D meson spectroscopy with the domain-wall fermions

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for the RBC collaboration

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Introduction

- Domain-wall fermions (DWF) :
  - better control of chiral extrapolation
  - negligible $O(a)$ error
- In simulations of heavy-light system, major uncertainties come from
  - chiral extrapolations
    $\Rightarrow$ DWF for light quarks
  - scaling violation [$O(am_Q) \not\ll 1$]
    $\Rightarrow$ DWF for heavy quarks

$$\Downarrow$$

Using DWF to describe both heavy and light quarks is promising.

Massive DWF?

RBC, in preparation?

There exists $am_{f,\mathrm{max}}$ up to which

- the behavior of the wave function in 5th dimension does not differ much from that for light quarks,
- am_{res} is still fairly small compared to $O(a\Lambda_{\mathrm{QCD}})$ and $O(a^2m_f^2)$.

No peculiar behavior is observed in hadronic observables, *e.g.* m_{PS} for am_f $<$1.

The value of $am_{f,\mathrm{max}}$ depends on the lattice parameters.

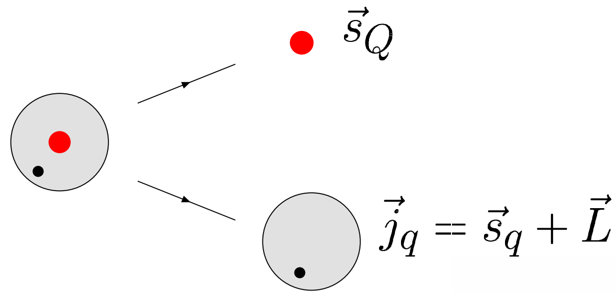
- DBW2 gauge action
- weaker coupling ($1/a$ $\sim$3 GeV)
- $L_s = 10$

$\Rightarrow$ $am_{f,\mathrm{max}} \sim$ 0.4–0.5, $am_c \sim 0.35$

Allows to simulate charm with DWF.

Classification of HL mesons

Heavy quark spin decouples from the other.



$$\Rightarrow J = s_Q + j_q$$

L	j_q	J^P		
S	$1/2$	0^-	pseudoscalar	$D_{(s)}$
		1^-	vector	$D^*_{(s)}$
P	$1/2$	0^+	scalar	$D^*_{(s)0}$
		1^+	pseudovector	$D'_{(s)1}$
	$3/2$	1^+	pseudovector	$D_{(s)1}$
		2^+	tensor	$D^*_{(s)2}$

Hereafter concentrate on 0^-, 1^-, 0^+, 1^+.

Experiments

BABAR, BELLE, CLEO, FOCUS

charm-strange mesons

J^P	Mass [MeV]
$D_s\ (0^-)$	1968.5(6)
$D_s^*\ (1^-)$	2112.4(7)
$D_{s0}^*\ (0^+)$	2317.0(4)
$D_{s1}'\ (1^+)$	2458.2(1.0)

charm-nonstrange mesons

J^P	Mass [MeV]
$D\ (0^-)$	1869.3(5)
$D^*\ (1^-)$	2010.0(5)
$D_0^*\ (0^+)$	2308(17)(15)(28)
$D_1'\ (1^+)$	2427(26)(20)(15)

† Some of them need confirmation.

$\Rightarrow$

Splittings between different parities: Δ_{qJ}

q	$0^+ - 0^-$ [MeV]	$1^+ - 1^-$ [MeV]
s	348.4(9)	345.9(1.2)
u, d	444(36)	420(36)

- $\Delta_{q0} \approx \Delta_{q1} \Rightarrow$ insensitive to J
  $\Leftrightarrow$ universal $\Delta_{\rm hf}$
- depends on m_q, and $\Delta_{udJ} > \Delta_{sJ}$

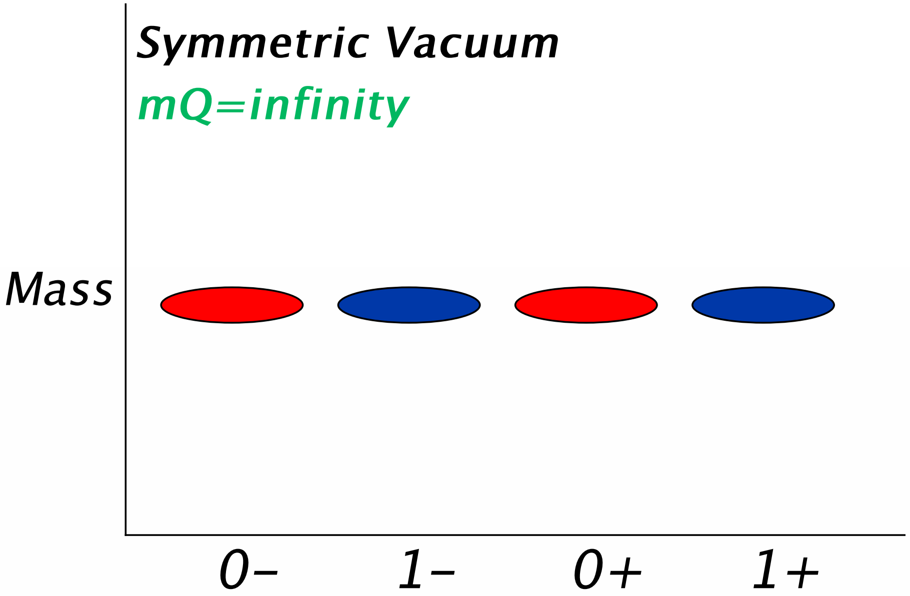
Hyperfine splittings: $\Delta_{\rm hf}$

q	$1^- - 0^-$ [MeV]	$1^+ - 0^+$ [MeV]
s	143.8(4)	141
u, d	140.64(10)	~ 120

$\Delta_{\rm hf}$ looks independent of m_l and parity.

Parity Doubling Model

Bardeen and Hill (1994), Bardeen,Eichten,Hill(2003)



- Start with hypothetical, symmetric vacuum, and impose HQ and χ Sym
  $\Rightarrow$ Four degenerate heavy-light mesons (any splittings = 0)

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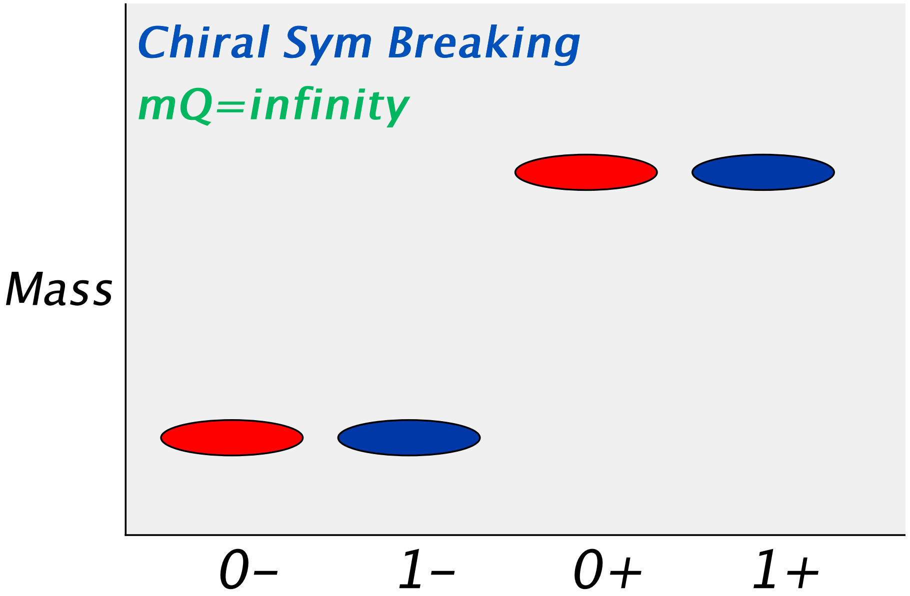

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  (Goldberger-Treiman relation $\Delta M = g_\pi f_\pi$)

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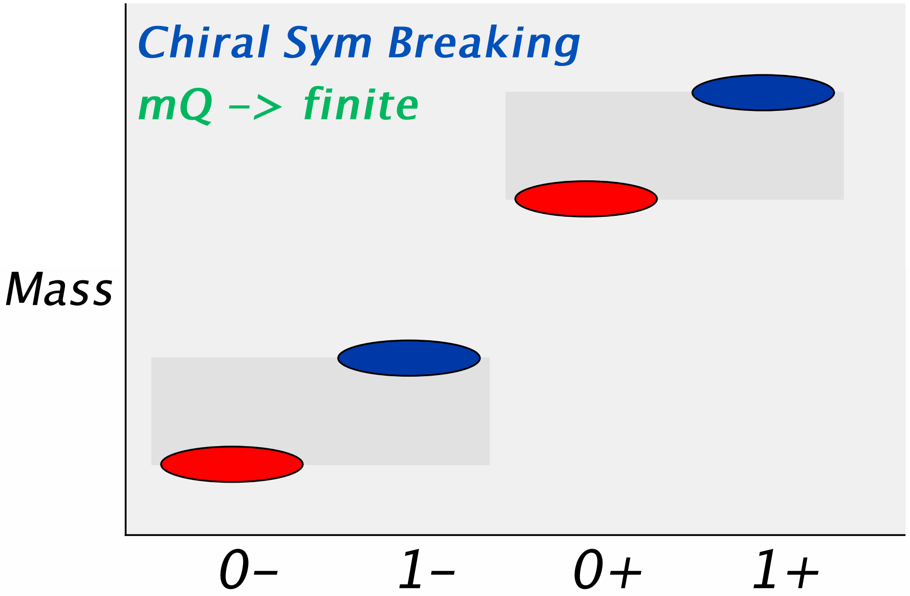

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- Spontaneous χ sym. breaking $\rightarrow \langle\sigma\rangle$,
  $\Rightarrow$ Splitting between + and $-$
  (Goldberger-Treiman relation $\Delta M = g_\pi f_\pi$)
- $m_Q \rightarrow$ finite
  $\Rightarrow$ Hyperfine Splitting

- "$\Delta_{q0} \approx \Delta_{q1}$" $\rightarrow$ understandable
- does not tell much about $\Delta_s < \Delta_{u,d}$.

Previous Lattice calculations

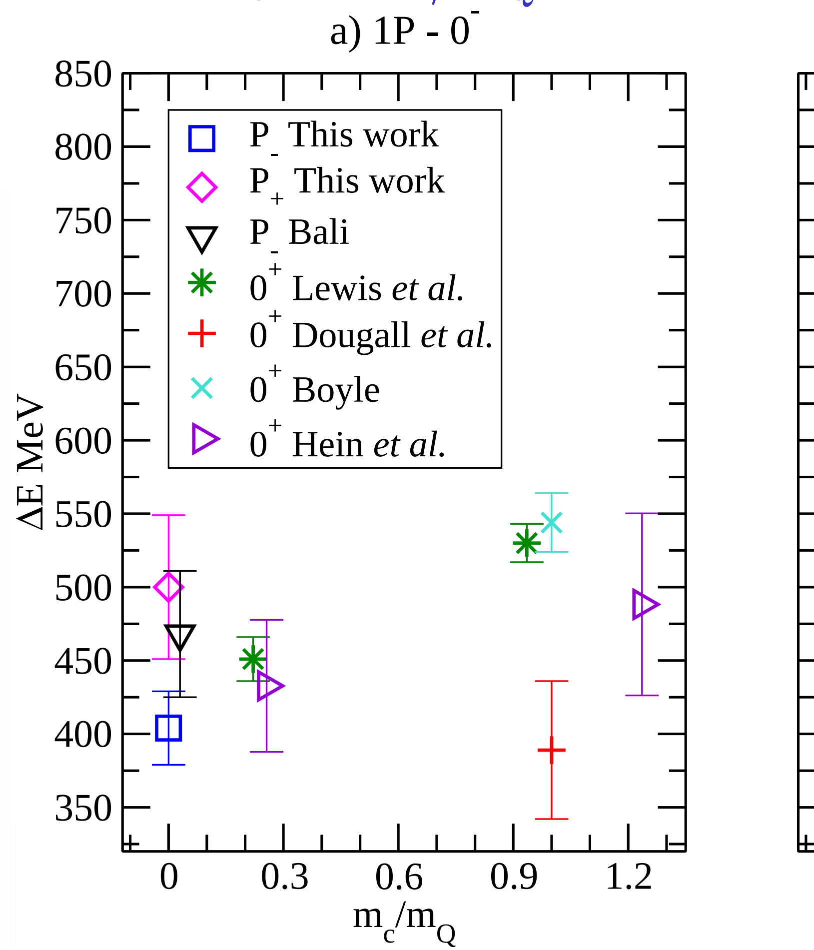
- In previous works,
  - Heavy : Clover/NRQCD/Static
  - Light : Wilson/Clover

  Most results $> \Delta_{\rm exp} \sim 350$ MeV

  † Most of potential models as well
- No systematic study on the light quark mass dependence

UKQCD (Green *et.al.*),Phys.Rev.D69(2004)

Δ_{s0} vs m_c/m_Q



When using DWF, it is interesting to see

† what is the absolute value of the splitting,

† heavy quark mass dependence below $\sim m_c$,

† light quark mass dependence.

Previous Lattice calculations (2)

How about the degeneracy between Δ_{s0} and Δ_{s1}?

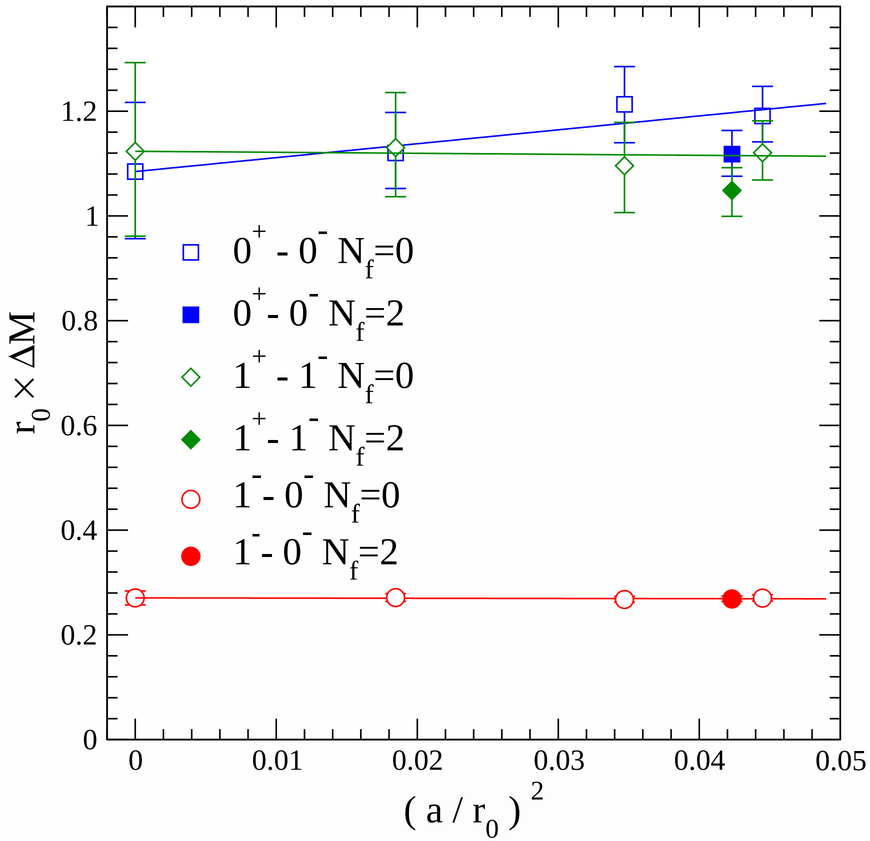
According to UKQCD (Clover/Clover), the degeneracy looks good at fine lattice.

When using DWF, it is interesting to see

† the degeneracy between Δ_{s0} and Δ_{s1}

UKQCD (Dougall *et al.*),Phys.Lett.B669(2003)

Δ_{s0} and Δ_{s1} vs a^2/r_0



Simulation parameters

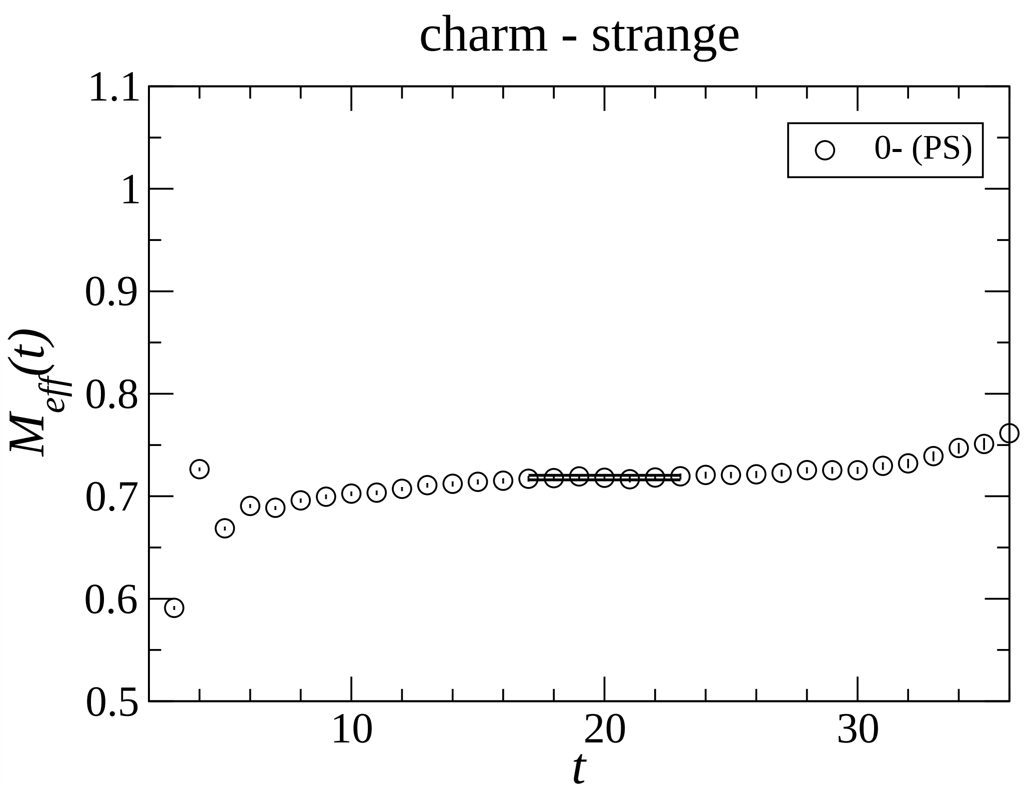
gauge action	quenched DBW2
quark action	DWF
β	1.22
size	$24^3 \times 48 \times 10$ ($\sim$1.6 fm)^3
M_5	1.65
$m_{\rm light}$	0.008, 0.016, 0.024, 0.032, 0.040
$m_{\rm heavy}$	0.1, 0.2, 0.3, 0.4, 0.5
# of config.	64

- $1/a = 2.91(5)$ GeV with M_ρ input
  ($1/a = 3.11(2)$ GeV for r_0 input)
- $\{M_K, M_{D_s}\} \rightarrow$ inputs to set $\{m_s, m_c\}$

$m_{\rm strange} \approx$0.032, $m_{\rm charm} \approx$0.35 are covered.

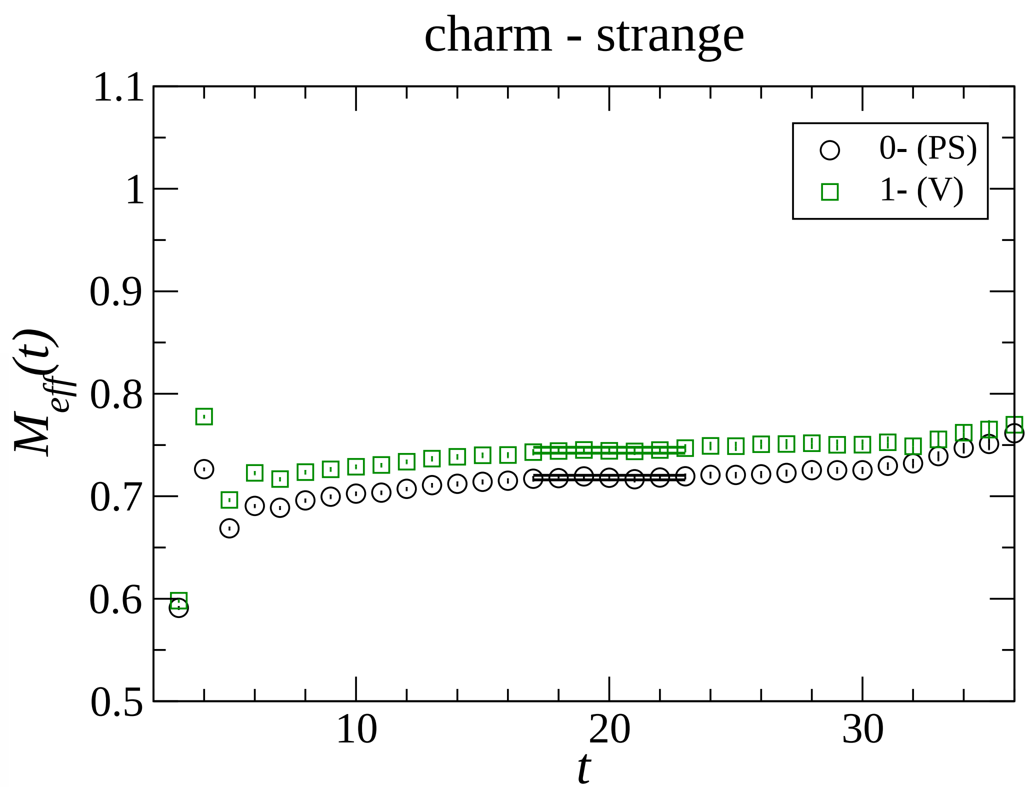
The calculation is in progress.

Effective mass plots



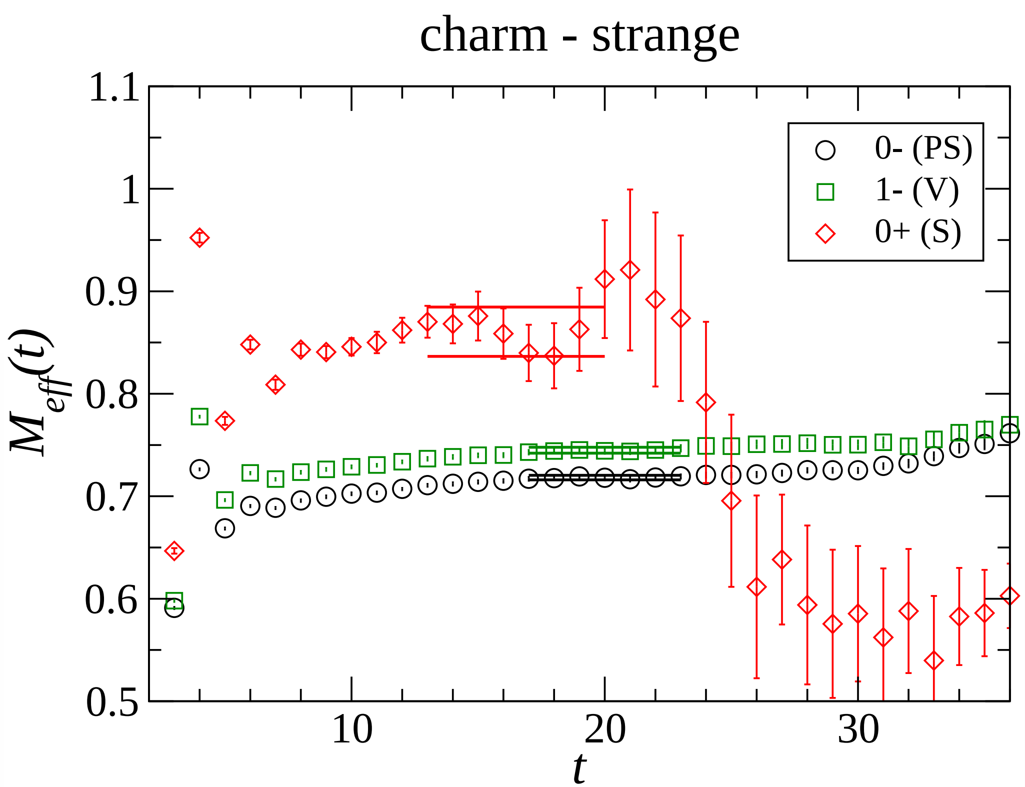
- Pseudo-scalar

Effective mass plots



- Pseudo-scalar
- Vector

Effective mass plots



- Pseudo-scalar
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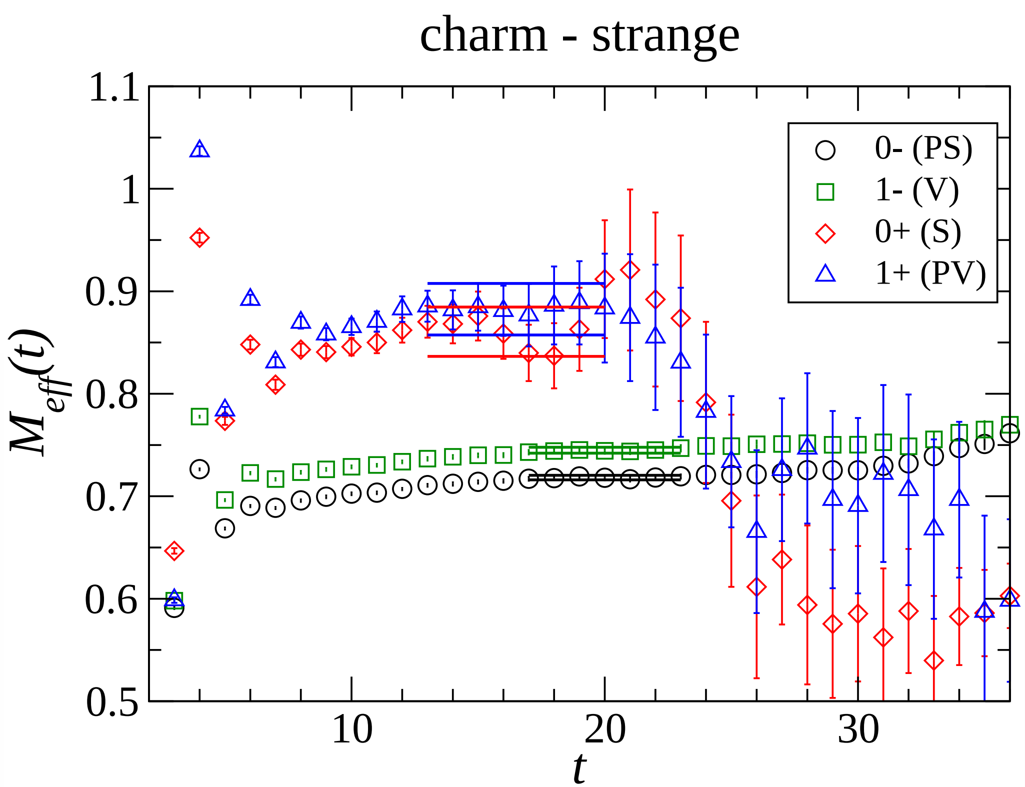
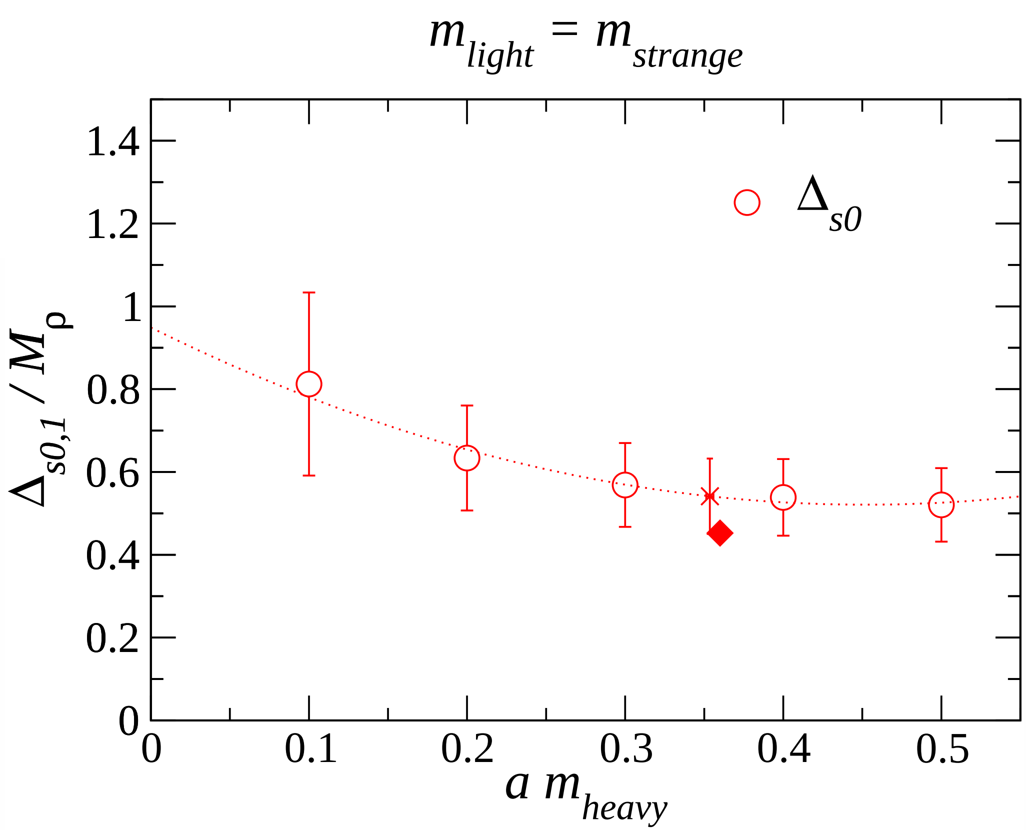
Effective mass plots



- Pseudo-scalar
- Vector
- Scalar
- Pseudo-vector

Reasonable plateaus for all mesons allows us to extract masses.

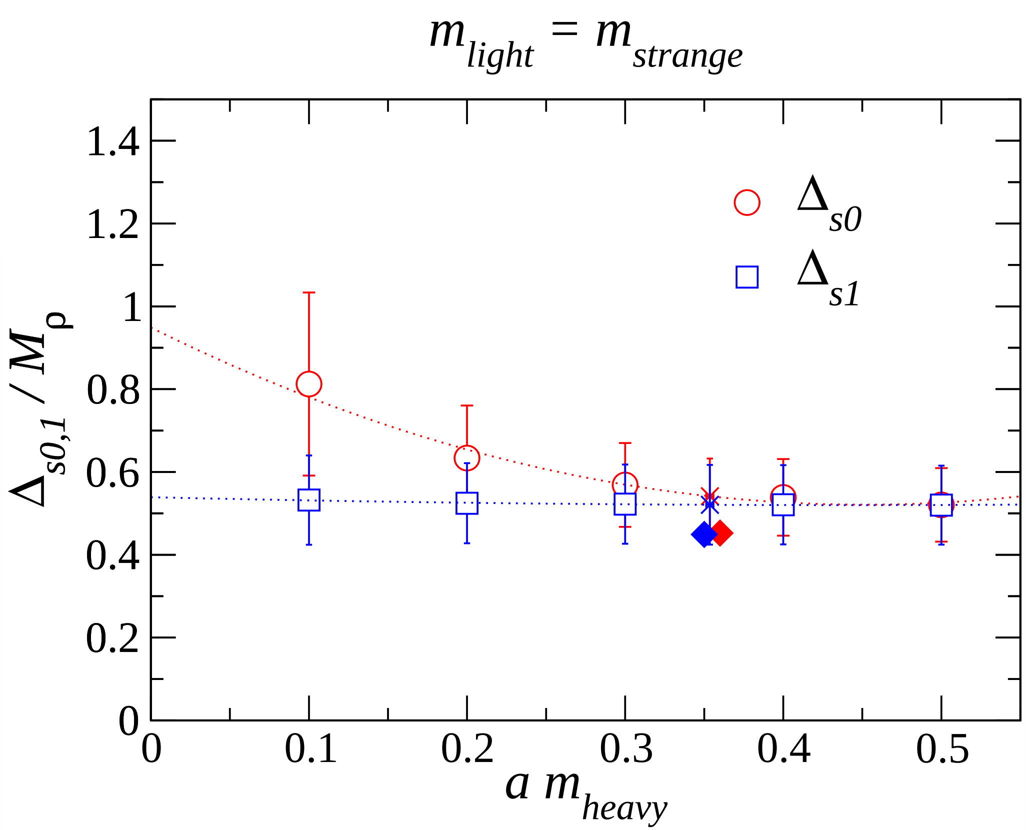
Results for D_{sJ}



- $\Delta_{s0} = M_{0^+} - M_{0^-}$
  increase as $m_{heavy} \to 0$?
  constant for $m_{heavy} \gtrsim m_c$

  Δ_{s0} = 417(70) MeV

Results for D_{sJ}



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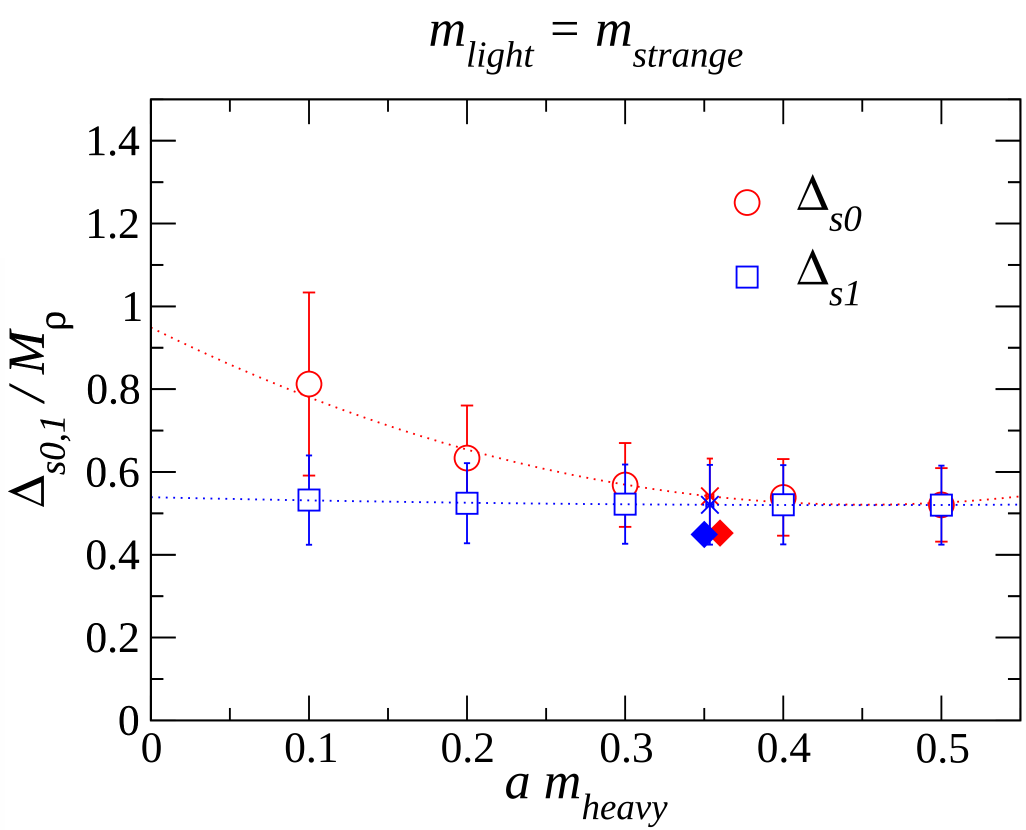
  Δ_{s0} = 417(70) MeV

- $\Delta_{s1} = M_{1+} - M_{1-}$
  constant for all m_{heavy}

  Δ_{s1} = 401(74) MeV

– Consistent with experiments within large statistical uncertainty.

Results for D_{sJ}



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– Degeneracy between Δ_{s0} and Δ_{s1} takes place in $m_Q > m_c$.

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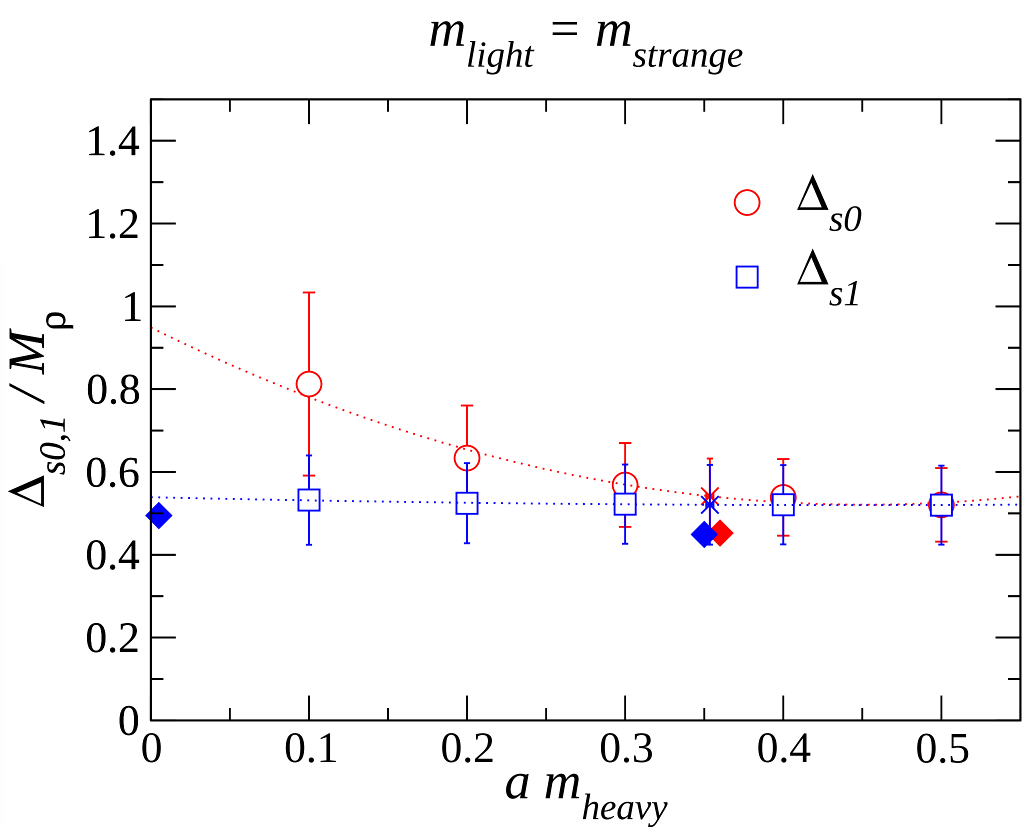


- $\Delta_{s0} = M_{0^+} - M_{0^-}$ increase as $m_{heavy} \to 0$? constant for $m_{heavy} \gtrsim m_c$

  Δ_{s0} = 417(70) MeV

- $\Delta_{s1} = M_{1^+} - M_{1^-}$ constant for all m_{heavy}

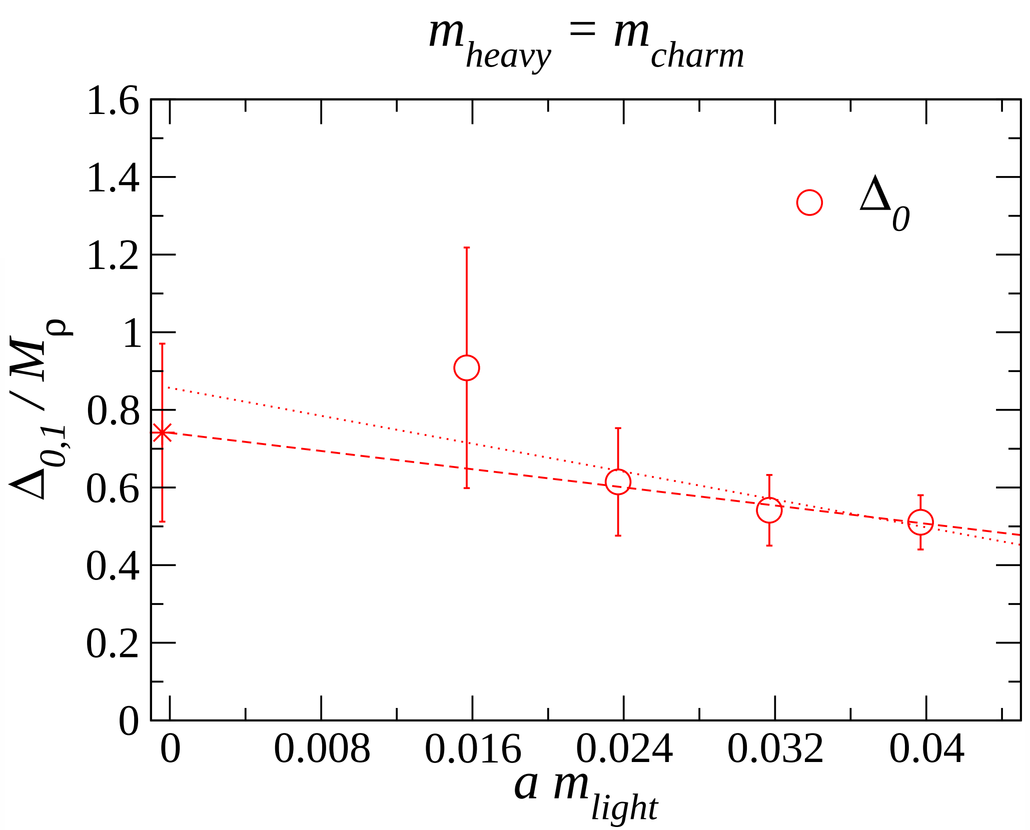
  Δ_{s1} = 401(74) MeV

– Consistent with experiments within large statistical uncertainty.

– Degeneracy between Δ_{s0} and Δ_{s1} takes place in $m_Q > m_c$.

– $K_1(1270) - K^*(892)$ splitting seems to support Δ_{s1}= constant.

Chiral extrapolation of $\Delta_{q0,1}$



- $\Delta_0 = M_{0+} - M_{0-}$
  increase as $m_{light} \rightarrow 0$?
  With 3 data points,
  Δ_0 = 571(177) MeV

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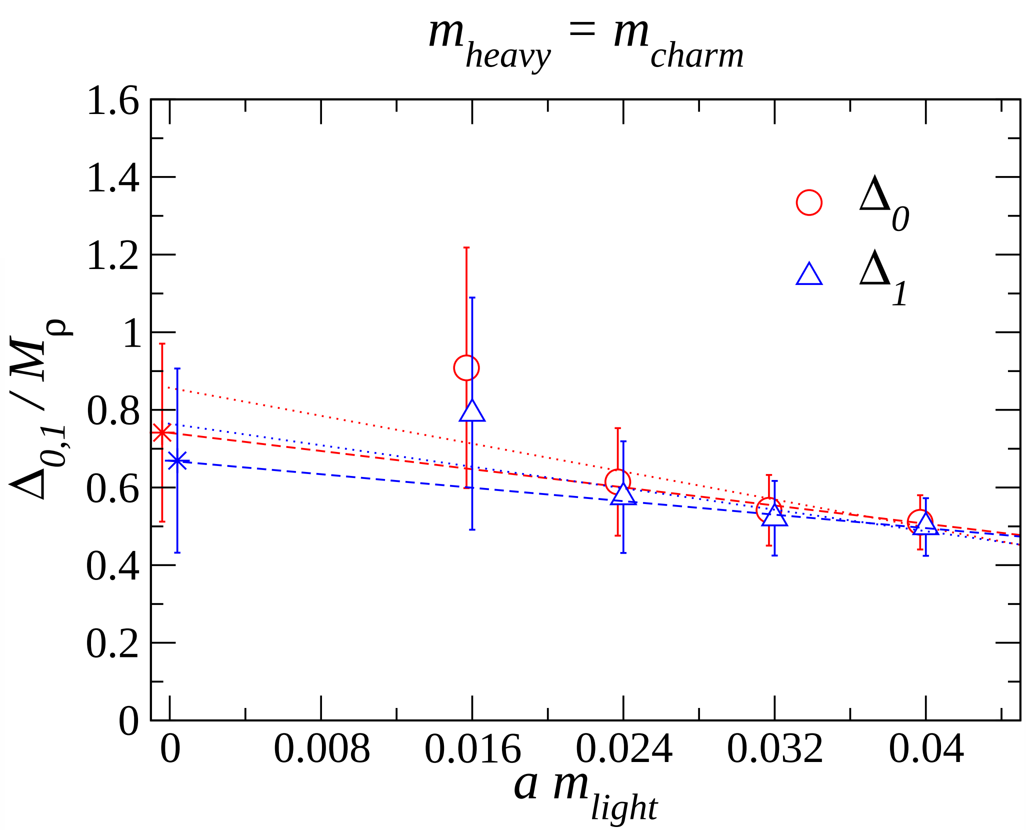
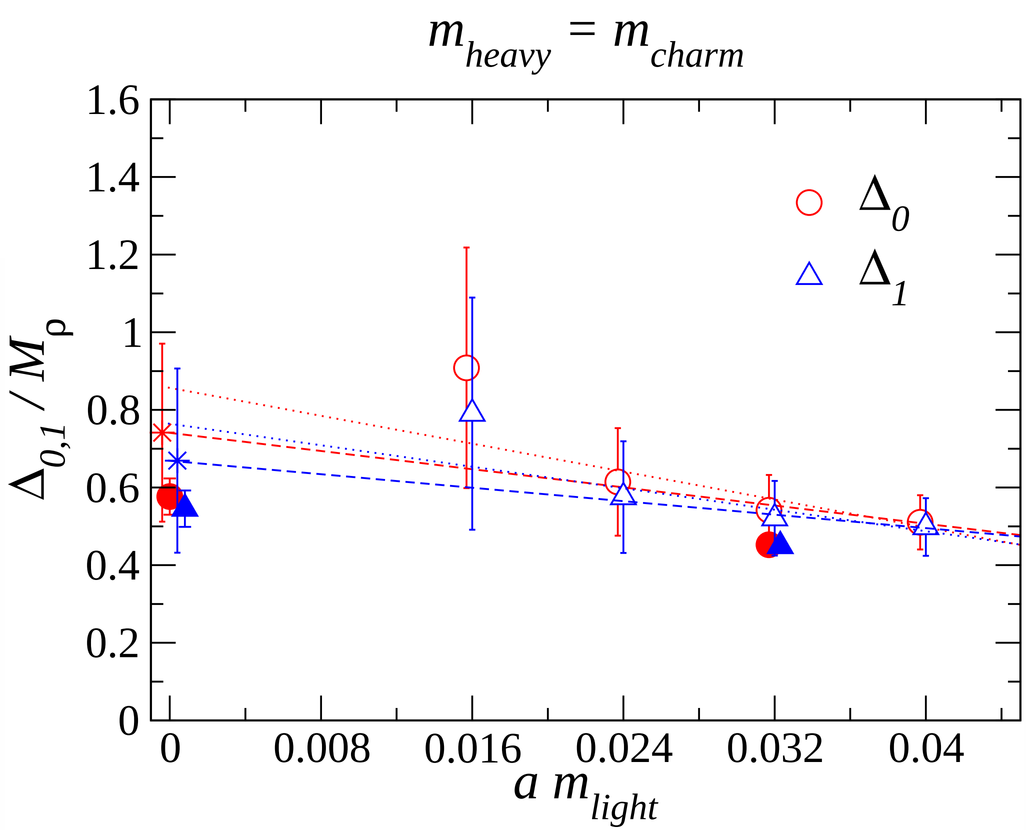


- $\Delta_0 = M_{0^+} - M_{0^-}$
  increase as $m_{light} \to 0$?
  With 3 data points,
  Δ_0 = 571(177) MeV
- $\Delta_1 = M_{1^+} - M_{1^-}$
  With 3 data points,
  Δ_1 = 515(183) MeV

Chiral extrapolation of $\Delta_{q0,1}$



- $\Delta_0 = M_{0^+} - M_{0^-}$
  increase as $m_{light} \to 0$?
  With 3 data points,
  Δ_0 = 571(177) MeV

- $\Delta_1 = M_{1^+} - M_{1^-}$
  With 3 data points,
  Δ_1 = 515(183) MeV

Consistent with experiments within large uncertainty.

Especially the moderate slope in exp. is well reproduced.

Leptonic decay constant

f_D : General remarks

- CLEO-c is expected to determine $f_{D_{(s)}}$ in a few % soon.

  Currently, $f_{D_s} = 266 \pm 32$ MeV [PDG'04],

  $f_D = 230 \pm 42 \pm 10$ MeV [CLEO-c@Lat'04]

In the following, $f_{D_{(s)}}$ are briefly discussed.

Z_A for the heavy-light current of DWF is not available.

$\Rightarrow$ very preliminary

Proper normalization for Massive DWF

NY, Aoki, Kuramashi (2004)

Defining $Z_{\rm dw}$ by $q_R = Z_{\rm dw}^{1/2}\, q_{\rm lat}$, the proper tree level normalization is given by

$$Z_{\rm dw}(am_f,\omega) = \frac{am_f\,(1+(am_f)^2)\cosh(am_p) - 2(am_f)^2\,\omega\sinh(am_p)}{(1-(am_f)^2)\sinh(am_p)},$$

where $\omega = 2 - M_5$ and

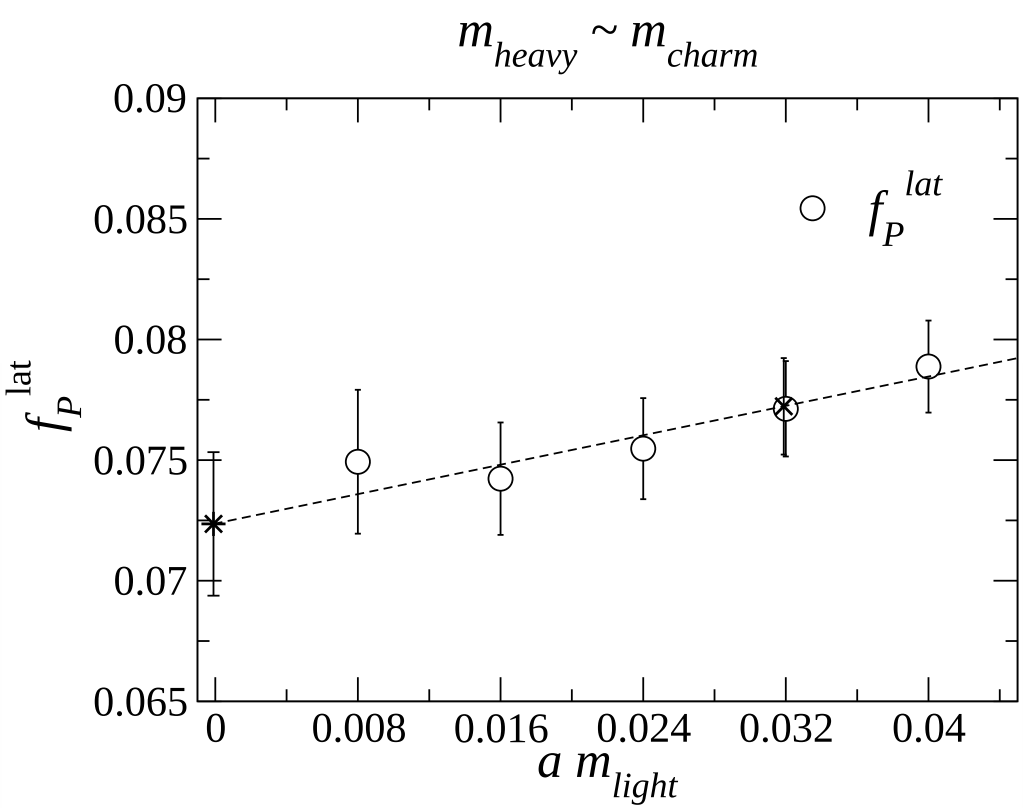
$$am_p = \ln\left|\frac{-(am_f)\omega^2 + \sqrt{(1+(am_f)^2)^2 + (am_f)^2\omega^2(\omega^2-4)}}{1+(am_f)^2 - 2\omega\,(am_f)}\right|.$$

In the massless limit, $Z_{\rm dw} \to 1/\omega\,(2-\omega)$, and $m_p \to \omega\,(2-\omega)\,m_f$.

With M_5=1.65, am_c=0.35 $\sqrt{Z_{\rm dw}^{\rm H}(m_c)/Z_{\rm dw}^{\rm L}(0)}$=1.179,
$Z_A^{\rm LL,NP} = 0.888$ for light-light currents is available.
Thus,

$$Z_A^{\rm HL} = Z_A^{\rm LL,NP} \times \sqrt{Z_{\rm dw}(am_c)/Z_{\rm dw}(0)} = 1.047$$

Results of $f_{D_{(s)}}$



With Z_A^{HL}=1.047,

the preliminary results:

$$f_{D_s} = 228(6) \text{ MeV},$$

$$f_D = 212(9) \text{ MeV},$$

$$f_{D_s}/f_D = 1.07(3).$$

(statistical error only)

Summary

- DWF is applied to charmed-light system
- Splittings between different parities are consistent with exp within large uncertainty, though the central values look a little higher than exp like the previous lattice calculations do.
- In $m_Q \gtrsim m_c$, degeneracy of splittings between different parities is observed.
- Experimental observation of $\Delta_{s0,1} < \Delta_{ud0,1}$ is likely to happen.
- To make sure all the above, we need more statistics.

Backup Slides

Domain-wall fermion

Kaplan(1992), Shamir(1993), Furman and Shamir(1995)

$$
\begin{aligned}
S_{\rm DW} &= \sum_{x,y}\sum_{s,t}\bar\psi_s(x)D_{\rm DW}(x,s;y,t)\psi_t(y),\\
D_{\rm DW}(x,s;y,t) &= D_{\rm W}(x,y)\,\delta_{s,t}+\delta_{x,y}D_5(s,t),\\
D_{\rm W}(x,y) &= \sum_\mu \gamma_\mu D_\mu - \frac{a}{2}\sum_\mu D_\mu^2 - M_5\,\delta_{x,y},\\
D_5(s,t) &= \delta_{s,t} - P_L\,\delta_{s+1,t} - P_R\,\delta_{s-1,t}\\
&\quad + m_f\left[P_L\,\delta_{s,N_5}\delta_{1,t} + P_R\,\delta_{s,1}\delta_{N_5,t}\right],
\end{aligned}
$$

physical quark field : $\left\{\begin{array}{l} q(x) = P_L\psi_1(x) + P_R\psi_{N_5}(x) \\ \bar q(x) = \bar\psi_1(x)P_R + \bar\psi_{N_5}(x)P_L \end{array}\right.$,

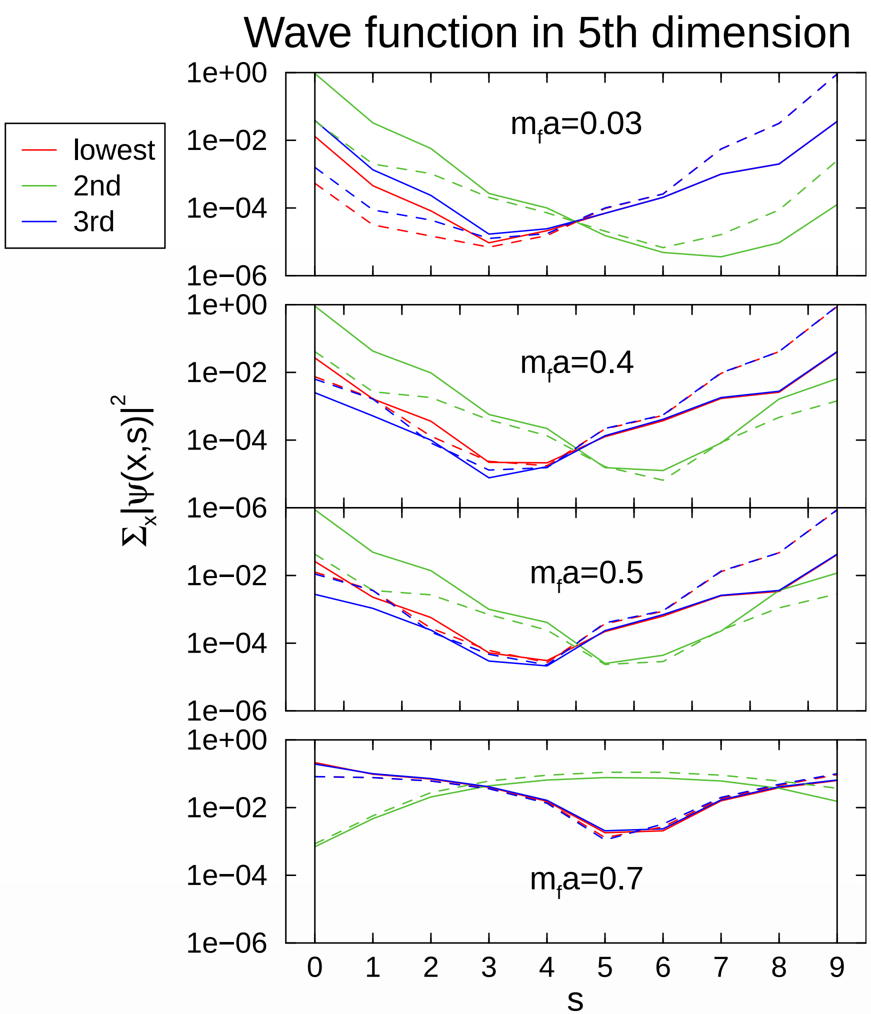
$$P_{R/L} = (1\pm\gamma_5)/2,$$

$$1\le s,t\le N_5 \quad (N_5\to\infty)$$

- Exact chiral symmetry at the finite lattice spacing
- Leading scaling violation $\sim O(a^2)$ without any tuning
- The space-time rotational symmetry

Wavefunction in 5th dimension

RBC collaboration



- The behavior of the wave function in fifth dimension does not change much if $am_f \lesssim$ 0.4–5.
- $O(a)$ error $\sim am_{\rm res} \ll 10^{-2}$