# Modern Hadron Spectroscopy : Challenges and Opportunities

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**Lecture 1: Hadrons as laboratory for QCD:**

- **Introduction to QCD**
- **Bare vs effective effective quarks and gluons**
- **Phenomenology of Hadrons**

**Lecture 2: Phenomenology of hadron reactions**

- **Kinematics and observables**
- **Space time picture of Parton interactions and Regge phenomena**
- **Properties of reaction amplitudes**

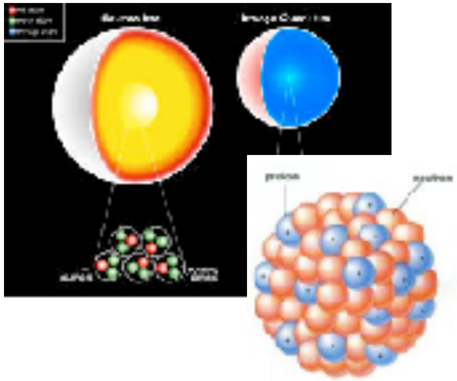
**Lecture 3: Complex analysis**

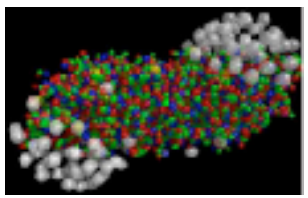
**Lecture 4: How to extract resonance information from the data**

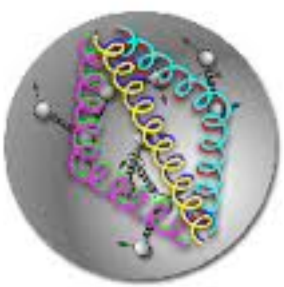
- **Partial waves and resonance properties**
- **Amplitude analysis methods (spin complications)**

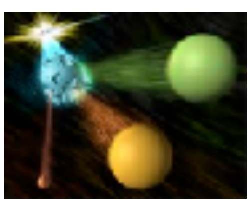
# Why QCD and Hadron Spectroscopy



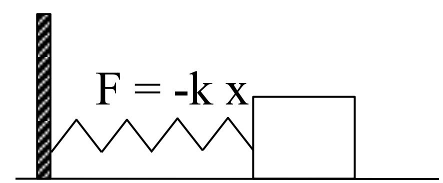








- A single theory describing nuclear phenomena at distance scales $O(10^{15}m)$ as well as $O(10^{4}m)$.
- It builds from objects (quarks and gluons) that do not exist. Gluons are responsible for mass generation and color confinement.
- ~99% mass comes from interactions!
- Complex ground state (vacuum) and excited (hadrons) states (monopoles, vortices, …)
- Predicts existence of exotic matter, e.g. matter made from radiation (glueballs, hybrids) and novel plasmas.
- A possible template for physics beyond the Standard Model
- It is challenging !



# Stranger Things (of the Nuclear World)

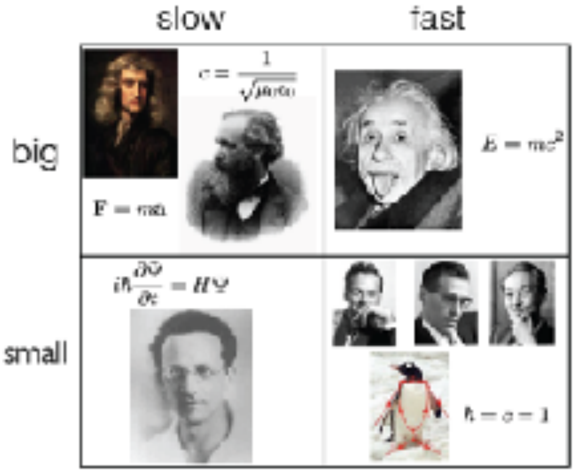



What are the constituents of hadrons, (quarks and gluons) ?

small world ($10^{-15}$m)

of fast (v~c) particles

exerting ~1T forces !!!




$$\hbar = c = 1$$

[length] = [time] = $[\text{energy}]^{-1}$ = $[\text{momentum}]^{-1}$

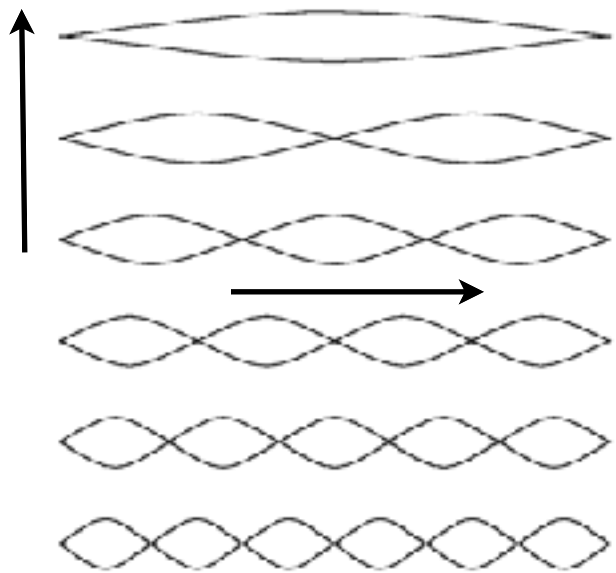
Unit energy = 1GeV

Unit lengt = $1\text{GeV}^{-1}$ = 0.197 fm

In relativistic quantum mechanics (QFT) particles are emergent phenomena

(i.e. fields are not physically measurable but their “consequences” are, cf. potential vs electric field density)

“excitation of the aether” → field

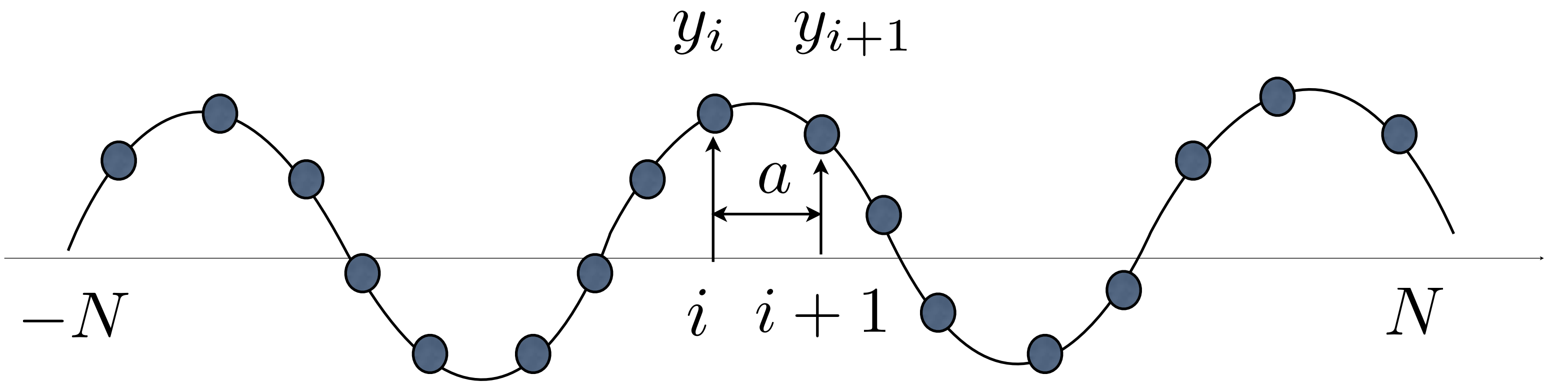


collective motion → particle

$H = H_{h.o} =$ (coupled) harmonic oscillators

“bare” particles : eigenstates of $H_{h.o.}$

The only physical mass parameter is the distance between “beads” a




$dim[p] = 1 \quad dim[q] = 0$

In the continuum limit

$[p(x), q(y)] = -i\delta(x-y)$

$a \to 0 \qquad q_i = \frac{y_i}{a}$

$$H = \frac{1}{2} a \sum_i \left[ p_i^2 + \frac{1}{a^2} (q_i - q_{i+1})^2 \right] \longrightarrow H = \frac{1}{2} \int dx \left[ p^2(x) + (\partial q(x))^2 \right]$$

Fourier transform linearize Hamiltonian $p(x) \to p(k) = \int dx e^{ikx} p(x) \qquad q(x) \to q(k) = \int dx e^{ikx} q(x)$

Particles associated with creation and annihilation operators

$$q(k) = a(k) + a^\dagger(k) \qquad |k\rangle = a^\dagger(k)|0\rangle \quad |k,q\rangle = a^\dagger(k) a^\dagger(q)|0\rangle, \cdots$$

# Renormalization



- The distance scale a was the only mass scale, e.g. $E = O(a^{-1})$ and there is now continuum limit for energy. This a reflation of scaling invariance of the continuum Hamiltonian.
  $$x \to \lambda x \quad H \to \frac{H}{\lambda}$$
- A calculable QCD "scheme" (e.g. lattice, S-D equations, etc) needs a distance scale. (aka anomalous symmetry breaking).
- All physical quantities are determined w.r.t to his scale, (e.g. pion mass in QCD, or electron mass in QED)
- Renormalizable QFT : scale is there, but it is arbitrary, i.e. the theory predicts how observables change with scale.
- Non-renormalizable (effective) QFT : scale if fixed, i.e. the theory is only valid (predictive) at a particular scale.

# Example:



In 0+1 dimension (Quantum Mechanics in 1 special dimension) find bound states of the Hamiltonian

$$H = p + \lambda\delta(x) = \sqrt{p^2} + \lambda\delta(x)$$

$$(\hat{p} + \lambda\delta(\hat{x}))|\psi\rangle = E|\psi\rangle$$

$$\langle k|\hat{p}|\psi\rangle + \lambda\langle k|\delta(\hat{x})|\psi\rangle = E\langle k|\psi\rangle$$

$$|k|\psi(k) + \lambda\int\frac{dk}{2\pi}\ \underbrace{\langle k|\delta(\hat{x})|k'\rangle}\ \psi(k') = E\psi(k)$$

$$= \int dx\, e^{i(k-k')x}\ \delta(x) = 1$$

$$|k|\psi(k) + \lambda\underbrace{\int_{-\infty}^{+\infty}\frac{dk}{2\pi}\ \psi(k)}_{N} = E\psi(k)$$

$$\psi(k) = \frac{-\lambda N}{|k| - E} \Rightarrow N = -\frac{\lambda N}{2\pi}\int_{-\infty}^{+\infty}\frac{dk}{|k| - E}$$

$\Rightarrow$ need $\lambda < 0$, $E < 0$ and cutoff $\pm\infty \to \pm\Lambda$

$$\Rightarrow 1 = \frac{(-\lambda)}{\pi}\int_0^{\Lambda}\frac{dk}{|k| + (-E)} = \frac{|\lambda|}{\pi}\ \ln\frac{\Lambda}{|E|}$$

$$\Rightarrow |E| = \Lambda e^{-\frac{\pi}{|\lambda|}}$$

Hamiltonian is scale invariant!

# Particles vs Fields: Hamiltonian vs Lagrangian 

Legendre transformation

$$H(p_i, q_i) \longleftrightarrow$$

Quantization

Quantization

Probabilistic interpretation

Quantum picture:
particles, states,
operators, etc.

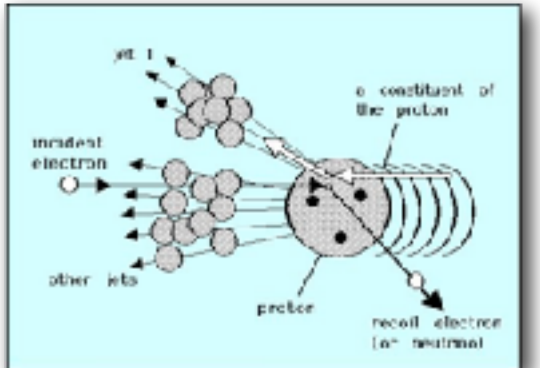
$\longleftrightarrow$

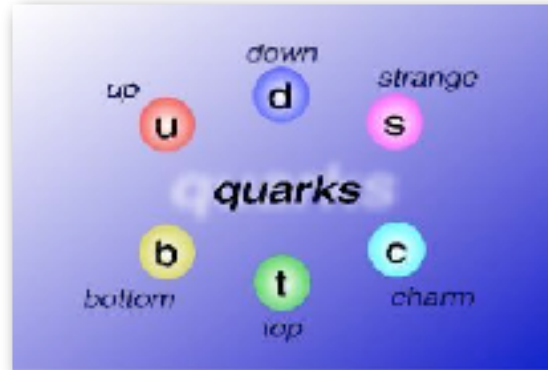
Semiclassical Picture:
path integral,
classical solution
(solitons), etc.

# Bare particles are eigenstates of free Hamiltonian 

## "Bare (free)" particles of QCD: quarks and gluons

e.g. because of asymptotic freedom
measured in high energy collisions





- Gluon ~ 8 copies of a photon
- Photons do not cary electric charge : they only interact the matter (e.g.) electrons that do carry charge
- Gluons carry charge, i.e. interact with each other and with quarks.

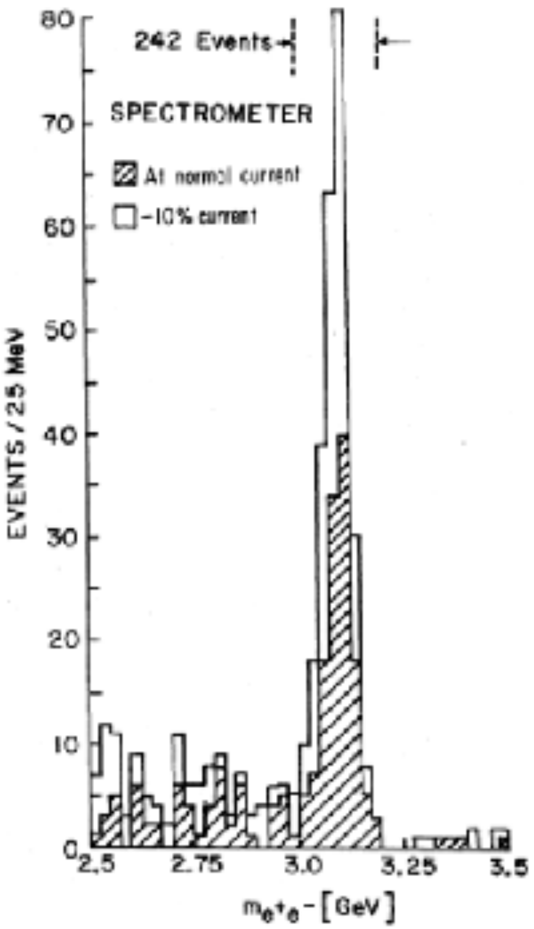
# Discovery of quarks e.g. the J/ψ



A narrow resonance was discovered in the 1974 November revolution of particle physics" in two reactions:

Proton + Be => $e^+$ $e^-$ + anything at the BNL J. J. Aubert et al., "Experimental observation of a heavy particle J," Phys. Rev. Lett. 33, 1404 (1974).

$$J/\psi = c\bar{c}$$




$e^+e^-$ annihilation to hadrons in the SPEAR storage ring at Stanford J. E. Augustin et al., "Discovery of a narrow resonance in $e^+e^-$annihilation," Phys. Rev. Lett. 33, 1406 (1974).

$$\text{mass} = 3096.87 \text{ MeV}$$

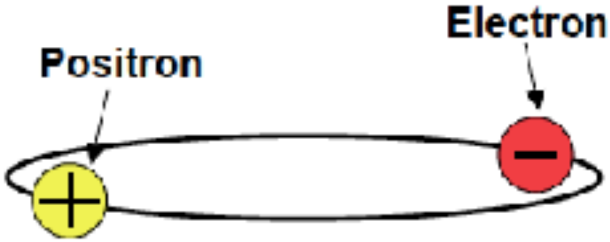
$$\Gamma = 87 \text{ keV}$$

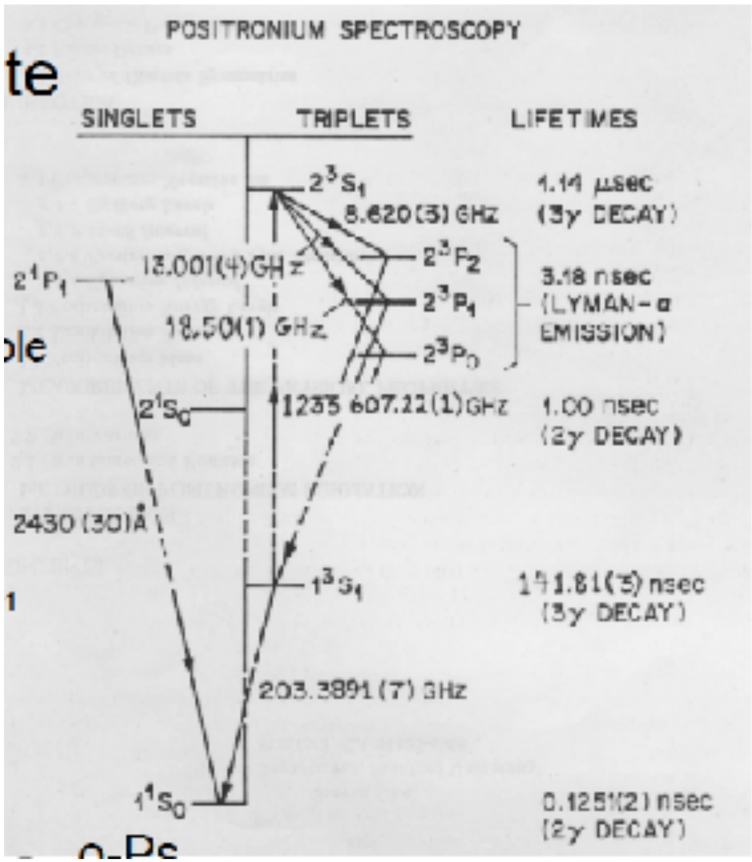
$10^3$ longer lifetime !

(weak interactions $10^{12}$) typical hadronic width $= O(100 \text{ MeV})$

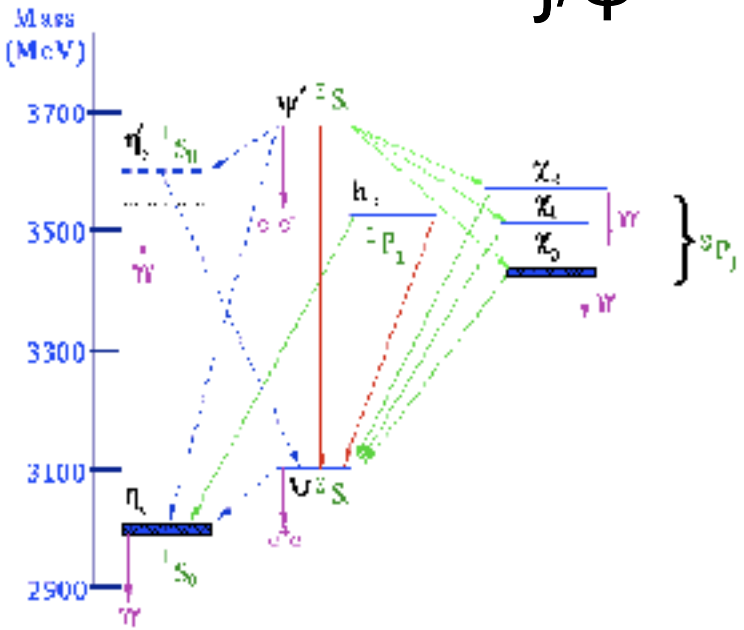
# Charmonium spectrum

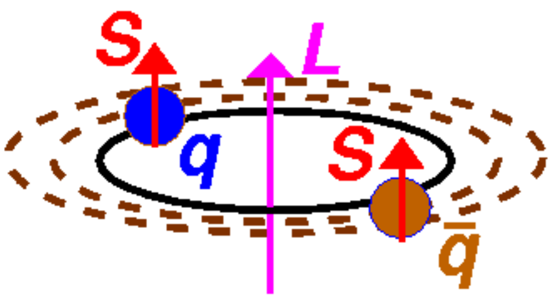





J/ψ



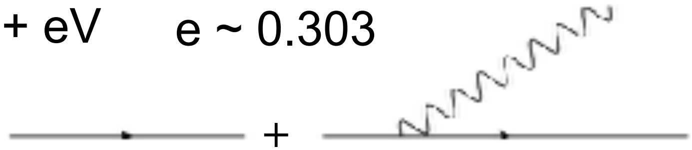




J/ψ is a bound state of $\bar{c}$ c

# QED vs QCD

- Bare particles are eigenstates of free Hamiltonian. If interactions are weak (QED) the "bare particle" ~ observed particle = (interacting particles)

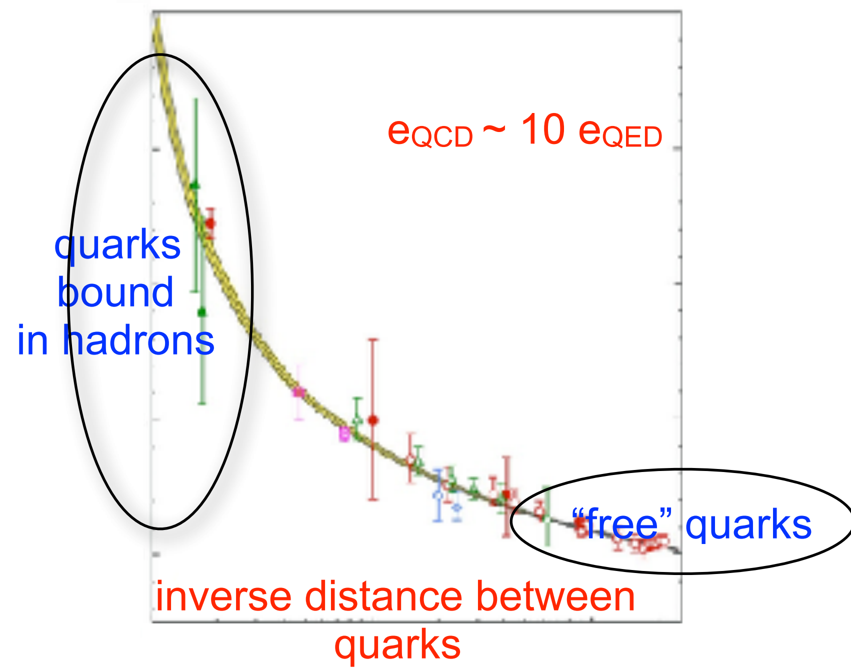
$H_{QED} = H_{c.h.o.} + eV \qquad e \sim 0.303$

|electron> =  $+ \; O(e^2)$

|bare electron> eV|bare electron>

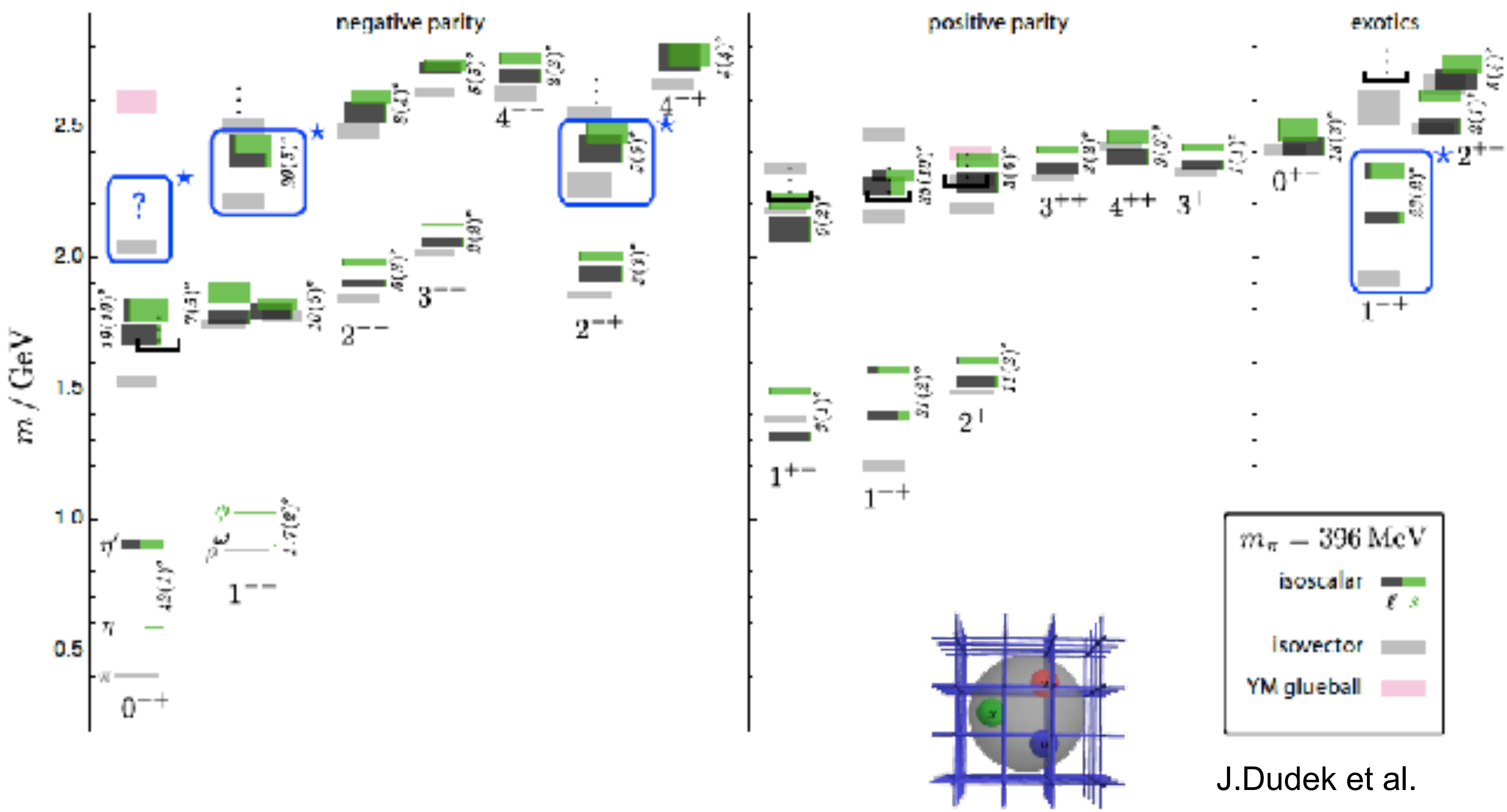
- Quarks in hadrons have effective color charge e > 3-4. There is no reason why quarks should retain their identify in presence of strong interactions …

…but it seems they do



# “Evidence” for Constituent Quarks: Light Quark Hadrons

Spectrum of mesons containing u,d,s quarks from numerical QCD simulations (lattice) resembles spectrum of quark models.




J.Dudek et al.

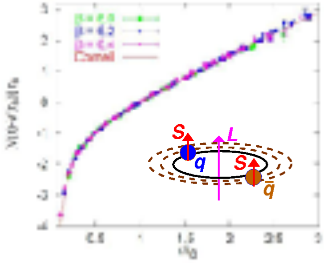
# Emergence of constituent quarks



$$H = H_{kin} + V = H_{h.o} + V$$

(Color) charge density     (Color) charge density

$$V = \int d\mathbf{x} d\mathbf{y} \rho(x) V(|\mathbf{x}-\mathbf{y}|)\rho(\mathbf{y})$$

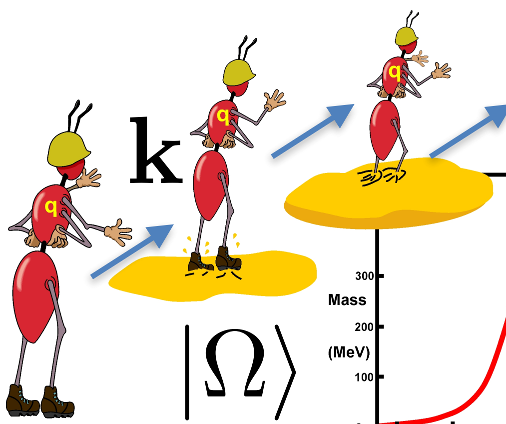


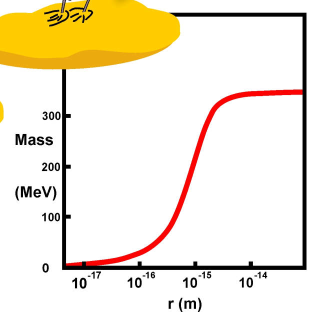

Instantaneous potential between (color) charges, e.g. Coulomb + Linear

**mass generation**

The ground state contains condensate of quarks

$$|\mathbf{k}\rangle = a^\dagger_{\mathbf{k}}|\Omega\rangle \qquad \delta m_{\mathbf{k}} = \langle \mathbf{k}|V|\mathbf{k}\rangle$$



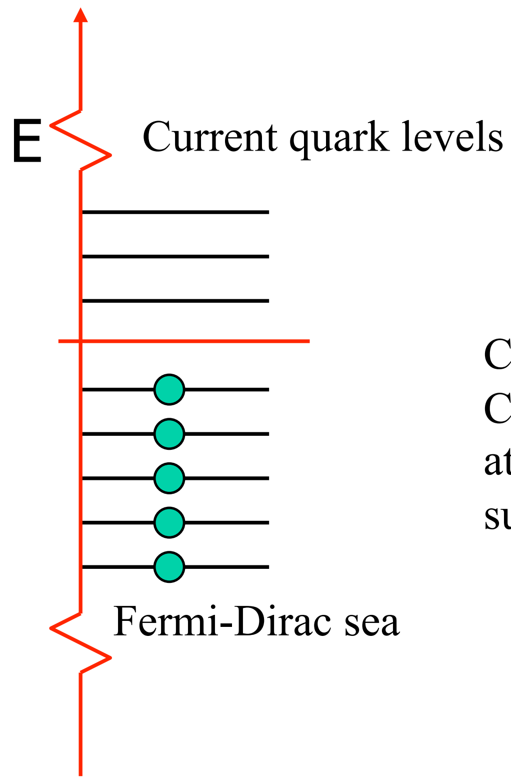

$$\delta m_{\mathbf{k}} = \int d\mathbf{x} e^{i\mathbf{k}\mathbf{x}} \left[ \int d\mathbf{y} V(|\mathbf{x}-\mathbf{y}|)\langle\Omega|\rho(\mathbf{y})|\Omega\rangle \right] + \cdots$$

Hartree + Fock

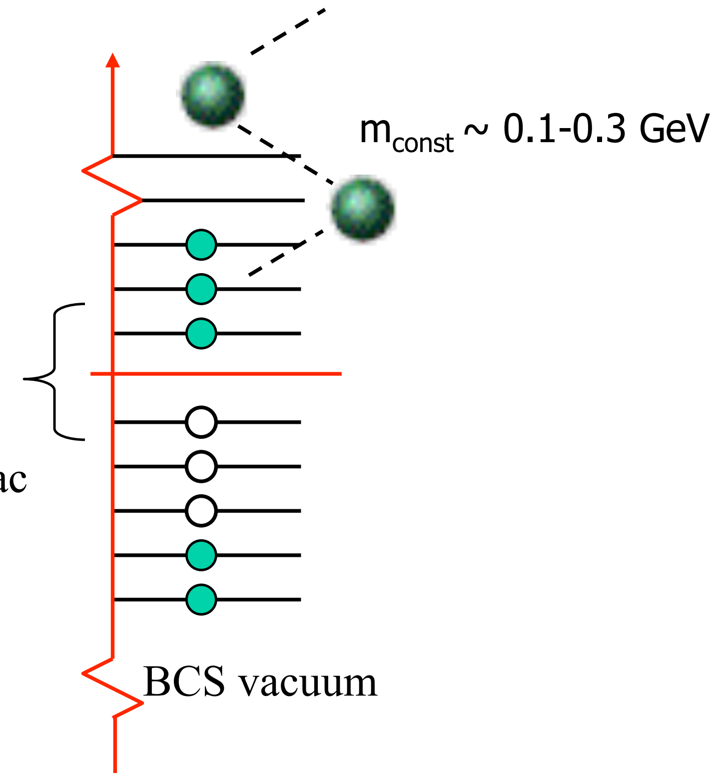
# QCD vacuum and Constituent Quarks



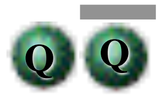
## Where do constituent quarks come from




Cooper pairs from Chromoelectric Coulomb attraction near Fermi-Dirac surface.

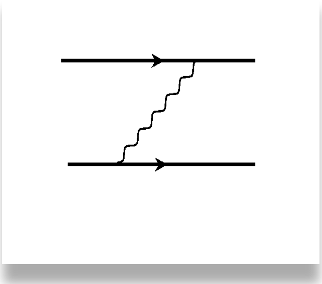



Meson =



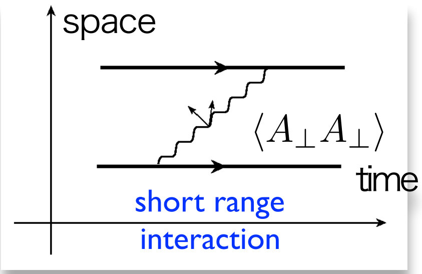
# QCD vacuum and Constituent Gluons

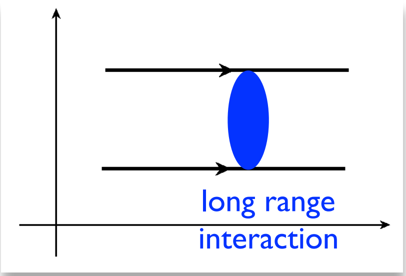
Gluons are responsible for confinement (aka effective potential between color charges) and are confined (aka contribute to the color charge)



Coulomb gauge

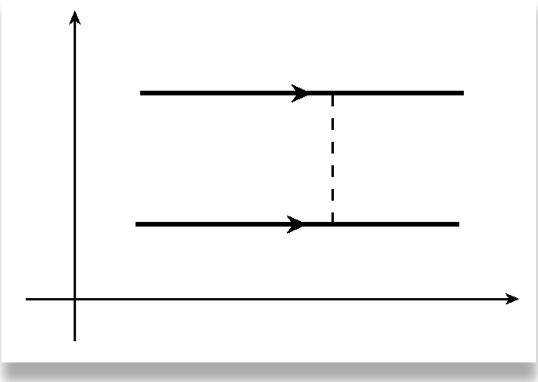
$$\nabla A^a(x) = 0$$



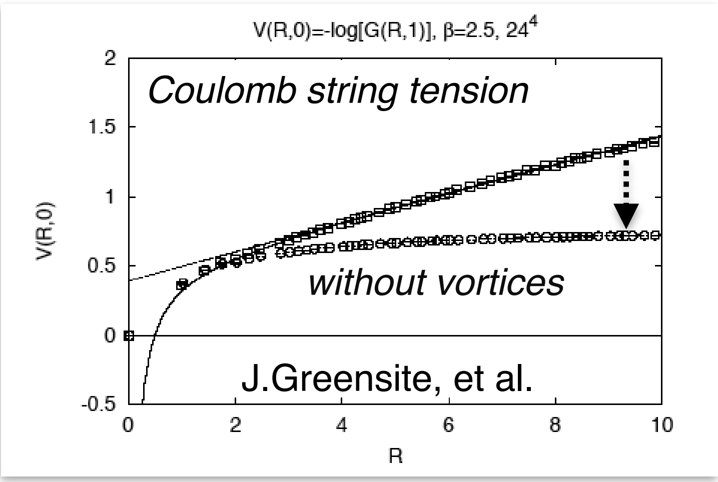



# Confining Potential and the gluon condensate

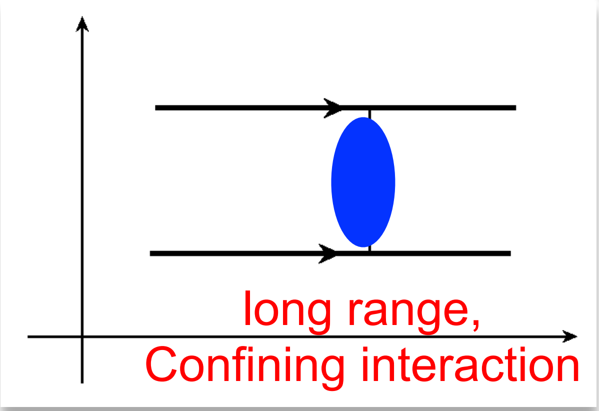
$$H = H_{kin} + V$$

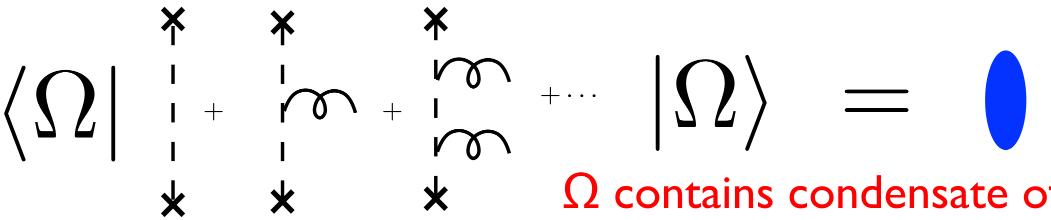


$$K \rightarrow -\frac{g^2}{\nabla^2} = \frac{\alpha}{|\mathbf{x}-\mathbf{y}|} =$$




- Coulomb "Potential" between external (i.e. quark charges) depends on the distribution of gluons.
- In presence of a gluon condensate it produces a Confining force been external color charge



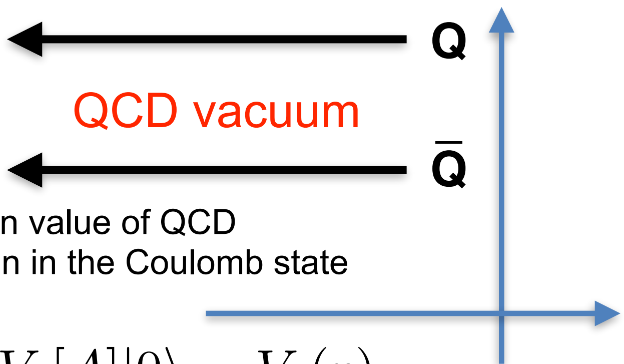
Ω contains condensate of monopoles, vortices, …

# How to Probe Gluons



1. Gluons in the vacuum:

   - Insert a quark pair and measure energy the instantaneous energy.



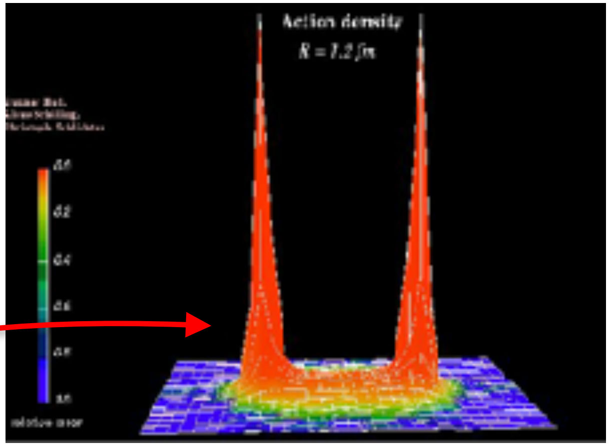

Expectation value of QCD Hamiltonian in the Coulomb state

$$\frac{1}{r} \rightarrow \langle 0|V_c[A]|0\rangle = V_c(r)$$

Coulomb state ≠ QCD eigenstate

2. Gluons in a physical e.g. quark-antiquark state:

   - Insert a quark pair, wait until it polarizes the vacuum and measure energy the state.




Wilson state = QCD eigenstate

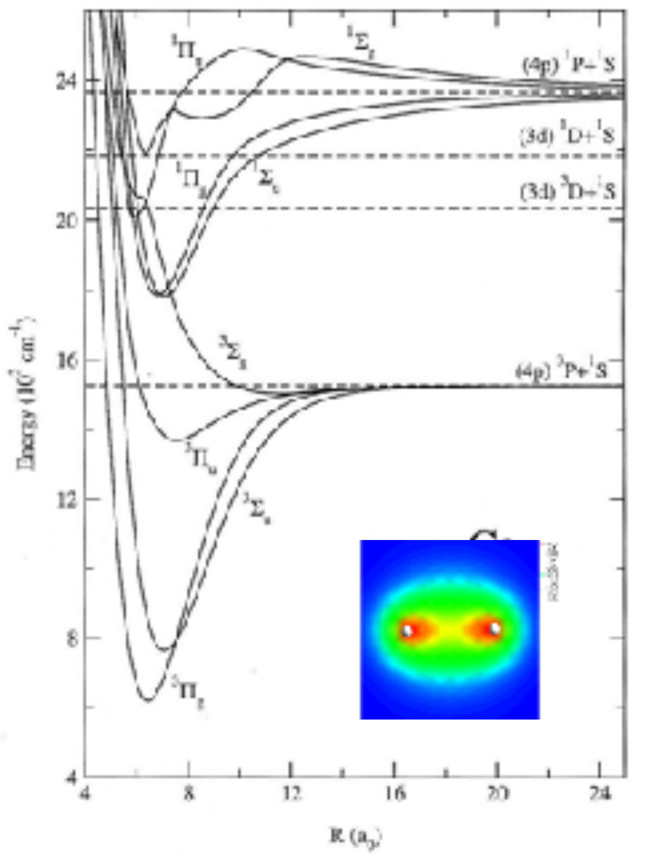
$$|Q\bar{Q}\rangle = Q^\dagger \bar{Q}^\dagger|0\rangle + Q^\dagger \bar{Q}^\dagger g^\dagger|0\rangle + \cdots$$

Coulomb state

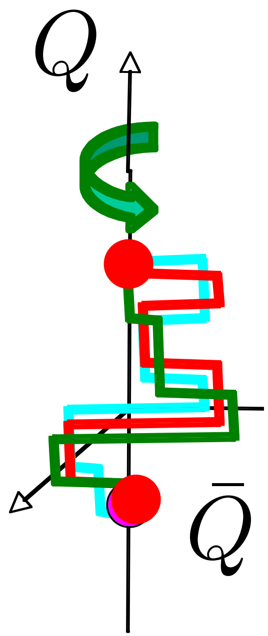
Coulomb state + extra gluons

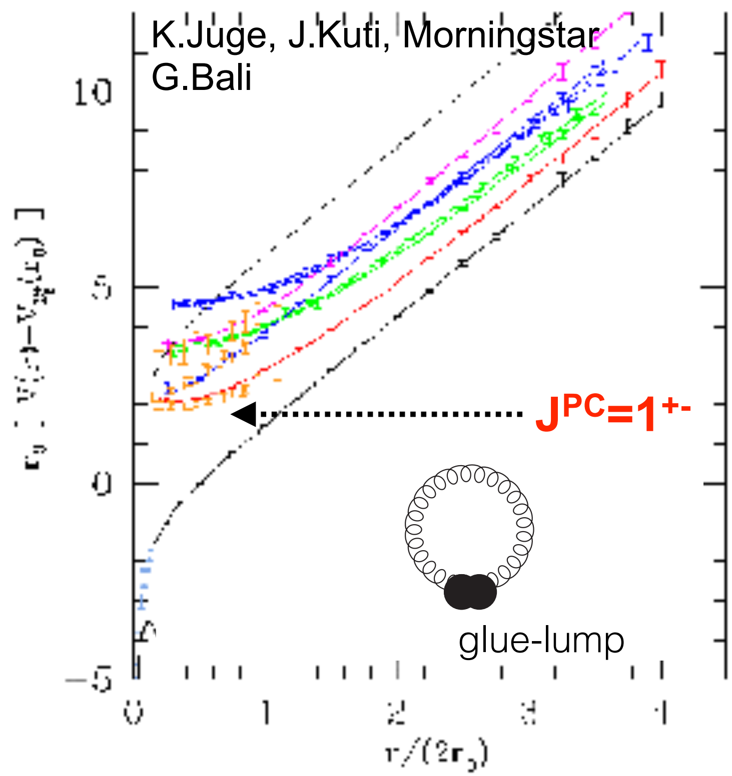
# Quasi-Gluon Properties






Potential energy curves for the excited valence states of $Ca_2$

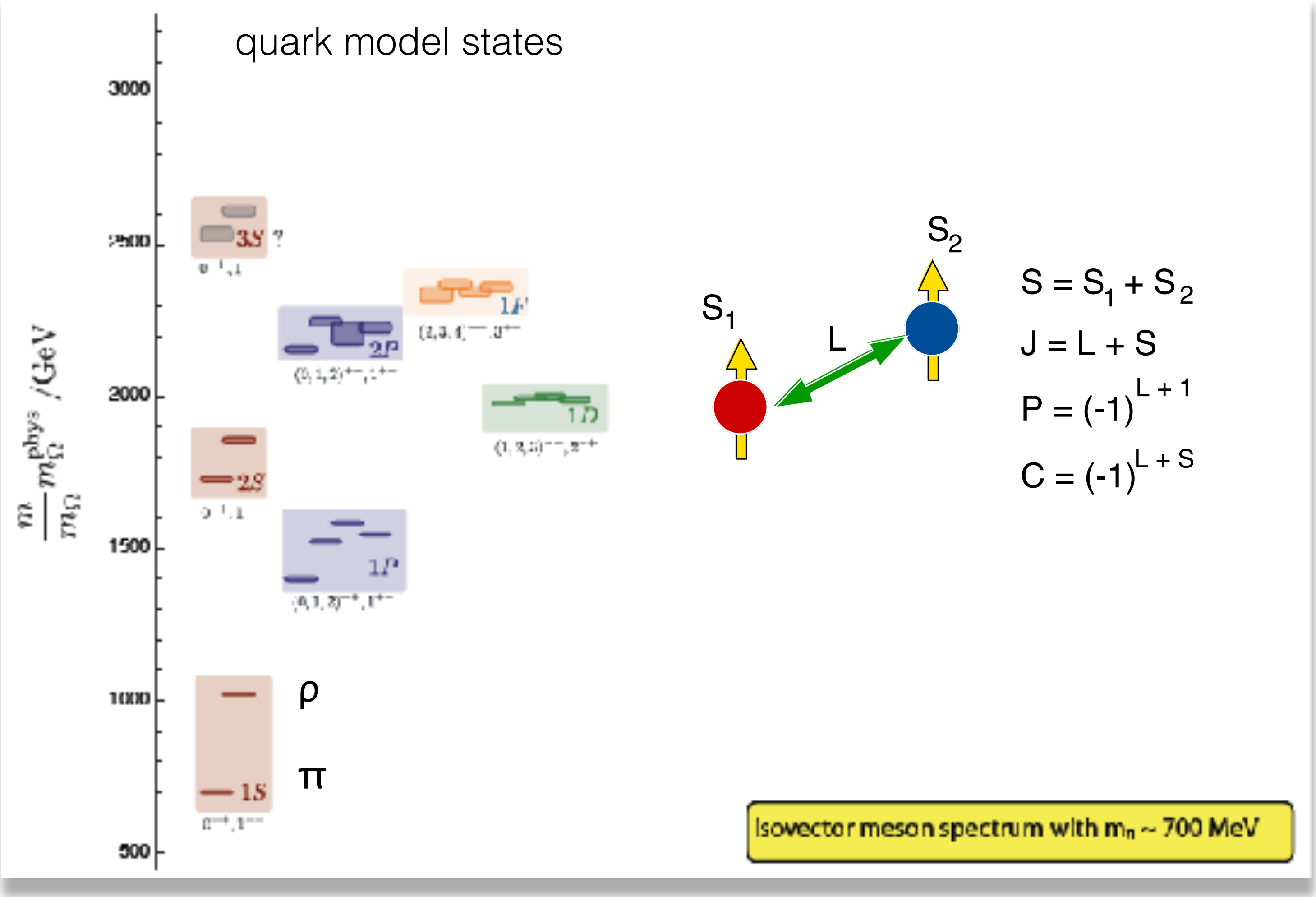



Adiabatic potentials map out distribution of exited gluons:

Gluons behave as quasiparticles with $J^{PC}=1^{+-}$

# Quark Model (without quasi-gluons)



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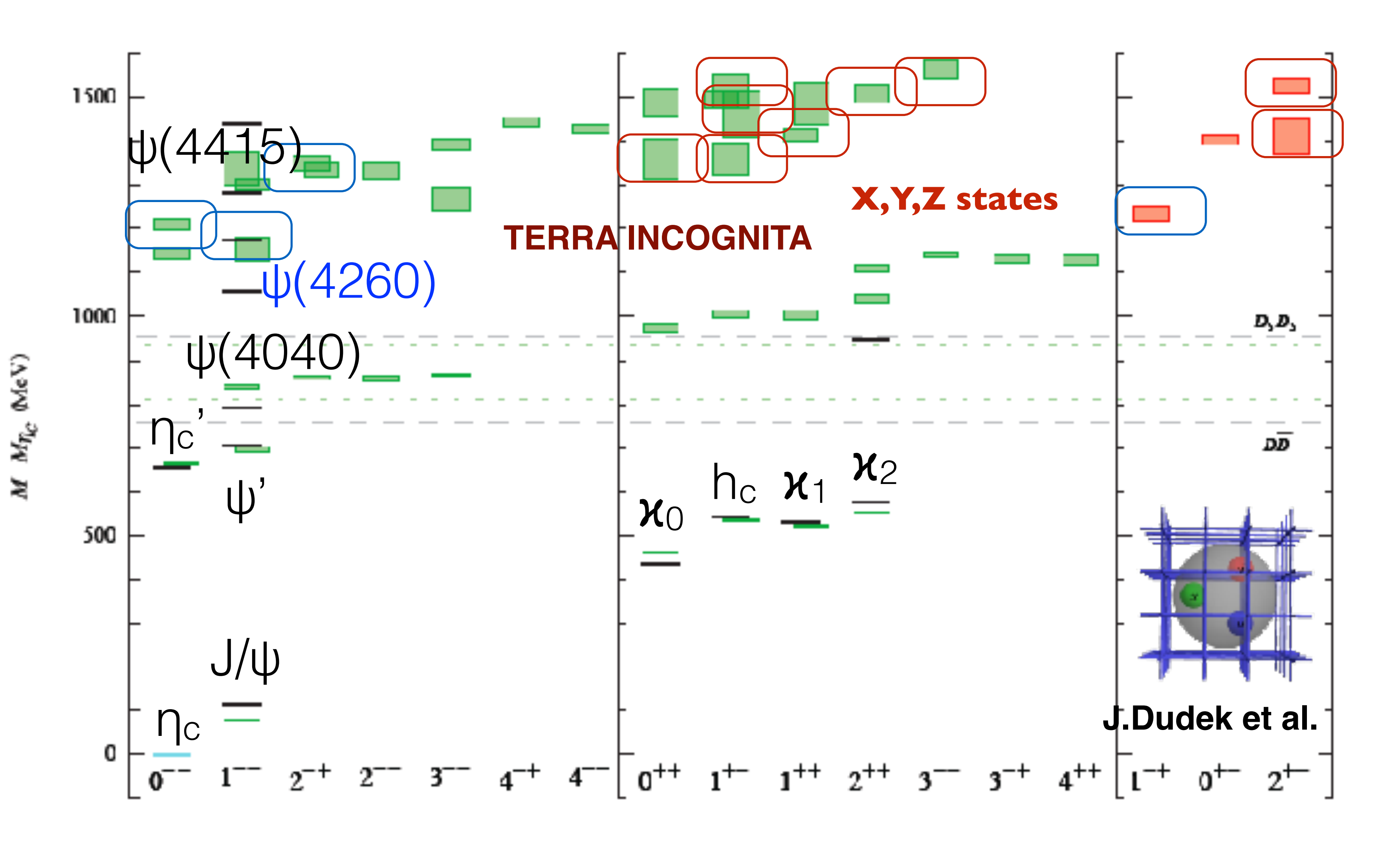
# Lattice Charmonium Spectrum

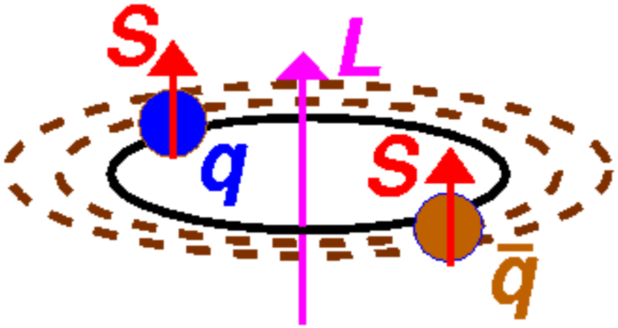





0-+ 1-+ 2-+ 1- -

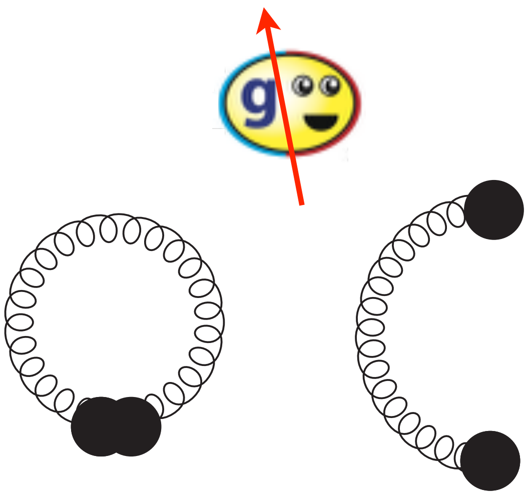
0++ 1++ 2++ 0+- 1+- 1+- 1+- 2+- 2+- 3+-

# Quark Model with Gluons : Hybrid States




$$P_{q\bar{q}} = (-1)^{L+1}$$

$$C_{q\bar{q}} = (-1)^{L+S}$$




$J^{PC}$ glue

$J^{PC}$ $Q\bar{Q}$

$\boxed{1^{--}}$

$J^{PC} = 1^{-+}$ is not a $q\bar{q}$ state

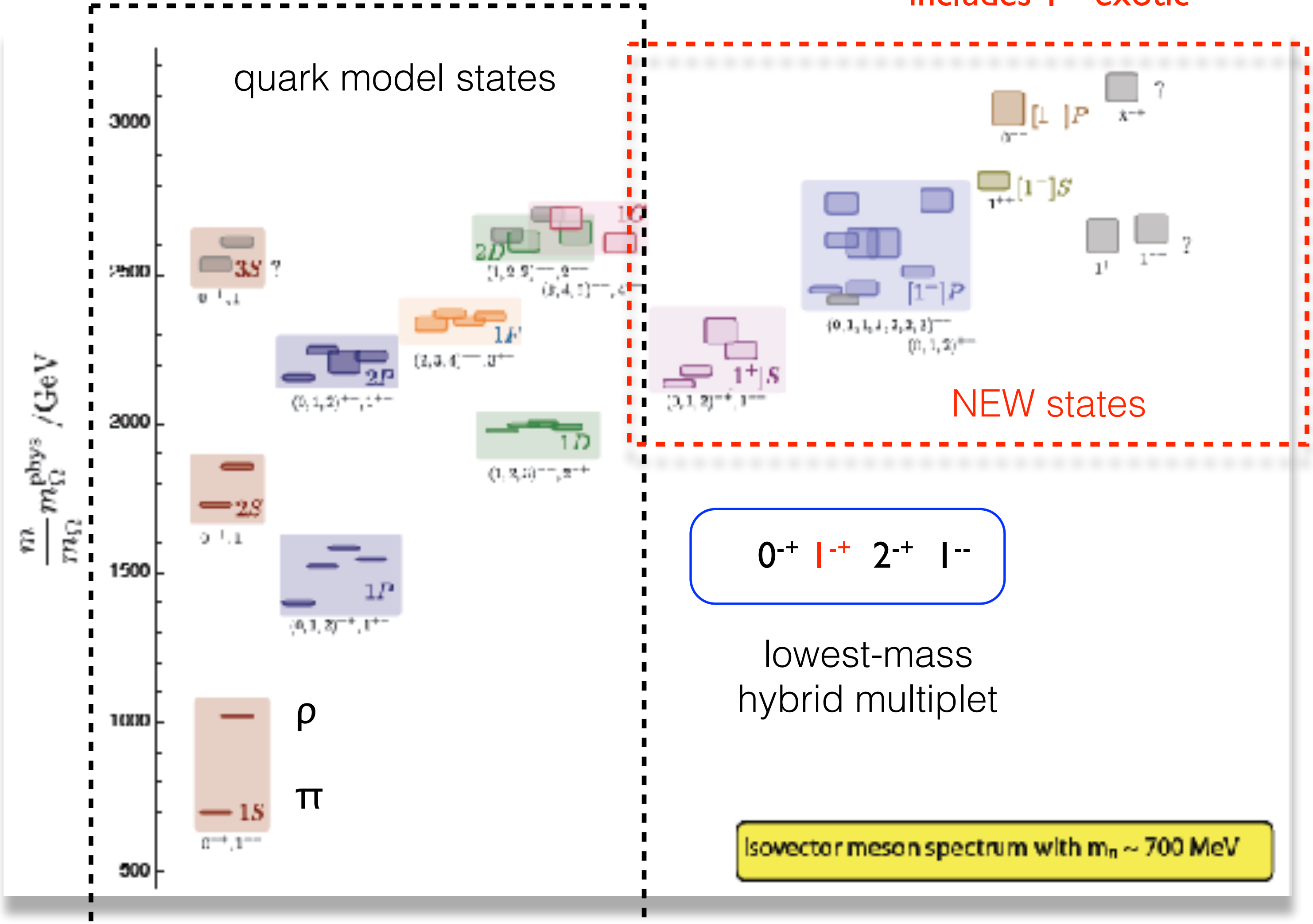
exotic quantum numbers

# Meson Spectrum on the Lattice



new multiplets from lattice

large overlap with
gluonic operators
includes $1^{-+}$ exotic



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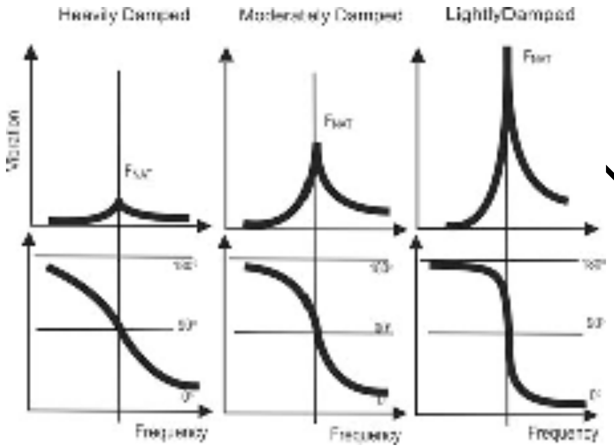
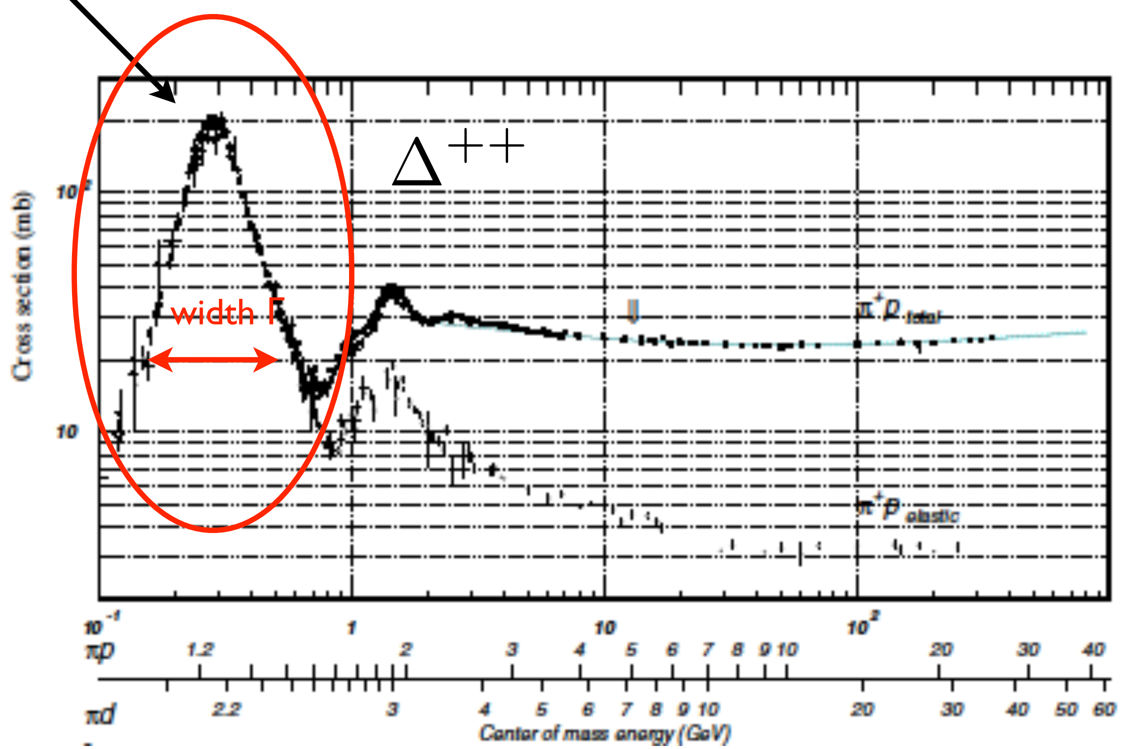
# Hunting for Resonances




peak in intensity
(cross section)

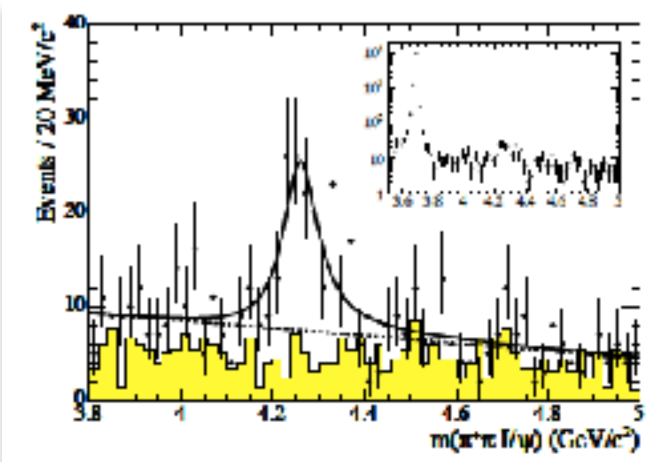
In 1952, E. Fermi and collaborators measured the cross section for $\pi^+ p \to \pi^+ p$ and found it steeply raising.

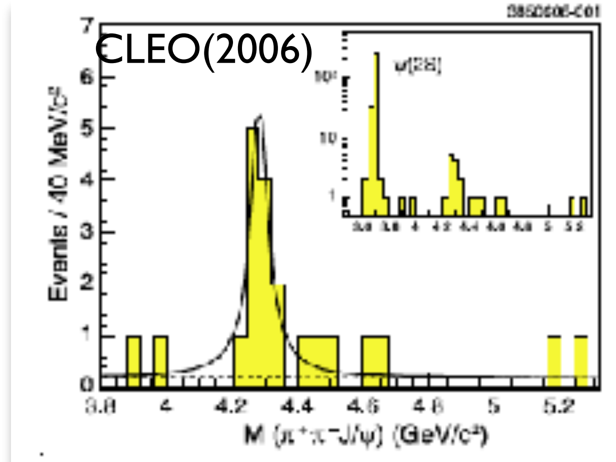
180$^0$ phase change
in the amplitude



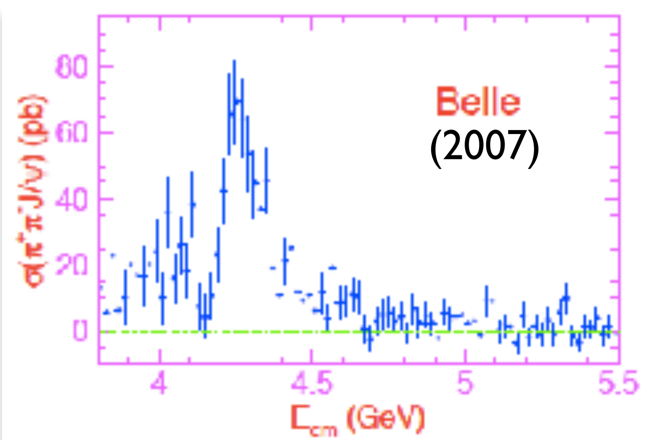
# Y(4260) as Hybrid Candidate

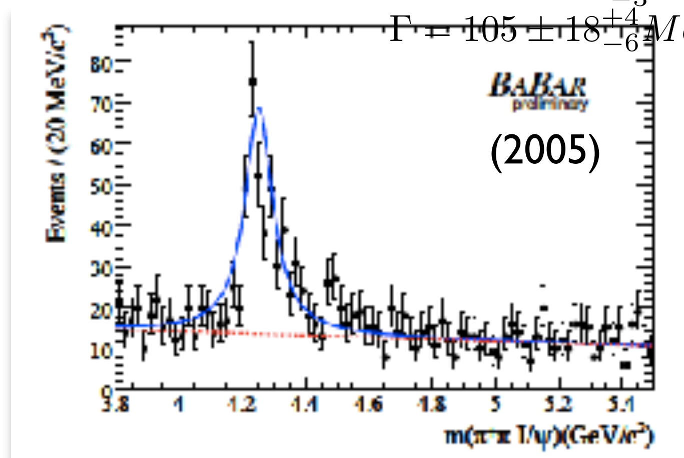
discovered by BaBar in J/ψ $\pi^+\pi^-$ (2005) confirmed by CLEO,Belle other modes from BaBar




$$M = 4252 \pm 6^{+2}_{-3} MeV$$
$$\Gamma = 105 \pm 18^{+4}_{-6} MeV$$




Theory: Hybrid candidate

# Light quark exotic candidate

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

$M = 1370 \pm 16^{+50}_{-30}$ MeV / $c^2$

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / $c^2$

$\pi^- p \rightarrow \eta\pi^0 n$

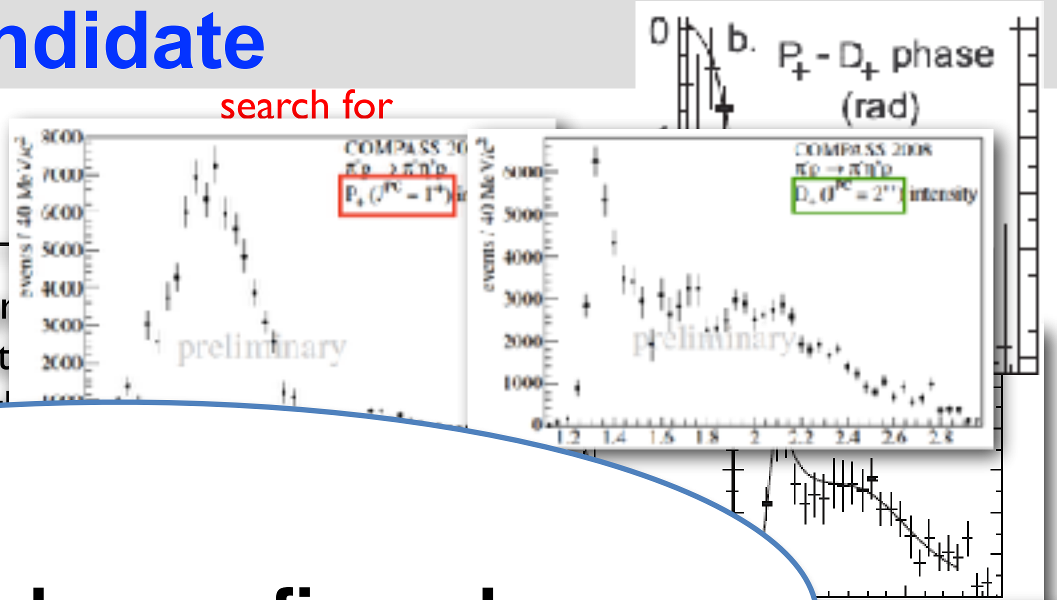
No consistent B-W interpr
possible but a weak ηπ int
exists and can reproduce th

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

$\pi^- p \rightarrow \rho^0\pi^- p$

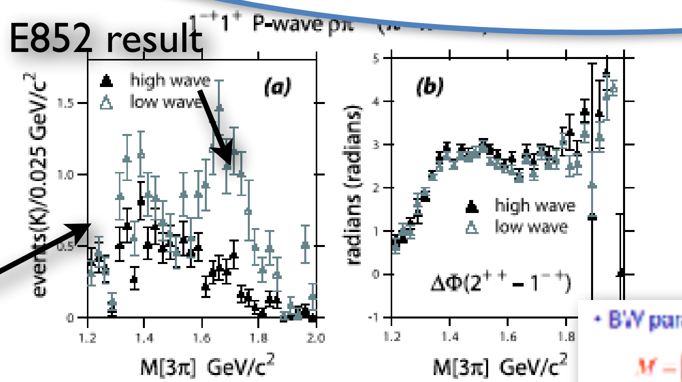
$\Gamma =$

search for



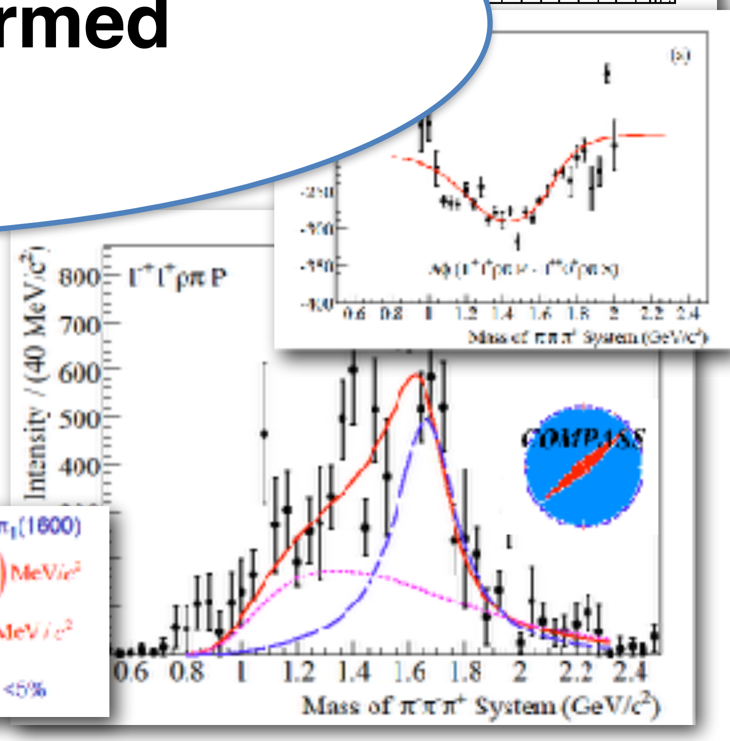

**Need to be confirmed**

E852 result



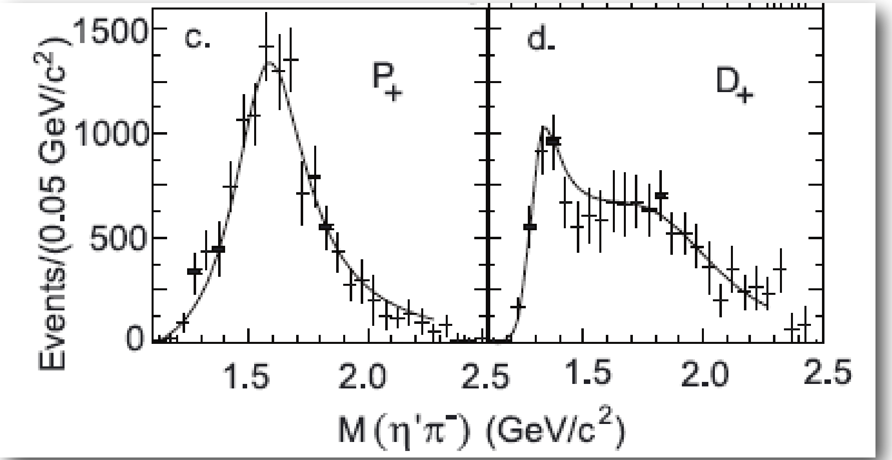

$$\pi^- p \rightarrow \pi_2^-(1600) p$$
$$\pi_2^- \rightarrow \rho^0 \pi^-$$
$$\rho^0 \rightarrow \pi^+\pi^-$$

FIG. 25: (a) The $1^{-+}1^+$ $P$-wave $\rho\pi$ partial wave charged mode ($\pi^-\pi^-\pi^+$) for the high-wave set PWA a low-wave set PWA and (b) the phase difference $\Delta\Phi$ b the $2^{++}$ and $1^{-+}$ for the two wave sets.



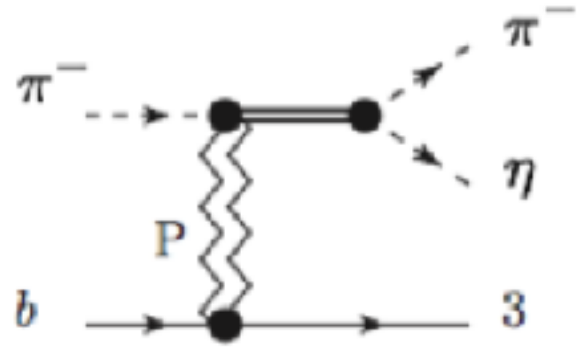

- BW parameters for $\pi_1(1600)$
  $M = \left(1660 \pm 10^{+0}_{-64}\right)$ MeV/$c^2$
  $\Gamma = \left(269 \pm 21^{+42}_{-64}\right)$ MeV/$c^2$
- Leakage negligible: <5%

# The Golden Channel: ηπ

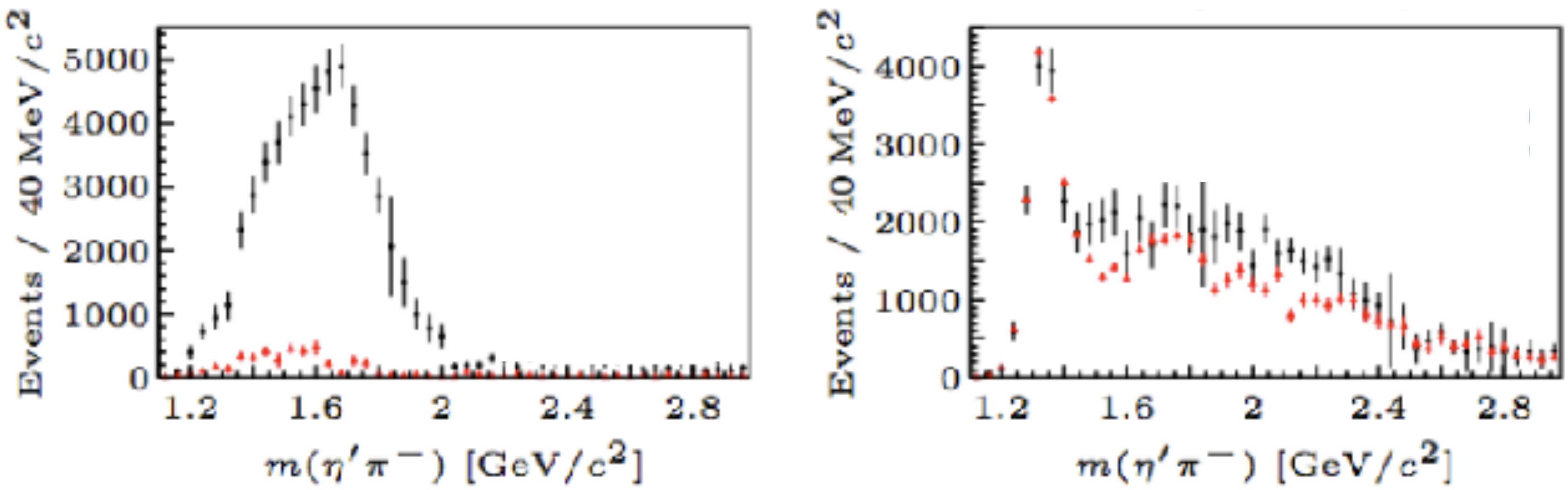



**E852**

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




**COMPASS**



# A possible scenario (Lecture 1 summary)



- QCD vacuum has gluon condensate in the form color monopolies, vortices,…
- The condensate leads to an effective, confining potential between color charges
- Light quarks propagating through this medium acquire effective mass
- Static color charges (i.e. “very heavy” quark) inserted into the vacuum polarize the condensate and change the background gluon distribution
- For large separation between the charges this leads to formation of a chromo electric flux tube (aka dual superconductor)
- For small separation between charges, the effect of vacuum polarization can be described as quasi-particles.
- Once the have quarks are allowed to move the polarized gluon filed (the quasi-particle of the flux tube) can result in a new type of hadrons -> hybrid mesons or baryons.