Overview of Light Meson Spectroscopy

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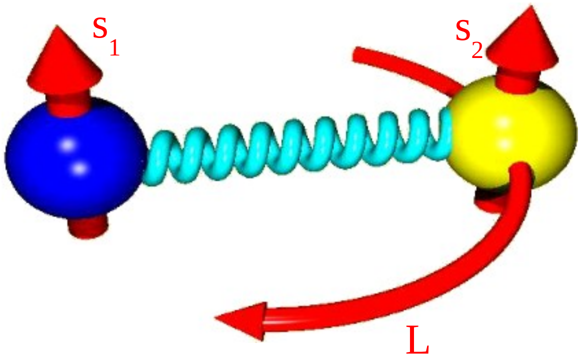
- quark model and beyond
- experimental techniques
- scalar mesons
- glueballs
- hybrid mesons
- future facilities

Quark Model Picture

Mesons = bound states of $q\bar{q}$



- Quark spins can be aligned or anti-aligned
  → couple to *total intrinsic spin* **S=0** or **S=1**
- Quark relative *orbital angular momentum* **L** couples with **S** to yield *total spin* **J=L⊕S**

- Mesons described by J^{PC} quantum numbers

Parity:	Charge conjugation (C-parity):
$\mathbf{P=(-1)^{L+1}}$	$\mathbf{C=(-1)^{L+S}}$

Allowed quantum numbers:
$0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{--}, 2^{-+}, 2^{++}, \ldots$

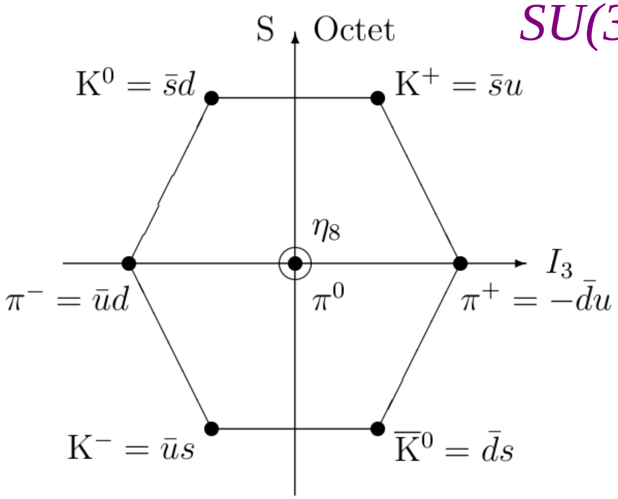
Disallowed: $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

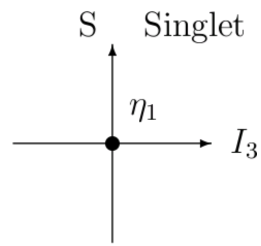
C-parity only defined for neutral states → *G-parity* $\mathbf{G=(-1)^{L+S+I}}$ for isospin I → frequently quantum numbers reported as $I^G J^{PC}$

Organization of Meson States

- Group into *flavor nonets*: e.g., pseudoscalars ($J^{PC}=0^{-+}$)

SU(3) symmetry





$$\eta_1 = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$$

$$\eta_8 = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

- Physical states η, η′ = admixture of η_1, η_8
  → mixing angle θ

$n^{2s+1}L_J$	J^{PC}	$I=1$	$I=\frac{1}{2}$	$I=0$	$I=0$
		$u\bar{d}\cdots$	$u\bar{s}\cdots$	f	f'
1^1S_0	0^{-+}	π	K	η	η'
1^3S_1	1^{--}	ρ	K^*	ω	ϕ
1^1P_1	1^{+-}	$b_1(1235)$	K_{1B}	$h_1(1170)$	$h_1(1380)$
1^3P_0	0^{++}	$a_0(1450)$	$K_0^*(1430)$	$f_0(1370)$	$f_0(1710)$
1^3P_1	1^{++}	$a_1(1260)$	K_{1A}	$f_1(1285)$	$f_1(1420)$
1^3P_2	2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2(1270)$	$f_2'(1525)$
1^1D_2	2^{-+}	$\pi_2(1670)$	$K_2(1770)$	$\eta_2(1645)$	$\eta_2(1870)$
1^3D_1	1^{--}	$\rho(1700)$	$K^*(1680)$	$\omega(1650)$	
1^3D_2	2^{--}		$K_2(1820)$		
1^3D_3	3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\omega_3(1670)$	$\phi_3'(1850)$
1^1F_4	4^{++}	$a_4(2040)$	$K_4^*(2045)$	$f_4(2050)$	
1^3G_5	5^{--}	$\rho_5(2350)$			
1^3H_6	6^{++}	$a_6(2450)$		$f_6(2510)$	
2^1S_0	0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1295)$	$\eta(1475)$
2^3S_1	1^{--}	$\rho(1450)$	$K^*(1410)$	$\omega(1420)$	$\phi(1680)$

Beyond the $q\bar{q}$ picture for mesons

- QCD: quarks are confined, force mediated by *gluons*, but no explicit "glue" in naive quark model...
- QCD Lagrangian:

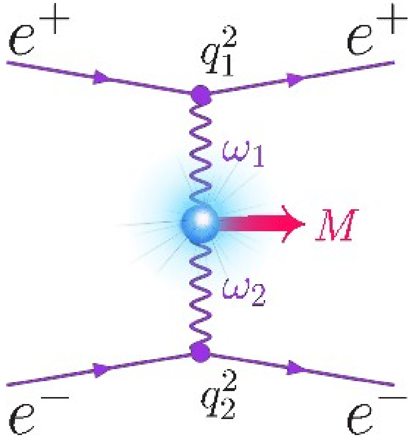
$$\mathcal{L}_{QCD} = \bar{q}_i(i\partial_\mu\gamma^\mu\delta_{ij} + g\frac{\lambda^a_{ij}}{2}A^a_\mu\gamma^\mu - m\delta_{ij})q_j - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu}$$

  - Gluons carry "color charge" $\rightarrow$ can interact with each other
  - Gluons not necessarily in ground state

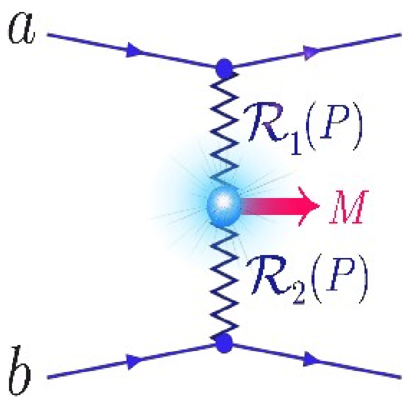
Non-$q\bar{q}$ combinations are possible:
$qq\bar{q}\bar{q}$, $q\bar{q}g$, glueballs (pure glue), ...

Experimental Techniques

Two-photon fusion



(hadronic) Central production



Pomeron exchange: "glue rich"

- Glueballs: look for observation of state in central production, non-observation (or reduced coupling) in two-photon fusion...

Gluiness:

$$G = \frac{9e_Q^4}{2}\left(\frac{\alpha}{\alpha_s}\right)^2 \frac{\Gamma_{R\to gg}}{\Gamma_{R\to\gamma\gamma}}$$

*Expect **G~1** for $q\bar{q}$ states*

Experimental Techniques II

- J/ψ decays: $e^+e^- \to J/\psi \to \gamma h$, VX
  - Flavor tagging: use vector meson V(=ω,ϕ) to tag X
  - Radiative decay: if $h \neq \eta_c$, $J/\psi \to \gamma gg$ to first order in perturbative QCD

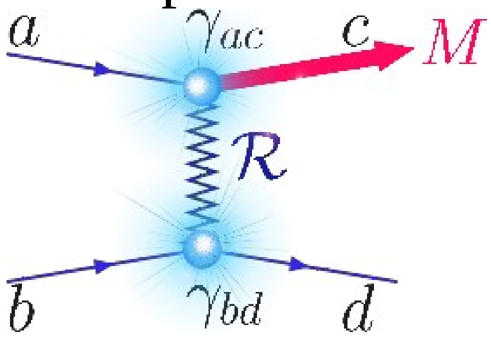
Stickiness:

$$S = C \left(\frac{M(h)}{k_\gamma} \right)^{2l+1} \frac{\Gamma(\psi \to \gamma h)}{\Gamma(h \to \gamma\gamma)}$$

Large for glueballs compared to $q\bar{q}$

- $p\bar{p}$ annihilation

- Peripheral production



- Exchange Reggeon with target, leaving target (essentially) intact
  - For example: $\pi^- p \to p \eta \pi^-$
- Tend to be forward-peaked (~exponential t-dependence)

Partial Wave Analysis

- Meson spectrum: many overlapping resonances (whose quantum numbers we want to determine) that could interfere ⇒ "bump hunting" not sufficient ⇒ *Amplitude-level analysis*
- Intensity:

$$I(\Omega) = \sum_{\alpha} \left| \sum_{\beta} V_{\alpha,\beta} A_{\alpha,\beta}(\Omega) \right|^2$$

$A(\Omega)$ = Resonance Angles
× Isobar Angles
× Isobar Breit Wigner

  - Fit for complex parameters $V_{\alpha,\beta}$ = weights for partial waves with definite J^{PC} values
- Unbinned extended likelihood fit:
  - Minimize

$$-2\ln(L) = -2\sum_{data} \ln(I(\Omega_i)) + 2\sum_{MC} I(\Omega_i)$$

Scalar Mesons

$J^{PC}=0^{++}$

- Lowest mass scalar mesons:
  - $f_0(600)$[“σ”]: low-mass ππ S-wave enhancement
  - $K^*_0(800)$[“κ”]: low-mass Kπ enhancement, Γ~500 MeV
  - $a_0(980)$[“δ”], $f_0(980)$[“S^*”]: close to $K\bar{K}$ threshold, large coupling to $K\bar{K}$
    - $K\bar{K}$ molecules? $qq\bar{q}\bar{q}$ tetra-quark states?
    - Fock components: $|a_0(980)^+>=\alpha|u\bar{d}>+\beta|u\bar{d}s\bar{s}>+\gamma|K^+\bar{K}^0>\cdots$
- Jaffe: $\{f_0(600),K^*_0(800),a_0(980),f_0(980)\}$=nonet of tetra-quark states
- Minkowski&Ochs: $\{a_0(980),f_0(980),K^*_0(1430),f_0(1500)\}$=$q\bar{q}$ nonet
  - $f_0(600)$ and $f_0(1370)$ part of background amplitude (“red dragon” → glueball?), *not genuine resonances*

Glueballs

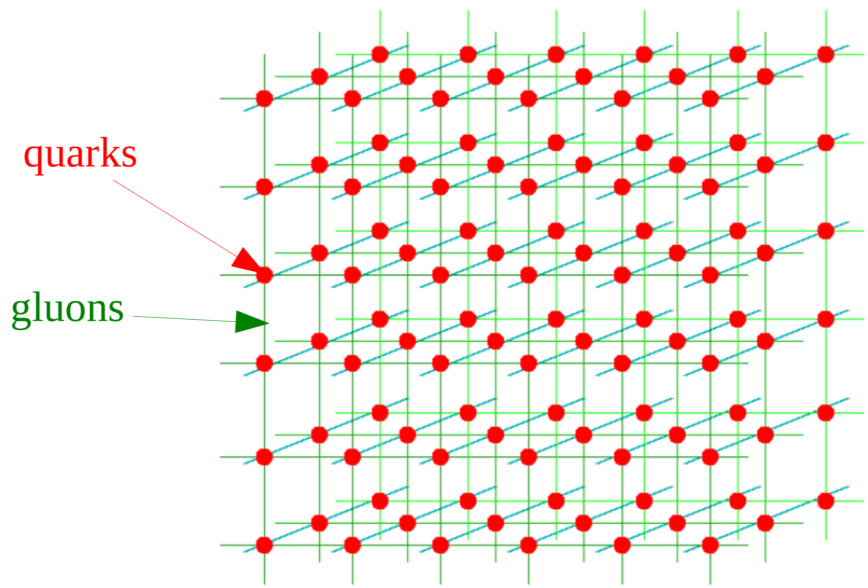
- Bound states of gluons containing no valence quarks → *gg*, *ggg*, ...
- Expect coupling to all flavors equally?
  - Flavor-blind assumption not universally accepted...
  - Predicted decay channels: $G \rightarrow K\bar{K}$, $\pi\pi$, $\eta\eta$, $\eta'\eta'$ but *not* $\eta\eta'$
- Model calculations: Bag model, Flux-tube model, QCD spectral sum rules, Coulomb-gauge Hamiltonian,...

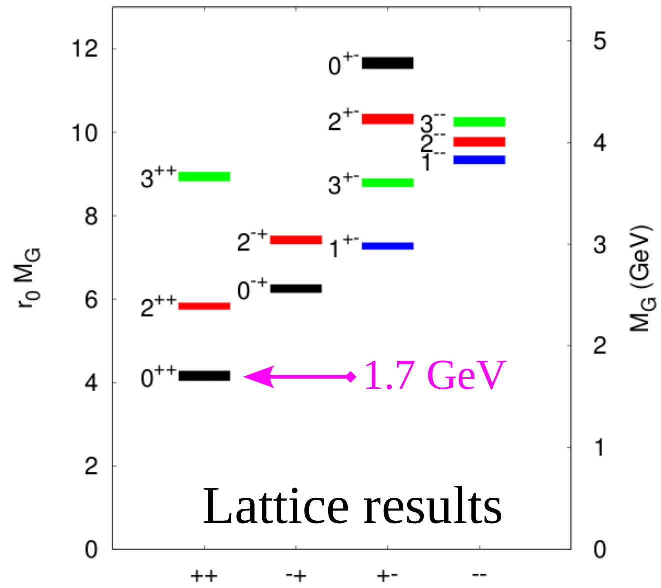
Lowest-lying glueball	
Model	**Mass[GeV]**
Bag model	0.96
Flux-tube	1.52
QSSR	0.3-0.6, 1.5
Hamiltonian	1.98

- **Lowest-lying states $J^{PC}=0^{++}, 2^{++}, 0^{-+}$ have $q\bar{q}$ quantum numbers**
  - May show up as "extra states" outside of $q\bar{q}$ nonets

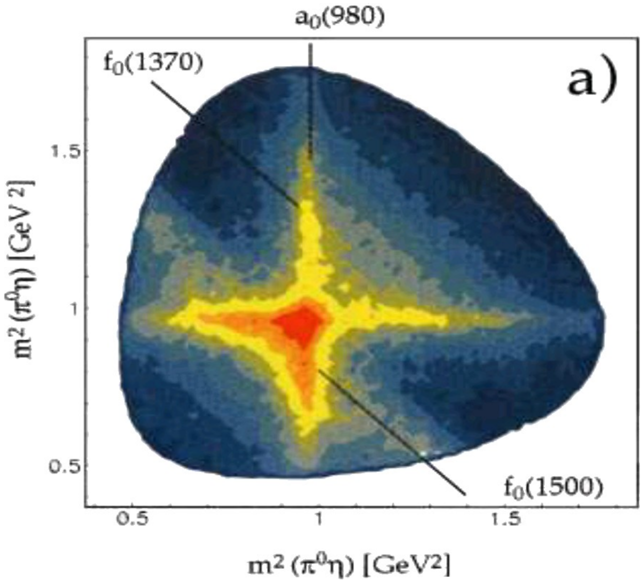
Glueballs on the Lattice

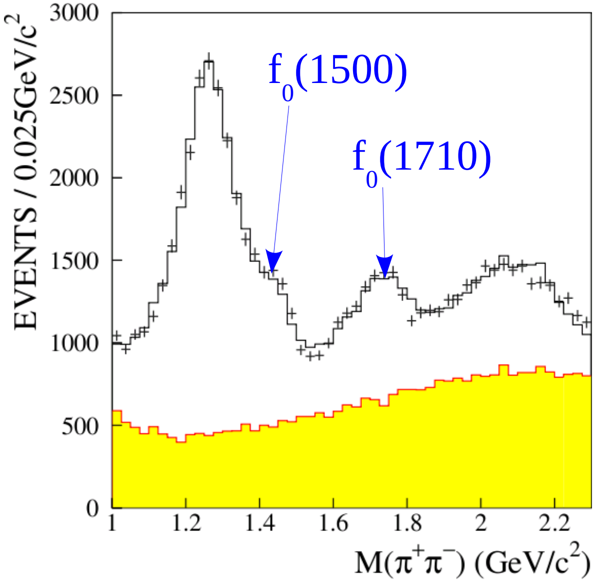
- Lattice QCD: Simulation of full QCD on a discrete space-time lattice
  - Quarks positioned on sites, gluons reside on links between sites
  - Light quark masses typically unphysically large, parametrized as pion mass
    - Need to extrapolate results to physical pion mass
    - Smaller quark masses $\rightarrow$ very computationally expensive

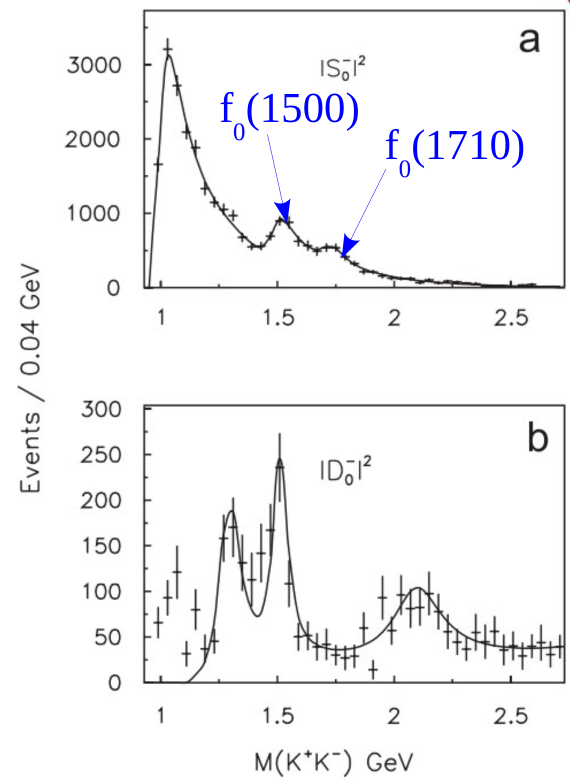




Glueball searches







- Crystal Barrel
  - $\bar{p}p \rightarrow \eta\eta\pi^0$, $\eta\pi^0\pi^0$
  - Coupled channel approach required $f_0(1370)$ and $f_0(1500)$
    - $\eta\eta$, $\pi^0\pi^0$ decay channels
- BES
  - $J/\psi \rightarrow \gamma\pi\pi$
  - PWA: J=0 for $f_0(1500)$
  - Shaded region: $J/\psi \rightarrow \pi^+\pi^-\pi^0$
- WA102
  - Central production: pp→ ppX

- *$f_0(1500)$ not observed in two-photon fusion...*
  - Good candidate for scalar glueball?

Interpretation of the Scalar Sector

- Physical states ($f_0(1370)$, $f_0(1500)$, $f_0(1710)$) are mixture of "bare" states

$$\begin{pmatrix} | f_1 \rangle \\ | f_2 \rangle \\ | f_3 \rangle \end{pmatrix} = \begin{pmatrix} M_{1n} & M_{1s} & M_{1g} \\ M_{2n} & M_{2s} & M_{2g} \\ M_{3n} & M_{3s} & M_{3g} \end{pmatrix} \cdot \begin{pmatrix} | n\bar{n} \rangle \\ | s\bar{s} \rangle \\ | G \rangle \end{pmatrix}$$

$$n\bar{n} = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$$

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

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

- Matrix elements depend on mass hierarchy of bare states
  - Case I: $|G\rangle$ mass < $|s\bar{s}\rangle$ mass
    - $f_0(1370)$: large SU(3) singlet component
    - $f_0(1500)$: large glueball component
    - $f_0(1710)$: large $s\bar{s}$ component
    - Glueball split over at least 2 states
  - Case II: $|G\rangle$ mass > $|s\bar{s}\rangle$ mass
    - $f_0(1370)$ ~ SU(3) singlet, $f_0(1500)$ ~ SU(3) octet, $f_0(1710)$ ~ glueball

Assumes $f_0(1370)$ exists...

Pseudoscalar mesons

$J^{PC}=0^{-+}$

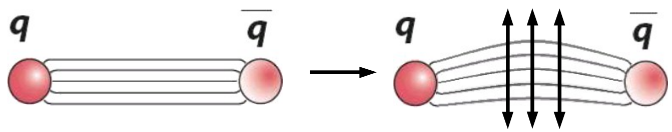
- Candidate for first radial excitation of η = η(1295)
  - Seen in pion-induced reactions, *not seen* in $\bar{p}p$, γγ-fusion, central production, or J/ψ decays...
- Glueball candidate in the 1400 MeV mass range = "η(1440)"
  - Stickiness: 79±26, Gluiness: 41±14 (L3 collab.)
  - More recent experiments: two pseudoscalar states in this mass range
    - Crystal Barrel: evidence for η(1405) and η(1475) but not η(1295)
    - OBELIX: $\eta(1405)\to a_0(980)\pi$, $\eta(1475)\to \bar{K}^*K+K^*\bar{K}$
    - Interpret η(1475) as radial excitation of η′?

→ *η(1405) does not fit into $q\bar{q}$ picture? ⇒ glueball?*

- Klempt and Zaitsev: only one η in 1200-1500 MeV mass region
  - η(1440) has node in wave function → apparent two states
    - radial excitation of η
  - "η(1295)" =feed through from $f_1(1285)$ + Deck effect?

Hybrid Mesons

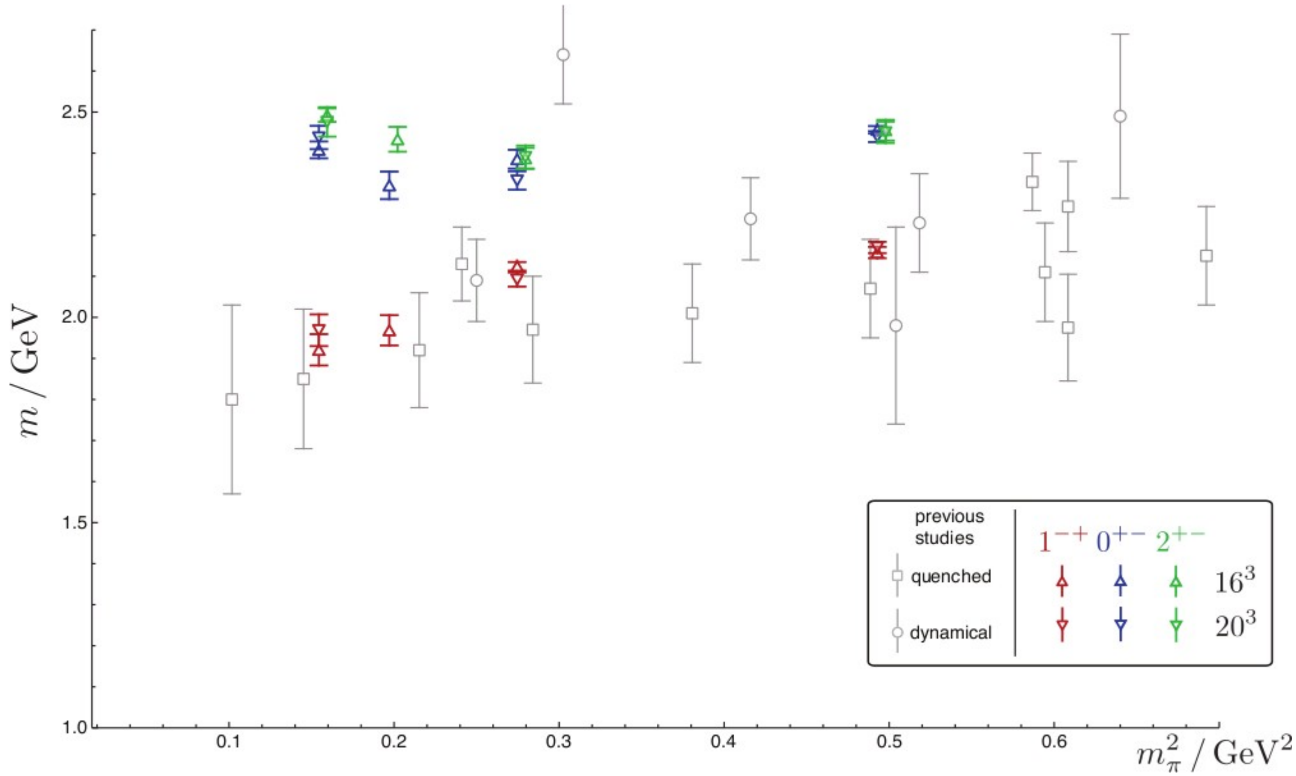
- Mesons with excited glue $\rightarrow$ $q\bar{q}g$
- Flux tube model:



  - Quarks tied to ends of relativistic string with constant energy/length
  - Tube carries angular momentum: $J^{PC}=1^{+-}$ or 1^{-+} for one unit
  - Hybrid mass ~ 1.9 GeV, eight degenerate nonets
  - "Exotic" (non-$q\bar{q}$) quantum numbers possible: 0^{+-}, 1^{-+}, 2^{+-}, ...
  - **Selection rule: preferred decay to *(L=0 meson)+(L=1 meson)***
    - E.g.: $\pi_1 \rightarrow b_1\pi$ rather than $\pi_1 \rightarrow \eta\pi$
- Other models: Bag model, QCD spectral sum rules, Coulomb-gauge Hamiltonian,...

Mass (GeV)	Model
1.0- 1.4	Bag Model
1.0-1.9	QSSR
1.8-2.0	Flux Tube
2.1-2.3	Hamiltonian

Hybrid Mesons on the Lattice



- Lightest hybrids are in **J^{PC}=1^{-+}** nonet, mass ~2 GeV
- 0^{+-}, 2^{+-} expected to be heavier > 2 GeV

Hybrid Meson Candidate: $\pi_1(1400)$

Mode	Mass (GeV)	Width (GeV)	Experiment
$\eta\pi^-$	1.405 ± 0.020	0.18 ± 0.02	GAMS
$\eta\pi^-$	1.343 ± 0.0046	0.1432 ± 0.0125	KEK
$\eta\pi^-$	1.37 ± 0.016	0.385 ± 0.040	E852
$\eta\pi^0$	1.257 ± 0.020	0.354 ± 0.064	E852
$\eta\pi$	1.40 ± 0.020	0.310 ± 0.050	CBAR
$\eta\pi^0$	1.36 ± 0.025	0.220 ± 0.090	CBAR
$\rho\pi$	1.384 ± 0.028	0.378 ± 0.058	Obelix
$\rho\pi$	~ 1.4	~ 0.4	CBAR
$\eta\pi$	1.351 ± 0.030	0.313 ± 0.040	PDG

- Interpretation as hybrid meson is problematic
  - Mass lower than most model predictions (and lattice results)
  - $\rho\pi$ state not the same as $\eta\pi$ state?
  - If seen only in $\eta\pi$ channel $\rightarrow$ inconsistent with model predictions
    - Close and Lipkin: $\eta'\pi$ favored for hybrids, $\eta\pi$ favored for multiquark states

- Alternate explanations:
  - Donnachie and Page: interference between $\pi_1(1600)$ and non-resonant background
  - Szczepaniak, et al.: dynamical generation via meson exchange forces
  - Close and Lipkin: $qq\bar{q}\bar{q}$ state

Hybrid Meson Candidate: $\pi_1(1600)$

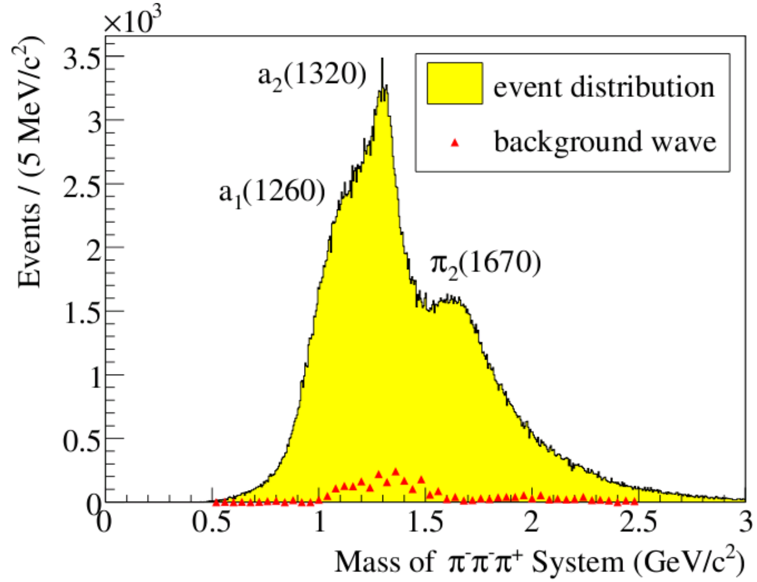
Mode	Mass (GeV)	Width (GeV)	Experiment
$\rho\pi$	1.593 ± 0.08	0.168 ± 0.020	E852
$\eta'\pi$	1.597 ± 0.010	0.340 ± 0.040	E852
$f_1\pi$	1.709 ± 0.024	0.403 ± 0.080	E852
$b_1\pi$	1.664 ± 0.008	0.185 ± 0.025	E852
$b_1\pi$	1.58 ± 0.03	0.30 ± 0.03	VES
$b_1\pi$	1.61 ± 0.02	0.290 ± 0.03	VES
$b_1\pi$	~ 1.6	~ 0.33	VES
$b_1\pi$	1.56 ± 0.06	0.34 ± 0.06	VES
$f_1\pi$	1.64 ± 0.03	0.24 ± 0.06	VES
$\eta'\pi$	1.58 ± 0.03	0.30 ± 0.03	VES
$\eta'\pi$	1.61 ± 0.02	0.290 ± 0.03	VES
$\eta'\pi$	1.56 ± 0.06	0.34 ± 0.06	VES
$b_1\pi$	~ 1.6	~ 0.23	CBAR
$\rho\pi$	1.660 ± 0.010	0.269 ± 0.021	COMPASS
all	$1.662^{+0.015}_{-0.011}$	0.234 ± 0.050	PDG

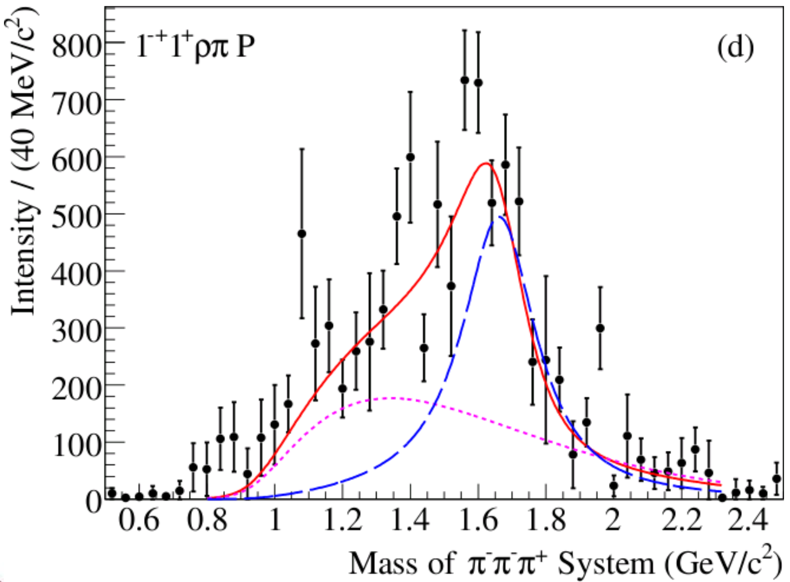
- Most promising hybrid candidate
  - Seen in $\eta'\pi$ + other channels favored by models...
- $\rho\pi$ channel is problematic
  - Not seen in CLAS photoproduction
  - E852 alternate analysis
    - Larger statistics
    - Larger wave set
    - $\pi_1(1600)$ signal consistent with leakage due to $\pi_2(1670)$

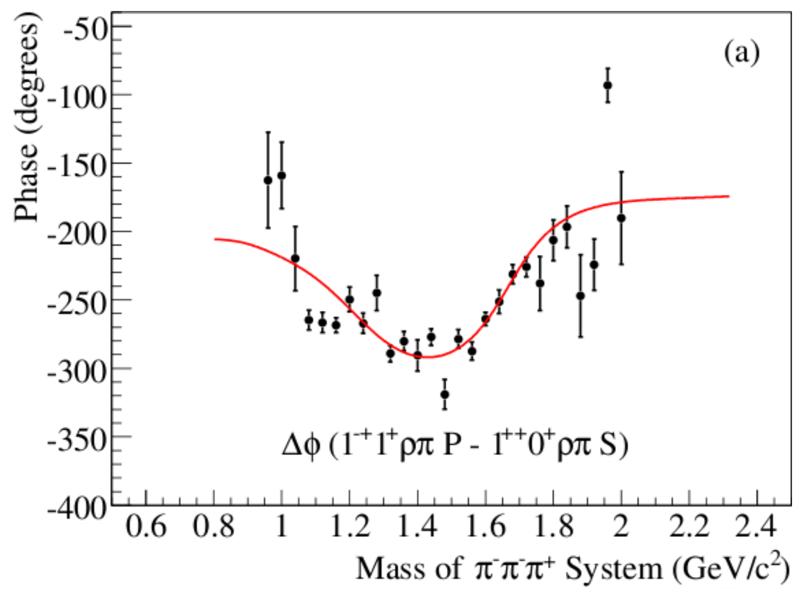
Results from COMPASS

- Peripheral production: $\pi^- Pb \to Pb\ \pi^-\pi^-\pi^+$
  - Evidence for $J^{PC}=1^{-+}$ wave decaying to $\rho\pi$
    - Small fraction (1.7%) of total intensity

Analysis of a larger data set has been shown at PANIC2011…

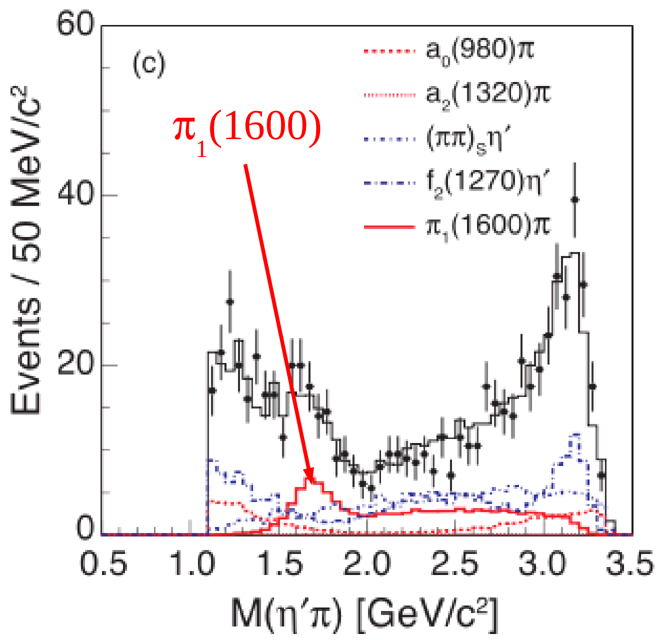






Results from CLEO-c

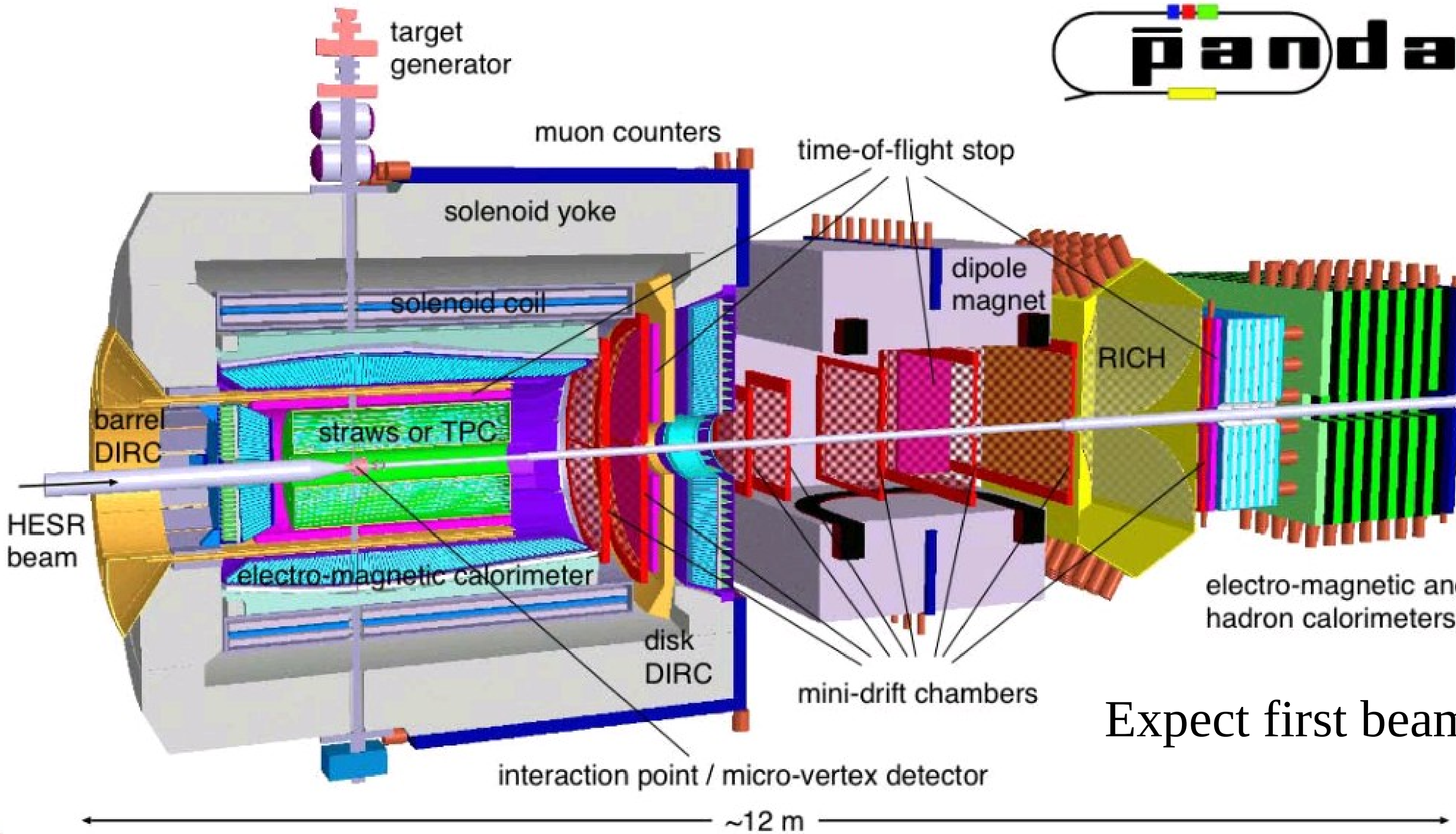
- $\psi(2S) \rightarrow \gamma\chi_{c1}$
  - $\chi_{c1} \rightarrow \eta\pi^+\pi^-, \eta'\pi^+\pi^-$
- Evidence for P-wave $\eta'\pi$ amplitude with $J^{PC}=1^{-+}$ $\rightarrow$ consistent with $\pi_1(1600)$
  - Tried fits without 1^{-+} wave but with additional non-exotic waves $\rightarrow$ none as significant as exotic case
  - Quote > 4σ significance for $\pi_1\pi$ amplitude



P̄ANDA

- Planned for construction at GSI, Darmstadt, Germany
  - Anti-proton beam on proton target
  - Dual magnetic spectrometer: solenoid+dipole
  - PID: DIRC, aerogel Cherenkov detector, scintillator arrays

- Physics program
  - $c\bar{c}$ spectroscopy
  - hybrid/glueball searches
  - hypernuclei
  - medium modification
  - ...

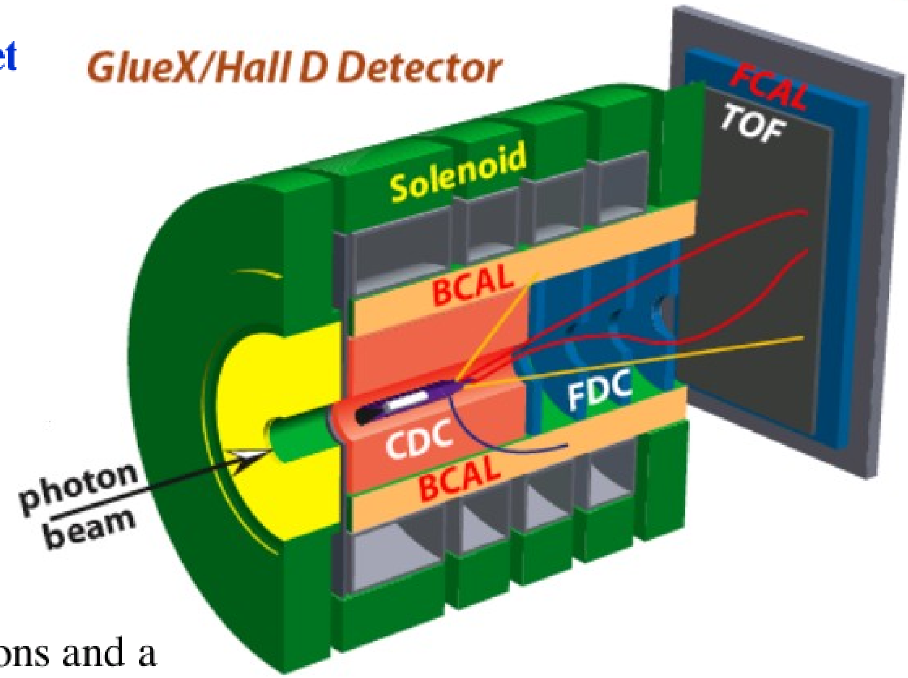


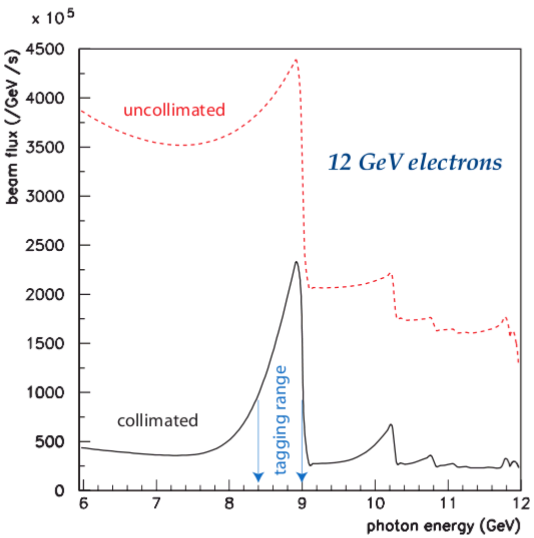
Expect first beam in 2018

The GlueX Experiment

Use **9 GeV polarized photons** on a **proton target** to produce **hybrid mesons** with exotic J^{PC}:

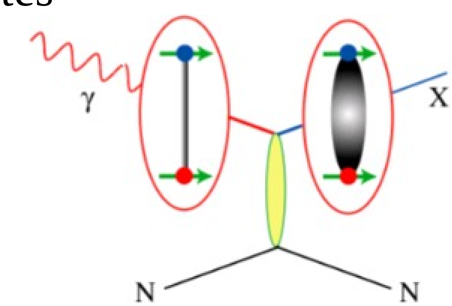
- part of the JLab 12 GeV upgrade
  (in Newport News, Virginia)
- data expected in 2014





- use 12 GeV electrons and a diamond radiator to produce **9 GeV polarized photons**
- $10^7 - 10^8$ γ/s on **proton target**

- Photo-production possibly conducive to production of exotic J^{PC} states



Conclusion and Outlook

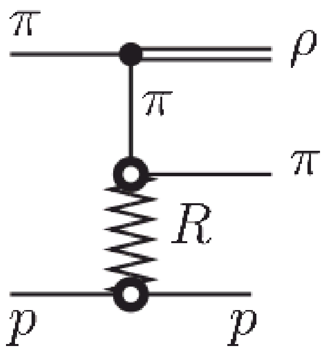
- Intriguing hints of physics beyond simple $q\bar{q}$ quark model picture of mesons
- New results from CLEO-c, COMPASS, ...
- BESIII: large data sets for J/ψ, ψ', $\psi'(3770)$,... channels, analysis ongoing...
- New experimental facilities (PANDA, GlueX) coming online soon

References

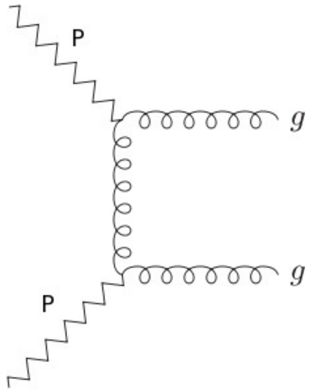
- E. Klempt, A. Zaitsev, ``Glueballs, Hybrids, Multiquarks. Experimental facts versus QCD inspired concepts," Phys. Rept. **454**, 1-202 (2007). [arXiv:0708.4016 [hep-ph]].
- V. Crede, C. A. Meyer, ``The Experimental Status of Glueballs," Prog. Part. Nucl. Phys. **63**, 74-116 (2009).[arXiv:0812.0600 [hep-ex]].
- C. A. Meyer, Y. Van Haarlem, ``The Status of Exotic-quantum-number Mesons," Phys. Rev. C**82**, 025208 (2010). [arXiv:1004.5516 [nucl-ex]].

Supplemental Information

Deck effect:



Red dragon:



COMPASS results from PANIC11

- Peripheral production: $\pi^- p \rightarrow p\pi^-\pi^-\pi^+$
  - Evidence for $J^{PC}=1^{-+}$ wave decaying to $\rho\pi$ with mass consistent with $\pi_1(1600)$
  - Claim structure near 1.1 GeV in 1^{-+} channel not stable with respect to fit model