Chiral excitations of heavy-flavored meson systems

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[XYG, Yonggoo Heo, Matthias F.M. Lutz, PRD98(2018)014510, PLB791(2019)86]

[XYG, Matthias F.M. Lutz, arXiv:2103.11323]

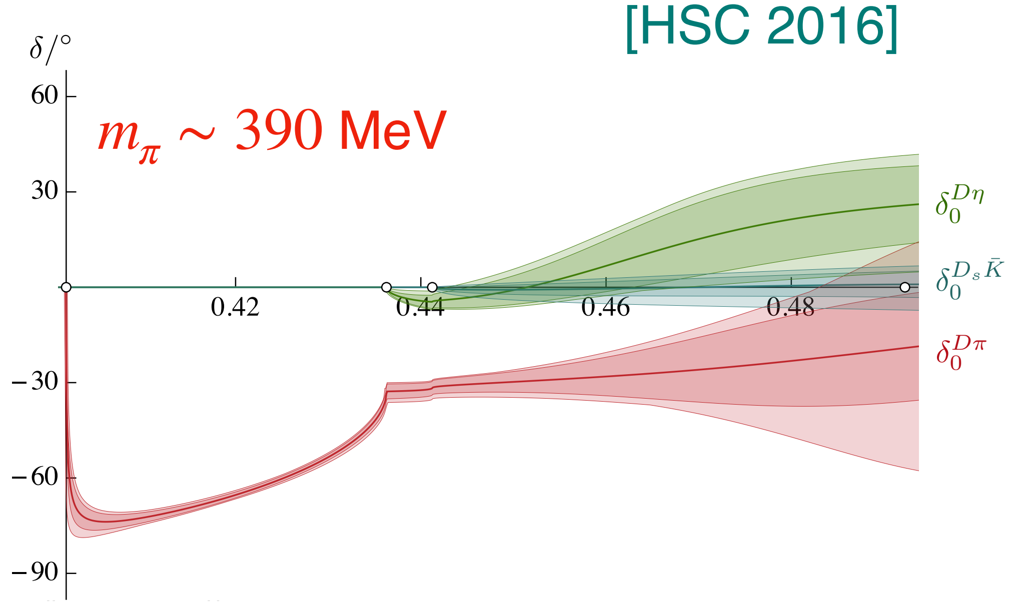
第二届强子与重味物理理论与实验联合研讨会，兰州大学

- **heavy-light quark systems**
  - light quark
    - chiral interactions with Goldstone bosons $\Phi\,(\pi, K, \eta)$
    - SU(3) Chiral perturbation theory
  - heavy quark symmetry
    - the mass splitting between heavy-quark spin partners $\sim O(1/m_Q)$
    - the energy difference from light-quark content in B and D $\sim O(1/m_Q)$
    - heavy-quark effective theory
  - combining different features of low-energy QCD

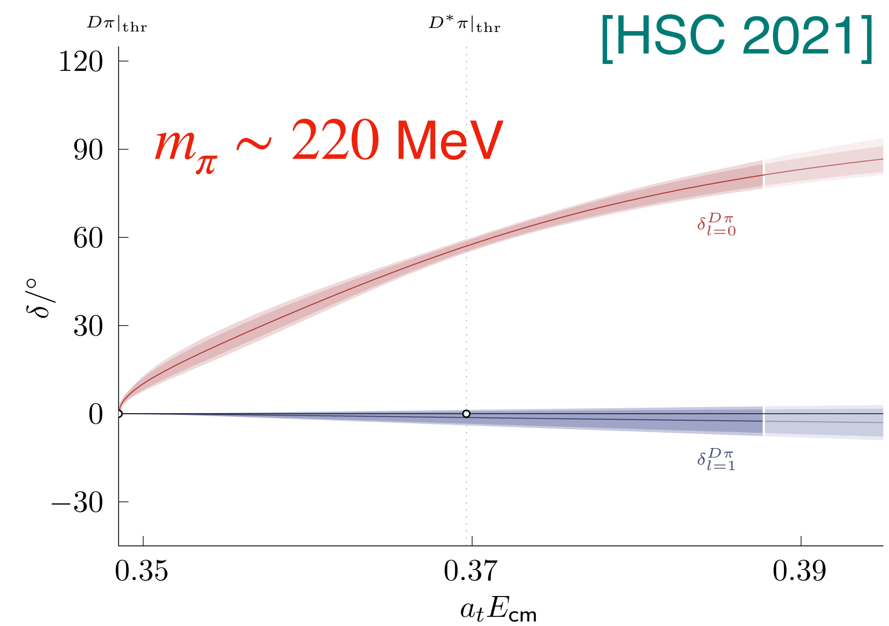
- **heavy-light meson spectrum**
  - discovery of 0^+ excitation $D_{s0}^*(2317)$ [BaBar 2003]
    - ~ 150 MeV lower than quark model [Godfrey,Isgur 1985]
    - its heavy-quark spin partner $D_{s1}(2460)$ (-70 MeV) than QM
    - they are right below $D^{(*)}K$ thresholds
  - molecular states due to chiral dynamics ?
    - dynamically generated from LO SU(3) chiral Lagrangian [Lutz et al 2003, Guo et al 2006]
    - lattice scatterings involving $D^{(*)}K$ interpolators
      - [Mohler et al 2013, Lang et al 2014]
      - [HSC 2020]

- the light-flavor anti-triplet partner of $D_{s0}^*(2317)$?
  - $(I, S) = (1/2, 0)$ broad resonance $D_0^*(2400)$ [Belle 2004]?
- lattice results on πD scattering [HSC 2016, 2021]

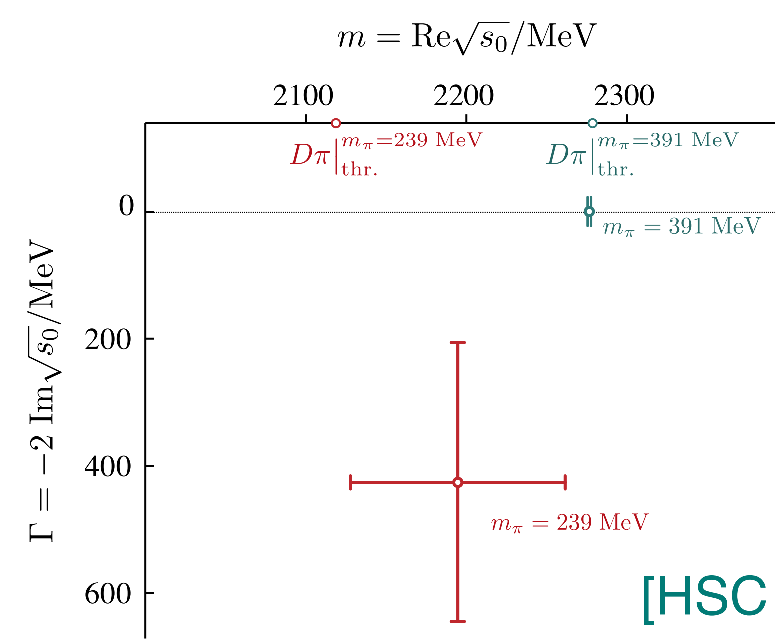
[HSC 2016]



[HSC 2021]



  - at $m_\pi \sim 390$ MeV, a bound state ~ 2.28 GeV
  - at $m_\pi \sim 220$ MeV, a resonance ~ 2.2 GeV
    - physical pion mass?



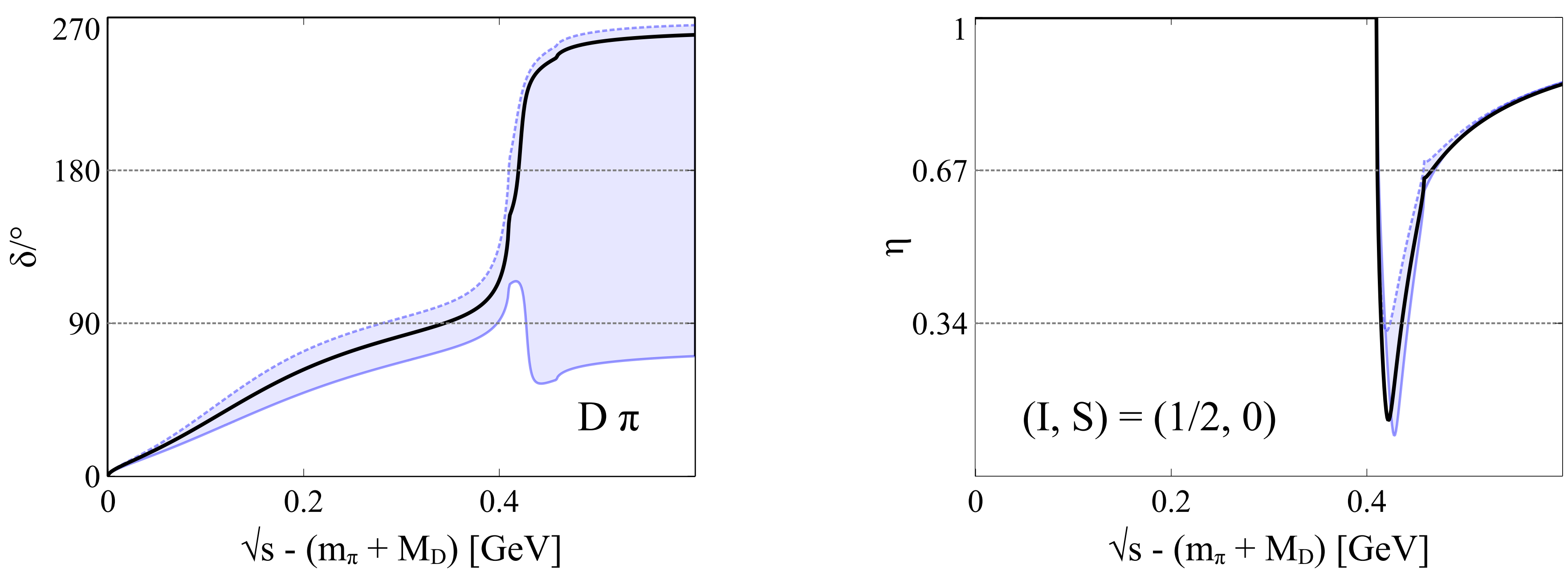
[HSC 2021]

- $(I, S) = (1/2, 0)$ coupled-channel dynamics with chiral interaction

  - two poles from LO chiral interaction between D-ground states ($J^P = 0^-, 1^-,$) and Goldstone bosons [Lutz et al 2003]

$$\mathscr{L}_{\text{kin}} = \partial_\mu H \partial^\mu \bar{H} - \left(\bar{M} - \frac{3}{4}\Delta\right)^2 H \bar{H} \quad - \partial_\mu H^{\mu\alpha} \partial^\nu \bar{H}_{\nu\alpha} + \frac{1}{2}\left(\bar{M} + \frac{1}{4}\Delta\right)^2 H^{\mu\alpha} \bar{H}_{\mu\alpha}$$
$$+ \frac{1}{8f^2}\left(\partial^\mu H [\Phi, \partial_\mu \Phi] \bar{H} - \partial^\mu H_{\mu\alpha} [\Phi, \partial_\nu \Phi] \bar{H}^{\nu\alpha} + h.c.\right)$$

    - at ~ 2.12 GeV [anti-triplet] (broad) and ~ 2.43 GeV [sextet] (narrow)



  - the experimental data can be accommodated into the two-pole description [Du et al 2017]

- how about the effects of higher-order chiral interaction?

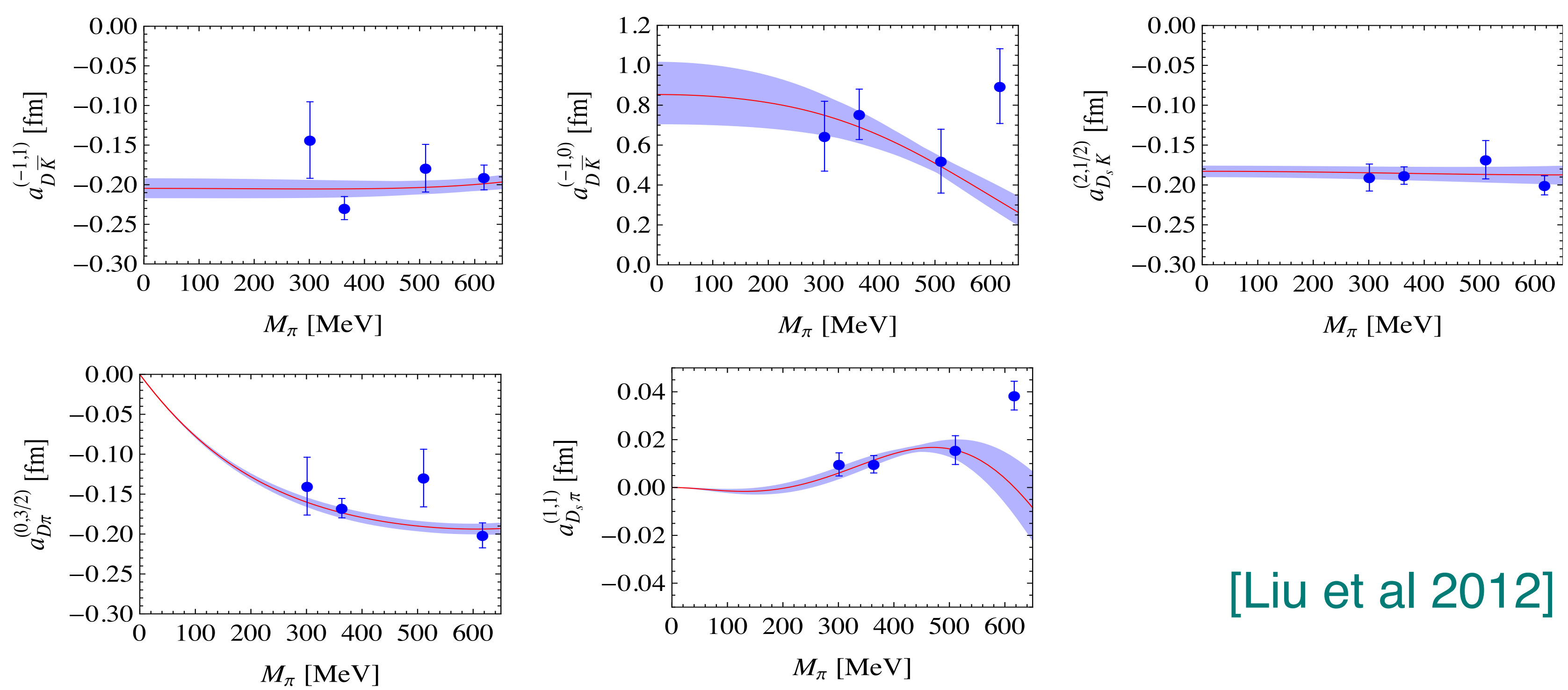
- chiral Lagrangian at NLO
  - chiral symmetry breaking $\sim m_{u,d,s}$

$$\mathscr{L}_\chi = -\left(4\,c_0 - 2\,c_1\right) H\,\bar{H}\,\mathrm{tr}\chi_+ - 2\,c_1\,H\,\chi_+\,\bar{H} + \left(2\,\tilde{c}_0 - \tilde{c}_1\right) H^{\mu\nu}\,\bar{H}_{\mu\nu}\,\mathrm{tr}\chi_+ + \tilde{c}_1\,H^{\mu\nu}\,\chi_+\,\bar{H}_{\mu\nu}$$

with $\chi_+ = \mathrm{diag}(m, m, m_s) + O(\Phi)$

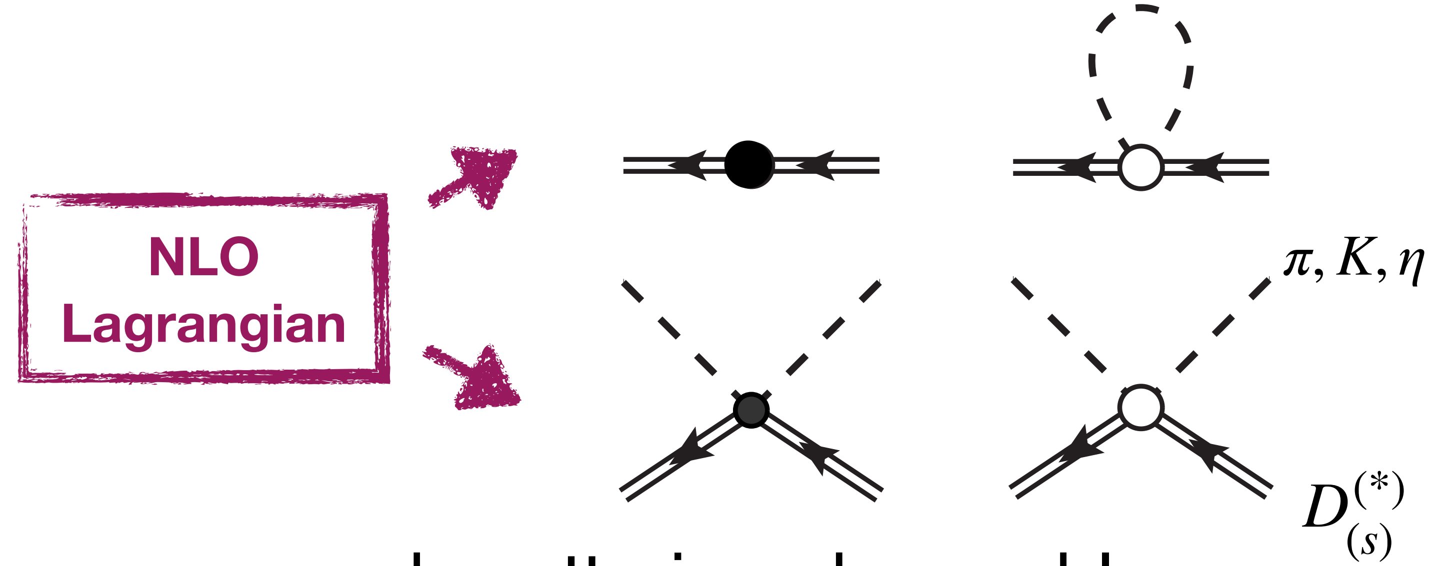
    - 4 LECs
  - chiral symmetry preserving $\sim \partial^2\Phi$
    - 8 more LECs $\xrightarrow{\text{heavy-quark spin symmetry}}$ 4 LECs

- fit to lattice $D-\Phi$ scattering lengths at unphysical m_π [Liu et al 2012, Geng et al 2014]



[Liu et al 2012]

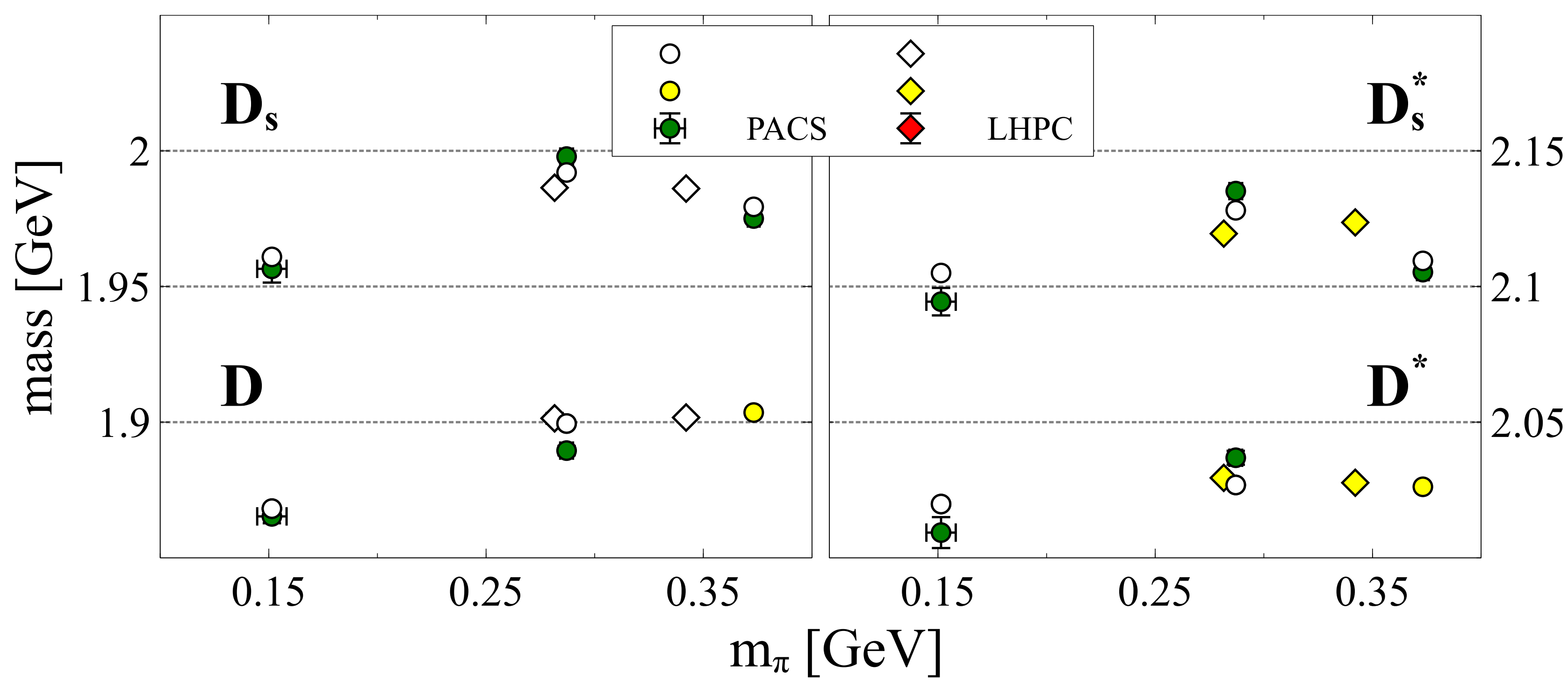
- the universality of LECs



- Fit to lattice data of D-meson masses and scattering observables — simultaneously

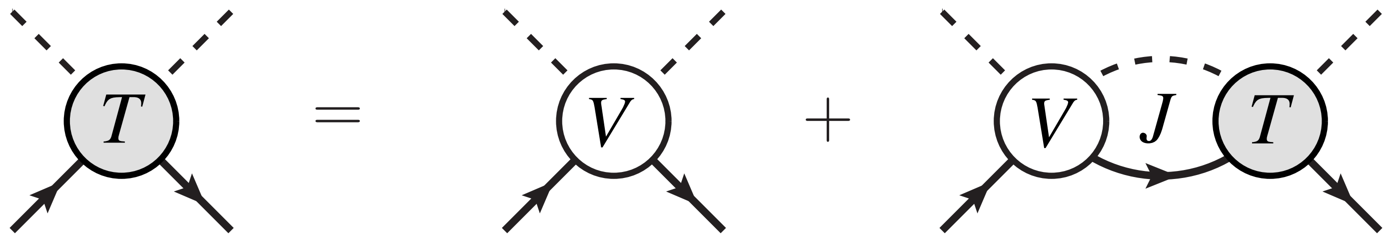
- D-ground state masses at various unphysical quark masses

  - 64 data points on ensembles from 5 lattice collaborations

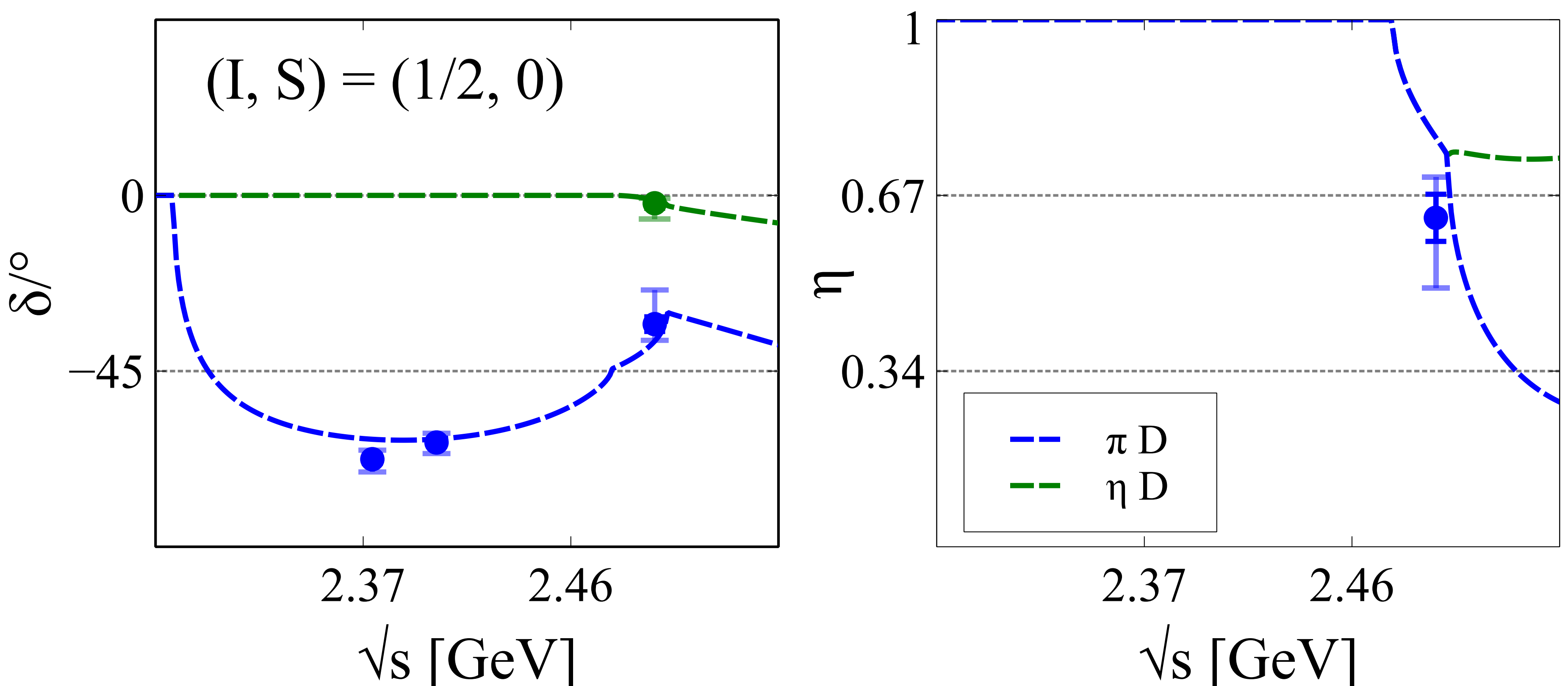


[XYG, Heo, Lutz 2018]

- scattering informations
  - s-channel unitarity guaranteed by resummation



- scattering lengths from Liu et al. on unphysical pion masses
- πD, ηD phase shifts from HSC on $m_\pi \sim 390$ MeV



[XYG, Heo, Lutz 2018]

- the effects of NLO chiral interactions:
  - confirm the two poles in the πD scattering channel
    - w/o ηD phase shift information on lattice ($m_\pi \sim 390$MeV)

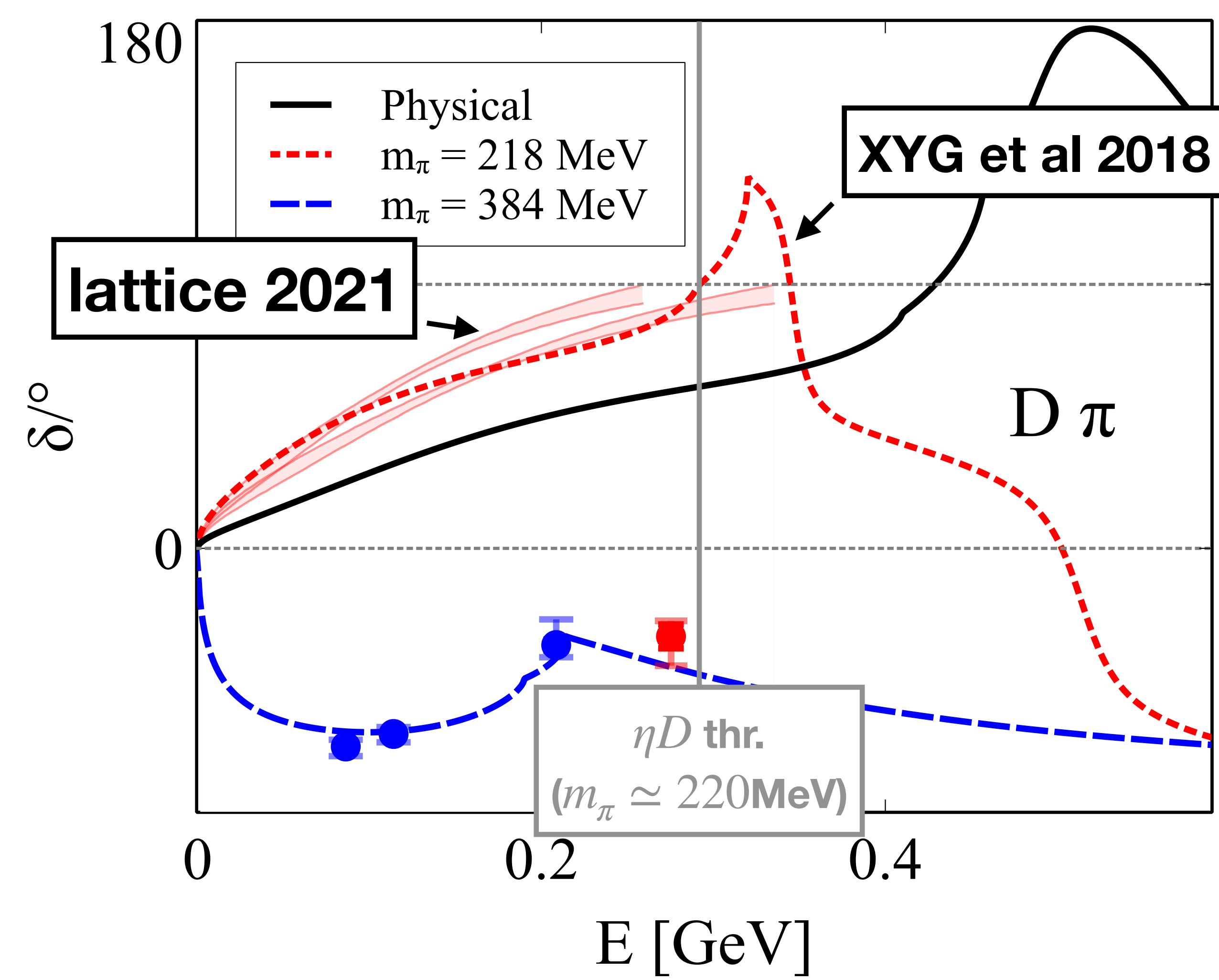
$$\sqrt{s}_{\rm pole} = 2.12(1) - 0.16(3)i \text{ (anti-triplet)}, \; 2.46(1) - 0.10(6)i \text{ (sextet) [GeV]}$$

    - w/ ηD phase shift information on lattice ($m_\pi \sim 390$MeV)

$$\sqrt{s}_{\rm pole} = 2.08(1) - 0.20(4)i \text{ (anti-triplet)}, \; 2.46(5) - 0.10(1)i \text{ (sextet) [GeV]}$$

  - predicted πD phase shift at $m_\pi \simeq 220$ MeV,

    amazingly agree with recent HSC result [HSC 2021]



[XYG, Heo, Lutz 2018]

- **the open-beauty partner ?**
  - where is the open-beauty partner of $D_{s0}^*(2317)$?
    - LO chiral interaction: $M \sim (5.64 - 5.73)$ GeV [Lutz et al 2003, Guo et al 2003]
    - NLO estimations: $M \sim (5.72 - 5.73)$ GeV [Geng et al 2014, Du et al 2018]
    - lattice out of BK scattering: $M \sim 5.71$ GeV [Lang et al 2015]
    - no experimental evidence yet
  - where is its anti-triplet partner in πB scattering channel?
  - could there be resonance at πB_s $(I, S) = (1,1)$ channel $\rightarrow$ X(5568) (?)
- what can we learn from our comprehensive chiral NLO study in the open-charm sector ?

- **projection of LECs in b-sector from c-sector → heavy quark scaling behavior**

  - the same Lagrangian describes D and B meson chiral interaction

$$\mathscr{L}_\chi = -(4\,c_0 - 2\,c_1)\,H\bar{H}\,\mathrm{tr}\chi_+ - 2\,c_1\,H\chi_+\bar{H} + (2\,\tilde{c}_0 - \tilde{c}_1)\,H^{\mu\nu}\bar{H}_{\mu\nu}\,\mathrm{tr}\chi_+ + \tilde{c}_1\,H^{\mu\nu}\chi_+\bar{H}_{\mu\nu}$$

    - → NLO chiral correction to heavy-light meson ground-state masses

$$M_H^2 = \begin{cases} \left(\bar{M} - \frac{3}{4}\Delta\right)^2 + (4\,c_0 - 2\,c_1)\,\Pi_H^{(2),0} + 2\,c_1\Pi_H^{(2),1} + \text{loops}, & H \in [J^P = 0^-] \\ \left(\bar{M} + \frac{1}{4}\Delta\right)^2 + (4\,\tilde{c}_0 - 2\,\tilde{c}_1)\,\Pi_H^{(2),0} + 2\,\tilde{c}_1\Pi_H^{(2),1} + \text{loops}, & H \in [J^P = 1^-] \end{cases}$$

	$\Pi_H^{(2),0}$	$\Pi_H^{(2),1}$
$H_{u/d}$	$2B_0(2m + m_s)$	$2B_0 m$
H_s	$2B_0(2m + m_s)$	$2B_0 m_s$

  - LO scaling

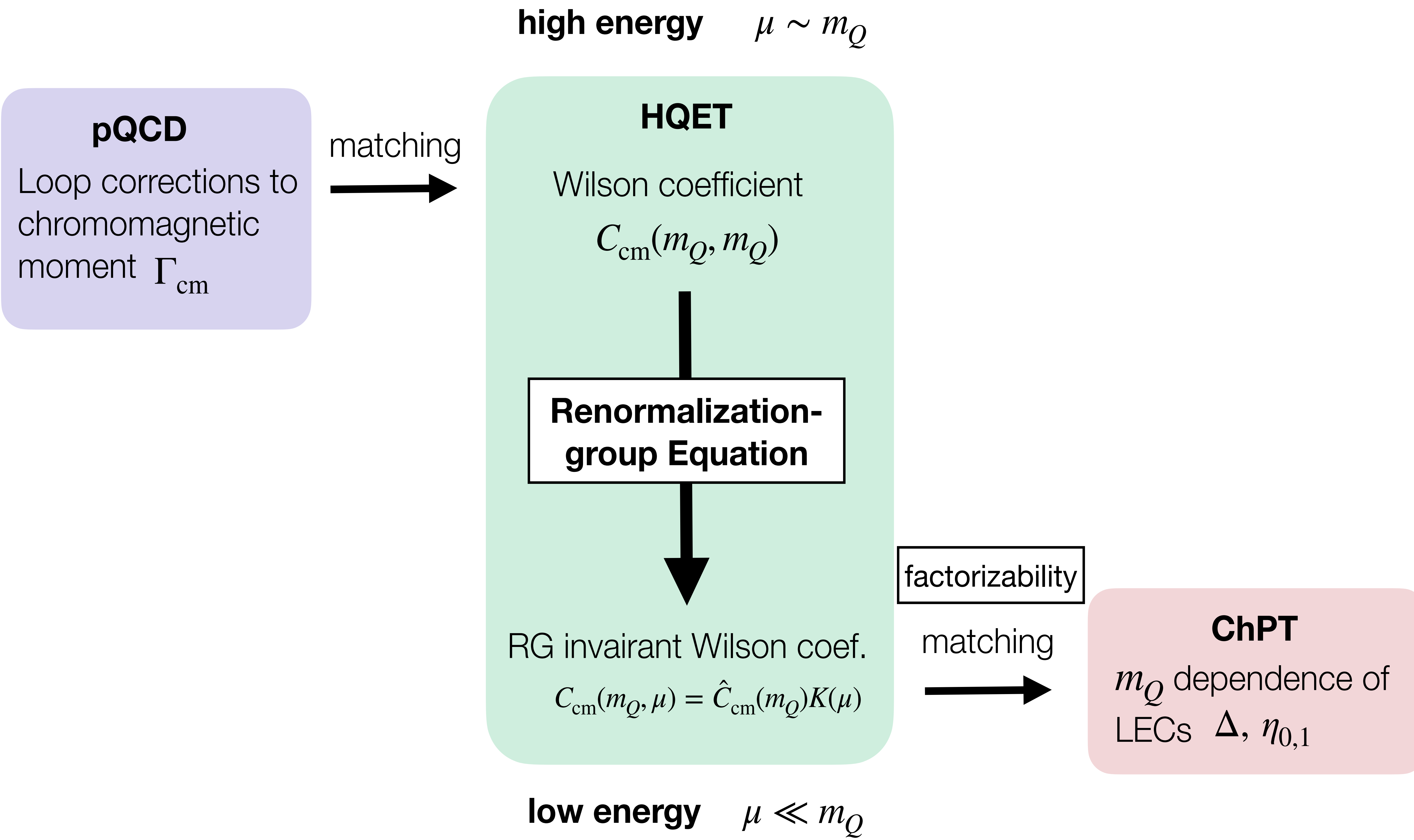
$$c_i(m_Q) \sim \tilde{c}_i(m_Q) \sim \bar{M}^{(Q)} \qquad \begin{cases} \bar{M}^{(c)} = \frac{1}{4}\left(M_D + 3M_{D^*}\right)_{\chi-\mathrm{limit}} \\ \bar{M}^{(b)} = \frac{1}{4}\left(M_B + 3M_{B^*}\right)_{\chi-\mathrm{limit}} \end{cases}$$

  - heavy-quark symmetry violation leads to

$$c_i(m_Q) = \bar{M}^{(Q)}\left(C_i + \frac{\zeta_i}{\bar{M}^{(Q)}} - \frac{3}{4}\frac{\eta_i^{(Q)}}{\bar{M}^{(Q)}}\right),$$

$$\tilde{c}_i(m_Q) = \bar{M}^{(Q)}\left(C_i + \frac{\zeta_i}{\bar{M}^{(Q)}} + \frac{1}{4}\frac{\eta_i^{(Q)}}{\bar{M}^{(Q)}}\right)$$

  - from high-energy physics → **matching to heavy-quark effective theory**


high energy $\mu \sim m_Q$
pQCD
Loop corrections to chromomagnetic moment $\Gamma_{\rm cm}$
matching
HQET
Wilson coefficient
$C_{\rm cm}(m_Q, m_Q)$
Renormalization-group Equation
RG invairant Wilson coef.
$C_{\rm cm}(m_Q, \mu) = \hat{C}_{\rm cm}(m_Q)K(\mu)$
factorizability
matching
ChPT
m_Q dependence of LECs Δ, $\eta_{0,1}$
low energy $\mu \ll m_Q$

high energy $\mu \sim m_Q$

pQCD

Loop corrections to chromomagnetic moment $\Gamma_{\rm cm}$

matching →

HQET

Wilson coefficient

$C_{\rm cm}(m_Q, m_Q)$

↓

Renormalization-group Equation

↓

RG invairant Wilson coef.

$$C_{\rm cm}(m_Q, \mu) = \hat{C}_{\rm cm}(m_Q) K(\mu)$$

low energy $\mu \ll m_Q$

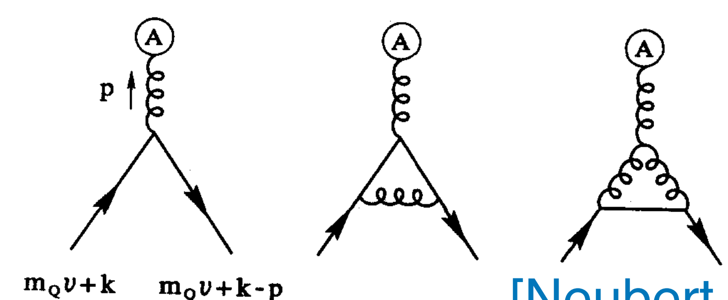
- $0^-, 1^-$ **mass from HQET**

$$M_H(m_Q) = \begin{cases} m_Q + \bar{\Lambda}_{(H)} + \dfrac{\mu^2_{\pi(H)}}{2\,m_Q} - \dfrac{\mu^2_{G(H)}}{2\,m_Q} & H \in [0^-] \\ m_Q + \bar{\Lambda}_{(H)} + \dfrac{\mu^2_{\pi(H)}}{2\,m_Q} + \dfrac{\mu^2_{G(H)}}{6\,m_Q} & H \in [1^-] \end{cases}$$

- light dof. energy $\bar{\Lambda}$
- h.q. kinetic-energy moment μ_π^2

m_Q-independent

- chromomagnetic moment μ_G^2 depends on m_Q
- assume factorizability
  $\mu_G^2(m_Q, m_q) = \hat{C}_{\rm cm}(m_Q)\,\hat{\mu}_G(m_q)$
- matching to perturbative QCD



[Neubert 1994]

  - at (1~2)-loop [Falk et al 1990, Neubert et al 1997, Grozin et al 1997]
  - ~~3-loop [Grozin et al 2007]~~
  - RG evolution $\rightarrow R = \dfrac{\hat{C}_{\rm cm}(m_b)}{\hat{C}_{\rm cm}(m_c)} \simeq 0.80(4)$

▸ matching the ChPT with HQET 0^-, 1^- self-energy

- LO relation
  [Wise et al 1992, Brambilla et al 2017]

$$\bar{M}^{(Q)} = \left(m_Q + \bar{\Lambda} + \frac{\mu_\pi^2}{2m_Q} \right)_{\chi\text{-limit}}, \quad \Delta^{(Q)} = \frac{2\,\mu_G^2}{3\bar{M}^{(Q)}}\Big|_{\chi\text{-limit}}$$

- the chiral decomposition of heavy-quark expansion moments

$$\bar{\Lambda}_{(H)} = \bar{\Lambda}\Big|_{\chi\text{-limit}} + (2\,C_0 - C_1)\,\Pi_H^{(2),0} + C_1\,\Pi_H^{(2),1} + \ldots$$

$$\mu^2_{\pi(H)} = \mu_\pi^2\Big|_{\chi\text{-limit}} + (4\,\zeta_0 - 2\,\zeta_1)\,\Pi_H^{(2),0} + 2\,\zeta_1\,\Pi_H^{(2),1} + \ldots$$

$$\hat{\mu}^2_{G(H)} = \hat{\mu}_G^2\Big|_{\chi\text{-limit}} + \frac{6\eta_0^{(Q)} - 3\eta_1^{(Q)}}{2\,\hat{C}_{\rm cm}}\Pi_H^{(2),0} + \frac{3\eta_1^{(Q)}}{2\,\hat{C}_{\rm cm}}\Pi_H^{(2),1} + \ldots$$

	$\Pi_H^{(2),0}$	$\Pi_H^{(2),1}$
$H_{u/d}$	$2B_0(2m+m_s)$	$2B_0 m$
H_s	$2B_0(2m+m_s)$	$2B_0 m_s$

- $C_{0,1},\ \zeta_{0,1}$ m_Q-independent; $C_i = \frac{1}{4\bar{M}^{(c)}}\left(c_i^{(c)} + 3\,\tilde{c}_i^{(c)} - 4\,\zeta_i\right)$,

- $$\frac{\bar{M}^{(b)}\Delta^{(b)}}{\bar{M}^{(c)}\Delta^{(c)}} = \frac{\eta_{0,1}^{(b)}}{\eta_{0,1}^{(c)}} = \frac{\hat{C}_{\rm cm}(m_b)}{\hat{C}_{\rm cm}(m_c)} \simeq 0.80(4) \qquad \eta_i^{(c)} = \left(\tilde{c}_i^{(c)} - c_i^{(c)}\right)$$

determined in charm sector

[XYG, Lutz, 2103.11323]

- **the LECs determined in the charm sector are translated to the beauty sector**
  - 3 free parameters $\bar{M}^{(b)}$, $\zeta_{0,1}$ fitted to 4 B-meson ground state masses
  - other parameters determined by the heavy-quark scaling behavior and the LECs in the charm sector

	Fit 1	Fit 2	Fit 3	Fit 4
$\bar{M}^{(b)}$ [GeV]	5.3743	4.8540	5.3303	5.3666
ζ_0	0.0921	-1.5072	-0.0839	0.0523
ζ_1	0.1689	0.1233	0.1585	0.1678
C_0 [GeV^{-1}]	0.0602	0.8777	0.1774	0.1145
C_1 [GeV^{-1}]	0.2376	0.3916	0.3382	0.3445
$\eta_0^{(b)}$	-0.0145	-0.0302	-0.0176	-0.0170
$\eta_1^{(b)}$	-0.0238	0.0318	-0.0276	-0.0238
$\Delta^{(b)}$ [GeV]	0.0562	0.0643	0.0563	0.0568

[XYG, Lutz, 2103.11323]

- **poles in unphysical Riemann sheets in open-beauty coupled-channel scattering amplitudes**

  - the open-beauty partners of $D_{s0}^*(2317)$, $D_{s1}(2460)$

	wo latt. $\delta_{\eta D}$ info.	w/ latt. $\delta_{\eta D}$ info.	**previous works**
0^+	5.63(4) GeV	5.57(6) GeV	5.64~5.72 GeV
1^+	5.68(4) GeV	5.62(6) GeV	5.69~5.78 GeV

  - poles in the $\pi B^{(*)}$ (coupled-channel) scatterings $(I, S) = (1/2,0)$

	anti-triplet		sextet	
	wo latt. $\delta_{\eta D}$ info.	w/ latt. $\delta_{\eta D}$ info.	wo latt. $\delta_{\eta D}$ info.	w/ latt. $\delta_{\eta D}$ info.
0^+ (GeV)	$5.52(3) - 0.10(3)i$	$5.51(2) - 0.12(5)i$	$5.81(1) - 0.01(0)i$	$5.75(3) - 0.05(2)i$
1^+ (GeV)	$5.57(2) - 0.10(3)i$	$5.56(2) - 0.12(5)i$	$5.86(1) - 0.02(0)i$	$5.80(3) - 0.06(2)i$

  - πB_s, $B\bar{K}$ scatterings $(I, S) = (1,1)$
    - sextet component with a pole far from the physical region $\sim 5.80(3) - 0.14(8)\, i$ GeV
    - cannot be X(5568)

[XYG, Lutz, 2103.11323]

- **Summary**
    - the LECs of NLO open-charm SU(3) chiral Lagrangian are determined,
        - by fitting to the lattice data on D-meson ground state masses and scatterings between D-Goldstone boson at various unphysical pion masses
        - anti-triplet and sextet resonances in $0^+,\ 1^+$ open-charm scatterings
        - rightly predicted the s-wave πD phase shifts on $m_\pi \sim 220$ MeV, recently confirmed by lattice calculation
    - project the LECs in the open-beauty sector
        - by matching the NLO chiral formula to HQET for $0^-,\ 1^-$ heavy-light meson masses, the heavy-quark scaling behavior of LECs determined by RG-invariant Wilson coefficient at 2-loop level
        - the $O(m_q)$ correction to the heavy-quark expansion moments are determined by the corresponding Wilson coefficient and the lattice data in open-charm sector
    - NLO effects of chiral interactions to open-beauty coupled-channel scatterings
        - refined prediction to open-beauty partners of $D^*_{s0}(2317)$, $D_{s1}(2460)$: $M =$ 5.59(8), 5.64(8) GeV
        - anti-triplet and sextet resonances in s-wave $(I, S) = (1/2, 0)$ open-beauty scatterings
        - X(5568) cannot be explained as chiral excitation

Thank you