The Hadron Spectrum

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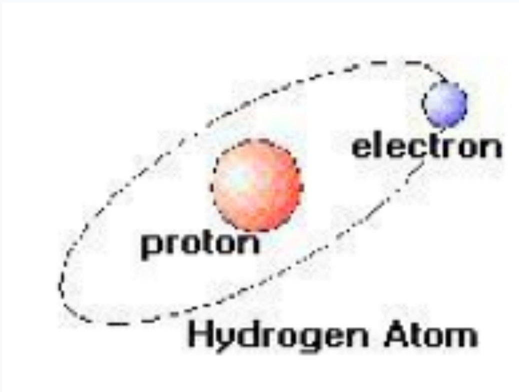
Outline

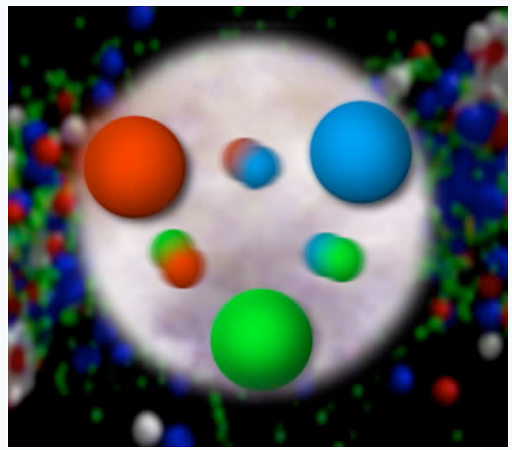
- Quantum chromodynamics and hadrons
- The baryons
- The mesons
- Glueballs
- Gluonic excitations of mesons
- The experimental situation.
- The future.

Quantum Chromo Dynamics

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

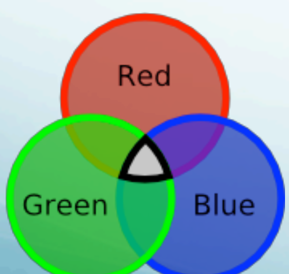


Atoms are electrically neutral: a charge and an anti-charge (+ -).



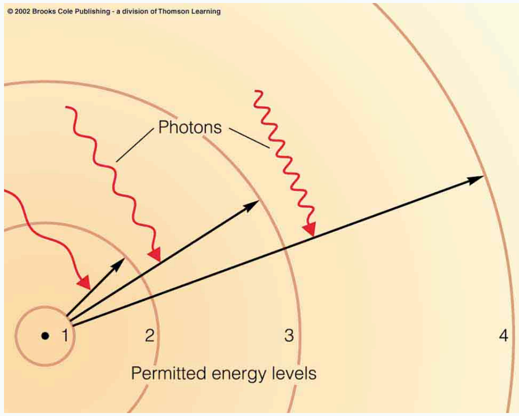
Quarks have color charge: red, blue and green. Antiquarks have anticolors: cyan, yellow and magenta.

Hadrons are color neutral (white), red-cyan, blue-yellow, green-magenta or red-blue-green, cyan-yellow-magenta.

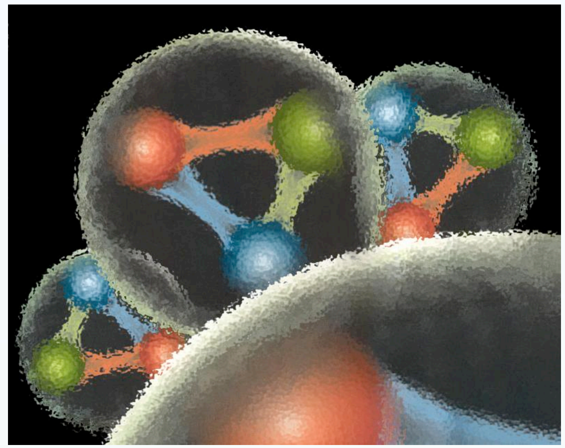


Quantum Chromo Dynamics

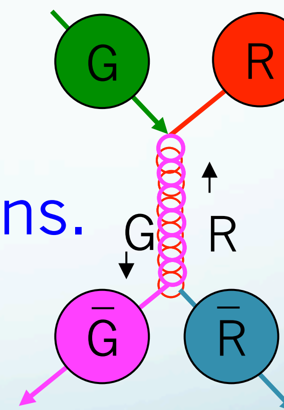
QCD describes the interactions of quarks and gluons.



Photons are the force carriers for the E-M force. Photons are electrically neutral.



Gluons are the force carriers of QCD. Gluons carry a color and an anticolor Charge.



In nature, QCD appears to have two configurations.

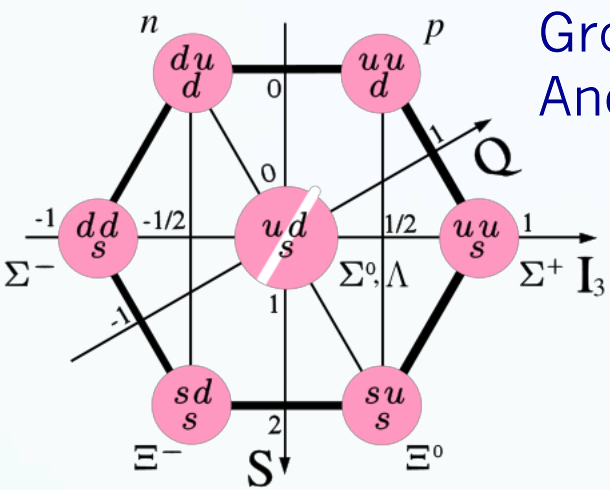
three quarks (qqq) Baryons

proton: uud neutron: udd

quark-antiquark $(q\bar{q})$ Mesons

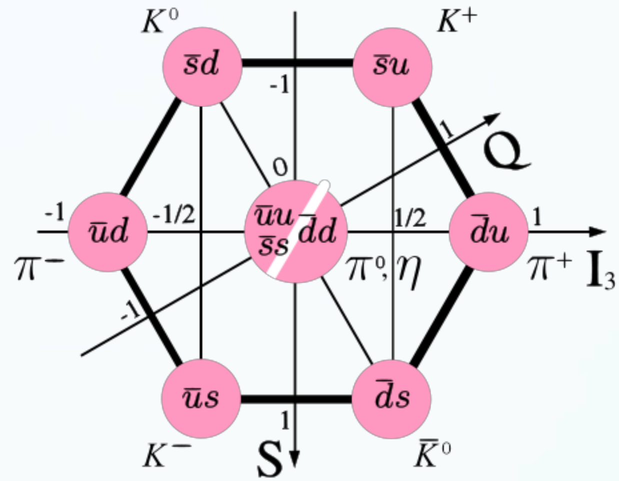
Observed Hadrons

Baryons



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

Mesons



Groups of
9 (nonet).

Other Configurations?

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

$gg \quad ggg$ glueballs

$qqq\bar{q}q$ pentaquarks

$q\bar{q}g$ hybrids

The Issues with Hadrons

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?

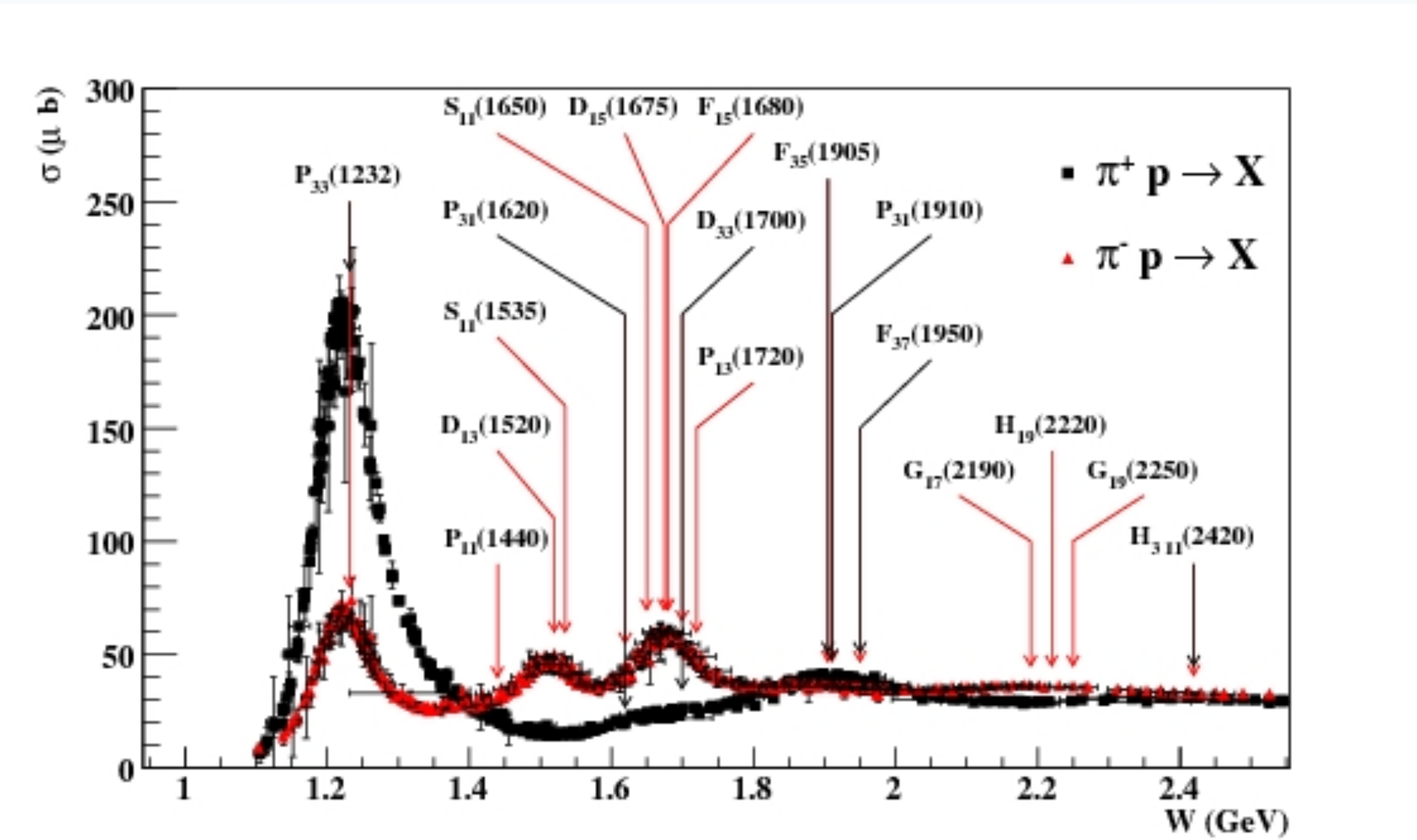
What are the properties of predicted states beyond simple quark-antiquark? $q\bar{q}g$

Need to map out new states.

The Baryon Spectrum

Measured in the reaction
Work done in 60's to early 90's.

$$\pi N \cdot \longrightarrow \pi N$$



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

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

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

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 quark 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.

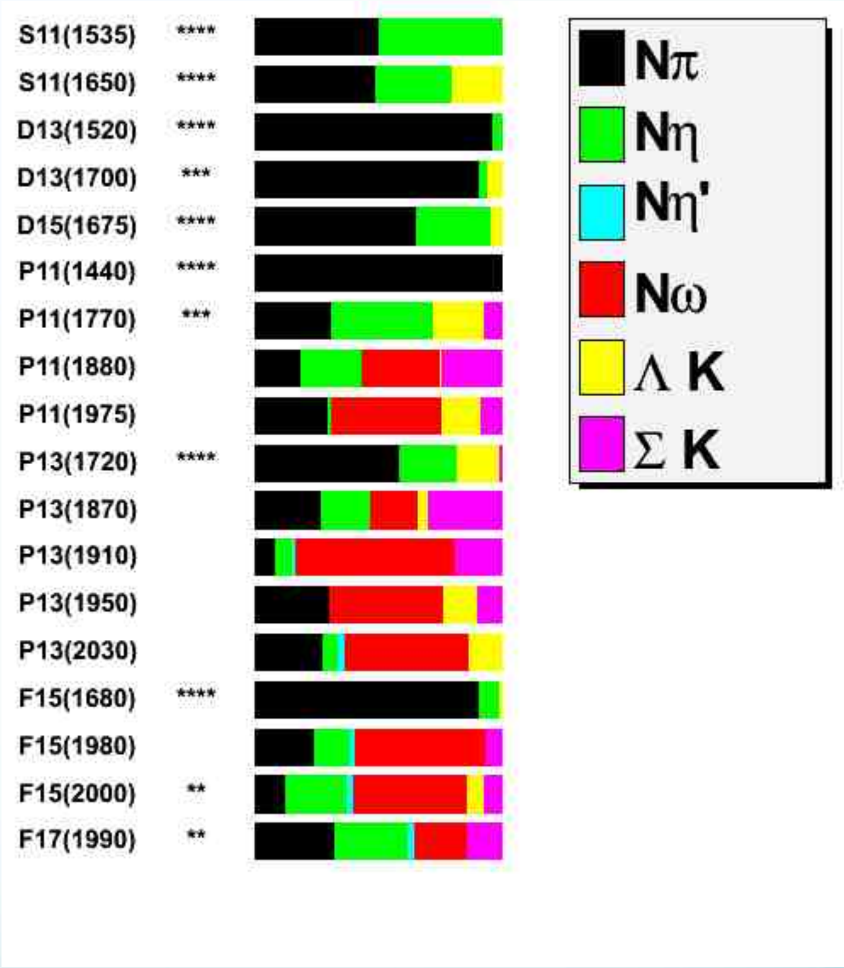
$\pi N \rightarrow \pi N$

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:

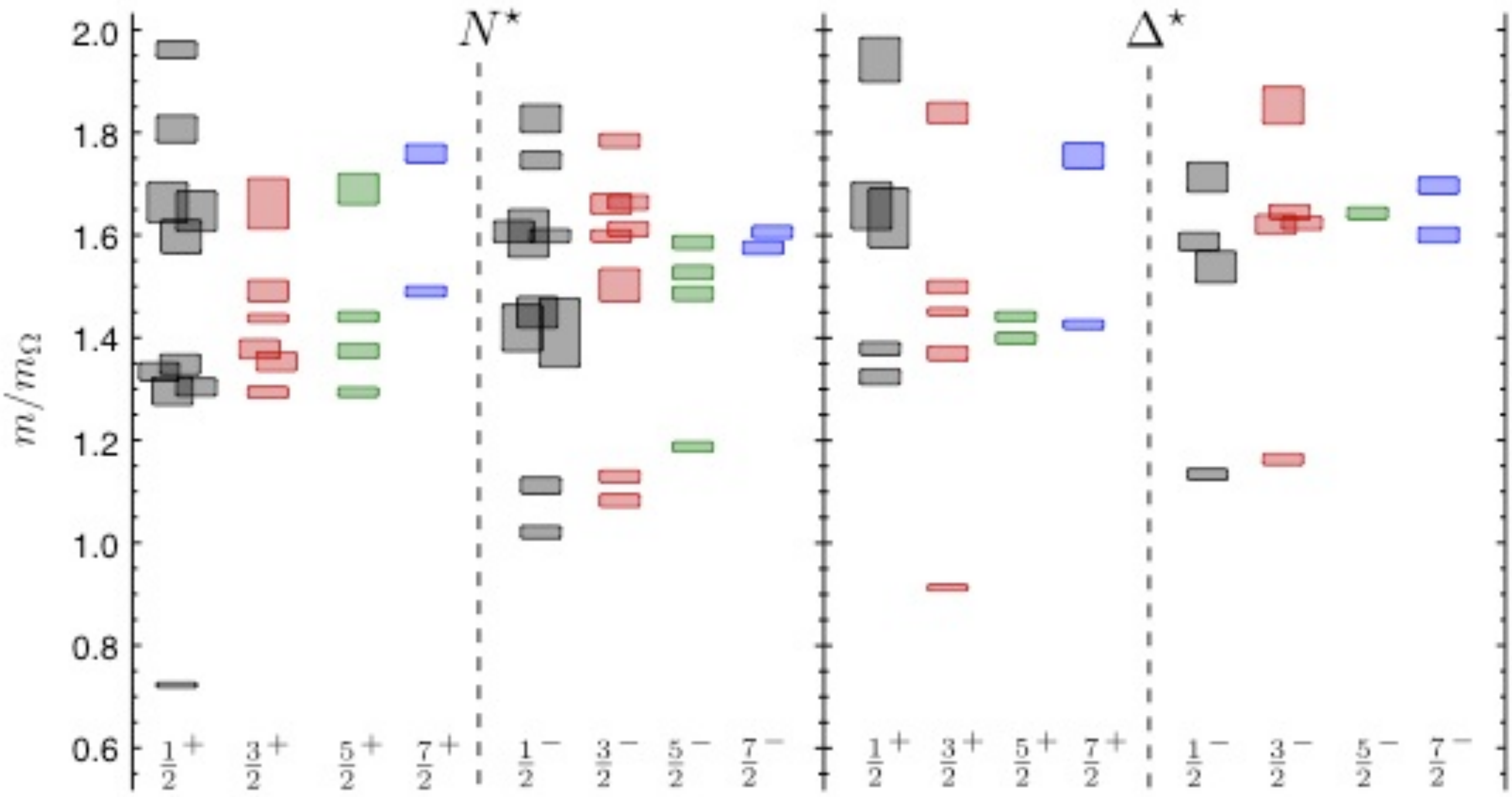
$N\eta \quad N\omega \quad \ldots$

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



Lattice Calculations

Lattice calculation for the baryon spectrum. Pion mass=396MeV/C



R. Edwards *et al.*, Phys. Rev. D**84** 074508 (2011).

Observables in Photo-production

Photo-production of pseudo scalar mesons:

$$\gamma(n,p) \rightarrow M(0^{-+})N'$$

Photon beam			Target			Recoil			Target-Recoil								
						x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
			x	y	z				x	y	z	x	y	z	x	y	z
Unpolarized		σ		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
Linearly	P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
Circular	P_γ		F		E	$C_{x'}$		$C_{z'}$	$O_{z'}$			G		H		$O_{x'}$	

There are 16 observables for these reactions.
Program in place with CLAS at Jefferson Lab to measure these for several systems.

Photo-production Data

$\gamma p \rightarrow p\pi^0$	CLAS, CBELSA
$\gamma p \rightarrow n\pi^+$	CLAS
$\gamma p \rightarrow p\eta$	CLAS,CBELSA,LNS,GRAAL
$\gamma n \rightarrow n\eta$	
$\gamma p \rightarrow p\eta'$	CLAS
$\gamma p \rightarrow \Lambda K^+$	CLAS
$\gamma p \rightarrow \Sigma K^+$	CLAS

Extensive data sets have recently been published. A large effort is pushing polarization measurements

Analysis of the physical observables is being undertaken by several groups to achieve a consistent description of these data sets. EBAC, SAID, η-MAID, Bonn-Gatchina.

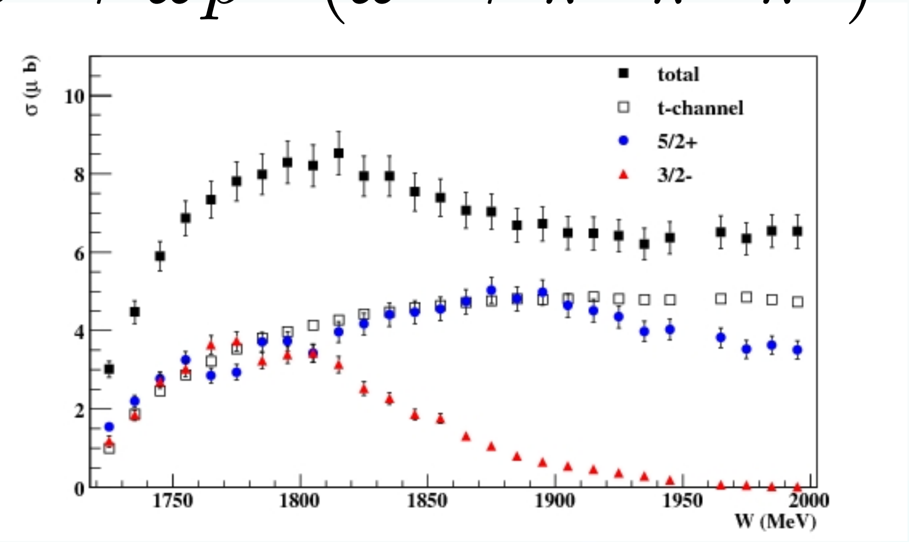
CLAS PWA Results $\gamma p \to \omega p \quad (\omega \to \pi^+\pi^-\pi^0)$

Fit showing three amplitudes.

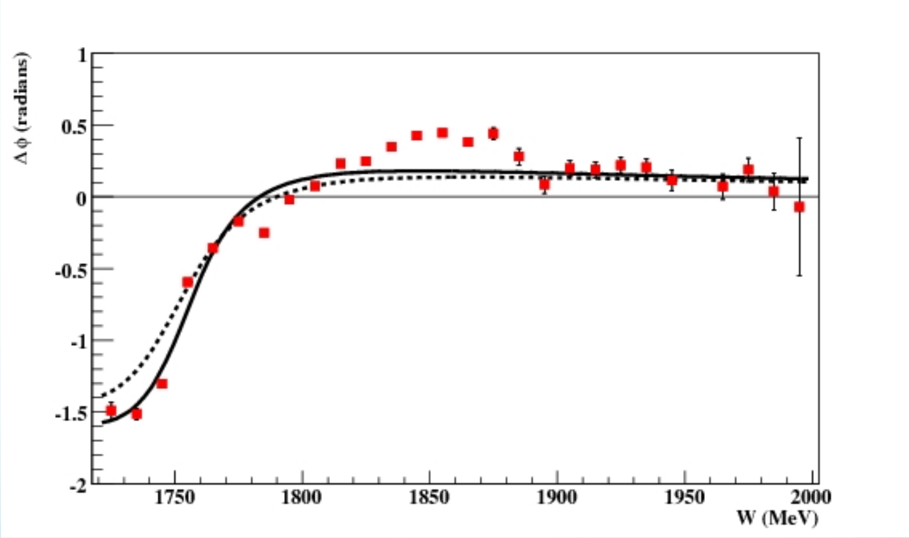
$(3/2)^-$ D_{13}
$(5/2)^+$ F_{15}
t-channel

Not Expected

Intensities



Phase Difference



Strong evidence for:

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

The strong signals are well known states!

What is seen?

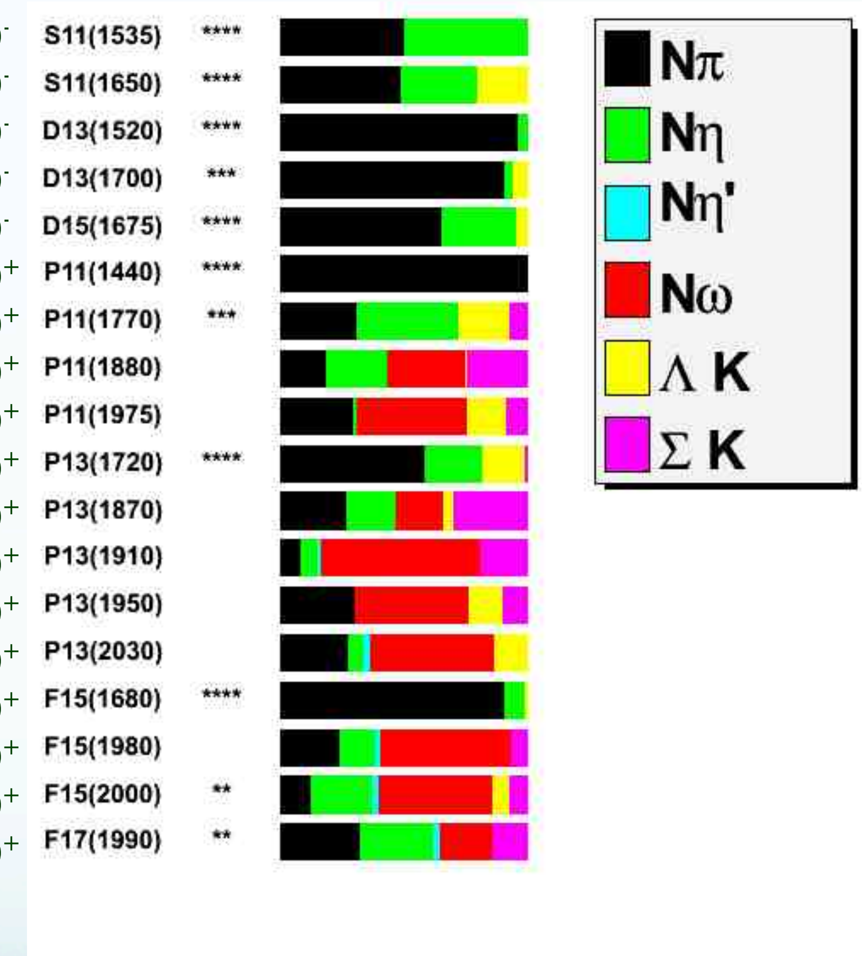
Strong evidence for:

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

Hints?

Good Evidence for:
(5/2)$^+$ N(2000)

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



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

Analysis

Bonn-Gatchina PWA coupling data from many channels together into a single analysis. Includes cross section, beam asymmetries, target asymmetries, recoil asymmetries, double-polarization observables and data to resolve isospin contributions. Data are not sufficient to converge to a unique solution.

γp	$\rightarrow$	$N\pi$	$\Delta(1232)P_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	$N(1535)S_{11}$
γp	$\rightarrow$	$p\eta$	$N(1535)S_{11}$	$N(1720)P_{13}$	$N(2070)D_{15}$	$N(1650)S_{11}$
γp	$\rightarrow$	$p\pi^0\pi^0$	$\Delta(1700)D_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	
γp	$\rightarrow$	$p\pi^0\eta$	$\Delta(1940)D_{33}$	$\Delta(1920)P_{33}$	$N(2200)D_{13}$	$\Delta(1700)D_{33}$
γp	$\rightarrow$	ΛK^+	$S_{11} - wave$	$N(1720)P_{13}$	$N(1900)P_{13}$	$N(1840)P_{11}$
γp	$\rightarrow$	ΣK	$S_{11} - wave$	$N(1900)P_{13}$	$N(1840)P_{11}$	
$\pi^- p$	$\rightarrow$	$n\pi^0\pi^0$	$N(1440)P_{11}$	$N(1520)D_{13}$	$S_{11} - wave$	

Analysis New Baryons from this Analysis.

Bonn-Gatchina PWA coupling data from many channels together into a single analysis. Includes cross section, beam asymmetries, target asymmetries, recoil asymmetries, double-polarization observables and data to resolve isospin contributions.

Several of the "missing states" have been observed!

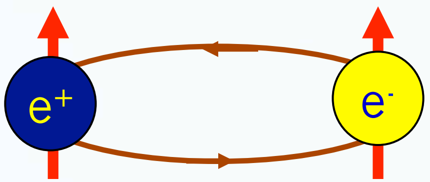
γp	$\rightarrow$	$N\pi$	$\Delta(1232)P_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	$N(1535)S_{11}$
γp	$\rightarrow$	$p\eta$	$N(1535)S_{11}$	$N(1720)P_{13}$	$N(2070)D_{15}$	$N(1650)S_{11}$
γp	$\rightarrow$	$p\pi^0\pi^0$	$\Delta(1700)D_{33}$	$N(1520)D_{13}$	$N(1680)F_{15}$	
γp	$\rightarrow$	$p\pi^0\eta$	$\Delta(1940)D_{33}$	$\Delta(1920)P_{33}$	$N(2200)D_{13}$	$\Delta(1700)D_{33}$
γp	$\rightarrow$	ΛK^+	$S_{11}-wave$	$N(1720)P_{13}$	$N(1900)P_{13}$	$N(1840)P_{11}$
γp	$\rightarrow$	ΣK	$S_{11}-wave$	$N(1900)P_{13}$	$N(1840)P_{11}$	
$\pi^- p$	$\rightarrow$	$n\pi^0\pi^0$	$N(1440)P_{11}$	$N(1520)D_{13}$	$S_{11}-wave$	

Baryon Summary

- A lot of work currently underway to add new data using polarized targets.
- Analysis efforts are taking advantage of large data sets.
- Lattice QCD is starting to make predictions for the spectrum.
- Starting to find some of the missing baryons, and what we see looks like 3 quarks.

Spectroscopy
A probe of QED

Positronium



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

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

Total Spin: $J=L+S$

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

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

… …

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

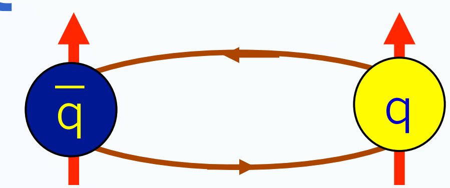
Particle<->Antiparticle:
Charge Conjugation: $C=(-1)^{(L+S)}$

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

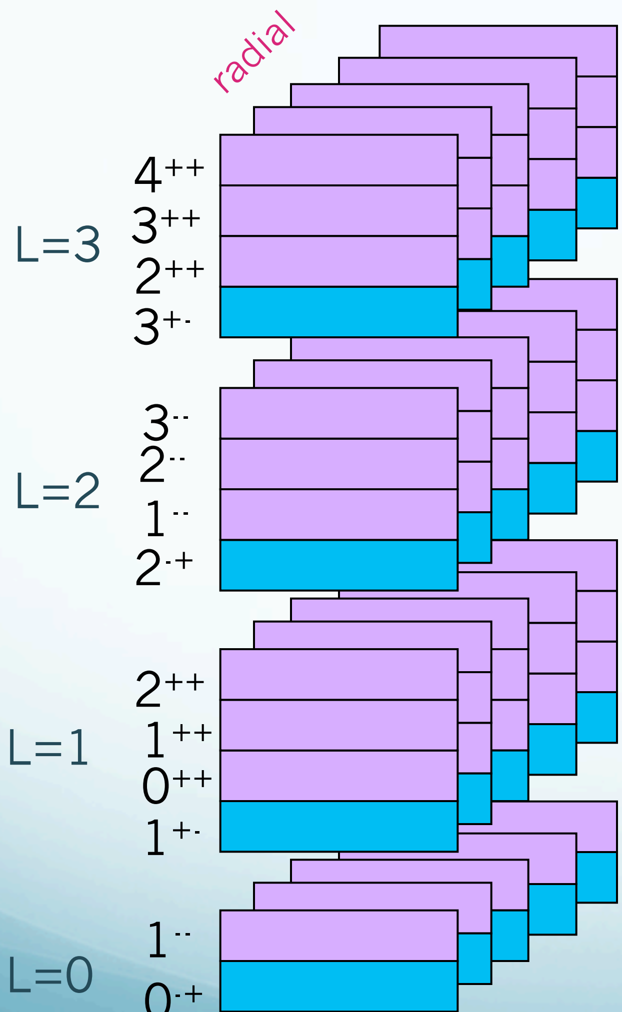
$^{(2S+1)}L_J$ $^1S_0, {}^3S_1, {}^1P_1, {}^3P_0, {}^3P_1, {}^3P_2,\ldots$

Spectroscopy and QCD

Quarkonium



Mesons



Consider the three lightest quarks

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

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

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

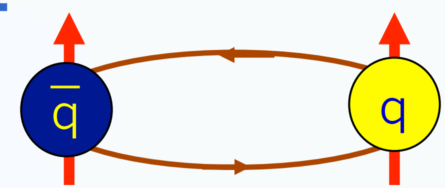
$$s\bar{d} \qquad s\bar{u}$$

S=1
S=0

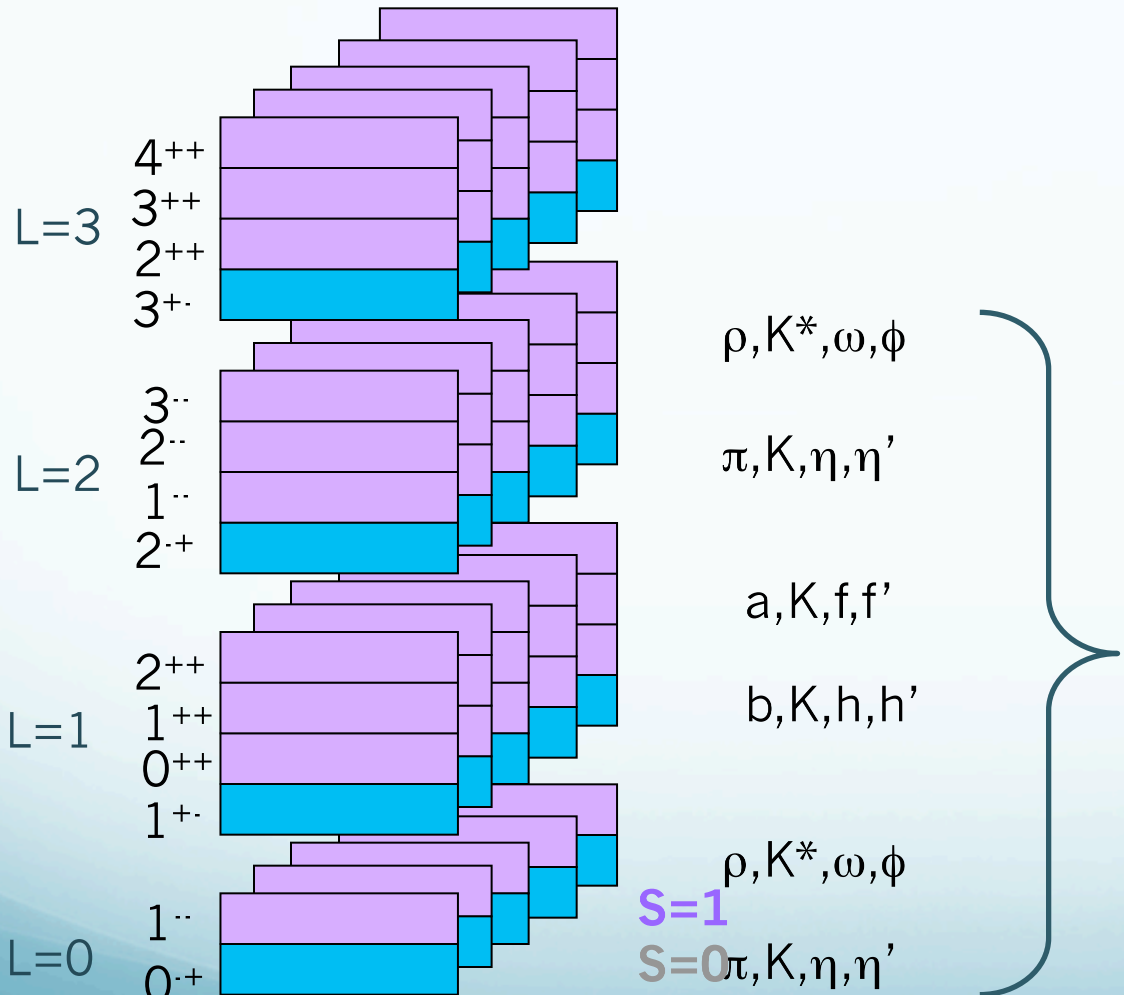
$$\frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right) \qquad \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

Spectroscopy an QCD

Quarkonium



Mesons



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

SU(3) is broken
Last two members mix

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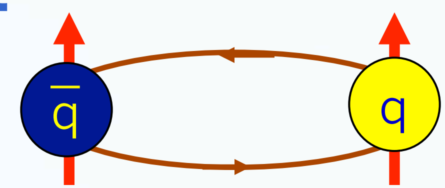
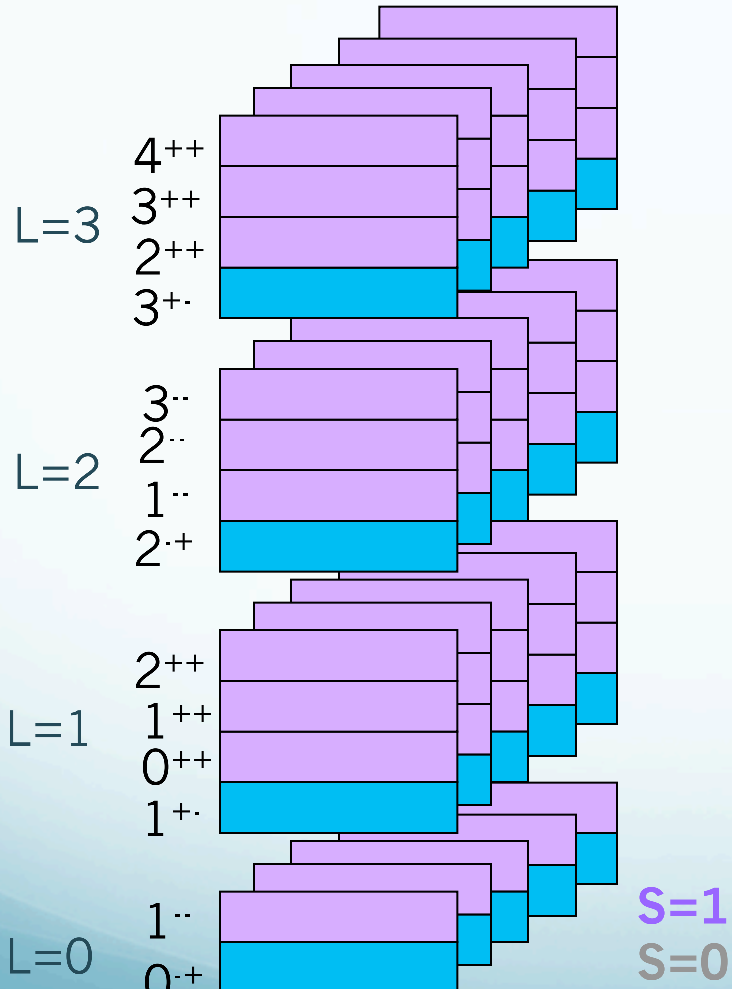
Spectroscopy an QCD

Quarkonium



Mesons



Allowed J^{PC} Quantum numbers:

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

Exotic Quantum Numbers

non quark-antiquark description

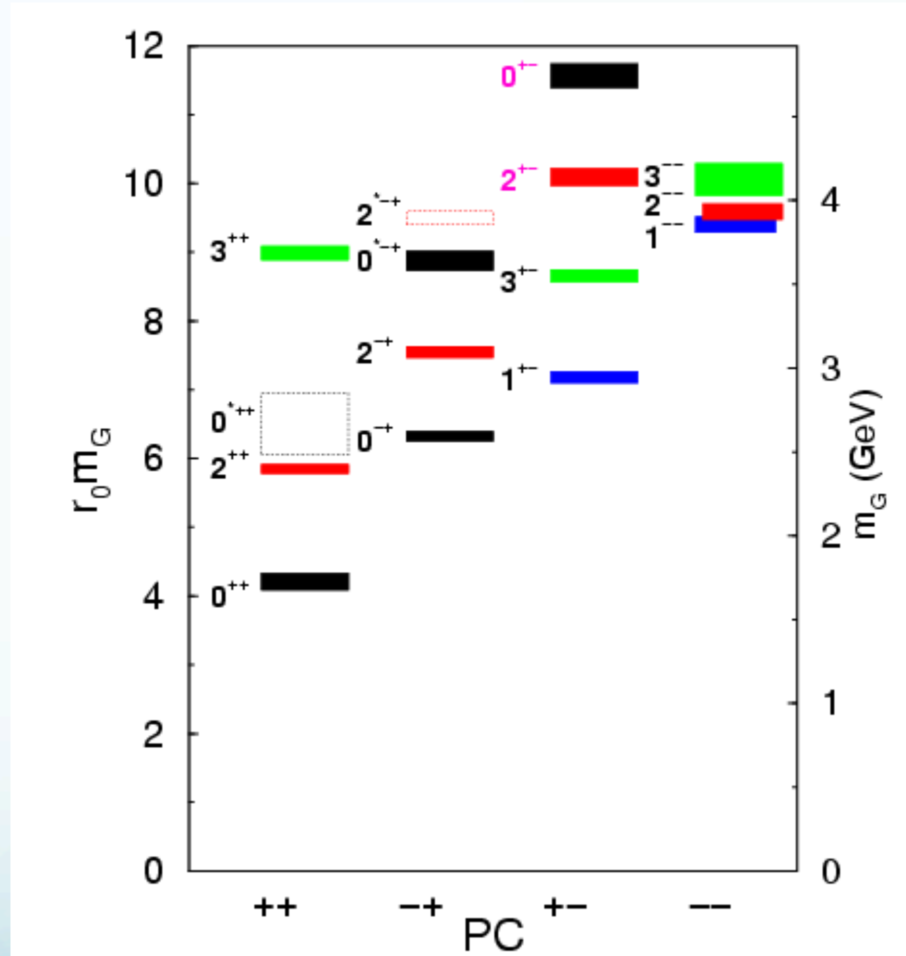
Lattice QCD Glueball Predictions

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.

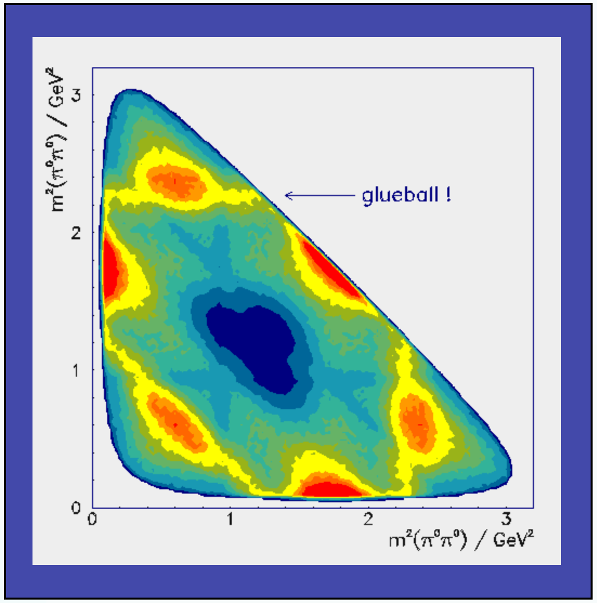
$$\pi\pi : K\overline{K} : \eta\eta : \eta'\eta' : \eta\eta' = 3 : 4 : 1 : 1 : 0$$

Production Mechanisms:

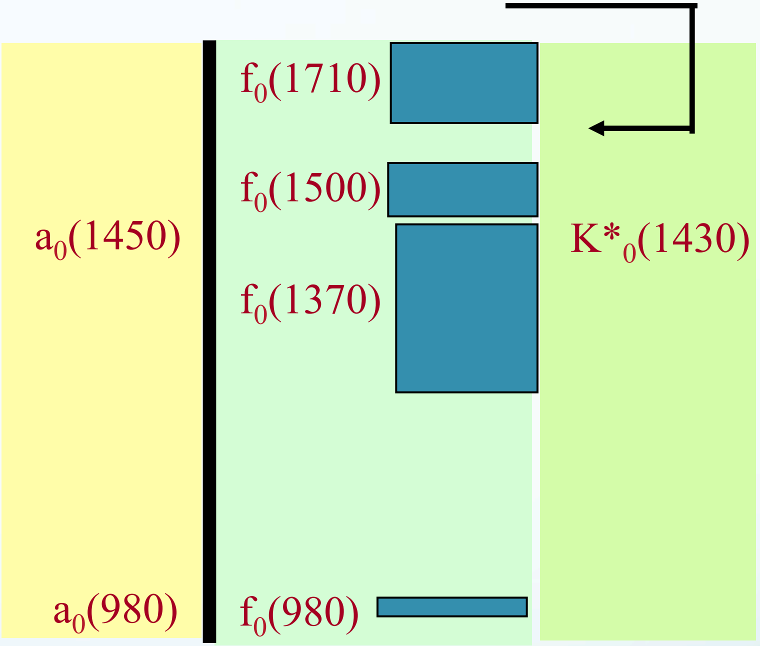
Certain are expected to by Glue-rich, others are Glue-poor. Where do you see them?

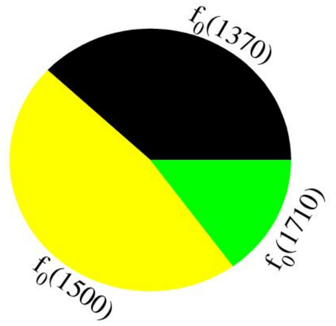
Proton-antiproton
Central Production
J/ψ decays

Experimental Evidence



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

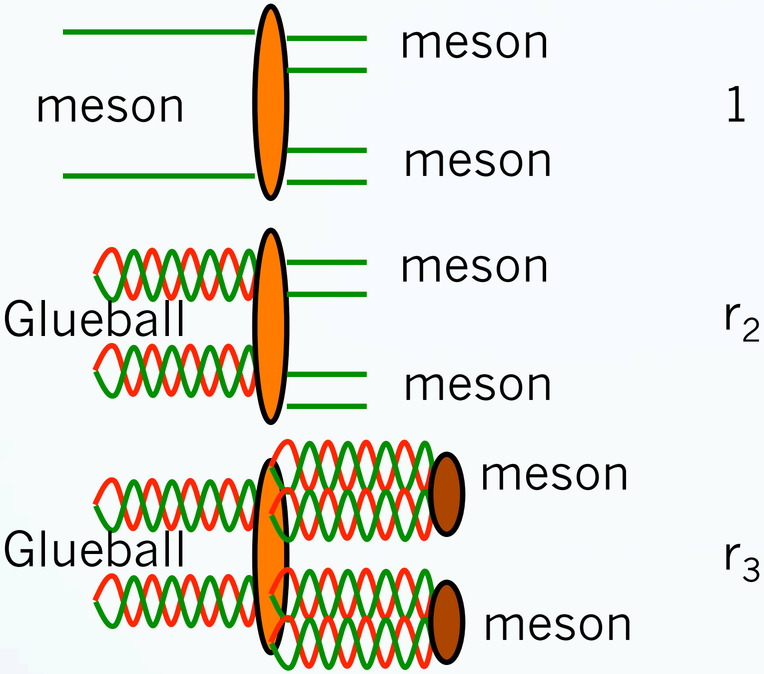




Glueball spread over 3 mesons

Are there other glueballs?

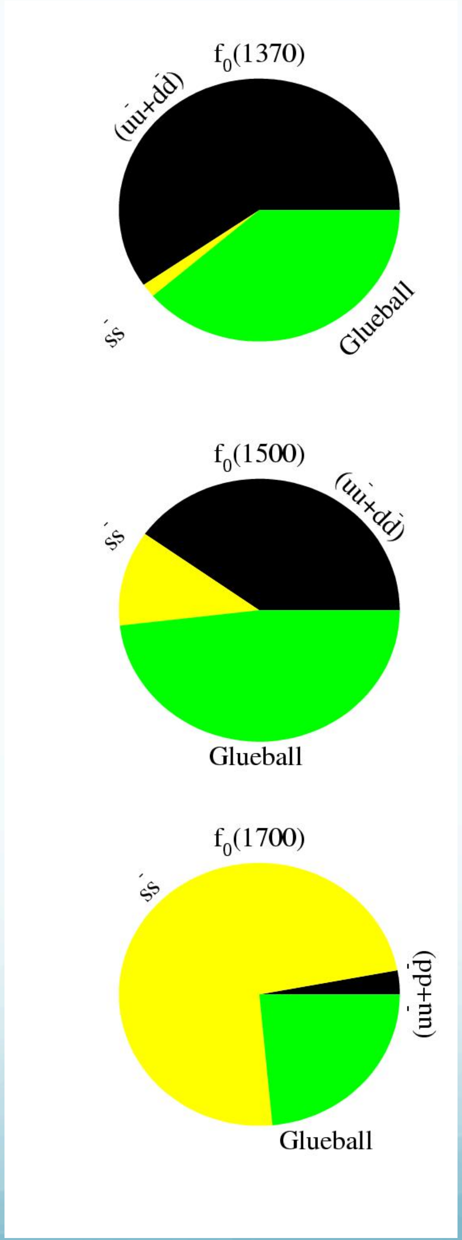
Glueball-Meson Mixing



$G \to q\bar{q}$ flavor blind? r

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

Solve for mixing scheme



Higher Mass Glueballs?

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

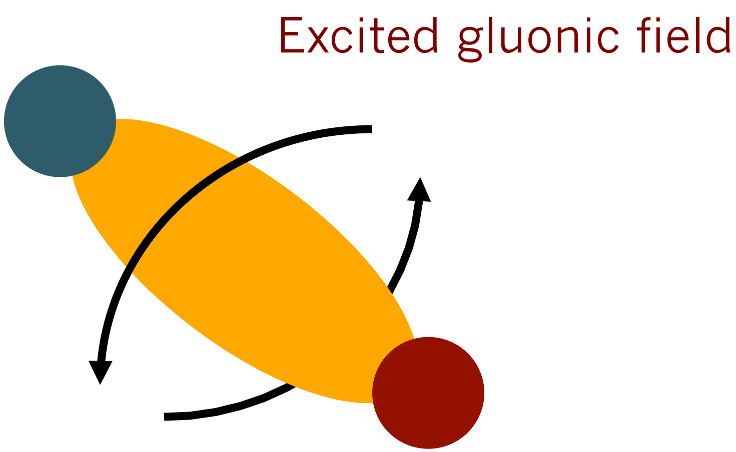
Lattice predicts that the 2^{++} and the 0^{-+} are the next two, with masses just above $2GeV/c^{2}$.

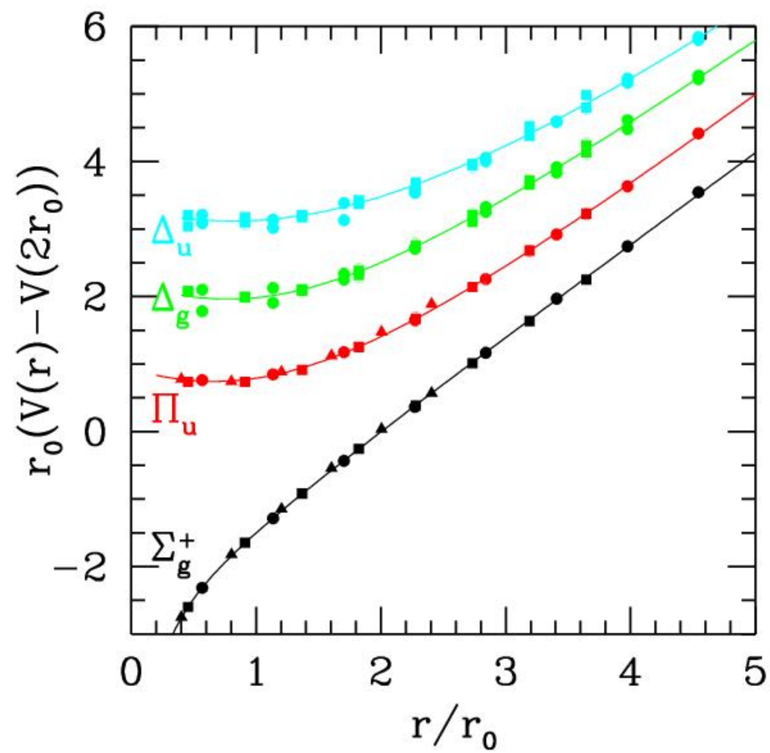
Radial Excitations of the 2^{++} ground state
L=3 2^{++} States + Radial excitations
f2(1950), f2(2010), f2(2300), f2(2340)...

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.

QCD Potential





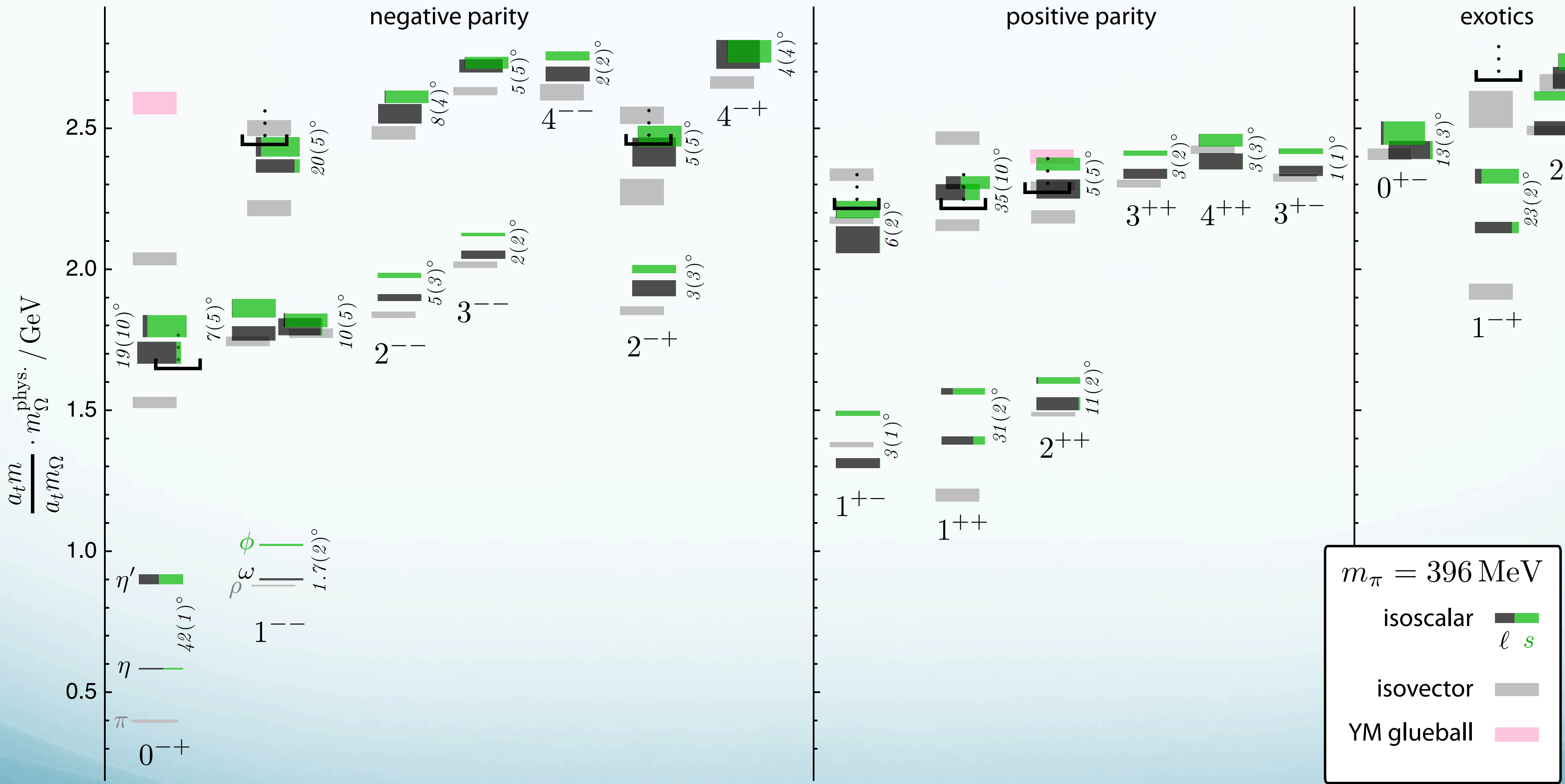
Gluonic Excitations provide an experimental measurement of the excited QCD potential.

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

Spectroscopy and QCD

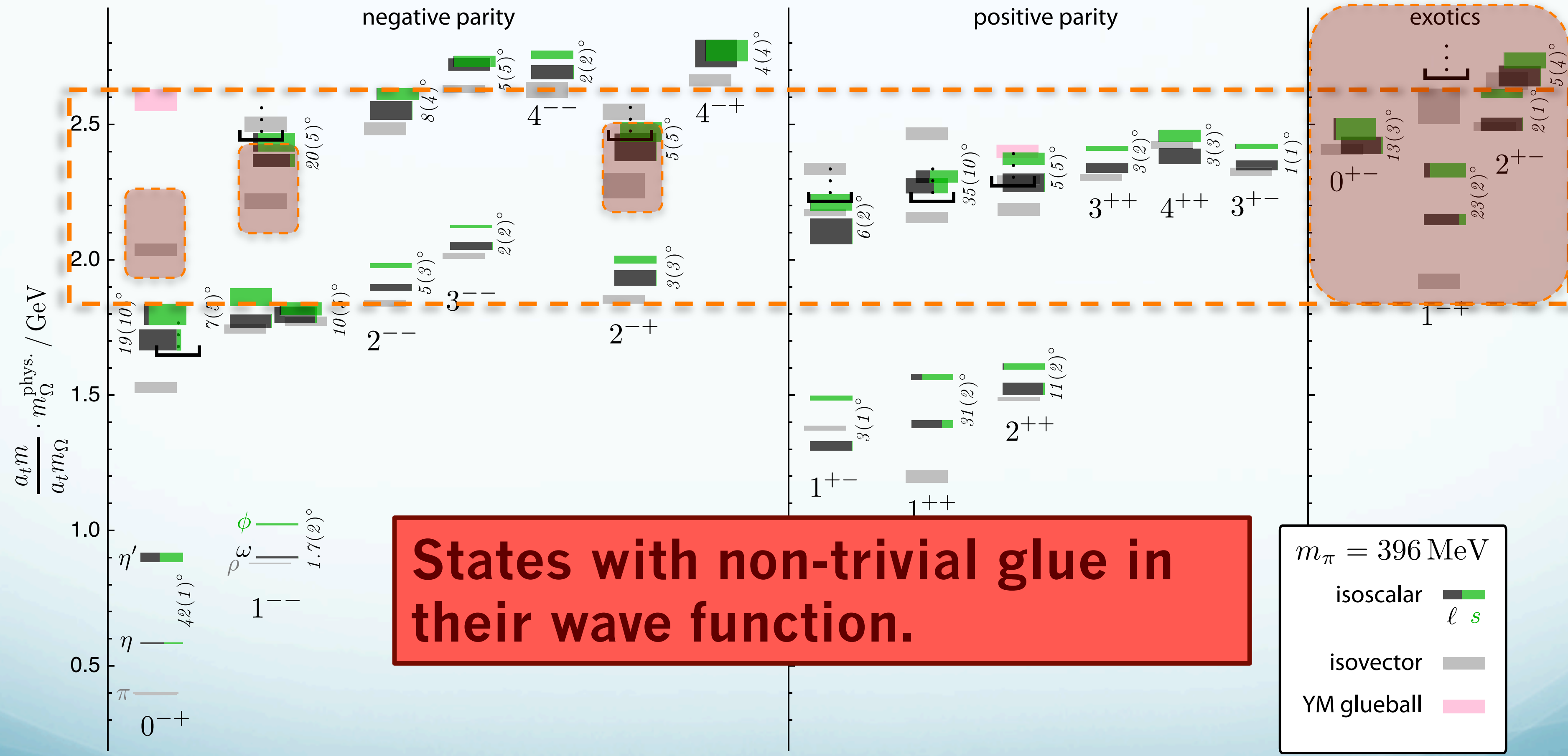
Lattice QCD Predictions

Phys. Rev. D83 (2011) 111502



Spectroscopy and QCD

Lattice QCD Predictions



States with non-trivial glue in their wave function.

Spectroscopy and QCD

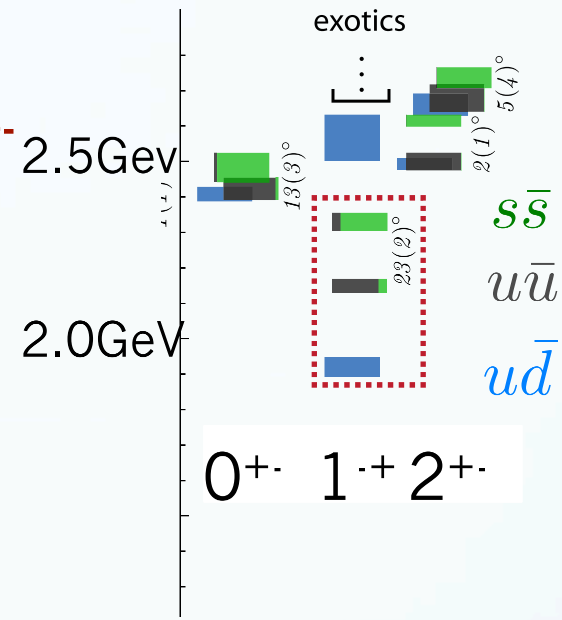
Phys. Rev. D84 (2011) 074023

``Constituent gluon'' behaves like it has $J^{PC} = 1^{+-}$

Mass ~ 1-1.5 GeV

Lightest hybrid nonets: 1^{--}, (0^{-+}, 1^{-+}, 2^{-+})

The 0+- and two 2+- exotic nonets:
also a second 1^{-+} nonet
p-wave meson plus a ``gluon''



Several nonets predicted

Spectroscopy and QCD

Experimental results on mixing:

$$J^{PC} = 0^{-+} : \ \pi, \eta, \eta', K \ : \ \theta = -11.5^\circ$$

$$J^{PC} = 1^{--} : \ \rho, \omega, \phi, K^* \ : \ \theta = 38.7^\circ$$

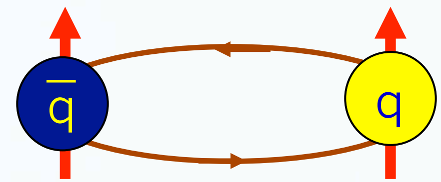
$$J^{PC} = 1^{+-} : \ b_1, h_1, h'_1, K_{1B} \ : \ \theta = 34^\circ$$

$$J^{PC} = 1^{++} : \ a_1, f_1, f'_1, K_{1A} \ : \ \theta = 13^\circ$$

$$J^{PC} = 2^{++} : \ a_2, f_2, f'_2, K^*_2 \ : \ \theta = 28^\circ$$

$$J^{PC} = 3^{--} : \ \rho_3, \omega_3, \phi_3, K^*_3 \ : \ \theta = 31^\circ$$

Quarkonium



Ideal Mixing: **θ = 35.3°**

$|u\bar{u} + d\bar{d} > \quad |s\bar{s} >$

Measure through decay rates:

$f_2(1270) \to KK \ / \ f_2(1270) \to \pi\pi \ \sim 0.05$

$f'_2(1525) \to \pi\pi \ / \ f'_2(1525) \to KK \ \sim 0.009$

Lattice QCD suggests some nonets do not have ideal mixing:

0^{-+} ground state and radial
1^{--} $^3D_1$ ground state.
1^{++} ground state
1^{-+} exotic

Looking for Hybrids

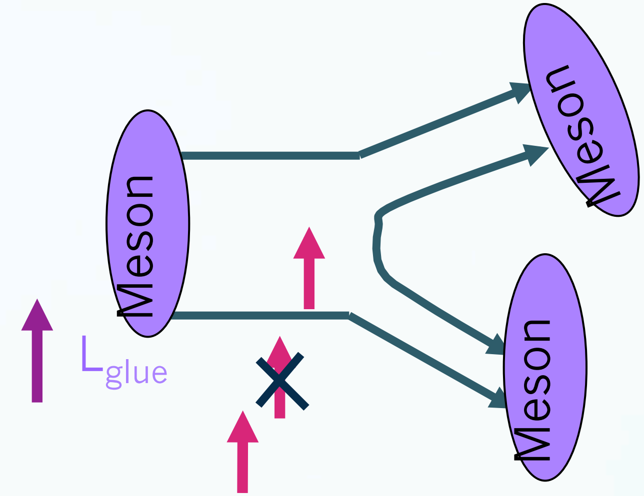
Analysis Method

Partial Wave Analysis

Fit n-D angular distributions

Fit Models of production and decay of resonances.

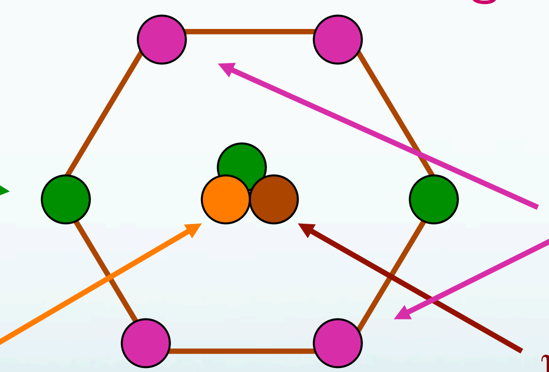
Decay Predictions



Angular momentum in the gluon flux stays confined.

π_1 $I^G(J^{PC})=1^-(1^{-+})$

Nine state



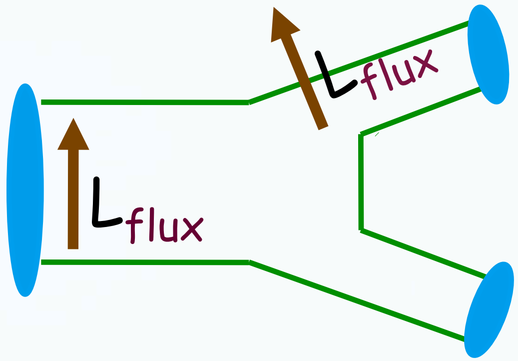
K_1 $I^G(J^{PC})=\frac{1}{2}(1^-)$

η'_1 $I^G(J^{PC})=0^+(1^{-+})$

η_1 $I^G(J^{PC})=0^+(1^{-+})$

This leads to complicated multi-particle final states.

Hybrid Decays



The angular momentum in the flux tube stays in one of the daughter mesons (an (L=1) and (L=0) meson).

Exotic Quantum Number Hybrids

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

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

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

Mass and model dependent predictions

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

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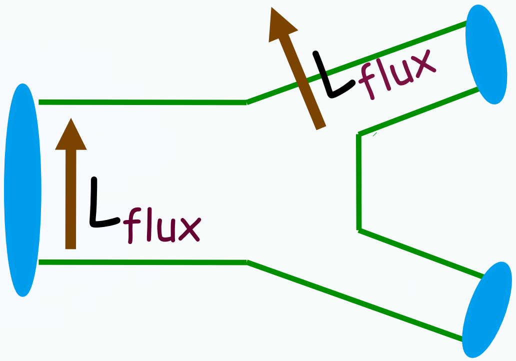

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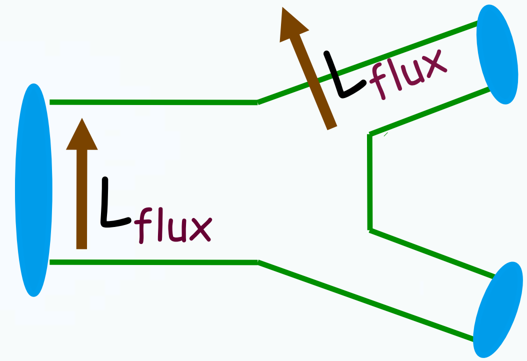
The good channels to look at with amplitude analysis.

Hybrid Decays



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Mass and model dependent predictions

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

The good channels to look at with amplitude analysis.

Other interesting channels for amplitude analysis.

Experimental Evidence for Hybrids

$\pi_1(1400)$

Mode	Mass	Width	Production
$\eta\pi^-$	1370±15+50-30	385±40+65-105	1^+
$\eta\pi^0$	1257±20±25	354±64±60	1^+
$\eta\pi$	1400	310	seen in $\bar{p}N$ annihilation

$\pi_1(1600)$

Mode	Mass	Width	Production
3π	1598 ±8+29-47	168±20+150-12	$1^+,0^-,1^-$
$\eta'\pi$	1597±10+45-10	340±40±50	1^+
$b_1\pi$	1664±8±10	185±25±38	$0^-,1^+$
$f_1\pi$	1709±24±41	403±80±115	1^+
3π	1660 ±10+64-0	269±21+42-64	1^+

$\pi_1(2015)$

Mode	Mass	Width	Production
$b_1\pi$	2014±20±16	230±32±73	1^+
$f_1\pi$	2001±30±92	332±52±49	1^+

Experimental Evidence for Hybrids

The most extensive data sets to date are from the **BNL E852 experiment**. There is also data from the **VES experiment** at Protvino and some results from the **Crystal Barrel experiment** at LEAR. Finally, there is a **CLAS (Jefferson Lab)** result. We have also just started to see results from the **COMPASS** experiment at CERN.

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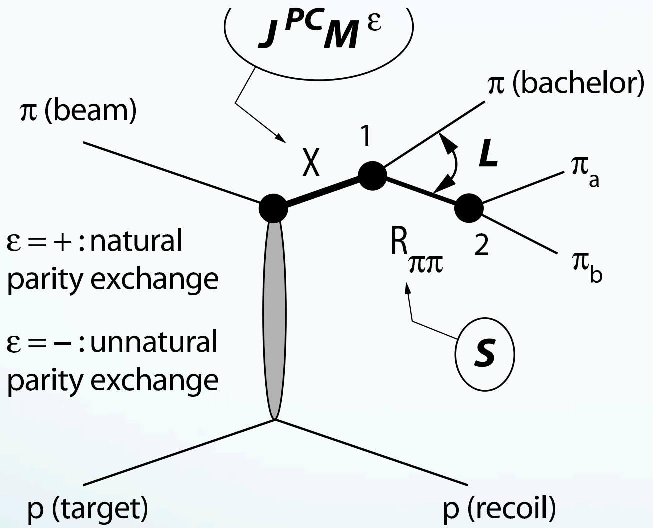


Diffractive production

E852: 18 GeV/c $\pi^- p \rightarrow (p,n)X^{(-,0)}$

VES 37 GeV/c $\pi^- A \rightarrow AX^-$

COMPASS:160 GeV/c $\pi^- Pb \rightarrow PbX^-$

$$(\pi^{\pm}p \rightarrow pX^{\pm}, pp \rightarrow p_s X^0 p_f)$$

M: spin projection
ε : reflectivity

Natural-parity-exchange: $J^P=0^+,1^-,2^+$, ...
Unnatural-parity-exchange: $J^P=0^-,1^+,2^-$, ...

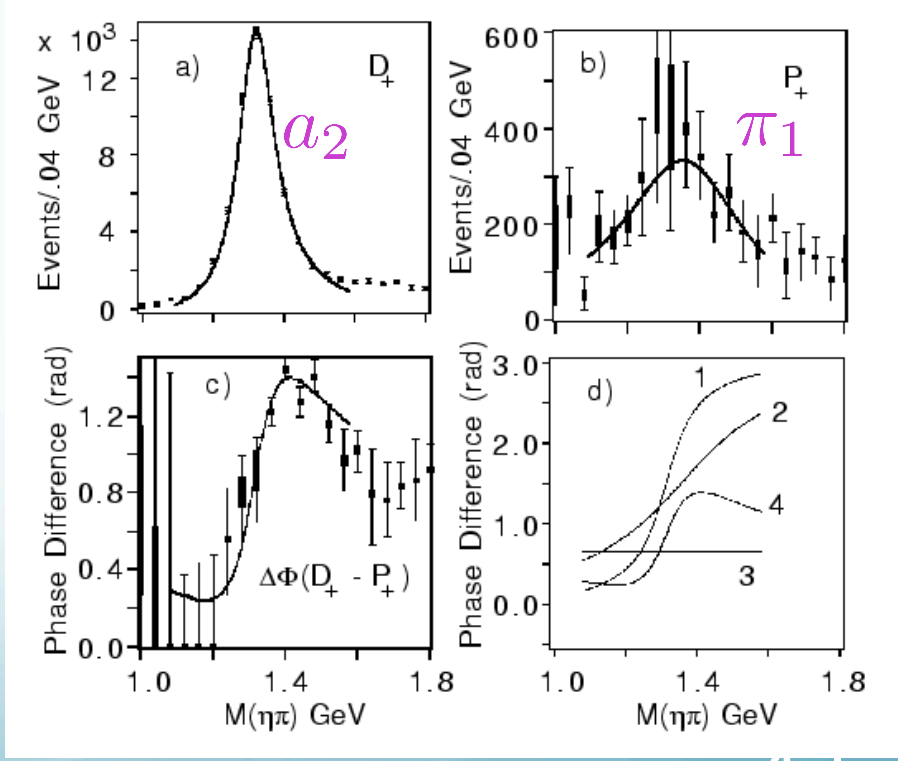
Experimental Evidence for Hybrids

	Mode	Mass	Width	Production
π_1(1400)	$\eta\,\pi^-$	1370±15+50-30	385±40+65-105	1^+
	$\eta\,\pi^0$	1257±20±25	354±64±60	1^+
	$\eta\,\pi$	1400	310 seen in $\overline{p}N$	annihilation

E852 + CBAR (1997)

While everyone seems to agree that there is intensity in the P^+ exotic wave, there are a number of alternative (non-resonant) explanations for this state.

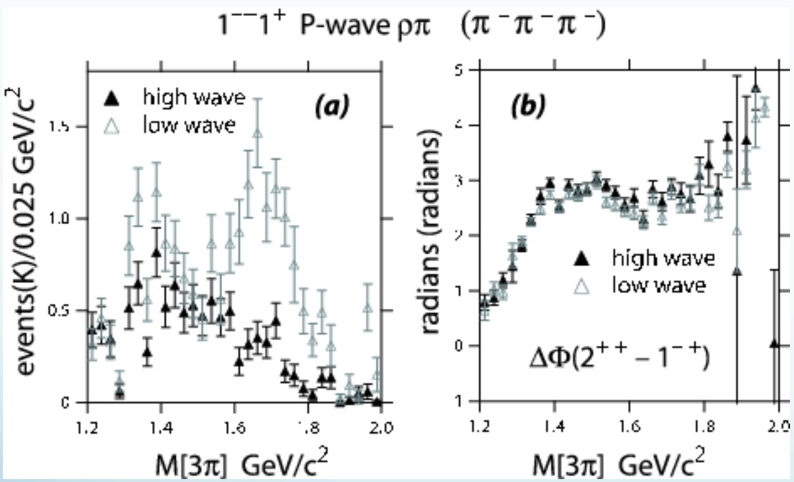
Unlikely to be a hybrid based on its mass. Also , the only observed decay should not couple to a member of an SU(3) octet. It could couple to an SU(3) decuplet state (e.g. 4-quark).



Experimental Evidence for Hybrids

	Mode	Mass	Width	Production
$\pi_1(1600)$	3π	$1598 \pm 8 + 29 - 47$	$168 \pm 20 + 150 - 12$	$1^+, 0^-, 1^-$ E852
	$\eta'\pi$	$1597 \pm 10 + 45 - 10$	$340 \pm 40 \pm 50$	1^+ E852,VES
	$b_1\pi$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 38$	$0^-, 1^+$ E852,VES,CBAR
	$f_1\pi$	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$	1^+ E852,VES
	3π	$1660 \pm 10 + 64 - 0$	$269 \pm 21 + 42 - 64$	1^+ COMPASS

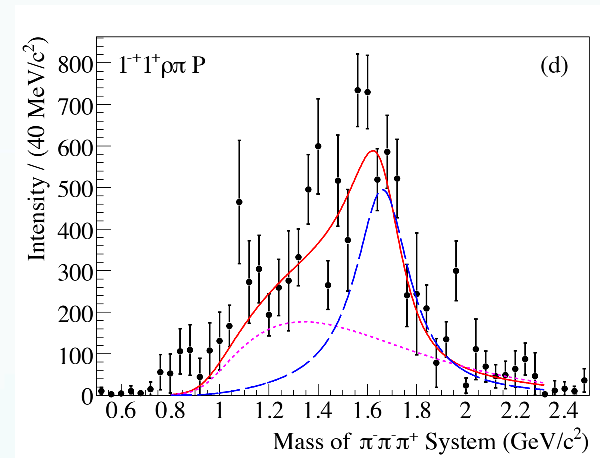
3π Decay mode sensitive to model

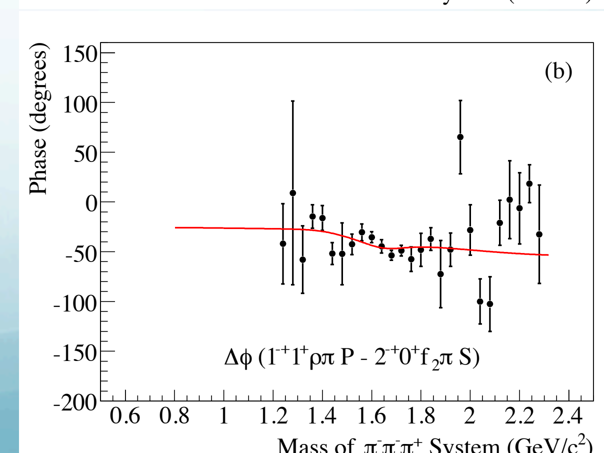


But not in COMPASS

Exactly the same mass and width as the $\pi_2(1670)$

Confused production in E852??





This is consistent with a hybrid meson

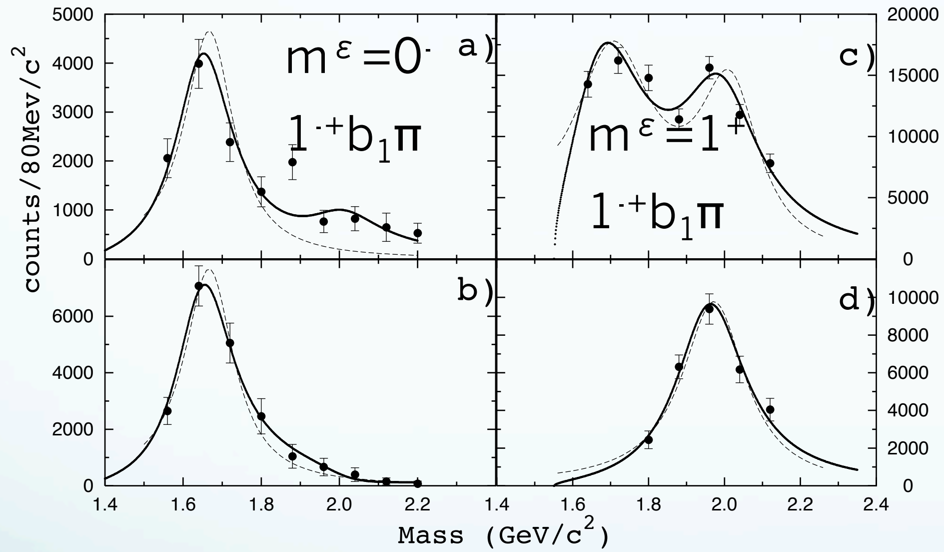
NNPSS 2013
Stony Brook, New York - July 15-26

Experimental Evidence for Hybrids

$\pi_1(2015)$

Mode	Mass	Width	Production	
$b_1\pi$	$2014\pm20\pm16$	$230\pm32\pm73$	1^+	E852
$f_1\pi$	$2001\pm30\pm92$	$332\pm52\pm49$	1^+	E852

Need two $J^{PC}=1^{-+}$ states



$\pi_1(2000)\to b_1\pi$

$M = 2014\pm20\pm16$ MeV/c^2

$\Gamma = 230\pm32\pm73$ MeV/c^2

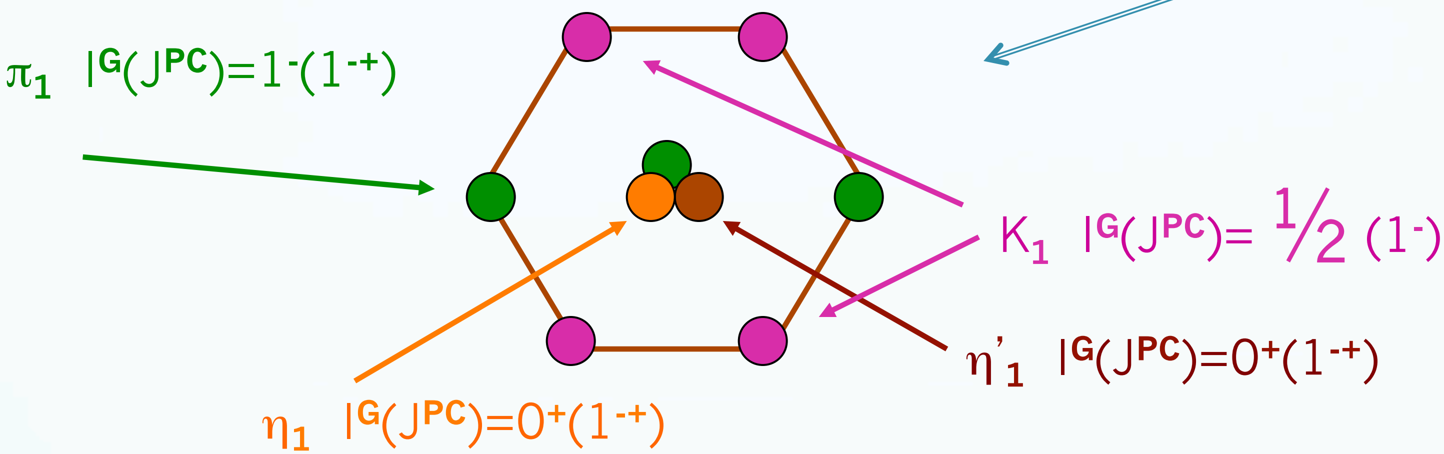
Seen primarily in natural parity exchange.

The natural dominates

Seen in one experiment with low statistics It needs confirmation. If this exists, it is also a good candidate for an exotic hybrid meson.

QCD Exotics

We expect 3 nonets of exotic-quantum-number mesons: 0^{+-}, 1^{-+}, 2^{+-}



- $\pi_1(2015)$
- $\pi_1(1600)$

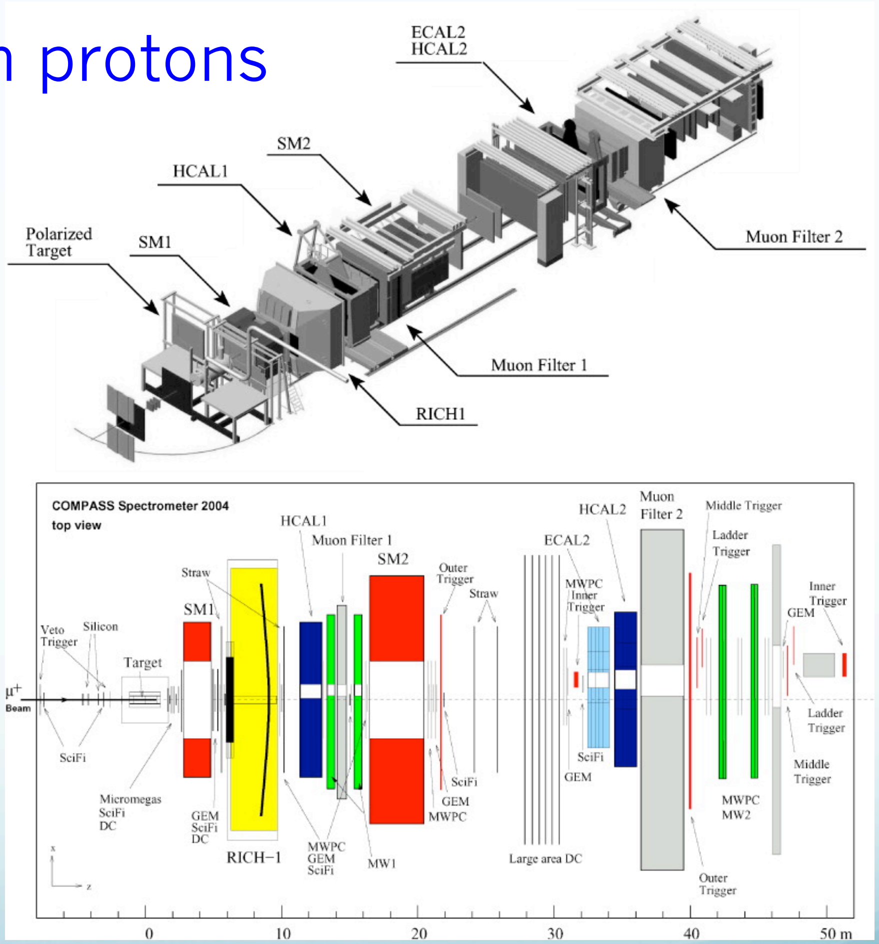
Lattice shows two nonets here.

$$\pi, \eta, \eta', K \rightarrow \begin{array}{ll} \pi_1, \eta_1, \eta'_1, K_1 & 1^{-+} \\ b_0, h_0, h_0', K_0 & 0^{+-} \\ b_2, h_2, h_2', K_2 & 2^{+-} \end{array}$$

What are the mixing angles between the isoscalar states?

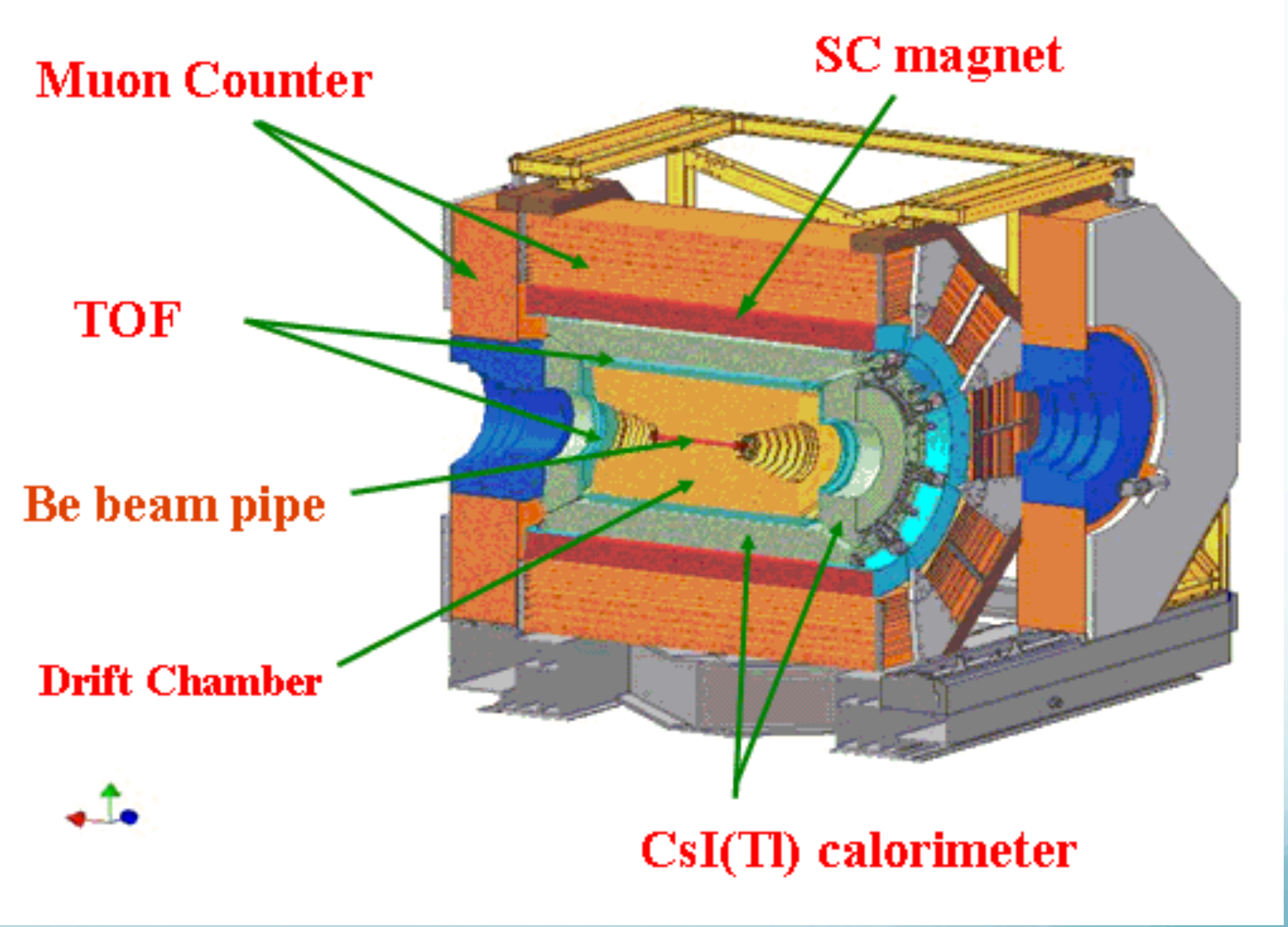
COMPASS (CERN)

180 GeV Pion beams on protons



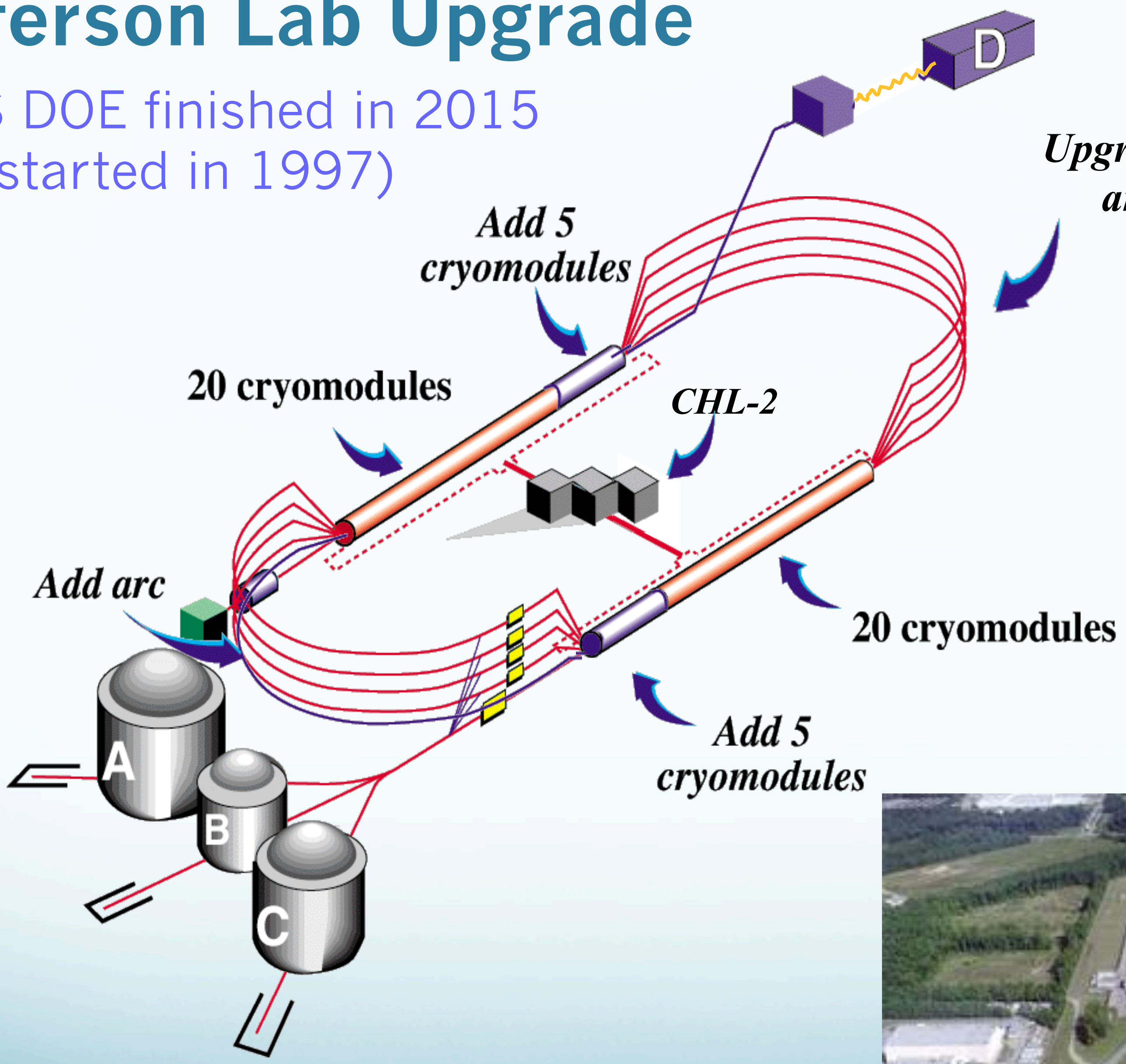
BES III

$$e^+e^- \to \psi s$$



Jefferson Lab Upgrade

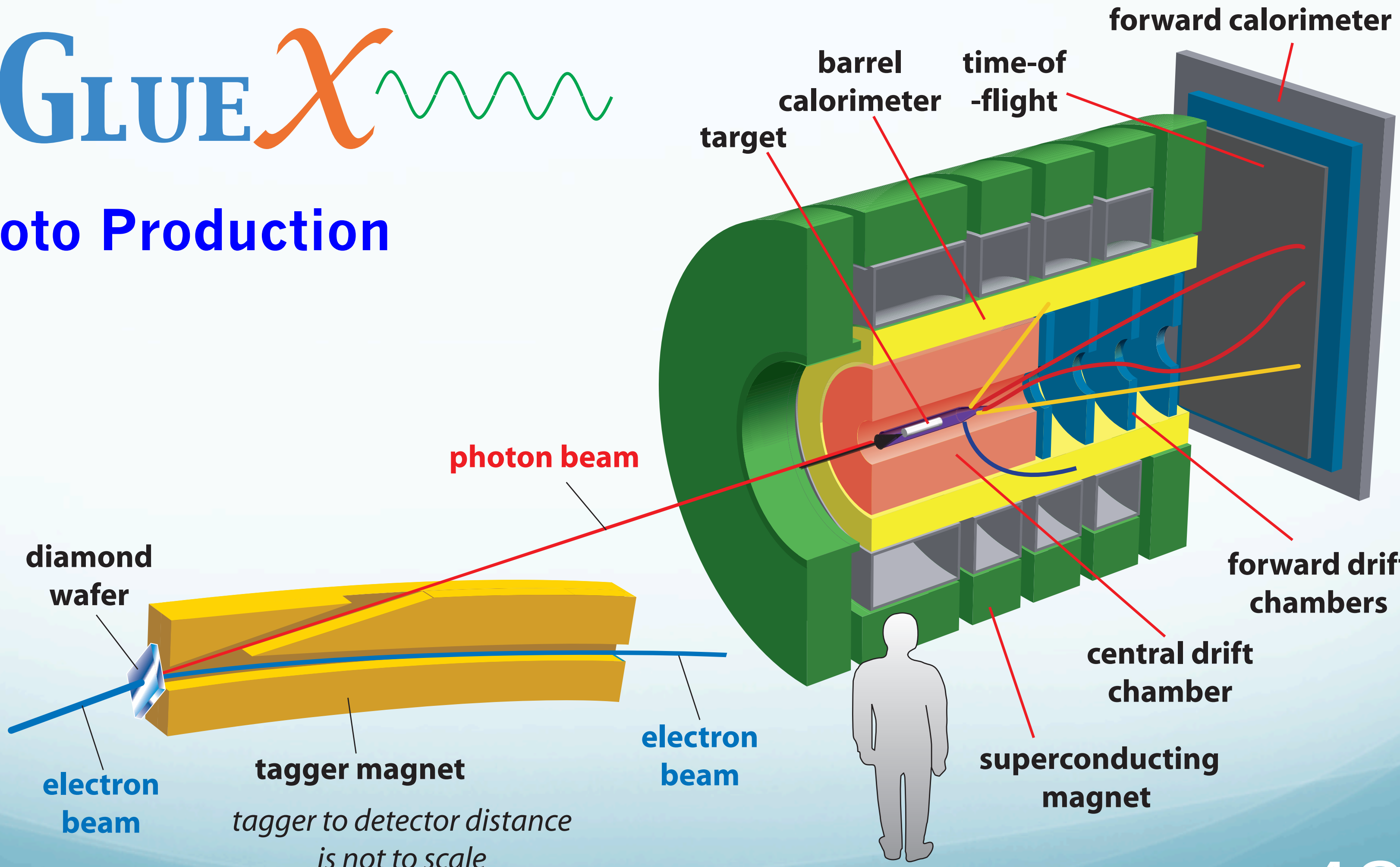
320M$ DOE finished in 2015
(I started in 1997)



The GlueX Experiment

GlueX

Photo Production

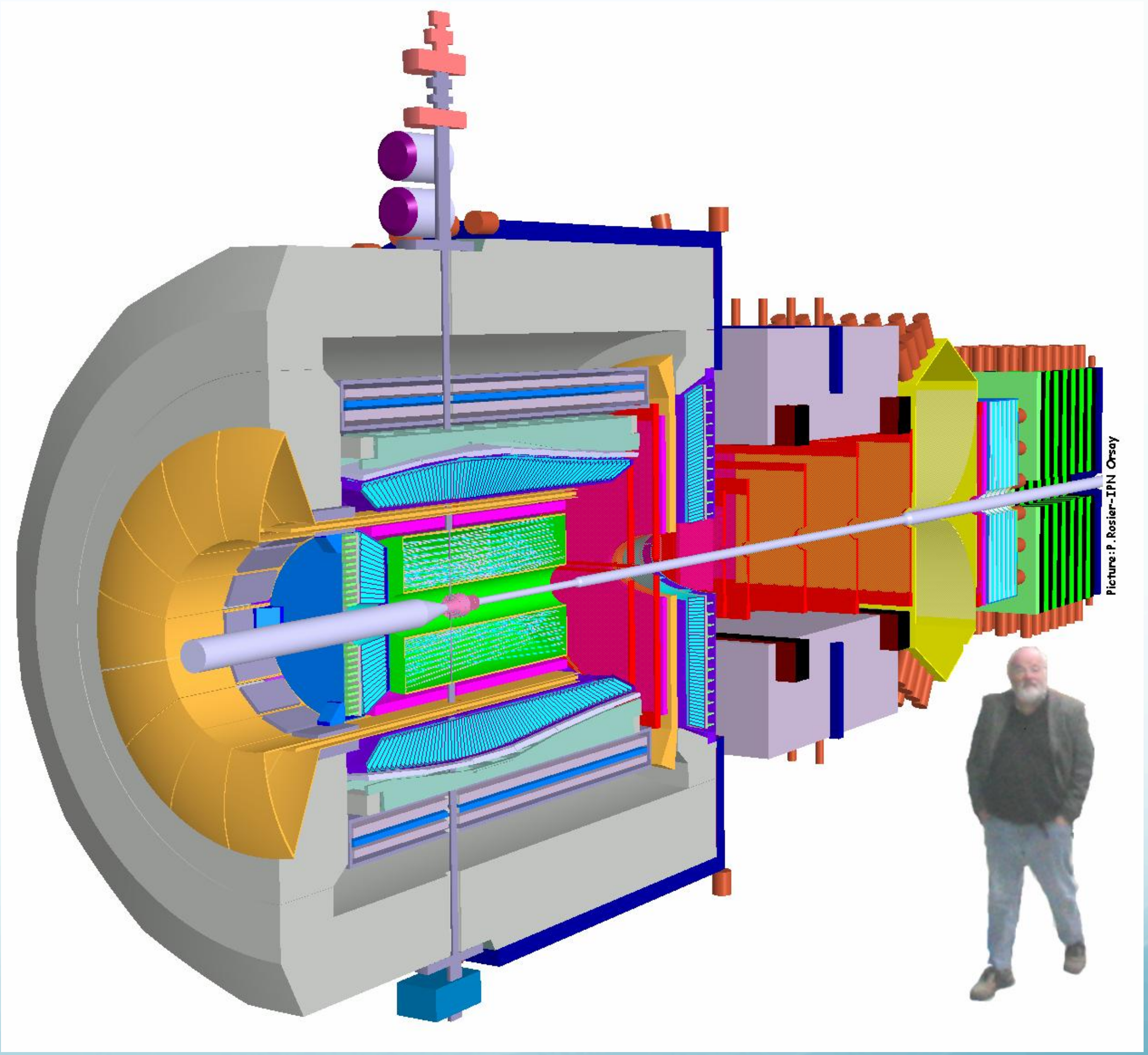


PANDA @ FAIR

$$\bar{p}p \rightarrow X(J^{PC})\pi$$

$c\bar{c}$ States

Glueballs



Physics in 2019?

Future Prospects:

- COMPASS at CERN collected a large data set in 2009. Analysis is underway.
- BES III in China has been running for over a year. Analysis on χ decays are looking for light-quark exotics.
- GlueX at Jefferson Lab will use photo-production to look for exotic mesons at Jefferson Lab. First physics in 2015.
- CLAS12 at Jefferson Lab will look at low-multiplicity final states in very-low Q**2 reactions, physics in 2018.
- PANDA at GSI will use antiprotons to search for charmed hybrid states physics in 2019.

The GlueX Program

Key enhancements for Phase IV running:

- Implementation of the level-3 (software) trigger.
- An order of magnitude more statistics than Phases I-III.

	Phase I	Phase II	Phase III	Phase IV
Duration (PAC Days)	30	30	60	200
Date of running (nominal)	2014	2015	2016	2017+
Minimum electron energy (GeV)	<10	11	12	12
Average photon flux (γ/s)	10^6	10^7	10^7	5×10^7
Average beam current (nA)	50-200	220	220	1100
Maximum beam emittance (mm-μr)	50	20	10	10
Level-1 (hardware) trigger rate (kHz)	2	20	20	200
Raw Data Volume (TB)	60	600	1200	2300