# Opportunities in hadron physics

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✔ **Hadron spectroscopy in the laboratory and QCD**

- Hadron spectroscopy and coupled-channel dynamics
  → one does not go without the other

- Coupled-channel dynamics and effective field theory
  → learn about the relevant degrees of freedom in QCD

- Coupled-channel interaction from Lattice QCD
  → an efficient way to go for physics in the laboratory

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

✔ **A specific example case**

- Chiral extrapolation for charmed meson masses
- Coupled-channel dynamics for charmed mesons

arXiv:1801.10122, arXiv:1809.01311, arXiv:1811.0478

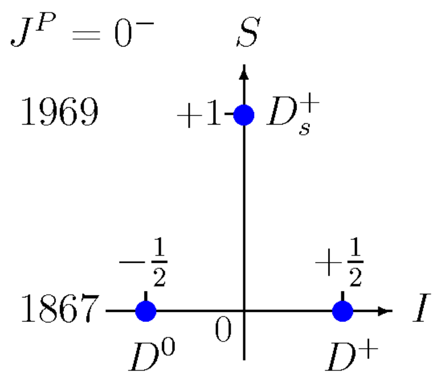
✔ **More results on light mesons and baryons**

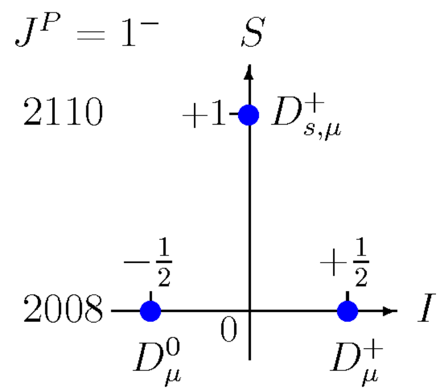
arXiv:1801.10522, arXiv:1810.07078, arXiv:1810.07376

arXiv:1801.06417, arXiv:1802.09365, arXiv:1806.08602

# 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 $f_\pi$
- 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

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

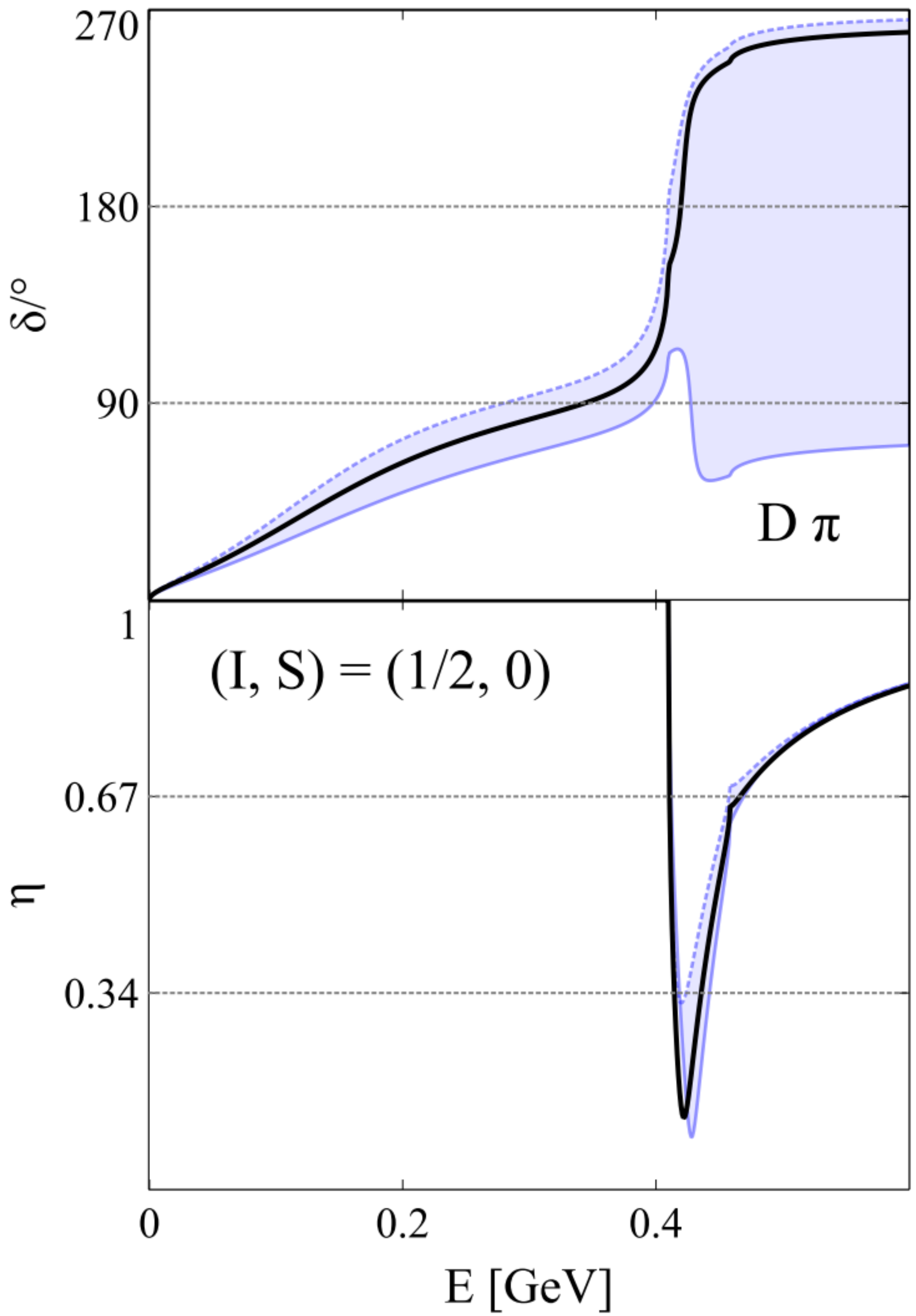
$$\mathcal{L}_{WT} = \frac{1}{8\,f^2}\,D\,[\Phi, (\partial_\mu \Phi)](\partial^\mu \bar{D}) + \cdots$$

- 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 $\pi D$ 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

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

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

## ✔ 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

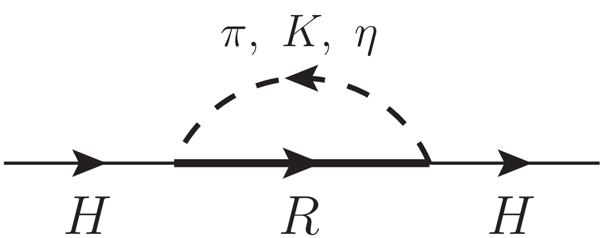
Nucl. Phys. A733 (2004) 142, Nucl. Phys. A948 (2016) 93

# Quark-mass dependence of hadron masses

## ✔ A challenge for chiral SU(3) symmetry

- the conventional formulation of three flavour $\chi$PT does not converge
- conventional $\chi$PT inconsistent with three-flavor QCD lattice simulations

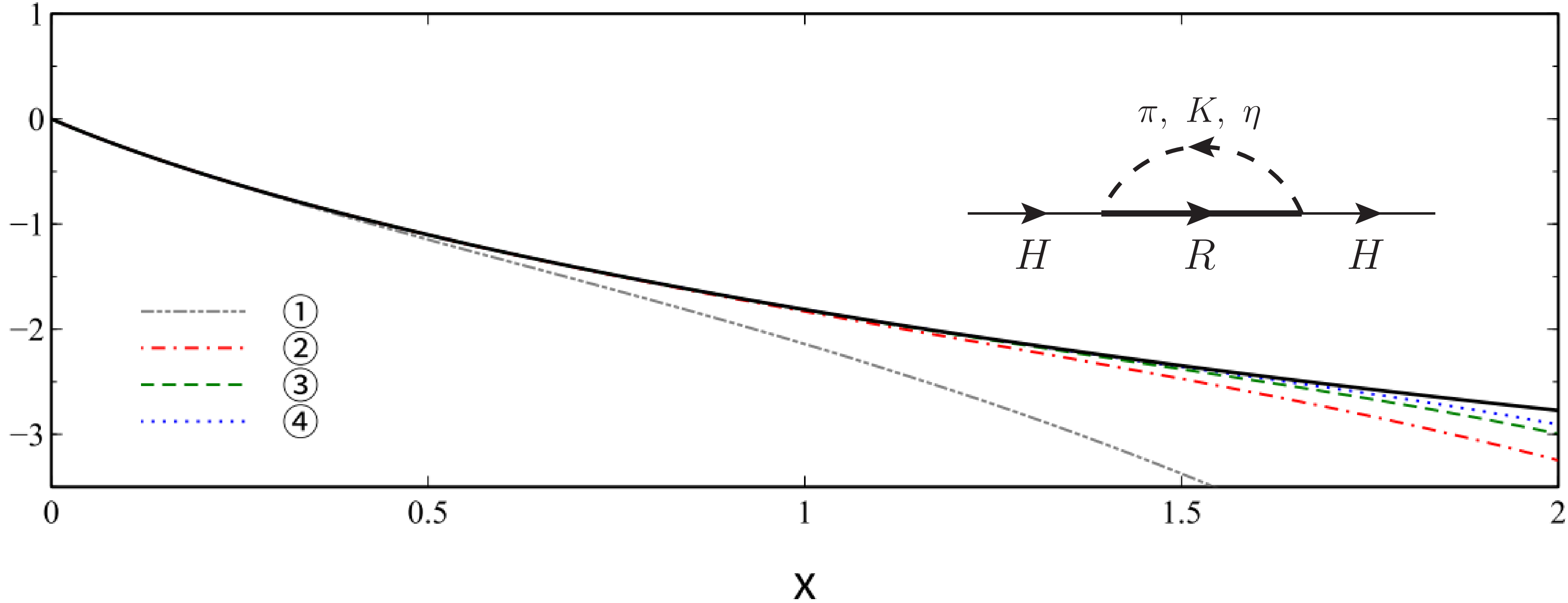
## ✔ Loops depend sensitively on internal masses




- develop a chiral expansion in terms of on-shell hadron masses
- reorganize conventional $\chi$PT 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 $(4\pi)^2 \bar{I}_{QR}$



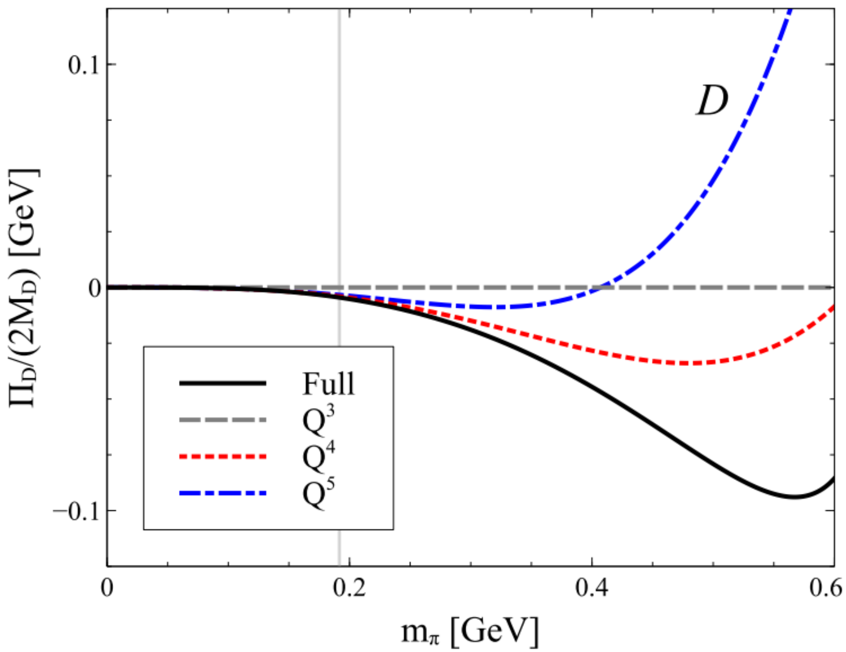

✔ **Convergence study for $M_R = M_H$ and $x = m_Q/M_R$**

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

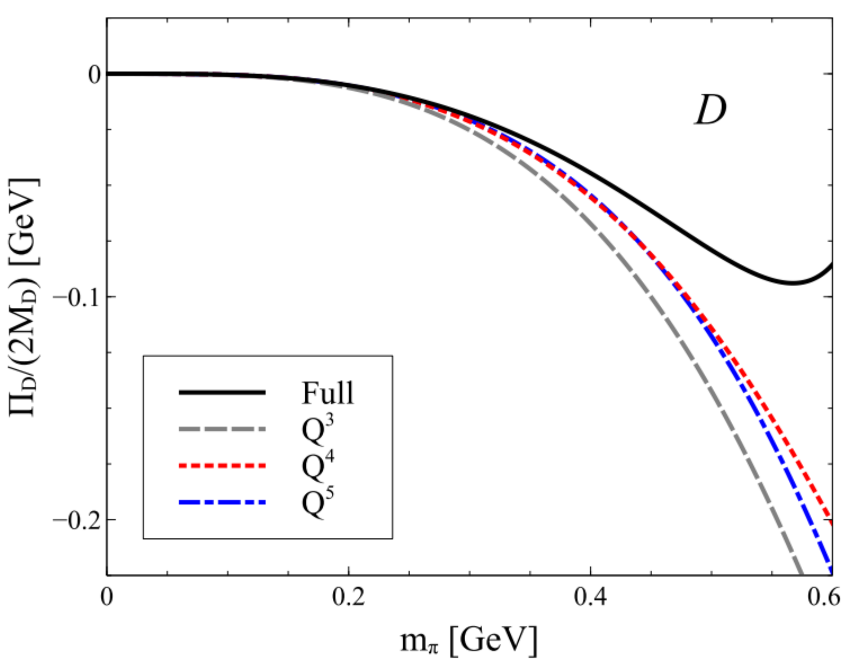
  $f_n(x^2) = 1 + \#x^2 + \#x^4 + \cdots$
- good convergence even for $m_K = M_N$ with $x \simeq 1$!

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

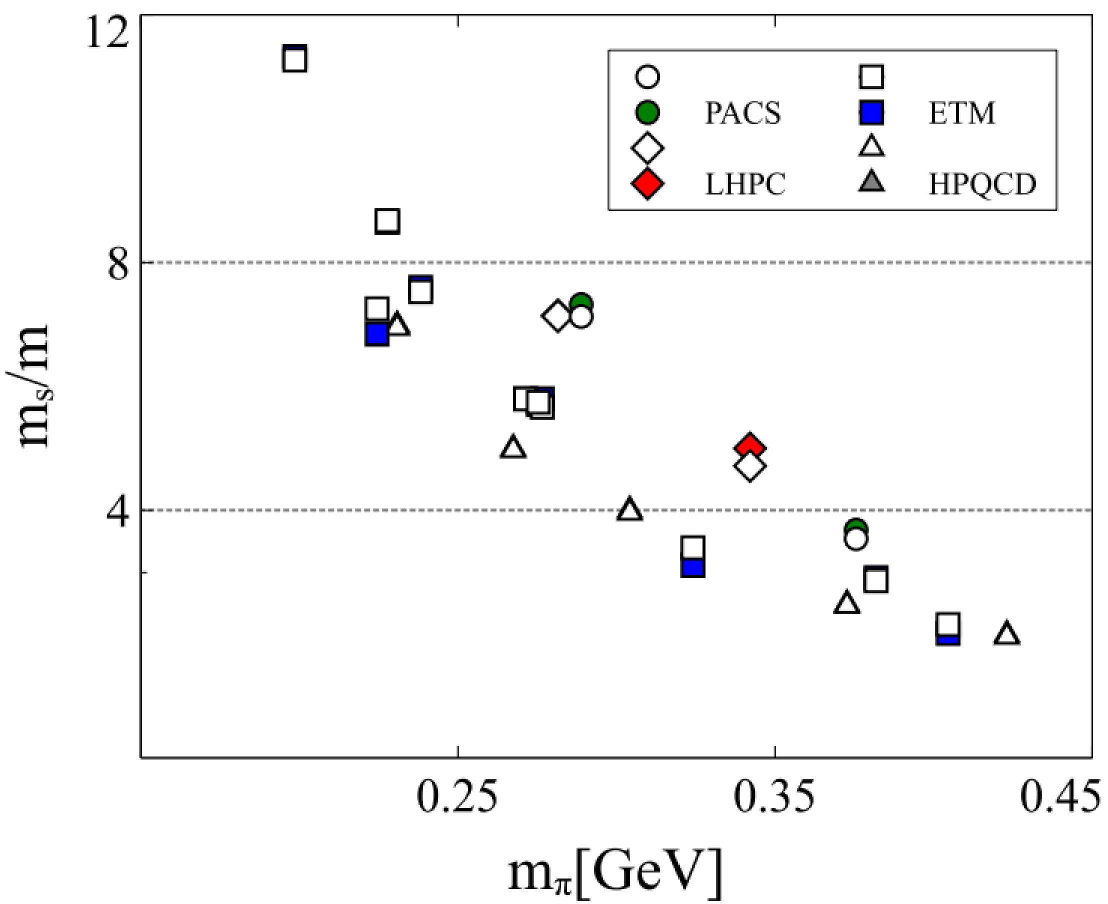
- expansion with on-shell masses well converging!

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

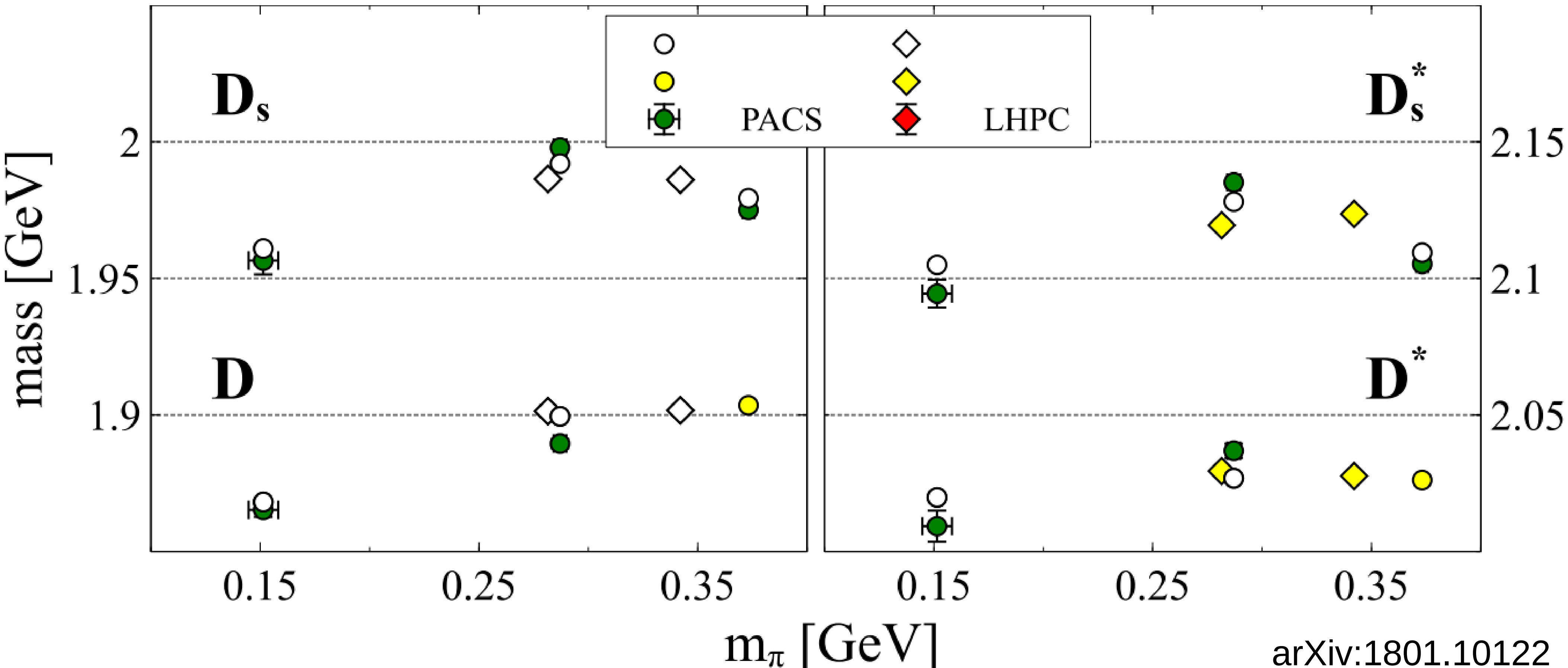
in Nucl. Phys. B887, 19 (2014)

arXiv:1801.10122

# Predictions for D meson masses in lattice ensembles

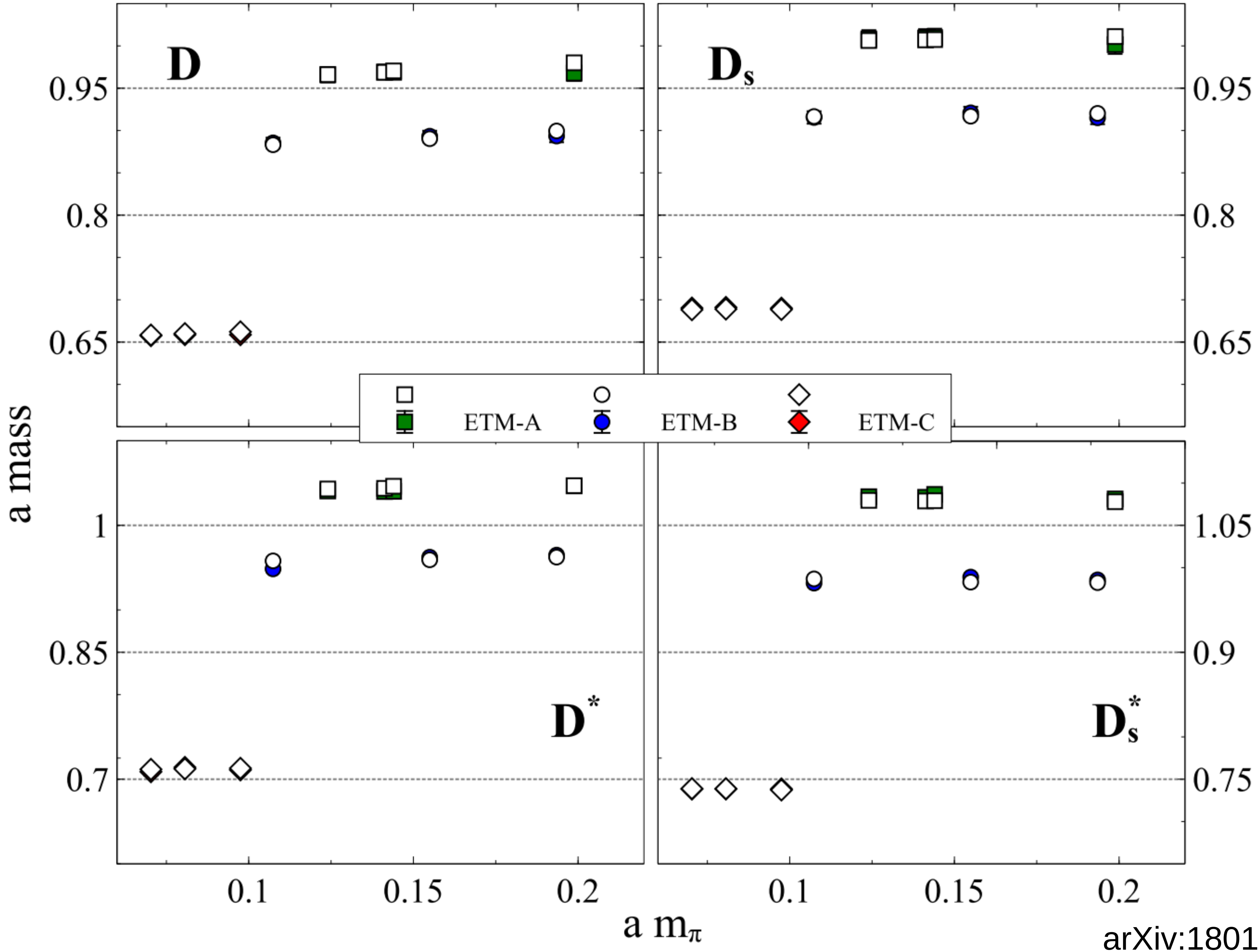
## ✔ How to fit the lattice data?

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



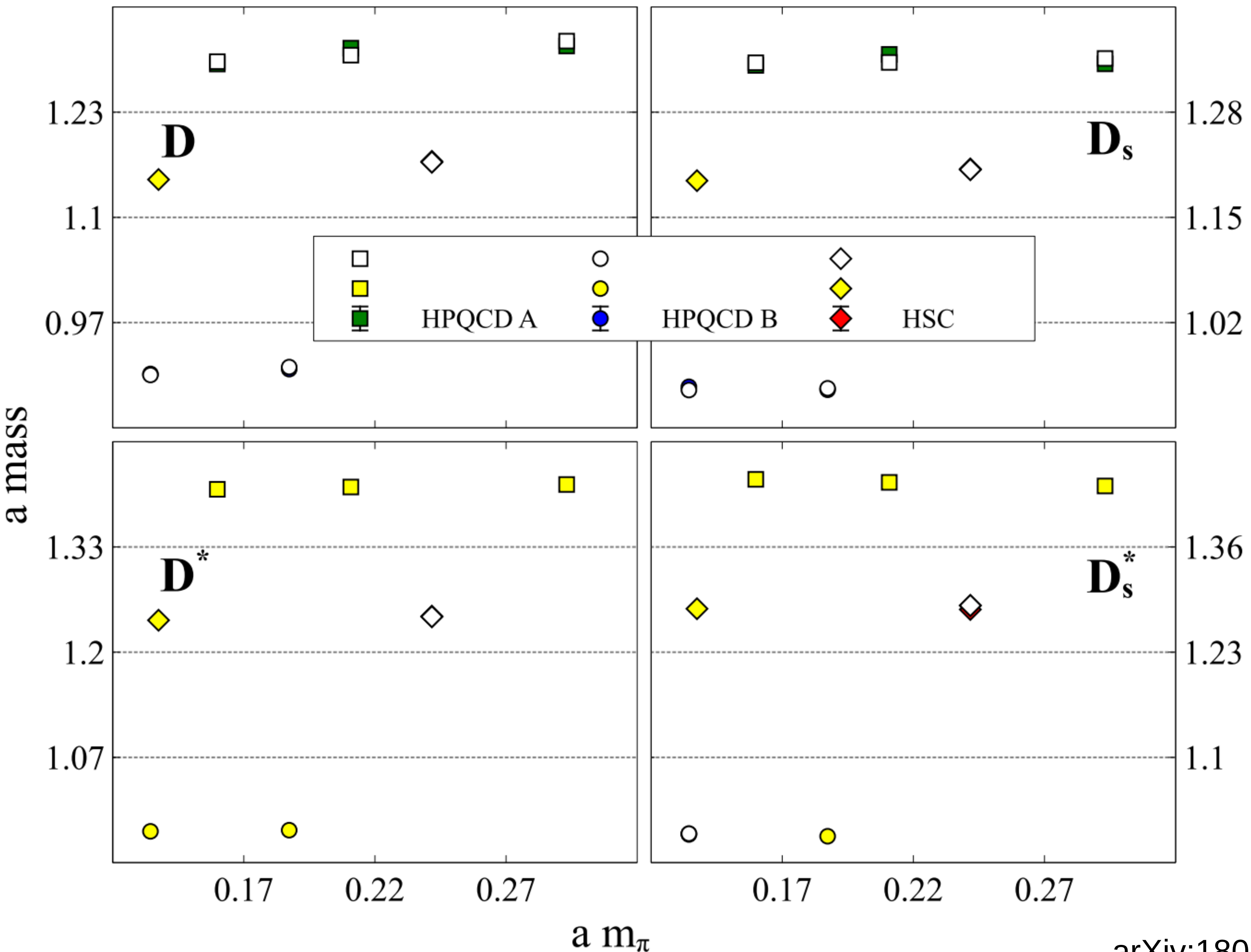

arXiv:1801.10122

# Lattice ensembles from ETMC at three different $\beta$ values




arXiv:1801.10122

# Lattice ensembles from HPQCD and HSC

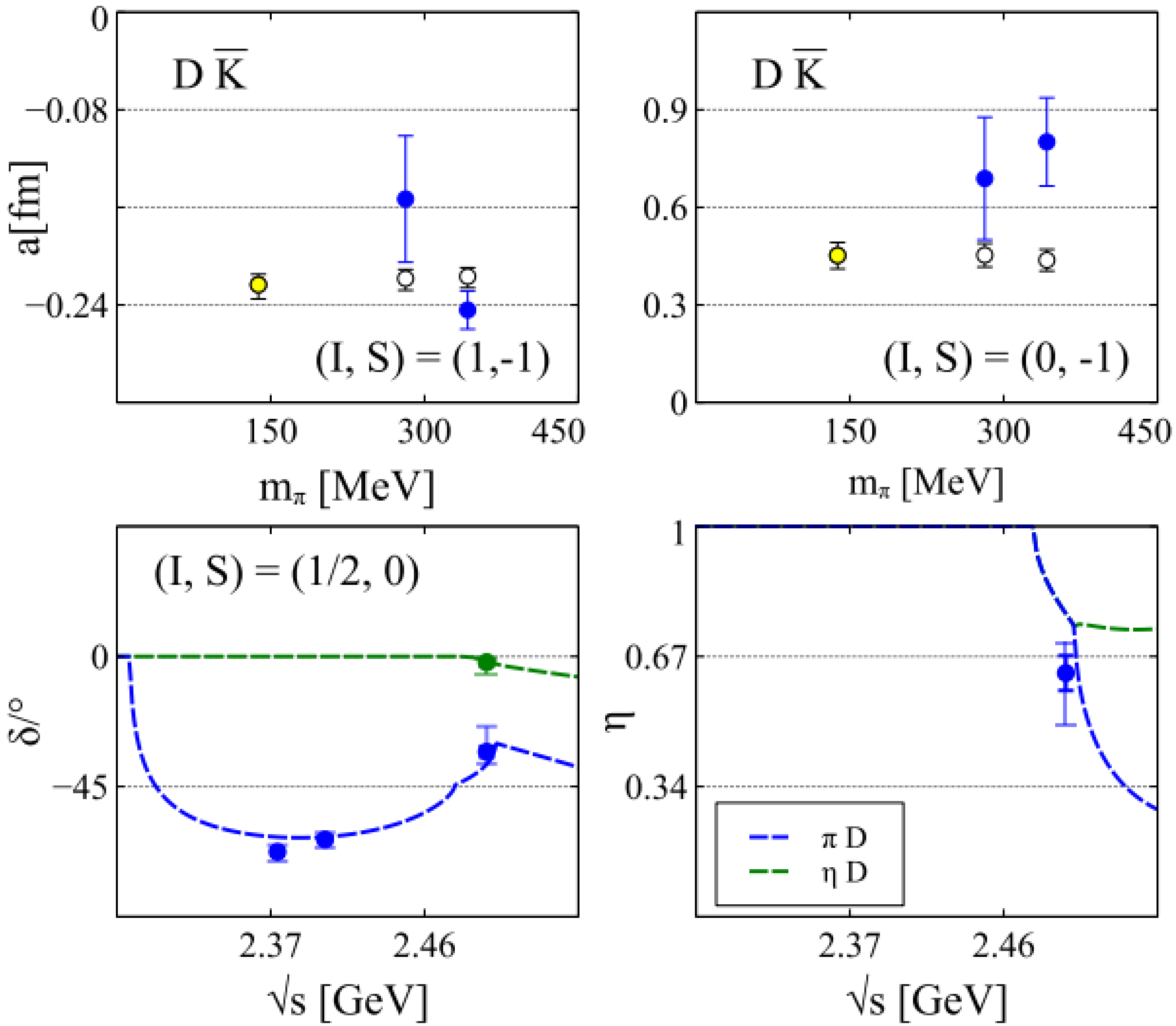



arXiv:1801.10122

# 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 $\pi D$ and $\eta D$ phase shifts (from HSC)




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

arXiv:1801.10122

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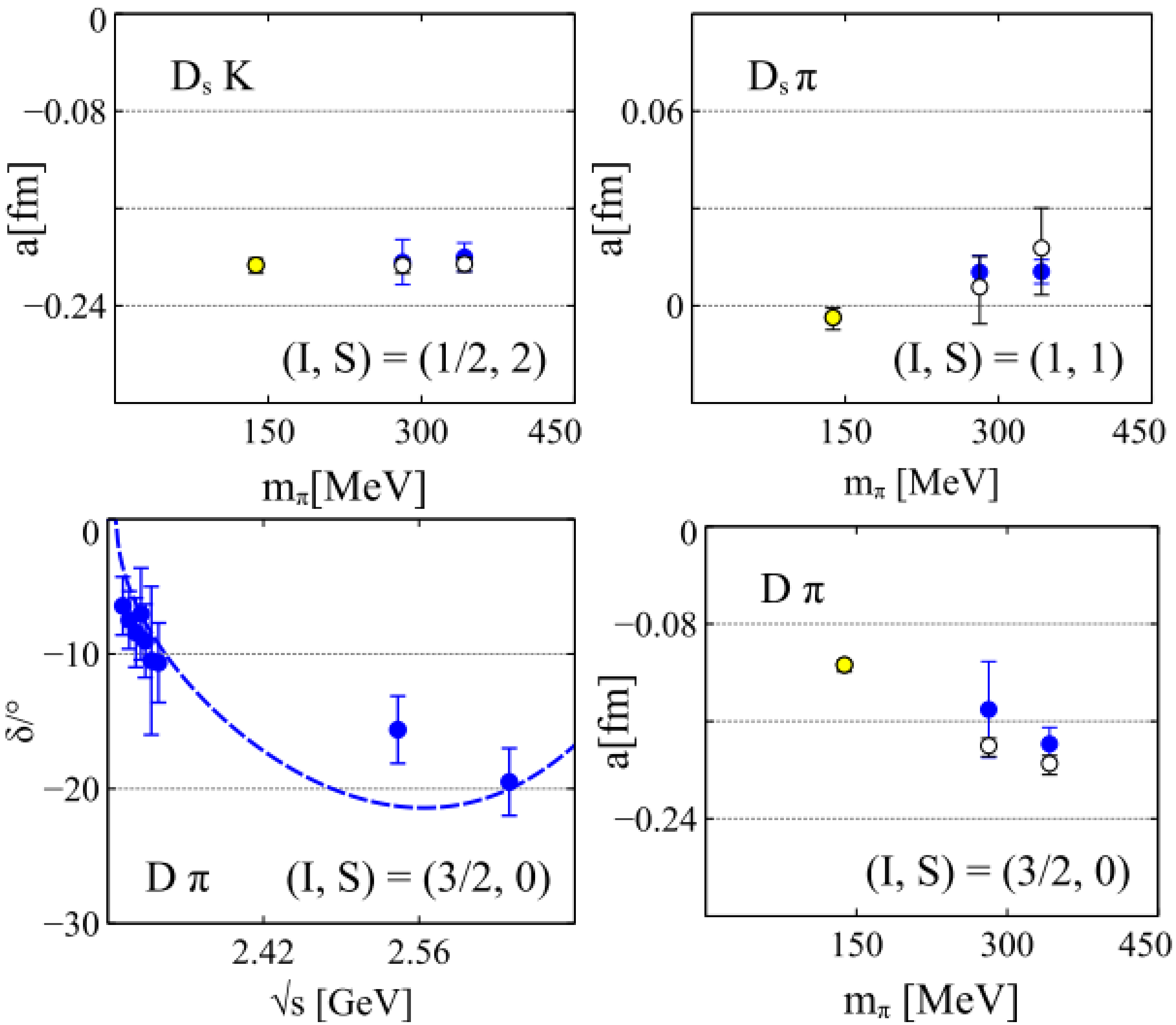


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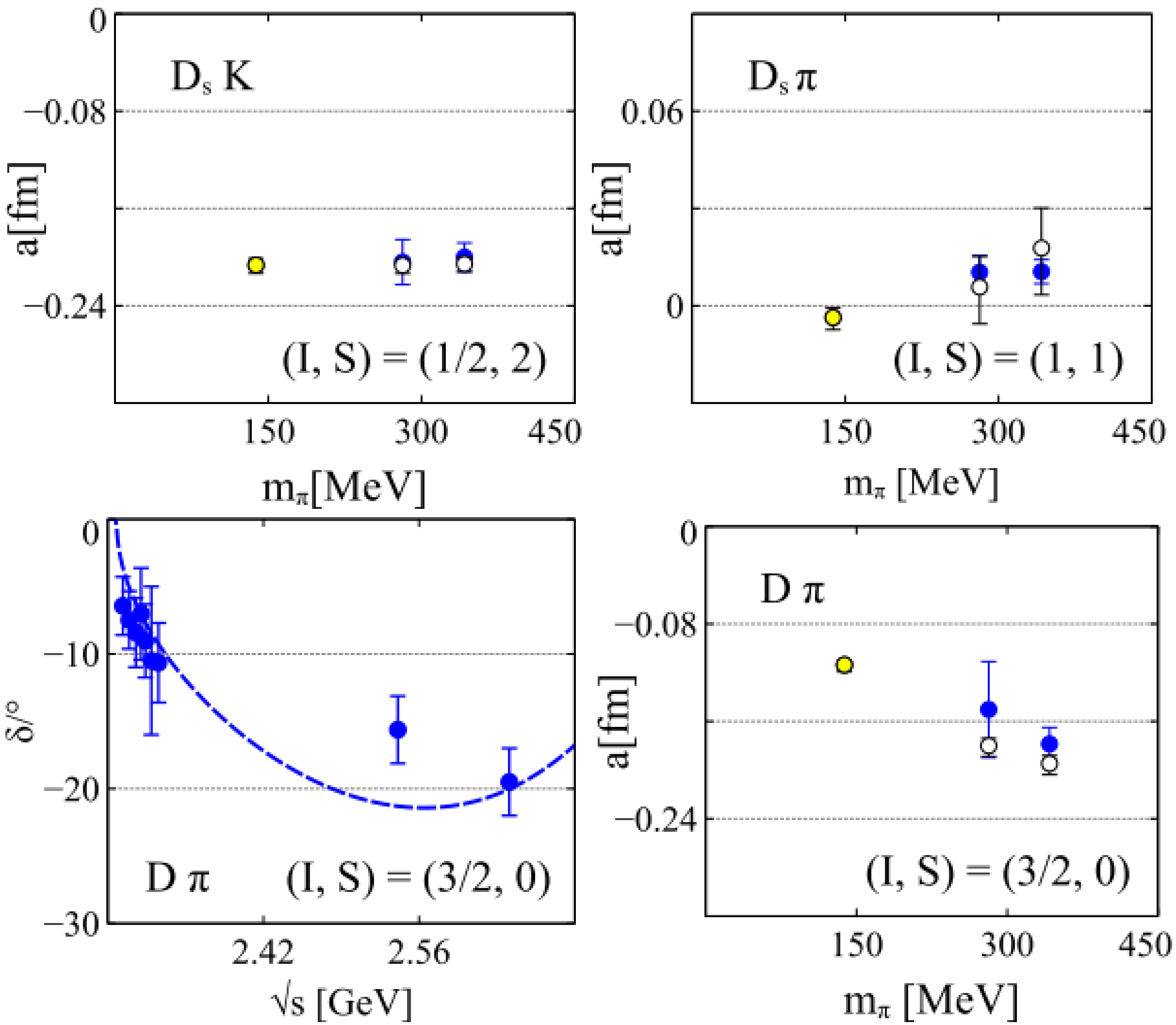
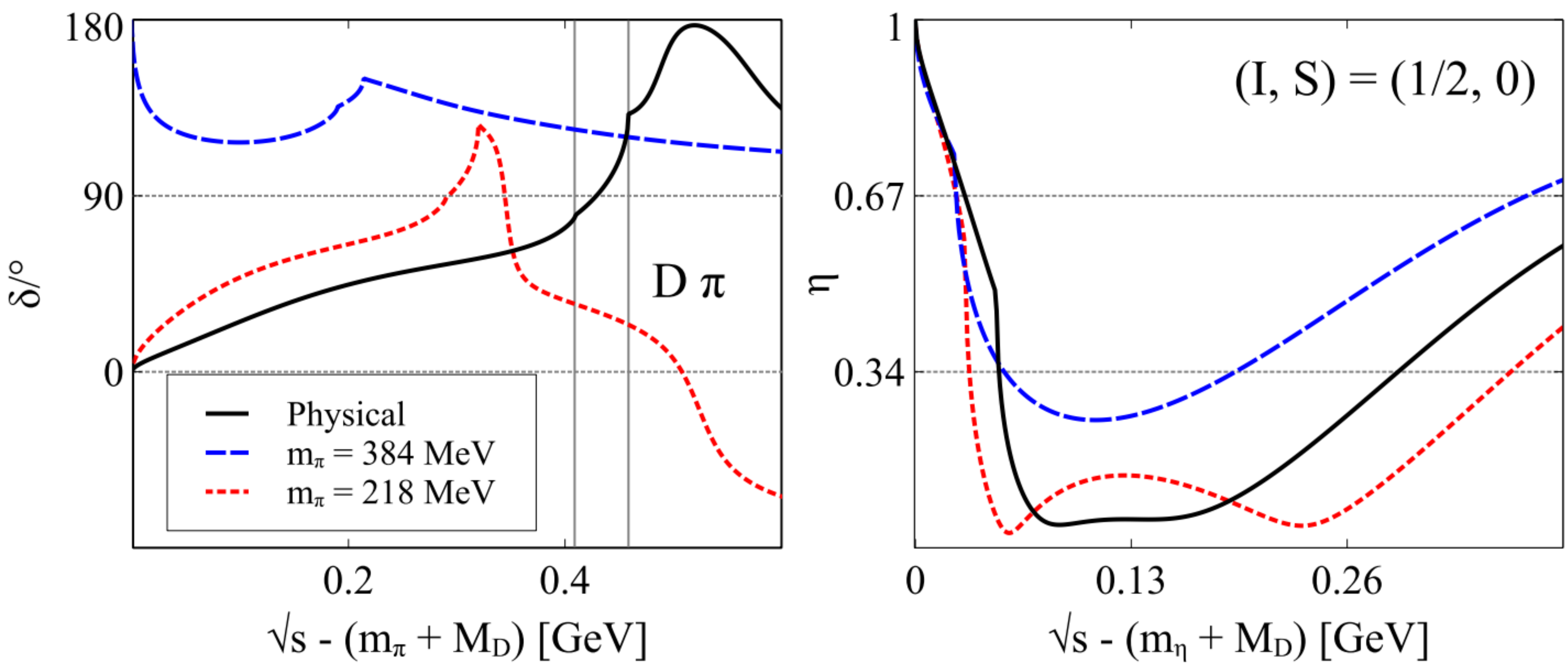



data from
Phys.Rev. D87 (2013) 014508
JHEP 10 (2016) 011

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)



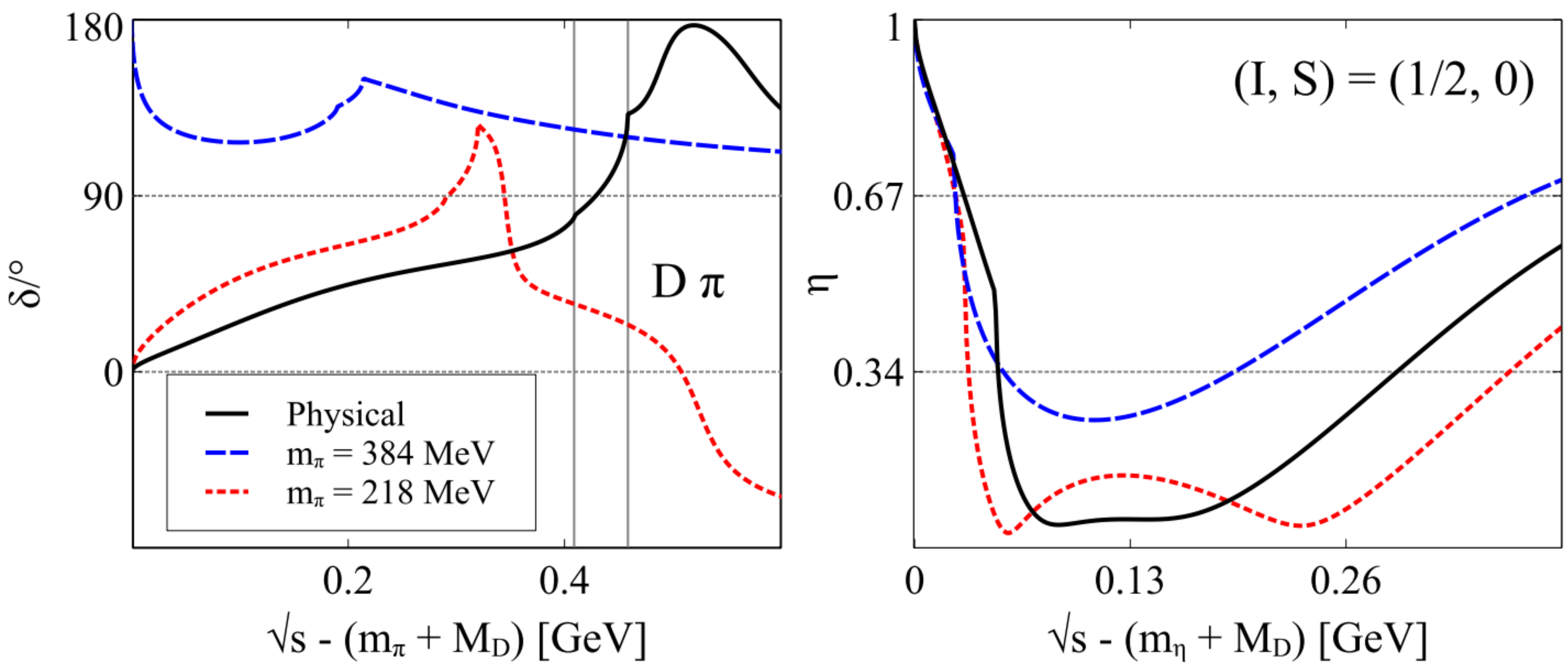
# Phase shifts: from unphysical to physical quark masses

- 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 $\pi D$ and $\eta D$ 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 $\pi D^*$ and $\eta D^*$ 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. $\eta D$ - channel)

# Summary & Outlook

## ✔ Chiral extrapolation of hadron masses

- resummed $\chi$PT : use on-shell masses in the loops
  - chiral expansion with up, down and strange quarks is well convergent
- so far we considered mesons and baryons at $\mathrm{N}^3$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
  - predict a large number of low-energy constants for the chiral Lagrangian of QCD

## ✔ QCD spectroscopy and coupled-channel dynamcis

- curent QCD lattice data constrain hadron-hadron interactions
- use as input in systematic coupled-channel computations
  - coupled-channel computations and kinematical constraints ( solved )
  - coupled-channel computations and micro causality ( solved )
  - coupled-channel computations and anomalous thresholds ( arXiv:1808.08695 )
- analyze and predict the quark-mass dependence of hadron resonances in QCD