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IS $\chi_{c1}(3872)$ GENERATED FROM STRING BREAKING ?

(THE DIABATIC APPROACH IN QCD)

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REFERENCES

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Diabatic description of charmoniumlike mesons.
Phys. Rev. D 102, 074002 (2020).

Coupled-channel meson-meson scattering in the diabatic framework.
Phys. Rev. D 104, 074025 (2021).

Is $\chi_{c1}(3872)$ generated from string breaking?
Phys. Rev. D 105, 054028 (2022).

$\chi_{c1}(2p)$ an overshadowed charmoniumlike resonance.
arXiv:2207.02740[hep-ph]

MOTIVATION

Almost twenty years after the discovery of $\chi_{c1}(3872)$, a deep dynamical understanding of this and other unconventional mesons is still lacking.

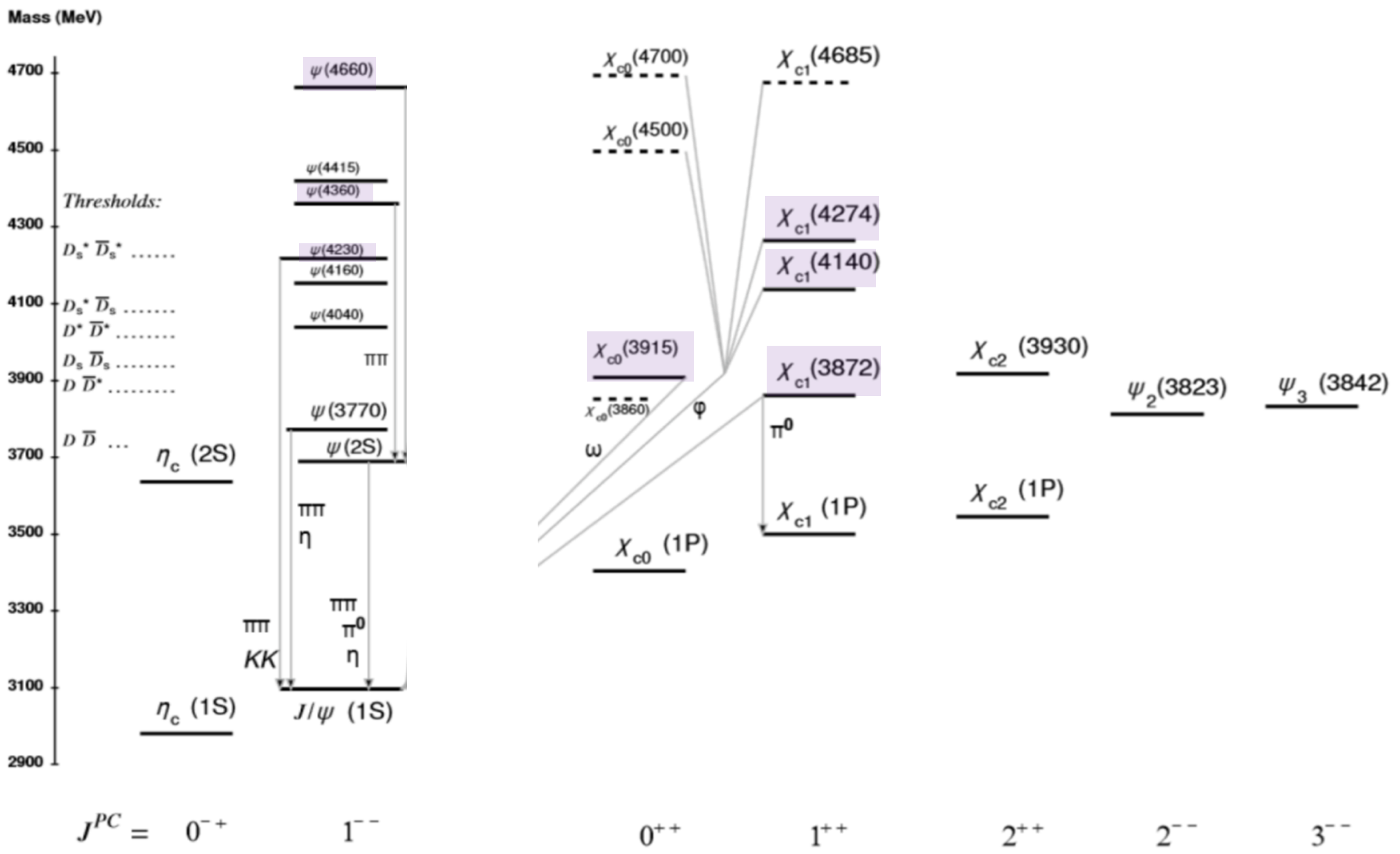
CHALLENGE

Unified and consistent description of heavy-quark mesons, conventional ($c\bar{c}$) and unconventional, from QCD.

R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

2003-2022

7 well established unconventional charmoniumlike states



OUTLINE

i) Heavy-quark meson description.

ii) String breaking potential.

iii) The Diabatic Approach in QCD.

iv) Charmoniumlike mesons.

iv) Summary.

HEAVY-QUARK MESON DESCRIPTION

General Requirement

An accurate description of heavy-quark mesons requires a suitable choice of the degrees of freedom and the implementation of the QCD dynamics.

Born-Oppenheimer type assumptions

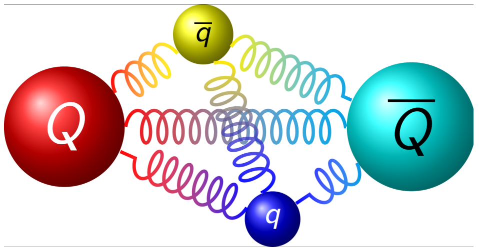
On the basis of the QCD energy scale Λ_{QCD} we can classify distinctively the heavy and light degrees of freedom.

Static approximation: the dynamics of the light fields can be solved by neglecting the motion of the heavy degrees of freedom.

Heavy degrees of freedom

There is nowadays compelling evidence of heavy quark- heavy antiquark, $Q\overline{Q}$, and open flavor meson-meson, $M\overline{M}$, degrees of freedom.

Light field degrees of freedom : Gluons and sea quarks



Static Approximation

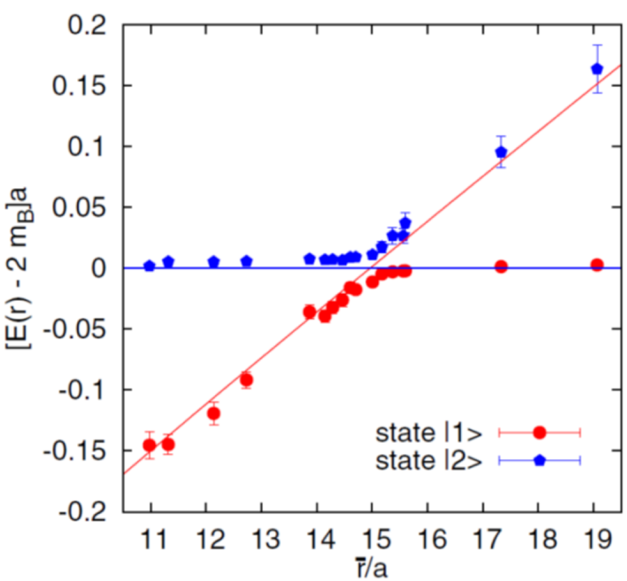
$$H\left|\psi\right\rangle = E\left|\psi\right\rangle \qquad H = K_{heavy} + H_{light}$$

For any fixed relative position of $Q\overline{Q}$: $$\left(H_{light}\left(\boldsymbol{r}\right) - V_i\left(\boldsymbol{r}\right)\right)\left|\zeta_i\left(\boldsymbol{r}\right)\right\rangle = 0$$

$$\{|\zeta_i(\boldsymbol{r})\rangle\} \quad \langle\zeta_j(\boldsymbol{r})|\zeta_i(\boldsymbol{r})\rangle = \delta_{ji}$$

$$V_i\left(\boldsymbol{r}\right)\ :\ \text{Eigenvalues of}\quad V=\begin{pmatrix}\left\langle \zeta_{Q\overline{Q}}\right| H_{light}\left|\zeta_{Q\overline{Q}}\right\rangle & \left\langle \zeta_{Q\overline{Q}}\right| H_{light}\left|\zeta_{M\overline{M}}\right\rangle \\ \left\langle \zeta_{M\overline{M}}\right| H_{light}\left|\zeta_{Q\overline{Q}}\right\rangle & \left\langle \zeta_{M\overline{M}}\right| H_{light}\left|\zeta_{M\overline{M}}\right\rangle\end{pmatrix}$$

The radial dependence of the eigenvalues and eigenvectors of the light fields have been calculated in Lattice QCD : G. S. Bali *et al*., PRD 71, 11453 (2005) G. Bulava *et al*., PLB 793, 493 (2019)



$$\left\langle \zeta_{Q\overline{Q}}\right| H_{light}\left|\zeta_{Q\overline{Q}}\right\rangle$$

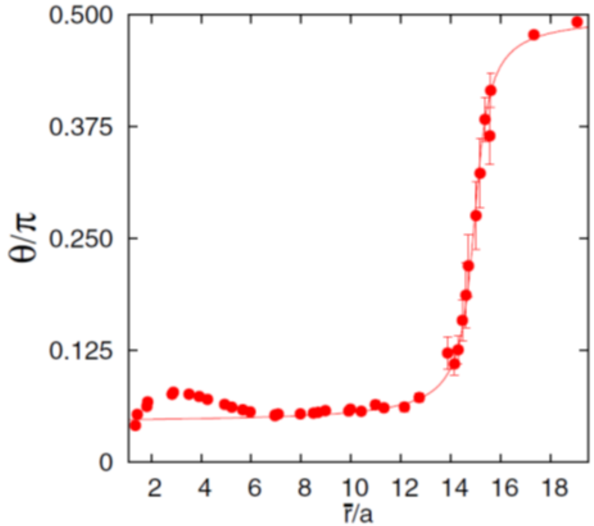
G. S. Bali, Phis. Rep. 343,1 (2001)

$$V_C\left(r\right)=\sigma r-\frac{\chi}{r}+2m_Q-\beta$$

$$\left\langle \zeta_{M\overline{M}}\right| H_{light}\left|\zeta_{M\overline{M}}\right\rangle$$

$$T_{M\overline{M}}=m_M+m_{\overline{M}}$$

Avoided Crossing of the energy levels

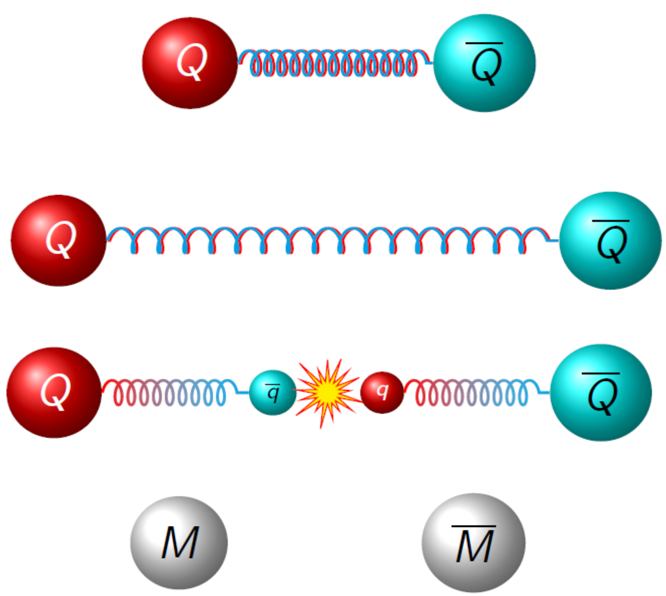


$$|\zeta_1(r)\rangle = \cos\theta(r)\left|\zeta_{Q\overline{Q}}\right\rangle + \sin\theta(r)\left|\zeta_{M\overline{M}}\right\rangle$$

$$|\zeta_2(r)\rangle = -\sin\theta(r)\left|\zeta_{Q\overline{Q}}\right\rangle + \cos\theta(r)\left|\zeta_{M\overline{M}}\right\rangle$$

$$\theta(r_c) = \frac{\pi}{4}$$

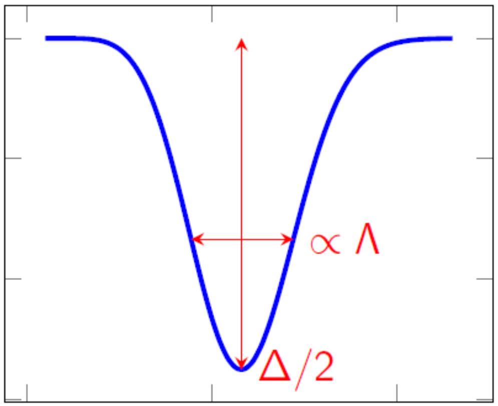
String Breaking



STRING BREAKING POTENTIAL

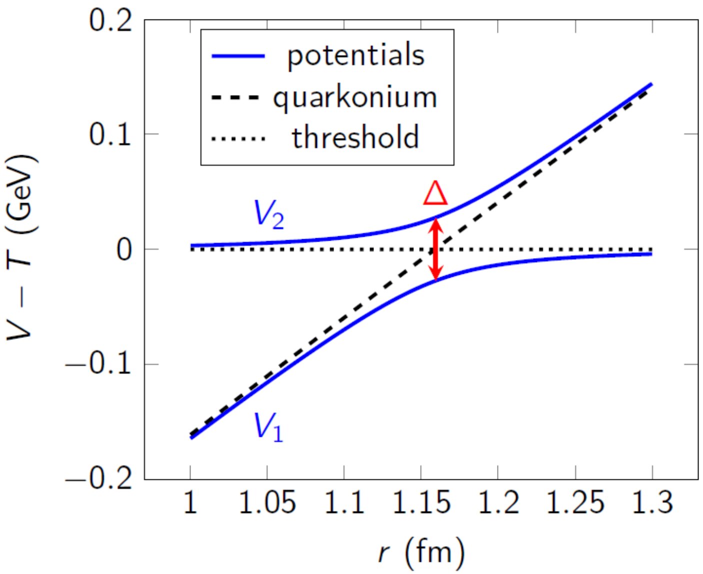
From the eigenvalues and the diagonal matrix elements the radial dependence of the string breaking potential can be parametrized.

$$\left\langle \zeta_{Q\overline{Q}} \right| H_{light} \left|\zeta_{M\overline{M}}\right\rangle \longrightarrow V_{mix}(r) = -\frac{\Delta}{2} e^{-\frac{\left(V_C(r)-T_{M\overline{M}}\right)^2}{2\Lambda^2}}$$

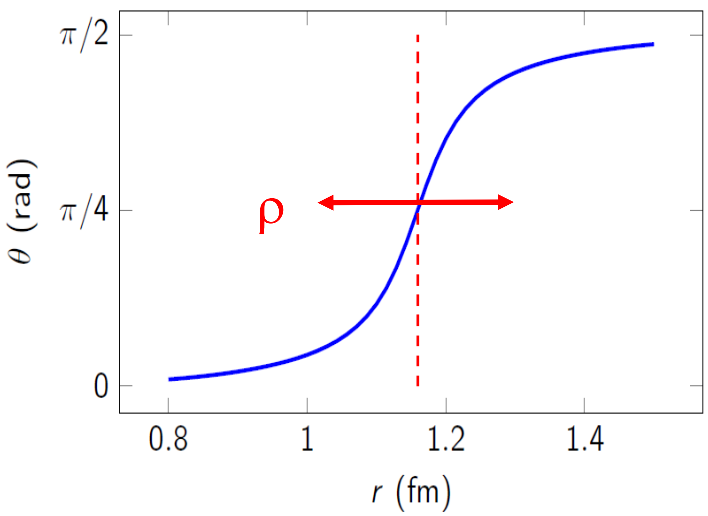


Δ is taken as an effective parameter (the same for all thresholds).

$$\begin{pmatrix} V_C(r) & V_{mix}(r) \\ V_{mix}^{\dagger}(r) & T_{M\overline{M}} \end{pmatrix} \rightarrow V_1(r), V_2(r)$$



The value of $\rho \equiv \dfrac{\Lambda}{\sigma}$ gives the size of the mixing region (the same for all thresholds).



$$|\zeta_1(r)\rangle = \cos\theta(r)\left|\zeta_{Q\overline{Q}}\right\rangle + \sin\theta(r)\left|\zeta_{M\overline{M}}\right\rangle$$

$$|\zeta_2(r)\rangle = -\sin\theta(r)\left|\zeta_{Q\overline{Q}}\right\rangle + \cos\theta(r)\left|\zeta_{M\overline{M}}\right\rangle$$

The mixing is only significant around the crossing radius

For $\boldsymbol{r}_0$ far from the crossing radius :

$$|\zeta_1(\boldsymbol{r}_0)\rangle \rightarrow \left|\zeta_{Q\overline{Q}}\right\rangle$$

$$|\zeta_2(\boldsymbol{r}_0)\rangle \rightarrow \left|\zeta_{M\overline{M}}\right\rangle$$

THE DIABATIC APPROACH IN QCD

Diabatic Expansión

From the physical point of view it is convenient to expand the heavy-quark meson state in terms of $Q\overline{Q}$ and $M\overline{M}$ states (simplified notation)

$$|\psi\rangle = \sum_i \int \mathrm{d}\boldsymbol{r}' \tilde{\psi}_i(\boldsymbol{r}', \boldsymbol{r}_0)|\boldsymbol{r}'\rangle|\zeta_i(\boldsymbol{r}_0)\rangle$$

$$\widetilde{\psi}_1(\boldsymbol{r}', \boldsymbol{r}_0) \to \psi_{Q\overline{Q}}(\boldsymbol{r}')$$

$$\widetilde{\psi}_2(\boldsymbol{r}', \boldsymbol{r}_0) \to \psi_{M\overline{M}}(\boldsymbol{r}')$$

Schrödinger Equation

$$H\,|\psi\rangle = E\,|\psi\rangle \longrightarrow \langle\zeta_j\,(\boldsymbol{r}_0)|\,\langle\boldsymbol{r}|\,(K_{heavy} + H_{light})\,|\psi\rangle = E\,\langle\zeta_j\,(\boldsymbol{r}_0)|\,\langle\boldsymbol{r}|\,\psi\rangle$$

Integrating out the light d. o. f

$$\langle\boldsymbol{r}|\,(K_{heavy} + V)\,|\boldsymbol{r}'\rangle \begin{pmatrix} \psi_{Q\overline{Q}}(\boldsymbol{r}') \\ \psi_{M\overline{M}}(\boldsymbol{r}') \end{pmatrix} = E \begin{pmatrix} \psi_{Q\overline{Q}}(\boldsymbol{r}) \\ \psi_{M\overline{M}}(\boldsymbol{r}) \end{pmatrix}$$

J^{PC} MESON

For the case of only one partial wave contributing for $Q\overline{Q}$ and $M\overline{M}$

$$\left[\begin{pmatrix} -\frac{1}{2\mu^{(0)}}\frac{d^2}{dr^2}+\frac{l_1^{(0)}(l_1^{(0)}+1)}{2\mu^{(0)}r^2} & \\ & -\frac{1}{2\mu^{(1)}}\frac{d^2}{dr^2}+\frac{l_1^{(1)}(l_1^{(1)}+1)}{2\mu^{(1)}r^2} \end{pmatrix} + \begin{pmatrix} V_C(r) & V_{mix}^{(1)}(r) \\ V_{mix}^{(1)}(r) & T^{(1)} \end{pmatrix}\right]\begin{pmatrix} u_{J^{PC};1}^{(0)}(r) \\ u_{J^{PC};1}^{(1)}(r) \end{pmatrix} = E\begin{pmatrix} u_{J^{PC};1}^{(0)}(r) \\ u_{J^{PC};1}^{(1)}(r) \end{pmatrix}$$

Solutions: Bound states and Scattering states

CHARMONIUMLIKE MESONS

(Spectral region: no threshold widths, no hybrid candidates)

$$V_C(r) = \sigma r - \frac{\chi}{r} + 2m_Q - \beta$$

E. Eichten and C. Quigg, PRD 49, 5845 (1994)

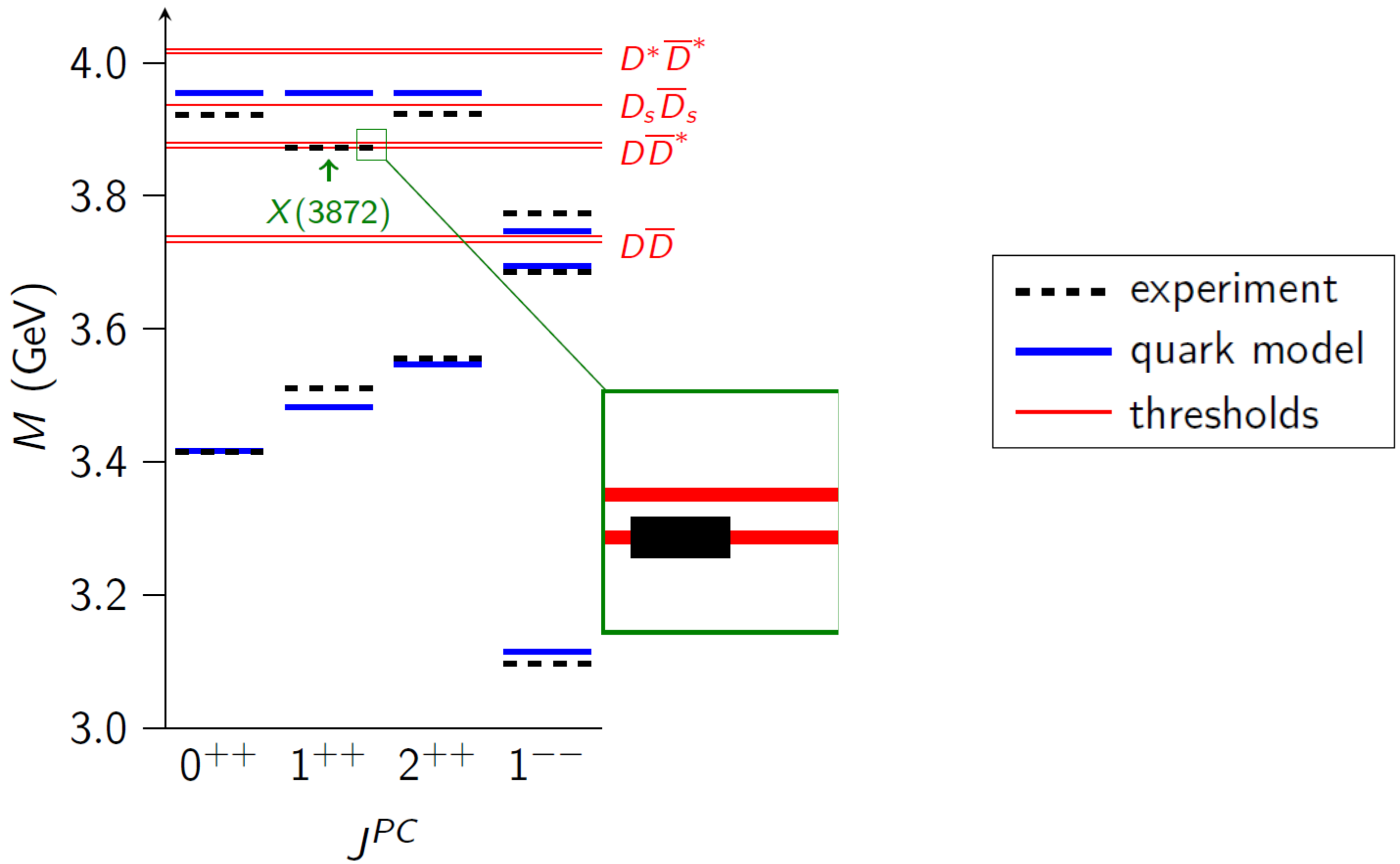
E. Eichten and F. Feinberg, PRD 23, 2724 (1981))

$\sigma = 925.6$ MeV/fm,

$\chi = 102.6$ MeV fm,

$\beta = 855$ MeV.

$m_c = 1840$ MeV



$T_{M\overline{M}}$: Experimental values

Channel	Threshold (MeV)
$D^0\bar{D}^0$	3729.6
D^+D^-	3739.4
$D^0\bar{D}^{*0}$	3871.7
D^+D^{*-}	3880.0
$D_s\bar{D}_s$	3936.6
$D^{*0}\bar{D}^{*0}$	4013.8
$D^{*+}D^{*-}$	4020.6

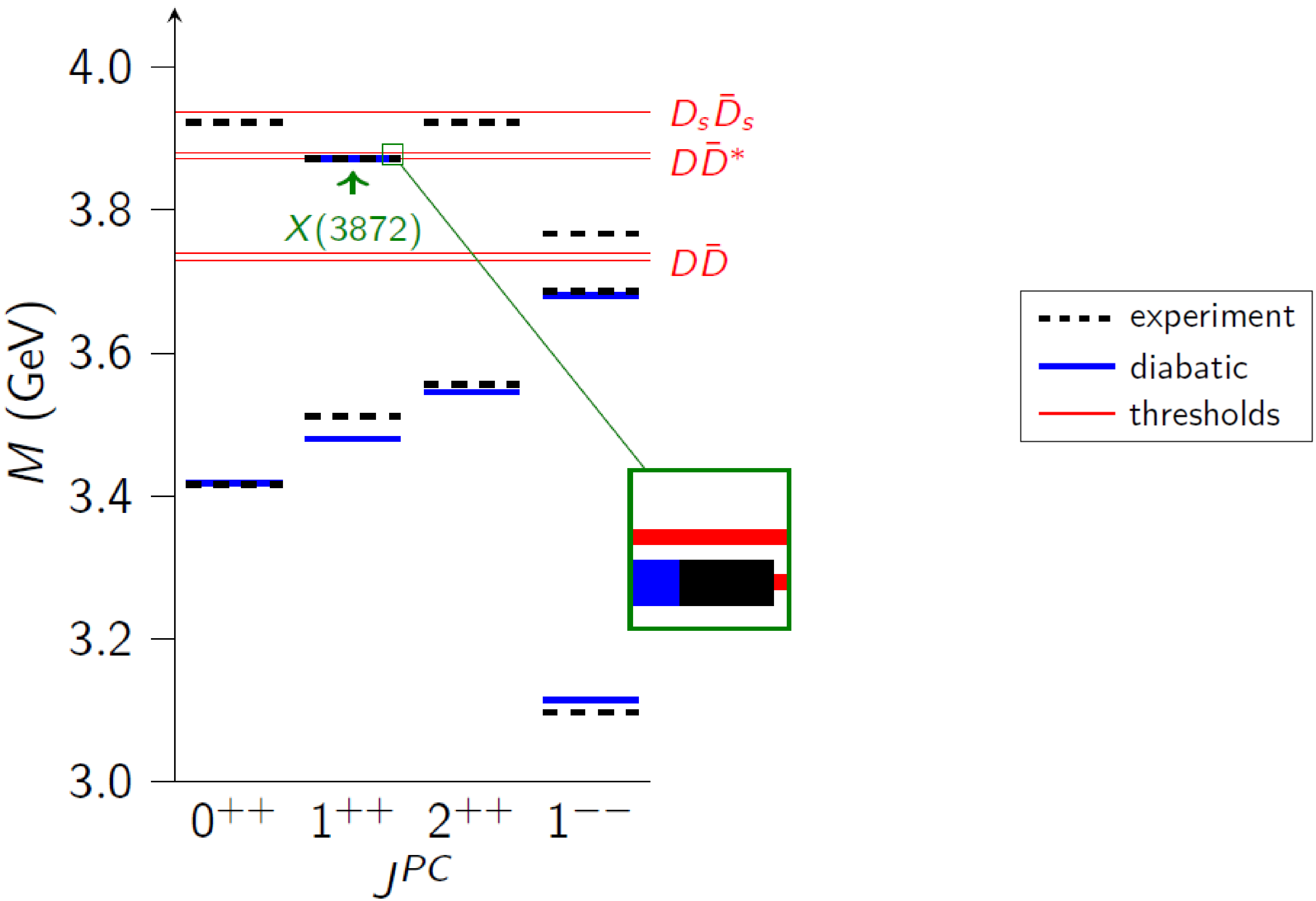
$$V_{mix}(r) = -\frac{\Delta}{2} e^{-\frac{\left(V_C(r) - T_{M\overline{M}}\right)^2}{2\Lambda^2}}$$

$\Lambda = \sigma\rho$

$\rho = 0.3$ fm

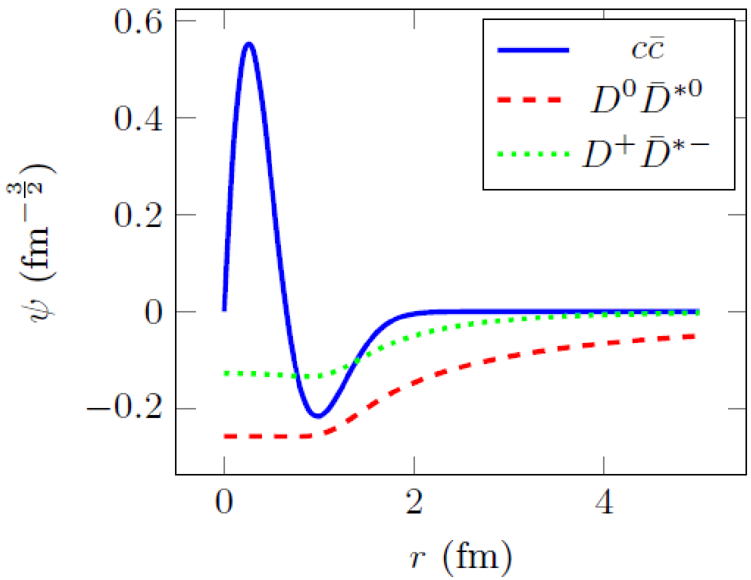
Can $\chi_{c1}(3872)$ be generated from string breaking ? $\Delta_c \approx 102.2$ MeV

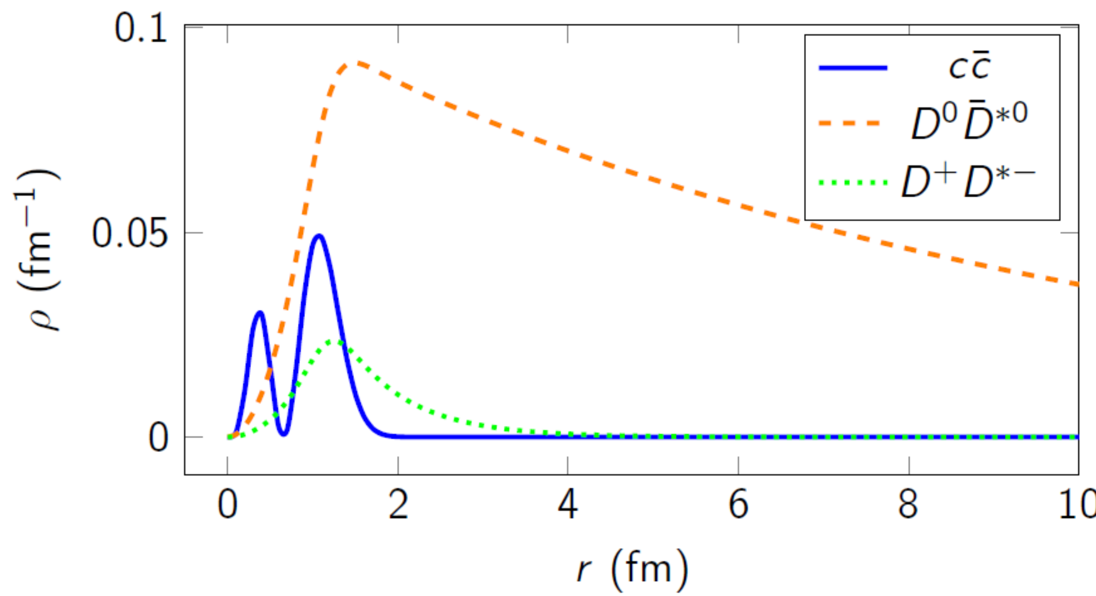
Diabatic Bound States



Predictions

$\chi_{c1}(3872)$



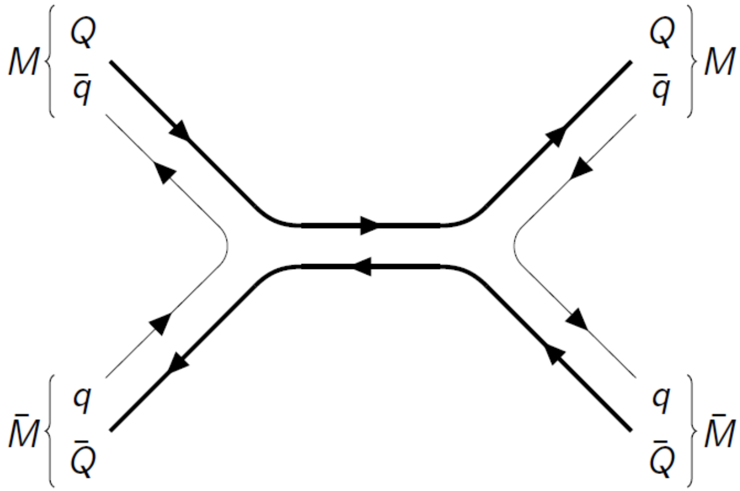


$$\sqrt{\langle r^2 \rangle} \approx 14 \text{ fm}$$

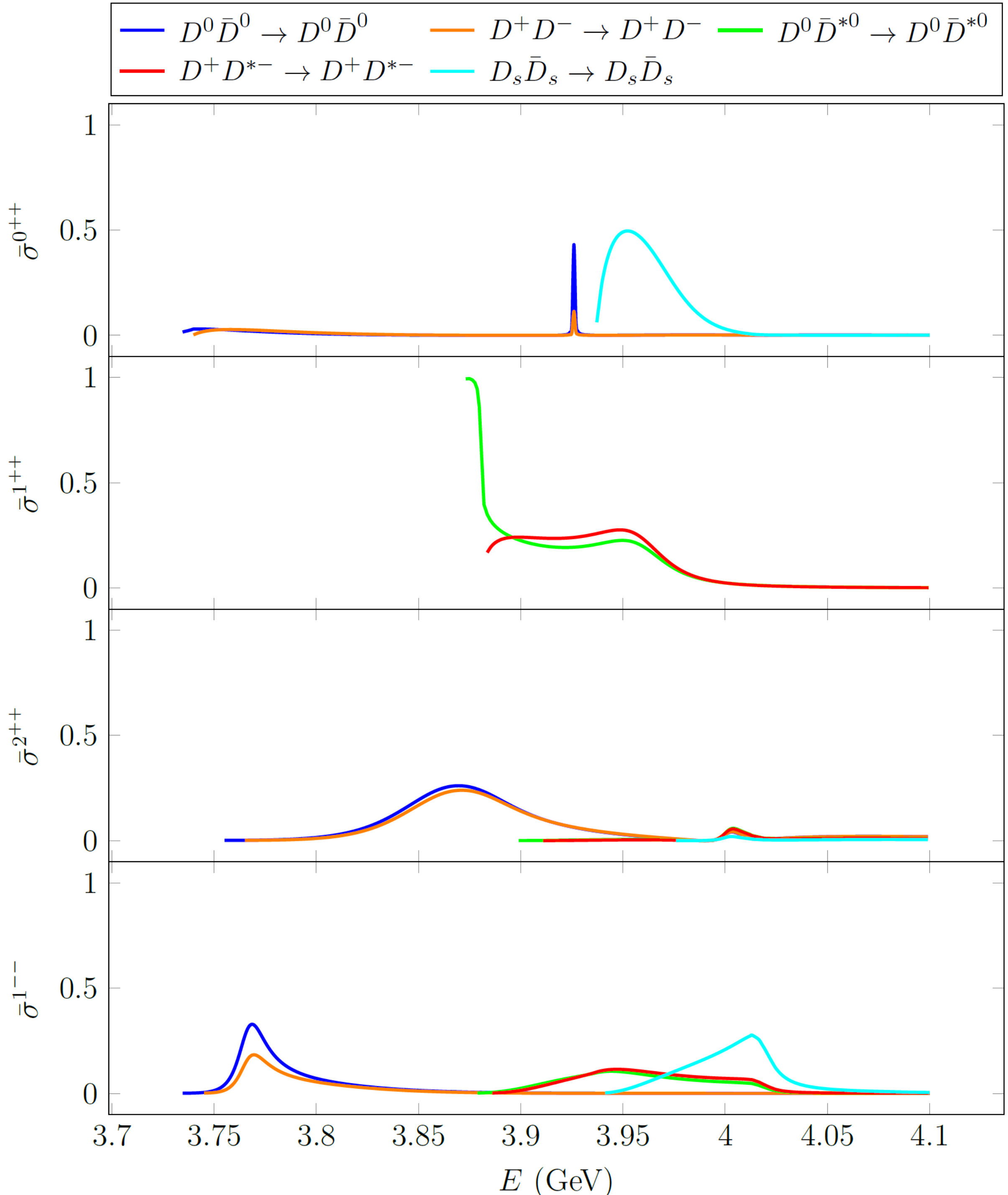
$$P_{c\bar{c}} = 4\%$$
$$P_{D^0\bar{D}^{*0}} = 93\%$$
$$P_{D^+D^{*-}} = 3\%$$

Diabatic Scattering States

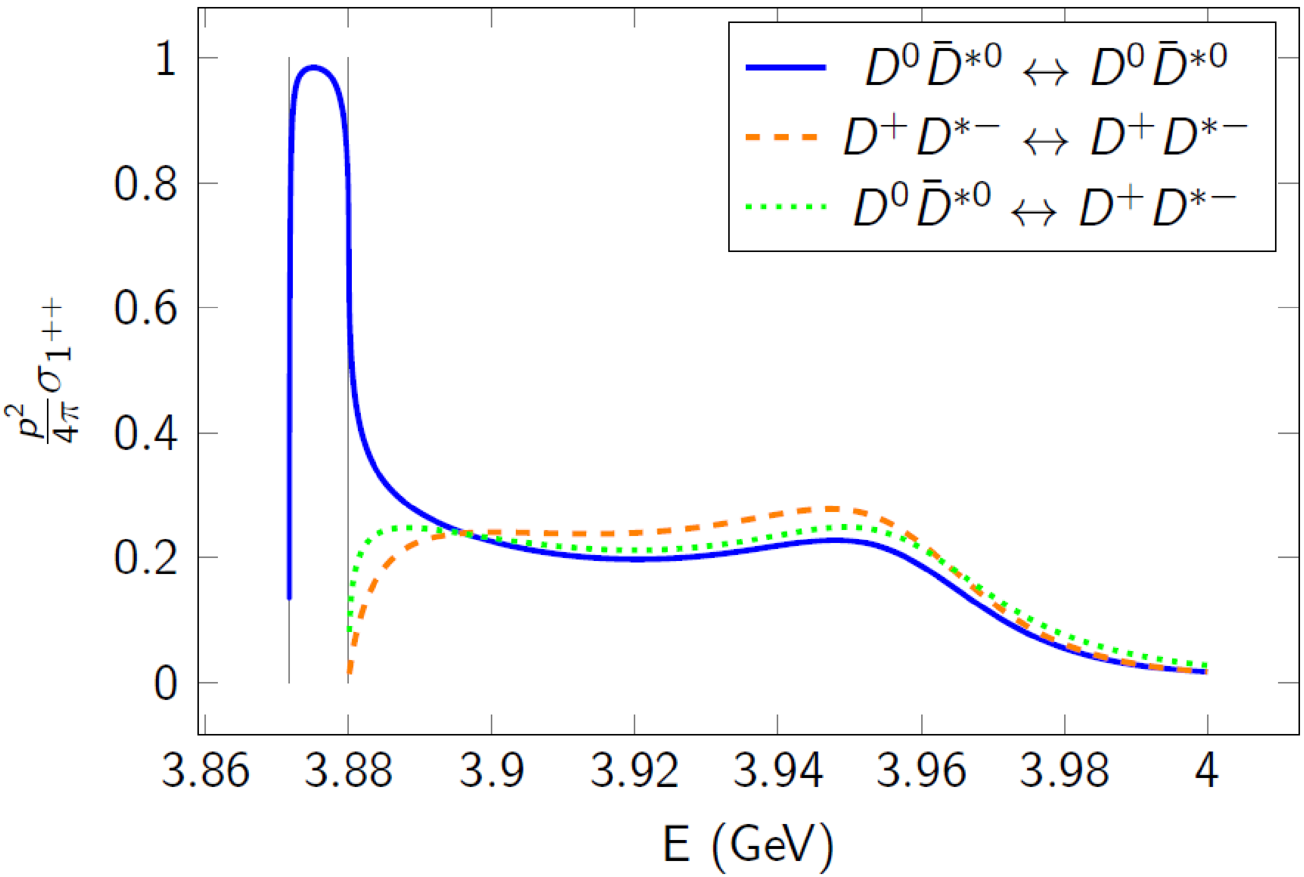
From the asymptotic behavior of the wave functions the $M\overline{M}$ scattering amplitude and the corresponding cross sections can be calculated.



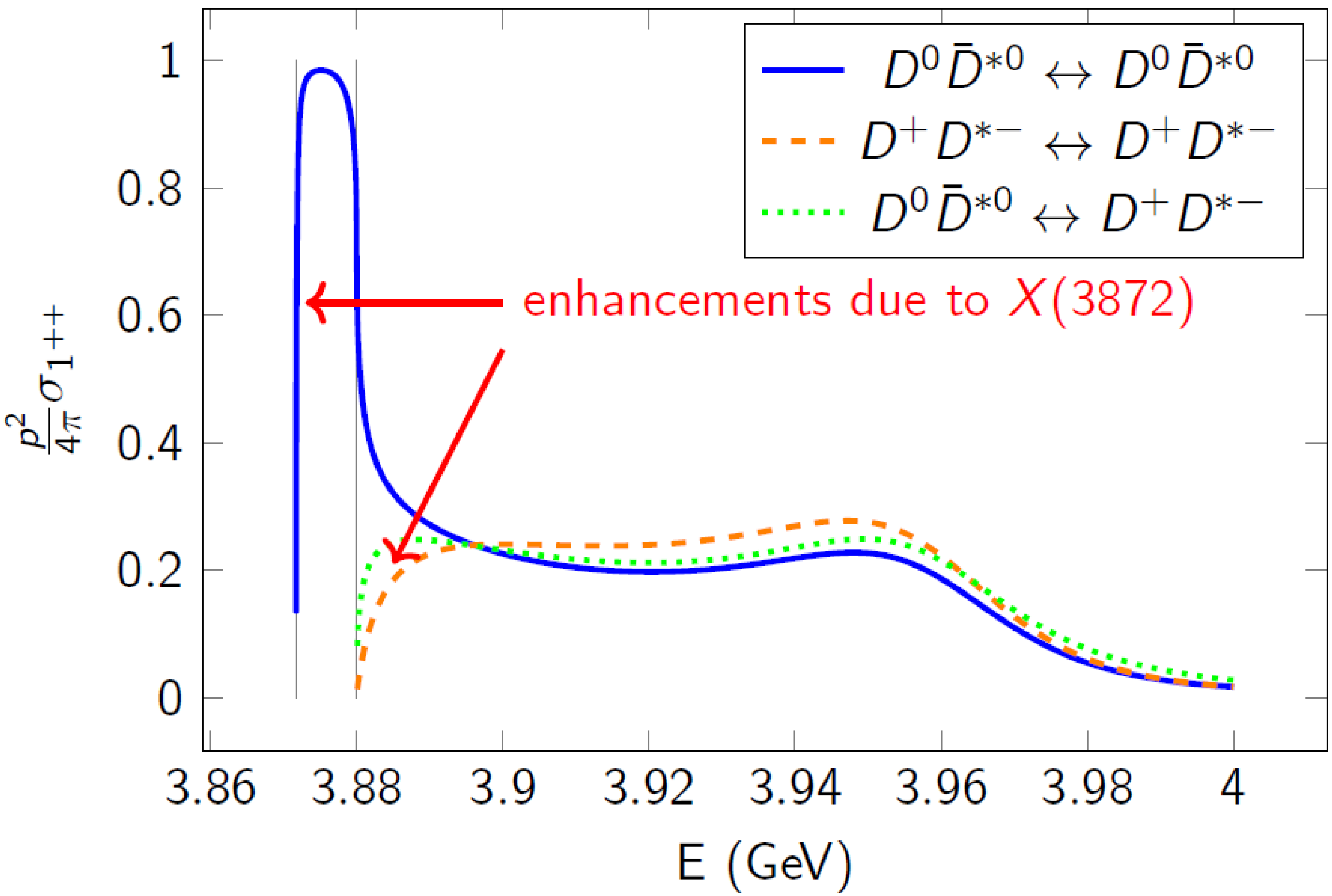
Completely nonperturbative scheme



$D^0\bar{D}^0 \to D^0\bar{D}^0$
$D^+D^- \to D^+D^-$
$D^0\bar{D}^{*0} \to D^0\bar{D}^{*0}$
$D^+D^{*-} \to D^+D^{*-}$
$D_s\bar{D}_s \to D_s\bar{D}_s$
$\bar{\sigma}^{0^{++}}$
$\bar{\sigma}^{1^{++}}$
$\bar{\sigma}^{2^{++}}$
$\bar{\sigma}^{1^{--}}$
0
0.5
1
3.7
3.75
3.8
3.85
3.9
3.95
4
4.05
4.1
E (GeV)

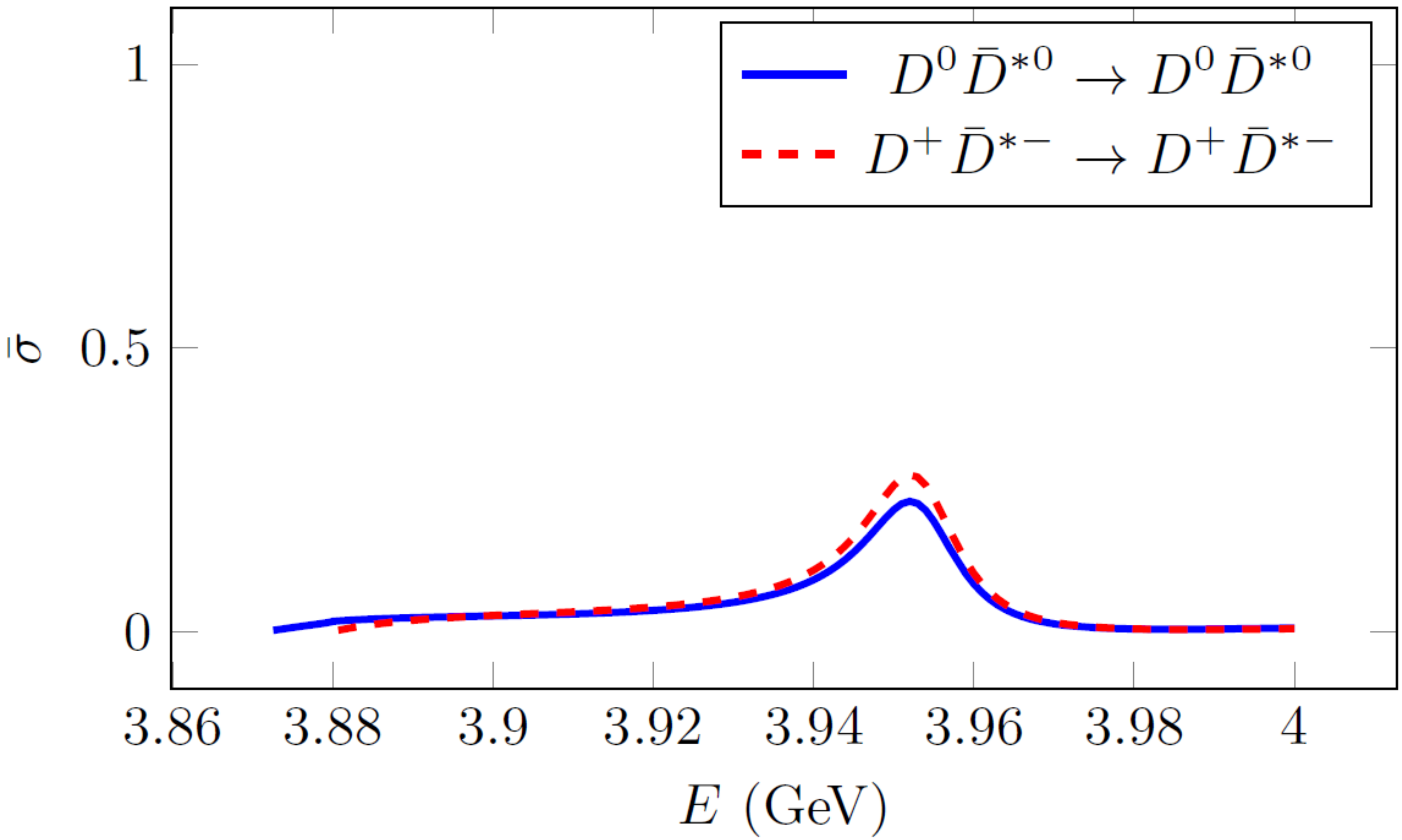


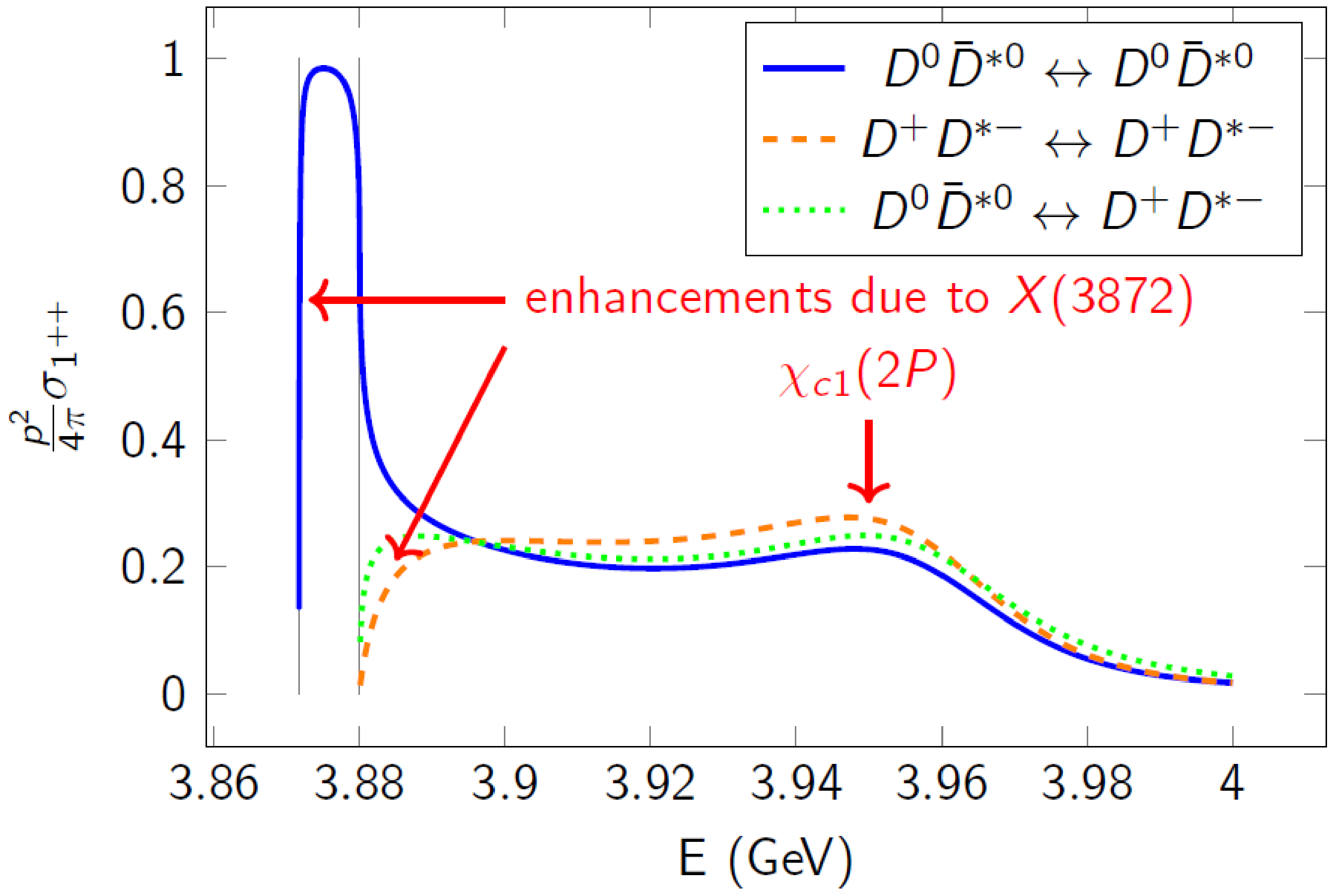
$D^0\bar{D}^{*0} \leftrightarrow D^0\bar{D}^{*0}$
$D^+D^{*-} \leftrightarrow D^+D^{*-}$
$D^0\bar{D}^{*0} \leftrightarrow D^+D^{*-}$
$\frac{p^2}{4\pi}\sigma_{1^{++}}$
1
0.8
0.6
0.4
0.2
0
3.86
3.88
3.9
3.92
3.94
3.96
3.98
4
E (GeV)



$D^0\bar{D}^{*0} \leftrightarrow D^0\bar{D}^{*0}$
$D^+D^{*-} \leftrightarrow D^+D^{*-}$
$D^0\bar{D}^{*0} \leftrightarrow D^+D^{*-}$
enhancements due to $X(3872)$
$\frac{p^2}{4\pi}\sigma_{1^{++}}$
0
0.2
0.4
0.6
0.8
1
3.86
3.88
3.9
3.92
3.94
3.96
3.98
4
E (GeV)

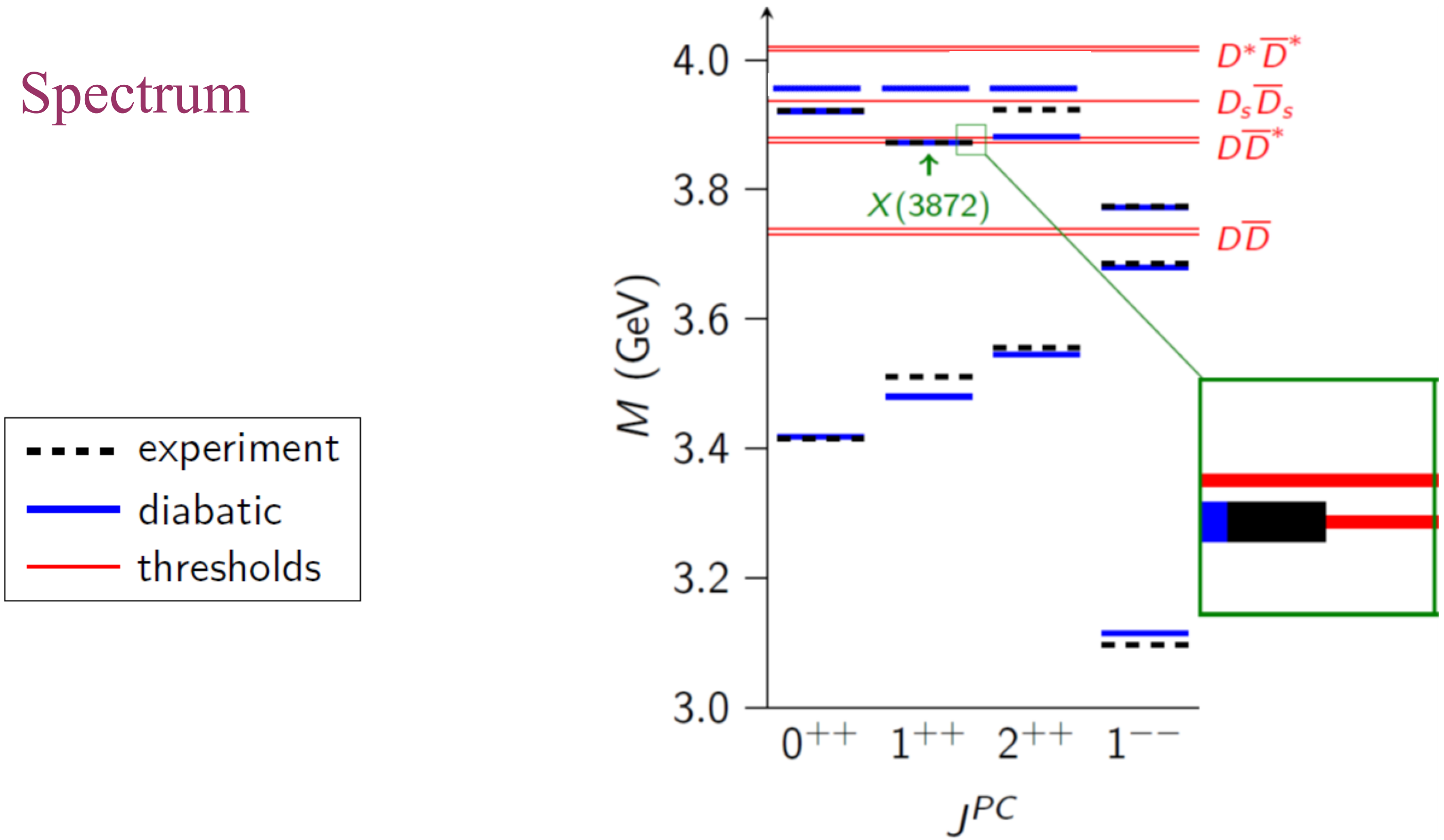
$\Delta_c = 50$ MeV





Quasiconventional states may be overshadowed by the presence of close unconventional states.

Spectrum



Heavy-quark meson spectral pattern

There are quasi-conventional resonances with masses close to those of Cornell bound states, as well as unconventional resonances with masses close to the energies of some meson-meson thresholds.

Decay Widths

J^{PC}	Mass	$\Gamma^{\text{Theor}}_{\text{strong}}$	State	$\Gamma^{\text{Expt}}_{\text{total}}$
0^{++}	3925.8	2.3	$\chi_{c0}(3915)$?	
1^{++}	3952.4	80.5	??	
1^{--}	3766.8	21.8	$\psi(3770)$	27.2 ± 1.0

Masses and widths in MeV units

SUMMARY

The Diabatic Approach in QCD allows for a unified and consistent description of conventional and unconventional heavy-quark mesons from Lattice QCD indications.

String breaking gives rise to a mixing of $Q\bar{Q}$ with open-flavor meson-meson configurations. This may be expressed through a mixing potential.

The heavy-quark meson spectrum is formed by a quasiconventional one, plus an unconventional one located close to some open-flavor meson-meson thresholds.

A detailed description of charmoniumlike mesons up to 1 GeV excitation energy is feasible.

THE END