# X(3872) and Other Exotic Mesons

A. Özpineci

Physics Department
Middle East Technical University

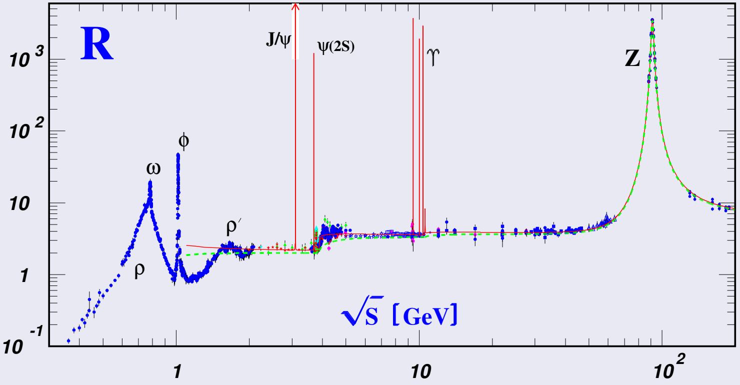
IPM-METU Joined Conference

# Introduction

- Study of hadronic spectrum has always brought many surprises.

# Introduction

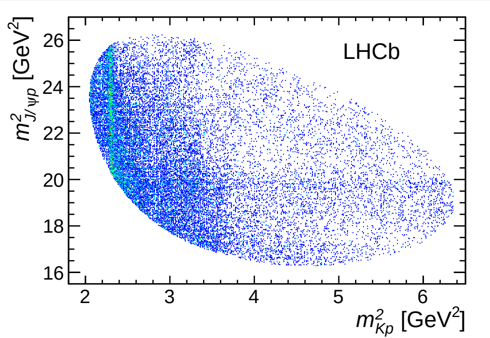
- Study of hadronic spectrum has always brought many surprises.
- Discovery of the charmonium




Ezhela, Lugovsky, Zenin, arXiv hep-ph/0312114v2

# Introduction

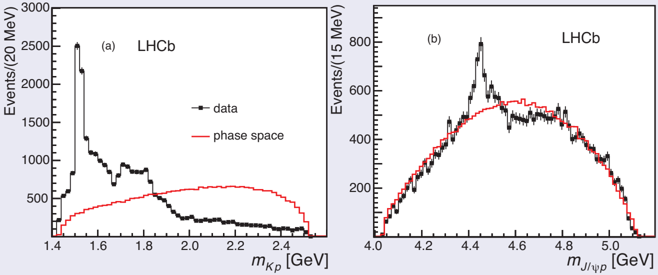
- Study of hadronic spectrum has always brought many surprises.
- Discovery of the charmonium
- Most recently, the discovery of possible pentaquark states by LHCb.



LHCb Collaboration, arXiv:1507.03414

# Introduction

- Study of hadronic spectrum has always brought many surprises.
- Discovery of the charmonium
- Most recently, the discovery of possible pentaquark states by LHCb.




LHCb Collaboration, arXiv:1507.03414

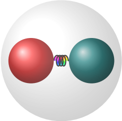
# Introduction

- The hadrons are made up of quarks and gluons
- The interactions of quarks and gluons are described by an SU(3) gauge theory called QCD
- QCD is a non-perturbative theory-difficult to extract predictions
- Two properties that interactions of quarks and gluons should have:
  - Asymptotic freedom-QCD is asymptotically free
  - Confinement-it is *believed* that QCD is confining

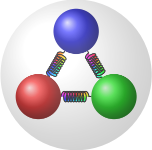
Department of Physics Fizik Bölümü 1960

# Conventional Hadrons, Confinement and QCD

- Quarks carry color charge (can have three different colors: rgb)
- Gluons carry a color and an anti-color charge
- Confinement: Physically observable states are colorless
- Simplest colorless combination: color+anti-color ($3 \otimes \bar{3} = 1 \oplus 8$):

Mesons: 

- The second simplest: 3 colors ($3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$)

Baryons: 

# Conventional Mesons and NRQM

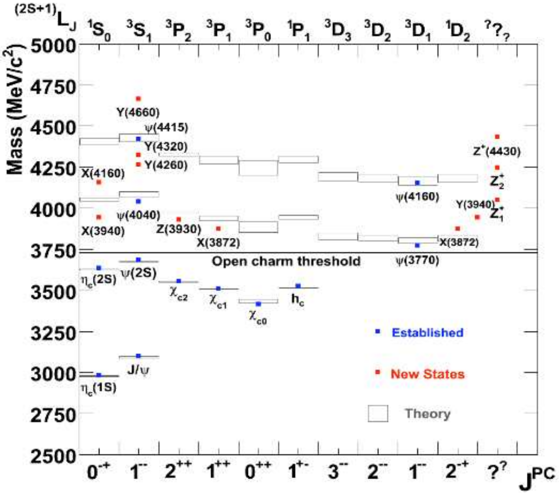
- In non-relativistic systems, the interaction between a quark and anti-quark can be described by a potential model.
- If the separation between quarks is small, one gluon exchange is enough to describe their interaction (asymptotic freedom): $\lim_{r\to 0} V(r) \propto \alpha_s(r)/r$.
- If the separation between quarks is large, the potential raises linearly (confinement): $\lim_{r\to\infty} V(r) \propto r$
- Cornell potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + kr$$

- Add S-L coupling, S-S interaction, relativistic corrections,

Department of Physics Fizik Bölümü 1960

## Challenge: hadronic states above open-charm thresholds

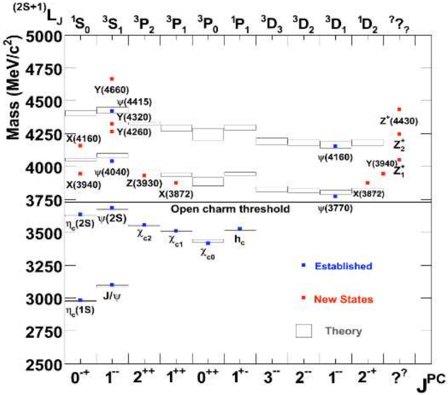



A. Nefediev, XHadrons Conference, 2015

# Conventional Mesons and NRQM

Introduction Coupled channels Interplay Practical parametrisation 3-body effects Conclusions

**Challenge: hadronic states above open-charm thresholds**




10 / 59

- Potential quark model is very successful below thresholds
- Close to and above thresholds, potential quark model is less successful.

Department of Physics Fizik Bölümü 1960

# Alternative Pictures

$$|\mathcal{M}\rangle = ()|\bar{q}^a q^a\rangle + ()|\bar{q}^a g^{ab} q^b\rangle + ()|(\bar{q}^a q^a)(\bar{q}^b q^b)\rangle + ()|(qq)^a(\bar{q}\bar{q})^a\rangle + \cdots$$

- They are conventional mesons, but potential quark models are not good enough.
- Molecules: Meson-Meson, Baryon-Baryon, or Meson-Baryon: Bound states of colorless objects
- Genuine tetraquarks, pentaquarks, etc.
- Hibrids: Valence gluons
- More exotic states

# Alternative Pictures

$$|\mathcal{M}\rangle = ()|\bar{q}^a q^a\rangle + ()|\bar{q}^a g^{ab} q^b\rangle + ()|(\bar{q}^a q^a)(\bar{q}^b q^b)\rangle + ()|(qq)^a(\bar{q}\bar{q})^a\rangle + \cdots$$

- They are conventional mesons, but potentional quark models are not good enough.
- Molecules: Meson-Meson, Baryon-Baryon, or Meson-Baryon: Bound states of colorless objects
- Genuine tetraquarks, pentaquarks, etc.
- Hibrids: Valence gluons
- More exotic states

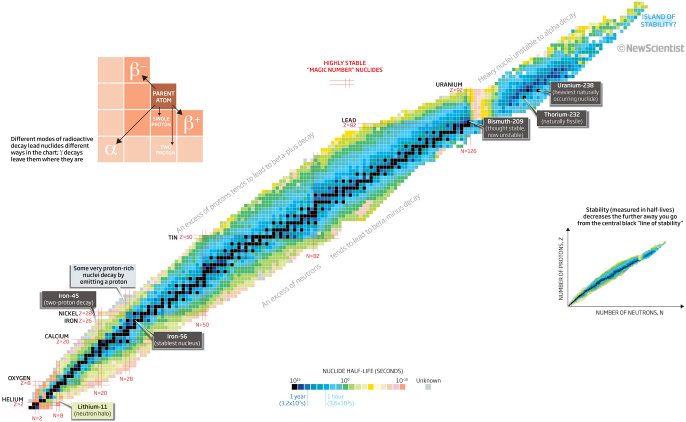
# Non Exotics Multi Quark States

What is a well known example of a hexa quark state?

What is a well known example of a hexa quark state? Deuteron

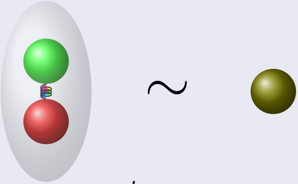
# Non Exotics Multi Quark States

What is a well known example of a hexa quark state? Deuteron



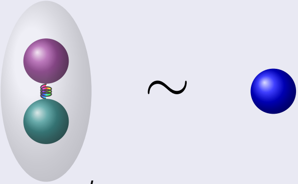

All nuclei are baryon molecules!

# Diquarks



$\epsilon_{abc} q^b q^c \sim \bar{q}_a$

Colorwise, 2 quarks can behave like an anti-quark: $3 \otimes 3 = \bar{3} \oplus 6$



$\epsilon^{abc} \bar{q}_b \bar{q}_c \sim q^a$

Color-wise, 2 anti-quarks can behave like a quark: $\bar{3} \otimes \bar{3} = 3 \oplus \bar{6}$

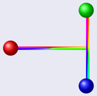
In a colorless state, if a quark (anti-quark) is replaced by an anti-diquark (diquark) it remains colorless.

# Tetraquarks and PentaQuarks-Diquark picture

## Meson

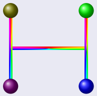
## Baryon

Replace anti-quark in a meson by a diquark:



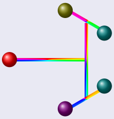
## Tetraquark

Replace quark in a baryon by an anti-diquark:



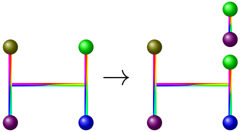
## Pentaquark

Raplace both quarks in a baryon by anti-diquarks



# Consequences of Diquark Picture

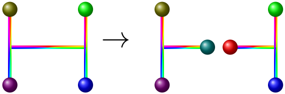
- Many excited states, hence many exotics
- Diquark can split into into a diquark and a meson



$(T \to T\mathcal{M})$

# Consequences of Diquark Picture

- Many excited states, hence many exotics
- Diquark can split into into a diquark and a meson



$(T \to B\bar{B})$

# Meson Molecules-X(3872)

- X(3872) first observed in 2003 by BELLE in $B \to J/\psi\pi\pi K$
- Quantum numbers determined to be $J^{PC} = 1^{++}$ by LHCb in 2013
- $m_X = 3871.69 \pm 0.17\ MeV$, $\Gamma < 1.2\ MeV$

# X(3872) Mass

- $m_X = 3871.69 \pm 0.17\ MeV$, $\Gamma < 1.2\ MeV$
- $m_{D^0} + m_{D^{*0}} - m_X < 1\ MeV$.
- A Meson molecule is a weakly bound state of two mesons due to contact interactions, exchange of other light mesons, etc.
- In the molecular picture, $m_X = m_{D^0} + m_{D^{*0}} - B$ where $B > 0$ is the binding energy.
- The mass is a coincidence in diquark picture

Department of Physics 1960 Fizik Bölümü

# $X(3872) \to \psi(nS)\gamma$

$$\frac{\Gamma(X \to \psi(2S)\gamma)}{\Gamma(X \to J/\psi(1S)\gamma)} = \begin{cases} < 2.1 & \text{BELLE 2011} \\ 3.4 \pm 1.4 & \text{BABAR 2009} \end{cases}$$

- In the quark model, X(3872) is a $2P$ state: $X \to \psi(2S)\gamma$ is the $\Delta L = 1$ transition
- Not so natural in the molecular picture.
- Even if $X(3872)$ is a molecule, likely to have a significant charmonium component.

Department of Physics Fizik Bölümü 1960

# X(3872) Strong Decays

- It decays into a final state with $I = 0$ and $I = 1$ with almost equal branching ratio:

$$\frac{B(X(3872) \to J/\psi\rho)}{B(X(3872) \to J/\psi\omega)} \simeq 1 \Rightarrow \frac{A(X(3872) \to J/\psi\rho)}{A(X(3872) \to J/\psi\omega)} \simeq 0.2$$

- There is a large isospin symmetry breaking.
- Isospin violation is naively expected to be of the order of

$$\delta = \frac{m_u - m_d}{\Lambda_{QCD}} \simeq 2 - 3\%$$

- Large isospin breaking naturally arises in the molecular picture due to the mass differences between the charged and neutral D mesons.

Department of Physics Fizik Bölümü 1960

# Isospin Structure

- In the molecular picture of $X(3872)$ can be written as

  Gamermann, Nieves, Oset, Arriola, PRD81 (2010) 014029

$$
\begin{aligned}
|X(3872)\rangle &= |\psi_1\rangle|D^0\bar{D}^{*0}\rangle + |\psi_2\rangle|D^+D^{*-}\rangle \\
&= \frac{1}{\sqrt{2}}\left(|\psi_1\rangle + |\psi_2\rangle\right)|I=0\rangle + \frac{1}{\sqrt{2}}\left(|\psi_1\rangle - |\psi_2\rangle\right))|I=1\rangle \\
&\equiv \cos\theta|I=0\rangle + \sin\theta|I=1\rangle \\
\langle\psi_1|\psi_1\rangle &+ \langle\psi_2|\psi_2\rangle = 1
\end{aligned}
$$

- In terms of the wave functions $\psi_1$ and $\psi_2$, the mixing angle can be written as

$$
\tan^2\theta = \frac{\int d^3r|\psi_1(\vec{r}) - \psi_2(\vec{r})|^2}{\int d^3r|\psi_1(\vec{r}) + \psi_2(\vec{r})|^2} \Rightarrow \theta \sim 39^\circ \qquad (1)
$$

- Note that $\theta_{max} = 45^\circ$.

Department of Physics Fizik Bölümü 1960

# Isospin Structure

- In the molecular picture of $X(3872)$ can be written as

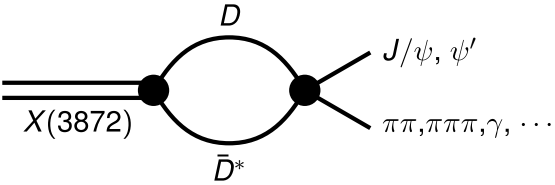
Gamermann, Nieves, Oset, Arriola, PRD81 (2010) 014029

$$\begin{aligned} |X(3872)\rangle &= |\psi_1\rangle|D^0\bar{D}^{*0}\rangle + |\psi_2\rangle|D^+D^{*-}\rangle \\ &= \frac{1}{\sqrt{2}}\left(|\psi_1\rangle + |\psi_2\rangle\right)|I=0\rangle + \frac{1}{\sqrt{2}}\left(|\psi_1\rangle - |\psi_2\rangle\right)|I=1\rangle \end{aligned}$$

- If $\theta \simeq \theta_{max}$, why $\frac{A(X(3872)\to J/\psi\rho)}{A(X(3872)\to J/\psi\omega)} \simeq 0.2$?
- The $I=1$ decay into $J/\psi\rho$ is suppressed by the wave function at the origin; $\psi_1(0)-\psi_2(0)$.
- To create a $J/\psi$, $D$ and $\bar{D}^*$ should come to the same point.
- Note that $\psi_i(r) \propto e^{-B_i r}$

Department of Physics Fizik Bölümü 1960

- The $I = 1$ decay into $J/\psi\rho$ is suppressed by the wave function at the origin; $\psi_1(0) - \psi_2(0)$.
- To create a $J/\psi$, $D$ and $\bar{D}^*$ should come to the same point.
- Note that $\psi_i(r) \propto e^{-B_i r}$



# Probing the Isospin structure

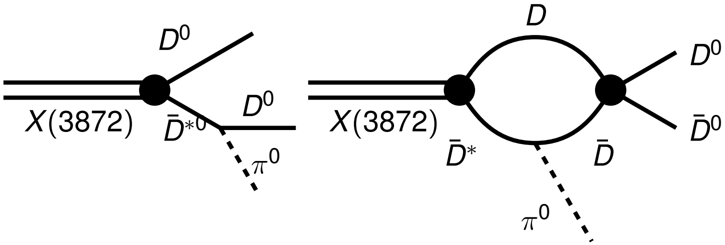
$$|X(3872)\rangle = \frac{1}{\sqrt{2}}\left(|\psi_1\rangle + |\psi_2\rangle\right)|I=0\rangle + \frac{1}{\sqrt{2}}\left(|\psi_1\rangle - |\psi_2\rangle)\right)|I=1\rangle$$

$$\psi_i(r) \propto e^{-B_i r}$$

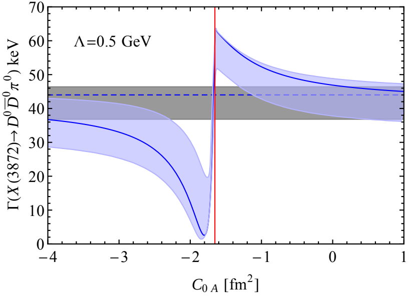
- How to probe the $I = 1$ component of the X(3872)?
- The decay should be sensitive to the wave functions at large separation (since $\psi_2$ decays faster with distance)
- Solution: look for a process where the mesons making the molecule decay independently: $X \to D^0 \bar{D}^0 \pi^0$

Department of Physics Fizik Bölümü 1960

- $X \to D^0 \bar{D}^0 \pi^0$ receives contributions both from large separations and also small separations.



# $\Gamma(X(3872) \to D^0 \bar{D}^0 \pi^0)$




FK Guo, C Hidalgo-Duque, J. Nieves, AO, MP Valderrama, arXiv:1404.1776

Gray: Only tree level

Blue: Tree level + FSI

Red: $D\bar{D}$ resonance is generated at the $D^0 \bar{D}^0$ threshold

# Conclusion

- Hadronic spectrum is still a rich subject to study
- The only discovered “new physics” upto now!
- Even more than 10 years after its discovery, we are still waiting for new measurements about X(3872)!
- There are lots of other exotic resonances already discovered, and waiting to be discovered

Department of Physics Fizik Bölümü 1960