The $D\bar{D}$ bound state in the $\psi(3770) \to \gamma D\bar{D}$ decay

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Outline

- The $D\bar{D}$ bound state
- Description of the $\psi(3770) \to \gamma D\bar{D}$ decay
- Results. Signature on invariant mass
- Conclusions

Molecular $D\bar{D}$ bound state

Predicted state

D. Gamermann, E. Oset, D. Strottman, M. Vicente Vacas, Phys. Rev. D **76**, 074016 (2007)

J. Nieves, M. Valderrama, Phys. Rev. D **86**, 056004 (2012)

C. Hidalgo-Duque, J. Nieves, M. Valderrama, Phys. Rev. D **87**, 076006 (2013)

Analogous to $K\bar{K}$ a good representation of $f_0(980)$

Chiral unitary approach for the meson-meson interaction in coupled channels found dynamically generated states

$$f_0(500), K_0^*(700), a_0(980)$$

J.A. Oller, E. Oset, Nucl. Phys. A **620**, 438 (1997). (**Erratum: [Nucl. Phys. A 652, 407 (1999)**])
N. Kaiser, Eur. Phys. J. A **3**, 307 (1998)
M.P. Locher, V.E. Markushin, H.Q. Zheng, Eur. Phys. J. C **4**, 317 (1998)
J. Nieves, E. Ruiz Arriola, Nucl. Phys. A **679**, 57 (2000)

Searches

$$e^+e^- \rightarrow J/\psi D\bar{D}$$

P. Pakhlov et al., [Belle], Phys. Rev. Lett. **100**, 202001 (2008)
K. Chilikin et al., [Belle], Phys. Rev. D **95**, 112003 (2017)
E. Wang, W.H. Liang, E. Oset, arXiv:1902.06461 [hep-ph]

An accumulation of strength close to DD threshold found a natural explanation in terms of the predicted bound state with a mass of 3730 MeV, but with large uncertainties, so far unconclusive

New reactions to observe

$$B^+ \rightarrow D^0\bar{D}^0K^-$$

$$B^0 \rightarrow D^0\bar{D}^0K^0$$

D. Gamermann, E. Oset, B. Zou, Eur. Phys. J. A **41**, 85 (2009)
C.W. Xiao, E. Oset, Eur. Phys. J. A **49**, 52 (2013)

Better suited to search for

Radiative decays

In this work we profit from previous studies and consider the case

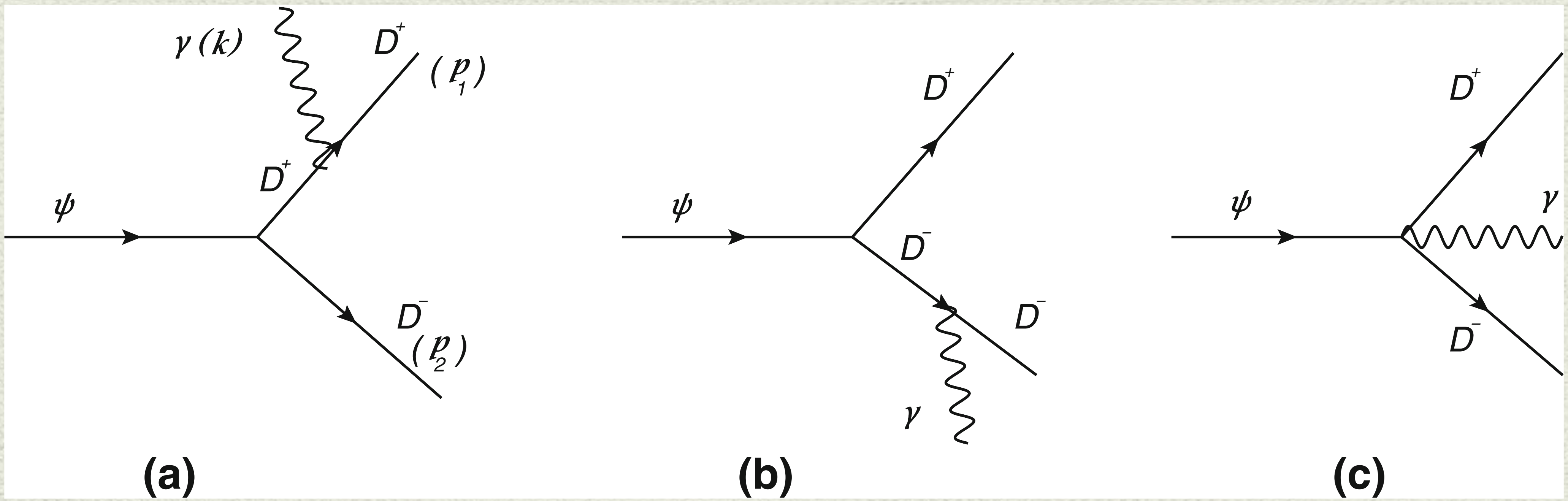
$$\psi(3770) \to \gamma D \bar{D}$$

$D^+ D^-$ Tree level and loop contributions

$D^0 \bar{D}^0$ Only loop contributions

Tree level

$$\psi(3770) \to \gamma D^+ D^-$$

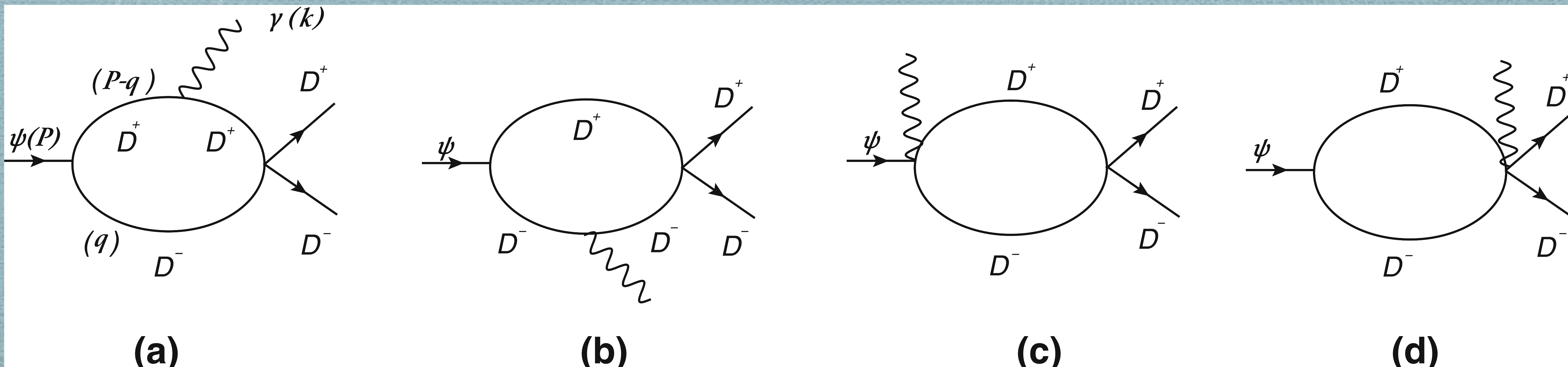


Amplitude
$$t_a + t_b + t_c = -2\, e\, g_\psi\, \epsilon^\mu(\psi)\epsilon^\nu(\gamma)$$
$$\times \left(g_{\mu\nu} + p_{2\mu} p_{1\nu} \frac{1}{p_1 \cdot k + i\epsilon} + p_{1\mu} p_{2\nu} \frac{1}{p_2 \cdot k + i\epsilon} \right)$$

$$g_\psi = 13.7$$

There is no tree level for the neutral case

Loop mechanism



This is the only contribution for the neutral case

Amplitude $t_L = \epsilon_\mu(\psi)\epsilon_\nu(\gamma)\, T^{\mu\nu}$

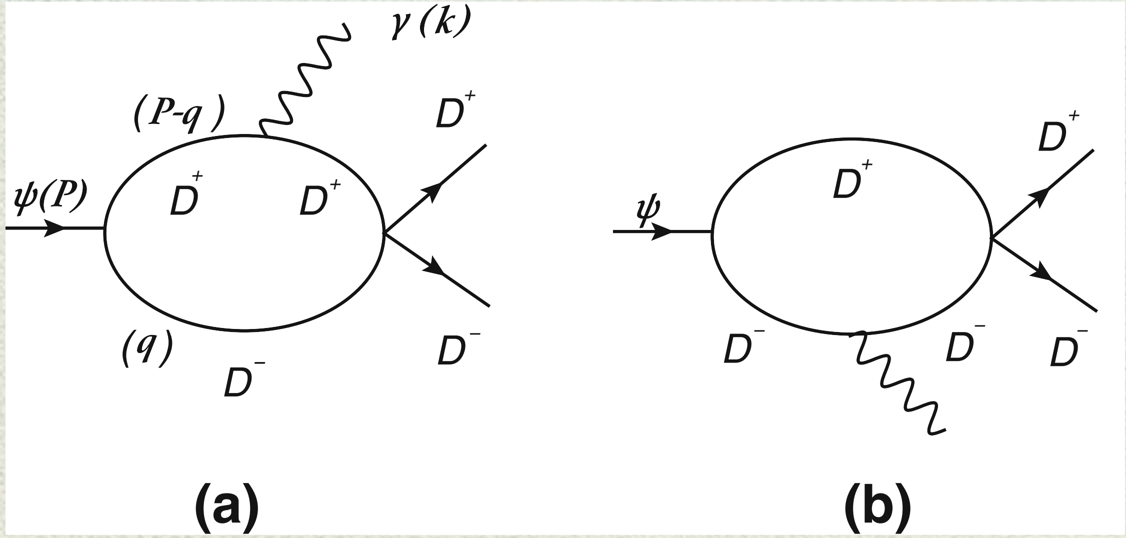
$$T^{\mu\nu} = a\, g^{\mu\nu} + b\, P^\mu P^\nu + c\, P^\mu k^\nu + d\, \underline{k^\mu P^\nu} + e\, k^\mu k^\nu\, .$$

Gauge invariance $T^{\mu\nu}k_\nu = 0$ $\quad a + d\,(P\cdot k) = 0$

Lorentz condition b, c, e do not contribute

$$t = a\epsilon_\mu(\psi)\epsilon^\mu(\gamma)\,; \qquad a = -d\,(P\cdot k)$$

Loop amplitude $D^0 \bar{D}^0$



$$
\begin{aligned}
t_L = & -2eg_{\psi}\epsilon^{\mu}(\psi)\epsilon^{\nu}(\gamma)i \\
& \times \int \frac{d^4q}{(2\pi)^4} 2q_{\mu}(2P-2q)_{\nu} t_{D^+D^- \to D^0\bar{D}^0} \\
& \times \frac{1}{(P-q)^2 - m_D^2 + i\epsilon} \\
& \times \frac{1}{q^2 - m_D^2 + i\epsilon} \frac{1}{(P-q-k)^2 - m_D^2 + i\epsilon},
\end{aligned}
$$

Loop amplitude, cont.

Propagator $D(q) \to \dfrac{1}{q^2 - m_D^2 + i\epsilon}$

$$\equiv \frac{1}{2\omega(\boldsymbol{q})}\left(\frac{1}{q^0 - \omega(\boldsymbol{q}) + i\epsilon} - \frac{1}{q^0 + \omega(\boldsymbol{q}) - i\epsilon}\right)$$

$$\to \frac{1}{2\omega(\boldsymbol{q})}\frac{1}{q^0 - \omega(\boldsymbol{q}) + i\epsilon}$$

with $\omega(\boldsymbol{q}) = \sqrt{\boldsymbol{q}^2 + m_D^2}$.

Perform the q° integration analytically, using Cauchy theorem

keeping only the $\epsilon^i(\gamma)$

Coulomb gauge, $\epsilon^0(\gamma) = 0, \boldsymbol{\epsilon}(\gamma)\cdot\boldsymbol{k} = 0,$

$$t_L = -2eg_\psi t_{D^+D^-\to D^0\bar{D}^0}\epsilon^i(\psi)\epsilon^j(\gamma)\,4\int\frac{d^3q}{(2\pi)^3}$$

$$\times\frac{1}{2\omega(\boldsymbol{q})}\frac{1}{2\omega(\boldsymbol{P}-\boldsymbol{q})}\frac{1}{2\omega(\boldsymbol{P}-\boldsymbol{q}-\boldsymbol{k})}$$

$$\times\,(\underline{q_i P_j - q_i q_j})\frac{1}{P^0 - \omega(\boldsymbol{q}) - \omega(\boldsymbol{P}-\boldsymbol{q}) + i\epsilon}$$

$$\times\frac{1}{P^0 - \omega(\boldsymbol{q}) - k^0 - \omega(\boldsymbol{P}-\boldsymbol{q}-\boldsymbol{k}) + i\epsilon}$$

in order to get the d coefficient we must look at the $k^i P^j$

Loop amplitude, cont.

$d\,P^i k^j \epsilon_j(\psi)\epsilon_i(\gamma)$

$$d = d_1 + d_2$$

$$d_1 = -8\,e\,g_\psi\,\frac{1}{\boldsymbol{k}^2}\int\frac{d^3q}{(2\pi)^3}\,\boldsymbol{q}\cdot\boldsymbol{k}\,\frac{1}{2\omega_1}\,\frac{1}{2\omega_1}\,\frac{1}{2\omega_2}\times\frac{1}{P^0-2\omega_1+i\epsilon}\,\frac{1}{P^0-k^0-\omega_1-\omega_2+i\epsilon}\times t_{D^+D^-,D^0\bar{D}^0}$$

$$d_2 = 4\,e\,g_\psi\,\frac{1}{\boldsymbol{k}^2}\int\frac{d^3q}{(2\pi)^3}\,\boldsymbol{q}\cdot\boldsymbol{k}\left\{\boldsymbol{q}^2-\frac{(\boldsymbol{q}\cdot\boldsymbol{k})^2}{\boldsymbol{k}^2}\right\}\times\frac{1}{2\omega_1}\,\frac{1}{2\omega_1}\,\frac{1}{2\omega_2}\times\frac{1}{P^0-2\omega_1+i\epsilon}\,\frac{1}{P^0-k^0-\omega_1-\omega_2+i\epsilon}\times\left\{\frac{1}{\omega_1^2}+\frac{1}{\omega_2^2}-\frac{1}{\omega_1(P^0-2\omega_1+i\epsilon)}-\frac{1}{\omega_1(P^0-k^0-\omega_1-\omega_2+i\epsilon)}\right\}t_{D^+D^-,D^0\bar{D}^0}$$

with $\omega_1 = \sqrt{\boldsymbol{q}^2+m_D^2}$ and $\omega_2 = \sqrt{(\boldsymbol{q}+\boldsymbol{k})^2+m_D^2}$.

Results: Signature on invariant mass

$$\frac{d\Gamma}{dM_{\text{inv}}(D^0\bar{D}^0)} = \frac{1}{8M_\psi^2}\frac{M_{\text{inv}}(D^0\bar{D}^0)}{(2\pi)^3} \times \int dE_1 \overline{\sum}\sum |t|^2\,\Theta(1-A^2)\,\Theta(M_\psi - k - E_1)$$

$$A \equiv \cos\theta(\boldsymbol{p}_1, \boldsymbol{k}) = \frac{1}{2p_1 k}\left\{(M_\psi - k - E_1)^2 - m_D^2 - \boldsymbol{p}_1^2 - \boldsymbol{k}^2\right\}$$

Angle between the photon and the D°

E_1 is the energy of the D^0

Scattering matrix element computed with the Bethe-Salpeter Eqn.

$$T = [1 - VG]^{-1} V$$

$D^+ D^-, D^0 \bar{D}^0, D_s \bar{D}_s, \eta\eta$ Channels, as done in

L.R. Dai, J.J. Xie, E. Oset, Eur. Phys. J. C **76**, 121 (2016)

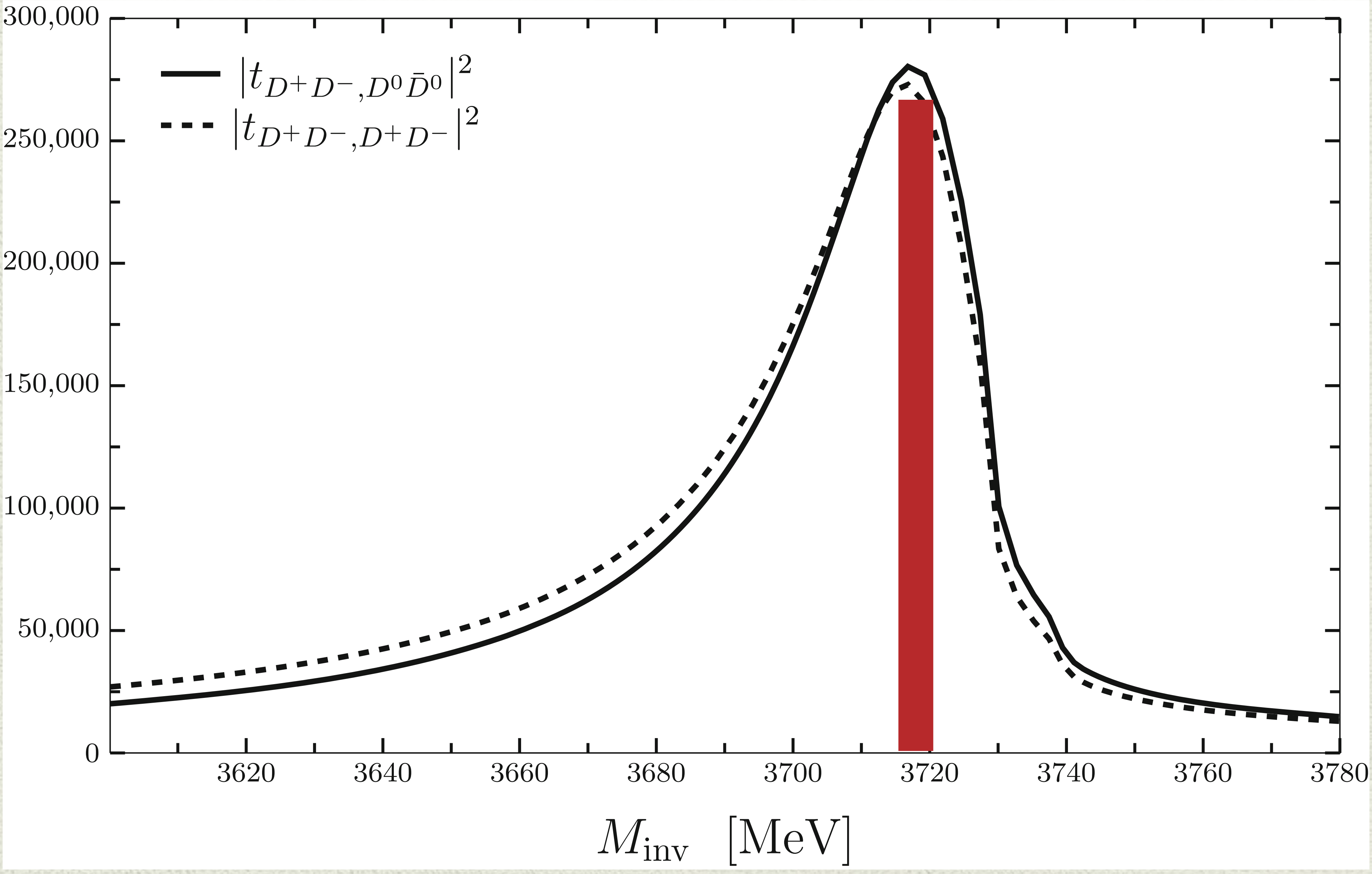
V_{ij} used in the prediction study D. Gamermann, E. Oset, D. Strottman, M. Vicente Vacas, Phys. Rev. D **76**, 074016 (2007)

$V_{D^+D^-,\eta\eta} = a,\ V_{D^0\bar{D}^0,\eta\eta} = a$ $a = 42$ in order to obtain a width $\Gamma \simeq 36$ MeV

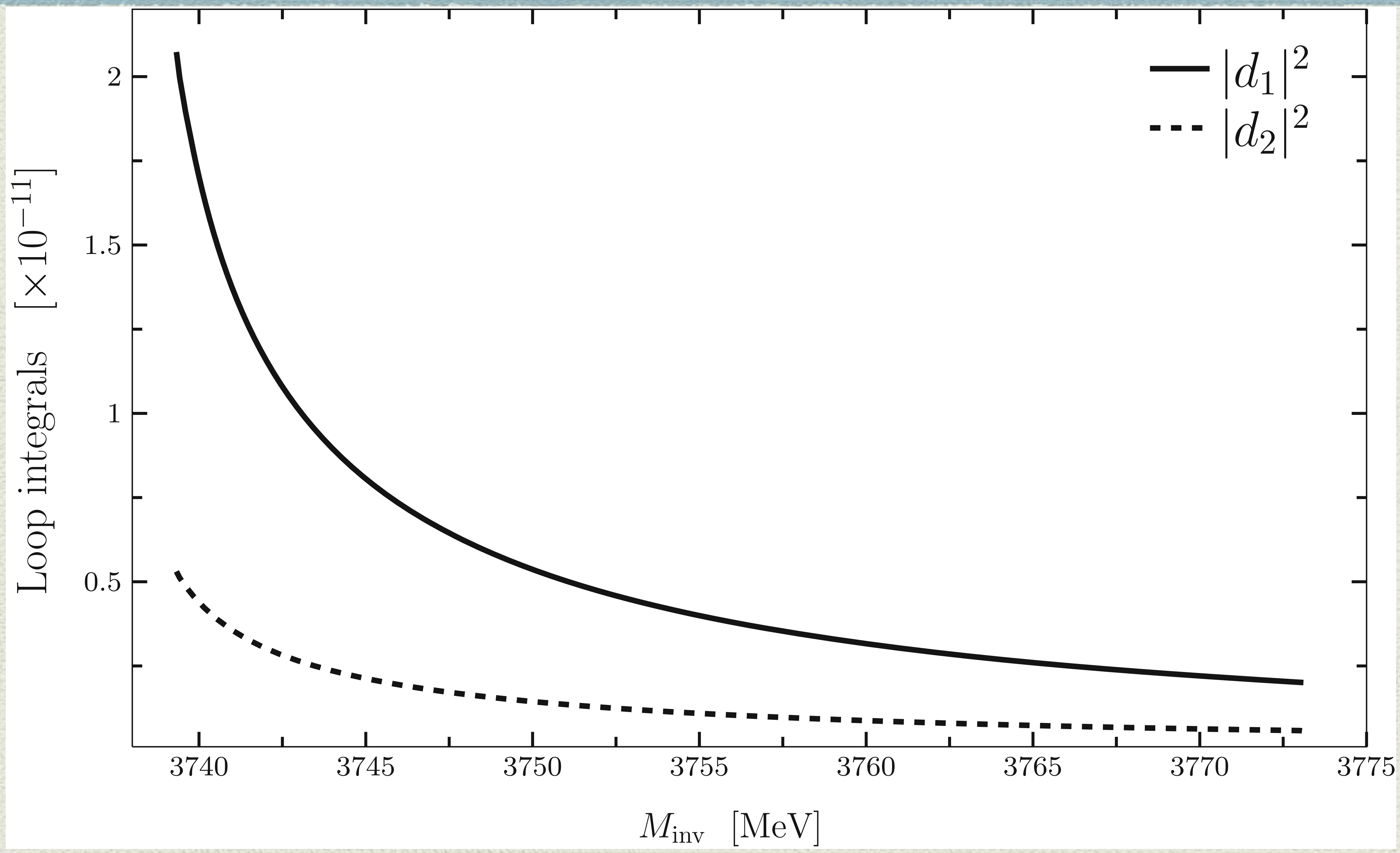
The G function is a diagonal function of the meson-meson loops, computed either using dimensional regularization or cut off regularization

$$G_{\eta\eta} = -i\frac{1}{8\pi}\frac{1}{M_{\rm inv}}q_\eta \qquad q_\eta = \frac{\lambda^{1/2}(M_{\rm inv}^2, m_\eta^2, m_\eta^2)}{2M_{\rm inv}}$$

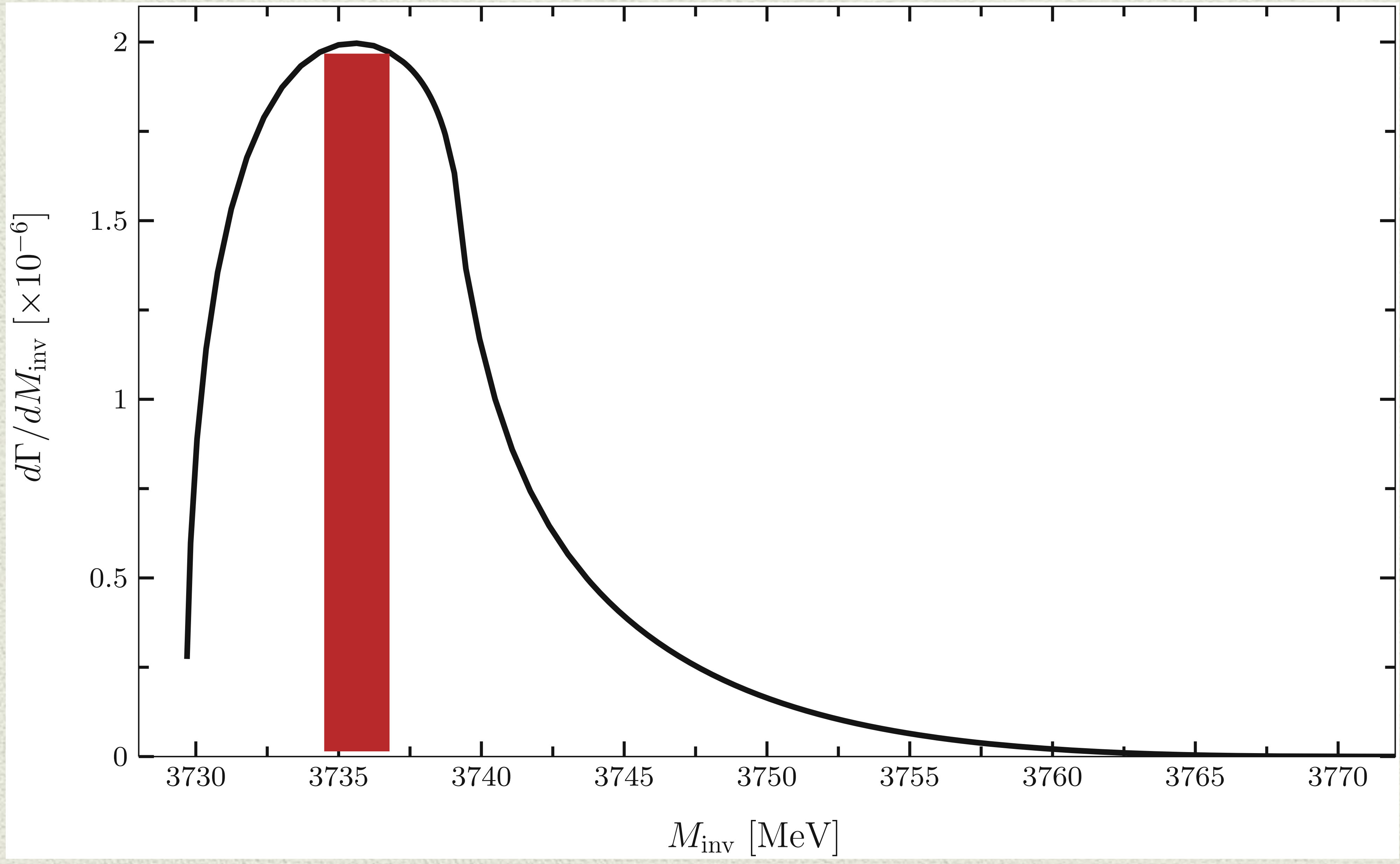
$D^0\bar{D}^0$ vs. D^+D^-



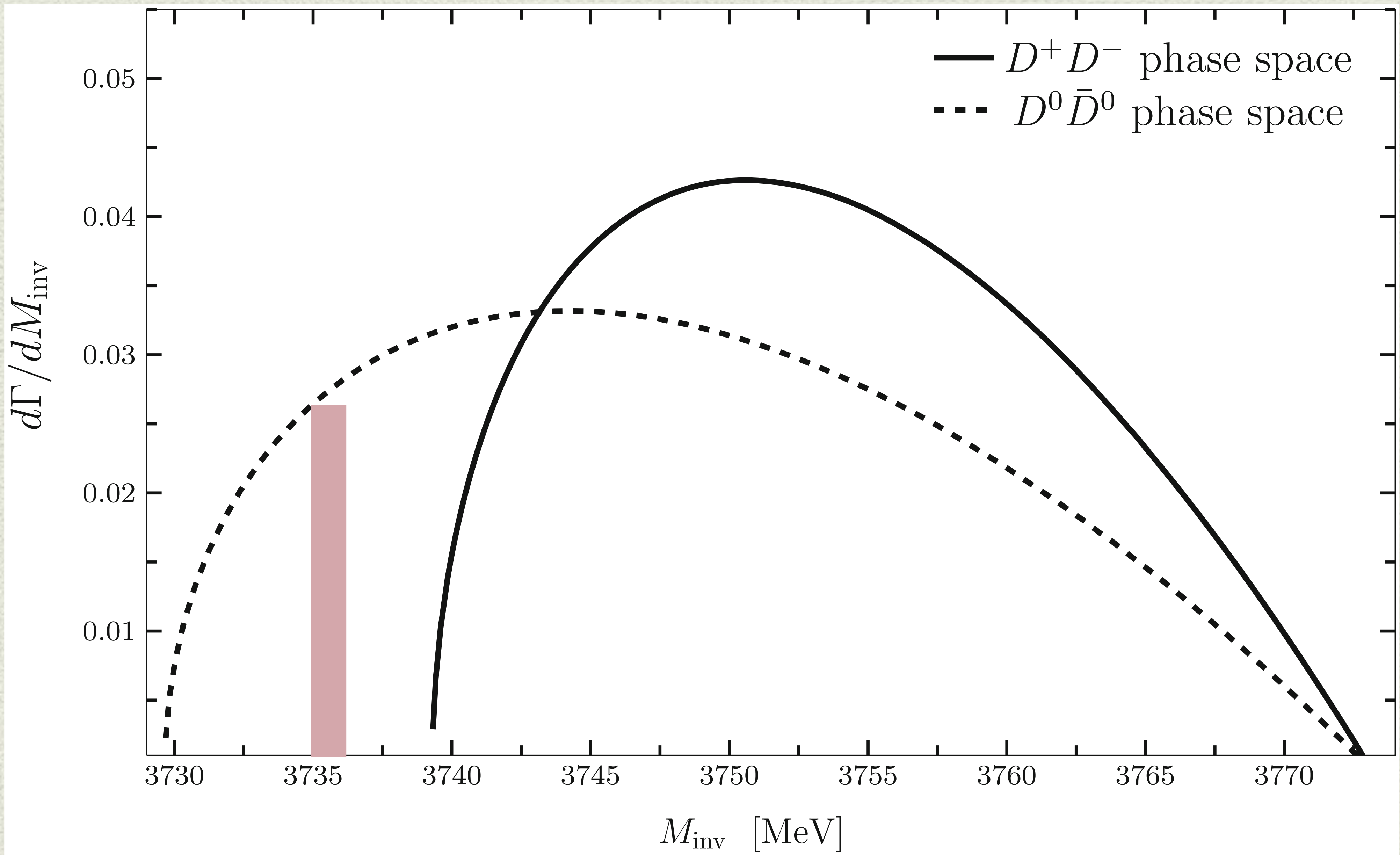
d functions


$|d_1|^2$
$|d_2|^2$
Loop integrals [$\times 10^{-11}$]
2
1.5
1
0.5
3740
3745
3750
3755
3760
3765
3770
3775
$M_{\rm inv}$ [MeV]

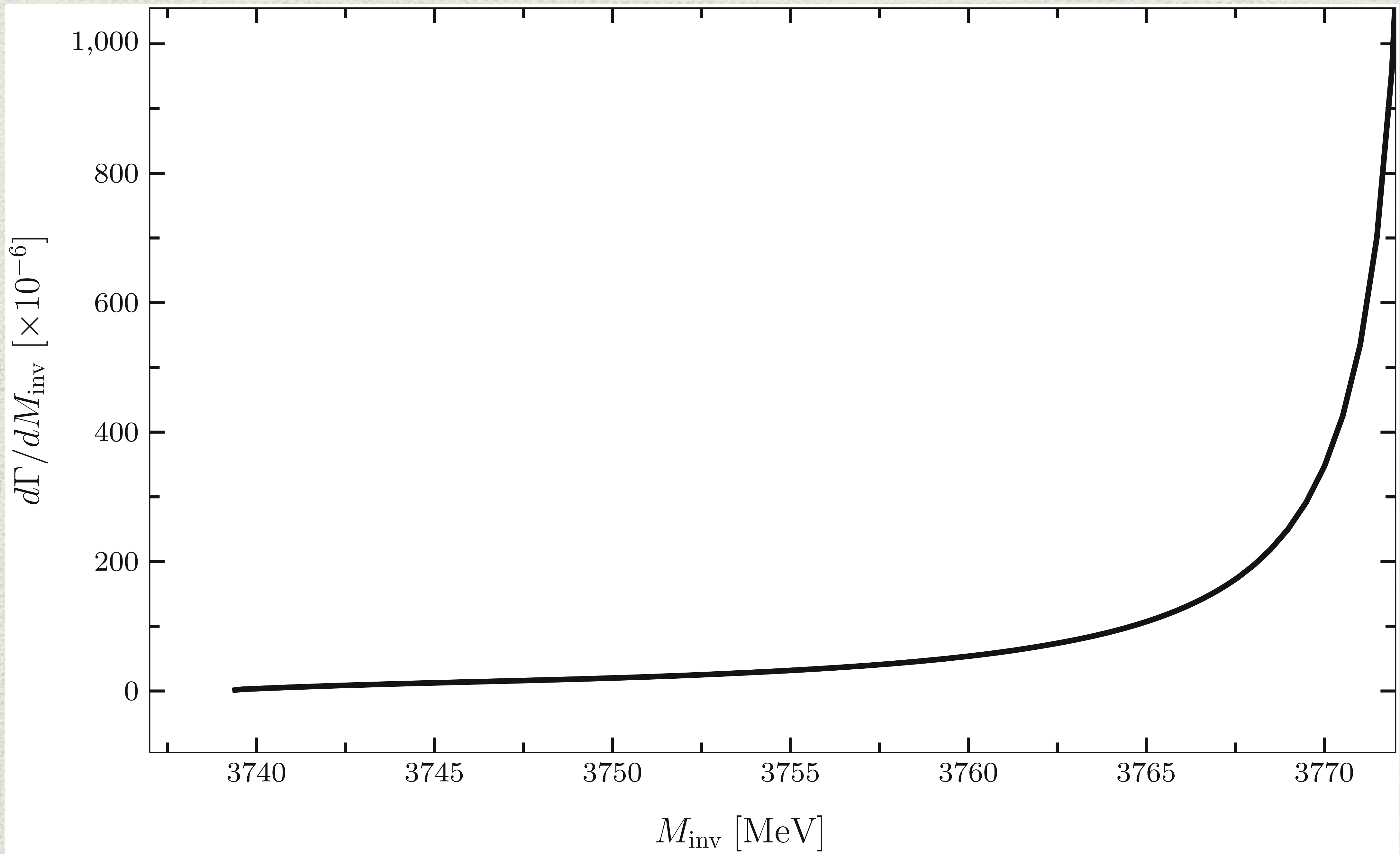
$D^0\bar{D}^0$ Signature on invariant mass



Invariant mass, phase space



D^+D^- Invariant mass



Tree level dominated

CONCLUSIONS

- We have made a study of the ψ (3770) → γ D D̄ decay, looking at the $D^+ D^-$ and $D^0 \bar{D}^0$ mass distributions close to threshold.
- The production of $D^0 \bar{D}^0$ is particularly suited in studying the dynamics of the DD̄ interaction because the tree level contribution is zero and the process goes with a loop mechanism that involves the D+ D− → D0 D̄ 0 scattering amplitude.
- We have used the results of a theory that predicts a DD̄ bound state and this has as a consequence that the D0 D̄ 0 mass distribution accumulates close to threshold and diverts drastically from a phase space distribution.
- The rates that we obtain for the mass distribution can be reachable at BESIII facility and we encourage the performance of the experiment that could shed light on the issue of this possible D D̄ bound state, and in any case it would provide information on the DD̄ → DD̄ interaction.

THANK YOU