Triangle Singularity in the Production of $T_{cc}^{+}(3875)$ and a soft Pion [arXiv: 2202.03900]

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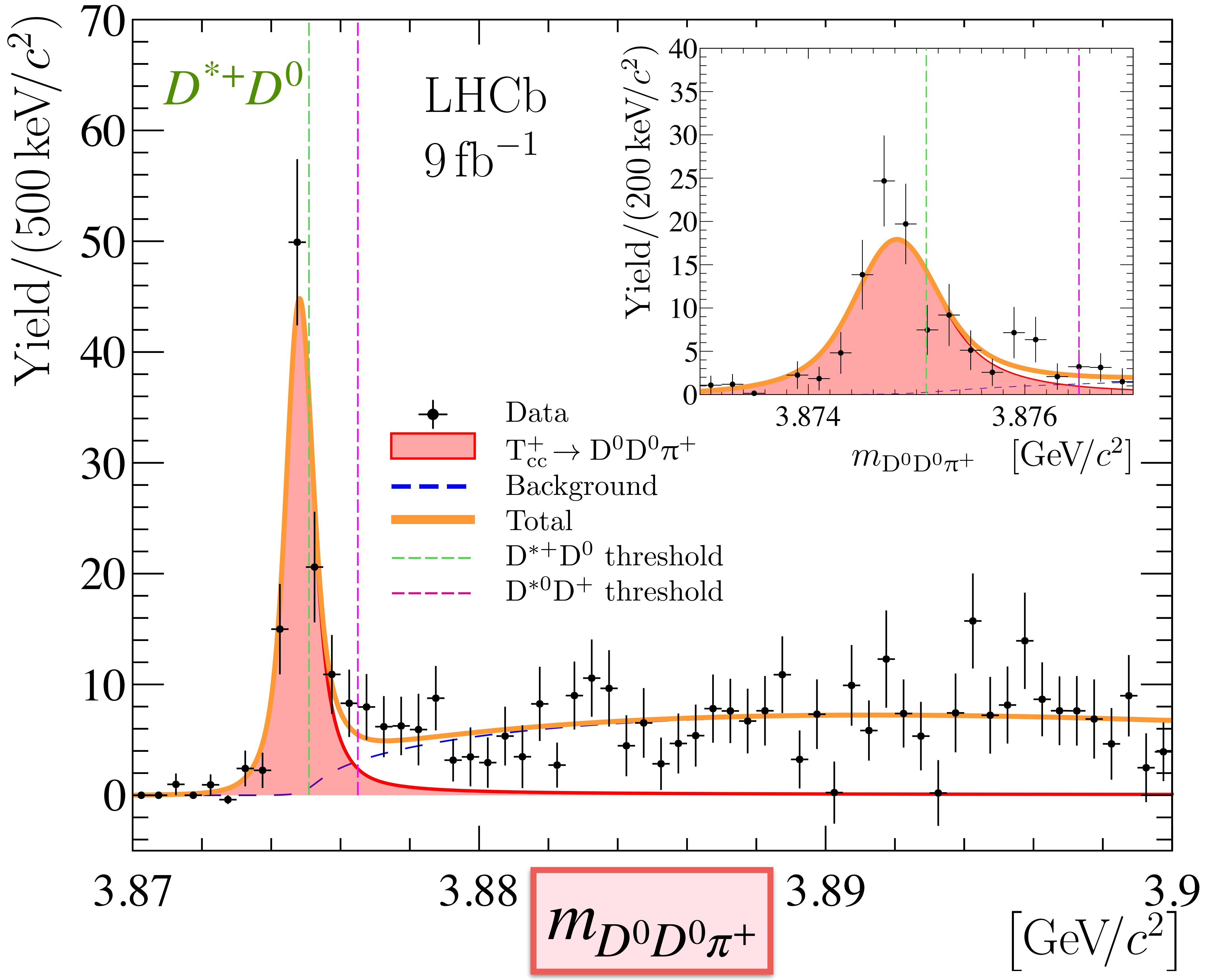
Outline

- Brief review of $T_{cc}^{+}(3875)$
- Loosely bound charm-meson molecule
- Production of T_{cc}^{+} and a soft pion at a hadron collider
  - charm-meson triangle singularity
  - cross sections in coupled-channel model
  - contribution from triangle singularity
- Summary and outlook

$T_{cc}^{+}(3875)$

discovery by LHCb [arXiv:2109.01038, arXiv:2109.01056]

$pp \to$ **anything**



many theoretical studies in the literature
[more than 100 citations for the LHCb papers]

- **quark contents:** $cc\bar{u}\bar{d}$
- **quantum numbers:**

  $I\,(J^P) = 0\,(1^+)$
- **mass (Breit-Wigner):**

  $\varepsilon_T = M_T - (M_{D^{*+}} + M_{D^0}) = (-273 \pm 63)$ keV
- **mass (pole energy)** [$D^{*+}D^0$ threshold effect]**:**

  $\varepsilon_T = M_T - (M_{D^{*+}} + M_{D^0}) = (-360 \pm 40)$ keV
- **width:**

  $\Gamma_{BW} = 410$ keV, $\Gamma_{pole} = 48$ keV
- **decay modes:** $D^+D^0\pi^0$, $D^0D^0\pi^+$, $D^+D^0\gamma$

See "*An updated review of the new hadron states*":
Chen *at al.*, arXiv: 2204.02649

$T_{cc}^{+}(3875)$

What is the $T_{cc}^{+}(3875)$?

$J^P = 1^+$ → S-wave coupling to $D^{*+}D^0$

$|\varepsilon_T| = 0.36 \pm 0.04$ keV → resonant coupling

S-wave loosely bound charm-meson molecule!!

$T_{cc}^{+} = D^{*+}D^0$ dominant component

at short distance

- $M[D^{*0}D^+] - M[D^{*+}D^0]$ = 1.4 MeV, there is $D^{*0}D^+$ component with small probability
  isospin = 0: $(D^{*+}D^0 - D^{*0}D^+)/\sqrt{2}$
- other possible components of wave functions:
  compact tetraquark $cc\bar{q}\bar{q}$,
  $\bar{q}\bar{q}$ bound to heavy diquark (cc)

$X(3872)$

$J^{PC} = 1^{++}$ → S-wave coupling to $D^{*0}\bar{D}^0 / \bar{D}^{*0}D^0$

$|E_X| < 0.22$ MeV → resonant coupling

loosely bound charm-meson molecule

What is the $T_{cc}^+(3875)$?

$J^P = 1^+$ → S-wave coupling to $D^{*+}D^0$

$|\varepsilon_T| = 0.36 \pm 0.04$ keV → resonant coupling

S-wave loosely bound charm-meson molecule!!

$T_{cc}^+ = D^{*+}D^0$ dominant component

Universal properties determined by the binding energy $|\varepsilon_T|$

* large scattering length: $|a| = 1/\sqrt{2\mu|\varepsilon_T|} = 1/\gamma$, $|a| >> R = 1/m_\pi$
* large mean separation: $\langle r \rangle = a/2$, $|\varepsilon_T|$ =360±40 keV implies $\langle r \rangle$ =3.7±0.2 fm
* scattering amplitude at $E \ll 1/(2\mu R^2)$: $f(E) = 1/\left(-1/a + i\sqrt{2\mu E}\right)$

XEFT effective field theory for charm mesons and pions

Fleming, Kusunoki, Mehen & van Kolck [PRD 76, 034006(2007)]

Galilean-invariant XEFT

Braaten [PRD 91, 114007(2015)]

Braaten, He & Jiang [PRD 103, 036014(2021)]

loosely bound charm-meson molecule

universal wave function

- momentum-space wave function: $\psi(k) = \dfrac{\sqrt{8\pi\gamma}}{k^2 + \gamma^2}$
- wave function at origin: $\psi(r=0) = \displaystyle\int \frac{d^3k}{(2\pi)^3}\psi(k) = +\infty$

unphysical results for some observables

model wave function

- momentum-space wave function (more physical qualitative behavior at large k):

$$\psi^{(\Lambda)}(k) = \frac{\sqrt{8\pi(\Lambda+\gamma)\Lambda\gamma}}{\Lambda-\gamma}\left(\frac{1}{k^2+\gamma^2} - \frac{1}{k^2+\Lambda^2}\right)$$

- wave function at origin: $\psi^{(\Lambda)}(r=0) = \sqrt{(\Lambda+\gamma)\Lambda\gamma/2\pi}$

loosely bound charm-meson molecule

including $D^{*0}D^{+}$ component at short distance with binding momentum $\gamma_{0+} = \sqrt{2\mu(\delta + |\varepsilon_T|)}$

model wave function for $D^{*0}D^{+}$ channel

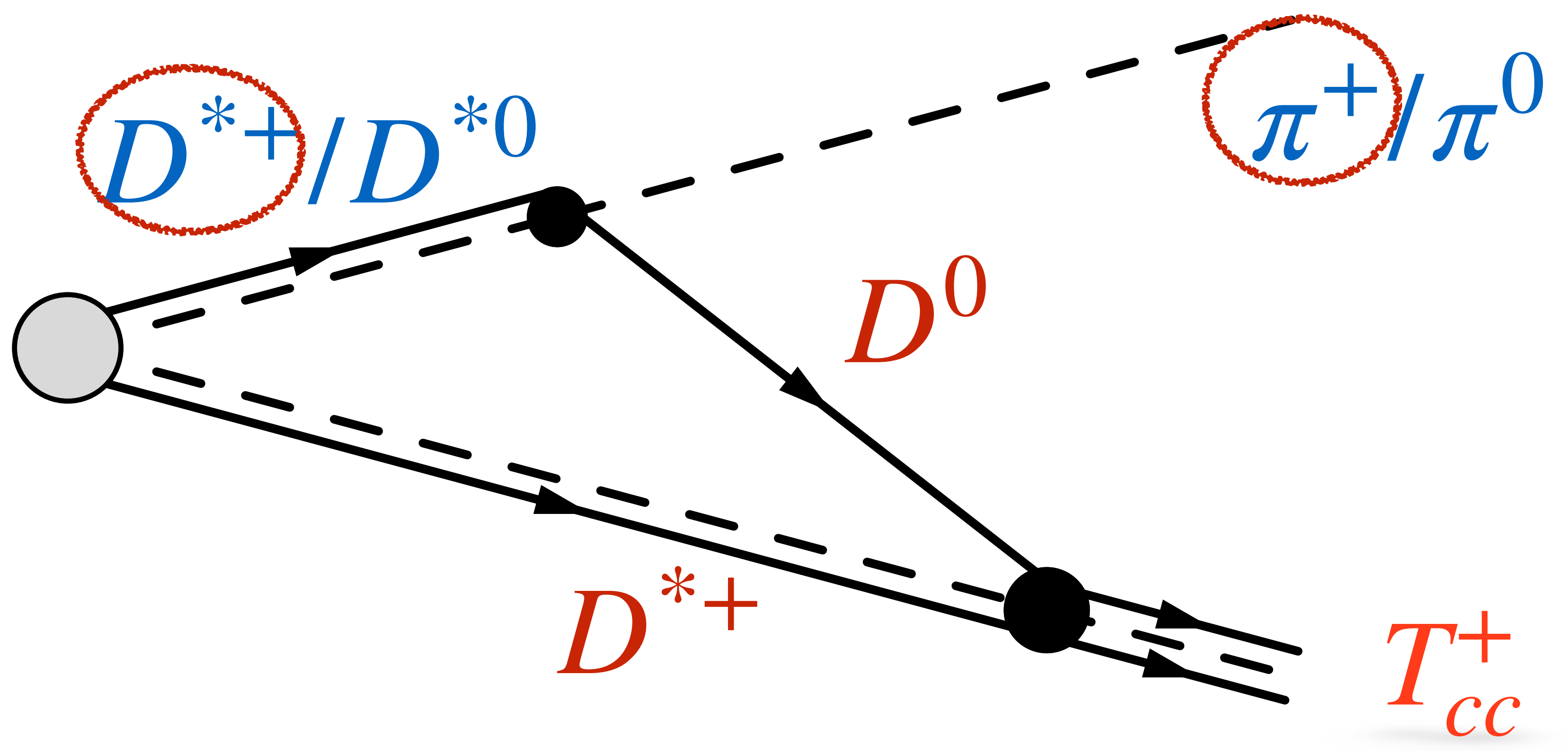
- momentum-space wave function: $\psi_{0+}^{(\Lambda)}(k) = \frac{\sqrt{8\pi(\Lambda+\gamma)\Lambda\gamma}}{\Lambda - \gamma_{0+}} \left(\frac{1}{k^2+\gamma_{0+}^2} - \frac{1}{k^2+\Lambda^2} \right)$
- wave function at origin (determined by symmetry between the two channels at short distances): $\psi_{0+}^{(\Lambda)} = \psi^{(\Lambda)}(r=0)$
- relative probability for the $D^{*0}D^{+}$ channel: $Z_{0+} = \frac{(\Lambda+\gamma)\gamma}{(\Lambda+\gamma_{0+})\gamma_{0+}} < 1$

amplitude in XEFT for the coupled-channel model

$$\frac{1}{k^2+\gamma^2} \to \frac{1}{\sqrt{1+Z_{0+}}} \frac{\psi^{(\Lambda)}(k)}{\sqrt{8\pi\gamma}}, \qquad \frac{1}{k^2+\gamma_{0+}^2} \to -\frac{1}{\sqrt{1+Z_{0+}}} \frac{\psi_{0+}^{(\Lambda)}(k)}{\sqrt{8\pi\gamma}}$$

Production of T_{cc}^{+} and a soft pion

charm-meson triangle singularity



for $\varepsilon_T = 0,\ \Gamma_{D*} = 0$

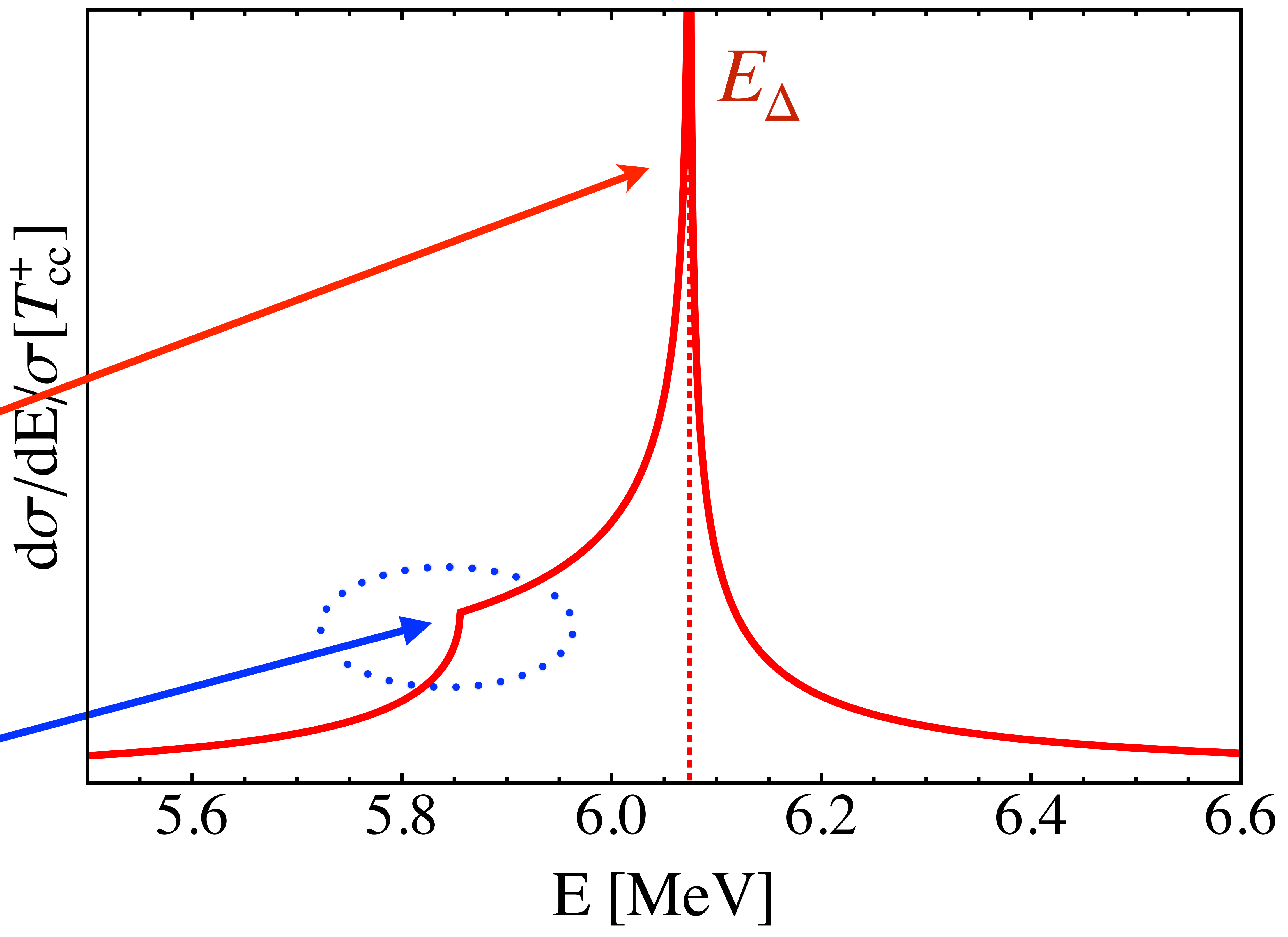
△ **triangle singularity:**
three charm mesons can be on shell simultaneously

$\log^2(E/E_\Delta)$ **divergence in reaction rate at** $E_\Delta = (M_T/2M_D)E_+$ **= 6.1 MeV**

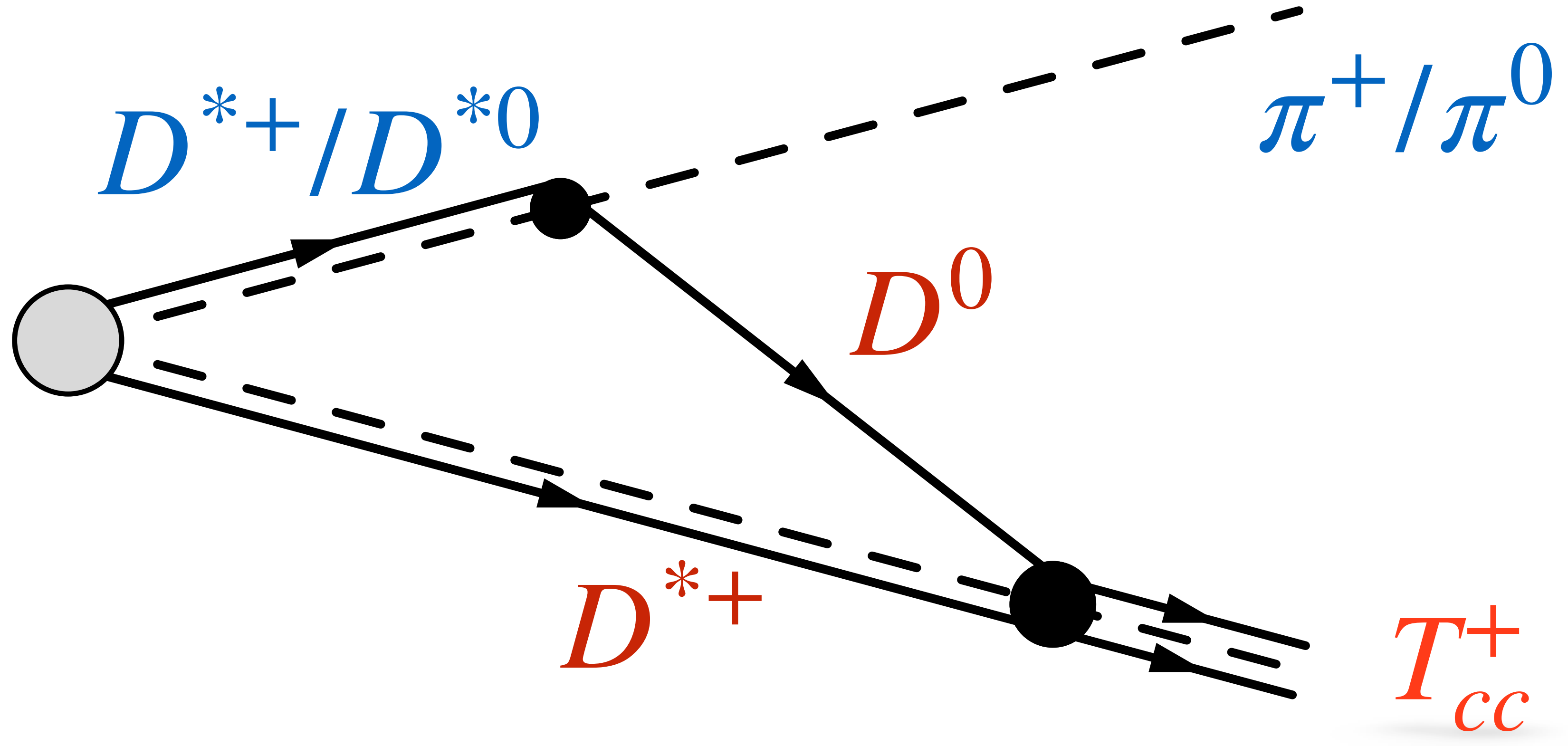
√ **square-root branch point at** $E = E_+$

cusp at $E = E_+$

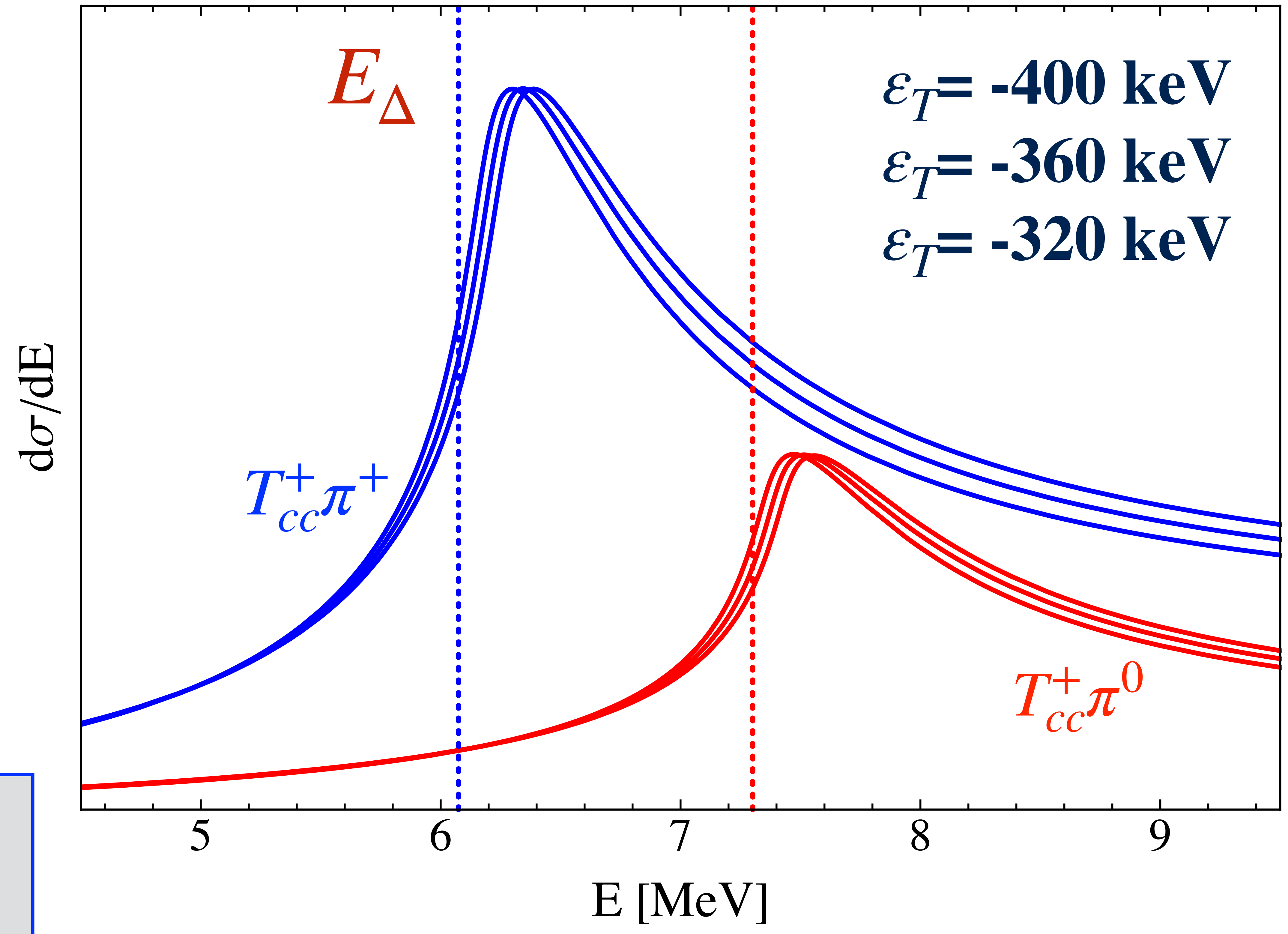
$$E_+ = M_{D^{*+}} - M_{D^0} - m_{\pi^0} = 5.9 \text{ MeV}$$



charm-meson triangle singularity



for $\varepsilon_T < 0,\ \Gamma_{D^*} > 0$



△ **triangle singularity:**

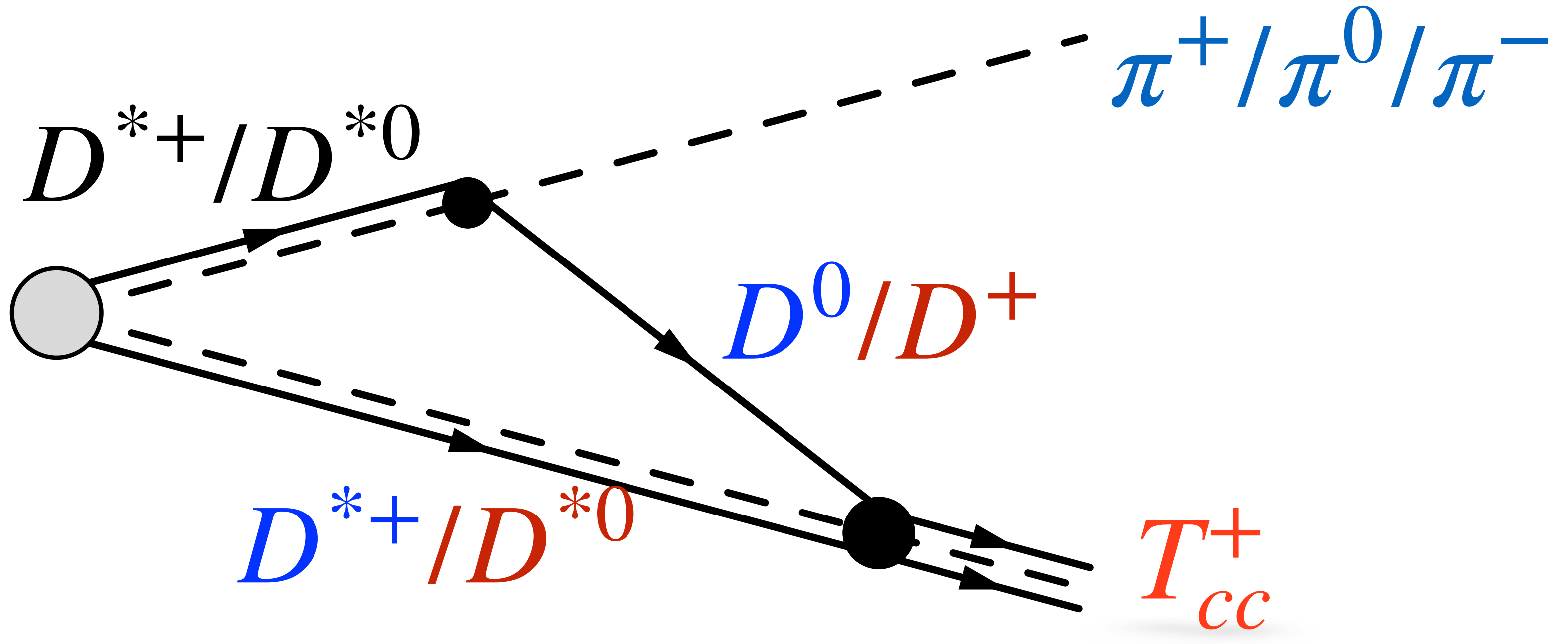
$\log^2(E/E'_\Delta)$ **divergence in dσ/dE at complex** E'_Δ

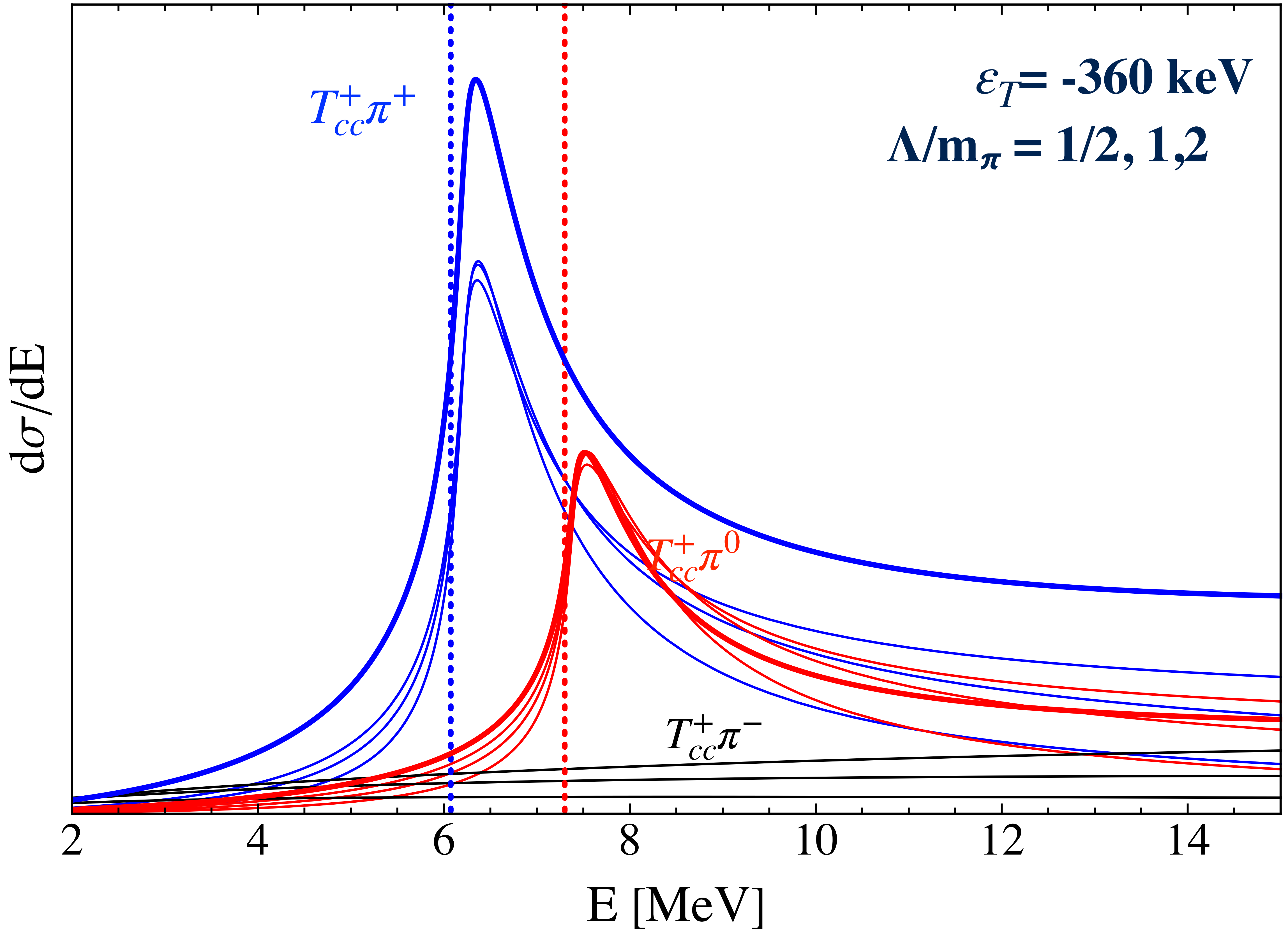
⇒ **narrow peak in reaction rate**

√ **square-root branch point at $E = E'_+$ (complex)**

The shape of dσ/dE near the peak is determined by the interplay between the logarithmic singularity and the square-root singularity in the triangle amplitude.

coupled-channel model



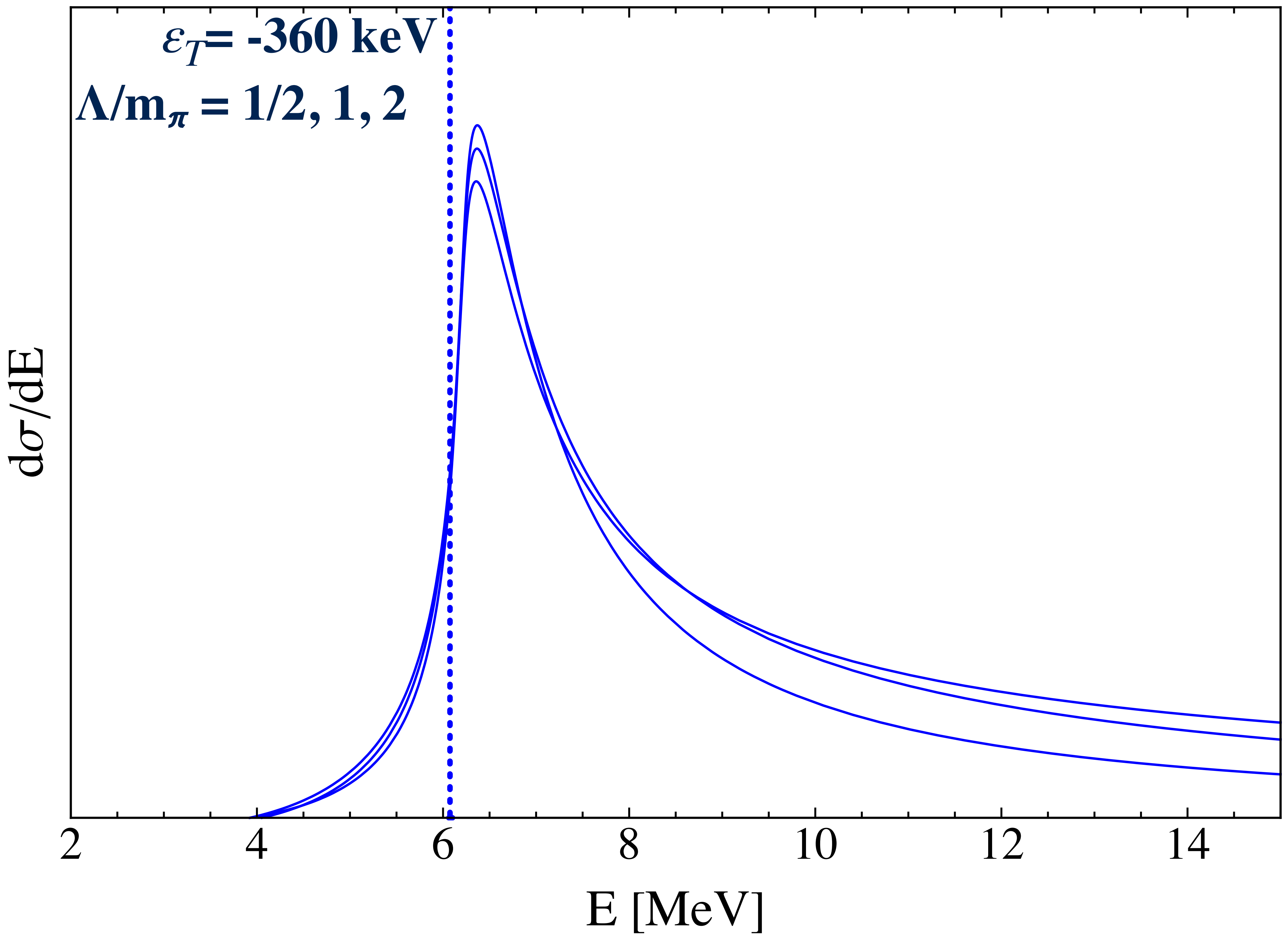


differential cross sections $d\sigma/dE$ for $T_{cc}^+\pi$

- **$T_{cc}^+\pi^-$: no triangle singularity peak**
- **$T_{cc}^+\pi^+(\pi^0)$: same shape as those with the universal triangle amplitudes**
- **$T_{cc}^+\pi^-$ approaches $T_{cc}^+\pi^+$ at large energy**
- **At large energy, $d\sigma/dE \propto E^{-1/2}$**

coupled-channel model

difference between $d\sigma/dE$ for $T_{cc}^+\pi^+$ and $T_{cc}^+\pi^-$ near triangle-singularity peak



difference between $\sigma[T_{cc}^+\pi]$ for $T_{cc}^+\pi^+$ and $T_{cc}^+\pi^-$

$$\sigma\left[T_{cc}^+\pi^+\right] - \sigma\left[T_{cc}^+\pi^-\right] \approx \left(1.3^{+1.5}_{-0.8}\right) \times 10^{-2} \sigma^{(\Lambda)}\left[T_{cc}^+, \text{no } \pi\right]$$

- **independent of E_{max}**
- **dominated by the triangle-singularity peak**
- **$T_{cc}^+\pi^-$ can be used to measure background**

contribution from triangle singularity

subtraction of $T_{cc}^{+}\pi^{-}$ subtracts the background for $T_{cc}^{+}\pi^{+}$ but keeps the peak from the triangle singularity.

fraction of $T_{cc}^{+}\pi^{+}$ events with $T_{cc}^{+}\pi^{+}$ in the peak from triangle singularity: 1.2%

a small fraction of events are from triangle singularity, but all within 1 MeV of the peak

LHCb observed 117 ± 16 events

more statistics to observe the triangle-singularity peak

Summary and Outlook

- ☑ charm-meson triangle singularities

  produce narrow peaks in $T_{cc}^{+}\pi$ invariant mass near *D*D threshold**

  smoking gun for T_{cc}^{+} as charm-meson molecule !!

  compact tetraquark would have suppressed coupling to $D^{*+}D^{0}$

- ☑ **At higher energy, $d\sigma/dE$ for $T_{cc}^{+} + \pi^{+}$ decreases as $E^{-1/2}$ for molecule**

  $d\sigma/dE$ for $T_{cc}^{+} + \pi^{+}$ increases as $E^{3/2}$ for compact tetraquark

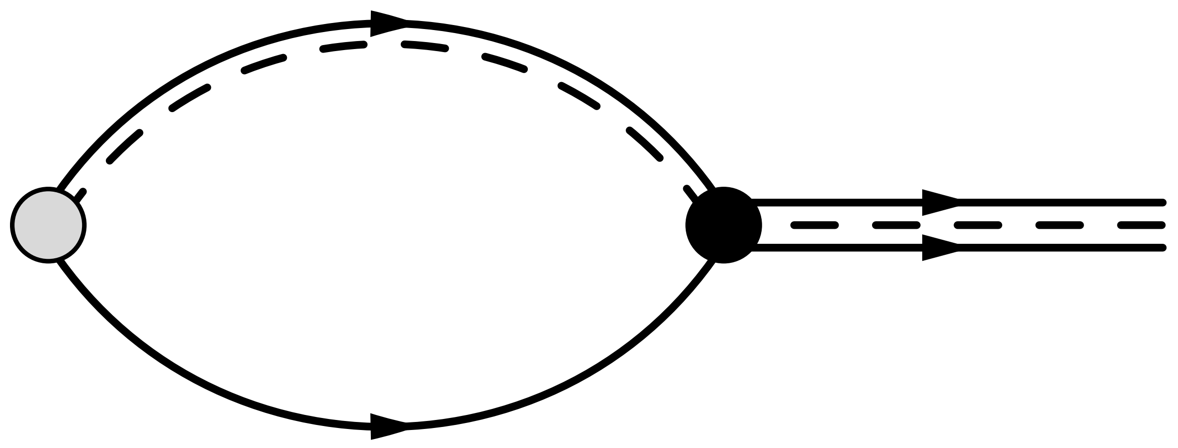
- ☑ Background of $T_{cc}^{+}+\pi^{+}$ can be determined experimentally by measuring $T_{cc}^{+}\pi^{-}$ events
- ☑ A small fraction of events are from triangle singularity, but within 1 MeV of the peak

Backup

Production of T_{cc}^{+} at a hadron collider

production mechanism of T_{cc}^{+}

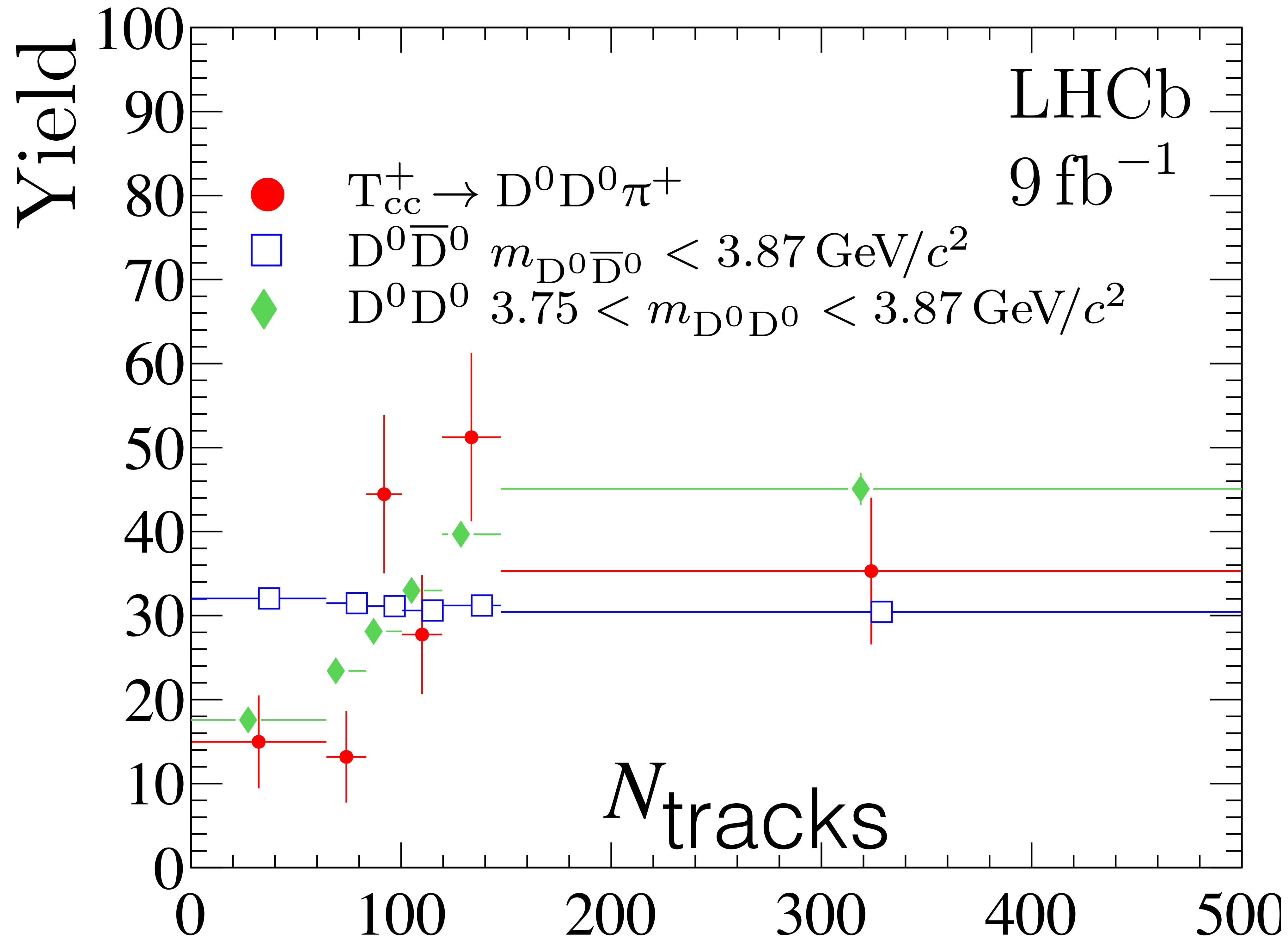
- creation of $D^{*+}D^0$ at short distances
- rescattering of virtual $D^{*+}D^0$ into T_{cc}^{+}



production of $D^{*+}D^0$ at short distances

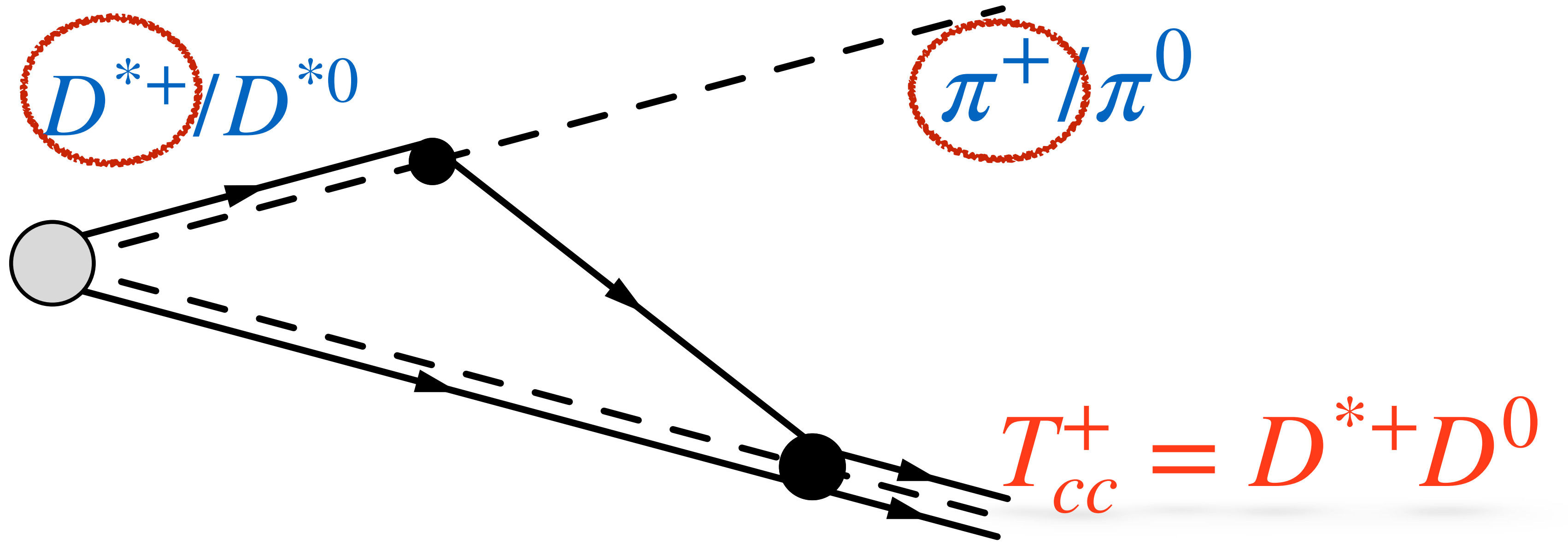
- single-parton scattering (SPS)
- double-parton scattering (DPS)

Multiplicity dependence



- two charm mesons are created at shorter distance from SPS than DPS
- increased yield for T_{cc}^{+} at larger Ntracks may arise from the DPS mechanism
- a larger fraction is produced by the SPS mechanism by the restriction Ntracks <80

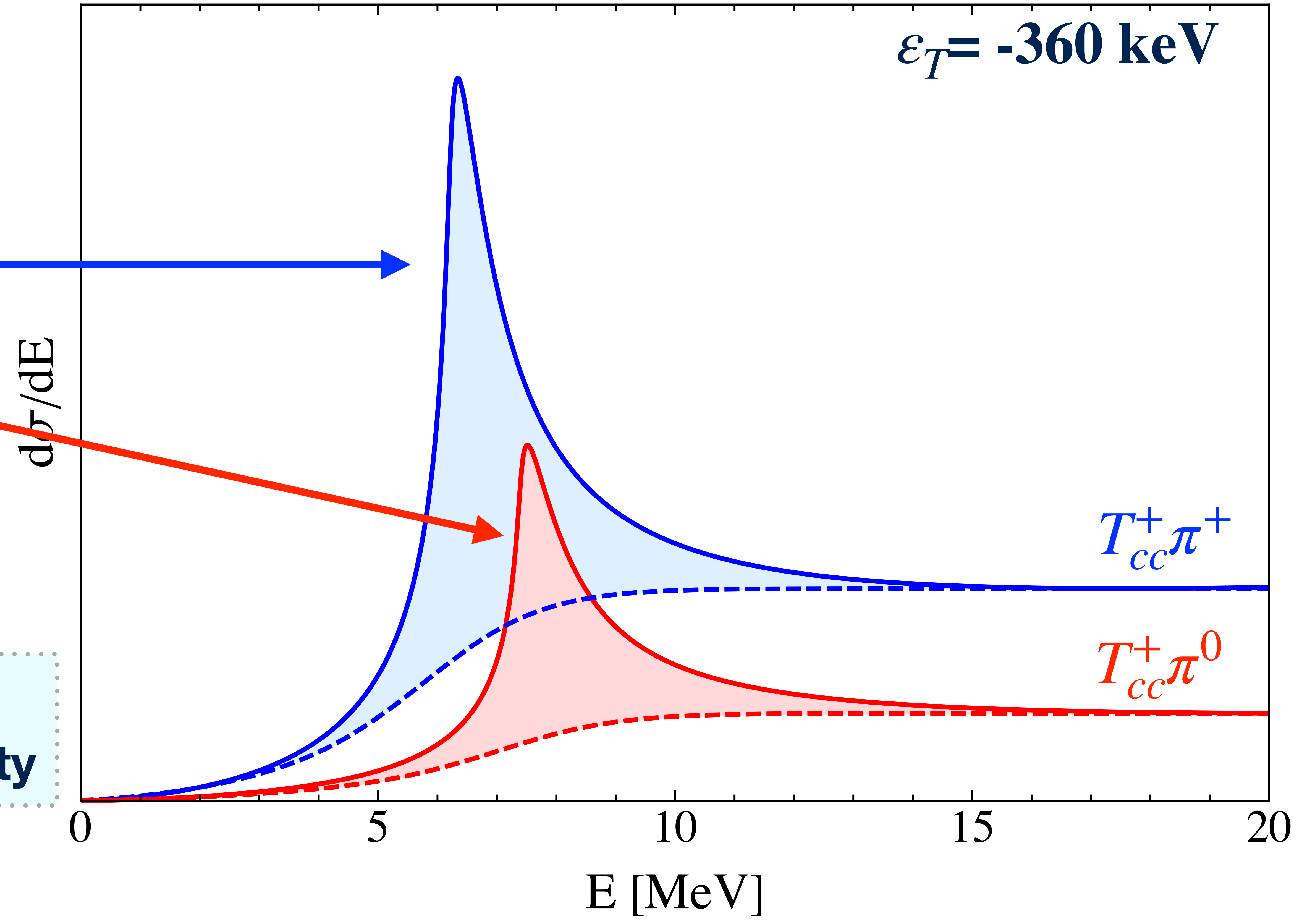
contribution from triangle singularity



model for background: interpolating between $E^{3/2}$ at small E and a constant at the local minimum

$\sigma\left[\left(T_{cc}^+\pi^+\right)_\Delta\right] \approx (8.6 \pm 0.5)\times 10^{-3}\sigma\left[T_{cc}^+, \text{no } \pi\right]$

$\sigma\left[\left(T_{cc}^+\pi^0\right)_\Delta\right] \approx (4.8 \pm 0.2)\times 10^{-3}\sigma\left[T_{cc}^+, \text{no } \pi\right]$



cross section at large energy increases as $E^{1/2}$
→ there is a local minimum near 17 MeV

unphysical behavior: artifact of using the universal approximation for T_{cc}^+ beyond its range of applicability

☑ A few of the T_{cc}^+ events observed by the LHCb should be from $T_{cc}^+ + \pi^+$ with $E_{\rm max} < m_\pi$