Shedding light on the color forces that bind matter

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Outline

- Fundamental Interactions
- Quantum Chromo Dynamics
- Color Charges and Gluons
- Exciting the Glue
- The GlueX Experiment

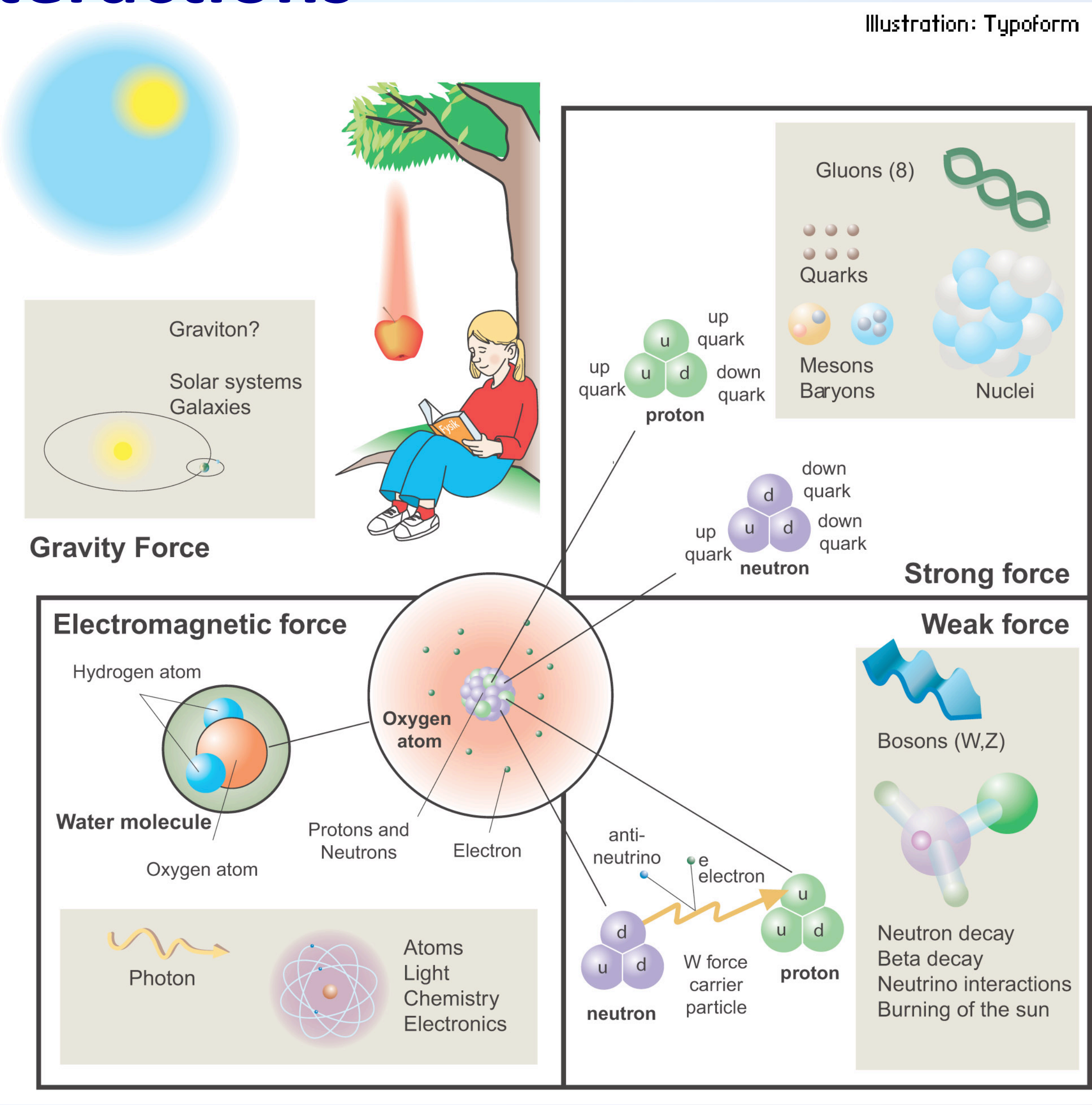
Fundamental Interactions

Interactions act on a large range of distance scales.

Each interaction involves its own charges.

Interactions cause forces and changes in configuration.

Interactions are associated with microscopic particles.



Microscopic Particles

Leptons Quarks

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} -e \\ 0 \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} +\frac{2}{3} \\ -\frac{1}{3} \end{pmatrix}$$

Electric Charge

Can effectively describe everything we see in the world around us.

Quarks build the protons and neutrons in the nucleus of atoms.

Microscopic Particles

Leptons

Quarks

Its not that easy ....

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}$$ 1 / >0

$$\begin{pmatrix} u \\ d \end{pmatrix}$$ ~4 / ~10

$$\begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}$$ 205 / >0

$$\begin{pmatrix} c \\ s \end{pmatrix}$$ ~3000 / ~1000

$$\begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}$$ ~3500 / >0

$$\begin{pmatrix} t \\ b \end{pmatrix}$$ ~350000 / ~10000

Mass (electron masses)

Microscopic Particles

Antimatter as well ....

Leptons Quarks

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix}\begin{pmatrix} e^+ \\ \bar{\nu}_e \end{pmatrix} \begin{pmatrix} u \\ d \end{pmatrix}\begin{pmatrix} \bar{u} \\ \bar{d} \end{pmatrix}$$

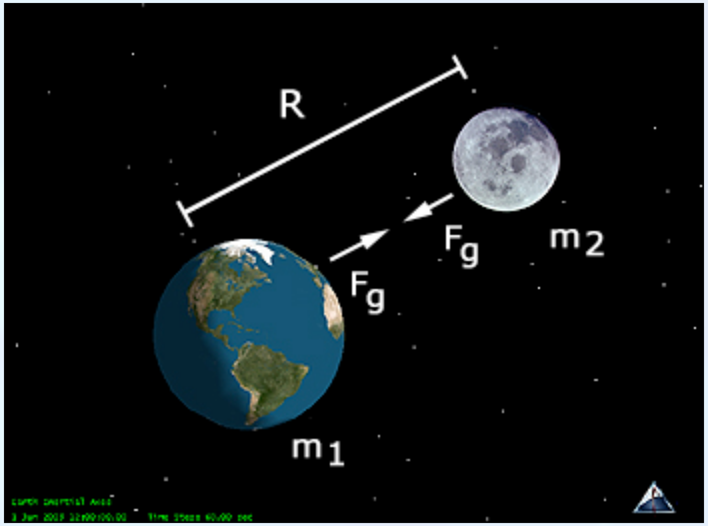
$$\begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix}\begin{pmatrix} \mu^+ \\ \bar{\nu}_\mu \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix}\begin{pmatrix} \bar{c} \\ \bar{s} \end{pmatrix}$$

$$\begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix}\begin{pmatrix} \tau^+ \\ \bar{\nu}_\tau \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix}\begin{pmatrix} \bar{t} \\ \bar{b} \end{pmatrix}$$

Gravitational Interaction

$$\vec{F} = -G\frac{m_1 m_2}{r^2}\hat{r}$$

Gravity has an infinite range. ``Mass'' is the ``charge'' of gravity.



Short-range limits look for deviations to gravitational force on very short distances. Limits on deviations can be probed to micron-level and better.

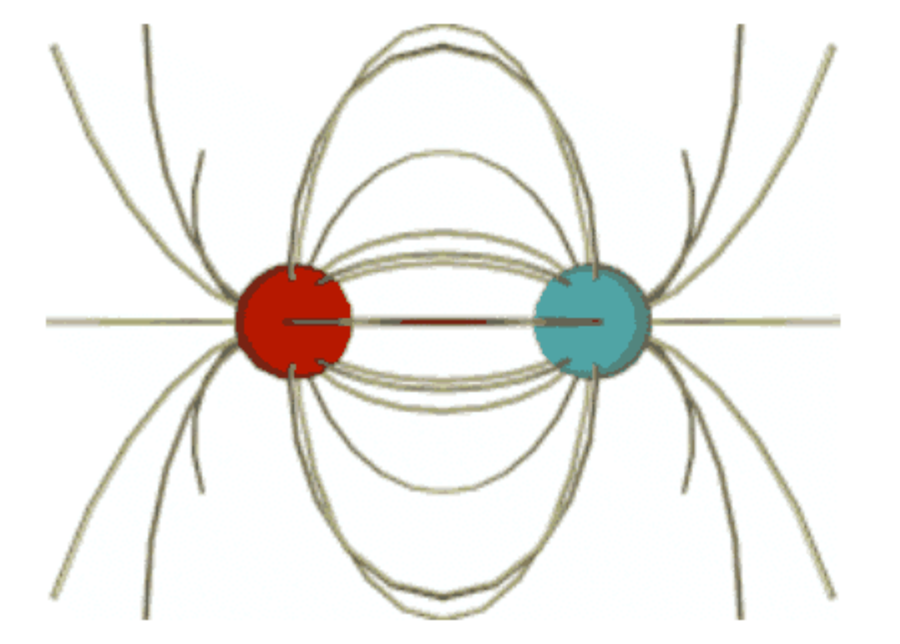
On very large distance scales, dark energy creates a repulsive force that counteracts gravity.

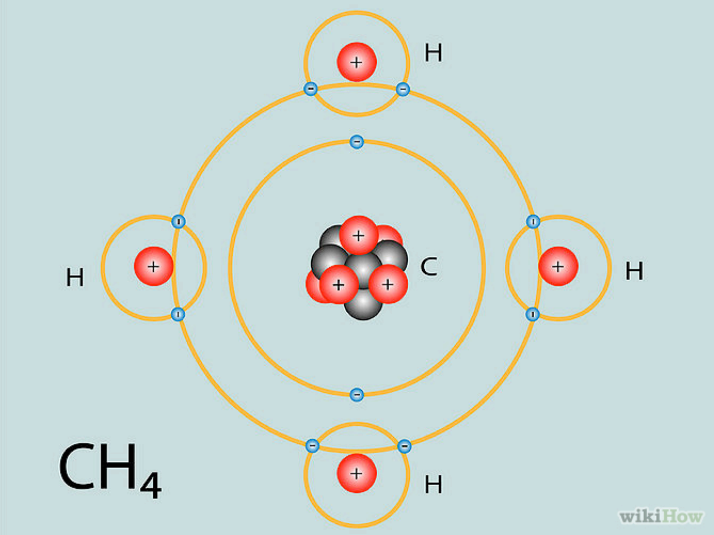
Electromagnetic Interaction

$$\vec{F} = \frac{1}{4\pi\epsilon_0}\frac{q_1 q_2}{r^2}\hat{r}$$

The Electric force has an infinite range.

``Electric Charge'' is the ``charge'' of the interaction.





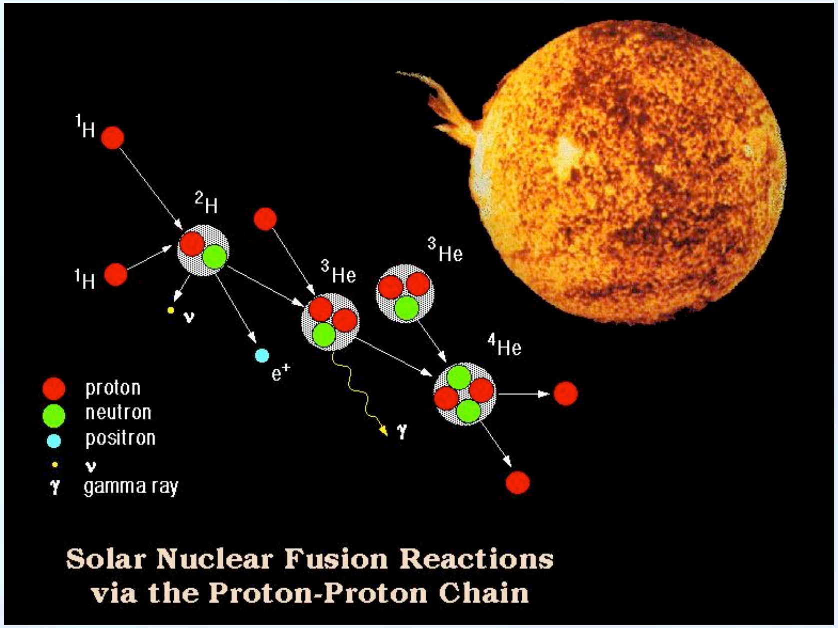
Responsible for friction and tension forces.

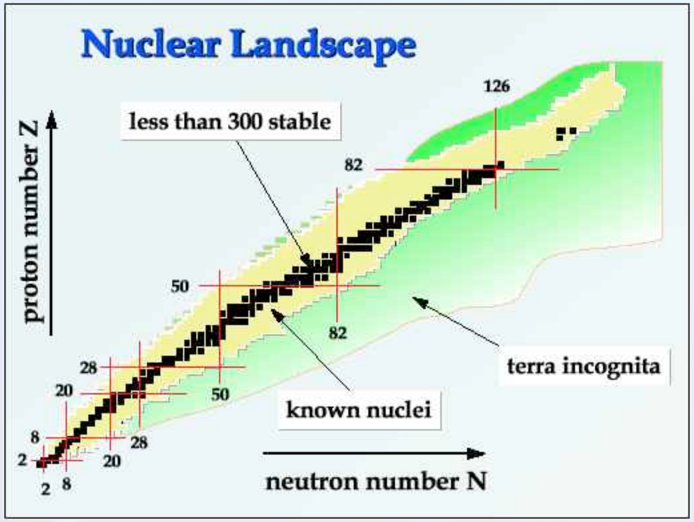
Responsible for chemistry and biology.

Weak Interaction

An interaction that changes particles into other particles.

$$n \rightarrow p e^- \bar{\nu}_e$$

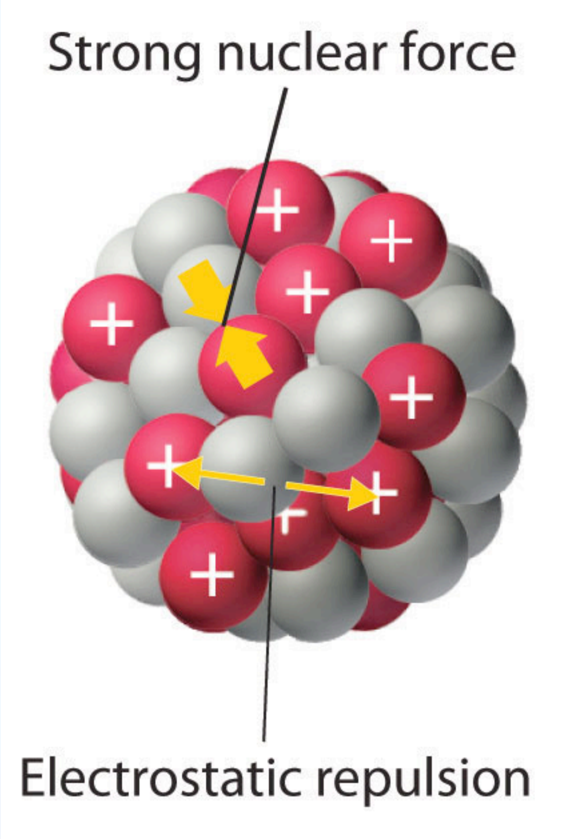




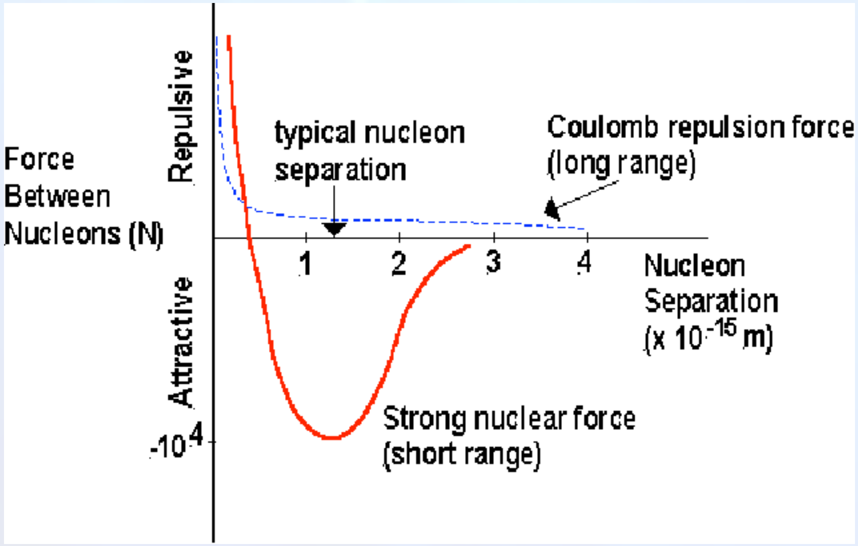
Responsible for fusion in the center of stars by fusing protons into heavier elements.

Responsible for which isotopes of nuclei are stable.

Strong Interaction



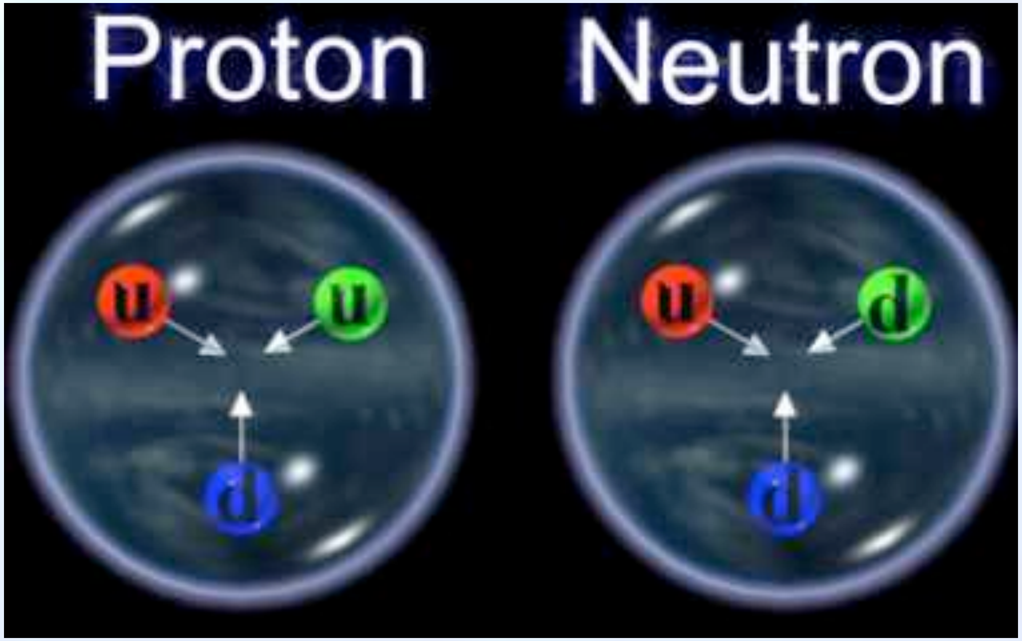
The classic nuclear physics force binds the protons and neutrons together in a nucleus. It is stronger than the electric force as it overcomes the electrostatic repulsion between the protons.



This is just a residual force from a more fundamental force that forms the protons and neutrons.

Strong Interaction – Interactions of Quarks

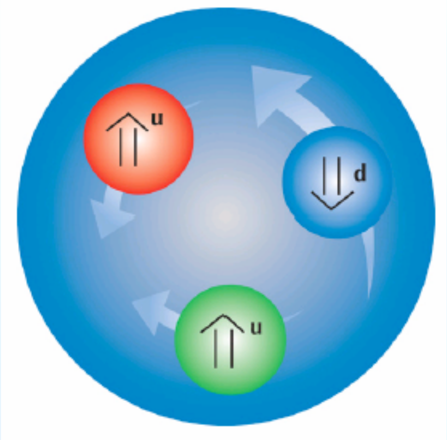
Protons and neutrons are made of three quarks. The proton is two ``up quarks'' and a ``down quark''. The neutron is two "down quarks'' and an ``up quark''.



Quarks carry electric charge, but there primary interaction is through there ``color charge'', of which there are three: **red**, **blue** and **green**.

Quantum Chromo Dynamics (QCD) describes the interactions involving color forces.

Quantum Chromo Dynamics

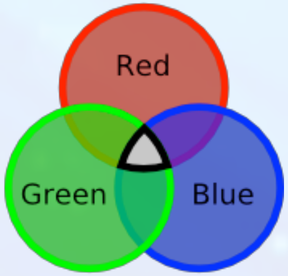


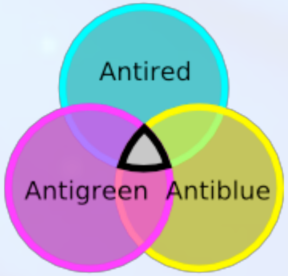
$$\mathcal{L}_{QCD} = \overline{\psi}(i\gamma_\mu \mathcal{D}^\mu - m) - \frac{1}{4} F_{j,\mu\nu} F_j^{\mu\nu}$$

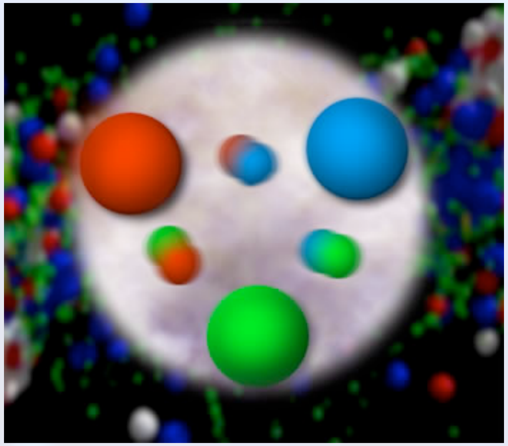
The rules that govern how the quarks froze out into protons and neutrons (hadrons) are given by QCD.

Quarks have color charge: red, blue and green.
Antiquarks have anticolors: cyan, yellow and magenta.

Bound states of quarks are color neutral, ``white''.

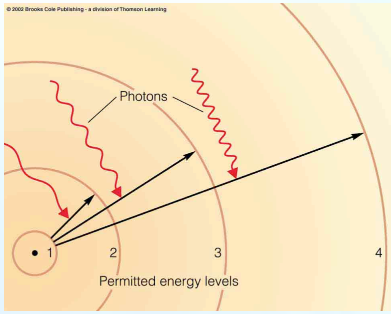






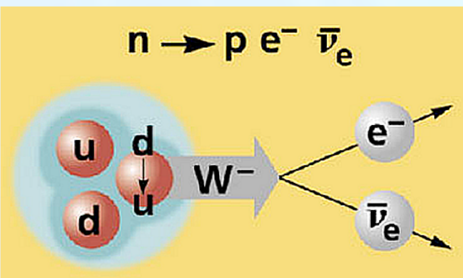
``White'' can be one of each color:
red-blue-green, cyan-yellow-magenta
or a color and an anticolor:
red-cyan, blue-yellow, green-magenta

Force Mediators



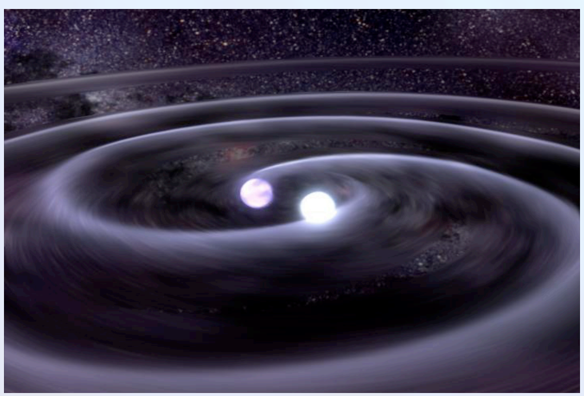
Electromagnetic Interactions

Photons are the force carriers for the E-M force.
Photons are electrically neutral.
Massless photons lead to infinite range.



Weak Interactions

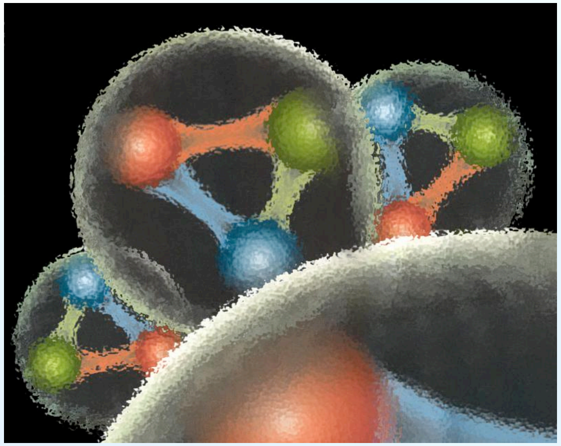
W and Z bosons mediate the weak interaction.
Massive particles lead to very short range.



Gravitational Interactions

Gravitons mediate the gravitational force.
Massless gravitons lead to infinite range.

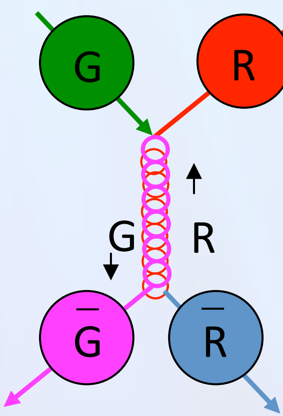
Force Mediators

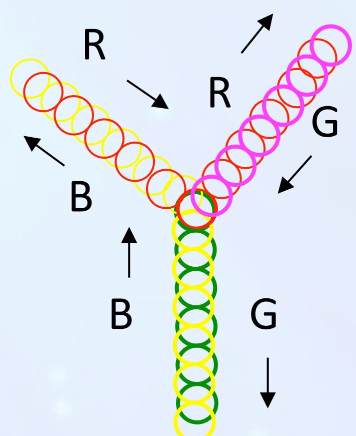


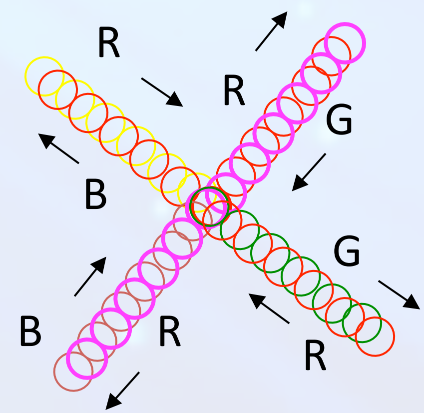
Quantum Chromo Dynamics

Gluons are the force carriers of QCD.
Gluons carry color and an anticolor charges.
Gluons are not white.

Gluons strongly interact with quarks

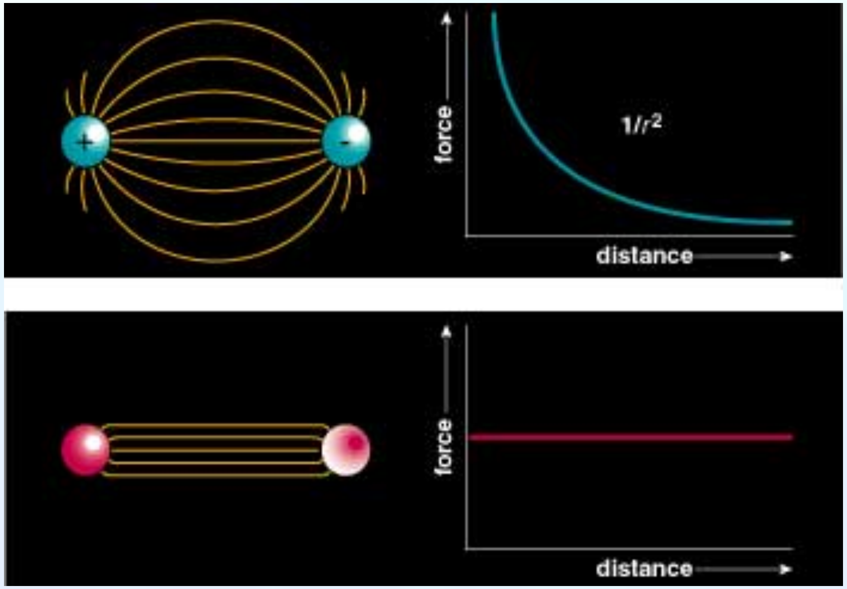


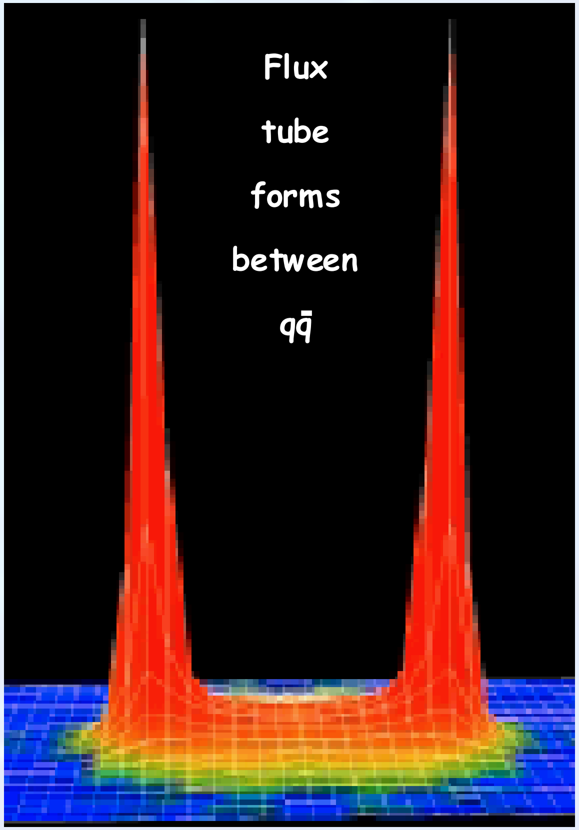




Gluons strongly interact with other gluons.
This makes QCD different than all other interactions.

Quantum Chromo Dynamics



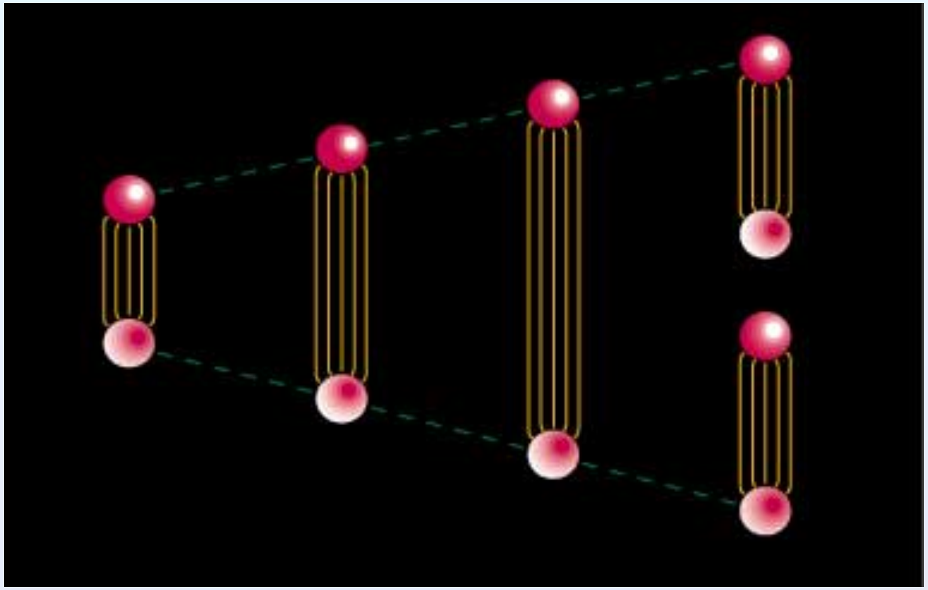


Color Field: Because of self interaction, confining flux tubes form between static color charges

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

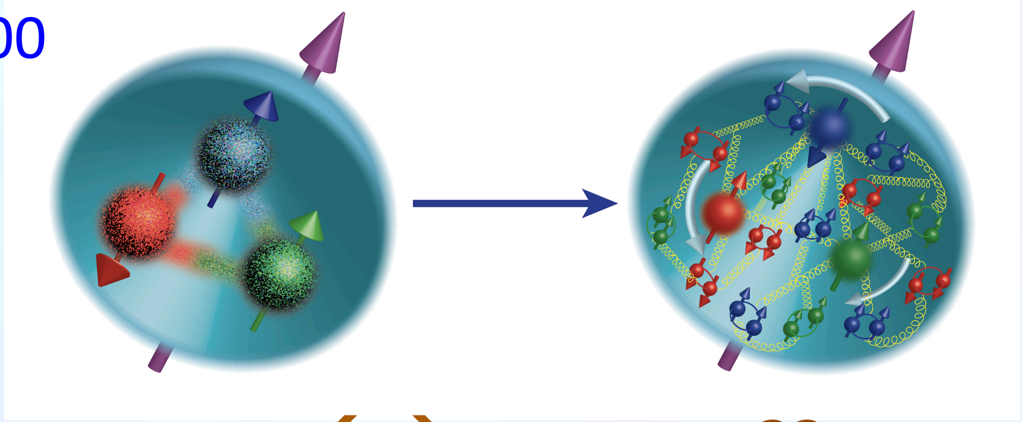
Quark Confinement

- Quarks can never be isolated.
- There is a linearly rising potential energy.
  - Constant 16-ton force between quarks.
  - Separation of quark from antiquark takes an infinite amount of energy
  - Gluon flux breaks, new quark-antiquark pair produced --- $E=mc^{2}$.



The Mass of The Proton?

- The proton has a mass ~1800 times that of the electron.
- The bare masses of the up and down quarks are
- ~18 times the mass of the electron.



18 m_e ←→ 1800 m_e ??

In many experiments, the proton behaves like it contains three objects of mass ~600 times the mass of the electron.

Three ``heavy" objects confined in a 1fm sized space.

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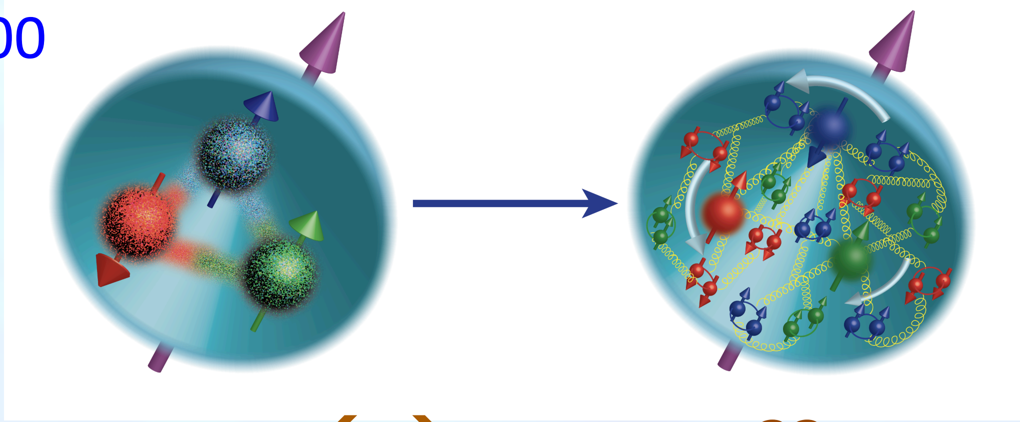

18 m_e ←→ 1800 m_e ??

If gluons did not carry color charges, QCD would look much more like the electromagnetic interaction.

The energy density is associated with color-charge density in a quark-gluon system.

An balancing of size and color charge has to occur.

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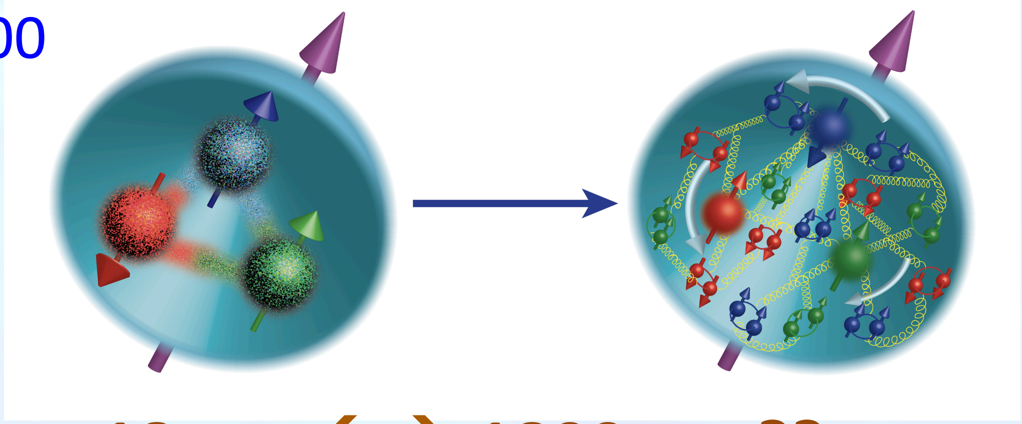


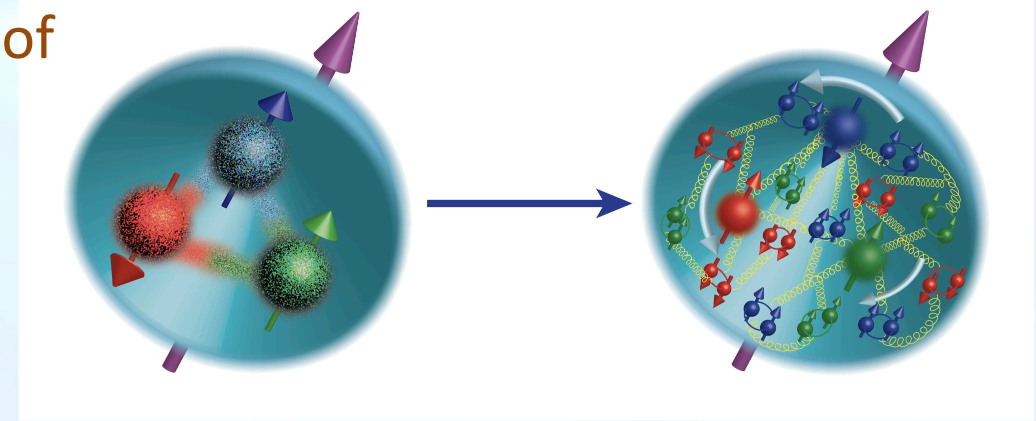
18 m_e ←→ 1800 m_e ??

The gluonic field binding the quarks generates the most of the proton's mass.

Most of the visible (not dark) mass of the universe is gluons!

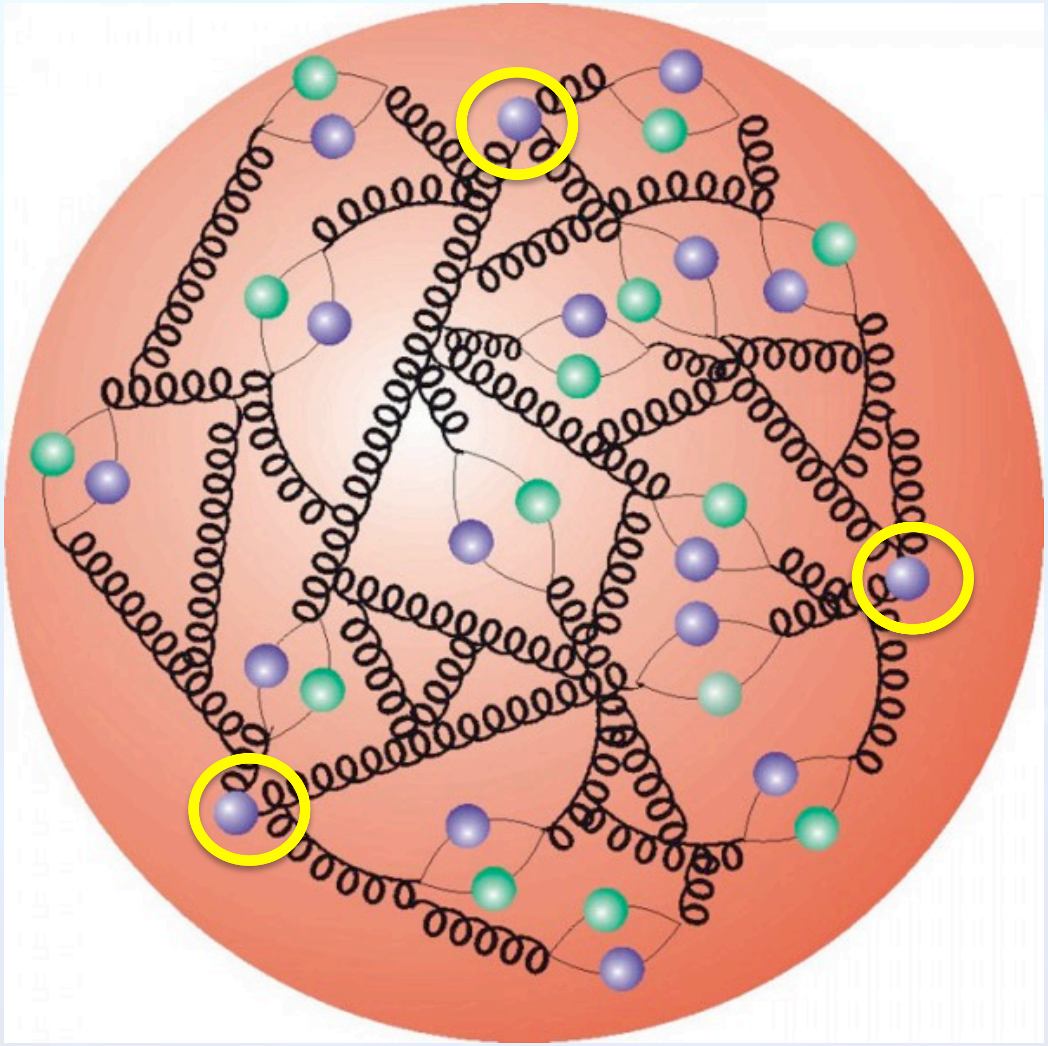
The Spin of the Proton?

- What makes up the spin ½ of the proton?
- Three Spin ½ quarks? $\Delta\Sigma$ is only 25% of the total spin!
- Spin of gluons? J_g is also only 25% of the total spin!
- Orbital motion? L_q is currently unexplored.



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

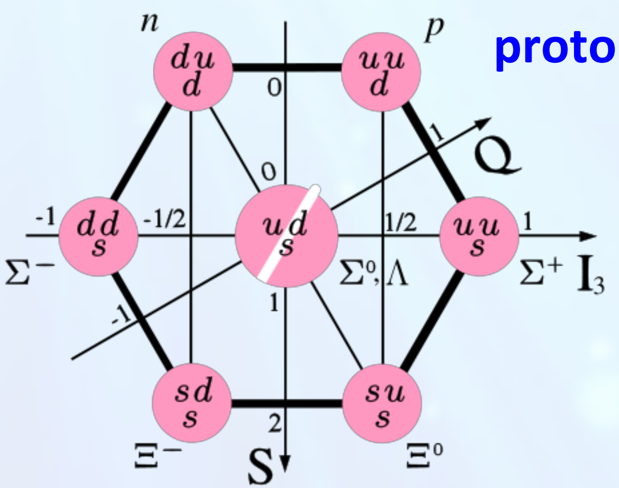
The Structure of The Proton



Observed Quark Configurations (u,d,s)

3-Quark Systems
Baryons

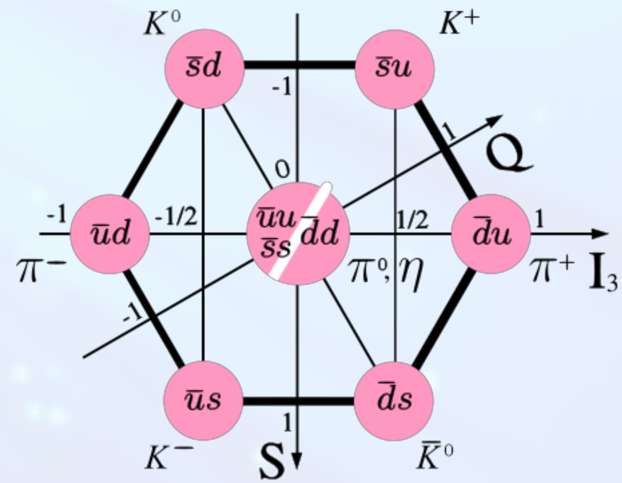
Groups of 8 (octet)
and 10 (decuplet).



proton and neutron

Quark-antiquark Systems
Mesons

Groups of
9 (nonet).



π meson or pion

Other Configurations?

$q\bar{q}q\bar{q}$ 4-quark

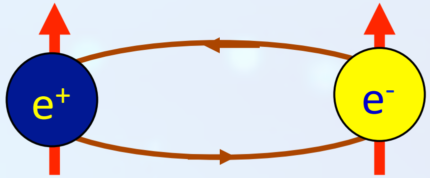
$qqq\bar{q}q$ pentaquarks

$gg \quad ggg$ glueballs

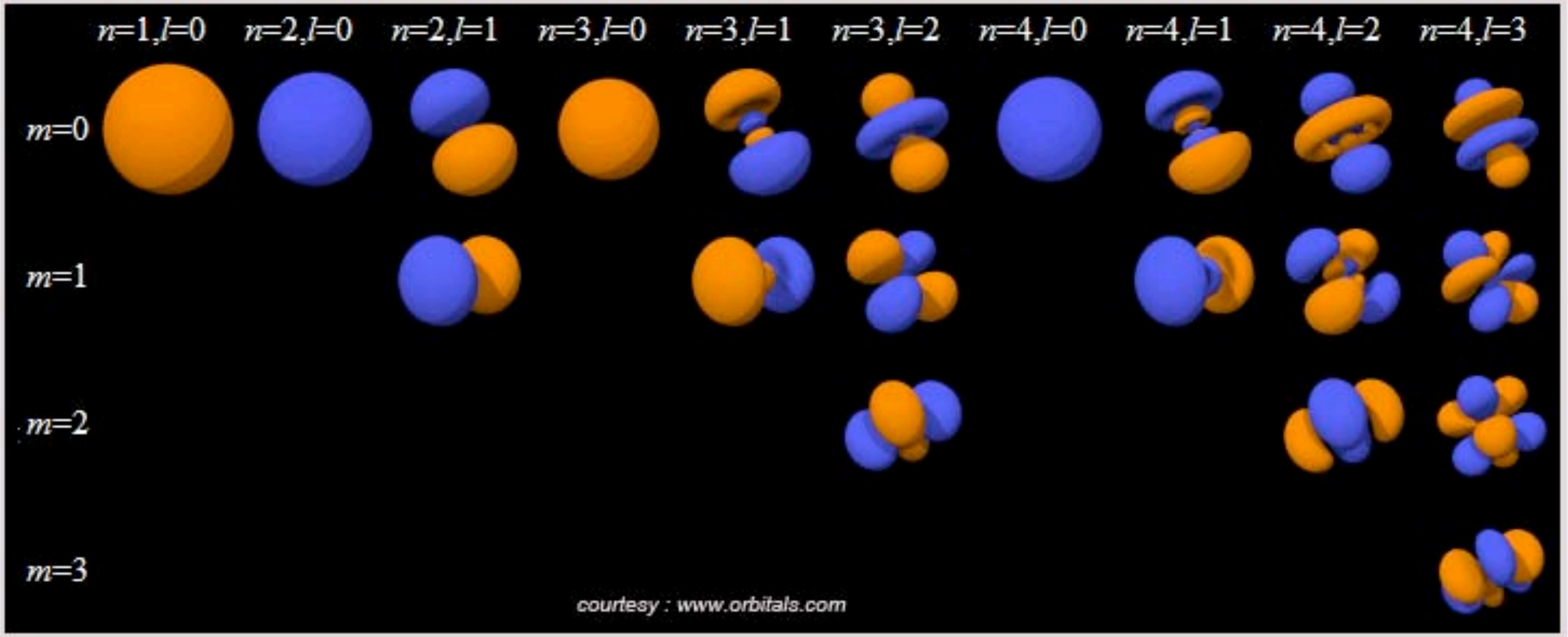
$q\bar{q}g$ hybrids

Spectroscopy - a probe of QED

Positronium



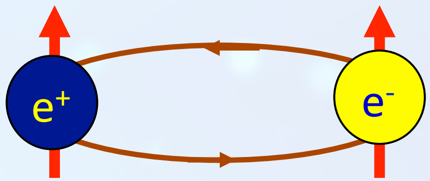
$$\psi(\vec{r}, S) = R_{nl}(r)\, Y_{LM}(\theta, \phi)\, \chi(S)$$



Include spin, S, total angular momentum J: J = L + S: $^{(2S+1)}L_J$

Spectroscopy - a probe of QED

Positronium



$$\psi(\vec{r}, S) = R_{nl}(r)\, Y_{LM}(\theta, \phi)\, \chi(S)$$

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

Orbital Angular Momentum: L=0,1,2,…

Total Spin: J=L+S

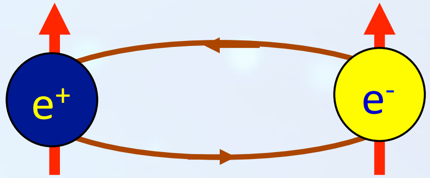
L=0, S=0 : J=0 L=0, S=1 : J=1

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

… …

Spectroscopy - a probe of QED

Positronium



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

… …

Reflection in a mirror:

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

Particle<->Antiparticle:

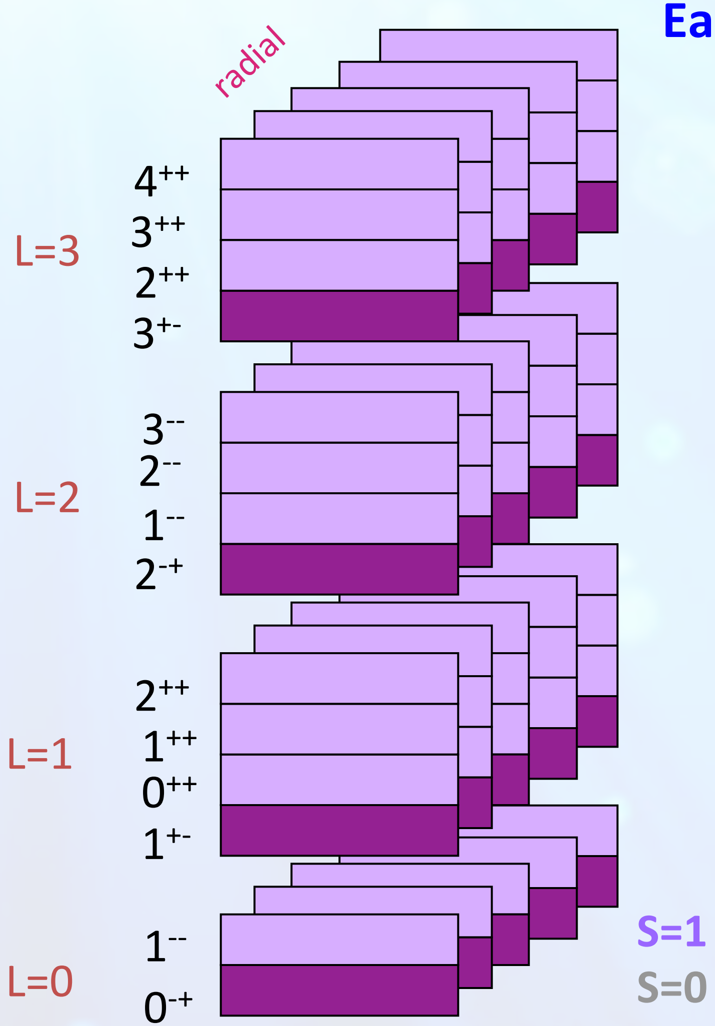
Charge Conjugation: $C=(-1)^{(L+S)}$

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

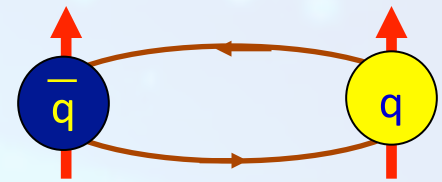
$^{(2S+1)}L_J$ $^1S_0$, $^3S_1$, $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$,…

QCD and Spectroscopy: quark-antiquark

Mesons



Quarkonium



Each state is a particle

Consider the three lightest quarks

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

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

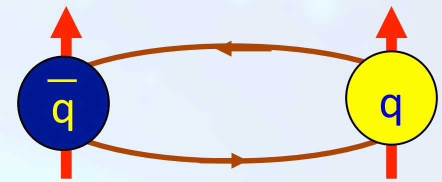
$$d\bar{u} \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad u\bar{d}$$

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

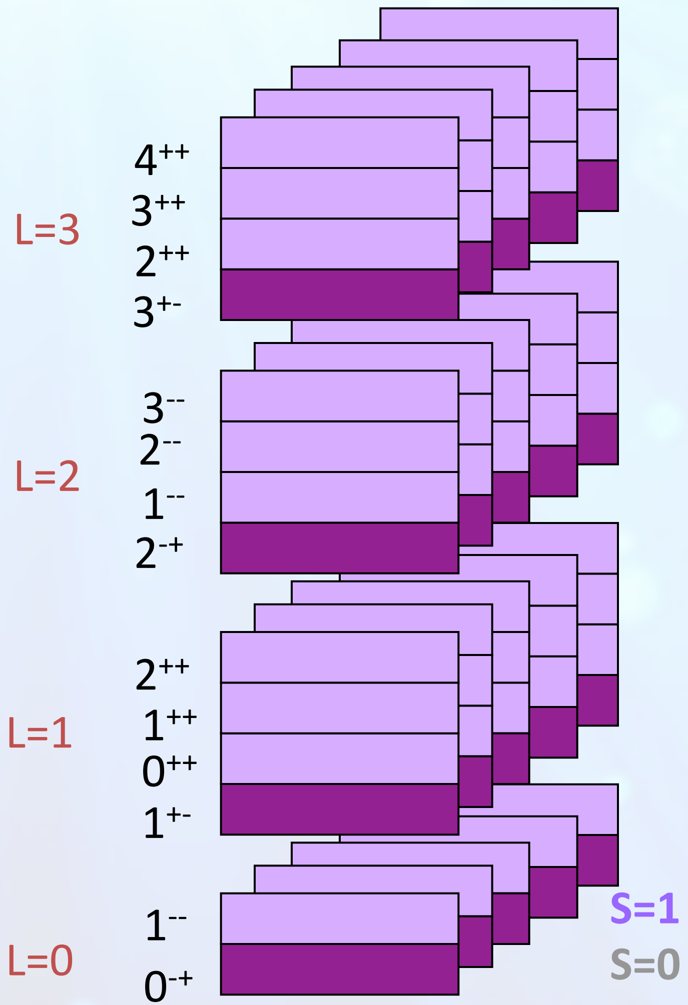
$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \quad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

QCD and Spectroscopy: quark-antiquark

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'

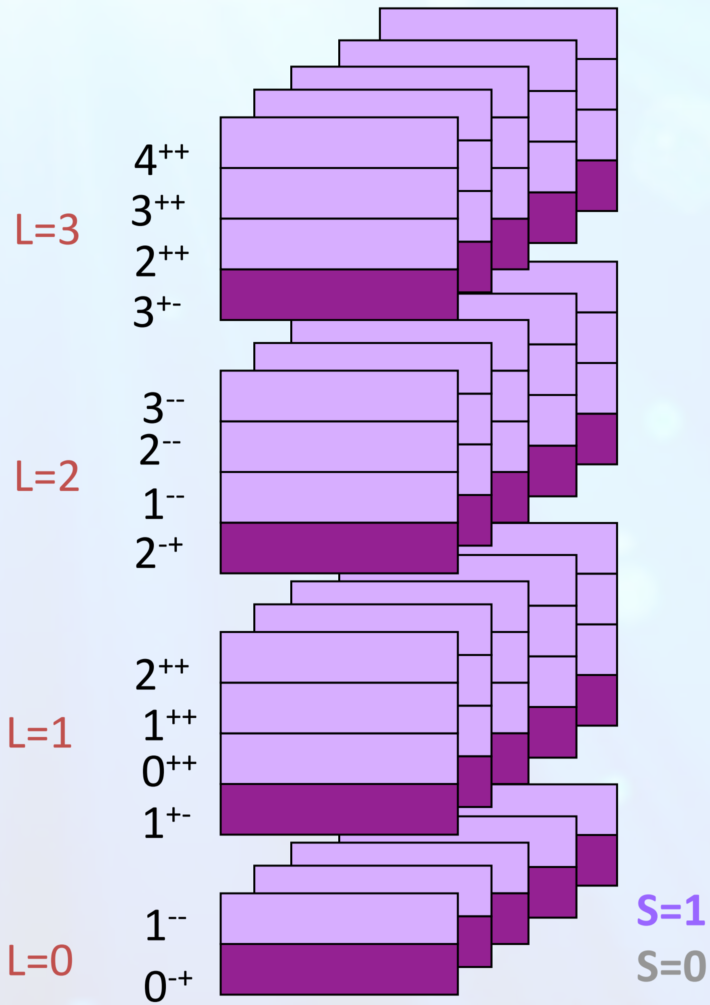
Mesons come in
Nonets of the same
J^{PC} Quantum Numbers

SU(3) is broken
Last two members mix

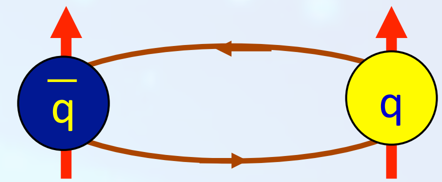
$$u\bar{u} + d\bar{d} \longleftrightarrow s\bar{s}$$

QCD and Spectroscopy: quark-antiquark

Mesons



Quarkonium



Allowed J^{PC} Quantum numbers:

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

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

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

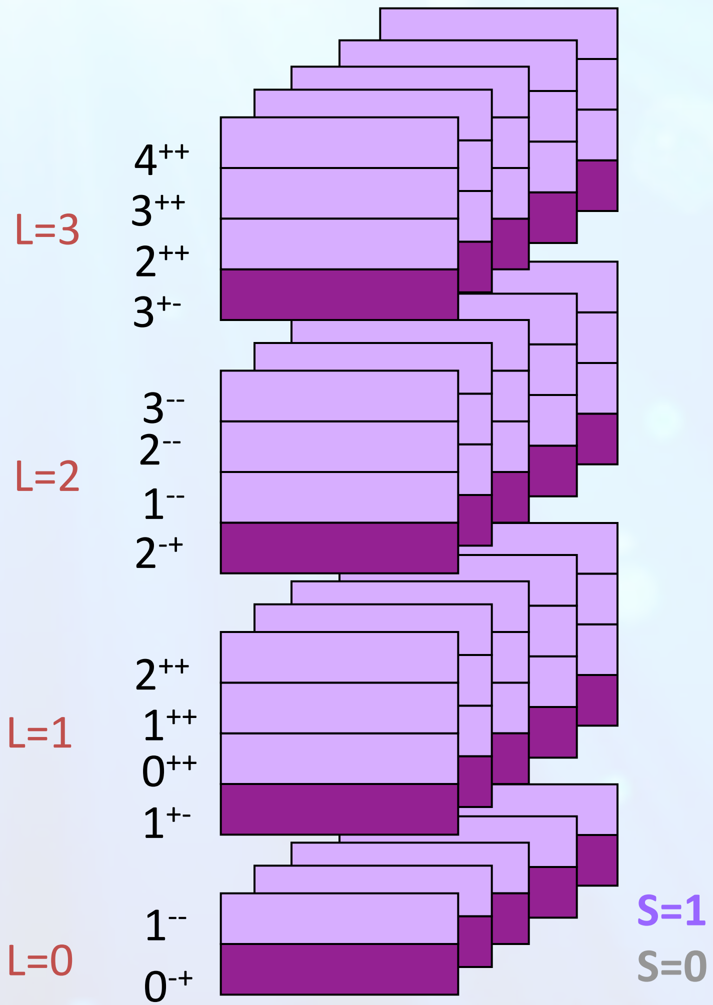
3^{--} 3^{++} 3^{+-}

4^{--} 4^{++} 4^{-+}

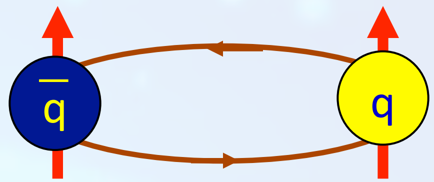
5^{--} 5^{++} 5^{+-}

QCD and Spectroscopy: quark-antiquark

Mesons



Quarkonium



Allowed J^{PC} Quantum numbers:

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

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

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

3^{--} 3^{++} 3^{-+} 3^{+-}

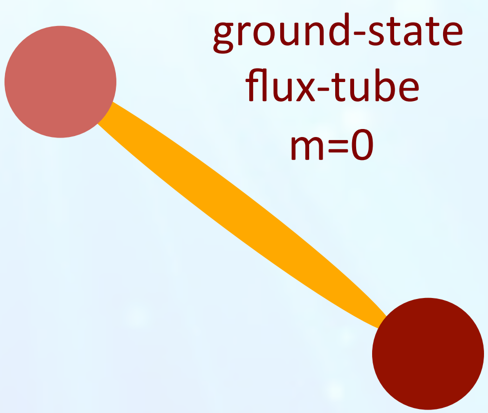
4^{--} 4^{++} 4^{-+} 4^{+-}

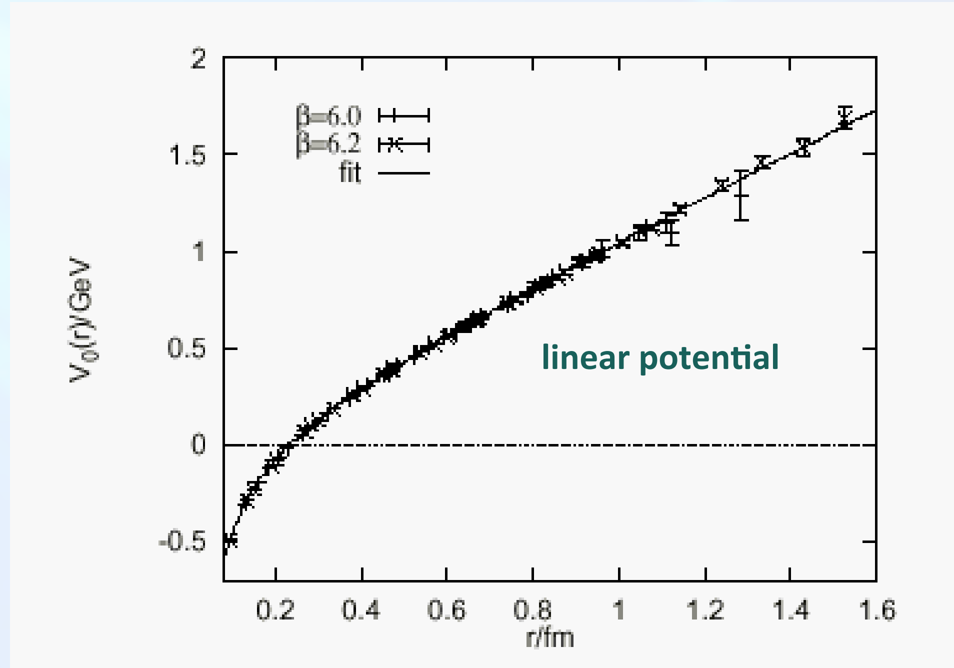
5^{--} 5^{++} 5^{-+} 5^{+-}

Exotic Quantum Numbers

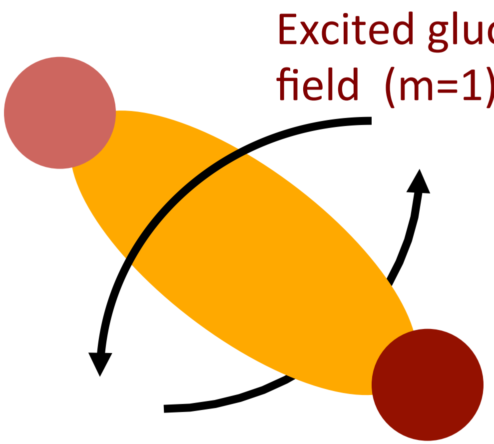
non quark-antiquark description

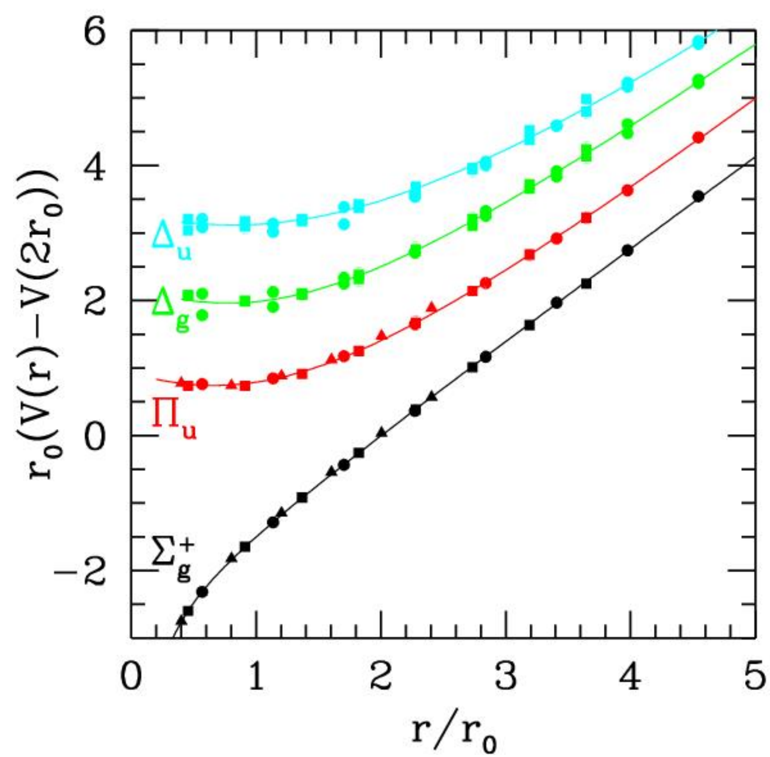
QCD Potential





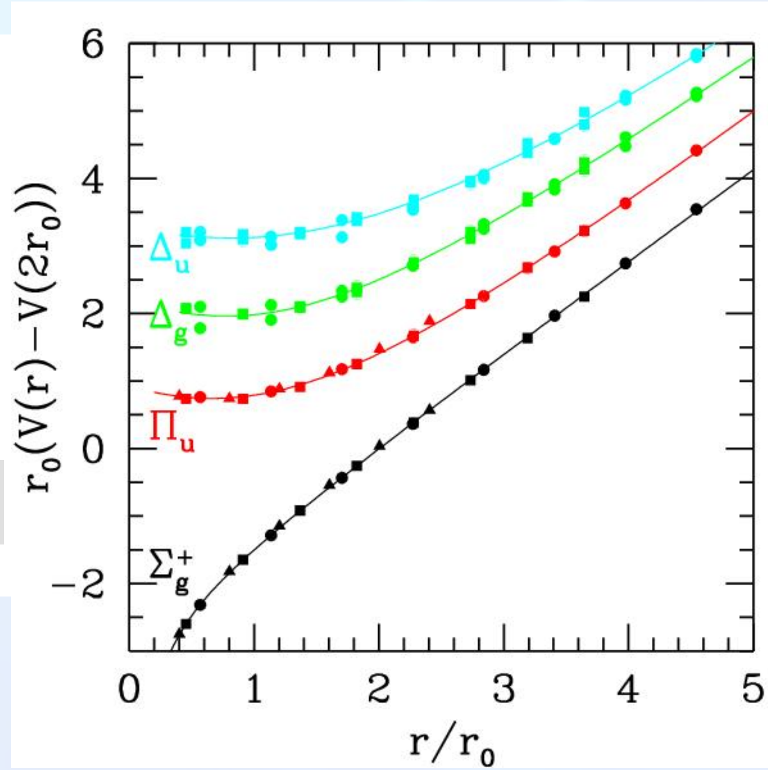
QCD Potential





Mapping the spectrum of meson states associated with excitations of the gluonic field. The light-quark systems will be measured at Jefferson Lab.

QCD Potential



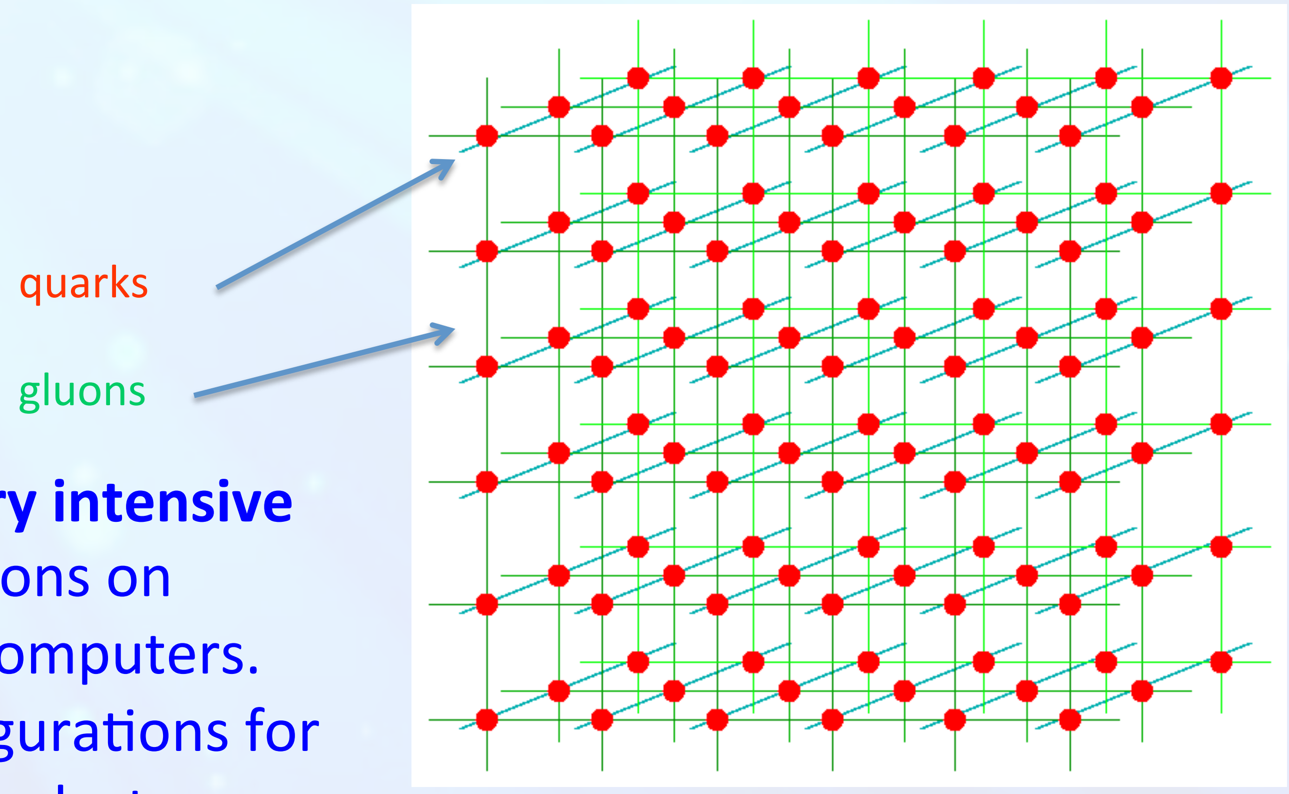
Exciting the Glue provides an experimental window to the confining potential of QCD.

Mapping out the families of hybrid mesons is the best experimental signature of gluonic excitations.

Lattice QCD

$$\mathcal{L}_{QCD} = \overline{\psi}(i\gamma_\mu \mathcal{D}^\mu - m) - \frac{1}{4} F_{j,\mu\nu} F_j^{\mu\nu}$$

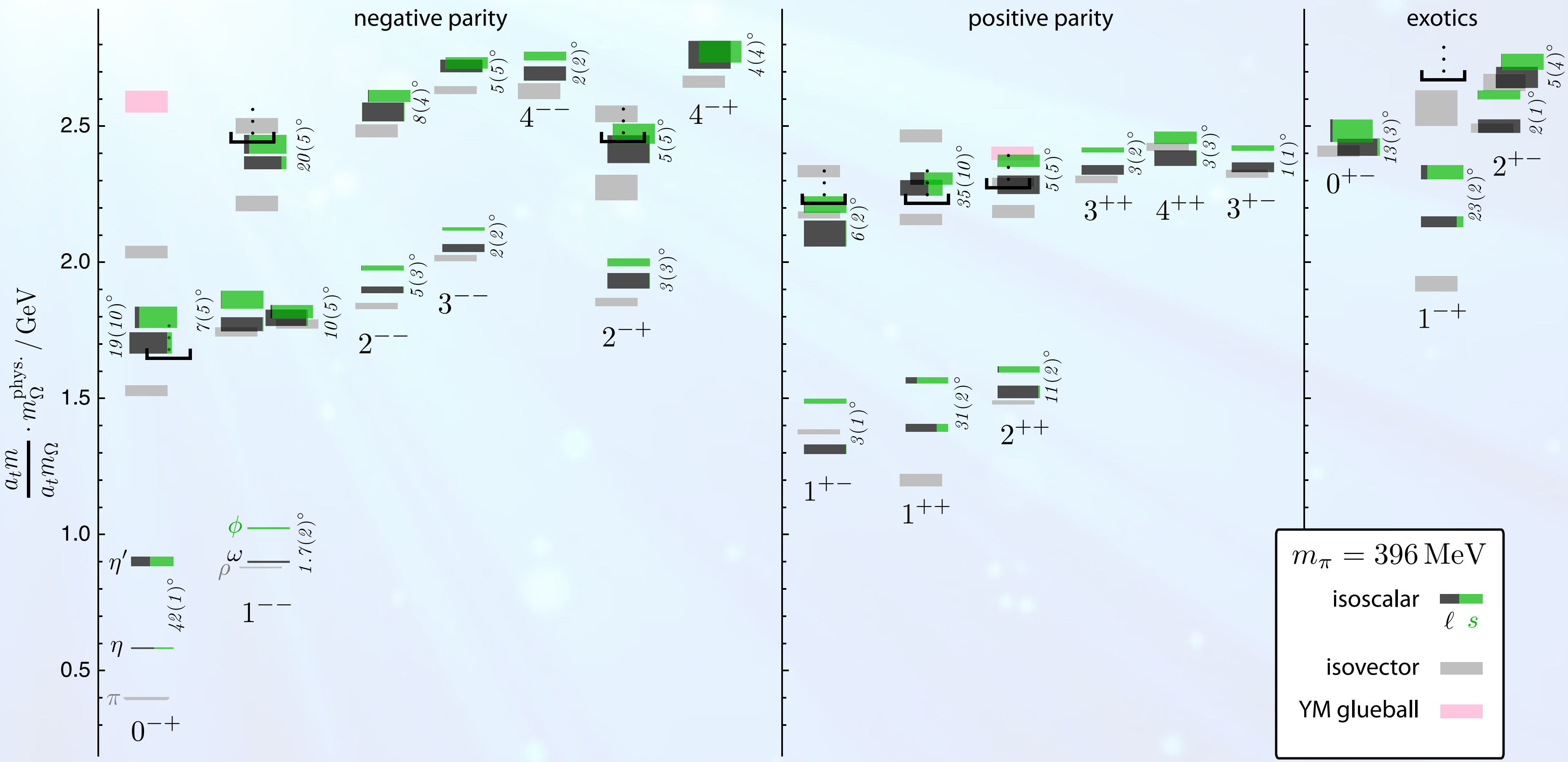
Numerically solve QCD on a space-time lattice.



Computationally very intensive

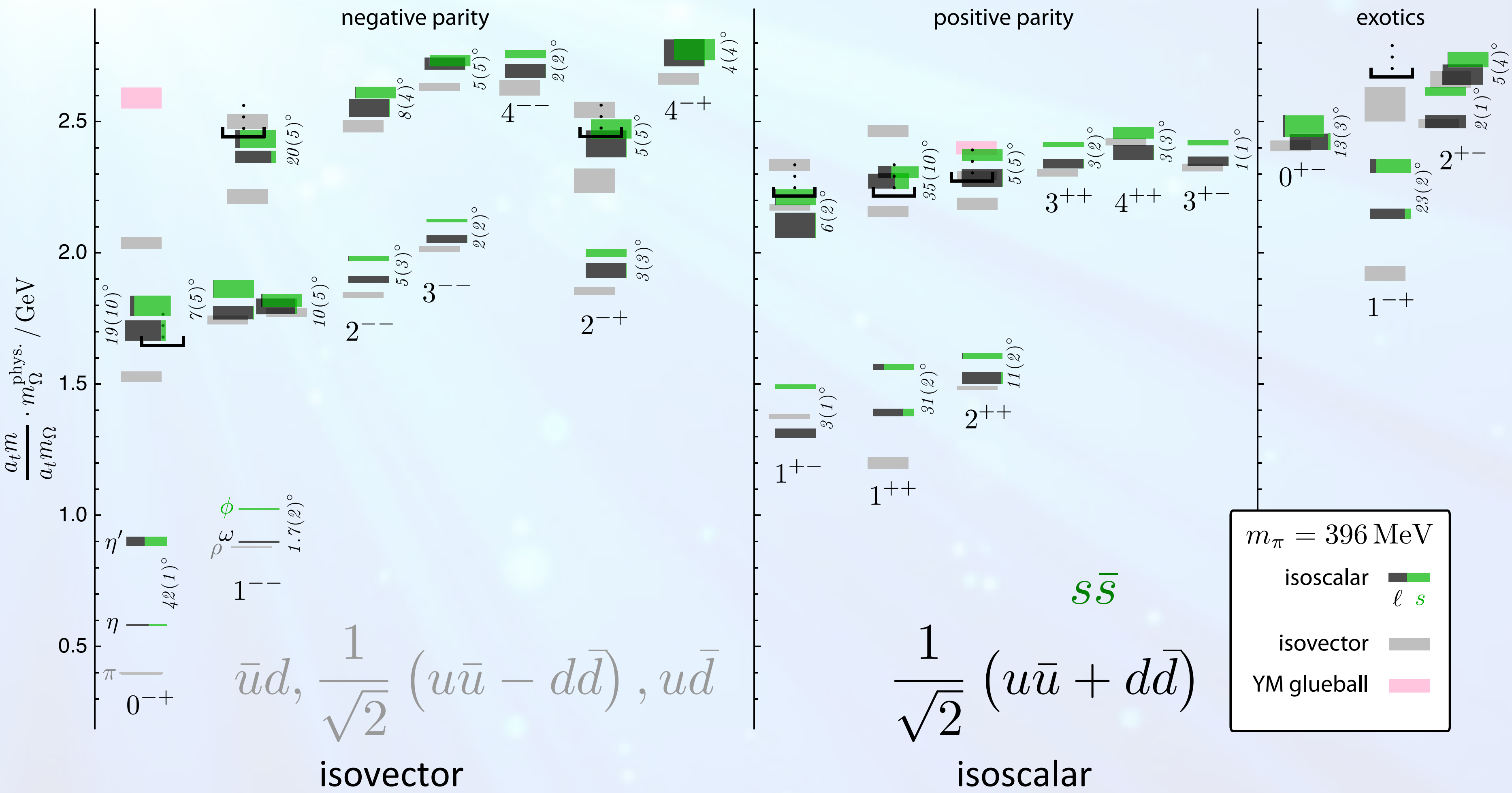
- Gauge configurations on leadership-class computers.
- ``Mine'' the configurations for physics on smaller clusters.

Lattice QCD Meson Spectrum

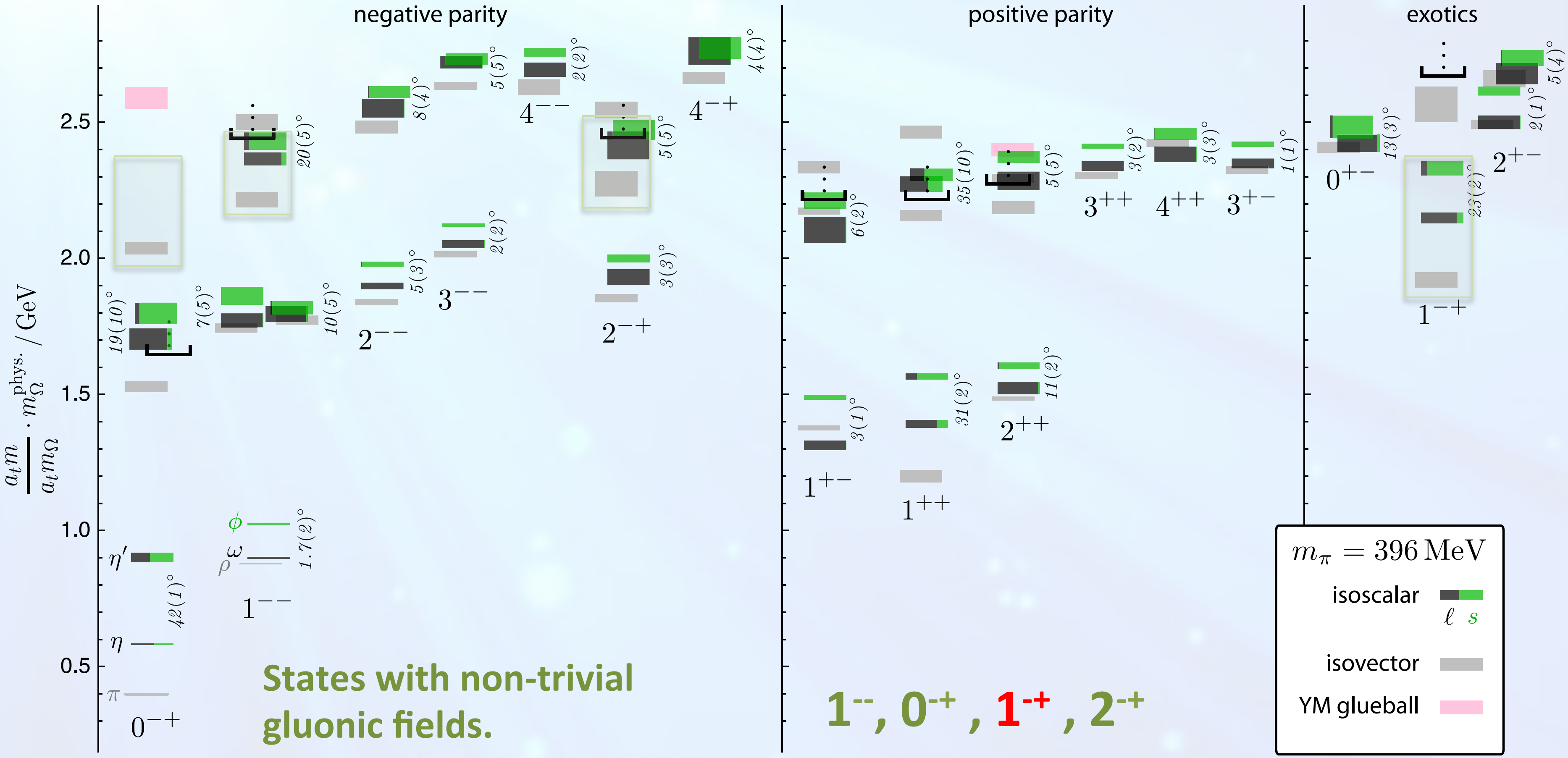


Dudek et. al, 2010, 2011,2012,2013

Lattice QCD Meson Spectrum



Lattice QCD Meson Spectrum



States with non-trivial gluonic fields.

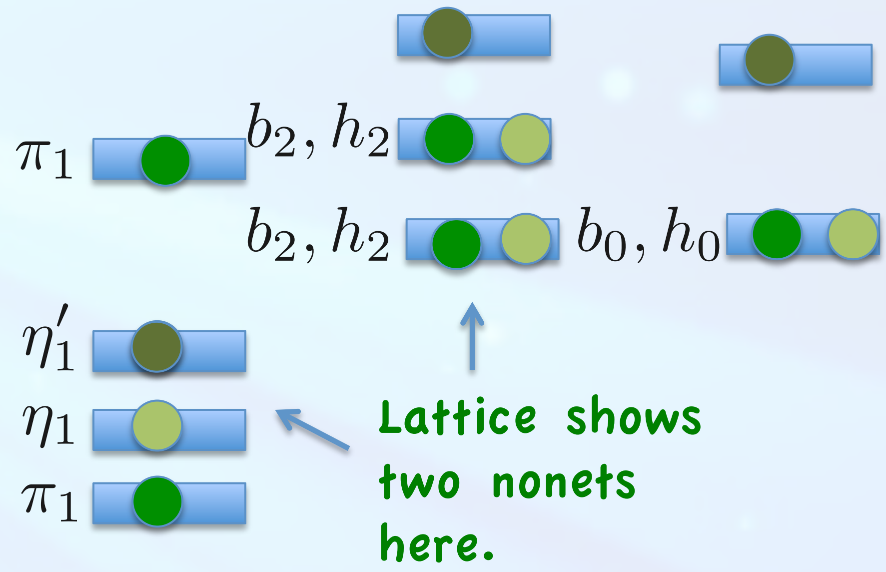
1^{--}, 0^{-+} , 1^{-+} , 2^{-+}

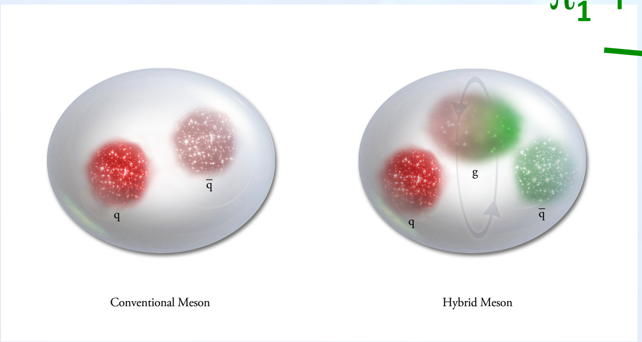
$$F_{j,\mu\nu}\, F_j^{\mu\nu}$$

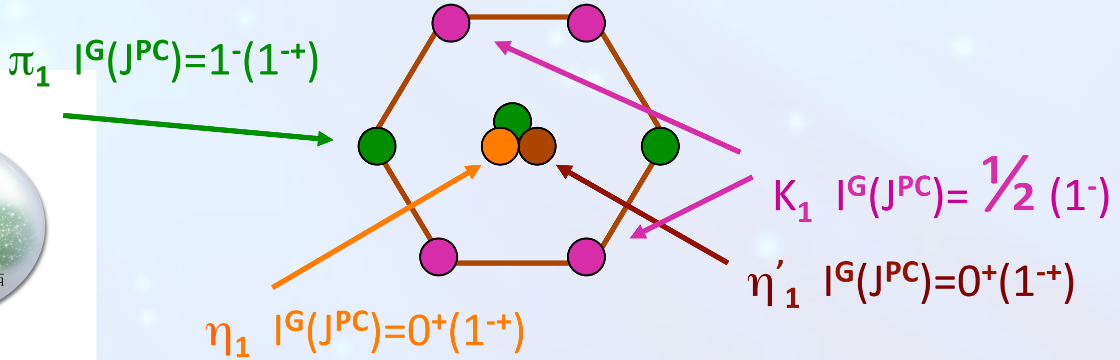
QCD Exotics

We expect 5 nonets of exotic-quantum-number mesons:

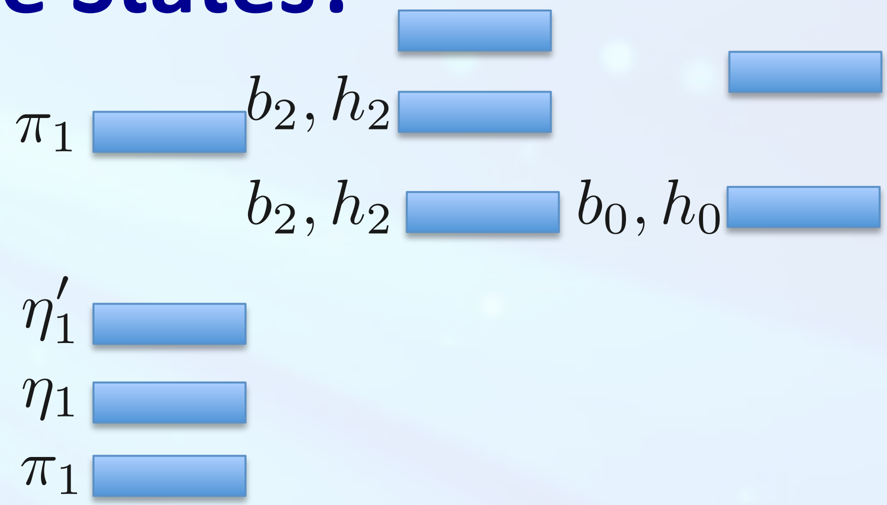
1 nonet of 0^{+-}
2 nonets of 1^{-+}
2 nonets of 2^{+-}





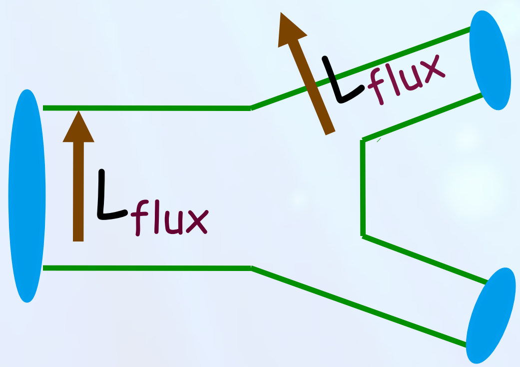


Finding the States?



Lattice QCD suggest where to look for exotic states:

Models suggest how the states should fall apart



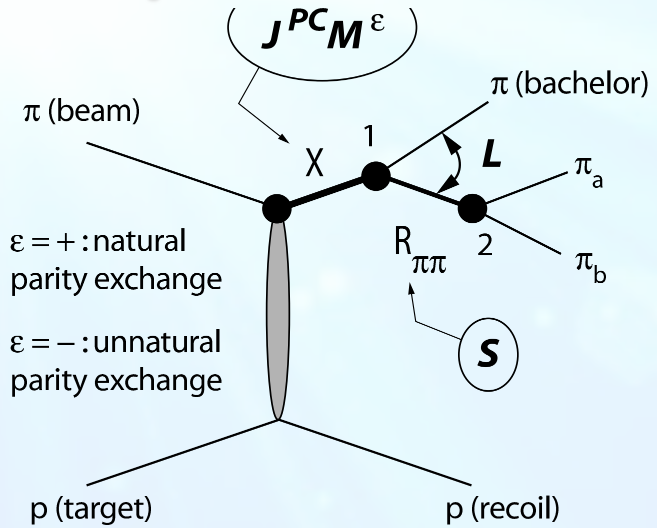
Populate final states with $\pi^{\pm}$,π^{0},$K^{\pm}$,K^{0},η, (photons)

$\pi_1 \to \pi b_1$, πf_1 , $\pi\rho$, ηa_1
$\eta_1 \to \pi(1300)\pi$, $a_1\pi$

$b_2 \to a_1\pi$, $h_1\pi$, $\omega\pi$, $a_2\pi$
$h_2 \to b_1\pi$, $\rho\pi$, $\omega\eta$

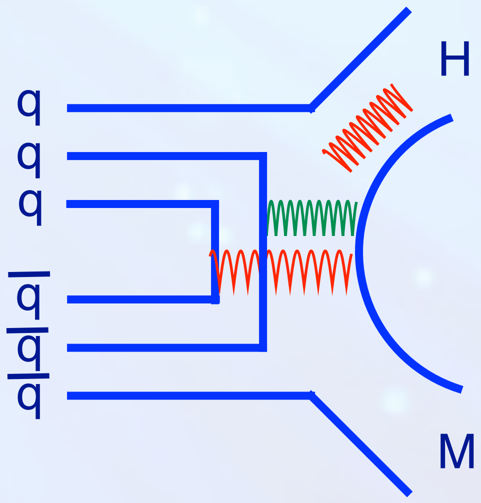
$b_0 \to \pi(1300)\pi$, $h_1\pi$
$h_0 \to b_1\pi$, $h_1\eta$

Experimental Evidence for Hybrids



Pion peripheral production:
The most extensive data sets to date are from the **BNL E852 experiment**. There is also data from the **VES experiment** at Protvino and from the **COMPASS** experiment at CERN.

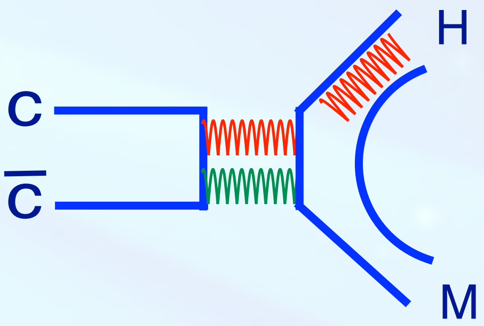
Proton-antiproton annihilation:
There is data from the **Crystal Barrel** experiment at LEAR. This is also one of the pushes of the future **PANDA** experiment.



Experimental Evidence for Hybrids

Charmonium Decays:

There is data from the **CLEO-c** at Cornell. This is also an area of interest of the **BES III** experiment in Beijing. This will also be part of the **PANDA** program at FAIR.



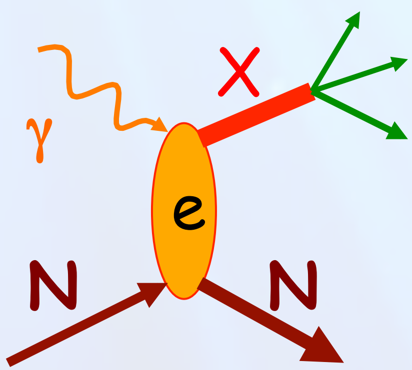
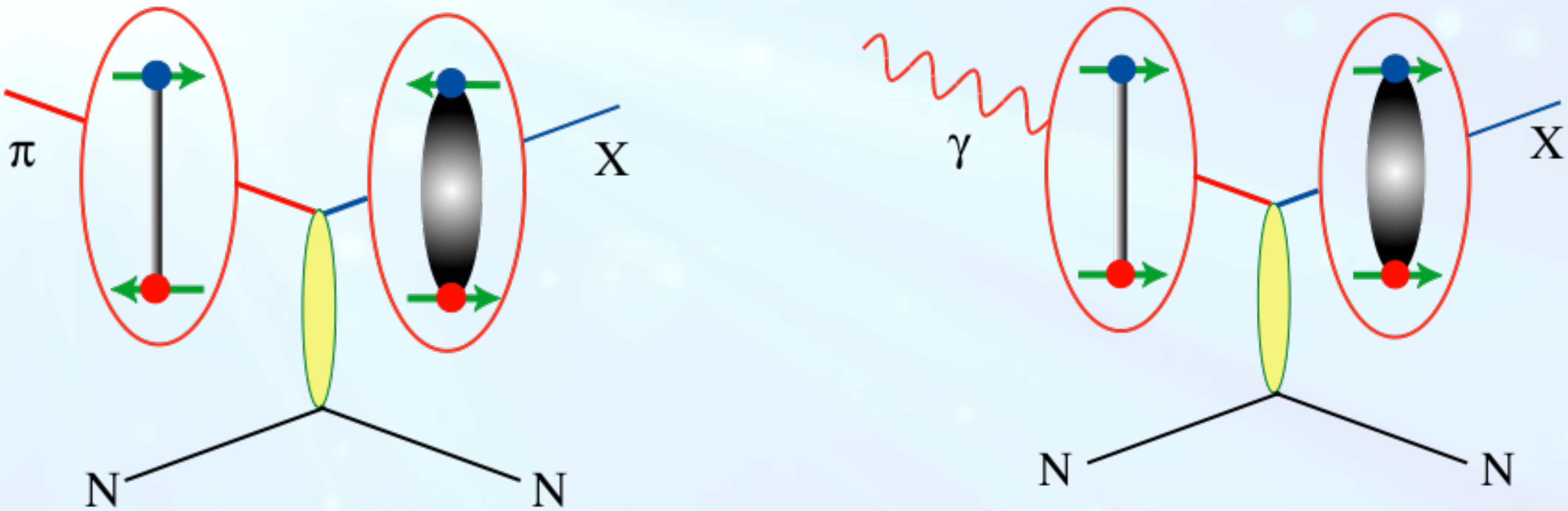


Photo Production:

There are limited results from the **CLAS** experiment at Jefferson Lab. This is the main push of the future **GlueX** experiment at Jefferson Lab.

How to Produce Hybrids



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

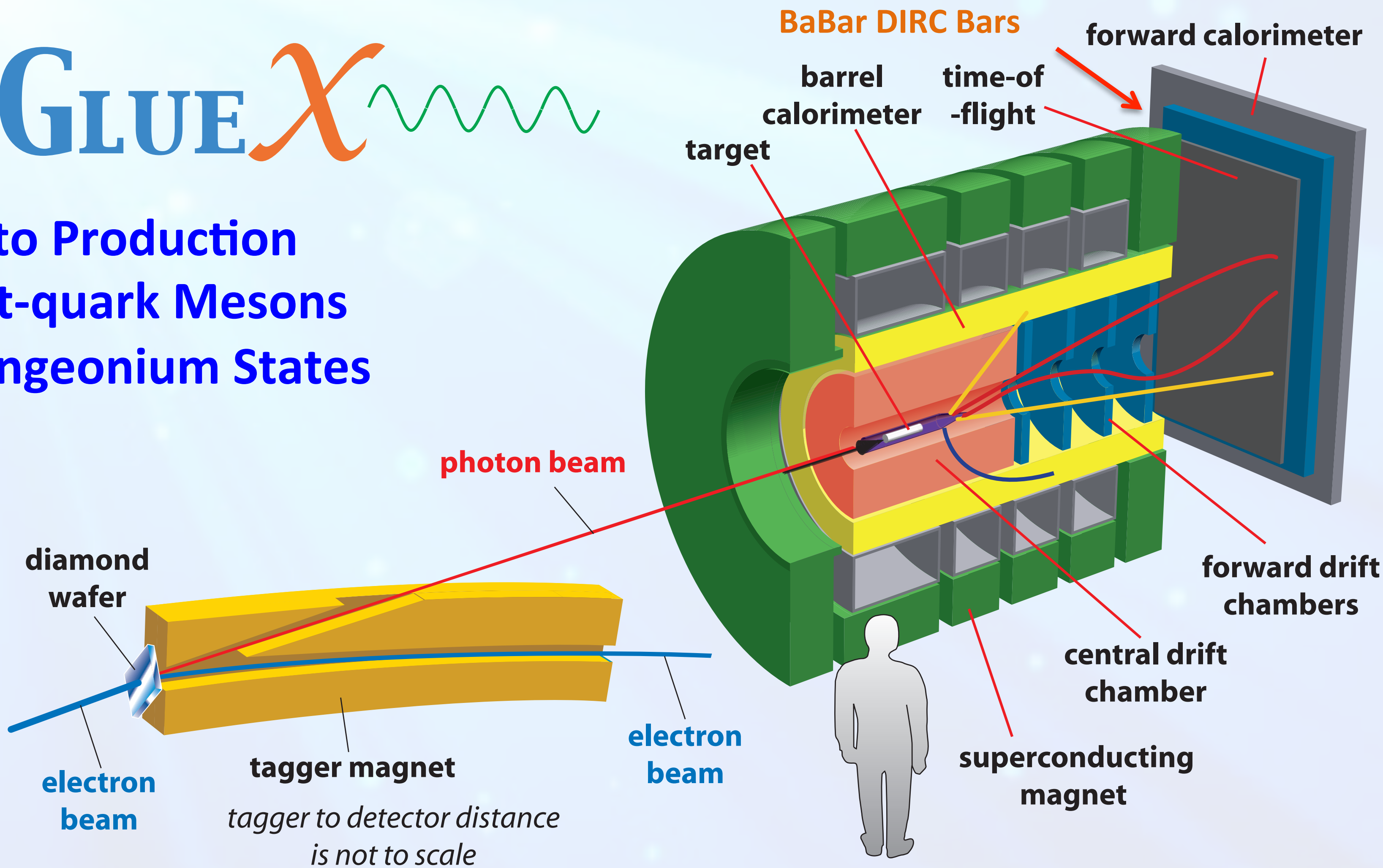
Simple Quantum Number counting leads to the exotics.

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

The GlueX Experiment at Jefferson Lab

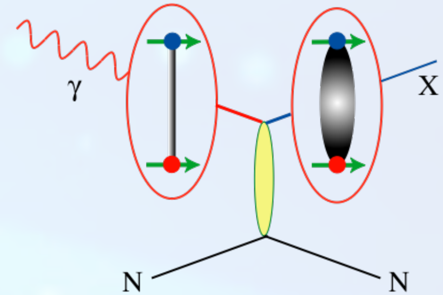
GlueX

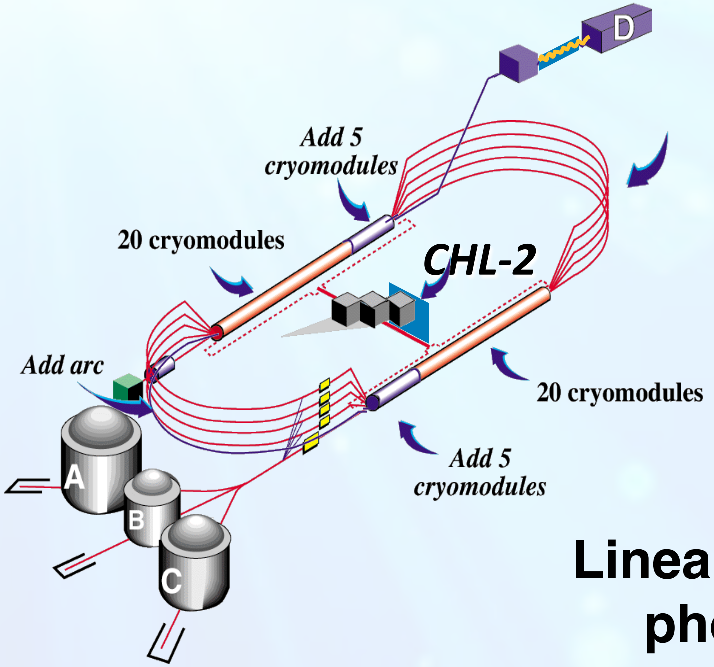
Photo Production
Light-quark Mesons
Strangeonium States



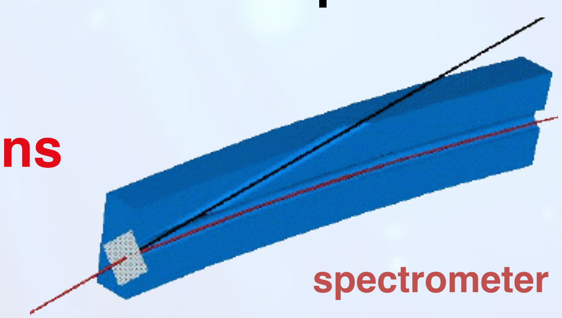
Physics in 2016

12-GeV CEBAF – Photoproduction





Linearly polarized photons out



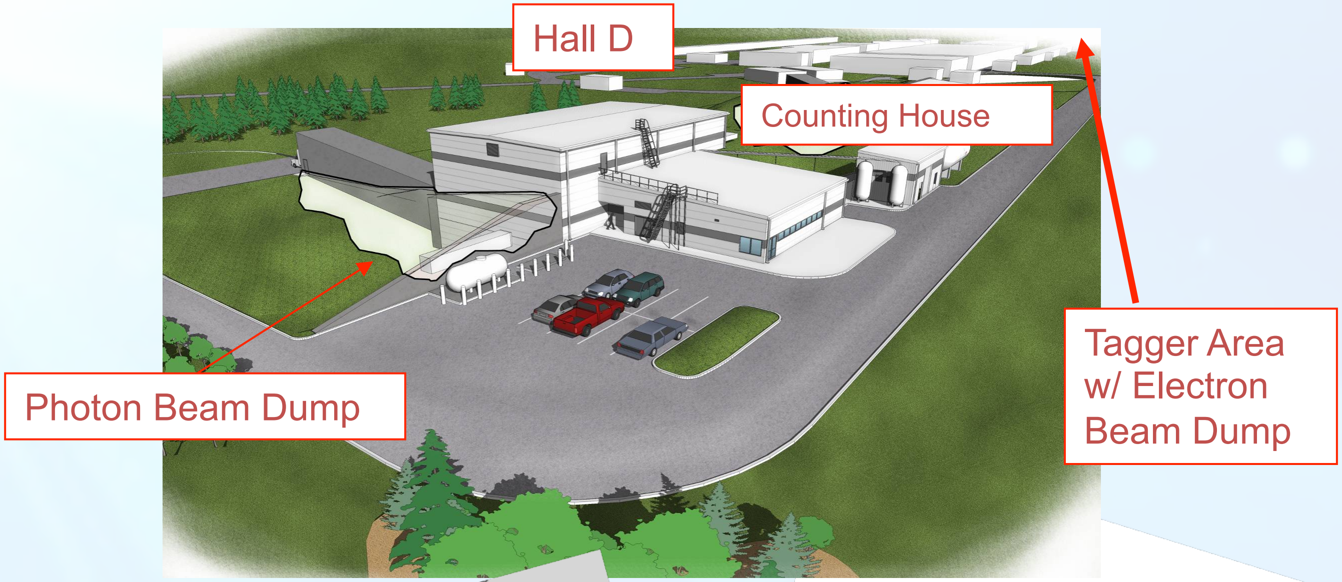
12GeV electrons

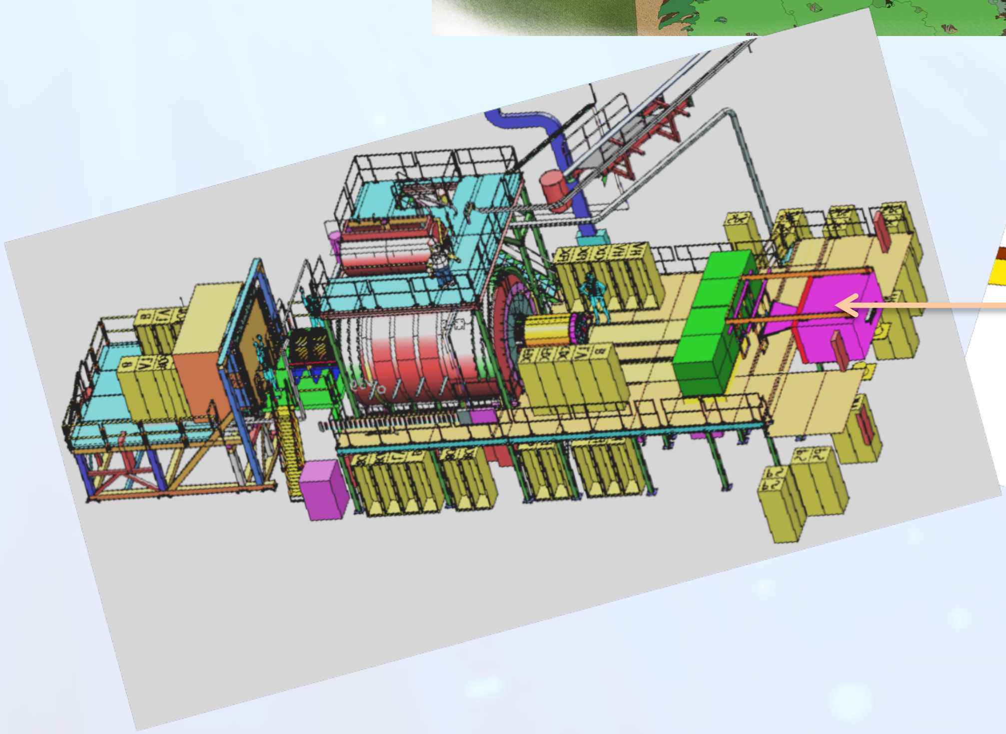
spectrometer

20 μm thick
Diamond crystal

Timeline to a New Experiment

- Planning started in 1998.
- The beginning of the DOE process started in 2004.
- Construction of Hall-D broke ground in April 2009.
- In 2015, the 12 GeV upgrade of Jefferson Lab is nearly complete.
- The GlueX Experiment is ready to start collecting data.


Hall D
Counting House
Tagger Area
w/ Electron
Beam Dump
Photon Beam Dump



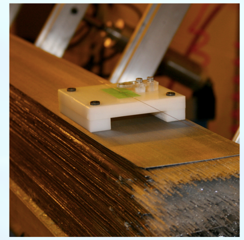
The Experimental Hall

CDC @ CMU

BCAL @ Regina
40/48 modules at JLab

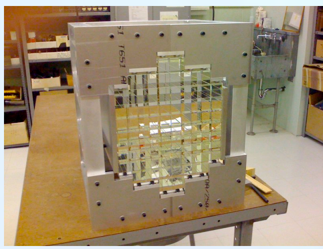
Future PID @ MIT

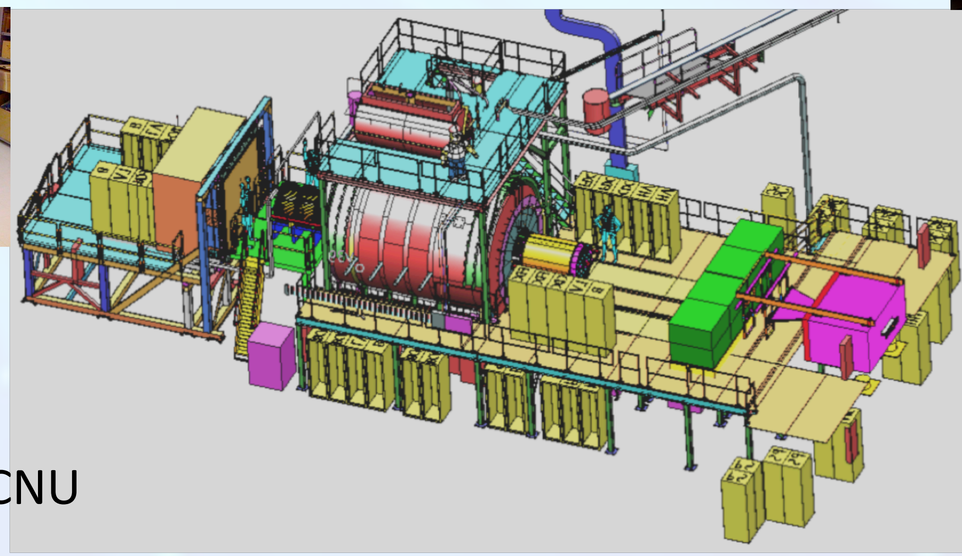
BCAL Readout @ USM



Calibration @ Athens

FCAL @ IU





FDC @ JLab

P.S. @ UNCW

TOF @ FSU

START @ FIU

TRIGGER @ Jlab, CNU

Calibration@Northwestern

Electronics @ JLab, ICO, UMASS, USM   Solenoid @ JLab, ICO   DAQ @ JLab

The GlueX Detector

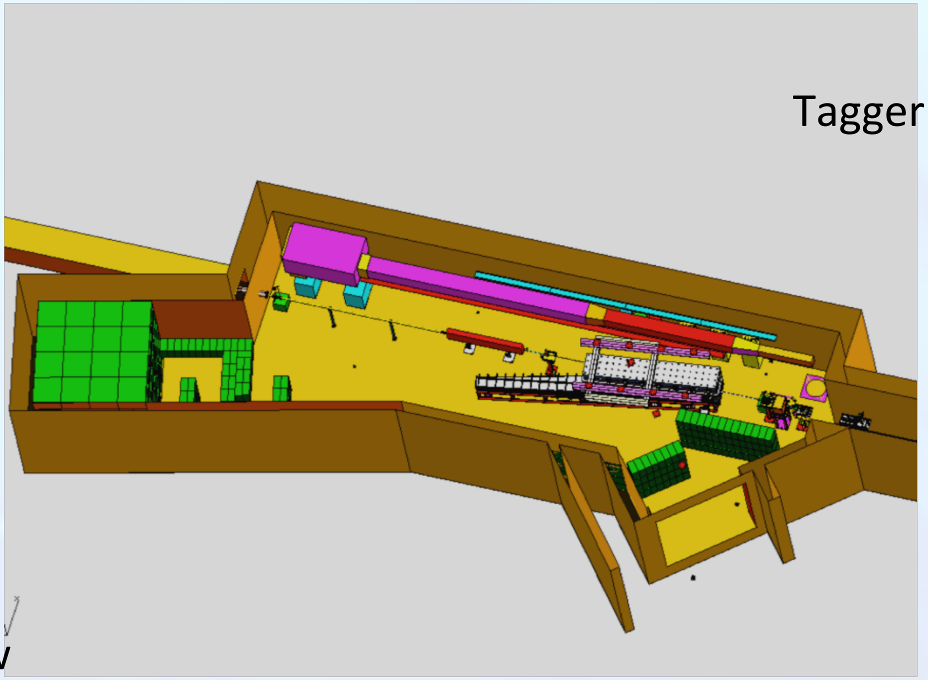
Photon Beam Production and Tagging

Microscope @ UCONN

Polarimetry @ ASU

Support @ UNC A&T

Tagger Magnet @ JLab



Support@Yervan

Tagger @ CUA

Diamond @ UCONN

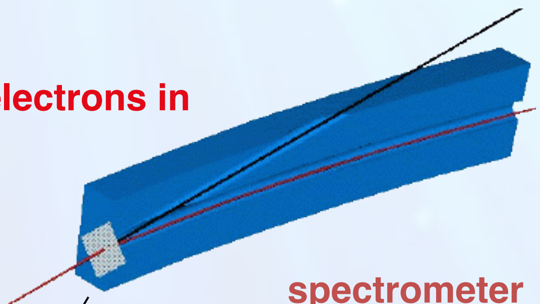
Goniometer@Glasgow

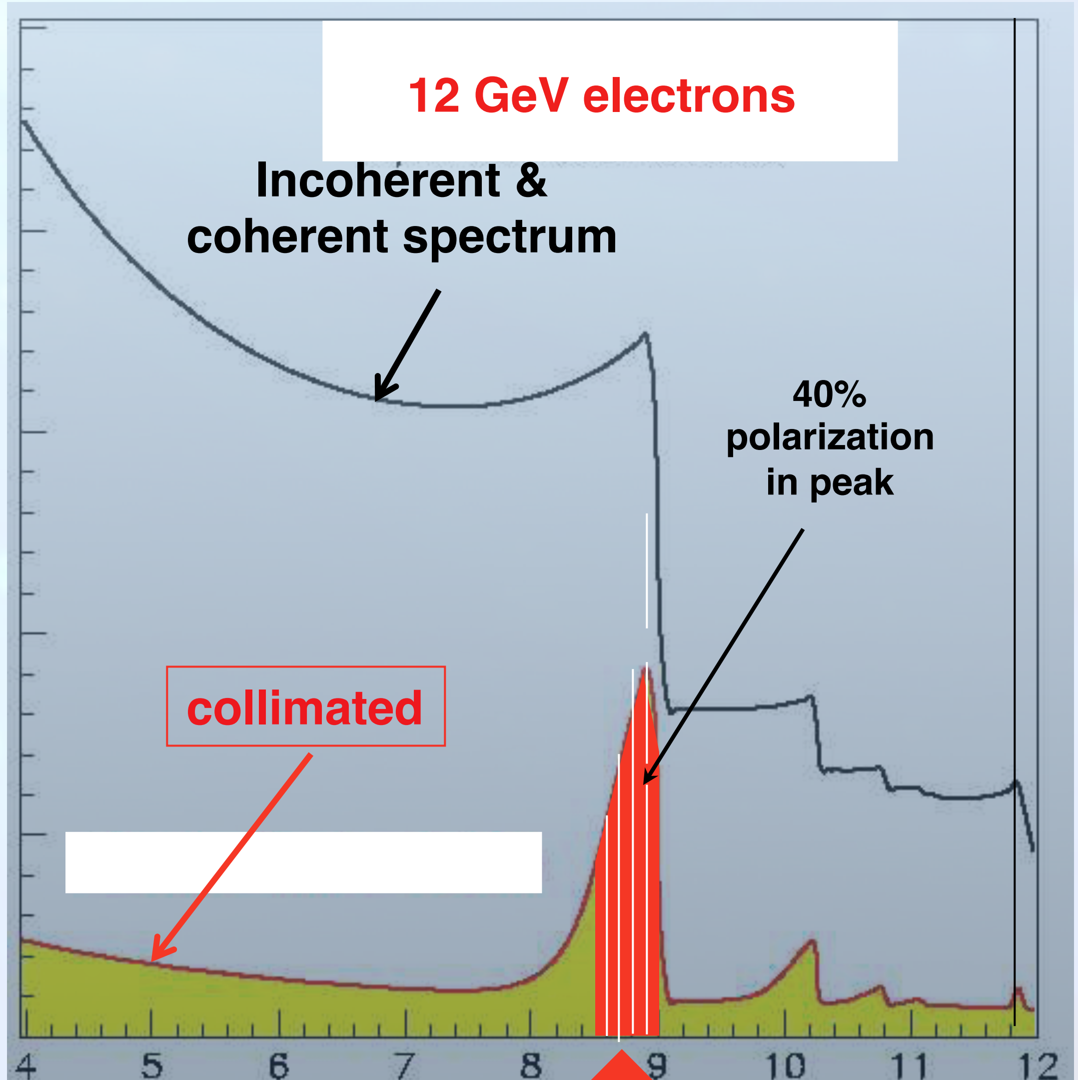
Active Collimator @ UCONN

Pair Spectrometer@UNC Wilmington

Coherent Bremsstrahlung

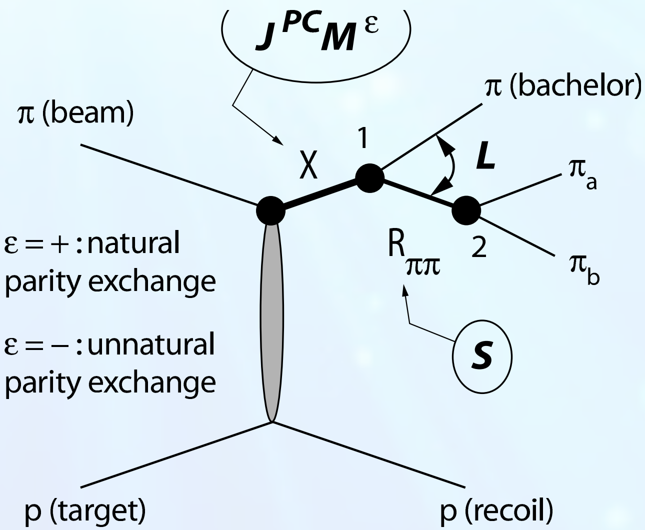
This technique provides requisite energy, flux and polarization





Amplitude Analysis

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

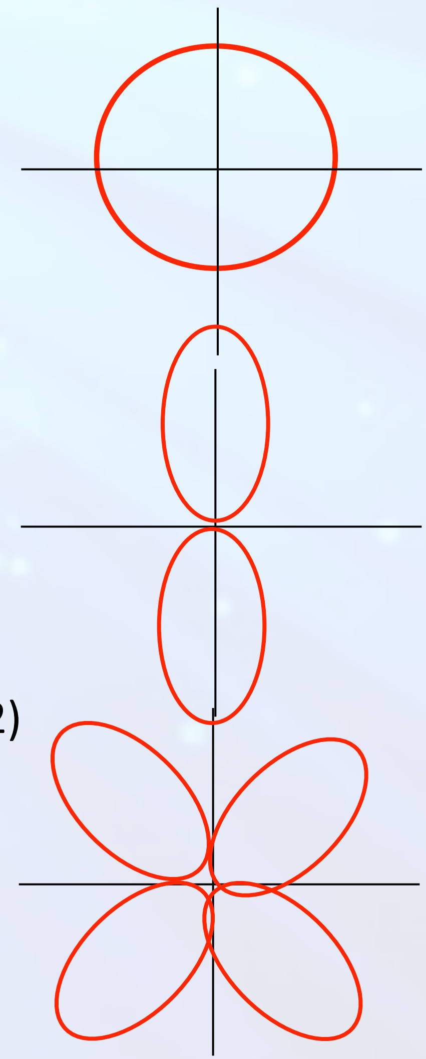


Classical Electrodynamics:

Monopole Radiation (L=0)

Dipole Radiation (L=1)

Quadrupole Radiation (L=2)

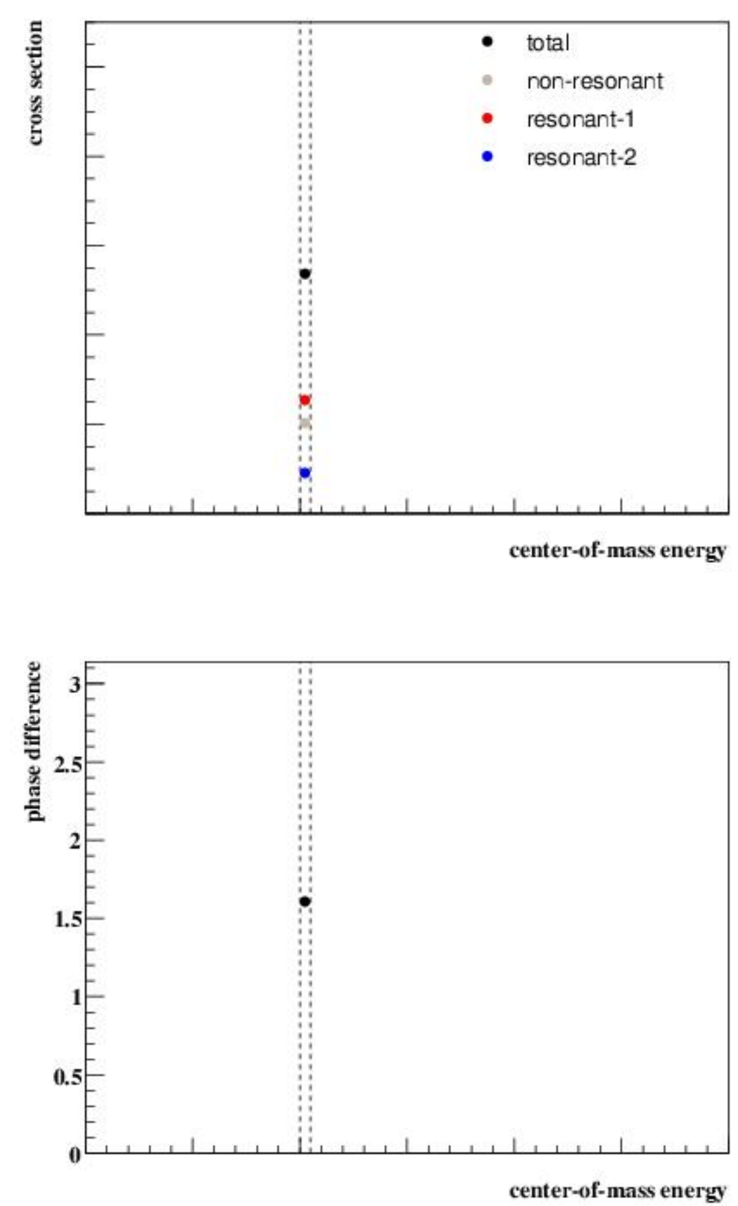


Amplitude Analysis

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.



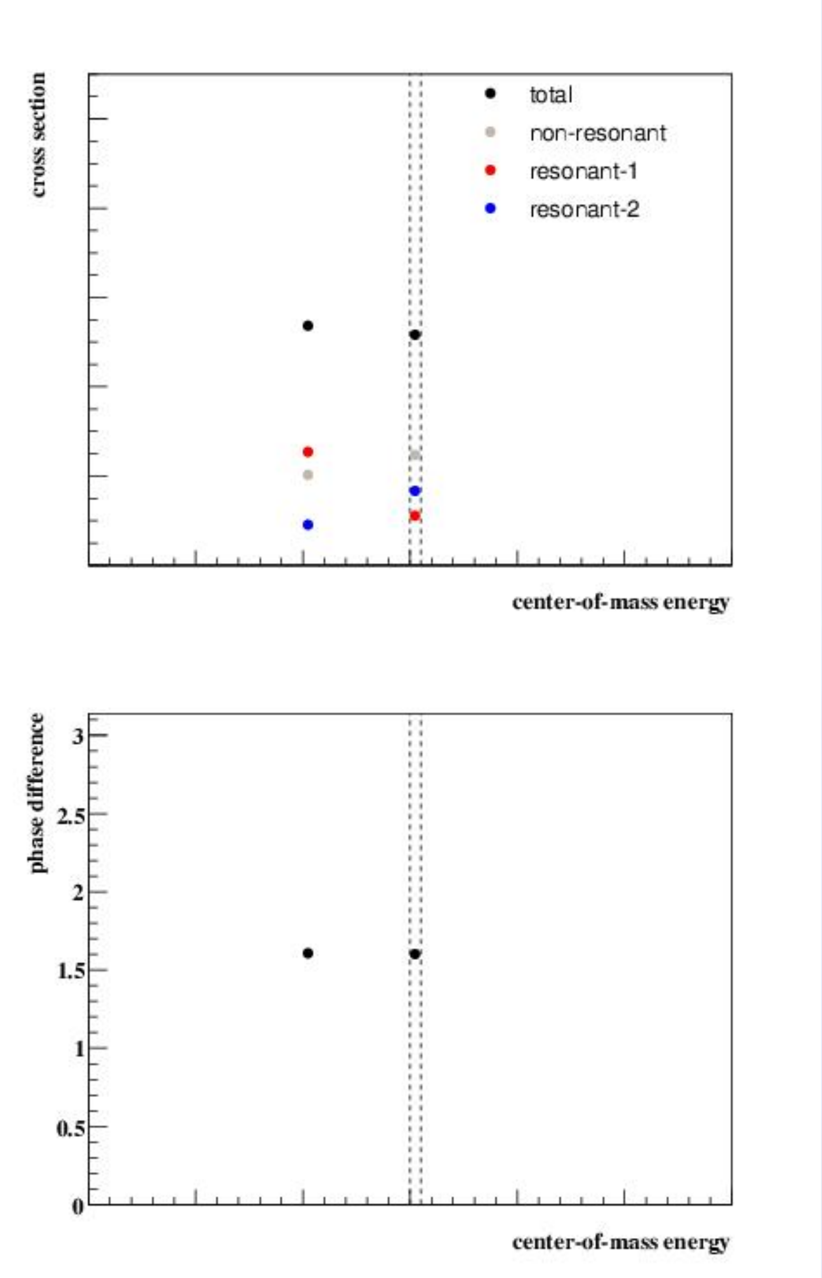
Amplitude Analysis

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.



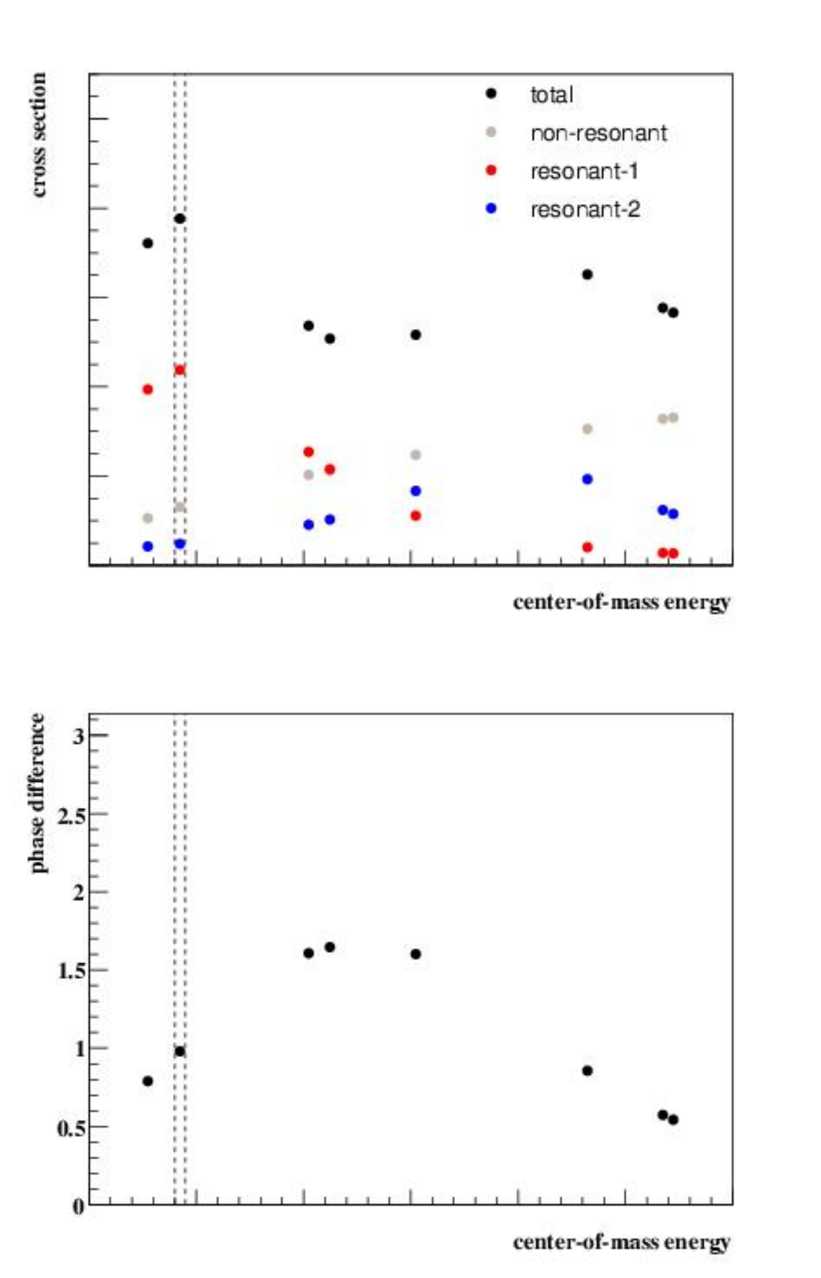
Amplitude Analysis

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 …



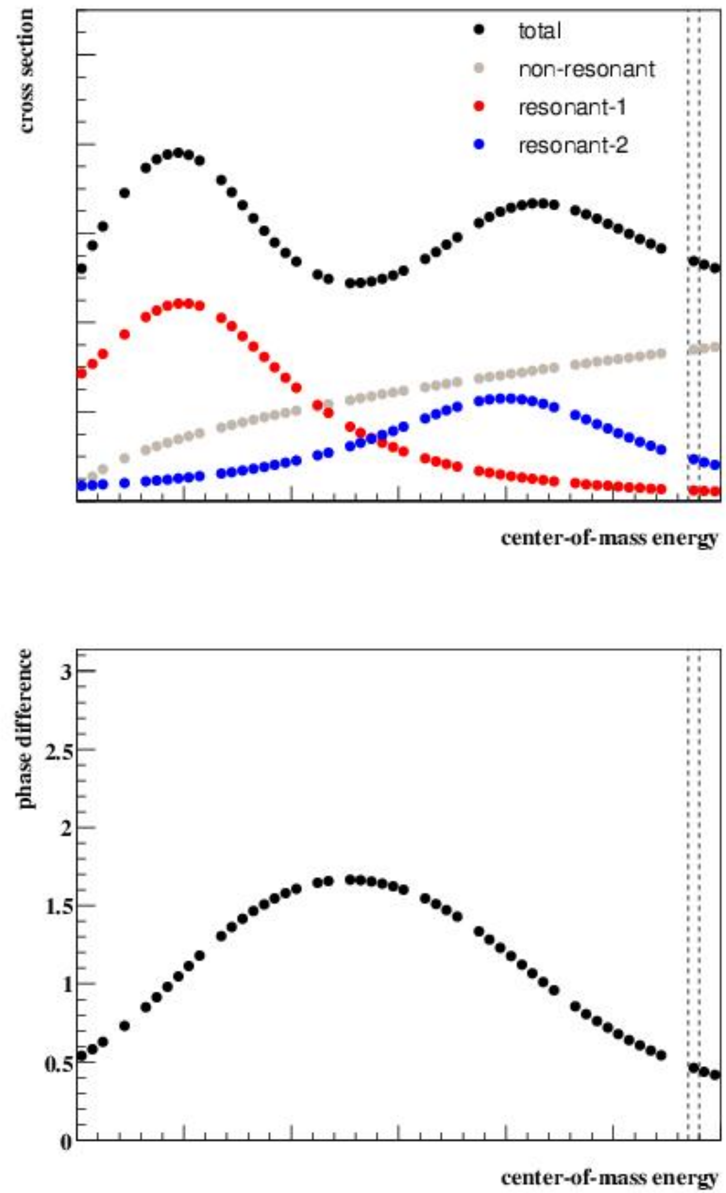
Amplitude Analysis

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 …

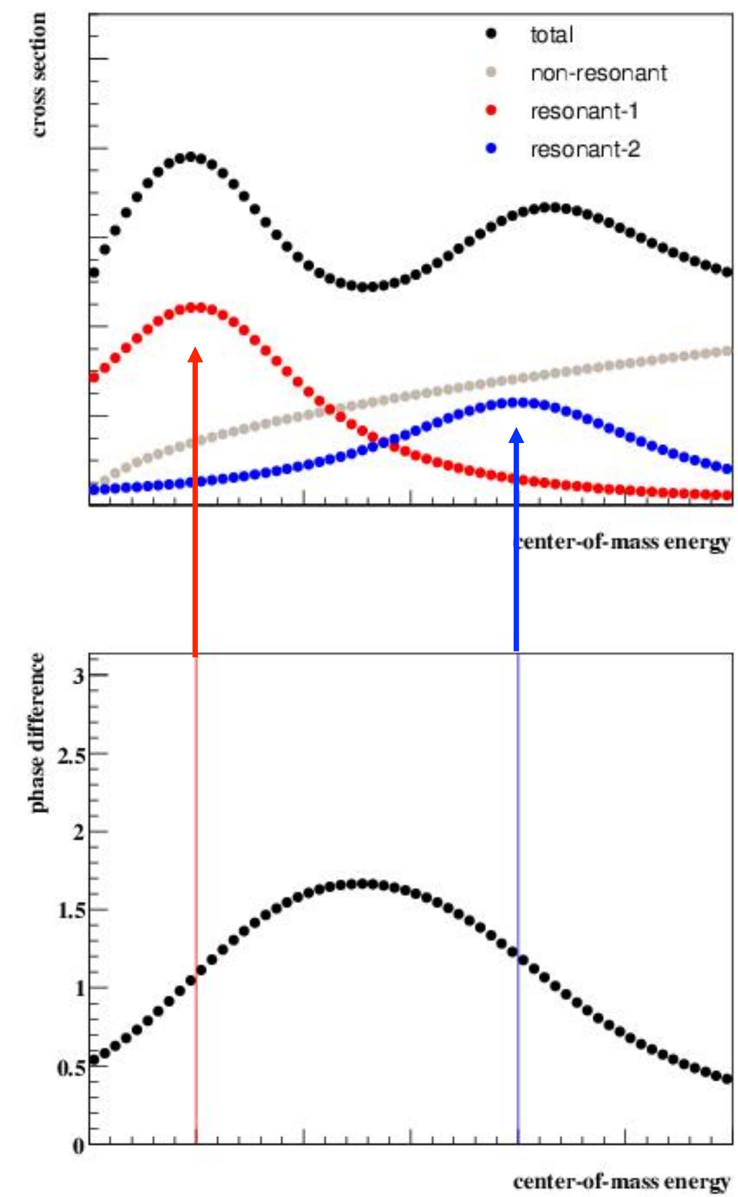


Amplitude Analysis

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.



Amplitude Analysis

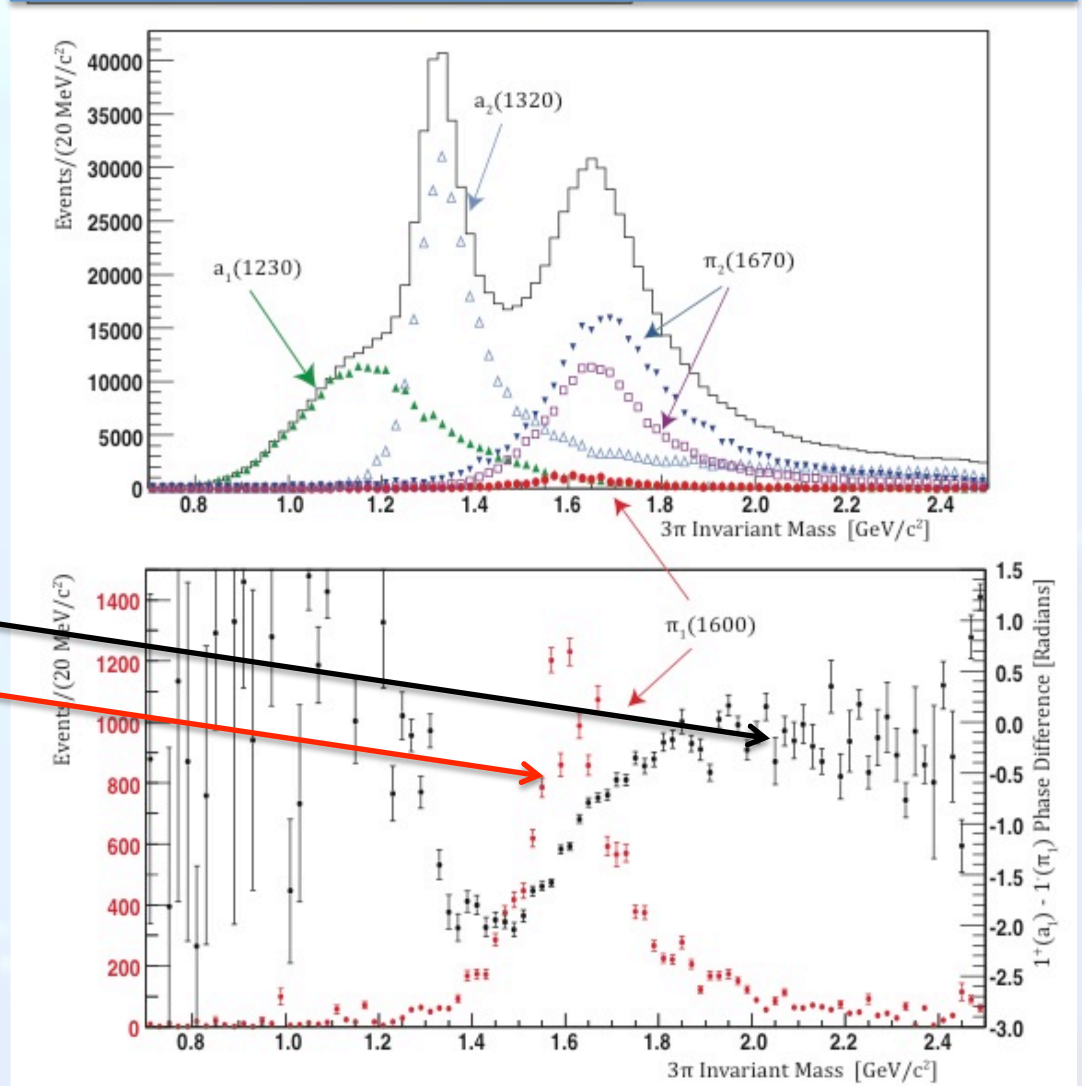
Fit the data event-by event to sums of high-dimensional angular distributions using complex weights.

$$W = \left| \sum \alpha_i A_i(\theta_1, \cdots) \right|^2$$

Intensity and phase differences

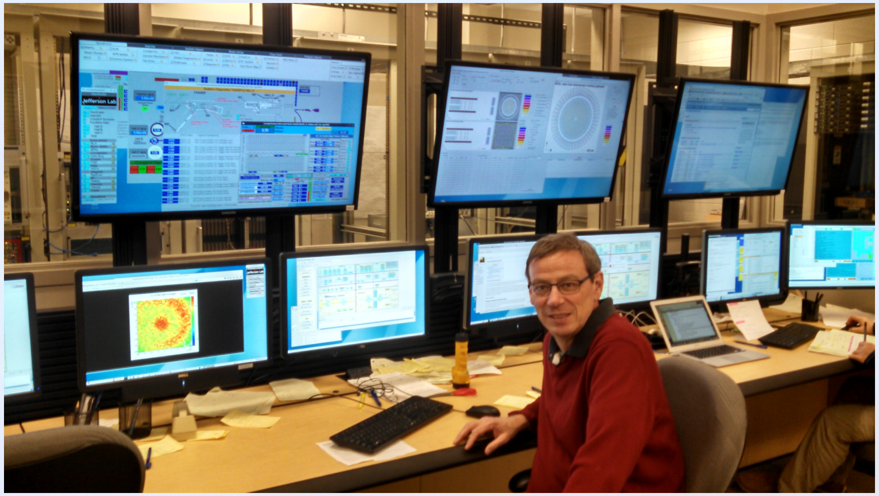
Search for particles in several final states at once.

3.5 Hours of beamtime



Fall 2014 GlueX Commissioning

- Ran from late October until just before Christmas.
- All systems worked and all detectors recorded data simultaneously.
- Multiple triggers tested.
- 120TB of data collected, all data have since been processed multiple times.
- Calibration and alignment is in an advanced state.
- Hoped to complete calibrations using Spring'15 commissioning data.



GlueX/Hall-D Data Challenges

Data formats defined for all levels of GlueX/Hall-D analysis.

EVIO Raw Data 18kbyte/evt.

REST DST Data 2.7kbyte/evt.

PART Physics Analysis (root tree).

EventStore

January 2015 (on going) – process 2014 data (150TB)

- 7000 ~20GB files on JLab Tapes, Run 6 threads per job
  - Data on cache disk (~4800 JLab threads)
  - Data from tape (~1200 JLab threads)

February 2015 (ongoing) – process simulated data from tape

- Optimize process of from tape to processors.
- Optimize threading of jobs.

Computing Needs

MC Generation: 0.16 s/evt

Reconstruction: 0.045 s/evt

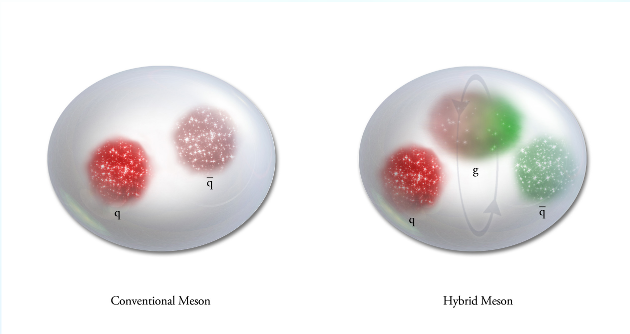
Event rate is 20 KHz

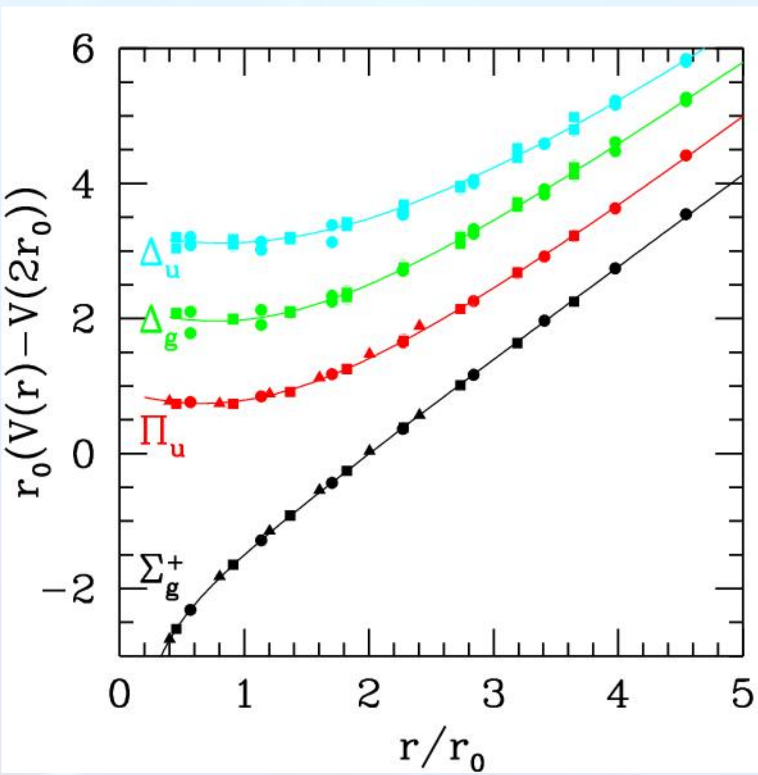
Raw Data Size: 18 kB/evt

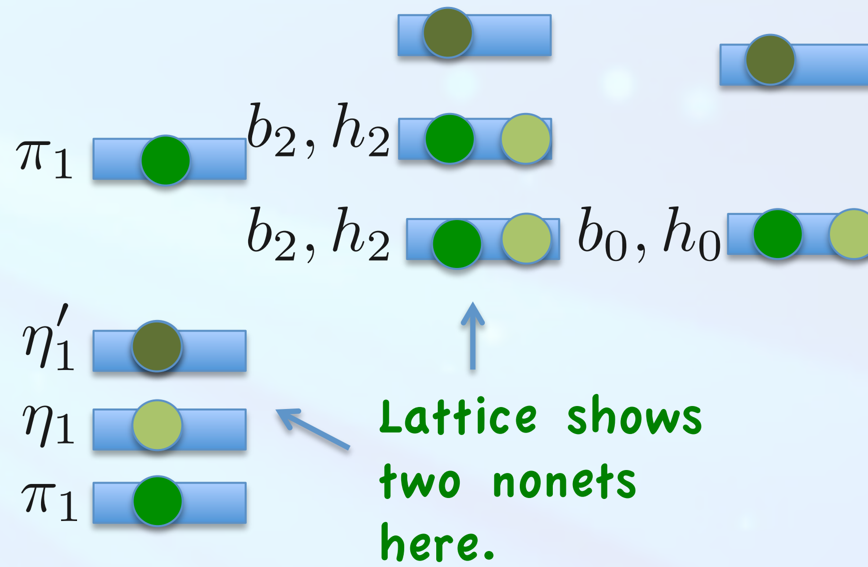
Produced Data: 2.7 kB/evt

Year	FY15	FY16	FY17	FY18	FY19
Cores	380	3080	4810	3460	4230
Raw Data	0.2PB	1.6PB	2.5PB	1.8PB	2.2PB
REST Data	75TB	240TB	371TB	267TB	327TB
MC Rest	~100TB	~500TB	~700 TB	~500TB	~650TB

QCD Exotics







We hope to be able to illuminate this spectrum of exotic-quantum-number mesons and ultimately understand the QCD potentials associated with exciting the glue in normal matter.

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 the role of glue in the spectrum of hadrons.

Definitive experiments to confirm or refute our expectations on the role of glue have just started.

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