The Hadron Spectrum and QCD

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03 December 2007

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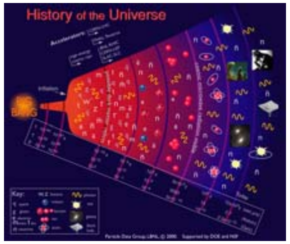
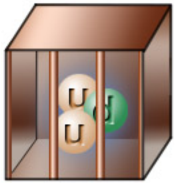
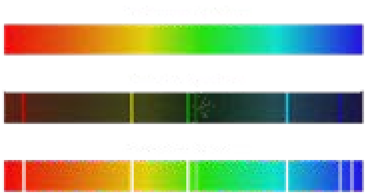


The beginning of time.

The strong force and QCD

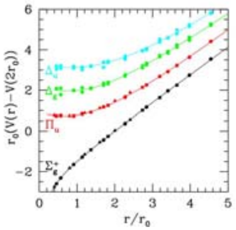




Baryon Spectroscopy

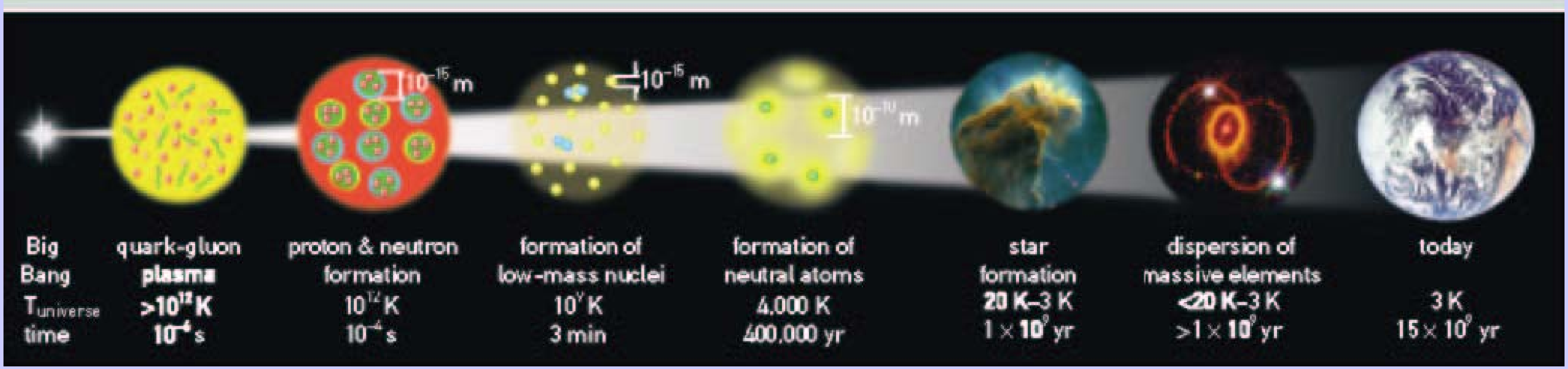
Color confinement

Finding Gluonic Hadrons

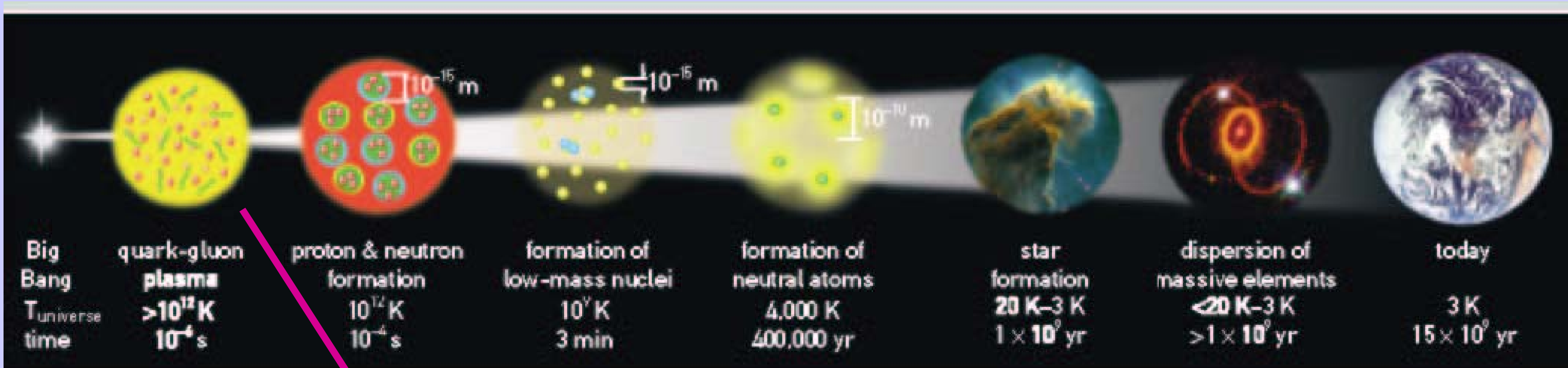


Confinement

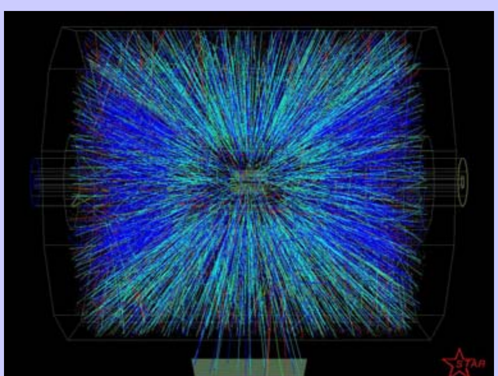
The First Seconds of The Universe



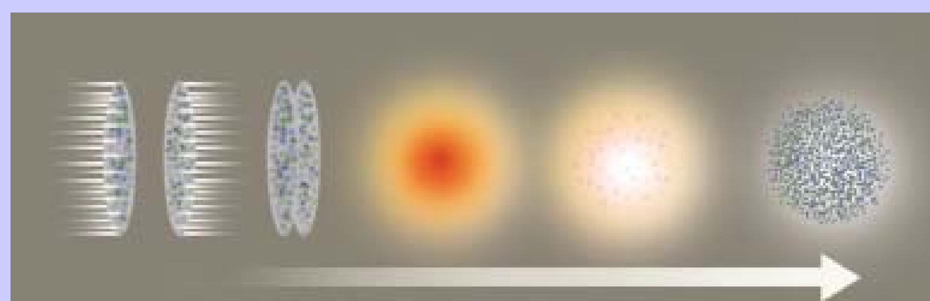
Quark Gluon Plasma



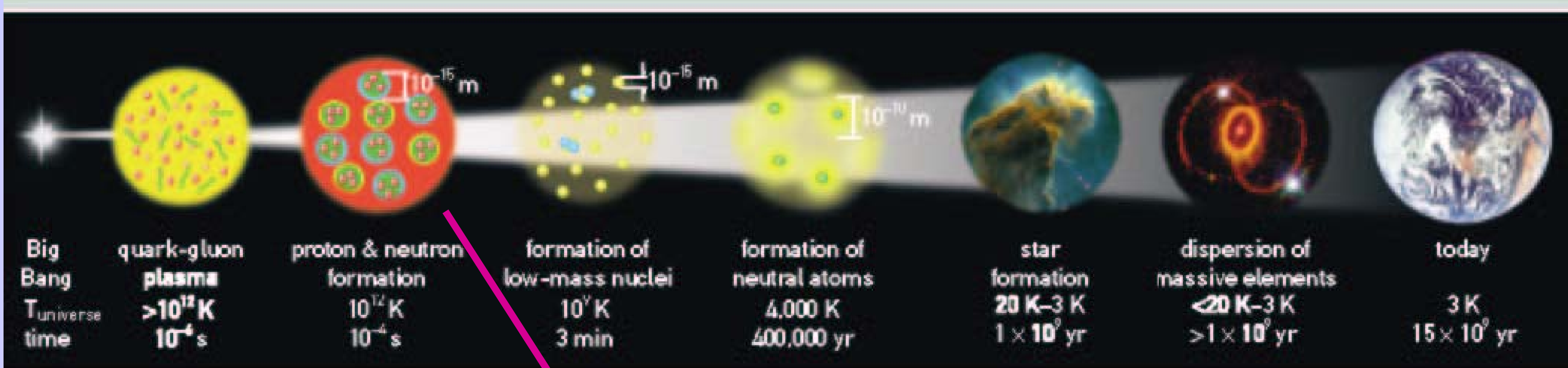
For a period from about 10^{-12} s to 10^{-6} s the universe contained a plasma of quarks, anti quarks and gluons.



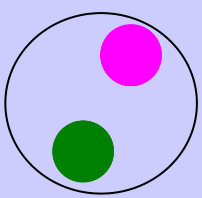
Relativistic Heavy Ion Collisions are trying to produce this state of matter in collisions



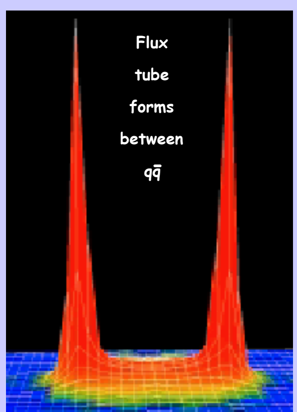
Confinement



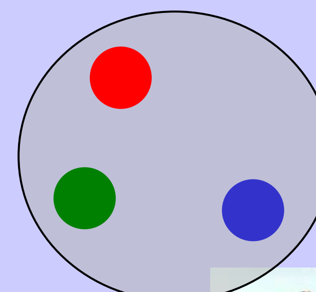
From about 10^{-6} s on, the quark and anti quarks became confined inside of Hadronic matter. At the age of 1s, only protons and neutrons remained.



Mesons

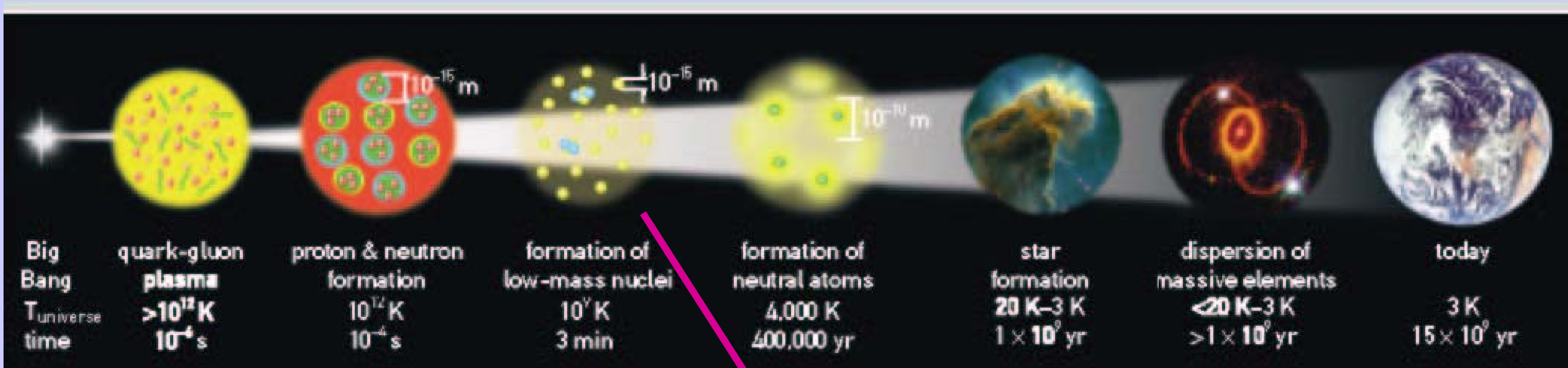


The gluons produce the 16ton force that holds the hadrons together.

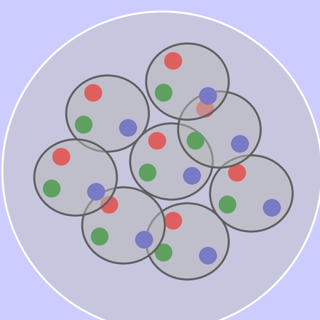


Baryons

The Formation of Nuclei



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

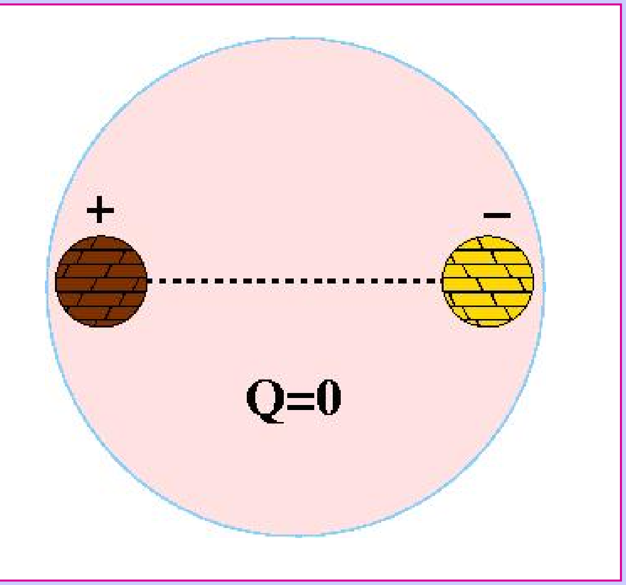


Primordial hydrogen, deuterium, helium and a few other light nuclei now exist.

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

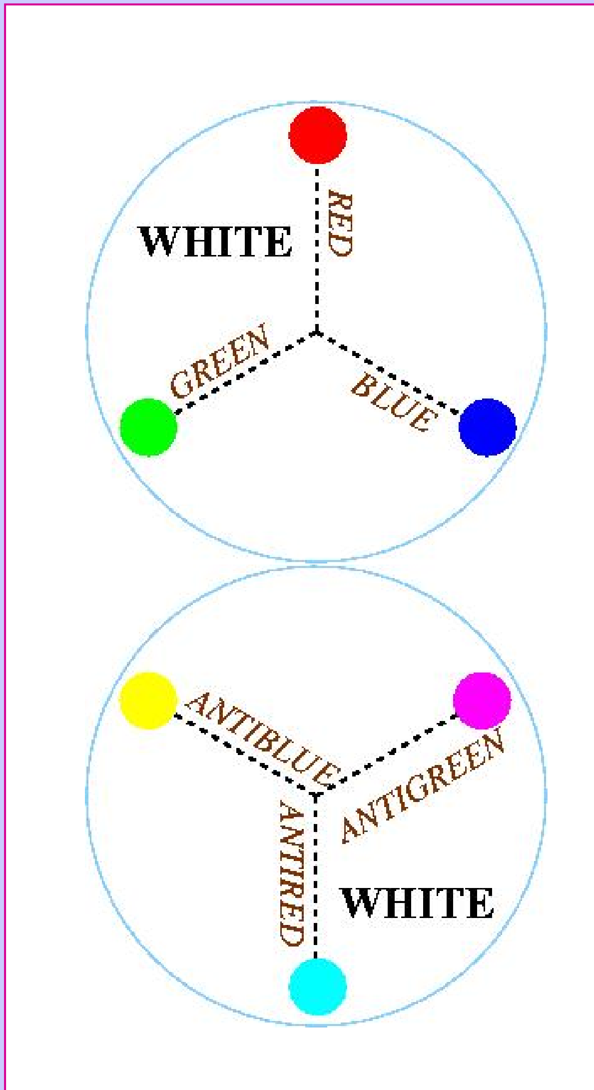
Quantum Chromo Dynamics

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.*

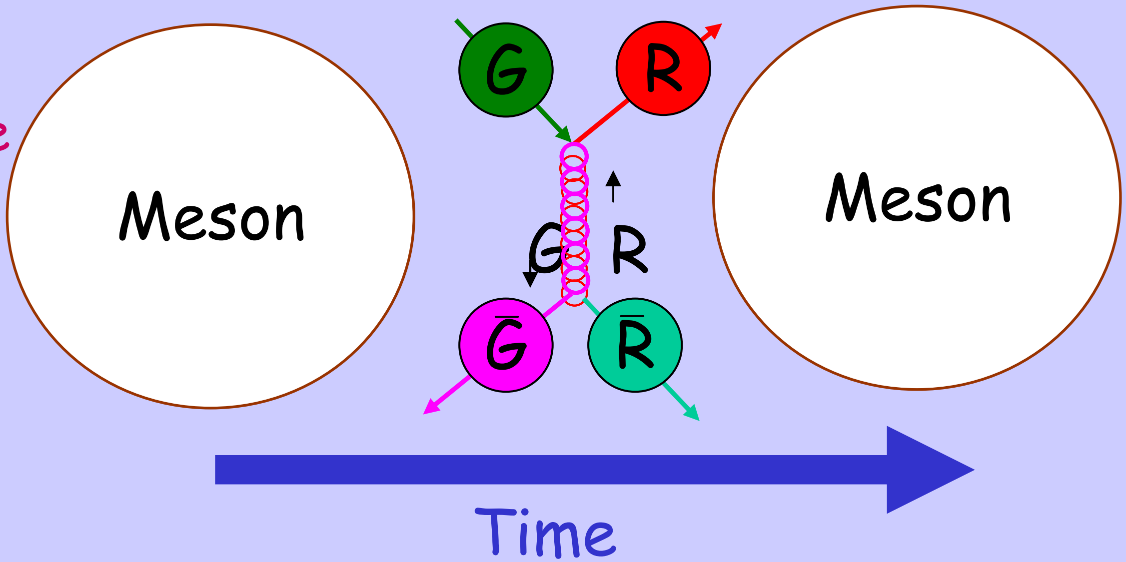
Color Charge

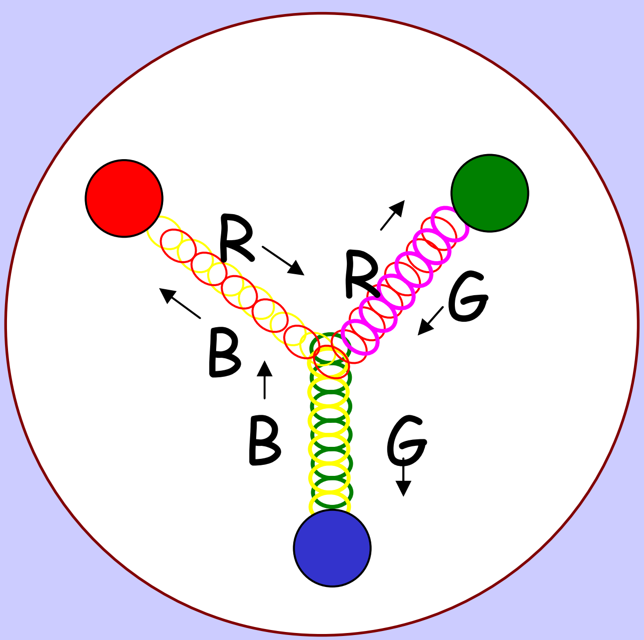


Three charges called RED, BLUE and GREEN, and three anti colors. The objects that form have to be color neutral:

Gluons Carry the Force

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





Gluons Carry the Force

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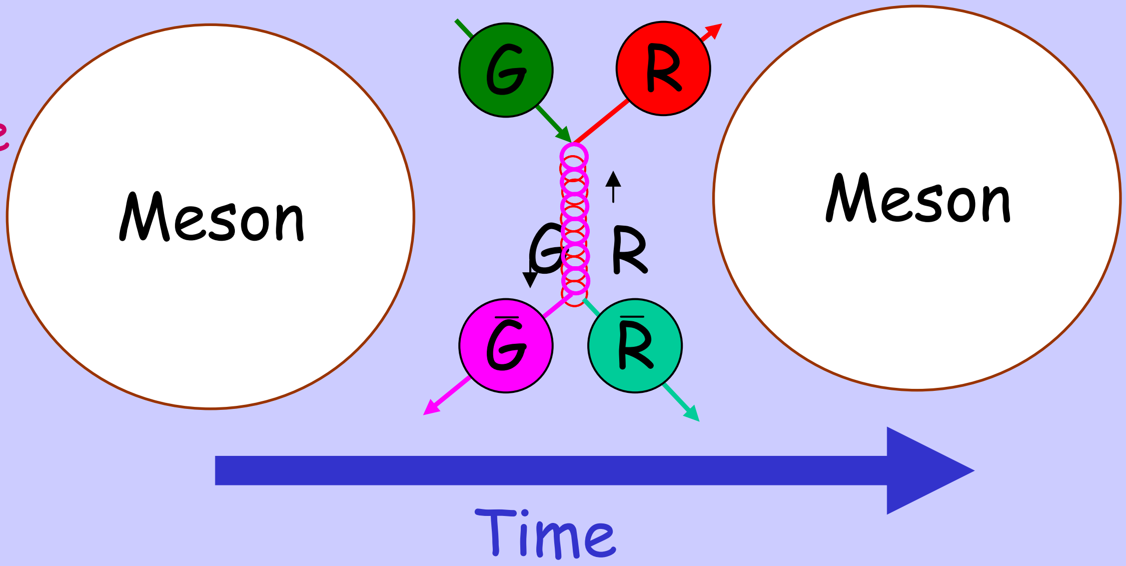

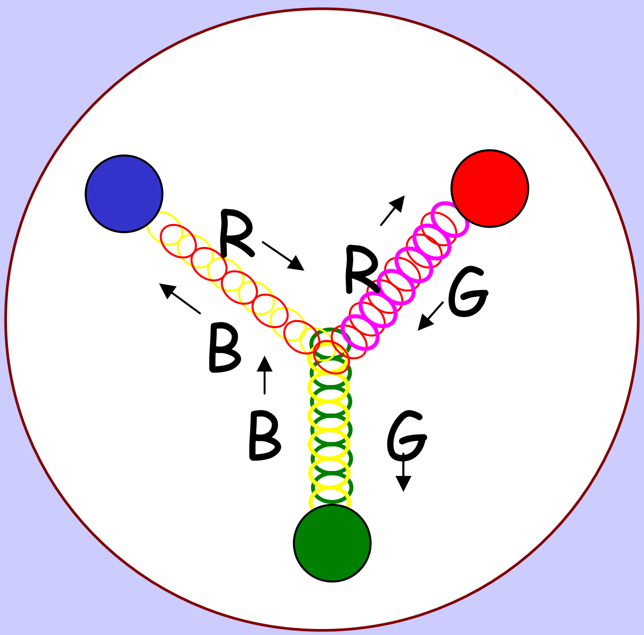

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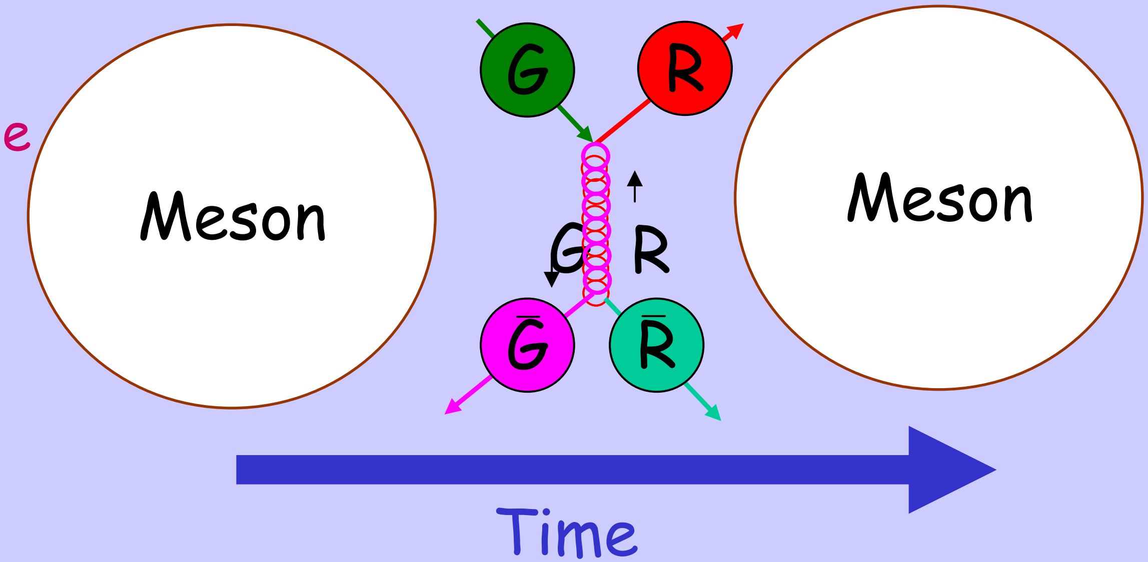
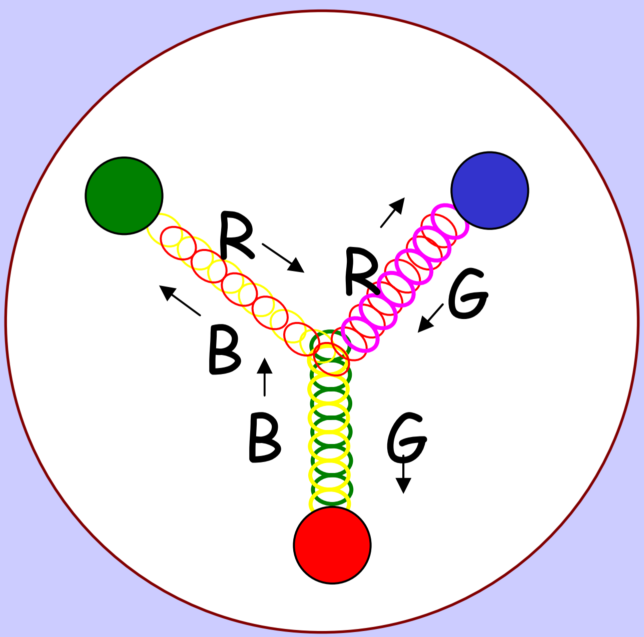
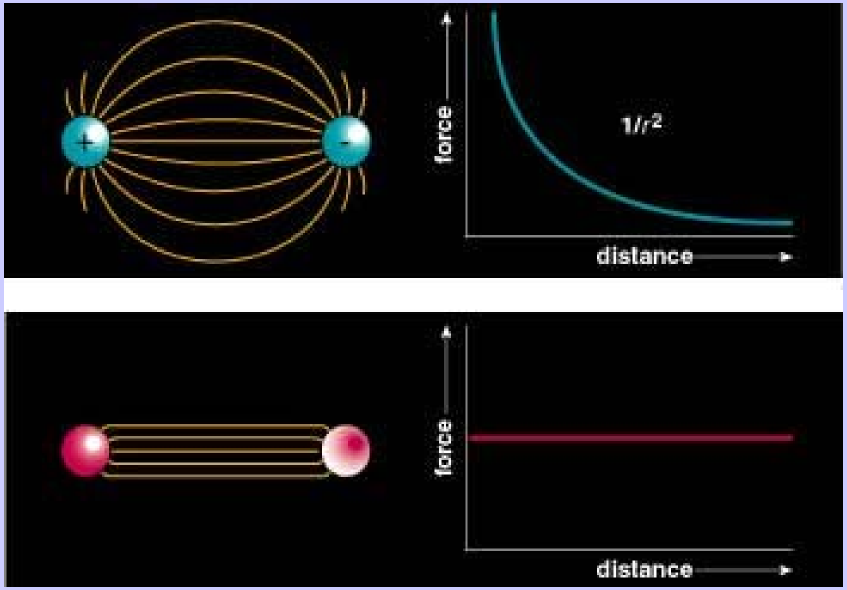


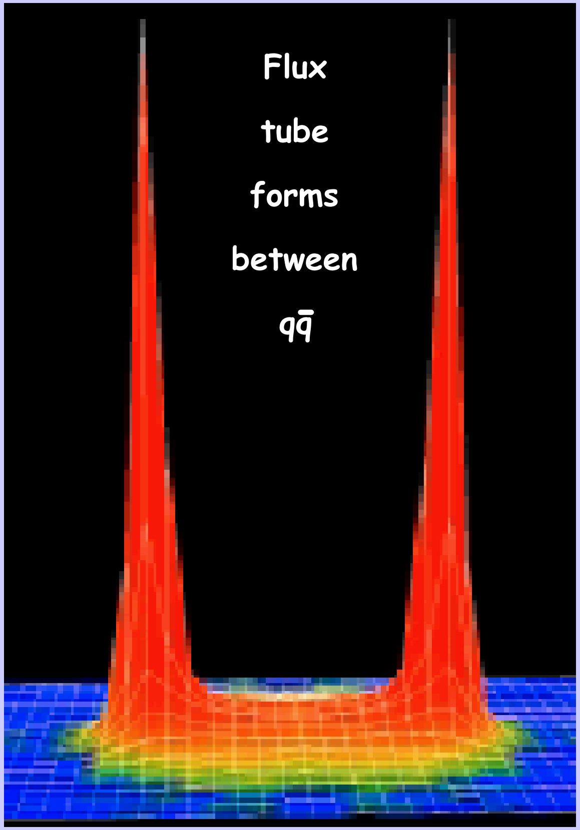


Gluons produce the forces that confine the quarks, but the gluons do not appear to be needed to understand normal hadrons

Flux Tubes

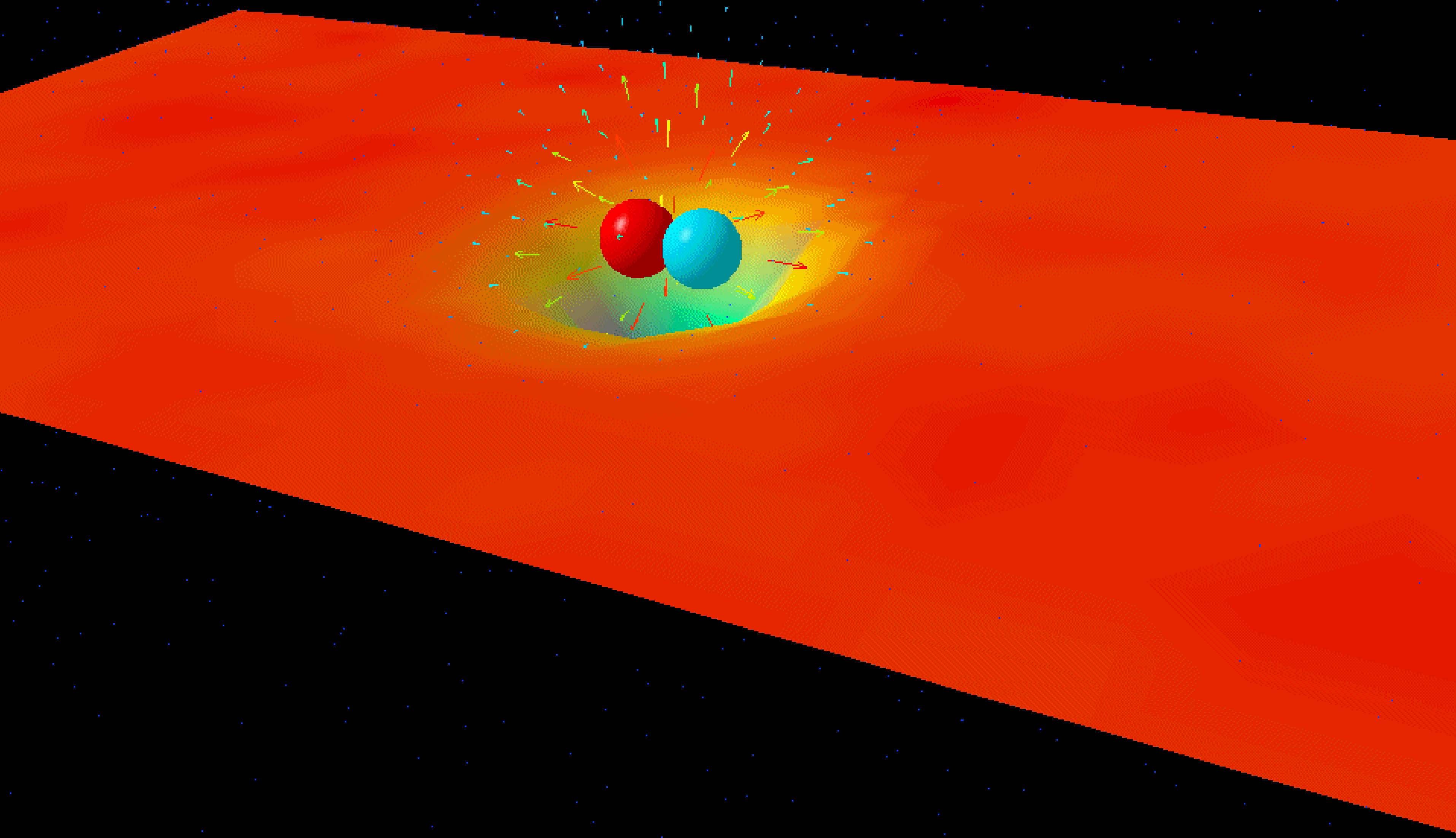


Col r Field: Because of self interaction, confining flux tubes form between static color charges



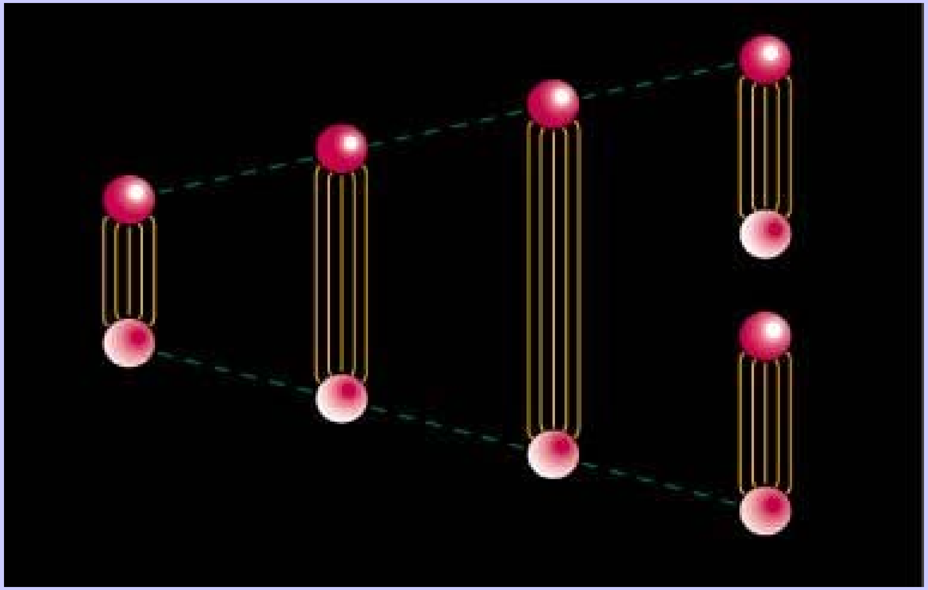
Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons

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



Observed Hadrons

Color singlet objects observed in nature:

In nature, QCD appears to have two configurations.

three quarks (qqq) Baryons

proton: uud neutron: udd

quark-antiquark (qq) Mesons

pion: $u\overline{d}\ ,\ \frac{1}{\sqrt{2}}\left(u\overline{u} - d\overline{d}\right),\ d\overline{u}$

There are a large number of excited states which are also considered particles. QCD should predict these spectra and we can compare them to experiment.

Beyond these simple systems, others are allowed

Allowed systems: $gg, ggg\ ,\ q\overline{q}g\ ,\ q\overline{q}q\overline{q}$
$qqqg$

The Baryons

What are the fundamental degrees of freedom inside of a proton and a neutron?

Quarks? Combinations of Quarks? Gluons?

The spectrum is very sparse.

The Mesons

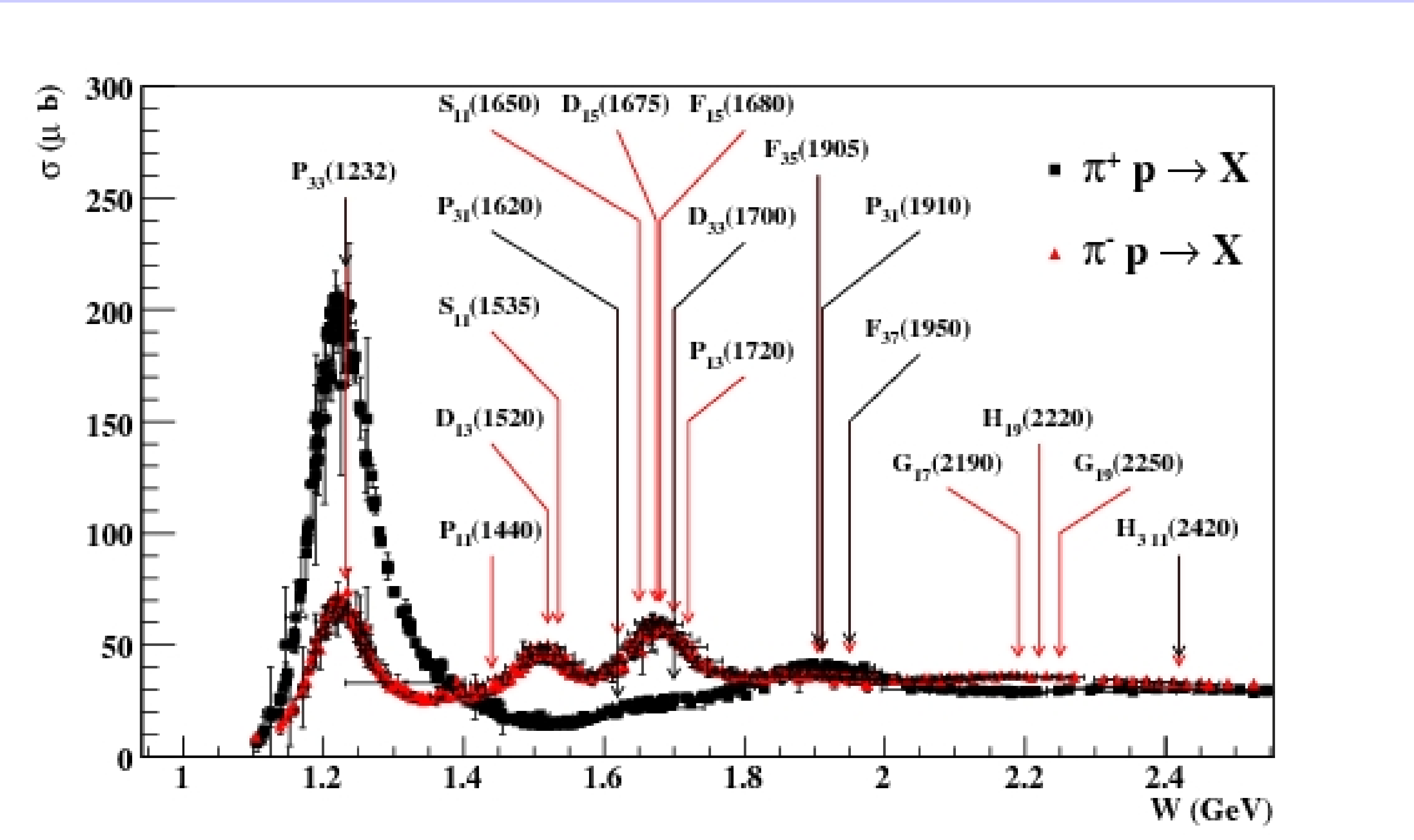
What is the role of glue in a quark-antiquark system and how is this related to the confinement of QCD?

What are the properties of predicted states beyond simple quark-antiquark? $q\bar{q}g$,

Need to map out new states.

The Baryon Spectrum

Measured in the reaction π N $\rightarrow$ π N. Work done in 60's to early 90's.



The Baryon Spectrum

****, *** Known   **, * Hints

In the quark model picture, allow individual quarks to be excited to higher levels:

baryon: q(1s)q(1s)q(1s)

1s -> 2s, 1s -> 2p

Nucleon

$L_{2I,2J}$ (Mass)	Parity	Status
$P_{11}(938)$	+	****
$S_{11}(1535)$	-	****
$S_{11}(1650)$	-	****
$D_{13}(1520)$	-	****
$D_{13}(1700)$	-	***
$D_{15}(1675)$	-	****

$P_{11}(1440)$	+	****
$P_{11}(1710)$	+	***
$P_{11}(1880)$	+	
$P_{11}(1975)$	+	
$P_{13}(1720)$	+	****
$P_{13}(1870)$	+	*
$P_{13}(1910)$	+	
$P_{13}(1950)$	+	
$P_{13}(2030)$	+	
$F_{15}(1680)$	+	****
$F_{15}(2000)$	+	**
$F_{15}(1995)$	+	
$F_{17}(1990)$	+	**

The Baryon Spectrum

****, *** Known **, * Hints

In the quark model picture, allow individual quarks to be excited to higher levels:

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$S_{11}(1650)$	-	****
$D_{13}(1520)$	-	****
$D_{13}(1700)$	-	***
$D_{15}(1675)$	-	****

Missing Baryons

$P_{11}(1440)$	+	****
$P_{11}(1710)$	+	***
$P_{11}(1880)$	+	
$P_{11}(1975)$	+	
$P_{13}(1720)$	+	****
$P_{13}(1870)$	+	*
$P_{13}(1910)$	+	
$P_{13}(1950)$	+	
$P_{13}(2030)$	+	
$F_{15}(1680)$	+	****
$F_{15}(2000)$	+	**
$F_{15}(1995)$	+	
$F_{17}(1990)$	+	**

The Baryon Spectrum

****, *** Known **, * Hints

Treat a quarks and a diquark as the fundamental particles. Allow excitations as before:

Nucleon

$L_{2I,2J}$ (Mass)	Parity	Status
$P_{11}(938)$	+	****
$S_{11}(1535)$	-	****
$S_{11}(1650)$	-	****
$D_{13}(1520)$	-	****
$D_{13}(1700)$	-	***
$D_{15}(1675)$	-	****

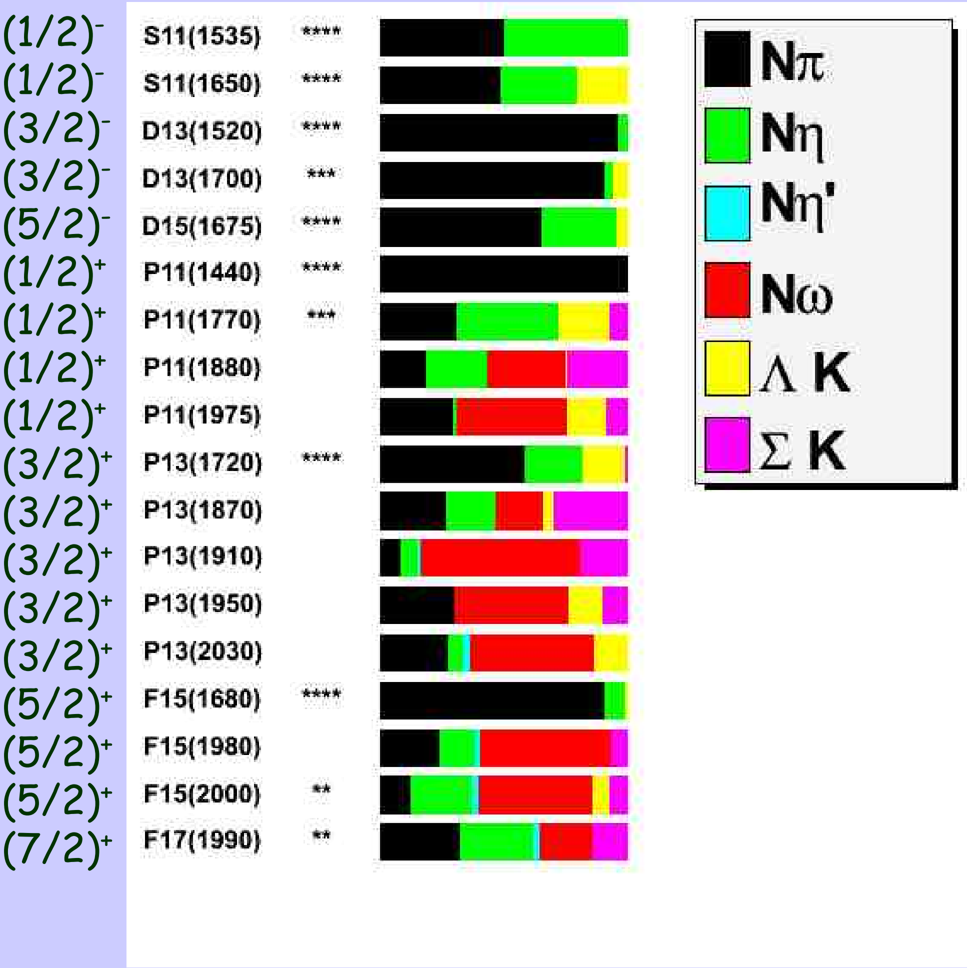
$P_{11}(1440)$	+	****
$P_{11}(1710)$	+	***
$P_{11}(1880)$	+	
$P_{11}(1975)$	+	
$P_{13}(1720)$	+	****
$P_{13}(1870)$	+	*
$P_{13}(1910)$	+	
$P_{13}(1950)$	+	
$P_{13}(2030)$	+	
$F_{15}(1680)$	+	****
$F_{15}(2000)$	+	**
$F_{15}(1995)$	+	
$F_{17}(1990)$	+	**

Looking in the wrong place

Nearly all the data used to identify baryons has come from π N scattering.

$$\pi N \to \pi N$$

What if the missing states do not couple to π N ?

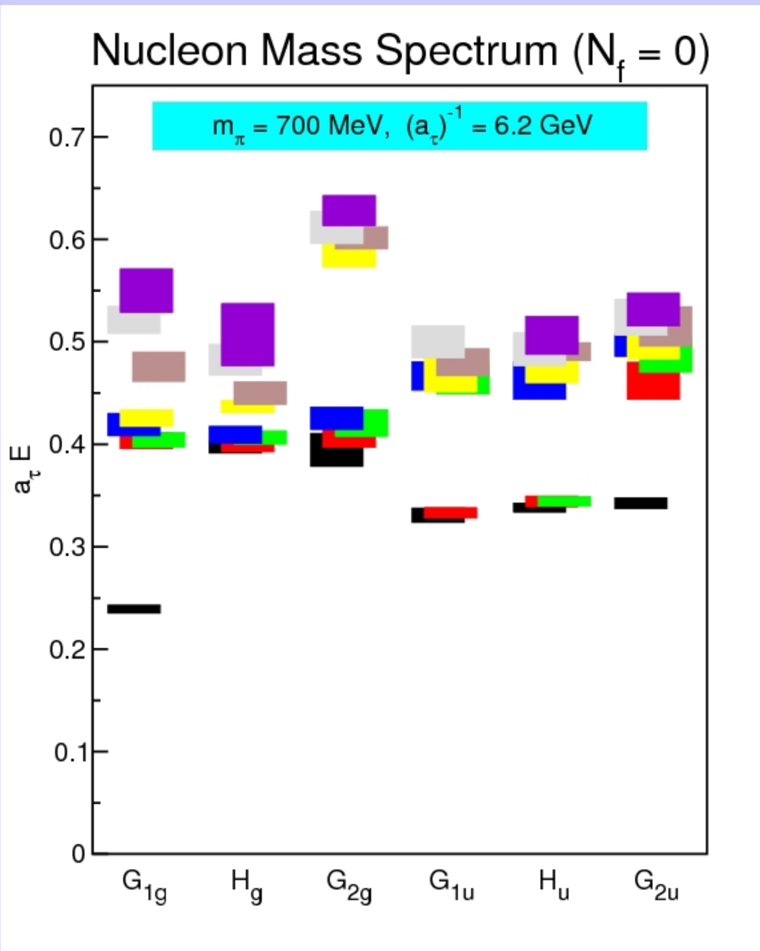


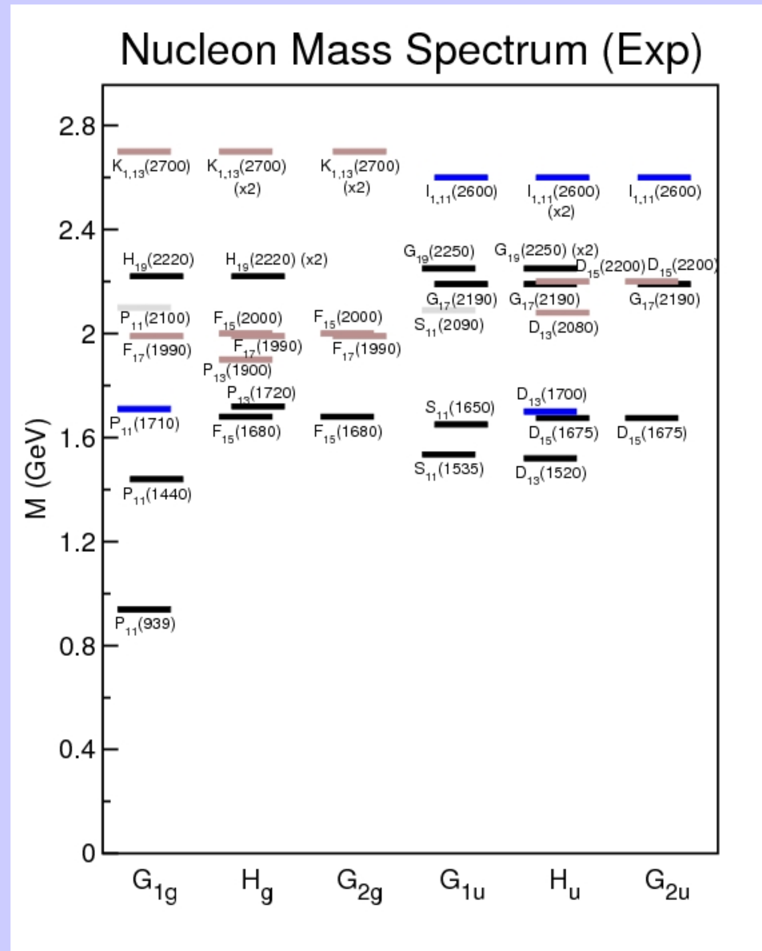
Quark model predictions that many of the missing states have strong couplings to other final states:

$N\eta \quad N\omega \quad \ldots$

Lattice Calculations

First lattice calculation for baryons (2006). Many approximations, but shows what will be possible.



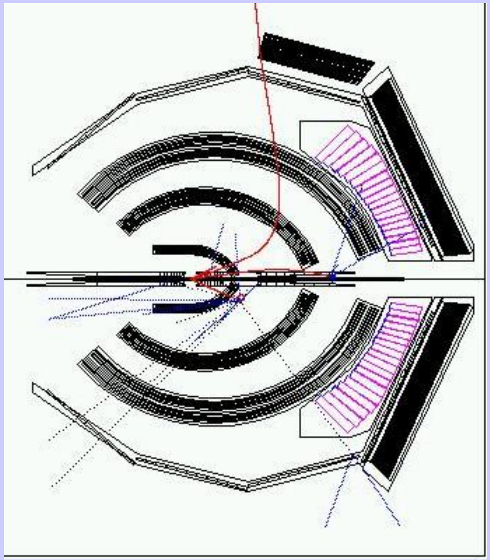


The CLAS Detector at JLab

Incident electron and tagged photon beams
(both polarized and unpolarized) (<6GeV)

Targets (H, D, ^{3}He …)
(both polarized and unpolarized)

Large acceptance detector with access to final states with several particles and PID



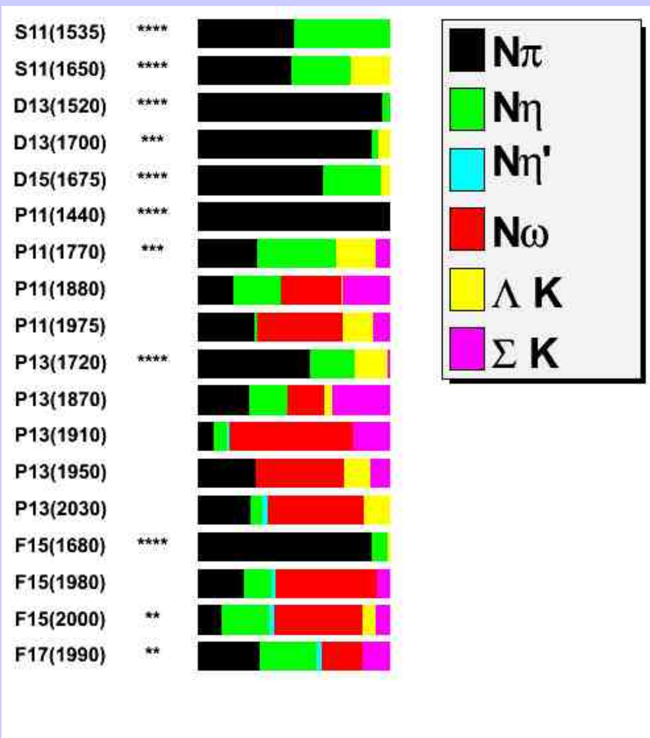
Large data sets both currently in hand as well as new ones expected in the next few years

Identify Baryons:
N*, Δ, Λ, Σ, Ξ

New Data Sets

None of these channels have been extensively studied, but are supposed to couple to some missing baryons.

Significant New Data



Using 11TB of CLAS data from a recent run period, simultaneously analyzing reactions:

$\gamma p \to p \eta$	**700,000 Events**
$\gamma p \to p \eta'$	**250,000 Events**
$\gamma p \to p \omega$	**8,000,000 Events**
$\gamma p \to \Lambda K^+$	**1,200,000 Events**
$\gamma P \to \Sigma^0 K^+$	**1,100,000 Events**
$\gamma p \to p\pi^+\pi^-$	$\approx \infty$ **Events**

Enormous data sets require new tools to carry out the needed analysis.

Partial Wave Analysis

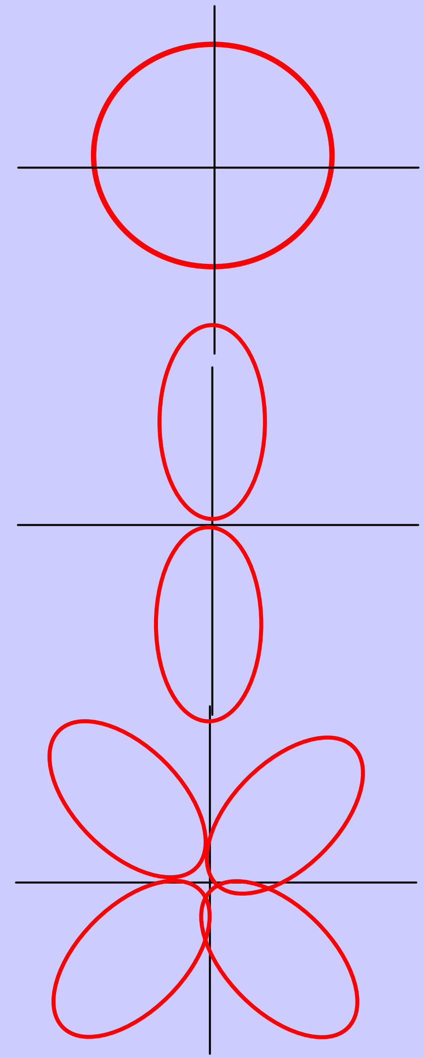
Angular distributions of reactions let you determine the spin and parity of intermediate resonances.

Classical Electrodynamics:

Monopole Radiation (L=0)

Dipole Radiation (L=1)

Quadrupole Radiation (L=2)



Partial Wave Analysis

For a given reaction energy, quantum mechanical amplitudes yields a probability distribution and predicts angular distributions.

Particles nominally occur as a resonance which has both an amplitude and phase as a function of the difference between its nominal mass and the reaction energy.

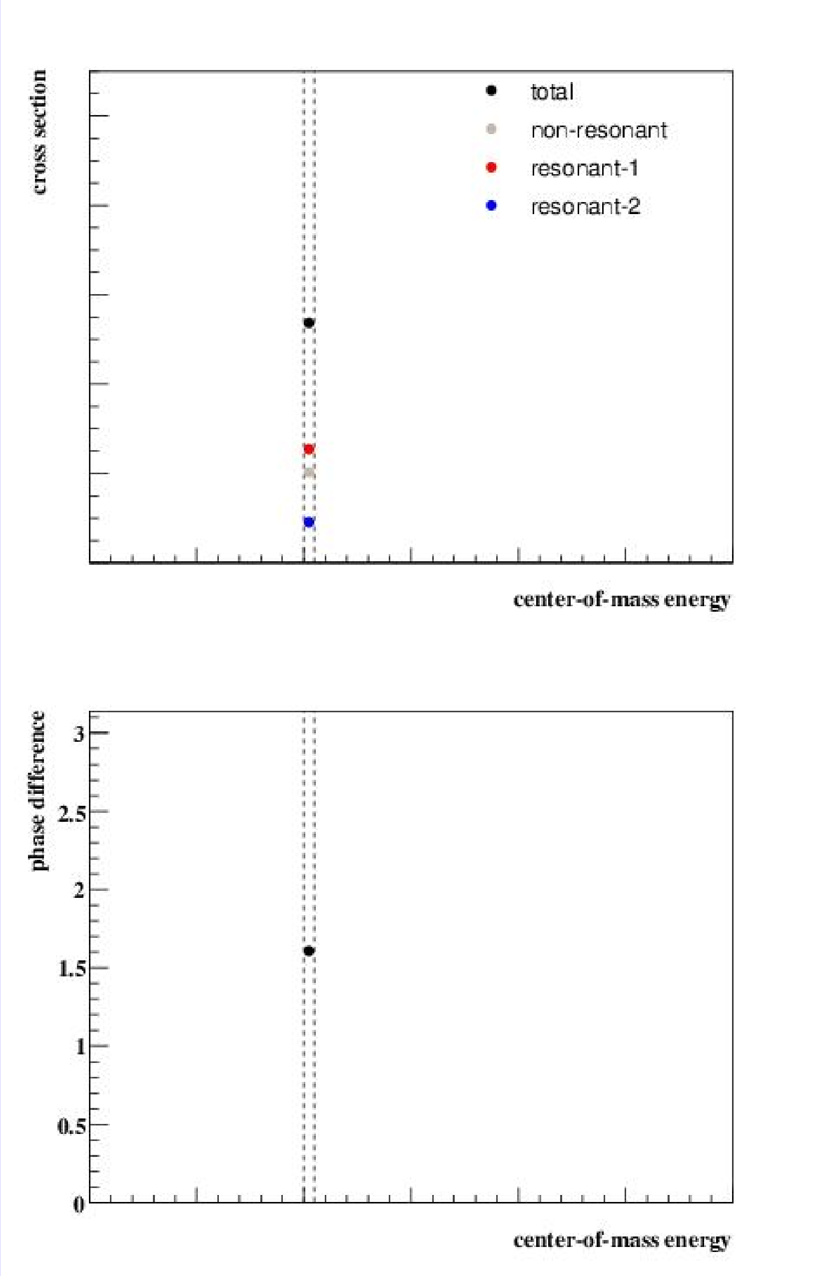
Fit the angular distribution as a sum of complex amplitudes which describe particular quantum numbers.

Partial Wave Analysis

A simple model with three complex amplitudes, 2 of which are particles with different QNs

Start with a single energy bin.

Fit to get the strengths and the phase difference between the two resonances.



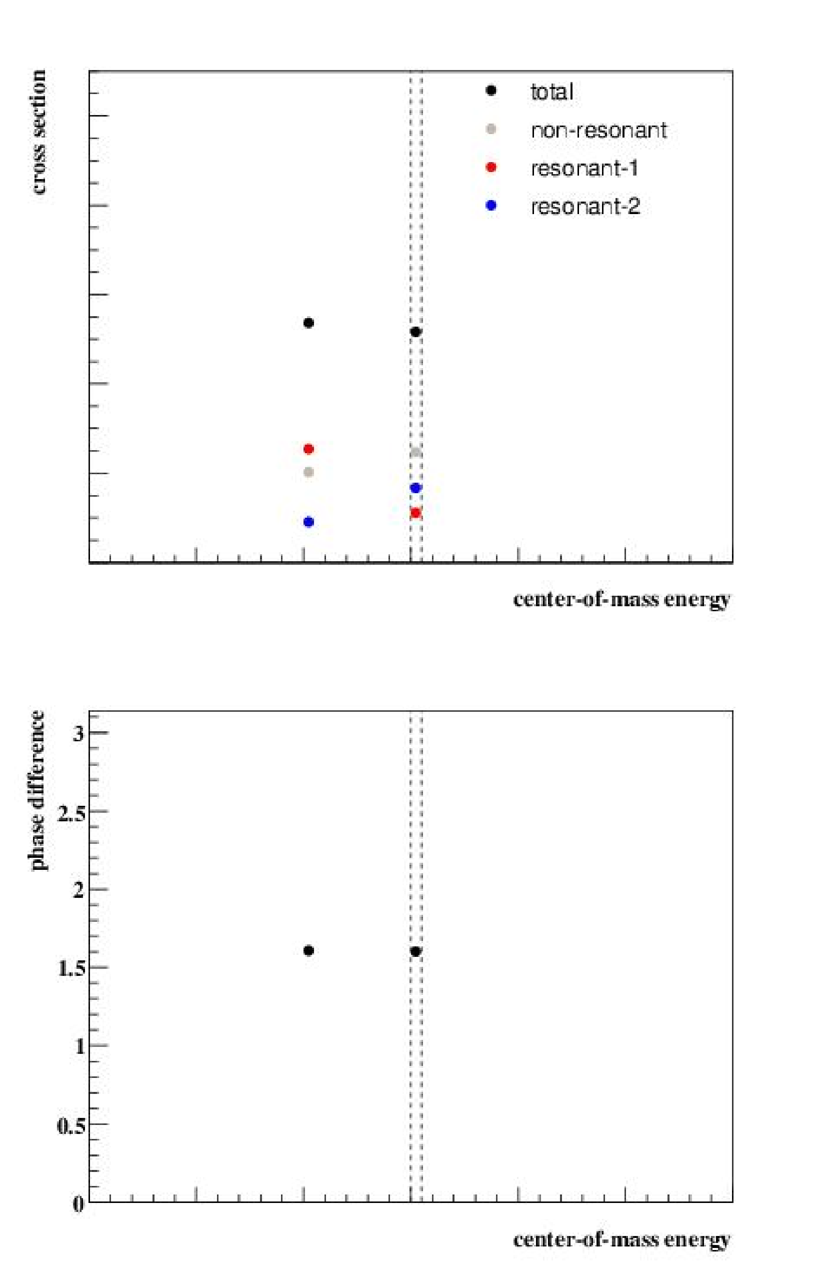
Partial Wave Analysis

A simple model with three complex amplitudes, 2 of which are particles with different QNs

Start with a single energy bin.

Fit to get the strengths and the phase difference between the two resonances.

Fit a 2nd bin.



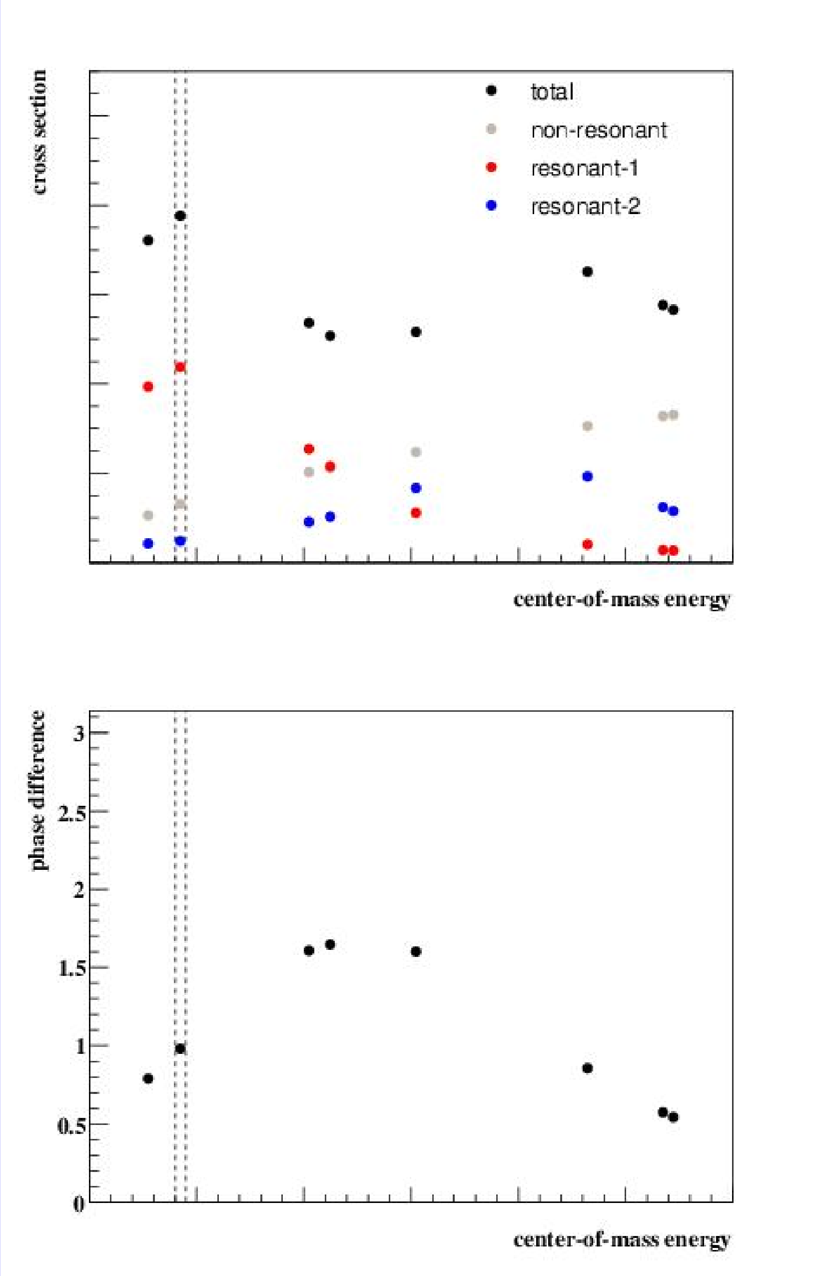
Partial Wave Analysis

A simple model with three complex amplitudes, 2 of which are particles with different QNs

Start with a single energy bin.

Fit to get the strengths and the phase difference between the two resonances.

Continue fitting bins …



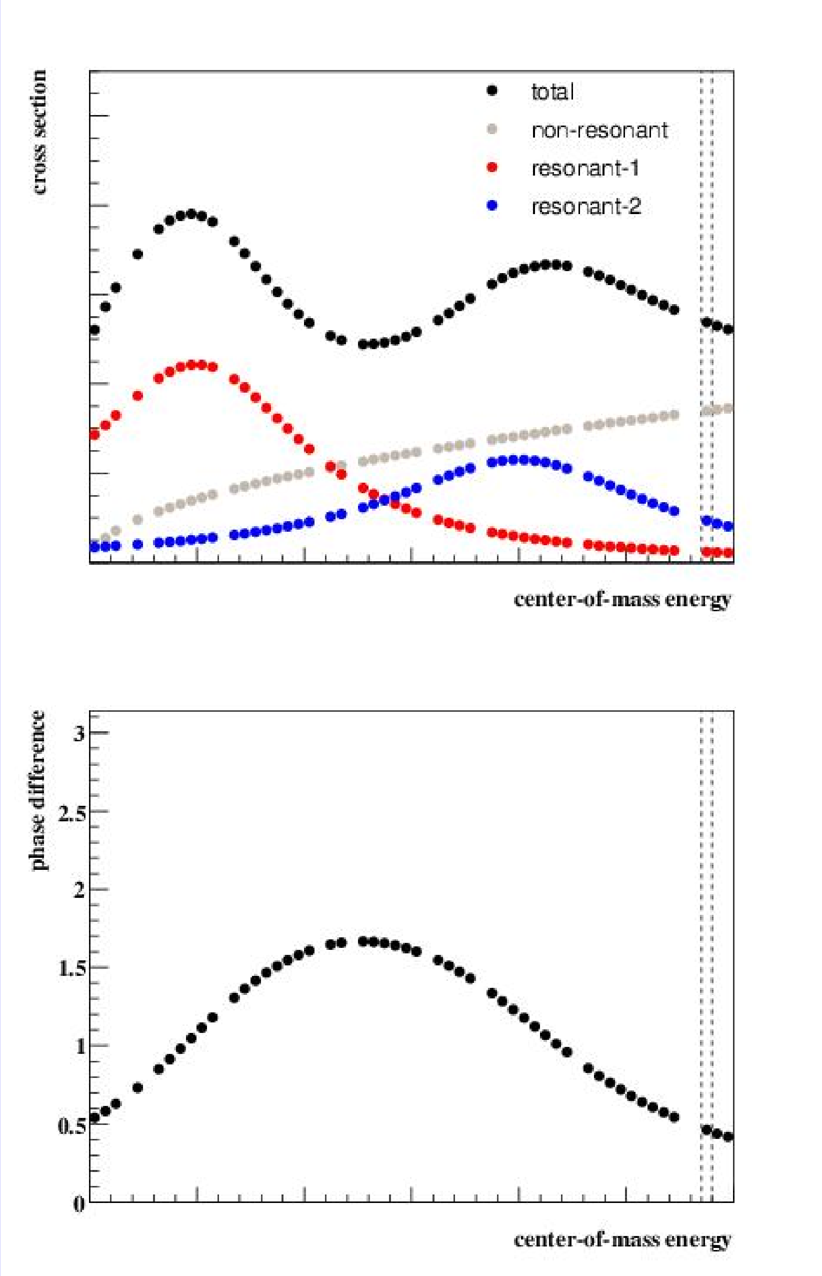
Partial Wave Analysis

A simple model with three complex amplitudes, 2 of which are particles with different QNs

Start with a single energy bin.

Fit to get the strengths and the phase difference between the two resonances.

… and continue …

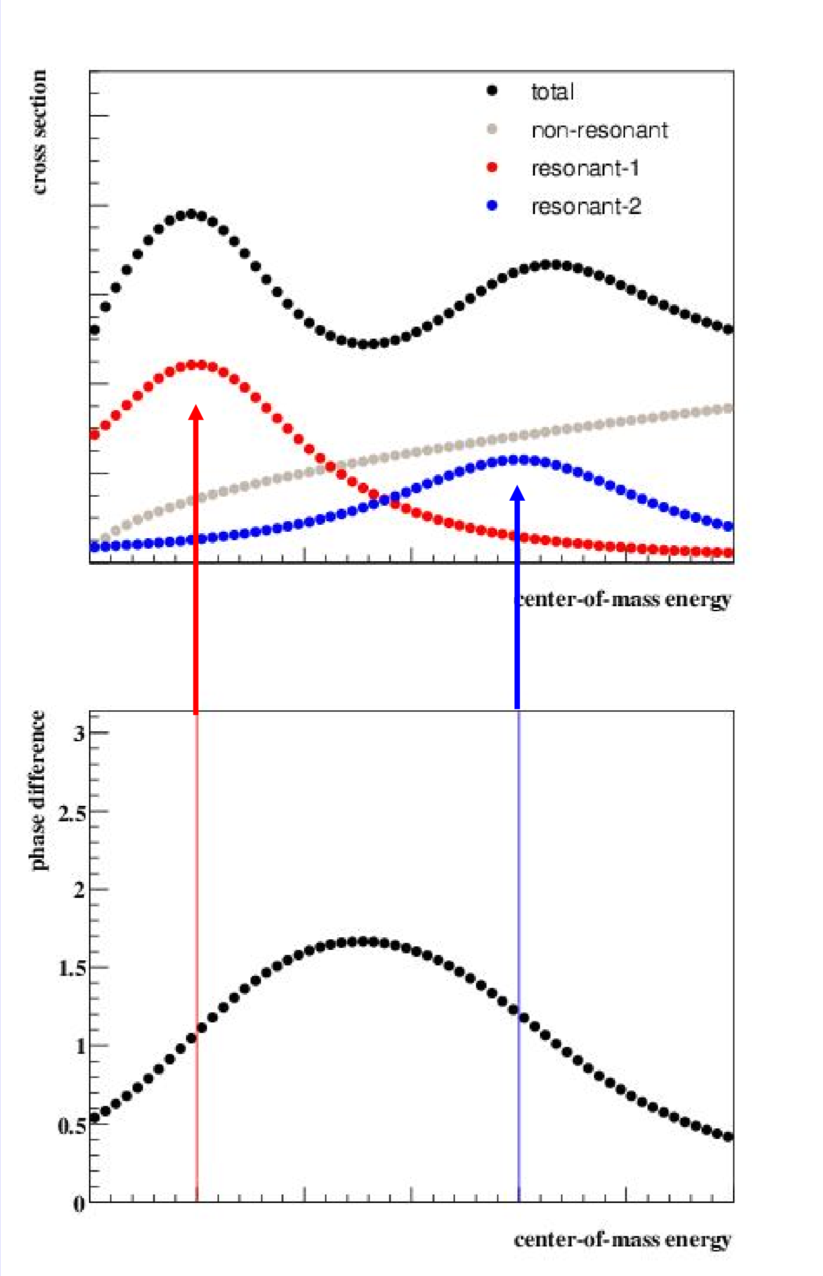


Partial Wave Analysis

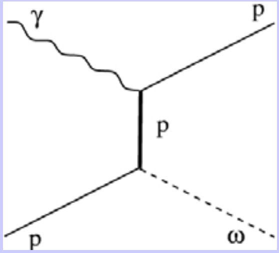
A simple model with three complex amplitudes, 2 of which are particles with different QNs. The masses peak where the two lines are.

The need for intensity and the phase difference are indicative of two resonances.

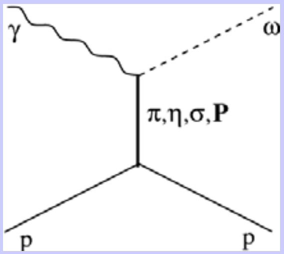
Can fit for masses and widths.



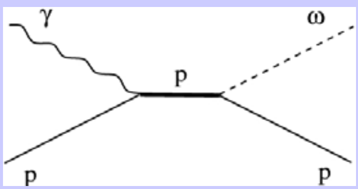
$\gamma\, p \rightarrow \omega\, p$ The ω p system has never been studied



Any analysis needs to incorporate many different processes. However, all the analyses of different channels need to be self consistent (E.g. coupling constants, production and decay …).



Tools developed at CMU over the last 3 years allow the easy input of any amplitude directly at the event level in the analysis



Theory $\Leftrightarrow$ Experiment

Partial Wave Analysis

$$I = \Sigma \,|\, a_{lmn} A_{lmn} \,|^{2}$$

Complex amplitudes and complex fit parameters.

About 13 million events in ~100 narrow energy bins

First time this type of PWA has been done for Baryons

PWA Results

Fit showing three amplitudes.

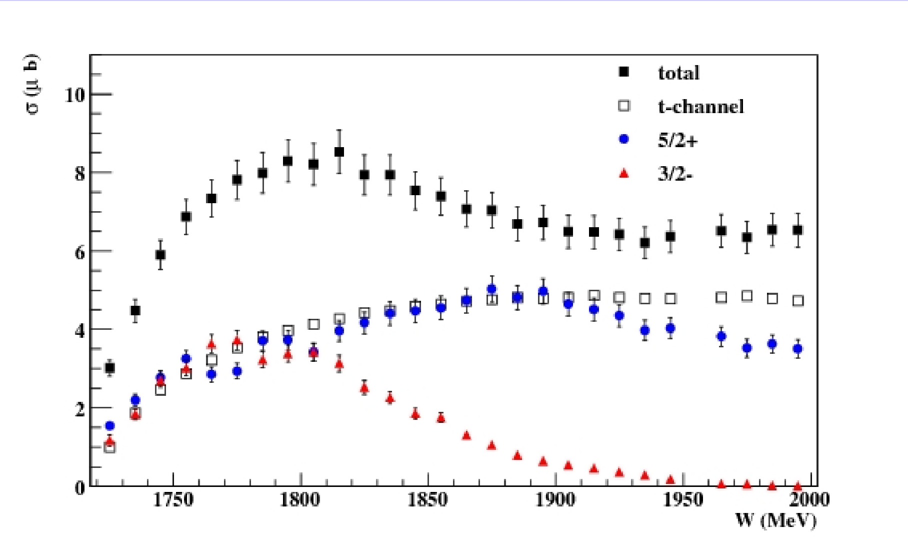
$(3/2)^-$ D_{13}
$(5/2)^+$ F_{15}
t-channel

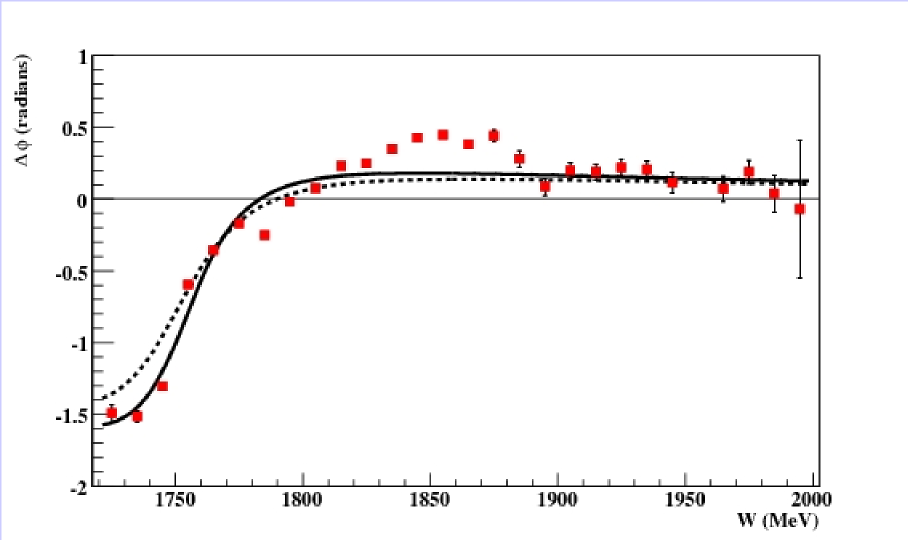
Not Expected

Intensities

Phase Difference

$\gamma\, p \rightarrow \omega\, p$





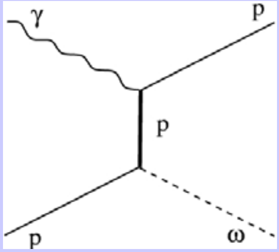
Strong evidence for:

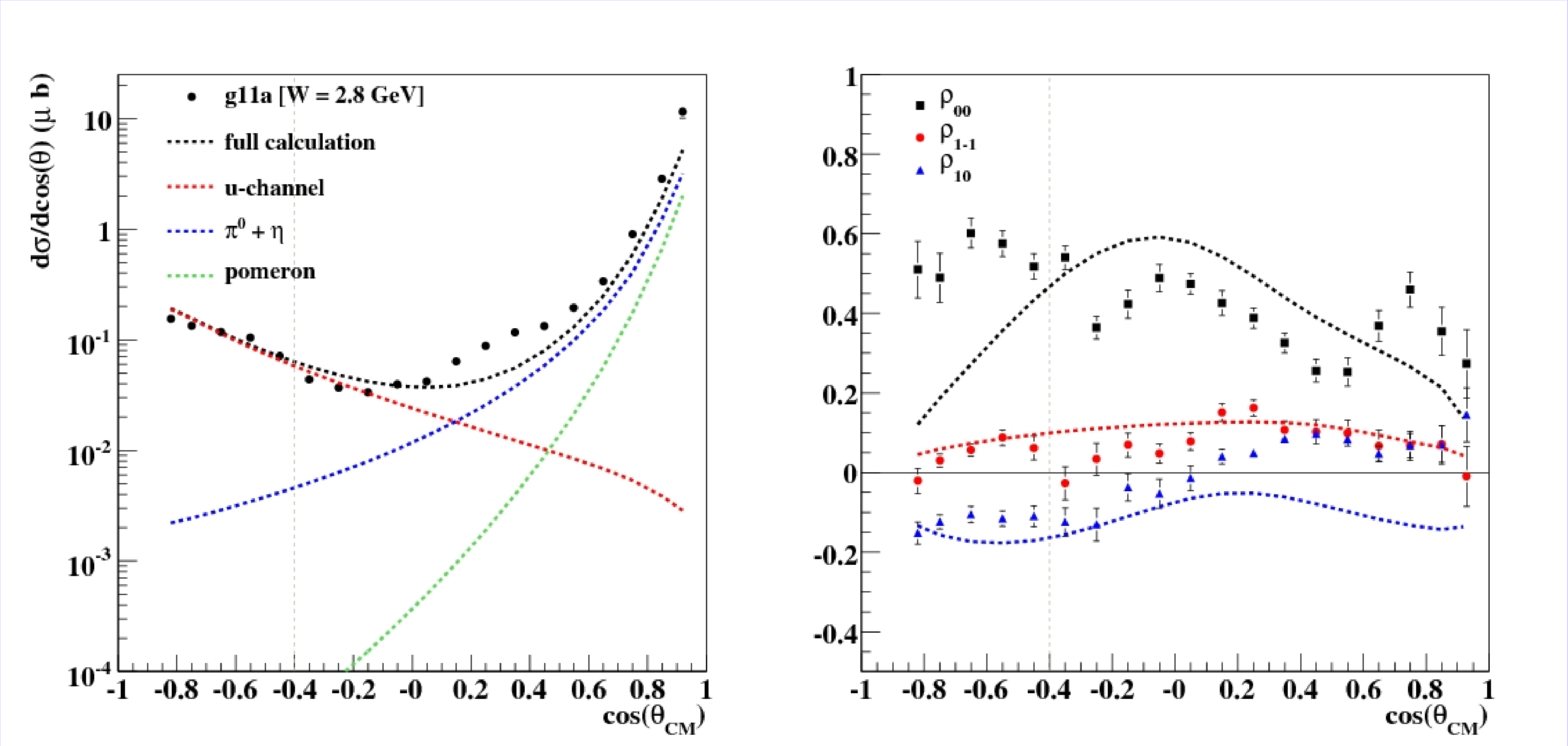
$(3/2)^-$ N(1700) ***
$(5/2)^+$ N(1680) ****
$(7/2)^-$ N(2190) ****

The strong signals are well known states!

Comparison to Models

t-channel is from models fit to earlier data





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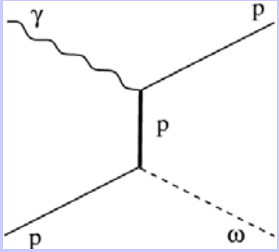
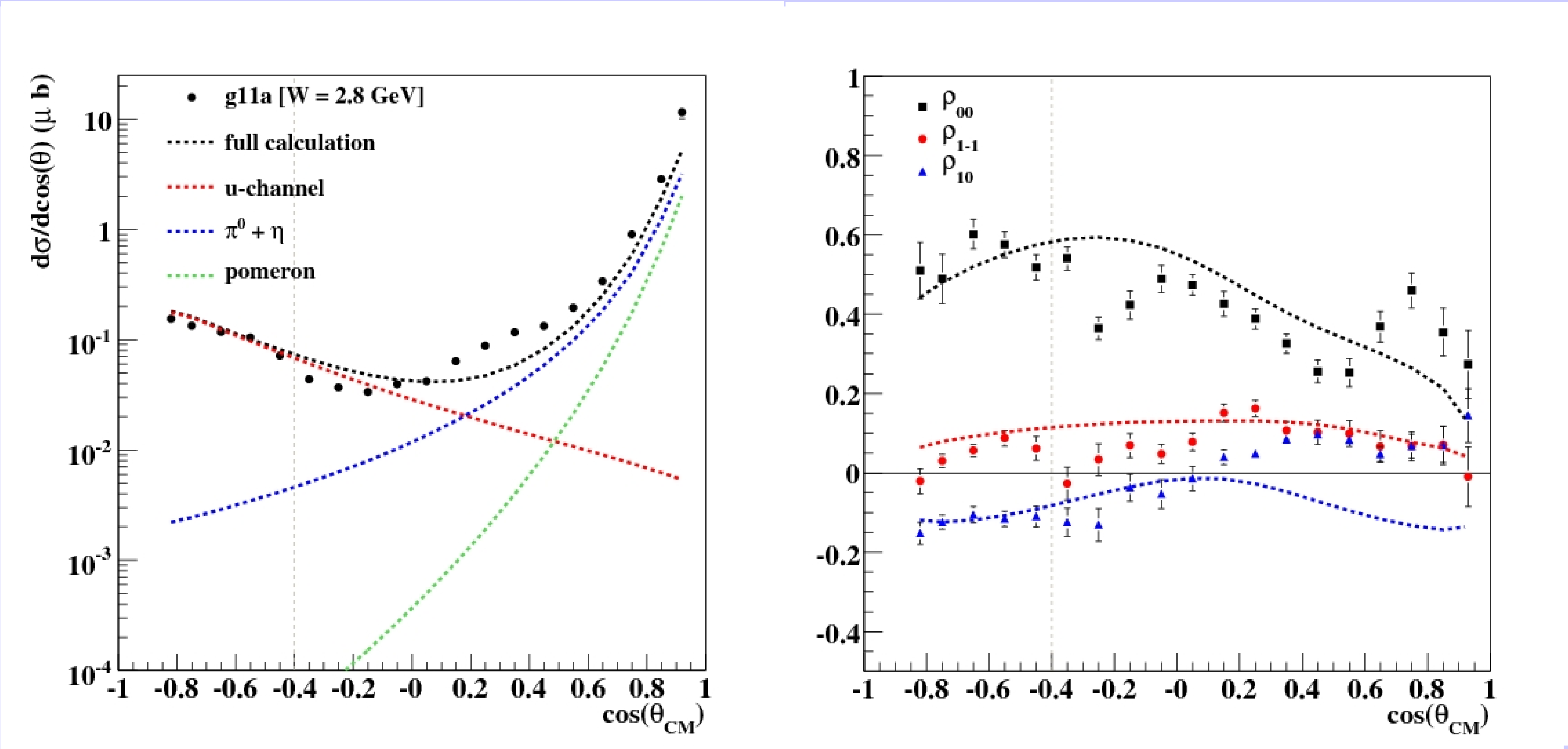




Improvement following recent predictions by Barnes.

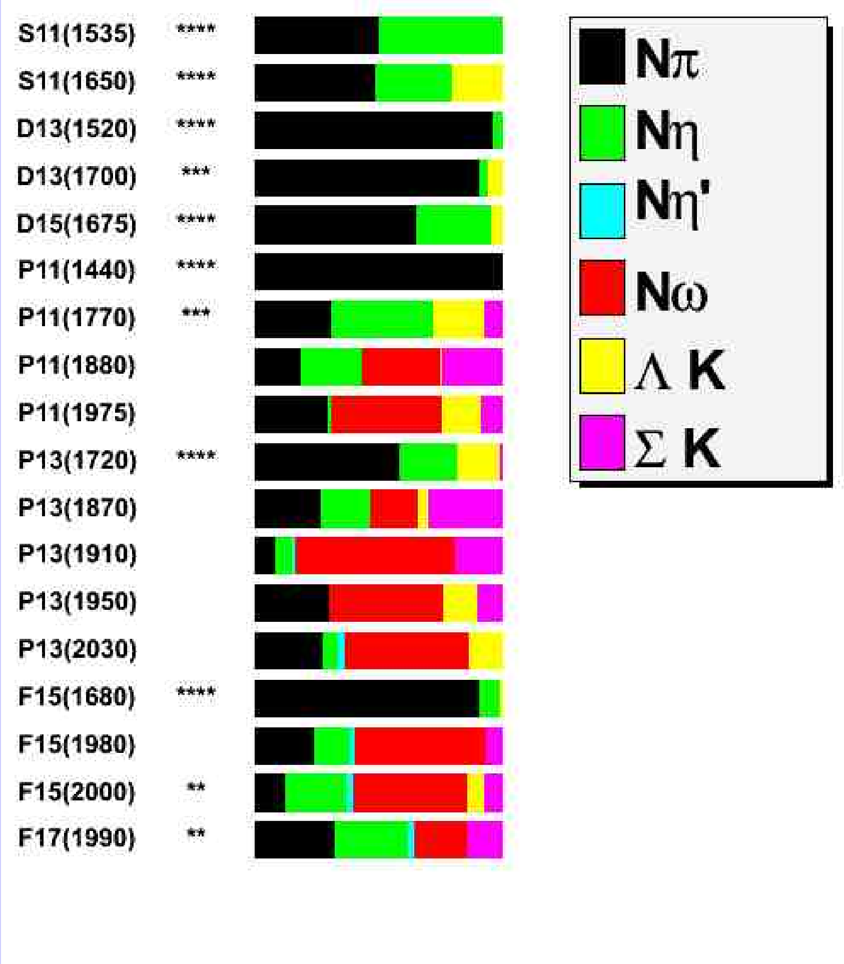
What is seen?

Strong evidence for:

$(3/2)^-$ N(1700) ***
$(5/2)^+$ N(1680) ****
$(7/2)^-$ N(2190) ****

Hints?

$(1/2)^-$
$(1/2)^-$
$(3/2)^-$
$(3/2)^-$
$(5/2)^-$
$(1/2)^+$
$(1/2)^+$
$(1/2)^+$
$(1/2)^+$
$(3/2)^+$
$(3/2)^+$
$(3/2)^+$
$(3/2)^+$
$(3/2)^+$
$(5/2)^+$
$(5/2)^+$
$(5/2)^+$
$(7/2)^+$



$(7/2)^-$ $G_{17}(2190)$ ****

Baryon Analysis

The data demand need three baryon resonances.
$(3/2)^-$, $(5/2)^+$ and $(7/2)^-$

These are not "missing states".

There may be some hints of missing baryons in the data, but the models for the non-resonant parts need to be improved (theoretical input).

We also have a number of other analysis efforts underway looking at other final states and anticipate more definitive statements in the next year or so.

Mesons: quark-antiquark systems

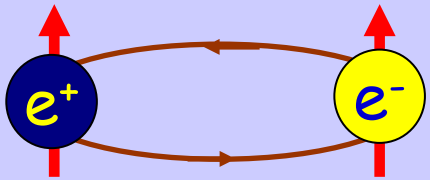
What is the role of glue in a quark-antiquark system and how is this related to the confinement of QCD?

What are the properties of predicted states beyond simple quark-antiquark? $q\bar{q}g$,

Need to map out new states.

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

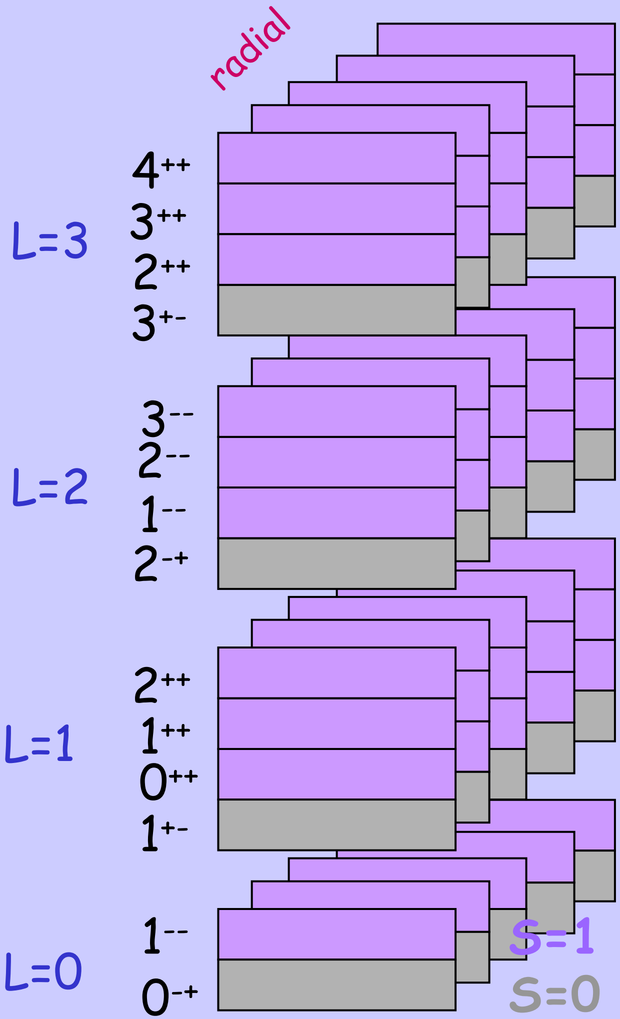
Particle<->Antiparticle:
Charge Conjugation: $C = (-1)^{(L+S)}$

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

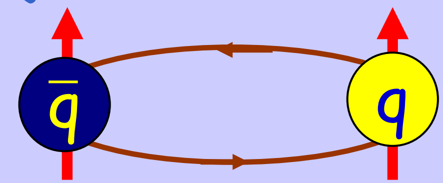
$^{(2S+1)}L_J$ $\quad$ $^1S_0,\ ^3S_1,\ ^1P_1,\ ^3P_0,\ ^3P_1,\ ^3P_2, \ldots$

Spectroscopy and QCD

Mesons



Quarkonium



Consider the three lightest quarks

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

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

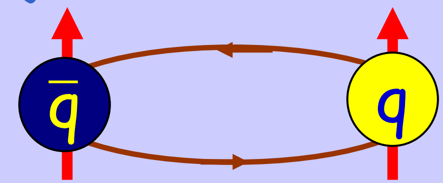
$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

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

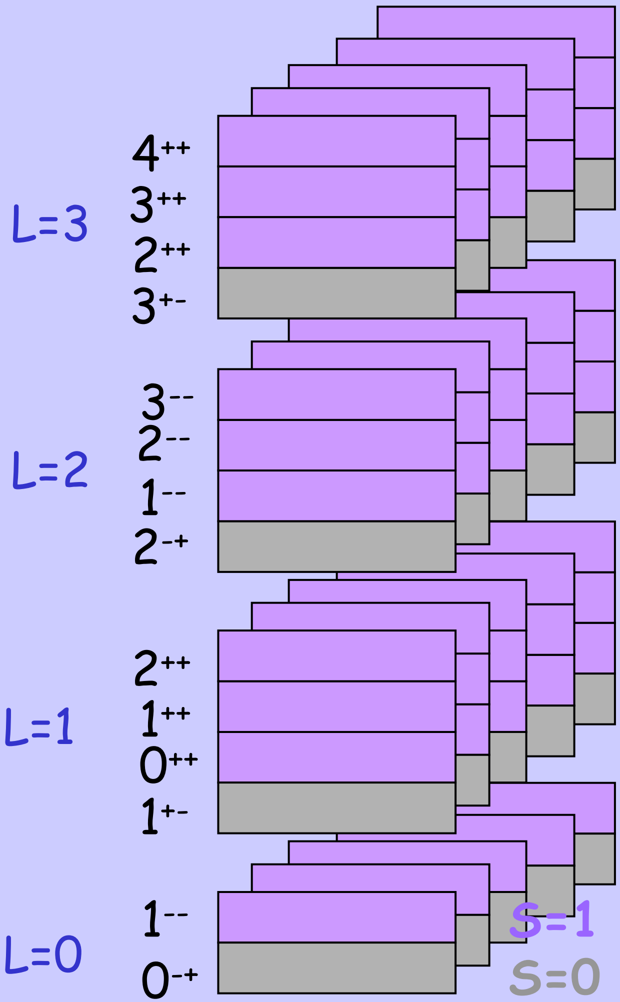
$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \quad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

Spectroscopy an QCD

Quarkonium



Mesons



ρ, K^*, ω, ϕ

π, K, η, η'

a,K,f,f'

b,K,h,h'

ρ, K^*, ω, ϕ

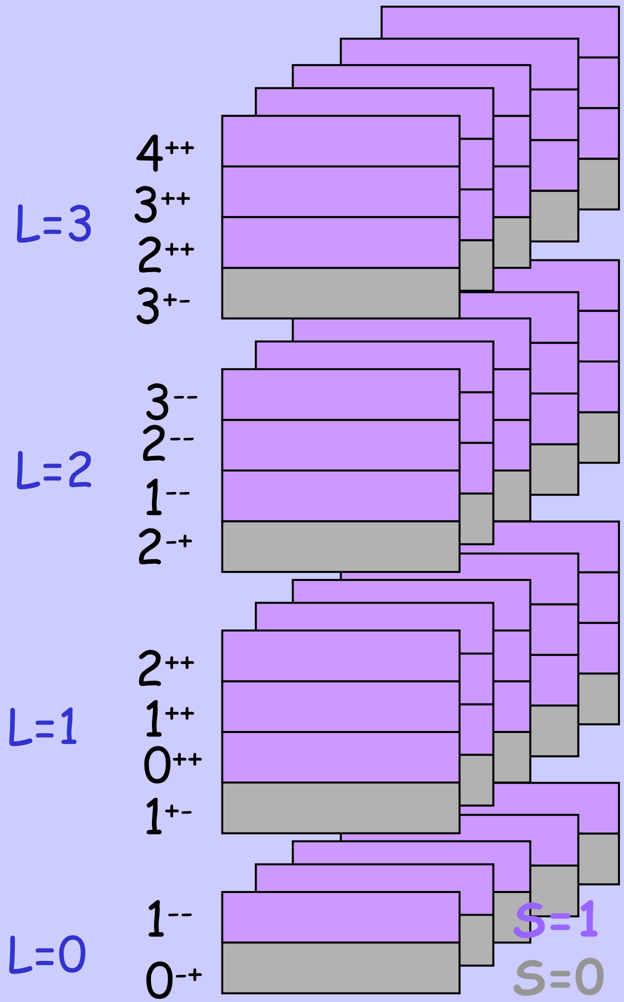
π, K, η, η'

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

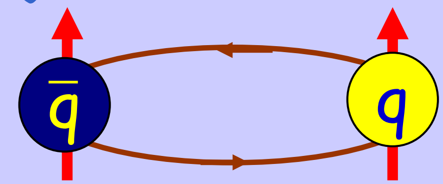
SU(3) is broken
Last two members mix

Spectroscopy an QCD

Mesons



Quarkonium



Nothing to do with Glue!

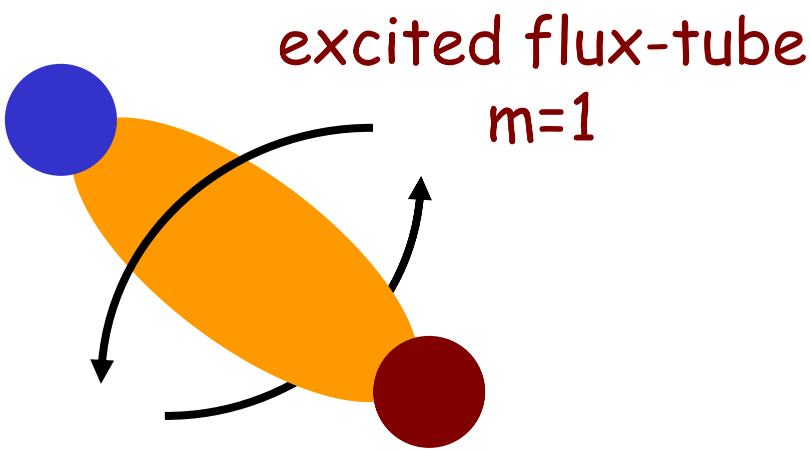
Allowed J^{PC} Quantum numbers:

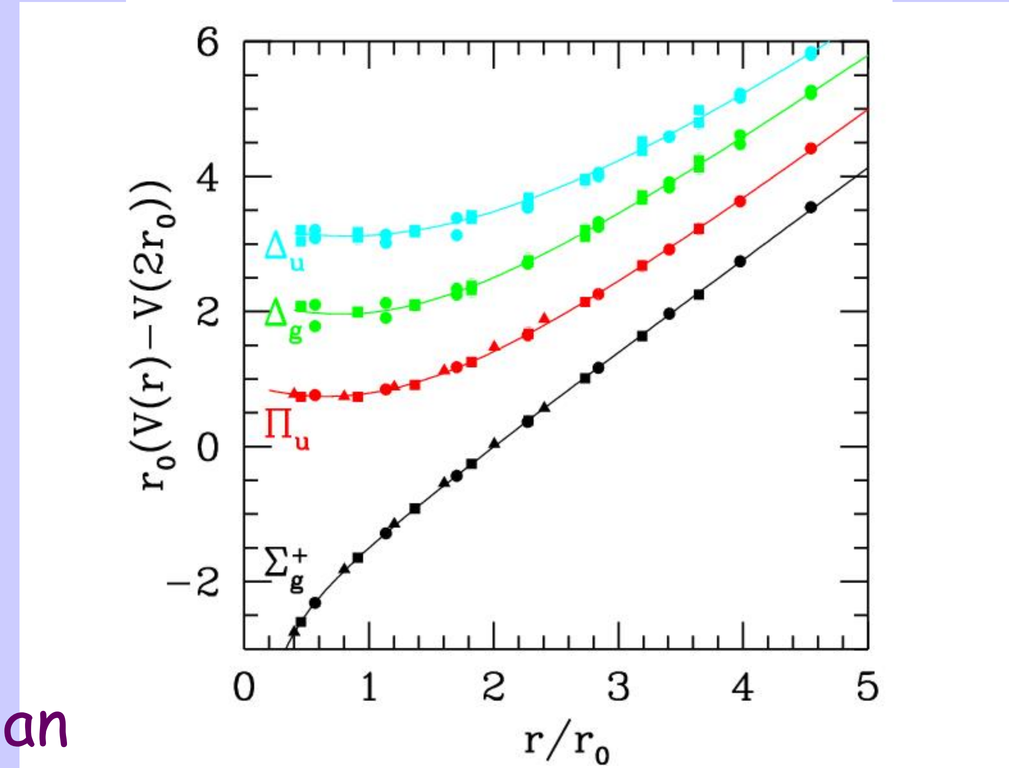
0^{--}	0^{++}	0^{-+}	0^{+-}
1^{--}	1^{++}	1^{-+}	1^{+-}
2^{--}	2^{++}	2^{-+}	2^{+-}
3^{--}	3^{++}	3^{-+}	3^{+-}
4^{--}	4^{++}	4^{-+}	4^{+-}
5^{--}	5^{++}	5^{-+}	5^{+-}

Exotic Quantum Numbers

non quark-antiquark description

QCD Potential





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

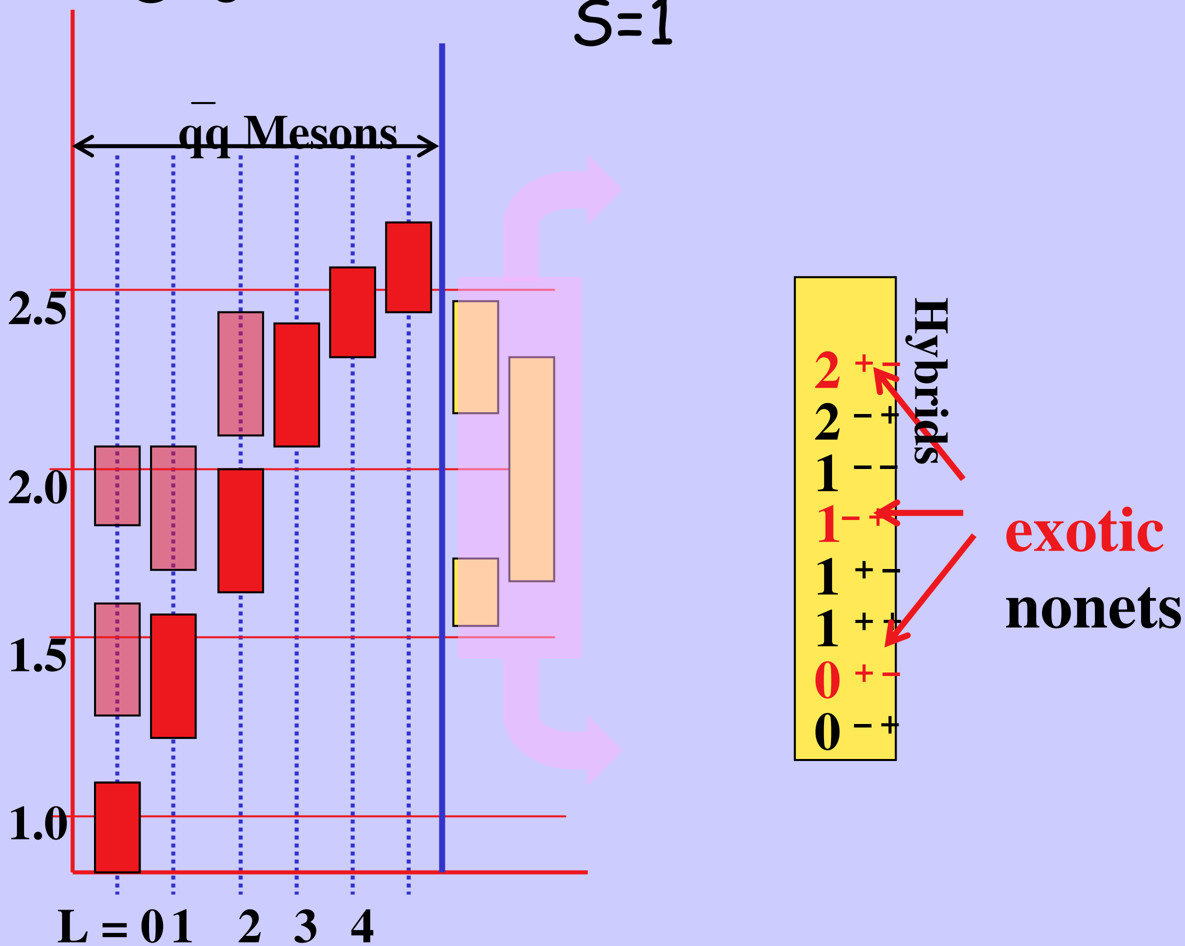
Observations of the nonets on the excited potentials are the best experimental signal of gluonic excitations.

Hybrid Meson Predictions

$q\bar{q}g$

Flux-tube model: 8 degenerate nonets

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



Start with S=0

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

Start with S=1

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

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

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

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

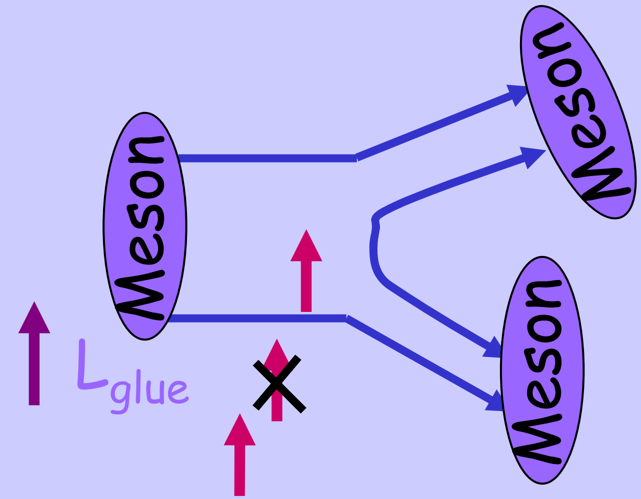
Decay Predictions

Analysis Method

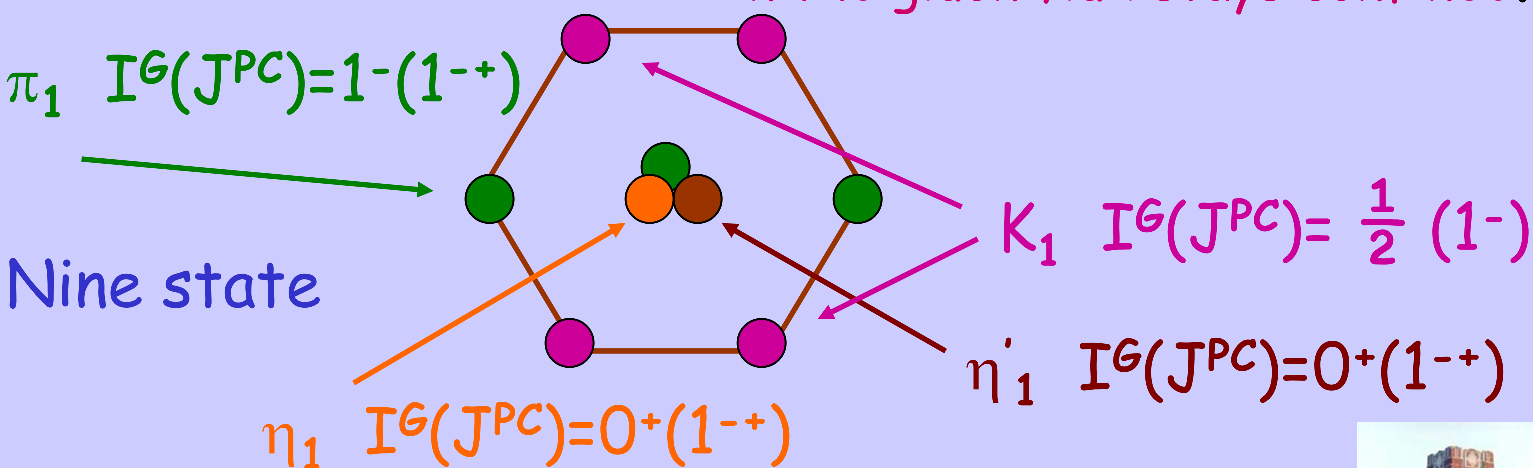
Partial Wave Analysis

Fit n-D angular distributions

Fit Models of production and decay of resonances.



Angular momentum in the gluon flux stays confined.



This leads to complicated multi-particle final states.

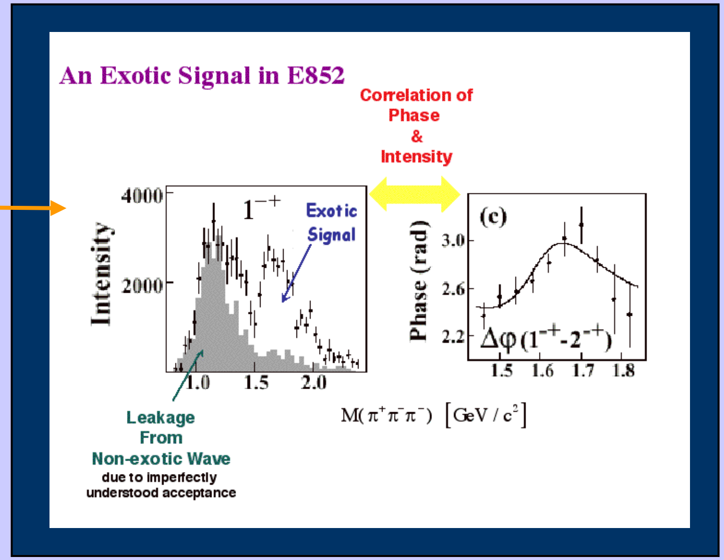
Experimental Evidence Hybrids

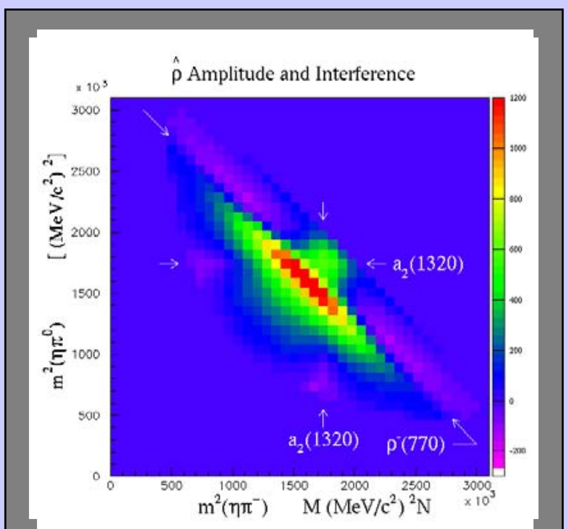
Exotic Mesons

1^{-+} mass 1.4

E852 BNL '97

CBAR CERN '97





Too light

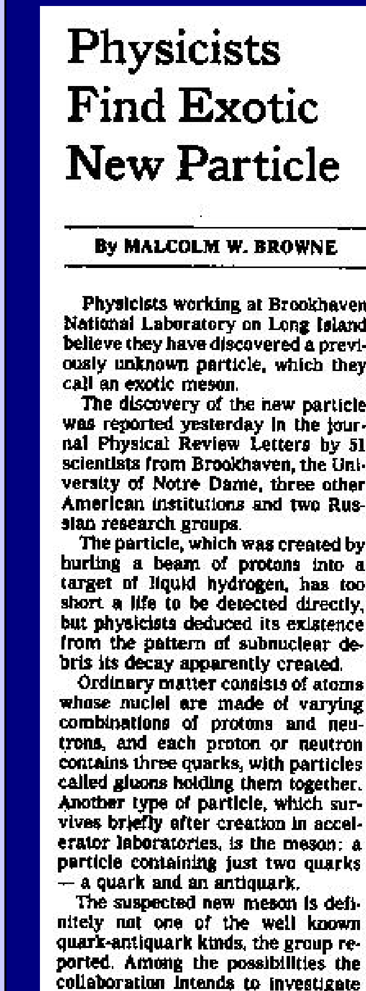
Not Consistent

Possible rescattering (?)

Decays are wrong (?)

Not a Hybrid

New York Times, Sept. 2, 1997



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The 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.

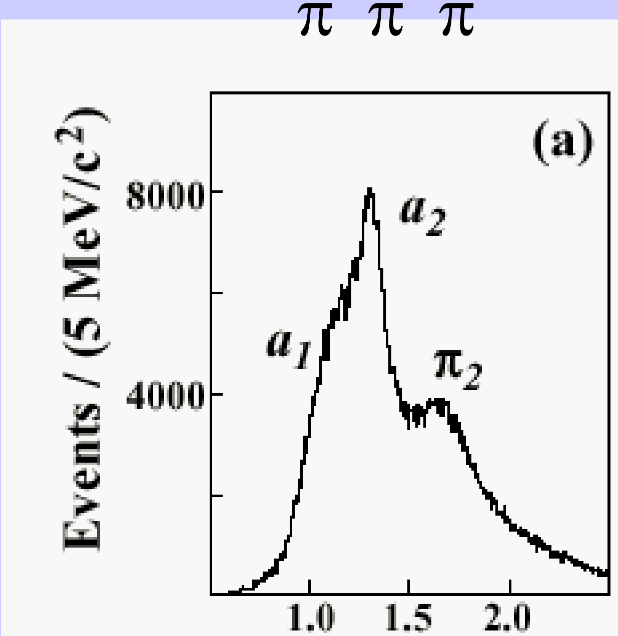
Ordinary matter consists of atoms whose nuclei are made of varying combinations of protons and neutrons, and each proton or neutron contains three quarks, with particles called gluons holding them together. Another type of particle, which survives briefly after creation in accelerator laboratories, is 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

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

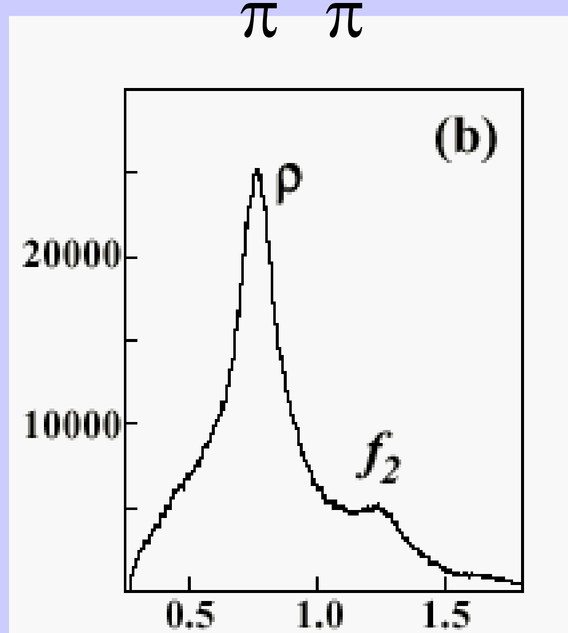
At 18 GeV/c

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



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

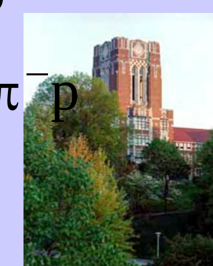
$\pi^+\pi^-$



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

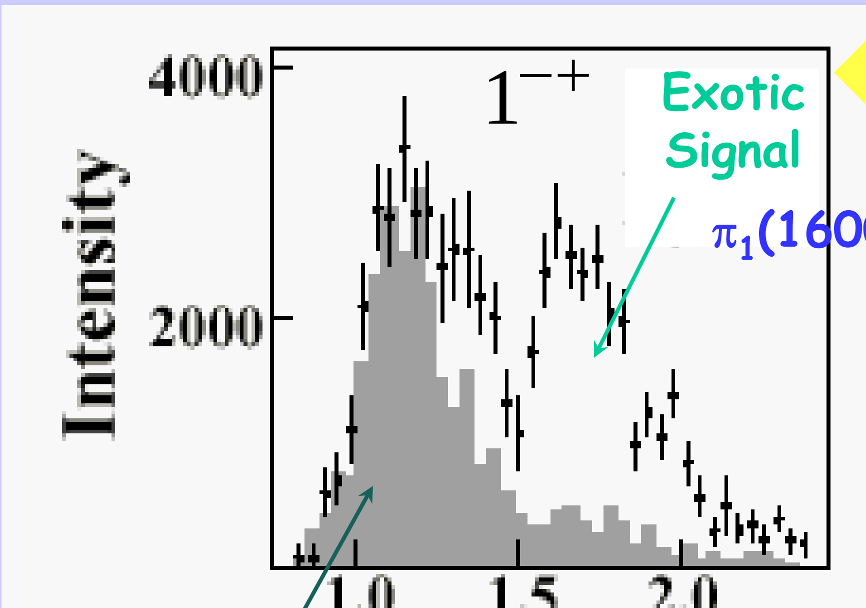
to partial wave analysis

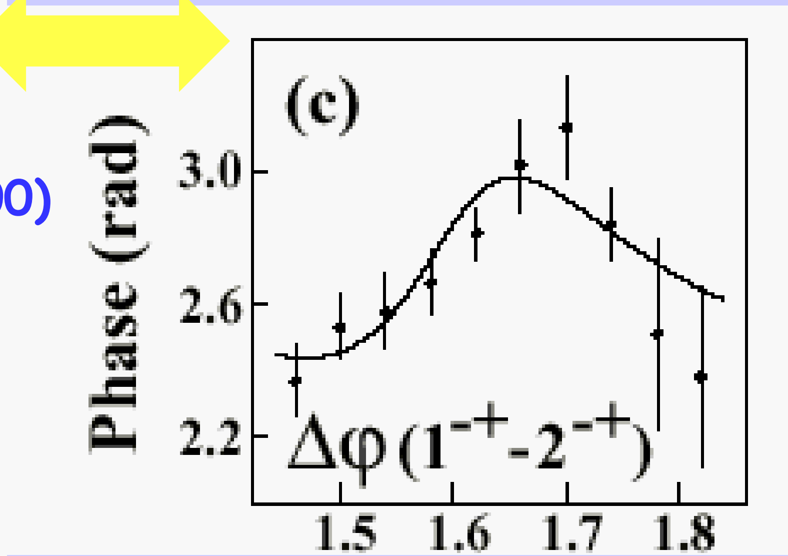
suggests $\pi^- p \to \rho^0 \pi^- p$
$\to \pi^+\pi^-\pi^- p$



An Exotic Signal

Correlation of
Phase
&
Intensity





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

Leakage
From
Non-exotic Wave
due to imperfectly
understood acceptance

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

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

In Other Channels

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

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

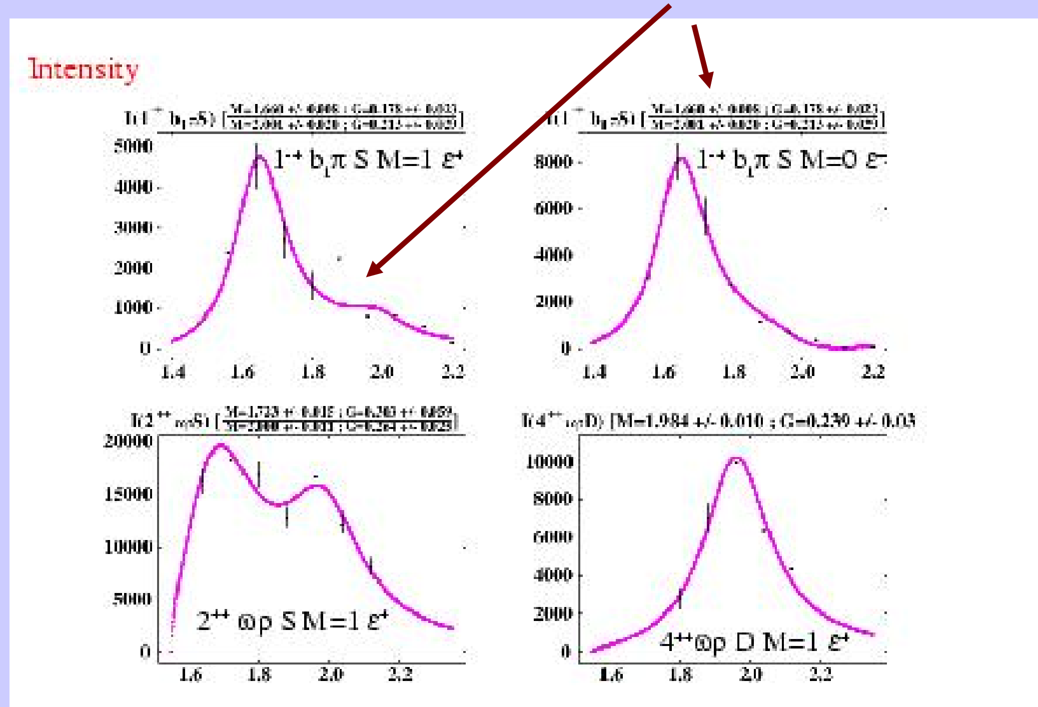
$\pi_1(1600) \rightarrow f_1\pi$

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

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

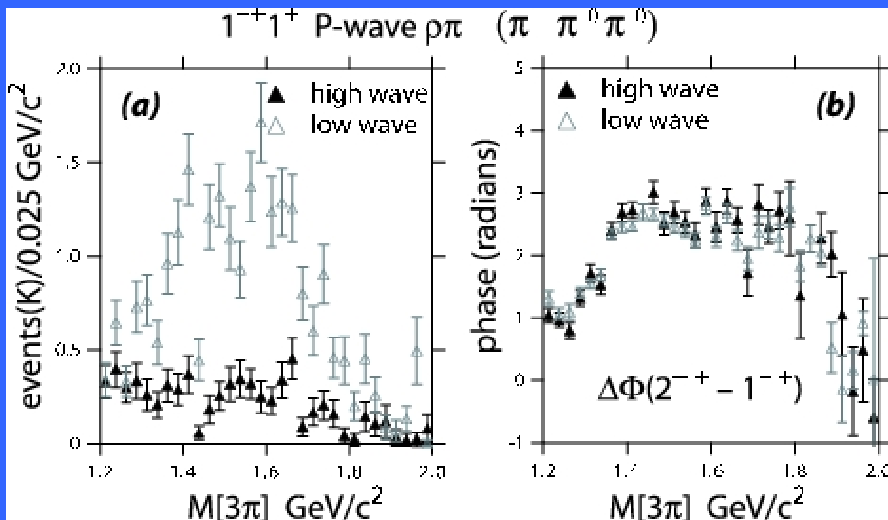


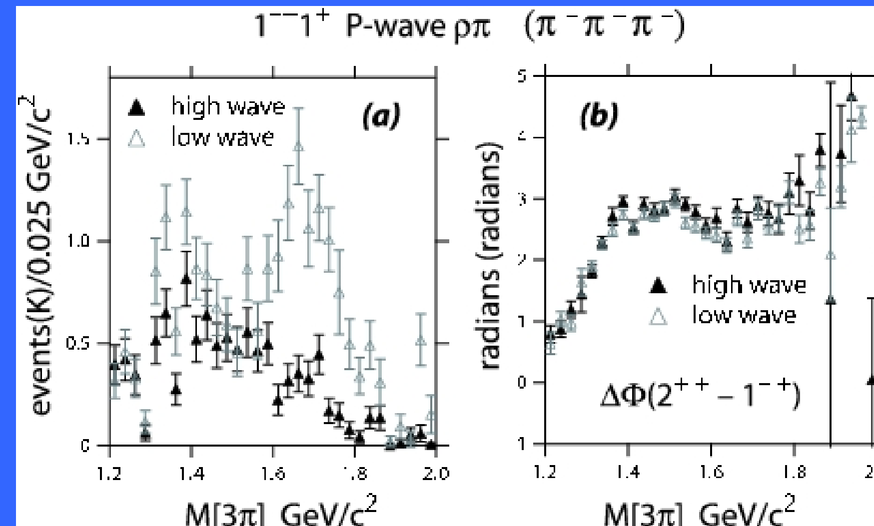
Mass = 1.687±0.011 GeV

Width = 0.206±0.03 GeV

New Analysis

Dzierba et. al. PRD 73 (2006)





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

No Evidence for the $\pi_1(1670)$

10 times statistics in each of two channels.

Get a better description of the data via moments comparison

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.

These are all the same member of a nonet.

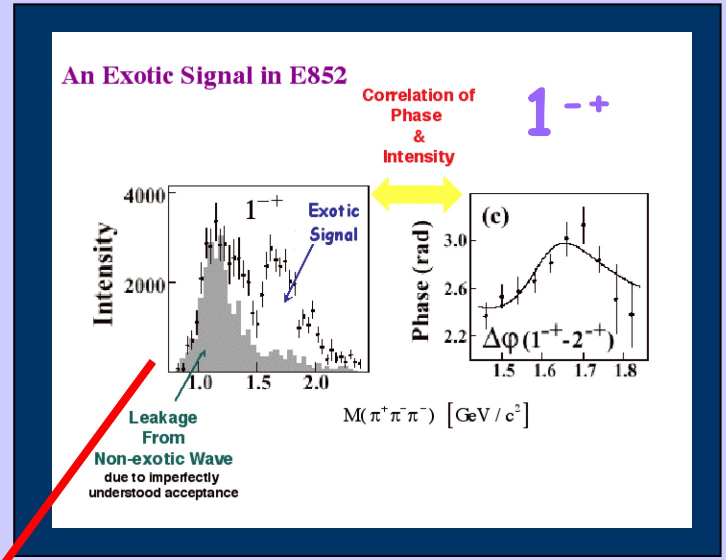
Experimental Evidence

Hybrid Nonets

Establish other Nonets:

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

Levels



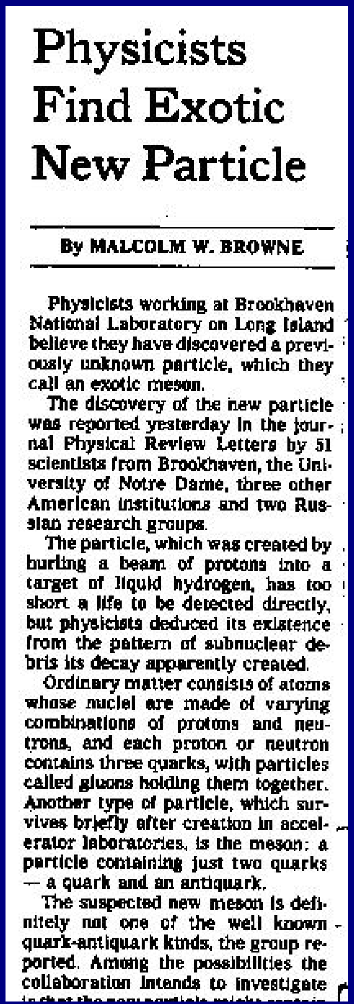
Built on normal mesons

$$
\begin{array}{ccc}
 & d\bar{s} \qquad\qquad u\bar{s} & \\
d\bar{u} & \frac{1}{\sqrt{2}}\left(u\bar{u}-d\bar{d}\right) & u\bar{d} \\
 & s\bar{d} \qquad\qquad s\bar{u} &
\end{array}
$$

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

Identify other states in nonet to establish hybrid

New York Times, Sept. 2, 1997



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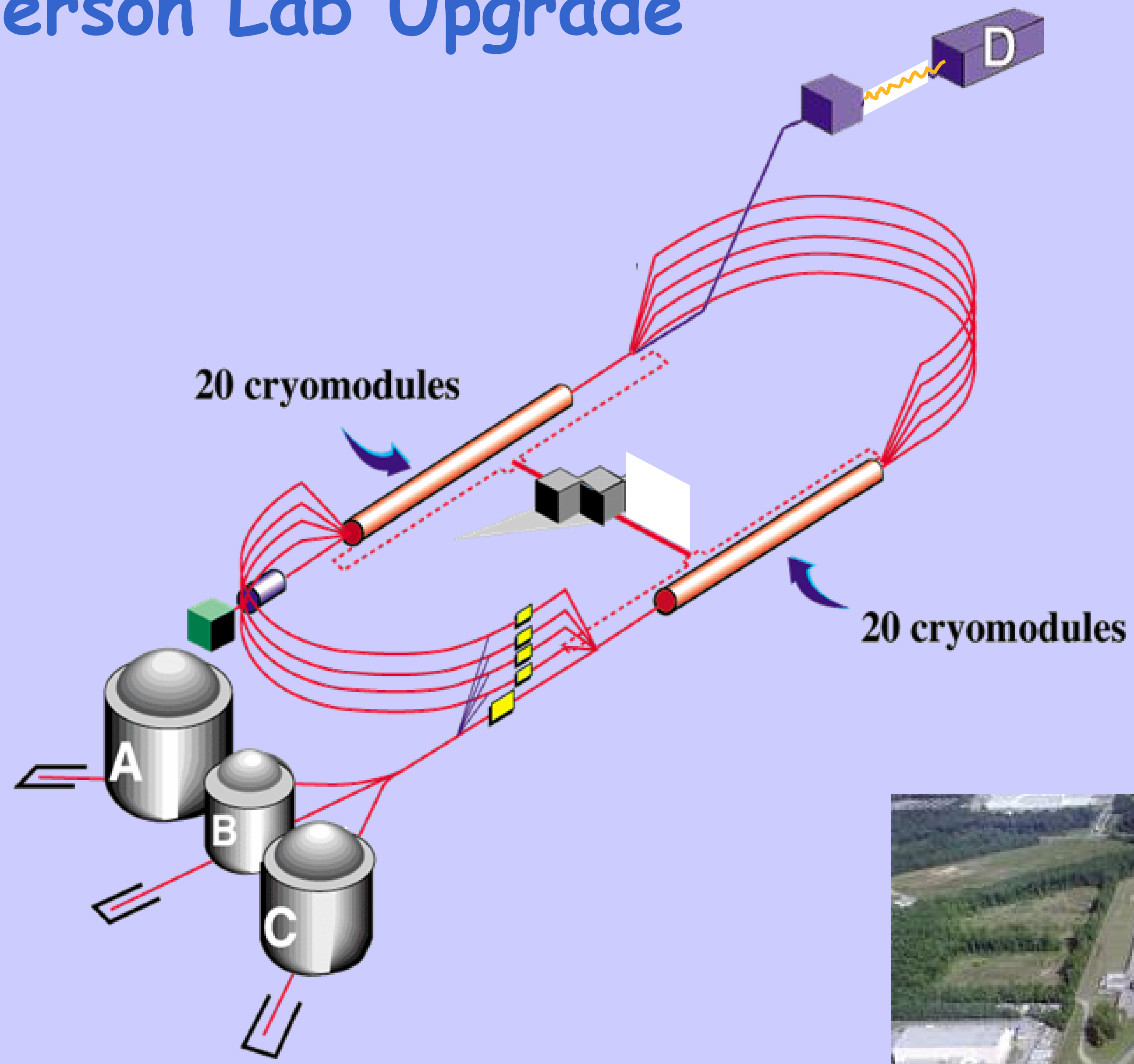
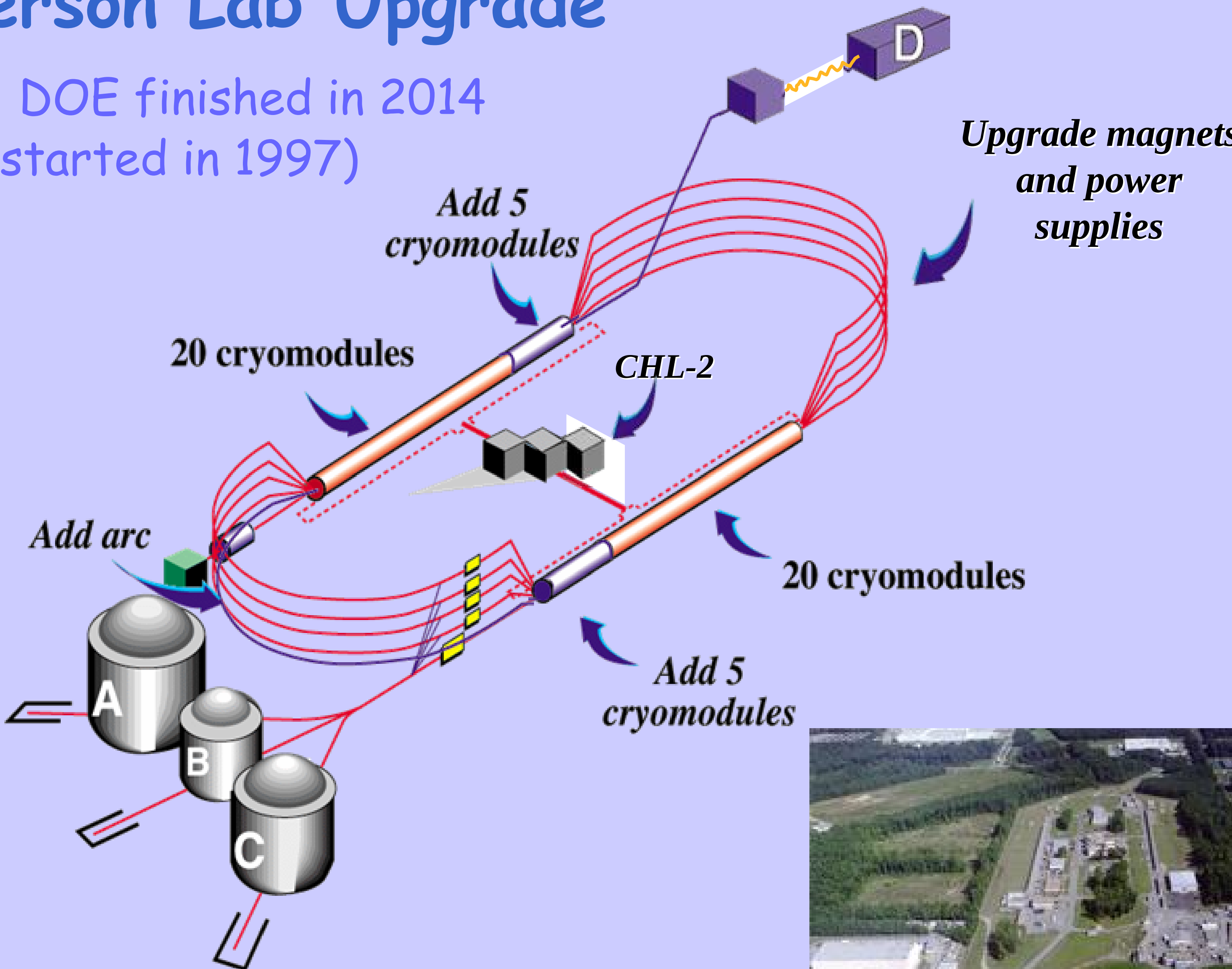
Jefferson Lab Upgrade



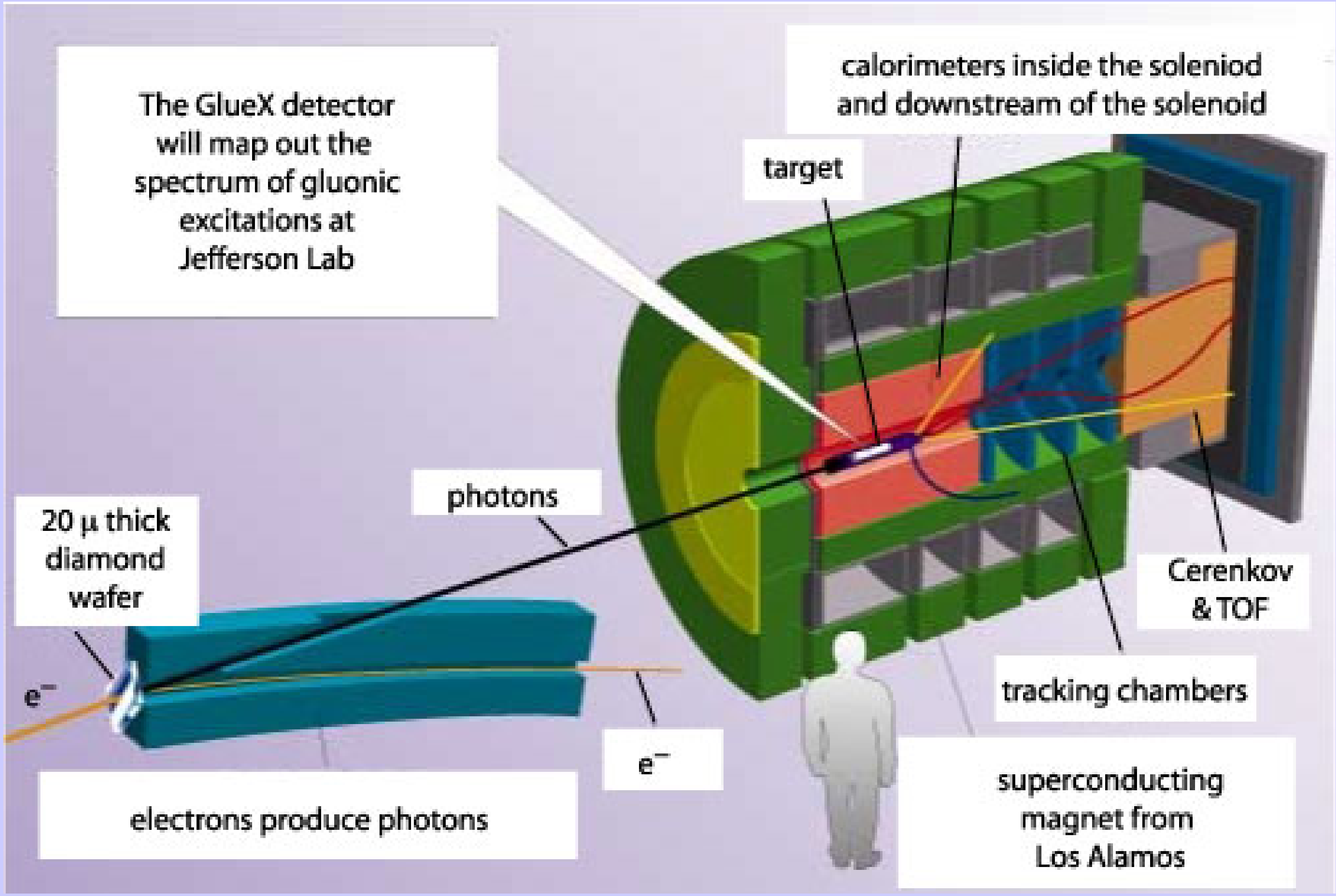
Jefferson Lab Upgrade

320M$ DOE finished in 2014
(I started in 1997)

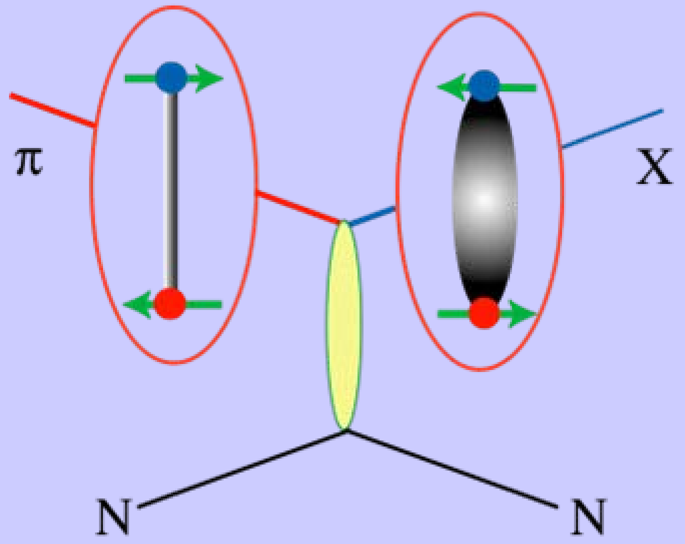


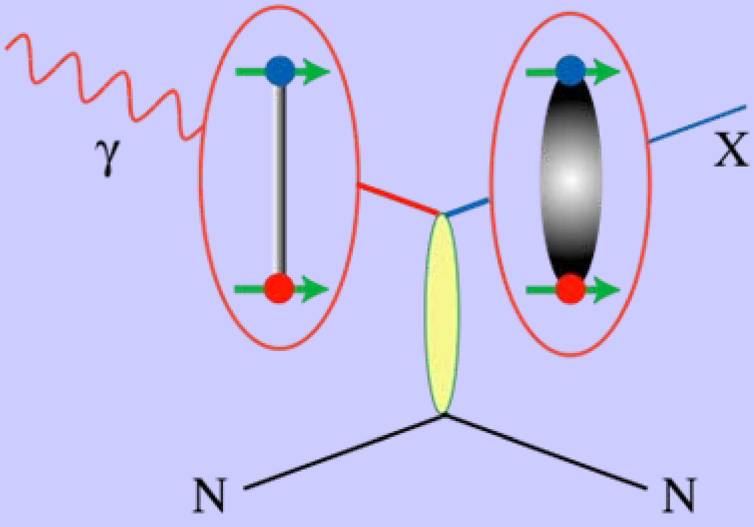
The GlueX Experiment

New Facility



How to Produce Hybrids





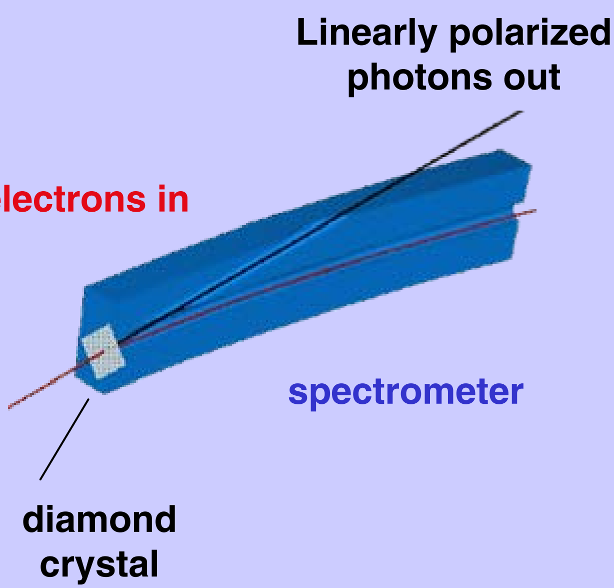
Beams of photons may be a more natural way to create hybrid mesons.

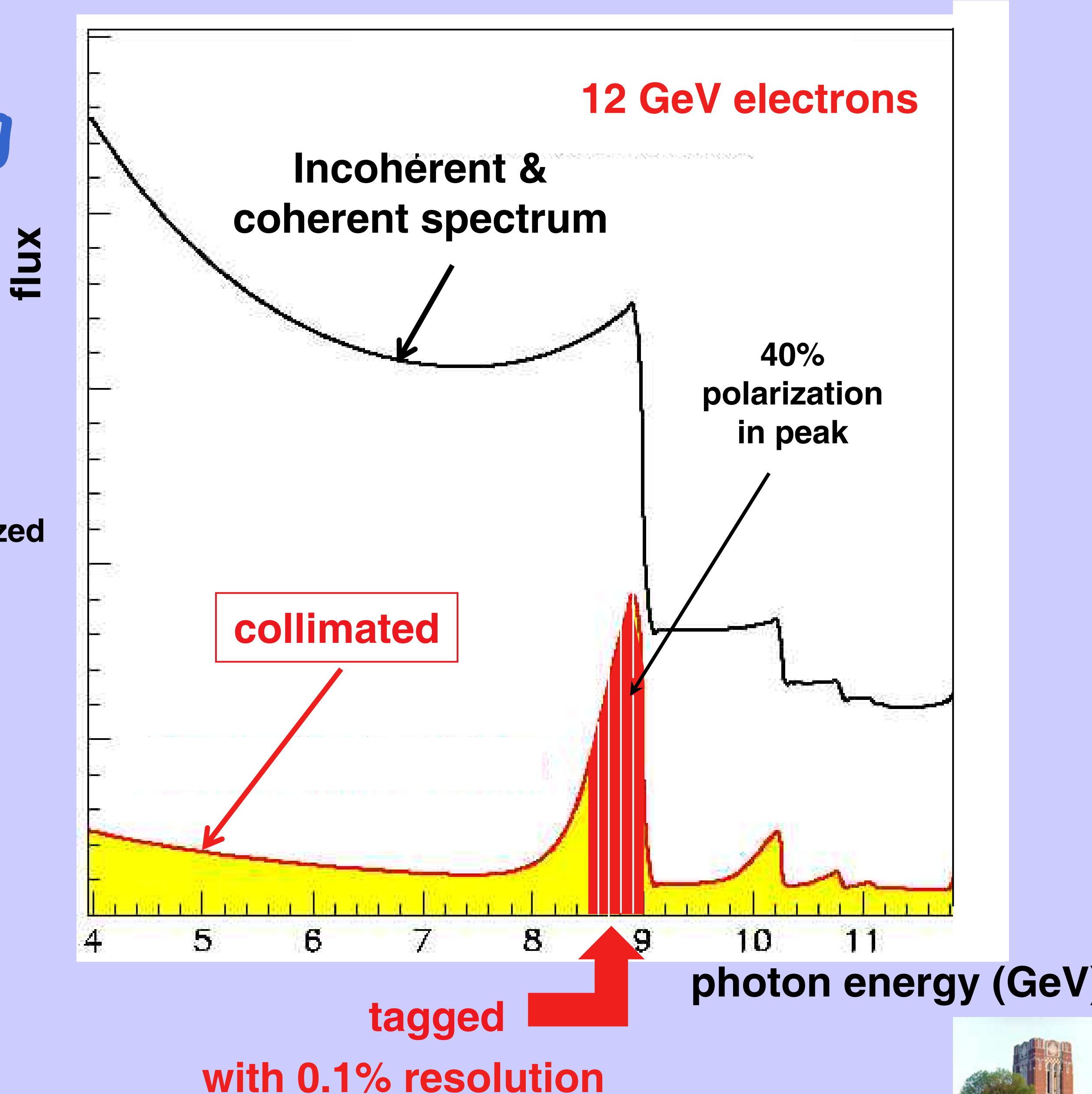
Simple QN counting leads to the exotic mesons

There is almost no data for photon beams at 9GeV energies. GlueX will increase data by 3-4 orders of magnitude.

Coherent Bremsstrahlung

This technique provides requisite energy, flux and polarization

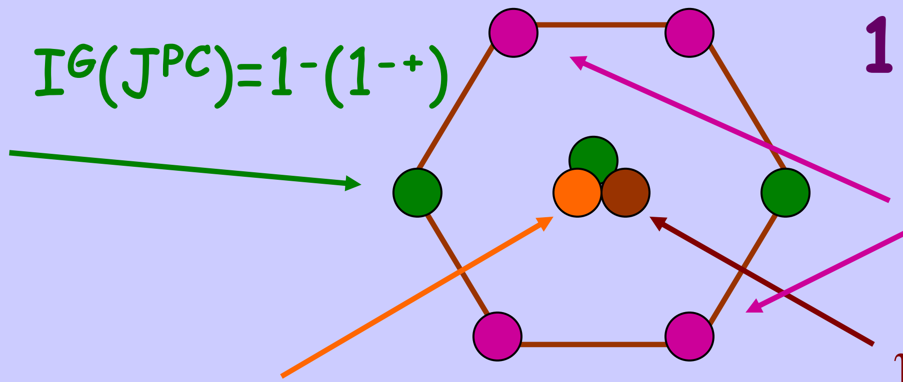




Exotics In Photoproduction

π_1 $I^G(J^{PC})=1^-(1^{-+})$

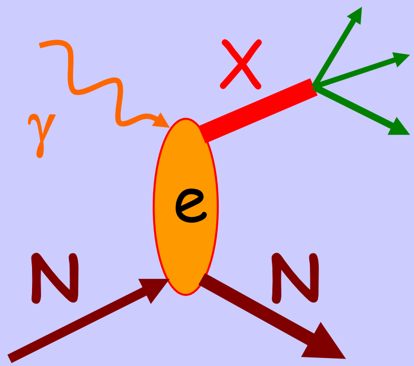
1^{-+} nonet



K_1 $I^G(J^{PC})=\frac{1}{2}(1^-)$

η'_1 $I^G(J^{PC})=0^+(1^{-+})$

η_1 $I^G(J^{PC})=0^+(1^{-+})$



Need to establish nonet nature of exotics: π η η'

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

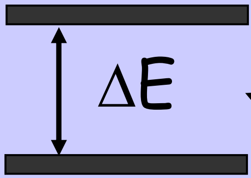
Need very good partial wave analysis.

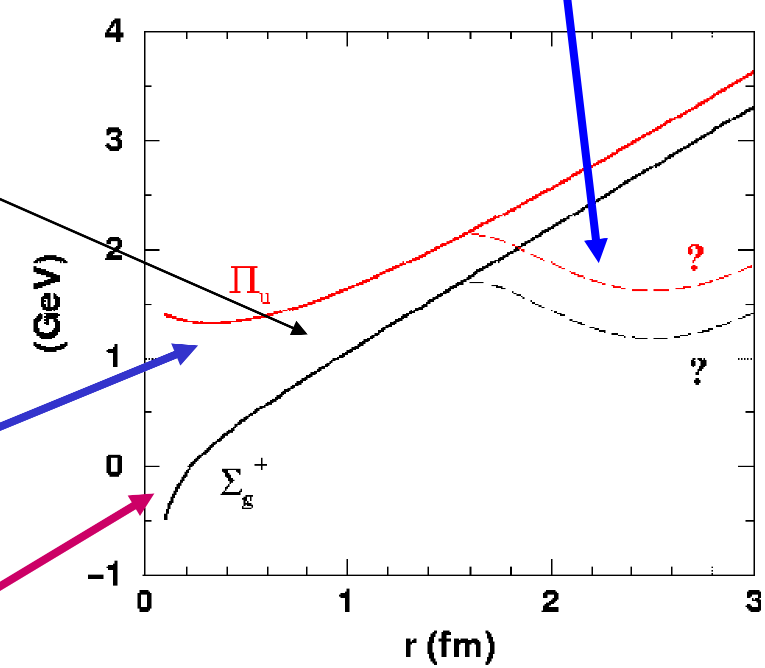
$\gamma \Leftrightarrow \rho,\omega,\phi$

Current DOE plan GlueX starts in 2014

Gluonic Hadrons and Confinement

What are the light quark Potentials doing?





Potentials corresponding To excited states of glue.

Non-gluonic mesons – ground state glue.

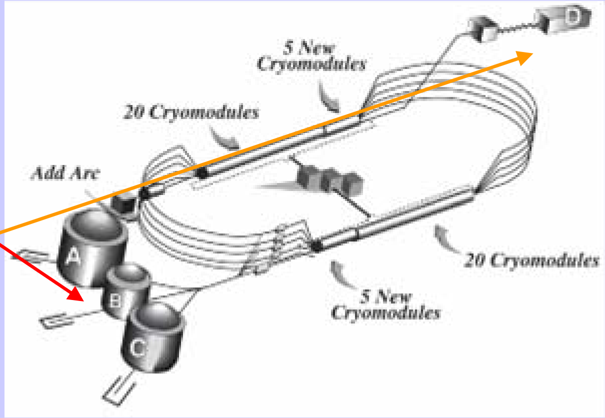
Lattice QCD potentials

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 baryon spectrum and the role of glue.

New results on baryons and theoretical work on models is near to giving us new insight on the observed baryons.



The definitive experiments to confirm or refute our expectations on the role of glue are being built.

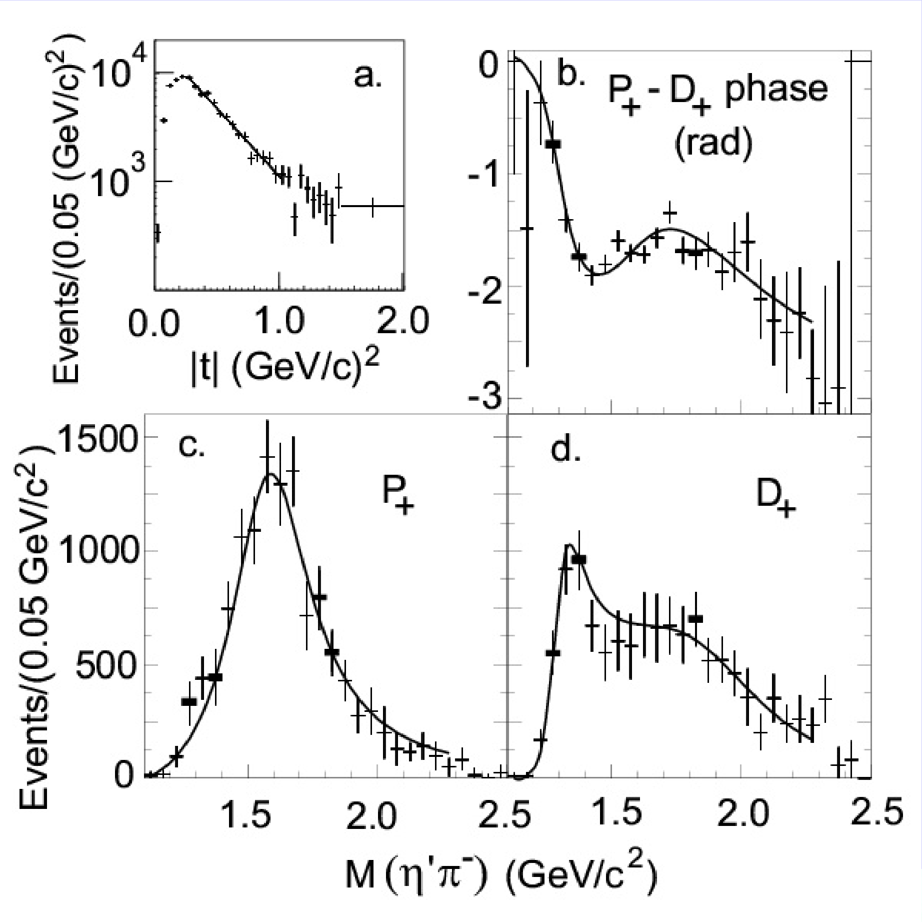
The synchronized advances in both areas will allow us to finally understand QCD and confinement.

In Other Channels

E852 Results

1-+ in η′π

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



The $\pi_1(1600)$ is the Dominant signal in $\eta'\pi$.

Mass = 1.597 ± 0.010 GeV

Width = 0.340 ± 0.040 GeV

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