Gluonic Hadrons: A Probe of Confinement

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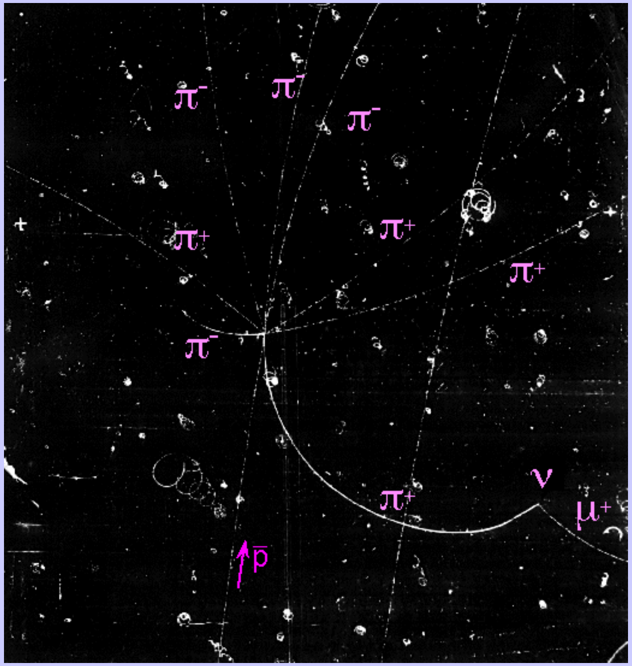
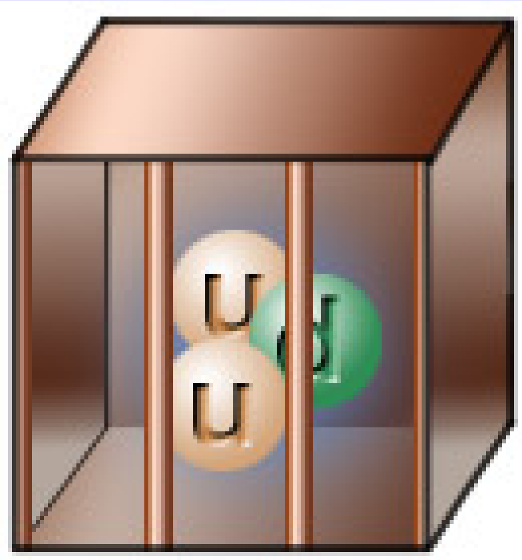
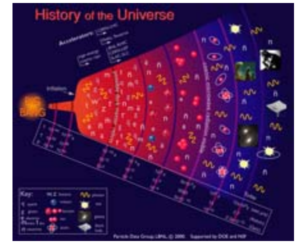


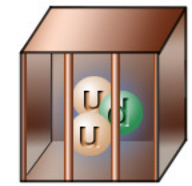


Outline



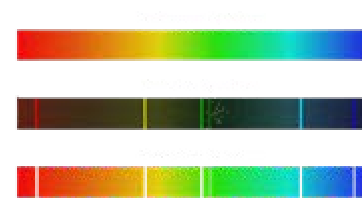
The beginning of time.

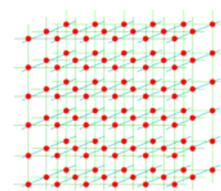
The strong force and QCD



Color confinement

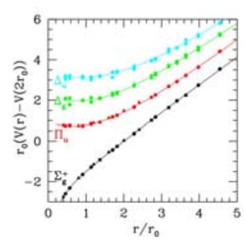
Spectroscopy





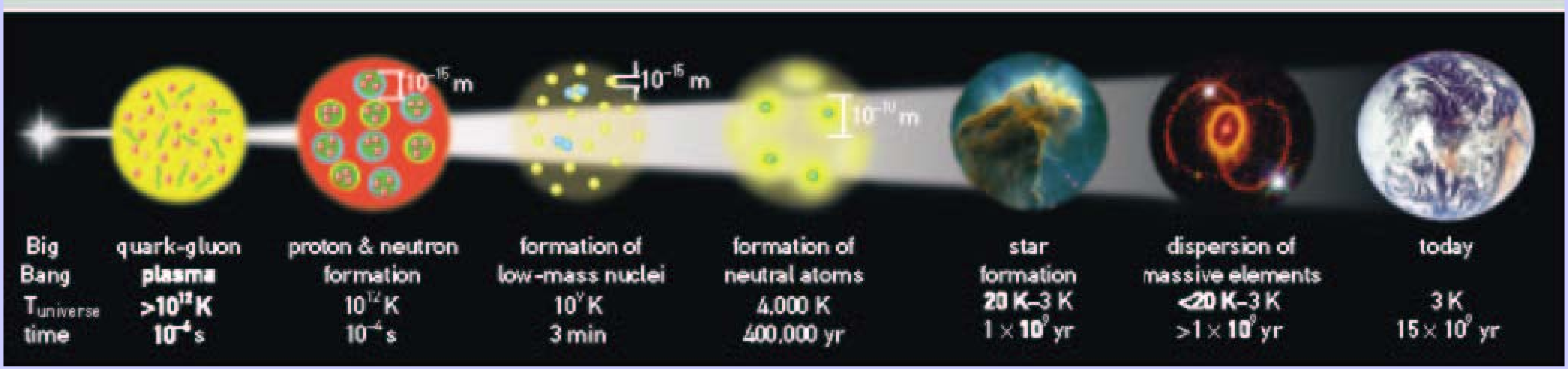
Lattice QCD

Finding Gluonic Hadrons

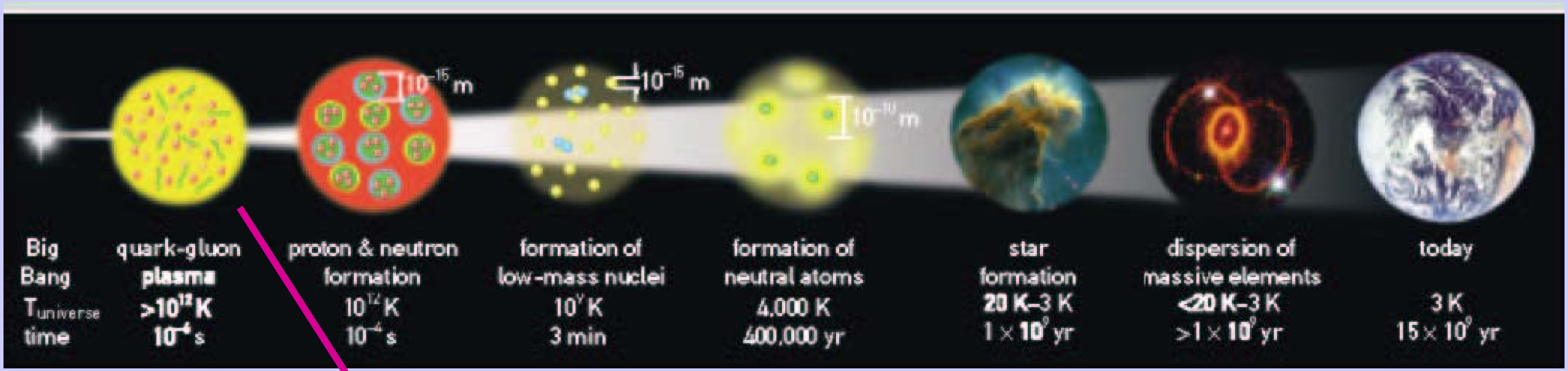


Confinement

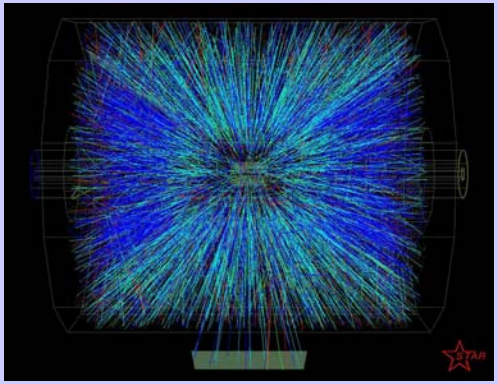
The First Seconds of The Universe



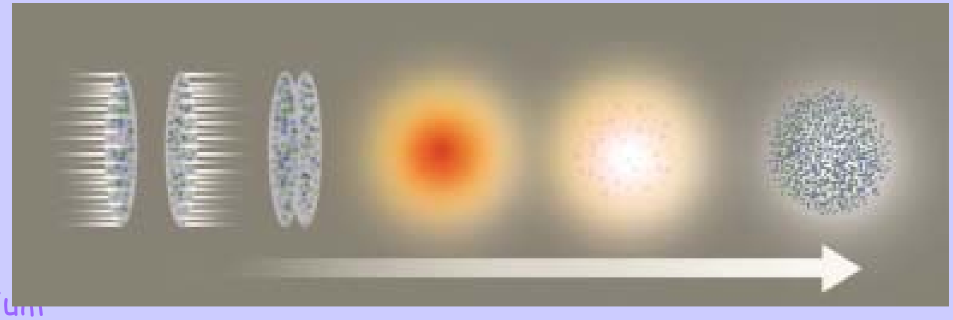
Quark Gluon Plasma



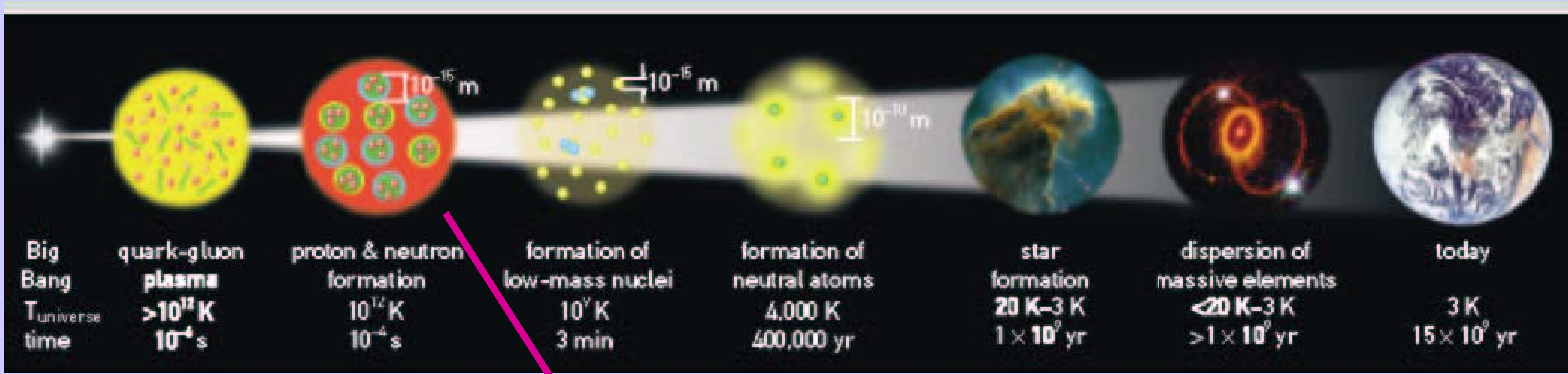
For a period from about 10^{-12} s to 10^{-6} s the universe contained a plasma of quarks, anti quarks and gluons.



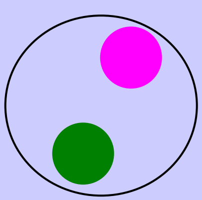
Relativistic Heavy Ion Collisions are trying to produce this state of matter in collisions



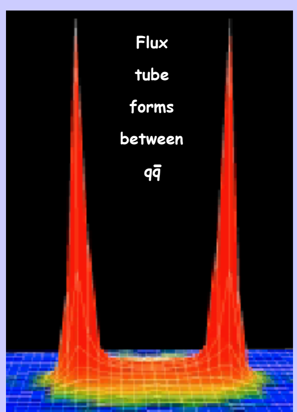
Confinement



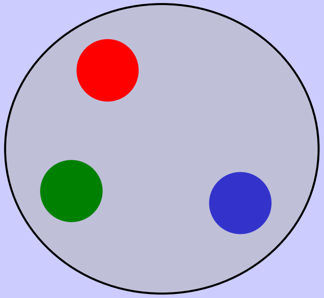
From about 10^{-6} s on, the quark and anti quarks became confined inside of Hadronic matter. At the age of 1s, only protons and neutrons remained.



Mesons

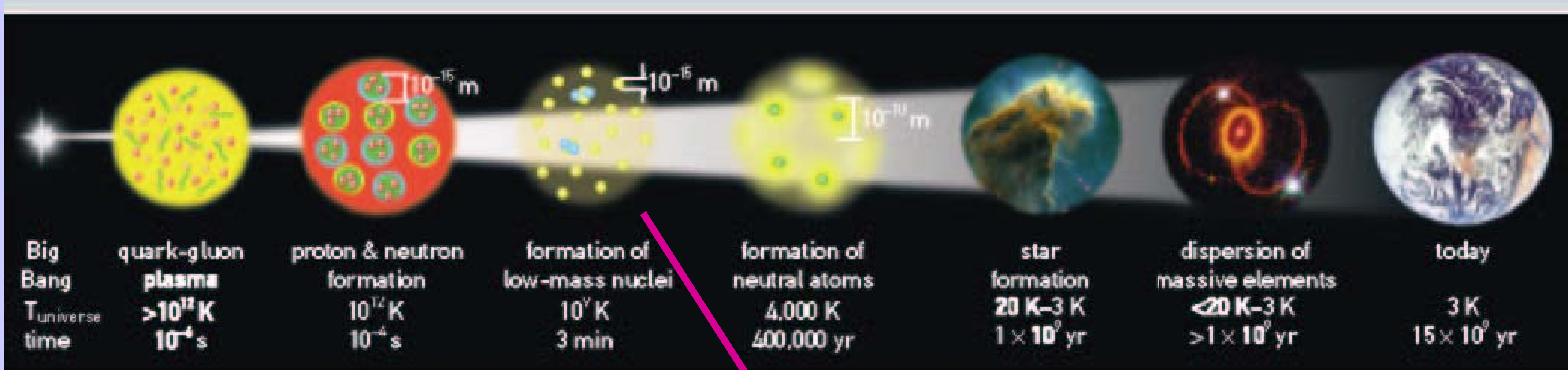


The gluons produce the 16ton force that holds the hadrons together.

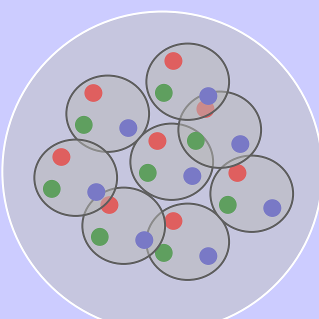


Baryons

The Formation of Nuclei



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

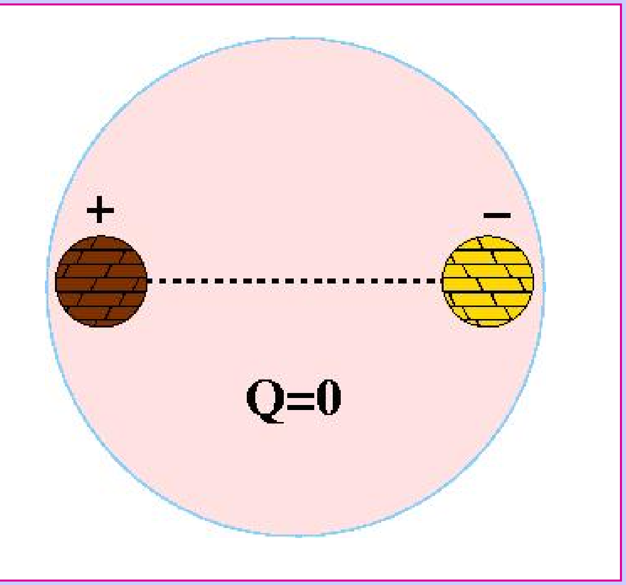


Primordial hydrogen, deuterium, helium and a few other light nuclei now exist.

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

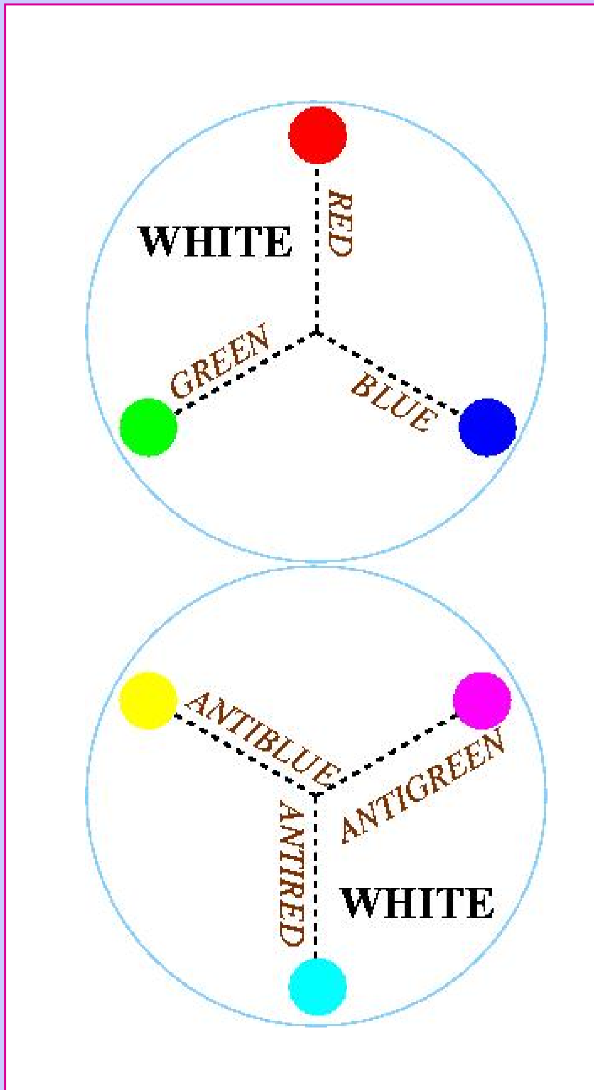
Quantum Chromo Dynamics

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*.

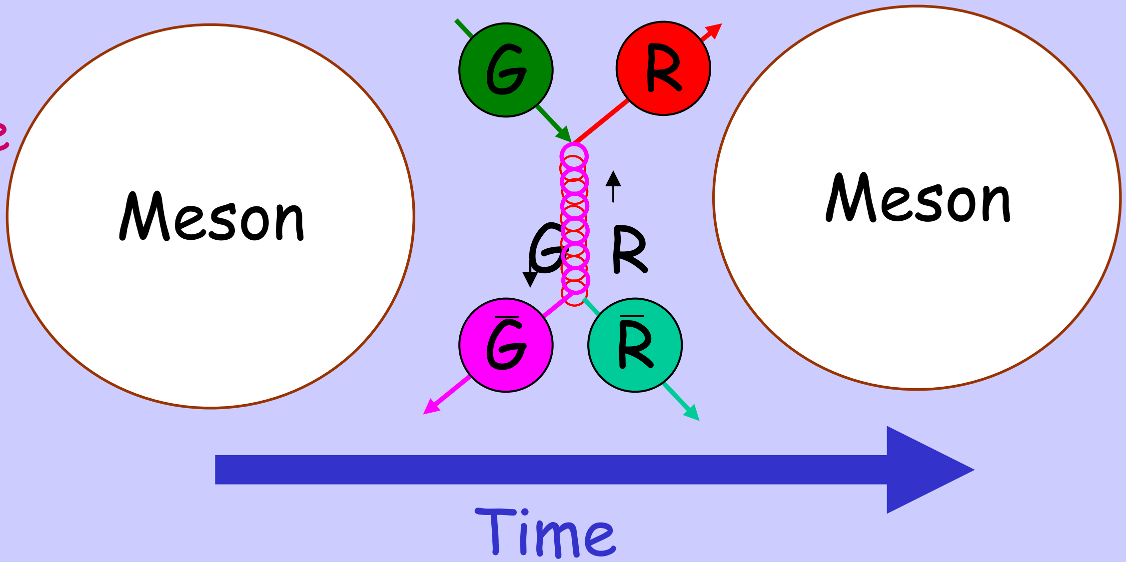
Color Charge

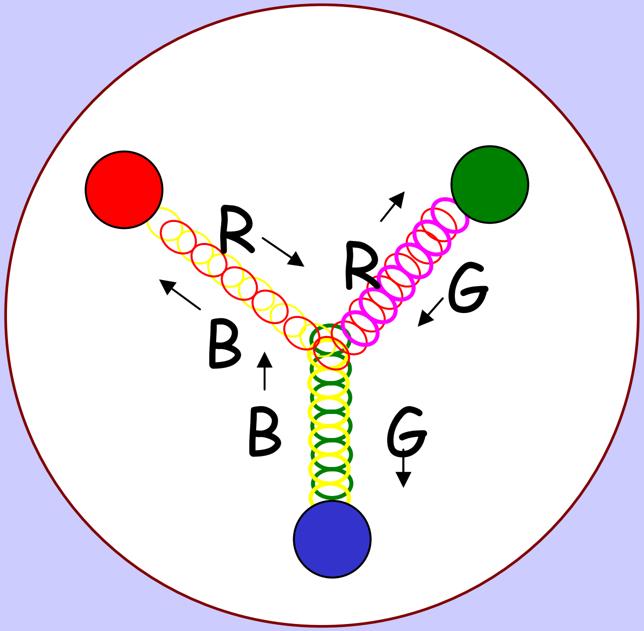


Three charges called RED, BLUE and GREEN, and three anti colors. The objects that form have to be color neutral:

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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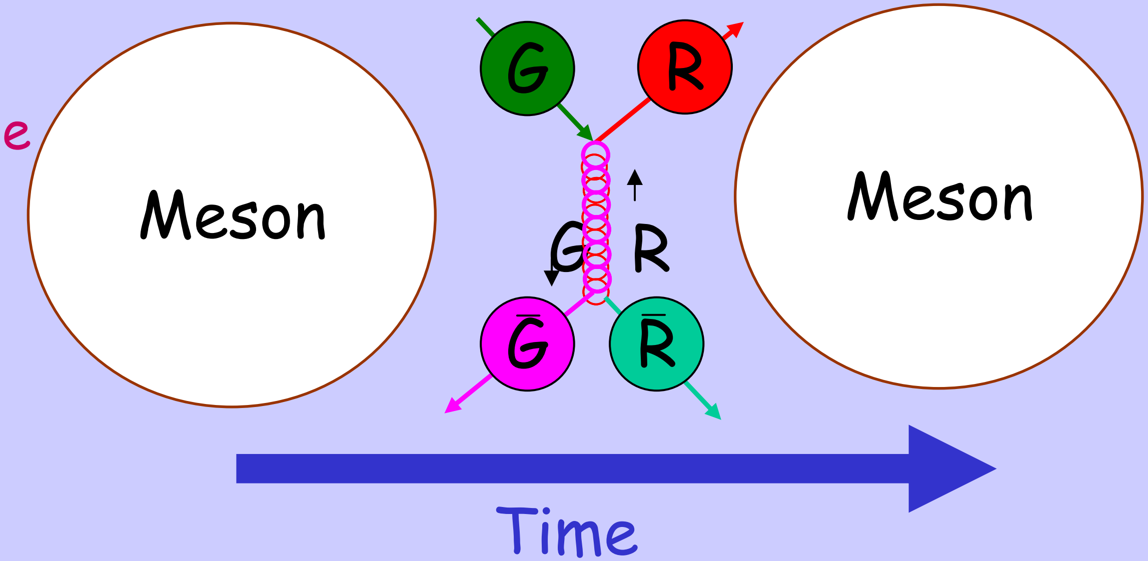

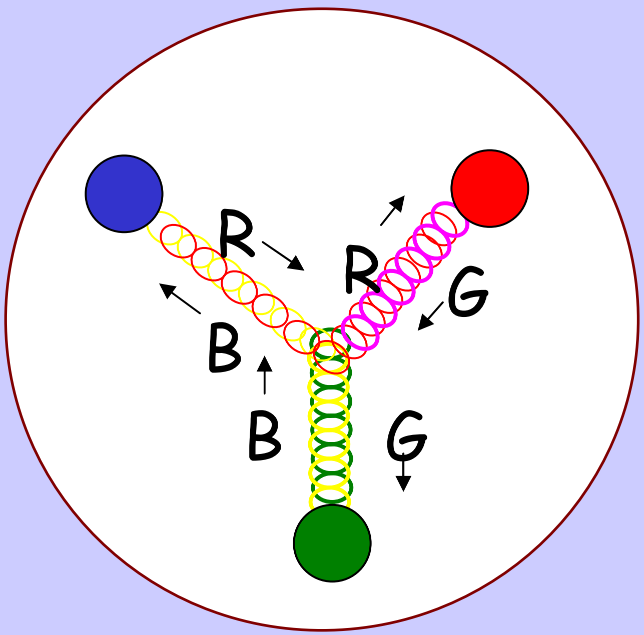

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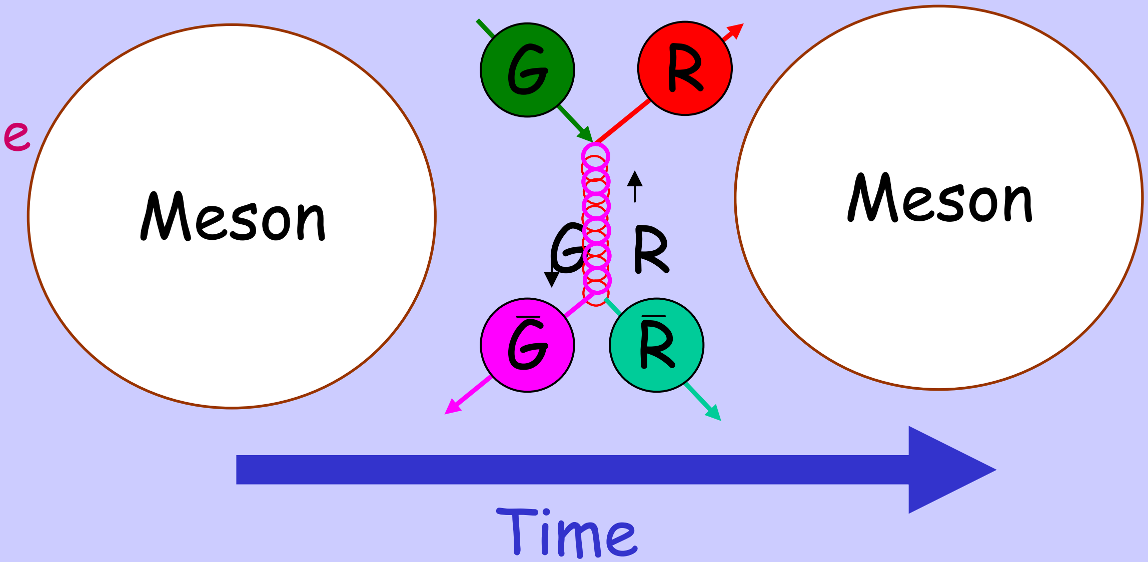
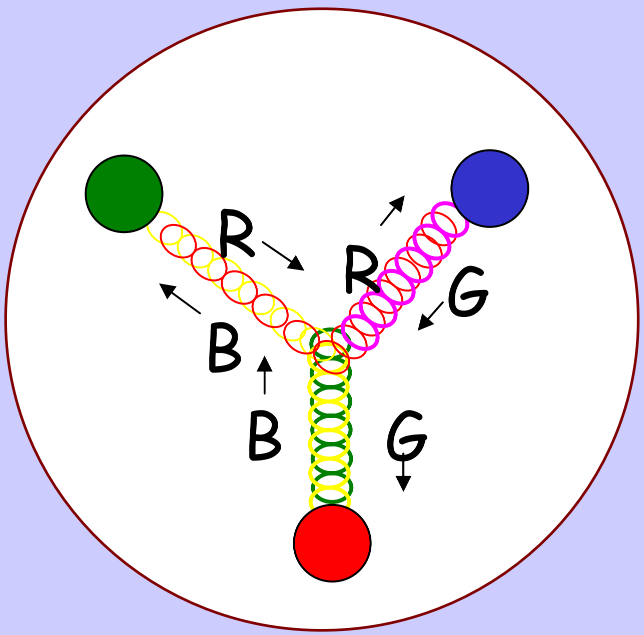
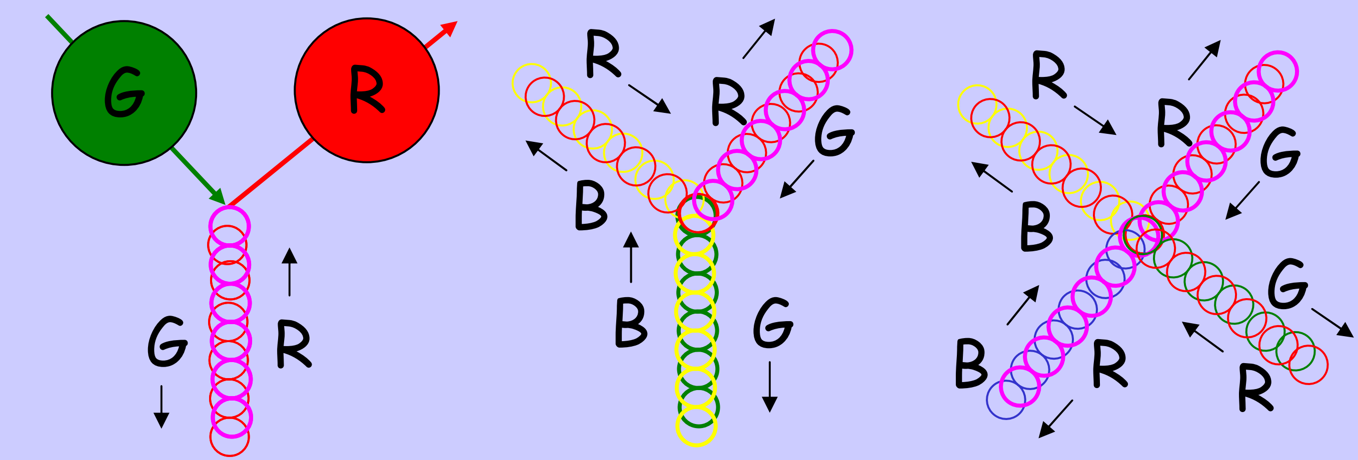




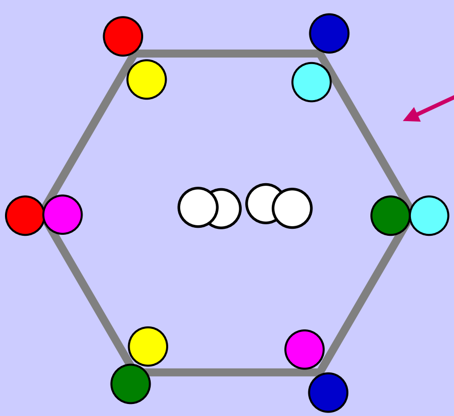
Gluons produce the forces that confine the quarks, but the gluons do not appear to be needed to understand normal hadrons

Gluon Interactions



3 Colors
3 Anti Colors

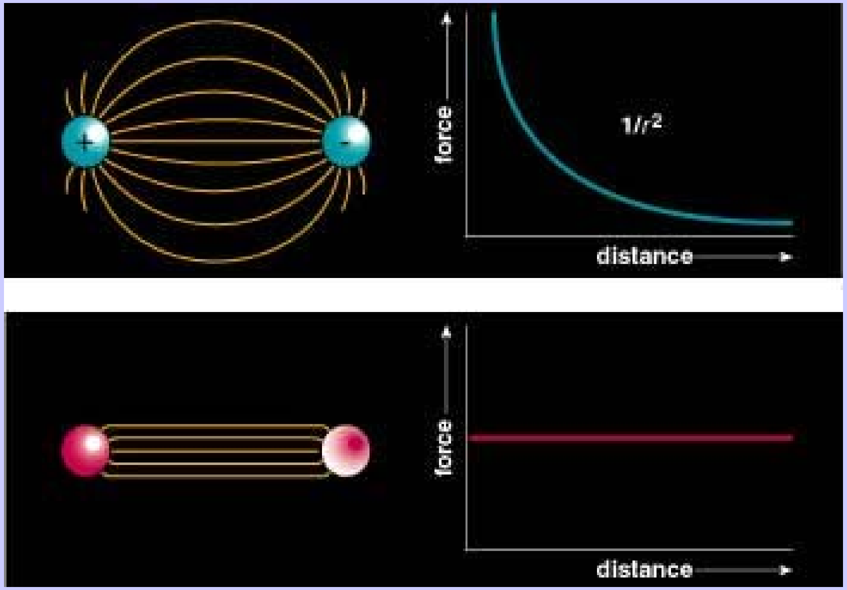
1 color neutral
8 colored objects

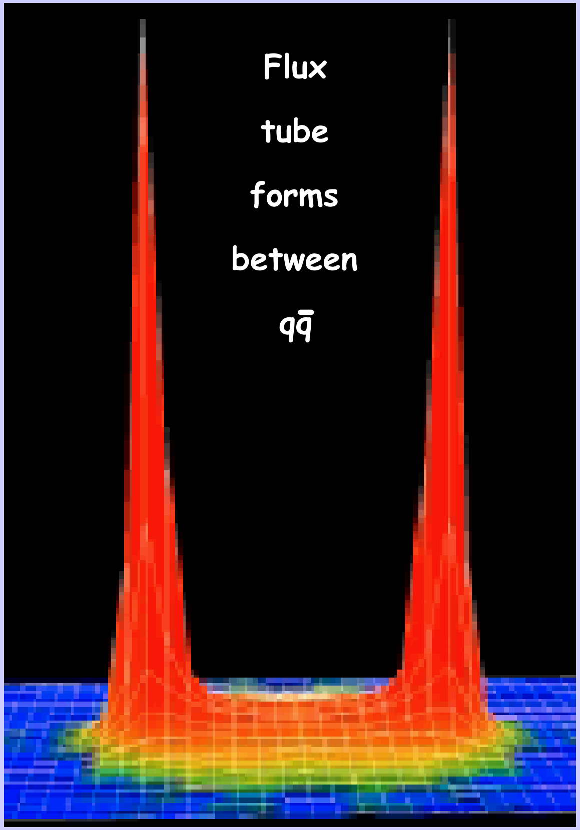


8 Gluons

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

Flux Tubes

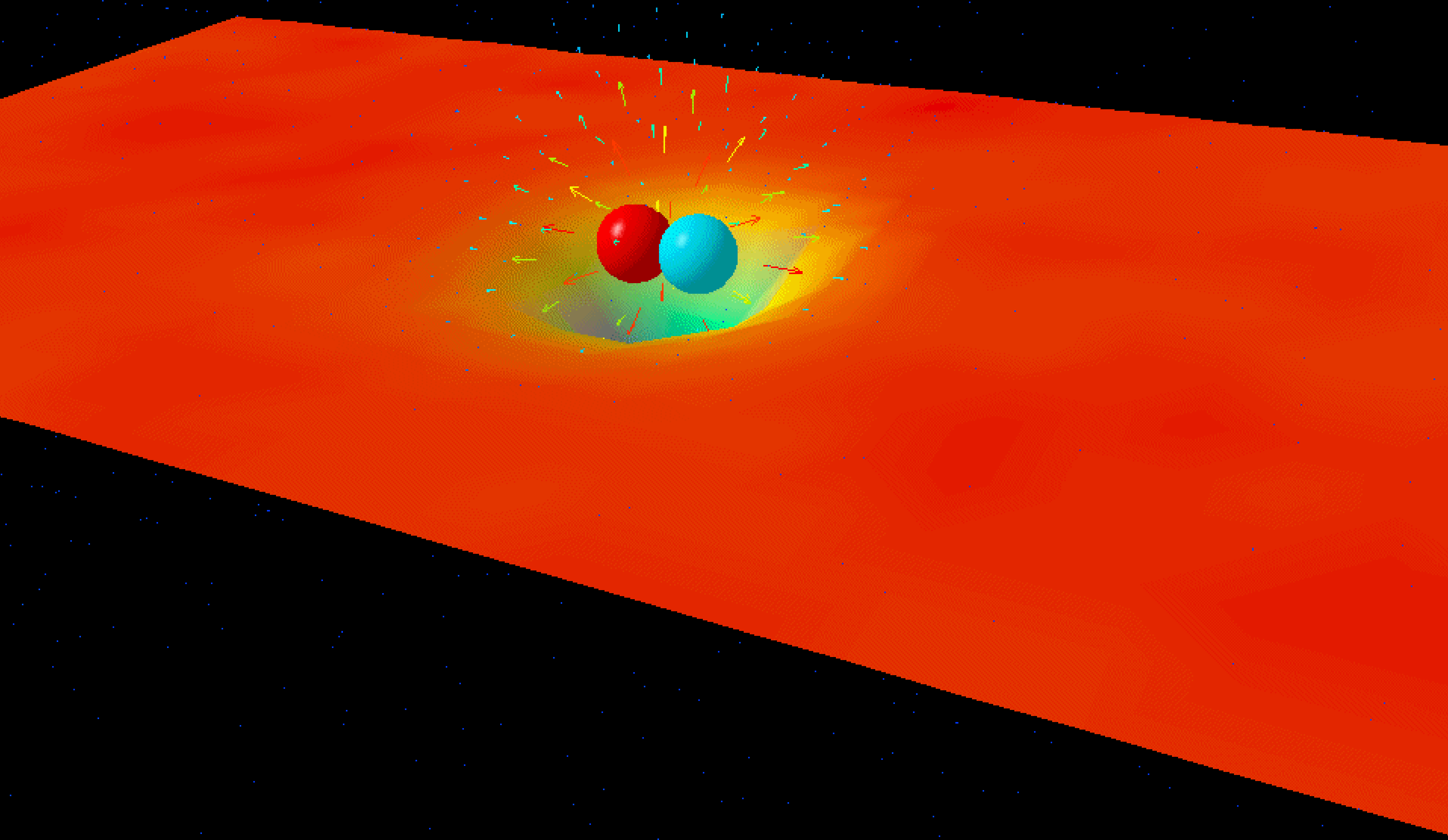




Col r Field: Because of self interaction, confining flux tubes form between static color charges

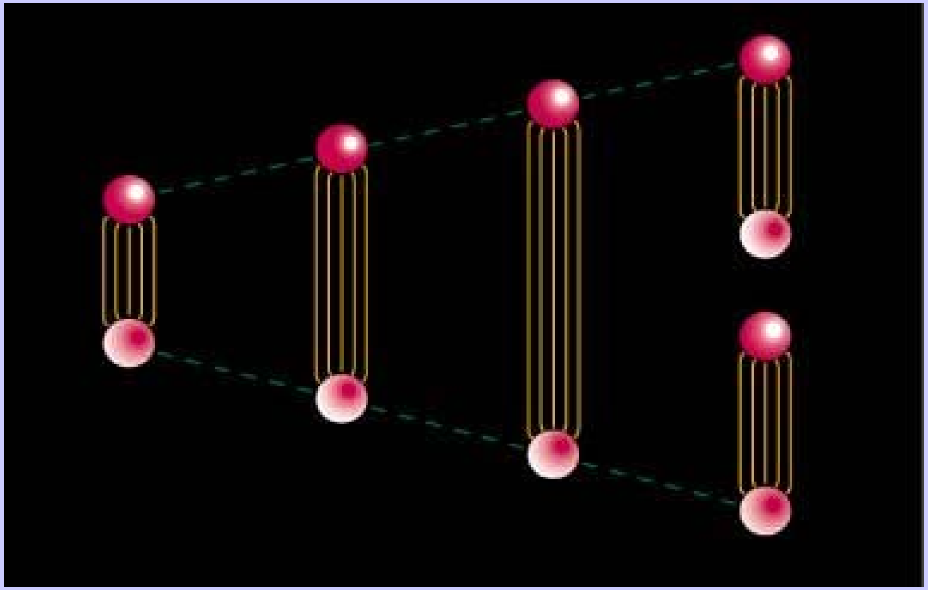
Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons

Flux Tubes



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

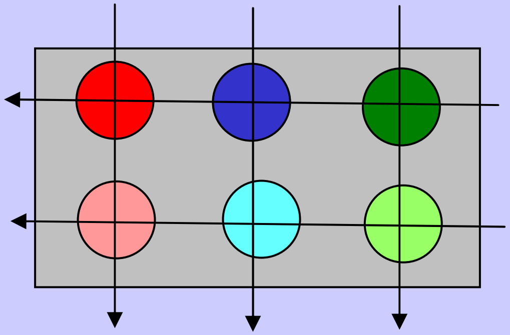


Strong QCD

See $q\bar{q}$ and qqq systems.

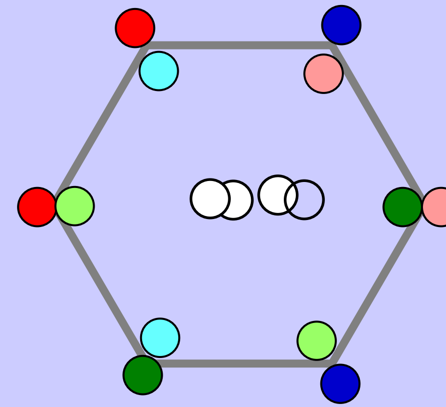
Color singlet objects observed in nature:

white



white

Nominally, glue is not needed to describe hadrons.



$u \quad \bar{u}$

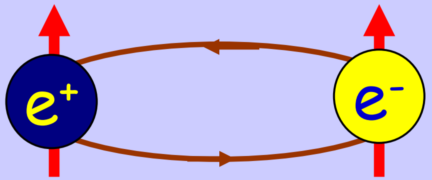
$d \quad \bar{d}$ Focus on "light-quark mesons"

$s \quad \bar{s}$

Allowed systems: $\overbrace{gg\,,\ ggg}^{\text{glueballs}}\,,\ \overbrace{q\bar{q}g}^{\text{hybrids}}\,,\ q\bar{q}q\bar{q}$

Spectroscopy
A probe of QED

Positronium



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

Orbital Angular Momentum: $L=0,1,2,\ldots$

Total Spin: $J=L+S$

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

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

... $\quad$ ...

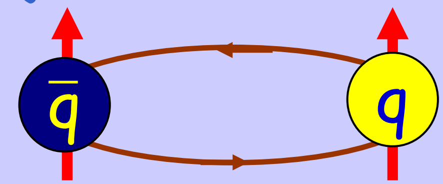
Reflection in a mirror:
Parity: $P=-(-1)^{(L)}$

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

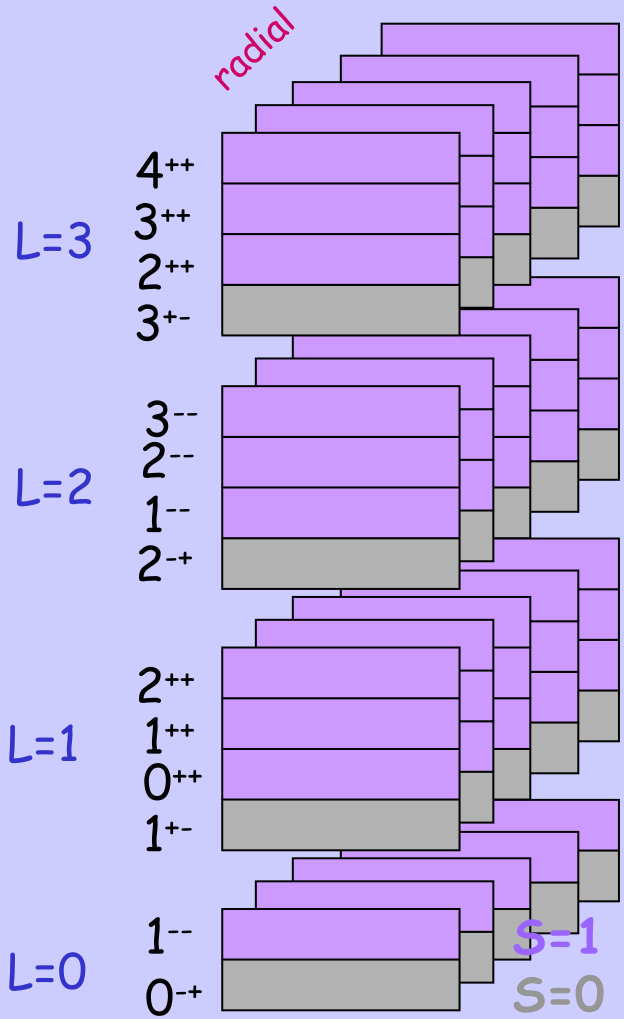
Notation: $J^{(PC)}$ $\quad$ $0^{-+},\ 1^{--},\ 1^{+-},\ 0^{++},\ 1^{++},\ 2^{++}$

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

Quarkonium



Mesons



Consider the three lightest quarks

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

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

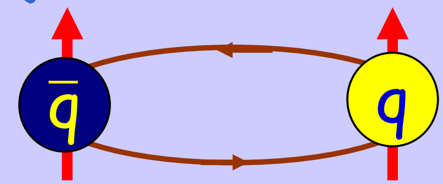
$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

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

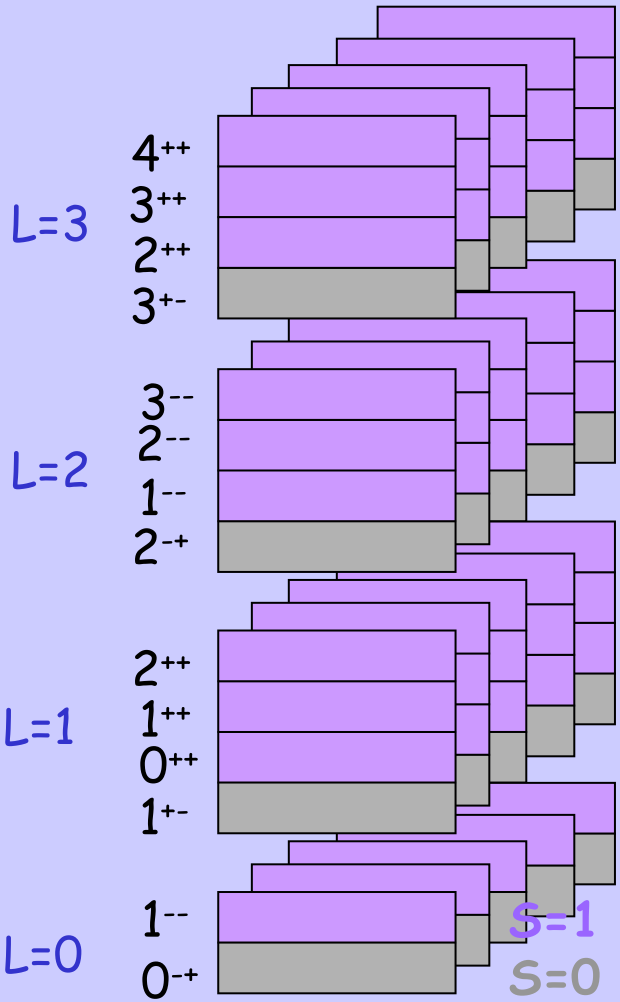
$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \quad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

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

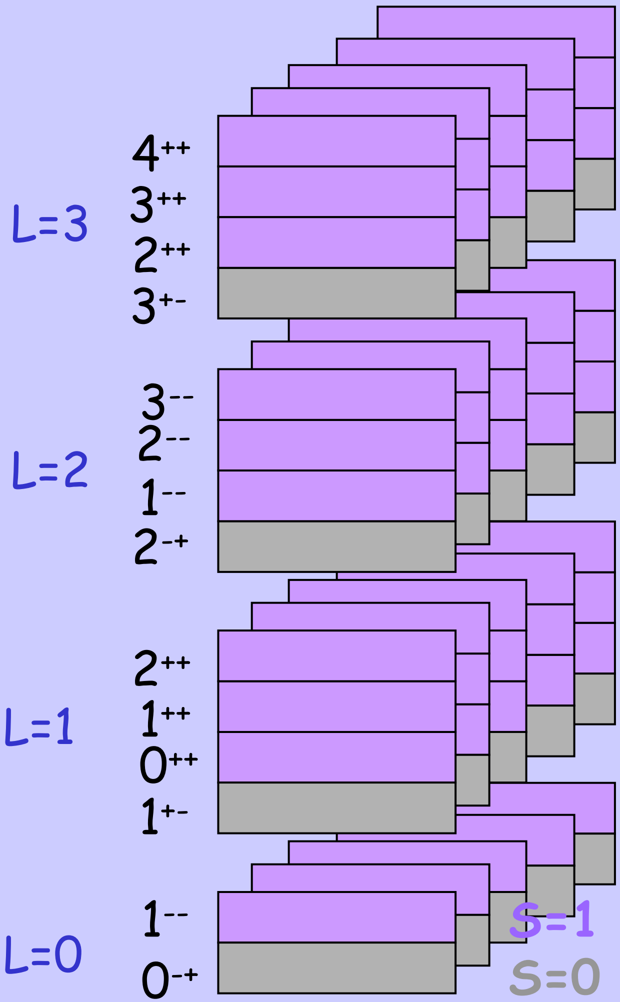
π, K, η, η'

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

SU(3) is broken
Last two members mix

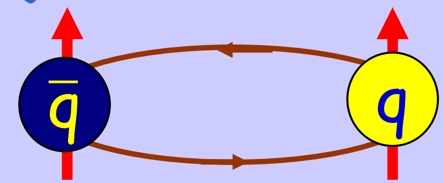
Spectroscopy an QCD

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

Quantum Mechanical Mixing

States with the same quantum numbers mix:

$$\left|1\right\rangle = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$$

$$\left|8\right\rangle = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

$$\text{SU(3)}\left|\begin{matrix} f \\ f' \end{matrix}\right\rangle = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\left|\begin{matrix} 1 \\ 8 \end{matrix}\right\rangle$$

physical states

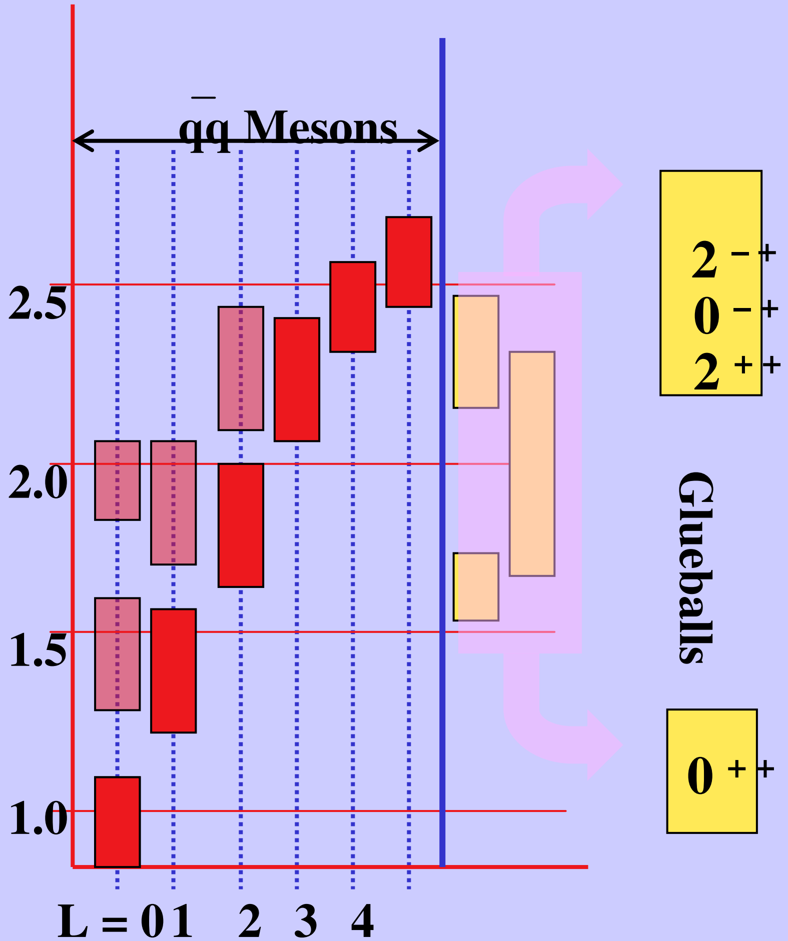
Ideal Mixing:

$$\cos\theta = \sqrt{\frac{2}{3}}$$

$$\sin\theta = \sqrt{\frac{1}{3}}$$

$$\left|\begin{matrix} f \\ f' \end{matrix}\right\rangle = \left|\begin{matrix} \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \\ s\bar{s} \end{matrix}\right\rangle$$

Glueball Predictions



All of these are normal quark-antiquark quantum numbers.

Lattice QCD Predictions

Gluons can bind to form glueballs

EM analogue: massive globs of pure light.

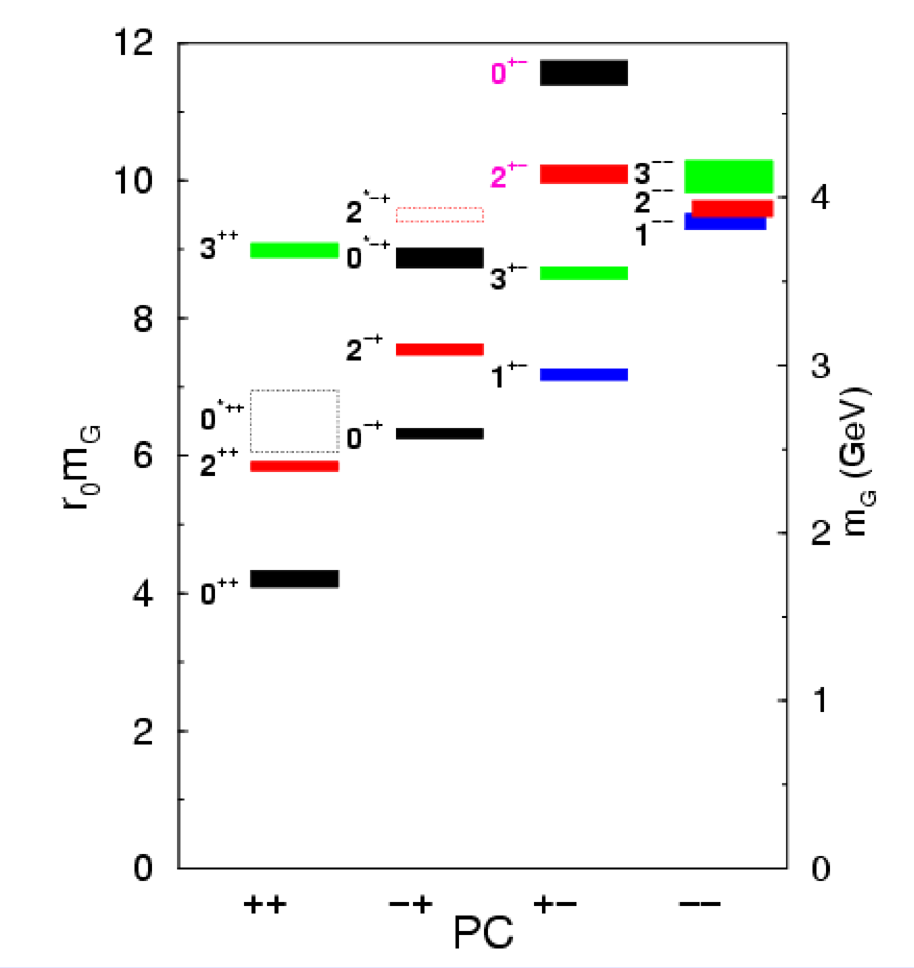
Lattice QCD predicts masses

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.



Identification of Glueballs

Lightest Glueball predicted near two states of same Q.N..

"Over population" Predict 2, see 3 states

Glueballs should decay in a flavor-blind fashion.

$$\boxed{\pi\pi : K\overline{K} : \eta\eta : \eta'\eta' : \eta\eta' = 3 : 4 : 1 : 1 : 0}$$

Production Mechanisms:

Certain are expected to by Glue-rich, others are Glue-poor. Where do you see them?

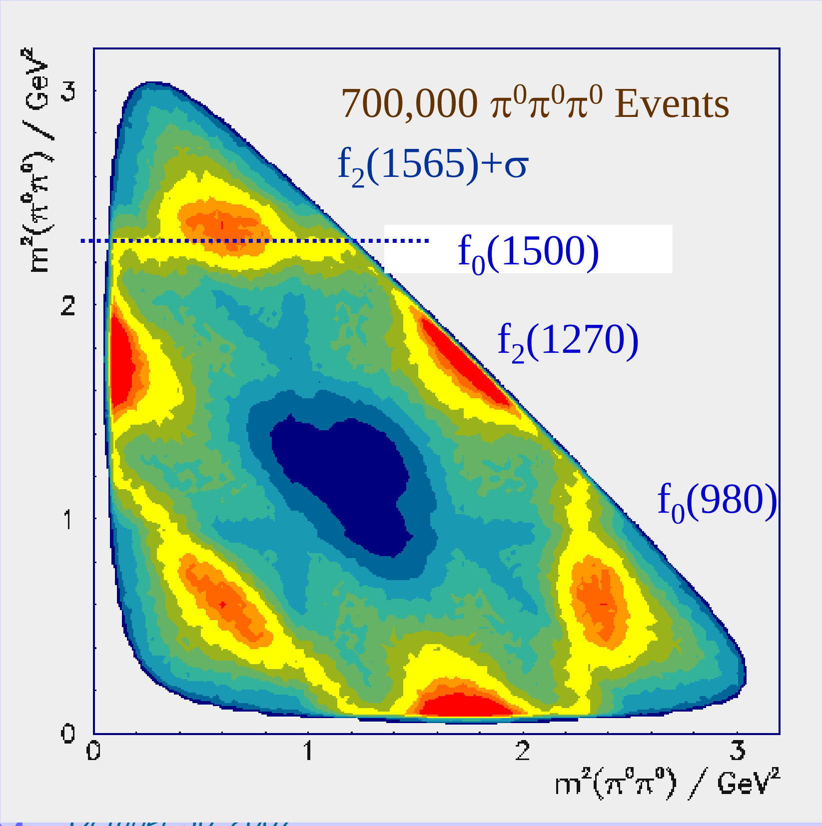
Proton-antiproton
Central Production
J/ψ decays

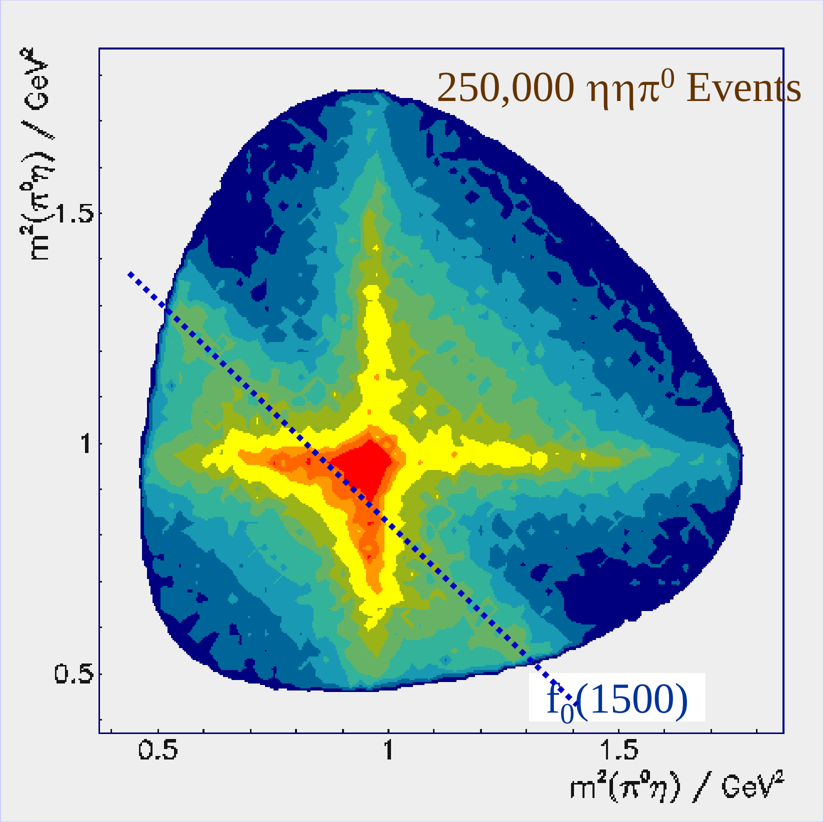
Crystal Barrel Results: antiproton-proton annihilation at rest

Discovery of the $f_0(1500)$ | $f_0(1500) \Rightarrow \pi\pi, \eta\eta, \eta\eta', KK, 4\pi$

Solidified the $f_0(1370)$ | $f_0(1370) \Rightarrow 4\pi$

Discovery of the $a_0(1450)$ → Establishes the scalar nonet

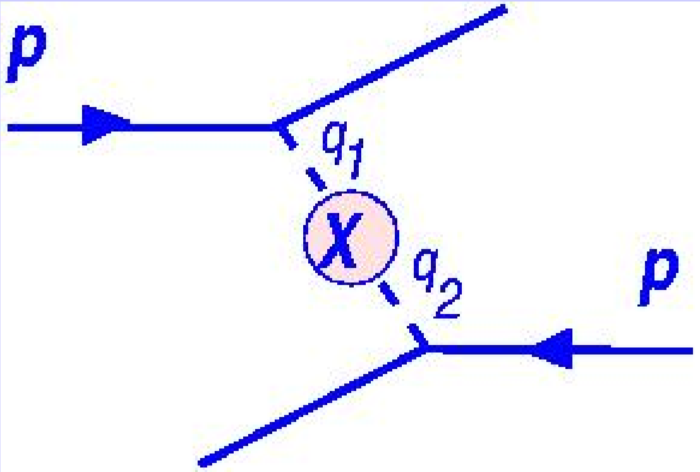




Wa102 Results

CERN experiment colliding p on a hydrogen target.

Central Production Experiment



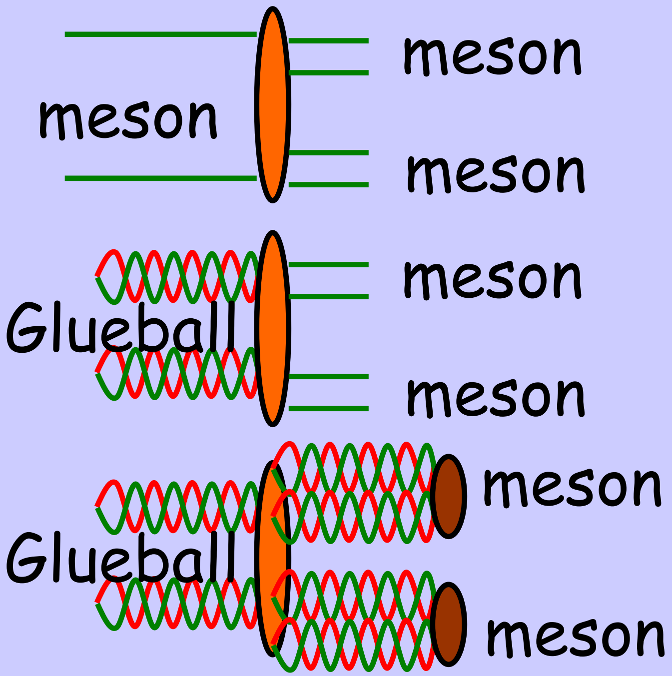
Recent comprehensive data set and a coupled channel analysis.

$$\left\{ \begin{aligned} &\frac{f_0(1370) \to \pi\pi}{f_0(1370) \to K\bar{K}} = 2.17 \pm 0.90 \\ &\frac{f_0(1370) \to \eta\eta}{f_0(1370) \to K\bar{K}} = 0.35 \pm 0.21 \end{aligned} \right.$$

$$\left\{ \begin{aligned} &\frac{f_0(1500) \to \pi\pi}{f_0(1500) \to \eta\eta} = 5.5 \pm 0.84 \\ &\frac{f_0(1500) \to K\bar{K}}{f_0(1500) \to \pi\pi} = 0.32 \pm 0.07 \\ &\frac{f_0(1500) \to \eta\eta'}{f_0(1500) \to \eta\eta} = 0.52 \pm 0.16 \end{aligned} \right.$$

$$\left\{ \begin{aligned} &\frac{f_0(1710) \to \pi\pi}{f_0(1710) \to K\bar{K}} = 0.20 \pm 0.03 \\ &\frac{f_0(1710) \to \eta\eta}{f_0(1710) \to K\bar{K}} = 0.48 \pm 0.14 \\ &\frac{f_0(1710) \to \eta\eta'}{f_0(1710) \to \eta\eta} < 0.05(90\%cl) \end{aligned} \right.$$

A Model for Mixing



1

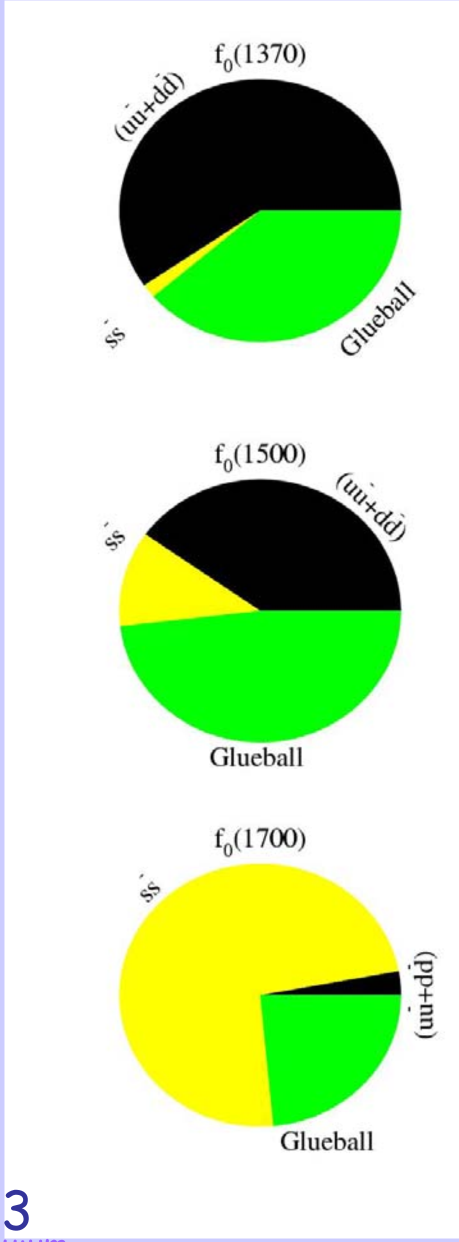
r_2

r_3

$G \rightarrow q\overline{q}$ flavor blind? r

$u\overline{u}, d\overline{d}, s\overline{s}$

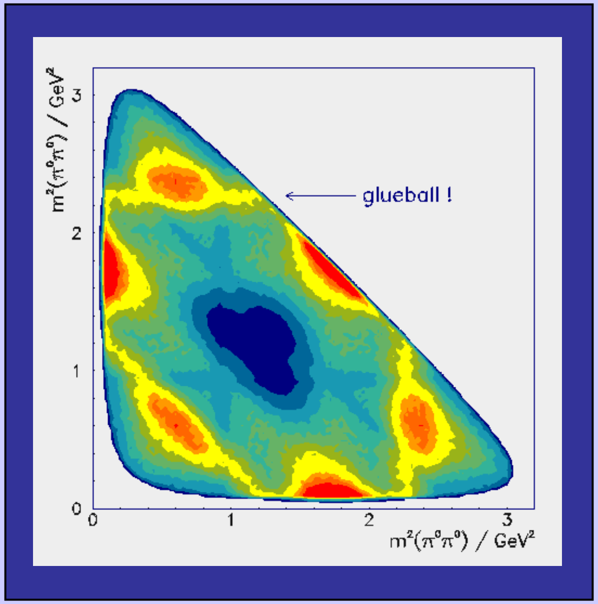
Solve for mixing scheme



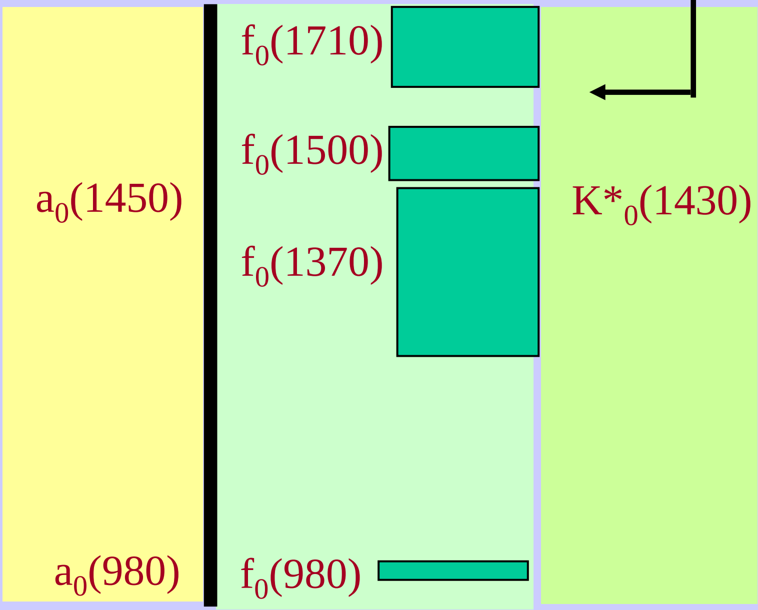
F.Close: hep-ph/0103173

Experimental Evidence

Glueballs



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



Glueball spread over 3 mesons

Are there other glueballs?

Higher Mass Glueballs?

Part of the BES-III program will be to search for glueballs in radiative J/ψ decays.

Lattice predicts that the 2^{++} and the 0^{-+} are the next two, with masses just above $2 GeV/c^2$.

Radial Excitations of the 2^{++} ground state
L=3 2^{++} States + Radial excitations
f2(1950), f2(2010), f2(2300), f2(2340)…

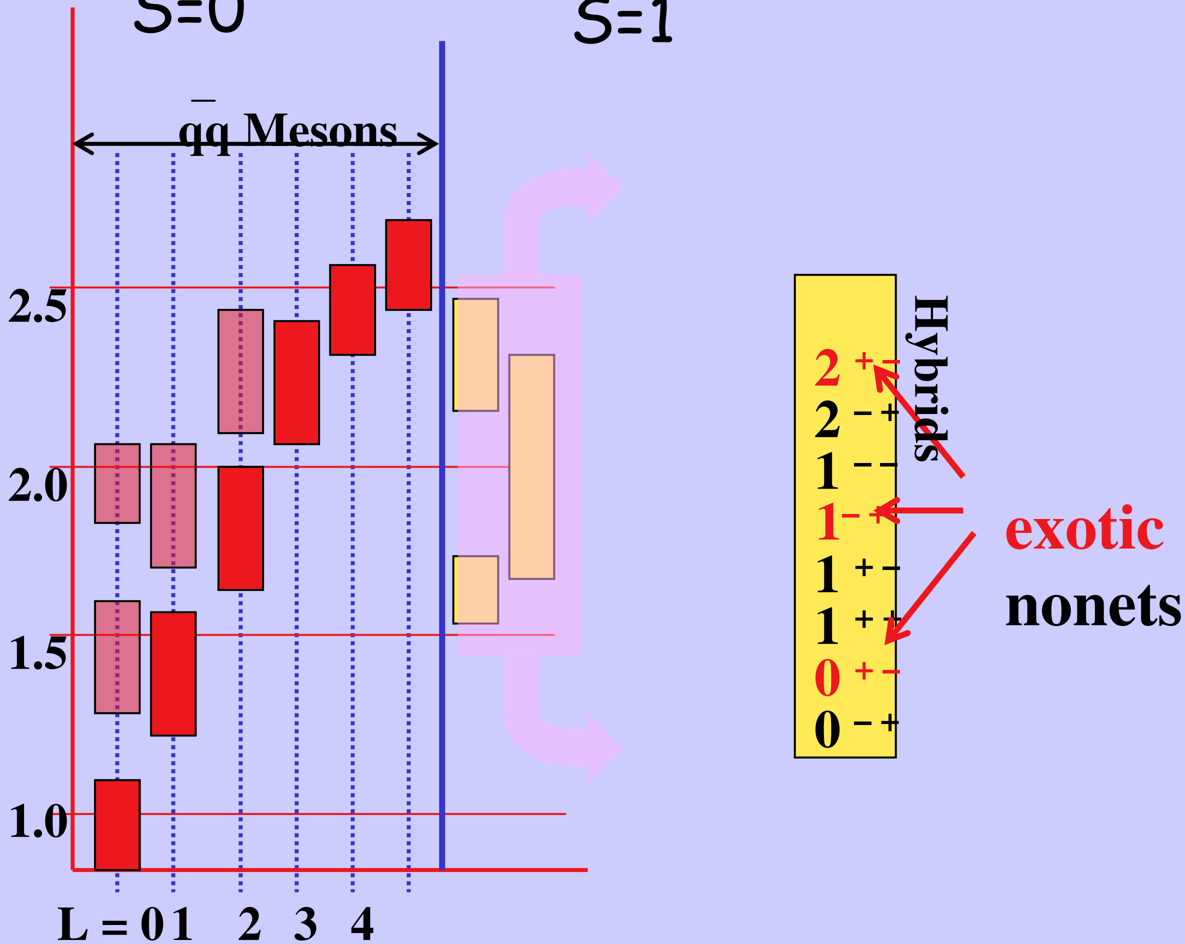
2'nd Radial Excitations of the η and η',
perhaps a bit cleaner environment! (I would
Not count on it though….)

I expect this to be very challenging.

Hybrid Meson 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^{--}

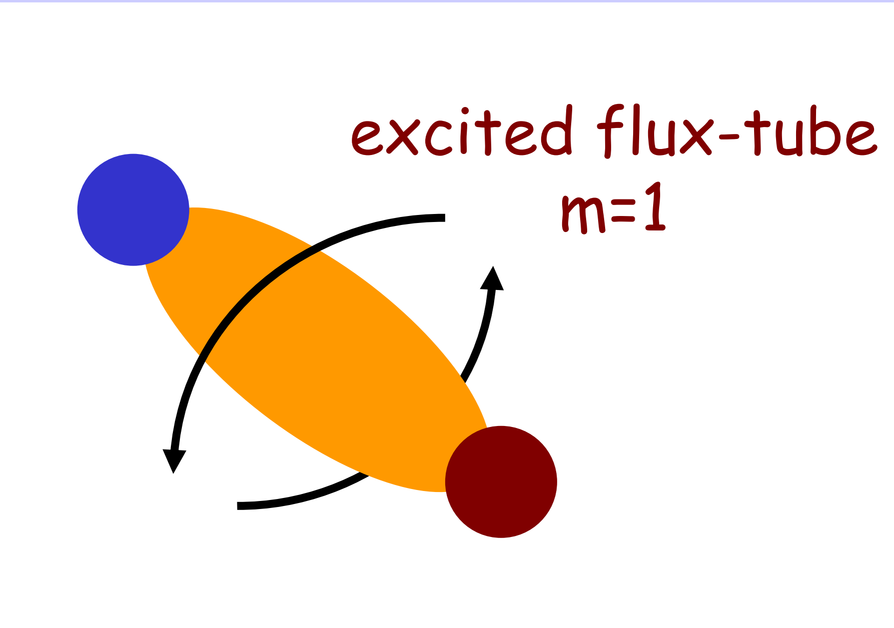
Start with S=1

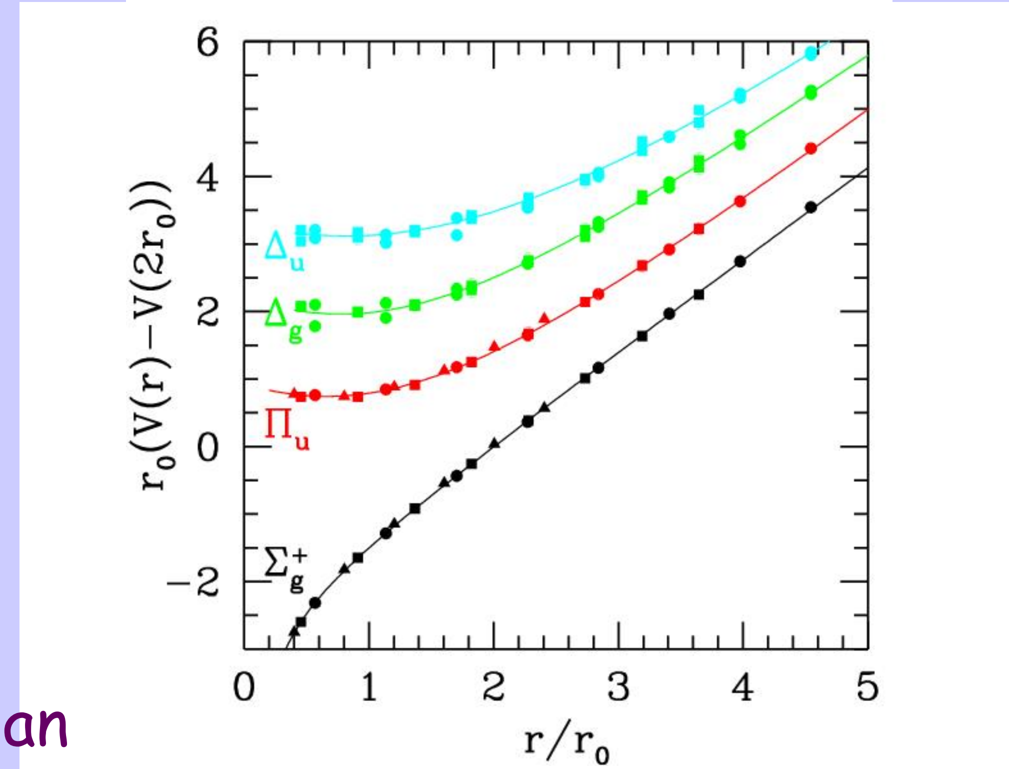
0^{-+} & 0^{+-}

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

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

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**

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
Bernard(04)	1.792§0.139

1^{-+}	1.9+/- 0.2
2^{+-}	2.0+/- 0.11
0^{+-}	2.3+/- 0.6

In the charmonium sector:

1^{-+}	4.39 ±0.08
0^{+-}	4.61 ±0.11

Splitting = 0.20

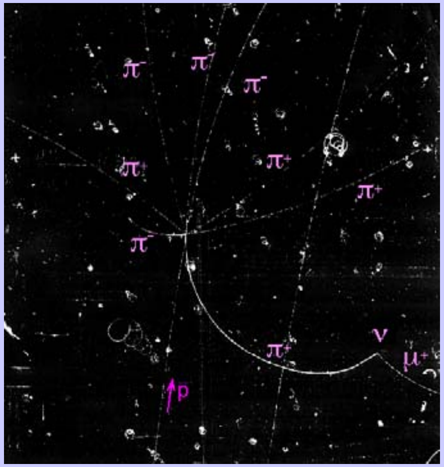
Looking for Hybrids

Analysis Method

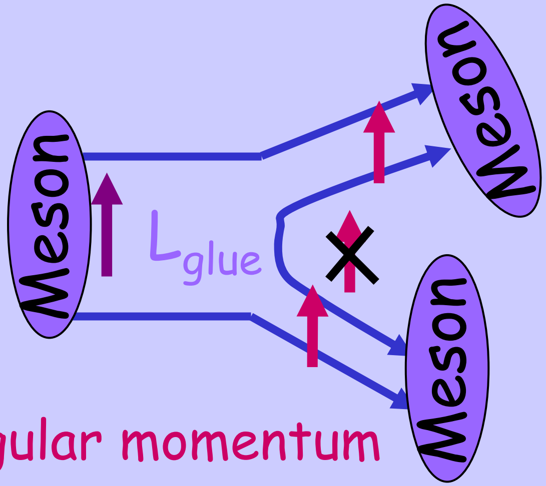
Partial Wave Analysis

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.

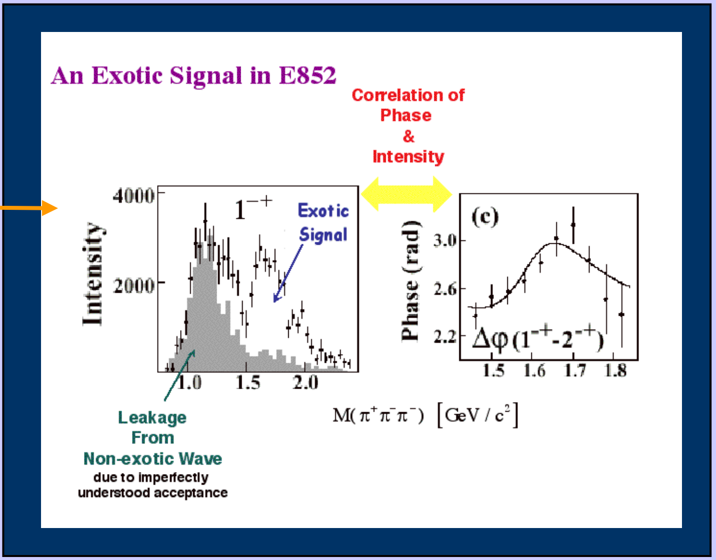
Experimental Evidence Hybrids

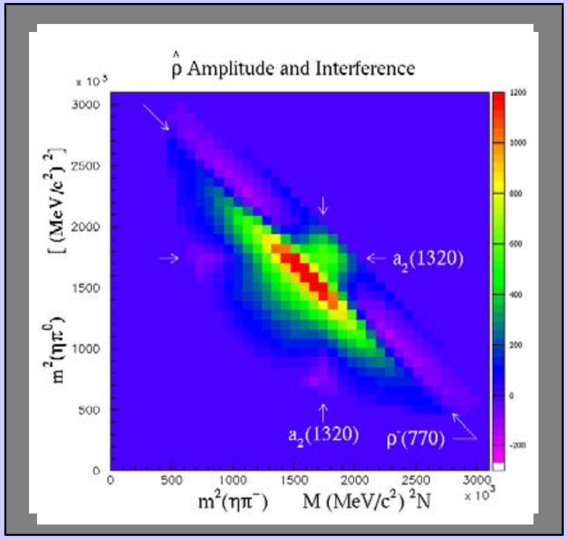
Exotic Mesons

1^{-+} mass 1.4

E852 BNL '97

CBAR CERN '97





Too light

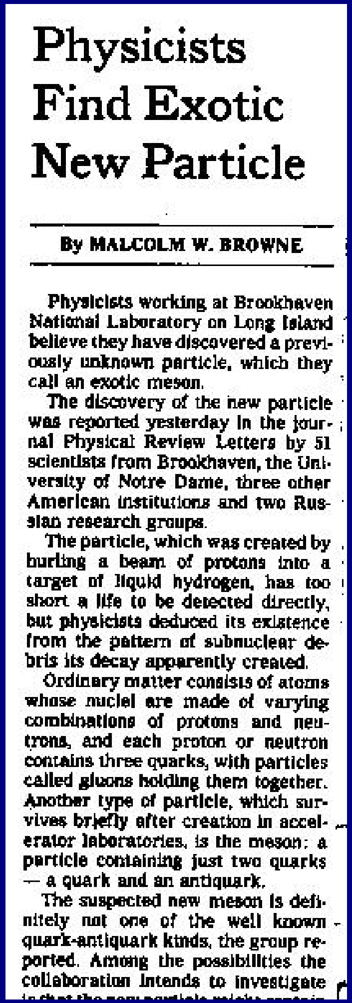
Not Consistent

Possible rescattering (?)

Decays are wrong (?)

Not a Hybrid

New York Times, Sept. 2, 1997



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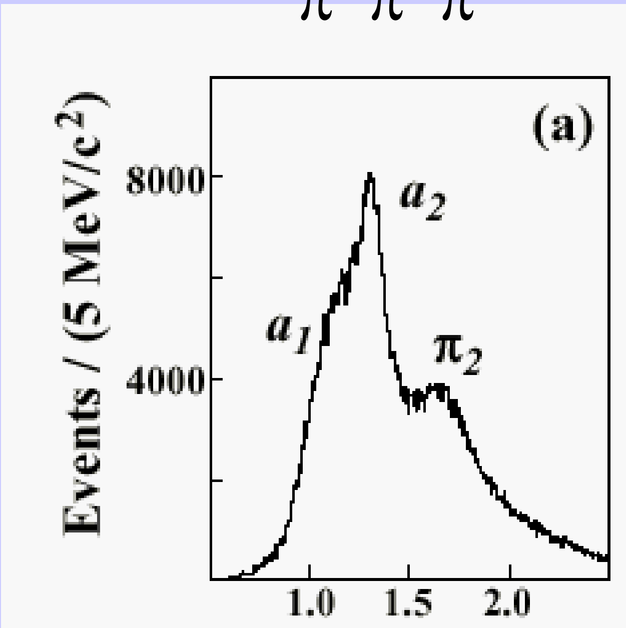
The suspected new meson is definitely not one of the well known quark-antiquark kinds, the group reported. Among the possibilities the collaboration intends to investigate

E852 Results $\pi^- p \to \pi^+ \pi^- \pi^- p$

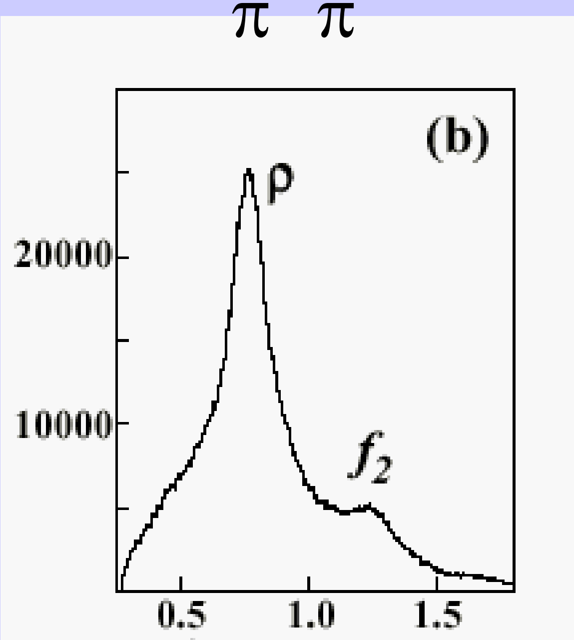
At 18 GeV/c

$\pi^+\pi^-\pi^-$



$M(\pi^+\pi^-\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

$\pi^+\pi^-$



$M(\pi^+\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

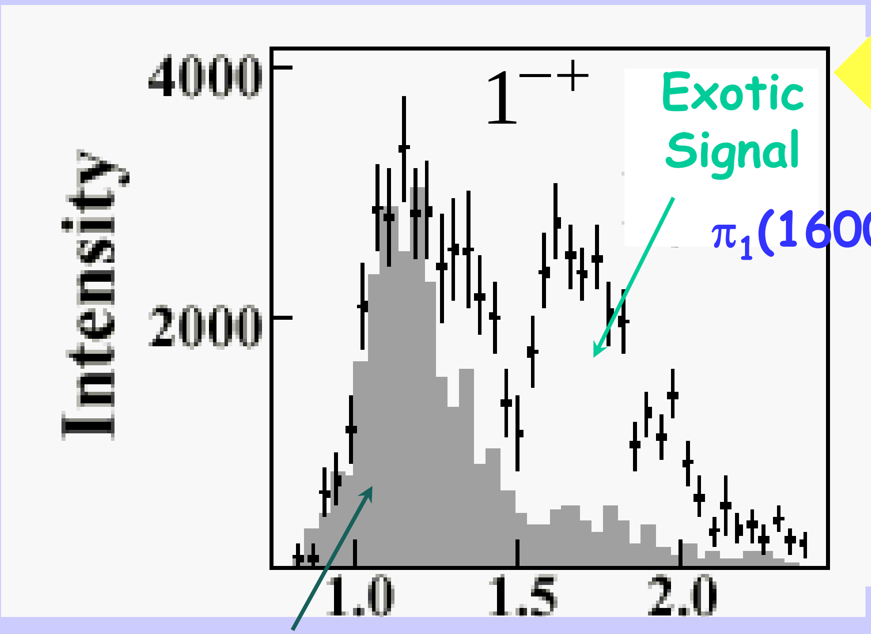
to partial wave analysis

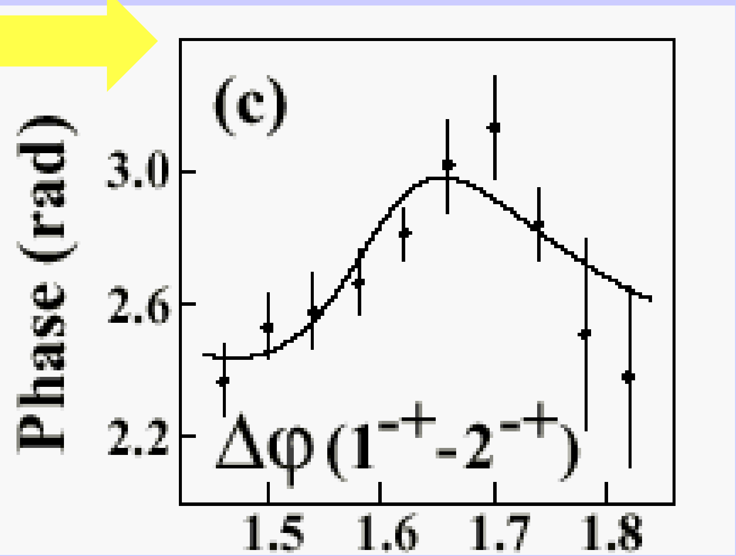
suggests $\pi^- p \to \rho^0 \pi^- p$

$\to \pi^+\pi^-\pi^- p$

An Exotic Signal

Correlation of
Phase
&
Intensity





$M(\pi^+\pi^-\pi^-)\ [\mathrm{GeV}/c^2]$

Leakage
From
Non-exotic Wave
due to imperfectly
understood acceptance

$3\pi\ \ m=1593{+-}8^{+28}_{-47}\quad \Gamma=168{+-}20^{+150}_{-12}$

$\pi\eta'\ m=1597{+-}10^{+45}_{-10}\ \ \Gamma=340{+-}40{+-}50$

In Other Channels

1-+ in η′π

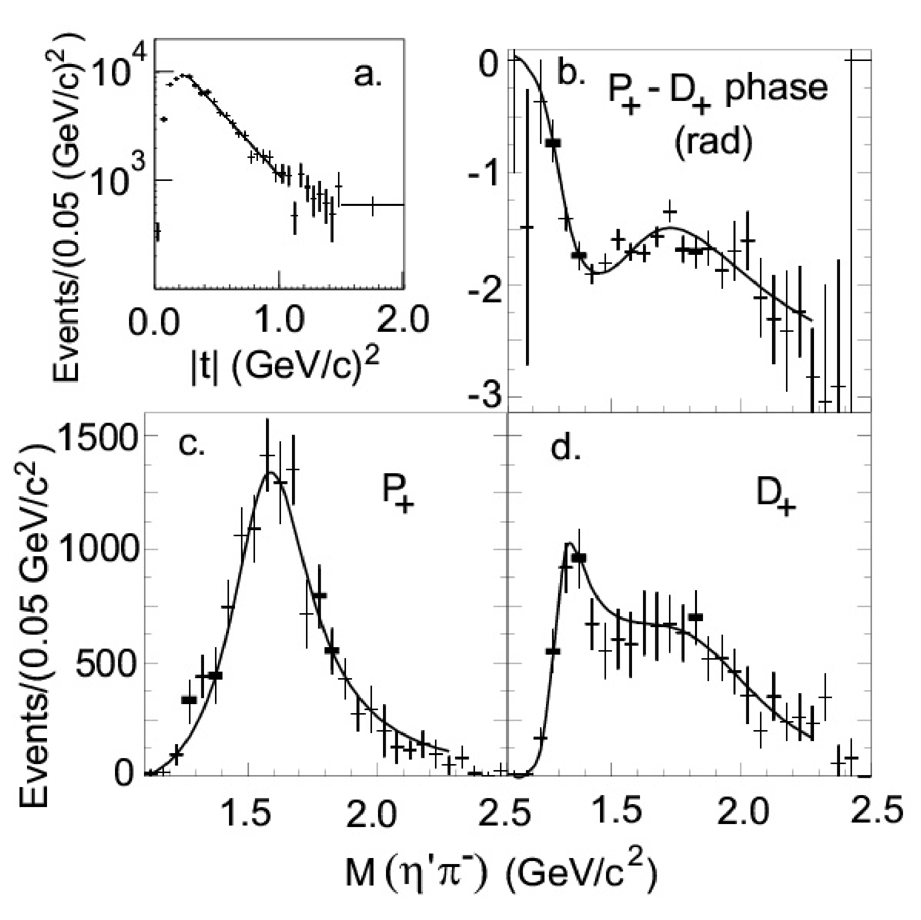
$\pi^- p \rightarrow \eta' \pi^- p$ at 18 GeV/c

The π_1(1600) is the Dominant signal in η′π.

Mass = 1.597±0.010 GeV

Width = 0.340±0.040 GeV

$\pi_1(1600) \rightarrow \eta'\pi$



In Other Channels

E852 Results

1-+ in $f_1\pi$ and $b_1\pi$

$\pi^- p \rightarrow \eta\pi^+\pi^-\pi^- p$

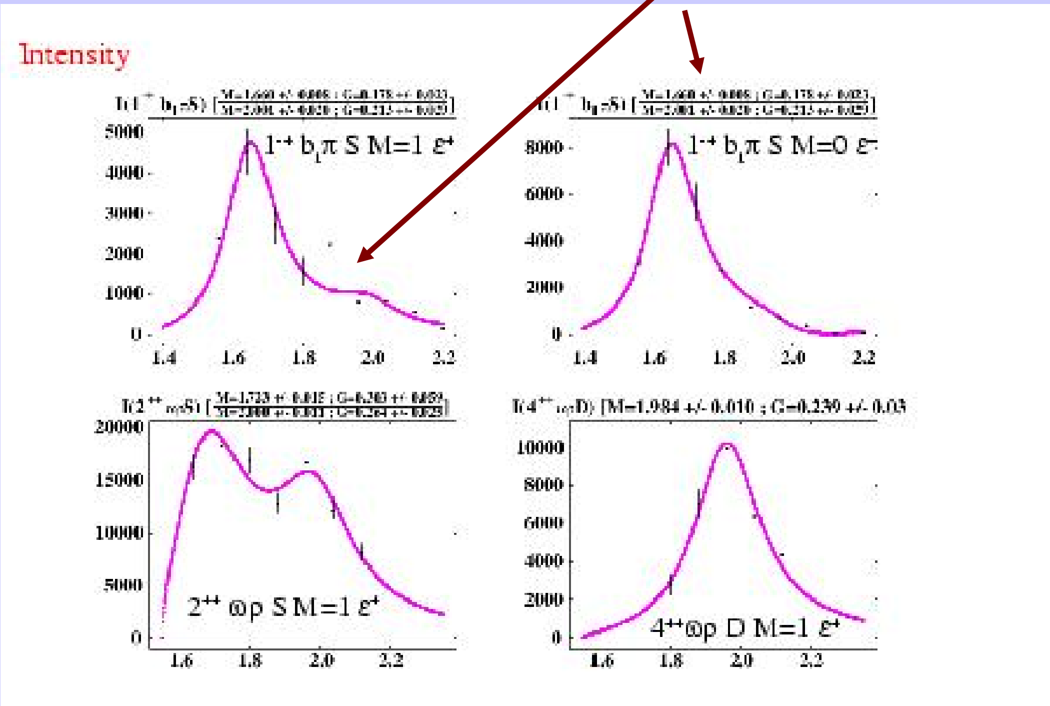
$\pi_1(1600) \rightarrow f_1\pi$

Mass=1.709±0.024 GeV

Width=0.403±0.08 GeV

In both $b_1\pi$ and $f_1\pi$, observe Excess intensity at about $2GeV/c^2$.
Mass ~ 2.00 GeV,
Width ~ 0.2 to 0.3 GeV

$\pi^- p \rightarrow \omega\pi^0\pi^- p$ $\quad$ $\pi_1(1600) \rightarrow b_1\pi$

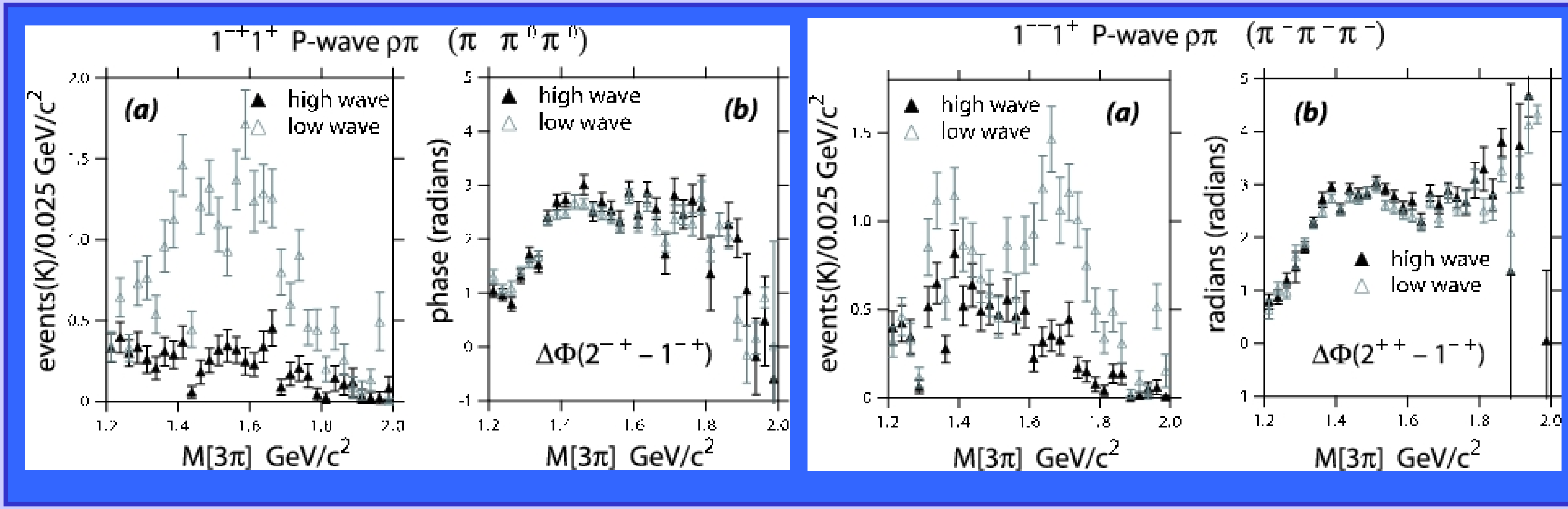


Mass = 1.687±0.011 GeV

Width = 0.206±0.03 GeV

New Analysis

Dzierba et. al. PRD 73 (2006)



Add $\pi_2(1670)$!$\rho\pi$ (L=3)
Add $\pi_2(1670)$!$\rho_3\pi$
Add $\pi_2(1670)$! $(\pi\pi)_S\pi$
Add a_3 decays
Add $a_4(2040)$

10 times statistics in each of two channels.

Get a better description of the data via moments comparison

No Evidence for the $\pi_1(1670)$

Exotic Signals

π_1**(1400)** Width ~ 0.3 GeV, Decays: only $\eta\pi$
weak signal in πp production (scattering??)
strong signal in antiproton-deuterium.

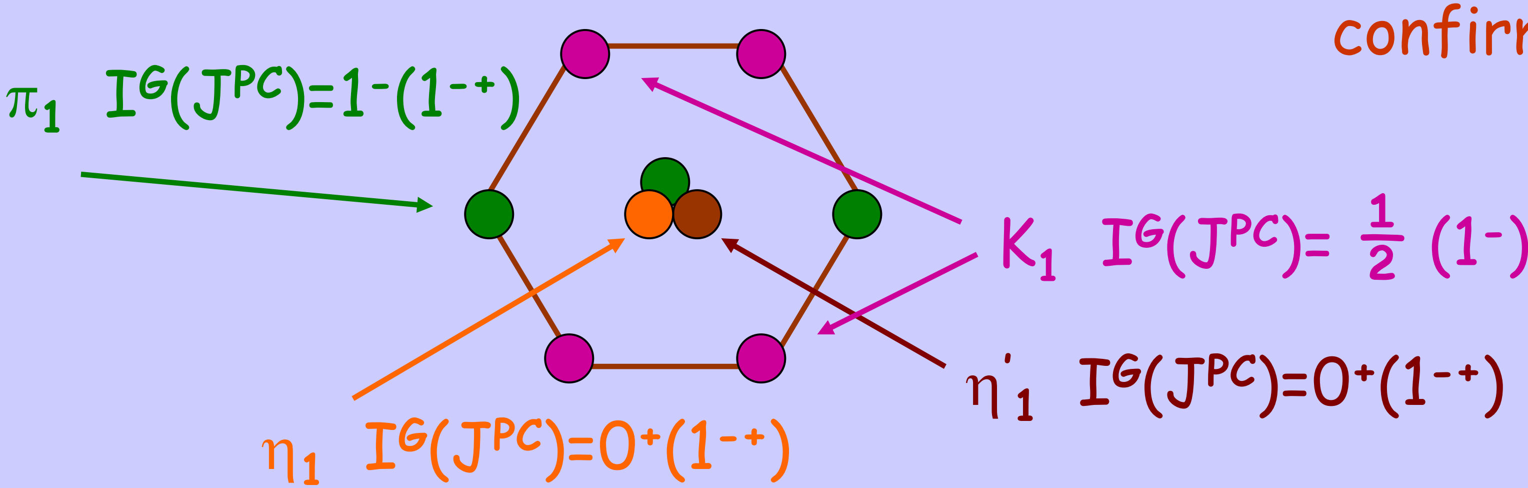
NOT A HYBRID

π_1(1600) Width ~ 0.16 GeV, Decays $\rho\pi, \eta'\pi, (b_1\pi)$
Only seen in πp production, (E852 + VES)

Does this exist?

π_1**(2000)** Weak evidence in preferred hybrid modes $f_1\pi$ and $b_1\pi$

The right place. Needs confirmation.



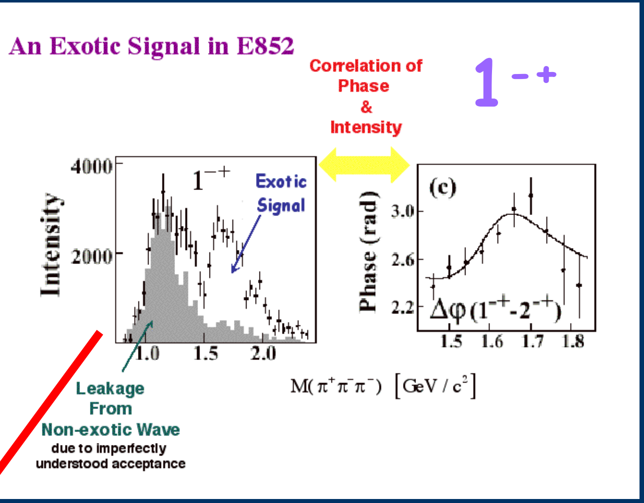
Experimental Evidence

Hybrid Nonets

Establish other Nonets:

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

Levels



Built on normal mesons

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

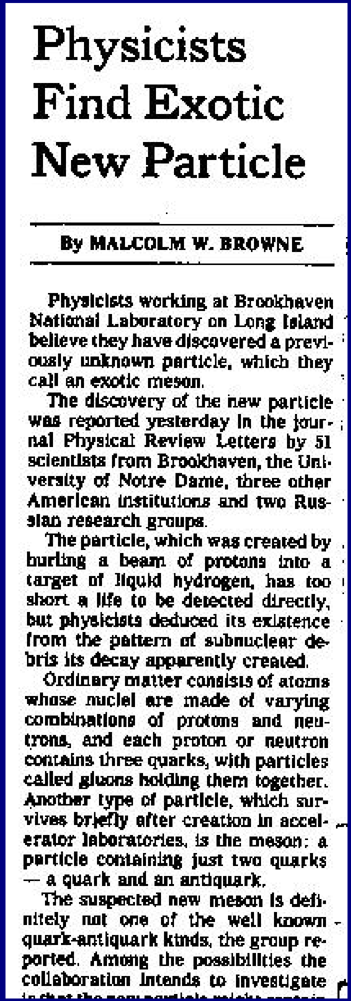
$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

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

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

Identify other states in nonet to establish hybrid

New York Times, Sept. 2, 1997



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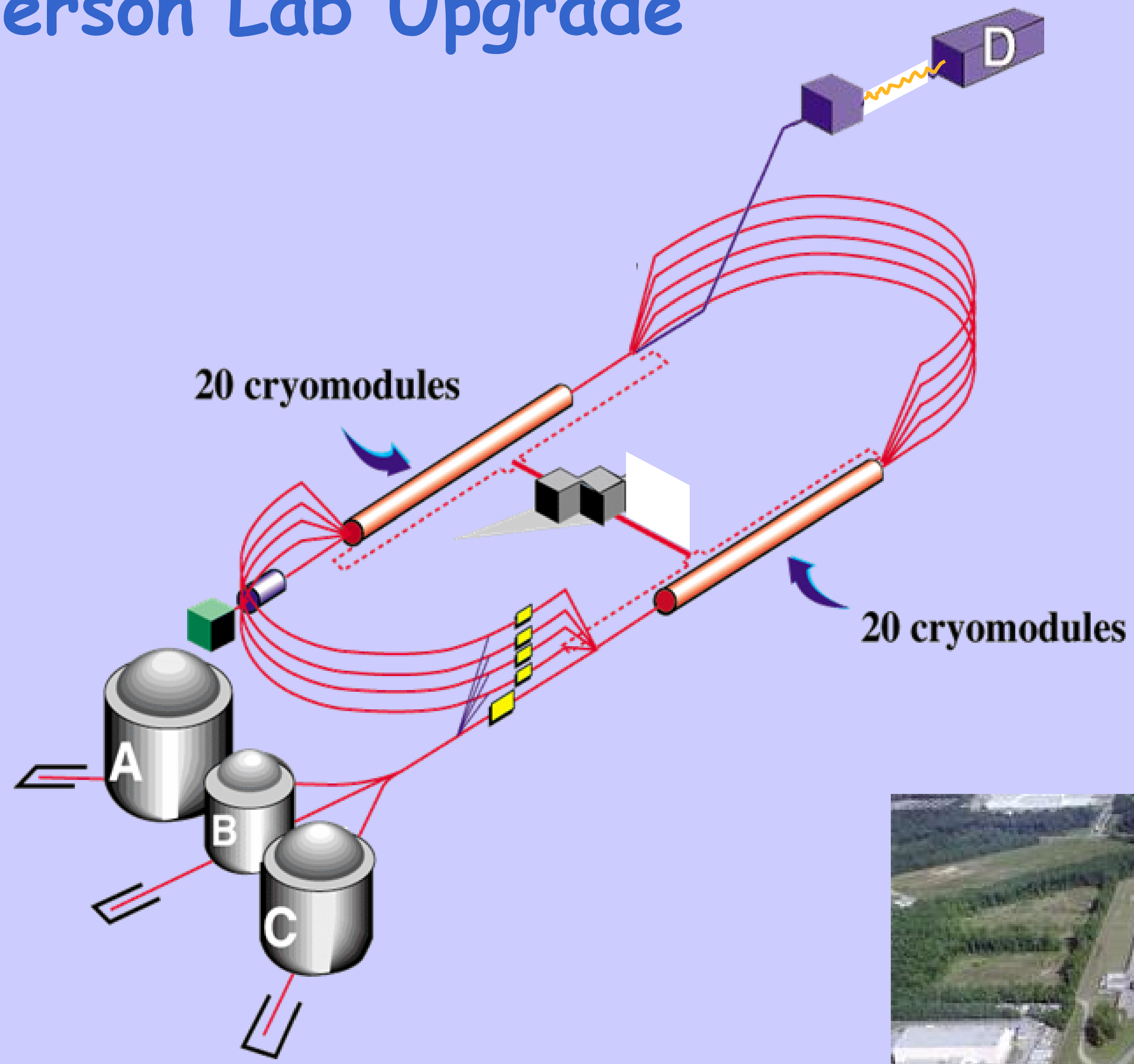
Jefferson Lab Upgrade



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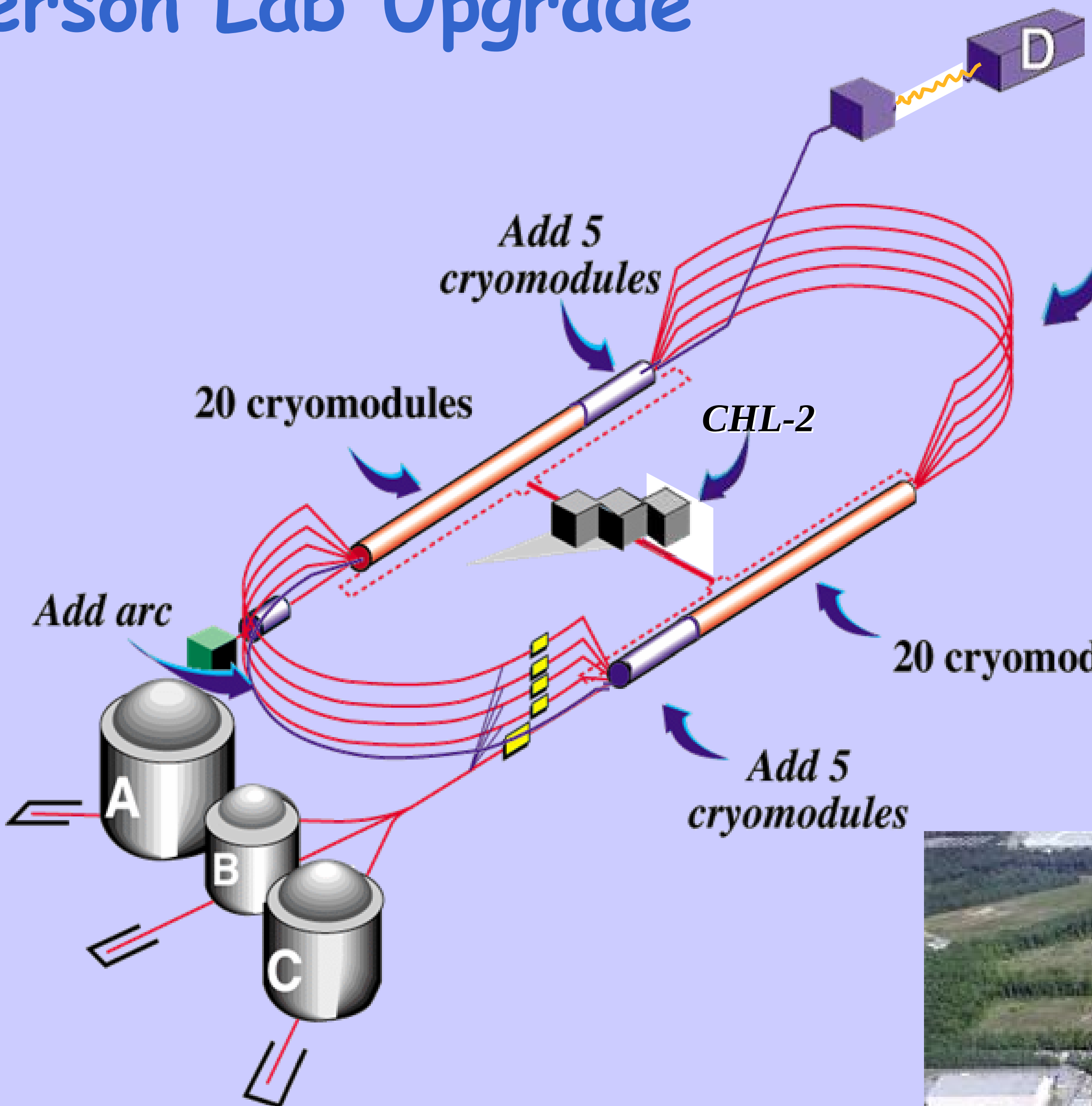
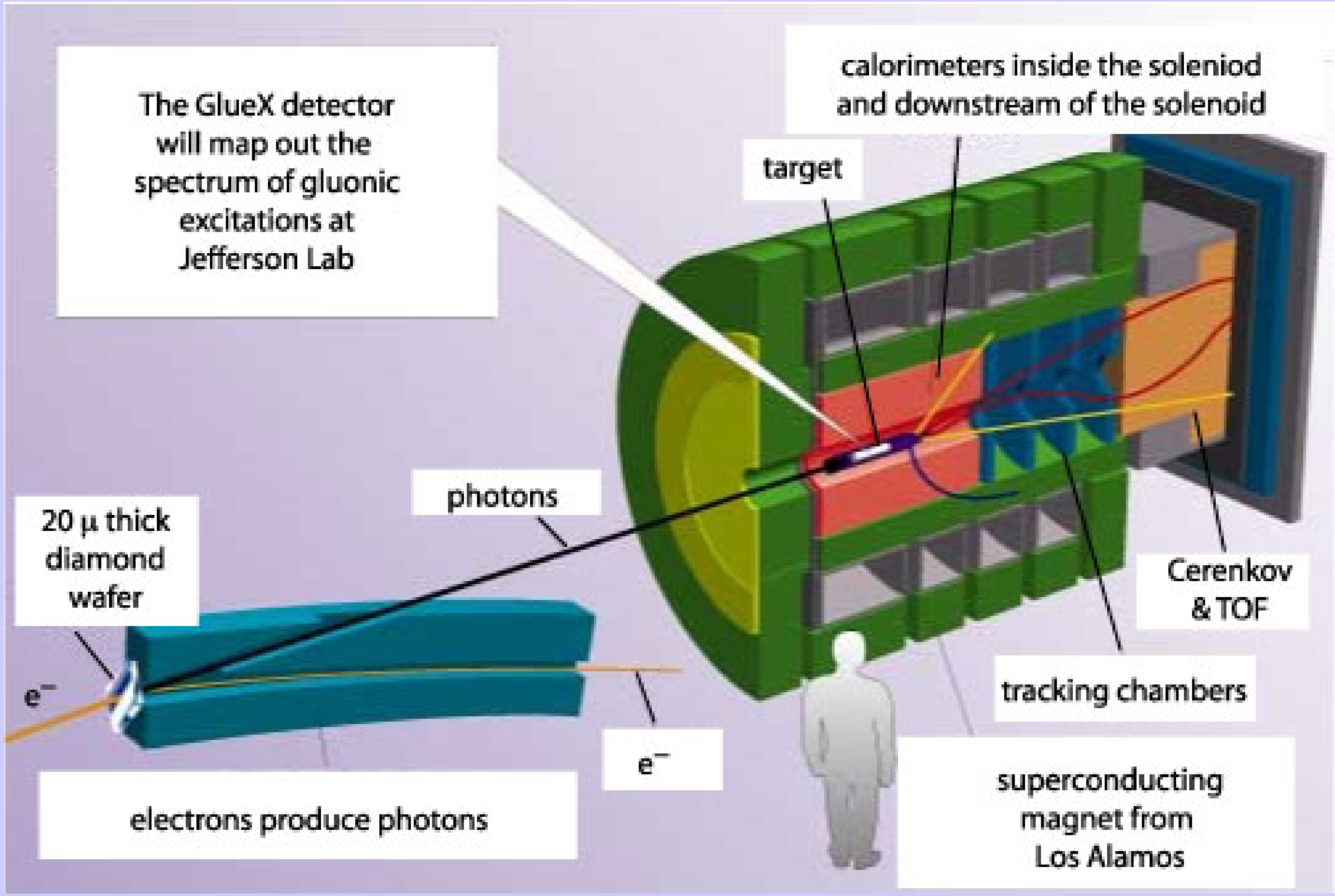
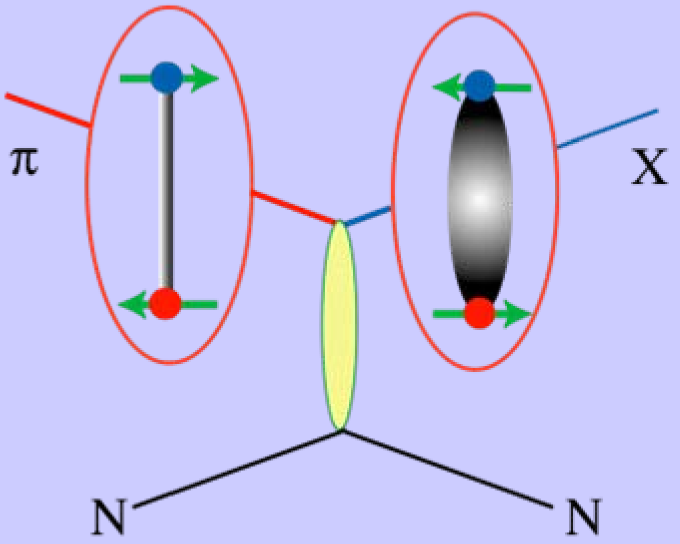
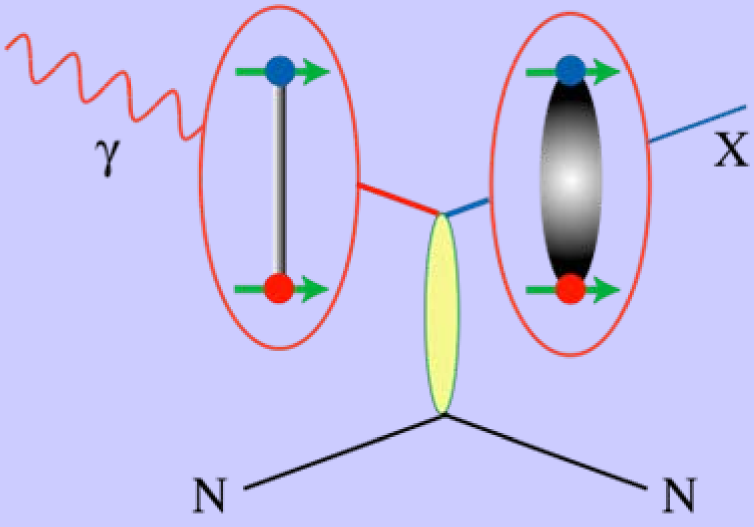


The GlueX Experiment



How to Produce Hybrids





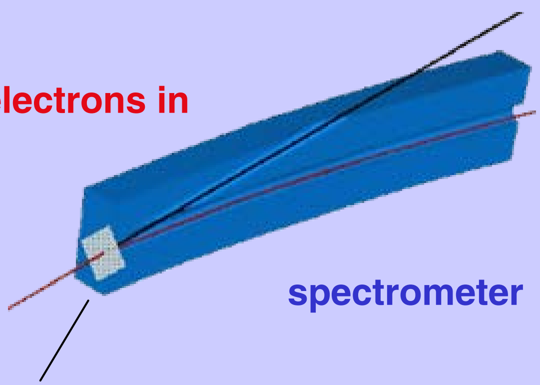
Beams of photons may be a more natural way to create hybrid mesons.

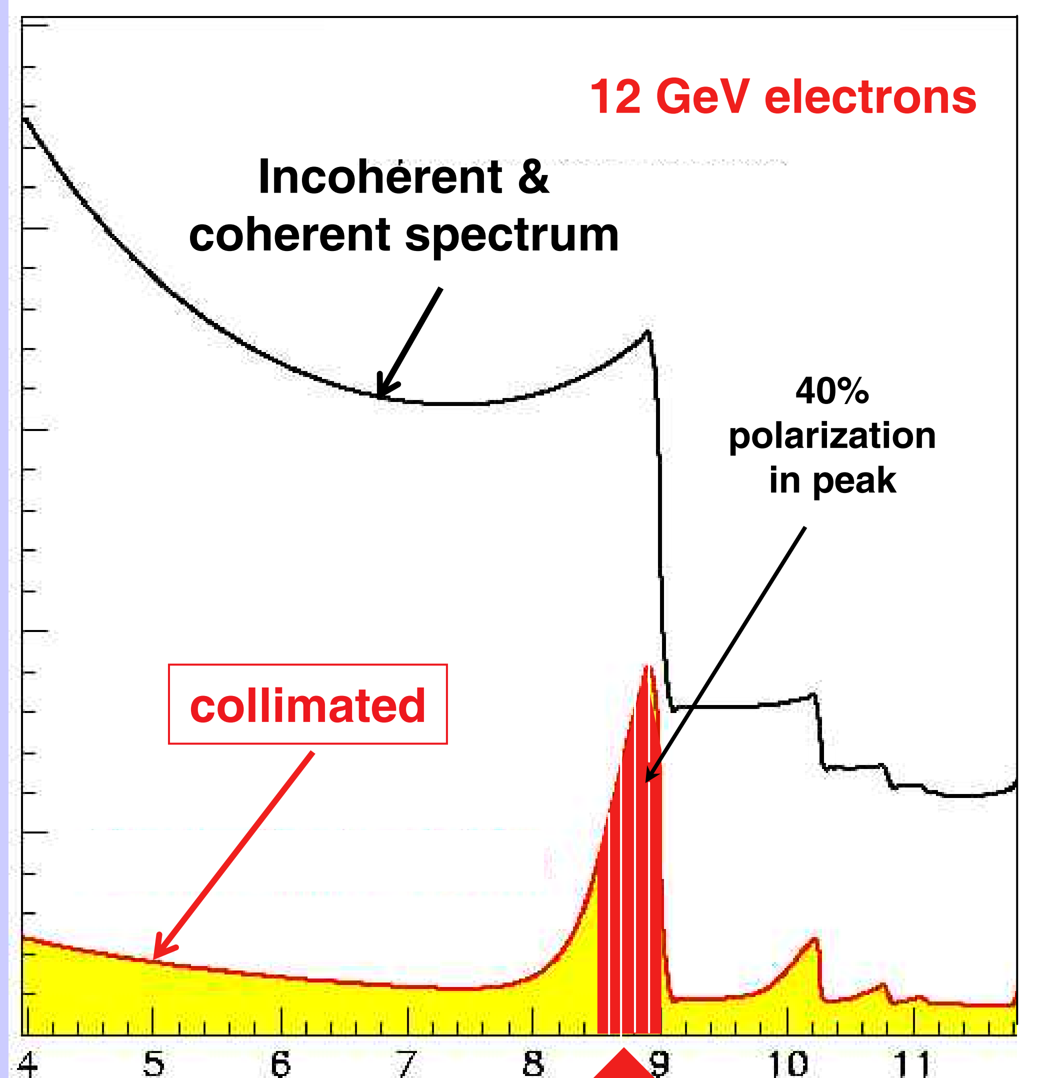
Simple QN counting leads to the exotic mesons

There is almost no data for photon beams at these energies. GlueX will increase samples by 3-4 orders of magnitude.

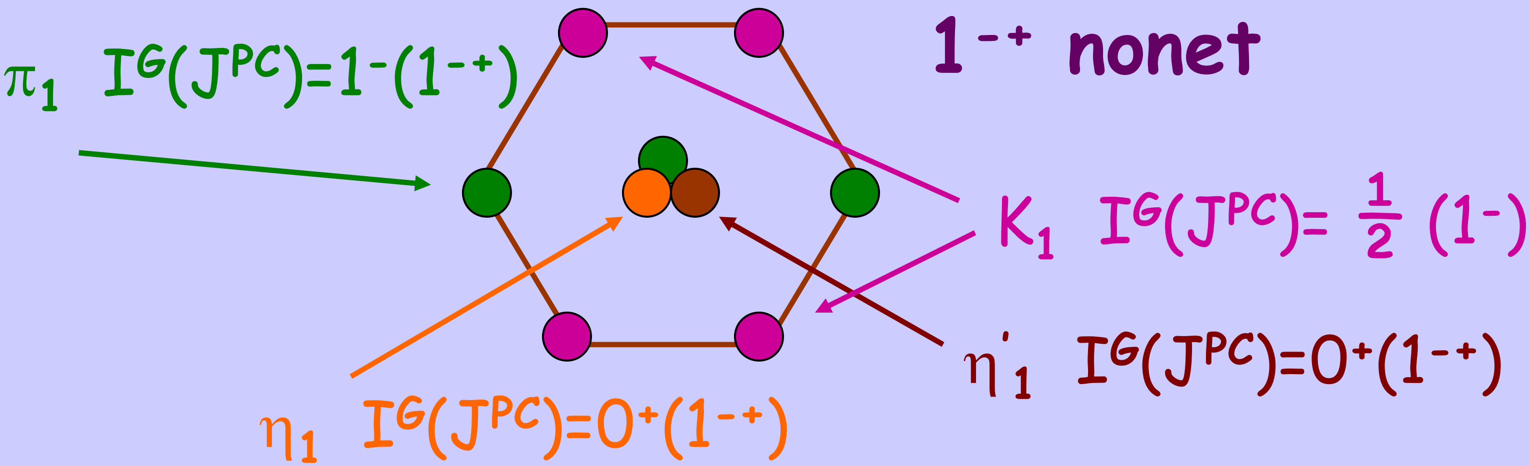
Coherent Bremsstrahlung

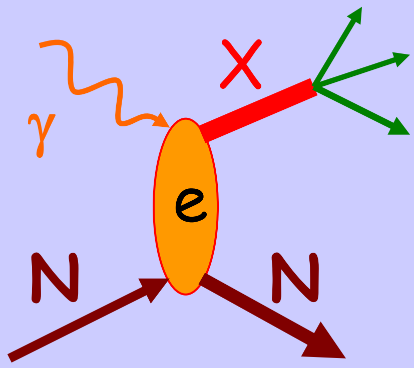
This technique provides requisite energy, flux and polarization





Exotics In Photoproduction





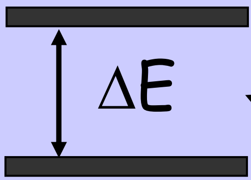
Need to establish nonet nature of exotics: π η η0

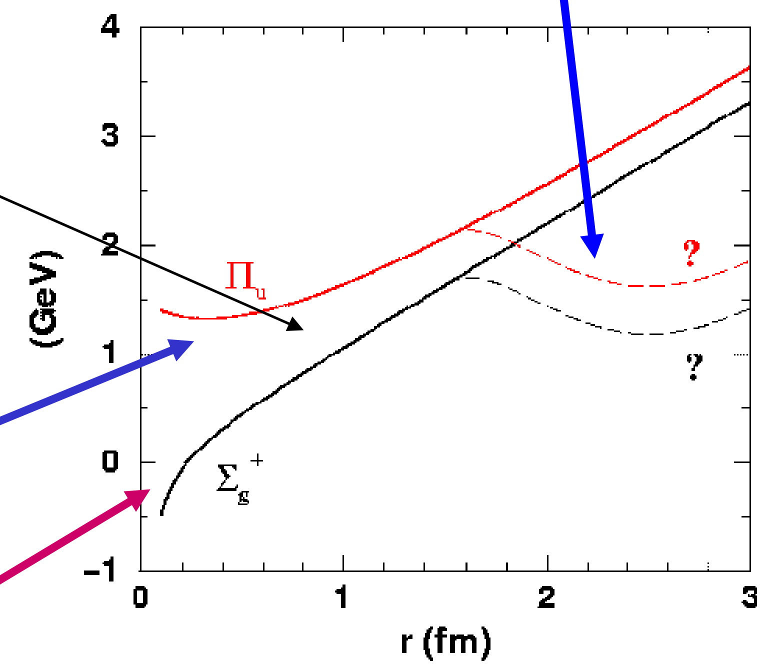
Need to establish more than one nonet: 0^{+-} 1^{-+} 2^{+-}

$\gamma \Leftrightarrow \rho, \omega, \phi$

Gluonic Hadrons and Confinement

What are the light quark Potentials doing?





Lattice QCD potentials

Potentials corresponding To excited states of glue.

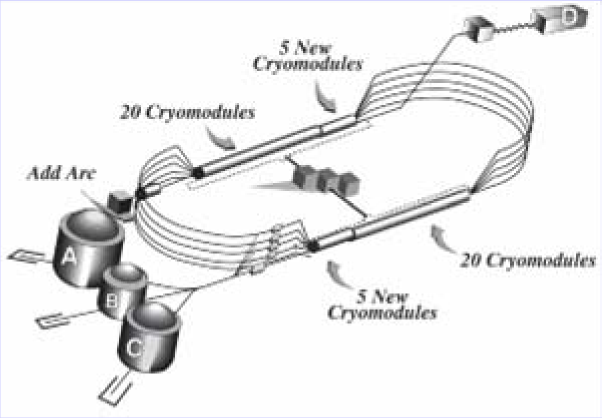
Non-gluonic mesons – ground state glue.

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 built.



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