

# Evidence for a hadronic molecule structure of the $Y(3940)$ and $Y(4140)$

TANJA BRANZ

INSTITUT FÜR THEORETISCHE PHYSIK  
UNIVERSITÄT TÜBINGEN

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EBERHARD KARLS  
UNIVERSITÄT  
TÜBINGEN



# Outline

## 1 Introductory remarks

- meson spectrum & hadronic molecules
- charmonia &  $X, Y, Z$  mesons

## 2 $Y$ mesons as hadronic molecules:

- $Y(3940) = D^* \bar{D}^*$  and  $Y(4140) = D_s^{*-} D_s^{*+}$

## 3 Theory

- Quantum field theoretical approach for composite objects
- Computation of decay properties

## 4 Conclusions

Together with:

Thomas Gutsche and Valery Lyubovitskij

EPJA 37 (2008) 303, Phys. Rev. D 78, 114004 (2008),

Phys. Rev. D 79, 014035 (2009), Phys. Rev. D 80, 054019 (2009).



# Meson spectroscopy

*QCD* soft limit  $\Rightarrow$  hadronic world (mesons & baryons)

**Theoretical understanding:** confinement region *QCD* is strongly coupled theory  $\Rightarrow$  cannot be accessed by perturbation theory.

How can we get further information on the hadron substructure?



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- **Meson spectrum** (quantum numbers & masses)
- **Decay/ production patterns** (decay widths & branching ratios)



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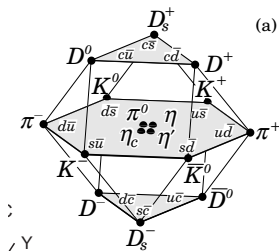
## Effective field approaches

- Effective models for hadron structure
- help to understand strongly coupled confinement region qualitatively and quantitatively

# Constituent quark model

Most successful model for hadronic matter on the quark level

- Mesons: quark-antiquark ( $q\bar{q}$ )
- Baryons: quark triplets ( $qqq$ )
- first  $SU(2)$
- extended by  $s, c, b$  quarks



## Problems

- 1 more states than expected (scalar sector)
- 2 predicted states not experimentally confirmed (missing states)
- 3 states that do not fit in the quark model

# The hidden-charm ( $c\bar{c}$ ) sector

## One of the best understood sector:

- long lifetime (small width) of states below open-charm threshold
- no broad and overlapping states as in the light scalar sector
- background is known
- charmonium mass spectrum is predicted by potential models and lattice calculations
- all states below  $D\bar{D}$  threshold experimentally confirmed



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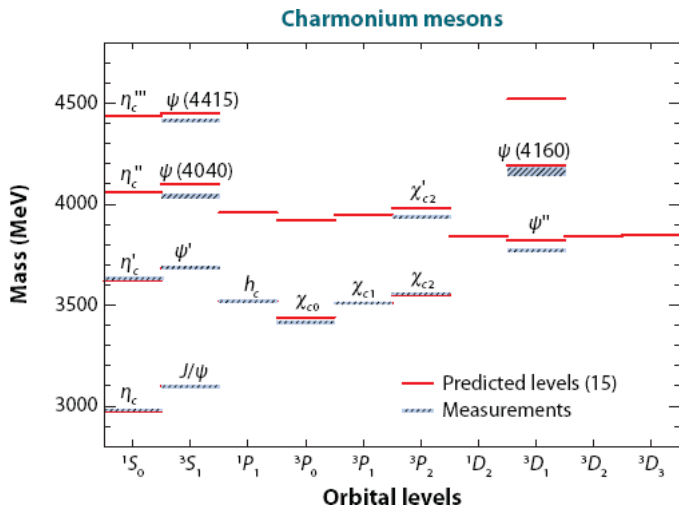
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$c\bar{c}$  meson sector offers well defined basis to study meson structure

⇒ Easy to distinguish between conventional  $c\bar{c}$  states and 'exotics'



# $c\bar{c}$ meson spectrum



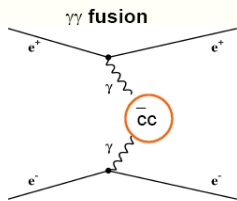
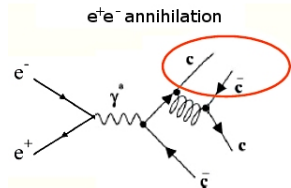
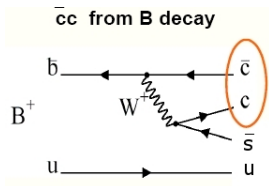
Picture taken from Godfrey, Olsen (2008)



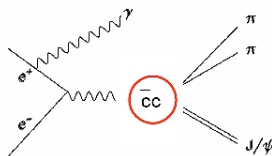
# Charmonium production mechanisms

**B-factories** BELLE, BaBar and CDF built to study  $B$ -physics

⇒ but also excellent environment for charmonium spectroscopy



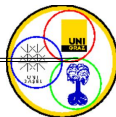
initial state radiation ( $J^{PC} = 1^{--}$ )



# Many new charmonium-like $X$ , $Y$ and $Z$ mesons

Are these the missing  $c\bar{c}$  states?

| state                       | $M$ (MeV)                        | $\Gamma$ (MeV)                          | $J^{PC}$                   | Decay Modes                        | Production Modes                                    | Observed by:          |
|-----------------------------|----------------------------------|---|----------------------------|------------------------------------|---|-----------------------|
| $Y_s(2175)$                 | $2175 \pm 8$                     | $58 \pm 26$                             | $1^{--}$                   | $\phi f_0(980)$                    | $e^+e^-$ (ISR), $J/\psi \rightarrow \eta Y_s(2175)$ | BaBar, BESII          |
| $X(3872)$                   | $3871.4 \pm 0.6$                 | $< 2.3$                                 | $1^{++}$                   | $\pi^+\pi^- J/\psi, \gamma J/\psi$ | $B \rightarrow KX(3872), p\bar{p}$                  | Belle, CDF, D0, BaBar |
| $X(3875)$                   | $3875.5 \pm 1.5$                 | $3.0^{+2.1}_{-1.7}$                     | ?                          | $D^0\bar{D}^0\pi^0(\gamma)$        | $B \rightarrow KX(3875)$                            | Belle, BaBar          |
| $Z(3940)$                   | $3929 \pm 5$                     | $29 \pm 10$                             | $2^{++}$                   | $D\bar{D}$                         | $\gamma\gamma \rightarrow Z(3940)$                  | Belle                 |
| $X(3940)$                   | $3942 \pm 9$                     | $37 \pm 17$                             | $J^{P+}$                   | $D\bar{D}^*$                       | $e^+e^- \rightarrow J/\psi X(3940)$                 | Belle                 |
| <b><math>Y(3940)</math></b> | <b><math>3943 \pm 17</math></b>  | <b><math>87 \pm 34</math></b>           | <b><math>J^{P+}</math></b> | <b><math>\omega J/\psi</math></b>  | <b><math>B \rightarrow KY(3940)</math></b>          | Belle, BaBar          |
| $Y(4008)$                   | $4008^{+82}_{-49}$               | $226^{+97}_{-80}$                       | $1^{--}$                   | $\pi^+\pi^- J/\psi$                | $e^+e^-$ (ISR)                                      | Belle                 |
| <b><math>Y(4140)</math></b> | <b><math>4130 \pm 4.1</math></b> | <b><math>11.7^{+12.0}_{-8.7}</math></b> | <b><math>J^{P+}</math></b> | <b><math>J/\psi\phi</math></b>     | <b><math>B^+ \rightarrow K^+Y(4140)</math></b>      | CDF                   |
| $X(4160)$                   | $4156 \pm 29$                    | $139^{+113}_{-65}$                      | $J^{P+}$                   | $D^*\bar{D}^*$                     | $e^+e^- \rightarrow J/\psi X(4160)$                 | Belle                 |
| $Y(4260)$                   | $4264 \pm 12$                    | $83 \pm 22$                             | $1^{--}$                   | $\pi^+\pi^- J/\psi$                | $e^+e^-$ (ISR)                                      | BaBar, CLEO, Belle    |
| $Y(4350)$                   | $4361 \pm 13$                    | $74 \pm 18$                             | $1^{--}$                   | $\pi^+\pi^- \psi'$                 | $e^+e^-$ (ISR)                                      | BaBar, Belle          |
| $Z(4430)$                   | $4433 \pm 5$                     | $45^{+35}_{-18}$                        | ?                          | $\pi^\pm\psi'$                     | $B \rightarrow KZ^\pm(4430)$                        | Belle                 |
| $Y(4660)$                   | $4664 \pm 12$                    | $48 \pm 15$                             | $1^{--}$                   | $\pi^+\pi^- \psi'$                 | $e^+e^-$ (ISR)                                      | Belle                 |
| $Y_b$                       | $\sim 10, 870$                   | ?                                       | $1^{--}$                   | $\pi^+\pi^- \Upsilon(1, 2S)$       | $e^+e^- \rightarrow Y_b$                            | Belle                 |

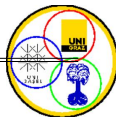


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Most of them do not fit!



## Two examples: $Y(3940)$ and $Y(4140)$

- $Y(4140)$  announced on 17 March 2009 by CDF at Fermilab in exclusive  $B^+ \rightarrow Y(4140)K^+$  with  $Y(4140) \rightarrow J/\psi\phi$

$$m_{Y(4140)} = 4130.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst}) \text{ MeV},$$

$$\Gamma_{Y(4140)} = 11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst}) \text{ MeV}$$

- $Y(3940)$  BELLE/BaBar (2005)

similar decay:  $B \rightarrow Y(3940)K$  with  $Y(3940) \rightarrow J/\psi\omega$

$$m_{Y(4140)} = 3914.6^{+3.8}_{-3.4}(\text{stat}) \pm 2(\text{syst}) \text{ MeV},$$

$$\Gamma_{Y(4140)} = 34^{+12}_{-8}(\text{stat}) \pm 5(\text{syst}) \text{ MeV}$$

- First estimates give binding for  $J^{PC} = 0^{++}$  or  $2^{++}$ .

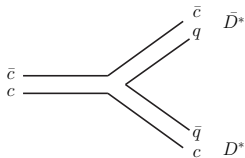


# Decay patterns of $\Upsilon$

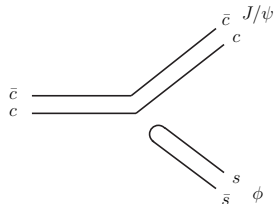
## Why do the $\Upsilon$ s not fit in the $c\bar{c}$ scheme?

- $c\bar{c}$  decays to **open charm** modes **dominant**
- $(c\bar{c}) \rightarrow J/\psi\omega$  or  $(c\bar{c}) \rightarrow J/\psi\phi$  **suppressed**

$c\bar{c}$  interpretation:  $\Gamma_{\Upsilon \rightarrow J/\psi\phi} \approx 1\text{-}10 \text{ keV}$  (see Liu (2009))



open charm decay (OZI-allowed)



hidden charm decay (OZI-suppressed)

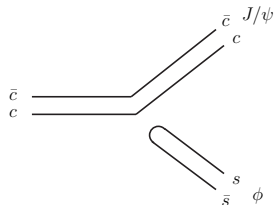
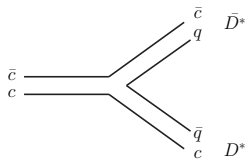


# Decay patterns of $Y$

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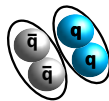
open charm decay (OZI-allowed)

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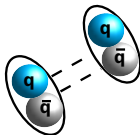
- Experiment:**  $Y \rightarrow J/\psi\omega(\phi) > 1 \text{ MeV}$   
(1 order of magnitude bigger than all charmonia!)

# Structures besides $q\bar{q}$ quark model

What could these states be?



Diquark-Antidiquark



Meson-Meson  
Molecule



quark-antiquark-gluon  
hybrid



# Structures besides $q\bar{q}$ quark model

## What could these states be?

### Hadronic molecules

- mesons loosely bound by strong interaction
- slightly below threshold  
 $m_{HM} < m_{M1} + m_{M2}$
- some candidates

$$f_0(980), a_0(980) = K\bar{K}$$

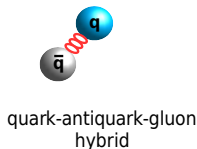
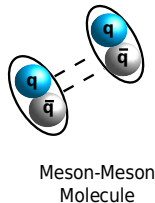
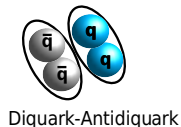
$$D_{s0}^*(2317) = DK$$

$$D_{s1}(2460) = D^*K$$

$$X(3872) = D^0\bar{D}^{*0} + c.c.$$

$$Y(3940) = D^*\bar{D}^*$$

$$Y(4140) = D_s^* + D_s^{*-}$$



# Y(3940) and Y(4140) - hadronic molecules

- $m_{Y(4140)} = 4130.0 \text{ MeV}$ ,  $D_s^{*+} D_s^{*-}$ -threshold  $\approx 4220 \text{ MeV}$ .

molecular structure  $|Y(4140)\rangle = |D_s^{*+} D_s^{*-}\rangle$

- $m_{Y(3940)} = 3914.6 \text{ MeV}$ ,  $D^* \bar{D}^*$ -threshold  $\approx 4014 \text{ MeV}$ .

interpretation as  $|Y(3940)\rangle = \frac{1}{\sqrt{2}} (|D^{*+} + D^{*-}\rangle + |D^{*0} \bar{D}^{*0}\rangle)$

- quantum numbers (first estimate)  $J^{PC} = 0^{++}$



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## Y(3940) and Y(4140) also dynamically generated

- **meson-meson exchange potentials** (Tornqvist (94), Lui *et al.* (09))  
 $D^* D^*$  bound by pion exchange,  $D_s^* D_s^*$  by  $\pi, \eta, \phi$  exchange
- **unitarized coupled channel** model (Oset *et al.* (09))  
Y(3940) is mostly a  $D^* \bar{D}^*$  bound state
- **QCD sum rule** study (Albuquerque *et al.*, Zhang *et al.* (09))  
give support for a  $Y(4140) = D_s^* D_s^*$  bound state with  $J^{PC} = 0^{++}$



# Model

Hadronic molecule  $H$  as bound state of mesons  $M_1$  and  $M_2$

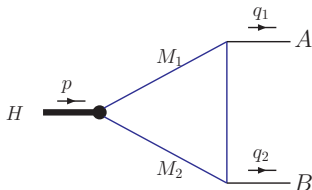
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**Decays of hadronic molecules:**

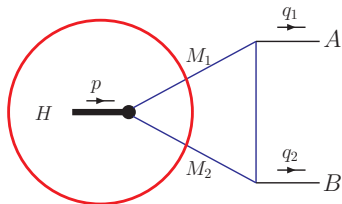
Decay proceeds via  
constituent mesons  $M_1$  &  $M_2$



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**Decays of hadronic molecules:**

Decay proceeds via  
constituent mesons  $M_1$  &  $M_2$

- 1 finite size of hadronic molecule  $\rightarrow$  form factors
- 2 determination of coupling constant  $g_H$



# Theoretical framework

Interaction of  $H$  with  $M_1$  and  $M_2$  characterized by **effective Lagrangian**:

$$\mathcal{L}_H(x) = g_H H(x) \int dy \Phi(y^2) M_1\left(x - \frac{y}{2}\right) M_2\left(x + \frac{y}{2}\right)$$



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$$\Phi(y^2) = \int \frac{d^4 k}{(2\pi)^4} e^{-iky} \tilde{\Phi}(-k^2)$$



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Gaussian form in momentum space:  $\tilde{\Phi}(k_E^2) = \exp(-k_E^2/\Lambda^2)$

**Size parameter**  $\Lambda = 0.7 - 1.3$  GeV

Local limit (pointlike interaction):  $\Lambda \rightarrow \infty$



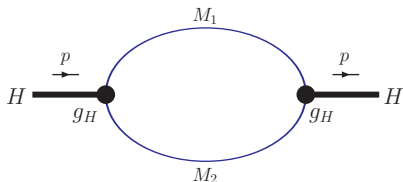
# Compositeness/Weinberg condition

- ② determination of the coupling constant  $g_H$

Description of hadronic bound states based on **compositeness condition**<sup>1</sup>

$$Z_H = 1 - g_H^2 \tilde{\Pi}'(p^2) \Big|_{p^2=m_H^2} = 0 .$$

with the mass operator  $g_H^2 \tilde{\Pi}(p^2)$



$$Z_H = |\langle H^{bare} | H^{dressed} \rangle|^2 = 0$$

Couplings  $g_H$  finite and fixed self-consistently

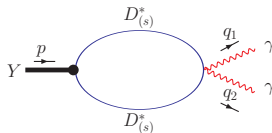
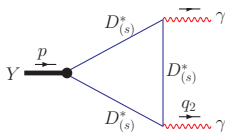
<sup>1</sup>Weinberg, PR 130 (1963) 776; Salam, Nuov. Cim. 25 (1962) 224;...



# Radiative decays $Y \rightarrow \gamma\gamma$

- ① minimal substitution  $M^\pm \rightarrow (\partial^\mu \mp ieA^\mu)M^\pm$

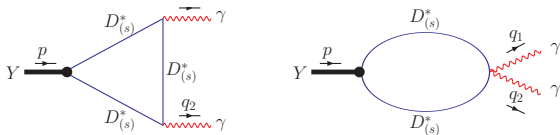
$$\mathcal{L}_{\text{em}} = eA_\alpha \left( g^{\alpha\nu} D_\mu^{*-} \overset{\leftrightarrow}{\partial}^\mu D_\nu^{*+} + \text{H.c.} \right) + e^2 D_\mu^{*-} D_\nu^{*+} \left( A^\mu A^\nu - g^{\mu\nu} A^\alpha A_\alpha \right).$$



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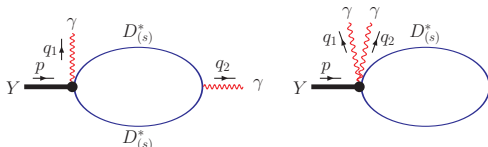
- ① minimal substitution  $M^\pm \rightarrow (\partial^\mu \mp ieA^\mu)M^\pm$

$$\mathcal{L}_{\text{em}} = eA_\alpha \left( g^{\alpha\nu} D_\mu^{*-} \overset{\leftrightarrow}{\partial}^\mu D_\nu^{*+} + \text{H.c.} \right) + e^2 D_\mu^{*-} D_\nu^{*+} \left( A^\mu A^\nu - g^{\mu\nu} A^\alpha A_\alpha \right).$$



- ② gauging the strong interaction Lagrangian with

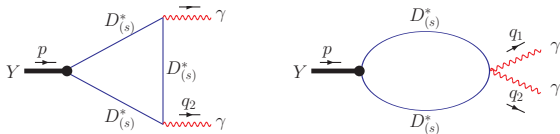
$$M^\pm(y) \rightarrow e \mp iel(y, x, P) M^\pm(y), \text{ where } I(x, y, P) = \int_y^x dz_\mu A^\mu(z).$$



# Radiative decays $Y \rightarrow \gamma\gamma$

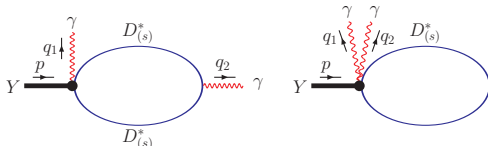
- ① minimal substitution  $M^\pm \rightarrow (\partial^\mu \mp ieA^\mu)M^\pm$

$$\mathcal{L}_{\text{em}} = eA_\alpha \left( g^{\alpha\nu} D_\mu^{*-} \overset{\leftrightarrow}{\partial}^\mu D_\nu^{*+} + \text{H.c.} \right) + e^2 D_\mu^{*-} D_\nu^{*+} \left( A^\mu A^\nu - g^{\mu\nu} A^\alpha A_\alpha \right).$$



- ② gauging the strong interaction Lagrangian with

$$M^\pm(y) \rightarrow e \mp iel(y, x, P) M^\pm(y), \text{ where } l(x, y, P) = \int_y^x dz_\mu A^\mu(z).$$



- two additional diagrams are generated
- necessary to guarantee full gauge invariance.



## Hidden-charm decays

$$Y \rightarrow J/\psi\phi, \quad Y \rightarrow J/\psi\omega$$

## Coupling to final states

HHChPT Lagrangian (Wise (1992), Colangelo (2004)):

$$\mathcal{L}_{D^*D^*J\psi} = ig_{D^*D^*J\psi} J_\psi^\mu \left( D_{\mu i}^{*\dagger} \overleftrightarrow{\partial}_\nu D_i^{*\nu} + D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}^\nu D_{\mu i}^* - D_i^{*\dagger\nu} \overleftrightarrow{\partial}_\mu D_{\nu i}^* \right),$$

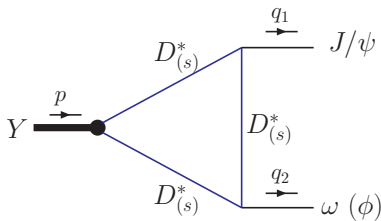
$$\mathcal{L}_{D^*D^*V} = ig_{D^*D^*V} V_{ij}^\mu D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}_\mu D_j^{*\nu} + 4if_{D^*D^*V} (\partial^\mu V_{ij}^\nu - \partial^\nu V_{ij}^\mu) D_{\mu i}^* D_j^{*\dagger\nu}$$

$$V_{ij} = \text{diag}\{\omega/\sqrt{2}, \omega/\sqrt{2}, \phi\}$$

$$g_{D^*D^*J/\psi} \approx 3.69$$

$$g_{D^*D^*V} \approx 4.61$$

$$f_{D^*D^*V} \approx 8.00$$



# Results

**Y(4140)**

$$\Gamma_{Y(4140)} = 11.7_{-5.0}^{+8.3}(\text{stat}) \pm 3.7(\text{syst}) \text{ MeV}$$

•  $\Gamma_{Y \rightarrow J/\psi\phi}$

|                   |                |                 |
|-------------------|----------------|-----------------|
| Experiment        | CDF (09)       | > 1 MeV         |
| Liu (09)          | ( $\bar{c}c$ ) | 1-10 keV        |
| <b>our result</b> | (HM)           | <b>3.26 MeV</b> |

•  $\Gamma_{Y \rightarrow \gamma\gamma} = 0.63 \text{ keV}$



# Results

## Y(4140)

$$\Gamma_{Y(4140)} = 11.7_{-5.0}^{+8.3}(\text{stat}) \pm 3.7(\text{syst}) \text{ MeV}$$

- $\Gamma_{Y \rightarrow J/\psi\phi}$

|            |                |          |
|------------|----------------|----------|
| Experiment | CDF (09)       | > 1 MeV  |
| Liu (09)   | ( $\bar{c}c$ ) | 1-10 keV |
| our result | (HM)           | 3.26 MeV |

- $\Gamma_{Y \rightarrow \gamma\gamma} = 0.63 \text{ keV}$

## Y(3940)

$$\Gamma_{Y(3940)} = 34_{-8}^{+12}(\text{stat}) \pm 5(\text{syst}) \text{ MeV}$$

- $\Gamma_{Y \rightarrow J/\psi\omega}$

|                   |                   |          |
|-------------------|-------------------|----------|
| Experiment        | BELLE (05)        | > 1 MeV  |
| Molina, Oset (09) | (coupled channel) | 1.52 MeV |
| our result        | (HM)              | 5.47 MeV |

- $\Gamma_{Y \rightarrow \gamma\gamma} = 0.33 \text{ keV}$

- Sizable  $\Gamma_{Y \rightarrow J/\psi\phi (J/\psi\omega)}$  can be explained by molecular model (TB, Gutsche, Lyubovitskij, Phys. Rev. D 80, 054019 (2009))



# Conclusions

- Overview of  $c\bar{c}$  mass spectrum
- Covariant and gauge invariant QFT approach to hadronic bound states
- Finite size effect characterized by free parameter
- Study of decay properties of charmonium-like mesons  $Y(3940)$  and  $Y(4140)$
- Large  $Y \rightarrow J/\psi V$  decay width can be explained by the hadronic molecule interpretation.



# Results for $2^{++}$ similar to $0^{++}$

## Results for $J^{PC} = 2^{++}$

- $\Gamma(Y(3940) \rightarrow J/\psi\omega) = 7.48 \pm 0.27 \text{ MeV}$ ,
- $\Gamma(Y(4140) \rightarrow J/\psi\phi) = 4.41 \pm 0.16 \text{ MeV}$ ,
- $\Gamma(Y(3940) \rightarrow \gamma\gamma) = 0.27 \pm 0.01 \text{ keV}$ ,
- $\Gamma(Y(4140) \rightarrow \gamma\gamma) = 0.50 \pm 0.01 \text{ keV}$ .

