Doubly charm and doubly bottom systems from D^*D and B^*B molecules.

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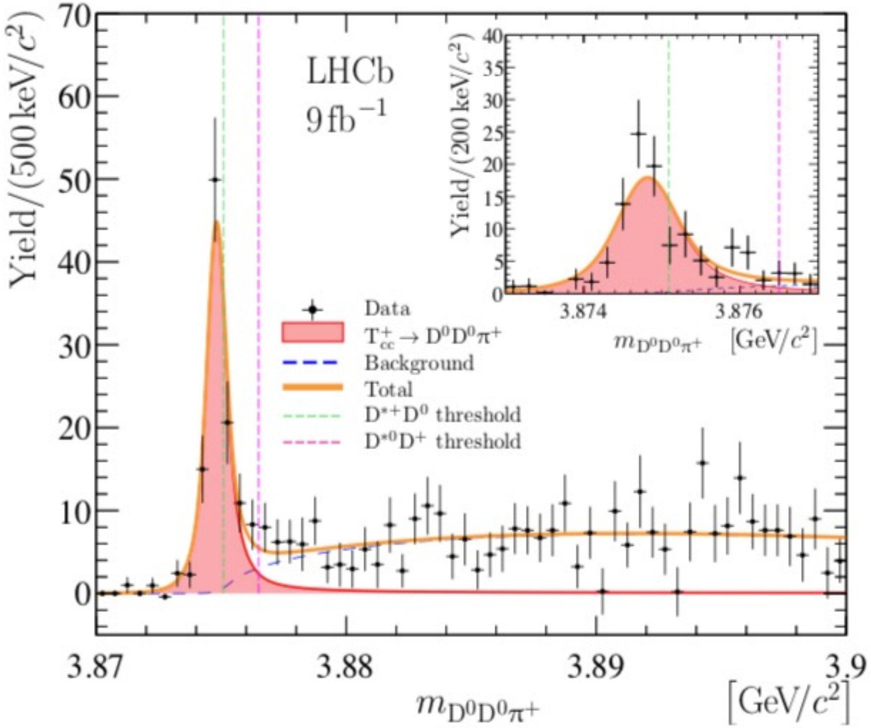
A narrow peak was observed in the $D^0D^0\pi^+$ spectrum at LHCb.

R. Aaij et al. [LHCb], arXiv:2109.01038 [hep-ex]



manifestly EXOTIC!

$$\text{minimal quark content} \to cc\bar{u}\bar{d}(D^0D^0\pi^+)$$

$$m_{\text{exp}} = m_{D^{*+}D^0} + \delta m_{\text{exp}}$$

$$m_{D^{*+}D^0} = 3875.09\, MeV$$

$$\delta m_{\text{exp}} = -273 \pm 61 \pm 5^{+11}_{-14}\ \text{keV}$$

$$\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}\ \text{keV}$$

The measured mass and width are consistent with the expected

$$T_{cc}^{+} \quad (J^P = 1^+, I = 0)$$

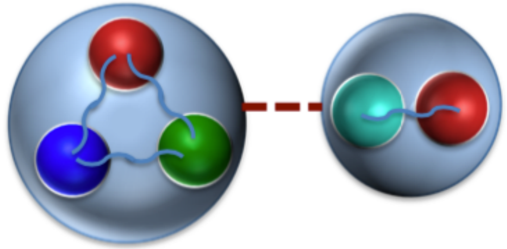
M. Karliner and J. L. Rosner, Phys. Rev. Lett. 119, 202001 (2017).

Exotic hadrons: whatever hadron not consisting of the conventional quark-model configurations, i. e. , baryons (qqq) and mesons $(q\bar{q})$.

- **Baryons**

Pentaquarks $(qqqq\bar{q})$

Compact 5-quark system

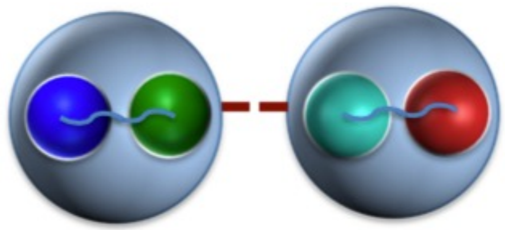


meson-baryon bound state (molecule)

- **Mesons**

Tetraquarks $(q\bar{q}q\bar{q})$

Compact 4-quark system



meson-meson bound state (molecule)

Glueballs

With all the information provided by the experimentalists, it seems plausible that the measured state can have a molecular nature consisting of $D^{*}D$ ***system.***

This structure was anticipated by:
N. Li, Z.-F. Sun, X. Liu, and S.-L. Zhu, Phys. Rev. D 88, 114008 (2013)
M.-Z. Liu, T.-W. Wu, M. P. Valderrama, J.-J. Xie, and L.-S. Geng, Phys. Rev. D 99, 094018 (2019)
Z. M. Ding, H. Y. Jiang, and J. He, Eur. Phys. J. C 80, 1179 (2020)

The proximity of this state to the $D^{*}D$ thresholds makes mandatory the consideration of these channels in its study, as was shown in
X. K. Dong, F. K. Guo, and B. S. Zou, Phys. Rev. Lett. 126, 152001 (2021)

By analogy, one can also get information from $D^{*}D^{*}$ molecular systems that were already studied
R. Molina, T. Branz, and E. Oset, Phys. Rev. D 82, 014010 (2010)

This important experimental breakthrough sparked a growing interest in the theoretical community:

- N. Li, Z. F. Sun, X. Liu, and S. L. ZHu, Chin. Phys. Lett. 38, 092001 (2021).
  reminder of a prediction for a molecular D^*D state whose mass matched $M^{exp}(T_{cc}^+)$ perfectly

- L. Meng, G. J. Wang, B. Wang, and S. L. Zhu, Phys. Rev. D 104, L051502 (2021).
  $D^{*+}D^0$ and $D^{*0}D^+$ coupled channels, $\Gamma(T_{cc}^+) \ll \Gamma^{exp}$

- X. Z. Ling, M. Z. Liu, L. S. Geng, E. Wang, and J. J. Xie, Phys. Lett. B 826, 136897 (2022).
  single channel D^*D molecule, $\Gamma(T_{cc}^+) \ll \Gamma^{exp}$

- S. S. Agaev, K. Azizi, and H. Sundu, Nucl. Phys. B 975, 115650 (2022).
  QCD sum rules, $M(T_{cc}^+) = 3868 \pm 124$ MeV

- A. Feijoo, W. H. Liang and E. Oset, Phys. Rev. D 104, no.11, 114015 (2021).
  $D^{*+}D^0$ and $D^{*0}D^+$ coupled channels, very approximately isoscalar state, $\Gamma(T_{cc}^+) \ll \Gamma^{exp}$

LHCb Coll. re-analyzed the raw data theoretically employing a unitarized three-body Breit-Wigner and taking into account the experimental resolution.

R. Aaij et al. [LHCb], arXiv:2109.01056 [hep-ex]

$$\delta m_{\rm exp} = -360 \pm 40^{+4}_{-0}\ \text{keV}$$
$$\Gamma = 48 \pm 2^{+0}_{-14}\ \text{keV}.$$

Notable difference with previous values!

$$m_{\rm exp} = m_{D^{*+}D^0} + \delta m_{\rm exp}$$
$$m_{D^{*+}D^0} = 3875.09\ MeV$$
$$\delta m_{\rm exp} = -273 \pm 61 \pm 5^{+11}_{-14}\ \text{keV}$$
$$\Gamma = 410 \pm 165 \pm 43^{+18}_{-38}\ \text{keV}$$

R. Aaij et al. [LHCb], arXiv:2109.01038

Isoscalar or isovector nature?

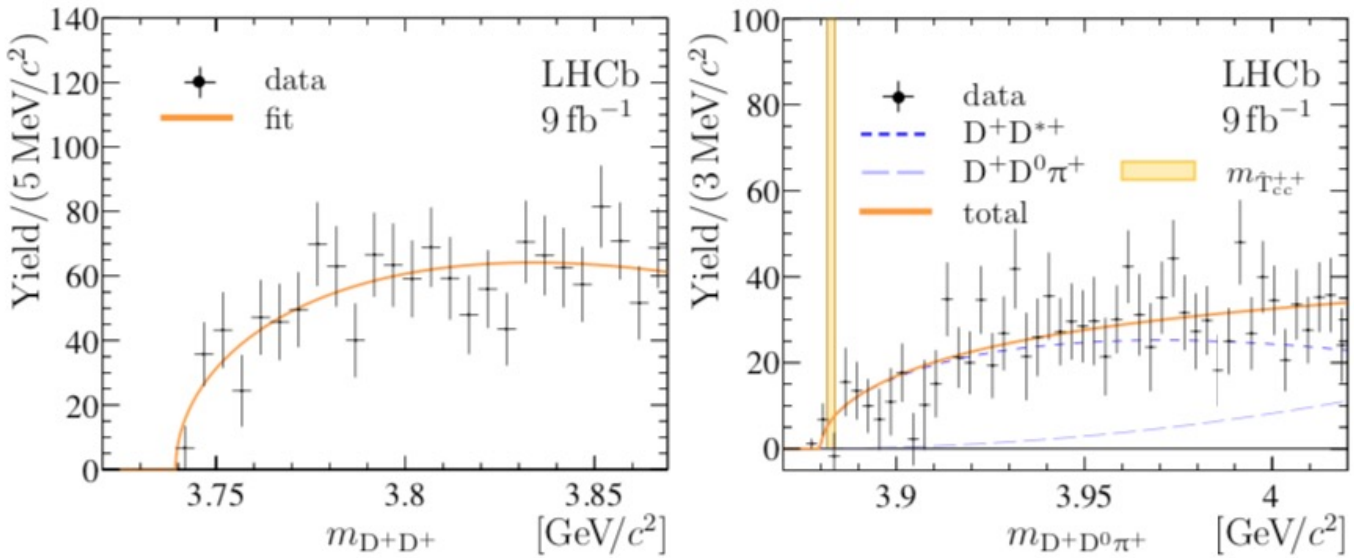
$$cc\bar{u}\bar{d}\ \begin{cases} T_{cc}^{+} \to |I=0, I_3=0\rangle \\ T_{cc}^{+} \to |I=1, I_3=0\rangle \end{cases}$$

$(T_{cc}^{0}, T_{cc}^{+}, T_{cc}^{++})$ Isotriplet

The exotic nature of T_{cc}^{+}

$$T_{cc}^{++} \to D^{+}D^{*+}$$

R. Aaij et al. [LHCb], arXiv:2109.01056 [hep-ex]



$$cc\bar{u}\bar{d} \begin{cases} T_{cc}^{+} \to |I=0, I_3=0\rangle \\ \sout{T_{cc}^{+} \to |I=1, I_3=0\rangle} \end{cases}$$

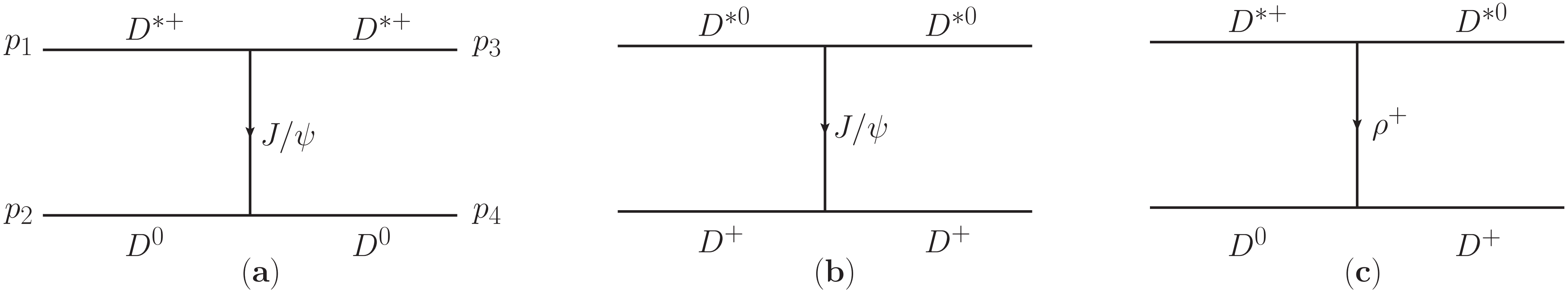
$D^* D$ molecule: Formalism

The basis considered consist of these 2 channels: $D^{*+}D^0, D^{*0}D^+$

$$\mathcal{L}_{VPP} = -ig\,\langle [P, \partial_\mu P] V^\mu \rangle$$

$$\mathcal{L}_{VVV} = ig\,\langle (V^\nu \partial_\mu V_\nu - \partial_\mu V^\nu V_\nu) V^\mu \rangle$$

The interaction is derived from hidden gauge Lagrangians. *P* and *V* are the SU(4) field matrixes (pseudoscalars and vector mesons).



$$V_{ij} = C_{ij}\, g^2\, \frac{1}{2}[3s - (M^2 + m^2 + M'^2 + m'^2) - \frac{1}{s}(M^2 - m^2)(M'^2 - m'^2)]\, \vec{\epsilon} \cdot \vec{\epsilon}\,'$$

$$g = \frac{M_V}{2\,f} \qquad C_{ij} = \begin{pmatrix} \frac{1}{M^2_{J/\psi}} & \frac{1}{m^2_\rho} \\ \frac{1}{m^2_\rho} & \frac{1}{M^2_{J/\psi}} \end{pmatrix}$$

$$C_{ij} = \begin{pmatrix} \frac{1}{M^2_{J/\psi}} & \frac{1}{m^2_\rho} \\ \frac{1}{m^2_\rho} & \frac{1}{M^2_{J/\psi}} \end{pmatrix}$$

None of the couplings connecting the channels individually is negative (and weak)!!!
We need an attractive interaction to have a bound state…

…but if we take the isospin combinations

$$(D^+, -D^0) \to |I=\frac{1}{2}, I_3=\frac{1}{2}\rangle, -|I=\frac{1}{2}, I_3=-\frac{1}{2}\rangle$$

$$(D^{*+}, -D^{*0}) \to |I=\frac{1}{2}, I_3=\frac{1}{2}\rangle, -|I=\frac{1}{2}, I_3=-\frac{1}{2}\rangle$$

$$|D^*D, I=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 - D^{*0}D^+)$$

$$|D^*D, I=1, I_3=0\rangle = -\frac{1}{\sqrt{2}}(D^{*+}D^0 + D^{*0}D^+)$$

$$C_{I_1 I_2} = \begin{pmatrix} C_{00} & C_{01} \\ C_{11} & C_{11} \end{pmatrix}$$

$$C_{00} = \frac{1}{M^2_{J/\psi}} - \frac{1}{m^2_\rho} < 0 \text{!!!}$$

$$C_{11} = \frac{1}{M^2_{J/\psi}} + \frac{1}{m^2_\rho} > 0$$

$$C_{01} = 0$$

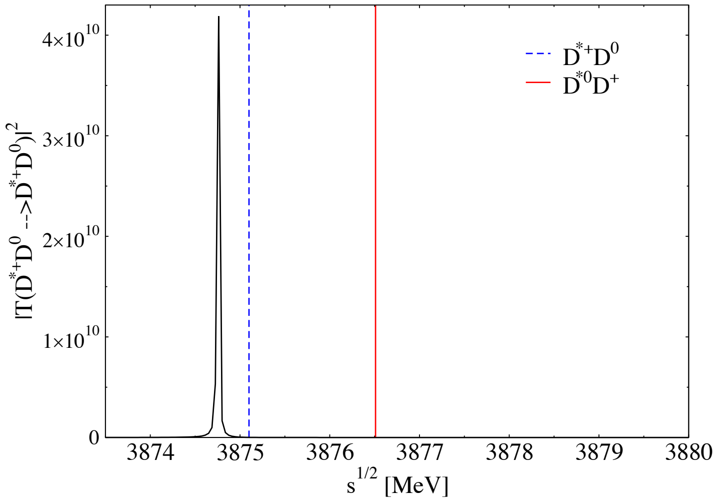
D^*D molecule: Formalism

Unitarized T-matrix from coupled-channel Bethe-Salpeter equation solved through On-shell factorization and following cutoff regularization scheme:

$$T = [1 - VG]^{-1} V$$

$$G_l = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1 \omega_2 \left[s - (\omega_1 + \omega_2)^2 + i\epsilon\right]}$$

q_{max} is the cutoff in the three momentum and the only parameter of the model. Its value has been tuned to get the experimental binding ($q_{max} = 420$ MeV).

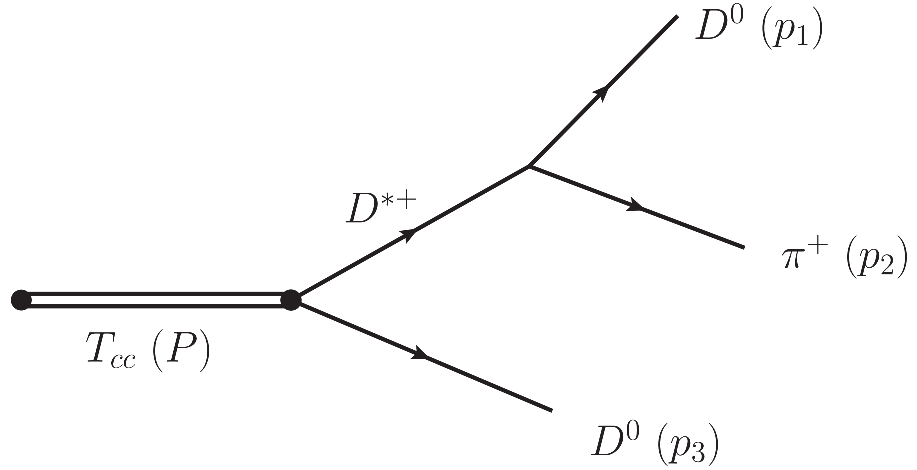


Finite width for a state below the D^*D thresholds requires the consideration of the width of the D^* states. This is accomplished performing a convolution of the G functions with the spectral function (mass distribution) of the D^* states.

D^*D molecule: Formalism

Theoretical calculation of the width for T_{cc}^+ state

$$\frac{d\Gamma}{dM_{12}^2\, dM_{23}^2} = \frac{1}{2}\,\frac{1}{(2\pi)^3}\,\frac{1}{s^{3/2}}\,|t|^2$$

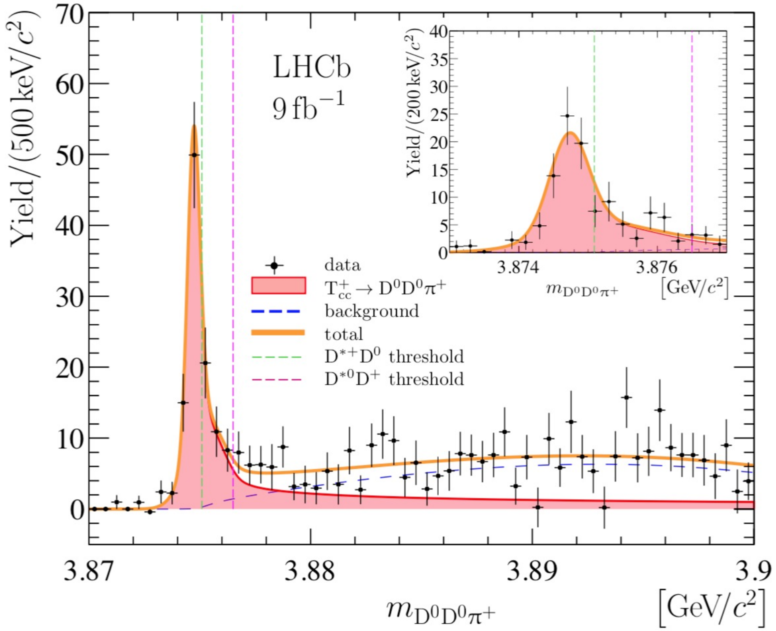


$$t = \mathcal{C}T(\sqrt{s})\left[\frac{\vec{\epsilon}\cdot(\vec{p}_1-\vec{p}_2)}{M_{12}^2 - m_{D^{*+}}^2 + iM_{12}\Gamma_{D^{*+}}(M_{12})} + \frac{\vec{\epsilon}\cdot(\vec{p}_3-\vec{p}_2)}{M_{23}^2 - m_{D^{*+}}^2 + iM_{23}\,\Gamma_{D^{*+}}(M_{23})}\right]$$

$$\Gamma_{D^{*+}}(M_{\rm inv}) = \Gamma(D^{*+})\left(\frac{m_{D^{*+}}}{M_{\rm inv}}\right)^2\left[\frac{2}{3}\left(\frac{p_\pi}{p_{\pi,\rm on}}\right)^3 + \frac{1}{3}\left(\frac{p'_\pi}{p'_{\pi,\rm on}}\right)^3\right] \qquad T \equiv T_{D^{*+}D^0\to D^{*+}D^0}$$

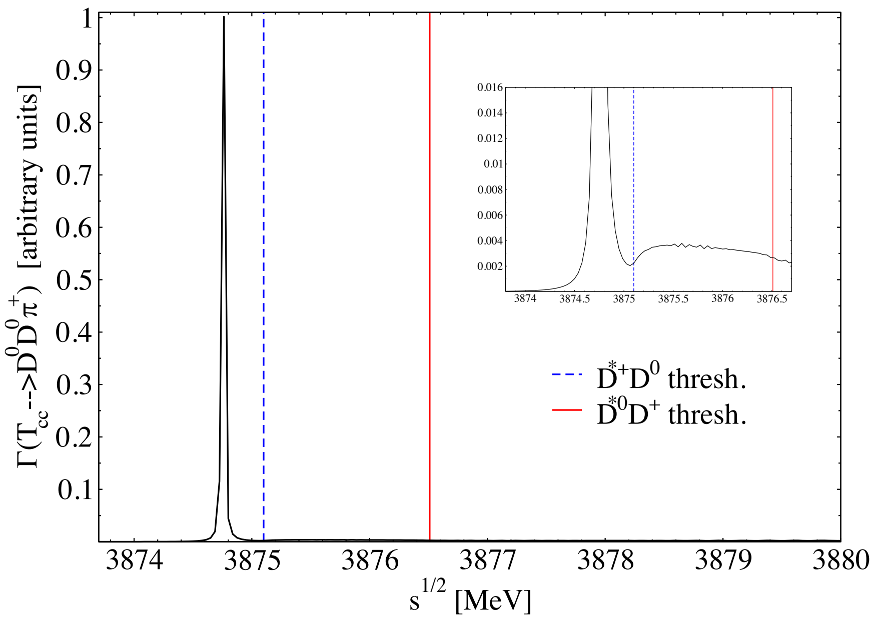
$D^* D$ molecule: Results

R. Aaij et al. [LHCb], arXiv:2109.01056 [hep-ex]



$$\Gamma^{\text{exp}} = 48 \pm 2^{+0}_{-14} \text{ keV}$$

Feijoo, Liang and Oset, Phys. Rev. D 104, no.11, 114015 (2021)



$$\Gamma \simeq 43 \text{ keV}$$

The observation of the $cc\bar{u}\bar{d}$ tetraquark close to $D^{*+}D^0$ threshold further supports the existence of a $ud\bar{b}\bar{b}$ tetraquark that is stable with respect to the strong and electromagnetic interactions.

The former study has been extended to the bottom sector to make a prediction for a B^*B counterpart state
L. R. Dai, E. Oset, A. F., R. Molina, L. Roca, A. M. Torres and K. P. Khemchandani, arXiv:2201.04840 [hep-ph]

The problem was addressed in the same way, yet with its own peculiarities:

Different characters

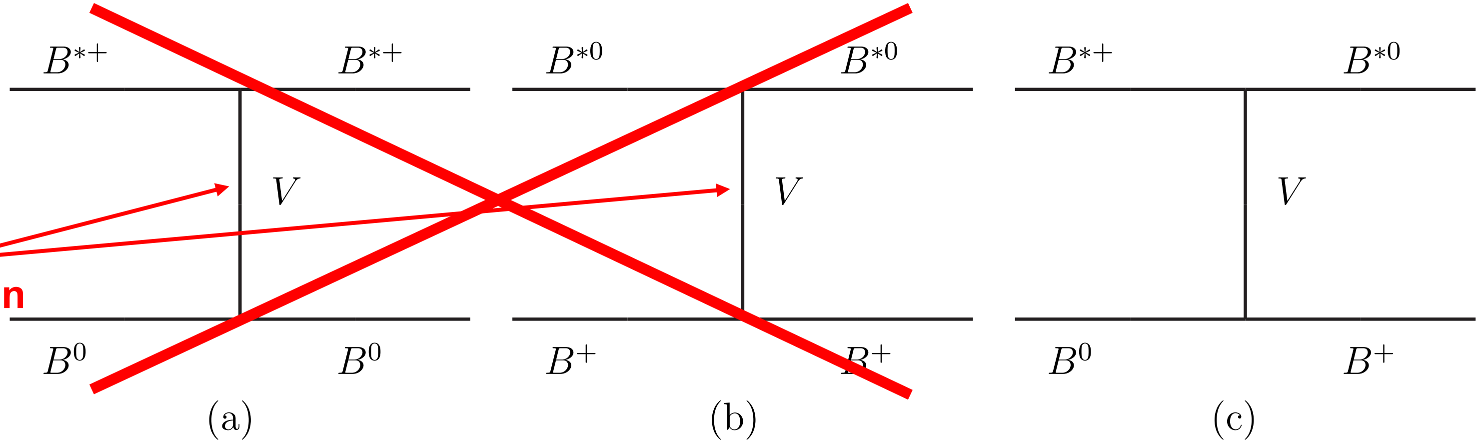
$$B^{*+}B^0,\ B^{*0}B^+$$

$$m_{B^+} = 5279.23 MeV$$
$$m_{B^0} = 5279.65 MeV$$
$$m_{B^*} = 5324.70 MeV$$

The only surviving mechanism of the interaction is the one depicted by diagram (c)

$$C_{ij} = \begin{pmatrix} 0 & \frac{1}{m_\rho^2} \\ \frac{1}{m_\rho^2} & 0 \end{pmatrix}$$

no $q\bar{q}$ light vector meson can be exchanged



Isoscalar or isovector???

$$|B^*B, I=0\rangle = \frac{1}{\sqrt{2}}(B^{*+}B^0 - B^{*0}B^+)$$

$$|B^*B, I=1, I_3=0\rangle = \frac{1}{\sqrt{2}}(B^{*+}B^0 + B^{*0}B^+)$$

$$C_{I_1 I_2} = \begin{pmatrix} C_{00} & C_{01} \\ C_{10} & C_{11} \end{pmatrix}$$

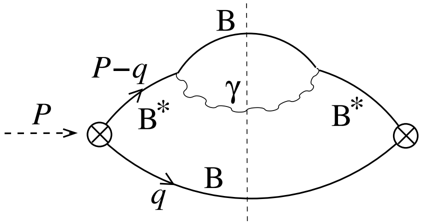
I=0 bound state

$$C_{00} = -\frac{1}{m_\rho^2}$$

$$C_{11} = \frac{1}{m_\rho^2}$$

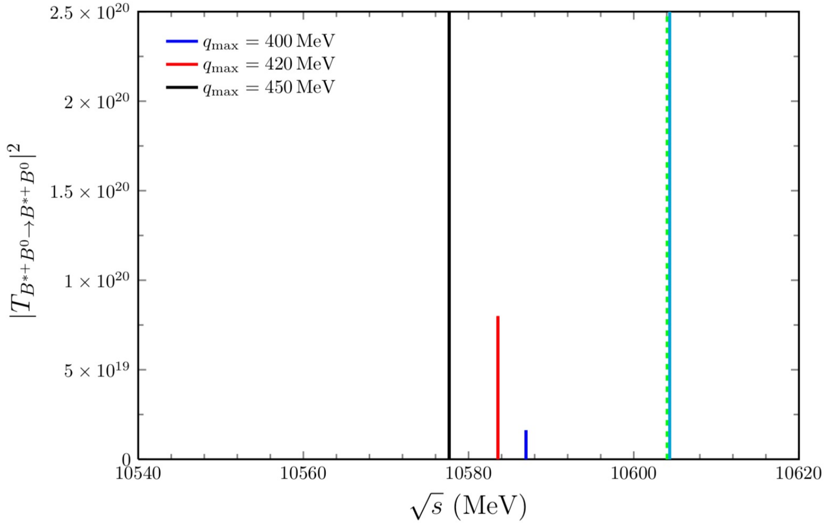
Width for the doubly bottom state

- The width is expected to be much smaller than in the doubly charm case
  only $B^* \to B\gamma$
- New strategy: we take into account the electromagnetic decay directly in the loop (instead of the convolution of the G with the spectral function).



$$G(s) \simeq \int_0^{q_{\max}} dq \frac{q^2}{4\pi^2} \frac{\omega_B + \omega_{B^*}}{\omega_B \omega_{B^*}} \frac{1}{\sqrt{s} + \omega_B + \omega_{B^*}} \frac{1}{\sqrt{s} - \omega_B - \omega_{B^*} + i\frac{\sqrt{s'}}{2\omega_{B^*}}\Gamma_{B^*}(s')}$$

B^*B molecule: Results



L. R. Dai, E. Oset, A. F., R. Molina, L. Roca, A. M. Torres and K. P. Khemchandani, arXiv:2201.04840 [hep-ph]

$$T_{11} = \frac{g_1^2}{s - s_R + iM_R\Gamma_R} \quad \Rightarrow \quad \Gamma_R = -\frac{g_1^2 Im\{T_{11}\}}{M_R|T_{11}|^2}$$

$$g_i g_j = \lim_{s \to s_R} (s - s_R) t_{ij}(s) \qquad q_{\max} = 420\, MeV$$

TABLE V. States of $J^P = 1^+$ obtained from different configurations. The binding B is referred to the closest threshold.

States	M (MeV)	B (MeV)	Γ
B^*B $(I=0)$	10583	21	14 eV
$B_s^*B - B^*B_s$ $(I=\frac{1}{2})$	10681	11	45 eV
B^*B^* $(I=0)$	10630	19	8 MeV
$B_s^*B^*$ $(I=\frac{1}{2})$	10728	12	0.5 MeV

Summary

We get a molecular state of $D^{*+}D^0$, $D^{*0}D^+$ with a mixing that corresponds very approximately to an $I = 0$ singlet.

The interaction has been derived from an extensión of the local hidden gauge framework.

The obtained decay width of such a state to $D^0D^0\pi$, as well as the reproduction of its invariant mass distribution, are in remarkable agreement with the analysis of the data reported by LHCb Collaboration.

We have also studied the interaction of the B^*B system with an extension of the local hidden gauge approach.

A bound $J^P = 1^+$ state was found in $I = 0$, with a binding energy around 20 MeV and a width of 14 eV.

The accuracy of the former prediction using the present framework could encourage the experimental search for this state.

Thank you for your attention!