Gluonic Hadrons: A Probe of Confinement

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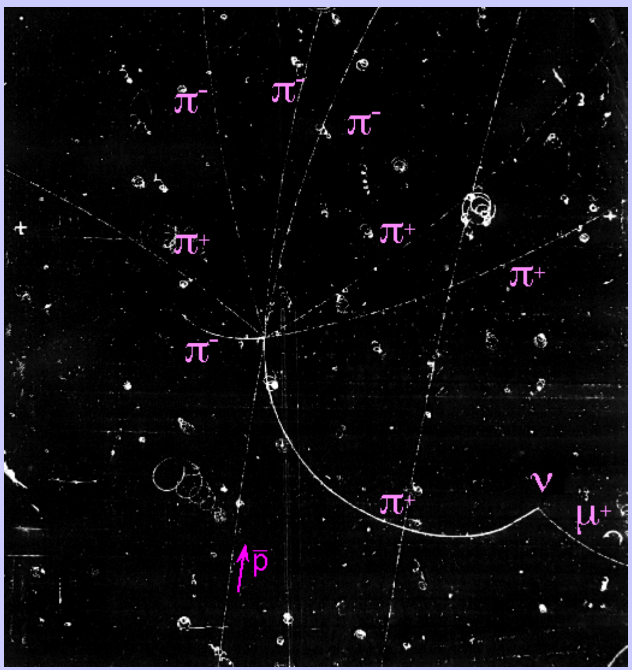
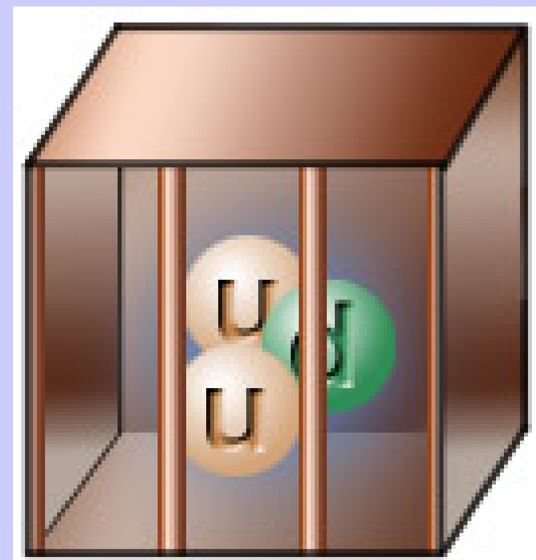
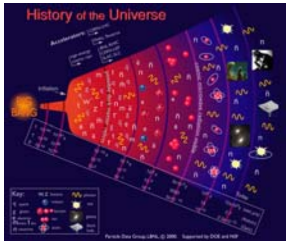


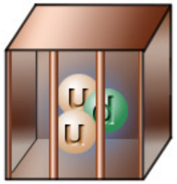


Outline

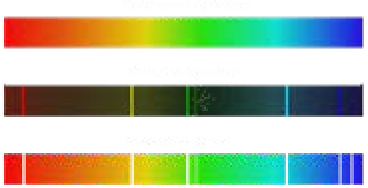


The beginning of time.

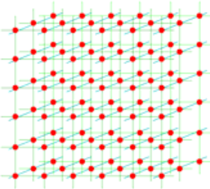
The strong force and QCD



Color confinement

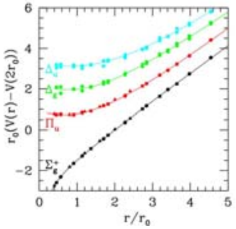


Spectroscopy



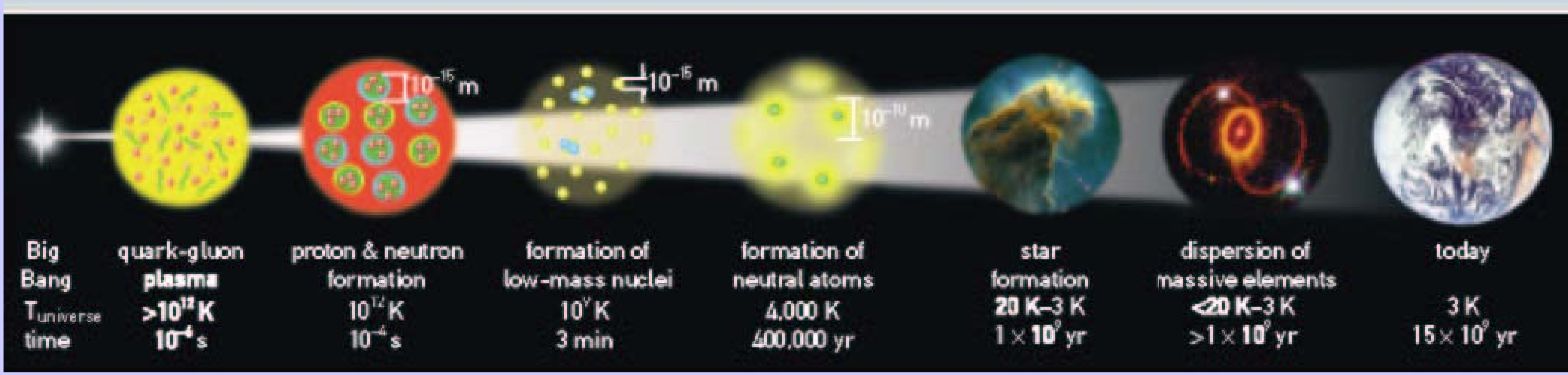
Lattice QCD

Finding Gluonic Hadrons

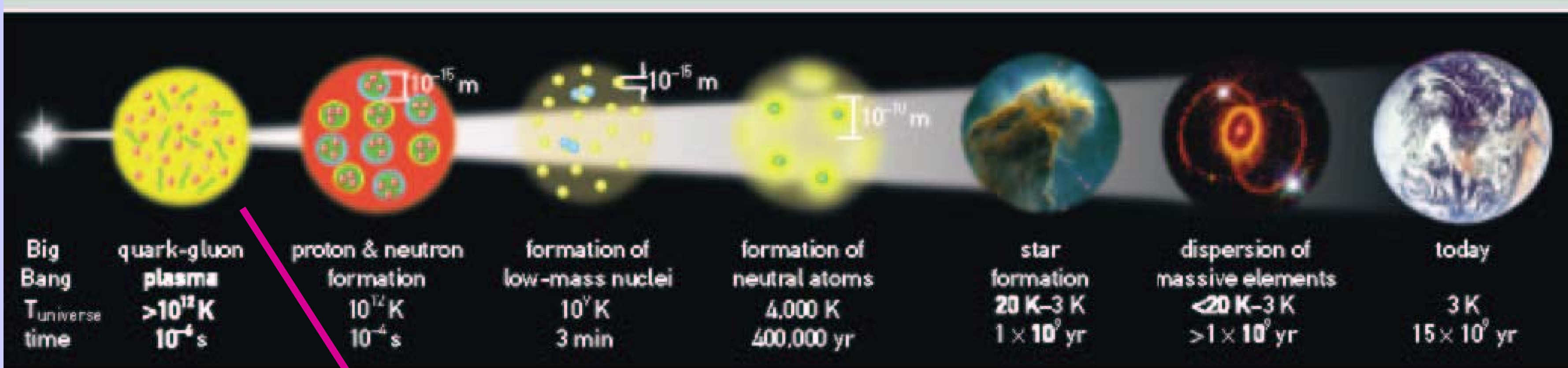


Confinement

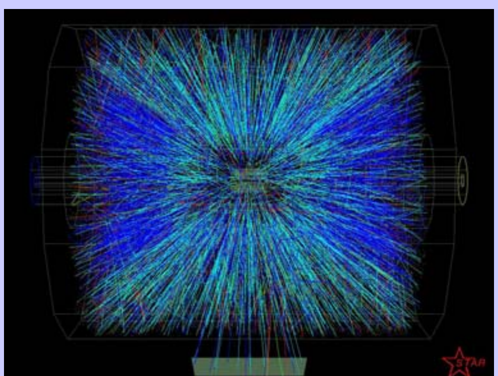
The First Seconds of The Universe



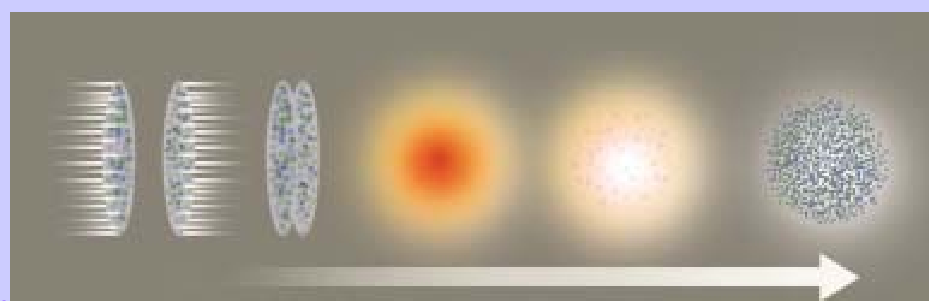
Quark Gluon Plasma



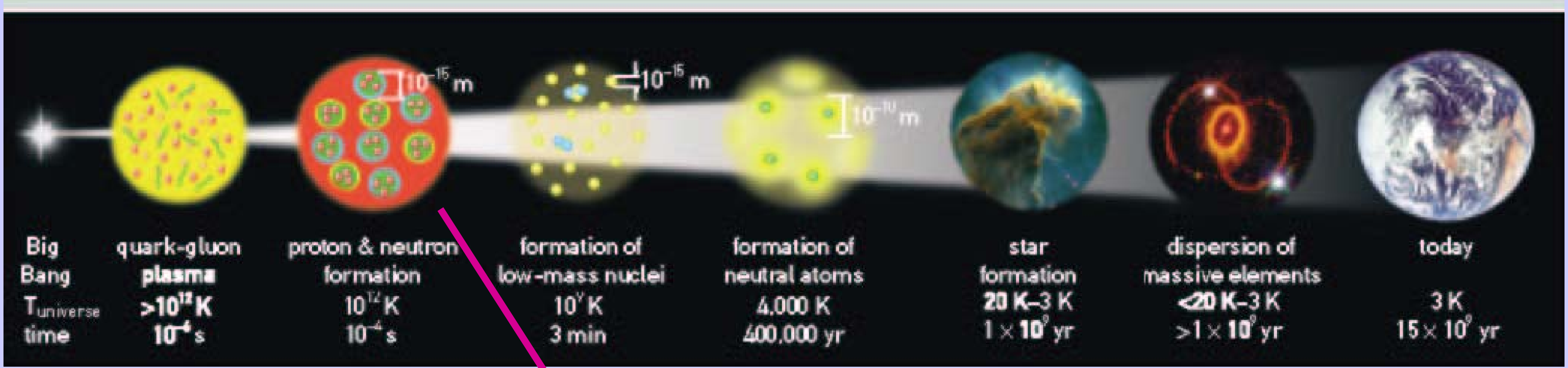
For a period from about 10^{-12} s to 10^{-6} s the universe contained a plasma of quarks, anti quarks and gluons.



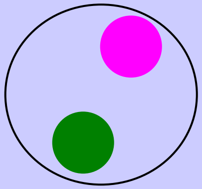
Relativistic Heavy Ion Collisions are trying to produce this state of matter in collisions



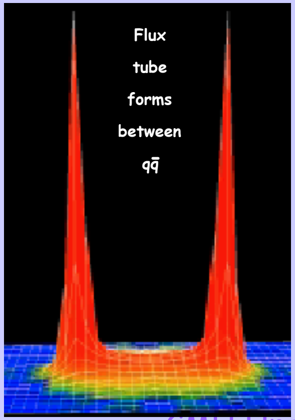
Confinement



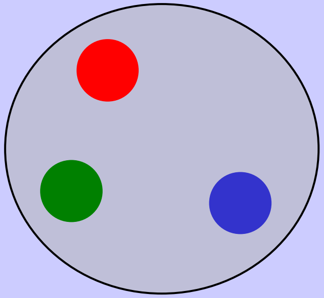
From about 10^{-6} s on, the quark and antiquarks became confined inside of Hadronic matter. At the age of 1s, only protons and neutrons remained.



Mesons

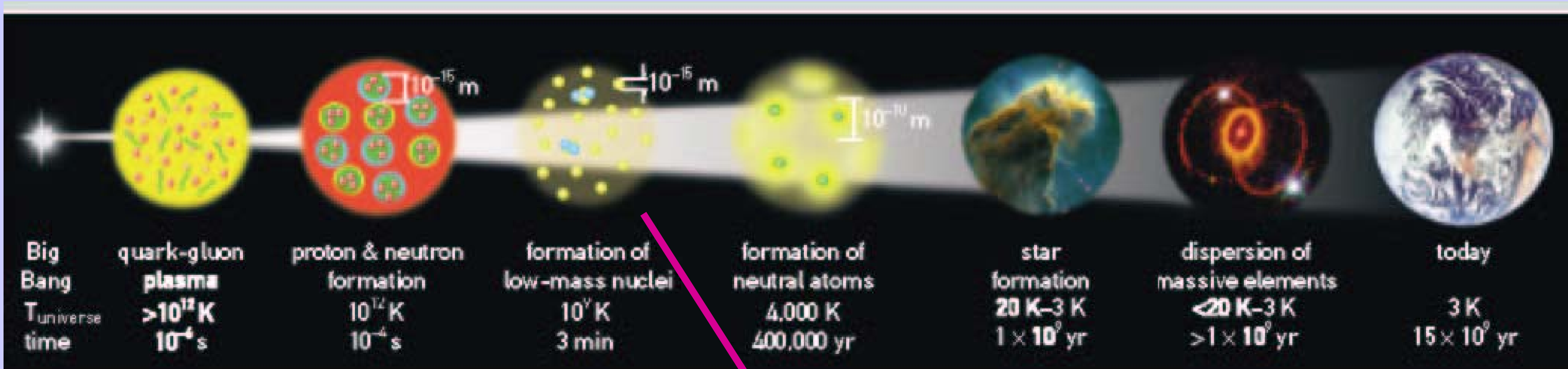


The gluons produce the 16 ton force that holds the hadrons together.

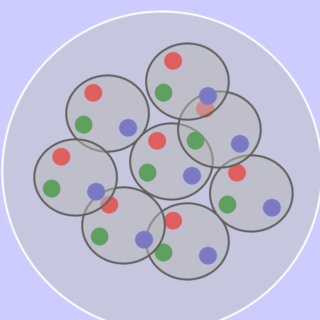


Baryons

The Formation of Nuclei



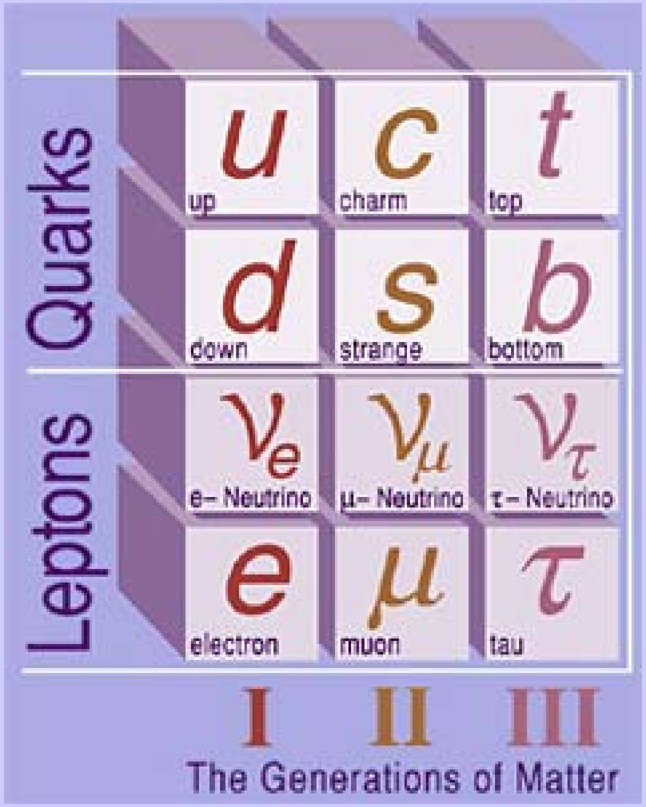
By the old age of three minutes, the formation of low mass nuclei was essentially complete.

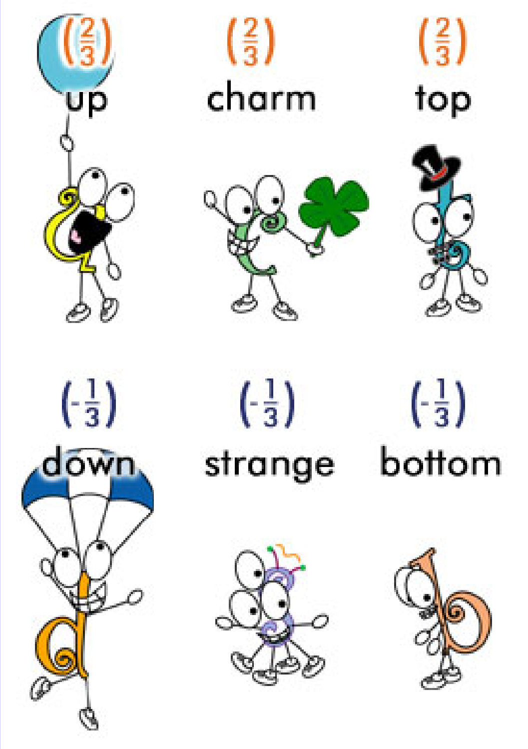


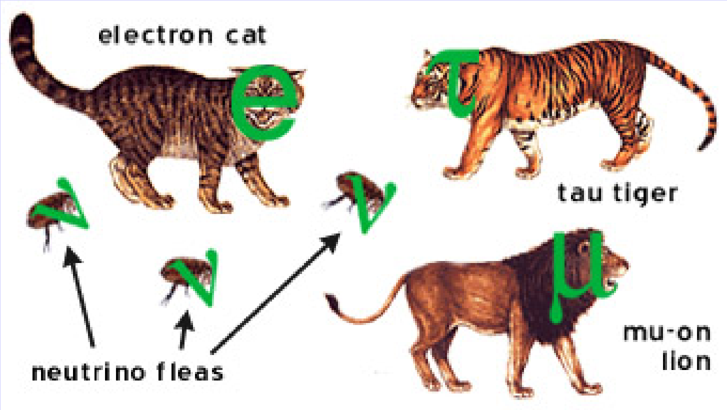
Primordial hydrogen, deuterium, helium and a few other light nuclei now exist.

It will be nearly a half a million years before neutral atoms will dominate matter.

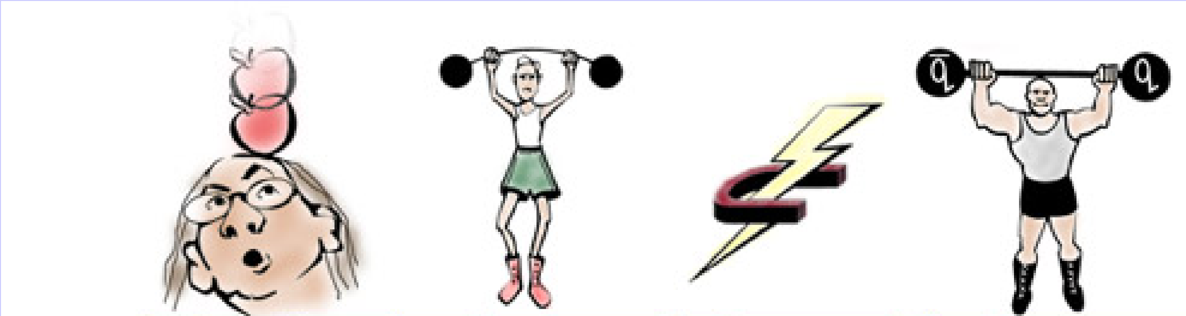
Quarks and Leptons



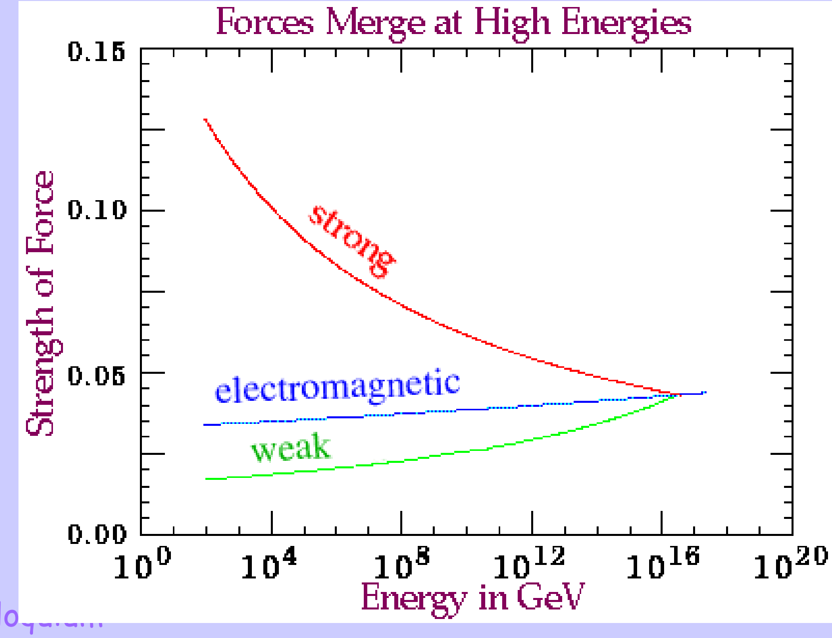




Forces and Interactions

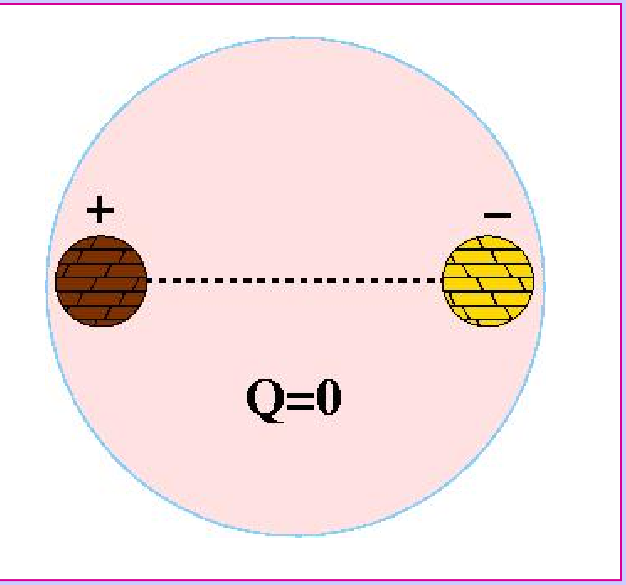


	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons



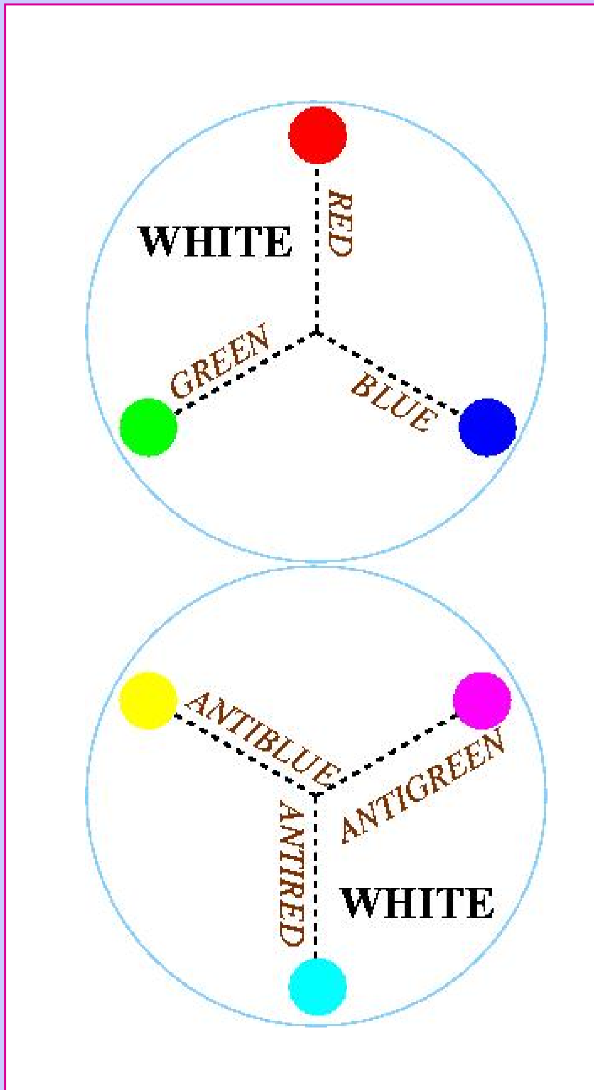
Quantum Chromo Dynamics

The rules that govern how the quarks froze out into hadrons are given by QCD.



Just like atoms are electrically neutral, hadrons have to be *neutral.*

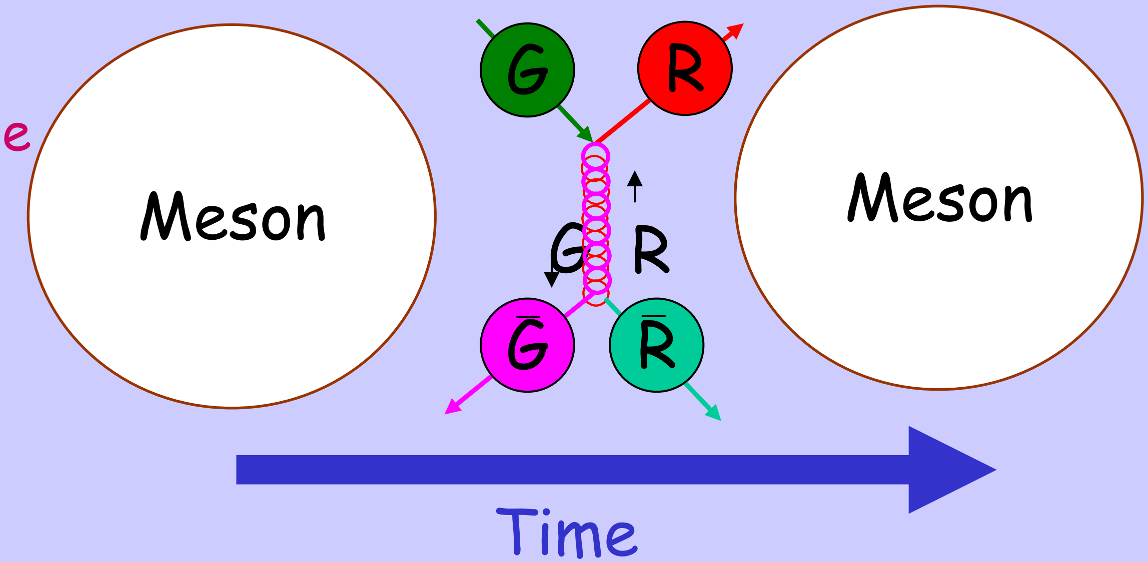
Color Charge

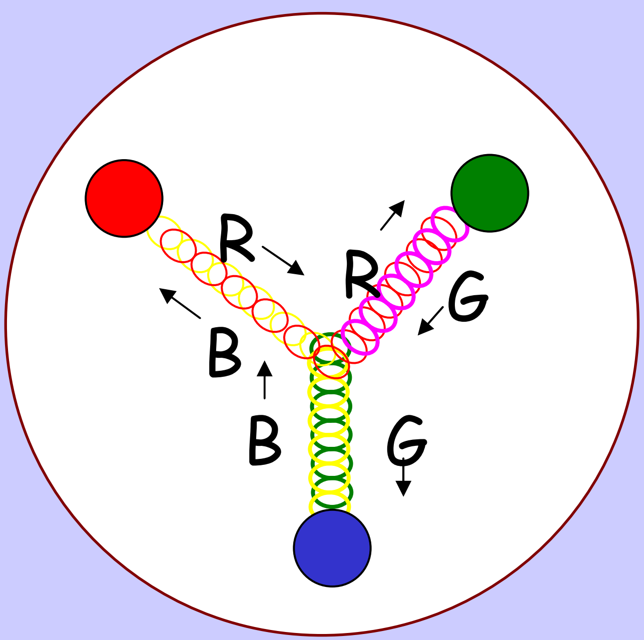


Three charges called RED, BLUE and GREEN, and three anti colors. The objects that form have to be color neutral.

Gluons Carry the Force

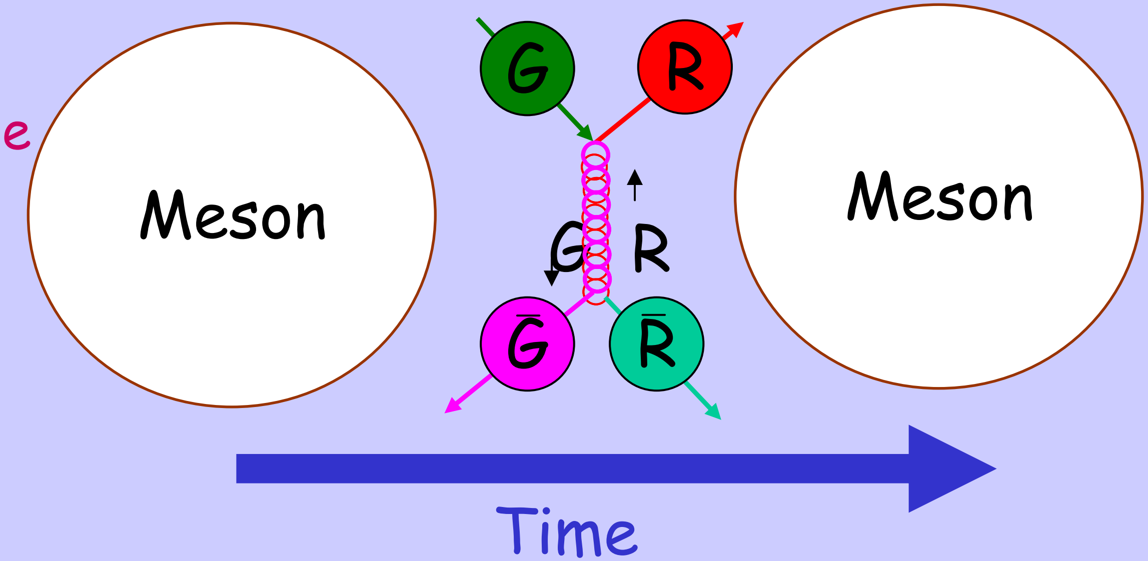
The exchange of gluons
is continually changing the
Individual colors of the
quarks, but the overall
Color remains neutral

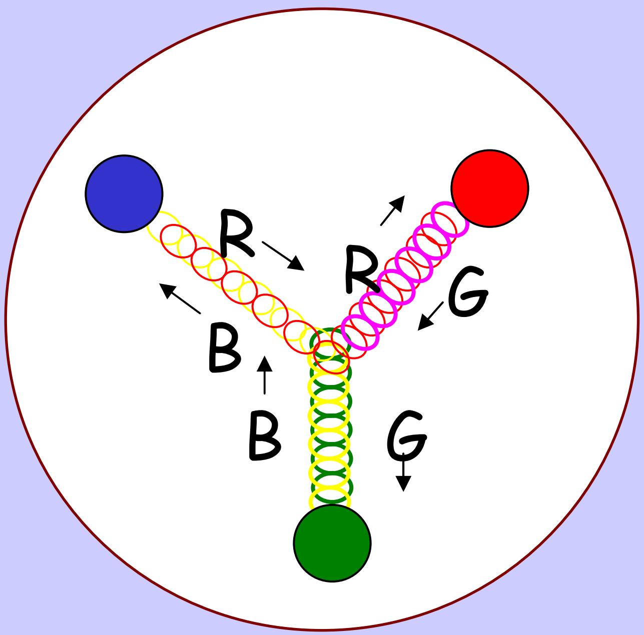




Gluons Carry the Force

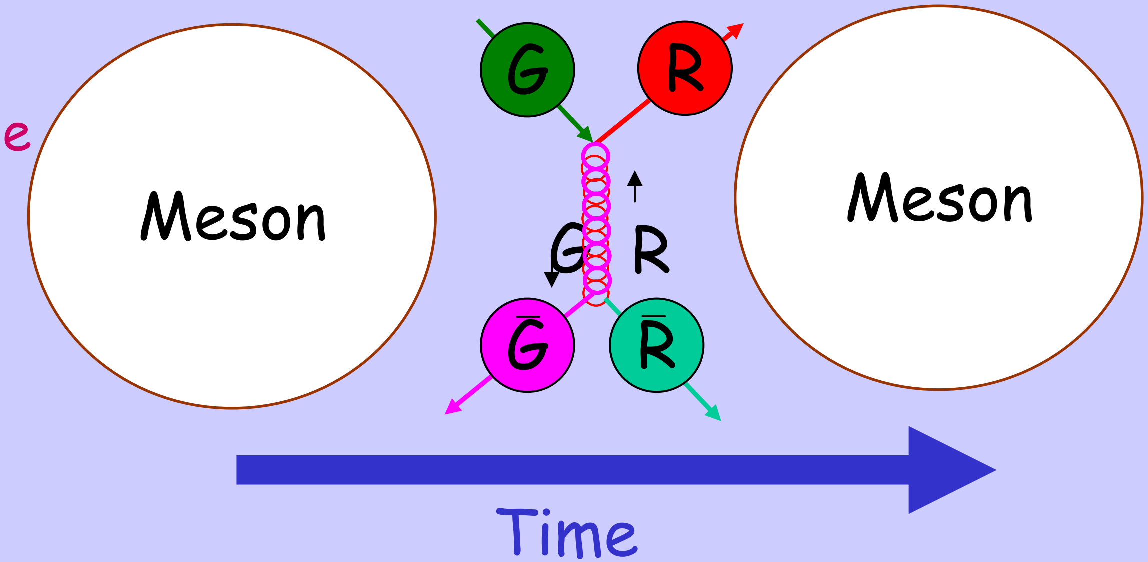
The exchange of gluons is continually changing the Individual colors of the quarks, but the overall Color remains neutral

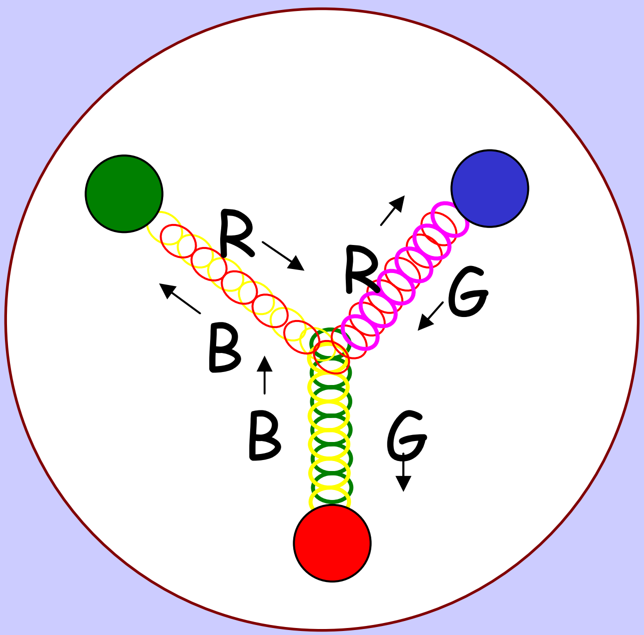




Gluons Carry the Force

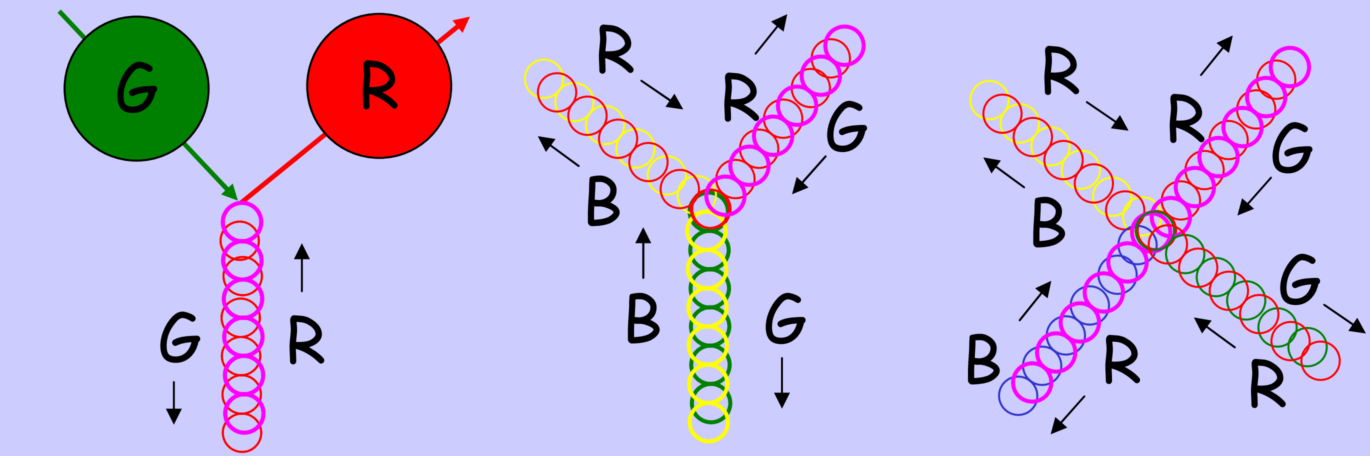
The exchange of gluons is continually changing the Individual colors of the quarks, but the overall Color remains neutral





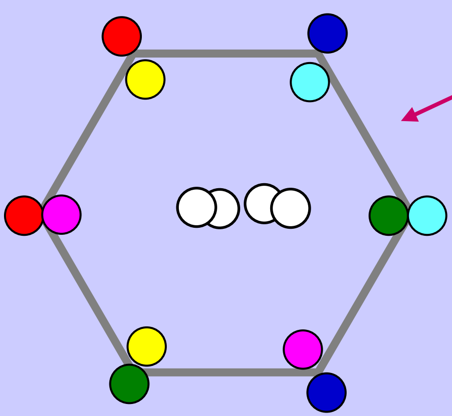
Gluons produce the forces that confine the quarks, but the gluons do not appear to be needed to understand normal hadrons

Gluon Interactions



3 Colors
3 Anti Colors

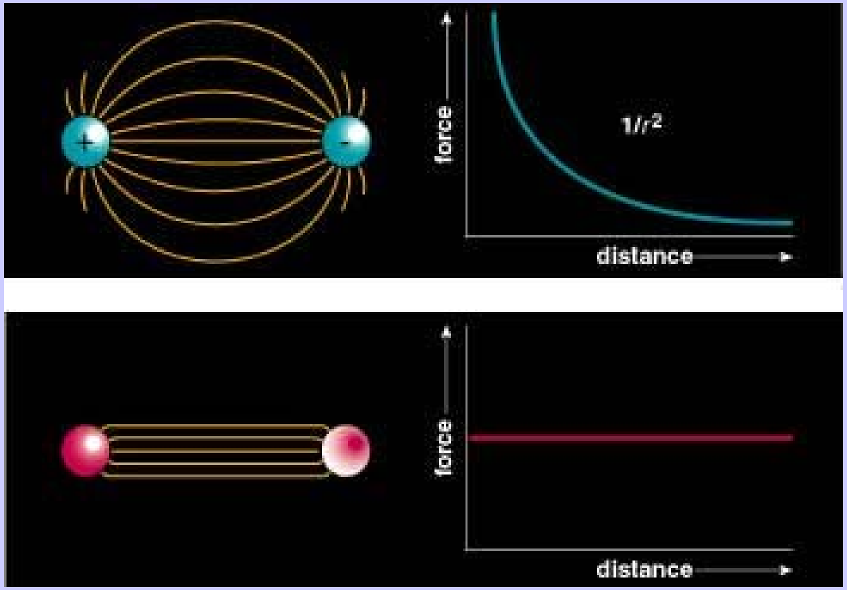
1 color neutral
8 colored objects

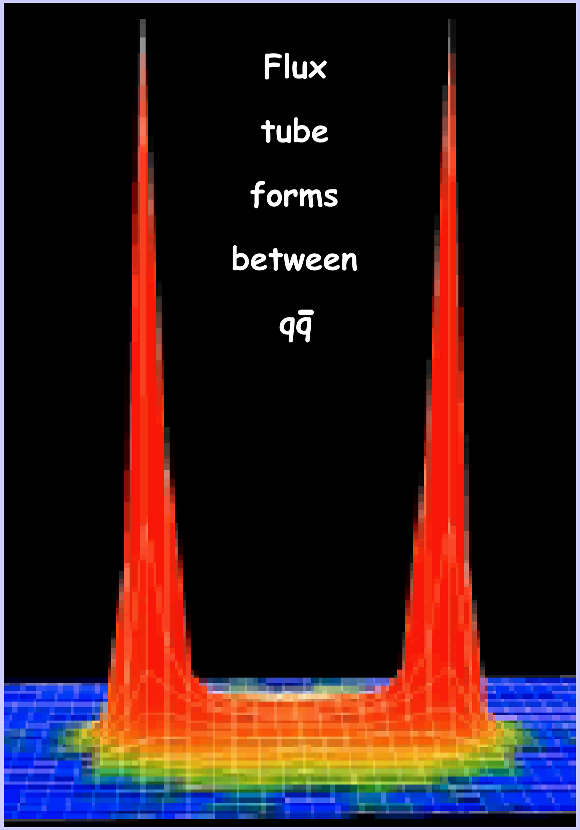


8 Gluons

self-interaction of gluons leads to both interesting behavior of QCD, and its extreme complications.

Flux Tubes



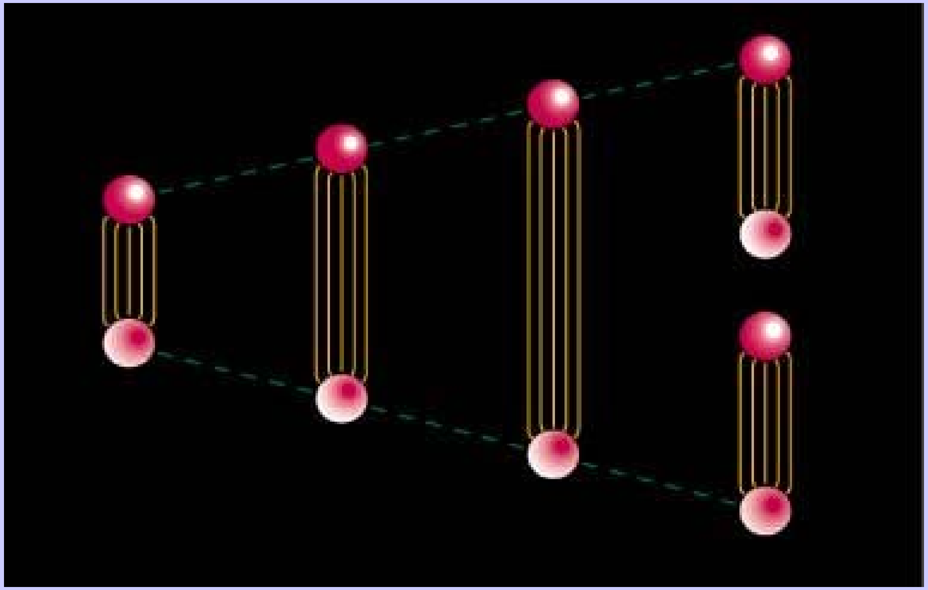


Color Field: Because of self interaction, confining flux tubes form between static color charges

Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons

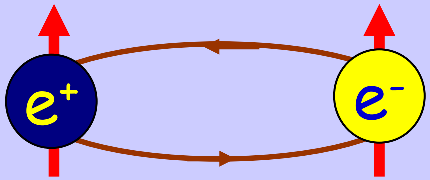
Quark Confinement

- quarks can never be isolated
- linearly rising potential
  - separation of quark from antiquark takes an infinite amount of energy
  - gluon flux breaks, new quark-antiquark pair produced



Spectroscopy
A probe of QED

Positronium



Spin: $S=S_1+S_2=(0,1)$

Orbital Angular Momentum: $L=0,1,2,...$

Total Spin: $J=L+S$

$L=0, S=0 : J=0$ $L=0, S=1 : J=1$

$L=1, S=0 : J=1$ $L=1, S=1 : J=0,1,2$

... ...

Reflection in a mirror:

Parity: $P=-(-1)^{(L)}$

Particle<->Antiparticle:

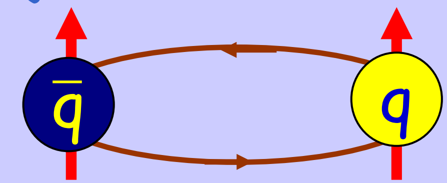
Charge Conjugation: $C=(-1)^{(L+S)}$

Notation: $J^{(PC)}$ $0^{-+}, 1^{--}, 1^{+-}, 0^{++}, 1^{++}, 2^{++}$

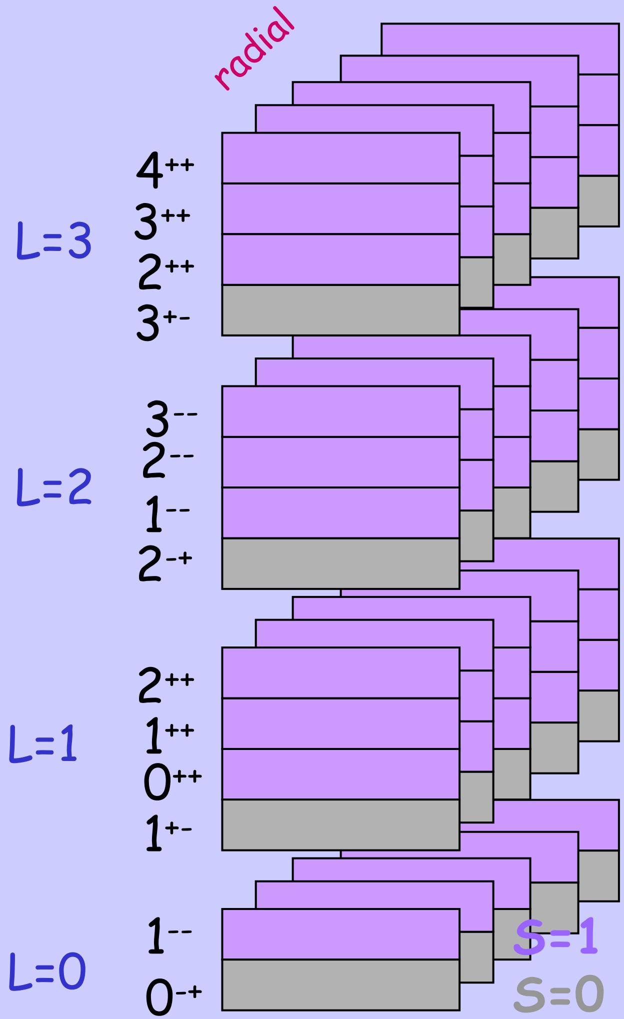
$^{(2S+1)}L_J$ $^1S_0, {}^3S_1, {}^1P_1, {}^3P_0, {}^3P_1, {}^3P_2, ...$

Spectroscopy and QCD

Quarkonium



Mesons



Consider the three lightest quarks

$$\left.\begin{matrix} u, d, s \\ \bar{u}, \bar{d}, \bar{s} \end{matrix}\right\}$$ 9 Combinations

$$d\bar{s} \qquad u\bar{s}$$

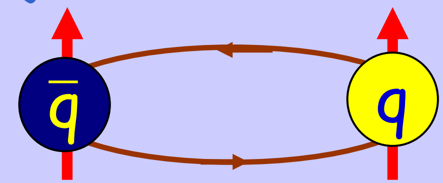
$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

$$s\bar{d} \qquad s\bar{u}$$

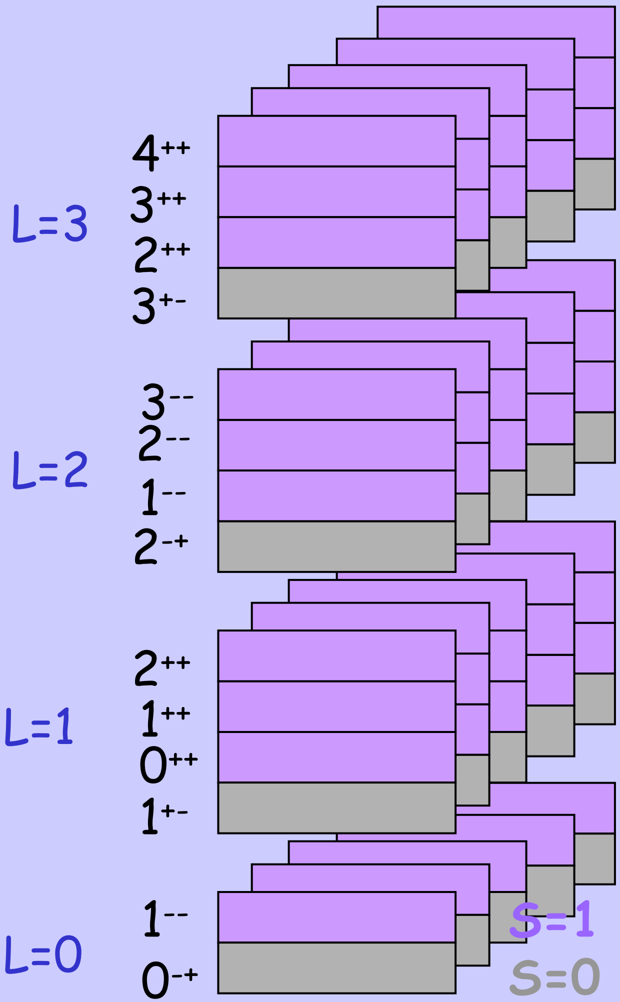
$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \quad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

Spectroscopy an QCD

Quarkonium



Mesons



ρ, K^*, ω, ϕ

π, K, η, η'

a, K, f, f'

b, K, h, h'

ρ, K^*, ω, ϕ

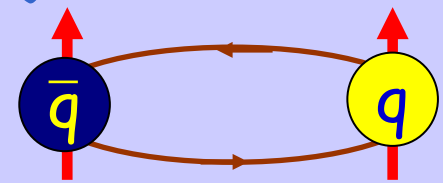
π, K, η, η'

Mesons come in Nonets of the same J^{PC} Quantum Numbers

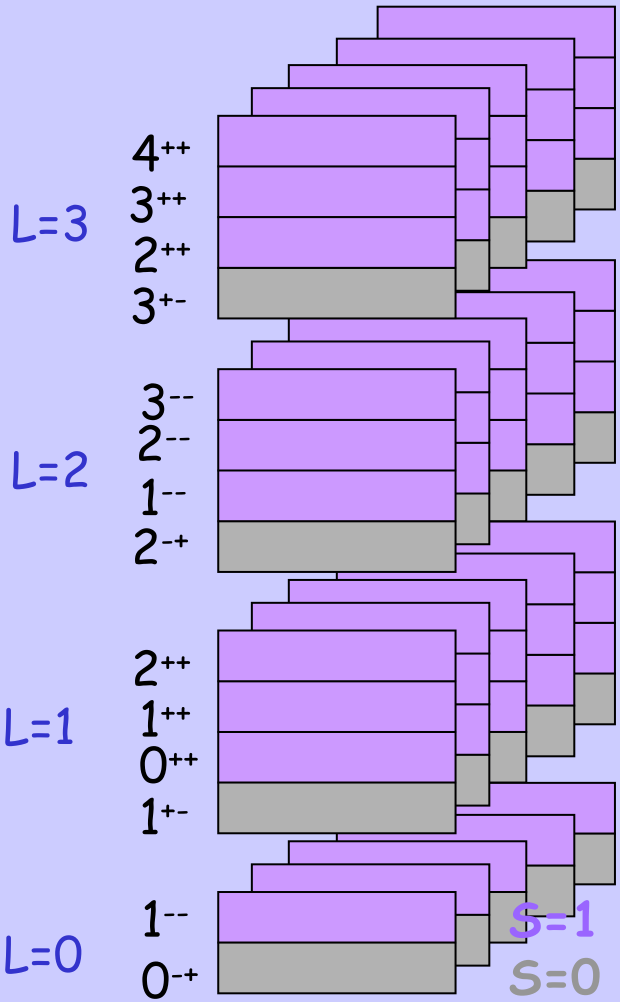
SU(3) is broken
Last two members mix

Spectroscopy an QCD

Quarkonium



Mesons



Nothing to do with Glue!

Allowed J^{PC} Quantum numbers:

0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

Exotic Quantum Numbers

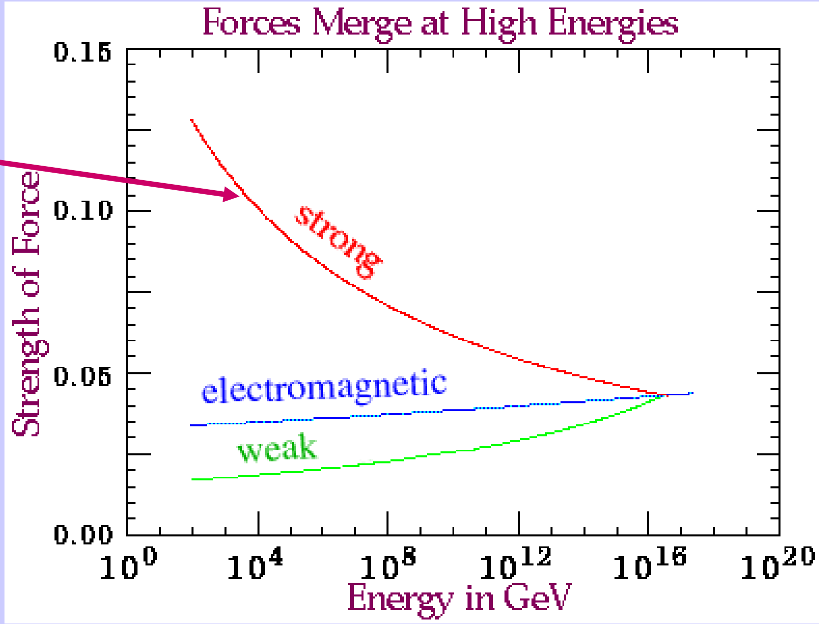
non quark-antiquark description

Lattice QCD

$$L_{QCD} = \overline{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - 1/2\, tr(G^{\mu\nu}G_{\mu\nu})$$

We can write down the QCD Lagrangian, but when we try to solve it on large distance scales such as the size of a proton, we fail…

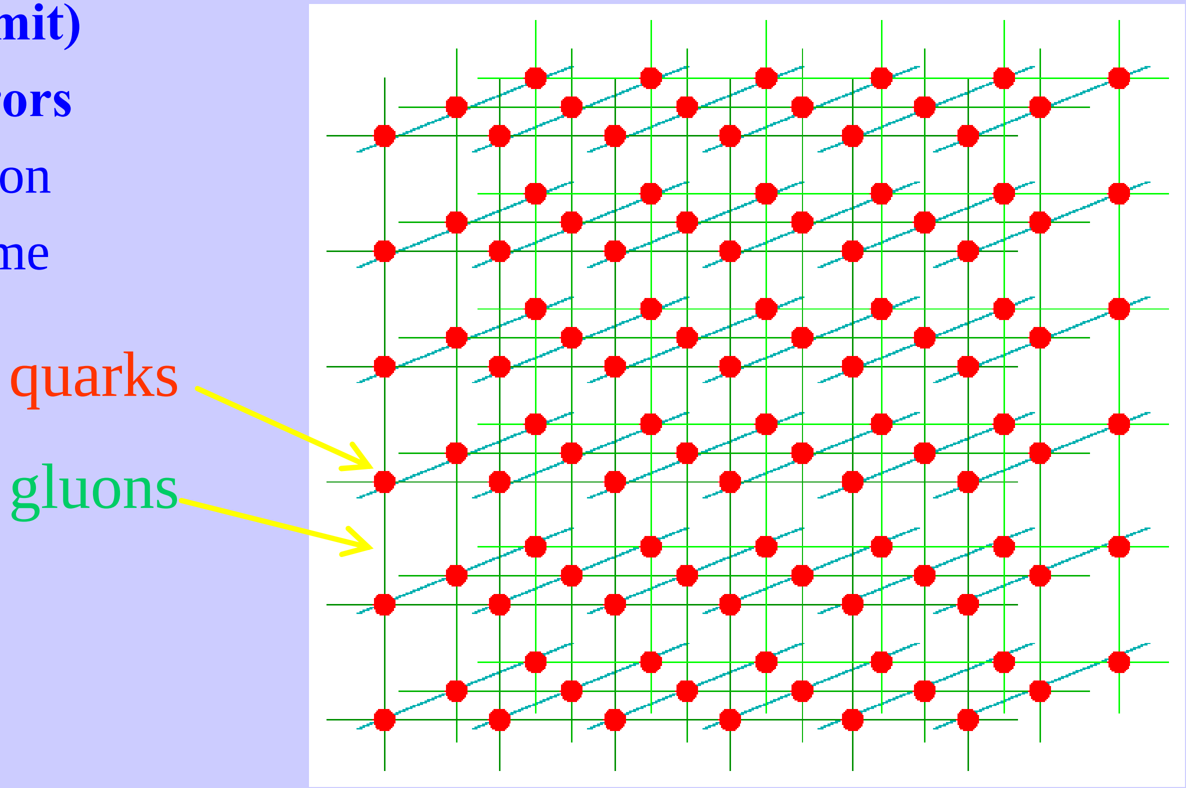
Perturbation parameter α_s is approximately 1.



Solve QCD on a discrete space-time lattice.

Lattice regularization

- **hypercubic space-time lattice**
- **quarks reside on sites, gluons reside on links between sites**
- **lattice excludes short wavelengths from theory (regulator)**
- **regulator removed using standard renormalization procedures (continuum limit)**
- **systematic errors**
  - discretization
  - finite volume



Work of Prof. Colin Morningstar

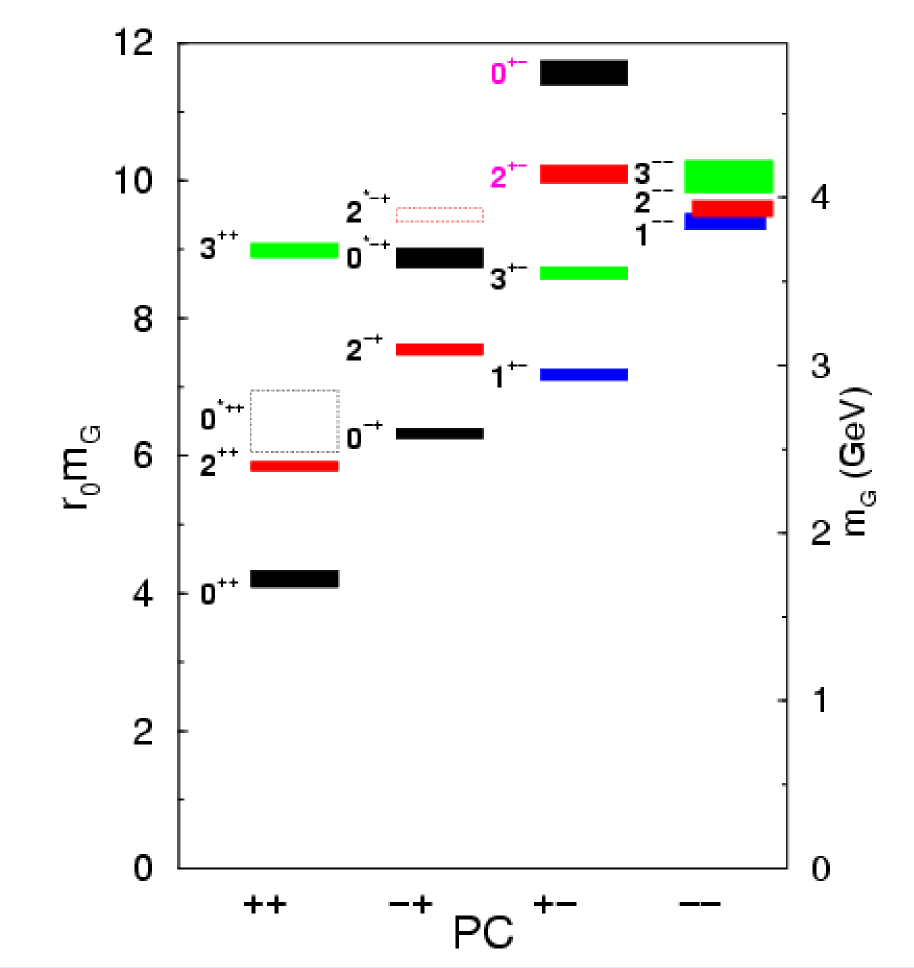
Lattice QCD Predictions

Gluons can bind to form glueballs
EM analogue: massive globs of pure light.

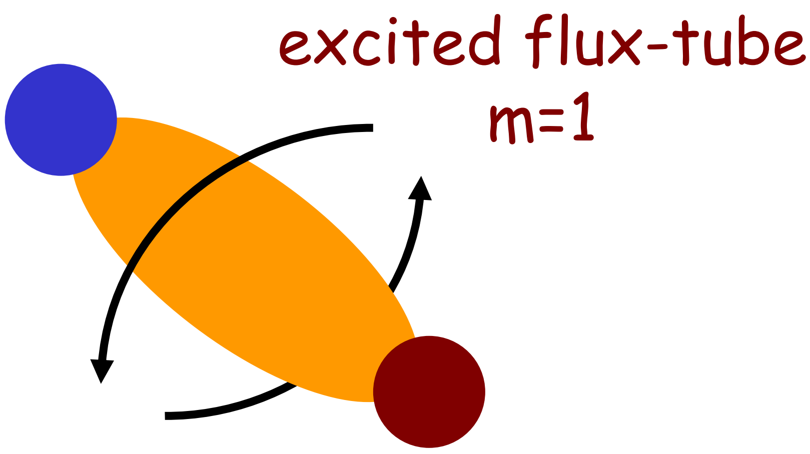
Lattice QCD predicts masses
The lightest glueballs have "normal" quantum numbers.

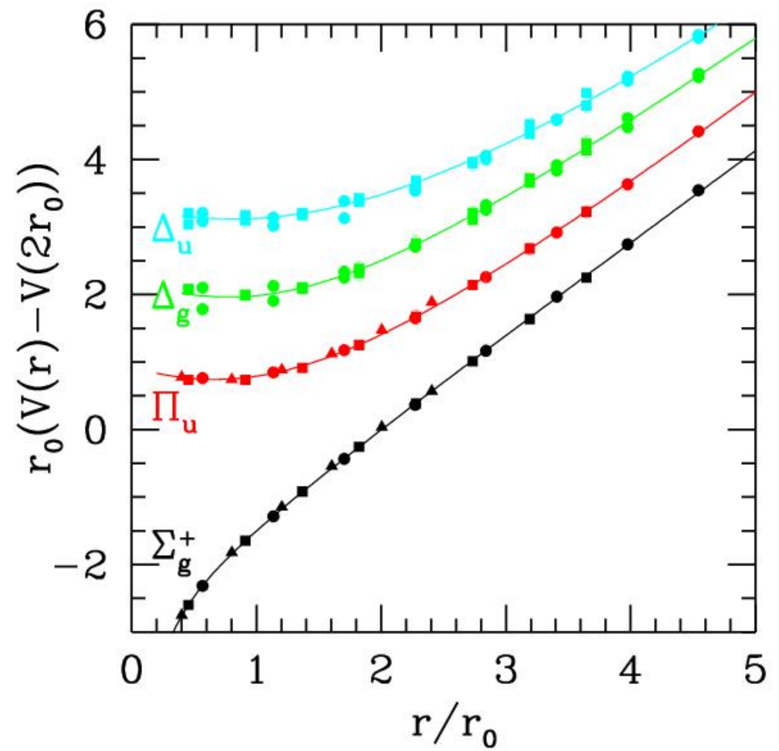
Glueballs will Q.M. mix
The observed states will be mixed with normal mesons.

Strong experimental evidence For the lightest state.



QCD Potential





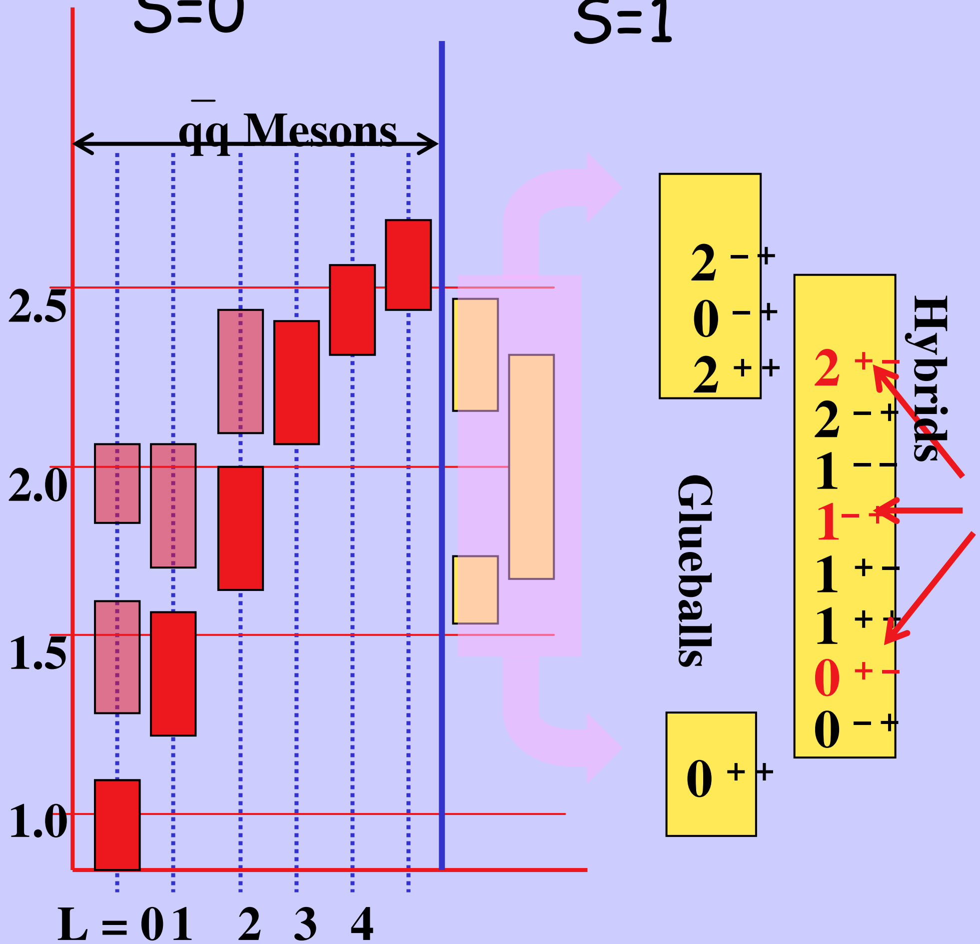
Gluonic Excitations provide an experimental measurement of the excited QCD potential.

Observations of the nonets on the excited potentials are the best experimental signal of gluonic excitations.

Hybrid Predictions

Flux-tube model: 8 degenerate nonets

$\underbrace{1^{++},1^{--}}_{S=0}\ \underbrace{0^{-+},0^{+-},1^{-+},1^{+-},2^{-+},2^{+-}}_{S=1}$ ~1.9 GeV/c²



Start with S=0

1^{++} & 1^{--}

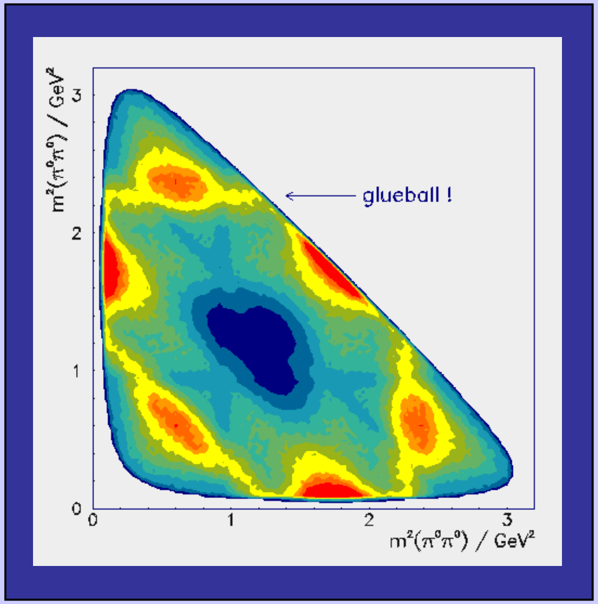
Start with S=1

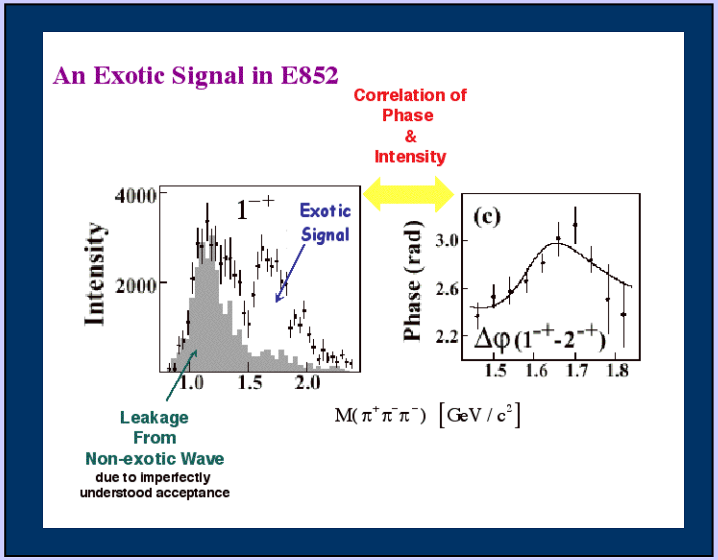
0^{-+} & 0^{+-}

1^{-+} & 1^{+-}

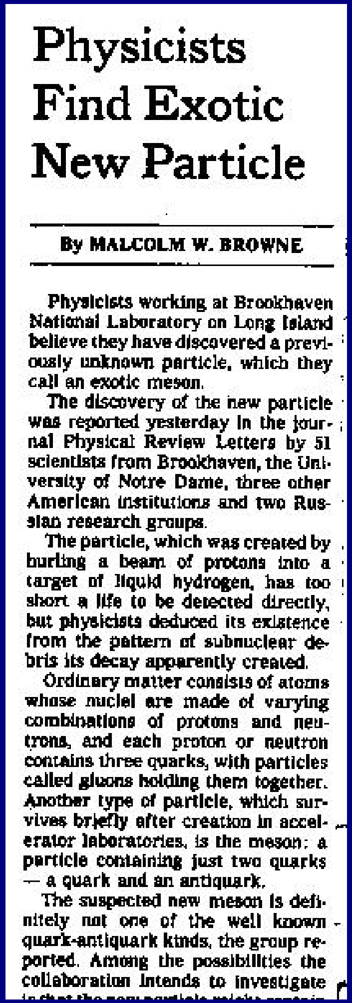
2^{-+} & 2^{+-}

Experimental Evidence





New York Times, Sept. 2, 1997



Physicists Find Exotic New Particle

By MALCOLM W. BROWNE

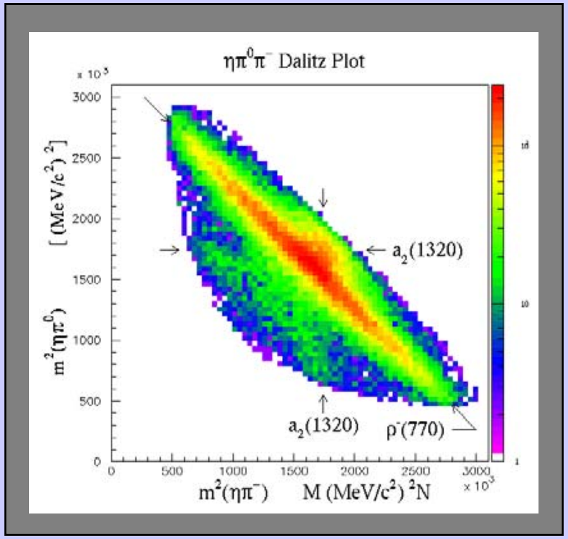
Physicists working at Brookhaven National Laboratory on Long Island believe they have discovered a previously unknown particle, which they call an exotic meson.

The discovery of the new particle was reported yesterday in the journal Physical Review Letters by 51 scientists from Brookhaven, the University of Notre Dame, three other American institutions and two Russian research groups.

The particle, which was created by hurling a beam of protons into a target of liquid hydrogen, has too short a life to be detected directly, but physicists deduced its existence from the pattern of subnuclear debris its decay apparently created.

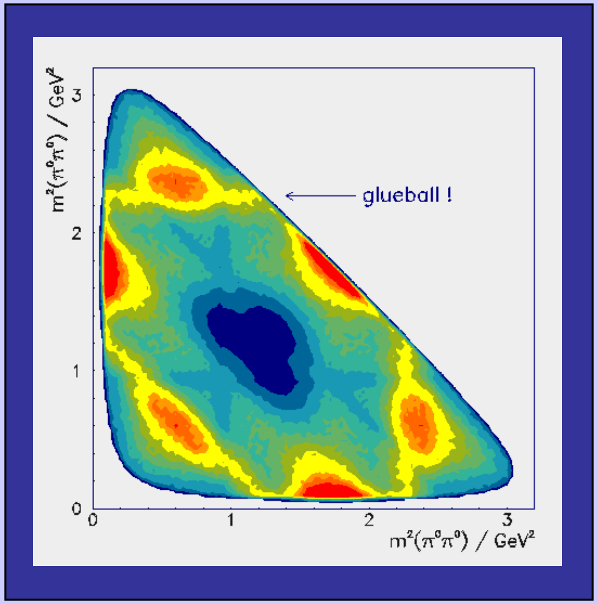
Ordinary matter consists of atoms whose nuclei are made of varying combinations of protons and neutrons, and each proton or neutron contains three quarks, with particles called gluons holding them together. Another type of particle, which survives briefly after creation in accelerator laboratories, is the meson: a particle containing just two quarks — a quark and an antiquark.

The suspected new meson is definitely not one of the well known quark-antiquark kinds, the group reported. Among the possibilities the collaboration intends to investigate

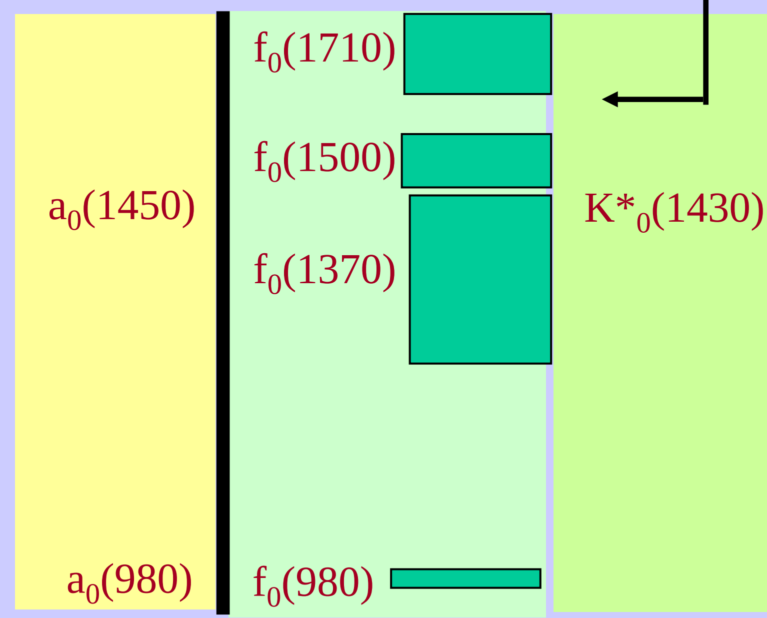


Evidence for both Glueball and Hybrid States

Experimental Evidence



Scalar (0^{++}) Glueball and two nearby mesons are mixed.



Glueball spread over 3 mesons

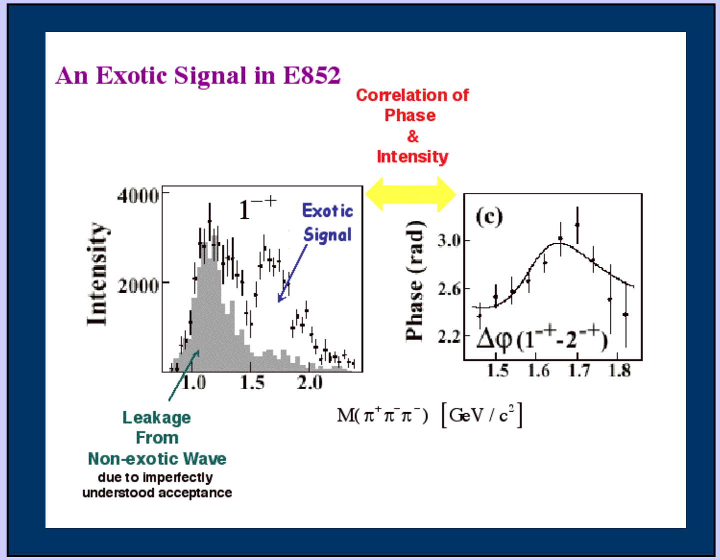
Are there other glueballs?

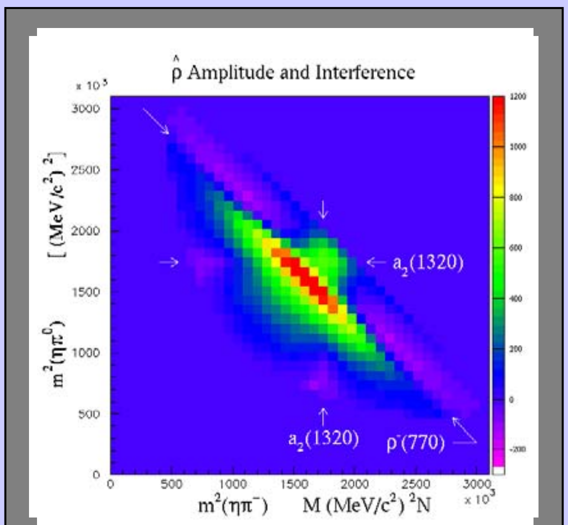
Experimental Evidence Hybrids

Exotic Mesons

1^{-+} mass 1.4
E852 BNL '97
CBAR CERN '97

Too light, decays are wrong … ?





Exotic Mesons

1^{-+} mass 1.6
E852 BNL '99
VES Russia '99

Is this the first hybrid?

New York Times, Sept. 2, 1997

Physicists Find Exotic New Particle

By MALCOLM W. BROWNE

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The particle, which was created by hurling a beam of protons into a target of liquid hydrogen, has too short a life to be detected directly, but physicists deduced its existence from the pattern of subnuclear debris its decay apparently created.

Ordinary matter consists of atoms whose nuclei are made of varying combinations of protons and neutrons, and each proton or neutron contains three quarks, with particles called gluons holding them together. Another type of particle, which survives briefly after creation in accelerator laboratories, is the meson: a particle containing just two quarks — a quark and an antiquark.

The suspected new meson is definitely not one of the well known quark-antiquark kinds, the group reported. Among the possibilities the collaboration intends to investigate

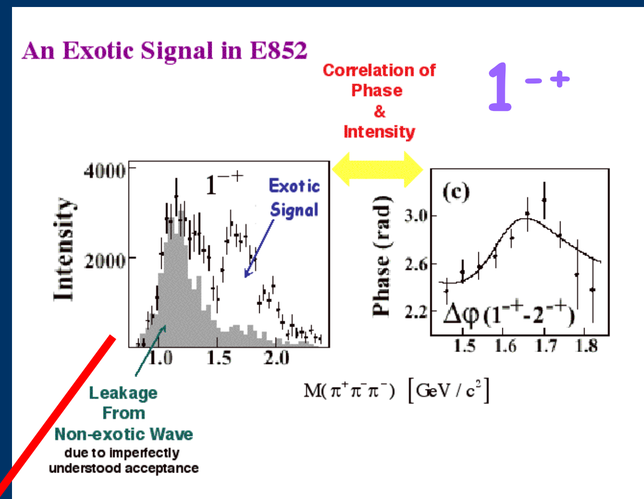
Experimental Evidence

Hybrid Nonets

Establish other Nonets:

0^{+-} 1^{-+} 2^{+-}

Levels



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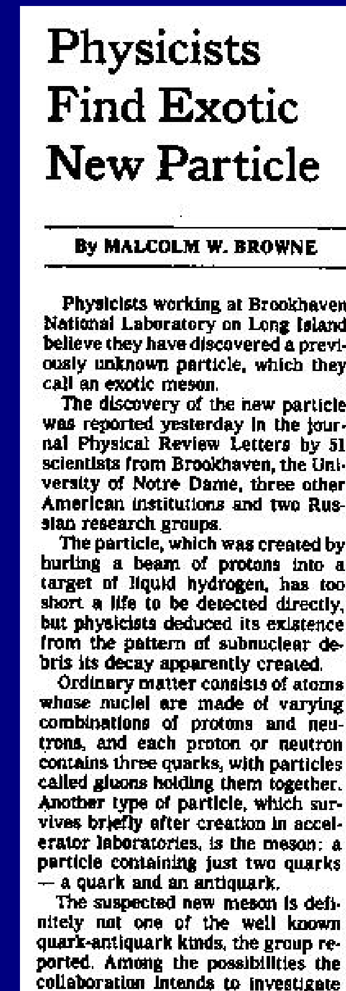

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Built on normal mesons

$$d\bar{s} \qquad u\bar{s}$$

$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

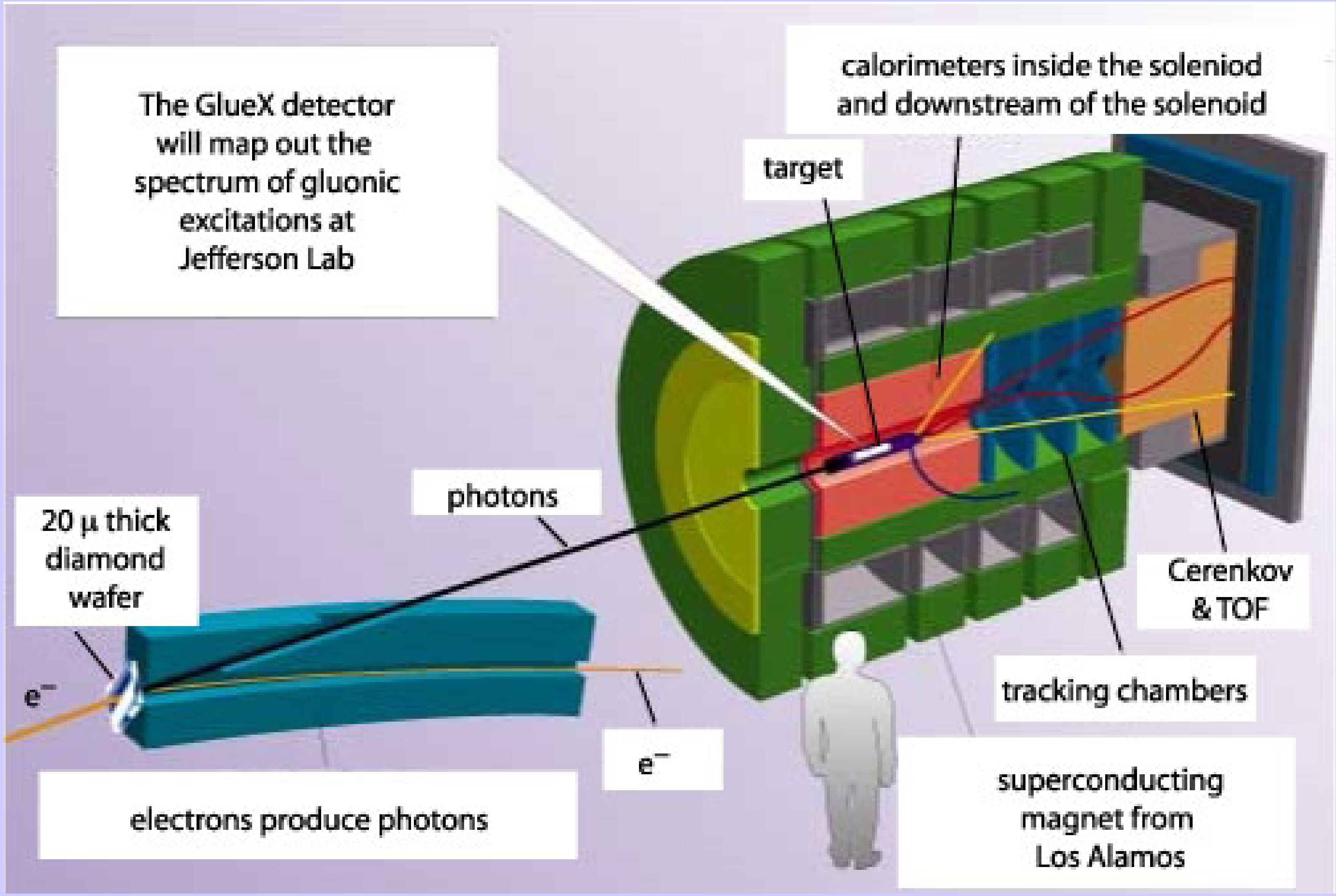
$$s\bar{d} \qquad s\bar{u}$$

$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \qquad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

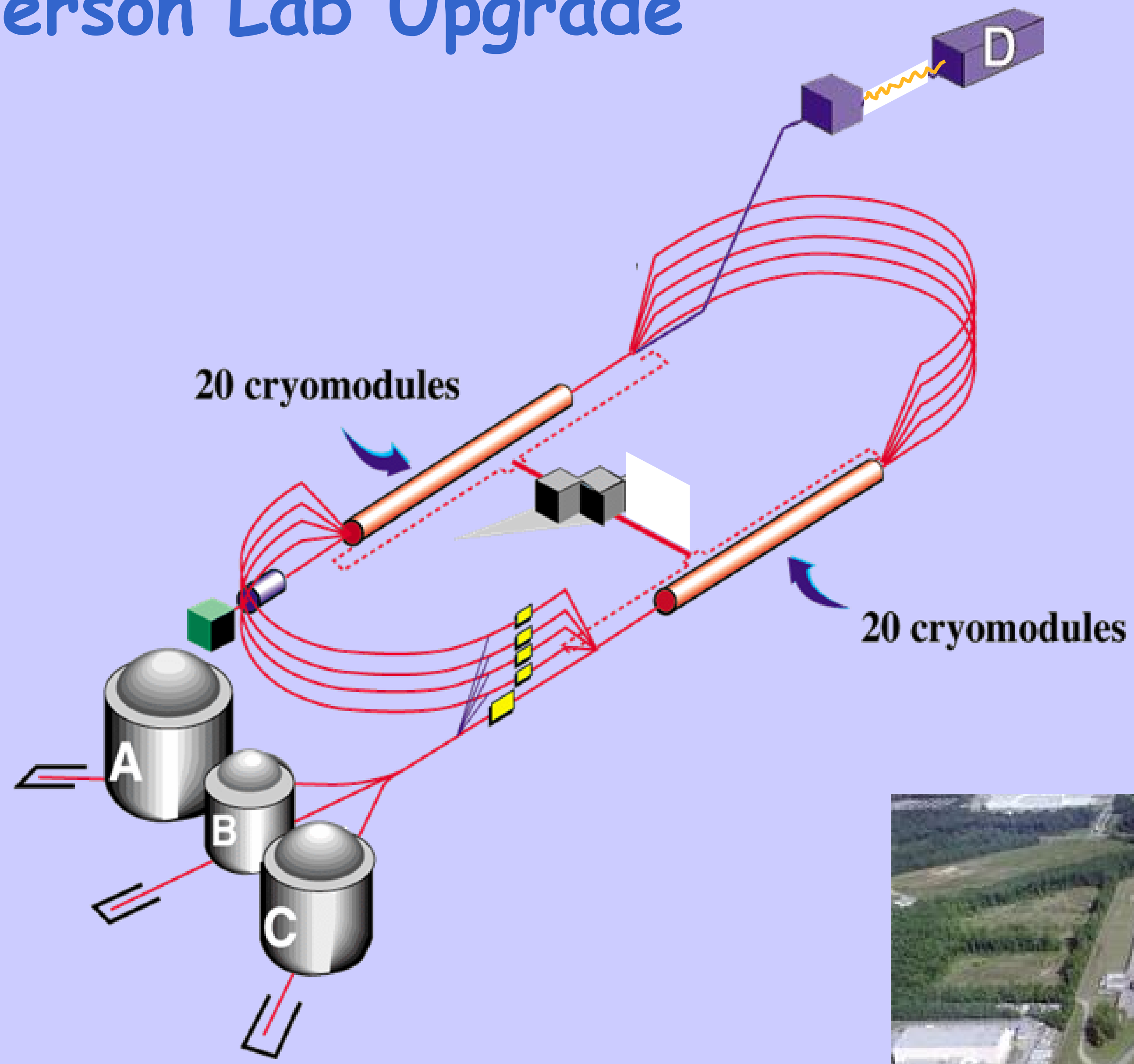
Identify other states in nonet to establish hybrid

Since 2005, this There is some doubt About the 1600 state

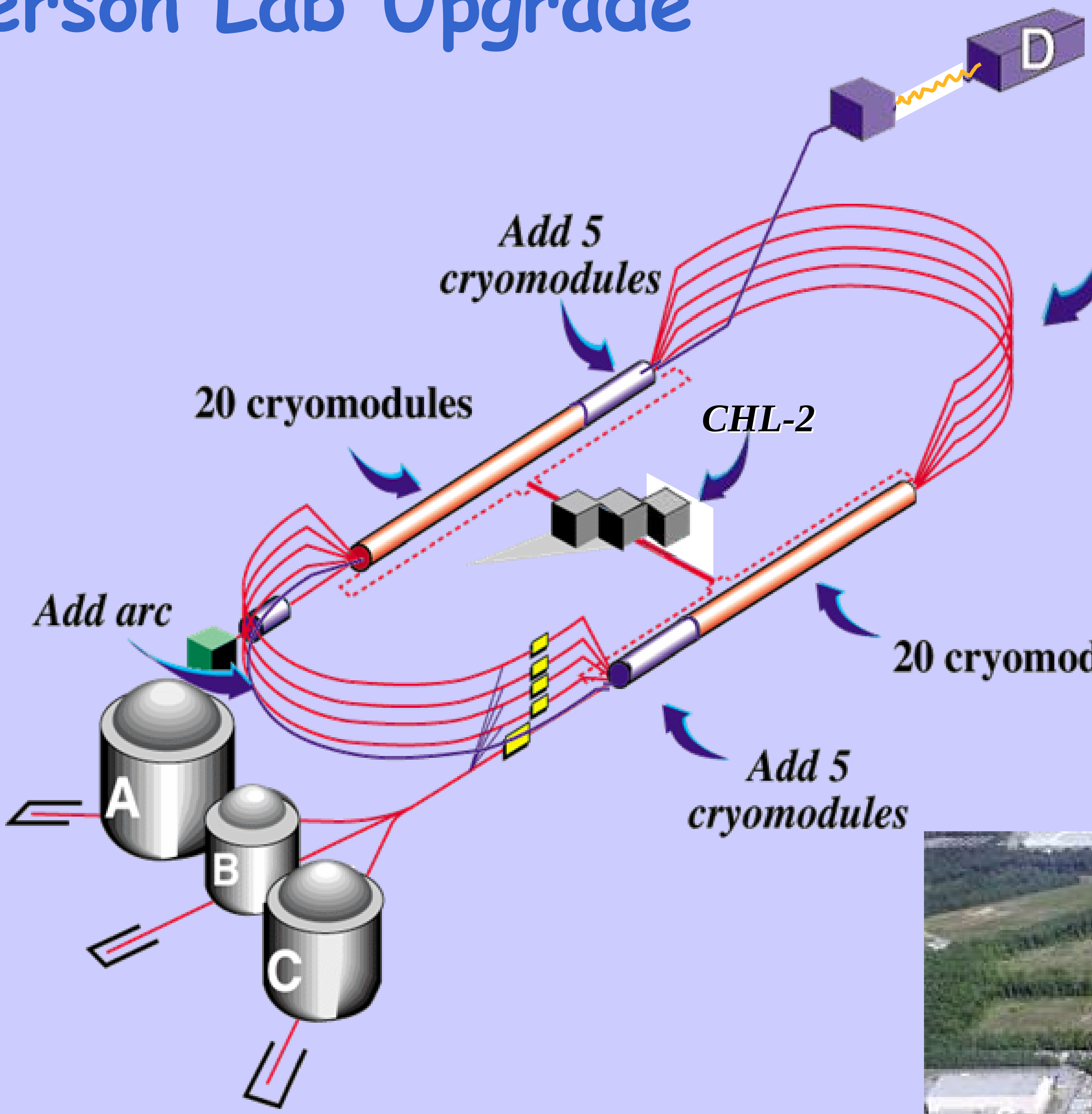
The GlueX Experiment



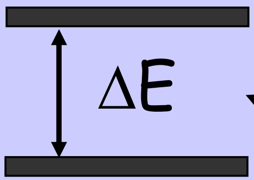
Jefferson Lab Upgrade



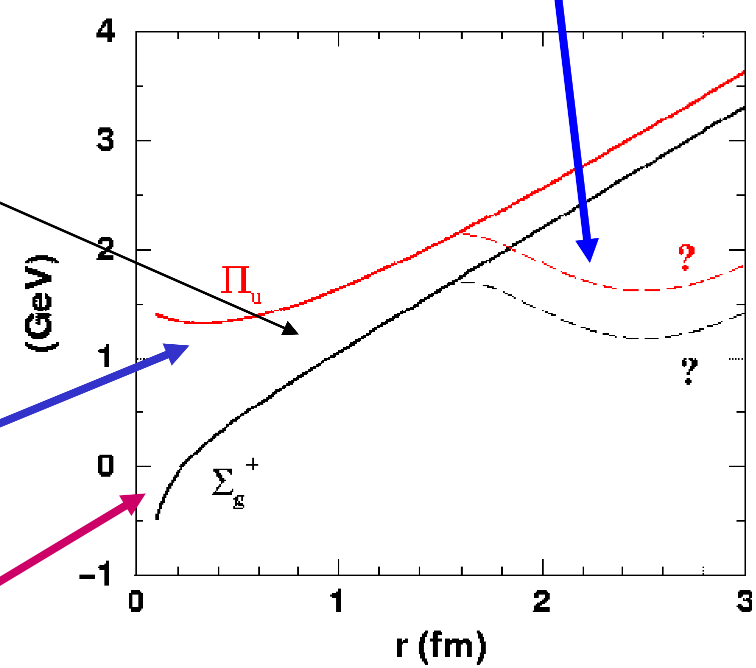
Jefferson Lab Upgrade



Gluonic Hadrons and Confinement



What are the light quark
Potentials doing?



Lattice QCD potentials

Potentials corresponding
To excited states of glue.

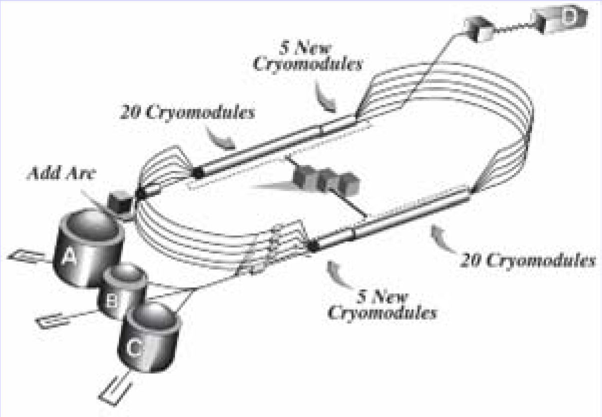
Non-gluonic mesons –
ground state glue.

Conclusions

The quest to understand confinement and the strong force is about to make great leaps forward.

Advances in theory and computing will soon allow us to solve QCD and understand the role of glue.

The definitive experiments to confirm or refute our expectations are being designed



The synchronized advances in both areas will allow us to finally understand QCD and confinement.

Gluonic Hadrons

Quantum Chromodynamics predicts two types of Hadrons that explicitly involve the gluonic field.

Glueballs - states of pure glue

Hybrids – states in which the gluonic field contributes directly to the quantum numbers.

Quantum Numbers

Hybrid Predictions

Flux-tube model: 8 degenerate nonets

$\underbrace{1^{++},1^{--}}_{S=0}\ \underbrace{0^{-+},0^{+-},1^{-+},1^{+-},2^{-+},2^{+-}}_{S=1}$ **~1.9 GeV/c²**

Lattice calculations --- 1^{-+} nonet is the lightest

UKQCD (97)	1.87 ±0.20
MILC (97)	1.97 ±0.30
MILC (99)	2.11 ±0.10
Lacock(99)	1.90 ±0.20
Mei(02)	2.01 ±0.10

~2.0 GeV/c²

$\left.\begin{array}{l}1^{-+}\\0^{+-}\end{array}\right\}$ Splitting ≈ 0.20

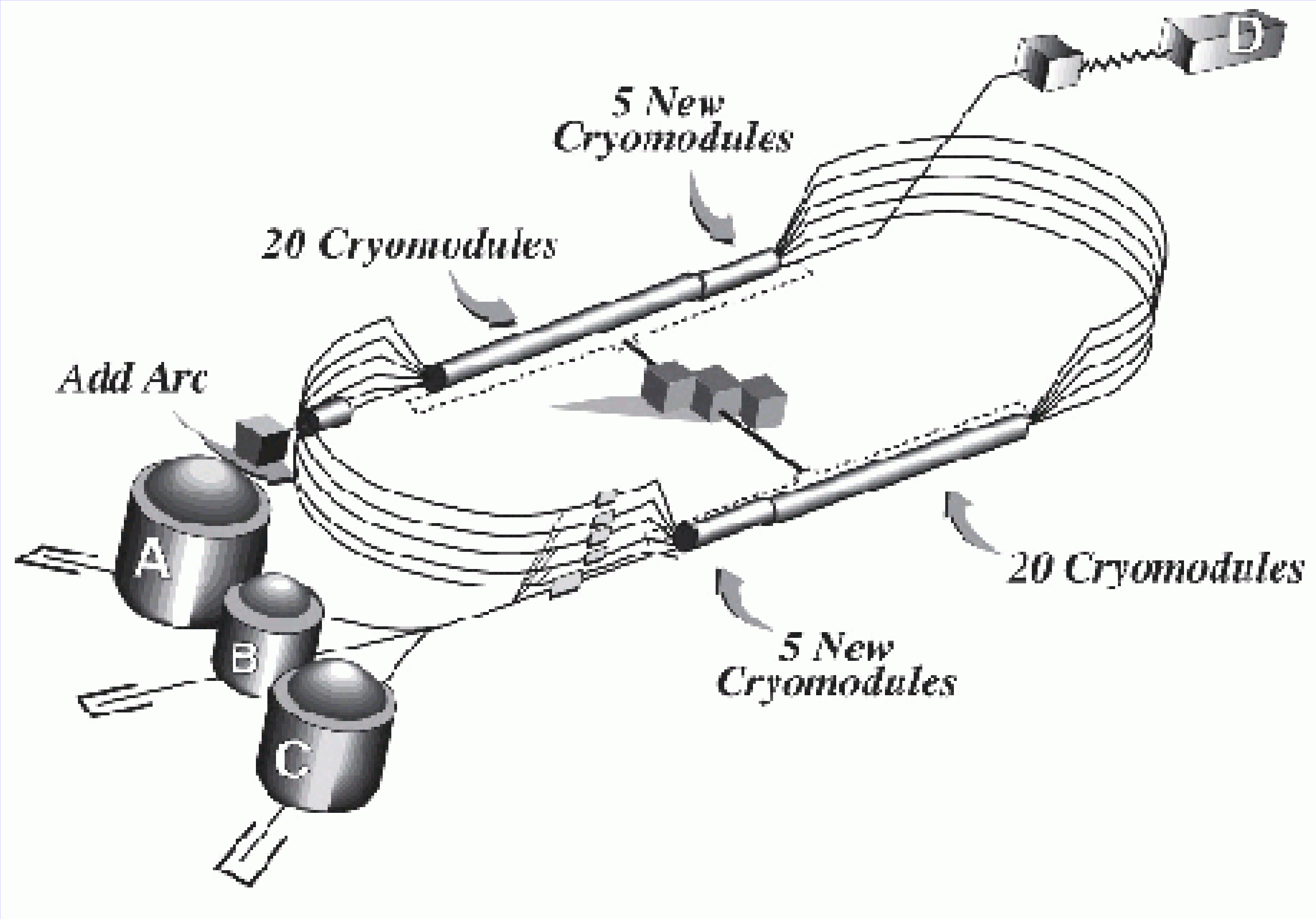
2^{+-}

In the charmonium sector:

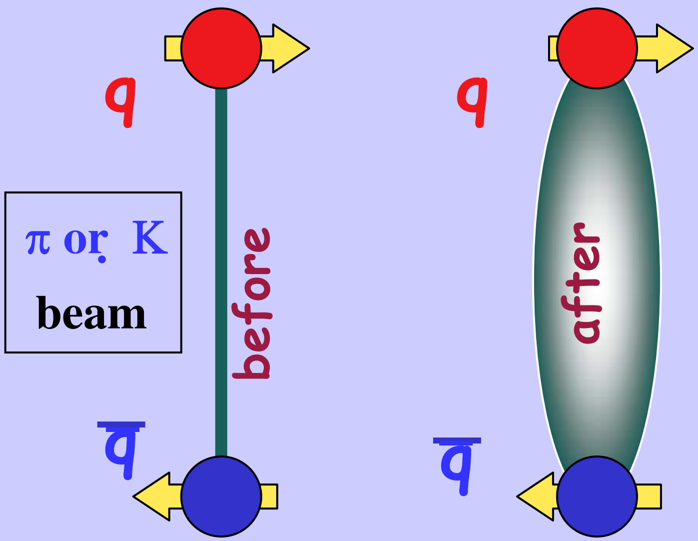
1^{-+}	4.39 ±0.08
0^{+-}	4.61 ±0.11

Splitting = 0.20

Jefferson Lab Upgrade



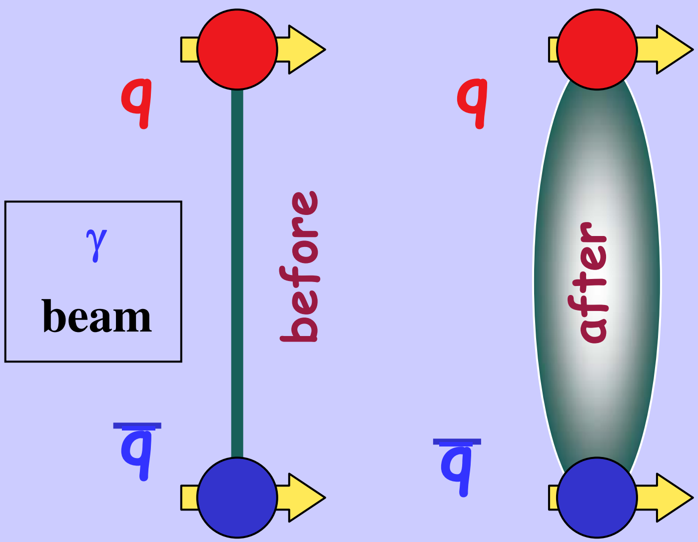
How to Produce Hybrids



Quark spins anti-aligned

A pion or kaon beam,
when scattering occurs,
can have its flux tube excited

Much data in hand with some
evidence for gluonic excitations
(tiny part of cross section)



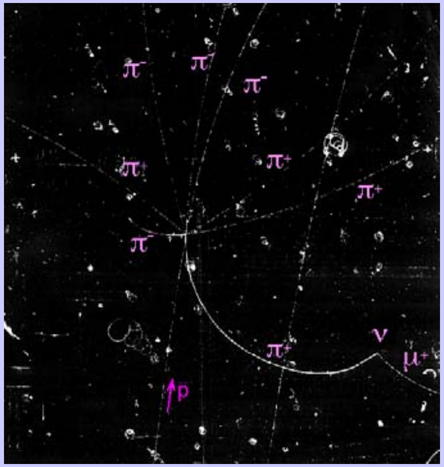
Quark spins aligned

Almost no data in hand
in the mass region
where we expect to find exotic hybrids
when flux tube is excited

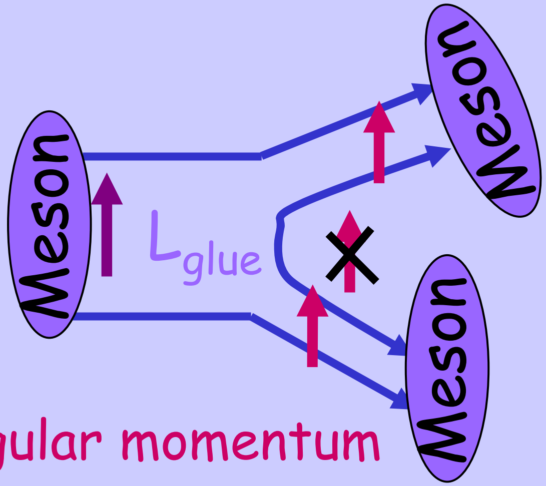
Looking for Hybrids

Analysis Method
Partial Wave Analysis

Fit 3D angular distributions
Fit Models of production and decay of resonances.



Decay Predictions



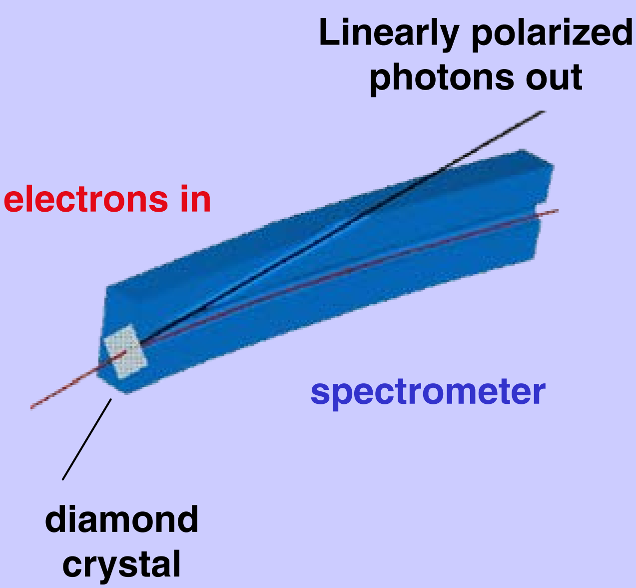
Angular momentum in the gluon flux stays confined.

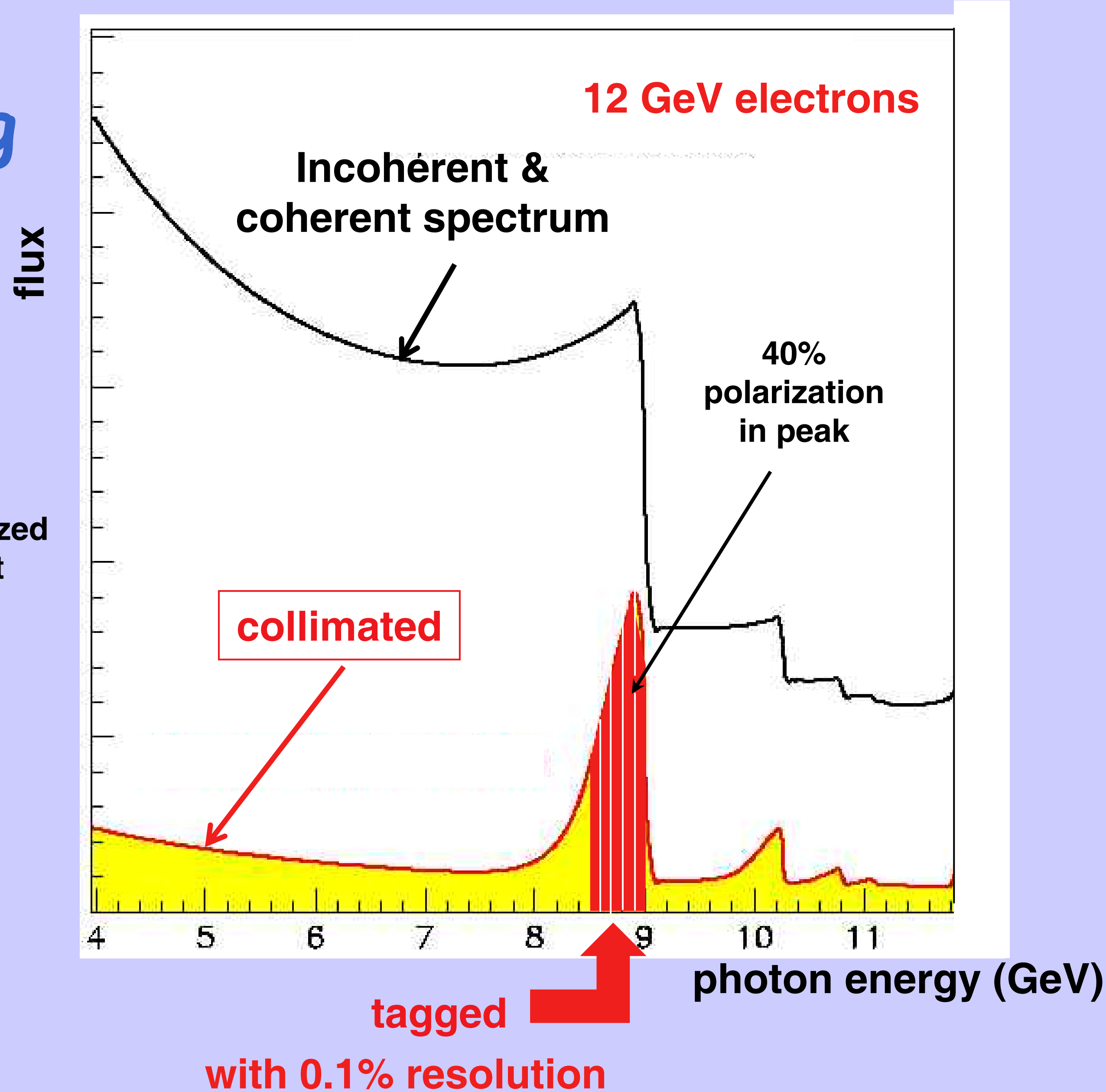
This leads to complicated multi-particle final states.

Detector needs to be very good.

Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization





Monte Carlo methods

- **vacuum expectation value in terms of path integrals**

$$\left\langle \Phi(t)\Phi^*(0) \right\rangle = \frac{\int D\Phi\ \Phi(t)\Phi^*(0)\ e^{-S[\Phi]}}{\int D\Phi\ e^{-S[\Phi]}}$$

- **S[Φ] is the Euclidean space action, $\Phi^*(t)$ creates state of interest**
- **evaluation of path integrals:**
  - Markov-chain Monte Carlo methods
    - Metropolis
    - heatbath
    - overrelaxation
    - hybrid methods
  - no expansions in a small parameter
  - statistical errors
- **first principles approach**