Doubly charmed exotic state T_{cc}^+ — nature, properties, pion dynamics and all that

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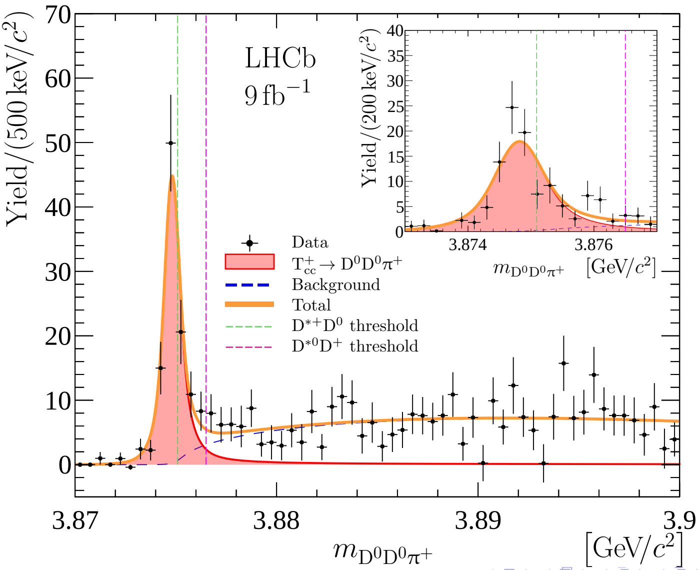
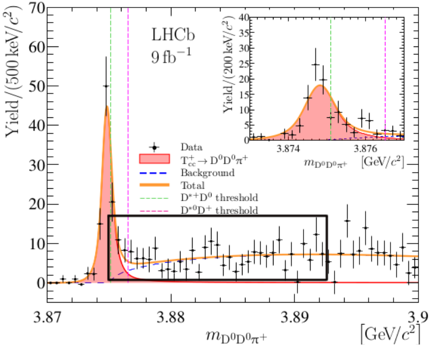
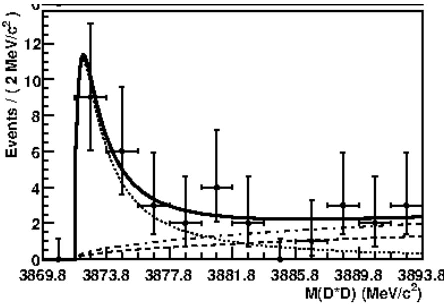
Benasque-2024

$T_{cc}^+(cc\bar{u}\bar{d})$ @ LHCb (Nature Phys. 18 (2022) 7, 751)



T_{cc}^+ versus $X(3872)$





- Higher precision: smaller bins & better known resolution function
- Larger statistics: small uncertainties
- Data below two-body threshold: clear below-threshold peak

T_{cc}^+ versus $X(3872)$

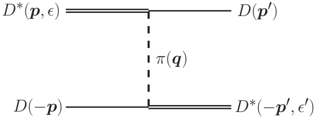
Common features:

- Isoscalars
- Definitely contain a pair of heavy quarks
- Reside incredibly close to 2-hadron thresholds $D\bar{D}^*/DD^*$
- Decay to open-charm final states $D\bar{D}\pi/DD\pi$ and $D\bar{D}\gamma/DD\gamma$
- Important consequences from $D^* \to D\pi$ decay

Difference:

- X contains $c\bar{c}$ pair while T_{cc}^+ contains cc
- X decays to hidden-charm states while T_{cc}^+ does not
- Short-range core (if any): $c\bar{c}$ charmonium vs tetraquark $cc\bar{u}\bar{d}$

Pion exchange in $I = 0$ DD^* system



$$V_\pi(\boldsymbol{p}, \boldsymbol{p}') = \left(\frac{g_c}{2f_\pi}\right)^2 \langle \boldsymbol{\tau} \cdot \boldsymbol{\tau} \rangle \frac{(\boldsymbol{\epsilon} \cdot \boldsymbol{q})(\boldsymbol{q} \cdot \boldsymbol{\epsilon}'^*)}{u - m_\pi^2}$$

$\Longrightarrow$ $I = 0$, central, ~~recoil~~

$$\left(\frac{g_c}{2f_\pi}\right)^2 \Bigg(-1 + \overbrace{\frac{\mu_\pi^2}{\boldsymbol{q}^2 + \underbrace{[m_\pi^2 - (m_{D^*} - m_D)^2]}_{\text{Effective mass } \mu_\pi^2}}}^{\text{Long-range OPE}}\Bigg)$$

- Short-range OPE absorbed by (re-fitted) contact interaction
- Perturbative long-range OPE as per

$$\alpha_\pi^{\rm eff} = \frac{g_c^2 |\mu_\pi^2|}{f_\pi^2} \ll 1$$

(XEFT: Voloshin'2004, Fleming et al.'2007,...)

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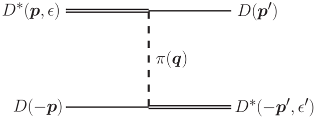

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Long-range OPE

$$\Longrightarrow \left(\frac{g_c}{2f_\pi}\right)^2 \left(-1 + \frac{\mu_\pi^2}{\ldots}\right)$$

Is pion exchange important in T_{cc}^+?

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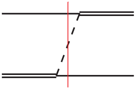
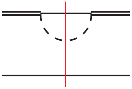
Comment on pion exchange in T_{cc}^+

- Physical T_{cc}^+ ($m_\pi < m_{D^*} - m_D \implies \mu_\pi^2 < 0$ & $|\mu_\pi| \ll m_\pi$):

$\implies$ 3-body unitarity:  + 

$\implies$ T_{cc}^+ spin partner at D^*D^* threshold

$$\alpha_\pi^{D\text{-wave}} \simeq g_c^2 q_{\rm typ}^2 / f_\pi^2 \simeq g_c^2 m_D (m_{D^*} - m_D)/f_\pi^2 > 1$$

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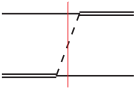
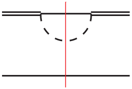
$\implies$ 3-body unitarity:  + 

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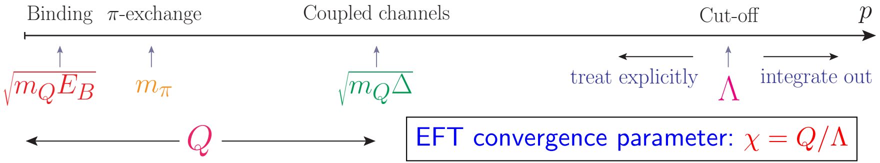
- Lattice T_{cc}^+ ($m_\pi^{\text{lat}} > m_{D^*}^{\text{lat}} - m_D^{\text{lat}} \implies (\mu_\pi^{\text{lat}})^2 > 0$ & $\mu_\pi^{\text{lat}} > m_\pi^{\text{ph}}$):

$\implies$ $\alpha_\pi = g_c^2\mu_\pi^2/f_\pi^2 \sim 1$

$\implies$ Left-hand cut in partial-wave amplitudes

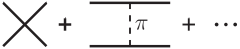
$$\int d\Omega_{\hat{\boldsymbol{k}}\hat{\boldsymbol{k}}'} V_\pi(\boldsymbol{k} - \boldsymbol{k}') \sim \log\frac{\mu_\pi^2 + (k+k')^2}{\mu_\pi^2 + (k-k')^2} \underset{k'=k=p}{\implies} \log\left(1 + \frac{4p^2}{\mu_\pi^2}\right)$$

Effective field theory for hadronic molecules



Interaction potential between heavy hadrons:

- Includes all relevant interactions



- Complies with relevant symmetries (chiral, HQSS, etc)
- Incorporates coupled-channel dynamics
- Expanded in powers of p^2/Λ^2 and truncated at necessary order (LO, NLO...)
- Iterated to all orders via (multichannel) Lippmann-Schwinger equation

$$T = V - VGT$$

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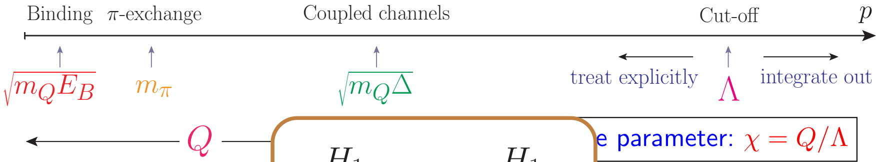

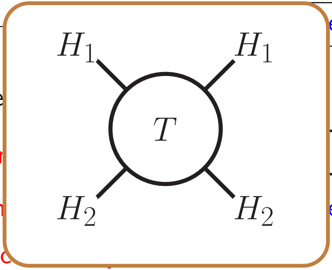

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EFT approach to T_{cc}^{+}

$$\left.\begin{aligned} \gamma_B &= \sqrt{m_D E_B} \simeq 25 \text{ MeV} \\ p_{\text{data}}^{\text{max}} &= \sqrt{m_D\, \Delta E_{\text{data}}} \simeq 100 \text{ MeV} \\ p_{\text{coupl.ch.}} &= \sqrt{m_D (m_{D^*} - m_D)} \simeq 500 \text{ MeV} \end{aligned}\right\} \Longrightarrow$$

$\Lambda = 500$ MeV
Potential at LO
OPE included
No couple channels

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- Lippmann-Schwinger equation for scattering amplitude (v_0 — free parameter)

$$T = V - VGT$$

$$V = v_0 + V_\pi$$

- Production amplitude (P — free parameter = overall normalisation)

$$U = P - PGT$$

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$\Longrightarrow$

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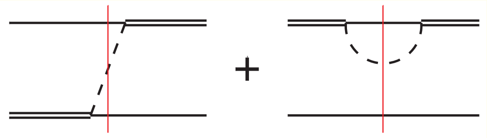
3-body effects:



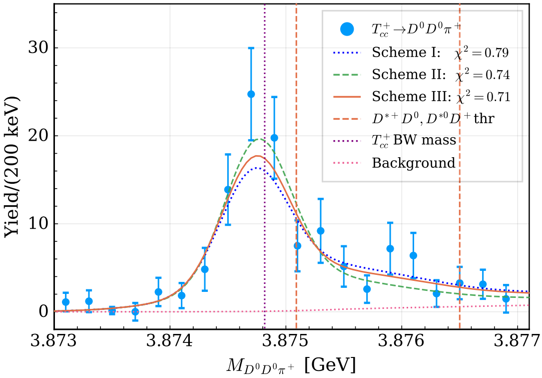
- Lippmann-S ... free parameter)

- Production amplitude (P — free parameter = overall normalisation)

$$U = P - PGT$$

Fitting schemes, results, and conclusions

	Γ_{D^*}=const, ~~OPE~~	$\Gamma_{D^*}(p, M)$, ~~OPE~~	$\Gamma_{D^*}(p, M)$, OPE
χ^2/d.o.f.	0.79	0.74	0.71
v_0 [GeV^{-2}]	-23.34 ± 0.08	$-22.88^{+0.08}_{-0.06}$	$-5.04^{+0.10}_{-0.08}$
Pole [keV]	$-368^{+43}_{-42} - i(37 \pm 0)$	$-333^{+41}_{-36} - i(18 \pm 1)$	$-356^{+39}_{-38} - i(28 \pm 1)$



- (Quasi)bound state just below $D^{*+}D^0$ threshold
- Compositeness: 70% & 30%

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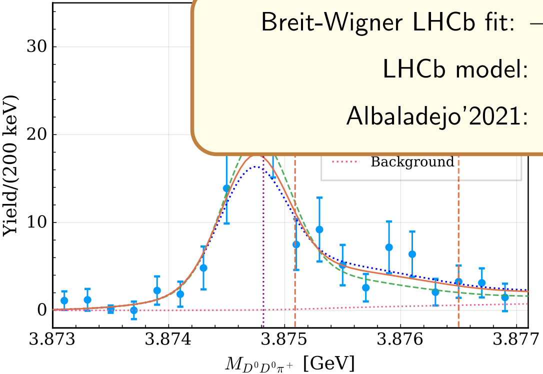

Breit-Wigner LHCb fit: $-273 - i410$ keV

LHCb model: $-360 - i24$ keV

Albaladejo'2021: $-356 - i39$ keV

- state just below D D threshold
- Compositeness: 70% & 30%

Spin partner T_{cc}^{*+}

HQSS: $V^{I=0}(D^*D^* \to D^*D^*, 1^+) = V^{I=0}(D^*D \to D^*D, 1^+) = v_0$

T_{cc}^+ at D^*D threshold hints existence of T_{cc}^{*+} at D^*D^* threshold

Scheme I:	$\delta_{cc}^{*+} = -1.4$ MeV
Scheme II:	$\delta_{cc}^{*+} = -1.1$ MeV
Scheme III:	$\delta_{cc}^{*+} = -0.5$ MeV

where $\delta_{cc}^{*+} = m_{T_{cc}^{*+}} - m_c^* - m_0^*$

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Disclaimer:

- Coupled-channel effects D^*D-D^*D^* neglected
- Multi-body effects & OPE included not selfconsistently

Conclusion: T_{cc}^{*+} is likely to exist but no reliable prediction is possible yet

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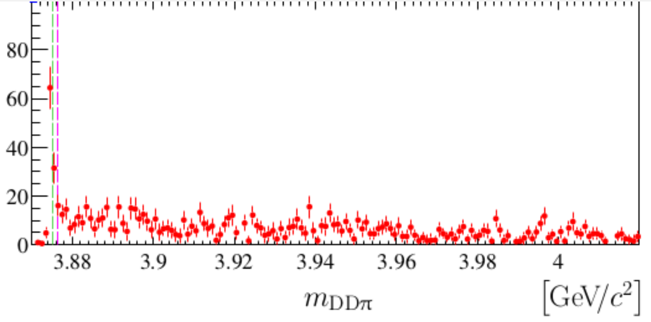
T_{cc}^+ at

LHCb Collab., Nature Communications, **13**, 3351 (2022)



Disclai

- C
- M

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T_{cc}^+ in lattice QCD

- "Signature of a Doubly Charm Tetraquark Pole in DD^* Scattering on Lattice," M. Padmanath and S. Prelovsek, Phys. Rev. Lett. **129**, 032002 (2022)

  $m_\pi = 280$ MeV 2 points in m_c (5-point update coming soon)

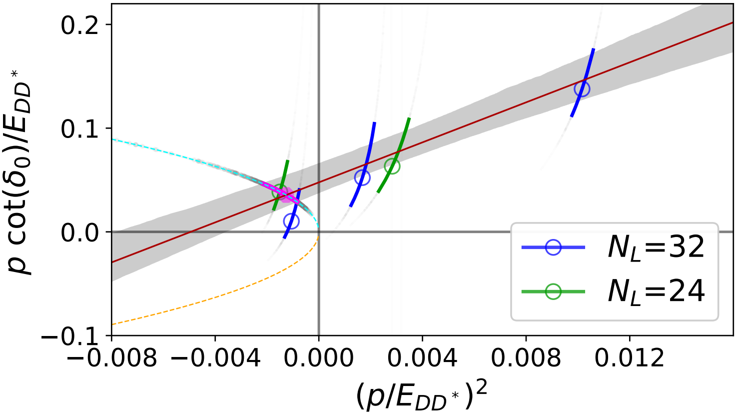
- "$T_{cc}^+(3875)$ relevant DD^* scattering from $N_f = 2$ lattice QCD," S. Chen, C. Shi, Y. Chen, M. Gong, Z. Liu, W. Sun and R. Zhang, Phys. Lett. B **833**, 137391 (2022)

  $m_\pi = 348$ MeV

- "Doubly Charmed Tetraquark T_{cc}^+ from Lattice QCD near Physical Point," Y. Lyu, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda and J. Meng, Phys. Rev. Lett. **131**, 161901 (2023)

  $m_\pi = 146$ MeV HALQCD technique

ERE analysis of lattice data for T_{cc}^+



(Padmanath & Prelovsek'2022)

$$-\frac{2\pi}{\mu}T^{-1}(E) = p\cot\delta - ip = \frac{1}{a_0} + \frac{1}{2}r_0 p^2 - ip$$

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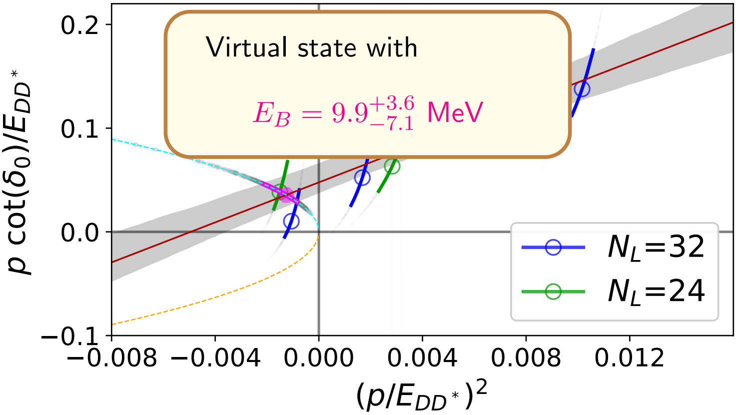

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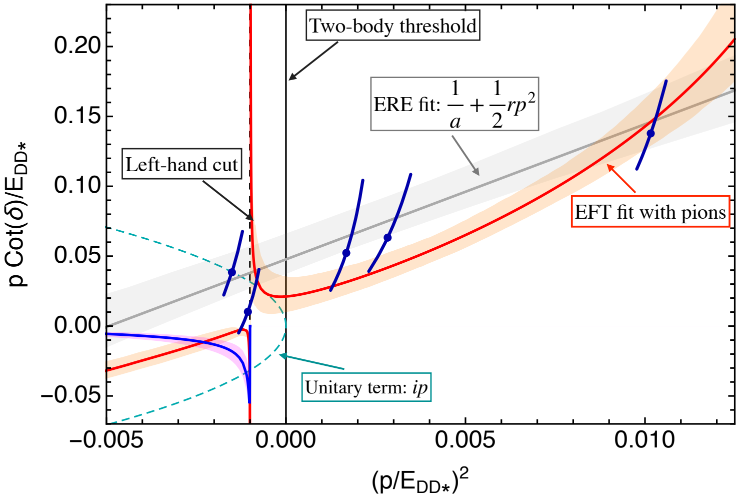

Lattice data: Padmanath & Prelovsek, Phys.Rev.Lett. 129 (2022), 032002
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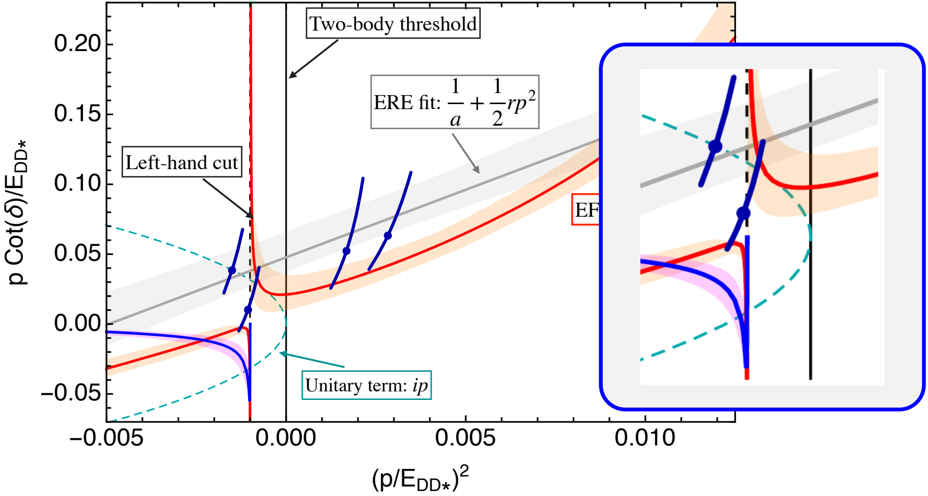

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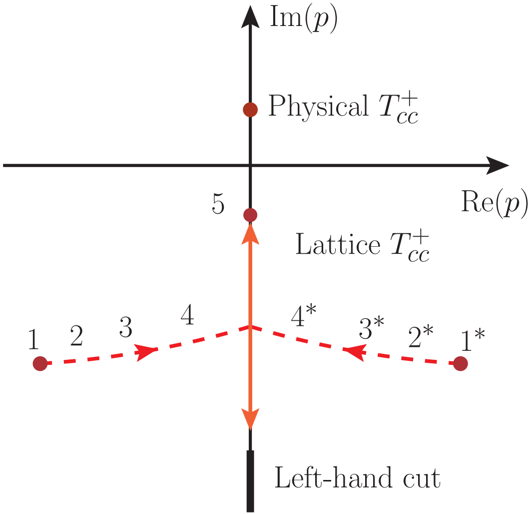
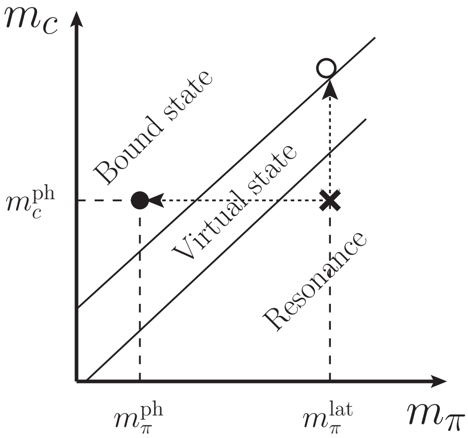
Lattice T_{cc}^+ pole motion with increased m_c



T_{cc}^+ pole motion on (m_c, m_π) plane



- Filled circle — physical T_{cc}^+
- Cross — starting lattice point
- Open circle — lattice T_{cc}^+ as shallow bound state

Conclusions

- T_{cc}^+ — a new surprise from experiment
- Another prominent example of hadronic molecule (bound state)
- Two complementary sources of information: experiment & lattice
- Well established theoretical tools $\Longrightarrow$ reliable conclusions
- Further questions to address:
  - Binding mechanisms?
  - Is T_{cc}^+ a cousin of $X(3872)$?
  - Do they have further siblings?
  - Spin & $SU(3)$ partners?
  - How about T_{bc} (lattice & experiment) and T_{bb} (lattice)?

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- Deuteron (100), X (20), Z (10), pentaquarks (9), $X(6900)$ (3), T_{cc}^+ (2),...

References & acknowledgments

Collaboration with colleagues from China, Germany, India, Slovenia, Spain is gratefully acknowledged!

- V. Baru, X. K. Dong, M. L. Du, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves, Q. Wang, "Effective range expansion for narrow near-threshold resonances," Phys. Lett. B **833**, 137290 (2022)
- M. L. Du, V. Baru, X. K. Dong, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves, Q. Wang, "Coupled-channel approach to T_{cc}^+ including three-body effects," Phys. Rev. D **105**, 014024 (2022)
- M. L. Du, V. Baru, X. K. Dong, E. Epelbaum, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves, Q. Wang, "Role of left-hand cut contributions on pole extractions from lattice data: Case study for $T_{cc}(3875)^+$", Phys. Rev. Lett. **131**, 13 (2023)
- S. Collins, A. Nefediev, M. Padmanath, S. Prelovsek, in preparation

Thank you for your attention!