Exotic Hadrons

How are exotic hadrons different from conventional hadrons?

- Quantum numbers of conventional baryons
- Quantum numbers of mesons: exotic mesons

Glueballs: lattice QCD predictions, experimental status

Models of mesons with excited glue (hybrids)

Exotic mesons in lattice QCD

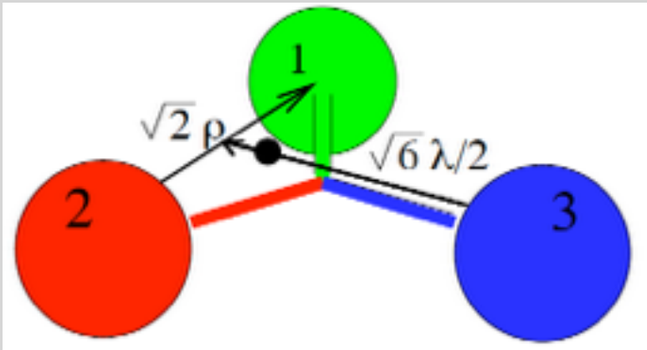
Experimental status of exotic mesons

The future: GlueX in Hall D at Jefferson Lab

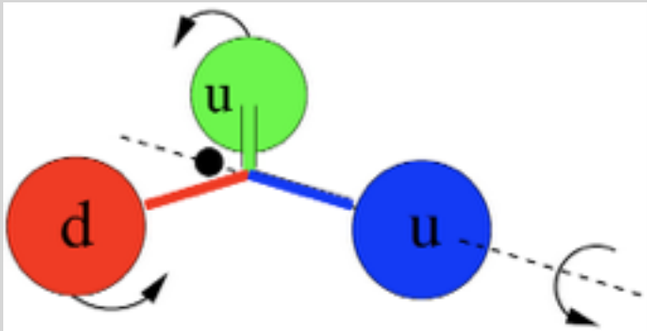
Parity of baryons

Spatial wave functions: separate CM motion by using Jacobi coordinates

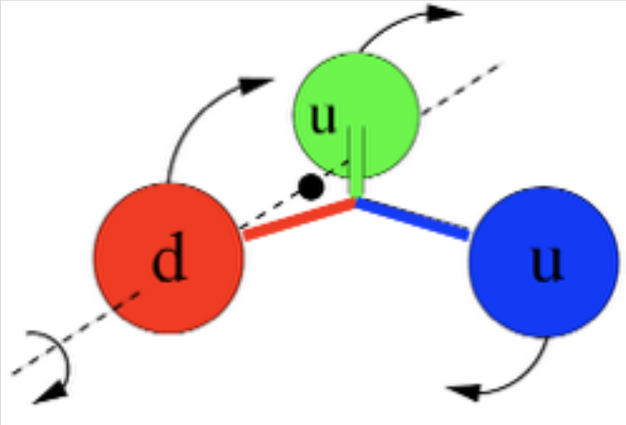
$$\vec{\rho} = \frac{1}{\sqrt{2}}(\vec{r}_1 - \vec{r}_2) \qquad \vec{\lambda} = \frac{1}{\sqrt{6}}(\vec{r}_1 + \vec{r}_2 - 2\vec{r}_3)$$



orbital excitations



$l_\rho = 1$



$l_\lambda = 1$

$$\vec{L} = \vec{l}_\rho + \vec{l}_\lambda$$

Under inversion $\psi(\vec{\rho}, \vec{\lambda}) \to \psi(-\vec{\rho}, -\vec{\lambda}) = (-1)^{l_\rho}(-1)^{l_\lambda}\psi(\vec{\rho}, \vec{\lambda})$

Radial excitations add even powers of ρ and λ, don't change parity; quarks all have the same (+ve) intrinsic parity

Baryon quantum numbers

Assuming only quark degrees of freedom, and a non-relativistic quark model picture, what are the allowable J^P quantum numbers for baryons? Note $P = (-1)^{l_\rho + l_\lambda}$

J^P	L=0	L=1	L=2...
S=1/2	1/2+	$1/2^-, 3/2^-$	$3/2^+, 5/2^+$
S=3/2	3/2+	$1/2^-, 3/2^-, 5/2^-$	$1/2^+, 3/2^+, 5/2^+, 7/2^+$

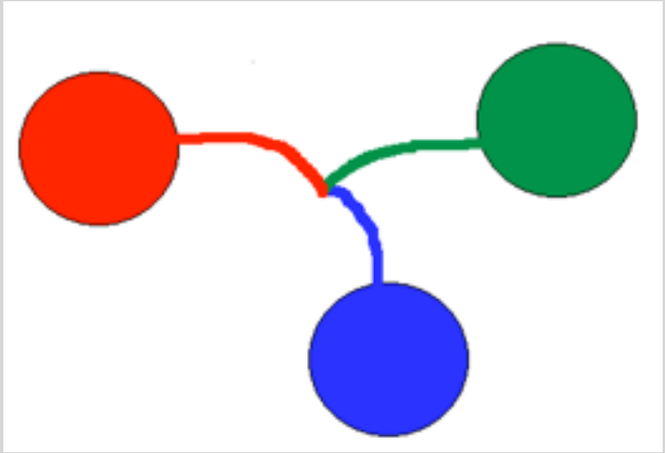
All possible J^P can be made by combining quark orbital angular momentum/parity with quark spin

No exotic baryon quantum numbers!

Unconventional baryons

The assumption of only quark degrees of freedom is unsafe

Baryons may contain excited glue, or any number of quark-antiquark pairs



Flux-tube model of hybrid baryons

If anti-quark has different flavor than quarks, can change flavor quantum numbers and get 'true' *pentaquark*, e.g. $uudd\bar{s}$ (called θ^+)

Despite a flurry of activity (experimental and theoretical) starting in 2003, the evidence for pentaquarks remains controversial (not discussed here!)

Constructing meson states

Start by describing mesons as made up of a quark and an anti-quark, using a non-relativistic quark model

hadrons are not non-relativistic systems

allows definition of conventional hadrons

$$\Psi = C\,\phi\,\Sigma_i\,\psi_i\,\chi_i$$

Sum performed to provide good J

$$C = \frac{1}{\sqrt{3}}(\,r\bar{r} + g\bar{g} + b\bar{b}\,)$$

neutral color

$$\phi(i_1, \bar{i}_2), i_j = u, d, s, c, b$$

flavor

$$\psi(\vec{r}_1, \vec{r}_2) \quad \chi(s_1, s_2), s_j = \uparrow, \downarrow$$

space, spin

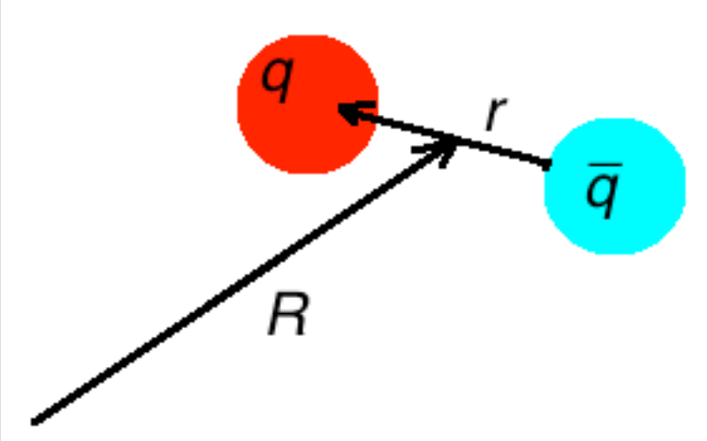
Quantum numbers of meson states

Parity: separate CM motion from spatial wave function

$$\psi(\vec{r}_q, \vec{r}_{\bar{q}}) = \psi(\vec{R})\psi(\vec{r}),\ \ \vec{R} = \frac{1}{2}(\vec{r}_q + \vec{r}_{\bar{q}}),\ \ \vec{r} = \vec{r}_q - \vec{r}_{\bar{q}}$$

Inversion of coordinates:

$$\psi_L(-\vec{r}) = (-1)^L \psi_L(\vec{r})$$



Quark and anti-quark have opposite intrinsic parities

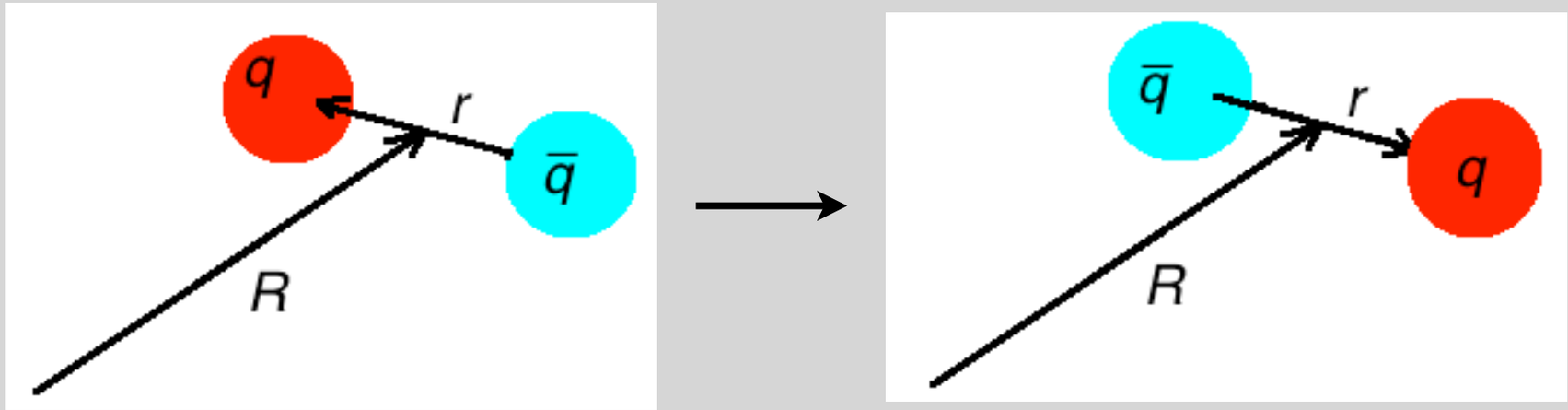
$$P\Psi = -(-1)^L \Psi = (-1)^{L+1} \Psi$$

Quantum numbers of meson states

Charge conjugation changes a particle into its anti-particle and vice-versa, and introduces a phase (intrinsic charge conjugation parity, opposite for fermion and anti-fermion)

$$\mathcal{C}\left\{u\bar{d}\right\} = -\left\{\bar{u}d\right\}, \ \mathcal{C}\left\{u\bar{u}\right\} = -\left\{\bar{u}u\right\}$$

This has the effect of inverting the coordinates



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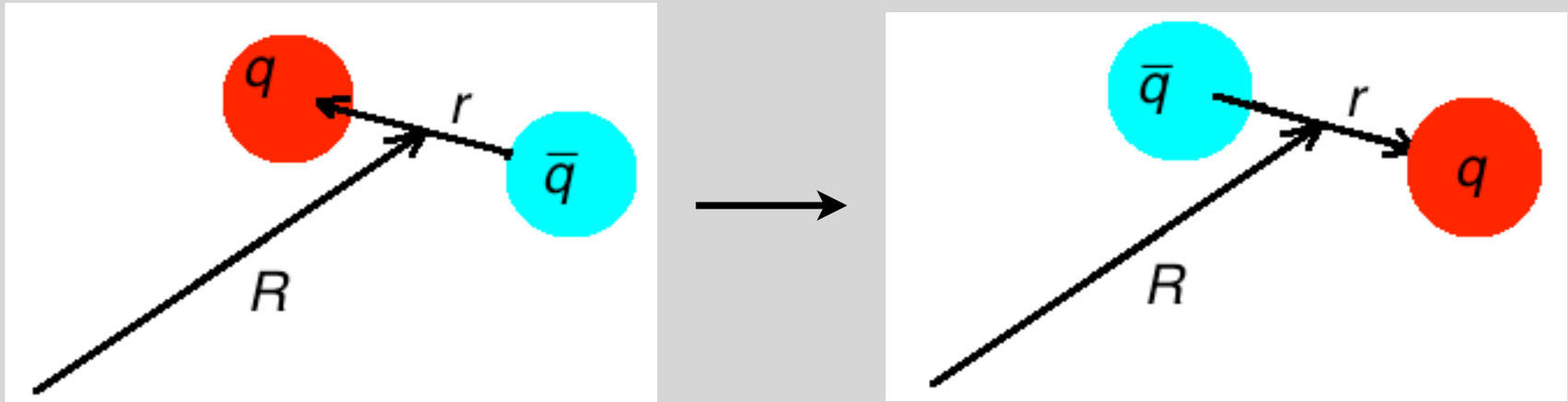
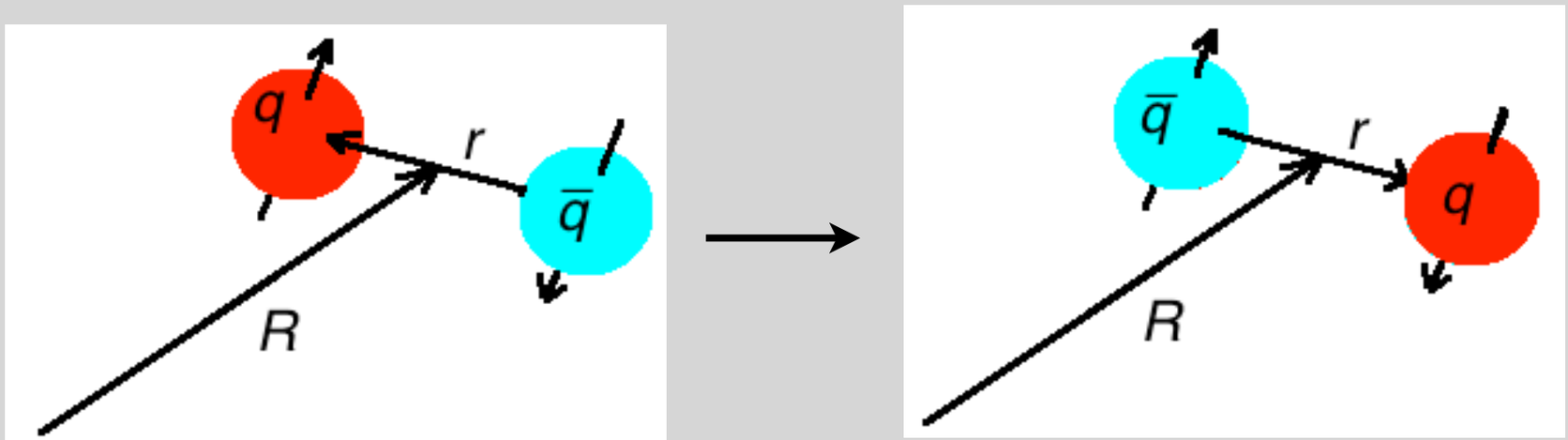


& exchanging the spin projections



Charge conjugation parity

Spin wave functions $\chi_0^0(s_1, s_2) = \frac{1}{\sqrt{2}}(\uparrow\downarrow - \downarrow\uparrow)$

$$\chi_1^1(s_1, s_2) = \uparrow\uparrow,\ \chi_0^1(s_1, s_2) = \frac{1}{\sqrt{2}}(\uparrow\downarrow + \downarrow\uparrow),\ \chi_{-1}^1(s_1, s_2) = \downarrow\downarrow$$

Exchanging the spins of the quark and anti-quark introduces a sign $-(-1)^S$

$$\mathcal{C}\chi^1 = \chi^1\mathcal{C},\ \mathcal{C}\chi^0 = -\chi^0\mathcal{C}$$

For self-conjugate mesons, made up of $u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b}$ e.g. $\pi^0, \rho^0, \omega, \phi, \ldots$ can define a charge-conjugation parity

$$\mathcal{C}\Psi = C\Psi = -(-1)^L(-1)(-1)^S\Psi = (-1)^{L+S}\Psi$$

Charge conjugation parity

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Exchanging the spins of the quark and anti-quark introduces a sign $-(-1)^S$

$$\mathcal{C}\chi^1 = \chi^1\mathcal{C},\ \mathcal{C}\chi^0 = -\chi^0\mathcal{C}$$

For self-conjugate mesons, made up of $u\bar{u},\ d\bar{d},\ s\bar{s},\ c\bar{c},\ b\bar{b}$ e.g. $\pi^0, \rho^0, \omega, \phi, \ldots$ can define a charge-conjugation parity

$$\mathcal{C}\Psi = C\Psi = -(-1)^L(-1)(-1)^S\Psi = (-1)^{L+S}\Psi$$

intrinsic inversion spin projection exchange

G parity

For charged, isospin 1 mesons (made up of light quarks and anti-quarks) e.g. $\pi^{\pm}, \rho^{\pm}, \ldots$ charge conjugation has the effect $\mathcal{C}\pi^{+} = \pi^{-}$ (up to a phase), which can be undone by a rotation about the y-axis in isospin space; define G-parity operator

$$\mathcal{G} = \mathcal{C} e^{i\pi I_2}$$

conserved by strong interactions

Usual angular momentum rules

$$e^{i\pi I_2}|I, I_3\rangle = (-1)^{I-I_3}|I, -I_3\rangle$$

$$\pi^{+} = -u\bar{d},\ \pi^{0} = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}),\ \pi^{-} = d\bar{u}$$

For *all* pions

$$\mathcal{G}\Psi = G\Psi = C(-1)^{I}\Psi = (-1)^{L+S+I}\Psi$$

Note G and C cannot be defined for $K,\ D,\ D_s,\ \ldots$

Exercise

Prove by expanding the exponential, writing I_2 in terms of I_+ and I_-, and using the commutation relations for isospin, i.e., SU(2), that

$$e^{i\pi I_2}|I, I_3\rangle = (-1)^{I-I_3}|I, -I_3\rangle$$

Use of G parity

The $\omega^0(782)$ meson is a ground-state vector meson ($L=0, S=1, J^P=1^-$) with one charge state and no strangeness, so $I=0$

$\rho(770)$ meson is a ground-state vector meson ($L=0, S=1, J^P=1^-$) with three charge states ρ^+, ρ^0, ρ^- so $I=1$

How can they decay to final states with only pions ($L=0, S=0, J^P=0^-$)?

$$G_\pi = (-1)^{L_\pi + S_\pi + I_\pi} = (-1)^{0+0+1} = -1$$

$$G_\rho = (-1)^{L_\rho + S_\rho + I_\rho} = (-1)^{0+1+1} = +1$$

$$G_\omega = (-1)^{L_\omega + S_\omega + I_\omega} = (-1)^{0+1+0} = -1$$

So $\rho \rightarrow \pi\pi$ (100%, Γ~150 MeV), $\omega^0 \rightarrow \pi^+\pi^-\pi^0$, (89%, Γ~8.5 MeV)

Quantum numbers of meson states

Can define isospin I, total angular momentum J=L+S, and parity P for all mesons, e.g. for kaon (L=S=0)

$$I(J^P) = \frac{1}{2}(0^-)$$

...plus G for charged, *I*=1 mesons, e.g. for π^+ (L=S=0, I=1)

$$I^G(J^P) = 1^-(0^-)$$

...plus C for self-conjugate (*I*=0 and *I*=1) mesons, e.g. ρ^0 (L=0, S=1, *I*=1)

$$I^G(J^{PC}) = 1^+(1^{--})$$

Quantum numbers of meson states

Assuming only quark and anti-quark degrees of freedom, and a non-relativistic quark model picture, what are the allowable J^{PC} quantum numbers?

J^{PC}	L=0	L=1	L=2	L=3
S=0	0^{-+} e.g. π	1^{+-} $b_1(1235)$, with $I^G=1^+$	2^{-+} $\eta_2(1235)$, with $I^G=0^+$	3^{+-}
S=1	1^{--} e.g. ρ	$0^{++}, 1^{++}, 2^{++}$ $f_0(980)$, $f_1(1285)$, $f_2(1430)$, with $I^G=0^+$	$1^{--}, 2^{--}, 3^{--}$	$2^{++}, 3^{++}, 4^{++}$

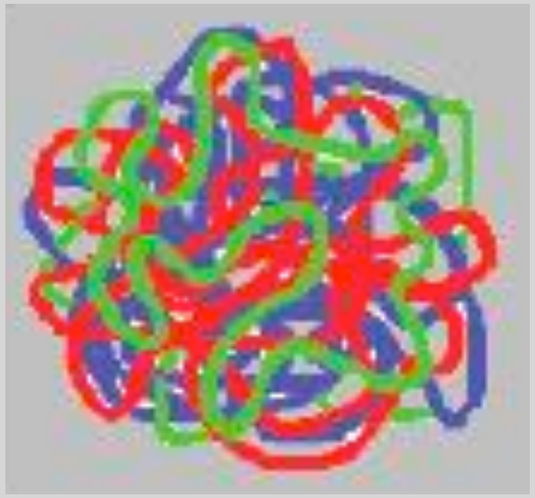
Quantum numbers of meson states

Remarkably, *only* these J^{PC} have been conclusively seen in nature (replace C by G for charged I=1 mesons)

Missing 0^{--}, and the sequence 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+},.... These are known as *exotic* quantum numbers

Glueballs

Because gluons self-interact in QCD, states of pure glue can, in principle, exist



These are bosons with the same quantum numbers as isoscalar mesons; can and will mix strongly with mesons via quark pair creation, complicates interpretation

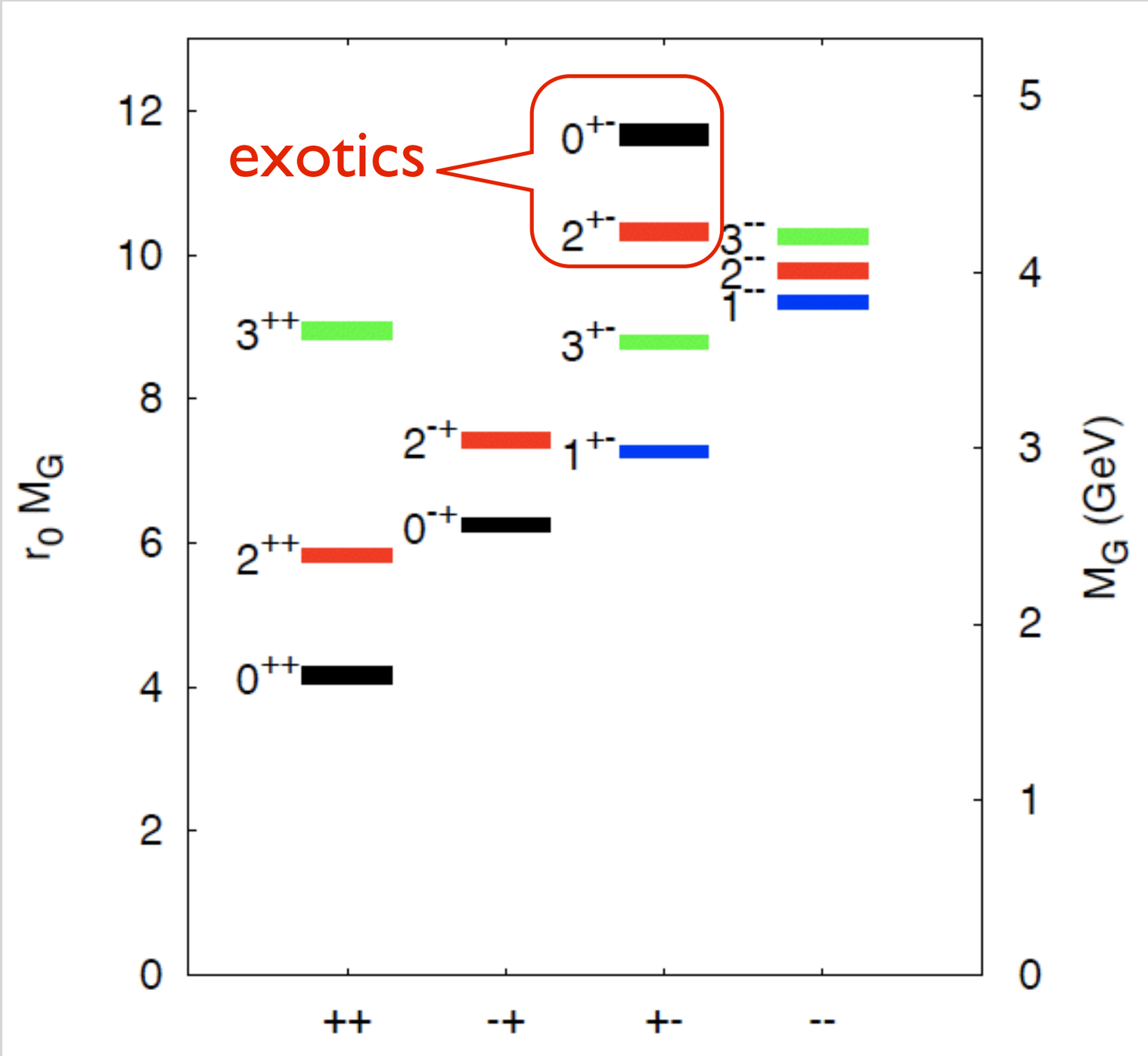
Discovery will rely on overpopulation of states in particular sector, especially light isoscalar scalar mesons

Exotic glueballs can exist

Lattice QCD calculations of glueballs

Y. Chen et al., 2006

Glueballs with exotic quantum numbers (*oddballs*) are high in the spectrum



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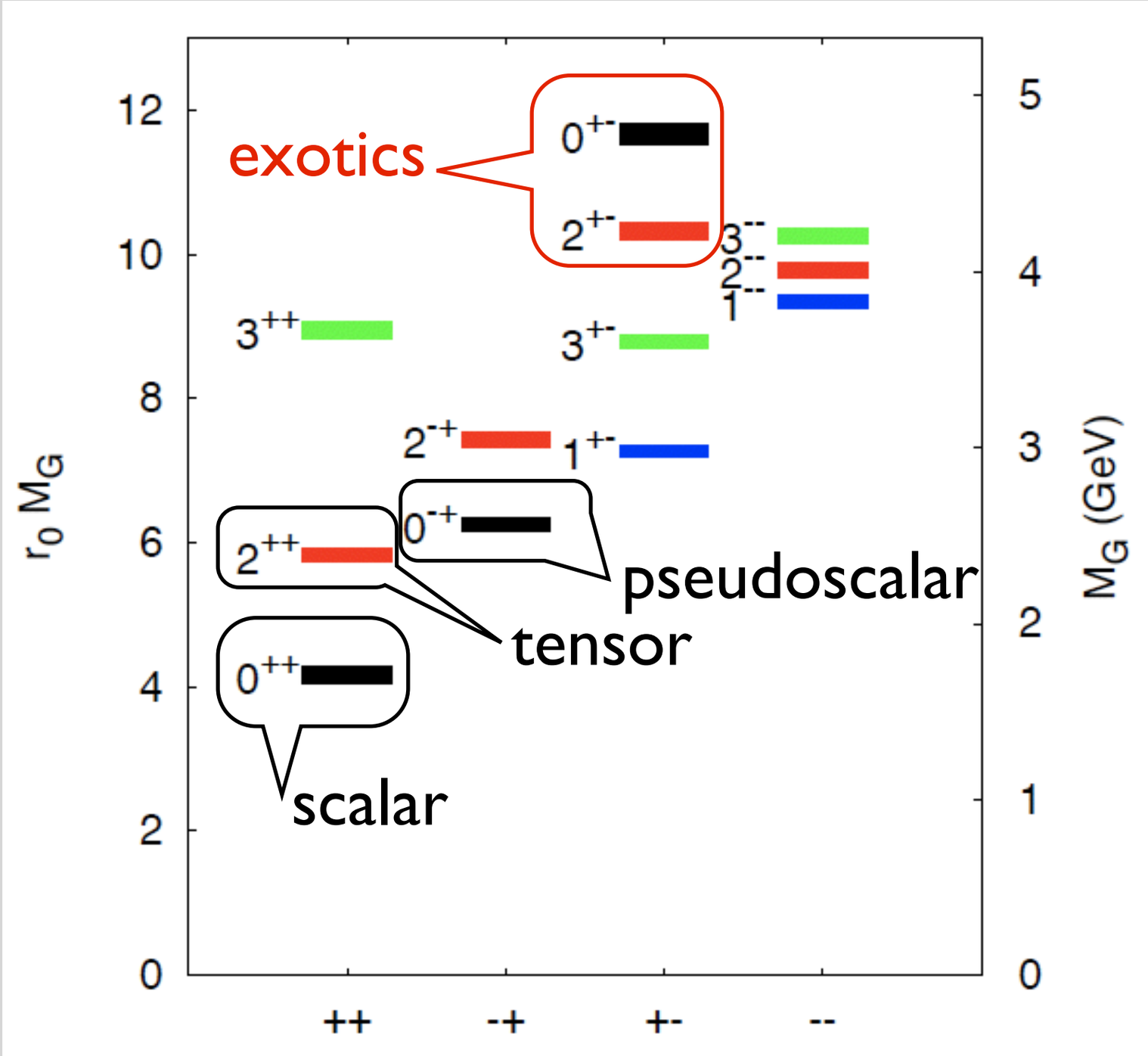
Expt'l. searches have looked for overpopulation and decay signatures in scalar, tensor and pseudoscalar mesons



Experimental signatures for glueballs

Excellent recent review article: V. Crede and C. Meyer (2009)

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	$\pi\pi$, $K\bar{K}$, $\eta\eta$

Isoscalar $J^{PC}=0^{++}$ meson states from Particle Data Group

($*$ means well established)

Experimental signatures for glueballs

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particle formerly known as σ

probably $K\bar{K}$ molecule, with isovector $a_0(980)$

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
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$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$

only two states required to complete a flavor nonet, with isovector $a_0(1450)$, and $K^*(1430)$

All three states may contain admixtures of a glueball; largest in $f_0(1500)$

Models of exotic quantum-number mesons

Recall 0^{--}, and the sequence 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+},.... are *exotic* quantum numbers

How could we extend the quark model to build *exotic* meson states with these quantum numbers?

Add excitations of the gluons binding the quarks; called *hybrid* mesons

Not all exotics!

Hybrid mesons in the bag model

In the bag model, could add a 'constituent gluon' confined to the same spherical cavity (bag) as the quarks

Barnes, Close, de Viron & Weyers, 1983
Chanowitz & Sharpe, 1983

Gluon (vector boson) in a spherical cavity has transverse electric (TE) mode, with $J^{PC}=1^{+-}$, and transverse magnetic (TM) mode, with $J^{PC}=1^{-+}$

TE mode lowest energy; combine with lowest energy L=0, S=0 (0^{-+}) & L=0, S=1(1^{+-}) quark quantum numbers:

Hybrid mesons in the bag model

constituent gluon in TE mode

$0^{-+} \otimes 1^{+-} = 1^{--}$

$1^{--} \otimes 1^{+-} = 0^{-+}, 1^{-+}, 2^{-+}$

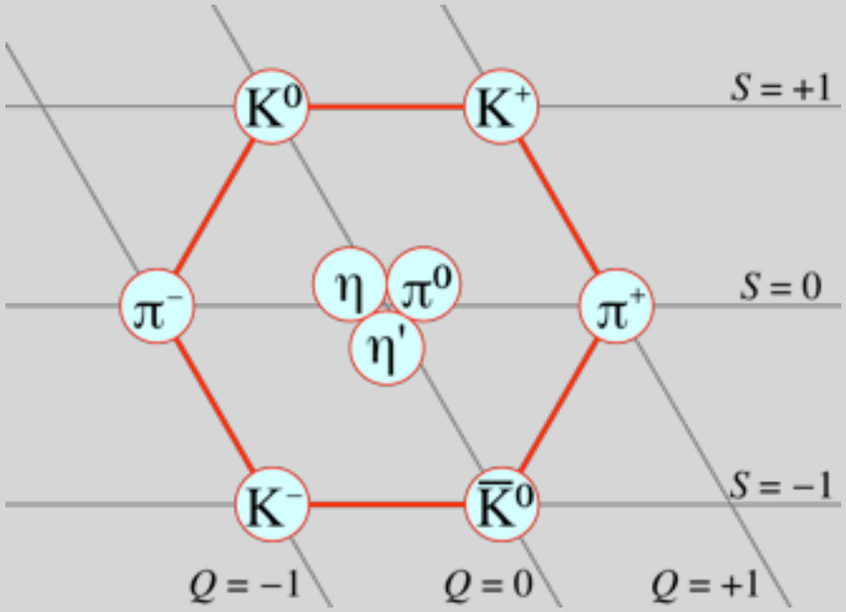
exotic

quarks: spin 0 (e.g. π) and 1 (e.g. ρ)

J^{PC}	I^G: name	I^G: name	I: name
1^{--}	1^+: ρ_1	0^-: ω_1, ϕ_1	½ : K_1^*
0^{-+}	1^-: π_0	0^+: η_0, η_0'	½ : K_0
1^{-+}	1^-: π_1	0^+: η_1, η_1'	½ : K_1^*
2^{-+}	1^-: π_2	0^+: η_2, η_2'	½ : K_2

exotics

Expect four roughly degenerate flavor nonets, ~1.2−1.4 GeV



name same as normal meson with same P, C(G), I

Hybrid mesons in the bag model

constituent gluon in TM mode

$0^{-+} \otimes 1^{-+} = 1^{++}$

exotic

$1^{--} \otimes 1^{-+} = 0^{+-}, 1^{+-}, 2^{+-}$

exotic

quarks, spin 0 (e.g. π) & 1(e.g. ρ)

TM mode is higher energy

J^{PC}	I^G: name	I^G: name	I: name
1^{++}	1^-: a_1	0^+: f_1, f_1'	½ : K_1^*
0^{+-}	1^+: b_0	0^-: h_0, h_0'	½ : K_0
1^{+-}	1^+: b_1	0^-: h_1, h_1'	½ : K_1^*
2^{+-}	1^+: b_2	0^-: h_2, h_2'	½ : K_2

exotics

name same as normal meson with same P, C(G), I

Isovector exotic hybrid mesons

Focus on isovector exotics, easier to see in experiments than isoscalars (see in more than one, independent expt.)

Bag model predicts isovector exotics b_0 (0^{+-}) and b_2 (2^{+-}) should have higher mass than the isovector exotic π_1 (1^{-+})

exotics

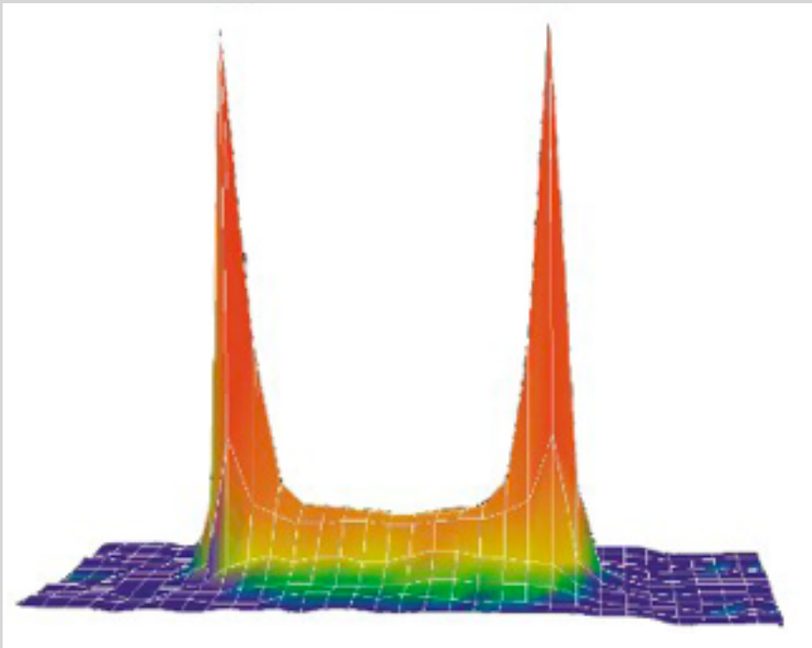
J^{PC}	quarks	glue	I^G: name
1^{-+}	L=0,S=1	TE	1^-: π_1
0^{+-}	L=0,S=1	TM	1^+: b_0
2^{+-}	L=0,S=1	TM	1^+: b_2

normal mesons

J^{PC}	quarks	I^G: name
0^{-+}	L=0, S=0	1^-: π
1^{+-}	L=1, S=0	1^+: $b_1(1235)$

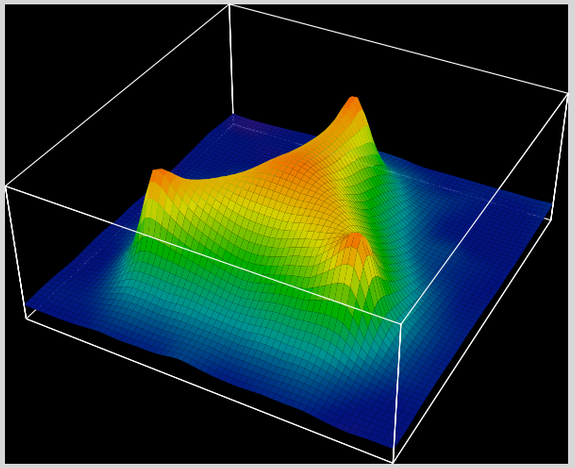
name same as normal meson with same P, C(G), I

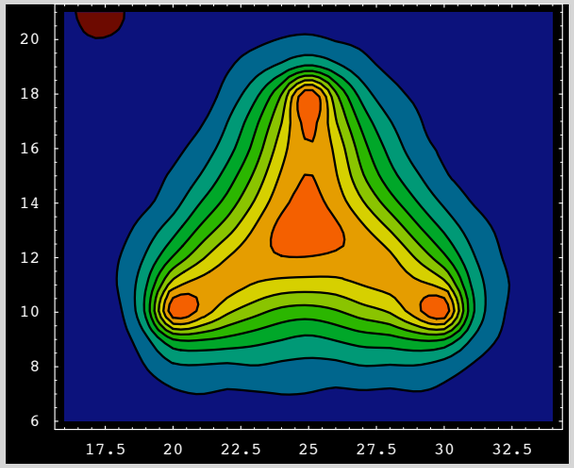
Hybrid mesons in the flux-tube model



Schlichter, Bali, & Schilling, 1997

Abelian action, quenched lattice QCD with static sources



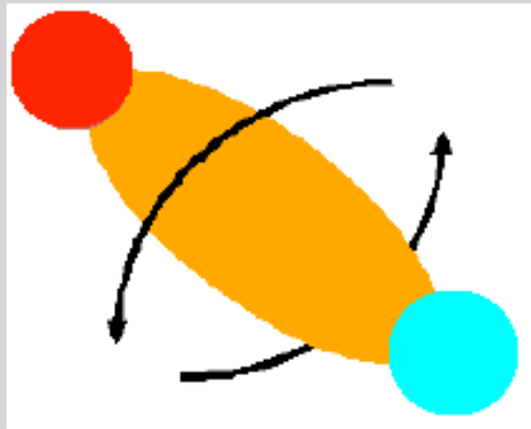


Ichie, Bornyakov, Streuer, & Schierholz (2002)

Abelian action for heavy quarks QQQ in full lattice QCD (with dynamical quarks)

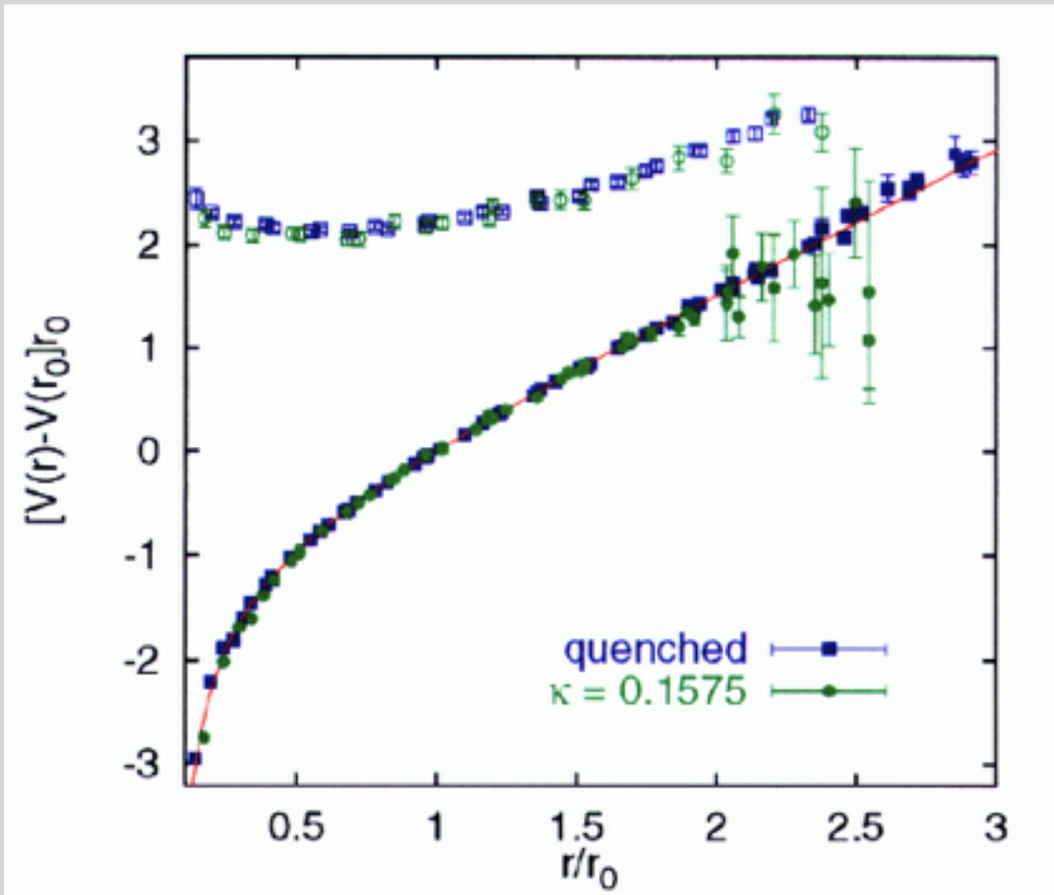
Hybrid mesons in the flux-tube model

Hybrid mesons have gluonic flux-tube between quarks in an excited state



Isgur & Paton, 1985
Isgur, Kokoski, & Paton, 1985

Juge, Kuti and Morningstar, 1999



Build hybrid mesons with quarks moving in potential of excited flux-tube (adiabatic approximation)

Hybrid mesons in the flux-tube model

Flux tube has definite angular momentum projection, m, along quark-antiquark axis

Normal mesons based on ground-state flux-tube, m=0;
$PC=(-1)^{L+1}(-1)^{L+S} = (-1)^{S+1}$

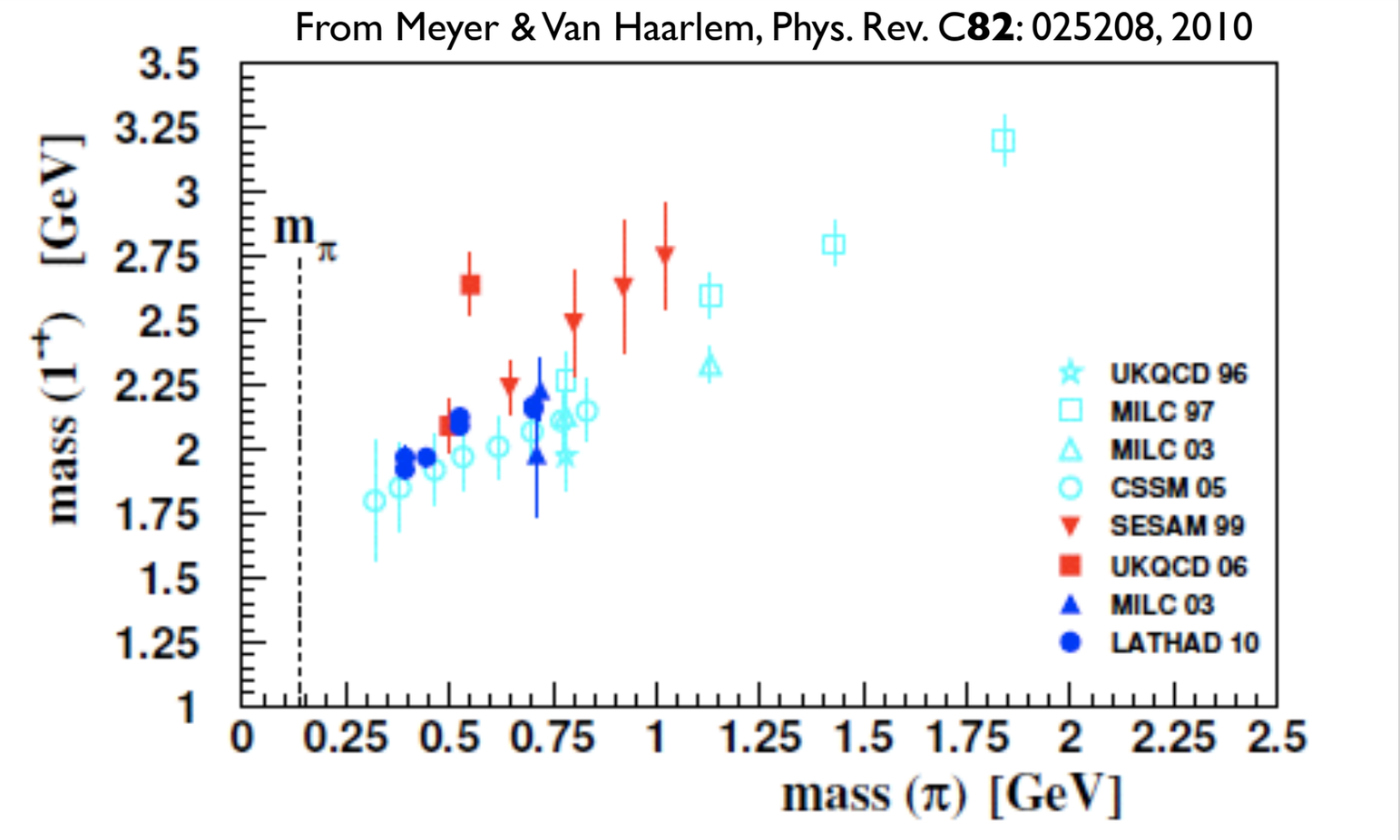
Hybrid mesons based on excited flux-tube, m=1;
$PC=-(-1)^{L+1}(-1)^{L+S} = (-1)^{S}$

Build hybrid meson states by adding one unit of angular momentum and PC=−1, i.e. $J^{PC}=1^{+-}$ or $J^{PC}=1^{-+}$ to quarks

Same hybrids as bag model, except all 8 nonets predicted degenerate in mass, at ~1.9 GeV

Lattice QCD calculations of hybrid mesons

Recent rapid progress; now include dynamical quarks (unquenched); pion masses approaching the physical mass



Lightest $J^{PC}=1^{-+}$ exotic hybrid, quenched, unquenched, unquenched calculations

- Latest results from Lattice Hadron Spectrum Collaboration (LHSC; JLab, Trinity College): Dudek, Edwards, Peardon, Richards and C.E. Thomas (2010)

Lattice Hadron Spectrum Collaboration

Include dynamical quarks (unquenched); two light flavors and one heavier (s) quark

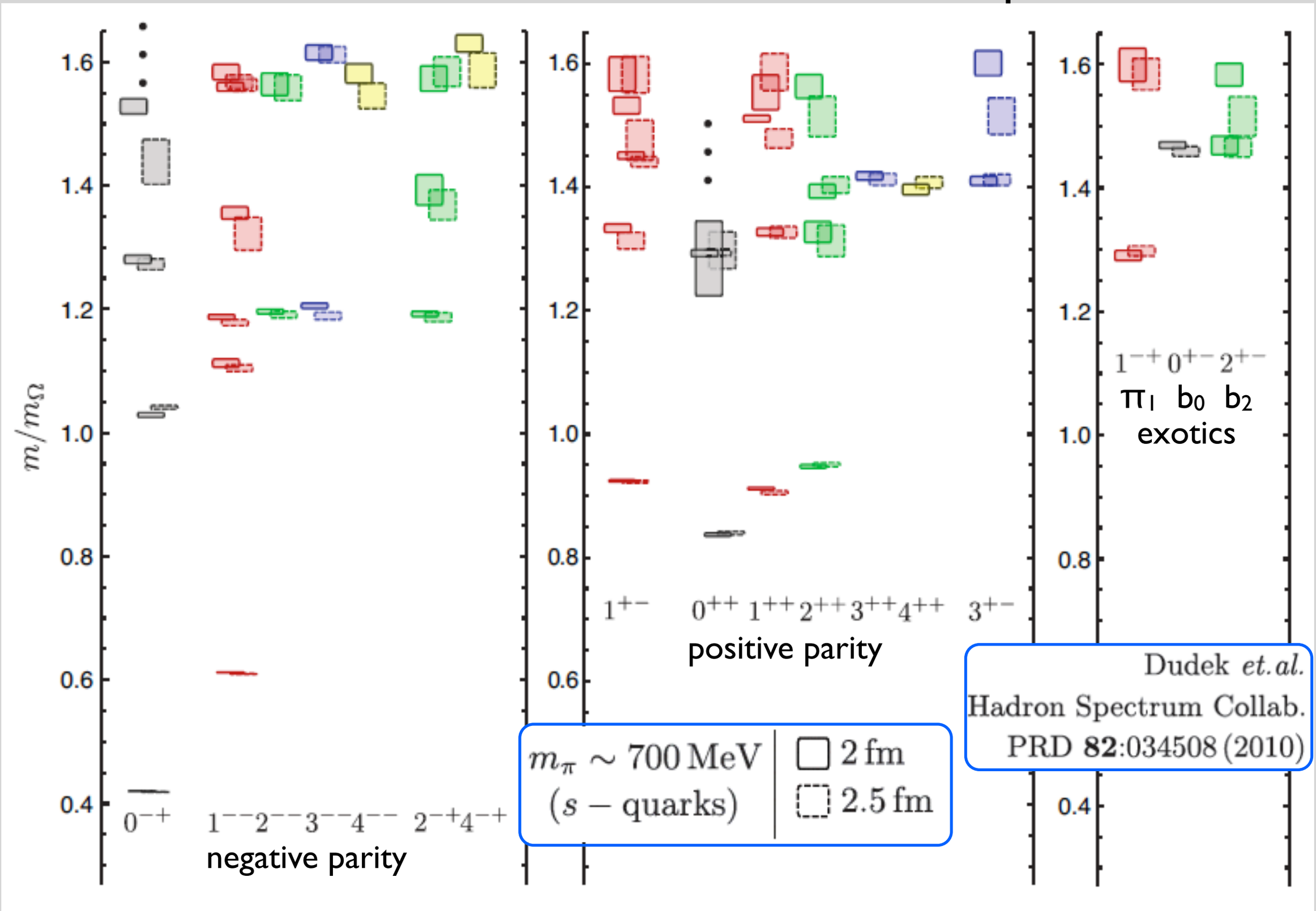
Finer lattice spacing in time direction to better see excited states

Variational calculation using a large basis of interpolating meson operators, allows extraction of masses of many excited states

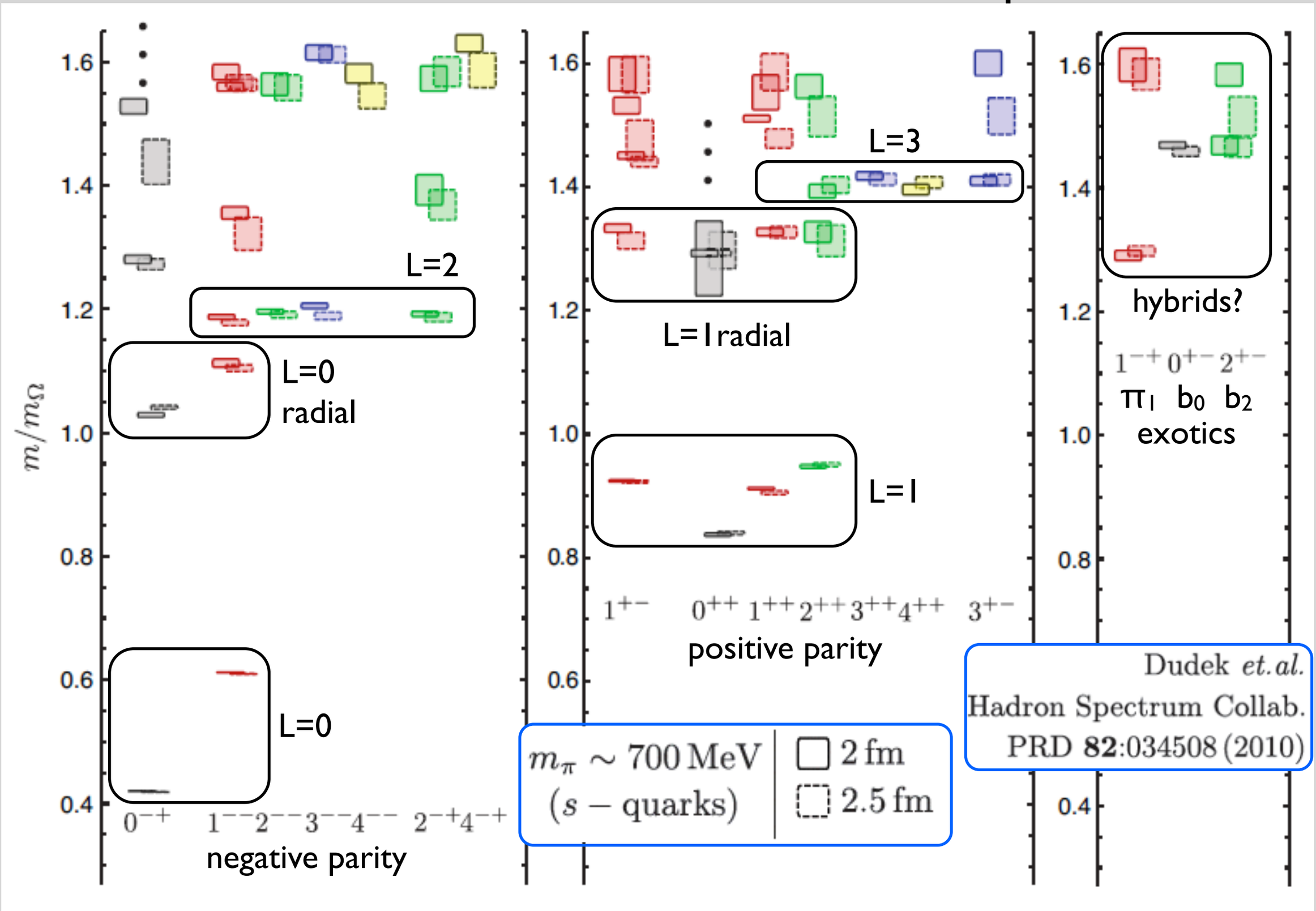
Operators constructed with known continuum behavior

Continuum meson operators (definite J,M) have their various M components distributed into cubic (lattice) irreducible representations

LHSC calculation of isovector meson spectrum



LHSC calculation of isovector meson spectrum

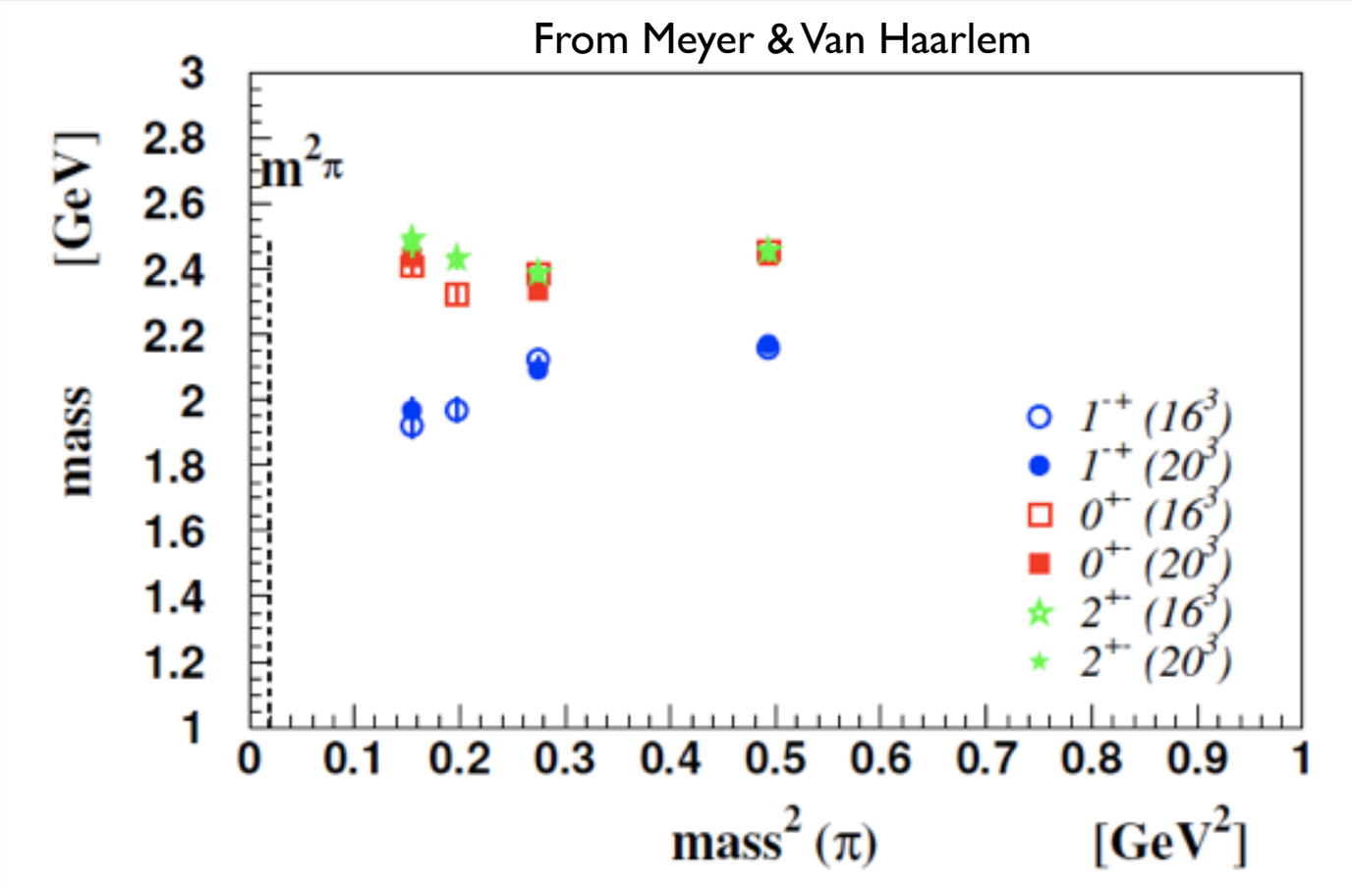


Lattice QCD calculations of hybrid mesons

π_1 ($J^{PC}=1^{-+}$) lighter than roughly degenerate b_0 (0^{+-}) and b_2 (2^{+-})

Lightest hybrid π_1 ~1.2 GeV above ρ

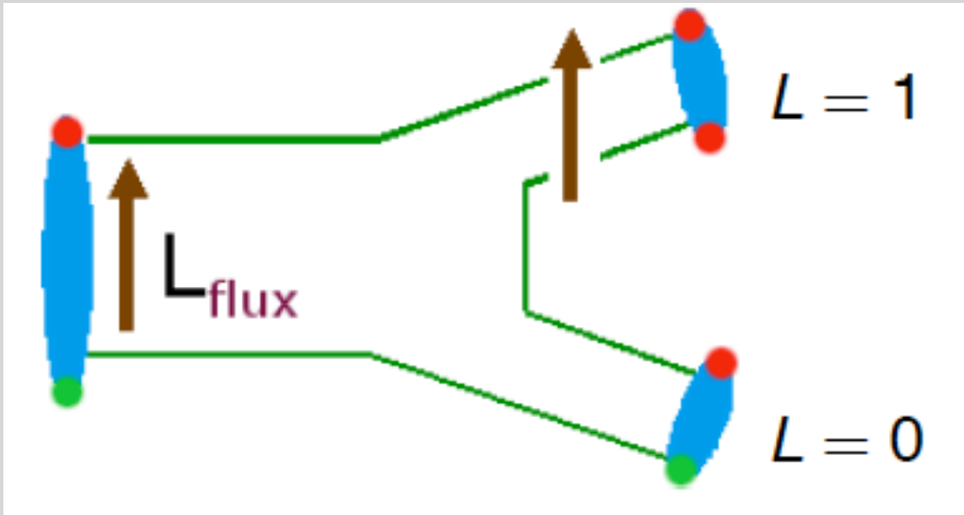
Looks like bag model spectrum, and *not* flux-tube model!



Pion-mass and lattice-size dependence of exotic masses

Experimental status of exotic mesons

To find them we need to know how they decay: flux-tube model predicts angular momentum of glue stays in one of daughter mesons



Isgur, Kokoski, & Paton, 1985

Close & Page, 1995

Page, Swanson, & Szczepaniak, 1999

Close and Page: decays to two L=0 mesons are suppressed, but not zero; π_1 hybrid has

$b_1\pi$	:	$f_1\pi$	:	$\rho\pi$	:	$\eta\pi$	:	$\eta'\pi$
170	:	60	:	$5-20$	:	$0-10$	:	$0-10$

Multi-particle final states with charged and neutral pions (→2 photons), e.g.

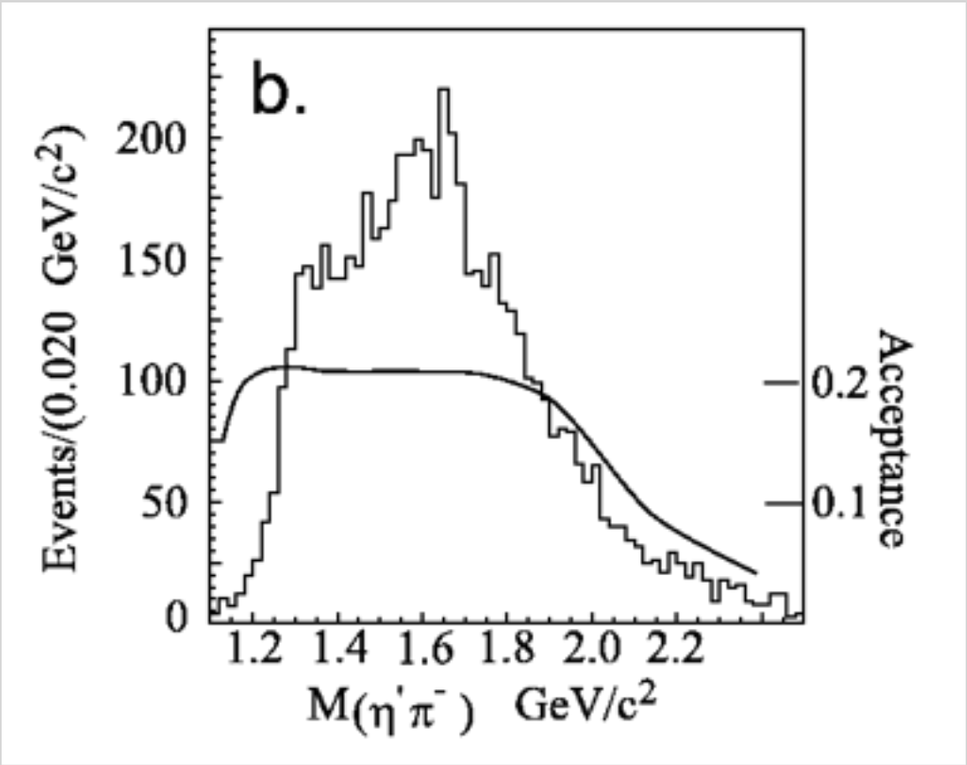
$$b_1\pi \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^0$$
$$f_1\pi \rightarrow \eta\pi\pi\pi$$

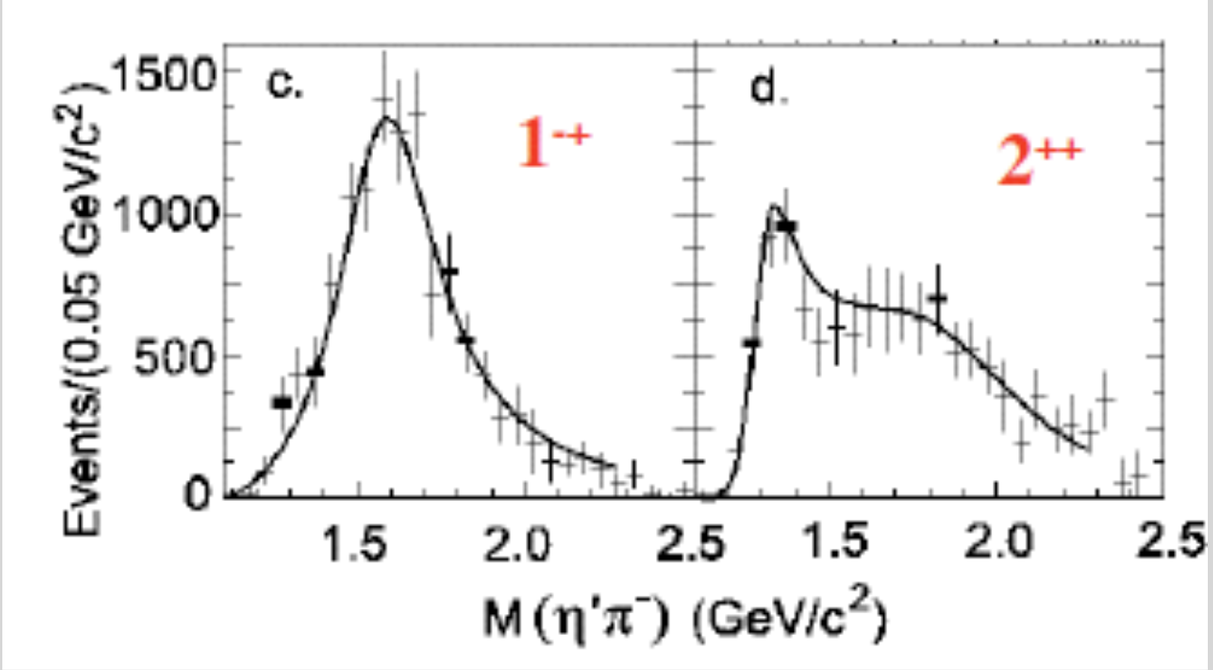
Experimental status of exotic mesons

Convincing evidence exists for effects in $J^{PC}=1^{-+}$ partial wave

BNL-E852 (2001)

$\pi^- p \rightarrow p\eta'\pi^-$





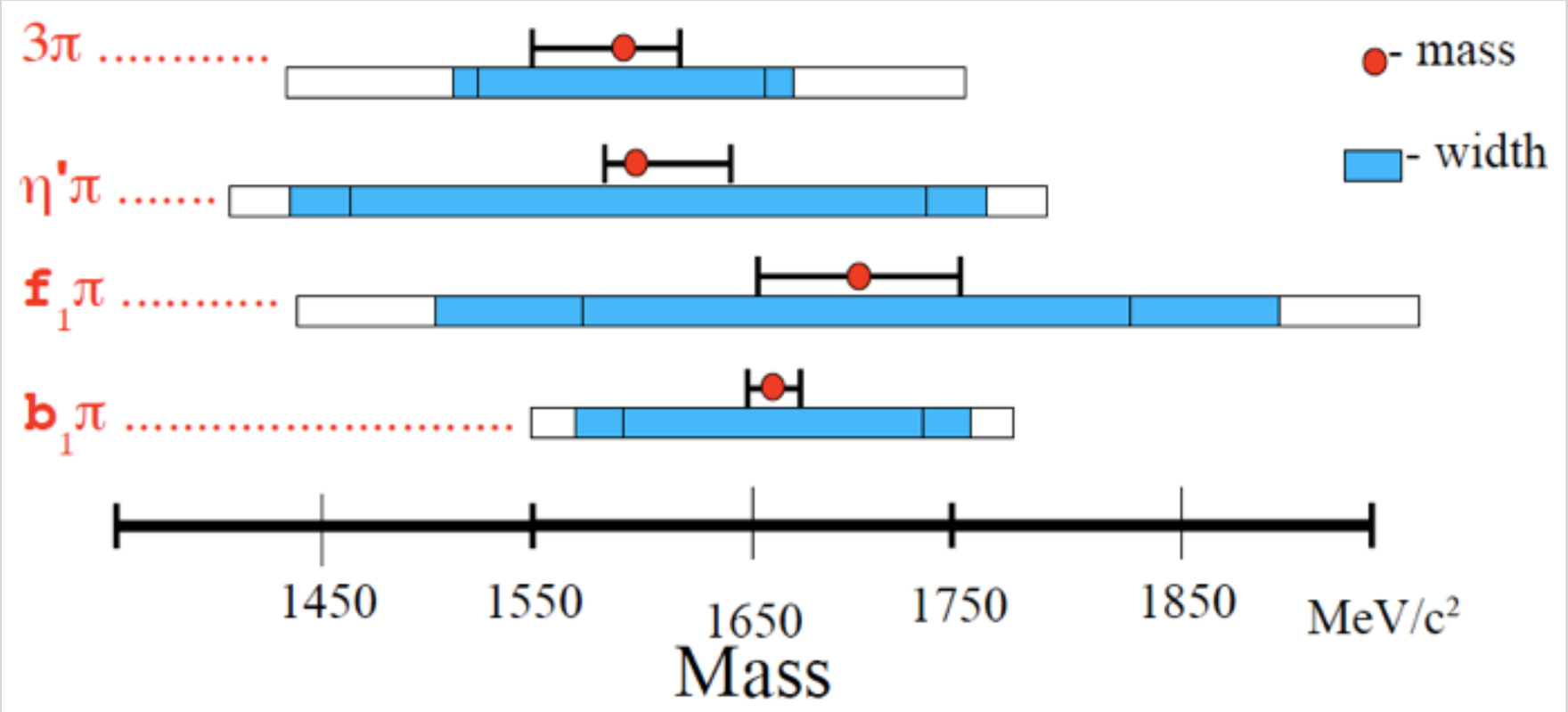
also seen by

VES (2005)

Also seen in flux-tube model favored modes $b_1(1235)\pi$, $f_1(1285)\pi$ by both collaborations, and in $\rho\pi$

Interpretation as $\pi_1(1600)$ hybrid is controversial!

Experimental status of exotic mesons



Reasonable, but not great, consistency between states seen using several decay modes

Results from all channels suggest Pomeron exchange mechanism for production from proton with pions

GlueX experiment at Jefferson Lab

Use a polarized photon beam on proton instead of pions

Vector beam (ρ) should enhance production of exotic hybrids compared to π beam

constituent TE gluon

$0^{-+} \otimes 1^{+-} = 1^{--}$

exotic

$1^{--} \otimes 1^{+-} = 0^{-+}, 1^{-+}, 2^{-+}$

quarks: spin 0 (e.g. π) and 1 (e.g. ρ)

GlueX detector optimized for partial wave analysis of multi-particle (neutral and charged) final state

GlueX Experiment

Goal: map the spectrum of exotic hybrid mesons

Method: Photo-produce hybrids off proton target and identify the quantum states using Partial Wave Analysis of decay product distributions

$\vec{\gamma} + p \rightarrow p + X$ ↳ $b_1\pi$ ↳ $\omega\pi$ ↳ $\pi\pi\pi$

9GeV linearly polarized — hybrid meson

$\vec{\gamma} + p \rightarrow p + X$ ↳ $f_1\pi$ ↳ $\eta\pi$ ↳ $\pi\pi\pi$

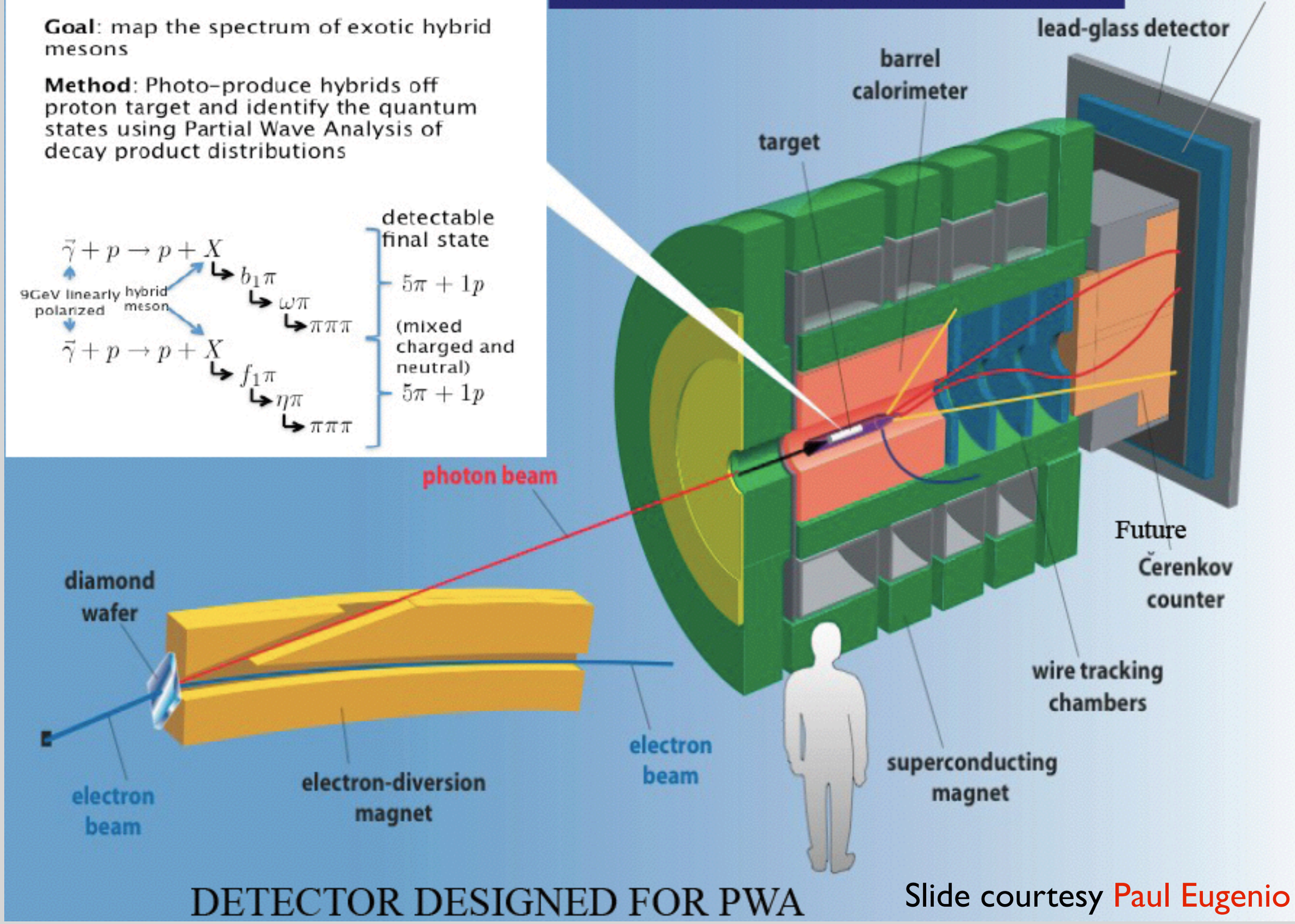
detectable final state

$5\pi + 1p$

(mixed charged and neutral)

$5\pi + 1p$

GlueX Detector



DETECTOR DESIGNED FOR PWA

Slide courtesy Paul Eugenio

Resources

C.A. Meyer and Y. Van Haarlem, *The Status of Exotic-quantum-number Mesons*, PRC (2010)

V. Crede and C.A. Meyer, *The Experimental Status of Glueballs*, Prog. Nuc. Part. Phys. (2010)

GlueX experiment at Jefferson Lab

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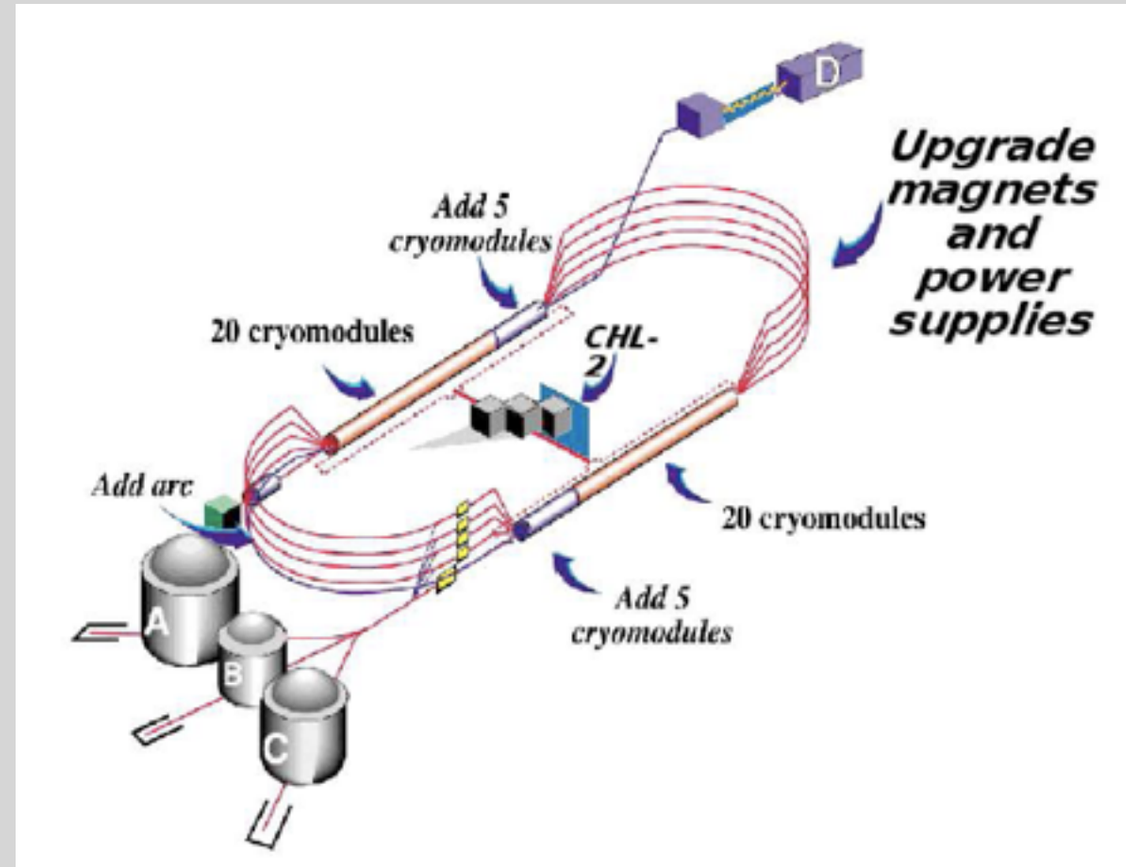

Hall D: ground broken April 2009

GlueX detector construction complete

Current plan: first beam in Hall D/GlueX late 2014