$\chi_{c1}(2P)$: an Overshadowed Charmoniumlike Resonance

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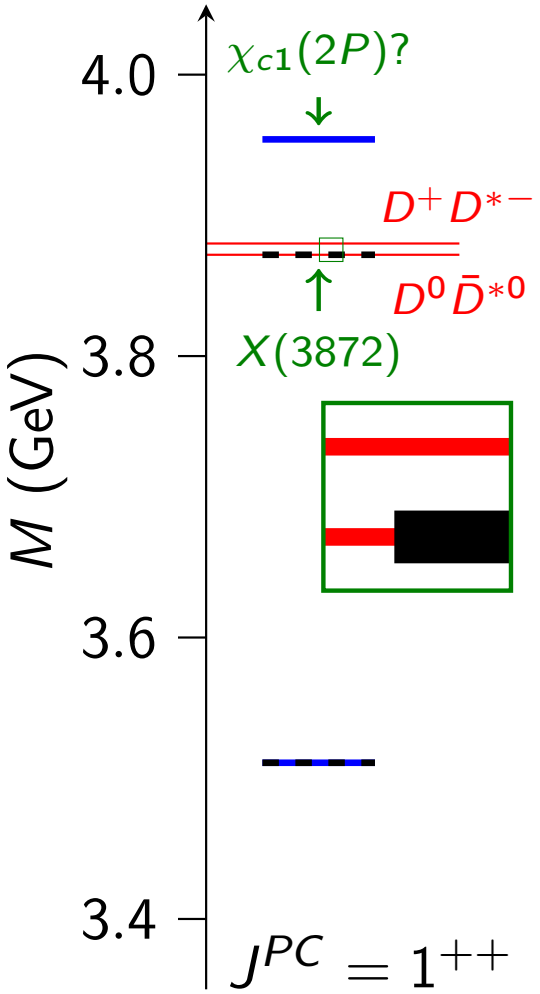
References

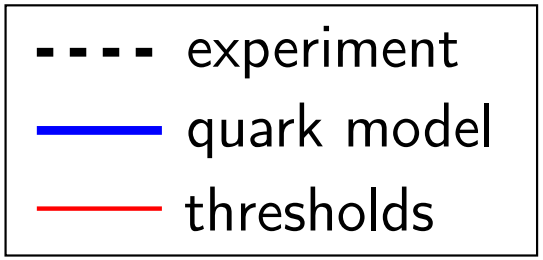
R.B. and P. González
Coupled-channel meson-meson scattering in the diabatic framework
Phys. Rev. D **104**, 074025 (2021)

R.B. and P. González
Is $\chi_{c1}(3872)$ generated from string breaking?
Phys. Rev. D **105**, 054028 (2022)

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

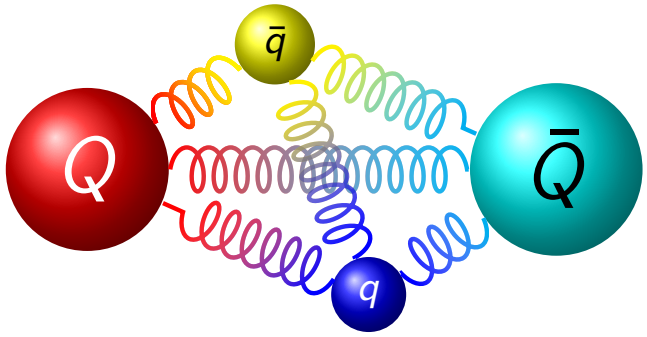
Where is the $2\,^3P_1$ Charmonium State?





- No well-established candidate in the PDG listing of $c\bar{c}$ mesons [Particle Data Group, 2020]
- $X(3940)$ peak in $D\bar{D}^*$? [BELLE collaboration, 2007]
- $X(3960)$ peak in $\omega J/\psi$? [BESIII collaboration, 2019]

The Born-Oppenheimer Approximation in QCD

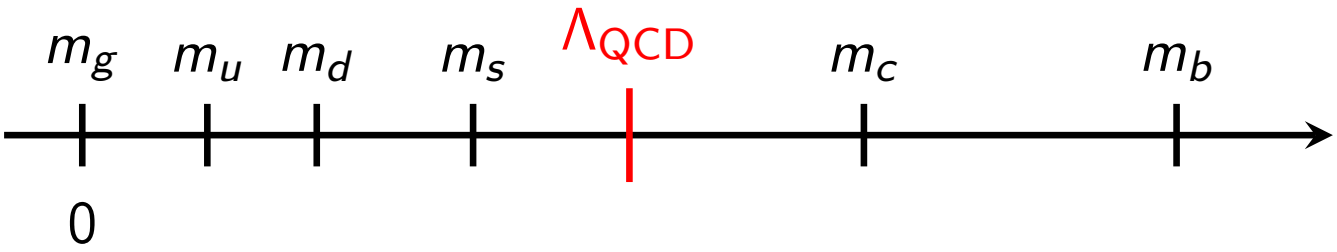


Heavy degrees of freedom

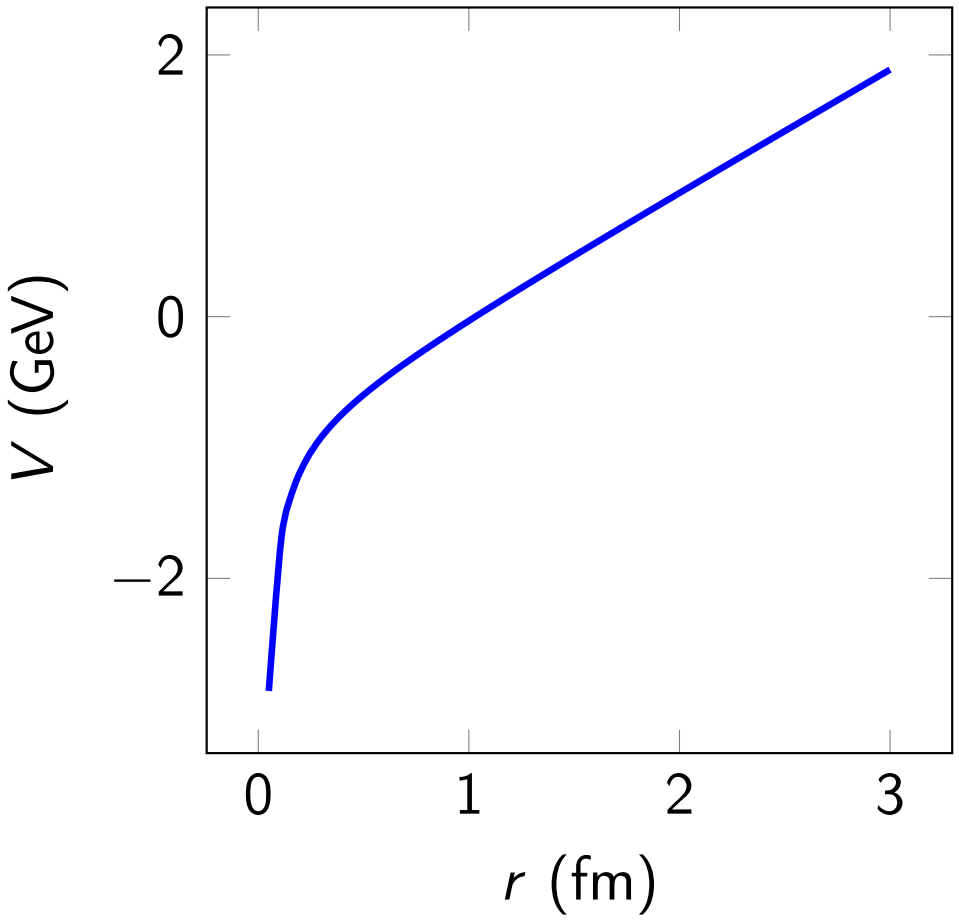
- heavy quarks c, b

Light fields

- gluons g
- light quarks u, d, s



Lowest Born-Oppenheimer Potential Without Sea Quarks



See, for example, [Bali, 2001].

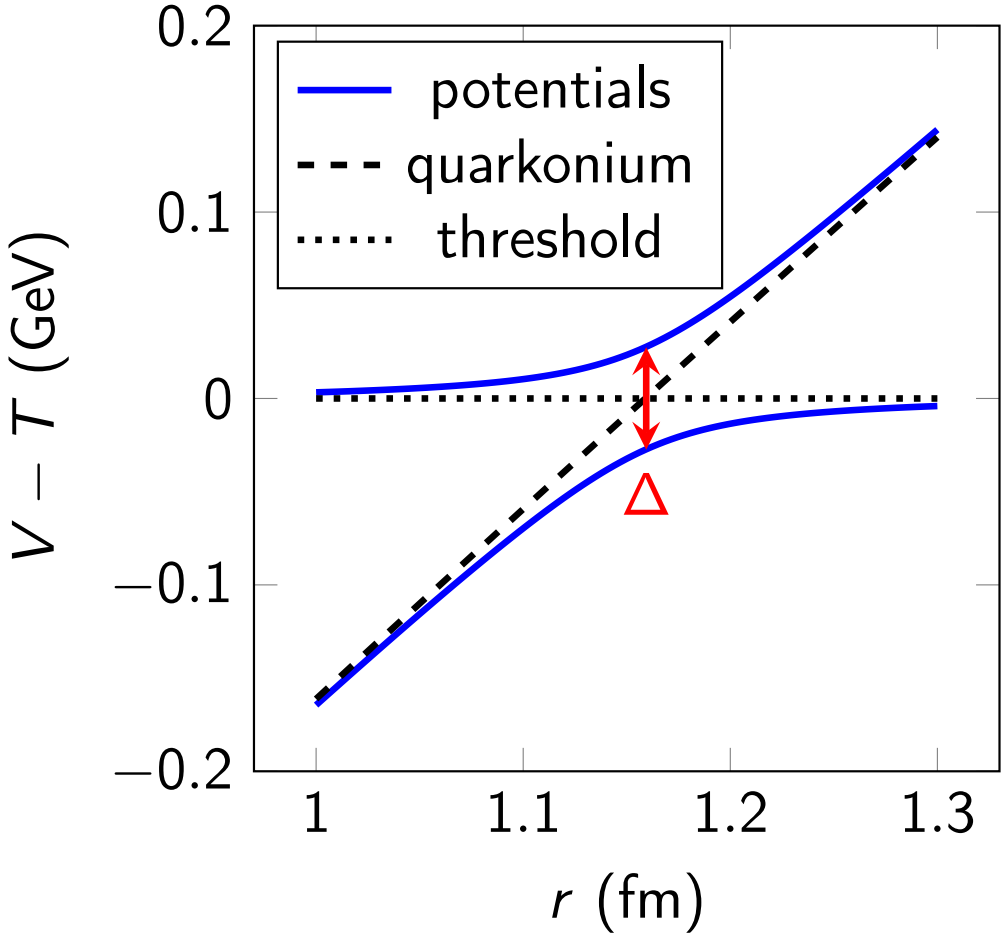
Quenched approximation

No dynamical light quarks

Quarkonium potential

- short-range: Coulomb attraction
- long-range: linear confinement

Born-Oppenheimer Potentials With Sea Quarks



Open-flavor threshold

Minimum required energy for the production of a open-flavor meson pair

String breaking

Quarkonium and threshold mix with each other.

See [SESAM collaboration, 2005], [Bulava *et al.*, 2019].

The Diabatic Schrödinger Equation

$$\left[\begin{pmatrix} -\frac{\nabla^2}{2\mu_{Q\bar{Q}}} & 0 \\ 0 & -\frac{\nabla^2}{2\mu_{M\bar{M}}} \end{pmatrix} + \begin{pmatrix} V_{Q\bar{Q}}(r) & V_{\text{mix}}(r) \\ V_{\text{mix}}(r) & T_{M\bar{M}} \end{pmatrix} - E\right]\begin{pmatrix} \psi_{Q\bar{Q}}(r) \\ \psi_{M\bar{M}}(r) \end{pmatrix} = 0$$

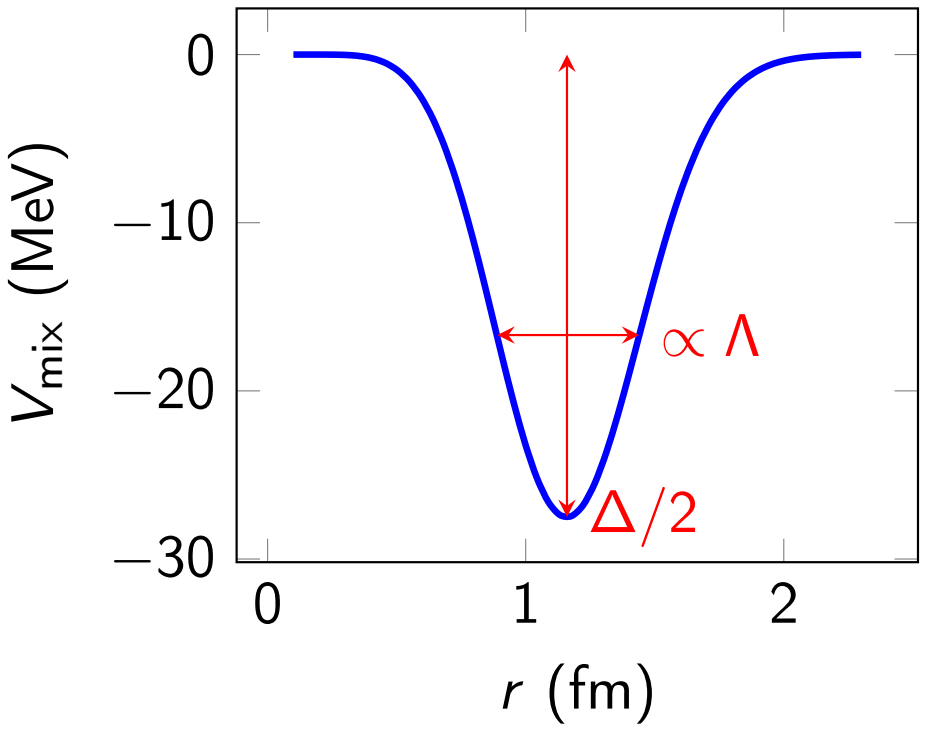
Diabatic potential matrix

The potential couples quark-antiquark and meson-meson.

Connection to lattice QCD

The eigenvalues of the diabatic potential matrix are the Born-Oppenheimer potentials calculated in lattice QCD.

Phenomenological Mixing Potential

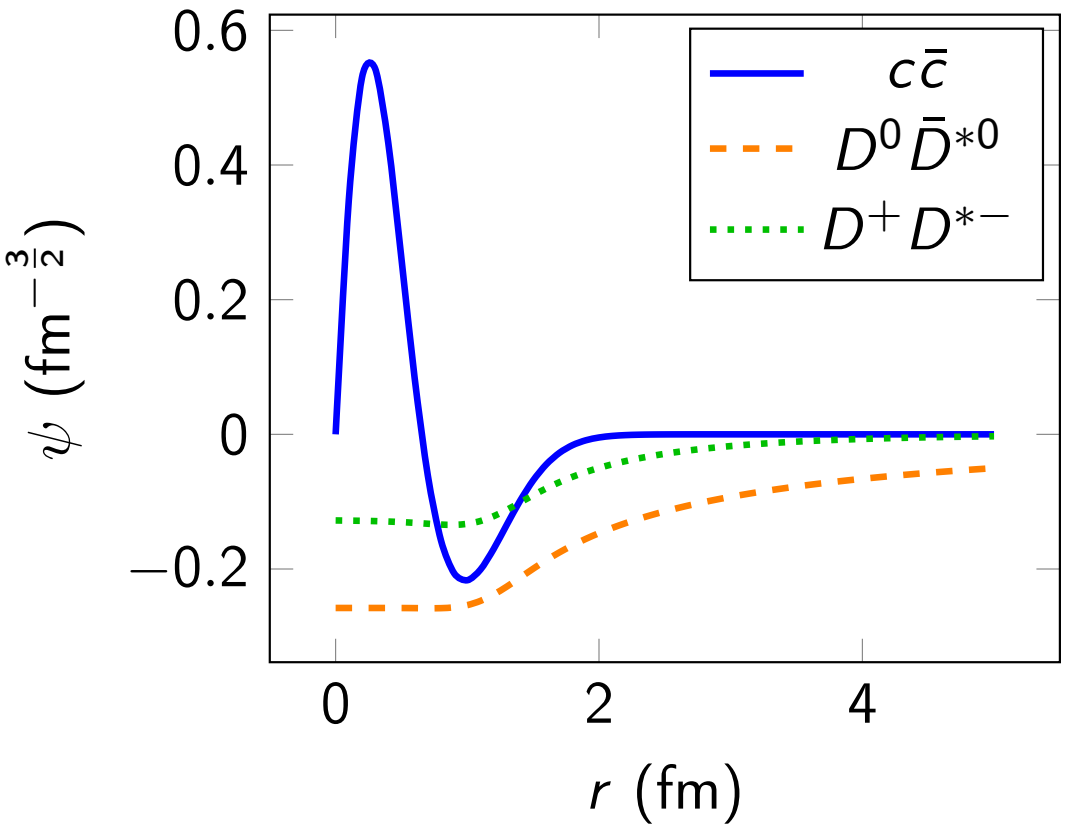


Gaussian parametrization

$$V_{\text{mix}}(r) = -\frac{\Delta}{2} e^{-\frac{(V_{Q\bar{Q}}(r) - T_{M\bar{M}})^2}{2\Lambda^2}}$$

- Δ: mixing strength
- Λ: mixing width

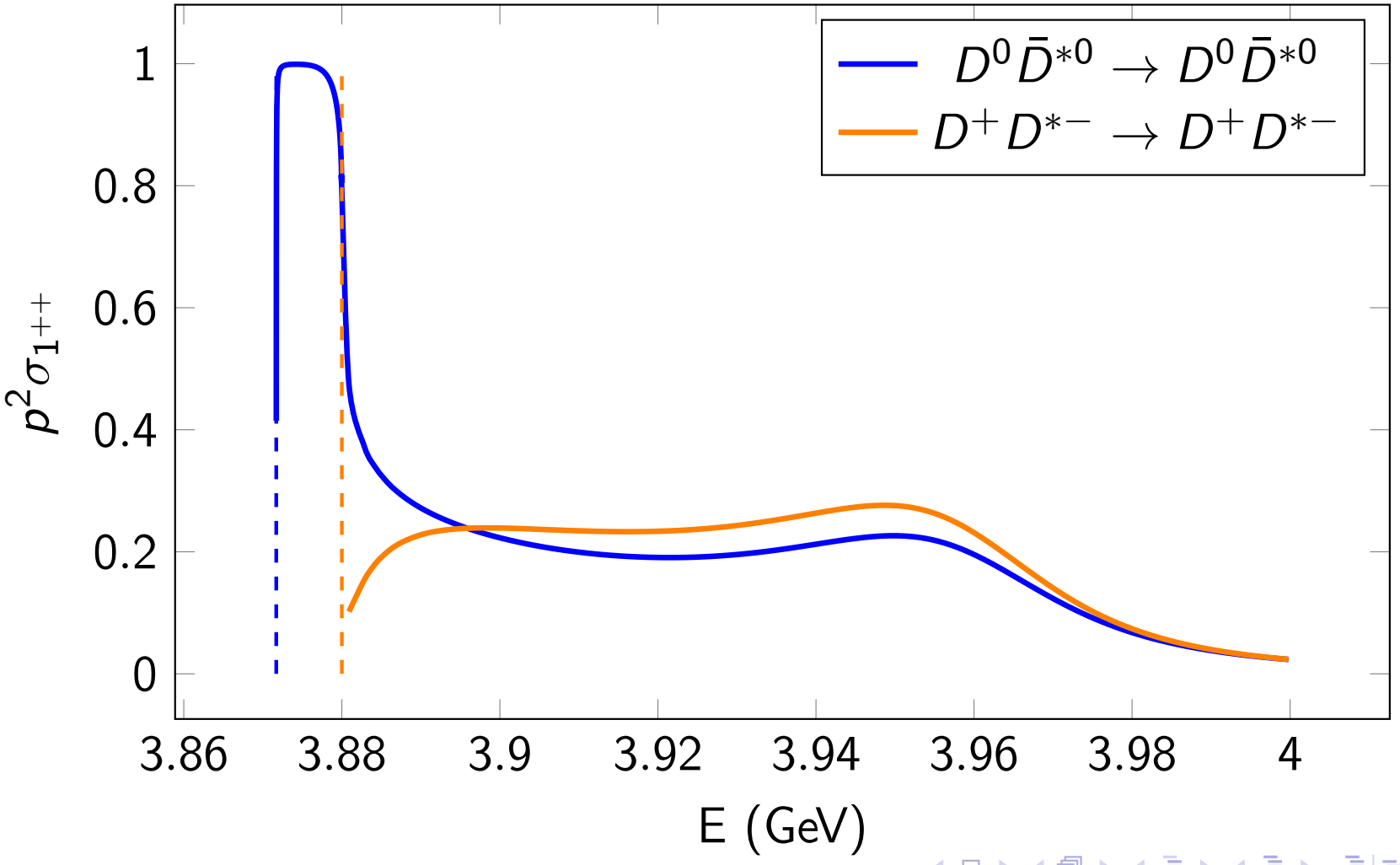
Diabatic $X(3872)$



- mass of 3871.6 MeV
- 4% of 2^3P_1 $c\bar{c}$
- 93% of S-wave $D^0\bar{D}^{*0}$
- 3% of S-wave D^+D^{*-}
- $\sqrt{\langle r^2 \rangle} \approx 14$ fm

Elastic $D\bar{D}^*$ Scattering with $J^{PC} = 1^{++}$

Cross-Sections



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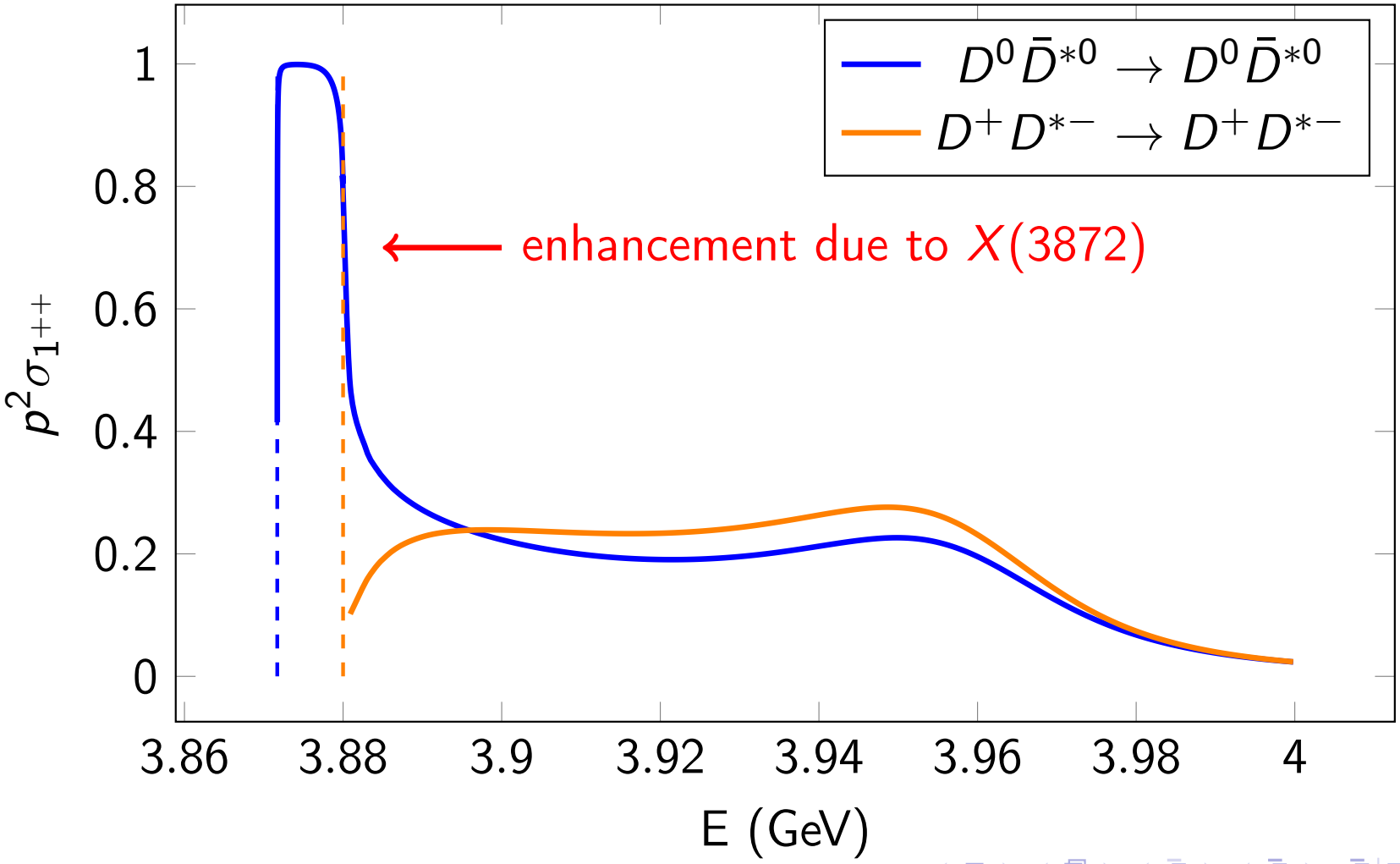

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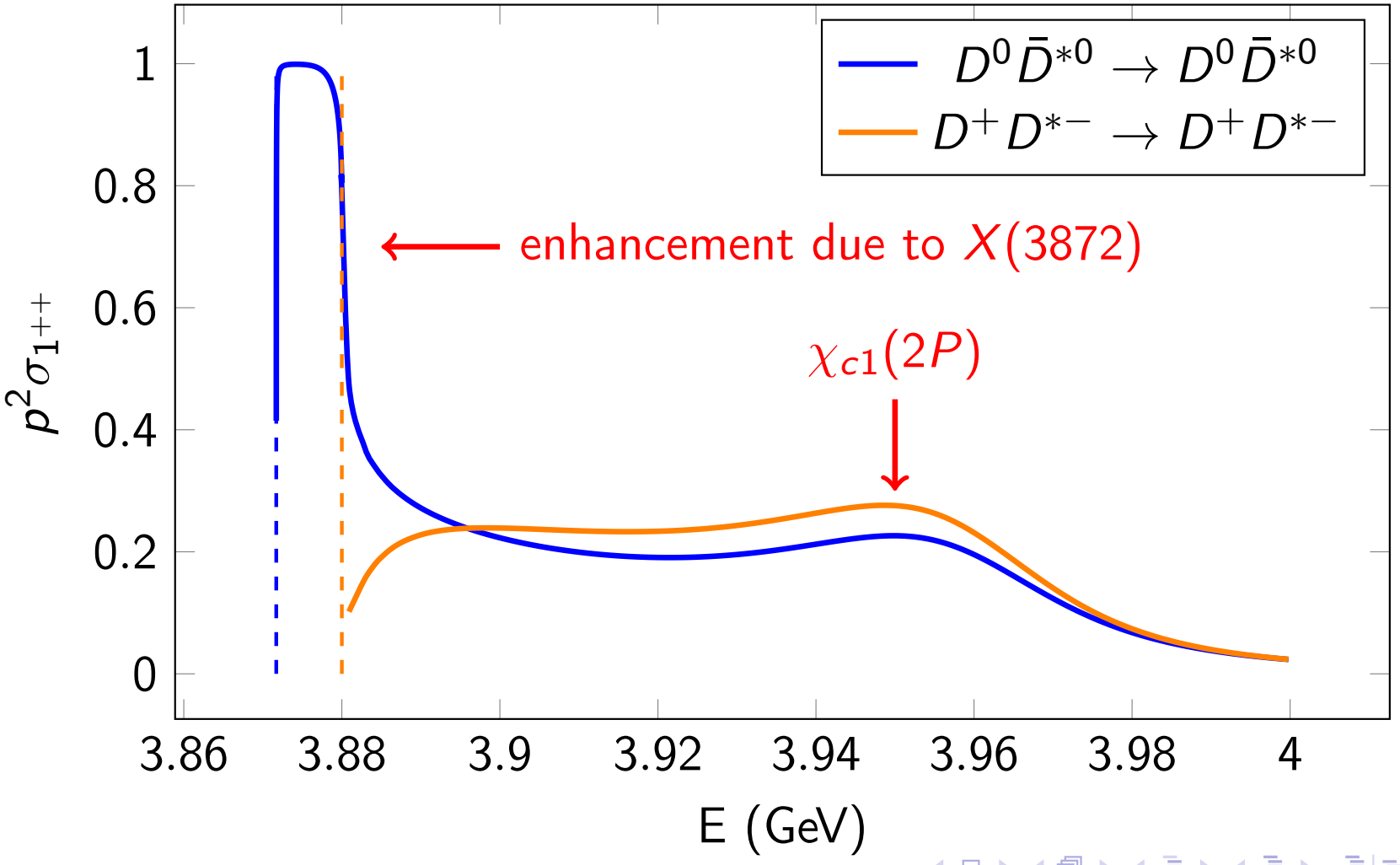
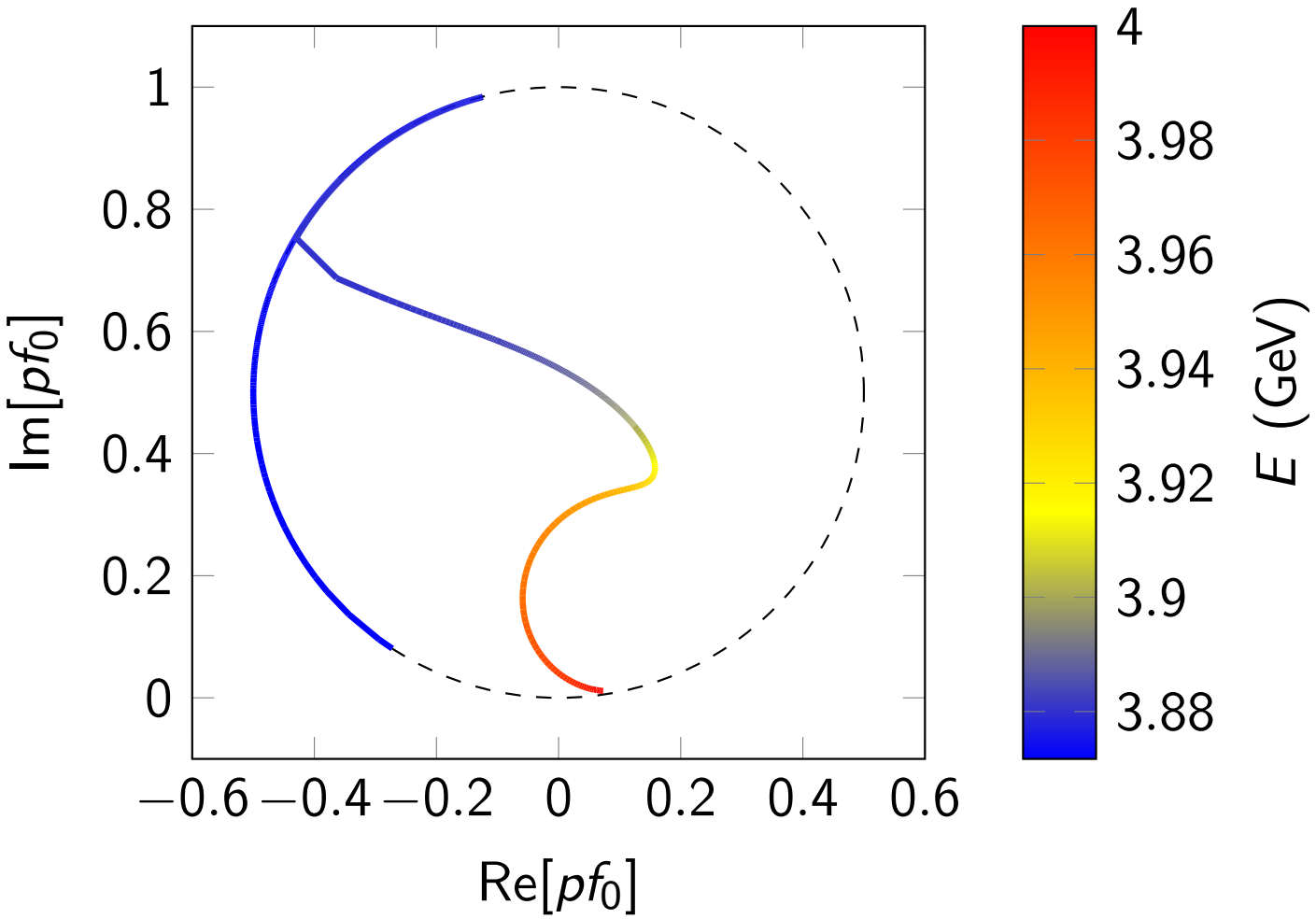


Elastic $D\bar{D}^*$ Scattering with $J^{PC} = 1^{++}$

S-Wave $D^0\bar{D}^{*0} \to D^0\bar{D}^{*0}$ Argand Diagram



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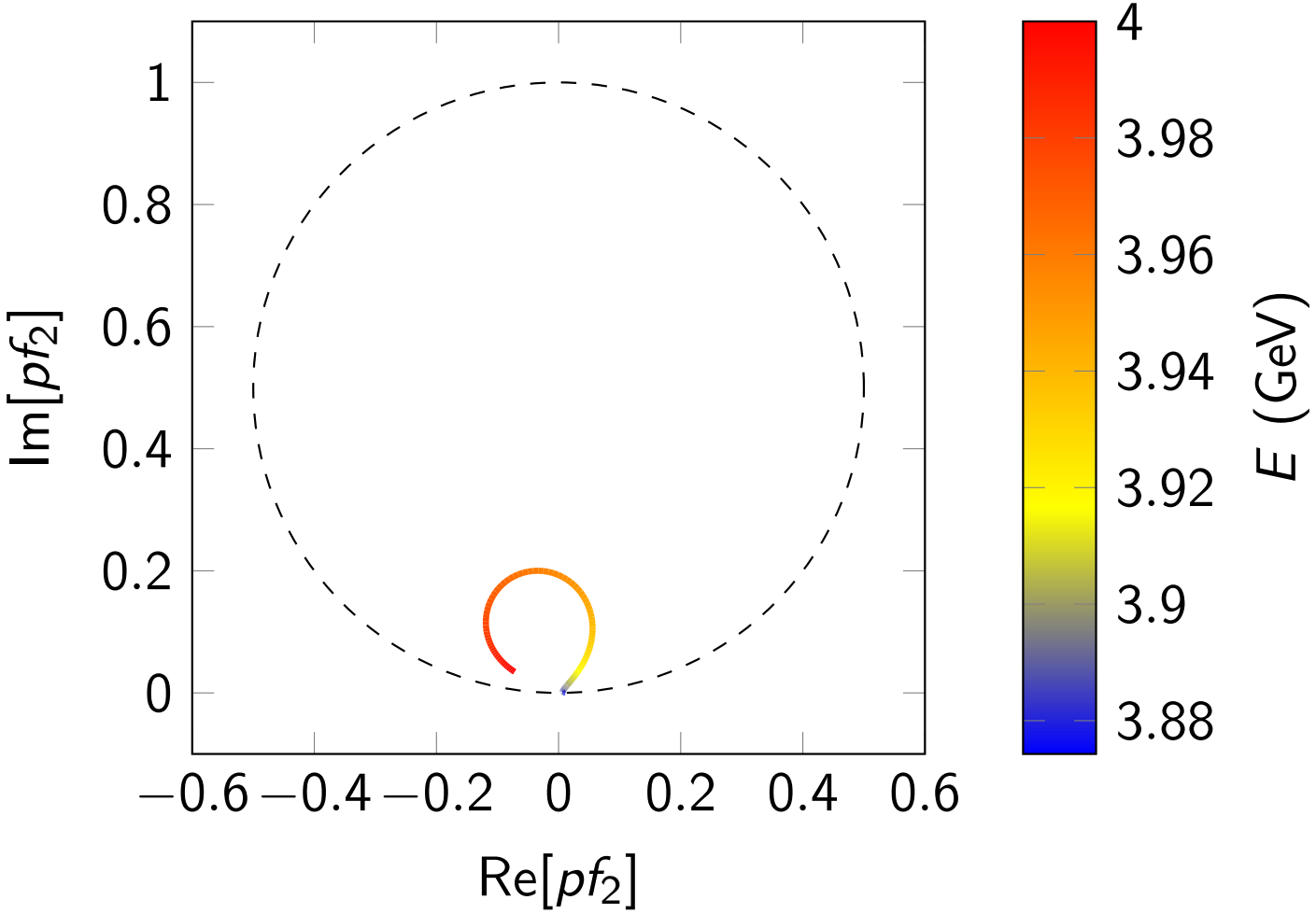


$X(3872)$ and the $2\,^3P_1$ Charmonium State

Formation of $X(3872)$

- The $2\,^3P_1$ charmonium state may provide a "core" for the formation of a $D^0\bar{D}^{*0}$ bound state.
- Depending on the strength of the mixing, the state may be virtual.

Where is the $\chi_{c1}(2P)$ resonance?

- The peak is predicted near 3.96 GeV.
- The cross-section enhancement due to $X(3872)$ may hinder its detection in open-charm channels.

Summary

- Lattice QCD potentials may be used to study the spectrum of hidden-flavor mesons and open-flavor meson-meson scattering.
- $X(3872)$ can be described as a bound or virtual $D^0\bar{D}^{*0}$ state with a compact $c\bar{c}$ core.
- Because of its composition and closeness to the $D^0\bar{D}^{*0}$ and D^+D^{*-} thresholds, $X(3872)$ may overshadow the $\chi_{c1}(2P)$ in its open-charm channels.
- This overshadowing may not occur for hidden-charm chanels, e.g., $\omega J/\psi$ or $\gamma\psi(2S)$.

4 Appendix

- Details on the Formalism
- String Breaking
- Spectral Description

Integrating the Light Fields

1. Separate the kinetic energy of the heavy quarks

$$H\,|\psi\rangle = E\,|\psi\rangle\,, \qquad H = K_{\text{heavy}} + H_{\text{light}}^{(\text{heavy})}.$$

2. Solve the light-field Hamiltonian for static heavy quarks

$$H_{\text{light}}^{(\text{heavy})} \to H_{\text{static}}(r), \qquad H_{\text{static}}(r)\,|\zeta_i(r)\rangle = V_i(r)\,|\zeta_i(r)\rangle\,.$$

Static energy levels

The static energies $V_i(r)$ can be calculated *ab initio* in lattice QCD.

Adiabatic Wave Function

Adiabatic expansion

$$|\psi\rangle = \sum_i \int \mathrm{d}r\, \psi_i(r)\, |r\rangle\, |\zeta_i(r)\rangle$$

- Light field states calculated at the same position of the heavy quarks
- One wave function for each light-field energy

The Born-Oppenheimer Schrödinger Equation

$$\sum_j \left[-\frac{1}{2\mu}(\delta_{ij}\nabla + \tau_{ij}(r))^2 + \delta_{ij}(V_i(r) - E) \right] \psi_j(r) = 0$$

- The potentials $V_i(r)$ are the lattice QCD static energies.
- In general, the kinetic energy may couple different channels.

Adiabatic approximation

Usually, mixing between different channels is neglected ($\tau_{ij}(r) \simeq 0$).

From Adiabatic to Diabatic

Diabatic expansion

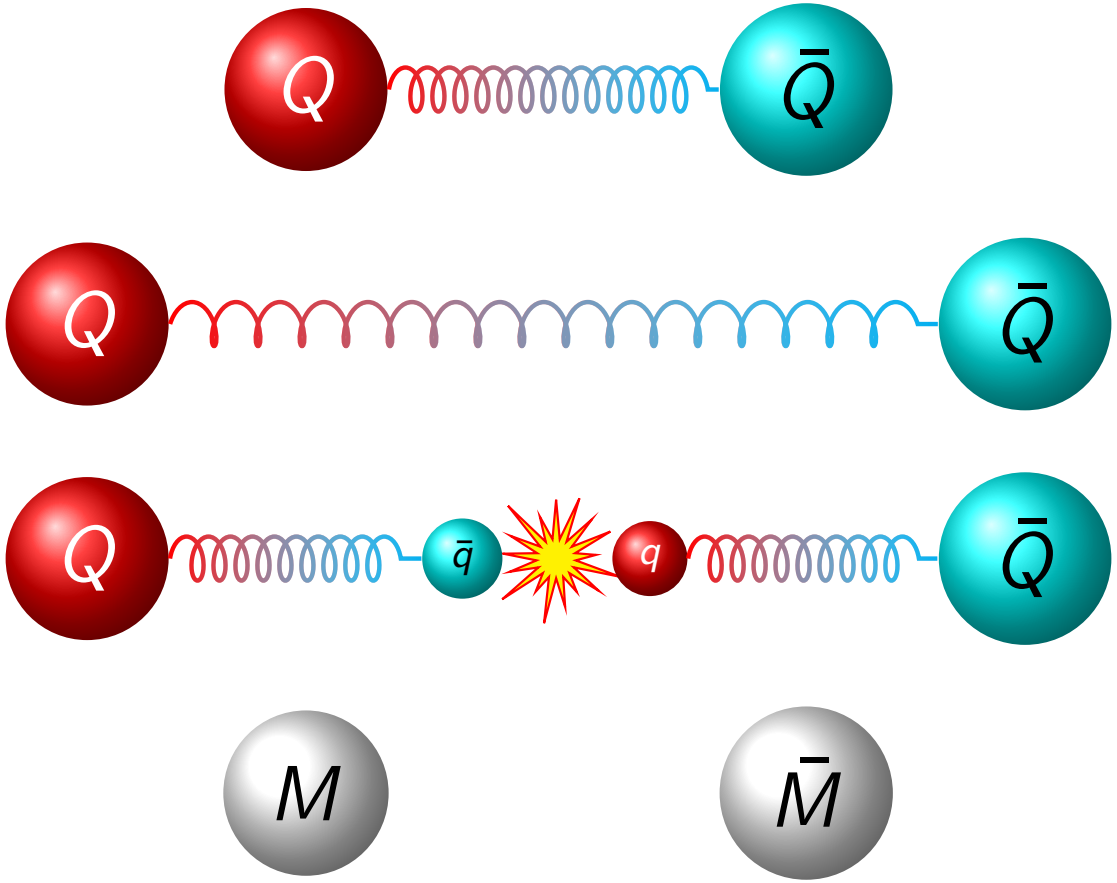
$$|\psi\rangle = \sum_i \int \mathrm{d}r\, \widetilde{\psi}_i(r, r_0)\, |r\rangle\, |\zeta_i(r_0)\rangle$$

Diabatic channels

$$\widetilde{\psi}_i(r, r_0) \to \psi_{Q\bar{Q}}(r),\, \psi_{M\bar{M}}(r)$$

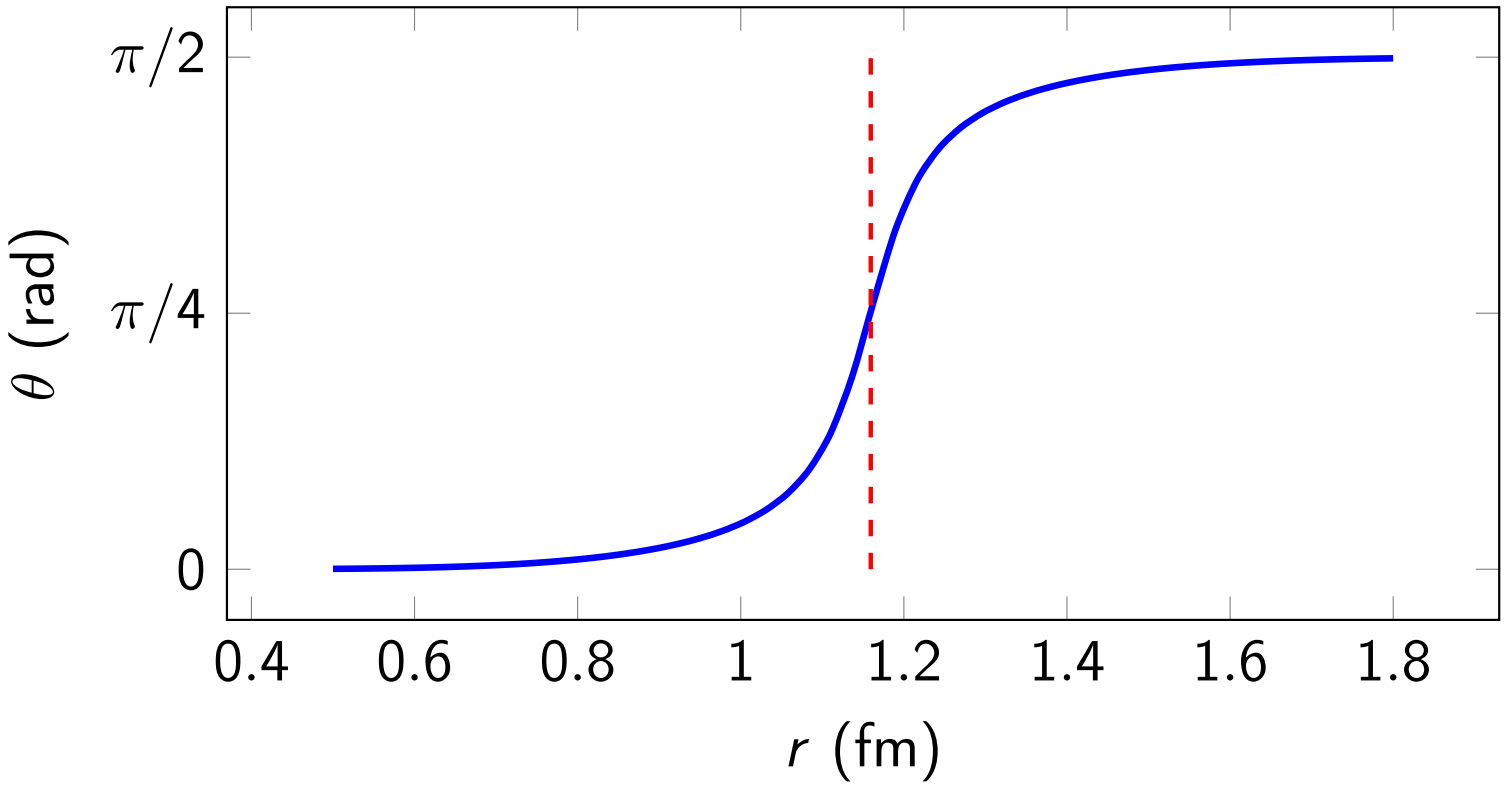
- Light field states are calculated at a fixed position r_0.
- For r_0 far from the avoided crossing, they correspond to quark-antiquark and meson-meson.

String Breaking: a Pictorial Representation



Quark-Antiquark–Meson-Meson Mixing Angle

$$|1\rangle = \cos\theta\,|Q\bar{Q}\rangle + \sin\theta\,|M\bar{M}\rangle$$
$$|2\rangle = -\sin\theta\,|Q\bar{Q}\rangle + \cos\theta\,|M\bar{M}\rangle$$



Mixing Potential and its Consequences

General mixing potential (two-channel case)

$$V_{\text{mix}}(r) = -\sin 2\theta(r)(V_2(r) - V_1(r))/2$$

Below threshold

- Bound state problem
- Molecular components

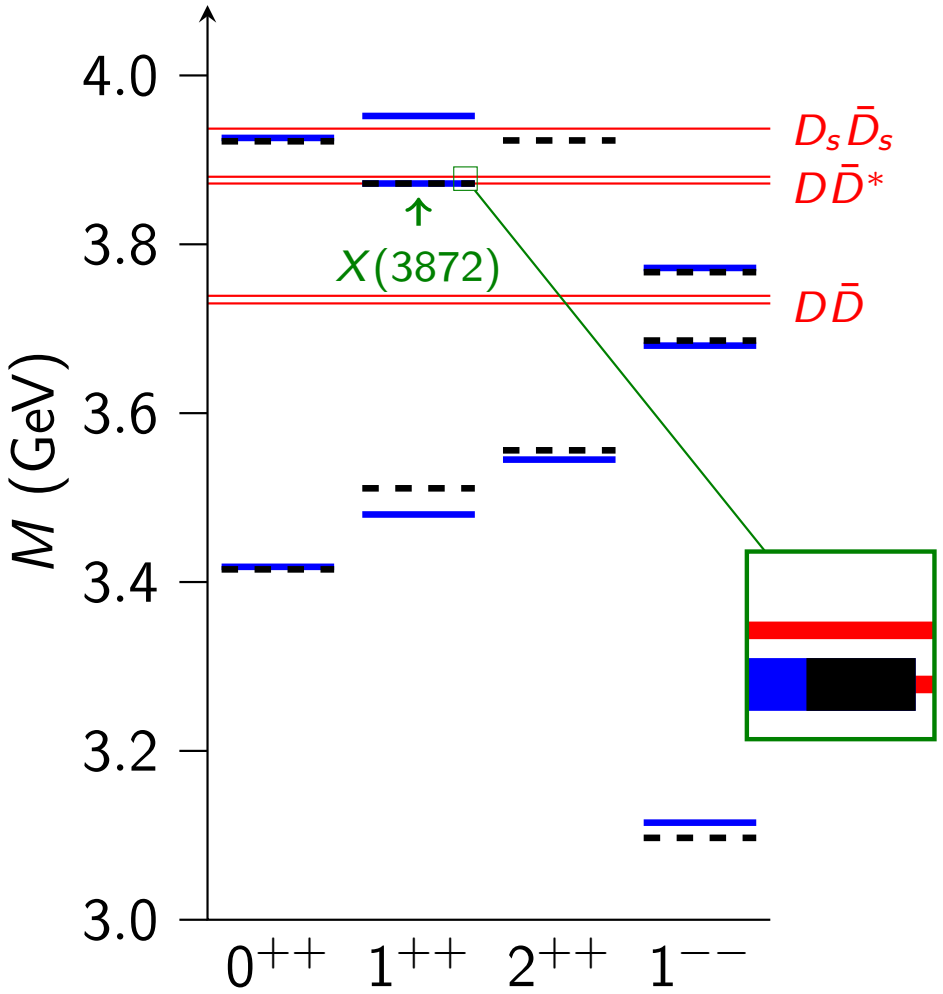
Above threshold

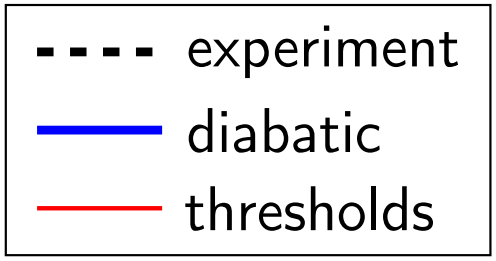
- Meson-meson scattering
- Resonances

Unconventional Quarkoniumlike Mesons

Additional unconventional states may emerge out of the mixing between open-flavor meson pairs and quarkonium states.

Diabatic Spectrum of Hidden Charm Mesons





Mixing potential

Can be modeled from lattice QCD and phenomenology.

Strong Decay Widths of Hidden Charm Mesons

J^{PC}	M	$\Gamma_{D^0\bar{D}^0}$	$\Gamma_{D^+D^-}$	$\Gamma^{\text{Theor}}_{\text{total}}$	$\Gamma^{\text{Expt}}_{\text{total}}$
0^{++}	3925.8	1.4	0.9	2.3	
1^{++}	3952.4	38.2	42.3	80.5	
1^{--}	3766.8	12.6	9.2	21.8	27.2 ± 1.0

Masses and widths in MeV units