Applications of the chiral symmetry to the B-meson decays

Meng-Lin Du

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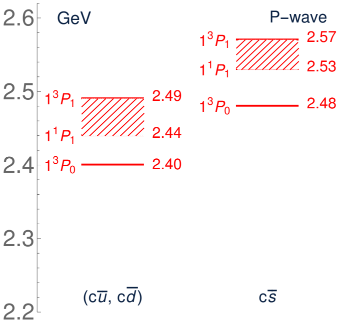
MLD, Albaladejo, *et al.*, Phys. Rev. D **98**, 094018 (2018)
MLD, Guo and Meißner, Phys. Rev. D **99**, 114002 (2019)
MLD, Guo *et al.*, Phys. Rev. Lett. **126**, 192001 (2021)

重味物理前沿论坛研讨会
2023.11.26 @ 华中师范大学，武汉

Positive parity ground state charm mesons



Godfrey and Isgur, PRD **32**, 189 (1985)

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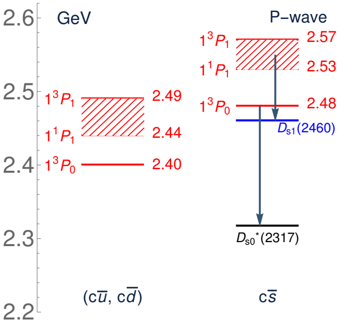

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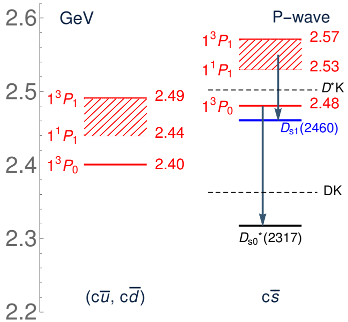

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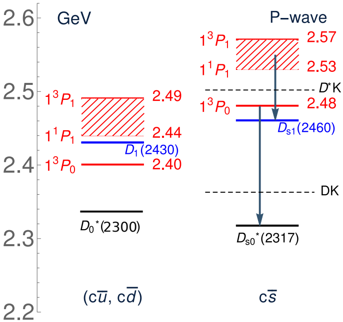

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SU(3) partners

$$D_0^*(2300),\ D_1(2430)$$
$$D_{s0}^*(2317),\ D_{s1}(2460)$$

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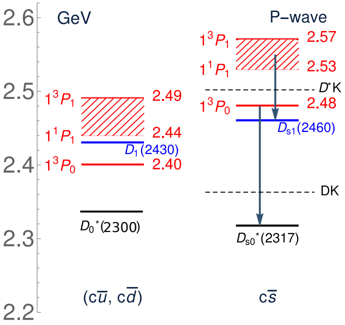

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SU(3) partners

$$D_0^*(2300),\ D_1(2430)$$
$$D_{s0}^*(2317),\ D_{s1}(2460)$$

- ⋆ why are the masses of the $D_{s0}^\star(2317)$ and the $D_{s1}(2460)$ much lower than the quark model predictions for $c\bar{s}$ mesons?
- ⋆ why $M_{D_{s1}(2460)} - M_{D_{s0}^\star(2317)} \simeq M_{D^\star} - M_D$? (within 1 MeV)
- ⋆ why $M_{D_0^\star(2300)} \gtrsim M_{D_{s0}^\star(2317)}$ and $M_{D_1(2430)} \simeq M_{D_{s1}(2460)}$?

Notice: all these experiments used a Breit–Wigner to extract the resonance

Implication of chiral symmetry on Breit-Wigner resonances

☞ Goldstone bosons: energy-dependent interactions

☞ The standard Breit-Wigner: constant coupling. ~~chiral symmetry~~

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- ☞ S-wave BW parameterization: $F_0(s) \propto \frac{1}{s-m_0^2+im_0\Gamma}$

$$\frac{d}{ds}|F_0(s)|^2\Big|_{s=s_{\text{peak}}} = 0 \quad \Longrightarrow \quad s_{\text{peak}} = m_0^2$$

- ☞ Modified parameterization: $F_0(s) \propto \frac{E_\pi}{s-m_0^2+im_0\Gamma}$

$$s_{\text{peak}} = (m_0+\Delta)^2, \qquad \Delta = \frac{\Gamma^2 E_D}{4m_0E_\pi - \Gamma^2}$$

Implication of chiral symmetry on Breit-Wigner resonances

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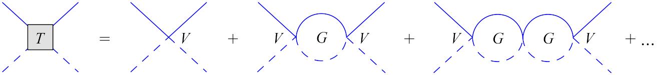
☞ ?$D_0^*(2400)$, $D_1(2430)$

Coupled-channel $\Longrightarrow$ chiral EFT + unitarization

ChPT + unitarization

- Low-energy interactions between the charm and the Goldstones: ChPT
- A nonperturbative treatment: unitarization Oller, Meißner, PLB**500**, 263 (2001)

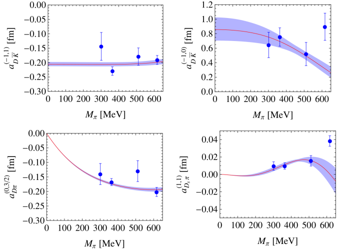
$$T^{-1}(s) = V^{-1}(s) + G(s)$$



$V(s)$: to be derived from SU(3) chiral effective Lagrangian

$G(s)$: two-point scalar loop functions, regularized with a subtraction constant

- NLO: Fit to lattice data in 5 simple channels: no disconnected diagrams



[$M_\pi = 600$ MeV not fitted]

L. Liu, Orginos, F.-K. Guo, Hanhart, Meißner, PRD86(2013)014508

$D_{s0}^*(2317)$ and $D_{s1}(2460)$ as hadronic molecules

- NLO: Pole in the $(S, I) = (1, 0)$ channel: 2315^{+18}_{-28} MeV

Liu, Orginos, Guo, Hanhart, Meißner (2013)

Experiment: $M_{D_{s0}^*(2317)} = (2317.8 \pm 0.5)$ MeV

- Hadronic molecular model: $D_{s0}^*(2317)[DK]$, $D_{s1}(2460)[D^*K]$

Barnes, Close, Lipkin(2003); van Beveren, Rupp(2003); Kolomeitsev, Lutz(2004); ...

- Weinberg compositeness $X = 1 - Z$

↪ From the lattice energy levels in C. Lang et al., PRD90(2014)034510

$D_{s0}^*(2317)$ contains $\sim 70\%$ DK Martínez Torres, Oset, Prelovsek, Ramos, JHEP1505,053

↪ $1 - Z = 1.04(0.08)(0.30)$, G. Bali et al., PRD96(2017)074501

↪ Bare $c\bar{s}$+DK: 68%, Z. Yang al., PRL128(2022)112001

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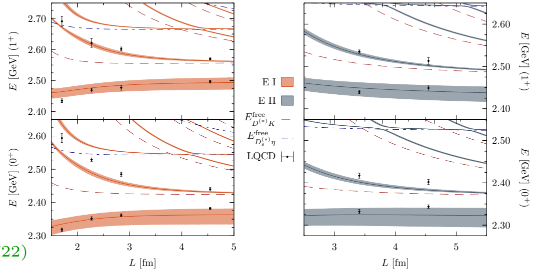
- Postdiction!

E I : $M_\pi = 290$ MeV

E II: $M_\pi = 150$ MeV

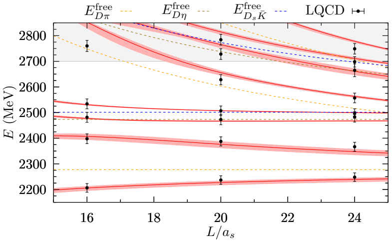


Albaladejo et al., EPJC78(2018(722)

What about the $D_0^*(2300)$? [Two-pole scenario in $I = 1/2$ sector]

NOT a fit!

- Two poles in $I = 1/2$ sector were found in Kolomeitsev, Lutz (2004); Guo, Shen, Chiang, Ping, Zou (2006); F.-K. Guo, Hanhart, Meißner (2009); Z.-H. Guo, Meißner, Yao (2015); X.-Y. Guo, Heo, Lutz (2018);...
- Postdicted finite volume energy levels in G. Moir et al. [Hadron Spectrum Collaboration], JEHP1610(2016)



Alabladejo et al., PLB(2017)465

- two states also in heavy meson sectors $(M, \Gamma/2)$ MeV:

	lower pole	higher pole	RPP
D_0^*	$\left(2105^{+6}_{-8}, 102^{+10}_{-11}\right)$	$\left(2451^{+35}_{-26}, 134^{+7}_{-8}\right)$	$(2343 \pm 10, 115 \pm 8)$
D_1	$\left(2247^{+5}_{-6}, 107^{+11}_{-10}\right)$	$\left(2555^{+47}_{-30}, 203^{+8}_{-9}\right)$	$(2412 \pm 9, 157 \pm 15)$

$\hookrightarrow$ solution to the third puzzle

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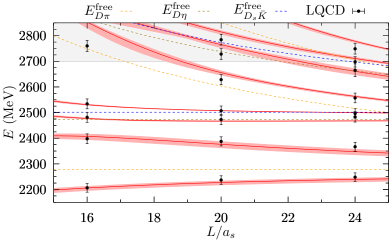

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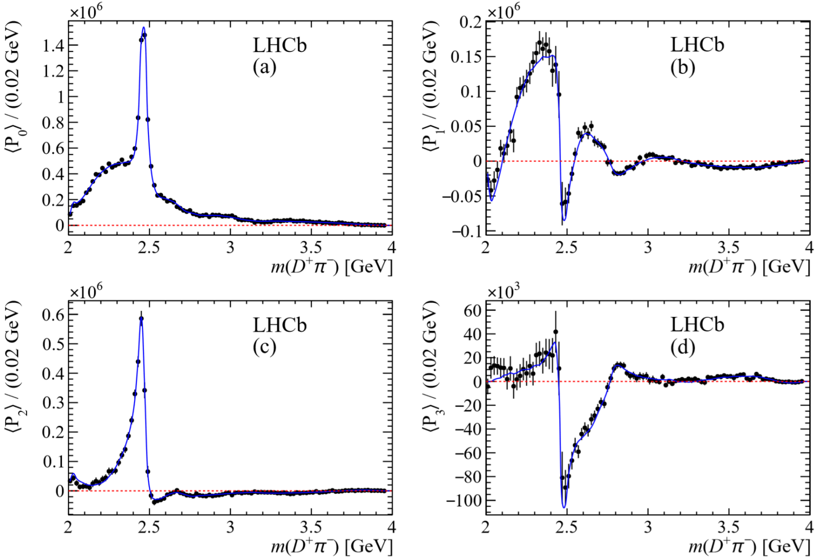
- But is their experimental support for this ?

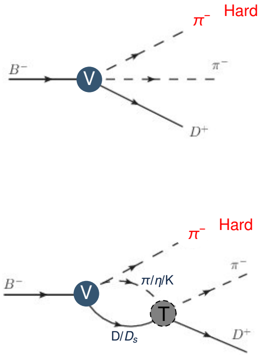
Angular moments of $B^- \to D^+\pi^-\pi^-$

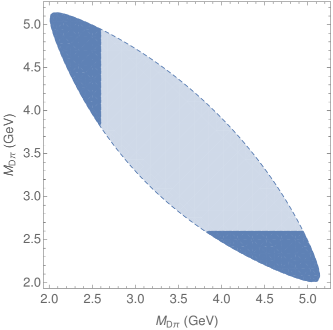
LHCb, PRD94(2016)072001



$$\langle P_\ell \rangle \propto \int dz P_\ell(z) |\mathcal{A}|^2$$

$B^+ \to D^+\pi^-\pi^-$ kinematics



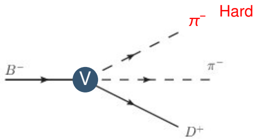


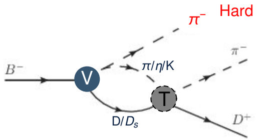
- $B^- \to D^+\pi^-\pi^-$ contains coupled-channel $D\pi$ FSI
- consider S, P, D waves: $\mathcal{A}(B^- \to D^+\pi^-\pi^-) = \mathcal{A}_0(s) + \mathcal{A}_1(s) + \mathcal{A}_2(s)$

  $\to$ P-wave: $D^\star, D^\star(2860)$; D-wave: $D_2(2460)$ as by LHCb

  $\to$ S-wave: use coupled channel $(D\pi, D\eta, D_s\bar{K})$ amplitudes with all parameters fixed before

Chiral effective Lagrangian for weak decay $B^+ \to D\pi\pi^-$





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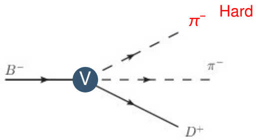

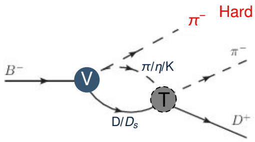

☞ Effective weak Hamiltonian H_{eff} for $\Delta b = 1$ and $\Delta c = 1$:

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ud} (C_1 \mathcal{O}_1^d + C_2 \mathcal{O}_2^d) + (b \to s) + h.c.,$$

$$\mathcal{O}_1^d = (\bar{c}_a b_b)_L (\bar{d}_b u_a)_L, \qquad \mathcal{O}_2^d = (\bar{c}_a b_a)_L (\bar{d}_b u_b)_L.$$

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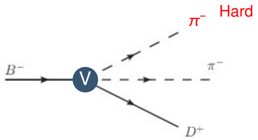

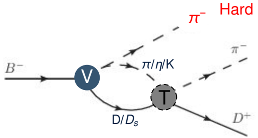

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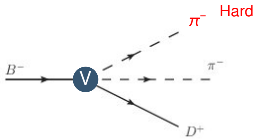
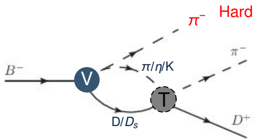
☞ Introducing a spurion H: $H_i^j \mapsto H_{i'}^{j'} (g_L)_i^{i'} (g_L^\dagger)_{j'}^j$,

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} V_{cb}^* H_i^j C (\bar{c}b)_L (\bar{q}^i q_j)_L, \quad H = \begin{pmatrix} 0 & 0 & 0 \\ V_{ud} & 0 & 0 \\ V_{us} & 0 & 0 \end{pmatrix}$$

Chiral effective Lagrangian for weak decay $B^+ \to D\pi\pi^-$





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☞ $g_L \times g_R \in SU(3)_L \times SU(3)_R$, $h \in SU(3)_V$

$$u \mapsto g_R u h^\dagger = h u g_L^\dagger, \quad u_\mu \mapsto h u_\mu h^\dagger,$$

$$B \mapsto B h^\dagger, \quad D \mapsto D h^\dagger, \quad M \mapsto h M h^\dagger,$$

$$t \mapsto h t h^\dagger, \qquad t = u H u^\dagger.$$

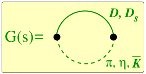
Amplitudes

☞ Effective weak Lagrangian

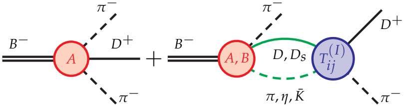
$$\mathcal{L}_{\text{eff}} = B\Big(c_1(u_\mu t M + M t u_\mu) + c_2(u_\mu M + M u_\mu)t + c_3 t(u_\mu M + M u_\mu)$$
$$+c_4(u_\mu\langle Mt\rangle + M\langle u_\mu t\rangle) + c_5 t\langle M u_\mu\rangle + c_6\langle(M u_\mu + u_\mu M)t\rangle\Big)\partial^\mu D^\dagger$$

- S-wave amplitude: $(C = (c_2 + c_6)/(c_1 + c_4))$

$$\mathcal{A}_0(s) \propto E_\pi \left[2 + G_{D\pi}(s)\left(\tfrac{5}{3}T_{11}^{1/2}(s) + \tfrac{1}{3}T_{11}^{3/2}(s)\right)\right]$$
$$+\tfrac{1}{3}E_\eta G_{D\eta}(s)T_{21}^{1/2}(s) + \sqrt{\tfrac{2}{3}}E_{\bar K}G_{D_s\bar K}(s)T_{31}^{1/2}(s)$$
$$+C\,E_\eta G_{D\eta}(s)T_{21}^{1/2}(s)$$



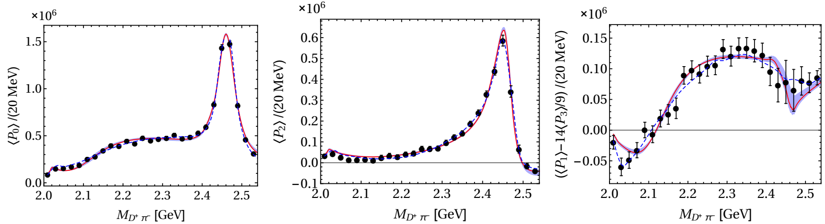
- Only two parameters in the S-wave (one combination of LECs and one subtraction constant in G)



- Unitarity ✓
- Chiral symmetry ✓

Angular moments: $B^- \to D^+\pi^-\pi^-$

MLD, Guo, Meißner, PRD(2018)094018



$$\langle P_0 \rangle \;\propto\; |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2,$$

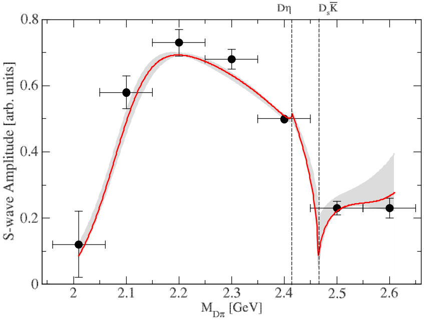
$$\langle P_2 \rangle \;\propto\; \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_0 - \delta_2),$$

$$\langle P_{13} \rangle \;\equiv\; \langle P_1 \rangle - \frac{14}{9}\langle P_3 \rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_0 - \delta_1)$$

- ☞ The S-wave $D\pi$ can be well described using pre-fixed scattering amplitudes
- ☞ Fast variation in [2.4, 2.5] GeV in $\langle P_{13} \rangle$: cusps at $D\eta$ and $D_s\bar{K}$ thresholds

S-wave amplitude

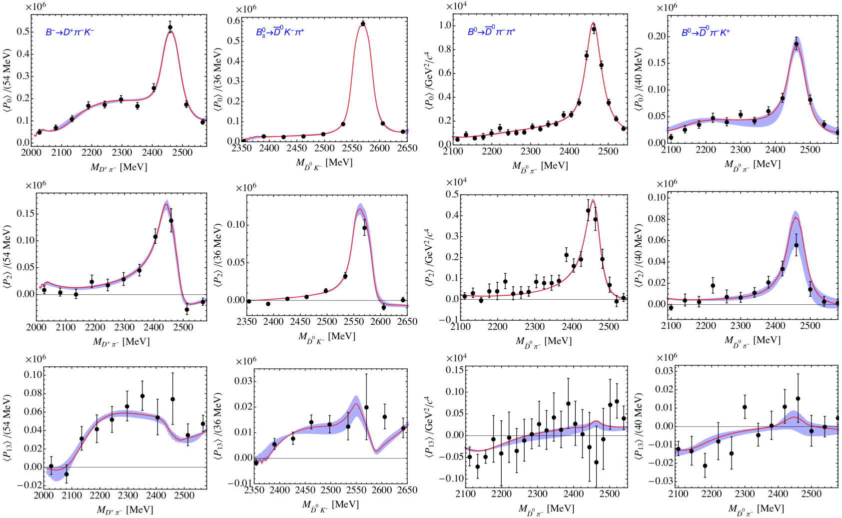
MLD, Guo, Meißner, PRD(2018)094018



Comparison between the S-wave amplitude determined and the S-wave anchor points found in the experimental analysis.

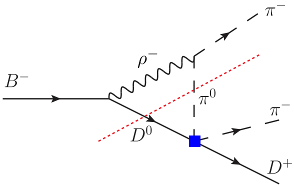
Applications to B decays

M.-L. Du et al., PRD99(2019)114002



Theory of $B^- \to D^+\pi^-\pi^-$ continued

MLD, Guo, Hanhart, Kubis, Meißner, PRL126(2021)192001



$$\mathcal{A}(B^- \to D^+\pi^-\pi^-)|_{p_{\pi^-}\to 0} = \frac{1}{F_\pi}\mathcal{A}(B^0 \to \bar{D}^0\pi^0),$$

$$\mathcal{A}(B^- \to D^0\pi^0\pi^-)|_{p_{\pi^0}\to 0} = -\frac{1}{F_\pi}\mathcal{A}(B^- \to D^0\pi^-),$$

$$\mathcal{B}(B^0 \to \bar{D}^0\pi^0) = 2.63 \times 10^{-4}$$

$$\mathcal{B}(B^- \to D^0\pi^-) = 4.68 \times 10^{-3}$$

☞ Isospin symmetry: $\mathcal{A}(B^- \to D^+\pi^-\pi^-) \sim 2\sqrt{2}\,\mathcal{A}(B^- \to D^0\pi^0\pi^-)$?

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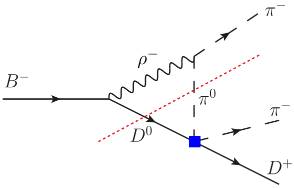

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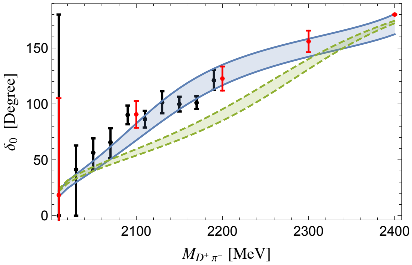
$$\langle P_0\rangle \propto |\mathcal{A}_0|^2 + |\mathcal{A}_1|^2 + |\mathcal{A}_2|^2,$$

$$\langle P_2\rangle \propto \frac{2}{5}|\mathcal{A}_1|^2 + \frac{2}{7}|\mathcal{A}_2|^2 + \frac{2}{\sqrt{5}}|\mathcal{A}_0||\mathcal{A}_2|\cos(\delta_2-\delta_0),$$

$$\langle P_{13}\rangle \equiv \langle P_1\rangle - \frac{14}{9}\langle P_3\rangle \propto \frac{2}{\sqrt{3}}|\mathcal{A}_0||\mathcal{A}_1|\cos(\delta_1-\delta_0),$$

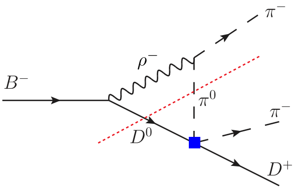
$$\cos(\delta_0-\delta_1) = \sqrt{\frac{3}{10}}\frac{\langle P_{13}\rangle}{\sqrt{\langle P_2\rangle}\sqrt{\langle P_0\rangle - \frac{5}{2}\langle P_2\rangle}}$$



Perturbatively!

Coupled- & crossed-channel effects Khuri-Treiman Equation

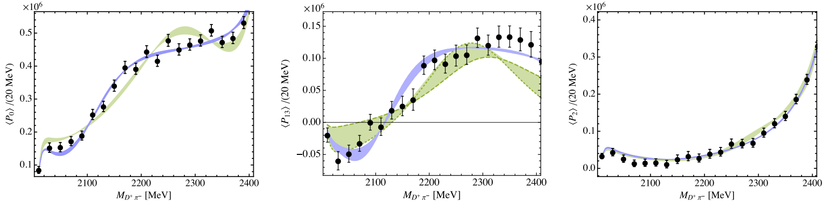
MLD, Guo, Hanhart, Kubis, Meißner, PRL126(2021)192001



$$\mathcal{A}_{+--}(s,t,u) = \mathcal{F}_0^{1/2}(s) + \frac{\kappa(s)}{4} z_s \mathcal{F}_1^{1/2}(s) + \frac{\kappa(s)^2}{16}(3z_s^2-1)\mathcal{F}_2^{1/2}(s) + (t \leftrightarrow s),$$

$$\mathcal{A}_{00-}(s,t,u) = -\frac{1}{\sqrt{2}}\mathcal{F}_0^{1/2}(s) - \frac{\kappa(s)}{4\sqrt{2}} z_s \mathcal{F}_1^{1/2}(s) - \frac{\kappa(s)^2}{16\sqrt{2}}(3z_s^2-1)\mathcal{F}_2^{1/2}(s) + \frac{\kappa_u(u)}{4} z_u \mathcal{F}_1^1(u),$$

$$\mathcal{F}_\ell^I(s) = \Omega_\ell^I(s)\left\{Q_\ell^I(s) + \frac{s^n}{\pi}\int_{s_{\rm th}}^\infty \frac{ds'}{s'^n}\frac{\sin\delta_\ell^I(s')\hat{\mathcal{F}}_\ell^I(s')}{|\Omega_\ell^I(s')|(s'-s)}\right\}, \qquad \hat{\mathcal{F}}_0^{1/2}(s) = -\frac{1}{4\sqrt{2}}\int_{-1}^1 dz_s (t-s)\mathcal{F}_1^1(u),$$



Summary

- Chiral symmetry

  $\hookrightarrow$ a shift of the BW peak

- Thanks to the recent experiment, lattice and EFT developments:

  $\hookrightarrow$ $D^*_{s0}(2317)$ and $D_{s1}(2460)$ are dominantly DK and D^*K molecules;

  $\hookrightarrow$ HQSS: $M_{D_{s1}(2460)} - M_{D^*_{s0}(2317)} \approx M_{D^*} - M_D$;

  $\hookrightarrow$ Two-pole structures of D^*_0 and D_1, the lower ones have smaller masses.

- Fully consistent with the high quality LHCb data on B decays

- Call for a change of paradigm for the positive-parity mesons:

  $\hookrightarrow$ dynamically genereated for ground states

  $\hookrightarrow$ already established for the light scalars

$D^*_0(2300)$ $I(J^P) = 1/2(0^+)$

was $D^*_0(2400)$

There is a strong evidence that recent data on $B \to D\pi\pi$ (AAIJ 2015Y, AAIJ 2016AH) and $B \to D\pi K$ (AAIJ 2014BH, AAIJ 2015V, AAIJ 2015X) call for two poles in the scalar $I = 1/2\ \pi D$ amplitude in this mass range. The data are consistent with a lower pole at $(2105\ ^{+6}_{-8}) - i(102\ ^{+10}_{-11})$ MeV and a higher pole at $(2451\ ^{+35}_{-26}) - i(134\ ^{+7}_{-8})$ MeV (DU 2018A, DU 2019, DU 2021). For details see review on "Heavy Non-$q\bar{q}$ Mesons."

Thank you very much for your attention!