Meson Spectroscopy:
Glueballs, hybrids, and other fun objects

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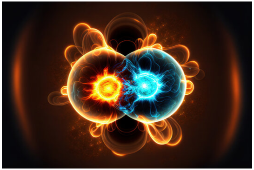
HUGS 2024



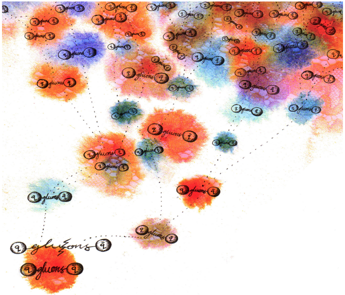
Jefferson Lab, Newport News

06/11/2024

Outline

Outline

Non-Perturbative Quantum Chromodynamics (QCD)

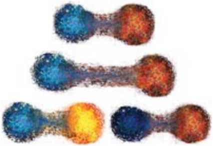


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

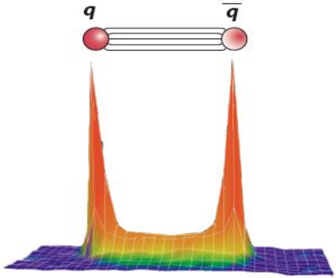
Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

Quarks are confined within hadrons.

Confinement of quarks and gluons within hadrons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of hadrons is still limited.



Non-Perturbative QCD



How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Hadron Spectroscopy: (Baryons) What are the effective degrees of freedom inside the nucleon? (Mesons) What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.
Hybrid baryons are possible but do not carry “exotic” quantum numbers.

The Quark Model of Hadrons

- Mesons ($q\bar{q}$) $\quad \mathrm{q} \otimes \bar{\mathrm{q}} = 3 \otimes \bar{3} = 8 \oplus 1$

- Baryons (qqq) $\quad \mathrm{q} \otimes \mathrm{q} \otimes \mathrm{q} = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter ...

The Quark Model of Hadrons

- **Mesons** ($q\bar{q}$) $\quad q \otimes \bar{q} = 3 \otimes \bar{3} = 8 \oplus 1$

- **Baryons** (qqq) $\quad q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

However, QCD also predicts so-called exotic states

➜ simplest possibility: $\underbrace{q \otimes \bar{q} \otimes q = 15 \oplus 6 \oplus 3 \oplus 3}$ *"SU(3) Color"*

Does not work: color singlets needed !

➜ multiple of (qqq) and ($q\bar{q}$) necessary

- **Glueballs:** $g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$
- **Hybrids:** $q \otimes \bar{q} \otimes g = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus 1$ ➜ $\boxed{(q\bar{q})^l((q)^3)^m(g)^n}$,

$l + m \geq 1$ for n = 1

Ordinary Mesons

$J^{PC} \equiv {}^{2S+1}L_J$

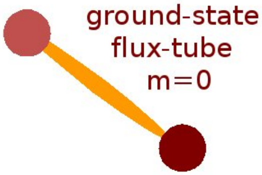
- Parity $P = (-1)^{L+1}$
- Charge Conjugation (defined for neutral mesons) $C = (-1)^{L+S}$
- G parity $G = C(-1)^I$

$L = 0,\ S = 1:$

$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$L = 0,\ S = 0:$

e.g. $\pi\ (J^{PC} = 0^{-+})$



Ordinary and Exotic Mesons

$J^{PC} \equiv {}^{2S+1}L_J$

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- G parity $G = C(-1)^I$

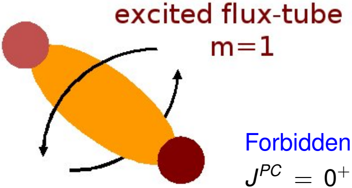
$\underline{L = 0,\ S = 1:}$

$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$\underline{L = 0,\ S = 0:}$

e.g. $\pi\ (J^{PC} = 0^{-+})$

12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan) "[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."



Forbidden States (Exotics):
$J^{PC} = 0^{+-},\ 0^{--},\ 1^{-+},\ \cdots$

Mesons and their Quantum Numbers

		J^{PC}	$^{2S+1}L_J$	$I = 1$	$I = 0\ (n\bar{n})$	$I = 0\ (s\bar{s})$	Strange
$L = 0$	$S = 0$	0^{-+}	$^1S_0$	π	η	η'	K
	$S = 1$	1^{--}	$^3S_1$	ρ	ω	ϕ	K^*
$L = 1$	$S = 0$	1^{+-}	$^1P_1$	b_1	h_1	h'_1	K_1
	$S = 1$	0^{++}	$^3P_0$	a_0	f_0	f'_0	K_0^*
	$S = 1$	1^{++}	$^3P_1$	a_1	f_1	f'_1	K_1
	$S = 1$	2^{++}	$^3P_2$	a_2	f_2	f'_2	K_2^*

Notation

1. J^{PC} s are measured quantities.
2. $^{2S+1}L_J$ s are internal quantum numbers in a non-relativistic quark model.

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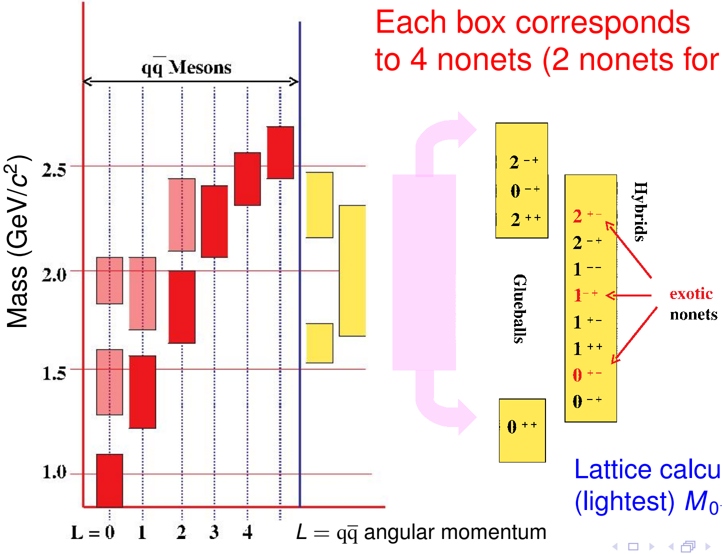
	$S = 1$	1^{++}	$^3P_1$	a_1	f_1	f'_1	K_1
	$S = 1$	2^{++}	$^3P_2$	a_2	f_2	f'_2	K^*_2

Notation

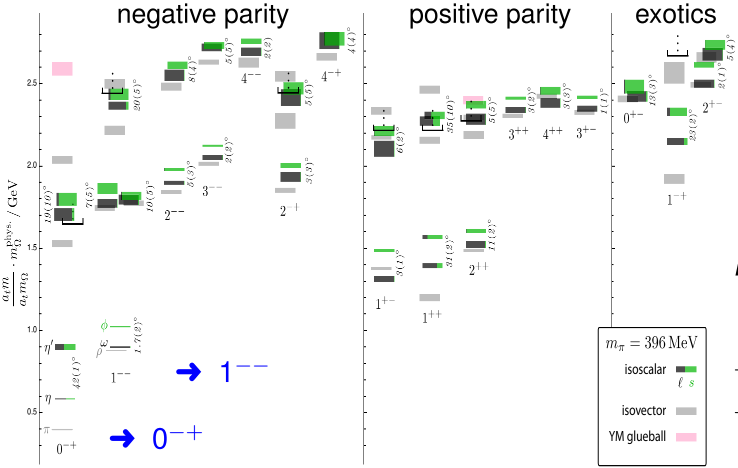
1. J^{PC} s are measured quantities.
2. $^{2S+1}L_J$ s are internal quantum numbers in a non-relativistic quark model.

Each box corresponds to 4 nonets (2 nonets for $L = 0$)



Lattice calculations:
(lightest) $M_{0^{++}} \approx 1.55$ GeV/c^2

Meson Spectroscopy on the Lattice



→ 1^{--}

→ 0^{-+}

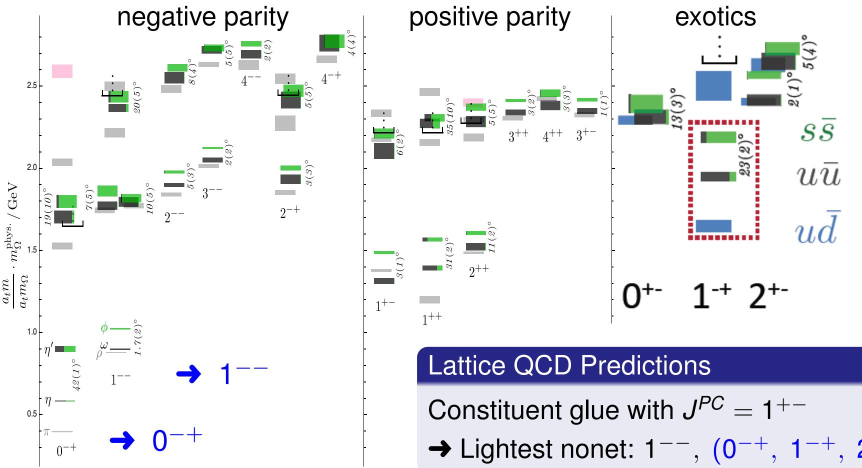
$m_\pi = 396$ MeV

→ isoscalar

→ isovector

J. J. Dudek *et al.*, Phys. Rev. D **84**, 074023 (2011)

Meson Spectroscopy on the Lattice



Lattice QCD Predictions

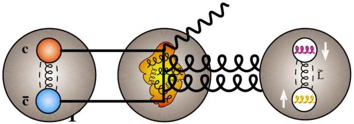
Constituent glue with $J^{PC} = 1^{+-}$

➜ Lightest nonet: 1^{--}, (0^{-+}, 1^{-+}, 2^{-+})

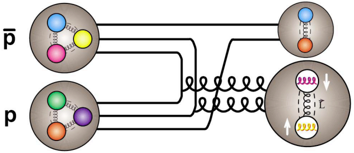
J. J. Dudek *et al.*, PRD **84**, 074023 (2011)

Glue-Rich Environments

Pictures: Ulrich Wiedner



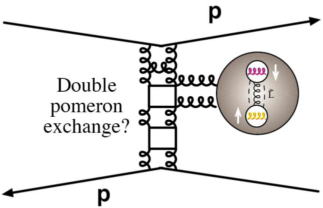
Mark III, DM 2, BES



Asterix, Obelix, Crystal Barrel

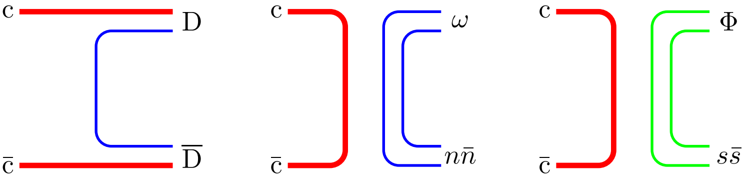
Different Production Mechanisms

1. J/ψ may convert into 2 gluons and a photon.
2. In $p\bar{p}$ annihilation, $q\bar{q}$ pairs annihilate into gluons forming glueballs.
3. Central production: two hadrons scatter diffractively, no exchange of valence quarks.



WA 79, WA 102

The OZI Rule and Flavor-Tagging Approach



The decay of J/ψ into mesons with open charm (left) is forbidden due to energy conservation.

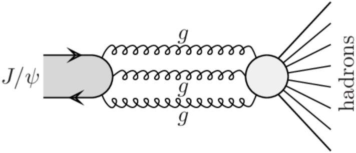
The two right diagrams require annihilation of $c\bar{c}$ into gluons:

- Recoiling against ω, mesons with $n\bar{n}$ quark structure are expected.
- If a ϕ is observed, we expect mesons with hidden strangeness $s\bar{s}$.

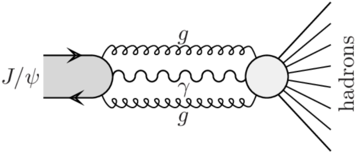
➜ OZI rule, e.g. ratio $\phi\eta'/\omega\eta' \sim$ ratio of $s\bar{s}/n\bar{n}$ in η' w.f.

The Decay of the J/ψ Meson

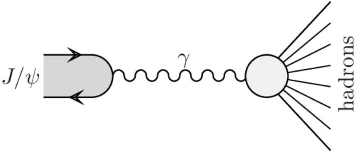
$Br = 64\,\%$



$Br = 9\,\%$



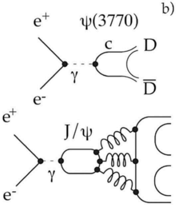
$Br = 14\,\%$



$J/\psi(1S)$, $\psi(2S)$

➜ $\psi(3770)$ 1^3D_1

Can fall apart to $D\overline{D}$.

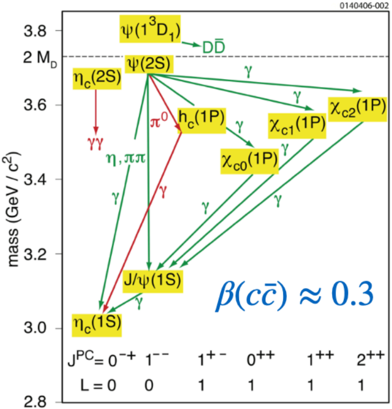


$\Gamma(J/\psi) = 93$ keV

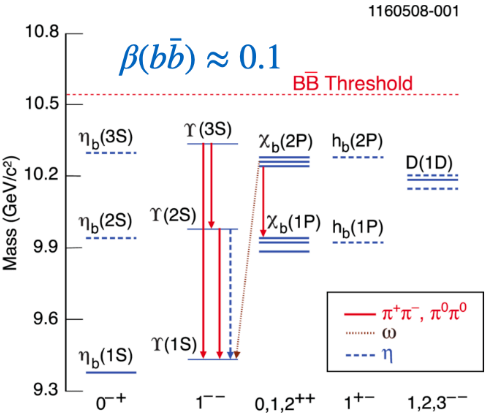
$\Gamma(\psi(2S)) = 294$ keV

$\Gamma(\psi(3770)) = 27$ MeV

Charmonium vs. Bottomonium



Charmonium $c\bar{c}$



Bottomonium $b\bar{b}$

Outline

The $I = 0$, $J^{PC} = 0^{-+}$ (Pseudoscalar) Mesons

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$\eta(548)$ *	547.51 ± 0.18	$1.30 \pm .07$ keV	$\gamma\gamma$, 3π
$\eta'(958)$ *	957.78 ± 0.14	0.203 ± 0.016	$\eta\pi\pi$, $\rho\gamma$, $\omega\gamma$, $\gamma\gamma$
$\eta(1295)$ *	1294 ± 4	55 ± 5	$\eta\pi\pi$, $a_0\pi$, $\gamma\gamma$, $\eta\sigma$, $K\bar{K}\pi$
$\eta(1405)$ *	1409.8 ± 2.5	51.1 ± 3.4	$K\bar{K}\pi$, $\eta\pi\pi$, $a_0\pi$, $f_0\eta$, 4π
$\eta(1475)$ *	1476 ± 4	87 ± 9	$K\bar{K}\pi$, $K\bar{K}^* + cc$, $a_0\pi$, $\gamma\gamma$
$\eta(1760)$	1760 ± 11	60 ± 16	$\omega\omega$, 4π
$\eta(2225)$	2220 ± 18	$150^{+300}_{-60} \pm 60$	$K\bar{K}K\bar{K}$

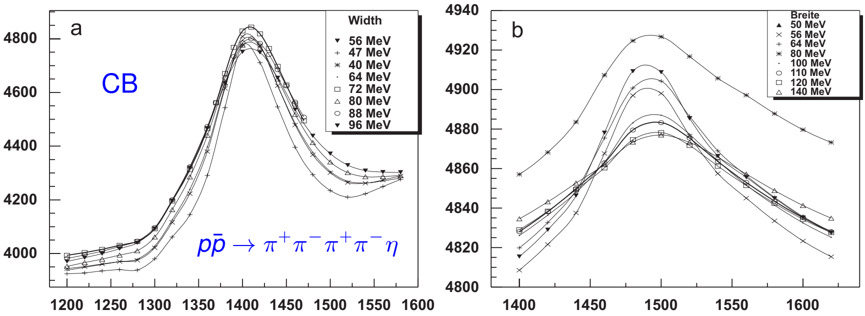
Five pseudoscalar states < 1500 MeV/c^2 listed in the PDG summary table

➜ Too many for two nonets!!

The Search for the Lightest Pseudoscalar Glueball

In 1990, Mark III reported two pseudoscalar states in the 1400 MeV/c^2 region in radiative J/ψ decays (with $J/\psi \to a_0(980)\pi$ and $J/\psi \to K^*K$).

- Both states confirmed by Crystal Barrel and Obelix at LEAR
- But: CB did NOT observe the $\eta(1295)$



The Search for the Lightest Pseudoscalar Glueball

In 2001, L3 observed $\eta(1475) \to K\bar{K}\pi$ in two-photon collisions.

- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?

The Search for the Lightest Pseudoscalar Glueball

In 2001, L3 observed $\eta(1475) \to K\bar{K}\pi$ in two-photon collisions.

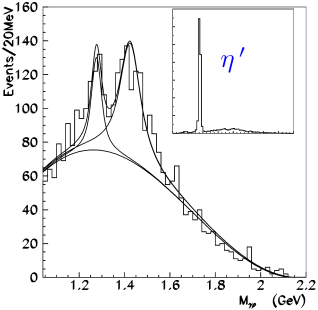
- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?
- In 2005, CLEO published (high-statistics) negative results on both states.

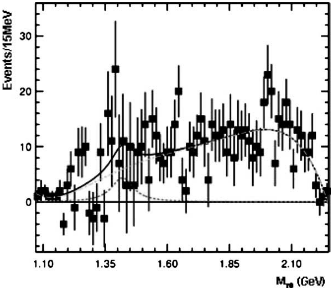
The Flavor Filter in the Decay $J/\psi \to \gamma[\gamma V]$

BES-II studied $J/\psi \to \gamma\gamma V(\rho, \phi)$

- Clear observation of peak at $M \approx 1424$ MeV/c^2 in $X(1424) \to \gamma\rho$ (left)
- No observation of $X(1424) \to \gamma\phi$ (right)!

  ➜ Glueball should decay to both final states.

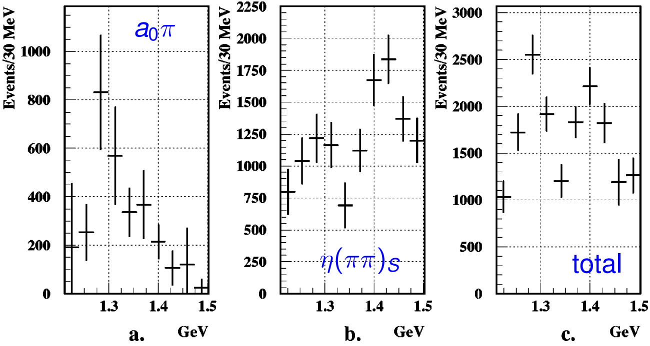




What about the $\eta(1295)$?

Often interpreted as first radial excitation of the η meson.

- Ideal mixing: degenerate in mass with $\pi(1300)$
- Problem: only observed in pion-induced reactions!



E852

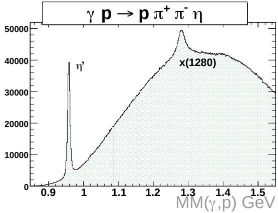
$\eta \rightarrow a_0(980)\pi$

Study of the $\eta(1295)$ in Photoproduction at CLAS

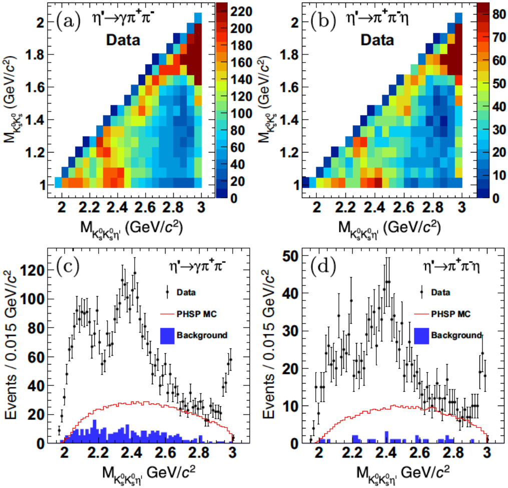
First photoproduction measurements of $x(1280)$

(Preliminary conclusions from talk at APS Spring Meeting 2009)

- Mass and width of the state consistent with the PDG values for $f_1(1285)$, not the $\eta(1295)$
- Cross sections being compared to models for both 0^- and 1^+
- Dalitz plot analysis of $\eta\pi\pi$ final state shows clear $a_0(980)$ intermediate state, with no charge asymmetry
- $KK\pi$ and $\eta\pi\pi$ final states measured; no $\rho^0\gamma$ final state seen.
  - ➜ inconsistent with $f_1(1285)$ (PDG: $(5.5 \pm 1.3)\,\%$ for $f_1 \to \gamma\rho^0$)



The BESIII Pseudoscalar Glueball of 2024

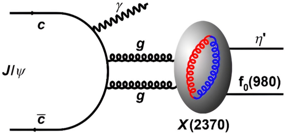


$$J/\psi \to \gamma\, K_S^0 K_S^0\, \eta'$$

$$J/\psi \to \gamma\, X(2370)$$

$$X(2370) \to f_0(980)\eta'$$

$$f_0(980) \to K_S^0 K_S^0$$



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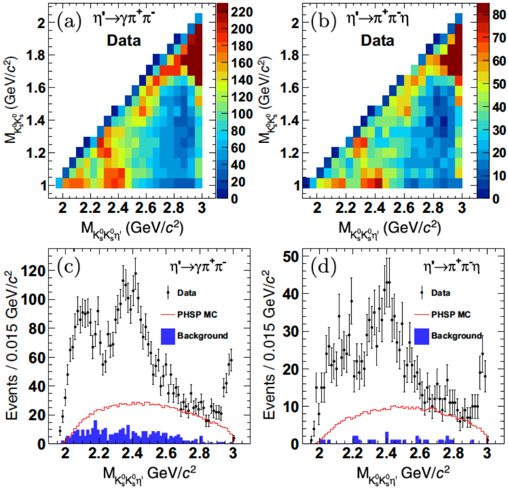


$$J/\psi \to \gamma\, K_S^0 K_S^0\, \eta'$$

$$J/\psi \to \gamma\, X(2370)$$

$$X(2370) \to f_0(980)\eta'$$

$$f_0(980) \to K_S^0 K_S^0$$

Mass and spin-parity consistent with predicted lightest pseudoscalar glueball.

➜ $J^{PC} = 0^{-+}$, significance of 11.7σ

The 2^{++} Tensor Glueball

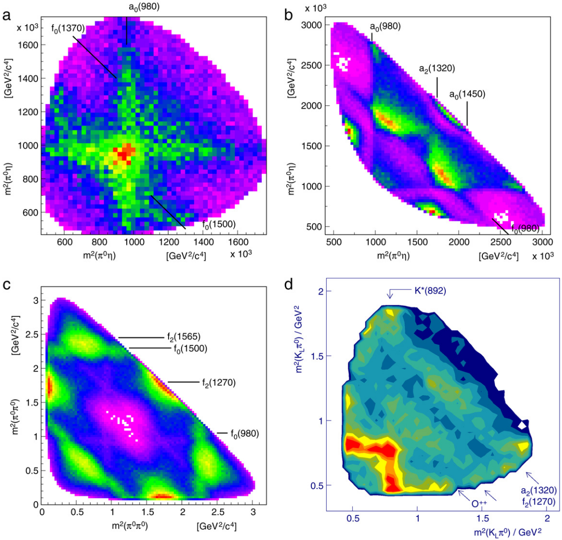
Evidence essentially non-existent!

- Two quark configurations yield 2^{++}:
  1. $L = 1,\ S = 1,\ J = 2 :\ {}^3P_2$ ➜
  2. $L = 3,\ S = 1,\ J = 2 :\ {}^3F_2$
- For both nonets, radial excitations are expected.
- Situation premature: none of the states can be assigned definitely to any of the above nonets.

Name	Mass [MeV/c^2]
$f_2(1270)\ *$	1275.4 ± 1.1
$f_2(1430)$	1430
$f_2'(1525)\ *$	1525 ± 5
$f_2(1565)$	1546 ± 12
$f_2(1640)$	1638 ± 6
$f_2(1810)$	1815 ± 12
$f_2(1910)$	1915 ± 7
$f_2(1950)\ *$	1944 ± 12
$f_2(2010)\ *$	2011^{+60}_{-80}
$f_2(2150)$	2156 ± 11
$f_2(2300)\ *$	2297 ± 28
$f_2(2340)\ *$	2339 ± 60

The $I = 0$, $J^{PC} = 0^{++}$ (Scalar) Mesons

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ $*$	$400 - 1200$	$600 - 1000$	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ $*$	980 ± 10	$40 - 100$	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ $*$	$1200 - 1500$	$200 - 500$	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ $*$	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ $*$	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$



Crystal Barrel

a $p\bar{p} \to \pi^0\eta\eta$
b $p\bar{p} \to \pi^0\pi^0\eta$
c $p\bar{p} \to \pi^0\pi^0\pi^0$
d $p\bar{p} \to \pi^0 K_L K_L$

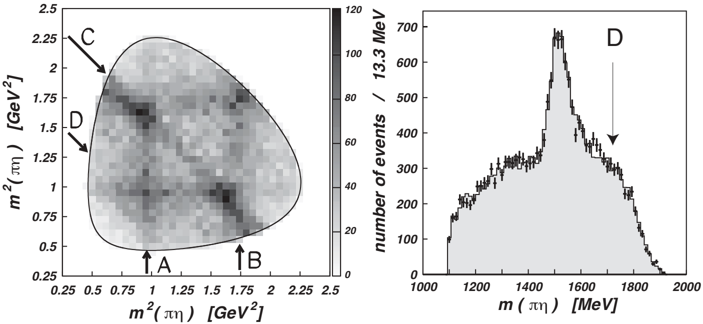
Good description with

- Two isoscalar states: $f_0(1370)$ / $f_0(1500)$
- In addition: Both have dominant 4π decay modes. ➜ $n\bar{n}$ structure

The $f_0(1710)$ Scalar Meson in Crystal Barrel

First discovered by Crystal-Ball in radiative J/ψ decays into $\eta\eta$

- Spin ($J = 0$ or 2) remained controversial for a long time
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$



The $f_0(1710)$ Scalar Meson

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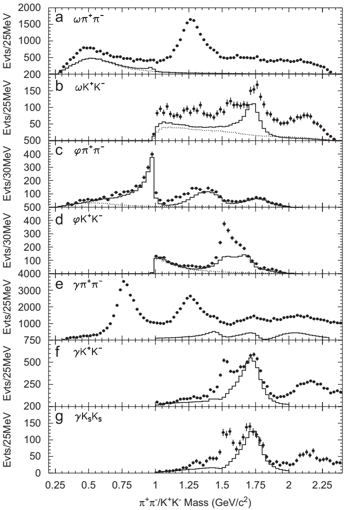
- Spin ($J = 0$ or 2) remained controversial for a long time.
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$.
- Consistent with a dominant $s\bar{s}$ assignment.
  - ➜ Confirmed by WA102 reporting a much stronger $K\bar{K}$ coupling of $f_0(1710)$ than $\pi\pi$ coupling.

BES spoils the Glueball Picture ...

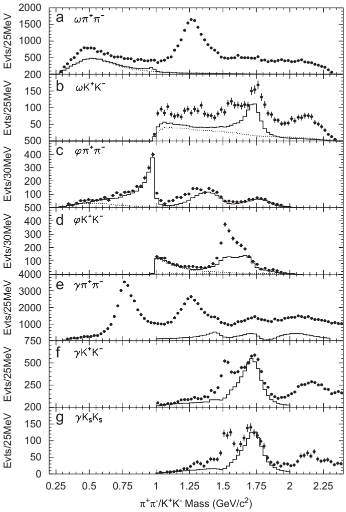


Flavor Tagging

ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

BES spoils the Glueball Picture ...



Flavor Tagging

ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

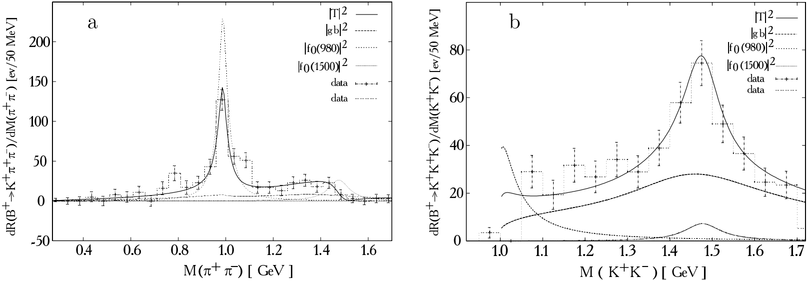
Solution: Two distinct scalar states

- The known $f_0(1710)$ decaying to $K\bar{K}$
- New broad $f_0(1790)$ coupling strongly to $\pi\pi$
  - Not confirmed by other experiments!
  - Mystery why $s\bar{s}$ recoils against ω

Belle makes it even worse ...

Belle measured scalar mesons in $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$
(Results essentially confirmed by BaBar)

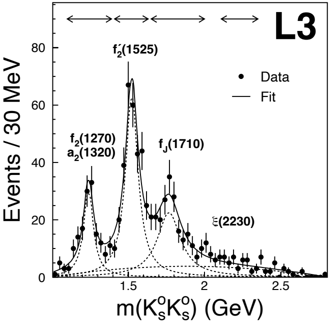
- No peak at 1500 MeV/c^2 for the $f_0(1500)$ (left),
- But a clear peak around 1500 MeV/c^2 decaying to K^+K^-
  ➜ Structure of $f_0(1500)$ remains unclear (or two states)!



Results on Scalar Mesons from $\gamma\gamma$ Fusion

Results were reported by the LEP collaborations at CERN:

- Three clear peaks in the $K_S^0 K_S^0$ mass by L3 (dominated by tensors)
- No peak for the $f_0(1500)$
  ➜ Consistent with known small $s\bar{s}$ component! What about $\pi\pi$ spectrum?



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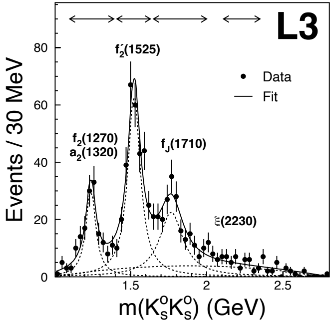

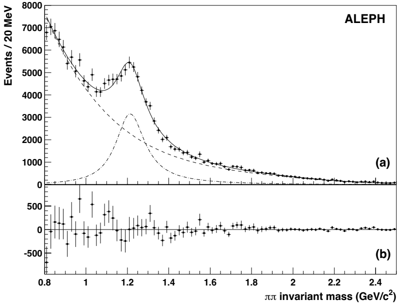

Scalar Mesons: Key Questions

The following key questions account for the major differences in the models on scalar mesons and need to be addressed in the future:

1. What is the nature of the $f_0(980)$ and $a_0(980)$?
   (There is the possibility of an exotic nonet below 1 GeV/c^2.)

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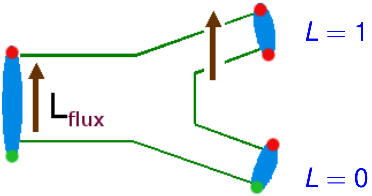
3. Is the $f_0(1500)$ the scalar glueball?
   Data on $J/\psi \to \gamma f_0(1500)$ is still statistically limited ➜ BES-III
4. Are the two states, $f_0(1710)$ and $f_0(1790)$ distinct states?
5. ...

Hybrid Meson Decays and Interesting Channels

Ideas on Hybrid-Meson Decays:
(angular momentum in the flux tube stays in one of the daughter mesons)

Evidence for $J^{PC} = 1^{-+}$ wave
➜ Interpretation controversial ...



Lattice calculations:
(lightest hybrid) $M_{1^{-+}} \approx (1.9 \pm 0.2)$ GeV/c^2

0^{+-} $h_0 \to b_1\pi \to \pi^+\pi^-\pi^0\pi^0\pi^0;\ h_1\eta$
$b_0 \to \pi(1300)\pi;\ h_1\pi$

1^{-+} $\eta_1 \to a_1\pi \to 2\pi^+2\pi^-;\ \pi(1300)\pi$
$\pi_1 \to f_1\pi \to \eta\pi\pi\pi;\ b_1\pi,\ \pi\rho,\ \eta a_1$

2^{+-} $h_2 \to \rho\pi \to \pi\pi\pi;\ b_1\pi,\ \omega\eta$
$b_2 \to a_2\pi;\ a_1\pi,\ h_1\pi,\ \omega\pi$

➜ Multi-particle final states with neutral and charged particles!

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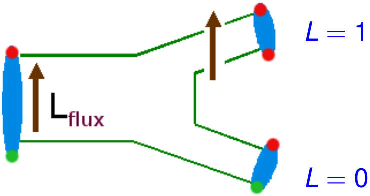

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Experimental Searches for Hybrid Mesons

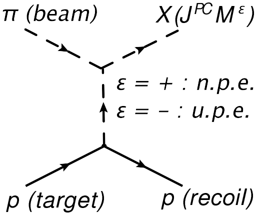
There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.
➜ The interpretation remains controversial.

Exotic waves are (all) observed in diffraction-like reactions.
➜ Observation of $\pi_1(1400) \to \eta\pi$ in $p\bar{p}$ remains exception.

1. $\pi_1(1400) \to \eta\pi$ ➜ Tetraquark? Nothing? (too low in mass for hybrid)
2. $\pi_1(1600)$ Appears to be robust signal.

Diffractive Production Process

- Natural parity exchange: $J^P = 0^+, 1^-, 2^+, \ldots$
  Unnatural parity exchange: $J^P = 0^-, 1^+, 2^-, \ldots$
- Same production mechanism, M^ϵ, expected for all decay modes.



Review: C. Meyer & Y. Van Haarlem, PRC **82**, 025208 (2010)

The $J^{PC} = 1^{-+}$ Exotic Wave: E852 Experiment

There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.

1. $\pi_1(1400) \to \eta\pi$
2. $\pi_1(1600) \to \eta'\pi;\ f_1(1285)\pi$ ➜ Natural-parity exchange.

?

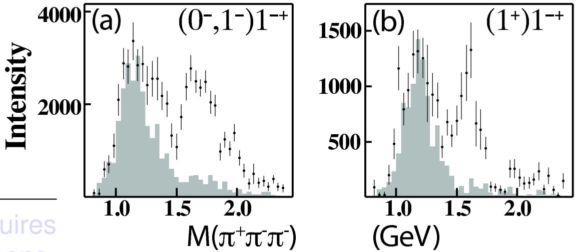
$\boxed{\begin{array}{l} \pi_1(1600) \to b_1\pi \\ \pi_1(1600) \to \rho\pi \end{array}}$ ➜ Unnatural-parity exchange dominates.

$\pi(1600) \to \rho\pi$
(E852 : $\pi^- p \to \pi^+ 2\pi^- p$)

$M = 1598 \pm 8^{+29}_{-47}$ MeV

$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV

$M^\epsilon = 0^-, 1^-$ $M^\epsilon = 1^+$



➜ Better understanding requires a spectrum of hybrid mesons.

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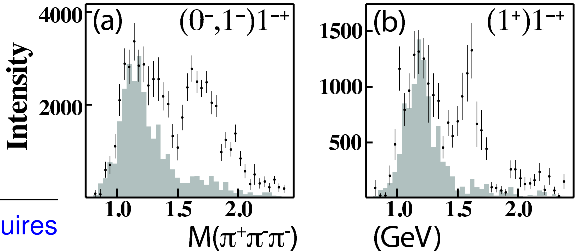
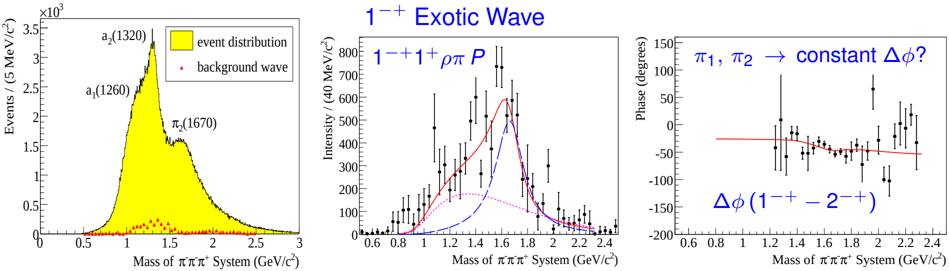


➜ Better understanding requires a spectrum of hybrid mesons.

COMPASS Experiment (1): $\pi^- Pb \to \pi^-\pi^-\pi^+ (Pb)$

M. Alekseev *et al.*, PRL **104**, 241803 (2010)



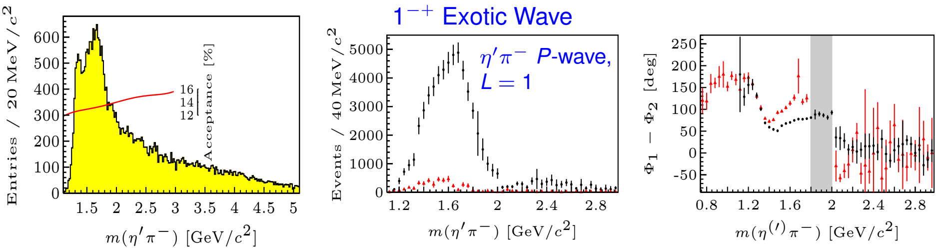
Based on $\sim 420,000$ events using a 180 GeV π beam:

$\pi_1(1600)$: $M = 1660$ MeV, $\Gamma = 269$ MeV | $\pi_2(1670)$: $M = 1658$ MeV, $\Gamma = 271$ MeV

➜ Exotic 1^{-+} wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.

COMPASS Experiment (2): $\pi^- p \to \eta^{(\prime)} \pi^- (p)$

C. Adolph *et al.*, PLB **740**, 303 (2015)



1^{-+} Exotic Wave

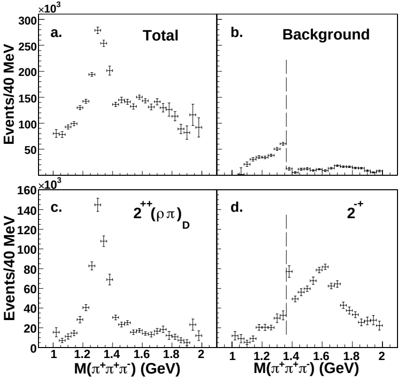
Collaboration refrains from proposing resonance parameters for exotic *P* wave.

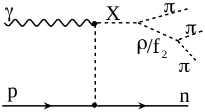
- Odd partial waves with $L = 1, 3, 5$ (non-$q\bar{q}$ QN) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$. Even partial waves similar (intensity & phase behavior).
- Dominant $\mathbf{8} \otimes \mathbf{8}$ $(\eta\pi)$ & $\mathbf{1} \otimes \mathbf{8}$ $(\eta'\pi)$ nature of $SU(3)$ flavor configurations
➜ $gq\bar{q}$ and $q\bar{q}q\bar{q}$ configurations predicted to have $\mathbf{1} \otimes \mathbf{8}$ character.

Meson Spectroscopy in Photoinduced Reactions

Results on light mesons from CLAS at Jefferson Lab

1. Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system (M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))





charge exchange

CLAS

The authors don’t observe a resonant structure in the 1^{-+} $(\rho\pi)_P$ partial wave.

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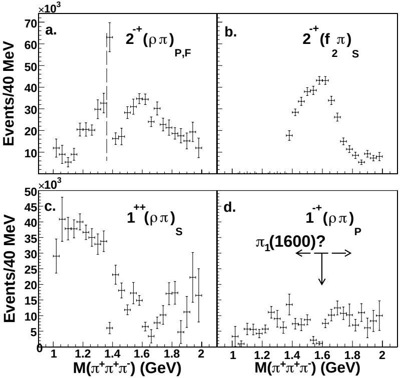

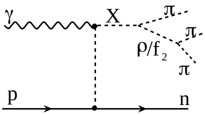

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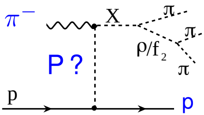

neutral exchange

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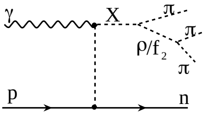
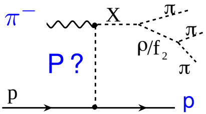
A $J^{PC} = 1^{-+}$ gluonic hybrid should be photo-produced at the same rate as the $a_2(1320)$, whereas in pion production it should be suppressed by a factor of 10.
(Close & Page, Phys. Rev. D **52**, 1706 (1995))



charge exchange

CLAS



neutral exchange

E852

- Upper limit for the $\pi_1(1600)$ of 13.5 nb, less than 2 % of the $a_2(1320)$.

BUSTED

- New HyCLAS data have an order of magnitude more statistics.
  ➜ e.g. $\gamma p \to p\pi^+\pi^+\pi^-$, $\gamma p \to p\pi^+\pi^-\pi^0$ ($J^{PC} = 1^{-+}$ isoscalar production?)
- GlueX proposed to map out the light exotic spectrum.

Meson Spectroscopy in Photoinduced Reactions

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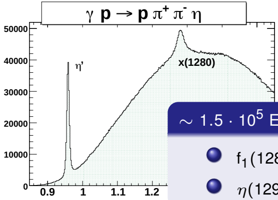
1. Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system
   (M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))
2. First measurement of direct $f_0(980)$ photoproduction on the proton
   (M. Battaglieri *et al.*, Phys. Rev. Lett. **102**, 102001 (2009))
3. Production and decay of the $f_1/\eta\,(1285)$ [*in the g*11 *data set*]
   (R. Dickson *et al.*, Ph.D. thesis)

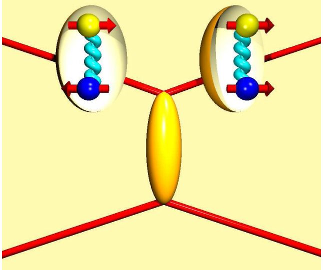


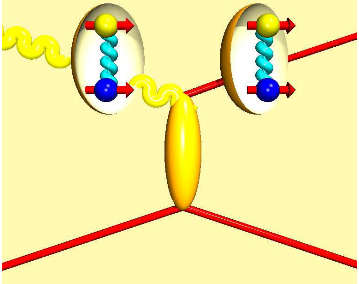
$\sim 1.5 \cdot 10^5$ Events, PDG Properties

- $f_1(1285)\ 1^{++}$, $\Gamma = 24$ MeV
- $\eta(1295)\ 0^{-+}$, $\Gamma = 55$ MeV

Channel	Measurements
$\eta\pi\pi$	dσ/dΩ, mass, and Γ
$a_0\pi$	Dalitz plot analysis
$KK\pi$	dσ/dΩ, B. F.
$\rho^0\gamma$	B. F. (upper limit)

The Advantage of a Photon Beam





Pion Beam

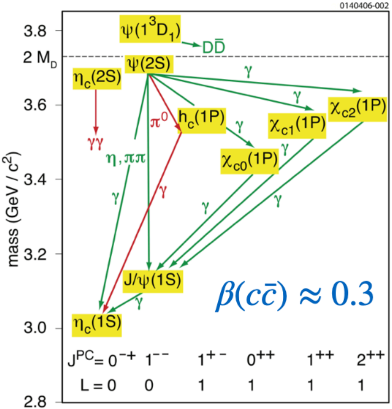
- π with $S = 0$, $L = 0$ and $m = 1$
  ➜ $J^{PC} = 1^{++}, 1^{--}$
- Spin flip required for exotic quantum numbers

Photon Beam

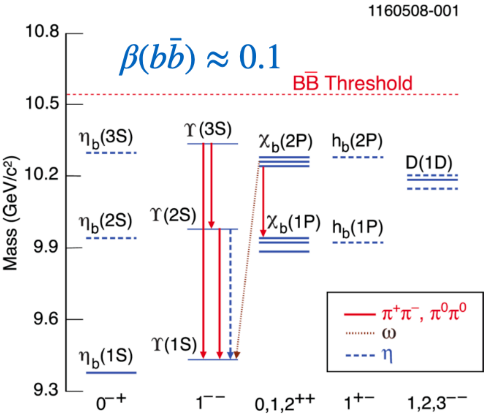
- γ with $S = 1$, $L = 0$ and $m = 1$
  ➜ $J^{PC} = 0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, \ldots$
- No spin flip needed for exotic QN's

Outline

Charmonium vs. Bottomonium

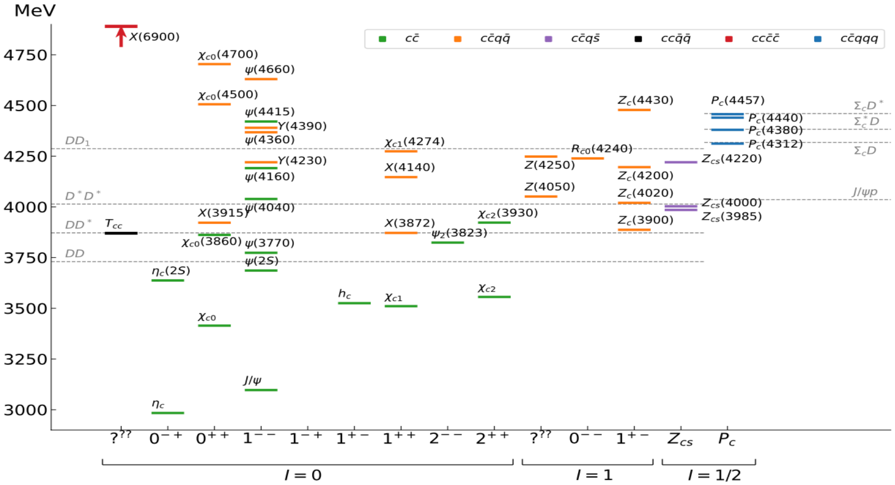


Charmonium $c\bar{c}$



Bottomonium $b\bar{b}$

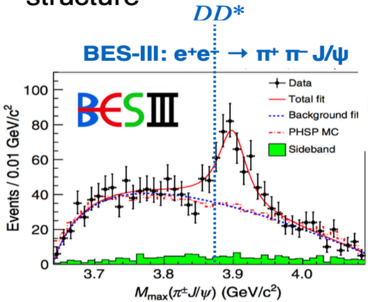
Charmonium Spectra in 2022

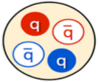


Charged Exotic Hadrons: Z_c^+ and P_c^+

- Resonances in charged final states imply exotic (4 or 5 quark) structure

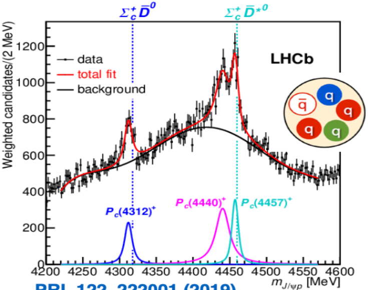
BES-III: $e^+e^- \to \pi^+\pi^- J/\psi$





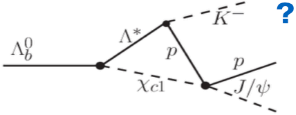
PRL 110, 252001 (2013)

LHCb: $\Lambda_b^0 \to J/\psi\, p\, K^-$



PRL 122, 222001 (2019)

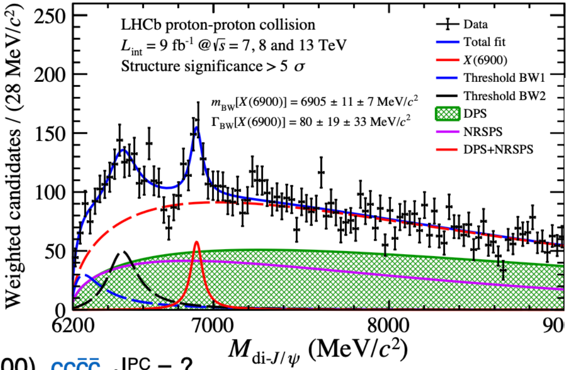
Currently:
6 Zc, 4 Zcs,
4 Pc, 1 Pcs



- Hadronic molecules?
  Virtual states? Rescattering effects?

Charged Exotic Hadrons: Z_c^+ and P_c^+

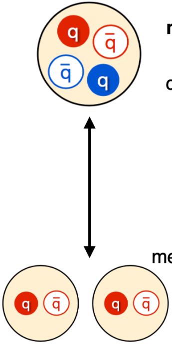
LHCb: pp → J/ψ J/ψ + X



X(6900), $c c \bar{c} \bar{c}$, J^{PC} = ?

Mass = 6905 ± 13 MeV

Width = 80 ± 38 MeV



compact multiquark

bound by color forces

r ≈ 1 fm

bound by meson exchange

r ≈ 5-15 fm

hadronic molecule

Outline

1. Introduction and Motivation
   - The Quark Model of Hadrons
   - Meson Spectroscopy
   - Glue-Rich Environments
2. Glueballs and Light Mesons
   - Glueball Searches
   - The Quest for the Scalar Glueball
   - Exotic Hybrid Mesons
   - Photoproduction
3. Heavy Mesons
4. Summary and Outlook

Summary and Outlook

QCD predicts glueballs and nonets of mesons with exotic quantum numbers.

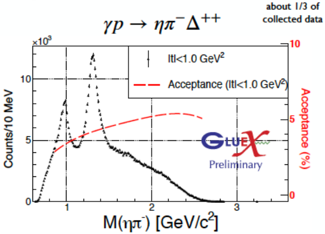
- There are *some* hints for a scalar glueball, but hard to pin down.
- The BESIII Collaboration made an announcement in May 2024 about the pseudoscalar glueball.
- There are hints for some states with exotic quantum numbers; one state is consistent with a π_1 $J^{PC} = 1^{-+}$ state. What about the other states?

  ➜ We have just started to see results from GlueX.
- The previous searches in photoproduction at CLAS have come up negative, but the acceptance has been poor, and the lower energy regime may not have been optimal.
- GlueX has high acceptance for multi-particle final states, sensitivity to photons, and a linearly-polarized photon beam.

Outlook

The GlueX experiment is ideally suited to study the spectrum of light-flavor mesons up to $M \approx 2.8$ GeV and – if existing – the pattern of the gluonic excitations produced in γp collisions:

- It is important to establish the existence and the nonet nature of the 1^{-+} state (and of 0^{+-}, 2^{+-})
- For a given produced resonance, linear polarization will allows us to distinguish between naturalities of exchanged particles.



Analysis of $\vec{\gamma} p \to \eta^{(\prime)}\,\pi^-\,(p)$ priority for GlueX

- Sufficient data available to explore the $\eta\pi$ and $\eta'\pi$ systems with competitive statistics
- Multiple charge combinations and decay modes accessible
- Close collaboration with JPAC

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- It is important to establish the existence and the nonet nature of the 1^{-+} state (and of 0^{+-}, 2^{+-})
- For a given produced resonance, linear polarization will allows us to distinguish between naturalities of exchanged particles.
- About 70 % of the photoproduction cross section in the energy region $E_\gamma \sim 7 - 12$ GeV has multiple neutrals and is completely unexplored.
  - ➜ Many opportunities for GlueX to make key experimental advances in our knowledge of excited mesons and baryons.

Advances in both theory and experiment will allow us to finally understand QCD and confinement.