

Quark mass dependence on hadron resonances

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What do we want to do? as an important question to answer

* We want to:

- Analyze the quark mass dependence on $D_{s0}(2317)$

* Why we want to do that?

- Quark model predicts them above their thresholds but they lie below them
- There is debate about whether they are quark states or if they are molecular states

What do we need to do?

as an important question to answer

* We need to:

- Compute the $D\bar{K} \rightarrow D\bar{K}$ scattering amplitude with $I=0, S=1, C=1$
- Calculate the pole of the amplitude, the resonance
- Obtain D meson masses as functions of pion mass
- Plot the curve of the resonance as function of quark masses

D and D_s meson mass functions

fitting

* Meson mass equations from HQET at one loop order

$$\frac{1}{4}(D + 3D^*) = m_H + \alpha_a - \sum_{X=\pi,K,\eta} \beta_a^{(X)} \frac{M_X^3}{16\pi f^2} + \sum_{X=\pi,K,\eta} (\gamma_a^{(X)} - \lambda_a^{(X)} \alpha_a) \frac{M_X^2}{16\pi^2 f^2} \log(M_X^2/\mu^2) + c_a$$

$$(D^* - D) = \Delta + \sum_{X=\pi,K,\eta} (\gamma_a^{(X)} - \lambda_a^{(X)} \Delta) \frac{M_X^2}{16\pi^2 f^2} \log(M_X^2/\mu^2) + \delta c_a$$

* E. E. Jenkins, Nucl. Phys. B 412, 181 (1994), hep-ph/9212295

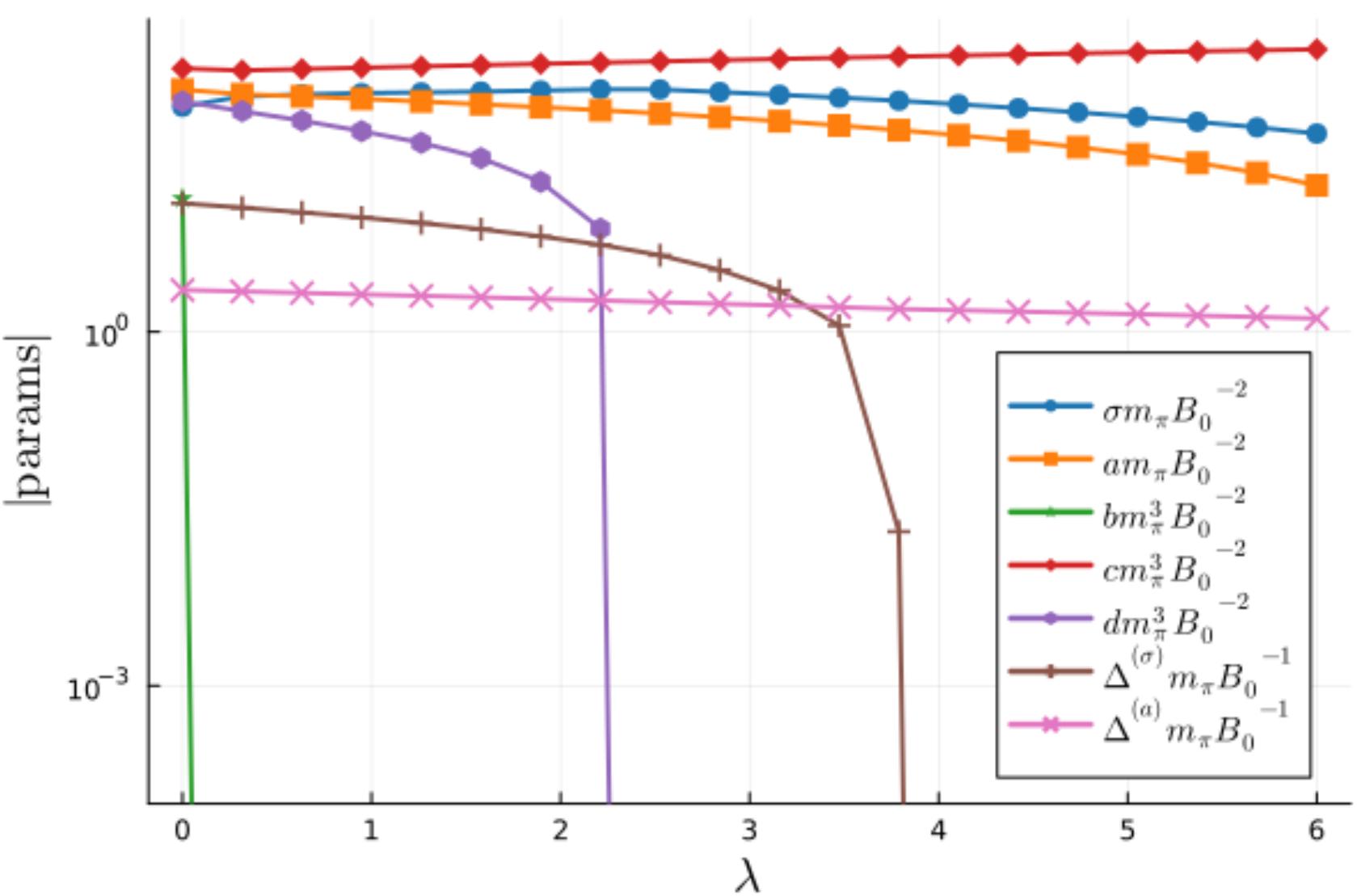
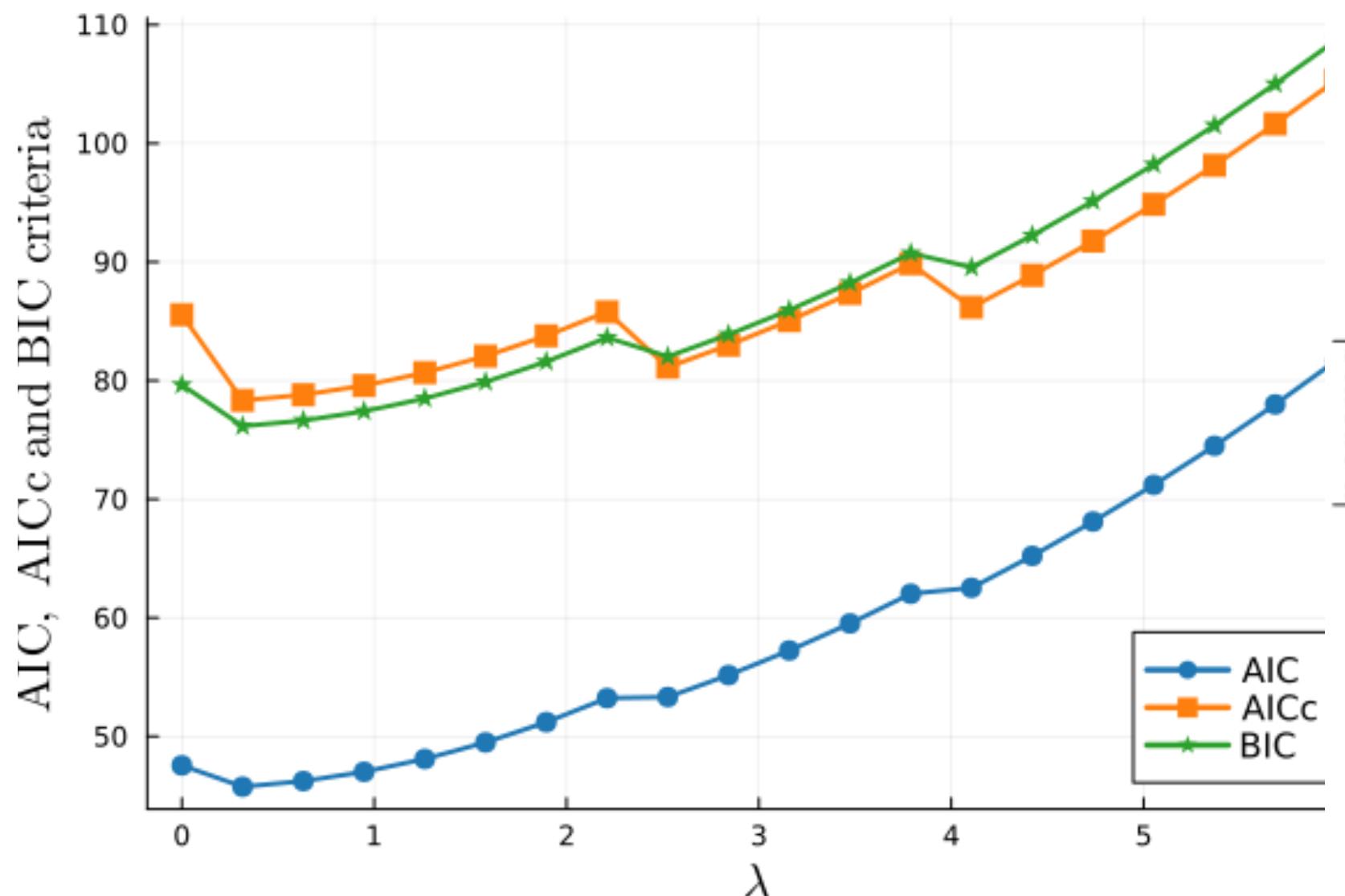
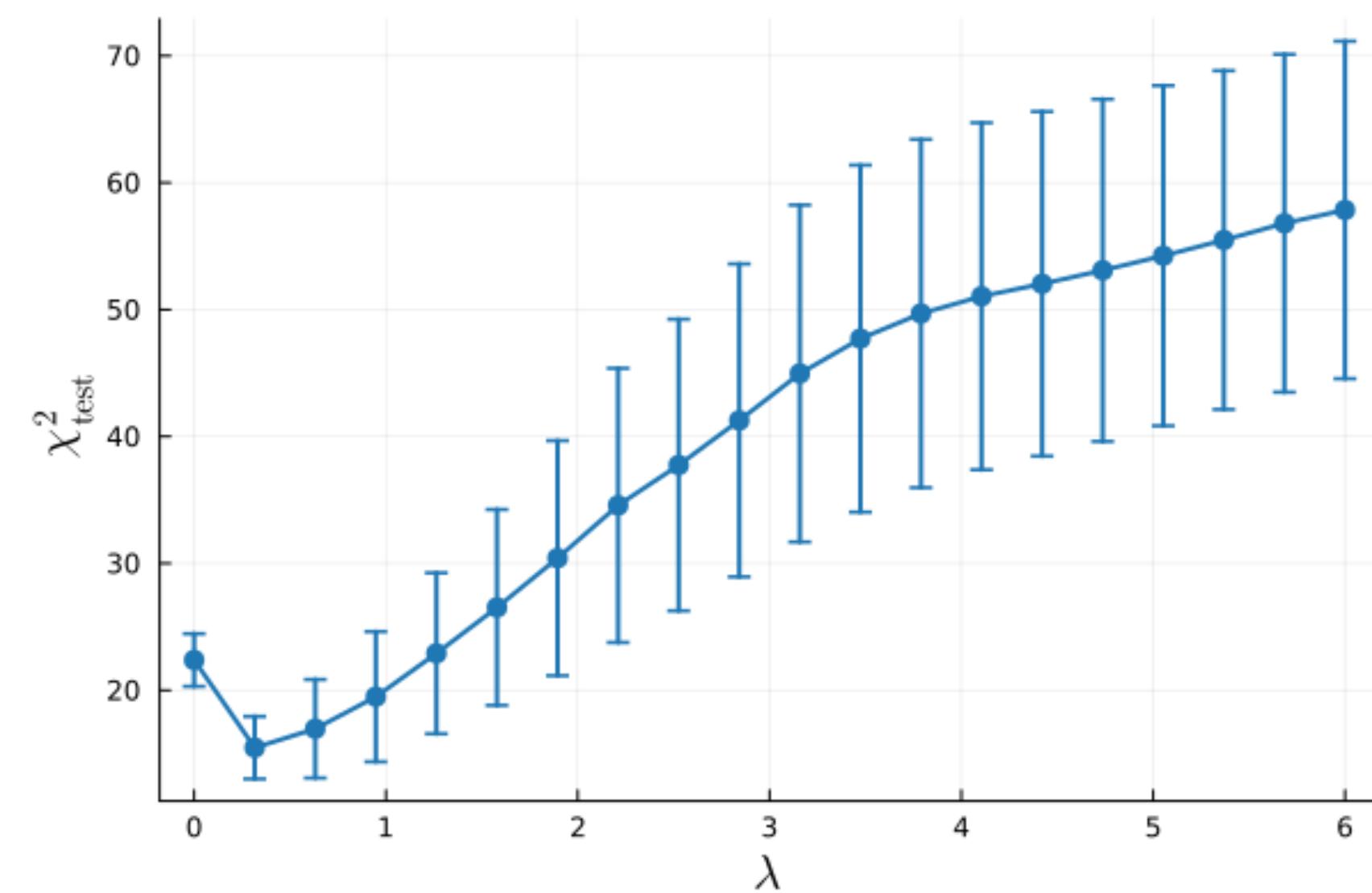
$$\left. \begin{array}{l} \frac{1}{4}(D + 3D^*) = m_H + f(\sigma, a, b, c, d) \\ (D^* - D) = \Delta + g(\Delta^{(\sigma)}, \Delta^{(a)}) \end{array} \right\} \begin{array}{c} 10 \text{ parameters} \\ + \\ 7 \text{ parameters} \end{array} \rightarrow \begin{array}{c} 17 \text{ parameters} \\ 72 \text{ points} \end{array}$$

LASSO

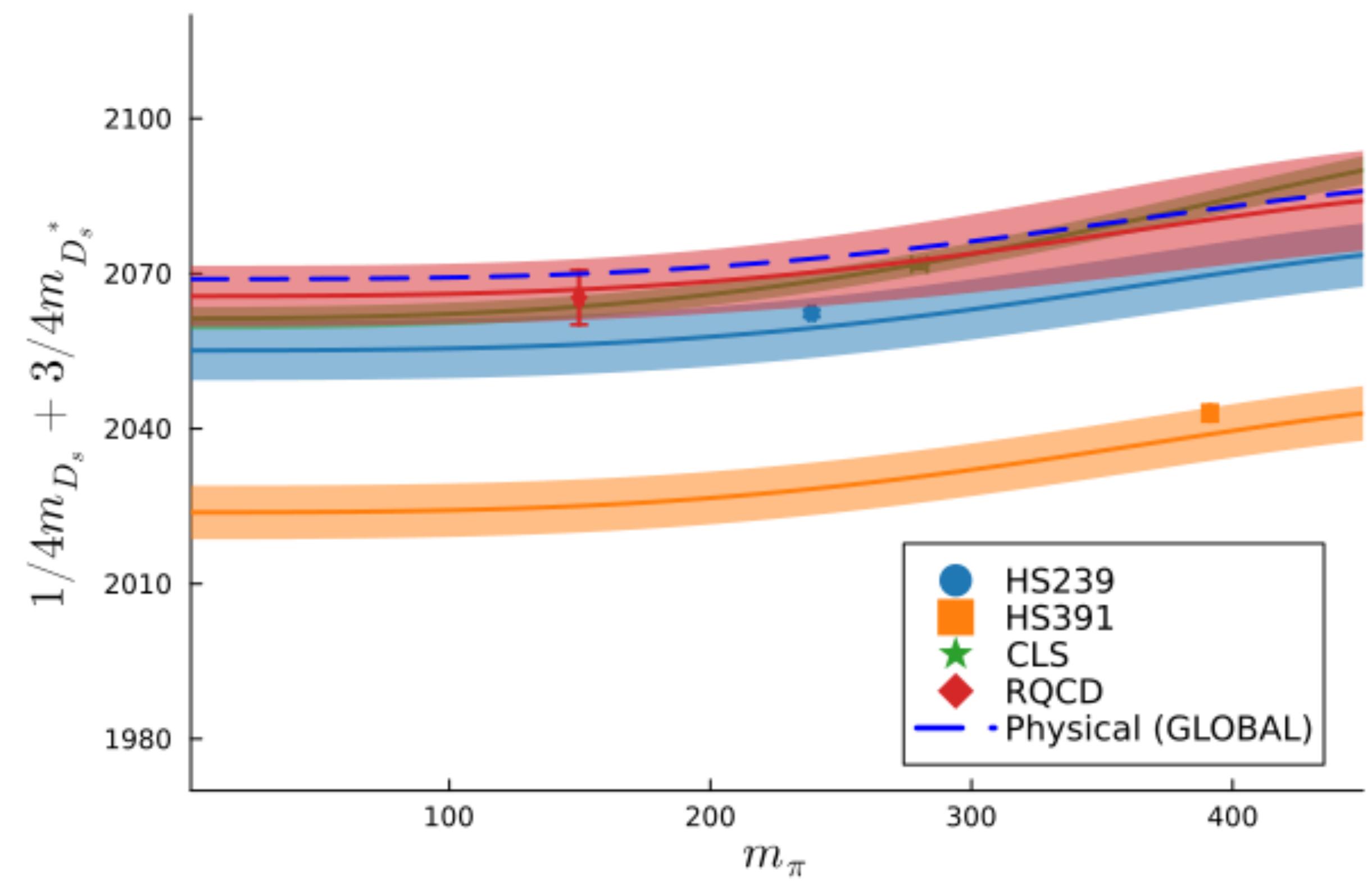
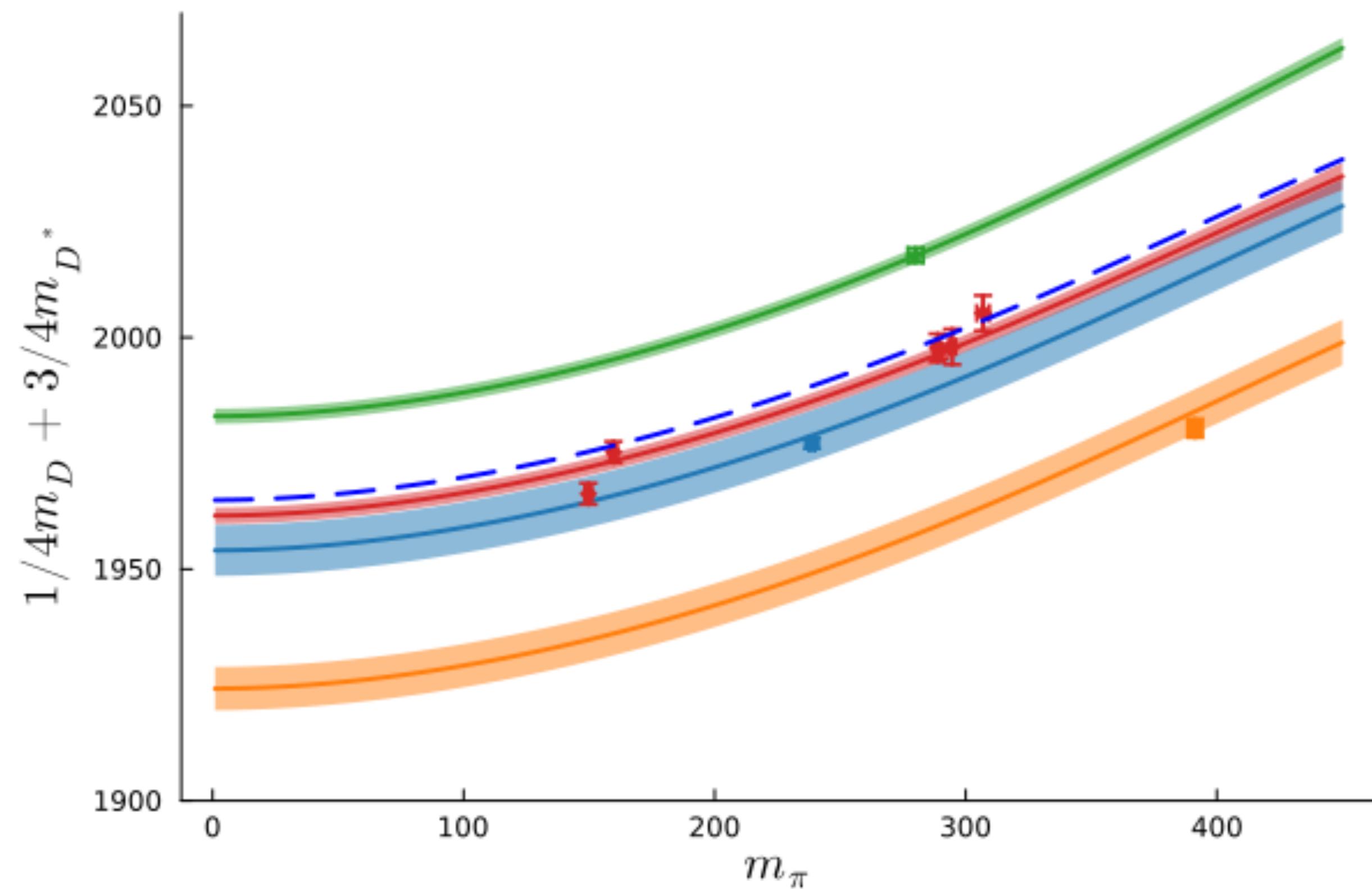
$$\chi_P^2(p, d) = \chi^2(p, d) + \lambda^4 \sum_i^n |p_i| \rightarrow$$

70% of data $\chi_P^2(p, d_{train})$
30% of data $\chi_P^2(p, d_{test})$

*J. Landay, M. Döring, C. Fernández-Ramírez, B. Hu, and R. Molina, Phys. Rev. C 95, 015203 (2017), 1610.07547.



D and D_s meson mass functions fitting (after LASSO)



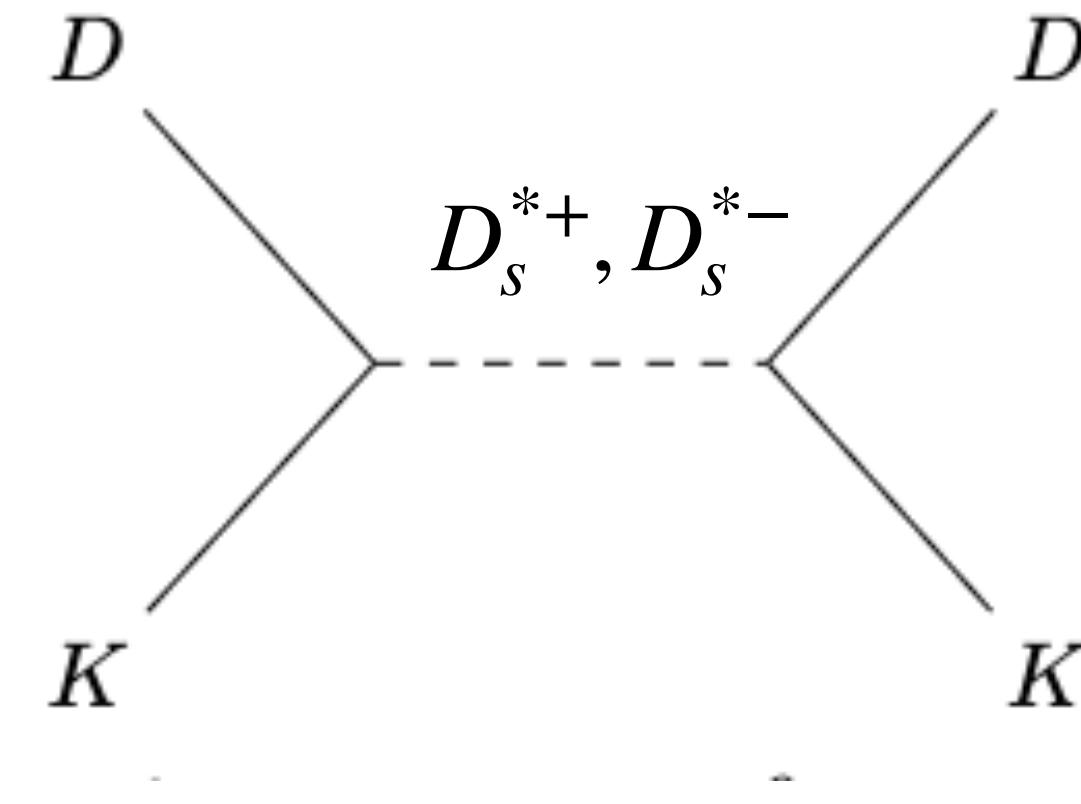
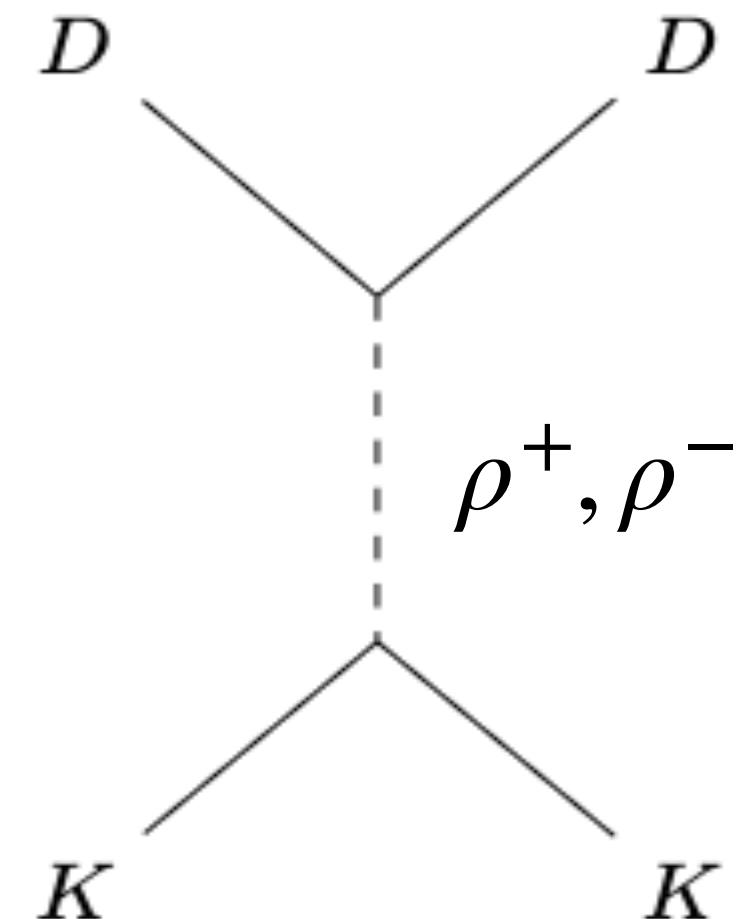
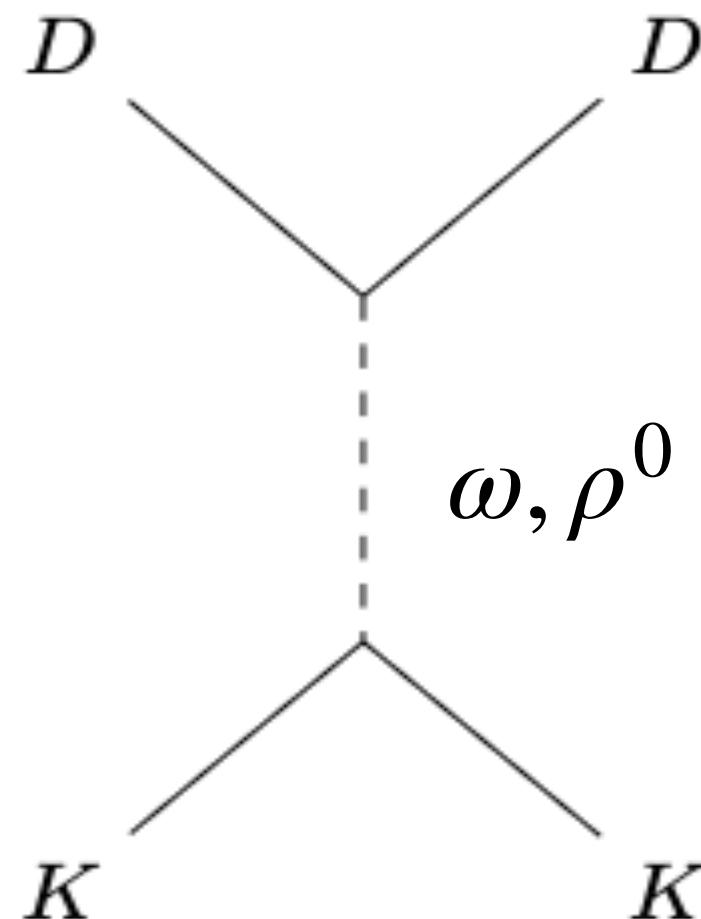
Scattering amplitudes

* Lagrangian from Hidden gauge symmetry formalism

- $\mathcal{L}_{VPP} = ig < [\partial_\mu \Phi, \Phi] V^\mu >$, $\mathcal{L}_{VVV} = ig < (\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu >$

* The total amplitude from

- Bethe-Salpeter equation $\rightarrow T = \frac{V}{1 - GV}$



Parameters for the energy levels fit

$$V_{ex} = \frac{V_{c\bar{s}}^2}{s - m_{c\bar{s}}^2}, \quad V_{c\bar{s}}(s) = -\frac{c}{f} \sqrt{M_D m_{c\bar{s}}} \frac{s + m_K^2 - M_D^2}{\sqrt{s}},$$

*M. Albaladejo, P. Fernandez-Soler, J. Nieves, and P. G. Ortega, Eur. Phys. J. C 78, 722 (2018), 1805.07104.

$$V \rightarrow V + V_{ex} \quad \rightarrow \quad c, m_{c\bar{s}}$$

$$G \quad a = a_1 + a_2 m_\pi^2 \quad \rightarrow \quad a_1, a_2$$

Finite volume energy levels

(one more) fit

* HSC energy levels

- $m_\pi = 239 \text{ MeV} \rightarrow 13 \text{ points}$
- $m_\pi = 391 \text{ MeV} \rightarrow 17 \text{ points}$

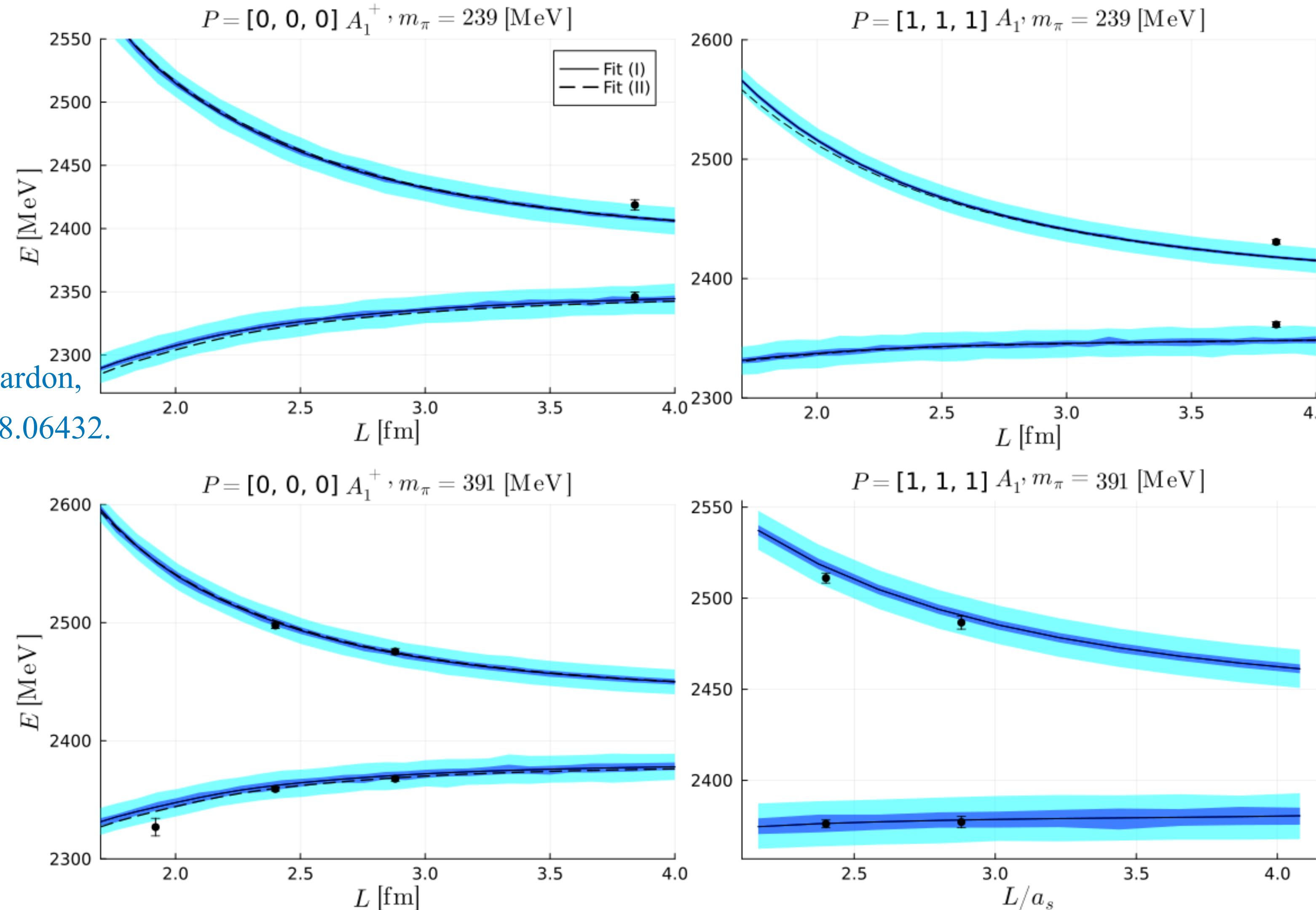
*G. K. C. Cheung, C. E. Thomas, D. J. Wilson, G. Moir, M. Peardon, and S. M. Ryan (Hadron Spectrum), JHEP02, 100 (2021), 2008.06432.

*Fit I

$$V_{ex} = 0 \rightarrow a_1, a_2$$

*Fit II

$$V_{ex} \neq 0 \rightarrow a_1, a_2, c, m_{c\bar{s}}$$



More energy levels

the global fit

* RQCD energy levels

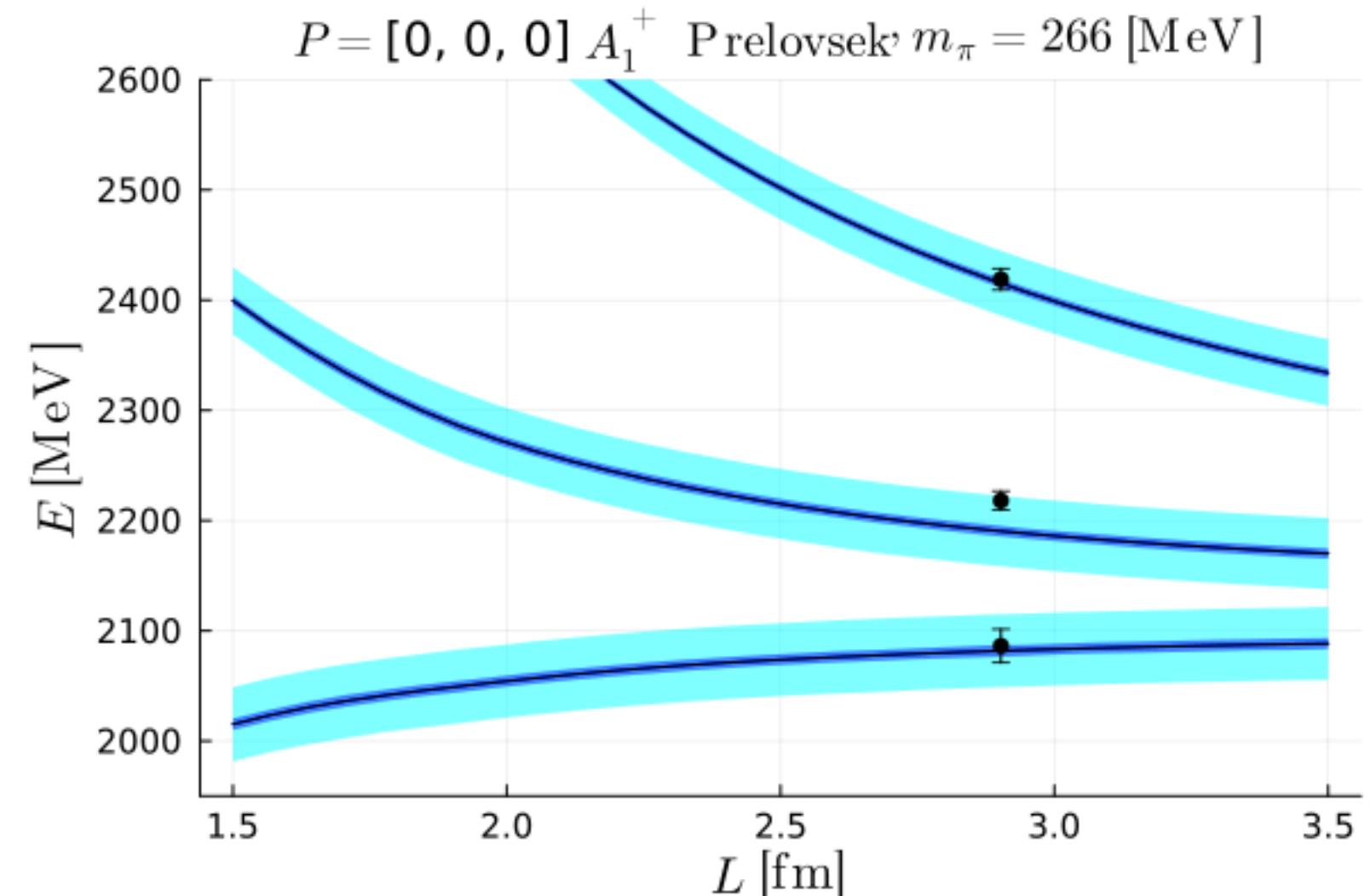
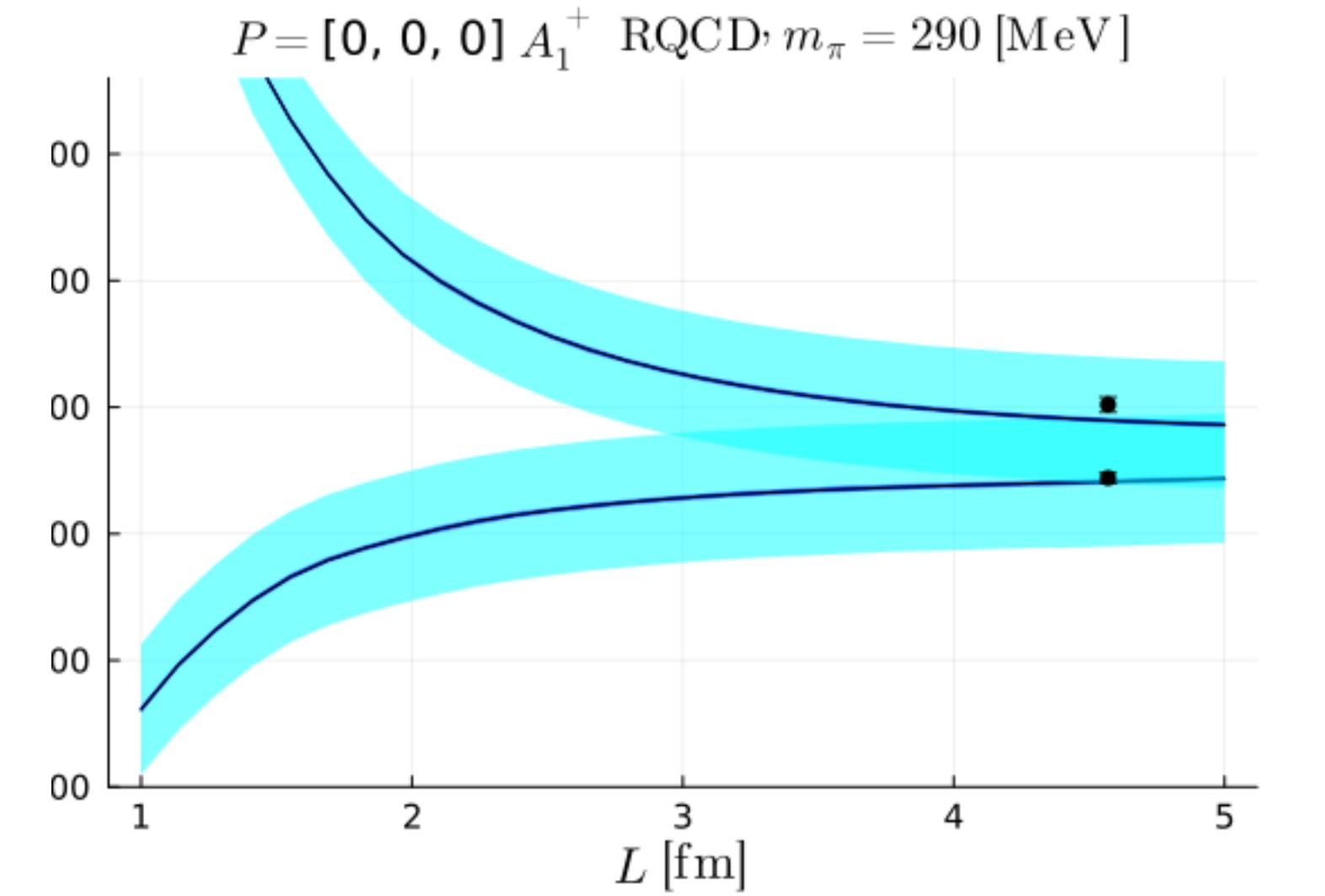
- $m_\pi = 150 \text{ MeV} \rightarrow 8 \text{ points}$
- $m_\pi = 290 \text{ MeV} \rightarrow 4 \text{ points}$

*G. S. Bali, S. Collins, A. Cox, and A. Schäfer,
Phys. Rev. D 96, 074501 (2017), 1706.01247.

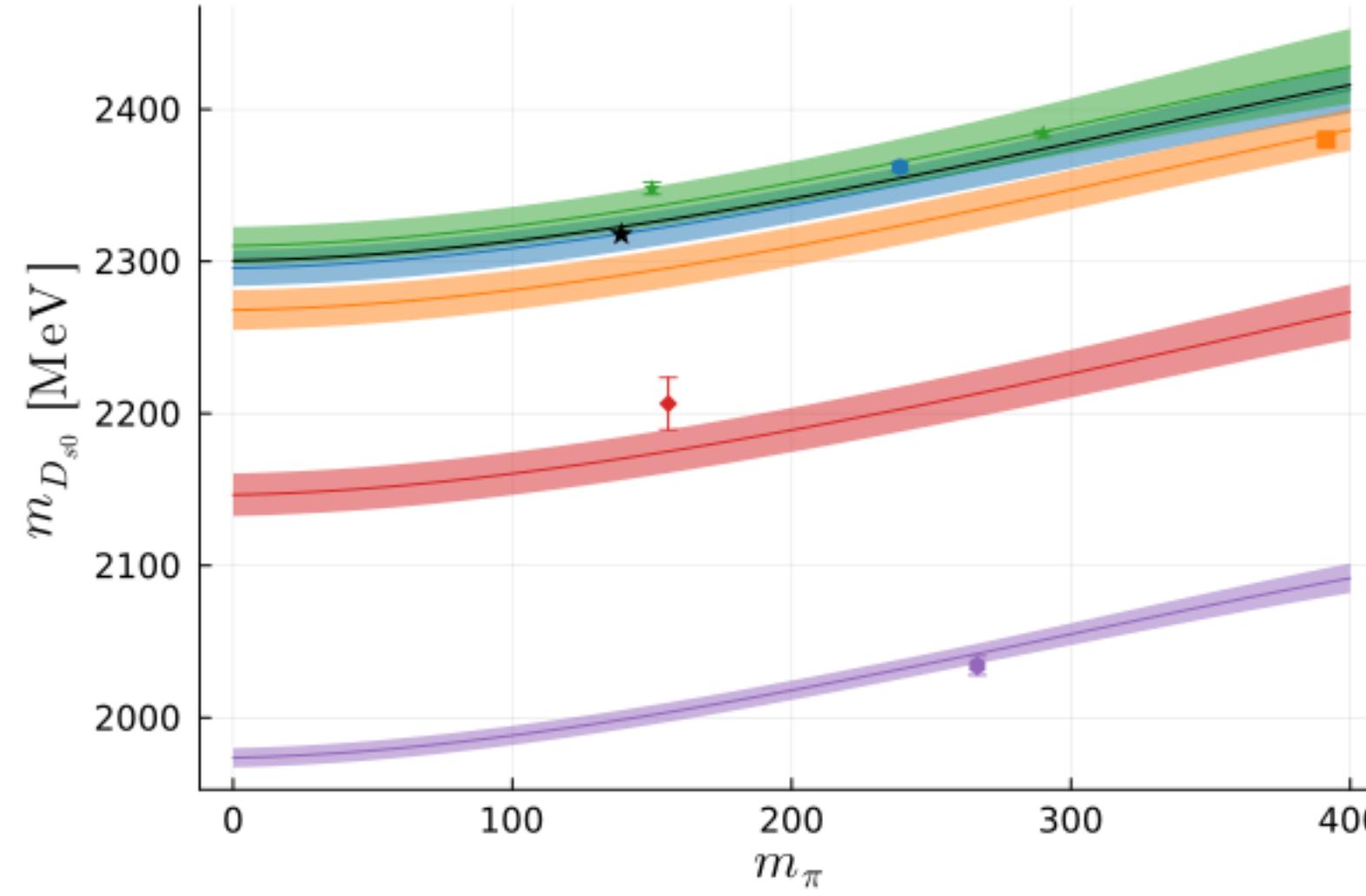
* PACS-CS, Prelovsek et al. energy levels

- $m_\pi = 156 \text{ MeV} \rightarrow 3 \text{ points}$
- $m_\pi = 266 \text{ MeV} \rightarrow 3 \text{ points}$

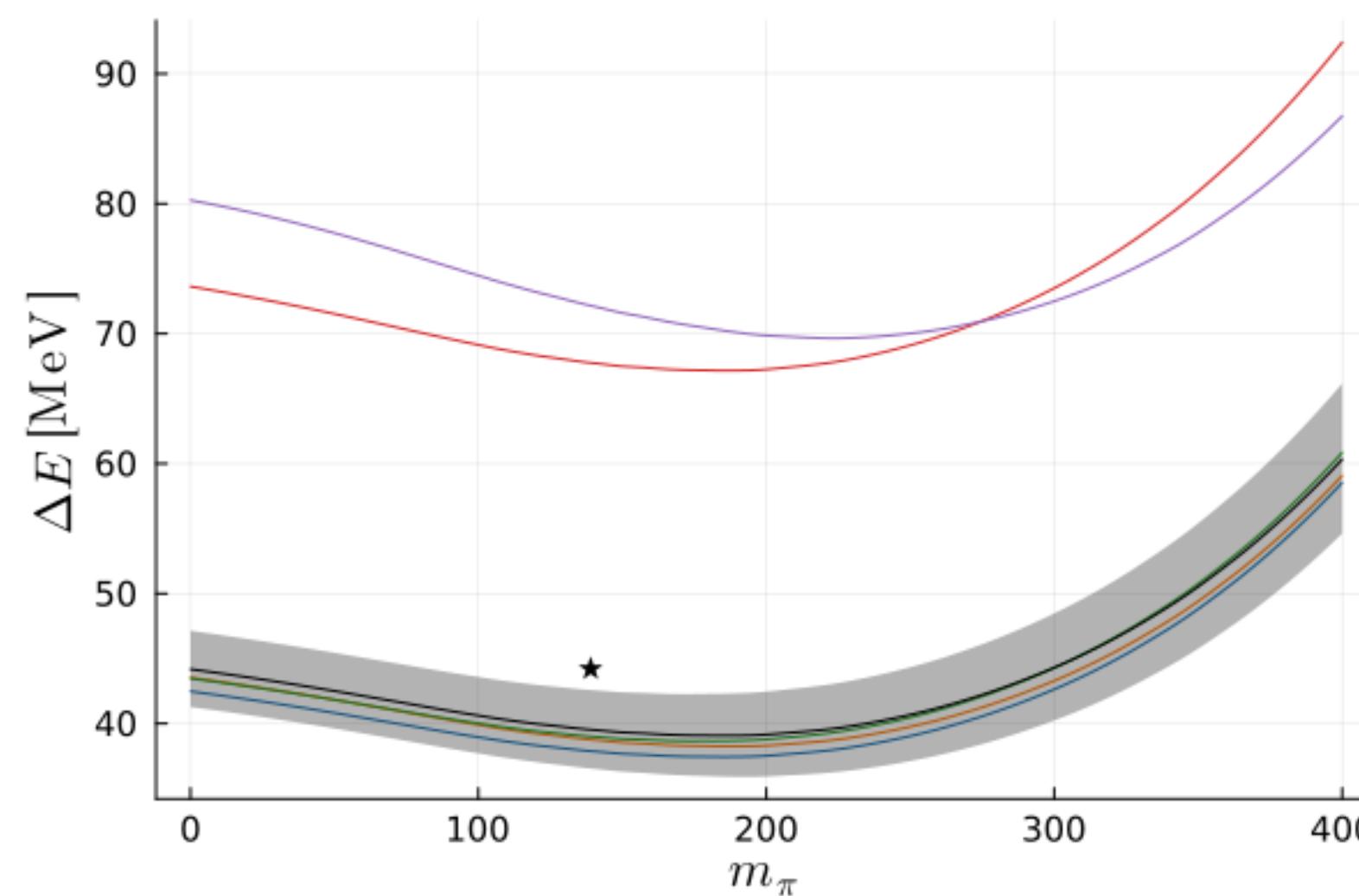
*D. Mohler, C. B. Lang, L. Leskovec, S. Prelovsek, and R. M. Woloshyn,
Phys. Rev. Lett. 111, 222001 (2013), 1308.3175.



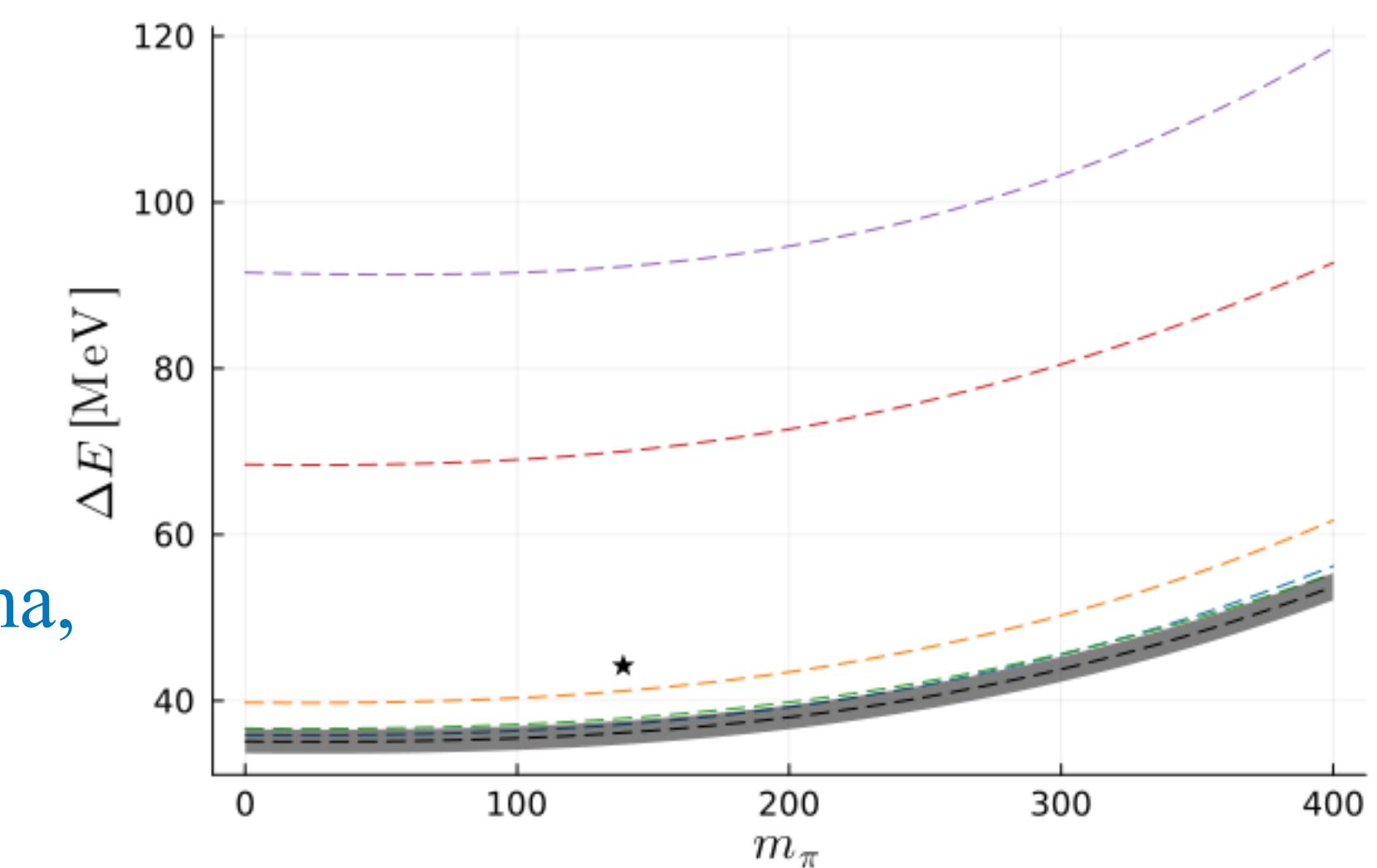
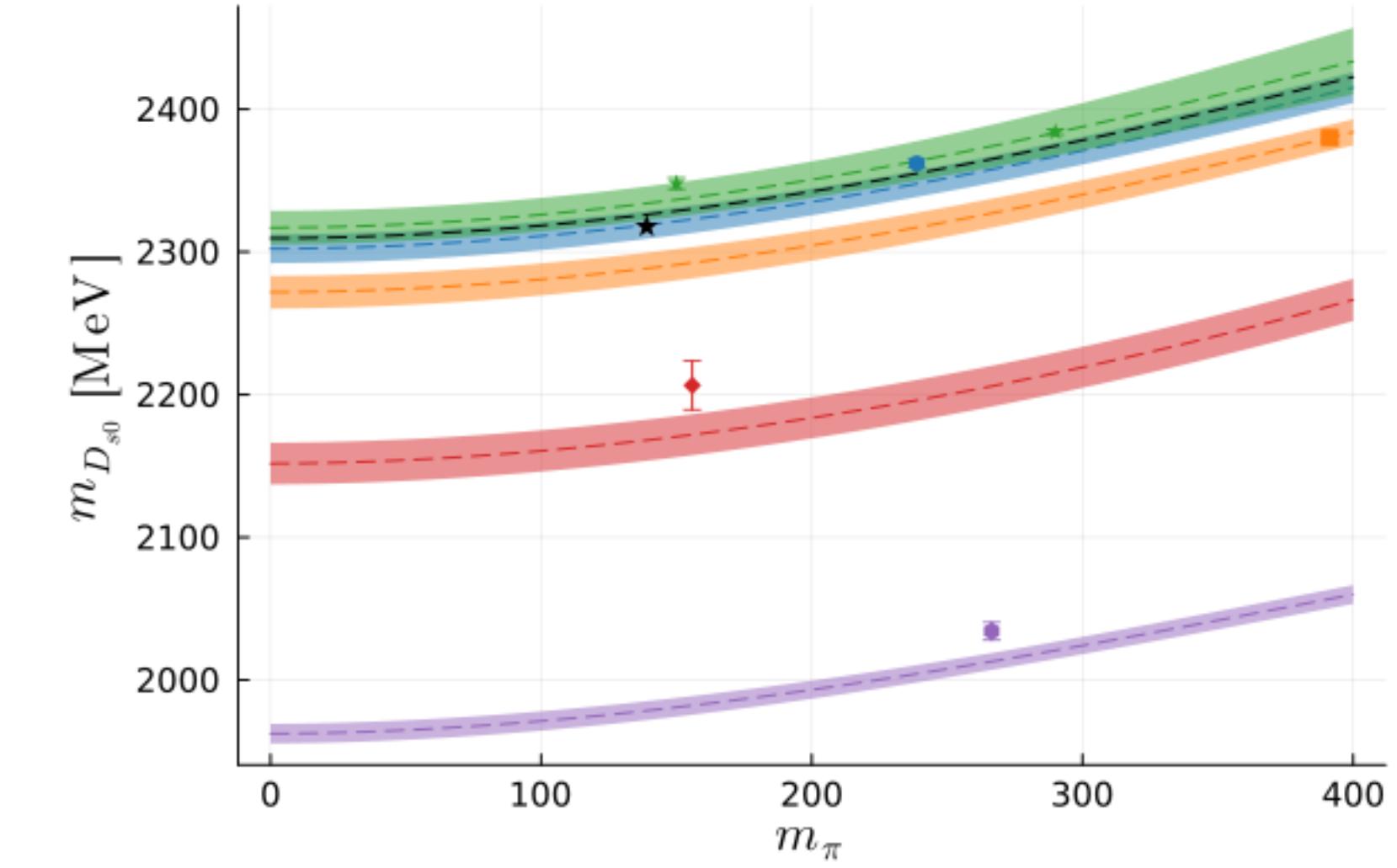
D_{s0} resonance finally



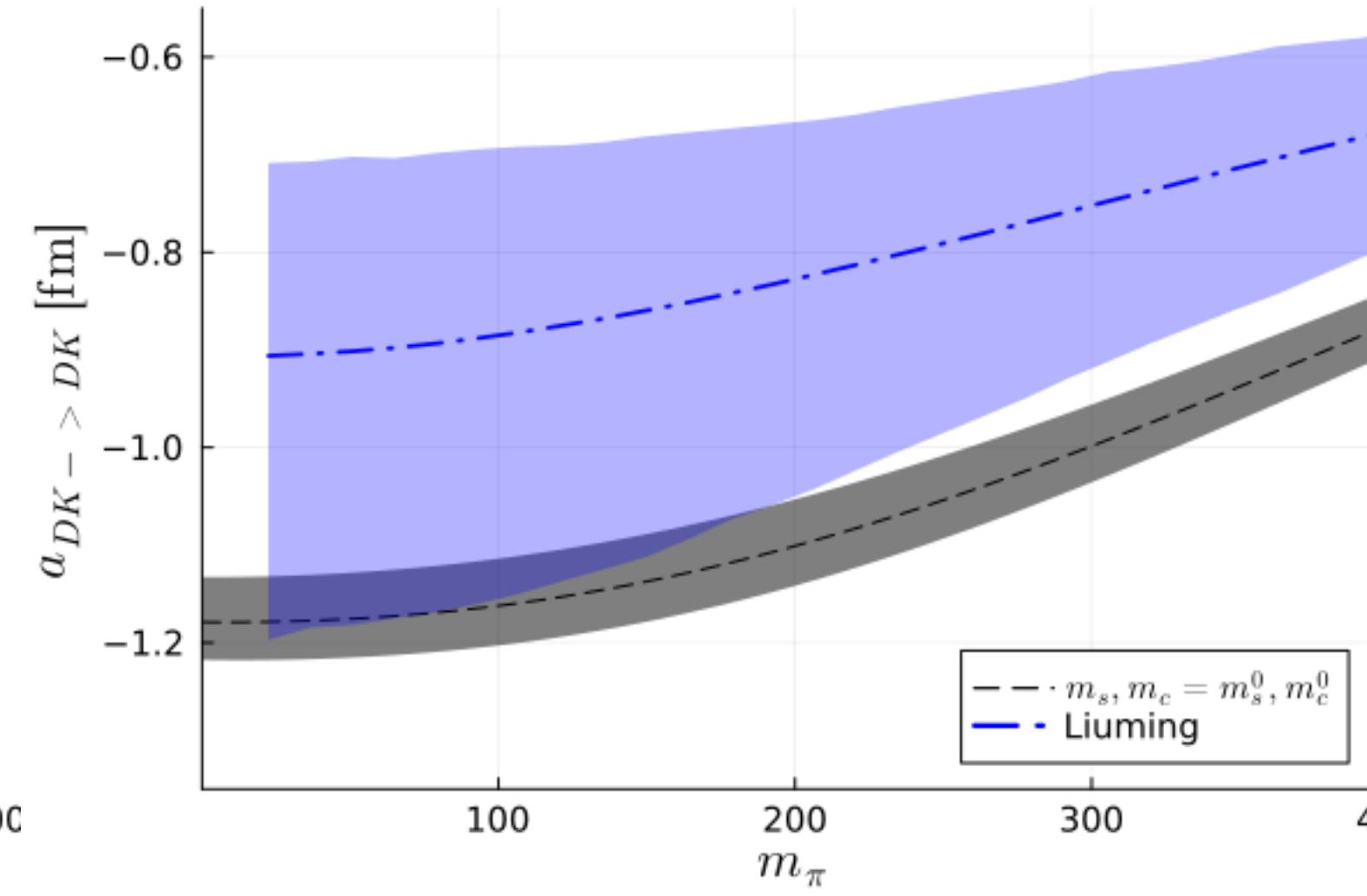
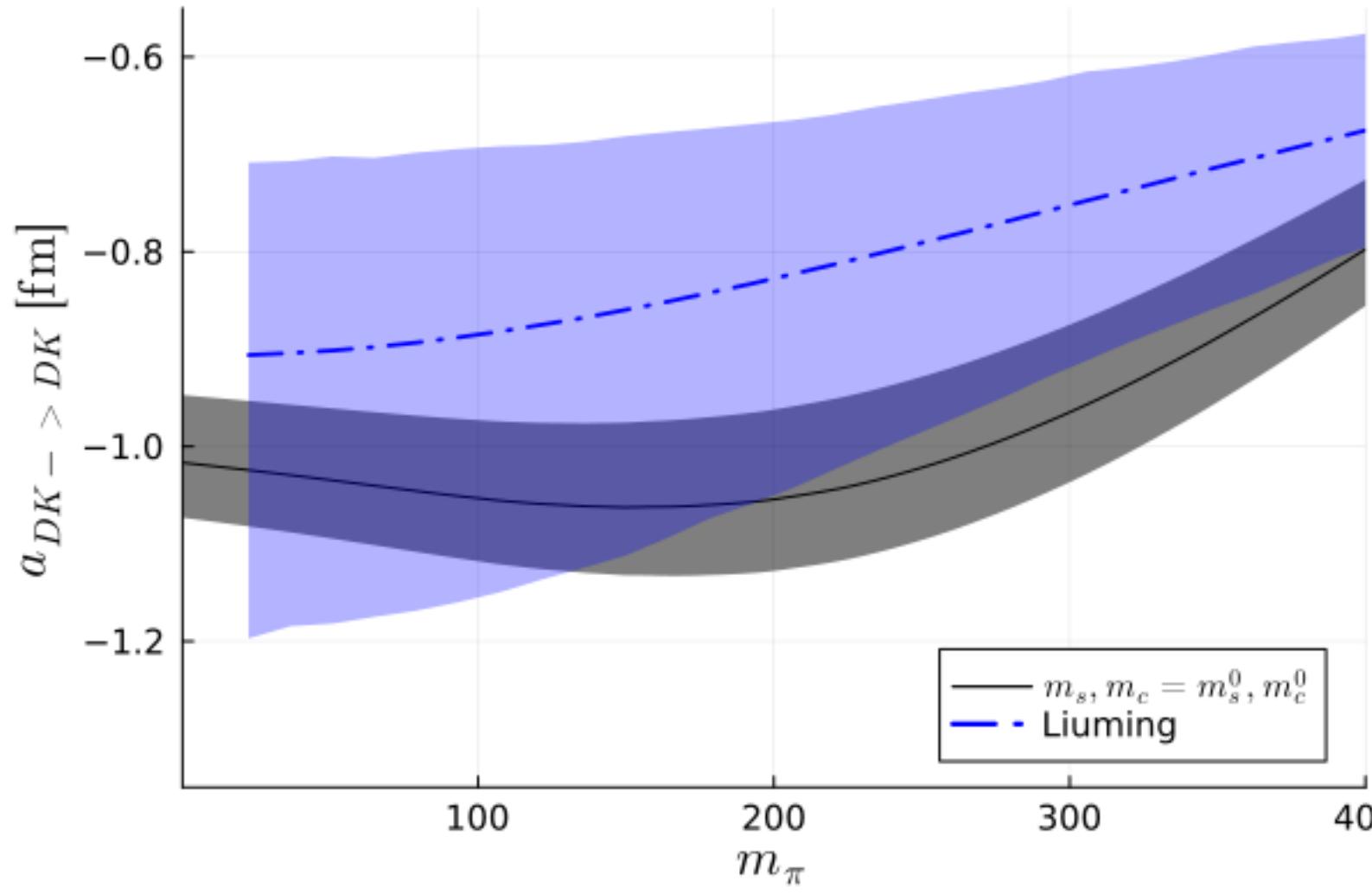
RQCD	$(m_{D_s} = 1977)$
$m_s, m_c = m_s^0, m_c^0$	$(m_{D_s} = 1968)$
HS239	$(m_{D_s} = 1967)$
HS391	$(m_{D_s} = 1951)$
PACS	$(m_{D_s} = 1809)$
Prelovsek	$(m_{D_s} = 1657)$
★ Experiment	



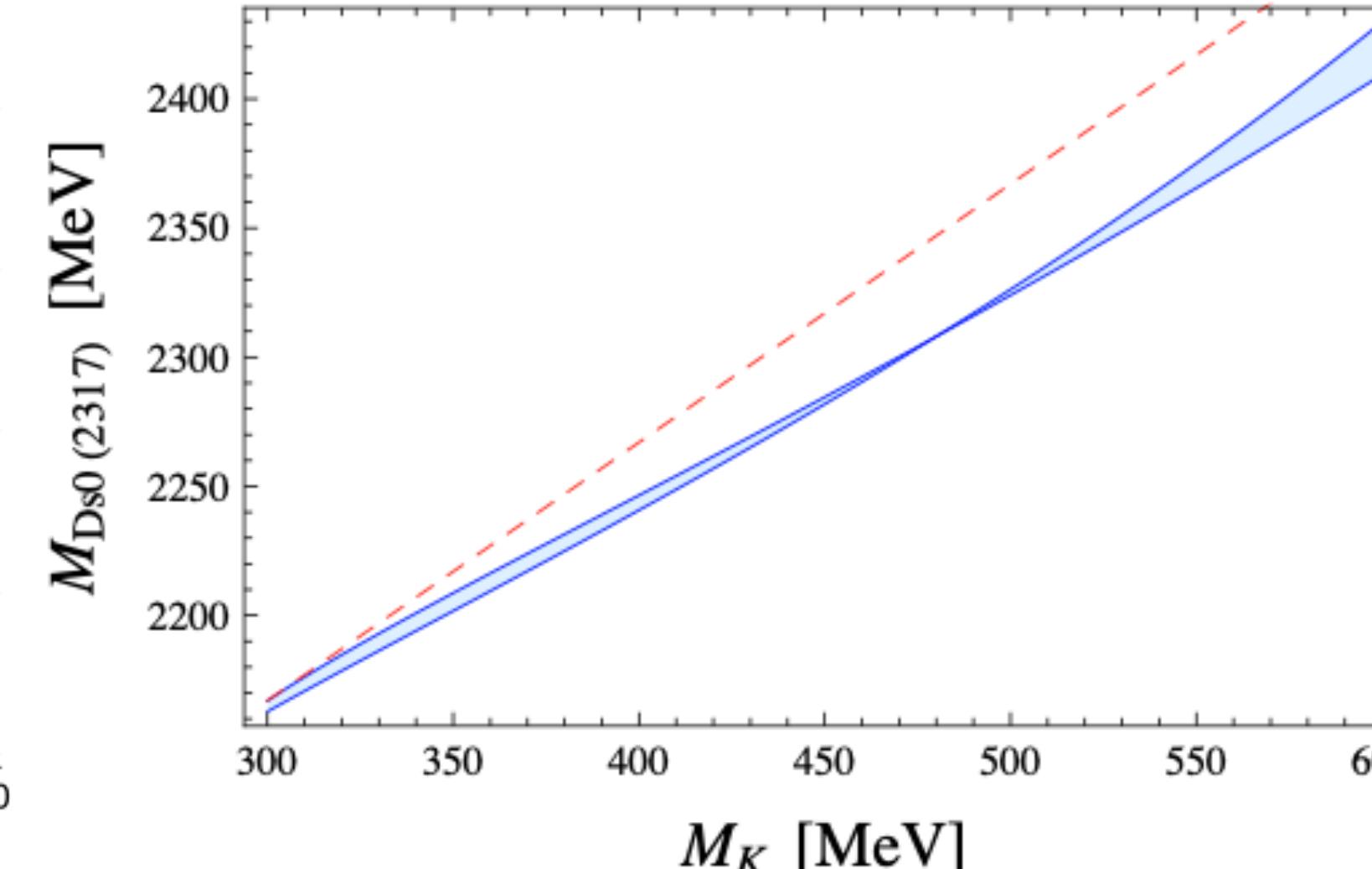
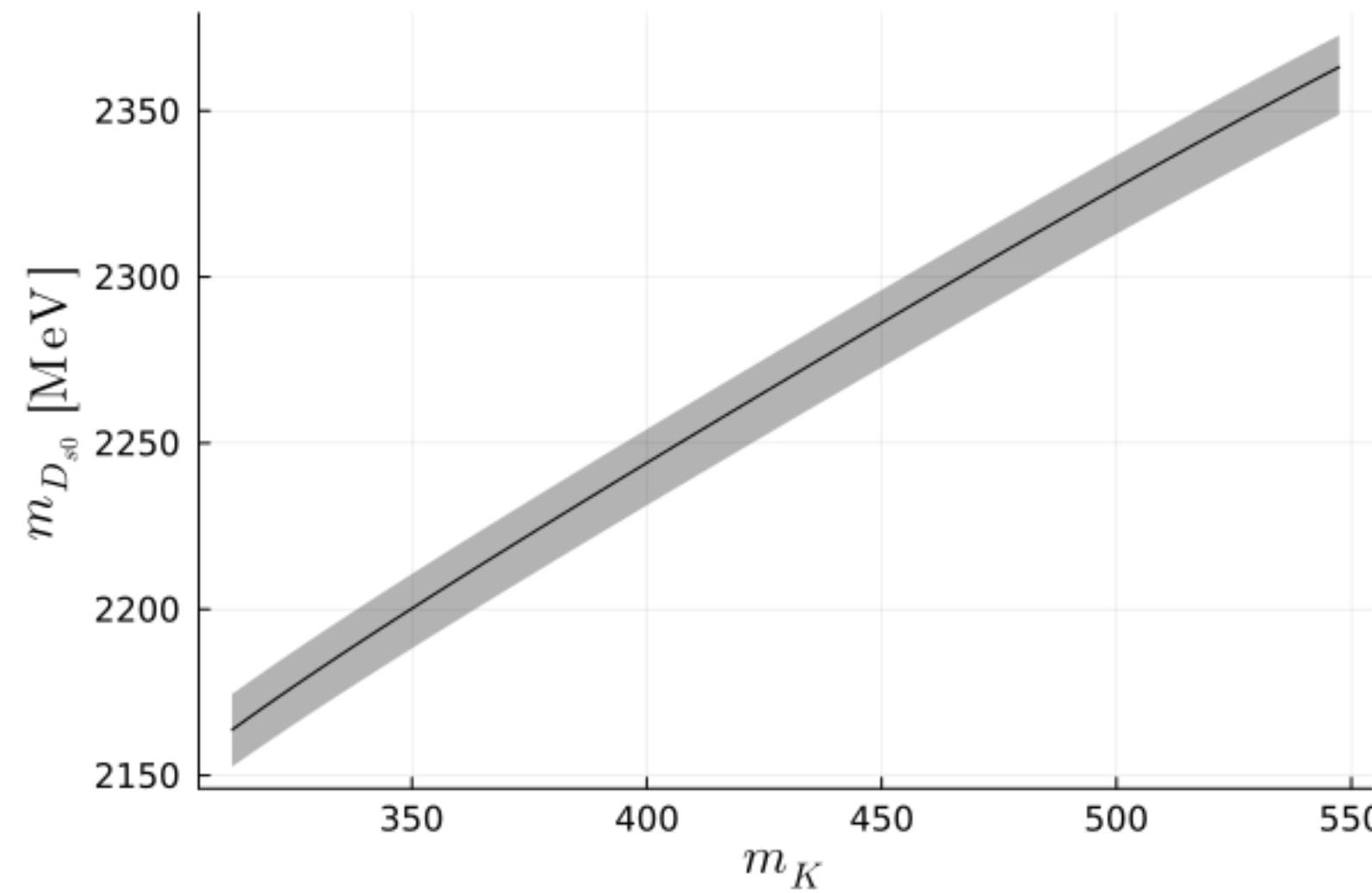
* F. Gil-Domínguez and R. Molina,
arXiv: 2306.01848



Comparison with previous results



*L. Liu, K. Orginos, F.-K. Guo,
C. Hanhart, and U.-G. Meissner,
Phys. Rev. D 87, 014508 (2013), 1208.4535.



*M. Cleven, F.-K. Guo,
C. Hanhart, and U.-G. Meissner,
Eur. Phys. J. A 47, 19 (2011), 1009.3804.

Conclusions

the end

- * The results of the HSC data analysis agree reasonably well with experiment, and with other previous LQCD studies on DK, suggesting the possibility of a global fit.
- * Our results suggest that the attractive DK interaction reduces with the charm quark mass, and becomes large for high pion masses. We obtain that this state is predominantly molecular.
- * Future LQCD data analyses for different pion masses than the ones included in our fit, could be a good test for this study.

Thank you for your attention!