Strong Decays of T_{cc}^{+} at NLO in an Effective Field Theory

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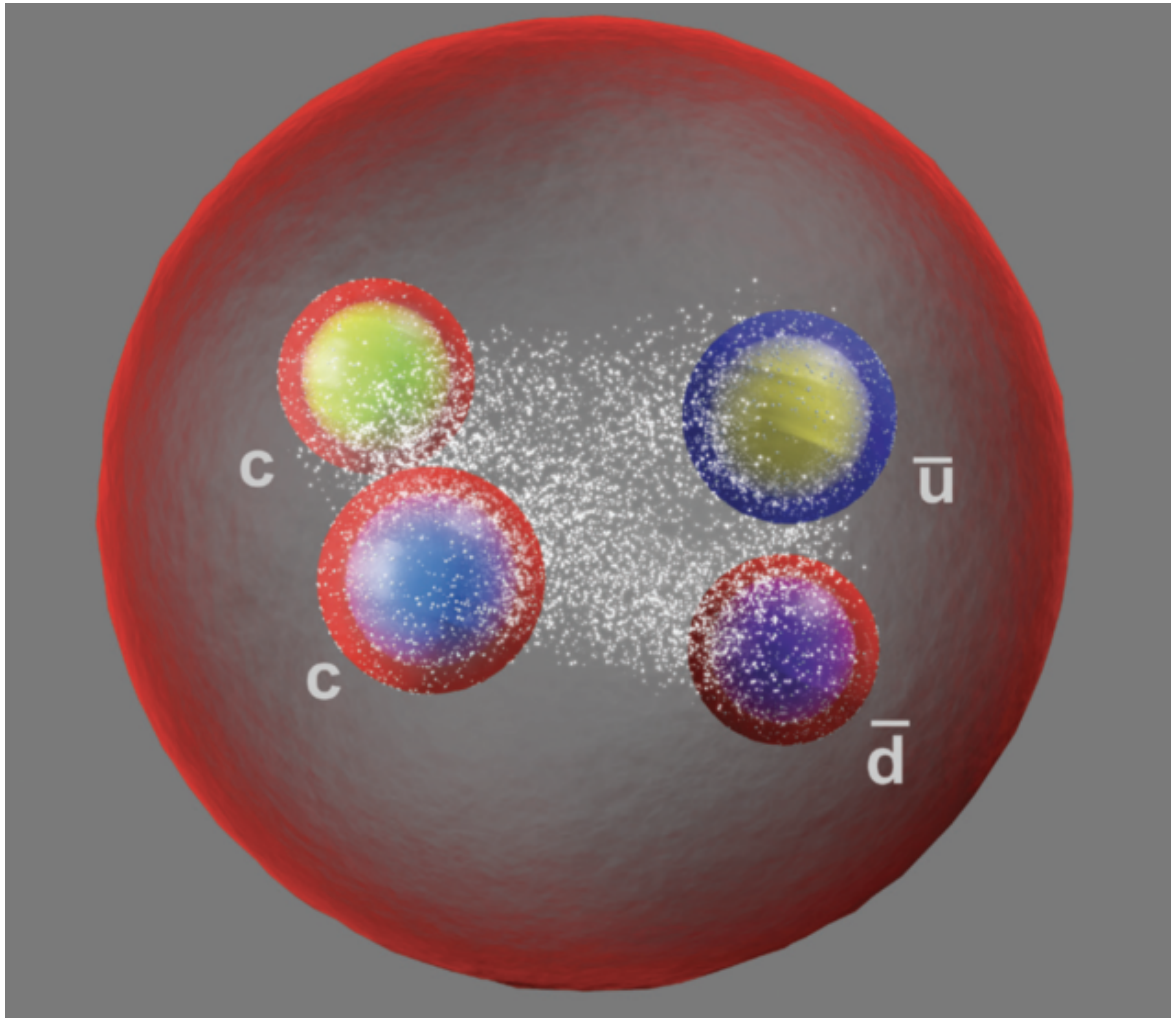
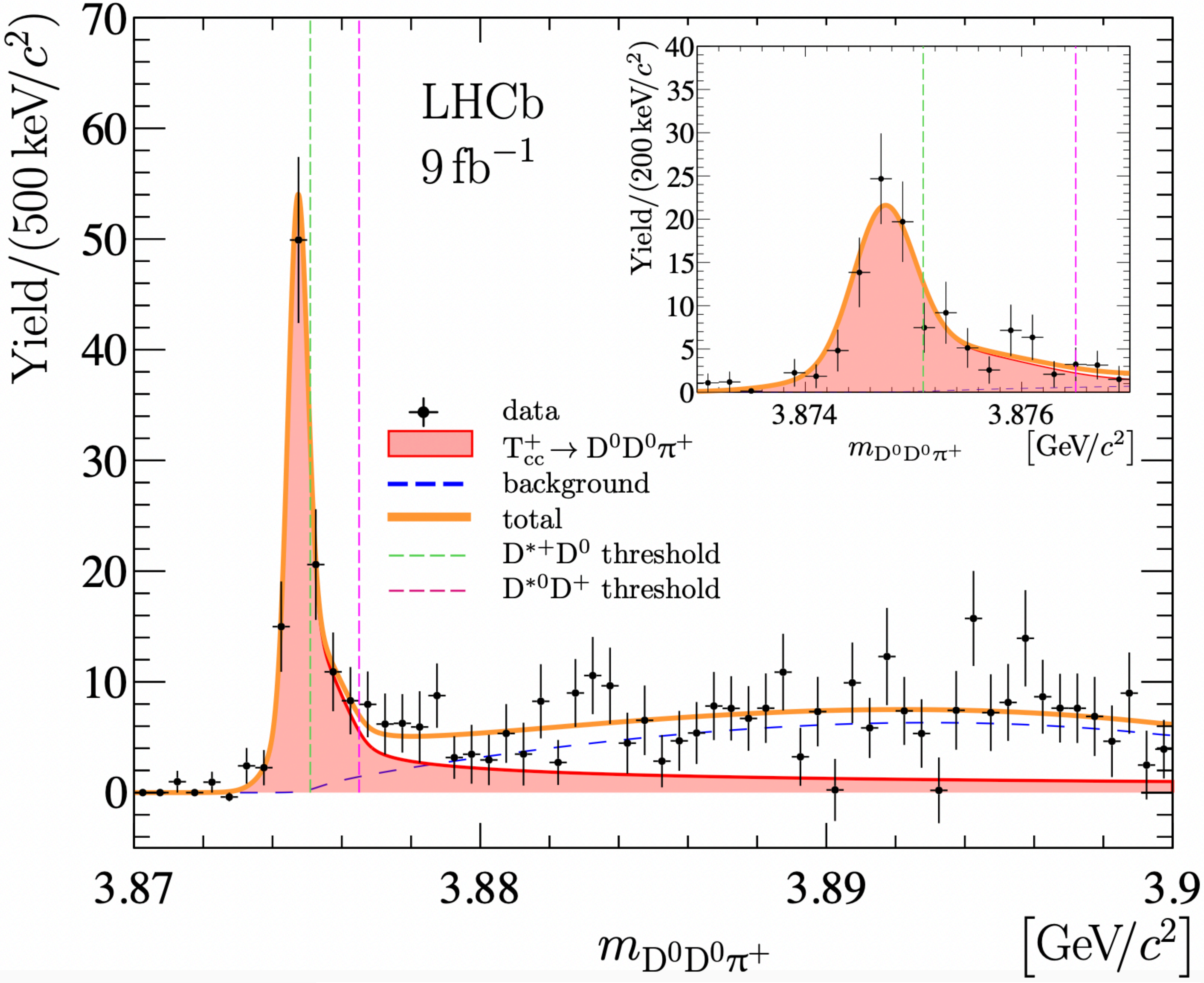
IISER Mohali, India, 3/1/2024

Discovered 7/2021: T_{cc}^{+} doubly charm tetraquark

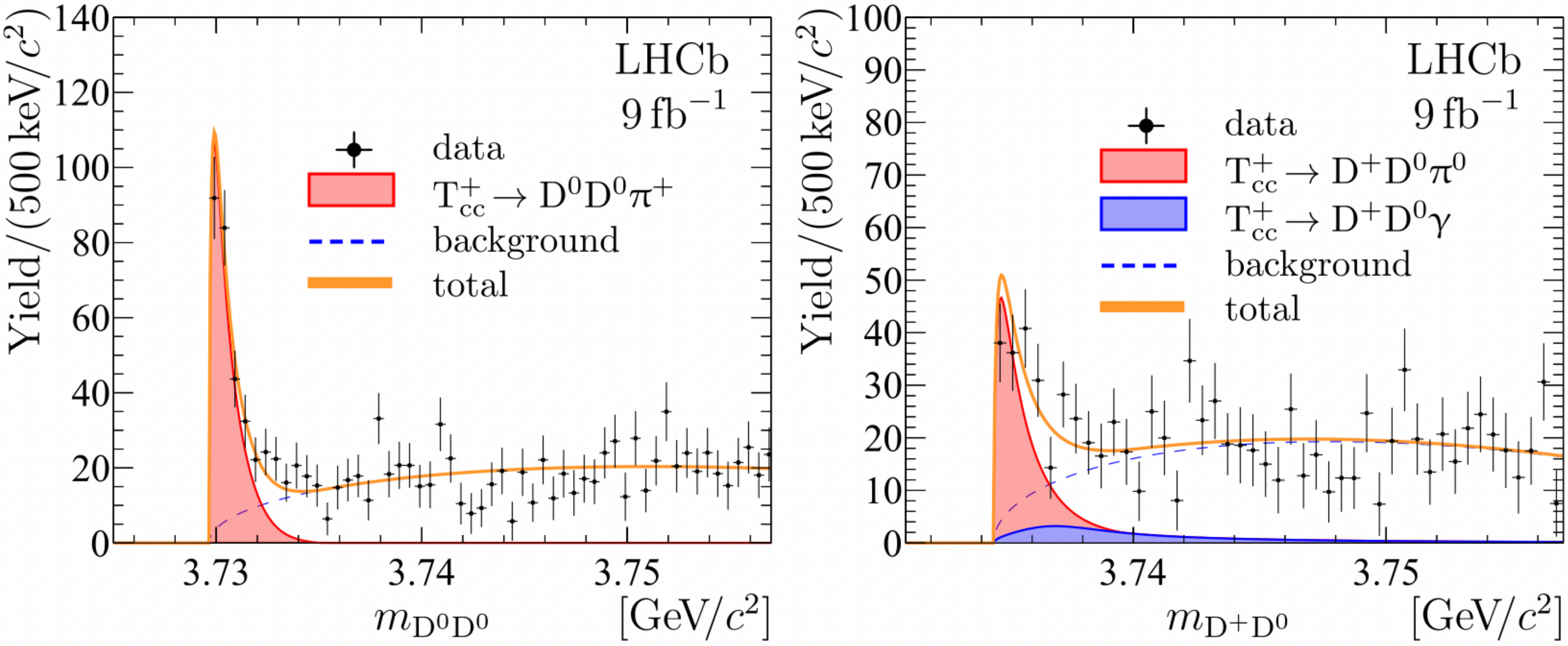


R. Aaij *et. al.* (LHCb), Nature Phys. 18 (2022) 7, 751-754, arXiv 2109.01038 [hep-ex]. (1)

R. Aaij *et. al.* (LHCb), Nature Commun. 13 (2022) 1, 3351, arXiv 2109.01056 [hep-ex]. (2)



$$\delta m_{pole} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$
$$\Gamma_{pole} = 48 \pm 2^{+0}_{-14}\,\text{keV}\,. \qquad (2)$$



LHCb
9 fb^{-1}
data
$T_{cc}^{+} \to D^0D^0\pi^+$
background
total
Yield/(500 keV/c^2)
$m_{D^0D^0}$ [GeV/c^2]
LHCb
9 fb^{-1}
data
$T_{cc}^{+} \to D^+D^0\pi^0$
$T_{cc}^{+} \to D^+D^0\gamma$
background
total
Yield/(500 keV/c^2)
$m_{D^+D^0}$ [GeV/c^2]

Heavy Hadron Chiral Perturbation Theory plus contact terms for S-wave D*D scattering

$$\mathcal{L} = H^{*i\dagger}\left(i\partial^0 + \frac{\nabla^2}{2m_{H^*}} - \delta^*\right)H^{*i} + H^\dagger\left(i\partial^0 + \frac{\nabla^2}{2m_H} - \delta\right)H$$
$$+\frac{g}{f_\pi}H^\dagger\partial^i\pi H^{*i} + \text{h.c.} + \frac{1}{2}H^\dagger\mu_D\vec{B}^i H^{*i} + \text{h.c.}$$
$$-C_0(H^{*T}\tau_2 H)^\dagger(H^{*T}\tau_2 H) - C_1(H^{*T}\tau_2\tau_a H)^\dagger(H^{*T}\tau_2\tau_a H)\,.$$

$$H = \begin{pmatrix} D^0 \\ D^+ \end{pmatrix}, \quad H^{*i} = \begin{pmatrix} D^{*0i} \\ D^{*+i} \end{pmatrix}$$

S. Fleming, R. Hodges, TM, Phys. Rev. D. 104 (2021) 11, 116010, arXiv:2109.02188

Similar to XEFT for X(3872), new feature is coupled channels

S. Fleming, M. Kusunoki, TM, U. van Kolck, Phys. Rev. D. 76 (2007) 034006, hep-ph/0703168

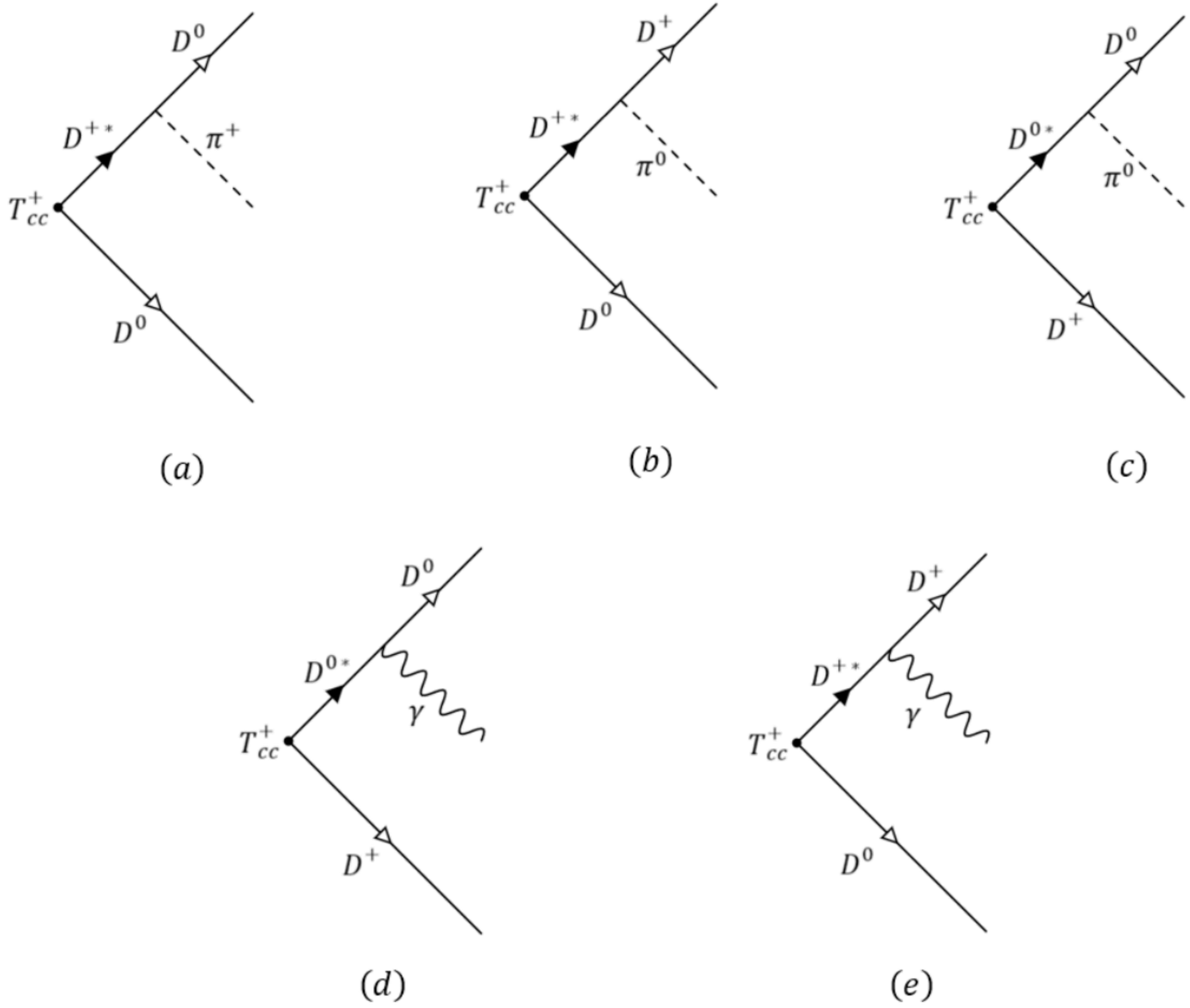
T-Matrix for D*D scattering

$$T = \frac{1}{E + E_T} \begin{pmatrix} g_0^2 & g_0 g_+ \\ g_0 g_+ & g_+^2 \end{pmatrix}$$

$$g_0^2 \Sigma_0'(-E_T) + g_+^2 \Sigma_+'(-E_T) = 1 \,;$$

Tune interactions to produce pole at T_{cc}^+

Decay Diagrams



Decay rate formulae

$$\frac{d\Gamma[T_{cc}^{+} \to D^0 D^0 \pi^+]}{dp_{D_1^0}^2\, dp_{D_2^0}^2} = c_\theta^2 \frac{g^2}{(4\pi f_\pi)^2} \frac{2\gamma_0 p_\pi^2}{3} \left[\frac{1}{p_{D_1^0}^2 + \gamma_0^2} + \frac{1}{p_{D_2^0}^2 + \gamma_0^2} \right]^2 ,$$

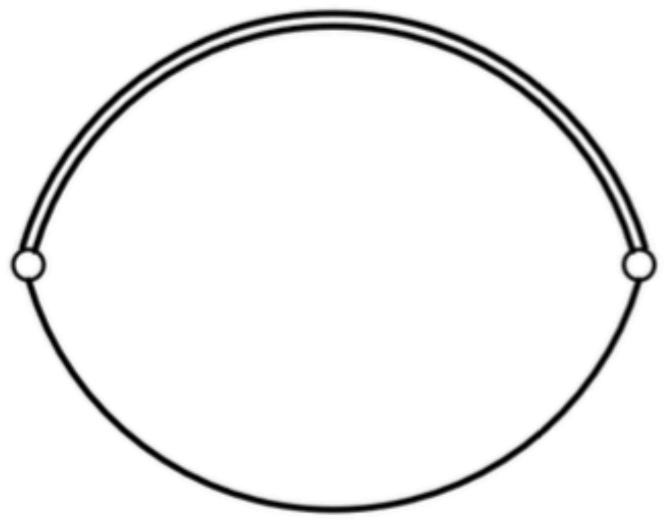
$$\frac{d\Gamma[T_{cc}^{+} \to D^+ D^0 \pi^0]}{dp_{D^+}^2\, dp_{D^0}^2} = \frac{g^2}{(4\pi f_\pi)^2} \frac{2 p_\pi^2}{3} \left[\frac{\sqrt{\gamma_0}\, c_\theta}{p_{D^+}^2 + \gamma_0^2} - \frac{\sqrt{\gamma_+}\, s_\theta}{p_{D^0}^2 + \gamma_+^2} \right]^2 ,$$

$$\frac{d\Gamma[T_{cc}^{+} \to D^+ D^0 \gamma]}{dp_{D^+}^2\, dp_{D^0}^2} = \frac{E_\gamma^2}{6\pi^2} \left[\frac{\sqrt{\gamma_0}\, c_\theta \mu_{D^0}}{p_{D^+}^2 + \gamma_0^2} - \frac{\sqrt{\gamma_+}\, s_\theta \mu_{D^+}}{p_{D^0}^2 + \gamma_+^2} \right]^2 .$$

$$\gamma_0^2 = 2\mu_0 (m_{D^0} + m_{D^{*+}} - m_T)$$
$$\gamma_+^2 = 2\mu_+ (m_{D^+} + m_{D^{*0}} - m_T)$$

$$g_0^2 = \frac{\cos^2\theta}{\Sigma_0'(-E_T)} \qquad g_+^2 = \frac{\sin^2\theta}{\Sigma_+'(-E_T)}$$

$i\Sigma_i(E) =$



LO Predictions for Decay Rate

	I=0	I=1	Γ_{max}
θ	$-32.4°$	$32.4°$	$-8.34°$
$\Gamma[T_{cc}^+ \to D^0 D^0 \pi^+]$	32	32	44
$\Gamma[T_{cc}^+ \to D^+ D^0 \pi^0]$	15	3.8	13
$\Gamma[T_{cc}^+ \to D^+ D^0 \gamma]$	6.1	2.8	1.9
$\Gamma[T_{cc}^+]$	52	38	58

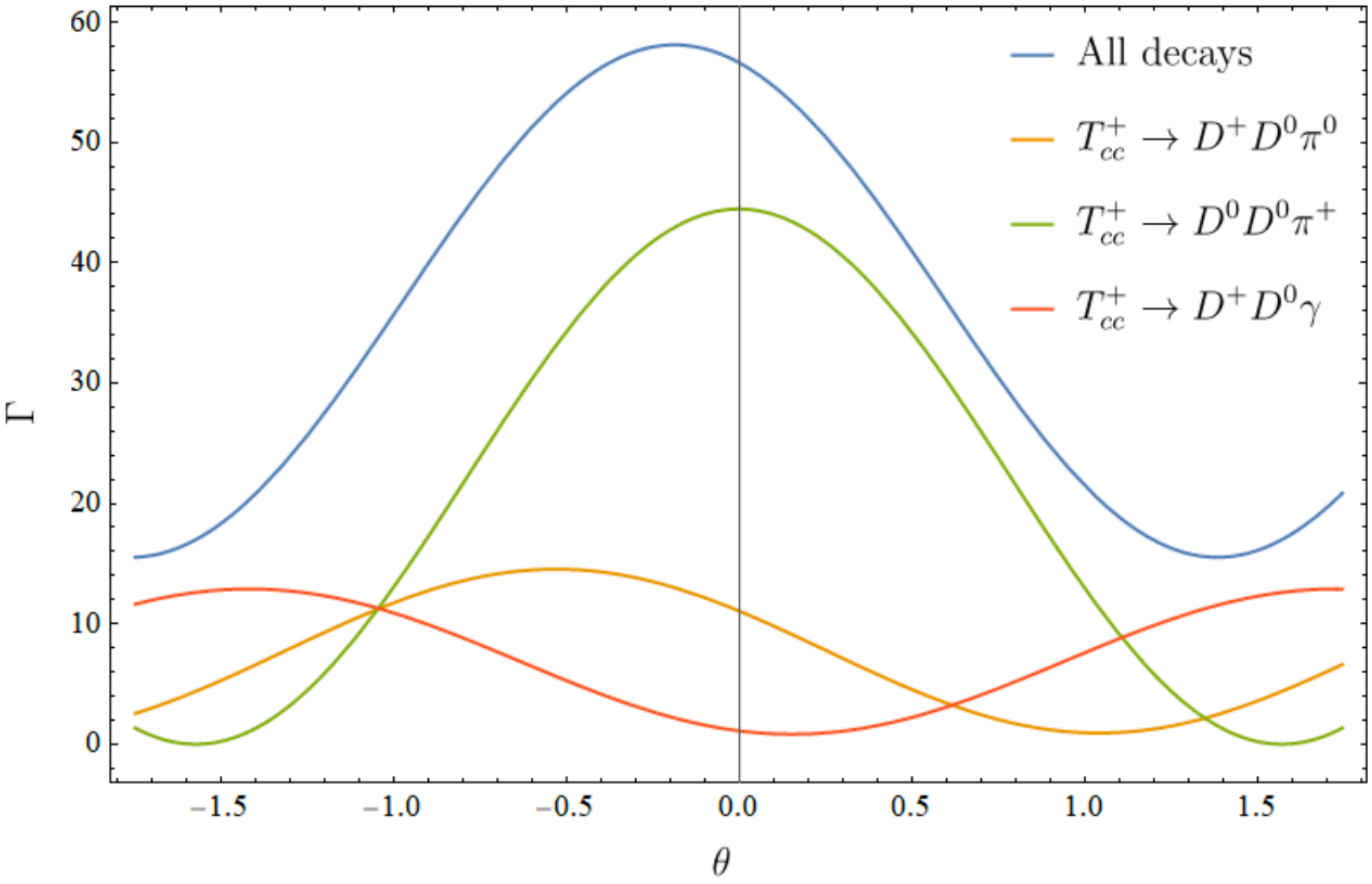
$$I = 0 : g_0 = -g_+$$

$$I = 1 : g_0 = g_+$$

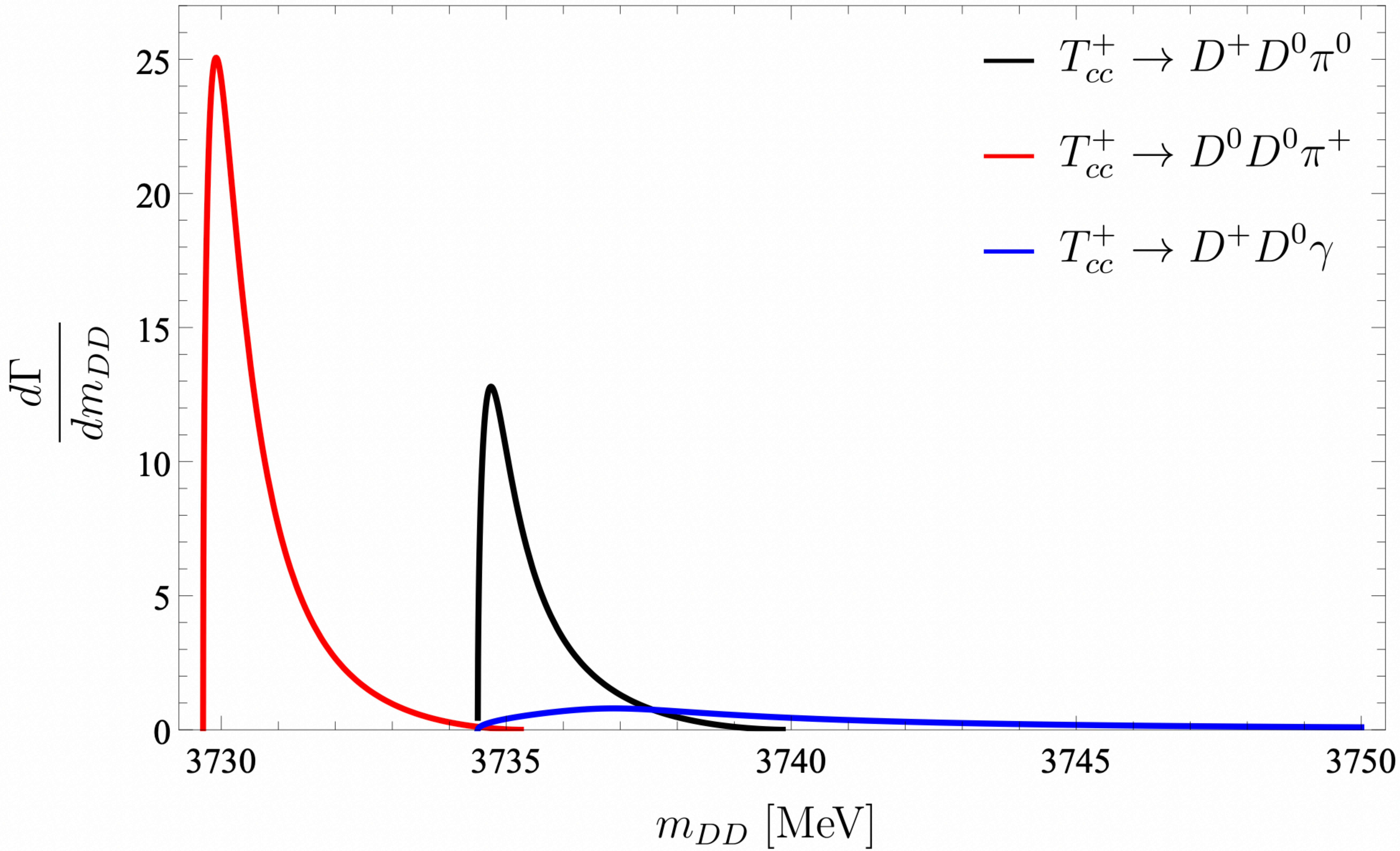
Other Predictions

	$\Gamma(T_{cc}^+)$ (keV)
Fleming et al.	**52**
Meng et al.	$46.7^{+2.7}_{-2.9}$
Ling et al.	53
Feijoo et al.	43
Yan & Valderrama	49 ± 16
Albaladejo	77

$$\delta m_{BW} = -273 \pm 61 \pm 5^{+11}_{-14}\,\mathrm{keV}\,,$$
$$\Gamma_{BW} = 410 \pm 165 \pm 43^{+18}_{-38}\,\mathrm{keV}\,. \quad (1)$$

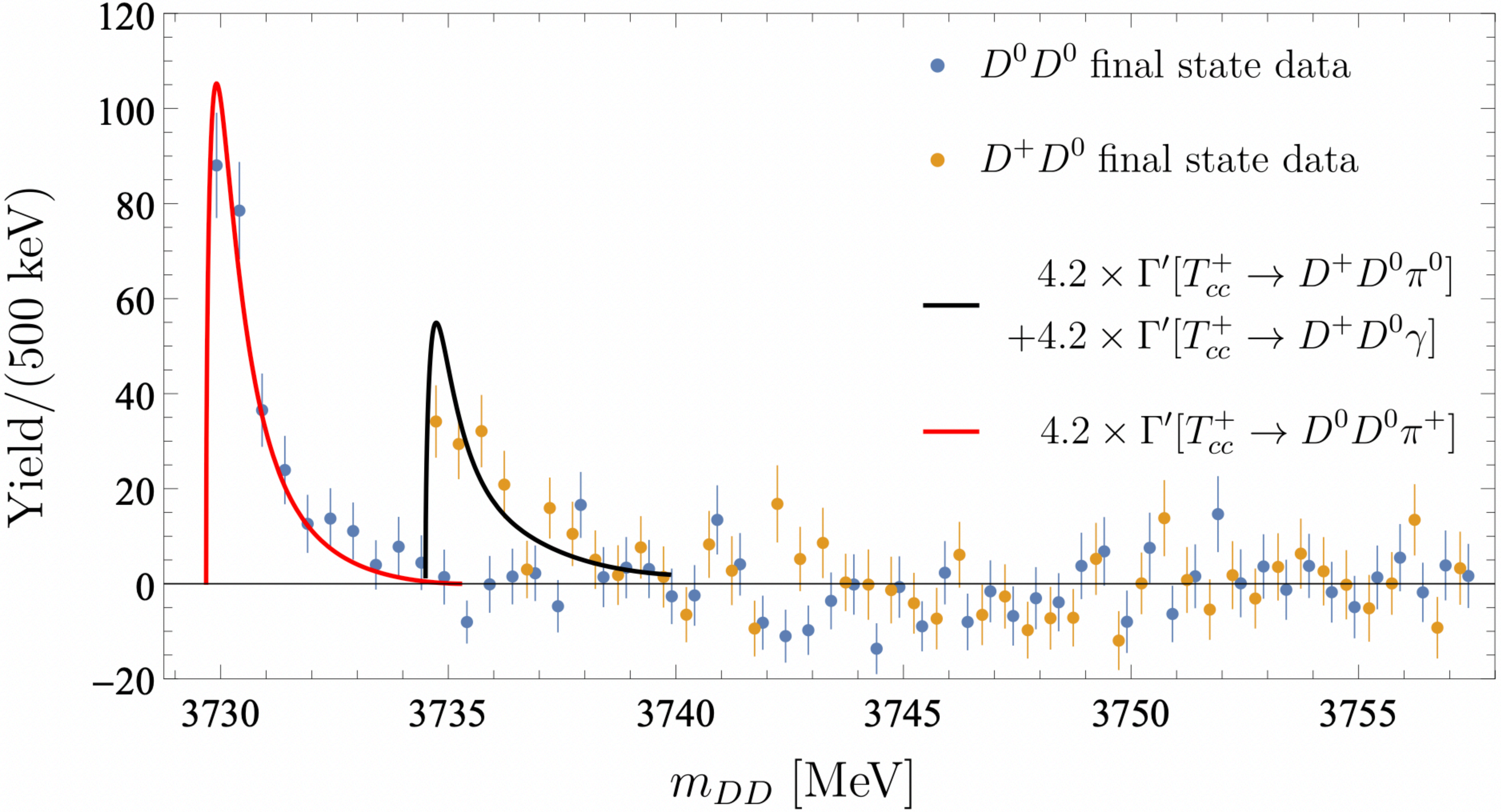


this agrees well with the same plot by Meng et al. (2107.14784)

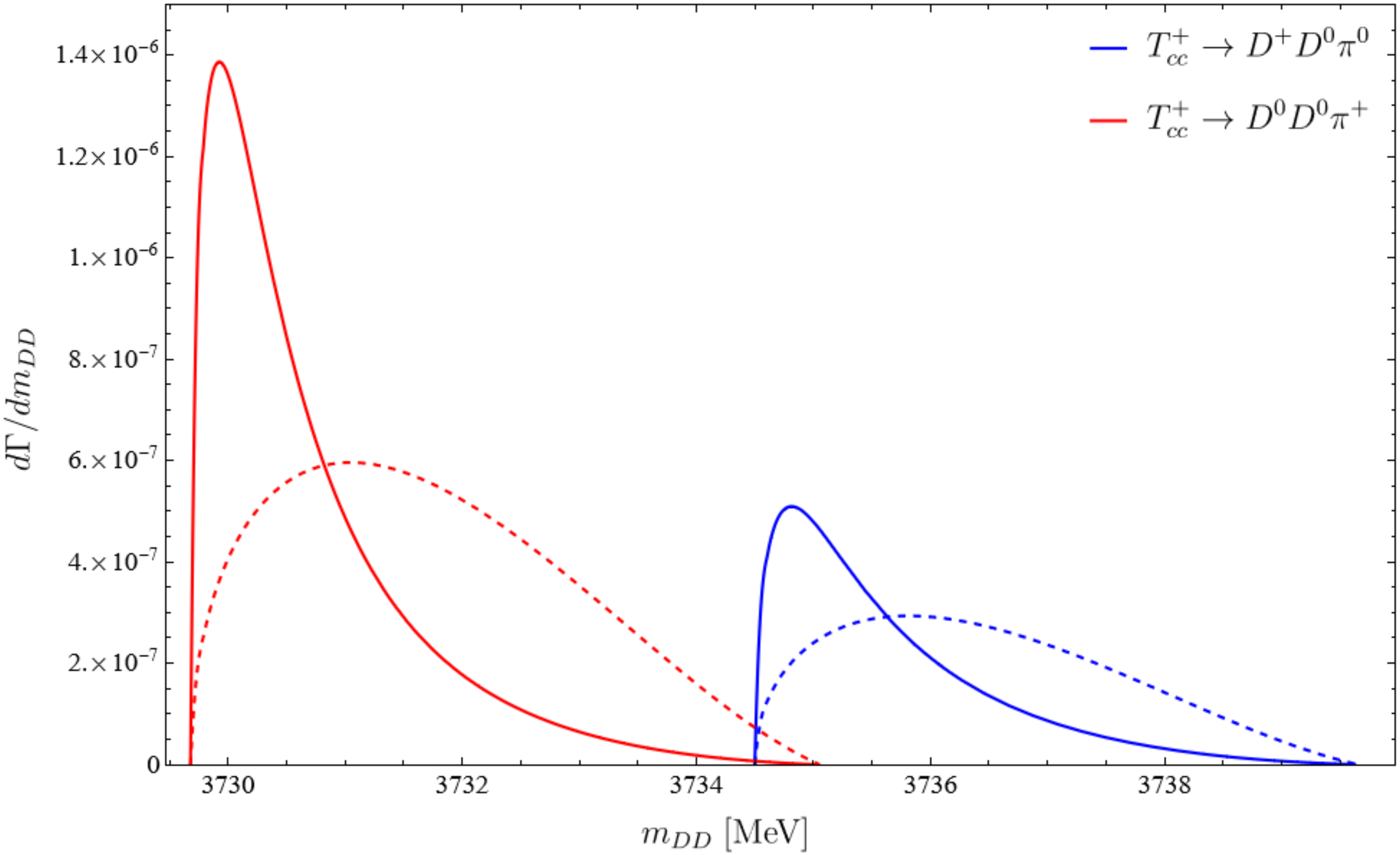


$T_{cc}^+ \to D^+ D^0 \pi^0$
$T_{cc}^+ \to D^0 D^0 \pi^+$
$T_{cc}^+ \to D^+ D^0 \gamma$
$\frac{d\Gamma}{dm_{DD}}$
m_{DD} [MeV]
0
5
10
15
20
25
3730
3735
3740
3745
3750

$d\Gamma/dm_{DD}$ vs. data

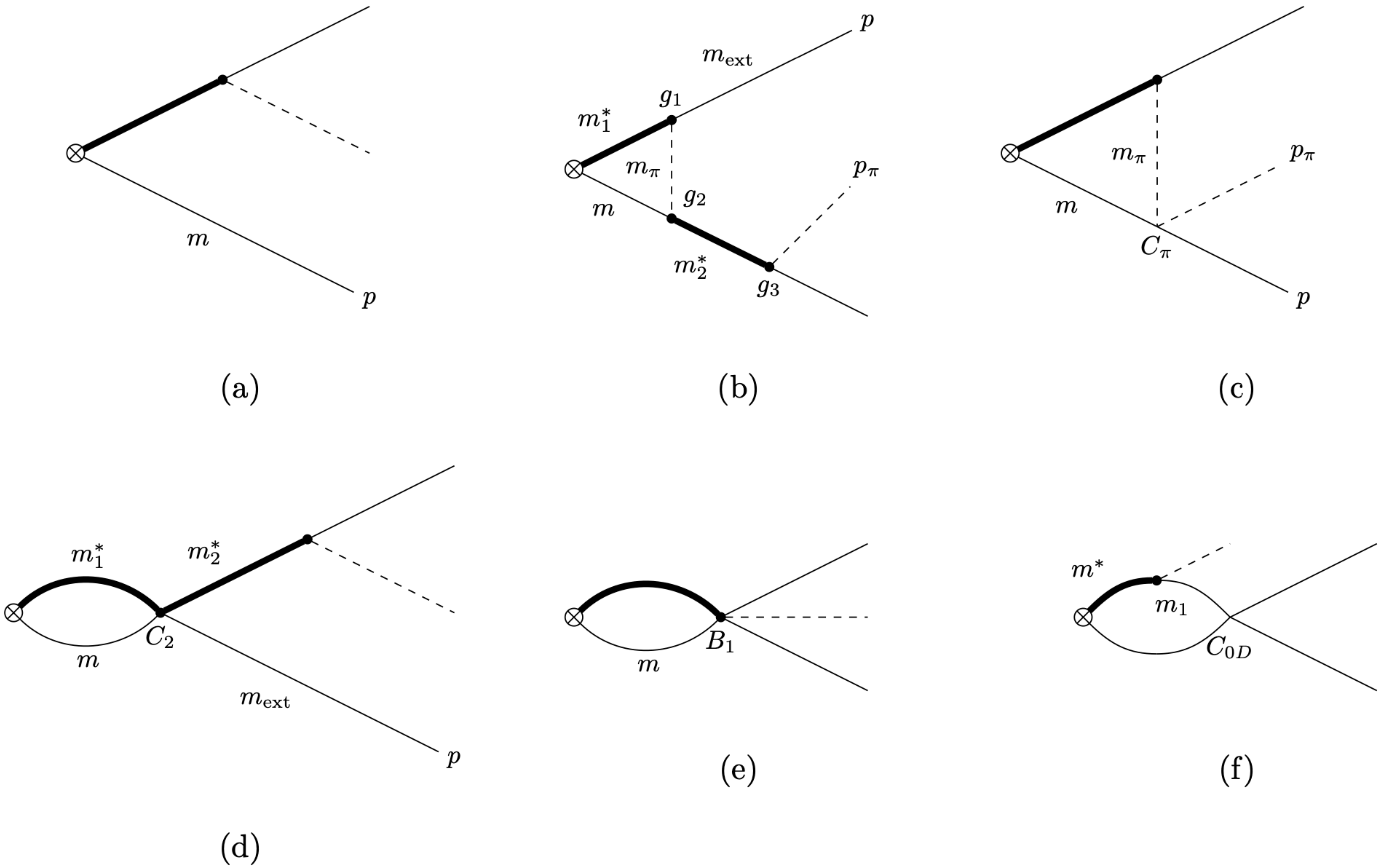


see also M.-L. Du, et.al., Phys. Rev. D, 105 (2022) 1, 014024



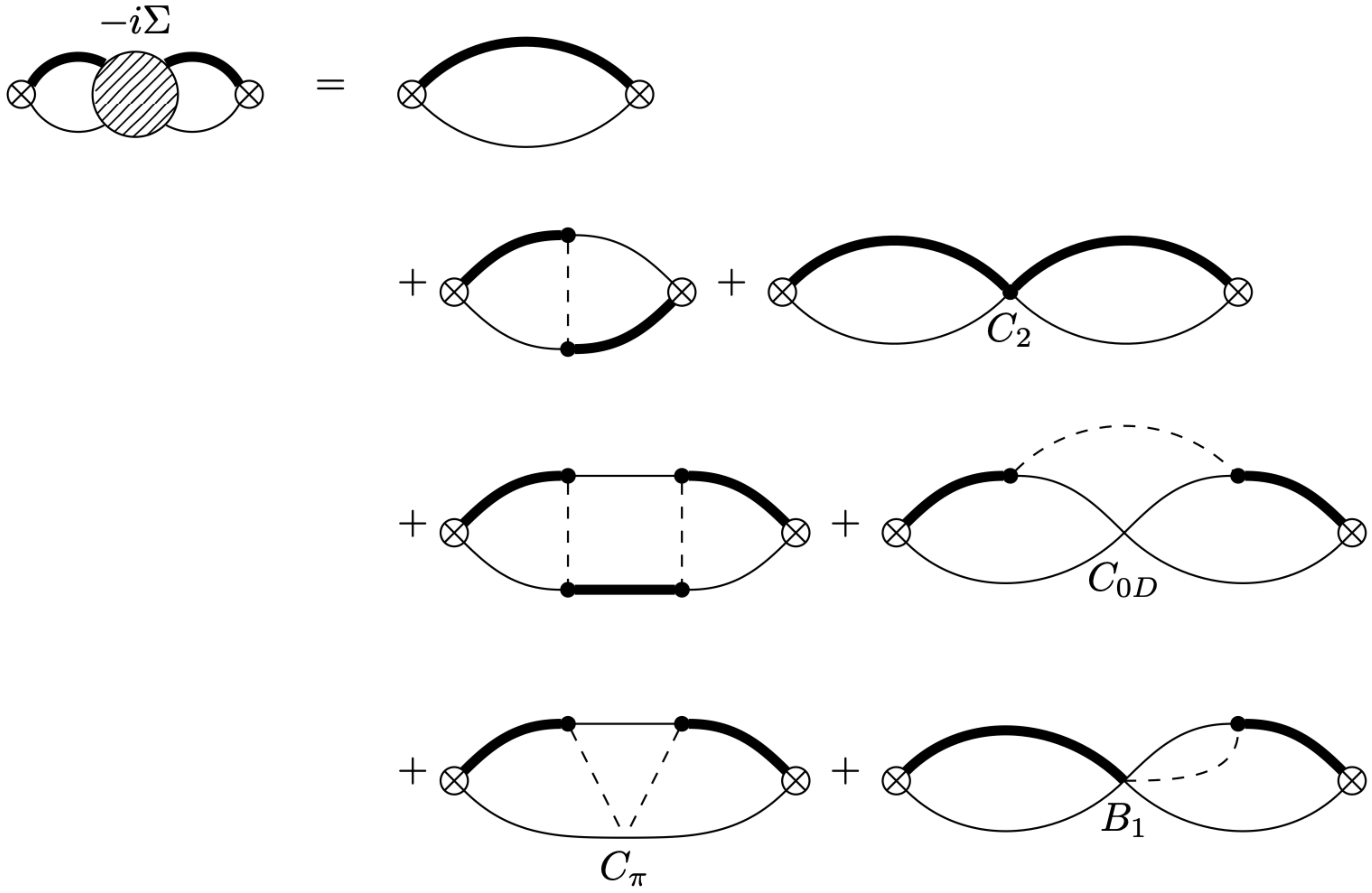
comparison with p_π^2 $\times$ phase space (dashed)

NLO Corrections to Decay Rate - assume I = 0 state



L. Dai, S. Fleming, R. Hodges, TM, Phys. Rev. D 107 (2023) 7, 076001, arXiv:2301.11950 [hep-ph]

$$\Gamma_0 \approx \Gamma^{LO}\left(1 - \frac{\mathrm{Re}\,\Sigma_0'^{NLO}(-E_T)}{\mathrm{Re}\,\mathrm{tr}\,\Sigma'^{LO}(-E_T)}\right) + \frac{2\,\mathrm{Im}\,\Sigma_0^{NLO}(-E_T)}{\mathrm{Re}\,\mathrm{tr}\,\Sigma'^{LO}(-E_T)}$$

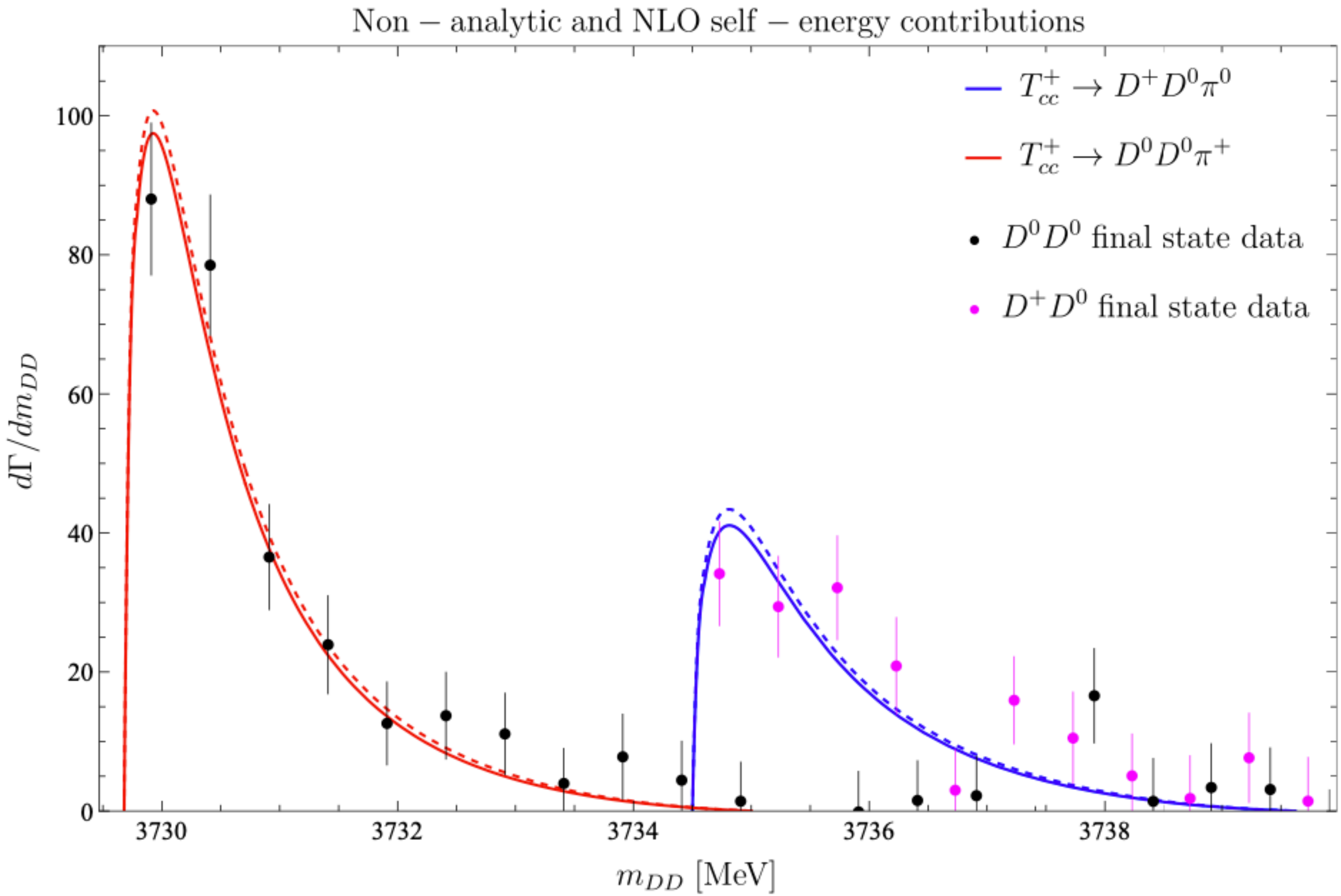


NLO Corrections to Decay Rate

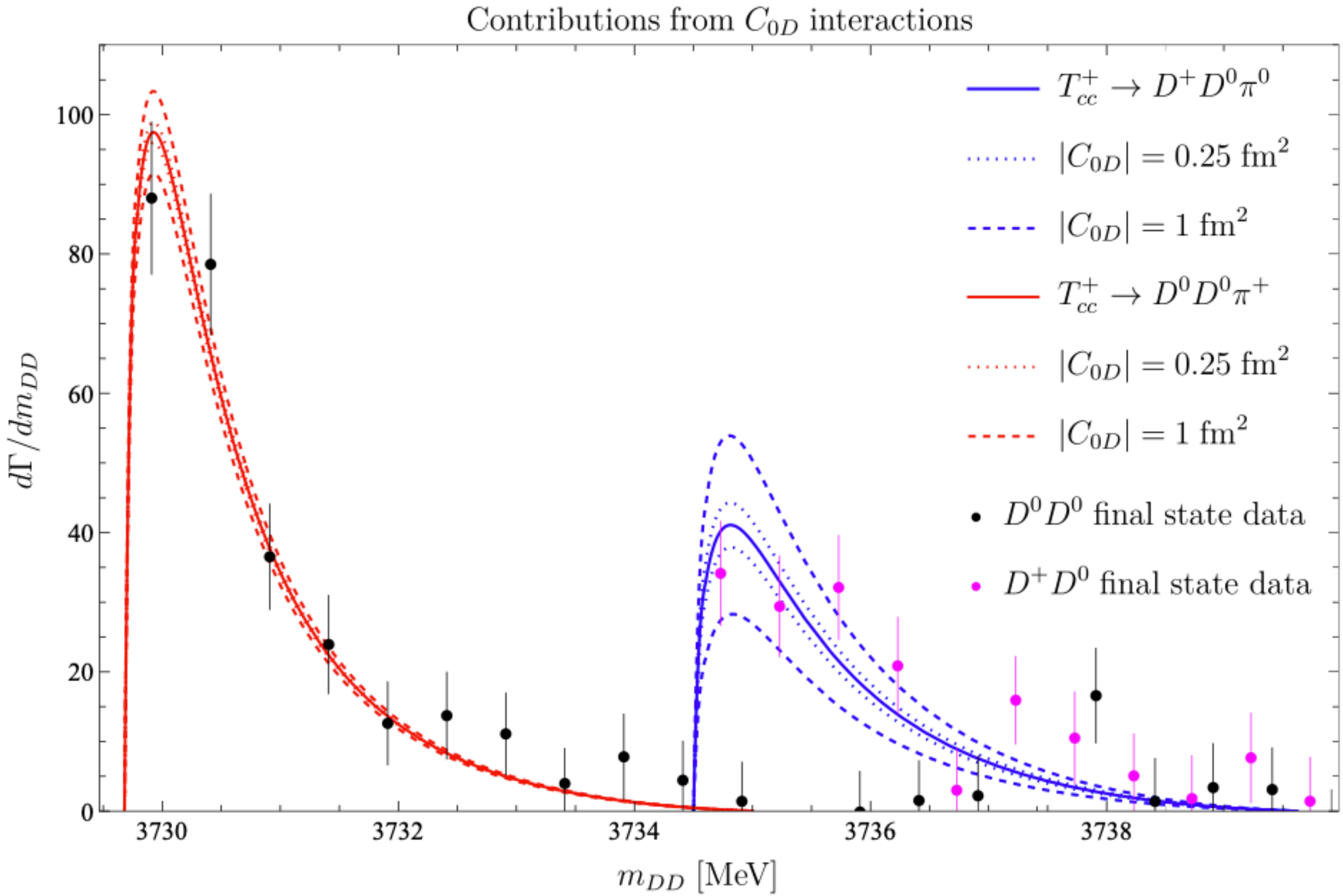
TABLE I: Partial and total widths in units of keV at LO and NLO.

	LO result	NLO lower bound	NLO upper bound
$\Gamma[T_{cc}^+ \to D^0 D^0 \pi^+]$	28	21	44
$\Gamma[T_{cc}^+ \to D^+ D^0 \pi^0]$	13	7.8	21
$\Gamma_{\text{strong}}[T_{cc}^+]$	41	29	66
$\Gamma_{\text{strong}}[T_{cc}^+] + \Gamma_{\text{EM}}^{LO}[T_{cc}^+]$	47	35	72

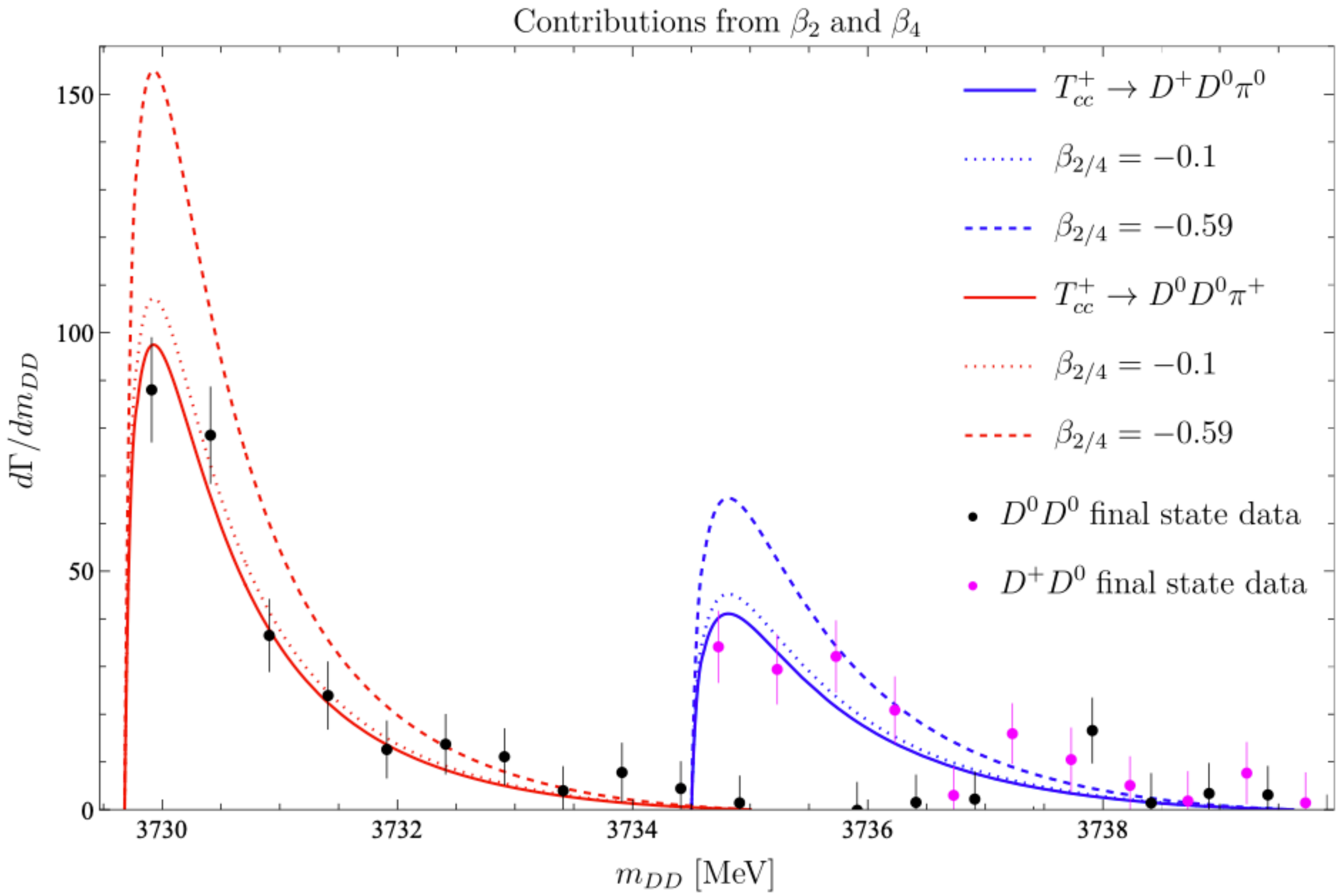
$$\delta m_{pole} = -360 \pm 40^{+4}_{-0}\,\text{keV}\,,$$
$$\Gamma_{pole} = 48 \pm 2^{+0}_{-14}\,\text{keV}\,. \quad (2)$$



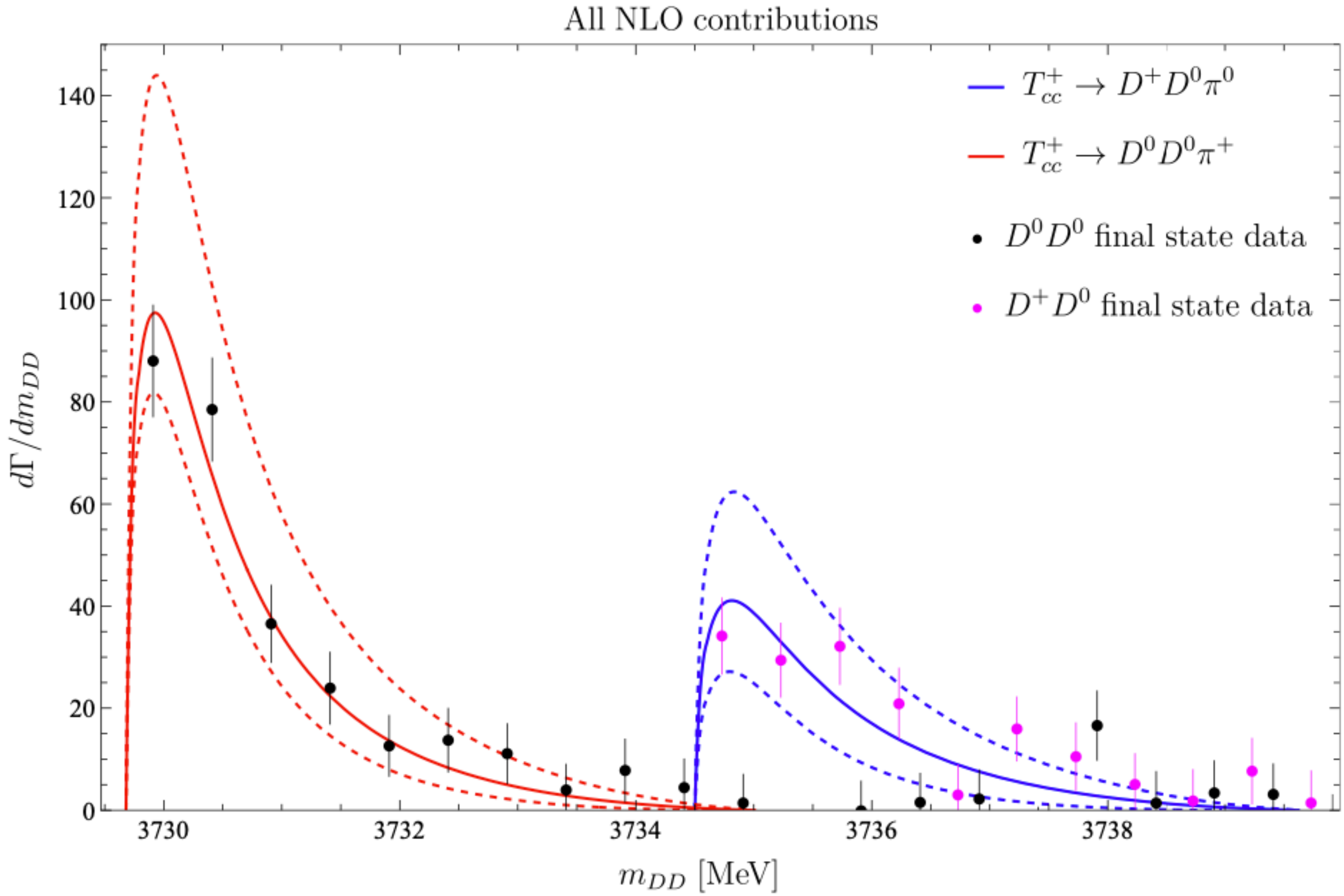
Non − analytic and NLO self − energy contributions
$T_{cc}^{+} \to D^{+}D^{0}\pi^{0}$
$T_{cc}^{+} \to D^{0}D^{0}\pi^{+}$
$D^{0}D^{0}$ final state data
$D^{+}D^{0}$ final state data
$d\Gamma/dm_{DD}$
m_{DD} [MeV]
0
20
40
60
80
100
3730
3732
3734
3736
3738



Contributions from C_{0D} interactions
$T_{cc}^+ \to D^+D^0\pi^0$
$|C_{0D}| = 0.25$ fm^2
$|C_{0D}| = 1$ fm^2
$T_{cc}^+ \to D^0D^0\pi^+$
$|C_{0D}| = 0.25$ fm^2
$|C_{0D}| = 1$ fm^2
D^0D^0 final state data
D^+D^0 final state data
$d\Gamma/dm_{DD}$
0
20
40
60
80
100
3730
3732
3734
3736
3738
m_{DD} [MeV]



Contributions from β_2 and β_4
$T_{cc}^+ \to D^+ D^0 \pi^0$
$\beta_{2/4} = -0.1$
$\beta_{2/4} = -0.59$
$T_{cc}^+ \to D^0 D^0 \pi^+$
$\beta_{2/4} = -0.1$
$\beta_{2/4} = -0.59$
$D^0 D^0$ final state data
$D^+ D^0$ final state data
$d\Gamma/dm_{DD}$
m_{DD} [MeV]
150
100
50
0
3730
3732
3734
3736
3738


All NLO contributions
$T_{cc}^+ \to D^+ D^0 \pi^0$
$T_{cc}^+ \to D^0 D^0 \pi^+$
$D^0 D^0$ final state data
$D^+ D^0$ final state data
$d\Gamma/dm_{DD}$
m_{DD} [MeV]
0
20
40
60
80
100
120
140
3730
3732
3734
3736
3738

Summary

T_{cc}^{+} decays described by XEFT-like theory w/ coupled channels

$\Gamma[T_{cc}^{+}], d\Gamma[T_{cc}^{+}]/dm_{DD}$ excellent agreement w/ LO EFT calculations

NLO corrections:	pion loops	negligble
	πD rescattering	negligble
	range corrections	dominant
	DD rescattering	significant

NLO calculations agree with data, could constrain D interactions