From hadrons at unphysical quark masses to coupled-channel reaction dynamics in the laboratory

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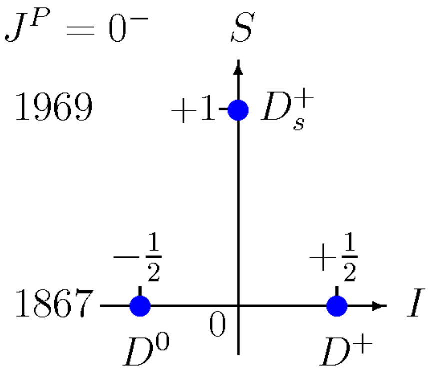
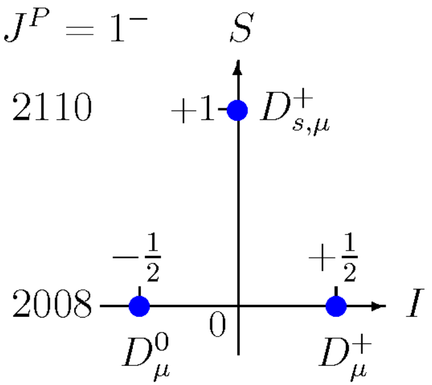
- ✔ **Chiral extrapolation for charmed meson masses**
- ✔ **Coupled-channel dynamics for charmed mesons**
- ✔ **Summary and outlook**

arXiv:1801.06417, arXiv:1801.10122, arXiv:1809.01311

Chiral Lagrangian for charmed mesons

✔ **Heavy-light mesons** $(c\,\bar q)$ SU(3) anti-triplet $[\bar 3]$





$$\mathcal{L} = (\partial_\mu D)(\partial^\mu \bar D) - M^2\, D\, \bar D - (\partial_\mu D^{\mu\alpha})(\partial^\nu \bar D_{\nu\alpha}) + \frac{1}{2}\,\tilde M^2\, D^{\mu\alpha}\, \bar D_{\mu\alpha}$$

$$+\,2\, g_P \left\{ D_{\mu\nu}\, U^\mu\, (\partial^\nu \bar D) - (\partial^\nu D)\, U^\mu\, \bar D_{\mu\nu} \right\}$$

$$-\,\frac{i}{2}\,\tilde g_P\, \epsilon^{\mu\nu\alpha\beta} \left\{ D_{\mu\nu}\, U_\alpha\, (\partial^\tau \bar D_{\tau\beta}) + (\partial^\tau D_{\tau\beta})\, U_\alpha\, \bar D_{\mu\nu}) \right\}$$

covariant derivative $\quad \partial_\mu \to \partial_\mu + \frac{1}{2}\, e^{-i\,\frac{\Phi}{2\,f}}\, \partial_\mu\, e^{+i\,\frac{\Phi}{2\,f}} + \frac{1}{2}\, e^{+i\,\frac{\Phi}{2\,f}}\, \partial_\mu\, e^{-i\,\frac{\Phi}{2\,f}}$

- chiral symmetry : $f \sim 90$ MeV chiral SU(3) limit value of f_π
- hadronic decay of $D^* \to D\pi$ implies $|g_P| = 0.57 \pm 0.07$
- heavy-quark spin symmetry : $\tilde g_P = g_P$ and $M = \tilde M$ as $m_c \to \infty$

Chiral SU(3) for heavy-light meson resonance

✔ Coupled-channel interaction from chiral SU(3) symmetry

S \ I	0	1/2	1	3/2
+2		$(D_s K)$		
+1	$(DK, D_s \eta)$		$(D_s \pi, DK)$	
0		$(D\pi, D\eta, D_s K)$		$(D\pi)$
-1	$(\overline{K} D)$		$(\overline{K} D)$	

$$\mathbf{8} \otimes \bar{\mathbf{3}} = \overline{\mathbf{15}} \oplus \mathbf{6} \oplus \bar{\mathbf{3}}$$

- Weinberg- Tomozawa interaction

$$V_{\mathrm{WT}}^{[15]} : V_{\mathrm{WT}}^{[6]} : V_{\mathrm{WT}}^{[3]} = -\mathbf{1} : \mathbf{1} : \mathbf{3}$$

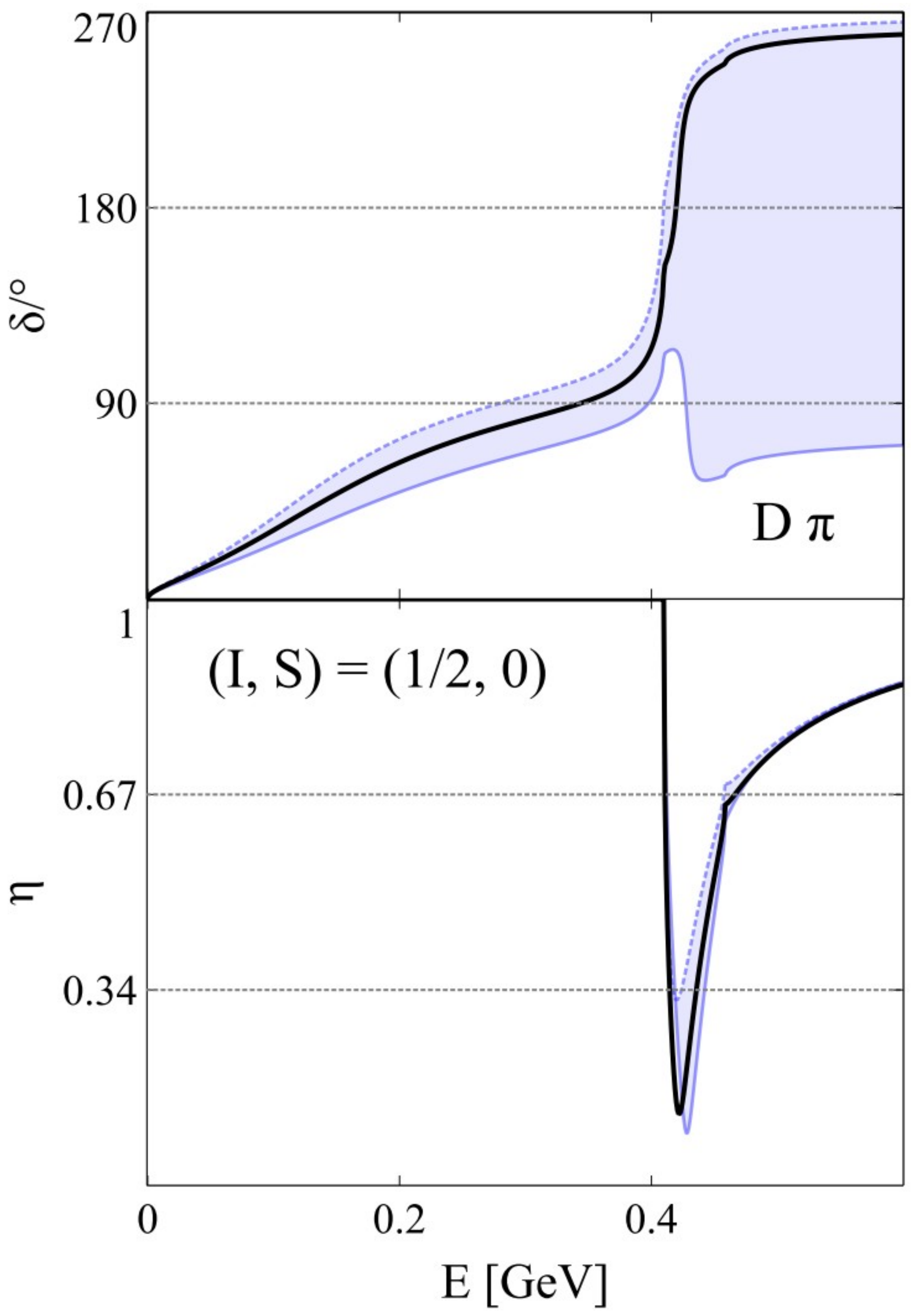
$$\mathcal{L}_{WT} = \frac{1}{8\, f^2}\, D\, [\Phi, (\partial_\mu \Phi)] (\partial^\mu \bar{D}) + \cdots$$

- strong attraction in anti-triplet and sextet
- dynamically generated $J^P = 0^+$ and $J^P = 1^+$ meson resonances in particular $D_{s0}^*(2317)$ and $D_{s1}^*(2460)$

✔ Are there exotic flavour sextet resonances?

Phys. Lett. B582 (2004) 39

Leading oder prediction for πD phase shift in $I = 1/2$



✔ Two resonances in phase shift

- a broad state from the anti-triplet
- a narrow state from the sextet
- a variation of the matching scale

- s-wave phase shift required in unitarity studies of CKM matrix from $B^0 \to \bar{D}^0\,\pi^+\,\pi^-$ decays (LHCb and Belle)

✔ How stable is the prediction?

- the broad state from the anti-triplet may move further into the complex plane
- the narrow state from the sextet always at $E \sim 0.4$ GeV
- are higher order counter terms important?

Phys. Lett. B582 (2004) 39

Chiral SU(3) correction terms for charmed mesons

$$
\begin{aligned}
\mathcal{L}^{(2)} = & -\left(4\,c_0 - 2\,c_1\right) D\,\bar{D}\,\mathrm{tr}\,\chi_+ - 2\,c_1\,D\,\chi_+\,\bar{D} \\
& - 4\left(2\,c_2 + c_3\right) D\bar{D}\,\mathrm{tr}\left(U_\mu\,U^\mu\right) + 4\,c_3\,D\,U_\mu\,U^\mu\,\bar{D} \\
& - \frac{1}{M^2}\left(4\,c_4 + 2\,c_5\right)(\partial_\mu D)(\partial_\nu \bar{D})\,\mathrm{tr}\left[U^\mu,\,U^\nu\right]_+ + \frac{1}{M^2}\,2\,c_5\,(\partial_\mu D)\left[U^\mu,\,U^\nu\right]_+(\partial_\nu \bar{D}) \\
& - i\,c_6\,\epsilon^{\mu\nu\rho\sigma}\Big(D\left[U_\mu, U_\nu\right]_-\,\bar{D}_{\rho\sigma} - D_{\rho\sigma}\left[U_\nu, U_\mu\right]_-\,\bar{D}\Big)
\end{aligned}
$$

covariant derivative $\partial_\mu \to \partial_\mu + \frac{1}{2}\,e^{-i\,\frac{\Phi}{2\,f}}\,\partial_\mu\,e^{+i\,\frac{\Phi}{2\,f}} + \frac{1}{2}\,e^{+i\,\frac{\Phi}{2\,f}}\,\partial_\mu\,e^{-i\,\frac{\Phi}{2\,f}}\,,$

✔ How to determine the low-energy constants?

- additional 6 terms parameterized by $\tilde{c}_n$ involving two $J^P = 1^-$ fields ($D_{\alpha\beta}...\bar{D}_{\mu\nu}$)
- from heavy-quark spin symmetry $\tilde{c}_n = c_n$ at $m_c \to \infty$
- from large-N_c $\quad c_0 \simeq \frac{c_1}{2}\,, \qquad c_2 \simeq -\frac{c_3}{2}\,, \qquad c_4 \simeq -\frac{c_5}{2}\,,$
- use QCD lattice data on the quark-mass dependence of the D meson masses

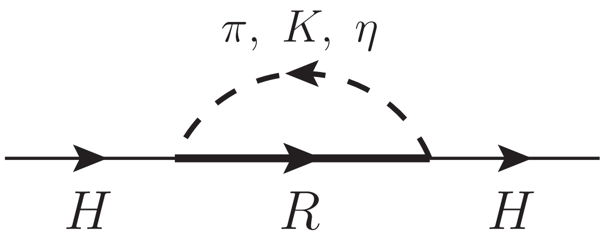
Nucl. Phys. A733 (2004) 142, Nucl. Phys. A948 (2016) 93

Quark-mass dependence of hadron masses

✓ A challenge for chiral SU(3) symmetry

- the conventional formulation of three flavour χPT does not converge
- conventional χPT inconsistent with three-flavor QCD lattice simulations

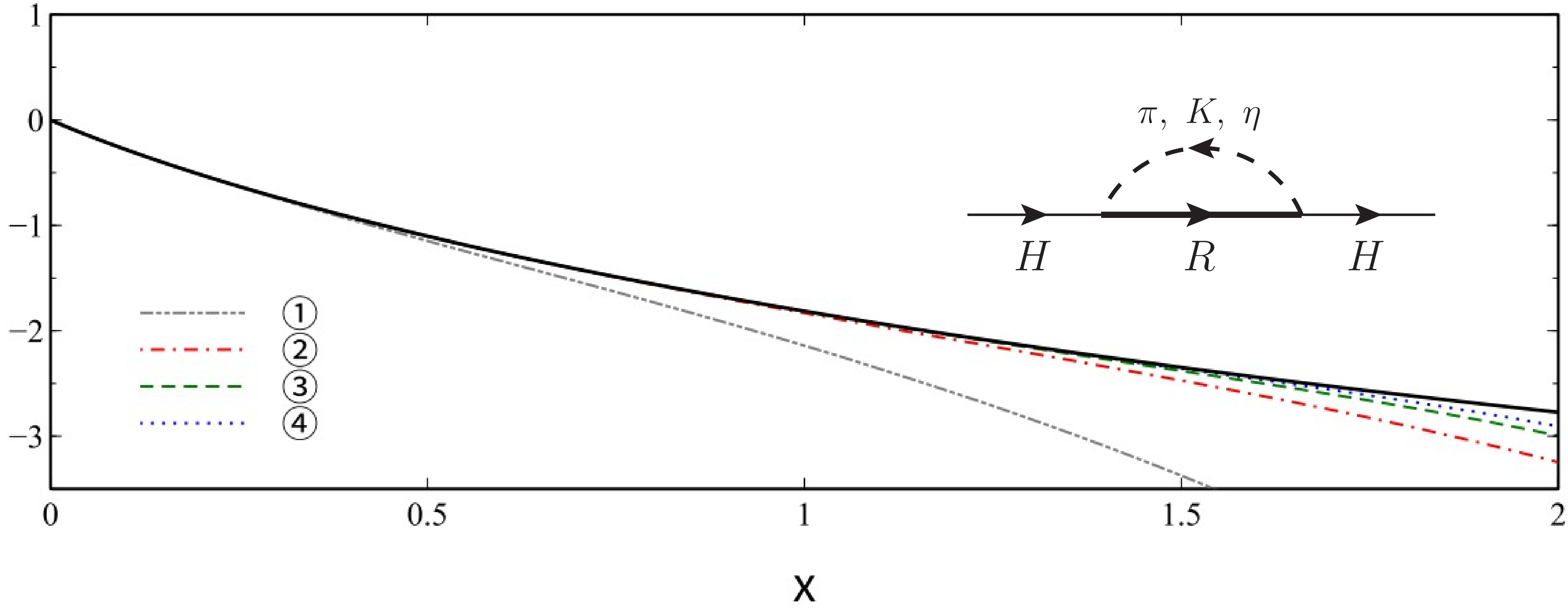
✓ Loops depend sensitively on internal masses



- develop a chiral expansion in terms of on-shell hadron masses
- reorganize conventional χPT keeping its model independence
- keep renormalization scale and reparametrization invariance

Phys.Rev. D51 (1995) 3697
Phys.Rev. D85 (2012) 034001
Phys.Rev. D86 (2012) 091502
Phys.Rev. D90 (2014) 054505

Chiral expansion of the scalar loop function $(4\pi)^2 \bar{I}_{QR}$



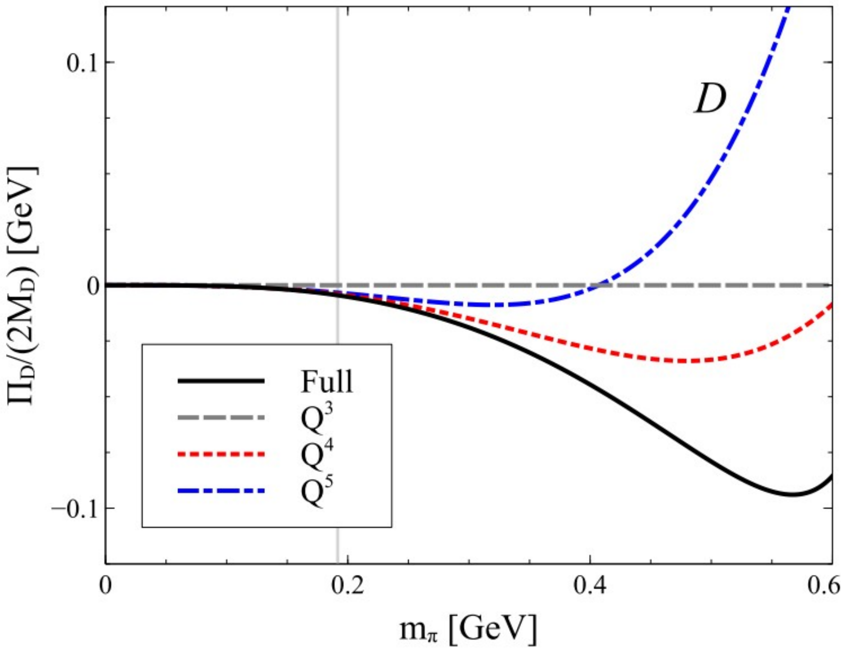
✔ **Convergence study for $M_R = M_H$ and $x = m_Q/M_R$**

- $(4\pi)^2\, \bar{I}_{QR} = -\pi\,\sqrt{x^2}\, f_1(x^2) + x^2\, f_2(x^2) - \frac{1}{2}\, x^2\, f_3(x^2)\, \log x^2$
- the functions $f_n(x^2)$ are analytic in x^2 for $|x| < 2$

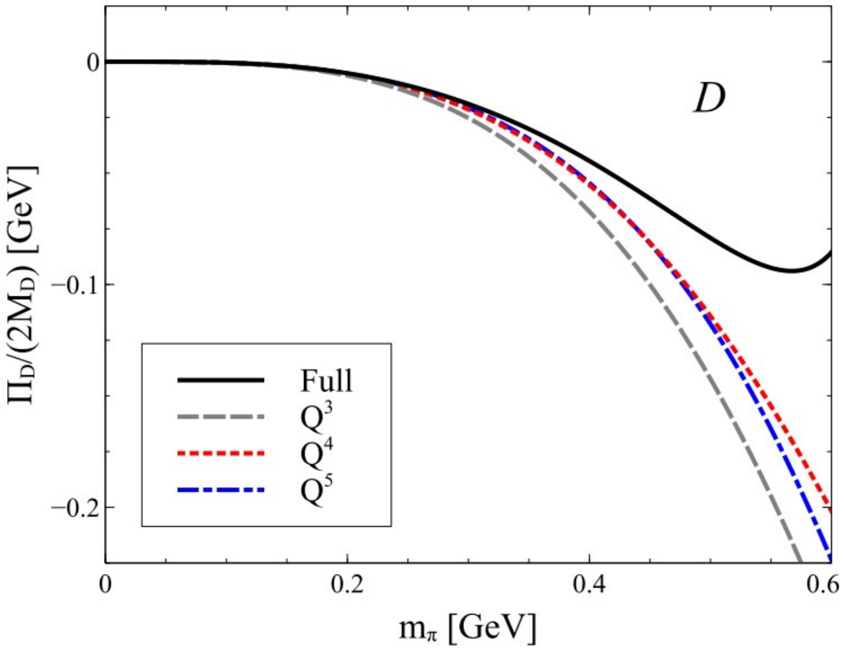
  $f_n(x^2) = 1 + \# x^2 + \# x^4 + \cdots$
- good convergence even for $m_K = M_N$ with $x \simeq 1$!

arXiv:1801.06417

Chiral decomposition of the loop: how to powercount



- flavour limit with $m_u = m_d = m_s$
- use bare mases $M \simeq 1.91$ GeV and $\Delta \simeq 0.19$ GeV
- expansion with $m_\pi/\Delta \sim Q$
- not useful for physical quark masses



- flavour limit with $m_u = m_d = m_s$
- use bare mases $M \simeq 1.91$ GeV and $\Delta \simeq 0.19$ GeV
- expansion with $m_\pi/\Delta \sim Q^0$
- not useful for physical quark masses

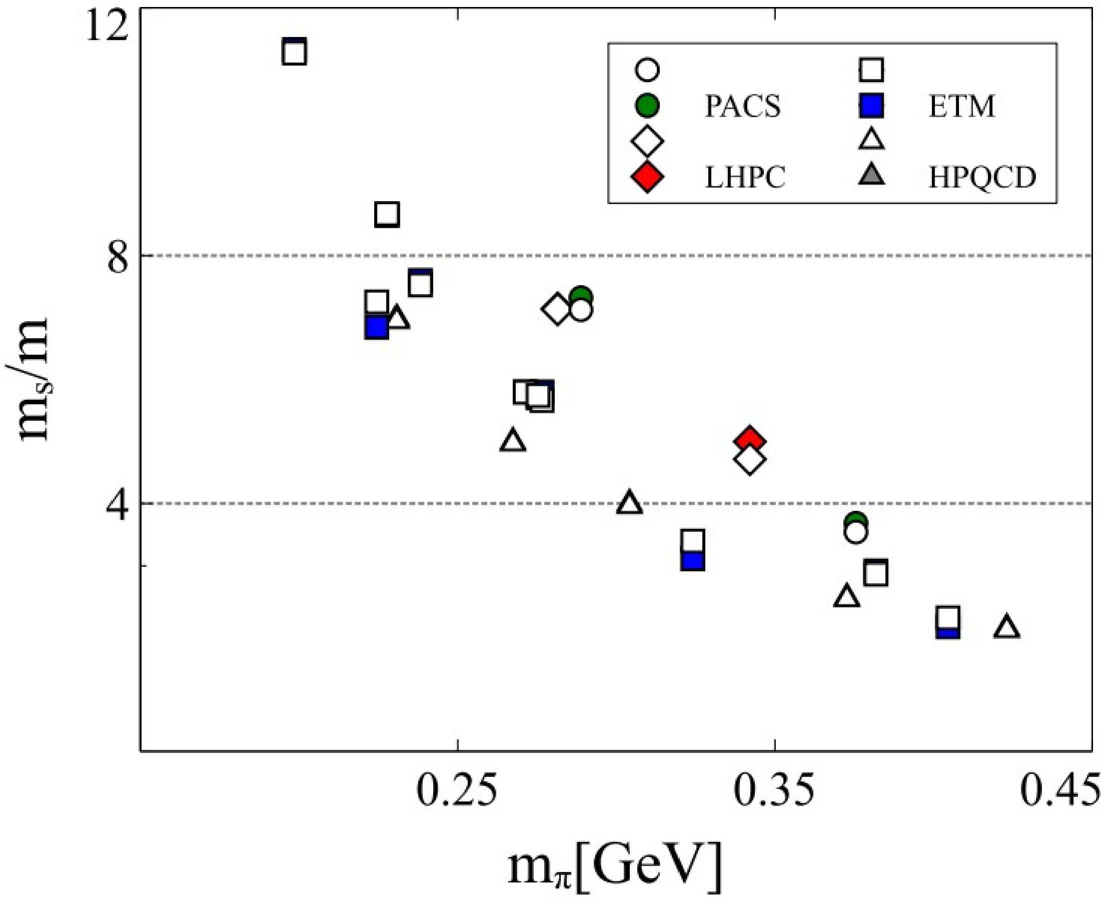
- expansion with on-shell masses well converging!

arXiv:1801.10122

Predictions for quark-mass ratios in lattice ensembles

How to fit the lattice data?

- take pion and kaon mass of the ensemble → compute quark masses
- this requires the low-energy constants $L_4 - 2\,L_6, L_5 - 2\,L_8, L_8 + 3\,L_7$
- we do not fit to the quark-mass ratios given by the lattice groups!



A fit to the D meson masses

- renormalization scale $\mu = 0.77$ GeV

$10^3\,(L_4 - 2\,L_6)$	-0.1575
$10^3\,(L_5 - 2\,L_8)$	-0.0370
$10^3\,(L_8 + 3\,L_7)$	-0.5207
m_s/m	26.600

- at physical quark masses our ratio compares well with lattice result

  $m_s/m = 26.66(32)$ from ETMC

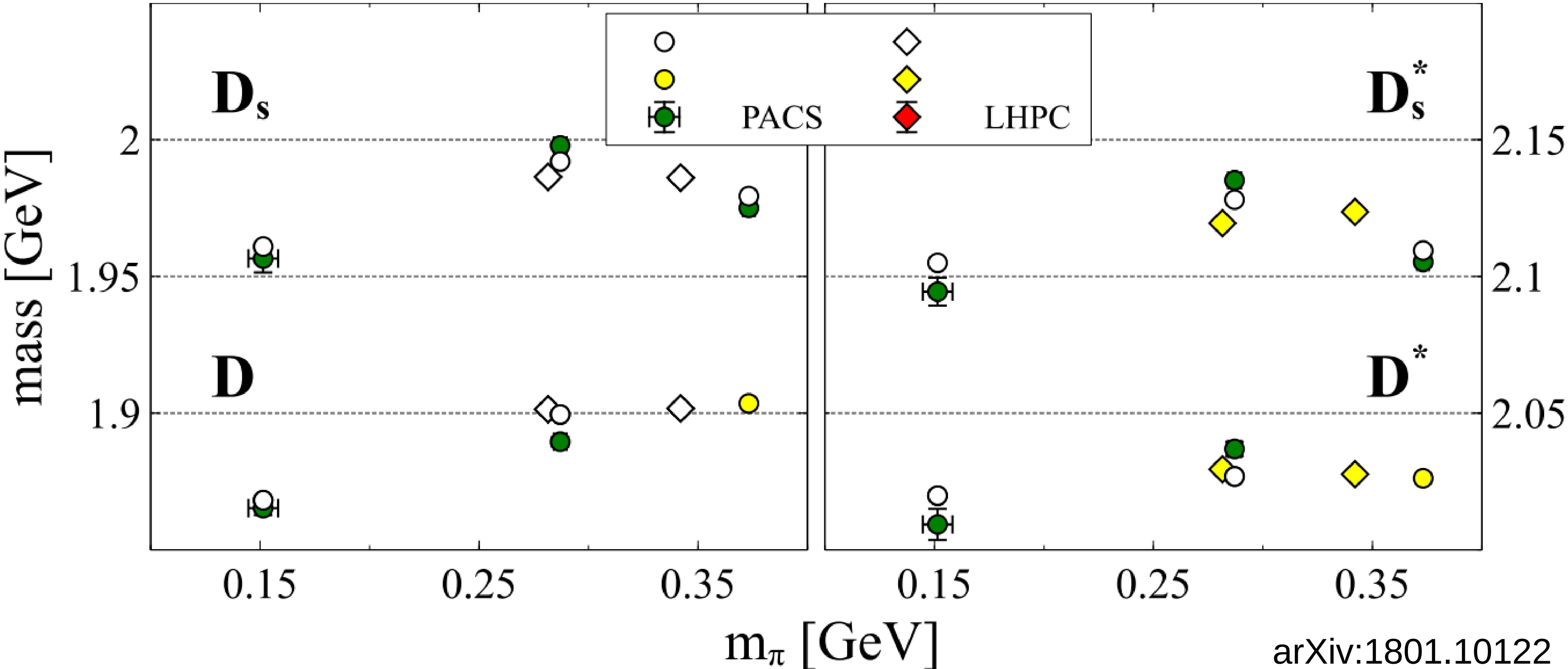
  in Nucl. Phys. B887, 19 (2014)

arXiv:1801.10122

Predictions for D meson masses in lattice ensembles

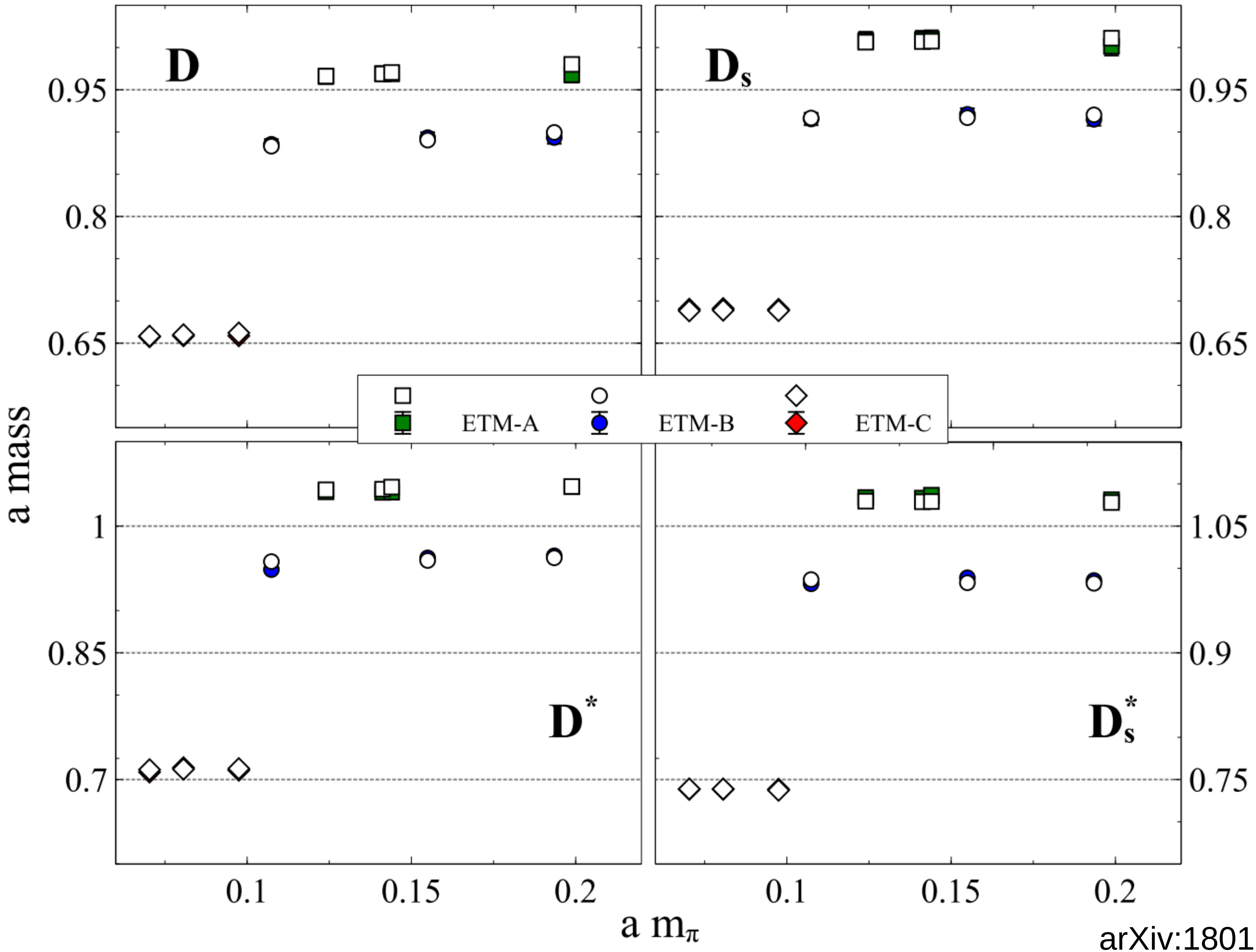
✔ How to fit the lattice data?

- always reproduce empirical D meson masses from PDG
- lattice scale determination for each β value
- tune the charm quark mass to its physical value
- yellow symbols: theory prediction (no lattice data yet)



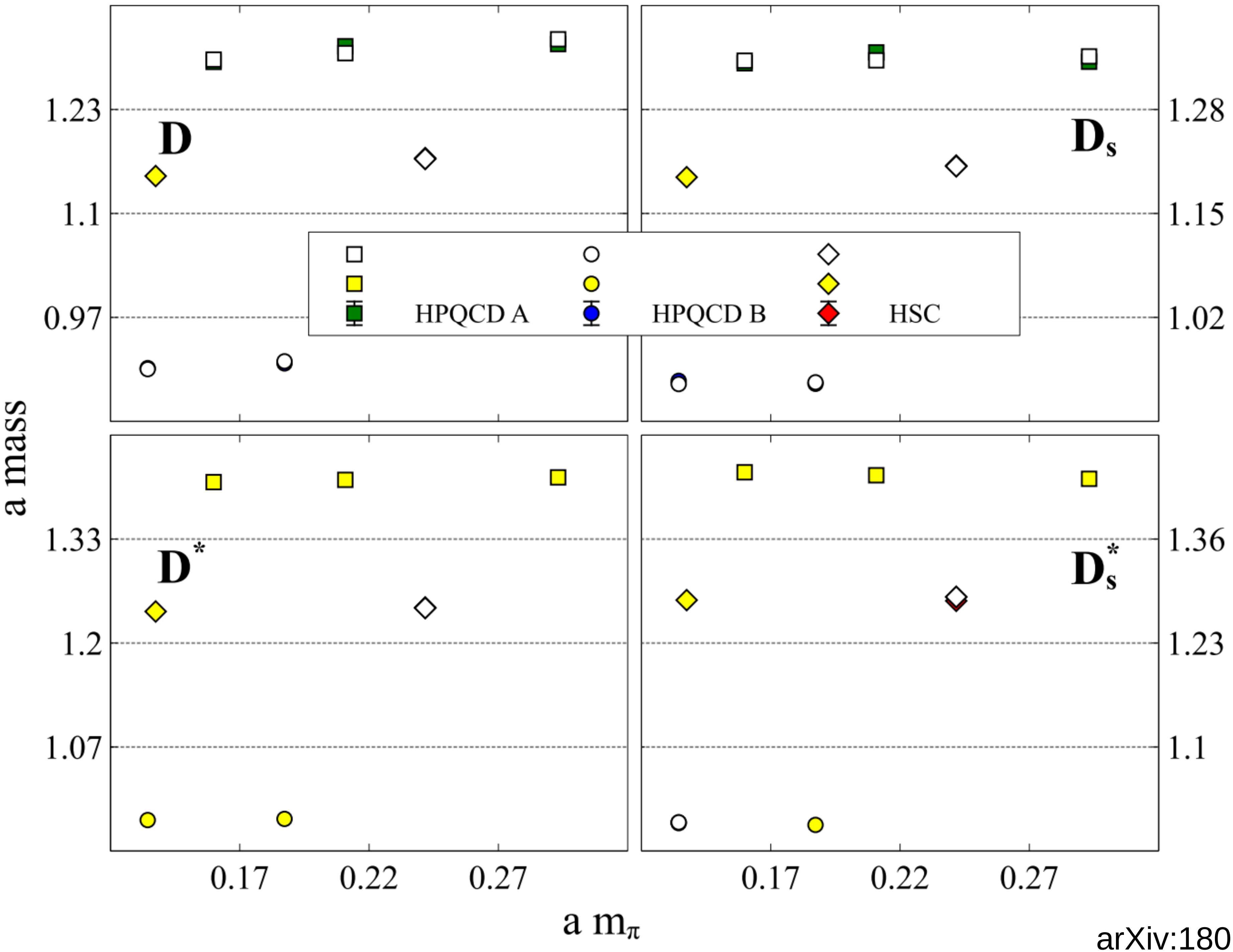
arXiv:1801.10122

Lattice ensembles from ETMC at three different β values



arXiv:1801.10122

Lattice ensembles from HPQCD and HSC

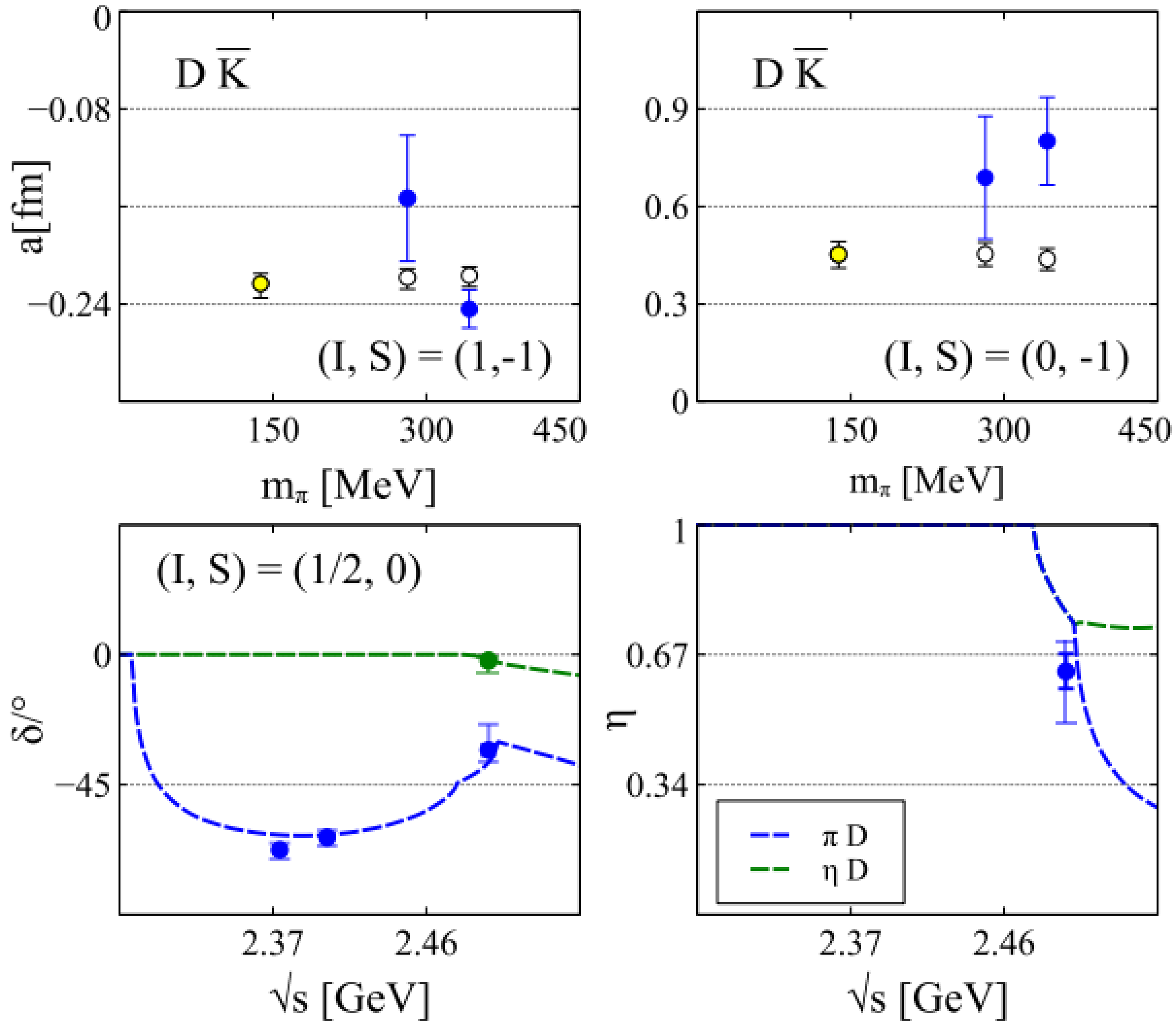


arXiv:1801.10122

S-wave scattering on MILC and HSC ensembles

✔ How to fit the lattice data?

- S-wave scattering lengths included if $m_K < 600$ MeV (from LHPC)
- S-wave πD and ηD phase shifts (from HSC)



data from
Phys.Rev. D87 (2013) 014508
JHEP 10 (2016) 011

arXiv:1801.10122

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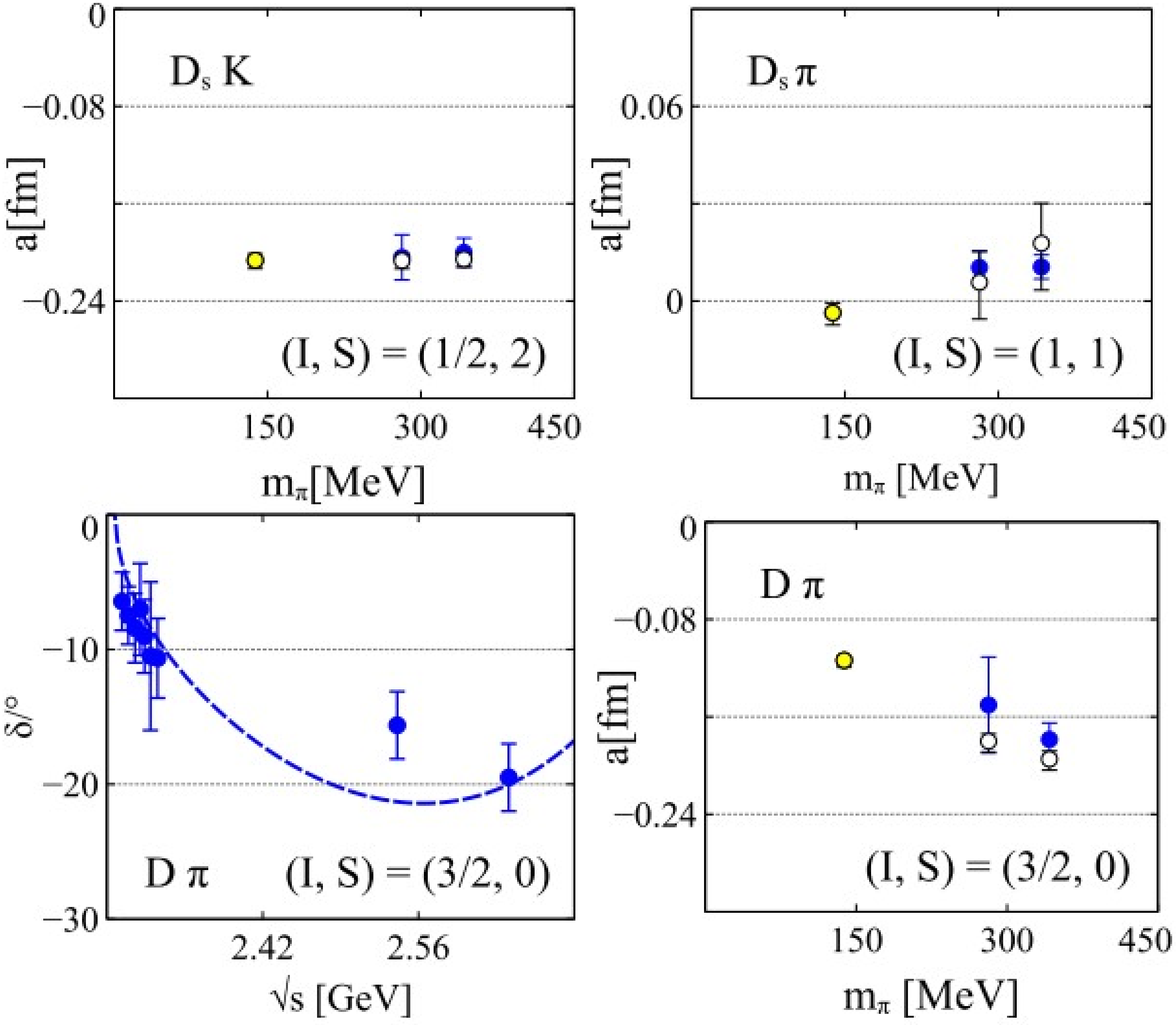

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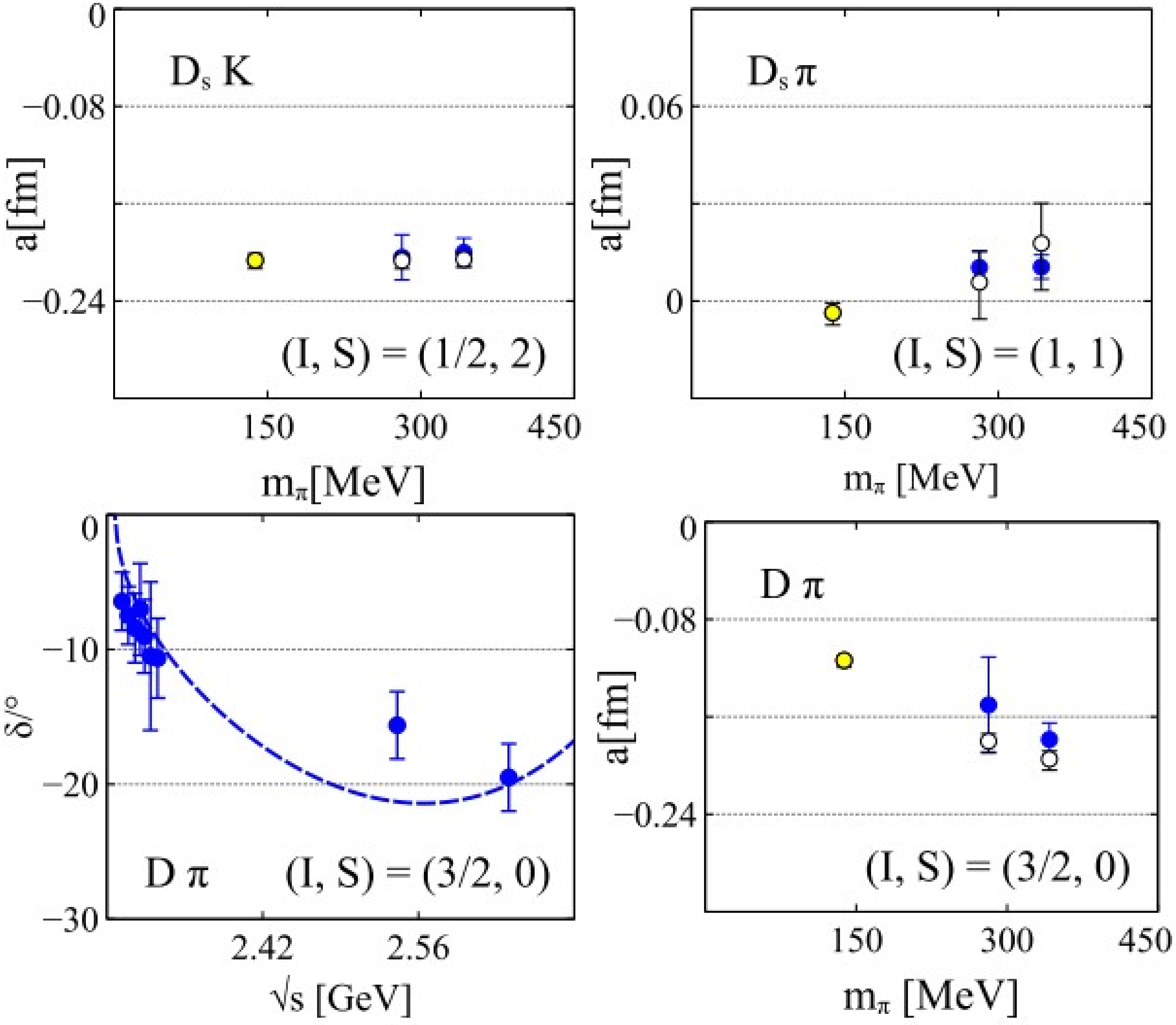
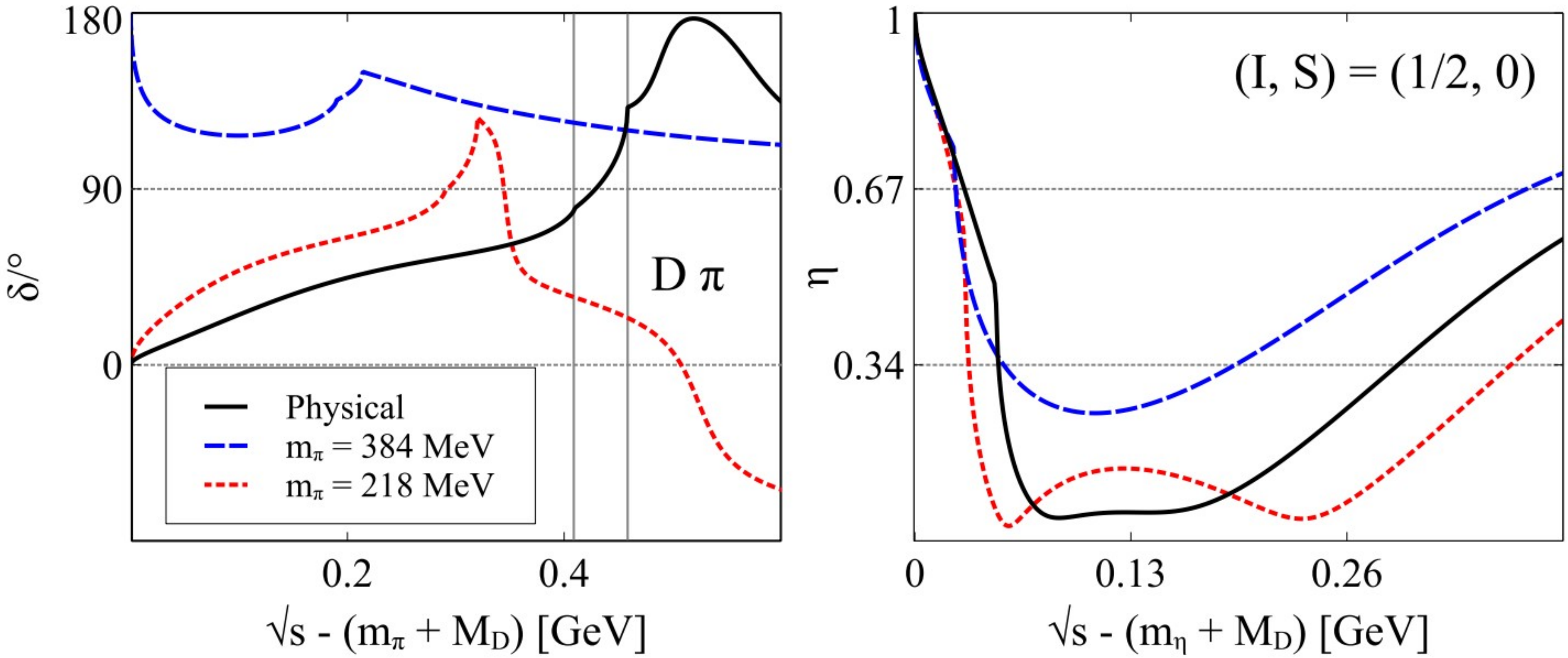


data from
Phys.Rev. D87 (2013) 014508
JHEP 10 (2016) 011

arXiv:1801.10122

Phase shifts: from unphysical to physical quark masses

- at unphysical quark masses (published HSC ensemble)
- black line: prediction of phase shifts at physical quark masses
- dashed red lines: prediction of phase shifts (unpublished HSC ensemble)



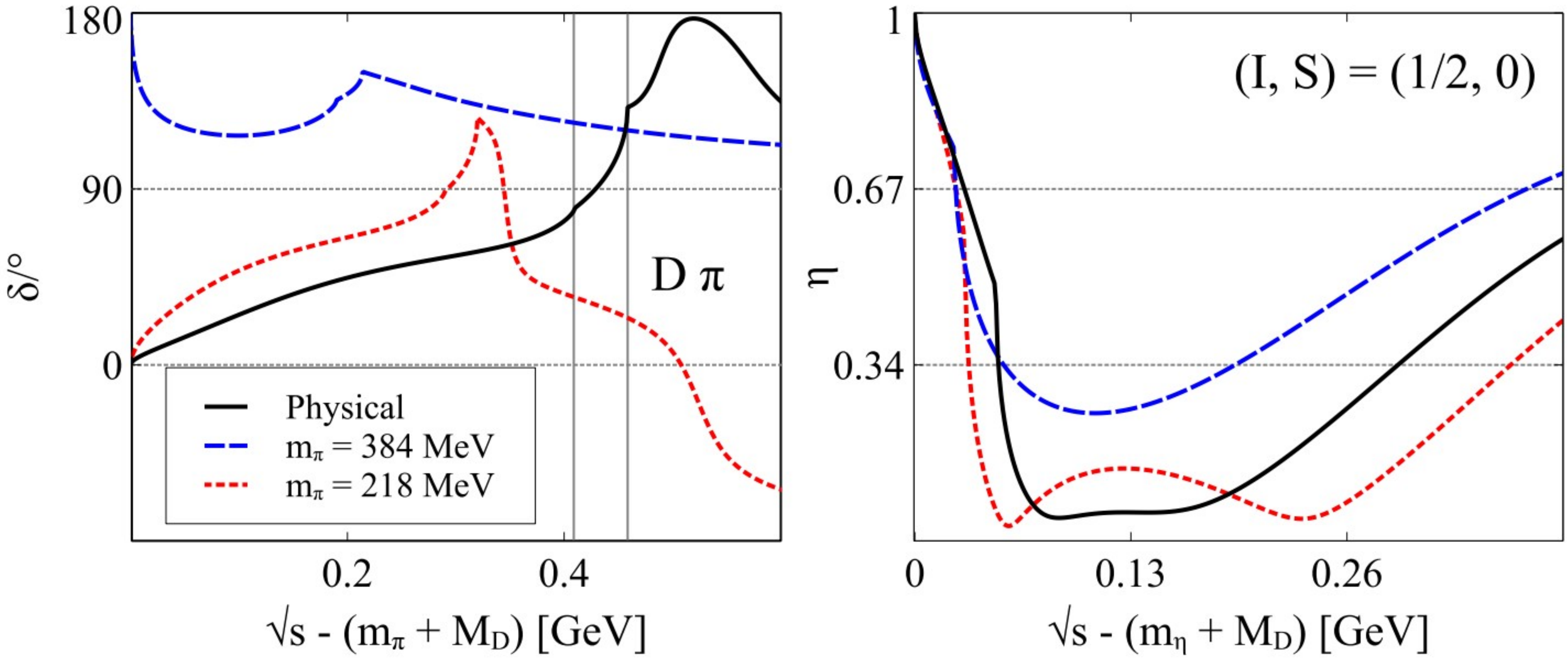
Phase shifts: from unphysical to physical quark masses

- predict that QCD forms a flavour sextet of $J^P = 0^+$ states
  expect two states $D_0(2082)$ and $D_0(2439)$
  the extra state just above the $\eta\, D$ threshold

arXiv:1801.10122
arXiv:1811.00478

- predict also a flavour sextet of $J^P = 1^+$ states
  expect three states $D_1(2232), D_1(2420), D_1(2575)$
  one extra state just above the $\eta\, D^*$ threshold

arXiv:1809.01311



Predictions for pole masses at physical quark masses

✔ An exotic flavour sextet of 0^+ states

- LEC derived from global fit to lattice data
- compare pole masses at LO with NLO

	$(I,S)=(1,1)$	$(I,S)=(1/2,0)$	$(I,S)=(0,-1)$
WT	$2.488^{+22}_{-19}-0.083^{+14}_{-5}i$	$2.390^{+20}_{-17}-0.038^{+0}_{-1}i$	2.335^{-43}_{+15}
NLO	$2.382^{+10}_{-10}-0.322^{+12}_{-10}i$	$2.439^{+42}_{-32}-0.092^{-7}_{+3}i$	$2.229^{-4}_{+3}-0.083^{+13}_{-11}i$

- NLO results in qualitative agreement with LO predictions
- clear signal of an 'unexpected' pole with $(I,S)=(1/2,0)$
- relevant for B meson decays into πD and ηD channels

arXiv:1811.00478

arXiv:1801.10122

Predictions for pole masses at physical quark masses

✔ An exotic flavour sextet of 1^+ states

- LEC from global fit to lattice data
- compare pole masses at LO with NLO

	$(I,S)=(1,1)$	$(I,S)=(1/2,0)$	$(I,S)=(0,-1)$
WT	$2.618^{+23}_{-19} - 0.080^{+14}_{-5}i$	$2.525^{+20}_{-18} - 0.036^{+0}_{-0}i$	2.484^{-32}_{+12}
NLO	$2.564^{+10}_{-10} - 0.290^{+12}_{-9}i$	$2.606^{+23}_{-30} - 0.059^{-25}_{+13}i$	$2.390^{-4}_{+3} - 0.095^{+18}_{-16}i$

- NLO results in qualitative agreement with LO predictions
- clear signal of an 'unexpected' pole with $(I,S)=(1/2,0)$
- relevant for B meson decays into πD^* and ηD^* channels

arXiv:1809.01311

Isospin violating decay width of $D_{s0}(2317)$

✓ $D_{s0}(2317)$ from chiral coupled-channel dynamics

- Hadronic decay width from $D_{s0}(2317) \to D_s(1968)\,\pi_0$
- LO prediction: $\Gamma = 75$ keV [NPA813(2008)14]
- corrections may significantly change this estimate

  NLO estimates: $\Gamma = 140$ keV [NPA813(2008)14]

  $\Gamma = 133$ keV [PRD87(2013)014508]
- global fit to QCD lattice data

  NLO prediction: $\Gamma = (104 - 116)$ keV [arXiv:1801.10122]

✓ Why to measure the width ?

- significant impact on chiral dynamics in QCD
- the low-energy constants are predicted from QCD lattice results
- closely related to exotic flavour sextet states (e.g. ηD - channel)

Summary & Outlook

✔ Chiral extrapolation of hadron masses

- resummed χPT : use on-shell masses in the loops
  - chiral expansion with up, down and strange quarks is well convergent
- so far we considered baryon and open-charm meson masses at N^{3}LO
  - fits to masses of ground states with $J^P = \frac{1}{2}^+, \frac{3}{2}^+$ and $J^P = 0^-, 1^-$
  - quantitative reproduction of the world lattice data set (about 400 data points)
- predict a large number of low-energy constants for the chiral Lagrangian of QCD
  - quantitative results for the baryon sigma terms
  - quantitative results for s-wave $\pi D, \eta D$ and $\pi D^*, \eta D^*$ phase shifts $\cdots$
  - predict that QCD forms exotic flavour sextet states with $J^P = 0^+$ and $J^P = 1^+$

✔ QCD spectroscopy with coupled-channel dynamcis

- curent QCD lattice data provide the counter terms for hadron-hadron scattering
- use as input in systematic coupled-channel computations
- analyze and predict the quark-mass dependence of hadron resonances in QCD

thanks to: Yonggoo Heo and Xiao-Yu Guo