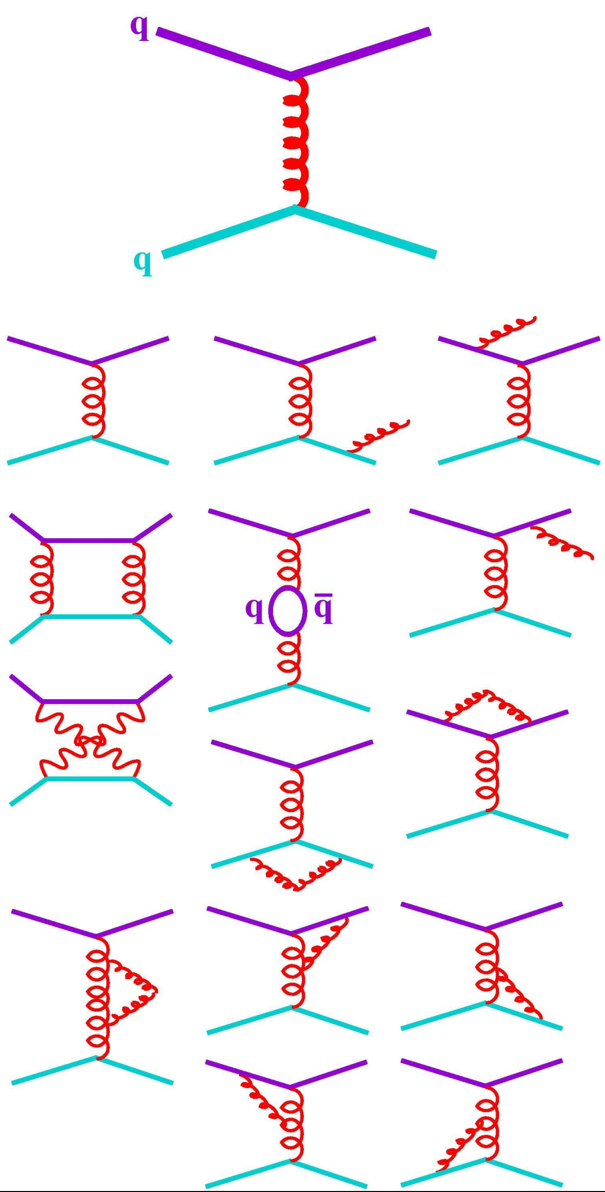


Further terms – much smaller



QCD: q-q Interactions, Hadronic Structure?

- In QCD, quark-quark interaction via exchange of a gluon is understood
- Higher order diagrams suppressed by factor $\alpha_S(Q^2)$
- Perturbative calculations possible but difficult at very high energy
  - $\alpha_S \sim 0.1 \rightarrow$ poor convergence
  - gg coupling $\rightarrow$ more higher order terms
- At lower energies, $\alpha_S(Q^2)$ becomes large
  - Perturbative calculations not possible
  - Can (sometimes) apply symmetry principles or find other expansion parameters
  - In general, cannot directly solve QCD or calculate hadronic structure from first principles



How bad is it?

- **Expansion in 1/N_c**
  - QCD: 3 colors.1/N_c < 1 → "useful" expansion parameter
  - $N_c=\infty$ becomes starting point
    - *Mesons: q-qbar*
    - *Baryons: qqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqqq*
  - 1/N_c corrections differ from small pertubation to couplings
  - One of few QCD approaches to "non-perturbative" regime
  - "So crazy, it just might work"
  - "Inspired genius" (inspired by desperation)

Nuclear structure analogy: 1/A expansion ***(Applied to ^{3}He)***

Maybe closer analogy: 1/$N_{nucleon\_isospins}$??

How might you describe this approach for nuclear structure?

Blindingly Stupid?

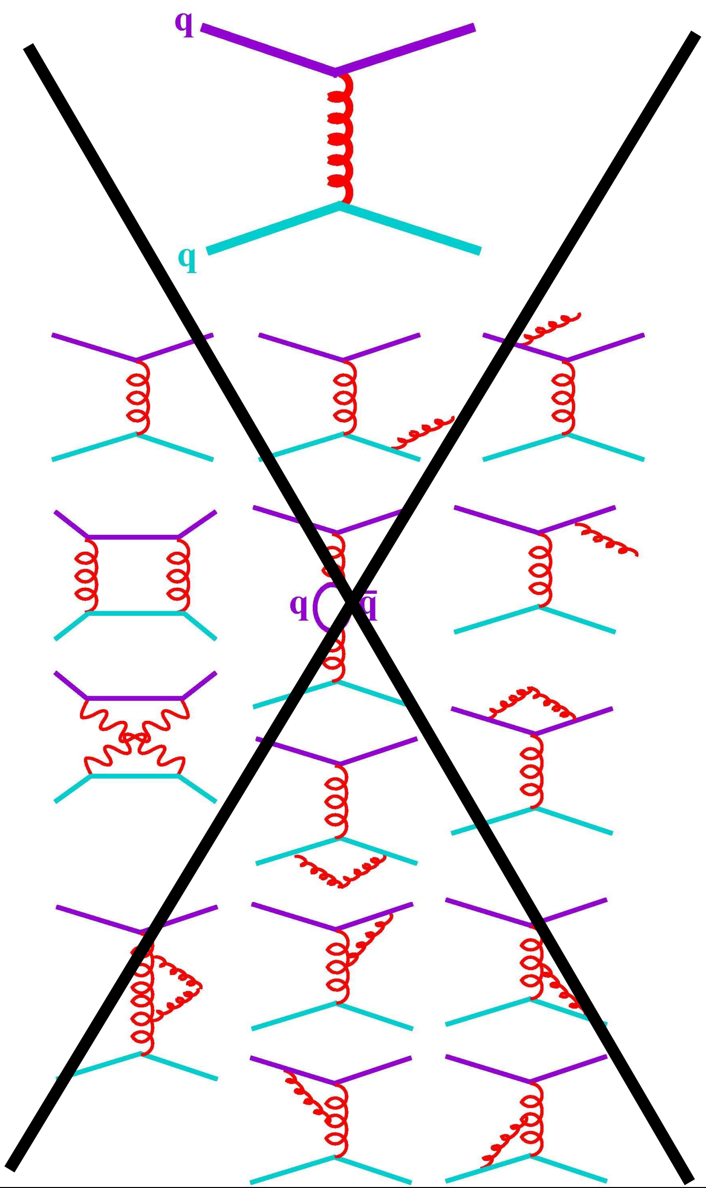
Evaluations of Hadron Structure?

Two main approaches that don't involve solving QCD

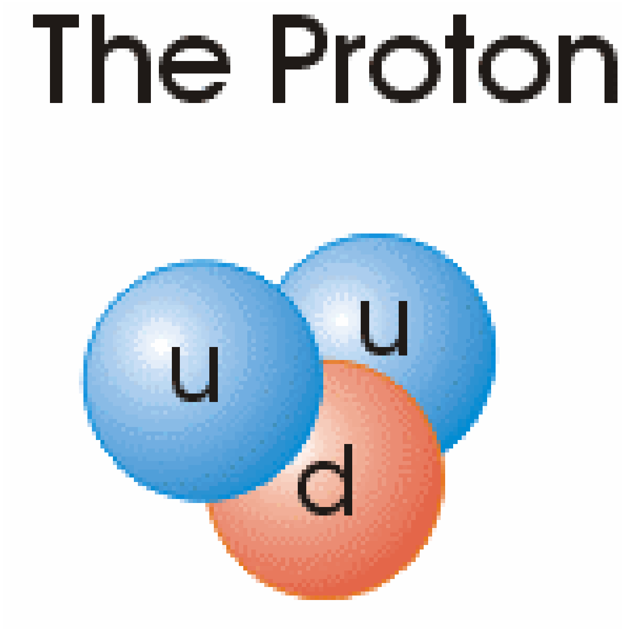
- **Build a simplified model that incorporates your best guess at the most important symmetries and degrees of freedom from QCD. Compare to data to evaluate the approach**

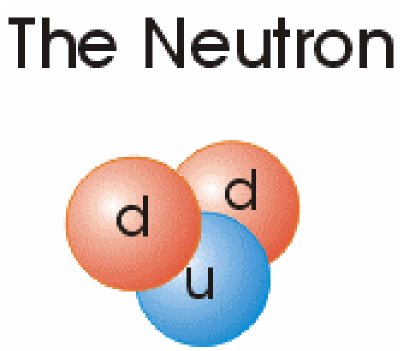
OR…

- **Cheat (i.e. look in the back of the book)**
  - **Nature has no problem solving QCD**
  - **Measure observables that are directly related to quark sub-structure**
  - **Provides <u>data needed to test models</u>**
  - **Yields <u>model-independent</u> information**



A Simple, Popular View of the Proton



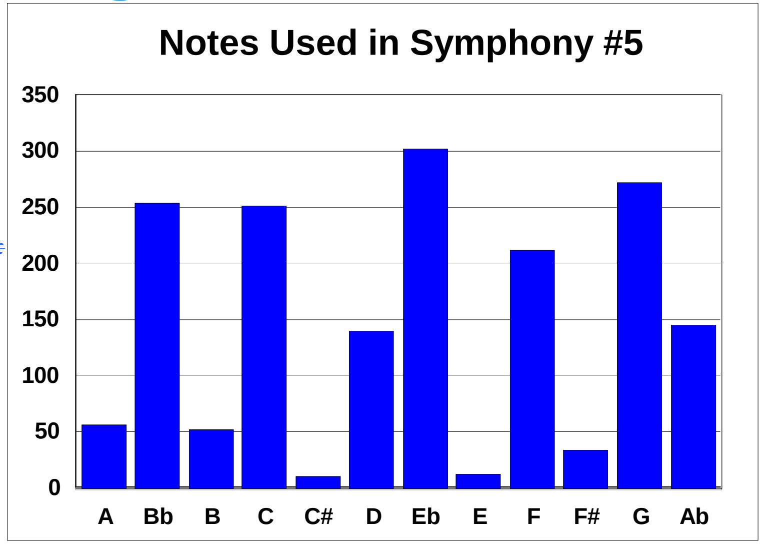


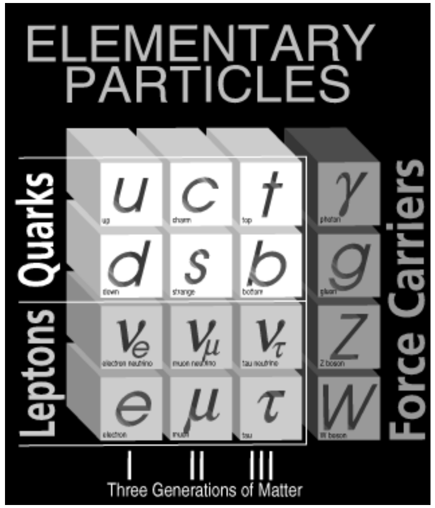
- The proton consists of two up (or *u*) quarks and one down (or *d*) quark.
  - A u-quark has charge +2/3
  - A d-quark has charge –1/3
- The neutron consists of two down, one up
  - Hence it has charge 0
- The u and d quarks mass is ≈1/3 the proton’s
  - Explains why m(n) = m(p) to ~0.1%
- But, very hard to explain zoo of hadrons
  - $M_{\pi,K,\eta,\rho} \approx$ 140, 490, 550, 780 MeV
  - $M_{\Lambda,\Sigma,\Delta} \approx$ 1120, 1190, 1230 MeV

  with 300 MeV quarks

Comparing Two Figures

A histogram of the notes used in Beethoven's 5th Symphony, first movement.



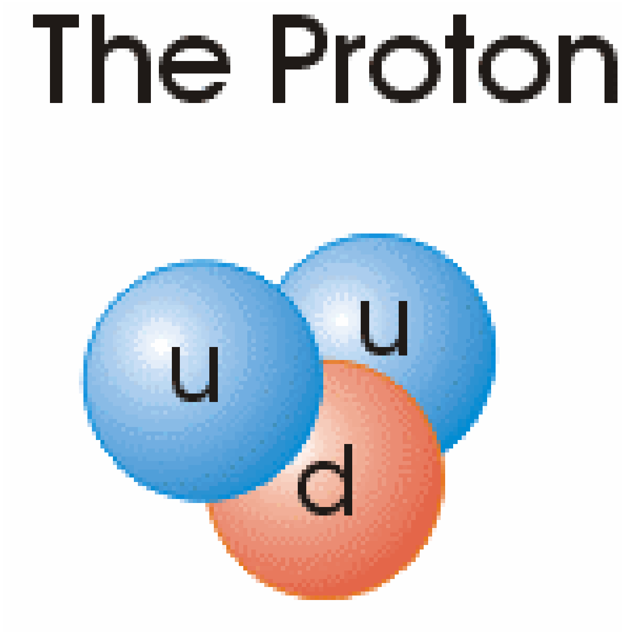


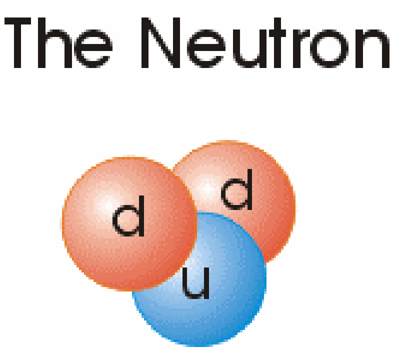
- Both plots focus on the constituents, rather than their interactions

- While there is meaning in both plots, it can be hard to see
  - A plot of a composition by A. Schoenberg would look different

- A model of the proton needs to do more than count constituents

A Simple, Popular, and Wrong View of the Proton





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- The u and d quarks mass is ≈1/3 the proton's
  - Explains why m(n) = m(p) to ~0.1%

So what's missing from this picture?

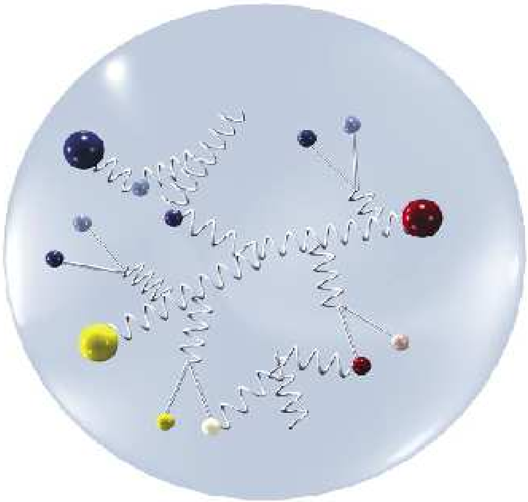
Energy is Stored in Fields

Thunder is good, thunder is impressive; but it is lightning that does the work.
(Mark Twain)

- We know energy is stored in electric & magnetic fields
  - Energy density ~ $E^2 + B^2$
  - The picture to the left shows what happens when the energy stored in the earth's electric field is released
- Energy is also stored in the gluon field in a proton
  - There is an analogous $E^2 + B^2$ that one can write down
  - There's nothing unusual about the idea of energy stored there
    - *What's unusual is the amount:*

	Energy stored in the field
Atom	$\sim 10^{-8}$ (13.6eV / 938MeV)
	$\sim 10^{-5}$ (13.6eV / 511keV)
Nucleus	~1% (10-20 MeV / nucleon)
Proton	99% (all but ~10 MeV valence quark masses)

The Modern Proton

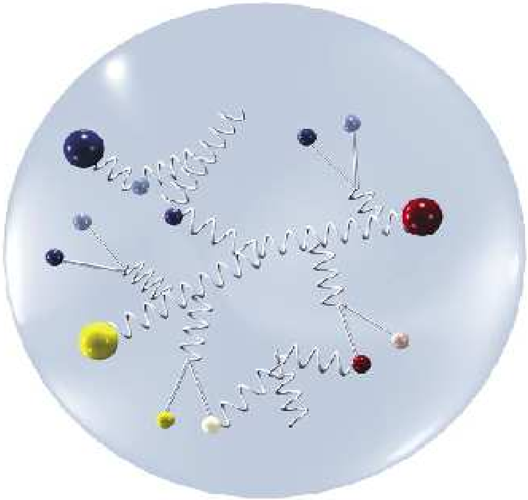


The Proton

Mostly a very dynamic self-interacting field of gluons, with three quarks embedded.

- 99% of the proton's mass/energy is due to this self-generating gluon field
- The two u-quarks and single d-quark
  - 1. Act as boundary conditions on the field (a more accurate view than generators of the field)
  - 2. Determine the electromagnetic properties (*quantum numbers*) of the proton
    - *Gluons are electrically neutral, so they can't affect electromagnetic properties*
- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Has almost nothing to do with the quarks

The Modern Proton



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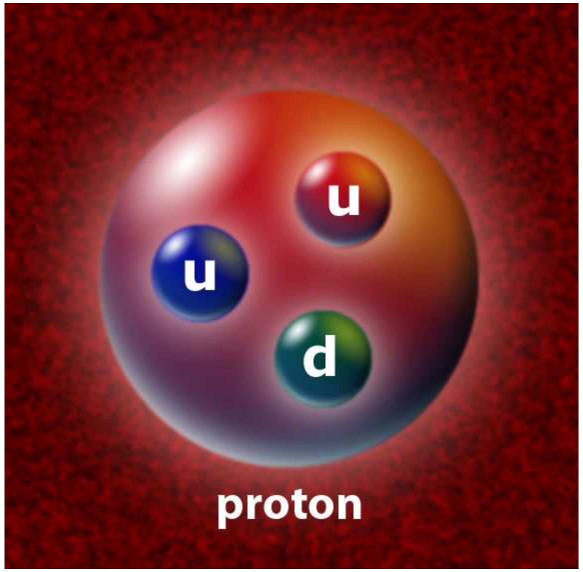
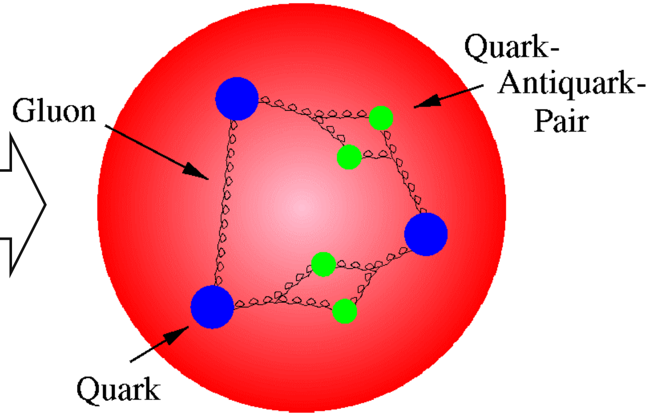
Atom, nucleus made up of constituents held together by some field

Proton is "made up" of the field itself (localized around the 'constituents')

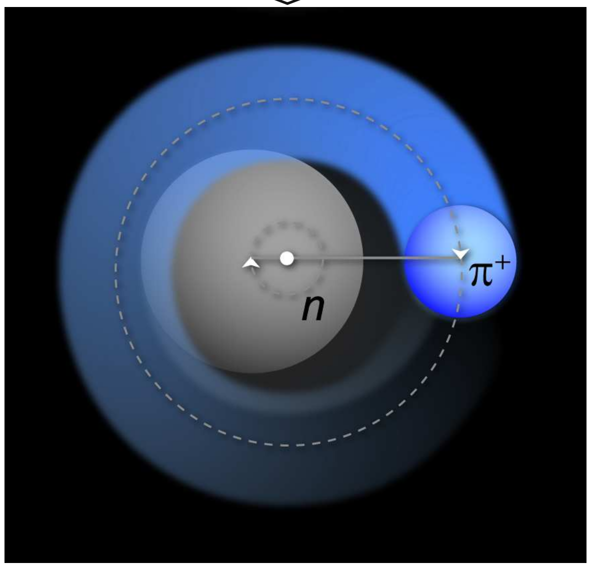
We have, in some sense, a better understanding of the 1% 'constituent' contributions than the other 99%

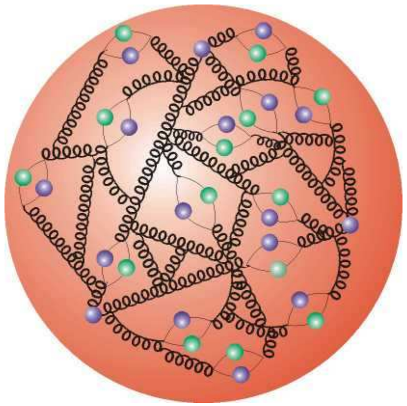
Evolving model of the proton





Each of these is a perfectly natural picture to use, for particular observables or scales. “most true” is not the same as “most correct”



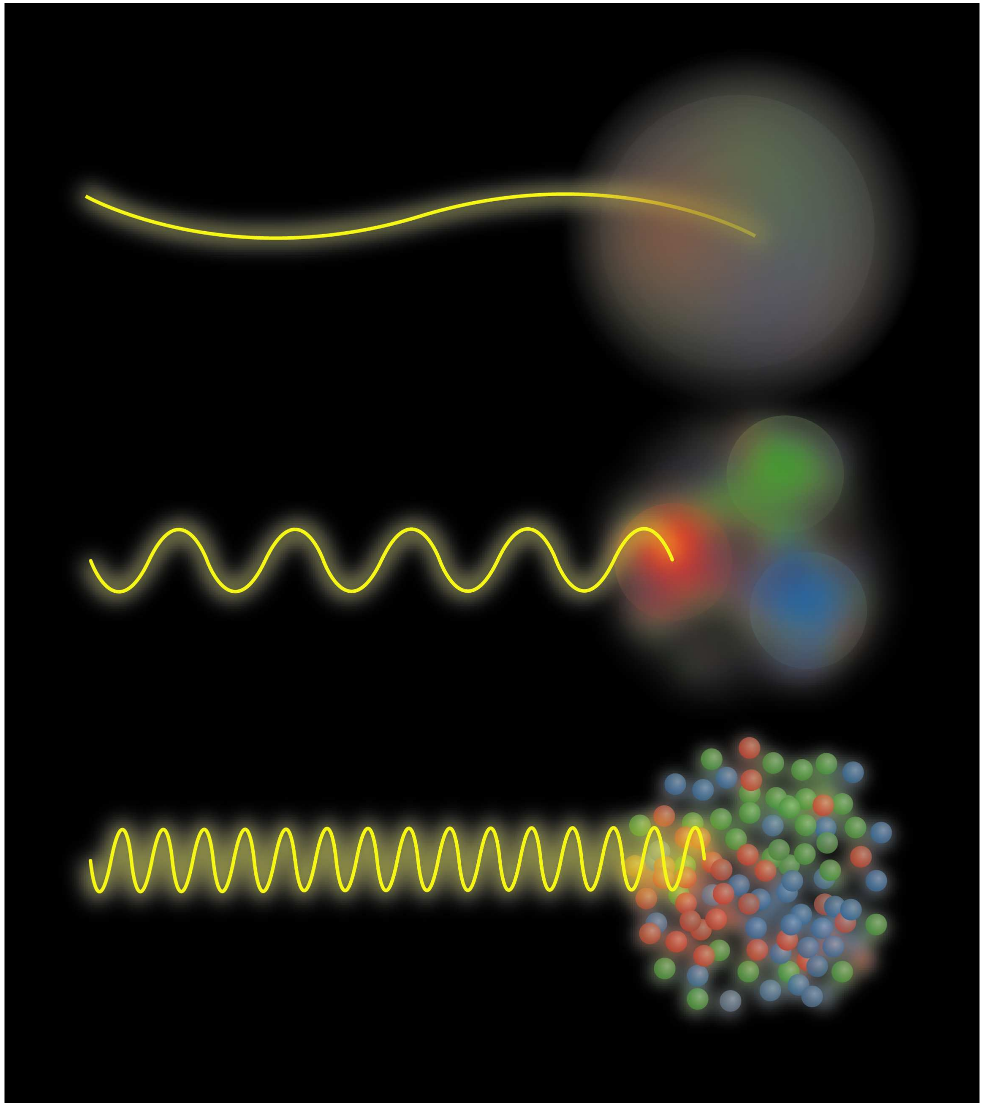


Where do we stand

- We do know what the constituents of hadrons are
- We do not know how many constituents there are

Scale dependence of parton distributions

- **Hadron structure is scale dependent**
  - **Comfortable picture: shorter wavelength probe sensitive to smaller scale structures – reveals details that are washed out when probed at long wavelength**
  - **Reality (or closer to it): There is a true scale dependence in the structure; number of constituents varies with scale**
  - **As probe goes to infinite Q^2, quark momentum distributions approach δ-function at x=0: infinite number of quarks each carrying 0 momentum.**



Where do we stand

- We do know what the constituents of hadrons are
- We do not know how many constituents there are
  - How much spin, Orbital angular momentum, etc… do they carry?
- We cannot calculate their interactions
- We cannot study their interactions directly
  - No phase shifts for q-q scattering
- Need to absorb all of this missing information into extremely simplified models

What does this imply for structure studies?

- Tools for studying atoms, nuclei
  - Relatively well defined constituents, orbitals, interactions
  - Scattering/break-up measurements: observe, count constituents
  - Direct scattering of constituents (N-N phase shifts)
  - Study bound states (e.g. Binding energy vs A)
  - Probe/test expected (possible) symmetries of system

  - Most are not possible for hadron structure; symmetries of QCD may be hidden (as color, quarks, gluons are hidden)
  - Symmetries often key to simplified models; even in imperfect models, symmetries often yield most model-independent predictions → most model-independent information
  - The more complicated the underlying theory, the more important the role of symmetries can be

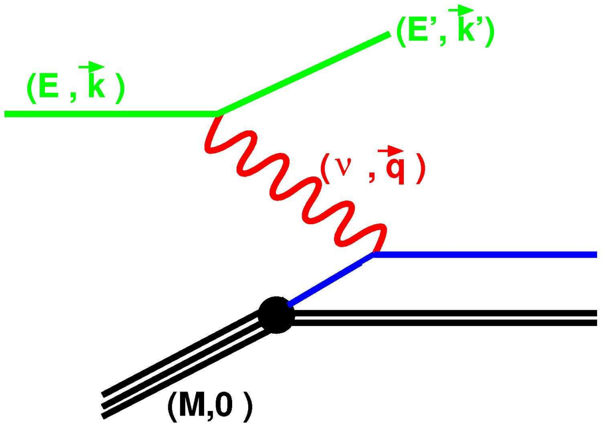
Simple pictures/models

- Dynamics [no color, glue, q-qbar pairs]
  - **Constituent quark model (3 static quarks, RCQM, quark-diquark models,…)**
  - **MIT bag model (original, 'cloudy' bag,…)**
- Assumed symmetries
  - **Identical u, d quark distributions?**
  - **Charge symmetry: $u_p = d_n$?**
- Overall success: test assumptions about key d.o.f., symmetries, dynamics
- Deviations from simple picture: indicate missing physics

- There **are** modern approaches that are more QCD-like
  - **Lattice QCD, DSE/BSE approach, NJL model,…**

but no global, *ab initio* QCD calculations

Inclusive scattering: e-p kinematics, 2 simple limits



$$\nu = E - E'$$

$$\vec{q} = \vec{k} - \vec{k}'$$

$$Q^2 = q^2 - \nu^2$$

$$x_{Bj} = \frac{Q^2}{2M\nu}$$

Deep Inelastic Scattering (single-quark scattering)

- ***x = quark momentum fraction (0 < x < 1)***
- ***In DIS limit (high ν, Q^2), cross section is convolution of quark distribution q(x) and known $\sigma_{e\text{-}q}$***
- ***Divide out $\sigma_{e\text{-}q}$ to extract structure function $F_2(x,Q^2) \rightarrow F_2(x)$***

Elastic e-p scattering

- ***Coherent scattering from entire proton (x = 1)***

Key observables in probing proton sub-structure

- **Form factors: Elastic e-p scattering**
  - **Deviation from point-like scattering as function of momentum transfer (Q^2)**
  - **Encode spatial distributions of charge, magnetization**
  - **Equal to charge (magnetic moment)-weighted spatial distribution of quarks in non-relativistic limit.**

- **Structure functions: Deep-Inelastic e-p scattering**
  - **Incoherent sum of 'billiard-ball' scattering from free quarks**
  - **Independent of Q^2 for sufficiently large Q^2**
  - **Yields (charge squared weighted sum of) quark momentum distributions (in *Infinite Momentum Frame)***

- **Studies began in '50s and '60s, but new experimental, theoretical tools are moving these in new directions**

Key observables in probing proton sub-structure

- **DIS: Recent developments**
  - **Proton vs. Neutron → up vs. down†**
  - **Spin degrees/freedom: spin-up vs. spin-down&**

Both of these can be used to test symmetries

† **Easy, except for lack of free neutron target**

& **Required significant technical development: polarized beams, polarized targets, polarimeters, etc…**

Limit as x→1: Struck quark carries most of protons momentum

proton wave function

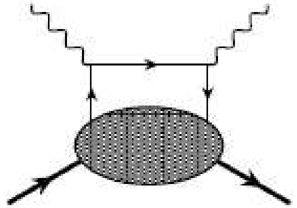
$$p^{\uparrow} = -\frac{1}{3} d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6} u^{\uparrow}(ud)_1 - \frac{1}{3} u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow}(ud)_0$$

interacting quark

spectator diquark

diquark spin

Take symmetry arguments, use these to select dominant terms for struck quark x→1



- SU(6): Symmetric up/down
- Scalar Diquark dominance: lowest energy diquark dominates at x→1: $(qq)_0$
- Helicity conservation: helicity of struck quark = hadron helicity

Assumes charge symmetry:

u(x) in proton = d(x) in neutron

d(x) in proton = u(x) in neutron

A_1^N ~ spin asymmetry in e-N scattering cross section (polarized e, polarized N)

x→1 predictions	**d(x)/u(x)**	**F2n/F2p**	**A1p,A1n**
SU(6)	**1/2**	**2/3**	**5/9 , 0**
Scalar diquark	**0**	**1/4**	**+1, -1/3**
Helicity conserv.	**1/5**	**3/7**	**+1, +1**

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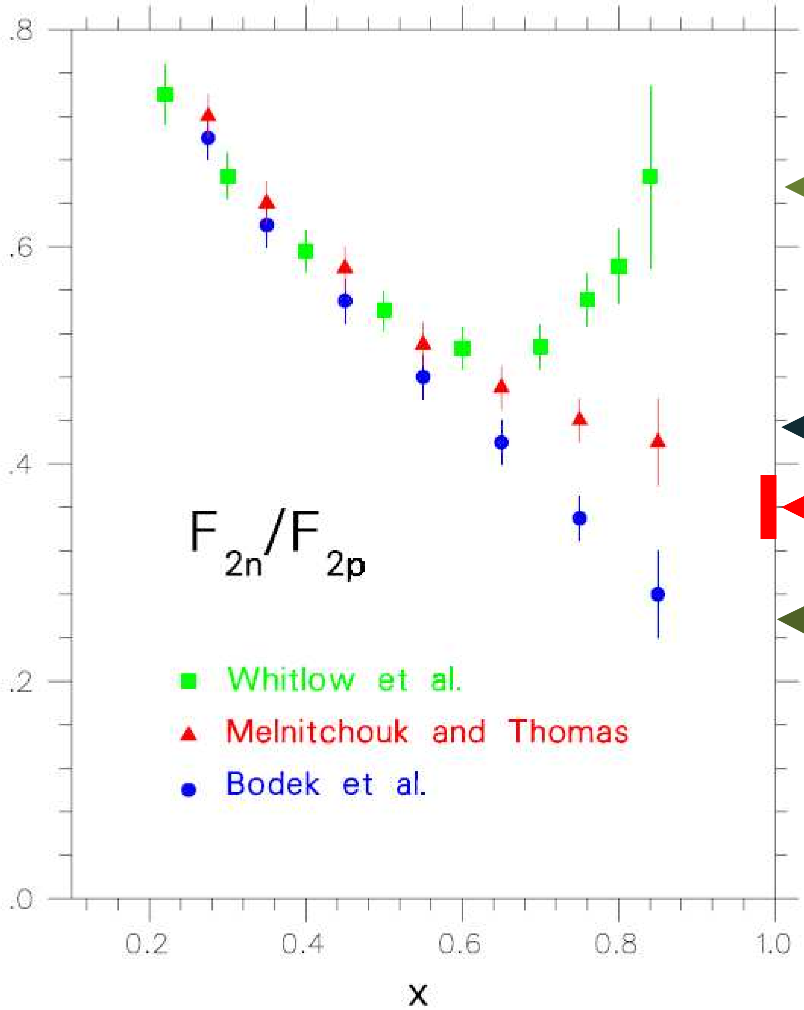
I.C. Cloët, C.D. Roberts, *et al*.
arXiv:0812.0416 [nucl-th]

Neutron Structure Function at high x

Reviews:
- S. Brodsky *et al.* NP B441 (1995)
- W. Melnitchouk and A.Thomas PL B377 (1996) 11
- N. Isgur, PRD 59 (1999)
- R. J. Holt and C. D. Roberts RMP (2010)

Extractions of F_{2n}/F_{2p} taken from deuteron/proton ratio; different points correspond to same data, different model of deuteron in getting F_{2n} from $F_2^{Deuteron}$

→ Significant effort to get F_{2n} using other techniques (as well as A_{1p}, A_{1n}) after JLab 12 GeV upgrade



SU(6) symmetry

pQCD (helicity conservation)

DSE: 0^+ & 1^+ qq

0^+ qq only