Exotics and Exotic Phenomena
in Heavy Ion Collisions (ExHic)
APCTP Headquarters, Pohang, Korea

RUHR UNIVERSITÄT BOCHUM RUB

Long-range structure of T_{cc}^{+} state

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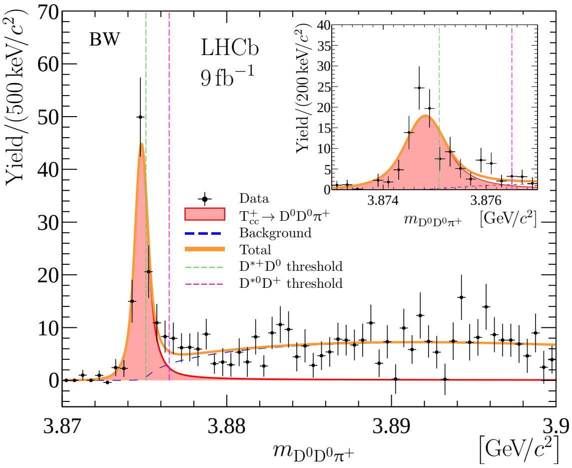
Background

Amazing results in LHCb: observation of T_{cc}^+



EPS-HEP conference, Ivan Polyakov's talk,29/07/2021; Nature Physics,22'

- Prompt production of 3-BODY final states: $D^0D^0\pi^+$
- Fitting with Breit-Wigner function

$$\delta m_{\text{BW}} \equiv m_{T_{cc}} - m_{D^{*+}D^0} = -273 \pm 61\text{keV},$$
$$\Gamma_{\text{BW}} = 410 \pm 165\text{keV}$$

$\Rightarrow$ Very close to $D^{*+}D^0$ threshold

$\Rightarrow$ Very narrow resonance

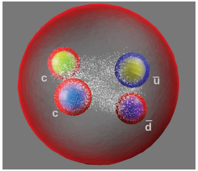
- The statistical significance of the hypothesis $\delta m_{\text{BW}} < 0$: 4.3σ

- The second doubly charmed hadron$\Rightarrow$manifestly exotic $(cc\bar{u}\bar{d})$, tetraquark !

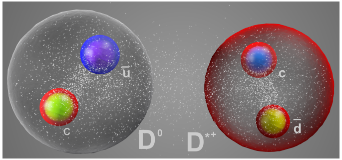
$\Rightarrow$ $QQ\bar{q}\bar{q}$ anticipated and debated for 40 yrs !!!

Two threads of theoretical works

- Before the observations, there were many theoretical predictions.
- In principle, there are two scenarios (or their hybrid)



Compact tetraquark



Hadronic molecule

- Two threads of history:

  ⇒ Motivation 1: $QQ\bar{q}\bar{q}$ is potential STABLE tetraquark state

  ⇒ Motivation 2: In molecular picture, analog of $X(3872)$ in the double heavy sector

History: $QQ\bar{q}\bar{q}$ is potential STABLE tetraquark state

- The potential stable $QQ\bar{q}\bar{q}$ was first proposed in 1980s J.P. Ader, J.M. Richard, P. Taxi,PRD25(1982) 2370

  "*...On the other hand, the genuine exotic $QQ\bar{Q}'\bar{Q}'$ can be stable against dissociation if the ratio of the quark masses is large enough.*"

- Further developments J. Carlson et al, PRD37,744; B. Silvestre-Brac et al,Z.Phys.C57,273-282; Valcarce et al, PLB393,119-123...

- In 2017, the observation of Ξ_{cc}^{++} in LHCb incited a new round discussions on $QQ\bar{q}\bar{q}$

  $\Rightarrow$ Quark model Luo et al,EPJC7710,709; Karliner et al,PRL119,202001; Eichten et al,PRL119,202002; W.Park et al,NPA983,1-19,...

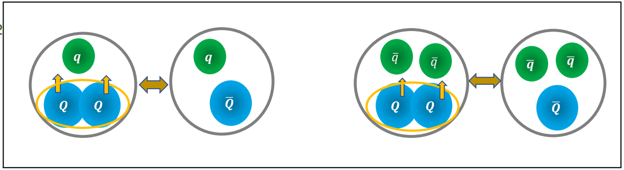
  $\Rightarrow$ Lattice QCD A. Francis et al,PRL118,142001; P. Junnarkar et al PRD99,034507; Hadron Spectrum Collaboration, JHEP11,033,...

  $\Rightarrow$ ...

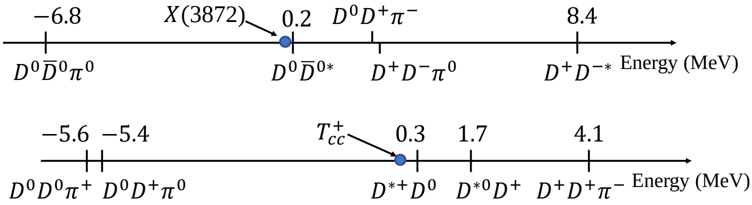
- E.g: when $M_Q/m_q \sim \infty$ Eichten et al, PRL119,202002

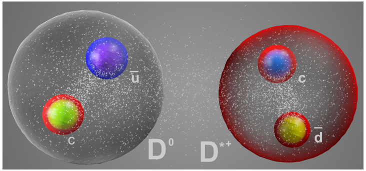
  heavy-diquark-heavy-antiquark symmtry

$$(QQ\bar{q}\bar{q}) = (QQq) + (Qqq) - (Q\bar{q})$$



- The molecule picture: (1) near-threshold state (2) $r = \frac{1}{\sqrt{2\mu\delta m_{BW}}} \sim 8$fm





	$X(3872)$	T_{cc}^+
Thresh./channels	$\bar{D}^{*0}D^0/\bar{D}^0D^{*0}$, $\delta m = (0.00 \pm 180)$ keV $D^{*-}D^+/D^-D^{*+}$ $J/\psi\rho$, $J/\psi\omega$	$D^{*+}D^0$:$\delta m_{\text{BW}} = -273 \pm 61$keV, $D^{*0}D^+$ None
Possible core	$\chi_{c1}(2P)$, $(c\bar{c}\bar{u}d)$	$(cc\bar{u}\bar{d})$
Narrow	$\Gamma = (1.19 \pm 0.21)$ MeV	$\Gamma_{\text{BW}} = 410 \pm 165$keV
Isospin violation	$\frac{\mathcal{B}[X\to J/\psi\omega(\omega\to 3\pi)]}{\mathcal{B}[X\to J/\psi\pi^+\pi^-]} \sim 1$	?

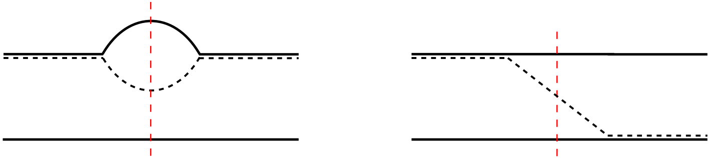
Molecular scenario: $X(3872)$ and T_{cc}^+

- In the isospin symmetry: same one-pion exchange interaction!!!

$$V[\bar{D}^*D/\bar{D}D^*; I(J^{PC})=0(1^{++})] = V[D^*D; I(J^P)=0(1^+)]$$

- Three-body effect

Du:2021zzh,Lin:2022wmj



(a)

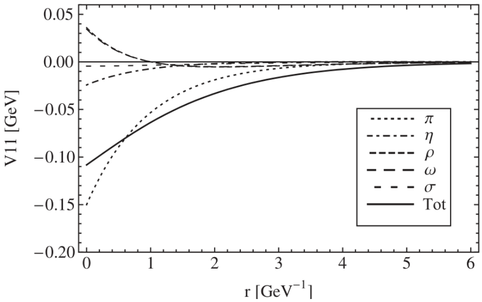
(b)

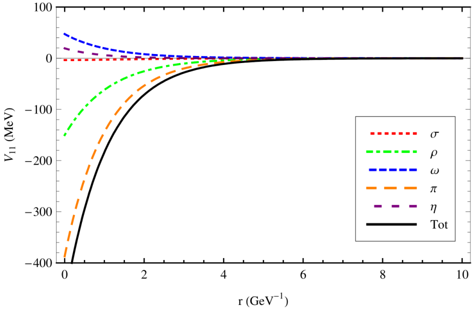
- Same puzzles for $X(3872)$ and T_{cc}
  - $\Rightarrow$ Why the they are close to the $\bar{D}^{*0}D^0$ and $D^{*0}D^+$ threshold? Fine-tuning?
  - $\Rightarrow$ Prompt production VS molecular picture? Bignamini:2009sk,Artoisenet:2009wk,Albaladejo:2017blx,Braaten:2018eov
    - ⋆ T_{cc}: Prompt production of 3-BODY final states: $D^0D^0\pi^+$

History: analog of $X(3872)$

- E.g 1: QCD sum rules: almost degenerate T_{cc} and $X(3872)$ J.M.Dias, S.Narison et al, PLB703(2011)274-280
- E.g 2: One-boson-exchange potential $\pi, \eta, \rho, \omega, \sigma$ N.Li, S.-L Zhu et al, PRD86(2012)074022, PRD88(2013)114008

  $\Rightarrow$ Reproduce the $X(3872)$ first and predict an D^*D molecule with $E_b \sim$ 400 keV



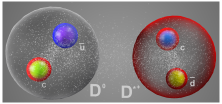


- These predictions should be attached more importance.

  $\Rightarrow$ Experimental similarities between $X(3872)$ and T_{cc}

Strong and radiative decays

Long-range properties of T_{cc}



- Theoretical frameworks for $X(3872)$ could be immigrated to T_{cc}
- T_{cc} as very loosely bound states: $\delta m_{BW} \sim 200$ keV, r ~8 fm
- Phase-space allowed decays $T_{cc} \to DD\gamma$, $T_{cc} \to DD\pi$: long-range properties

  $\Rightarrow$ Insensitive to the short-range structure

  $\Rightarrow$ Bound information (e.g. ψ or $g_{T_{cc}D^*D}$)+ properties of its components

  $\Rightarrow$ Effective field theory (EFT): framework make use of separated scales
- Coupled channels : $|1\rangle \equiv |D^{*+}D^0\rangle, \quad |2\rangle \equiv |D^{*0}D^+\rangle$

  $\Rightarrow$ Isospin violation effect

- Our work: The BW width (410 ± 165keV) is over-estimated. arXiv:2107.14784, Release in 30/07/2021

  $\Rightarrow$ Long-range properties can be determined with little uncertainty in NREFT

Effective field theory: scales and power counting

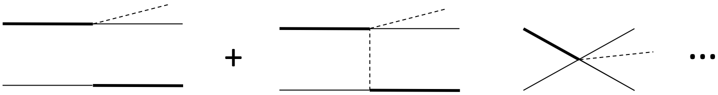
- Power counting: Naive dimensional analysis S. Weinberg

  $\Rightarrow$ Small scale: $Q \sim \sqrt{2\delta m_{T_{cc}} \mu_{DD^*}} \sim 20-60$ MeV, large scale m_π

- Diagram: $D^*D \to D^*D$: LO: contact terms, OPE subleading order

(LO)

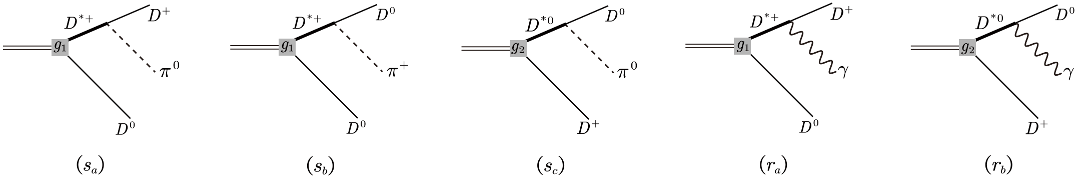
- Diagram: $D^*D \to DD\pi$: LO: One-body operator



(LO)

- $v_D \sim 0.075$: Non-relativistic dynamics

Strong and radiative decays



- Parameters: g_1, g_2 (bound information), g_π, g_γ (properties of components)

  $\Rightarrow$ g_π extracted from $D^{*+} \to D^+\pi^0$ and $D^{*+} \to D^0\pi^+$

  $\Rightarrow$ g_γ extracted from the partial decay widths of $D^{*+,0} \to D^{+,0}\gamma$, take $\Gamma_{D^{*0}} =$ 40-80 keV

  $\Rightarrow$ g_1 and g_2 extract from the D^*D scattering or bound state wave function

- Calculation

Similar calculation for $X(3872)$: M.B. Voloshin,...

$$\mathcal{A}[D^{*+} \to D^+\pi^0] = g_\pi q_\pi \cdot \epsilon_{D^*}, \quad \mathcal{A}[T_{cc}^+ \to D^+D^0\pi^0] = \frac{g_1 \epsilon_T^\mu (g_{\mu\nu} - \frac{p_{12\mu}p_{12\nu}}{m_{D^*}^2}) g_\pi p_2^\nu}{p_{12}^2 - m_{D^*}^2 + i m_{D^*}\Gamma_{D^*}}$$

D^*D scattering: Coupled-channel EFT

- Coupled-channel Lippmann-Schwinger equation

$$T = V + VGT,$$

- Extracting g_1 and g_2 from residues of T-matrix:

$$\lim_{E \to E_0} (E - E_0) t_{ij} \sim g_j$$

- Contact interaction with cutoff regulator

$$V(\boldsymbol{p}, \boldsymbol{p}') = \begin{bmatrix} v_{11}(\Lambda) & v_{12}(\Lambda) \\ v_{12}(\Lambda) & v_{11}(\Lambda) \end{bmatrix} \Theta(\Lambda - p)\Theta(\Lambda - p'),$$

- For 2-channel problem, Λ-dependence of $v_{ij}(\Lambda)$ can be fixed explicitly make the T-matrix free of cutoff

  $\Rightarrow$ Coupled-channel EFT

Phys.Lett.B 588 (2004) 57-66

D^*D scattering: Coupled-channel EFT

Lippman Schwinger formalism	Schrodinger formalism
$t = v + vGt,$	$(H_0 + V)\|\psi\rangle = E_0\|\psi\rangle$
$G_i(E) = \int^{\Lambda} \frac{d^3\boldsymbol{q}}{(2\pi)^3}\frac{1}{E-E_{i,q}+i\epsilon},\ E_{i,q} = \delta_i + \frac{q^2}{2\mu}$	$\langle \boldsymbol{p}\|\psi\rangle = \cos\theta\phi_1(p)\|1\rangle + \sin\theta\phi_2(p)\|2\rangle,$
Pole : $E_0,\ \kappa_i \equiv \sqrt{2\mu(-E_0+\delta_i)}$	$\phi_i(p) \sim \Theta(\Lambda - p)(E_0 - \frac{p^2}{2\mu} - \delta_i)^{-1}$

- Three equivalent sets of parameters

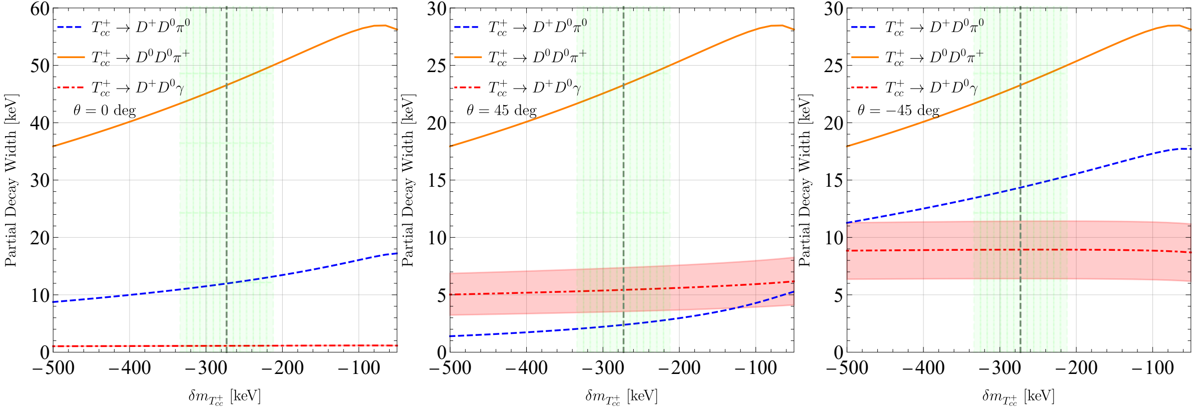
$$\{v_{11}, v_{12}\} \leftrightarrow \{E_0, \theta\} \leftrightarrow \{g_1, g_2\}$$

θ is mixing angle of the two channel

$$g_1 \sim \sqrt{\kappa_1}\cos\theta, \quad g_2 \sim \sqrt{\kappa_2}\sin\theta.$$

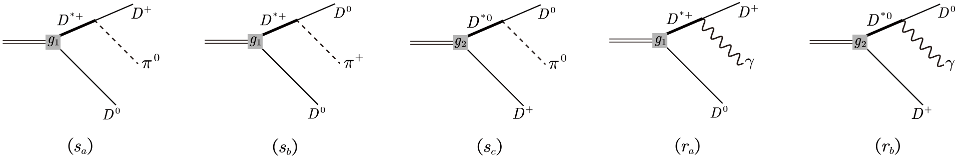
- 1) Renormalization group invariant 2) coupled-channels 3) explicit isospin violation δ_i

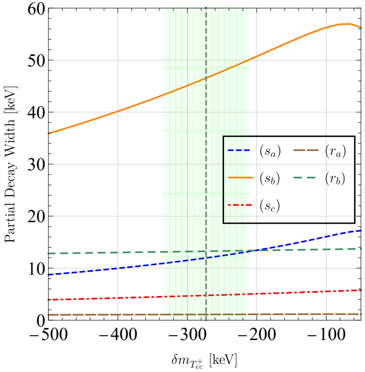
Numerical results



- $\theta = 0$: $D^{*+}D^0$single channel (Left) ; $\theta = 45$, $I = 1$(Middle); $\theta = -45$: $I = 0$ (Right).
- The uncertainties: $\delta m_{T_{cc}^+}$, $\Gamma[D^{*0} \to D^0\gamma]$
- The dominant decay mode is $T_{cc}^+ \to D^0D^0\pi^+$ (observation channel in experiment)

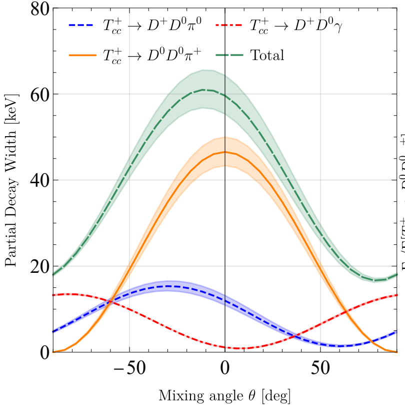
Amplitude analysis

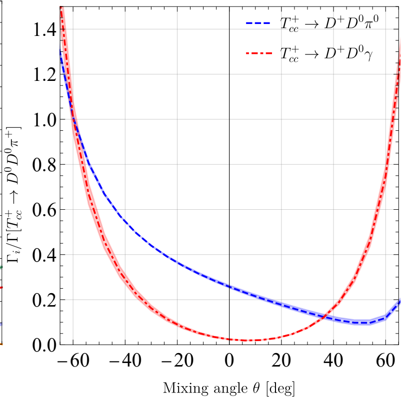




- Dominant diagrams to the strong interaction (s_b):
  - $\Rightarrow$ Extra isospin factor $\sqrt{2}$ and constructive interference effect
- Dominant diagrams to the radiative interaction:(r_b)
  - $\Rightarrow$ M1 radiative transition roughly proportional to the electric charge of the light quarks

Final results





- Our results are inconsistent with the BW fitting
- The ratio of partial decay widths is sensitive to the mixing angle

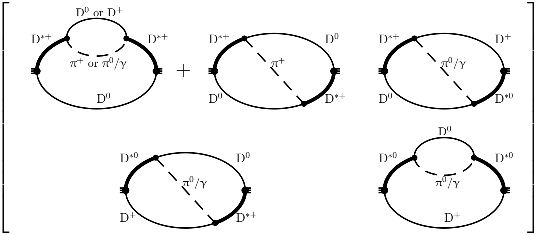
$$\Gamma_{\text{str}} + \Gamma_{\text{EM}} = \begin{cases} 46.7^{+2.7}_{-2.9}\ \text{keV} & I = 0 \\ 59.7^{+4.6}_{-4.4}\ \text{keV} & I = 1 \\ 31.2^{+2.2}_{-2.4}\ \text{keV} & D^{*+}D^0 \end{cases} \quad \text{VS} \quad \Gamma_{\text{BW}} = 410 \pm 165\text{keV}$$

Discussions

- Similar calculations: assuming $I=0$ of T_{cc}^{+}; relativistic framework   PLB826,136897;PRD104,116010
- Subleading effects:2-body operator, DD FSI, compact tetraquark effect   M.-J Yan et al, PRD105,014007
- Coupled-channel approach including 3-body effect: $\Gamma = 56 \pm 2$ keV   Du:2021zzh
- The 2nd analysis from LHCb considering unitary: $\mathfrak{F}_f^U(s) = \rho_f(s)\left|[m_U^2 - s - |g|^2\Sigma(s)]^{-1}\right|^2$

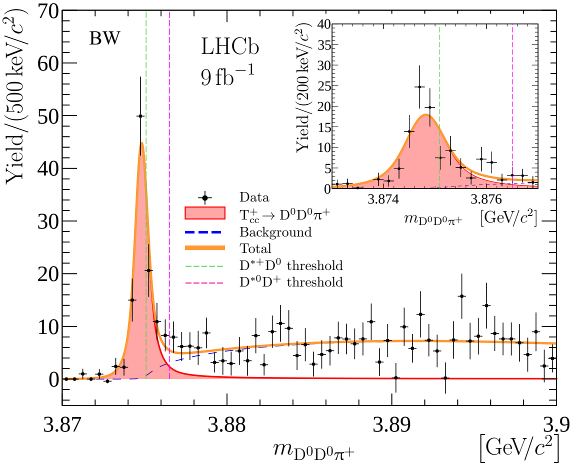
where $f \in \{D^0D^0\pi^+, D^0D^+\pi^0, D^0D^+\gamma\}$ $\rho_f(s)$: 3-body phase space,   LHCb, Nature Commun. 13 (2022) 1, 3351

$$|g|^2\Sigma(s) = (g^* \quad -g^*)G\begin{pmatrix} g \\ -g \end{pmatrix}$$

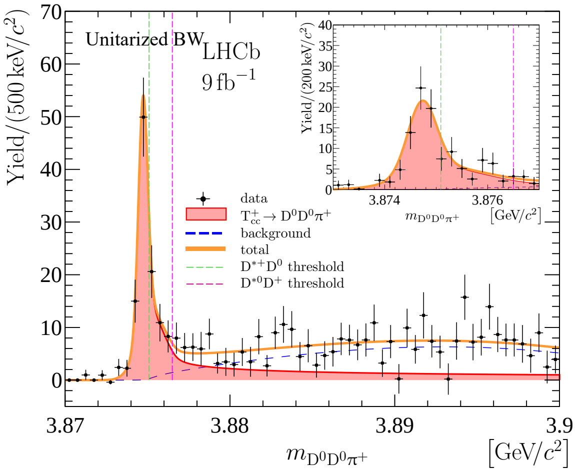
$G =$ 

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

Related works



EPS-HEP conference, Ivan Polyakov's talk,29/07/2021; Nature Physics,'22



LHCb, Nature Commun. 13 (2022) 1, 3351

$$\Gamma_{BW} = 410 \pm 165\text{keV} \quad \text{VS} \quad \Gamma^{U}_{pole} = 48 \pm 2^{+0}_{-14}\text{ keV} \quad \text{VS} \quad \Gamma^{I=0} = 46.7^{+2.7}_{-2.9}\text{ keV}$$

Molecular state VS compact tetraquark state

- The present result supports the molecular interpretation
- The closeness to thresholds (~200 keV) need fine-tuning mechanisms Discussions for X(3872):PRD69,074005

  ⇒ Mechanism 1: fine-tuning of D^*D potential

  ⇒ Mechanism 2: fine-tuning of the mass of compact core
- The low-energy properties can not reflect the short structures

  ⇒ E.g. universal low energy properties for system ($\frac{1}{a_s} \sim \sqrt{2\mu E_B} \ll m_\pi$) PRD69,074005
- The proportion of the compact core could be small (decreasing with mass approaching threshold), but it could be important to generate the bound state PRD105,116024
- To uncover the short-range structure $\rightarrow$ processes associated with higher energy scale

  ⇒ Prompt production (pp collision, heavy ion collision)

  ⇒ ...

Summary

Summary

- In the molecular scheme, the strong and radiative decays of T_{cc}^+ are investigated

$$\Gamma_{BW} = 410 \pm 165\text{keV} \quad \text{VS} \quad \Gamma^U_{pole} = 48 \pm 2^{+0}_{-14}\ \text{keV} \quad \text{VS} \quad \Gamma^{I=0} = 46.7^{+2.7}_{-2.9}\ \text{keV}$$

  ⇒ Inconsistent with the original experimental analysis (even considering the uncertainties)

  ⇒ Coincide with the unitarized analysis

- Coupled channel EFT: 1) Λ-independent 2) coupled-channels 3) explicit isospin violation
- The separation of the long-range dynamics and short-range dynamics

  ⇒ The long-range dynamics can be determined by only two parameters E_b and θ

  ⇒ Two edge sword: the short-range structure is hard to detect

- Remaining puzzles

  ⇒ Prompt production, relation of X(3872) and T_{cc}, fine-tuning mechanisms, short range interaction and structures,...

Thanks for your attention!