Gluonic Hadrons: A Probe of Confinement

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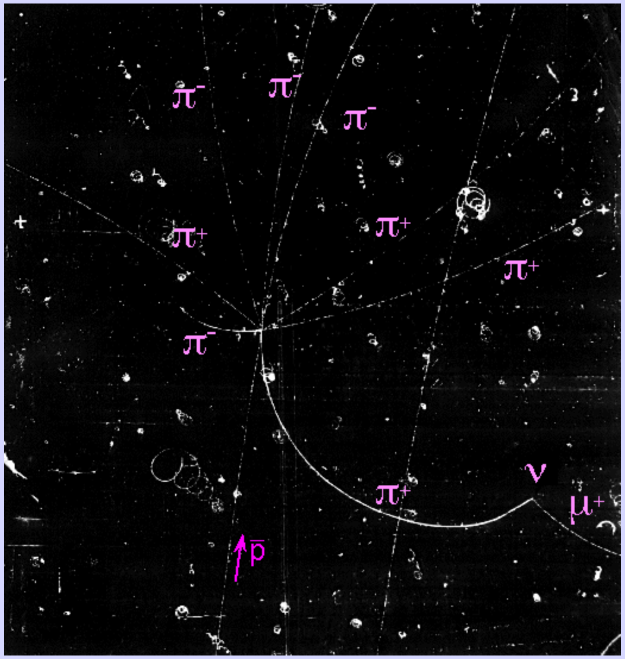
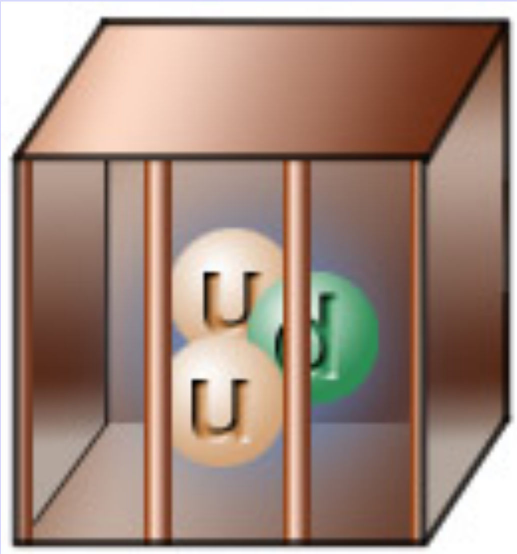
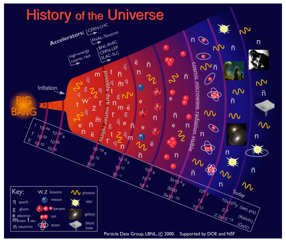
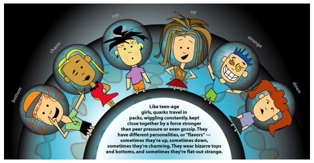




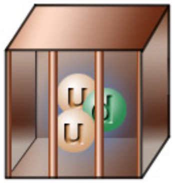
Outline



The beginning of time.

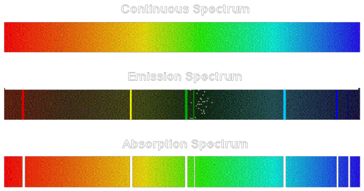


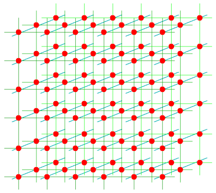
The strong force and QCD



Color confinement

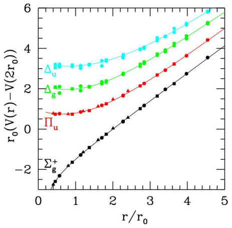
Spectroscopy





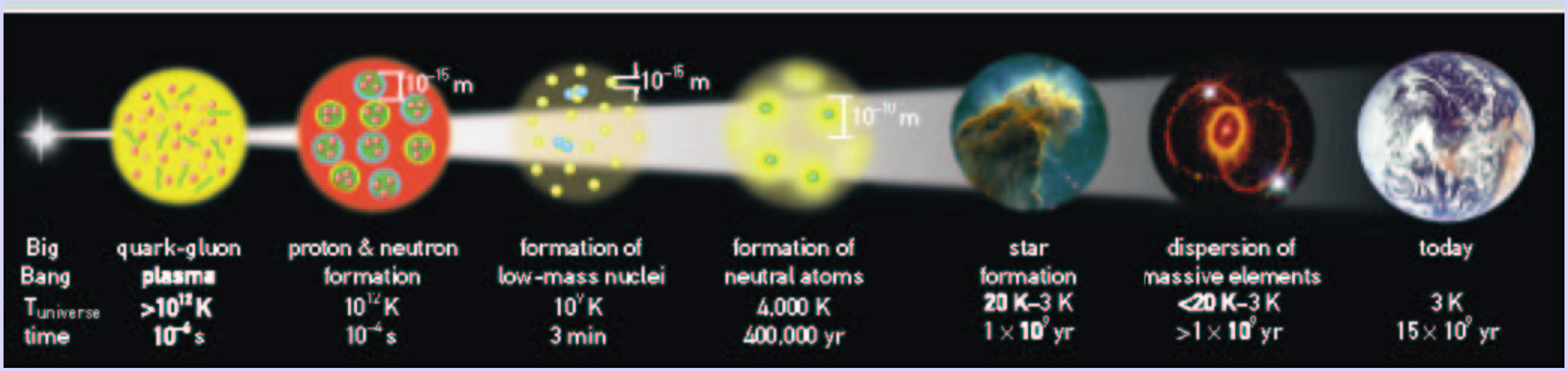
Lattice QCD

Finding Gluonic Hadrons

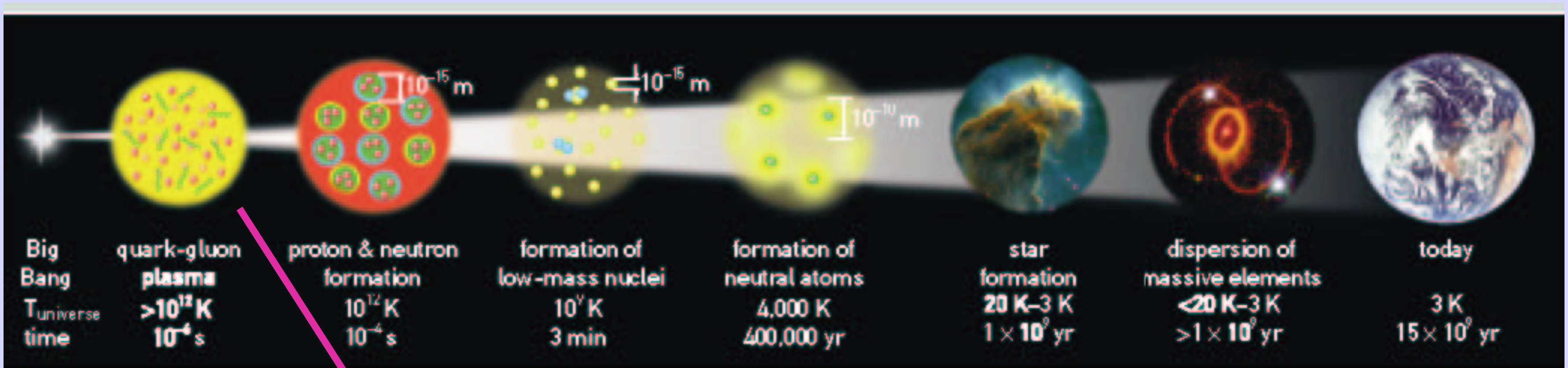


Confinement

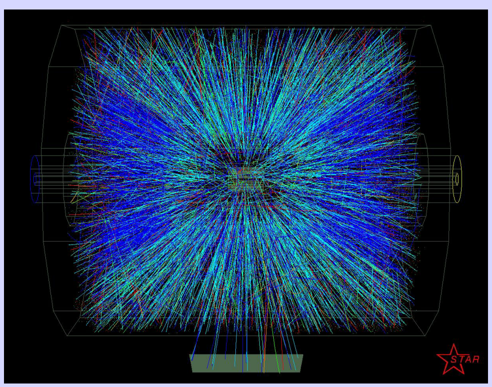
The First Seconds of The Universe



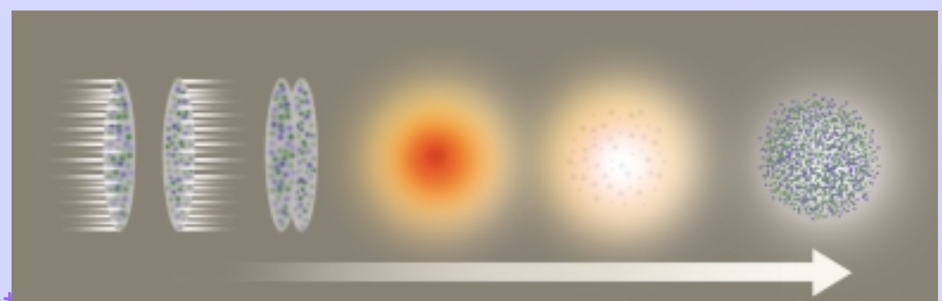
Quark Gluon Plasma



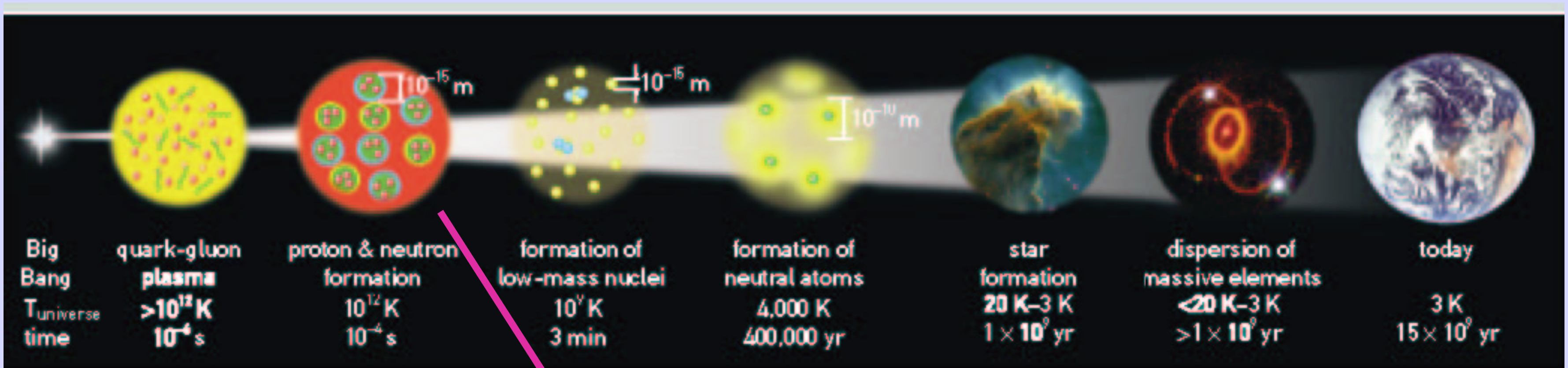
For a period from about 10^{-12} s to 10^{-6} s the universe contained a plasma of quarks, anti quarks and gluons.



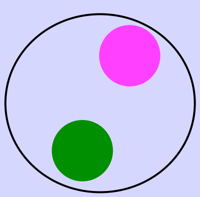
Relativistic Heavy Ion Collisions are trying to produce this state of matter in collisions



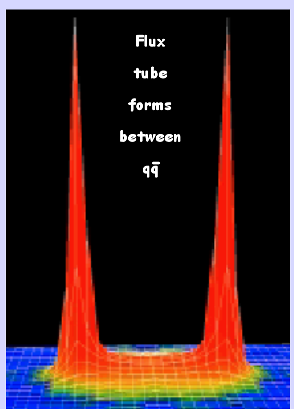
Confinement



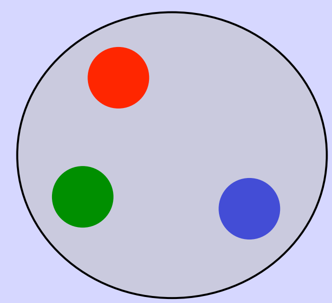
From about 10^{-6} s on, the quark and antiquarks became confined inside of Hadronic matter. At the age of 1s, only protons and neutrons remained.



Mesons

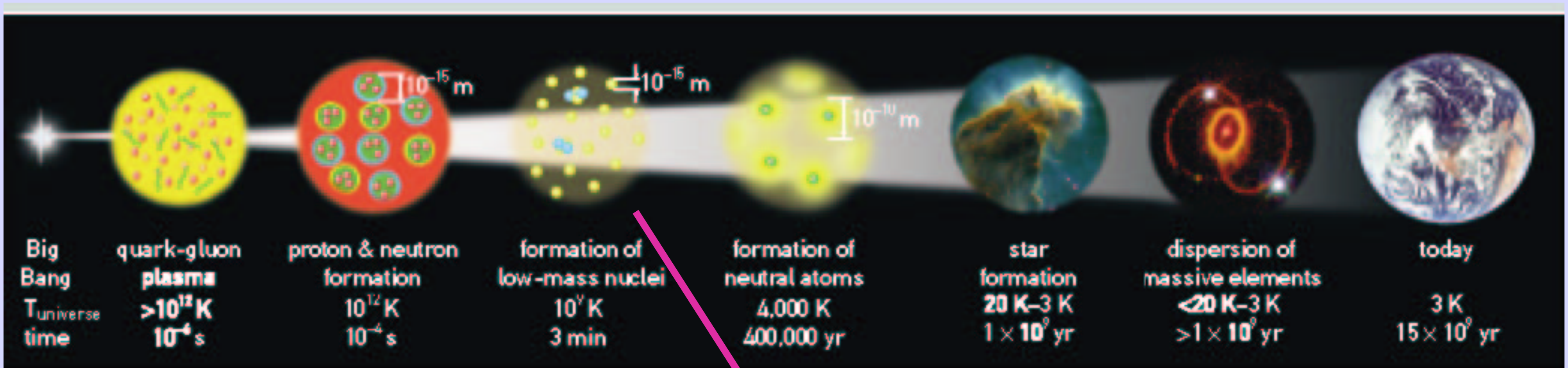


The gluons produce the 16 ton force that holds the hadrons together.

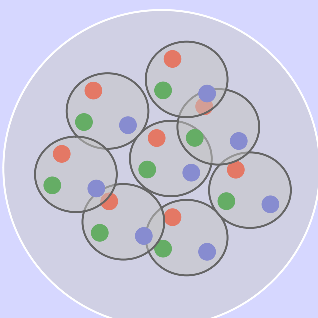


Baryons

The Formation of Nuclei



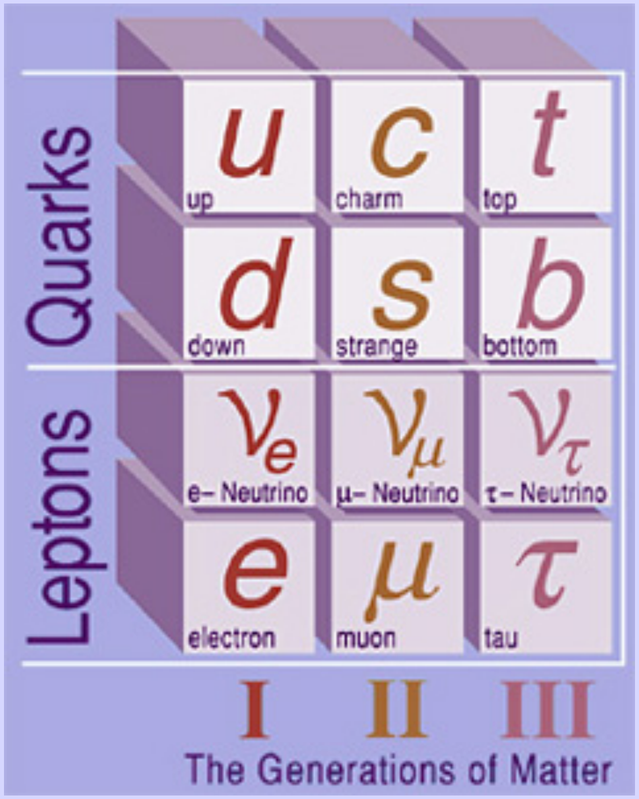
By the old age of three minutes, the formation of low mass nuclei was essentially complete.

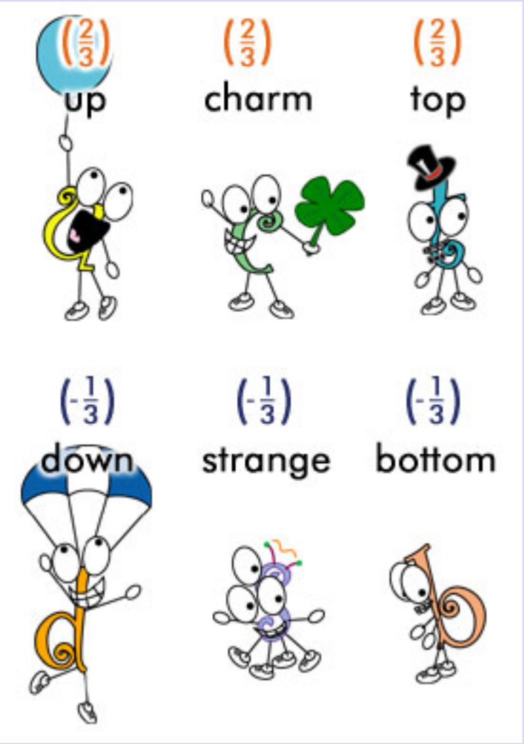


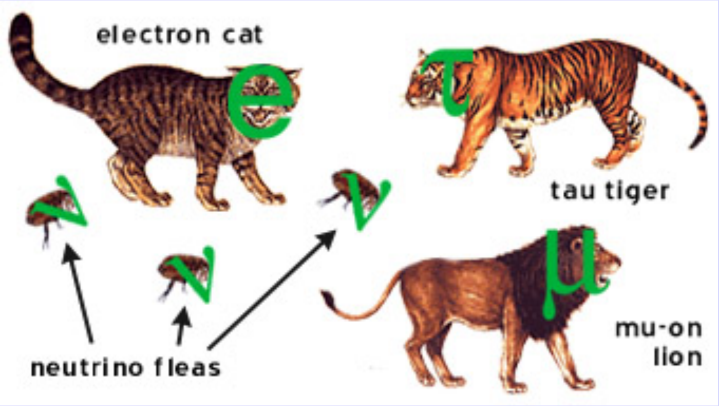
Primordial hydrogen, deuterium, helium and a few other light nuclei now exist.

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

Quarks and Leptons

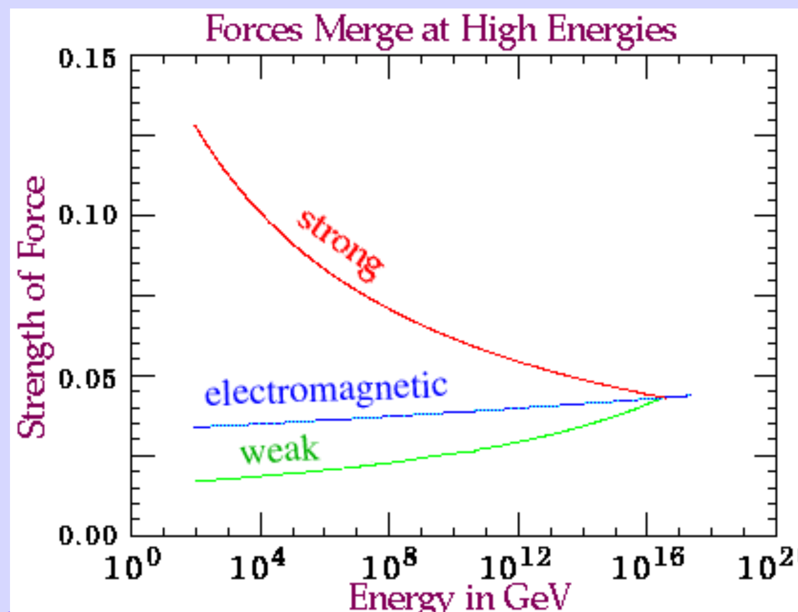






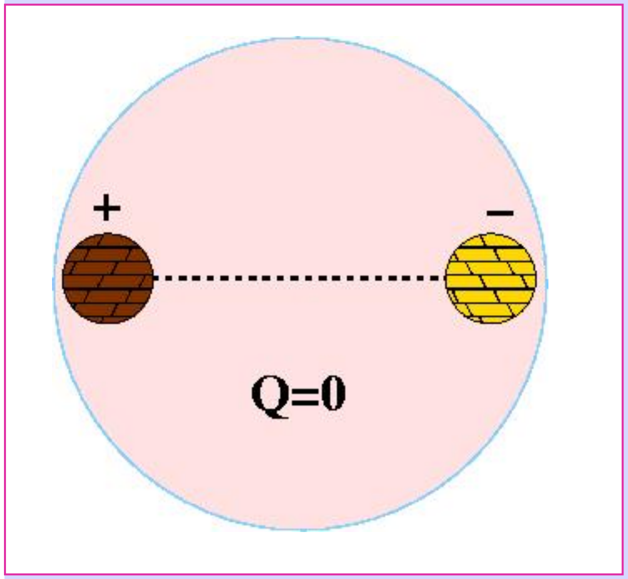
Forces and Interactions

	Gravity	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong
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



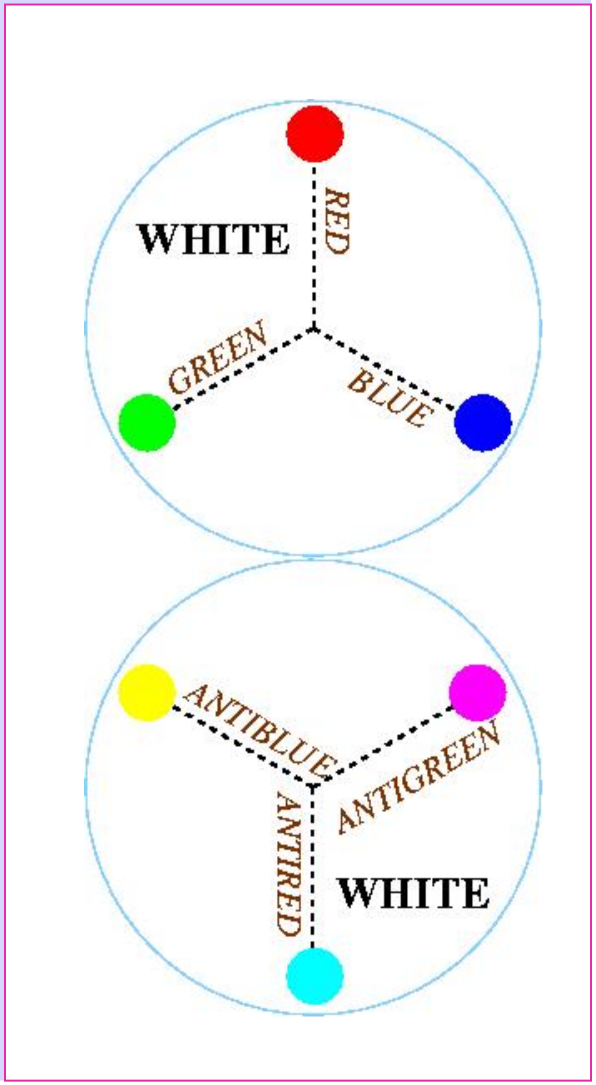
Quantum Chromo Dynamics

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*.

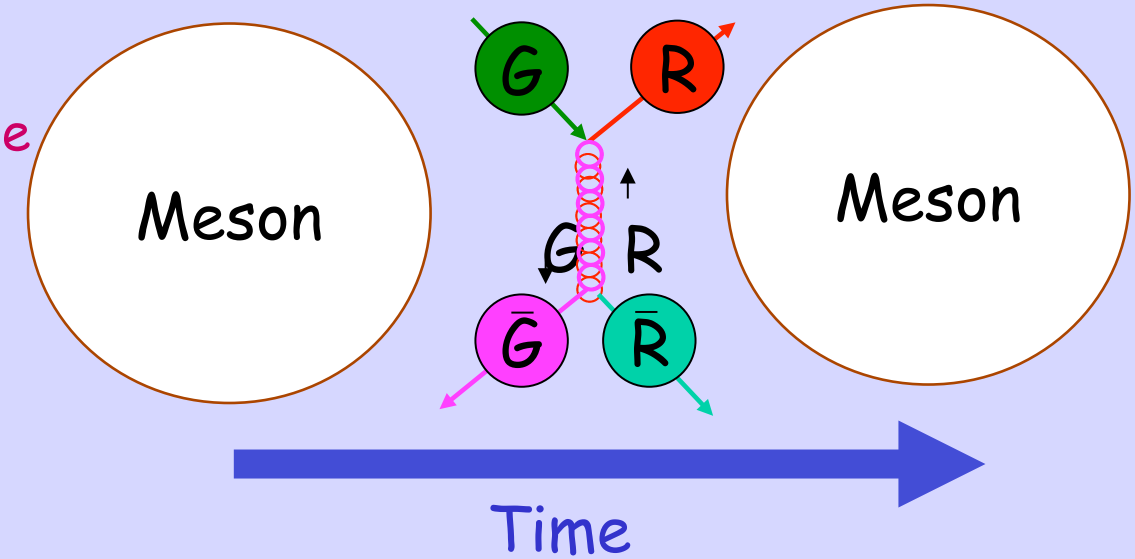
Color Charge

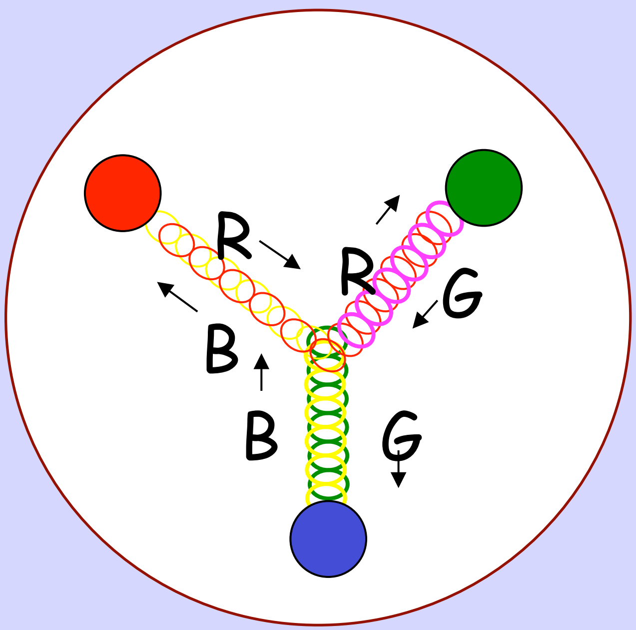


Three charges called RED, BLUE and GREEN, and three anti colors. The objects that form have to be color neutral.

Gluons Carry the Force

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





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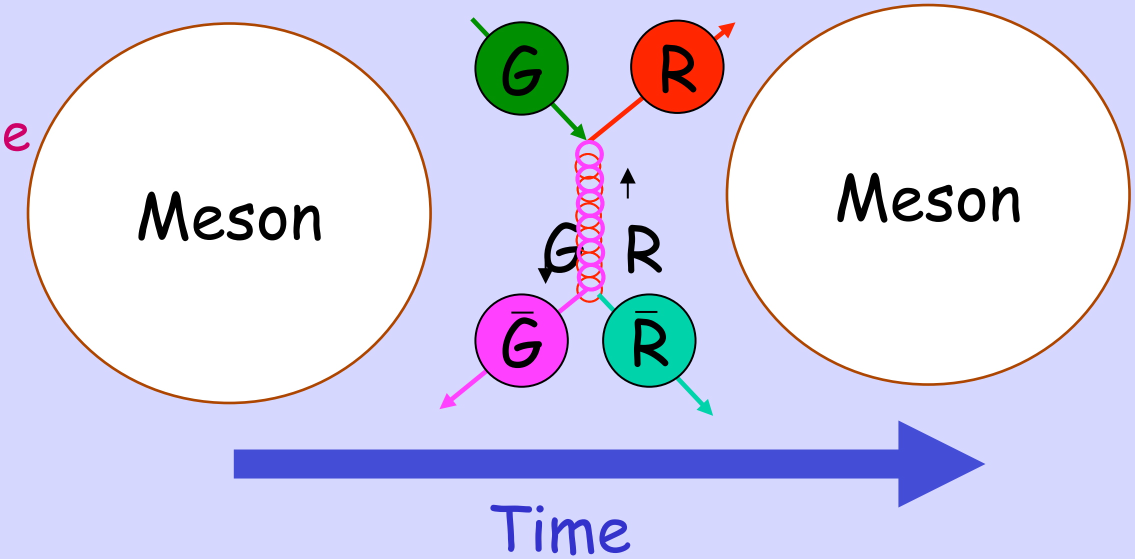

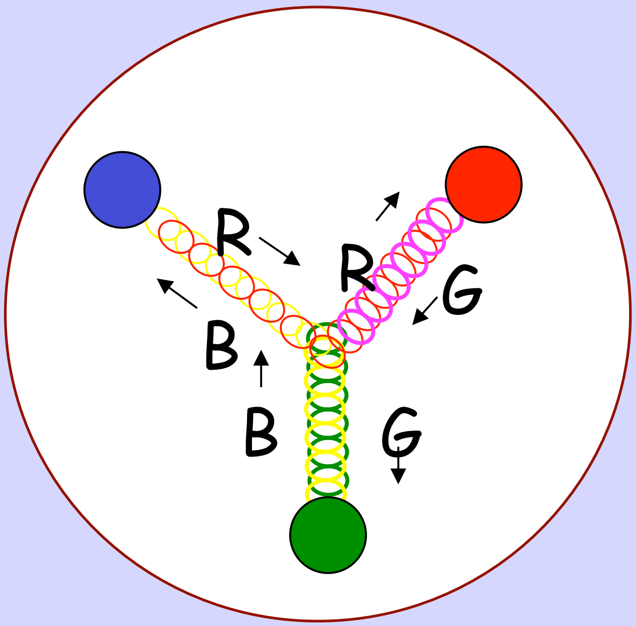

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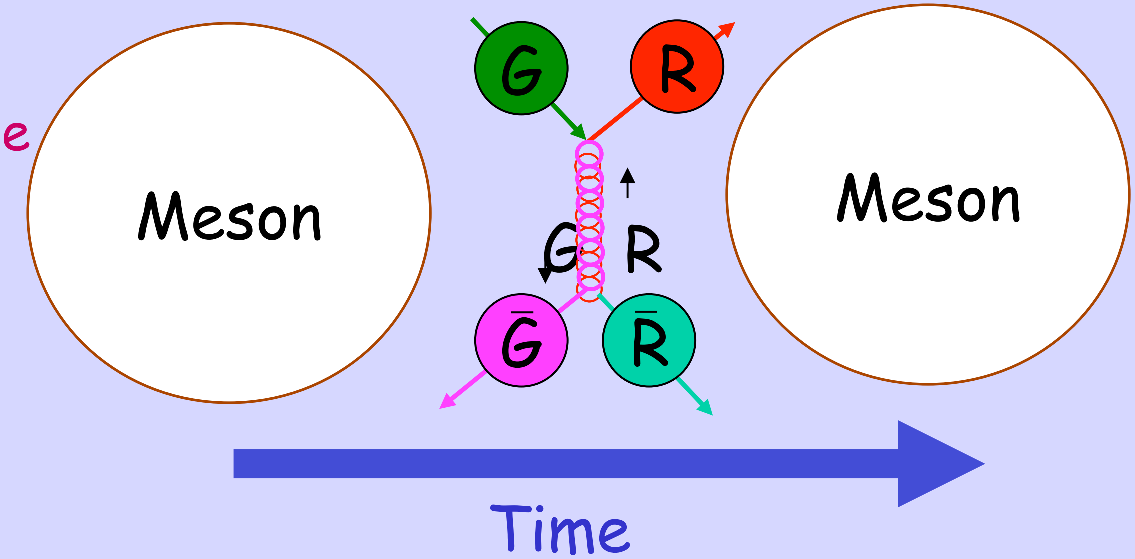
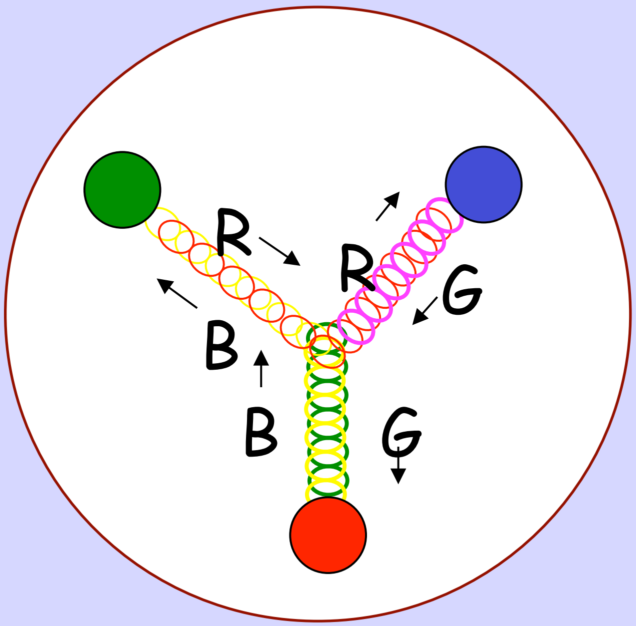
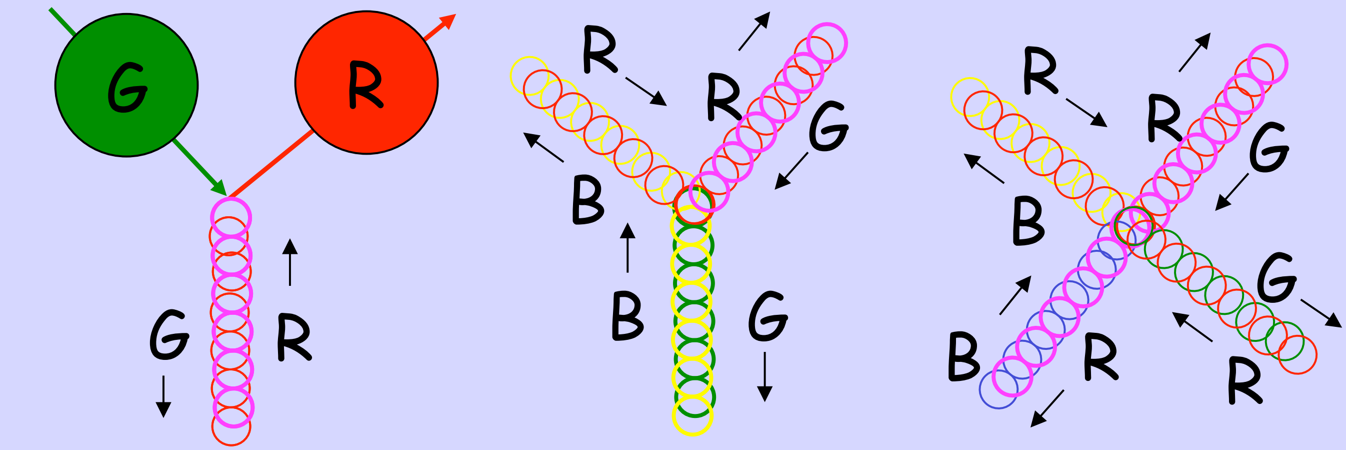




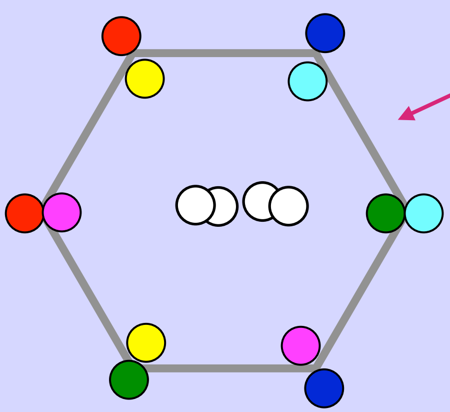
Gluons produce the forces that confine the quarks, but the gluons do not appear to be needed to understand normal hadrons

Gluon Interactions



3 Colors
3 Anti Colors

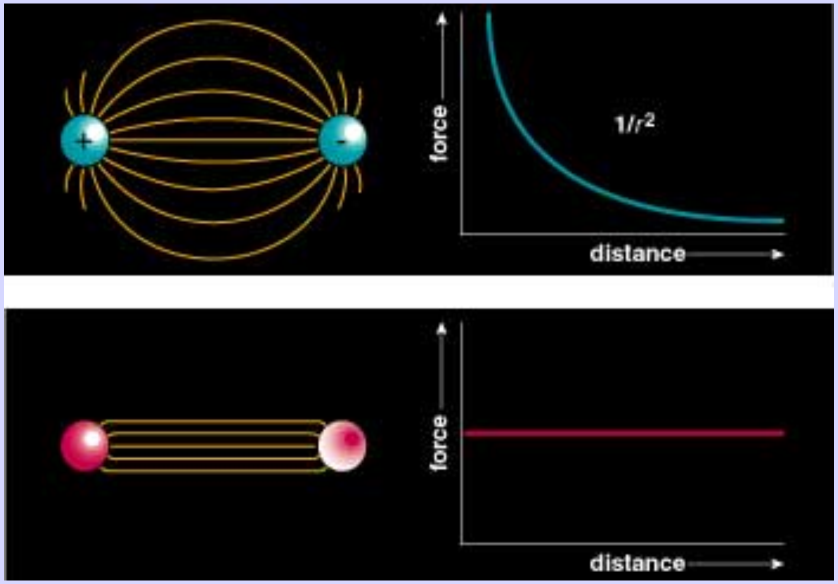
1 color neutral
8 colored objects

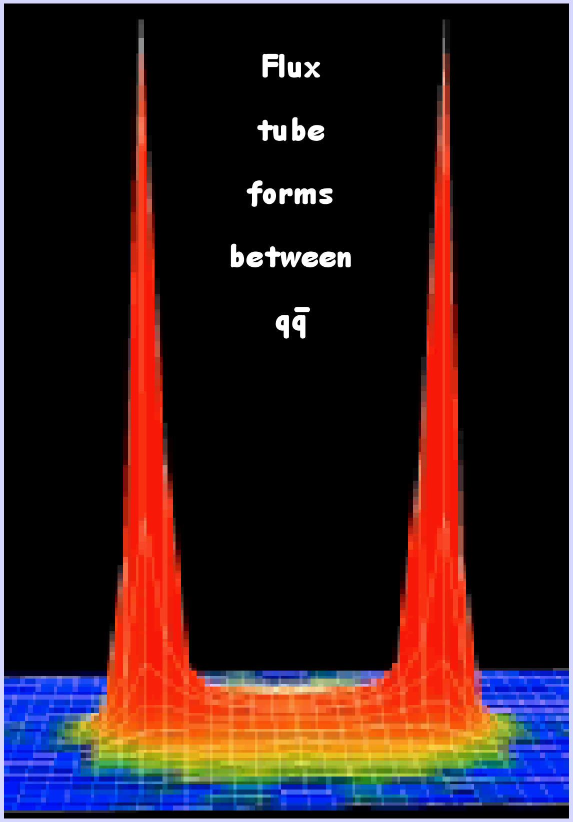


8 Gluons

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

Flux Tubes



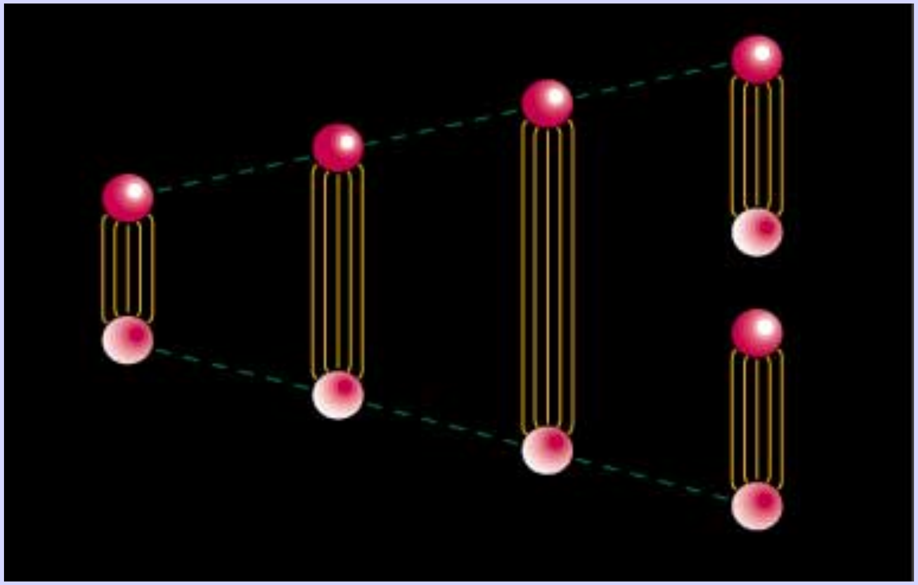


Color Field: Because of self interaction, confining flux tubes form between static color charges

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

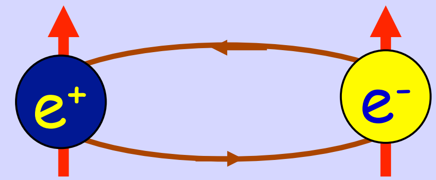
Quark Confinement

- 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: $L=0,1,2,\ldots$

Total Spin: $J=L+S$

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

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

... $\quad$ ...

Reflection in a mirror:
Parity: $P=-(-1)^{(L)}$

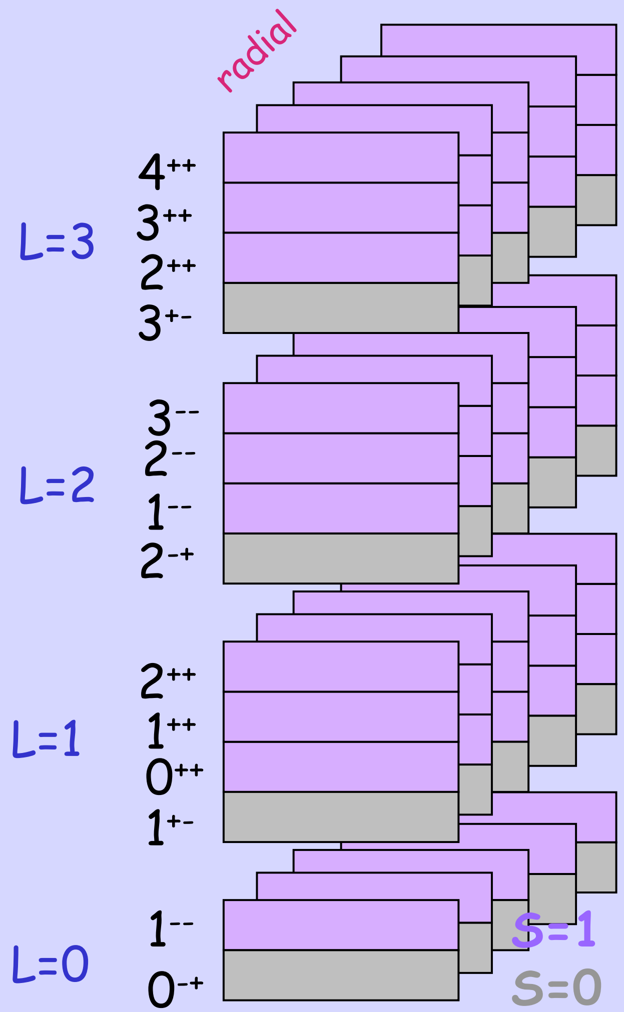
Particle<->Antiparticle:
Charge Conjugation: $C=(-1)^{(L+S)}$

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

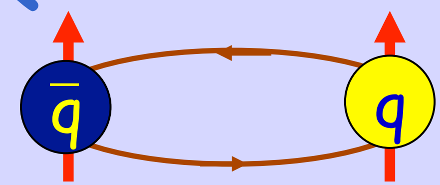
$^{(2S+1)}L_J$ $\quad$ $^1S_0, {}^3S_1, {}^1P_1, {}^3P_0, {}^3P_1, {}^3P_2, \ldots$

Spectroscopy and QCD

Mesons



Quarkonium



Consider the three lightest quarks

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

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

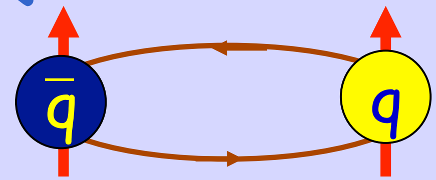
$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

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

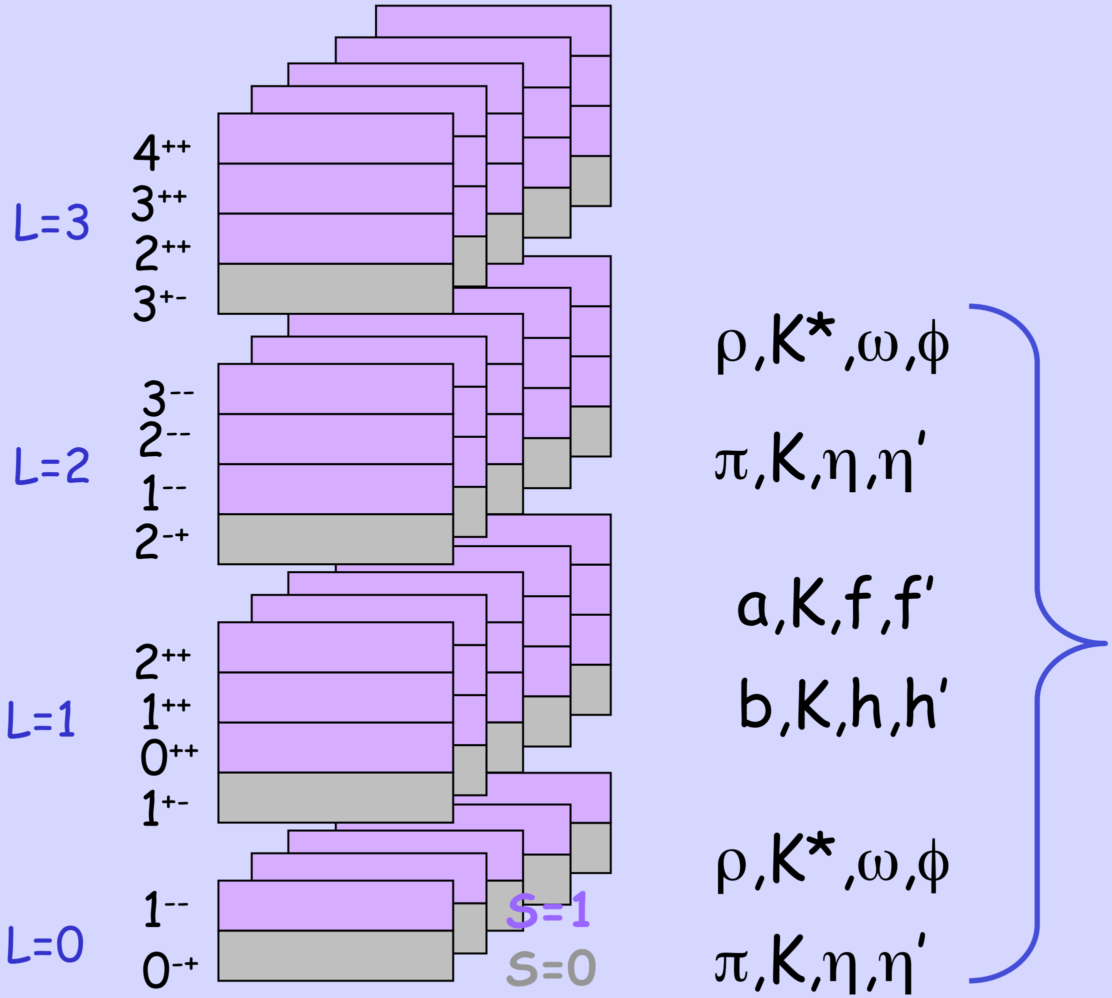
$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \quad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

Spectroscopy an QCD

Quarkonium



Mesons

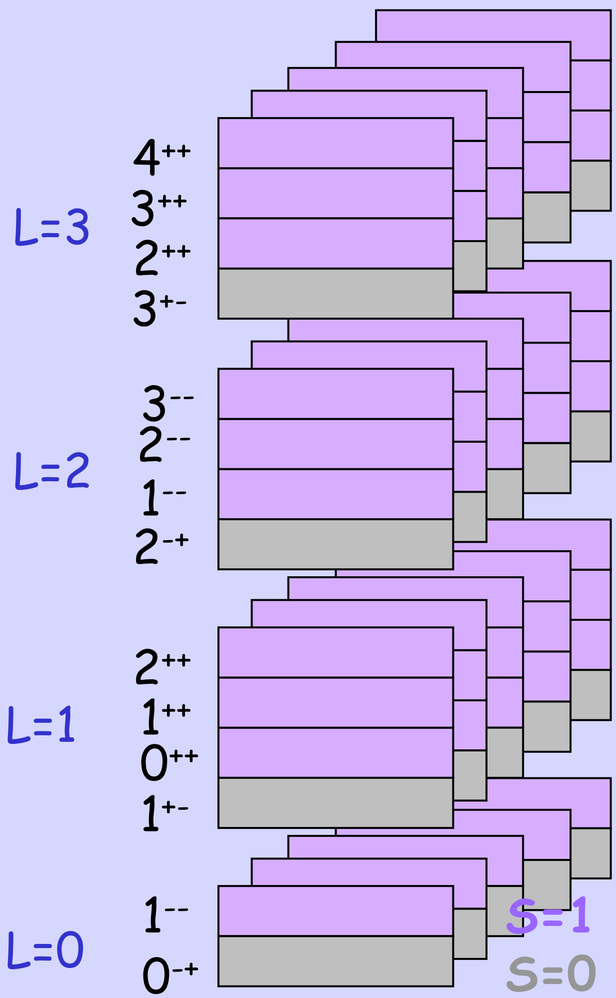


Mesons come in Nonets of the same J^{PC} Quantum Numbers

SU(3) is broken
Last two members mix

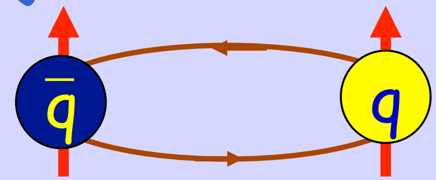
Spectroscopy an QCD

Mesons



Nothing to do with Glue!

Quarkonium



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

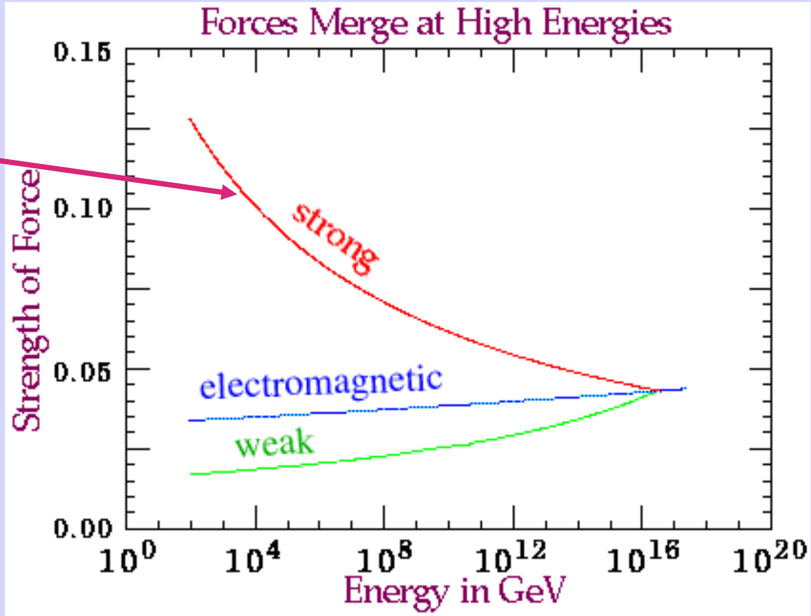
non quark-antiquark description

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…

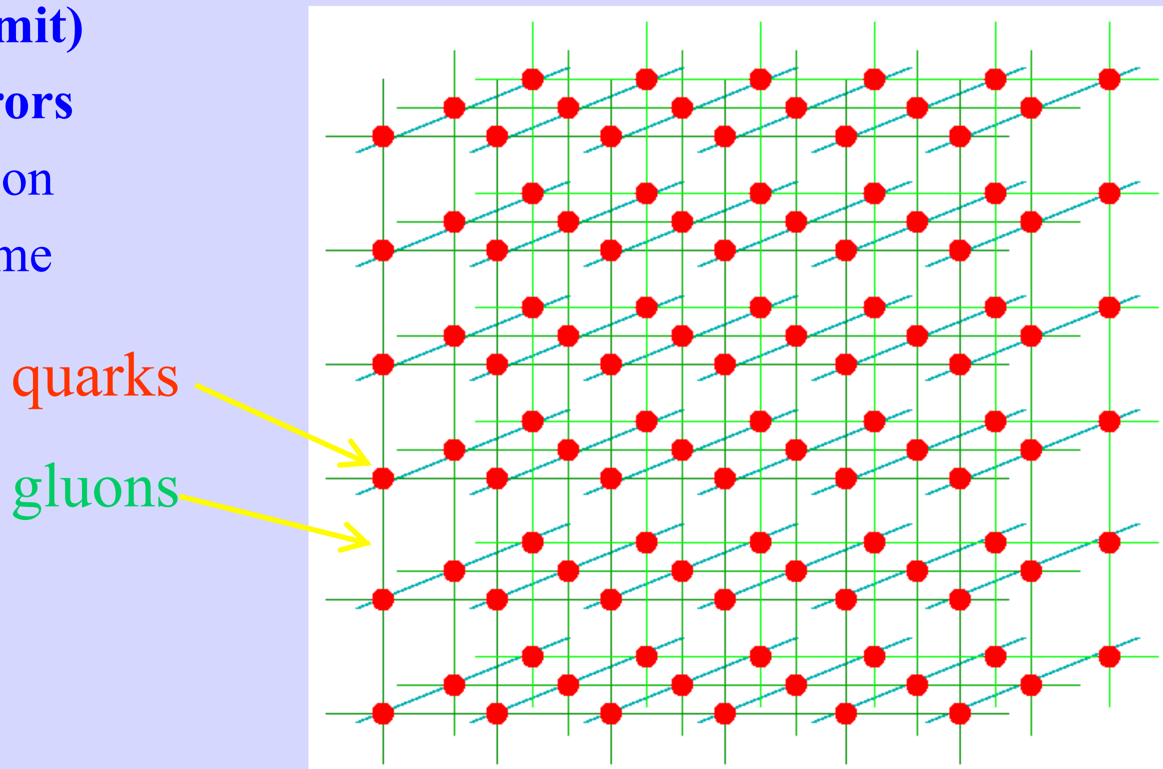
Perturbation parameter α_s is approximately 1.



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.

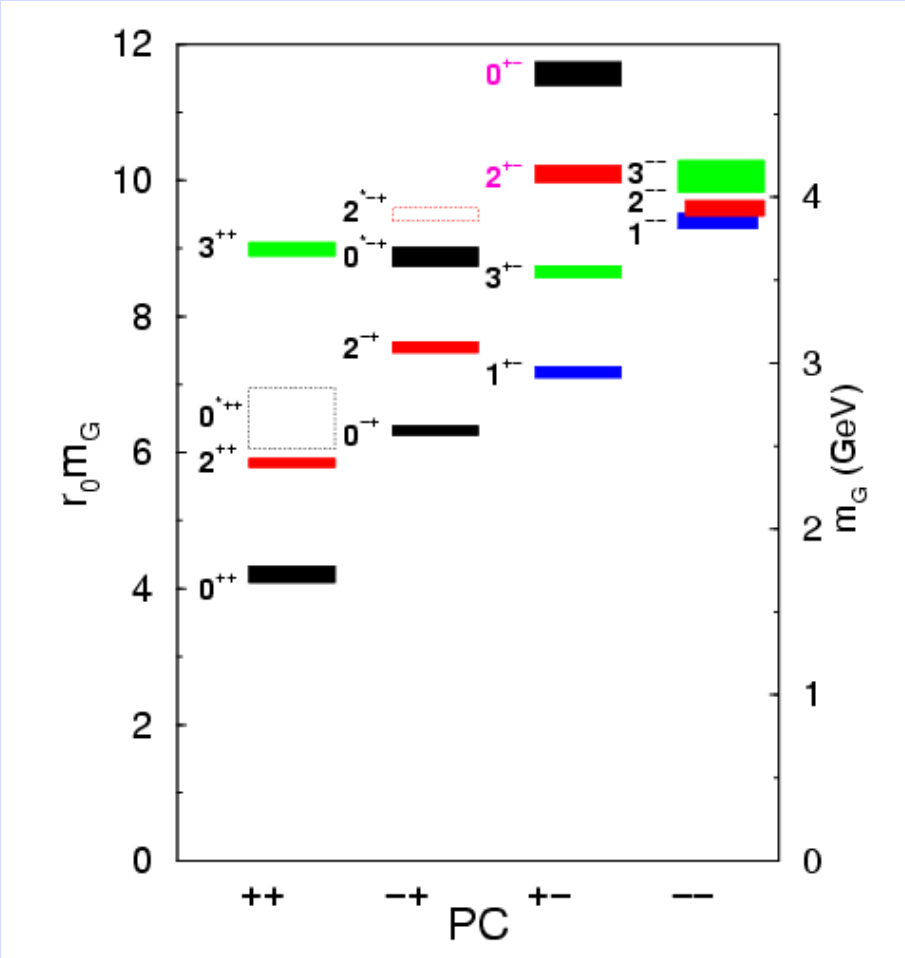
Lattice QCD predicts masses

The lightest glueballs have "normal" quantum numbers.

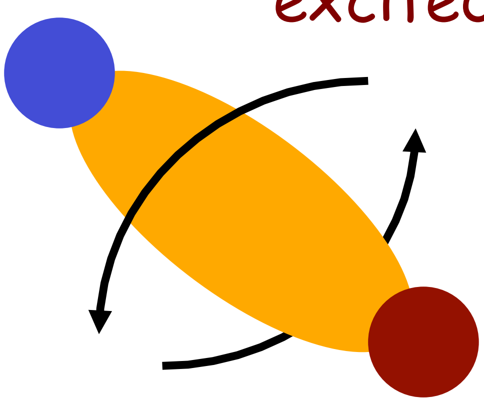
Glueballs will Q.M. mix

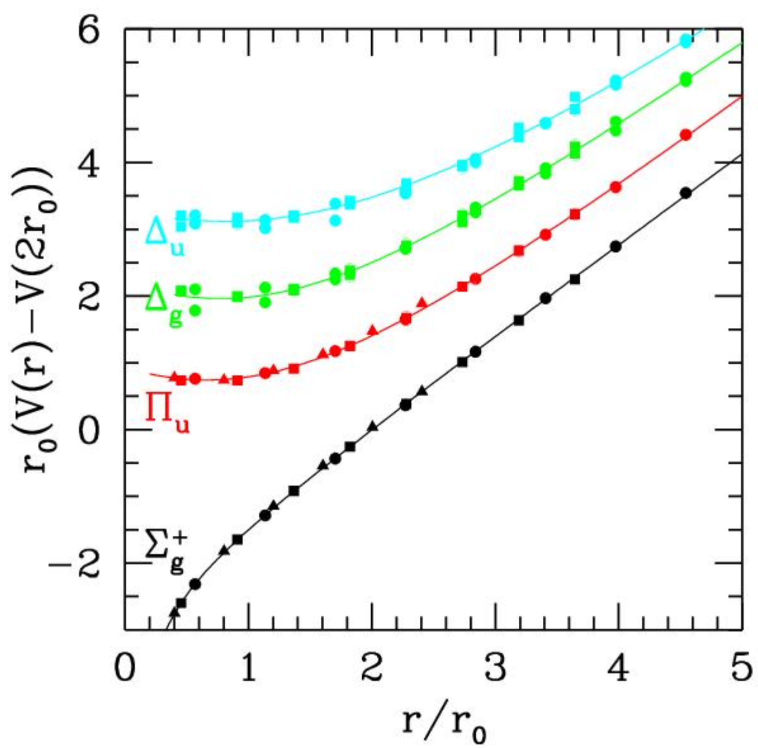
The observed states will be mixed with normal mesons.

Strong experimental evidence For the lightest state.



QCD Potential





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

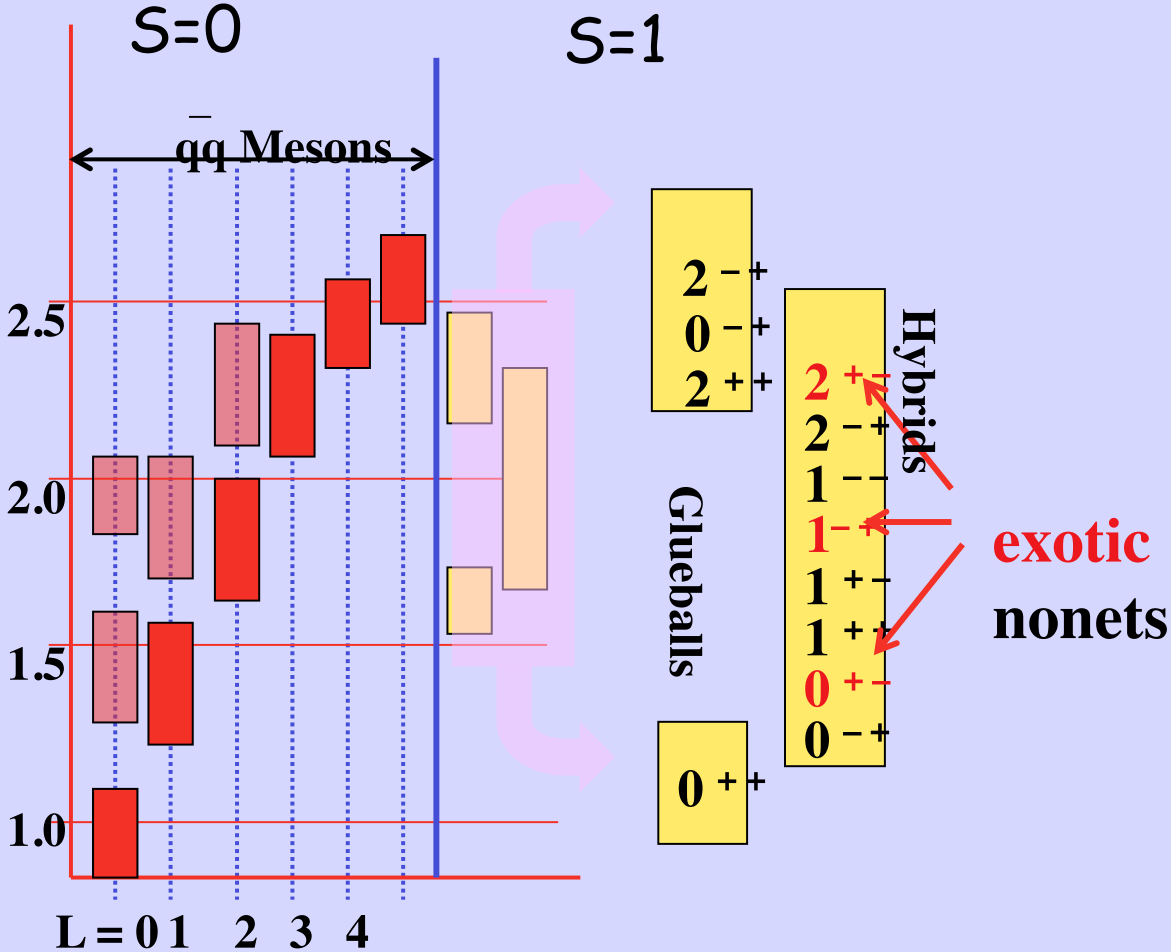
Observations of the nonets on the excited potentials are the best experimental signal of gluonic excitations.

Hybrid Predictions

Flux-tube model: 8 degenerate nonets

$1^{++}, 1^{--}$ $0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$ ~1.9 GeV/c²

S=0 S=1



Start with S=0

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

Start with S=1

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

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

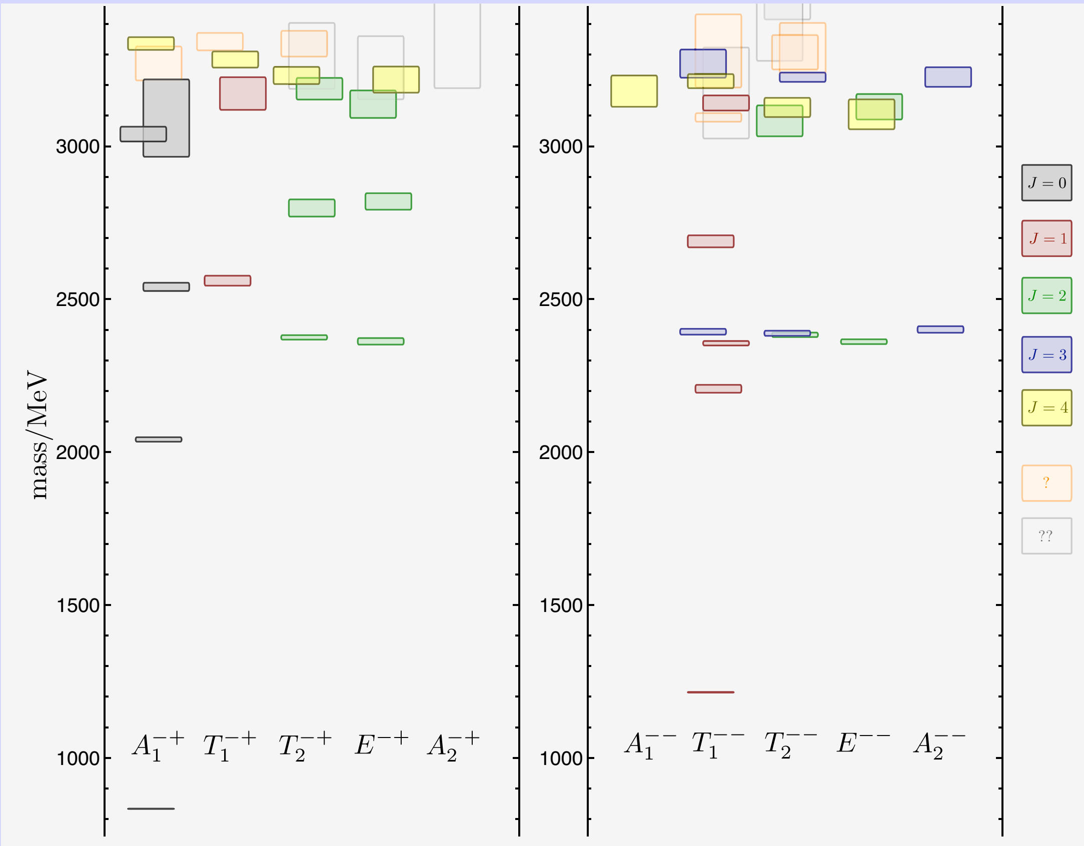
2^{-+} & 2^{+-}

Meson and Hybrid Meson Spectrum

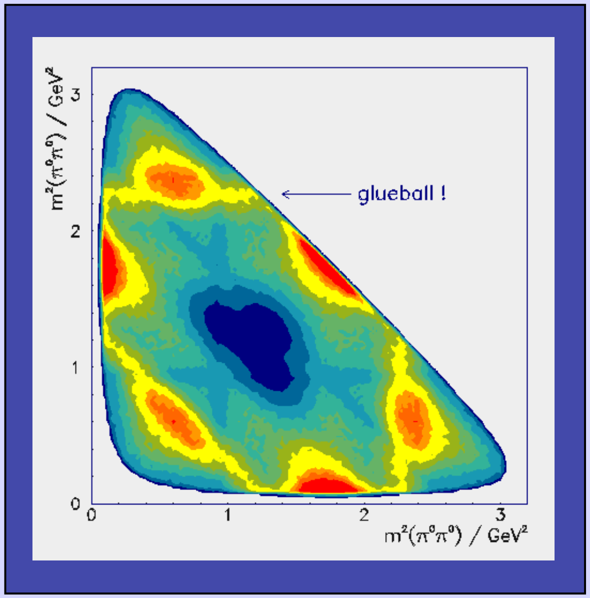
Lattice calculations predict that the lightest exotic particle should have a mass about twice that of the proton.

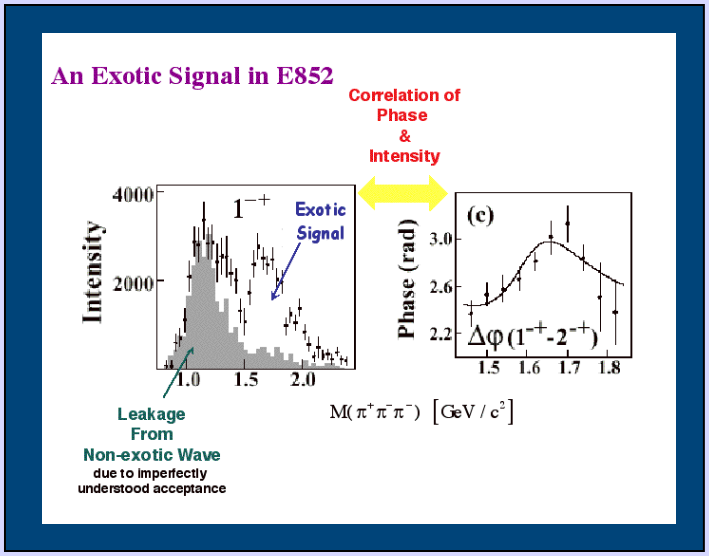
Calculational breakthrough by CMU Professor Colin Morningstar makes spectrum calculations possible.

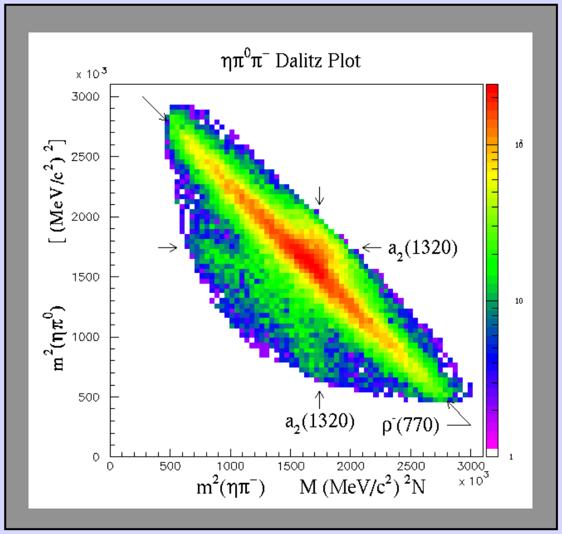
2009: Lattice calculation of ground state and excited spectrum.



Experimental Evidence

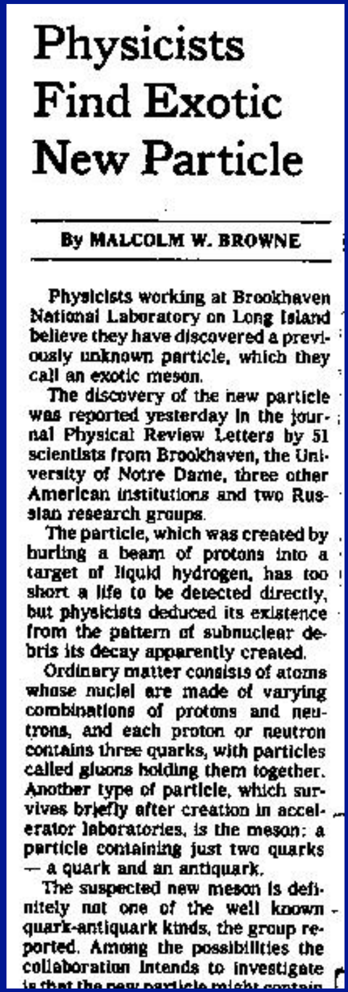






Evidence for both Glueball and Hybrid States

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.

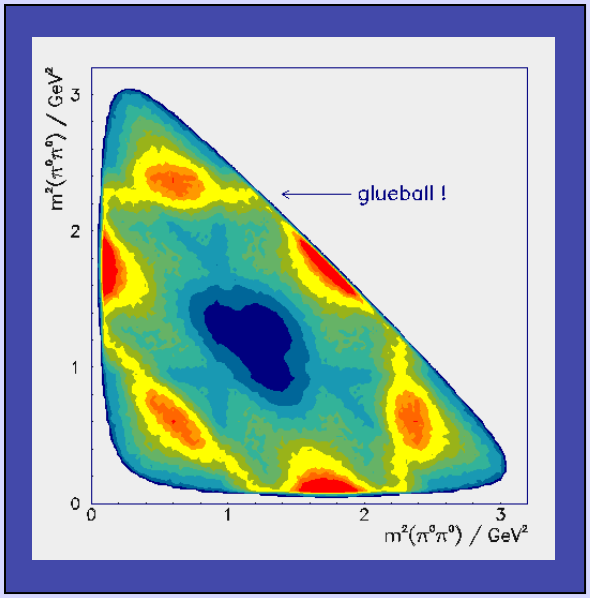
The particle, which was created by hurling a beam of protons into a target of liquid hydrogen, has too short a life to be detected directly, but physicists deduced its existence from the pattern of subnuclear debris its decay apparently created.

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.

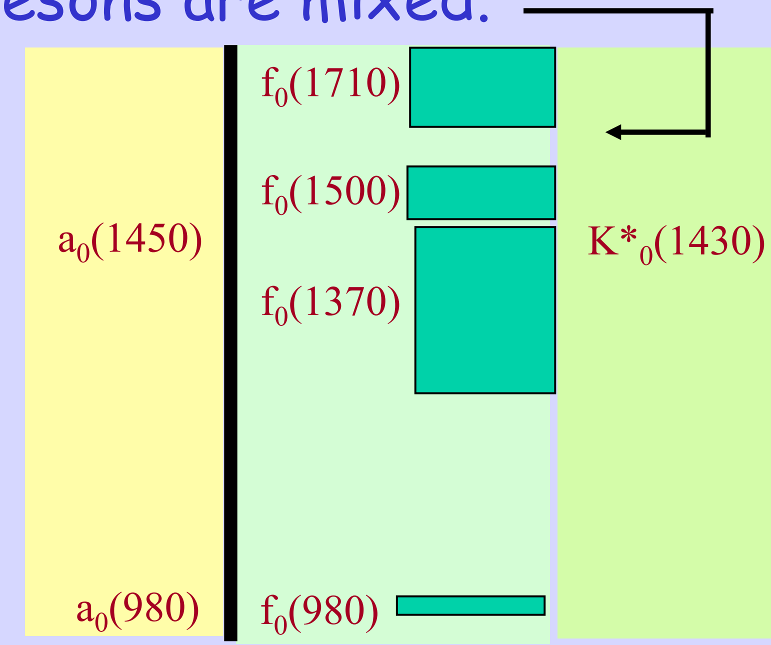
The suspected new meson is definitely not one of the well known quark-antiquark kinds, the group reported. Among the possibilities the collaboration intends to investigate

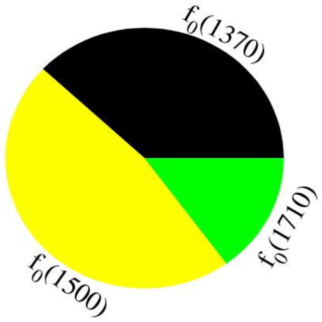
Experimental Evidence

Glueballs



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





Glueball spread over 3 mesons

Are there other glueballs?

Crede & Meyer, Prog. Part. Nucl. Phys. **63**, 74, (2009).

Experimental Evidence Hybrids

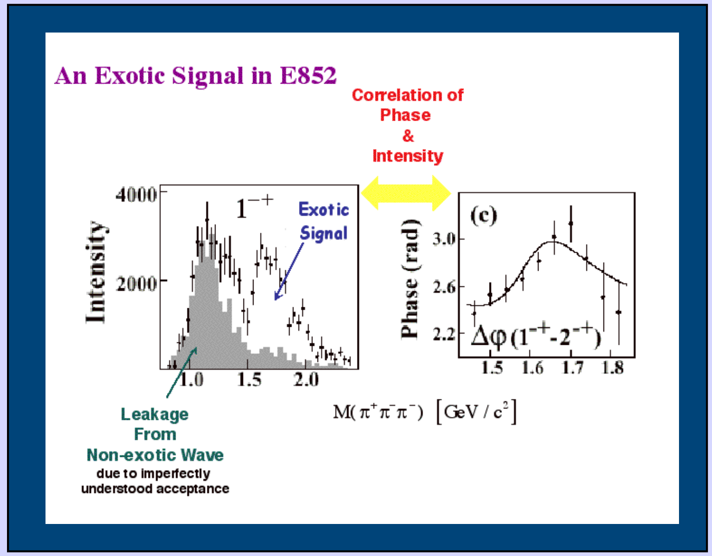
Exotic Mesons

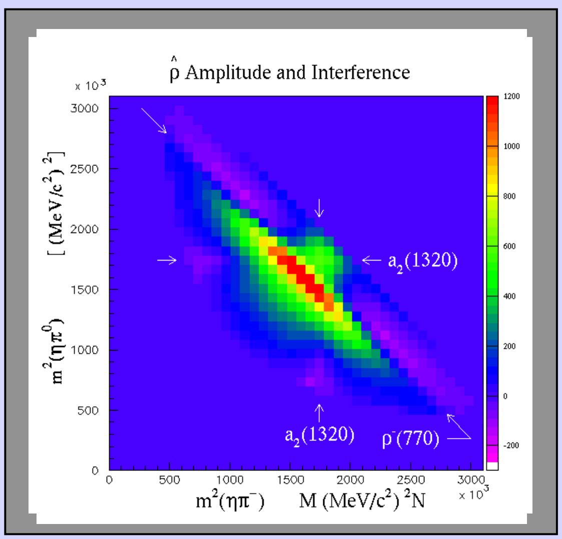
1^{-+} mass 1.4

E852 BNL '97

CBAR CERN '97

Too light, decays are wrong … ?





Exotic Mesons

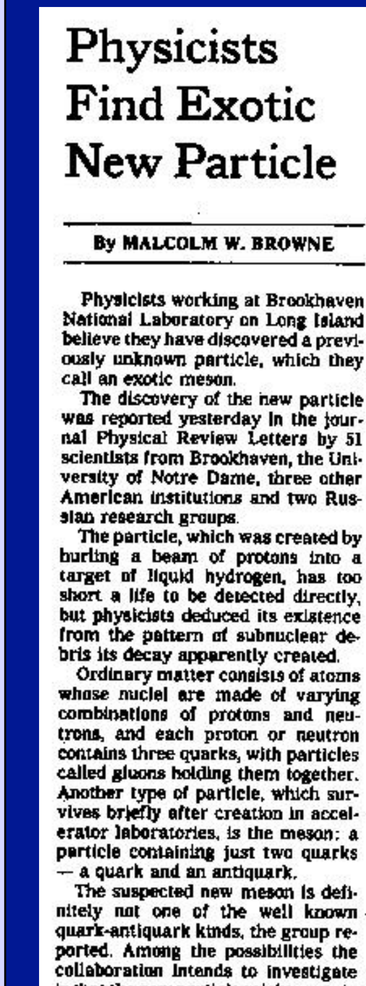
1^{-+} mass 1.6

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

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 is that the new particle might contain

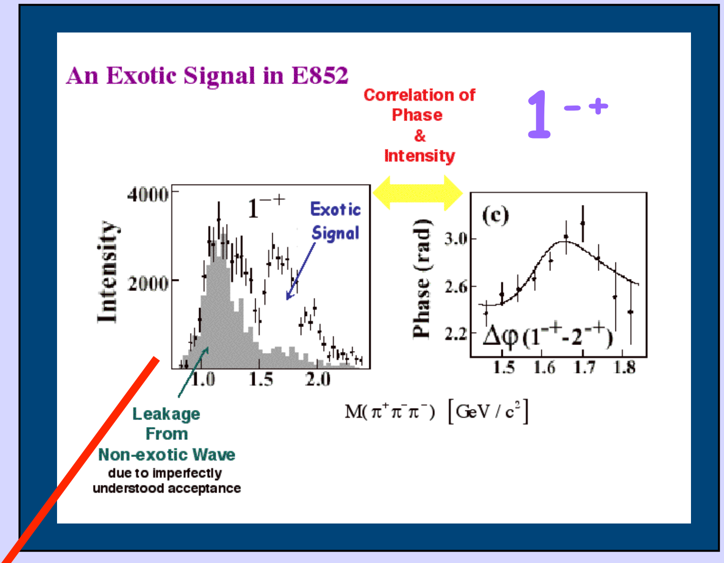
Experimental Evidence

Hybrid Nonets

Establish other Nonets:

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

Levels



Built on normal mesons

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

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

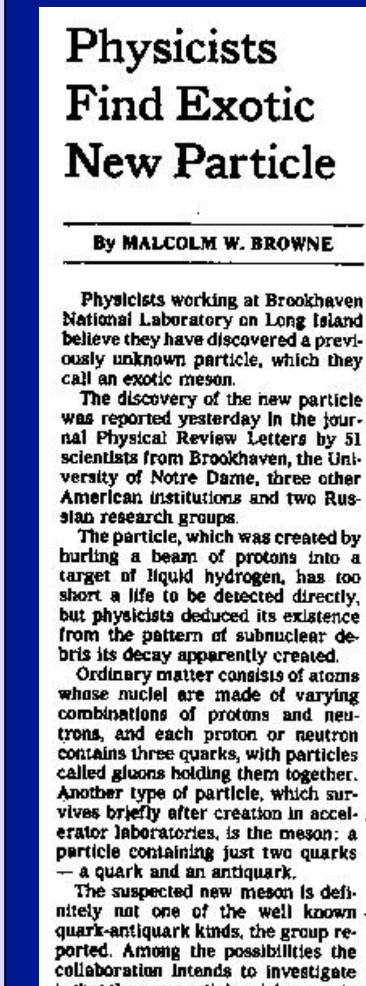
$$s\bar{d} \qquad s\bar{u}$$

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

Identify other states in nonet to establish hybrid

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

New York Times, Sept. 2, 1997



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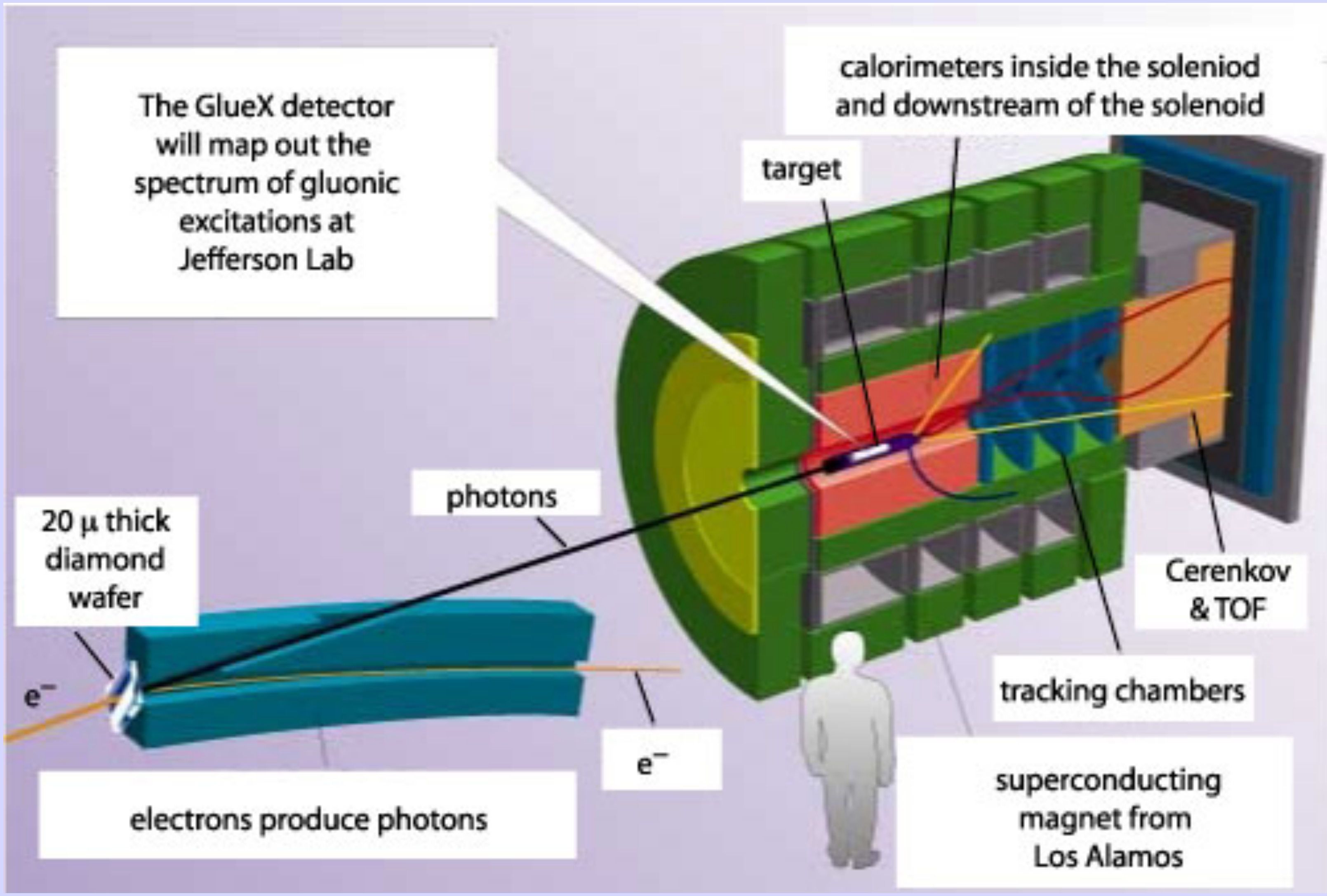
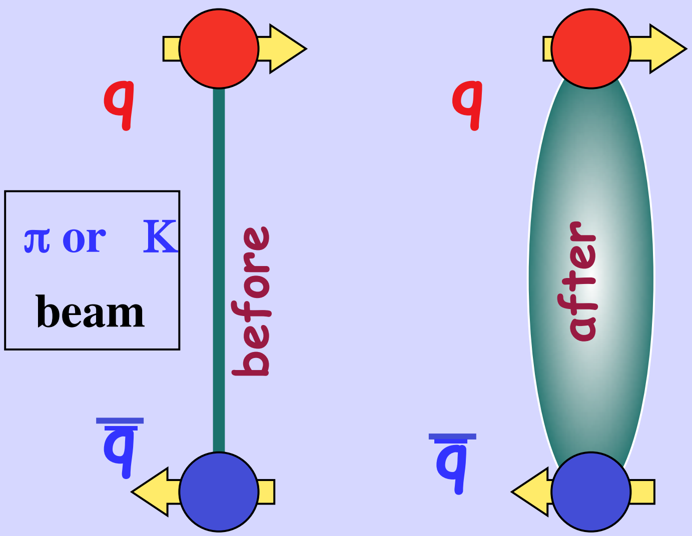
The GlueX Experiment



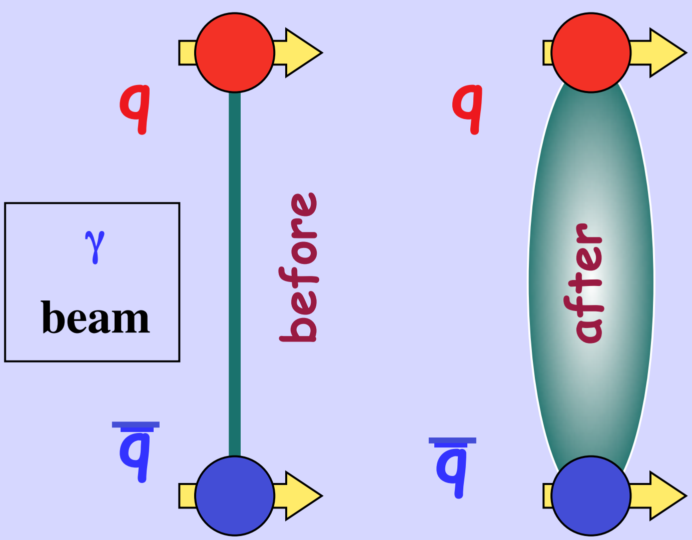
How to Produce Hybrids



Quark spins anti-aligned

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

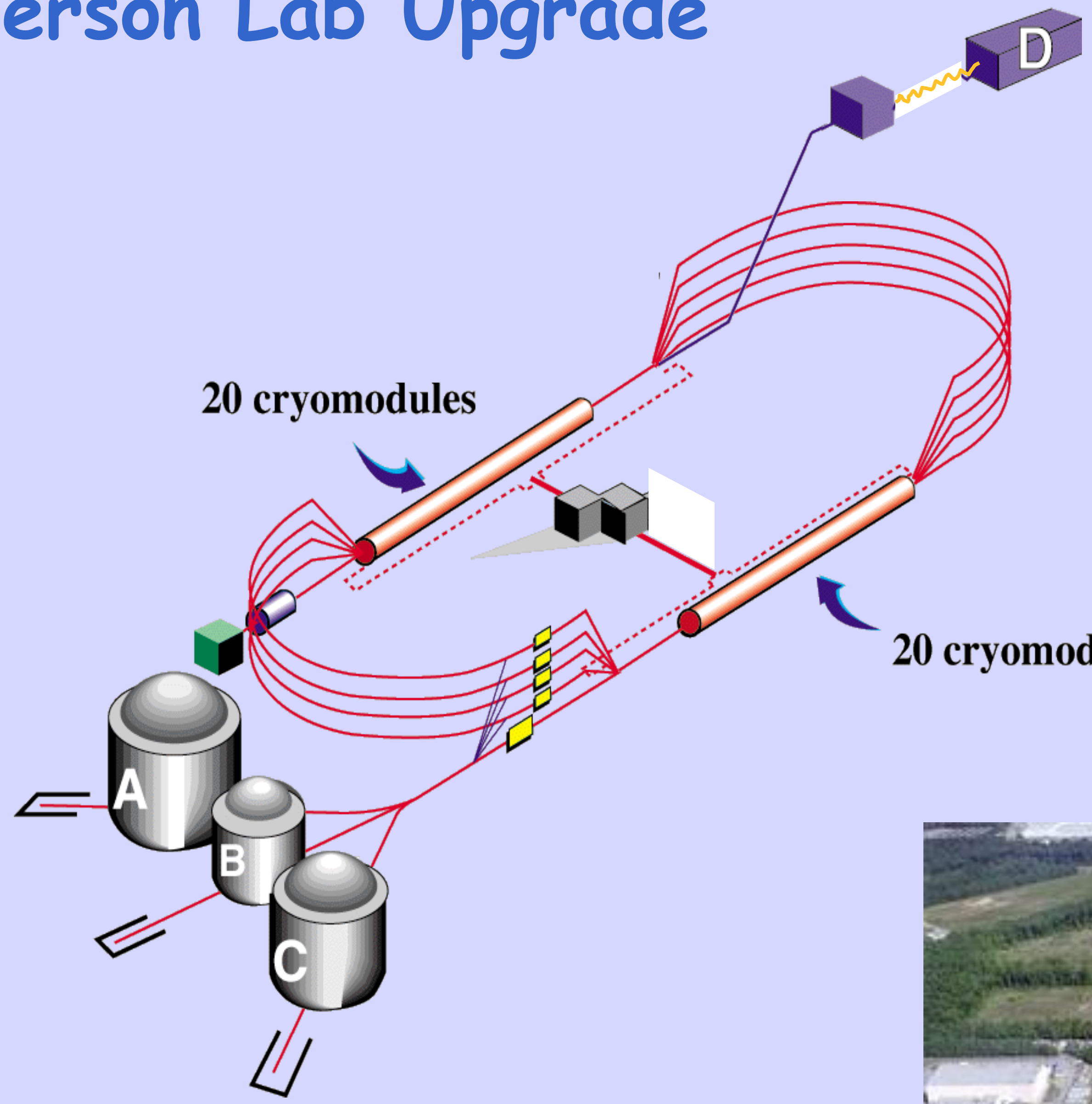
Much data in hand with some
evidence for gluonic excitations
(tiny part of cross section)



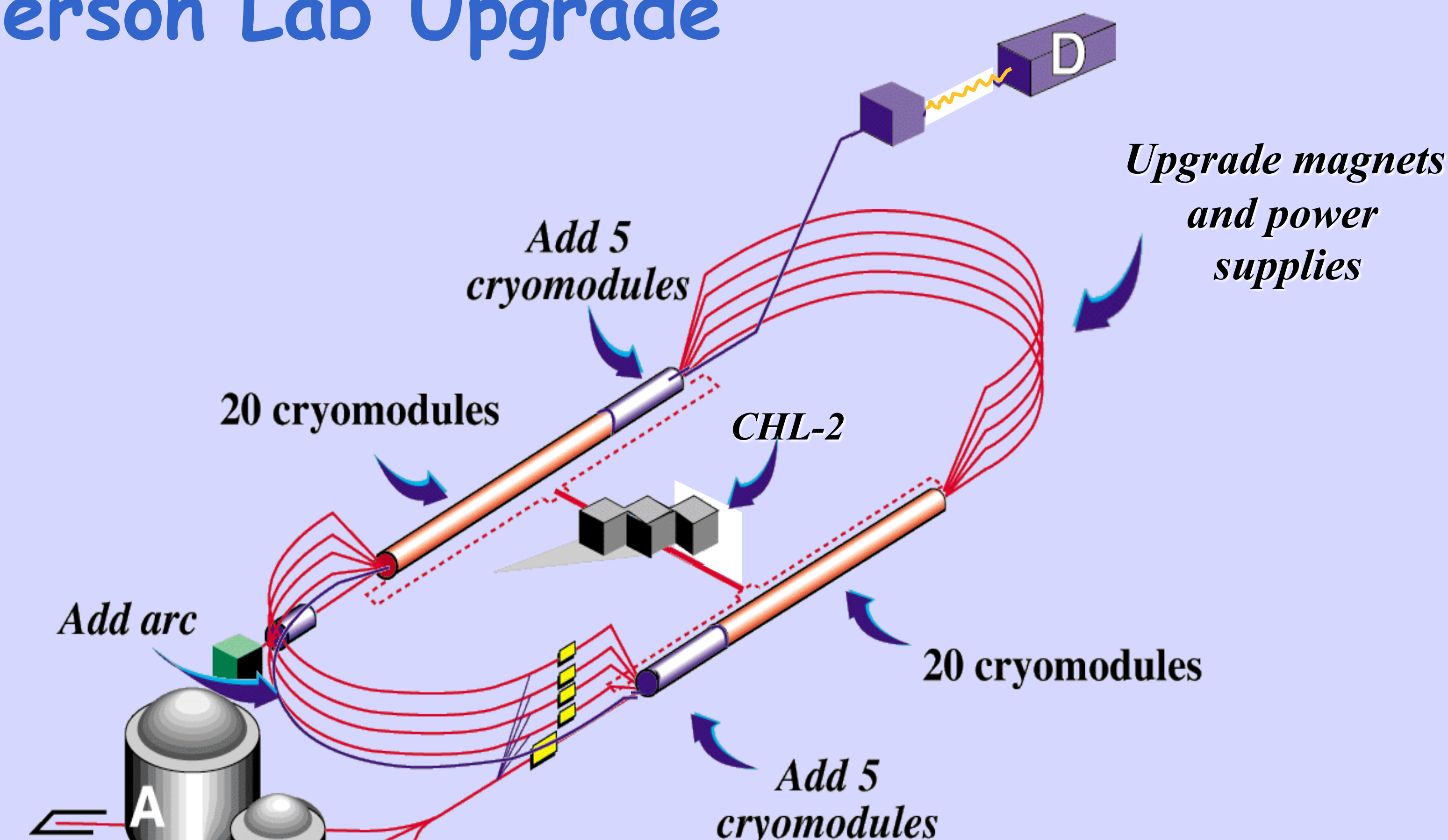
Quark spins aligned

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

Jefferson Lab Upgrade

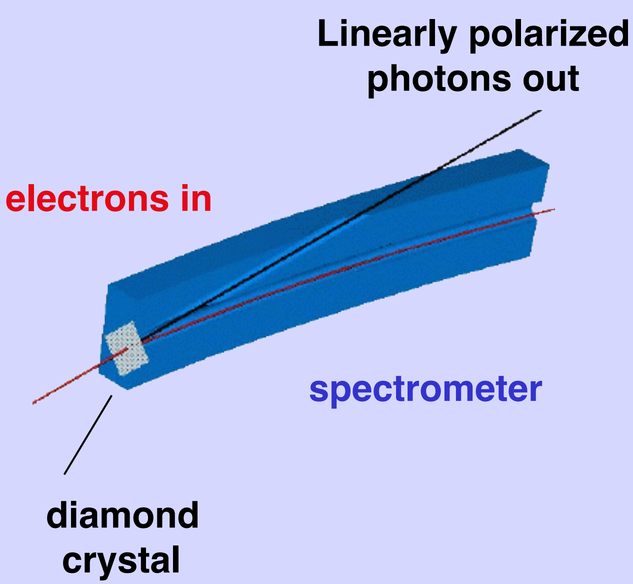


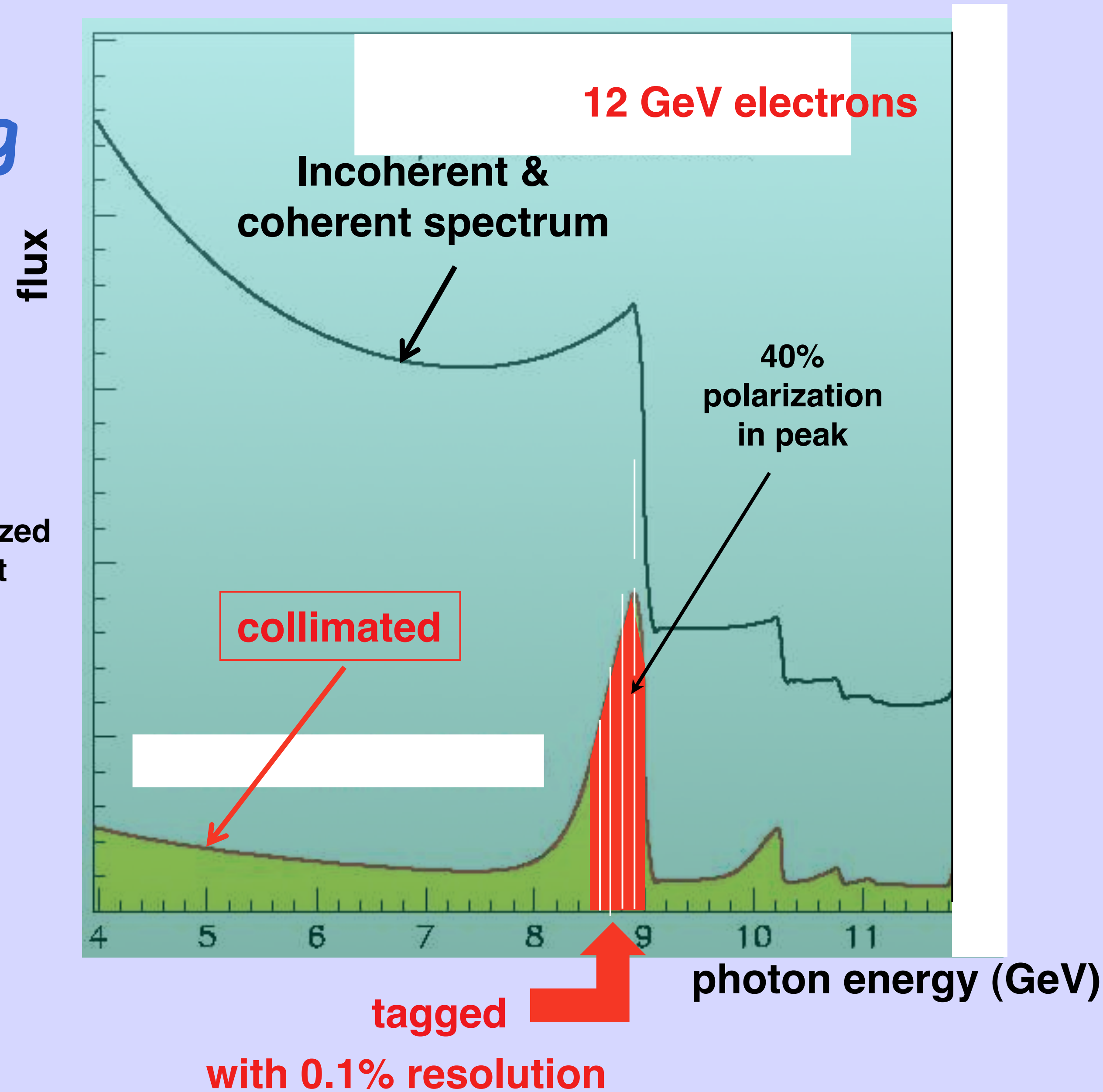
Jefferson Lab Upgrade



Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization





Jefferson Lab Upgrade

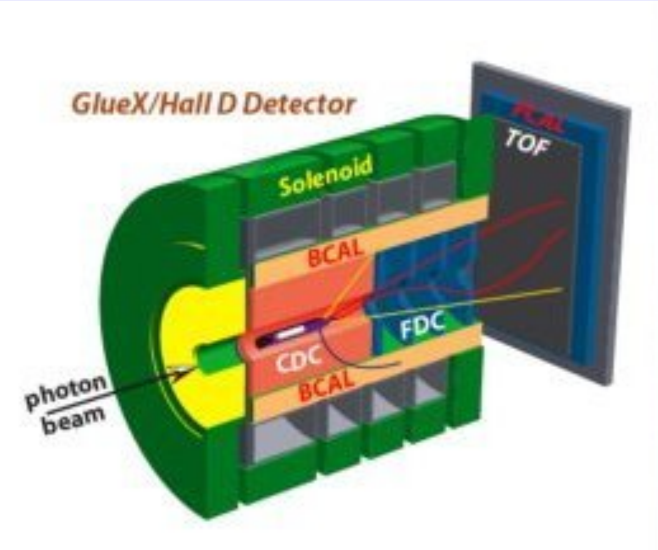
Timeline for GlueX

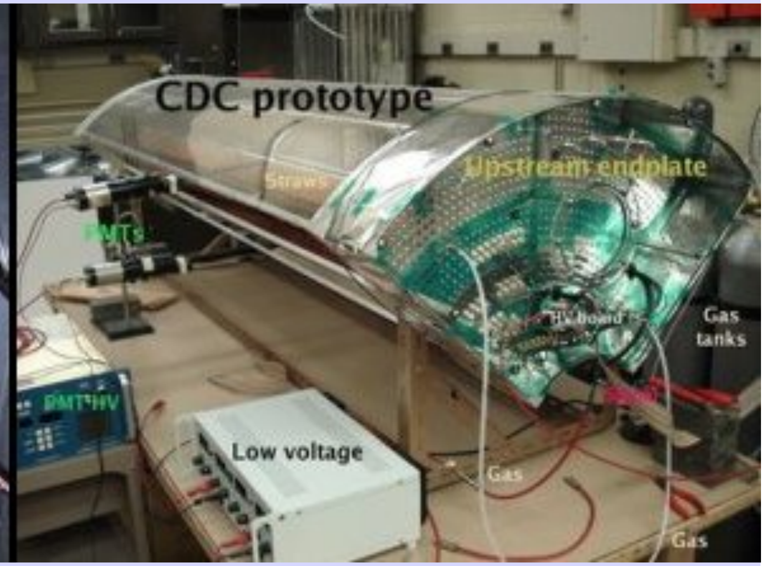
1997 – first meeting.
2001 – NSAC LRP
2004 – CD0
2006 – CD1
2007 – CD2
2007 – NSAC LRP
2008 – CD3
2009 – Construction
2010 - Const @ CMU
2014 – Beam
2014 – CD4
2015 - Physics

Hall-D on September 21, 2009

The GlueX Experiment

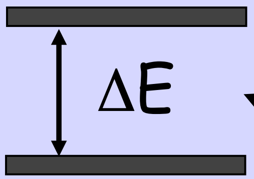
CDC @ CMU



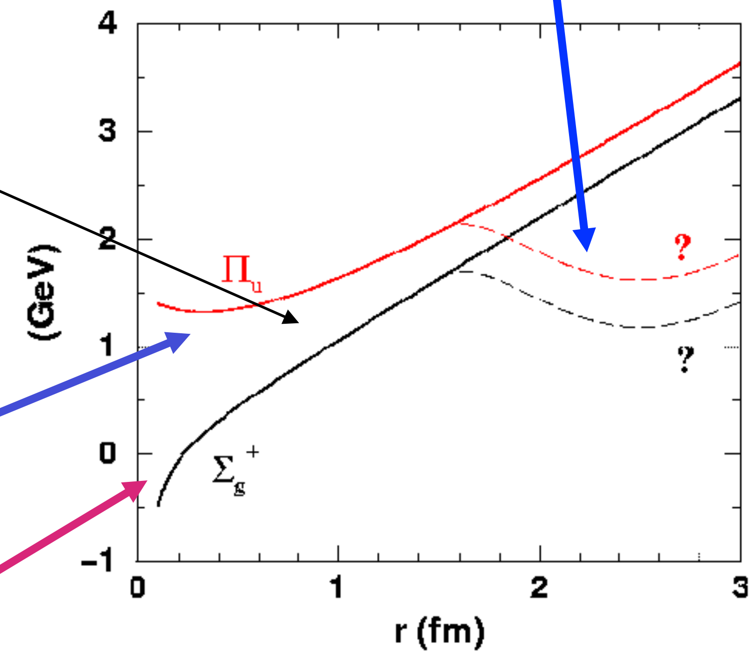


At CMU, we will be building a 3500 channel drift chamber for the GlueX experiment. Construction starts in early 2010 and continues through 2012. Unique opportunity to be involved in the construction of hardware.

Gluonic Hadrons and Confinement



What are the light quark Potentials doing?



Lattice QCD potentials

Potentials corresponding To excited states of glue.

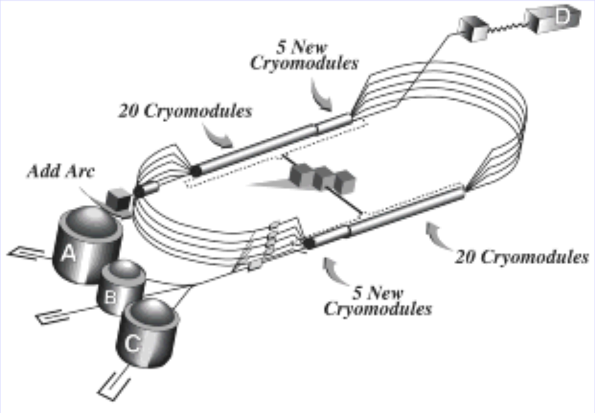
Non-gluonic mesons – ground state glue.

Conclusions

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

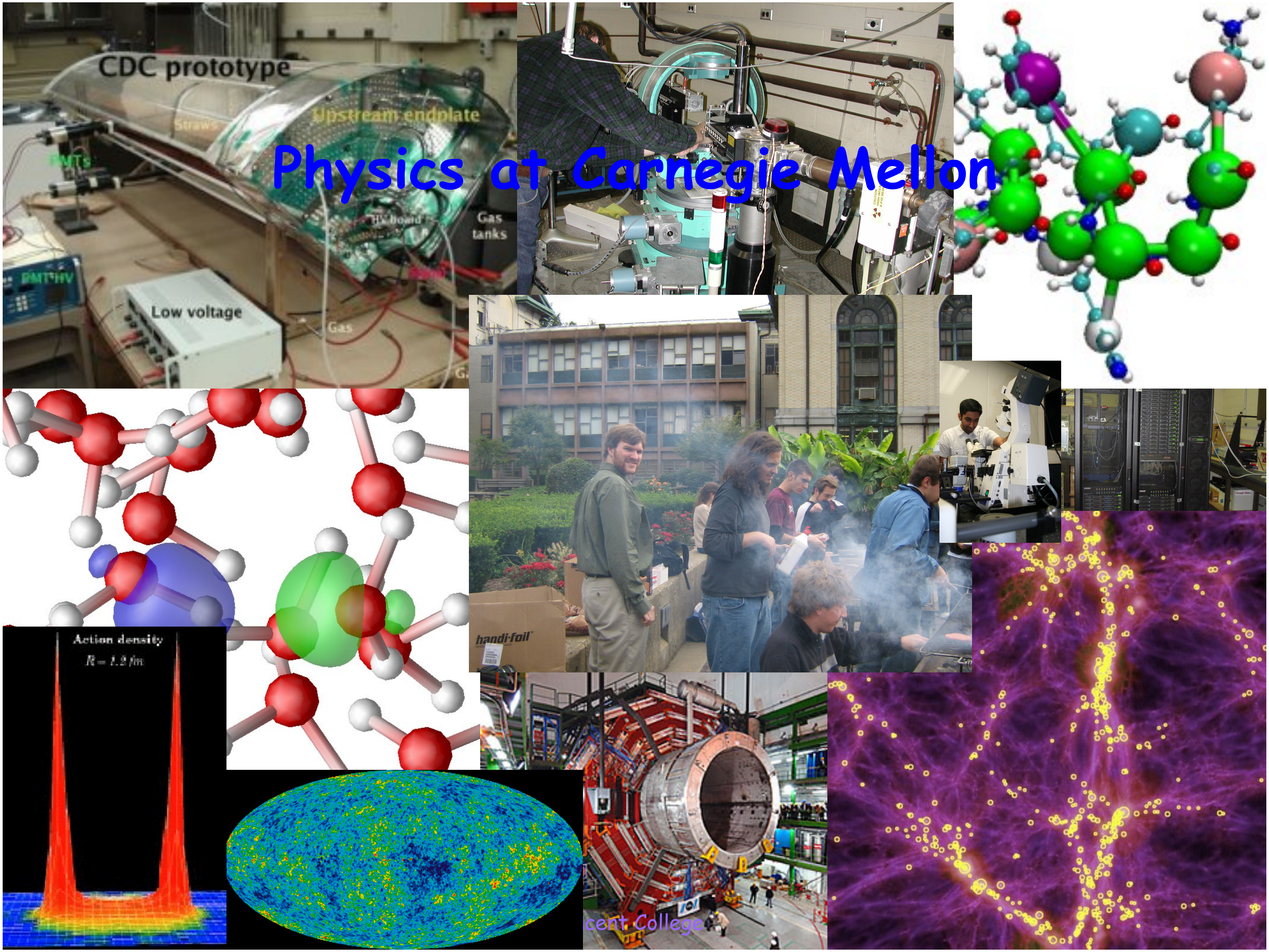
Advances in theory and computing will soon allow us to solve QCD and understand the role of glue.

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.

Physics at Carnegie Mellon



Astrophysics/Cosmology

Croft

Di Matteo

Holman

Peterson

Trac

2+ Hires

Griffiths

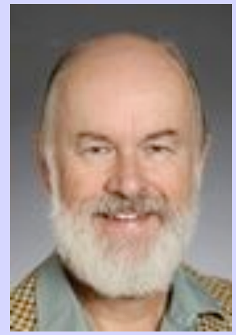
McWilliams Center for Cosmology
Emphasis on early universe modeling.

Biological Physics

Deserno

Evilovitch

Loesche



Nagle

T-Nagle

Widom

Swendsen

Garoff

Majetic

Woods

Very strong efforts in experiment, computation and theory with strong connections to outside groups.

Computational Physics


Croft


Deserno


Di Matteo


Meyer


Morningstar


Suter


Swendsen


Widom


Sekerka

A diverse group of people solving physics problems with large scale Computing resources. Utilize in-house clusters and facilities like PSC.

Condensed Matter

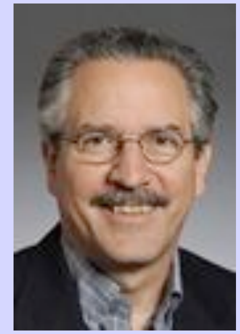
Feenstra

Garoff

Islam

McHenry

Sekerka



Suter

Swendsen

Widom

Majetic

Strong connections to groups in other departments. Many lab facilities on campus.

High Energy Physics


Briere


Ferguson


Gilman


Holman


Paulini


Rothstein


Russ


Vogel


Wolfenstein

Work carried out at FNAL, CERN and BES (China). Strong Experimental and theory program.

Medium Energy Physics


Franklin


Kisslinger


Meyer


Morningstar


Quinn


Schumacher

Strong experimental, computational and theoretical programs. Experimental work carried out at Jefferson Lab. In-house resources to build large detectors. Largest computational facilities in the department.

Links outside Physics

Other CMU Departments:
Biology
Chemistry
Chemical Engineering
Electrical Engineering
Computer Science
Material Science
Math

Outside CMU
Argonne Natl. Lab
BES (China)
Brookhaven Natl. Lab
CERN
Jefferson Lab
Fermi Lab
NIST
SLOAN (SDSS)
LSST

Going to Graduate School?

Crucial Elements:

1) Grades

At CMU, 3.5 in upper level physics and math courses.

2) Undergraduate Research

At least one semester, more is better. Understand what you did.

3) GRE Subject

Physics is crucial, 40^{th} percentile is ok.

4) Letters of Recommendation

Get people that know your physics ability. An instructor, research advisors, ….

5) Personal Statement

This is your chance to talk about what you did and what you want to do. It is also your chance to explain issues in your record.

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	~2.0 GeV/c²
MILC (97)	1.97 ±0.30	
MILC (99)	2.11 ±0.10	
Lacock(99)	1.90 ±0.20	
Mei(02)	2.01 ±0.10	

1^{-+}, 0^{+-} } Splitting ≈ 0.20

2^{+-}

In the charmonium sector:

1^{-+}	4.39 ±0.08	Splitting = 0.20
0^{+-}	4.61 ±0.11	