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# A combined analysis of $D$ and $D^*(\bar{D}^*)$ system


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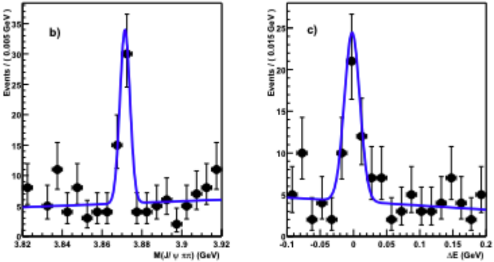
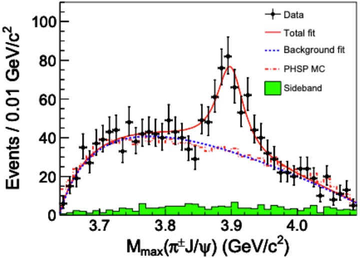
# Introduction

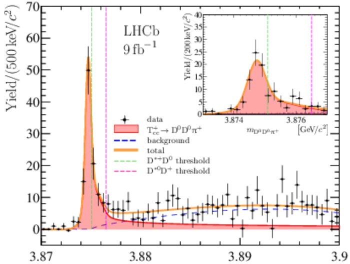
Belle, PRL91262001



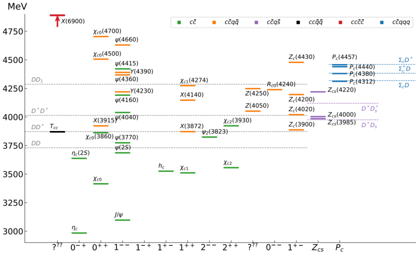

BESIII, PRL110252001




LHCb,NP18(2022)7,NC13(2022)13351




JPAC,Prog.Part.Nucl.Phys.127(2022)103981



# Main Content

A combined analysis matters to shed light on:

- long- and contact-range interactions
- nature of these resonances $\Rightarrow$ short-range kernels
- $\cdots$

In this talk, I want to review and discuss in two aspects briefly:

- How to describe such quantum systems in molecular picture?(Symmetry)
- How to understand the underlying mechanism?(Dynamics)

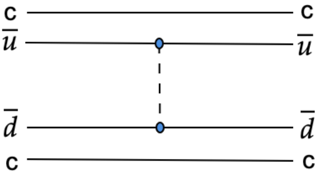
# (Heavy)Meson-Meson Interaction On Quark Level(1)

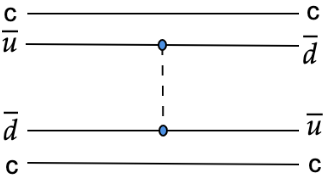
To acheive a unified treatment, one can derive the formalism on quark level explicitly,
C.E.Thomas et al., PRD78,034007

$$P: \frac{\{q(1)\bar{Q}(2)\} + \{\bar{Q}(1)q(2)\}}{\sqrt{2}} \quad \bar{P}: \frac{\{\bar{q}(1)Q(2)\} + \{Q(1)\bar{q}(2)\}}{\sqrt{2}}$$

$$V: \frac{[q(1)\bar{Q}(2)] - [\bar{Q}(1)q(2)]}{\sqrt{2}} \quad \bar{V}: \frac{[\bar{q}(1)Q(2)] - [Q(1)\bar{q}(2)]}{\sqrt{2}}$$

with $\{\bar{Q}q\} = \frac{1}{\sqrt{2}}(\bar{Q}^{\uparrow}q^{\downarrow} - \bar{Q}^{\downarrow}q^{\uparrow})$ for $S = 0$ and $[\bar{Q}q] = \bar{Q}^{\uparrow}q^{\uparrow}$ for $S_z = 1$.




Spatial? Spin? Flavour?

# (Heavy)Meson-Meson Interaction On Quark Level(2)

C.E.Thomas et al., PRD78,034007

$$V_{\text{OPE}} \propto [(-1+\frac{\mu^2}{|\vec{q}|^2+\mu^2})\sigma_i\cdot\sigma_j - \frac{|\vec{q}|^2}{|\vec{q}|^2+\mu^2}S_{ij}(\hat{q})]\tau_i\cdot\tau_j$$

As for S-wave composite particles, the factors of central terms($\sigma_i\cdot\sigma_j\tau_i\cdot\tau_j$), respecting spin&flavour&charge conjugation, are:

- $PV$: $(2I(I+1)-3)$
- $P\bar{V}$: $C(-1)(2I(I+1)-3)$
- $VV$: $(S(S+1)-4)(I(I+1)-3/2)$
- $V\bar{V}$: $(S(S+1)-4)(-1)(I(I+1)-3/2)$

The OPE in $PV$ and $P\bar{V}(C=+)$ has opposite signs due to the negative G parity of pion

# (Heavy)Meson-Meson Interaction On Hadronic Level

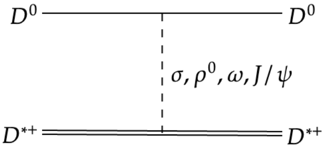
$$|DD^*, I=0\rangle = \frac{1}{\sqrt{2}}(\bar{u}\bar{d} - \bar{d}\bar{u}) \otimes \frac{1}{\sqrt{2}}(PV + VP)$$

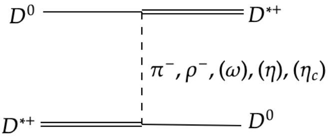
$$= \frac{1}{\sqrt{2}}\Big(\overbrace{\frac{1}{\sqrt{2}}(|D^0 D^{*+}\rangle - |D^{*+} D^0\rangle)}^{I=0} - \overbrace{\frac{1}{\sqrt{2}}(|D^+ D^{*0}\rangle - |D^{*0} D^+\rangle)}^{I=0}\Big)$$

$\pi^-$

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

$$+ (-1)^{I-I_1-I_2}(-1)^{J-J_1-J_2}\frac{1}{\sqrt{2}}(|D^{*+} D^0\rangle - |D^{*0} D^+\rangle)\Big)$$




The presence of $X(3872)$ and $T_{cc}^+$ implies/confirms the pion interaction may be subleading

# Power Counting And EFT Treatment

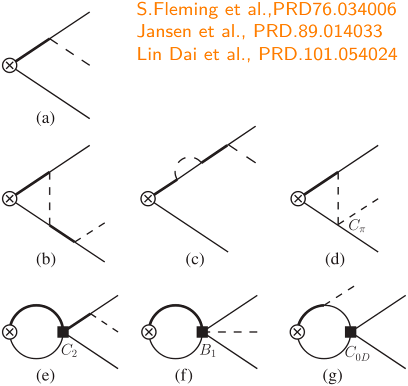
Naively, the iteration of pion-exchange is estimated to be,

$$\frac{g^2 M_{DD^*}\mu}{4\pi f_\pi^2} \approx \frac{1}{20} - \frac{1}{10} \quad \ll \quad \frac{g_A^2 M_N m_\pi}{8\pi f_\pi^2} \approx \frac{1}{2}$$

In the power counting scheme, the following holds fairly well @Charm $\sim$ physical point, M.P.Valderrama, PRD.85.114037

S.Fleming et al.,PRD76.034006
Jansen et al., PRD.89.014033
Lin Dai et al., PRD.101.054024

- LO contact potential $\Leftrightarrow$ VMD
- Perturbative pionful interaction(NLO)
- Coupled-channel effect suppressed(NLO)



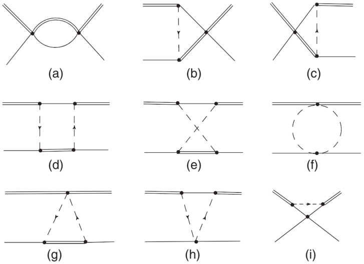
# Chiral Matching And Resonance Saturation

Extra counter terms required @1-loop,

$$\delta T^{(1)}_{++,SS} = -\frac{\Lambda}{\pi^2(M_D+M_{D^*})}\left(\frac{1}{4}\lambda^2 + \lambda\frac{2g_\pi^2}{3f_\pi^2} + \frac{4g_\pi^4}{3f_\pi^4}\right)$$

$\eta, \rho, \omega, etc$ $\pi$

P.Wang et al., PRL.111.042002
V.Baru et al.,PRD.91.034002




Consider the OPE in the coordinate space again,

$$V_{\mathrm{OPE}} \propto \left(-\delta(\vec{r}) + \frac{\mu^2 e^{-\mu r}}{4\pi r}\right)\sigma_i\cdot\sigma_j\tau_i\cdot\tau_j + \frac{\mu^2 e^{-\mu r}}{4\pi r}\left(1+\frac{3}{\mu r}+\frac{3}{\mu^2 r^2}\right)S_{ij}(\hat{q})\tau_i\cdot\tau_j$$

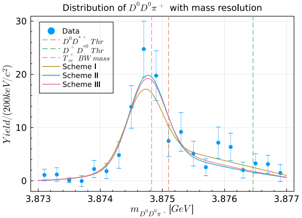
T. Ericson et al., Pions and Nuclei
F.Z.Peng et al., PRD.102.114020

N.Yalikun et al., PhysRevD.104.094039 T.Ji et al., PRL.129.102002

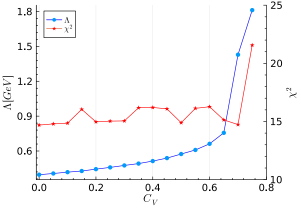
- $1/m_\pi \gg 1/\Lambda$: strongly suppressed
- $1/m_{\eta,\rho,\omega} \approx 1/\Lambda$: introduce counter terms $C_{P/V}$
- $1/M_{J/\psi,\eta_c} \ll 1/\Lambda$: removed

# Double-Charm Sector

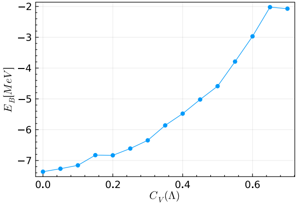
Schemes: BW-type: $\Gamma_{D^*}$; Flatte-type: $\Gamma_{D^*}(E, \boldsymbol{q})$;Three-body: OPE+$\Gamma_{D^*}(E, \boldsymbol{q})$




Fitting results




$\Lambda - C_V$




$E_B(D^*D^*) - C_V(\Lambda)$

V.Baru et al.,PRD84.074029

| | Schemes | $\chi^2/d.o.f$ | Λ[GeV] | $\sqrt{s}_{\text{pole}}$[keV] |
|---|---|---|---|---|
| $\Gamma_{D^*}$ | Scheme I | 0.740 | 0.399 | $-379.9^{+15.7}_{-15.5} - i \cdot 37.0^{+0.0}_{-0.0}$(RS-I) |
| $\Gamma_{D^*}$ | Scheme II | 0.859 | 0.390 | $-304.2^{+10.8}_{-10.6} - i \cdot 19.7^{+0.3}_{-0.2}$(RS-II) |
| $\Gamma_{D^*}$ | Scheme II(best) | 0.81 | $0.510(C_V = 0.5)$ | $-347.4^{+11.3}_{-11.2} - i \cdot 18.5^{+0.2}_{-0.2}$(RS-II) |
| S-D / S-wave | Scheme III | 0.773 | 0.396 | $-350.4^{+18.3}_{-18.2} - i \cdot 24.6^{+0.3}_{-0.2}$(RS-II) |
| S-D / S-wave | LHCb's[1] | | | $(-360 \pm 40^{+4}_{0}) - i(48 \pm 2^{+0}_{-14})/2$ |
| S-D | Du's[2] | | | $(-356^{+39}_{-38}) - i(28 \pm 1)$ |

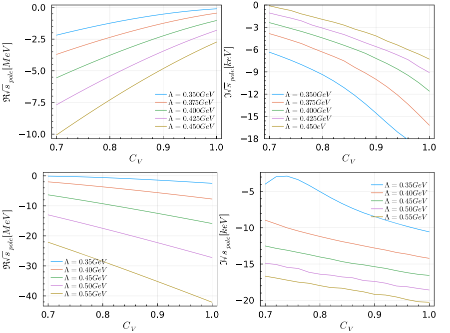
[1] LHCb,NP18(2022)7,NC13(2022)13351

[2] Meng-Lin Du et al., PhysRevD.105.014024

# Hidden-Charm Sector

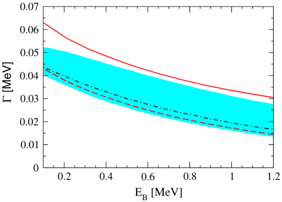
| System | $J^{PC}$ | Pole[MeV]($\Lambda = 0.35$GeV) | Pole[MeV]($\Lambda = 0.65$GeV) |
|---|---|---|---|
| $D\bar{D}$ | $0^{++}$ | $(1, 0.3)$ | $(1, 33.6)$ |
| $D^*\bar{D}^*$ | $0^{++}$ | $(1, 0.006) - (1, 12.4)$ | $(1, 0.5) - (1, 39.3)$ |
| | $1^{+-}$ | $(1, 0.4) - (1, 6.4)$ | $(1, 4.1) - (1, 37.7)$ |
| | $2^{++}$ | $(2, 3.3) - (1, 3.2)$ | $(1, 46.6) - (1, 117.7)$ |

$X(3872)$(top) and $\tilde{X}(3872)$(bottom)




$X(3872)$ from EFT,

Lin Dai et al., PRD.101.054024




$\tilde{X}(3872)$ from COMPASS:

$$M_{\tilde{X}(3872)} = 3860.4 \pm 10.0\text{MeV}/c^2$$

# Summary

- The OPE, which introduces large unphysical contact term, has opposite signs in $X(3872)$ and $T_{cc}^{+}$
  $\Rightarrow$ pion-full theory or perturbative treatment
- The interaction is dominated by LO contact potential, driven by vector mesons in potential model
- A combined analysis is strongly required to reveal the nature of resonances, especially in hidden-charm sector
- Critical issues(coupling, scaling, etc) must be noticed within OBE framework

# Thank you!

# Resonance saturation

We define functions:

$$\tilde{\mathcal{X}}_{\text{ex}} = \frac{\vec{\epsilon}_i \cdot \vec{\epsilon}_f^{\,*}}{|\vec{q}|^2 + \mu_{\text{ex}}^2}, \qquad \mathcal{X}_{\text{ex}} = \frac{(1 - \frac{q^{0\,2}}{m_{\text{ex}}^2})\vec{\epsilon}_i \cdot \vec{\epsilon}_f^{\,*}}{|\vec{q}|^2 + \mu_{\text{ex}}^2}$$

$$\mathcal{Y}_{\text{ex}} = \frac{\vec{\epsilon}_i \cdot \vec{q}\vec{\epsilon}_f^{\,*} \cdot \vec{q}}{|\vec{q}|^2 + \mu_{\text{ex}}^2} \sim \frac{1}{3}(-\frac{\mu_{\text{ex}}^2}{|\vec{q}|^2 + \mu_{\text{ex}}^2} + C_{\text{ex}})\hat{S}(\vec{\epsilon}_i, \vec{\epsilon}_f^{\,*})$$

$$\mathcal{Z}_{\text{ex}} = \frac{(\vec{\epsilon}_i \times \vec{q}) \cdot (\vec{\epsilon}_f^{\,*} \times \vec{q})}{|\vec{q}|^2 + \mu_{\text{ex}}^2} \sim \frac{2}{3}(-\frac{\mu_{\text{ex}}^2}{|\vec{q}|^2 + \mu_{\text{ex}}^2} + C_{\text{ex}})\hat{S}(\vec{\epsilon}_i, \vec{\epsilon}_f^{\,*})$$

Thus, the potentials for isoscalar($-$) $DD^*$ are:

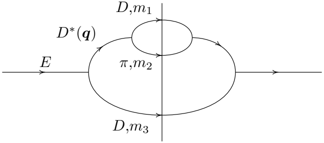
1. $D^0 D^{*+} \to D^0 D^{*+} / D^+ D^{*0} \to D^+ D^{*0}$

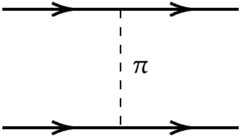
$$V^{[DD^*]\mp} = -\frac{g_V^2 \beta^2}{4}\mathcal{X}_{\rho^0} + \frac{g_V^2 \beta^2}{4}\mathcal{X}_{\omega} - g_S^2 \tilde{\mathcal{X}}_{\sigma} \pm \frac{g^2}{f_\pi^2}\mathcal{Y}_{\pi^-} \pm 2g_V^2 \lambda^2 \mathcal{Z}_{\rho^-} + \frac{g_V^2 \beta^2}{2}\mathcal{X}_{J/\psi}$$

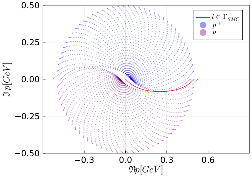
2. $D^0 D^{*+} \to D^+ D^{*0}$

$$V^{[DD^*]\mp} = \frac{g_V^2 \beta^2}{2}\mathcal{X}_{\rho^-} \mp \frac{g^2}{2f_\pi^2}\mathcal{Y}_{\pi^0} \pm \frac{g^2}{6f_\pi^2}\mathcal{Y}_{\eta} \mp g_V^2 \lambda^2 \mathcal{Z}_{\rho^0} \pm g_V^2 \lambda^2 \mathcal{Z}_{\omega} \pm \frac{g^2}{f_\pi^2}\mathcal{Y}_{\eta_c} \pm 2g_V^2 \lambda^2 \mathcal{Z}_{J/\psi}$$

# Analytical continuation




1) $D^*[D\pi]$ self energy

$$p_{cm} = \mathcal{F}(E, \boldsymbol{q}, m_1, m_2, m_3) = \sqrt{2\mu_{D\pi}\left(E + m_{D^*} - \sqrt{m_{D^*}^2 + \boldsymbol{q}^2} - \sqrt{m_D^2 + \boldsymbol{q}^2} - m_D - m_\pi\right)}$$

$$\tilde{\mathcal{F}}(E, \boldsymbol{q}, m_1, m_2, m_3) = \begin{cases} -\mathcal{F}(E, \boldsymbol{q}, m_1, m_2, m_3), & \text{if } \Im(E'(E, \boldsymbol{q})) < 0 \text{ and } \Re(E'(E, \boldsymbol{q})) > m_1 + m_2 \\ \mathcal{F}(E, \boldsymbol{q}, m_1, m_2, m_3), & \text{else} \end{cases}$$

2) OPE:

$$\int_{-1}^{1} \frac{dz}{z - \xi} = \begin{cases} \log(1-\xi) - \log(-1-\xi) + 2\pi i, & |\Re\xi| < 1 \text{ and } \Im\xi < 0 \\ \log(1-\xi) - \log(-1-\xi), & \text{else} \end{cases}$$

with $\xi = \frac{p_1^2 + p_4^2 + m_\pi^2 - (E_4 - E_1)^2}{2p_1p_4}$.