# The nature of near–threshold $XYZ$ states

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## Only color neutral objects can be observed:

- Mesons:

  $q\bar{q}$, $qq\bar{q}\bar{q}$(tetraquark), $qqq\bar{q}\bar{q}\bar{q}$ (baryonium),... $GG$, $GGG$,... (glueball)

  Now many candidates for non-$q\bar{q}$ configuration:

  Examples:

| | | |
|---|---|---|
| $\pi_1(1400)$ | $J^{PC} = 1^{-+}$ | exotic quantum number |
| $X(3872)$ | $J^{PC} = 1^{++}$ | lower than the $\chi_{c1}(2P)$ in QM |
| $Z_c^{(\prime)\pm}(3900)$ | $J^{PC} = 1^{+-}$ | charged state but decay to $Q\bar{Q}$ |
| $Y(4260)$ | $J^{PC} = 1^{--}$ | not seen both in R-value measurement and open-charmed decay channels |
| ... | ... | |

- Baryons:

  $qqq$, $qqqq\bar{q}$ (penta-quark), ...

  Examples: $\Lambda(1405)$ $J^P = \frac{1}{2}^-$ lower than other excited $\frac{1}{2}^-$ baryons ...

- $m_Q \gg \Lambda_{QCD} \rightarrow$ physics at the $m_Q$ scale is perturbative
- Heavy quark limit $\rightarrow$ spin symmetry & flavor symmetry

To the leading order,

$$\mathcal{L}_{QCD} = \bar{h}_v iv \cdot D h_v + \mathcal{O}(\Lambda_{QCD}/m_Q)$$

No Dirac matrix:

$\rightarrow$ spin symmetry,

$\rightarrow s_Q$ and light degrees of freedom conserved individually

$\rightarrow$spin doublet: $s_l = \frac{1}{2}^-$ $(D, D^*)$, $s_l = \frac{3}{2}^+$ $(D_1, D_2)$

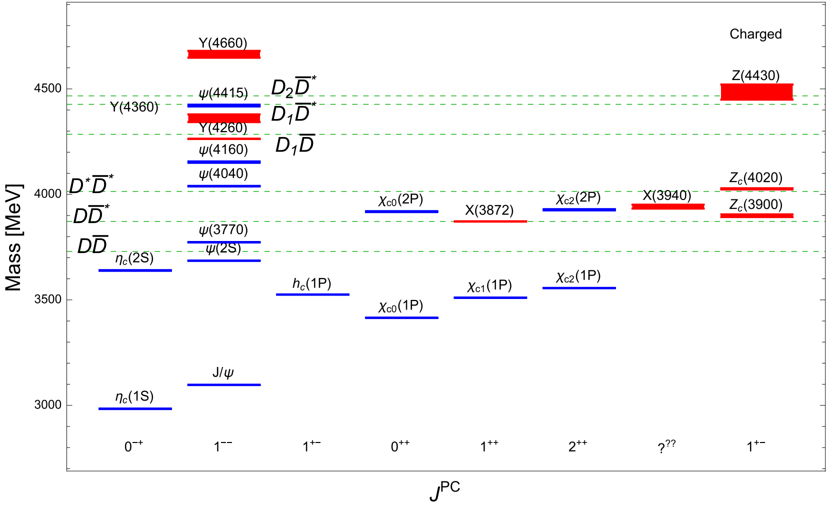
$\rightarrow m_{D^*} - m_D \sim \Lambda_{QCD}$, $m_{D_2} - m_{D_1} \sim \Lambda_{QCD}$

No heavy quark mass:

$\rightarrow$ flavor symmetry

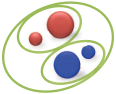
Heavy system is expected to be easier!

# Rich experimental data




More states than simple QM predictions!

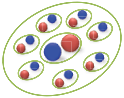
PDG 2014



## Tetraquark

⇒ Compact object formed from $Qq$ and $\bar{Q}\bar{q}$

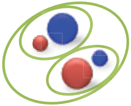
L. Maiani et al., PRD89(2014)114010, L. Maiani et al., PRD87(2013)111102,...



## Hadro-Quarkonium

⇒ Compact $Q\bar{Q}$ embedded in light quarks

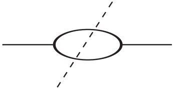
M.B. Voloshin, Prog.Part.Nucl.Phys.61(2008)455, S. Dubynskiy et al., PLB666(2008)344,...



## Molecule

⇒ Extended object made of $Q\bar{q}$ and $\bar{Q}q$

N. A. Tö rnqvist, PLB590(2004)209, C.E. Thomas, PRD78(2008)034007, ...



## Threshold effects

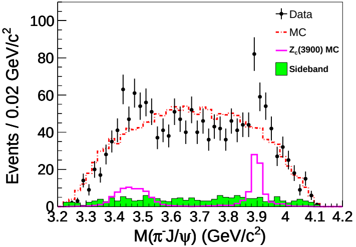
Bugg, PLB598(2004)8; Chen et al, PRD84(2011)094003;Swanson PRD91(2015)034009,...

Dynamics? Or kinematics?

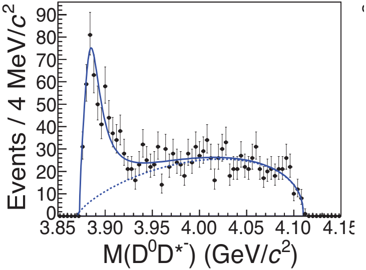
# Not simple threshold effects

$Z_c(3900)$: $Y(4260) \to \pi^{\mp}(J/\psi\pi^{\pm}), \pi^{\mp}(D\bar{D}^*)^{\pm}$

BESIII, Belle, Xiao et al(2013)



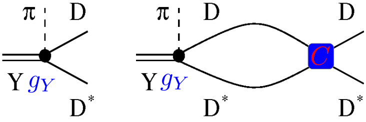

BESIII, PRL112(2014)022001

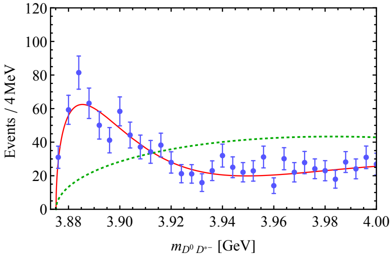



- Observed in elastic & inelastic channels
- Narrow pronounced structure near-threshold
- The same origin → pole of the $S$-matrix

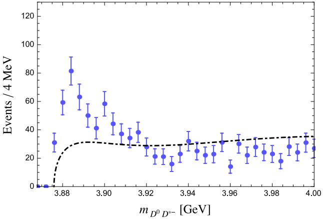
# Not simple threshold effects

Argument I: Perturbative input → non-perturbative output




Argument II: Perturbative requirement → no pronounced peak in elastic channels

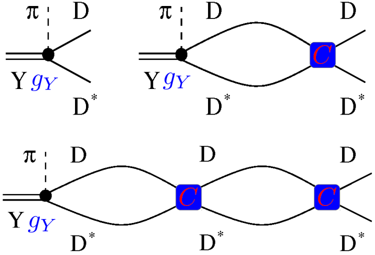


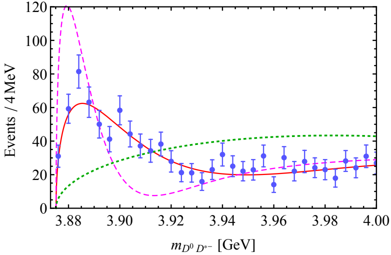

- Narrow pronounced
- Near-threshold
- Elastic channel

F.K. Guo, C. Hanhart, QW, Q. Zhao, PRD91(2015)051504

# Not simple threshold effects

**Argument I:** Perturbative input → non-perturbative output

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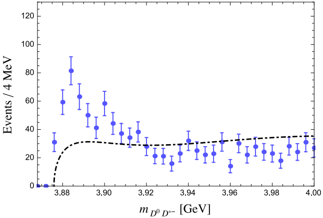
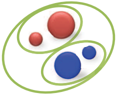



- Narrow pronounced
- Near-threshold
- Elastic channel

F.K. Guo, C. Hanhart, QW, Q. Zhao, PRD91(2015)051504

## Tetraquark

- Compact diquark-antidiquark bound systems
- Straightforward extension of the quark model
- Spin-spin interaction within these diquark systems



$$M = M_{00} + B_c \frac{\boldsymbol{L}^2}{2} - 2a\boldsymbol{L}\cdot\boldsymbol{S} + 2\kappa_{cq}[(\boldsymbol{s}_q \cdot \boldsymbol{s}_c) + (\boldsymbol{s}_{\bar{q}} \cdot \boldsymbol{s}_{\bar{c}})]$$

$\rightarrow$ $\kappa_{cq} > \kappa_{c\bar{c}}$ & $\kappa_{cq} > \kappa_{q\bar{q}}$

$\rightarrow$ Degenerate isospin singlet and isospin triplet ($\rho$ & $\omega$ )

$\rightarrow$ Parameters are fixed from the experimental data (positive)

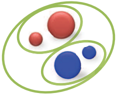
$\rightarrow$ Mass will decrease with the growing $J$

L. Maiani, et. al., PRD89(2014)114010, A. Esposito, et. al., Int.J. Mod.Phys. A30, 1530002, M. Cleven et. al., arXiv: 1505.01771[hep-ph]

# Disentangle different models from the spectrum

## Tetraquark

- Compact diquark-antidiquark bound systems
- Straightforward extension of the quark model
- Spin-spin interaction within these diquark systems



$$M = M_{00} + B_c \frac{L(L+1)}{2} + a[L(L+1) + S(S+1) - J(J+1)] + \kappa_{cq}[s(s+1) + \bar{s}(\bar{s}+1) - 3]$$

→ $\kappa_{cq} > \kappa_{c\bar{c}}$ & $\kappa_{cq} > \kappa_{q\bar{q}}$

→ Degenerate isospin singlet and isospin triplet ($\rho$ & $\omega$ )

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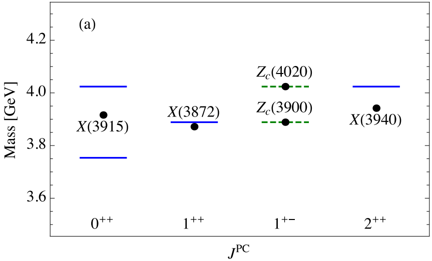
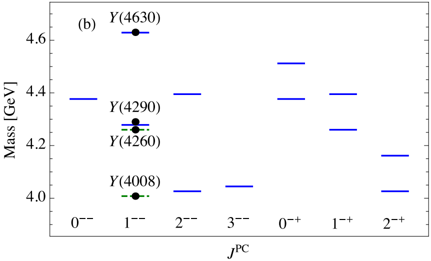


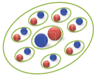




- Deviation from the existing data
- 9/24 $S$-wave tetraquark,
  4/56 $P$-wave tetraquark
- Two $0^{-+}$ states
- $Y(4360)$ and $Y(4660)$ excitations of $Y(4008)$ and $Y(4260)$
- Lower $3^{--}$ tetraquark
- Exotic quantum numbers: $0^{--}$ and $1^{-+}$

L. Maiani, et. al., PRD89(2014)114010, A. Esposito, et. al., Int.J. Mod.Phys. A30, 1530002, M. Cleven et. al., arXiv: 1505.01771[hep-ph]

## Hadro-quarkonium

- Observed in charmonium plus some pions,
  $Y(4260) \to J/\psi\pi\pi$, $Y(4360) \to \psi'\pi\pi$
- A compact heavy quarkonium embedded in a light cloud
- $Y(4260) \to h_c\pi\pi$ @ BESIII
- Hadro-charmonium mixing by including HQSS breaking



### Hadro-charmonium basis

$$\psi_1 \sim (1^{+-})_{c\bar{c}} \otimes (0^{-+})_{q\bar{q}}, \quad \psi_3 \sim (1^{--})_{c\bar{c}} \otimes (0^{++})_{q\bar{q}}$$

$\to$ Heavy core $h_c$ & $\psi'$, $(\psi_1, \psi_3) \xrightarrow{R(\theta)} (Y(4260), Y(4360))$

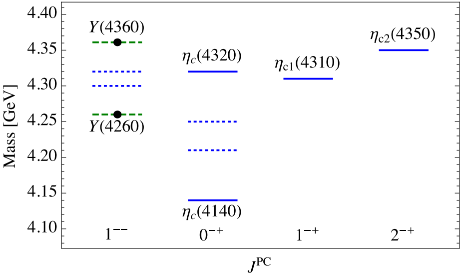
### Mass

$$\begin{pmatrix} m_{Y(4260)} & 0 \\ 0 & m_{Y(4360)} \end{pmatrix} = R(\theta) \begin{pmatrix} m_{\psi_1} & m_{13} \\ m_{13} & m_{\psi_3} \end{pmatrix} R(\theta)^T$$

M.B. Voloshin, Prog.Part.Nucl.Phys.61(2008)455, S. Dubynskiy et. al., PLB666(2008)344,

X.Li and M.B. Voloshin, Mod.Phys.Lett. A29(2014)1450060, M. Cleven et. al., arXiv: 1505.01771[hep-ph]

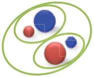
## Hadro-quarkonium $\psi' \rightarrow \eta_c'$ & $h_c \rightarrow \chi_{cJ}$




- $M1 \times E1$ transition between color neutral heavy core and light cloud
- $\eta_c(4140)$ and $\eta_c(4320)$: $B^\pm \rightarrow K^\pm \eta_c^{(\prime)} \pi^+\pi^-$
- $\eta_c(4310)$ and $\eta_c(4350)$: $e^+e^- \rightarrow \gamma\chi_{c1}(\chi_{c2})\pi^+\pi^-$

M. Cleven et. al., arXiv: 1505.01771[hep-ph]

## Hadronic Molecules



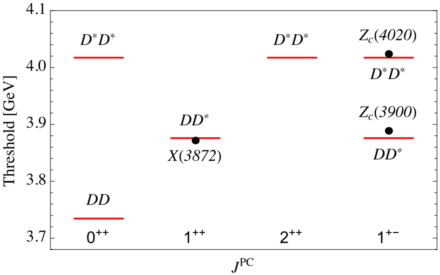
- Extended object made of two hadrons or more
- Examples:
  $X(3872) : DD^*$, $Z_c(3900) : DD^*, Y(4260) : D_1 D$
- Bound state can only be formed by narrow states
  $\rightarrow$ Examples: $\frac{1}{2} + \frac{1}{2}$ and $\frac{1}{2} + \frac{3}{2}$, with $(D, D^*) \sim \frac{1}{2}$, $(D_1, D_2) \sim \frac{3}{2}$
- If the long-range pion exchange potential plays a crucial role, then either isoscalar or isovector state may exist, but not both of them

$$\langle II_3|\vec{\tau}_{(1)} \cdot \vec{\tau}_{(2)}|II_3\rangle = 2\left[I(I+1) - \frac{3}{2}\right] = \begin{cases} 1 & (I = 1) \\ -3 & (I = 0) \end{cases}$$

M. Cleven et. al., arXiv: 1505.01771[hep-ph]

# Disentangle different models from the spectrum

## Hadronic Molecules $\frac{1}{2} + \frac{1}{2}$



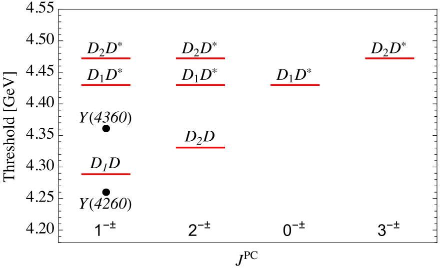

- Pion-exchange long range potential
- $V_{1^{++}} = V_{2^{++}}$ to the leading order

- Without dynamic analysis
- Relevant thresholds for fixed quantum numbers
- $X(3872)$ isosinglet $1^{++}$ $\rightarrow$ isosinglet $2^{++}$
- $Z_c(3900)$ & $Z_c(4020)$ isotriplet $\rightarrow$ no isosinglet $1^{+-}$
- No diagonal pion transition for $DD(0^{++})$

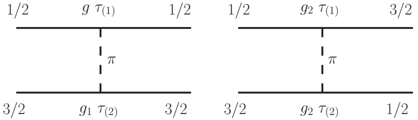
J.Nieves, et. al., PRD86(2012)056004, F.K.Guo, et. al., PRD88(2013)054007, M. Cleven et. al., arXiv: 1505.01771[hep-ph]

# Disentangle different models from the spectrum

## Hadronic Molecules $\frac{1}{2} + \frac{3}{2}$




- Three $1^{-\pm}$, $2^{-\pm}$ channels
- Lowest state of $1^{-\pm}$ near $D_1 D$
- $0^{-+}$ near $D_1 D^*$ $\leftrightarrow$ higher than $Y(4260)$ compared to hadro-charmonium




- $t$-channel and $u$-channel
- Unkown coupling $g_1$
- Isoscalar $0^{--}$& $3^{-+}$
- Isovector $0^{-+}$& $3^{--}$
- $3^{--}$ is much higher than that in tetraquark picture

QW, C. Hanhart, Q. Zhao, PRL111(2013)132003, QW, PRD89(2014)114013, M. Cleven et. al., arXiv: 1505.01771[hep-ph]

- Tetraquark: $Qq$ diquark configuration $\rightarrow Qq + Q$ in double charmed baryon? Or $QQ + q$ ?
- $\Lambda(1405)$: $\bar{K}N$ molecule? Or conventional excited baryon ?
- $\cdots$

# Summary

- A pronounced, narrow near-threshold peak in the elastic channel cannot be produced by purely kinematic perturbative effects
- Heavy quark spin symmetry helps us to disentangle the spectra for the *XYZ* states in different scenarios

  $\rightarrow$ one $0^{-+}$ near $D_1 D^*$ (4.43 GeV) threshold in molecular picture; two $0^{-+}$ states, i.e. 4.14 GeV and 4.32 GeV in hadro-charmonium picture

  $\rightarrow$ the masses of $J = 3$ in molecular scenario is much higher than those in tetraquark scenario
- Searching exotic quantum number states is another method to disentangle them, such as $0^{--}$, $1^{-+}$, $3^{-+}$

Thank you very much!