How a coupled-channel approach to T_{cc}^+ discloses its nature

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Talk based on

M. L. Du, V. Baru, X. K. Dong, A. Filin, F. K. Guo, C. Hanhart, A. Nefediev, J. Nieves and Q. Wang,

“Effective range expansion for narrow near-threshold resonances,” PLB833 (2022) 137290

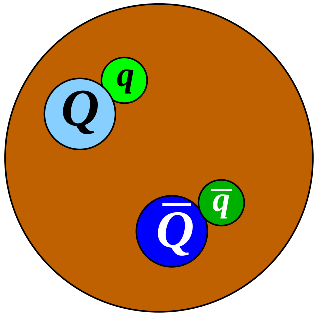
and

“Coupled-channel approach to Tcc+ including three-body effects,” PRD105 (2022)014024

Review article with focus on molecular states:

F.-K. Guo, C.H., U.-G. Meißner, Q. Wang, Q. Zhao, B.-S. Zou, Rev. Mod. Phys. 90(2018)015004

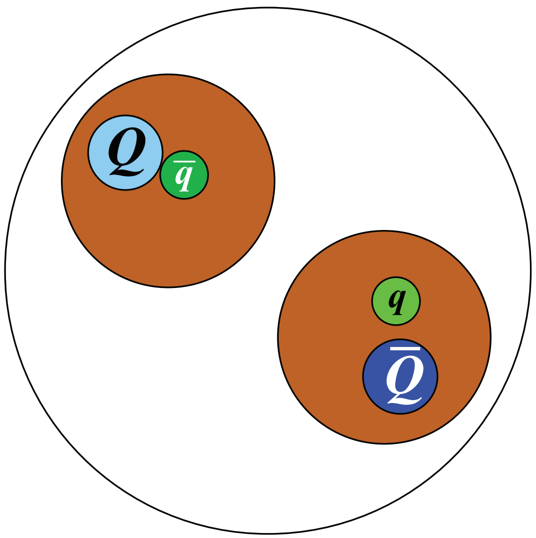
We want to distinguish



e.g. Quarkonia or Tetraquarks

$\rightarrow$ Compact object formed from $\bar{Q}Q$ or (Qq) and $(\bar{Q}\bar{q})$

and



Hadronic-Molecules

$\rightarrow$ Extended object made of $(\bar{Q}q)$ and $(Q\bar{q})$

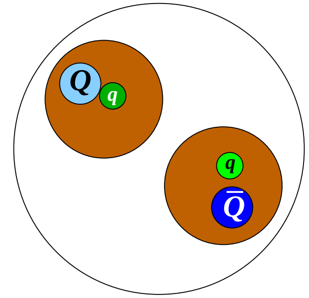
Bohr radius = $1/\gamma = 1/\sqrt{2\mu E_b}$

$\gg 1$ fm $\gtrsim$ confinement radius

for near threshold states

Tool: The Weinberg compositeness criterion

Hadronic Molecules



→ are few-hadron states, bound by the strong force

→ do exist: light nuclei.

→ are observable (Weinberg compositeness):

$$\frac{g_{\rm eff}^2}{4\pi} = \frac{4M^2\gamma}{\mu}(1-\lambda^2) \rightarrow a = -2\left(\frac{1-\lambda^2}{2-\lambda^2}\right)\frac{1}{\gamma}\,; \quad r = -\left(\frac{\lambda^2}{1-\lambda^2}\right)\frac{1}{\gamma}$$

where $(1-\lambda^2)$=probability to find molecular component in bound state wave function

Corrections Δa & $\Delta r \sim (\gamma/\beta)$ where β is either

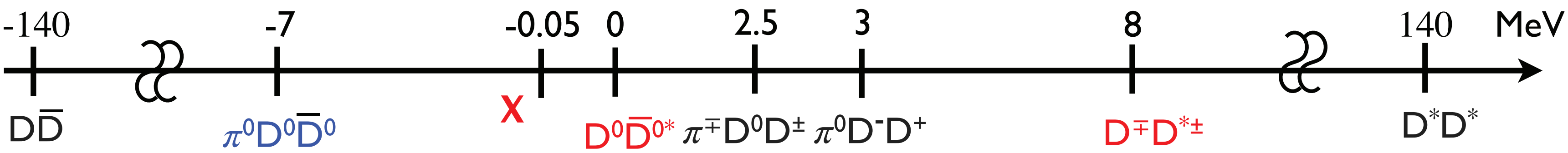
- ▷ mass of lightest exchange particle
  postive contribution to r: $\Delta r > 0 \rightarrow$ molecule
- ▷ distance to next threshold: $\Delta r < 0$ Matuschek et al., EPJA57(2021)3
  $\Longrightarrow$ can shield the signature

Subtle interplay of scales in the presence of isospin violation!

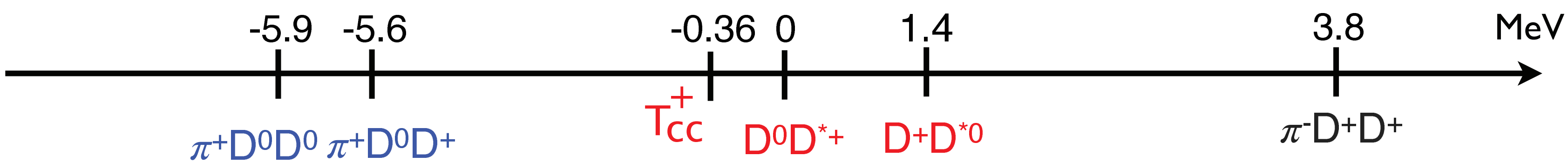
Two case studies

Both $\chi_{c1}(3872)$ aka $X(3872)$ and the T_{cc}^+ are isoscalar states:

$$|X\rangle = \frac{1}{2}\left\{|D^0\bar{D}^{*0}\rangle + |D^+\bar{D}^{*-}\rangle\right\} + \text{charge conjugate}$$



$$|T_{cc}\rangle = \frac{1}{2}\left\{|D^0 D^{*+}\rangle - |D^+ D^{*0}\rangle\right\}$$



In both cases: $\rightarrow$ Channel splitting δ larger than binding energy

$\rightarrow$ Three-body effects potentially important

Model indep. statements

General parametrisation of line shapes (for stable constituents):

$$\frac{d\sigma}{dE} \sim \frac{\text{function of E}}{\left|R(E) + \frac{i}{2}[g_1^2\sqrt{2\mu_1 E} + g_2^2\sqrt{2\mu_2(E-\delta)} + \Gamma_{\rm inel.}(E)]\right|^2}$$

where $g_1 = g_2 = g$ encodes isoscalar nature of the state, and

$\rightarrow$ $R(E)$ analytic in E: effective range expansion:

$$2R(E)/g^2 = -1/a - (r_0/2)k^2 + \mathcal{O}(k^4) \implies r_0 = -\frac{2}{\mu_1 g^2}\left(\frac{dR}{dE}\Big|_{E=0}\right)$$

modify for unstable constituents

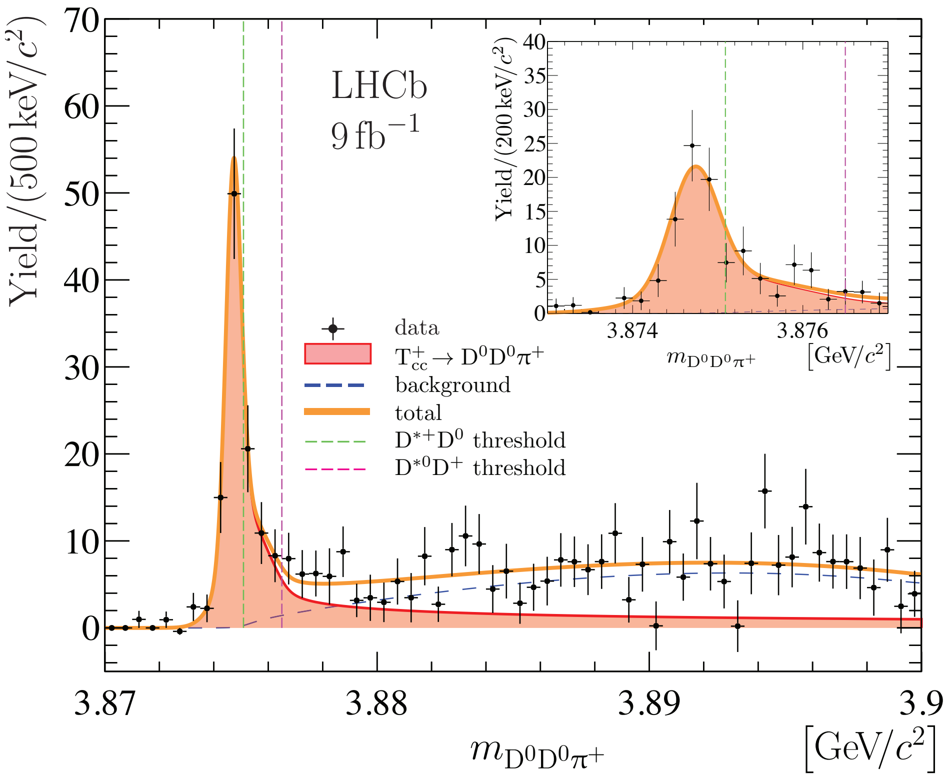
$\rightarrow$ for $|E| \approx E_b \ll \delta$:

$$i\sqrt{2\mu_2\left(\frac{k^2}{2\mu_1} - \delta\right)} = -\sqrt{2\mu_2\delta} + \underbrace{\frac{1}{2}\sqrt{\frac{\mu_2}{2\mu_1^2\delta}}}_{-(r_\delta/2)}k^2 + \mathcal{O}(k^4)$$

$\implies r_\delta \to \infty$ in the isospin limit

$\implies$ Only $r_0 \propto 1/g^2$ contains structure information!

The T_{cc}^+



R. Aaij et al. [LHCb], Nature Phys.18(2022)751

→ no signal in D^+D^{*+}
$\Longrightarrow$ isoscalar

→ 90%: $D^0D^{*+} \to D^0[D^0\pi^+]$
$\Longrightarrow$ D^{*+} building block

→ Width from D^* decay
$\Longrightarrow$ $\Gamma_{T_{cc}} < \Gamma_{D^*}$: phase sp.

→ only lower bound for g^2
$\Longrightarrow$ $|r_0| \propto 1/g^2$ small

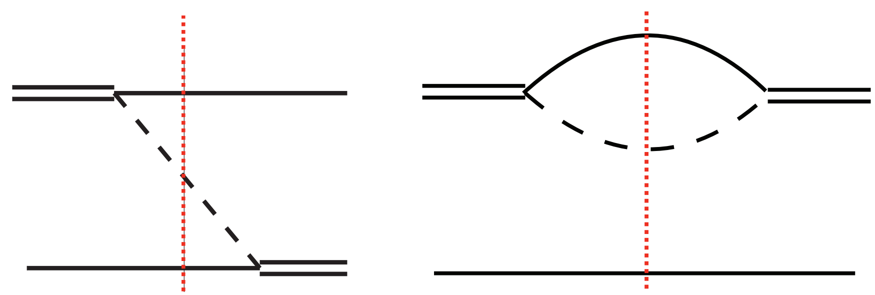
→ no other inelasticities

Excellent candidate for a molecular state!

For a more refined study:

Effective field theory for T_{cc}

study effect of three-body cuts



Chiral EFT for shallow bound states

Schemes currently proposed (only initial work cited)

→ Contact EFT: no pions — AlFiky et al., PLB640(2006)238

→ X-EFT: pert. pions — Fleming et al., PRD76(2007)034006

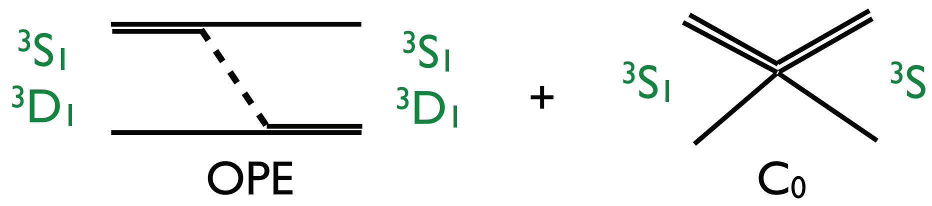
→ chiral EFT: non.-pert. pions — Baru et al., PRD84(2011)074029

- ▷ largest energy range of applicability
- ▷ Pion dynamics fully under control

$\Longrightarrow$ use this in what follows

Thus we solve LS-equation — Du et al., PRD105(2022)014024

$T = V + VGT$ with $V_{LO} =$

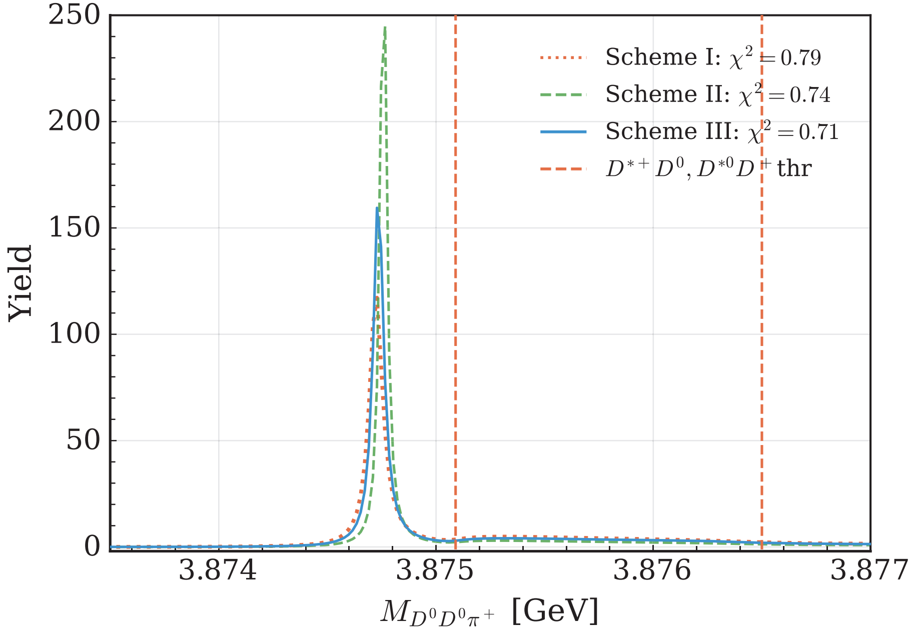


employing the expansion parameter $\chi = \sqrt{2\mu\delta}/\Lambda_\chi \approx 0.05$

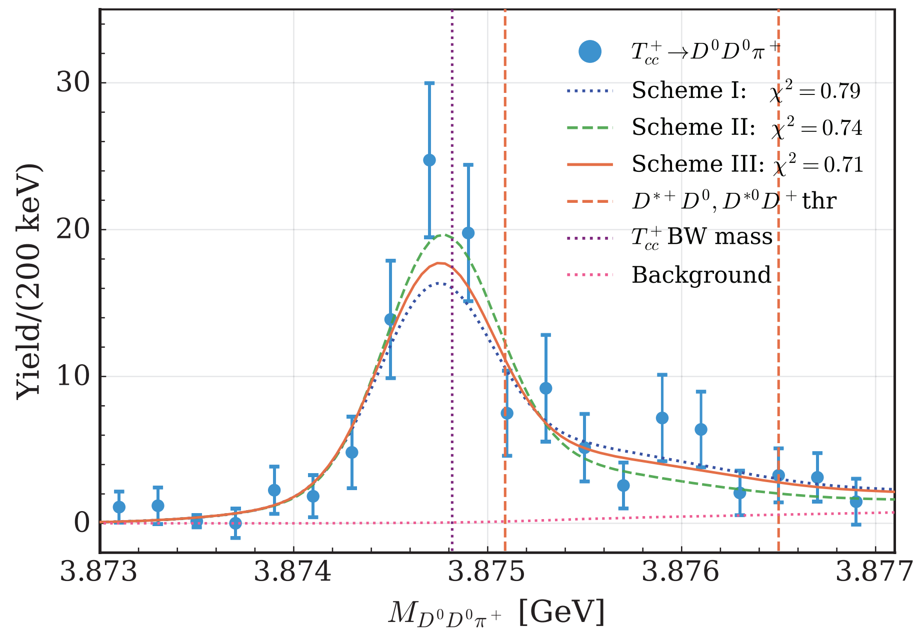
At NLO: Energy dep. counter terms + loops

Results and Discussion

w/o resolution



with resolution



Scheme	I	II	III
Description	2-body unitarity: No OPE, static D^* width	Incomplete 3-body unitarity: No OPE, dynamical D^* width	full 3-body unitarity: OPE + dynamical D^* width
Pole [keV]	$-368^{+43}_{-42} - i(37 \pm 0)$	$-333^{+41}_{-36} - i(18 \pm 1)$	$-356^{+39}_{-38} - i(28 \pm 1)$
χ^2	0.79	0.74	0.71

→ Precision needs 3 body dynamics

→ $r = -2.4 \pm 0.01 \pm 0.85$ fm, but $r_0 = +1.38 \pm 0.01 \pm 0.85$ fm

$\Longrightarrow$ T_{cc}^+ qualifies as isoscalar DD^* molecule

Summary

→ The Weinberg criterion allows one to identify hadronic molecules

→ In particular: effective range $r > 0$ points at molecule

→ But not necessarily the other way around: For example, for very shallow bound states 'remove' isospin breaking

→ High precision needs full three body dynamics

→ In the spirit of this talk both $\chi_{c1}(3872)$ aka $X(3872)$ as well as T_{cc}^+ qualify as hadronic molecules

Thanks a lot for your attention