Experiment Overview on Meson Spectroscopy: Current and Future

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2014 Long-range plan Joint Town Meeting on QCD

Outline

- Mesons and Gluonic Excitations.
- Experimental Status.
- Jefferson Lab at 12-GeV.
- The Charm Sector.
- The International Scene.

Mesons and QCD

Bound states of quarks and glue with baryon number zero.

$q\bar{q}$ Mesons

$q\bar{q}g$ Hybrid mesons

$q\bar{q}q\bar{q}$ 4-quark states/molecules

$gg + ggg$ Glueballs

Characterize by $(I^G)J^{PC}$

Isospin (I) , G-parity,
Total Spin (J), Parity (P),
Charge Conjugation (C)

u, d, s, c and b quarks can form mesons.

``onium'' $s\bar{s}$ $c\bar{c}$ $b\bar{b}$

light-quark mesons: u, d, s

Beyond the Quark Model

Other configurations can be color-neutral:

- Hybrid Mesons where the gluonic field plays an active role.
- 4-quark states

Should we expect to see these?

MIT Bag Model – quarks confined to a finite space, add a TE gluon $J^{PC}=1^{+-}$.
This leads to four new nonets of "hybrid mesons" $\mathbf{1^{--}}$ $\mathbf{0^{-+}}$ $\mathbf{1^{-+}}$ and $\mathbf{2^{-+}}$.
Mass($\mathbf{1^{-+}}$) = 1.0 – 1.4 GeV

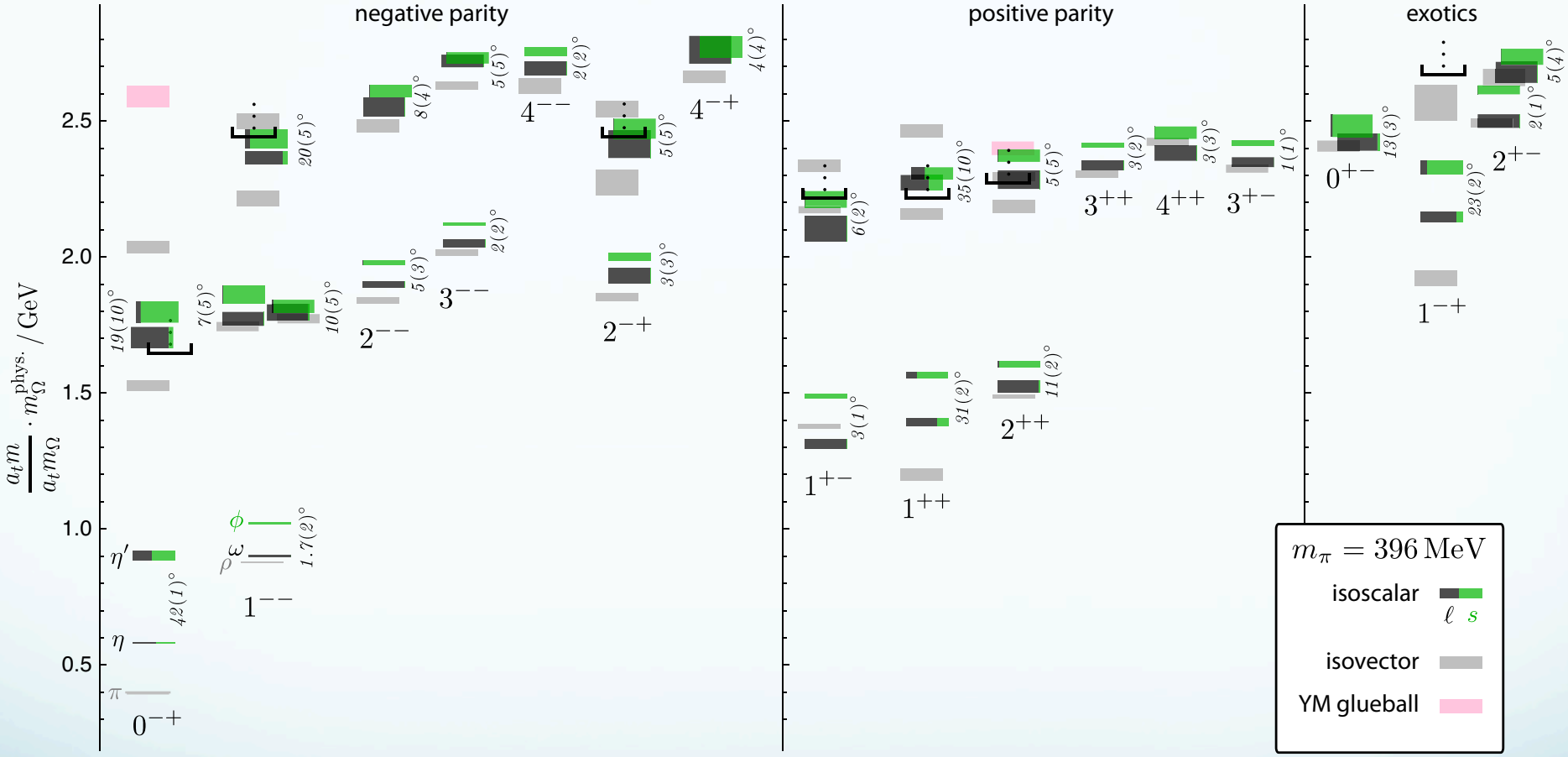
QCD spectral sum rules – a two-point correlator related to a dispersion relation. This predicts a $\mathbf{1^{-+}}$ hybrid meson.
Mass($\mathbf{1^{-+}}$) = 1.0 – 1.9 GeV

Flux-tube Model – model the gluonic field as 1^{+-} and 1^{-+} objects.
This leads to eight new nonets $\mathbf{0^{+-}}$ $\mathbf{0^{-+}}$ $\mathbf{1^{--}}$ $\mathbf{1^{++}}$ $\mathbf{1^{-+}}$ $\mathbf{1^{+-}}$ $\mathbf{2^{-+}}$ and $\mathbf{2^{+-}}$.
Mass($\mathbf{1^{-+}}$) = 1.8 – 2.0 GeV

QCD Coulomb Gauge Hamiltonian: Lightest hybrids not exotic, need to go to L=1 to get $\mathbf{1^{-+}}$ $\mathbf{3^{-+}}$ and $\mathbf{0^{--}}$.
Mass($\mathbf{1^{-+}}$) = 2.1 – 2.3 GeV

Lattice QCD

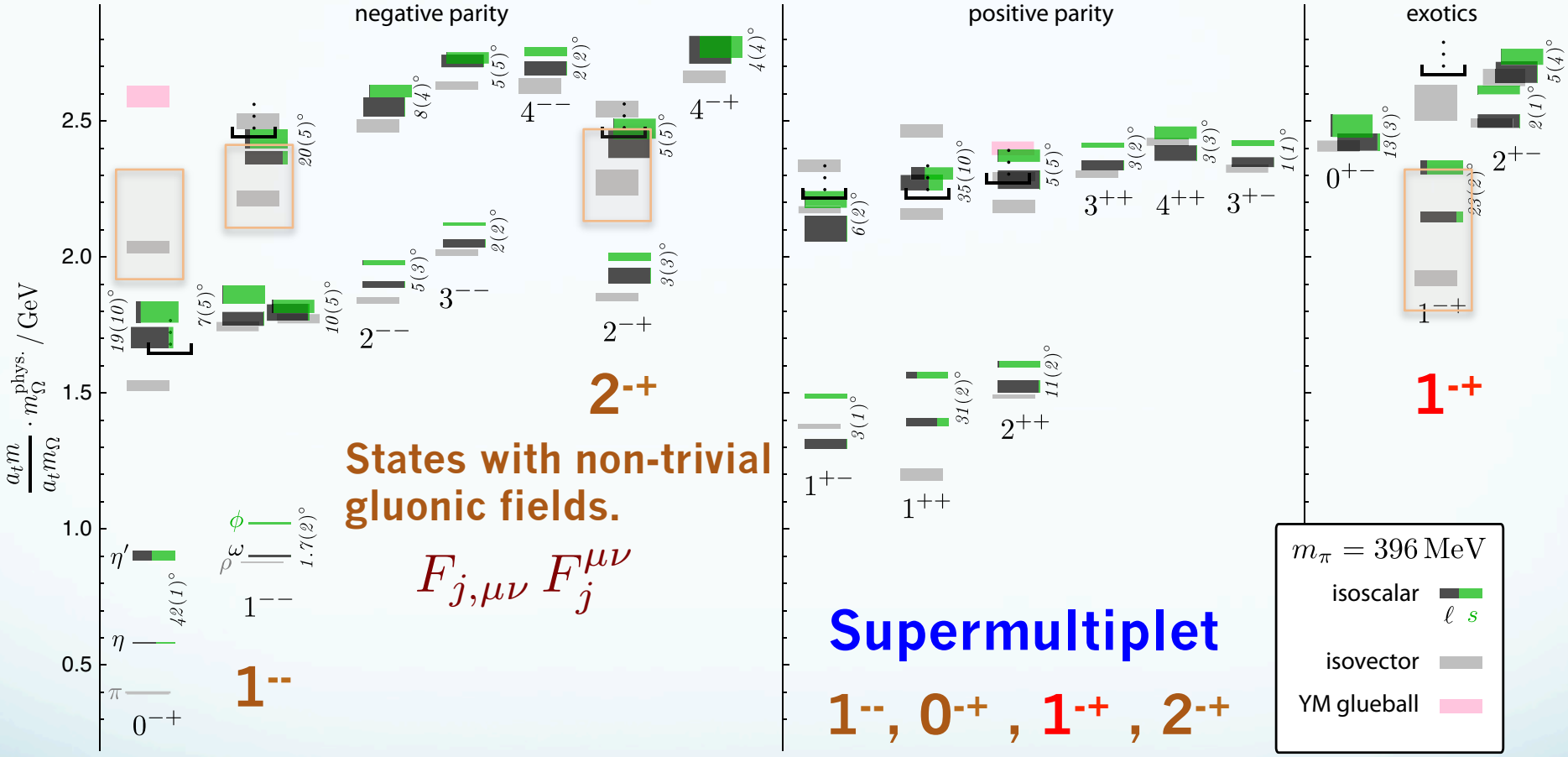
Light-quark Mesons (u,d,s)



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

Lattice QCD

Light-quark Mesons (u,d,s)



States with non-trivial gluonic fields.

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

2-+

1--

1-+

Supermultiplet

1--, 0-+ , 1-+ , 2-+

0-+

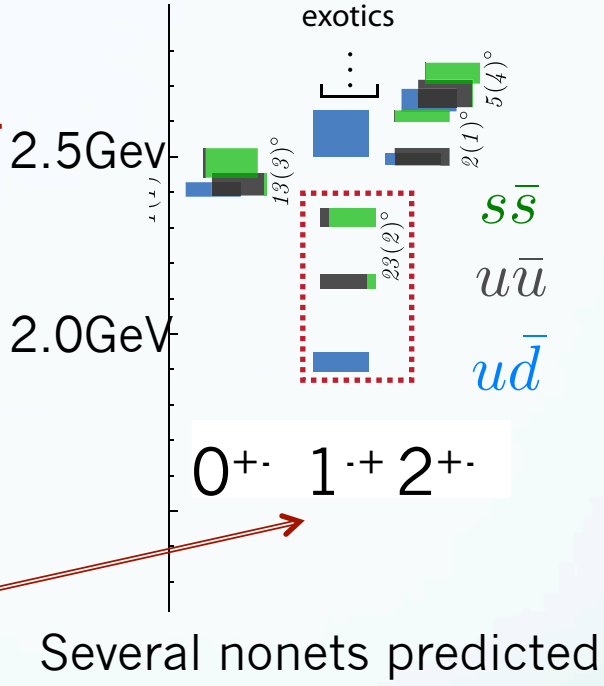
$$\frac{1}{\sqrt{2}}\left(u\bar{u} - d\bar{d}\right) \qquad \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \qquad \left(s\bar{s}\right)$$

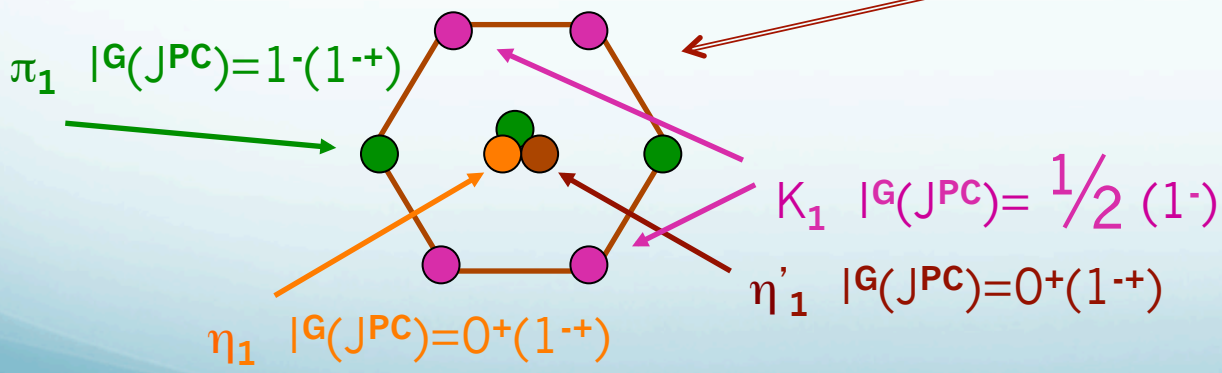
Spectroscopy and QCD

Phys. Rev. D84 (2011) 074023

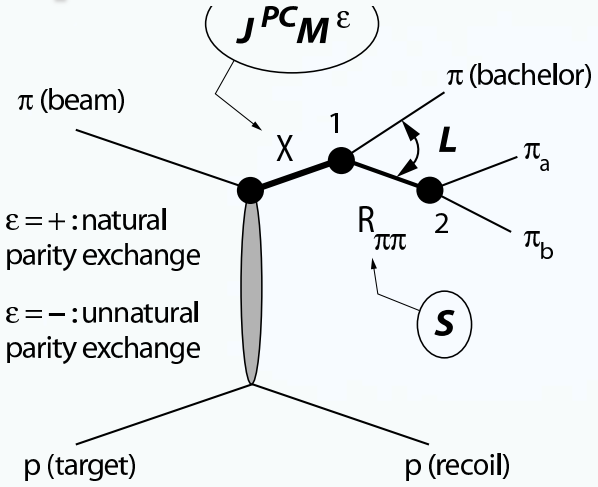
``Constituent gluon'' behaves like it has $J^{PC} = 1^{+-}$
Mass ~ 1-1.5 GeV
Lightest hybrid nonets: 1^{--}, (0^{-+},1^{-+}, 2^{-+})

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



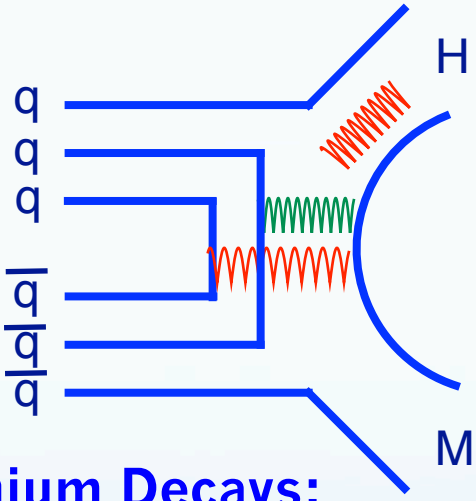


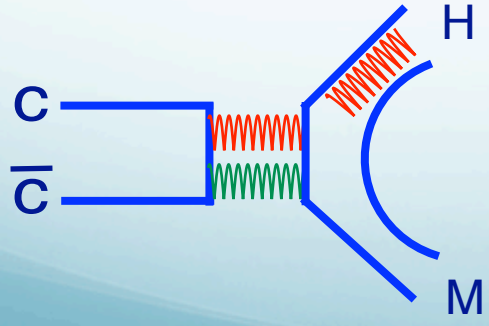
Experimental Evidence for Hybrids



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.





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.

Experimental Evidence for Hybrids

Pion peripheral production on nucleon and nuclear targets:

VES at Protvino
E852 at BNL
COMPASS at CERN

Largest statistics and most most decay modes studies.
Three π_1 states reported.

J/ψ Decays:

CLEO-c
BES-III

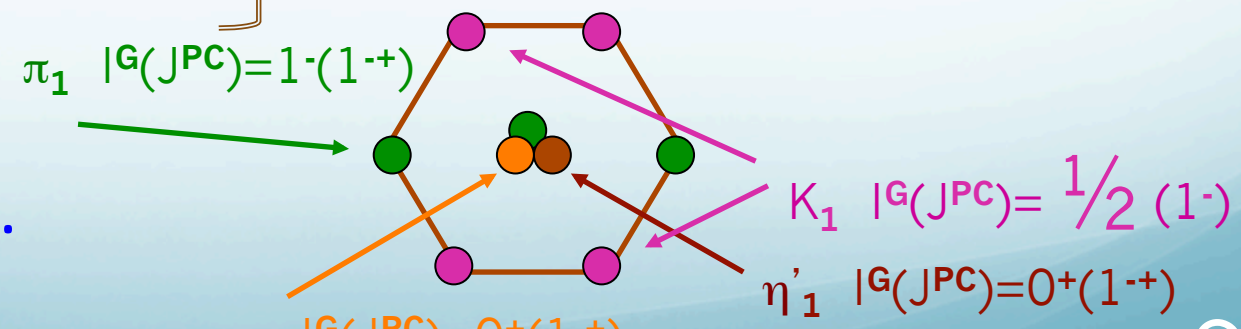
One decay mode studied.
One π_1 state reported.

Proton-antiproton annihilation at rest:

Crystal Barrel at LEAR
Obelix at LEAR

One π_1 state reported.

No η_1 or η_1' seen.

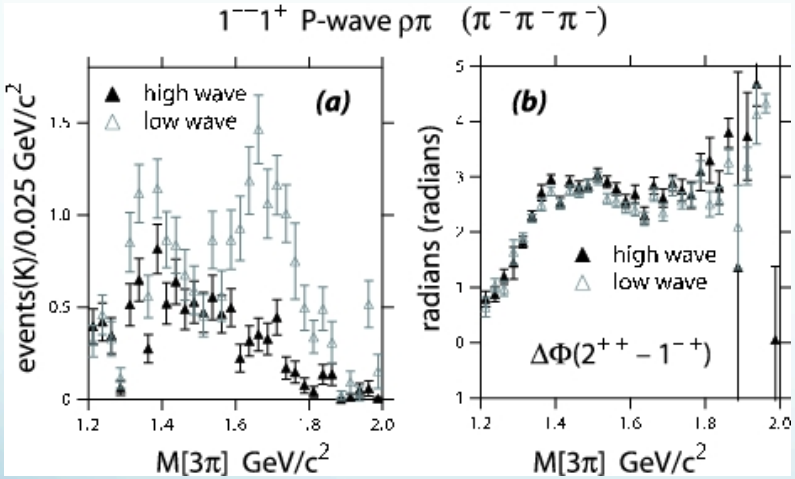


Experimental Evidence for Hybrids

$\pi_1(1600)$

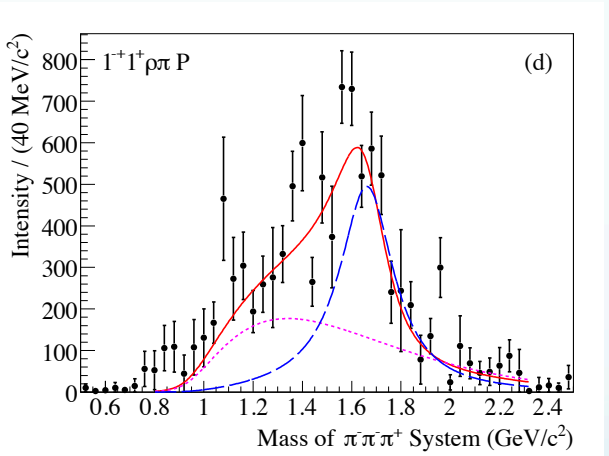
Mode	Mass	Width	Production
3π	$1598 \pm 8^{+29}_{-47}$	$168 \pm 20^{+150}_{-12}$	$1^+, 0^-, 1^-$ E852
$\eta'\pi$	$1597 \pm 10^{+45}_{-10}$	$340 \pm 40 \pm 50$	1^+ E852,VES,CLEO-c
$b_1\pi$	$1664 \pm 8 \pm 10$	$185 \pm 25 \pm 38$	$0^-, 1^+$ E852,VES,CBAR
$f_1\pi$	$1709 \pm 24 \pm 41$	$403 \pm 80 \pm 115$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

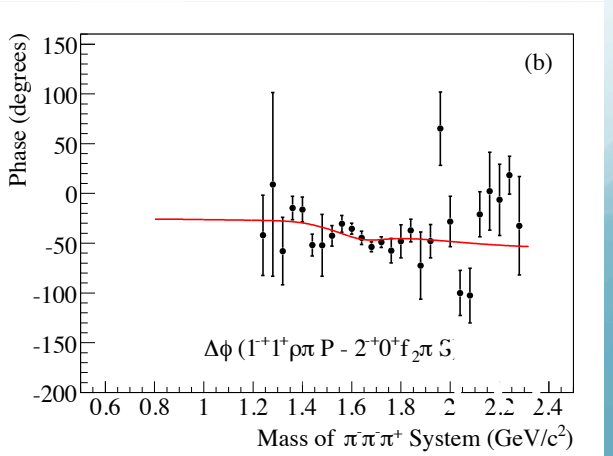
3π Decay mode sensitive to model



But not in COMPASS

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





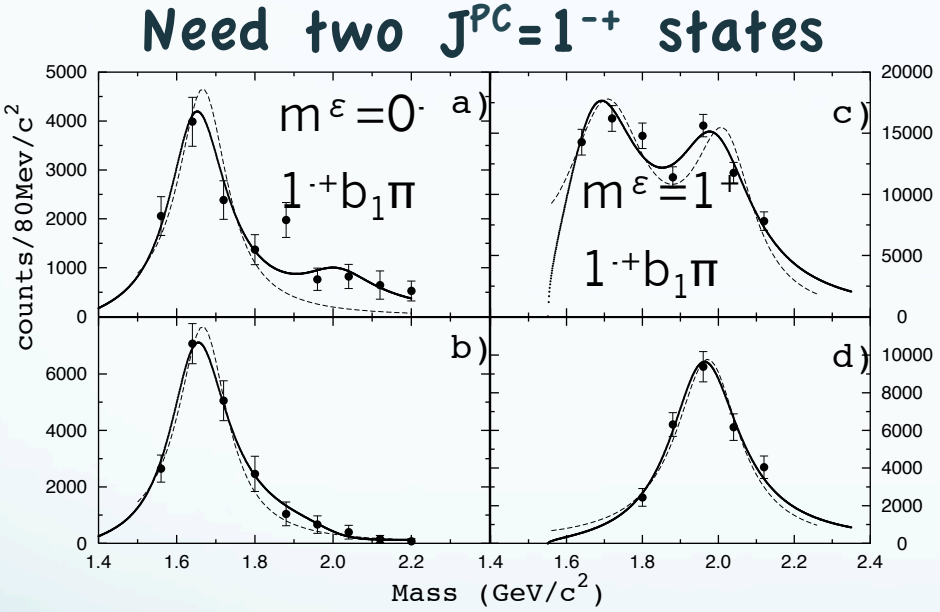
Confused production in E852??

This is consistent with a hybrid meson

Experimental Evidence for Hybrids

$\pi_1(2015)$

Mode	Mass	Width	Production	
$b_1\pi$	2014±20±16	230±32±73	1^+	E852
$f_1\pi$	2001±30±92	332±52±49	1^+	E852



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

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

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

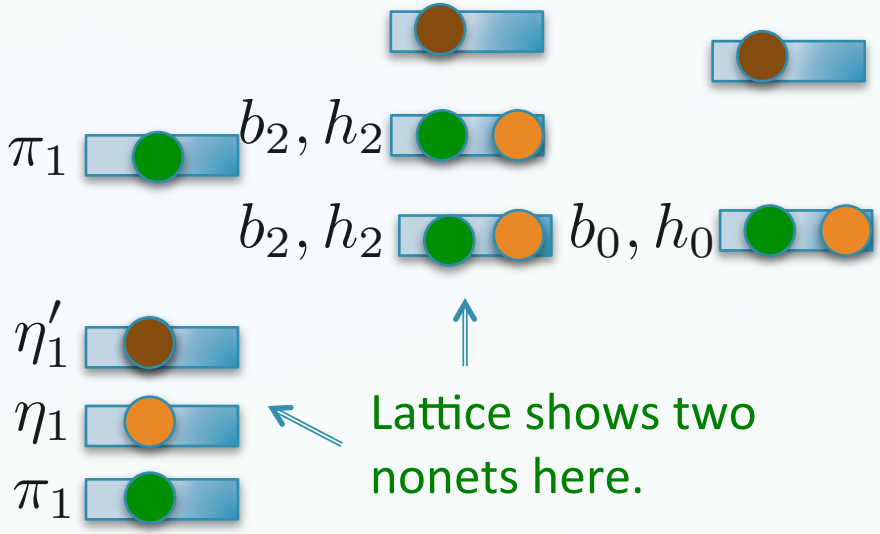
Seen primarily in natural parity exchange.

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.

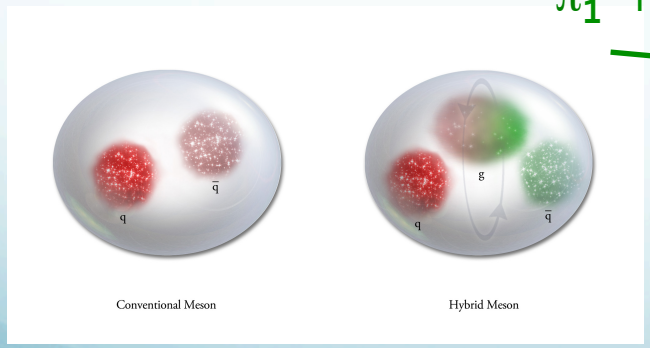
QCD Exotics

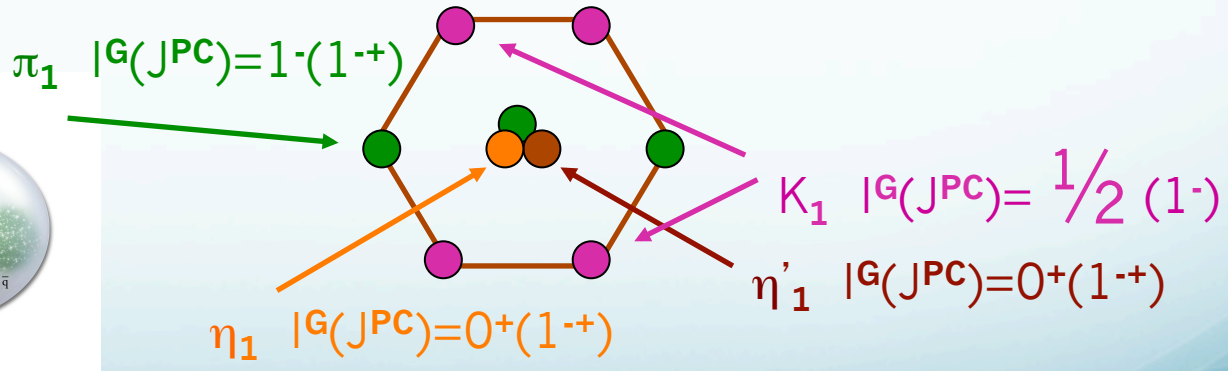
Lattice QCD suggests 5 nonets of mesons with exotic quantum number:



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

Experimental evidence exists for π_1 states.

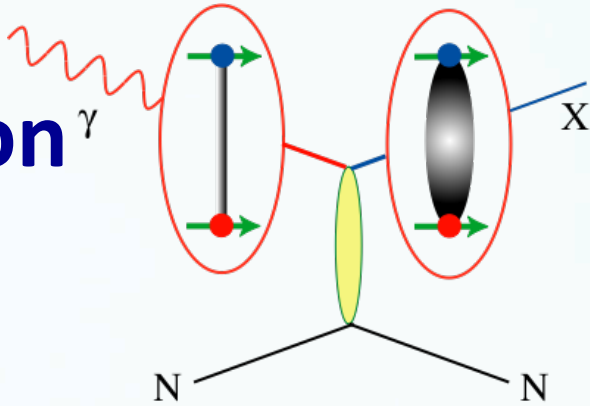


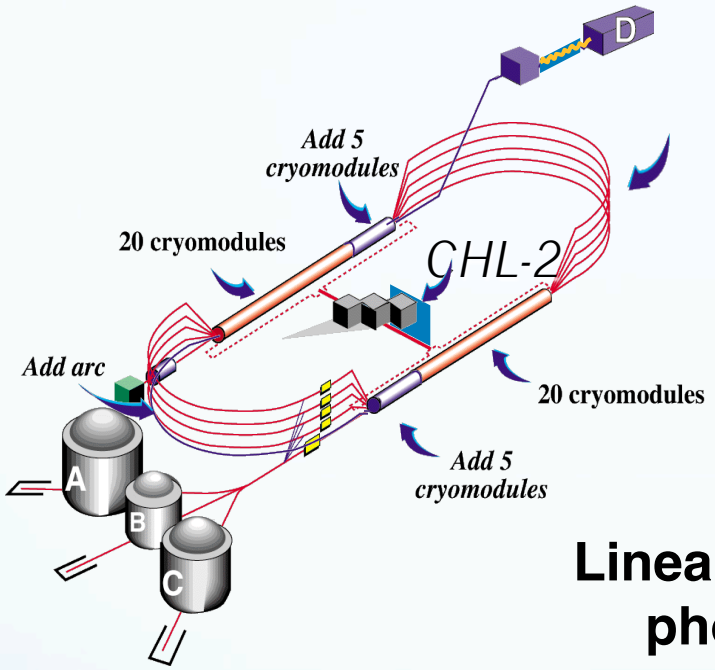


Making Progress

- Large and uniform acceptance detectors.
- Photon and charged particle reconstruction.
- Very high statistics.
- Multiple production mechanisms.
- Consistent analyses and theoretical support.
- Independent confirmation.

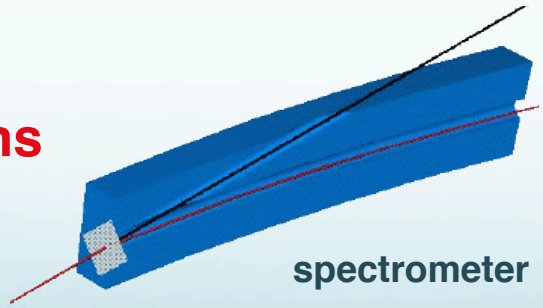
12-GeV CEBAF – Photoproduction





Linearly polarized photons out

12GeV electrons



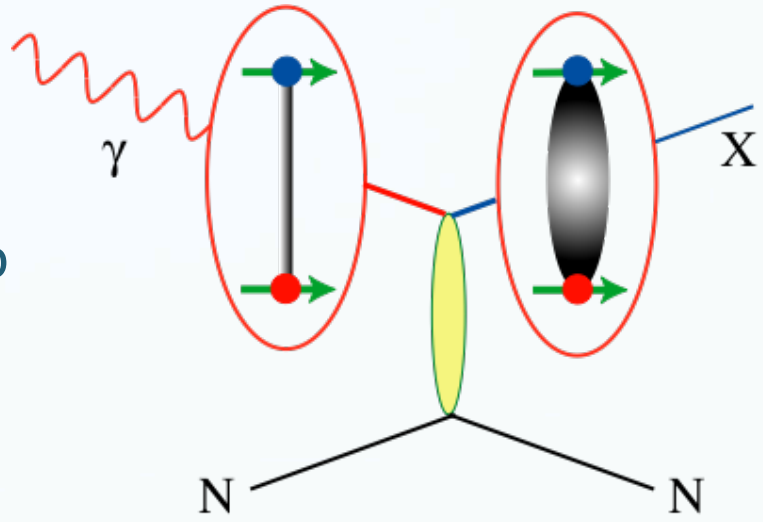
spectrometer

20 μm thick Diamond crystal

Experimental Evidence for Hybrids

Photo Production:

There are limited results from the **CLAS** at 6 GeV from Jefferson Lab. No π_1 that decays to $\rho\pi$ produced in π exchange.

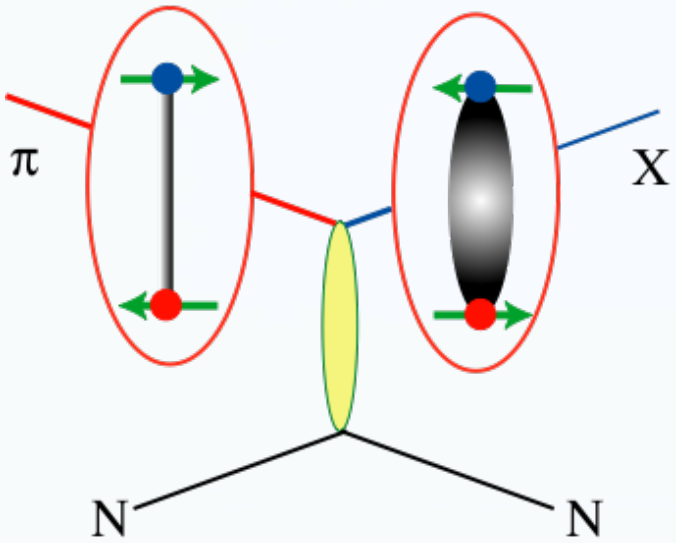


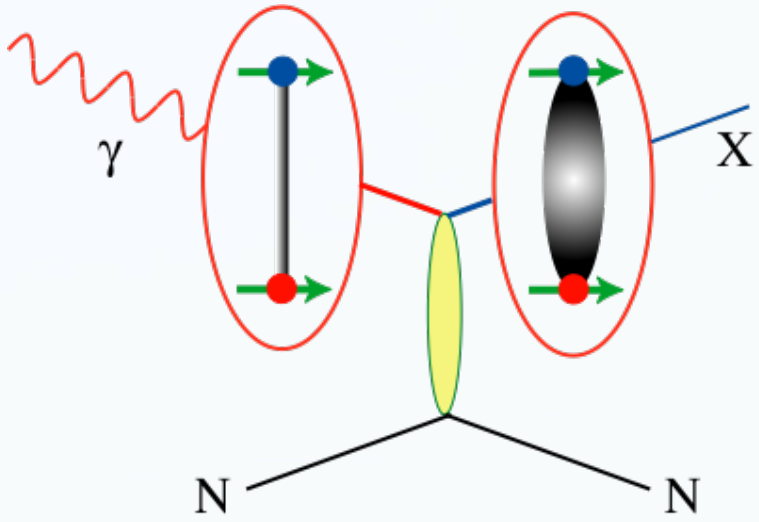
The **GlueX** experiment at Jefferson Lab will start physics in 2015. Double the photon energy, much better acceptance, linear polarization and higher rates.

Unexplored production mechanism.

Photoproduction

More likely to find mesons with spin-aligned quarks using photons.





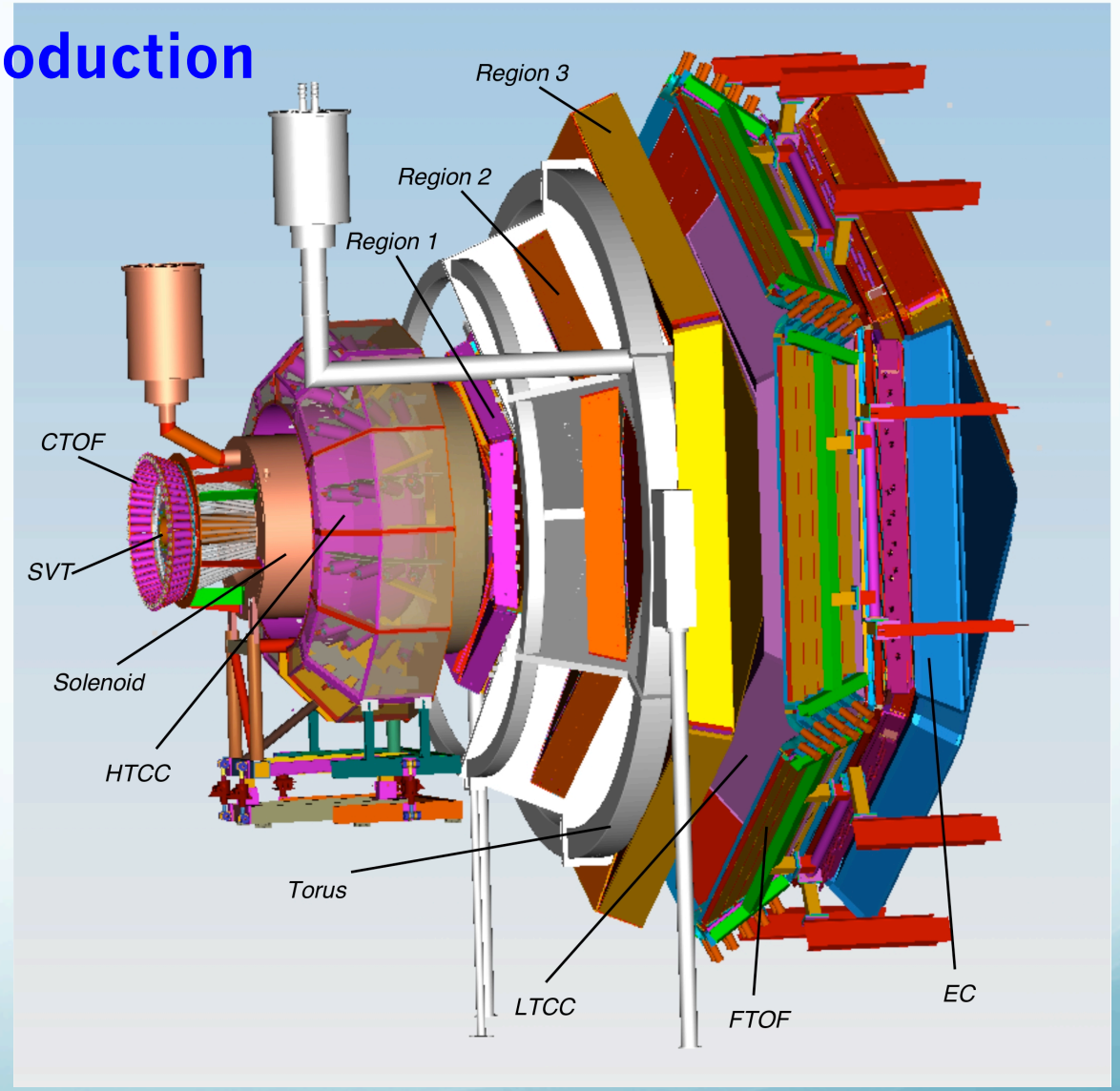
Simple (0^{++}) exchange with L=1: 0^{+-},1^{+-},2^{+-}
Simple (0^{-+}) exchange with L=1: 0^{-},1^{-},2^{-}
Simple (1^{--}) exchange with L=1: 0^{-+},1^{-+},2^{-+}

Dudek (2009) Radiative decays in charmonium to normal and hybrid mesons have comparable rates.

8.4-9 GeV tagged, linearly polarized photon beam, up to 10^8/s

The CLAS12 Experiment at Jefferson Lab

Quasi-Real Photo Production Light-quark Mesons

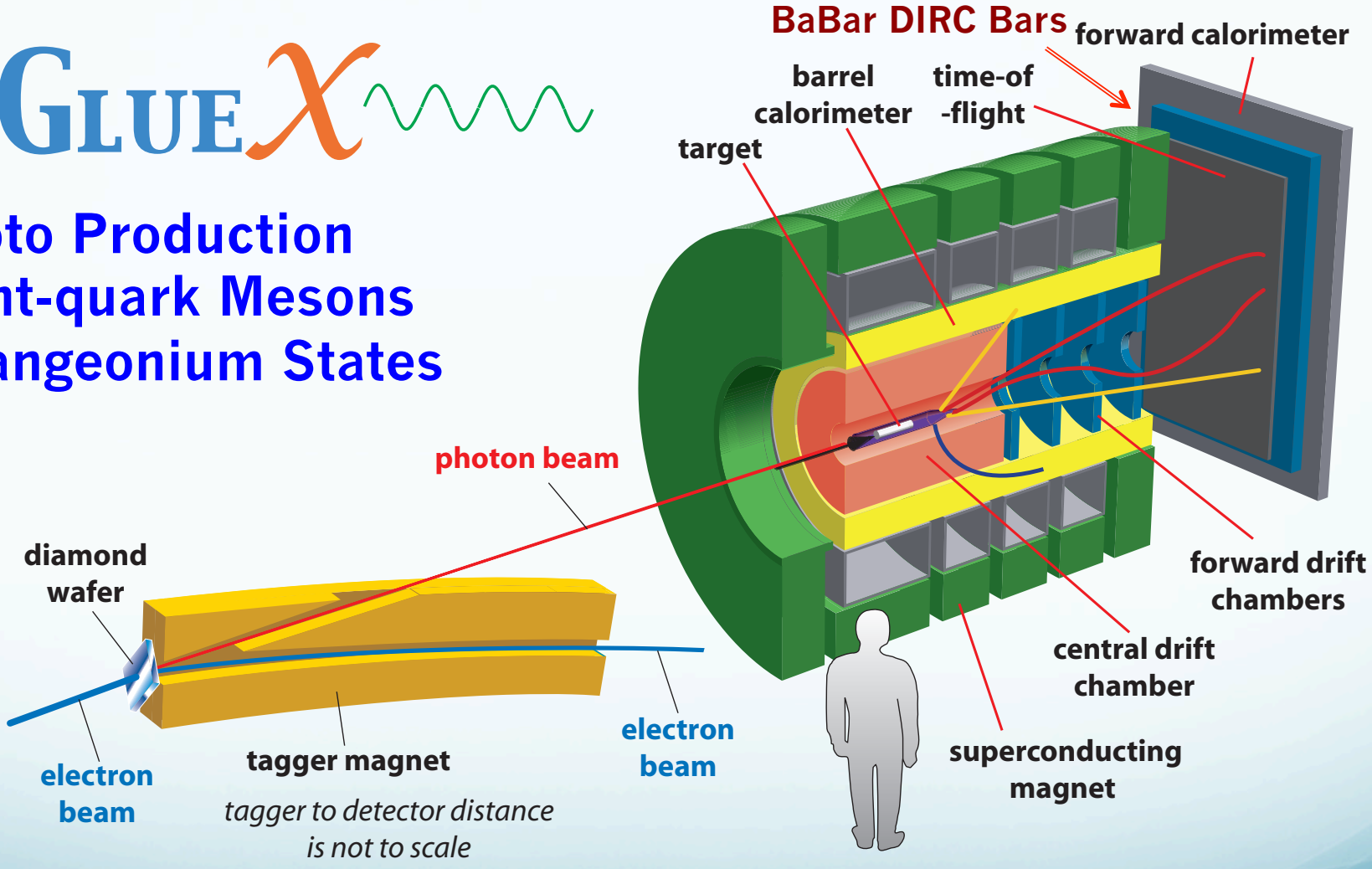


Physics in 2017

The GlueX Experiment at Jefferson Lab

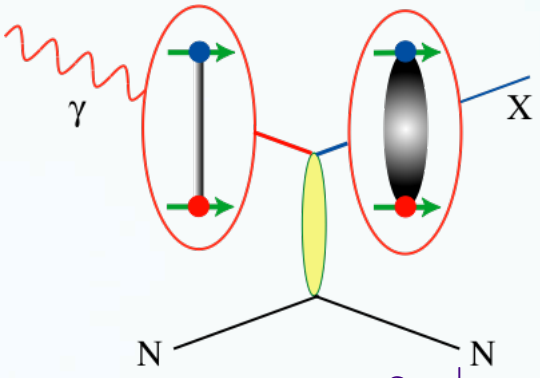
GLUEX

Photo Production
Light-quark Mesons
Strangeonium States



Physics in 2015

Expected Decay Modes



$\pi_1 \rightarrow \pi\rho,\ \pi b_1,\ \pi f_1, \pi\eta',\ \eta a_1$

$\eta_1 \rightarrow \eta f_2, a_2\pi, \eta f_1,\ \eta\eta',\ \pi(1300)\pi,\ a_1\pi,$

$\eta_1' \rightarrow K^*K,\ K_1(1270)K,\ K_1(1270)K,\ \eta\eta'$

$b_2 \rightarrow \omega\pi,\ a_2\pi,\ \rho\eta,\ f_1\rho,\ a_1\pi,\ h_1\pi,\ b_1\eta$

$h_2 \rightarrow \rho\pi, b_1\pi, \omega\eta,\ f_1\omega$

$h'_2 \rightarrow K_1(1270)K,\ K_1(1270)K,\ K_2^*K,\ \phi\eta,\ f_1\phi$

$b_0 \rightarrow \pi(1300)\pi,\ h_1\pi,\ f_1\rho,\ b_1\eta$

$h_0 \rightarrow b_1\pi,\ h_1\eta$

$h'_0 \rightarrow K_1(1270)K,\ K(1460)K,\ h_1\eta$

Early Reach **With Statistics** **Hard**

Kaons do not have exotic QN's

$n2\pi^+\pi^-$

$n\pi^+\eta$

$n2\pi^+\pi^-\pi^0$

$n2\pi^+\pi^-2\pi^0$

$p\pi^+\pi^-\pi^0$ $n2\pi^+\pi^-\eta$

$p\pi^+\pi^-\eta$ pK^+K^-

$p\pi^+\pi^-2\pi^0$ $pK^+K^-\pi^0$

$p\pi^+\pi^-3\pi^0$ $pK^+K^-\pi^+\pi^-$

$p2\pi^+2\pi^-$ $pK^+K^-\eta$

$p2\pi^+2\pi^-\pi^0$ $pK_SK^\pm\pi^\mp$

$p2\pi^+2\pi^-\eta$ $\Lambda K^+n\pi$

Amplitude Analysis

Describe the process of producing a particular final state as a set of possible amplitudes : $\mathcal{A}_j(\gamma p \to p\pi^+\pi^-\pi^0)$

E.g. $\mathcal{A}_1(\gamma p \to pX_i \to p\rho^+\pi^- \to p\pi^+\pi^-\pi^0)$

Build a total amplitude by coherently summing all the individual amplitudes. This total amplitude yields a probability that the given sum describes a particular event ``k''.

$\mathcal{N}$ is a normalization factor and a_j are complex coefficients.

$$P(e_k) = \frac{1}{\mathcal{N}} |\sum_j a_j \mathcal{A}_j(e_k)|^2$$

Form the likelihood and then minimize the natural log of it with respect to the a_j . This is a CPU-intensive problem $\ln \mathcal{L} = \sum_k \ln P(e_k)$ that we have found scales very well on graphical processor units (**GPUs**). To do this requires the four-vectors of all events plus a comparable Monte Carlo data sample to do the normalization.

GlueX Physics Analysis

Strong theoretical support from the Jefferson Lab and international theory community.

- Very strong and integrated presence at Jefferson Lab.
- Series of Workshops and Summer Schools.
- Strong desire work with the experimentalists.

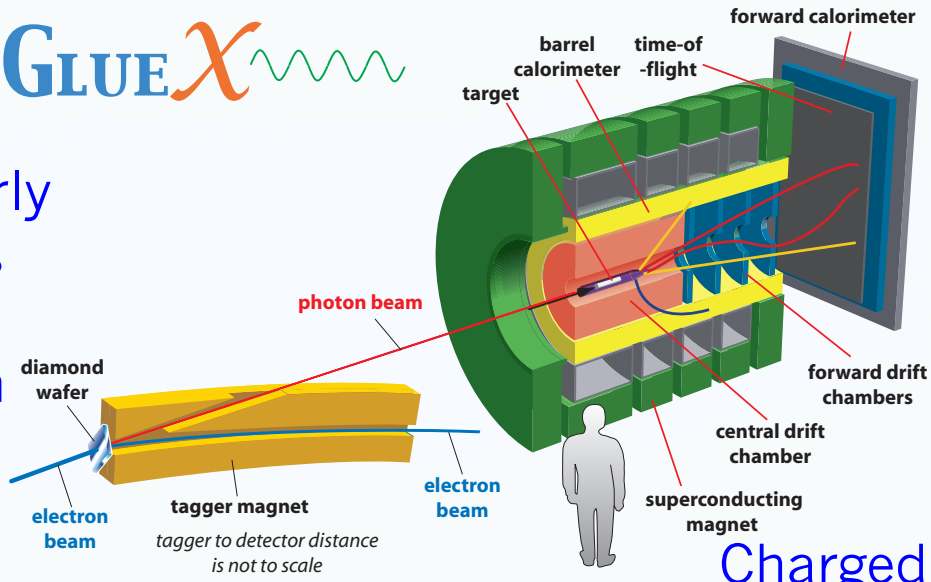
A strong Lattice QCD Effort.

- Important results on the meson spectrum that guide the experimental program.
- Ongoing work focused on production and decay.

Very important for the success of the entire program.

Physics in GlueX

8.4-9.0 GeV linearly polarized photons from 12 GeV electrons in a thin diamond wafer



Charged particle tracking + timing and photon detection in a 2T magnetic field.

$$\gamma p \to X(J^{PC})(p,n)$$
$$\pi_1(1^{-+}) \to \rho\pi \to \pi\pi\pi$$
$$h_0(0^{+-}), \pi_1(1^{-+}), h_2(2^{+-})$$
$$\to b_1\pi \to \omega\pi\pi \to 5\pi$$

$\pi^+\pi^-\pi^0 p$

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

$\pi^+\pi^-\pi^+\pi^-\pi^0 p$

$\pi^0\pi^0\pi^0\eta p$

Fully reconstruct final states

- These channels have been studied in Monte Carlo to understand the acceptance.
- These studies stress the offline reconstruction software.

GlueX Physics Analysis

GlueX ready to do physics, analyses being worked out in advance using the full suite of GlueX/Hall-D software and data from large-scale data challenges.

Physics reactions of interest:

Understand the detector

$\gamma p \to \pi^0 p$

$\gamma p \to \eta p$

$\gamma p \to \rho p$

$\gamma p \to \omega p$

$\gamma p \to \eta' p$

$\gamma p \to \phi p$

Initial exotic hybrid searches

$\gamma p \to \eta\pi(n,p)$

$\gamma p \to \eta'\pi(n,p)$

$\gamma p \to \rho\pi(n,p)$

$\gamma p \to \omega\pi(n,p)$

$\gamma p \to \omega\pi\pi(n,p)$

$\gamma p \to \eta\pi\pi(n,p)$

Strange Baryons

$\gamma p \to K^+\Lambda$

$\gamma p \to K\Sigma$

$\gamma p \to KK\Xi$

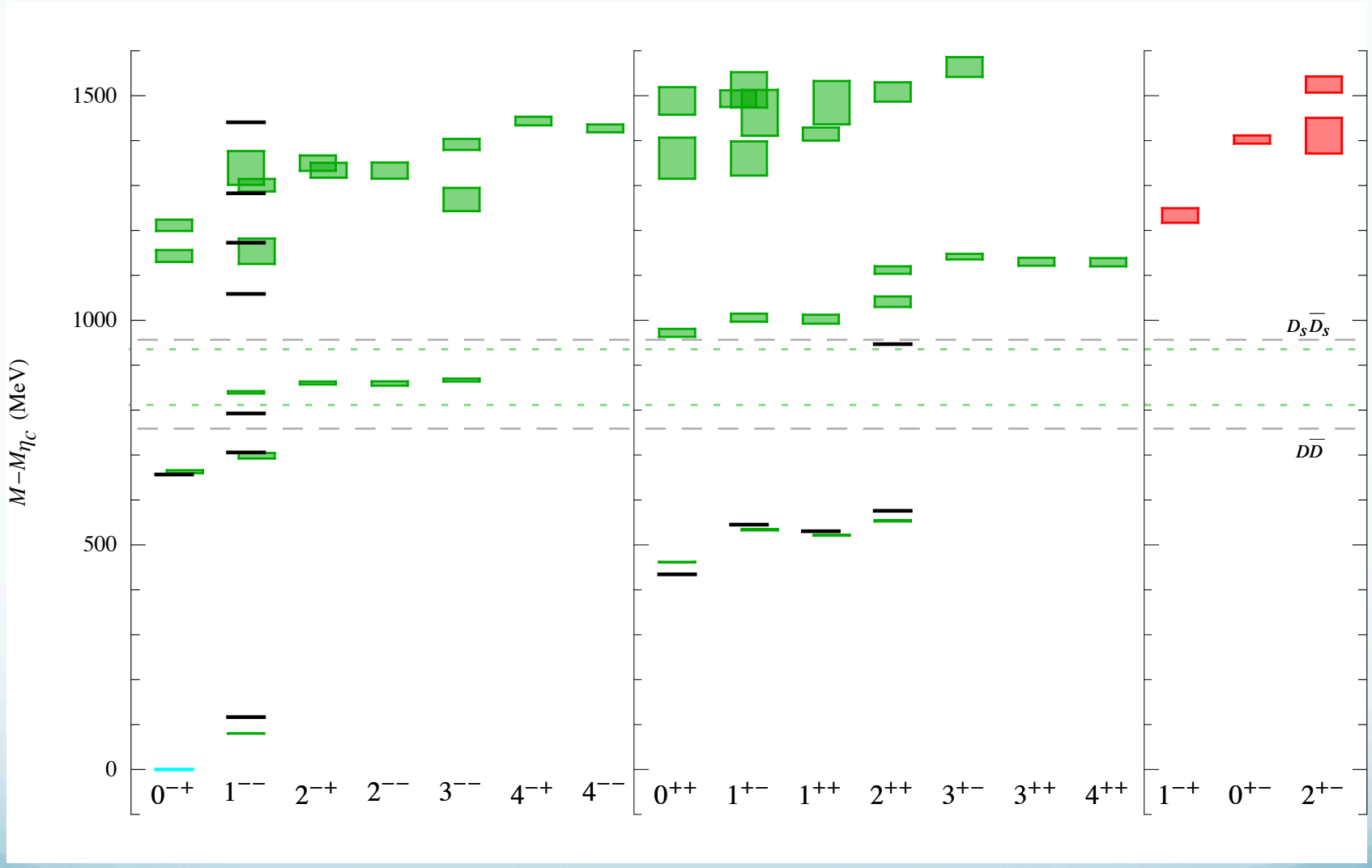
Activity in the physics working group has shifted to physics analysis.

Other Physics Interests

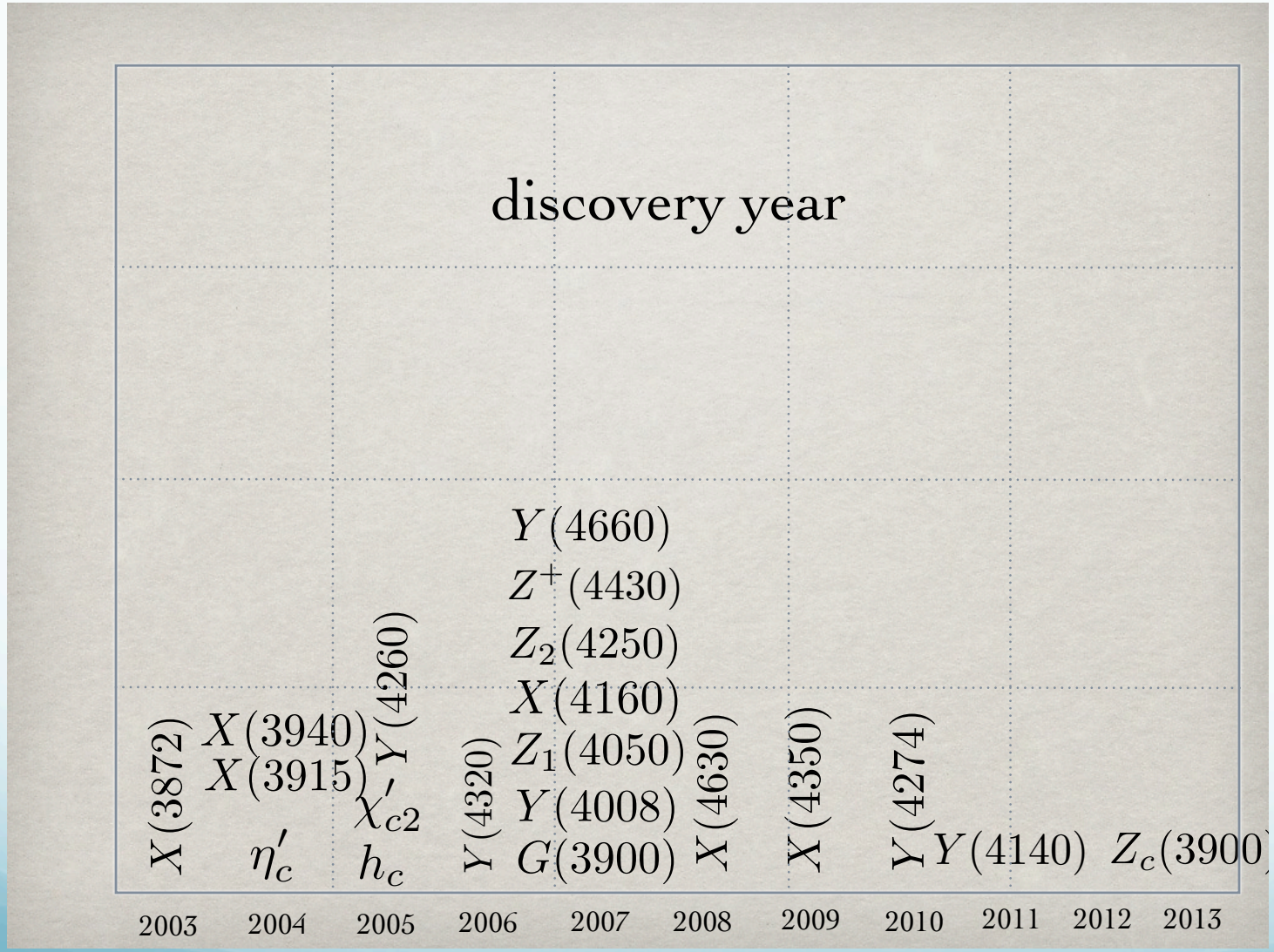
- η Decays
- η Primakov
- J/ψ Production
- ...

Lattice QCD

Charmonium States ($c\bar{c}$)



Charmonium: Many Discoveries



X $J^{PC} <> 1^{--}$

Y $J^{PC} = 1^{--}$

Z $c\bar{c}\pi^{\pm}$

Taken from E. Swanson hadron 2013

What are these States?

4-quark state

$$Z^-(4430) \to \psi' \pi^- \quad (c\bar{c}d\bar{u}) \quad J^P = 1^+$$

Non-exotic Hybrid?

$$Y(4260) \to \psi \pi^+ \pi^- \quad J^P = 1^{--}$$

Near DD* Threshold

$$X(3872) \to \psi \pi^+ \pi^- \quad J^P = 1^{++}$$

$$Z^{\pm}(3900) \to \psi \pi^{\pm} \qquad Z^{\pm}(4020) \to \eta_c \pi^{\pm}$$

What about strange-quark States?

Does something similar happen in the 2-GeV mass range for strangeonium states?

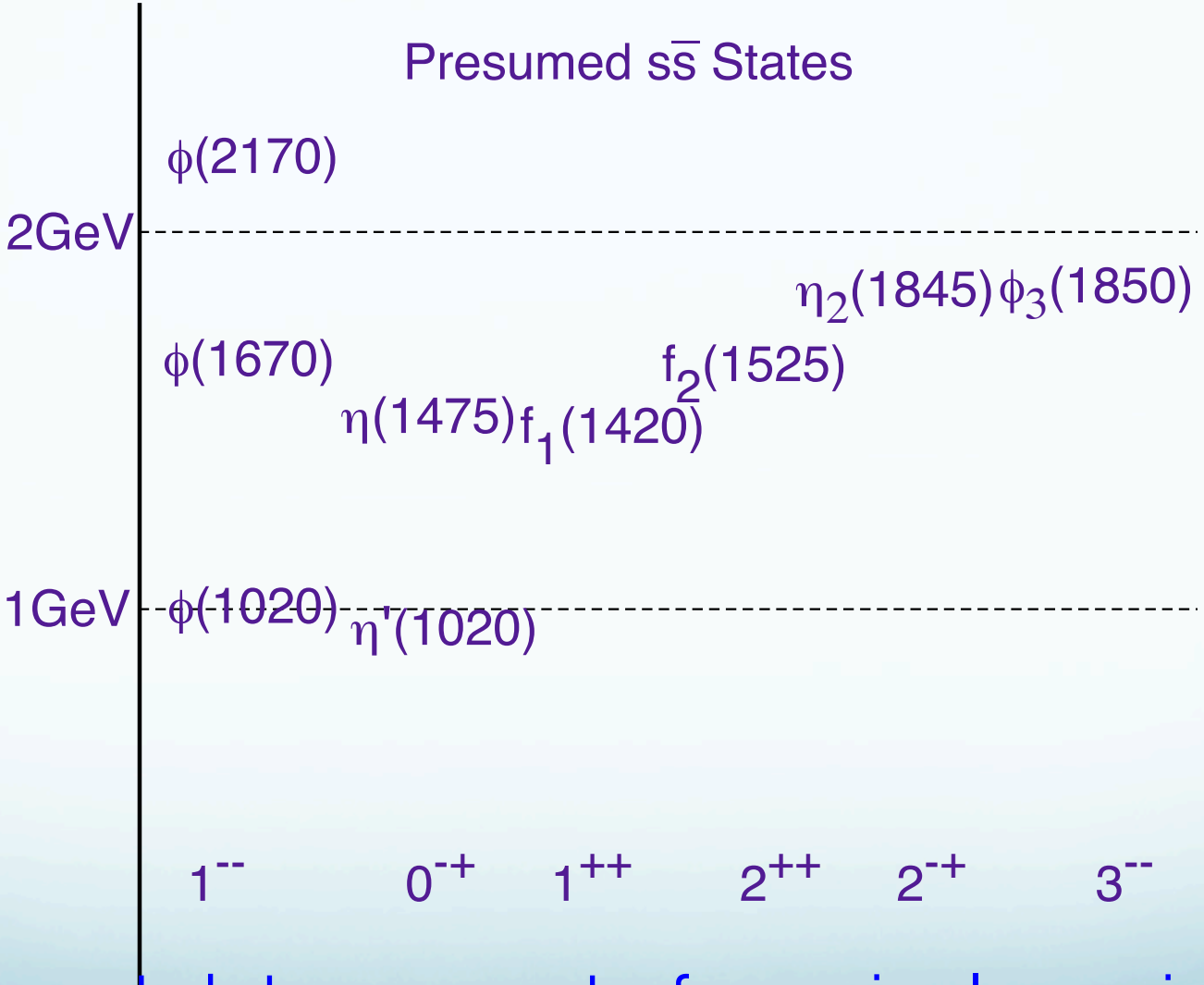
Non-exotic Hybrid?

$$Y(2170)/\phi(2170) \rightarrow \phi\pi^+\pi^-$$

Do ``Z'' states exist ?

$$Z^{\pm} \rightarrow \phi\pi^{\pm}$$

What about strange-quark States?

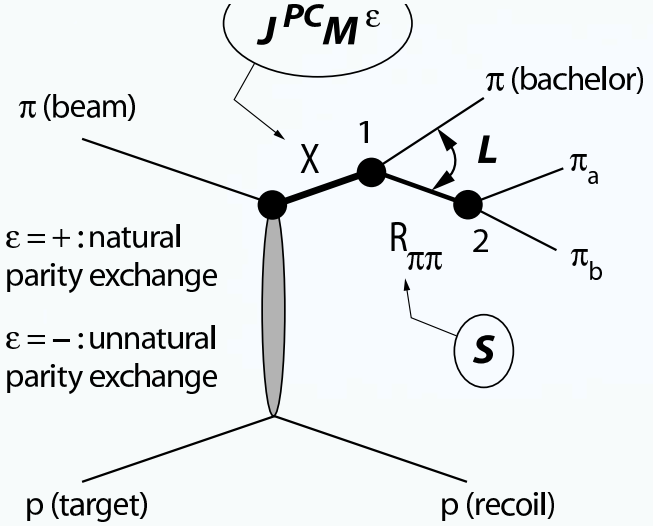


The relevant data are part of nominal running.

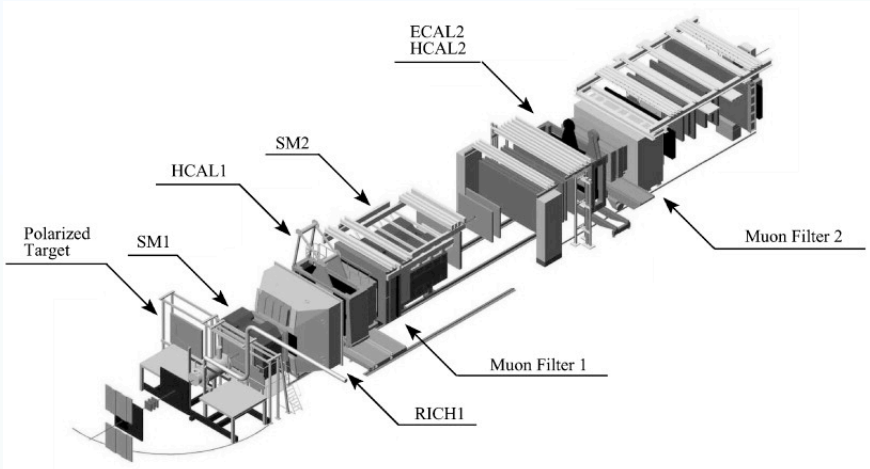
Experimental Program

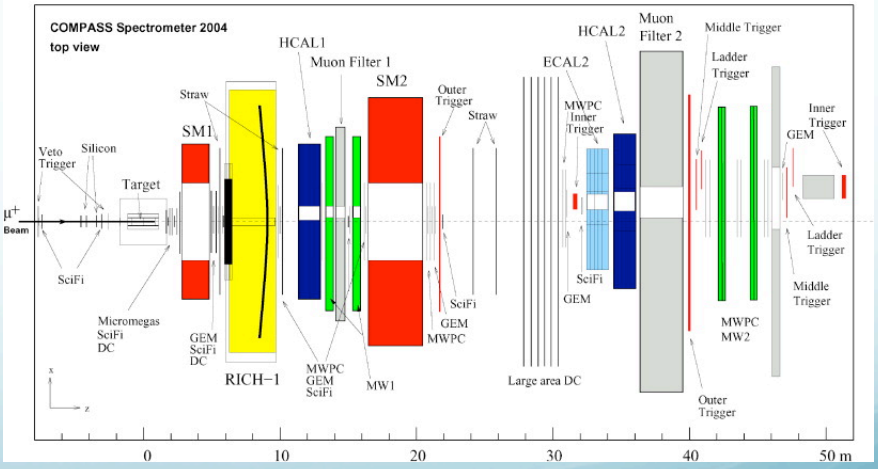
- Light-quark sector
  - COMPASS @ CERN (analyzing data)
  - GlueX @ 12-GeV Jefferson Lab (2015)
  - CLAS-12 @ 12-GeV Jefferson Lab (2017)
  - PANDA @ FAIR (2019)
- Charmonium – X,Y,Z states
  - BES III @ Bejing (now)
  - LHCb @ CERN (now)
  - PANDA @ FAIR (2019)

The COMPASS Detector at CERN



$$\pi^-(p, Pb) \rightarrow X(p, A)$$





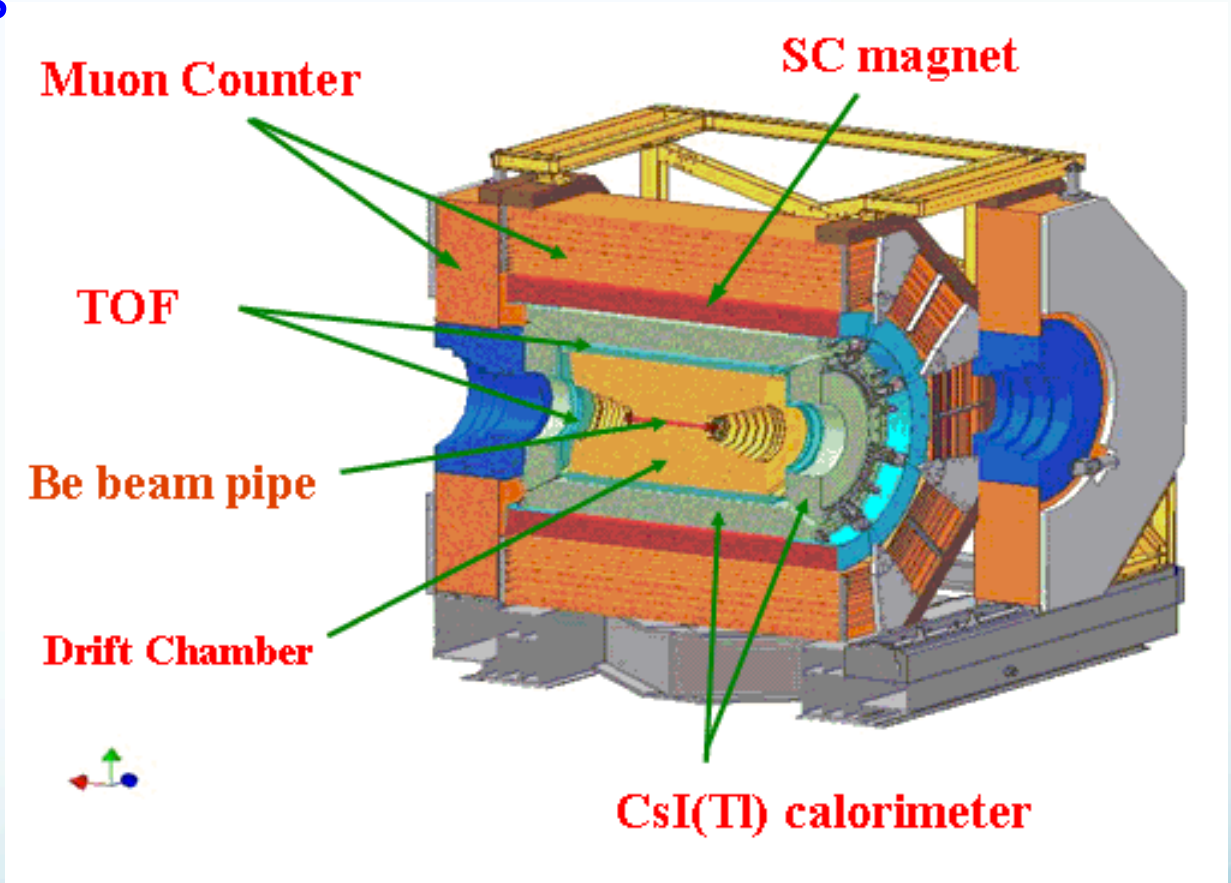
Light-quark Mesons

COMPASS: 180 GeV/c π beam. Detects photons and charged particles in the final state.

BES III in Beijing

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

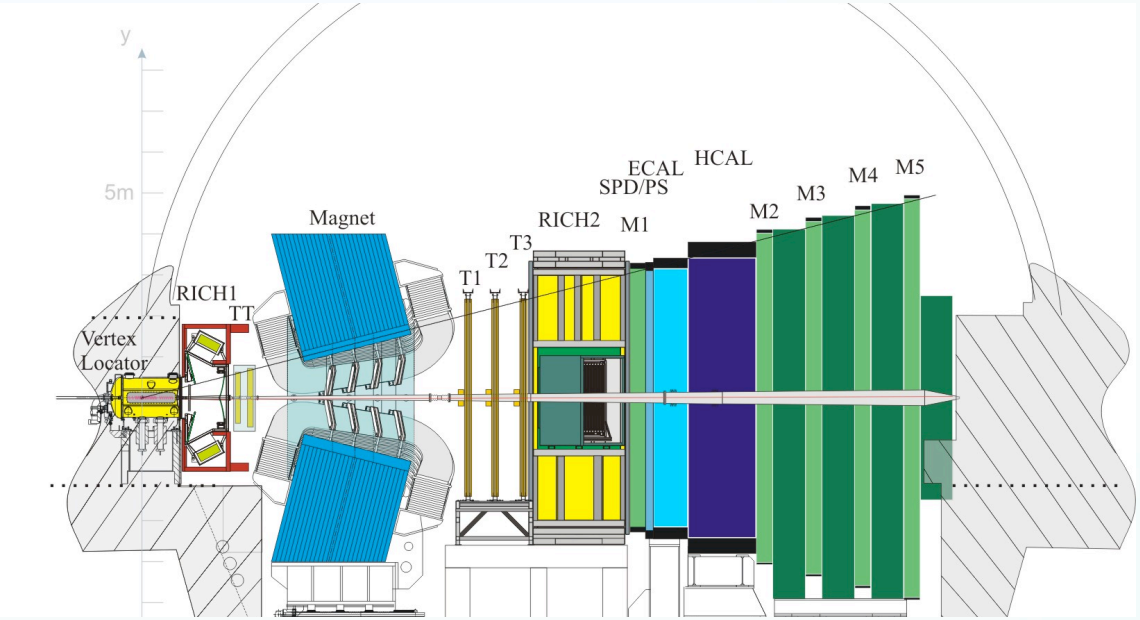
Charmonium States
Glueballs
X,Y,Z States



Running

The LHCb Experiment at CERN

X,Y,Z States

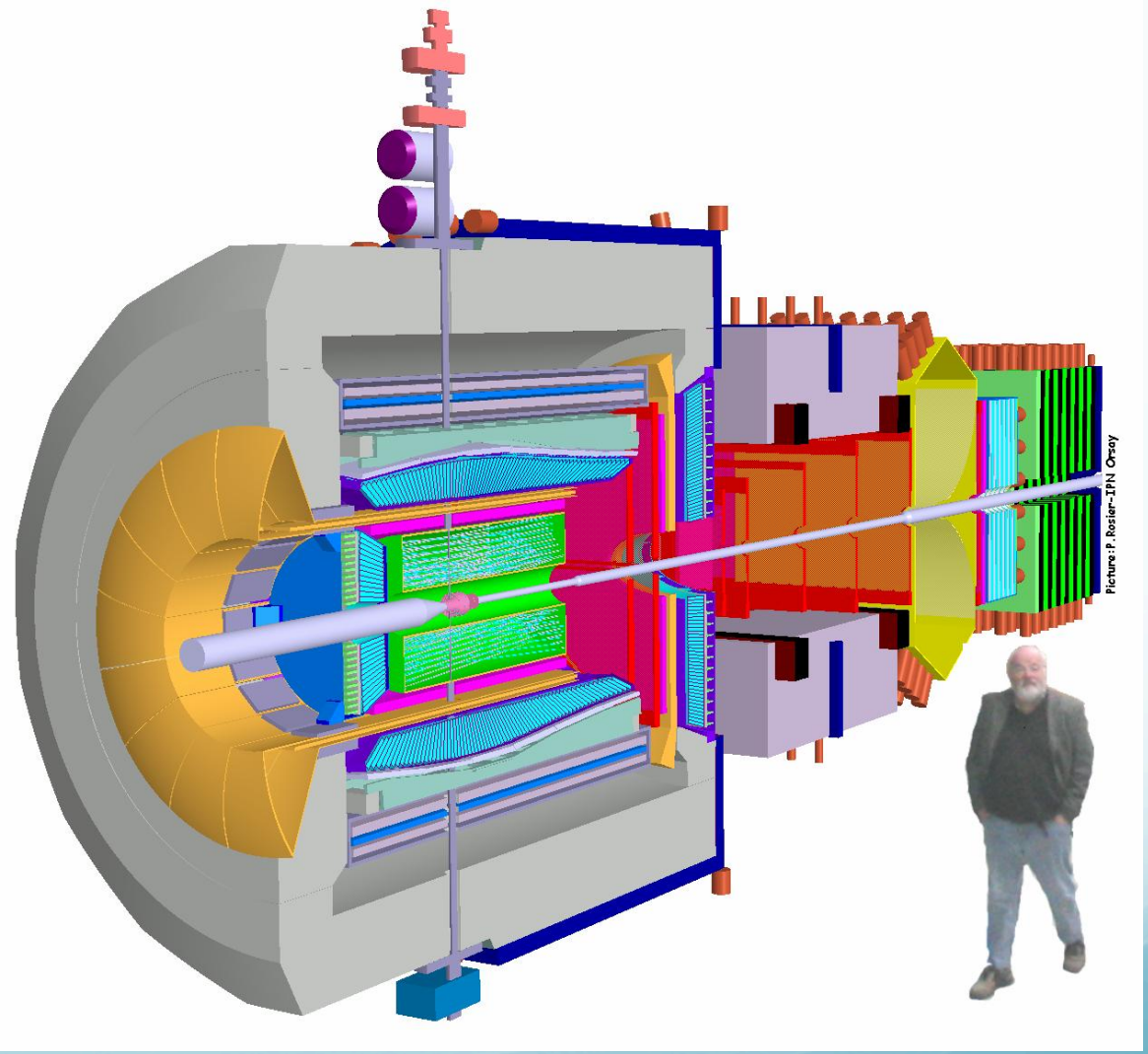


Running

PANDA @ FAIR

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

Light-quark Mesons
Charmonium States
Glueballs



Physics in 2019?

Summary

- Where are the QCD states with static glue?
- Photoproduction programs starting in 2015.
- Very exciting meson program over the next 10 years.
- Charmonium is very intriguing. Does it carry over to lighter quarks? Is it a heavy-quark phenomena?