Charm quark system on the physical point in $2+1$ flavor lattice QCD

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1 Introduction

[Progress of lattice QCD]
Simulations become realistic, thanks to the development of computers and algorithms.

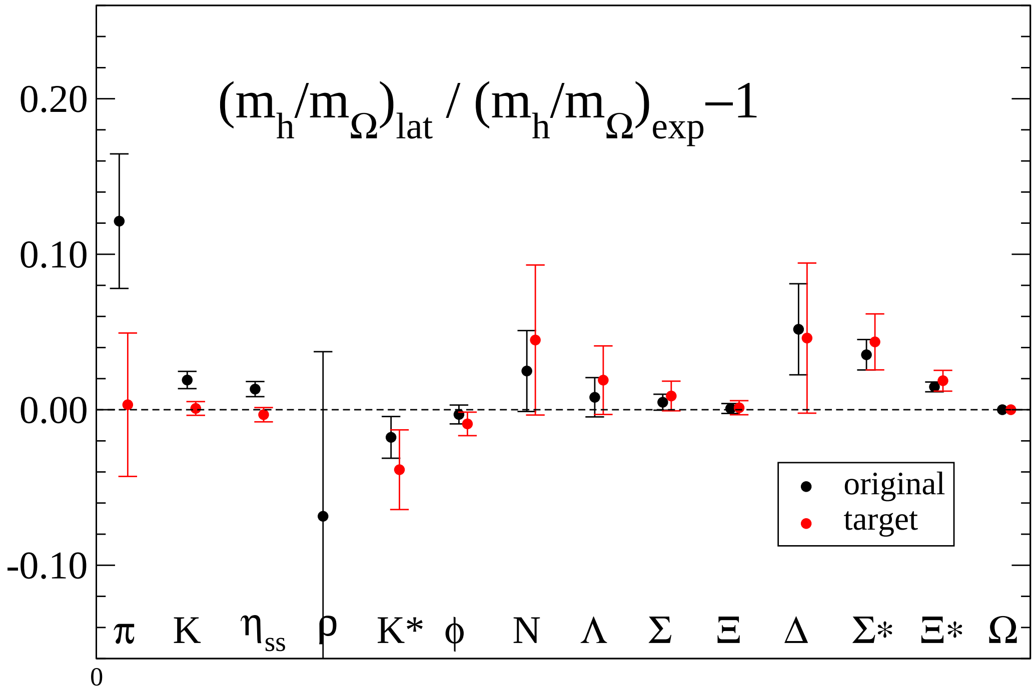
- $N_f = 2 + 1$ full QCD is performed, which includes dynamical effects of up-down and strange quarks.

- Dynamical up-down and strange quark masses can be set to their physical values (i.e. $m_\pi = 135$ MeV).
  $\leftarrow$ So far, up-down quark masses are higher than their physical value, because of the computational cost.

[Progress of lattice QCD(continued)]

Light hadron spectrum has been reproduced within 5% accuracy.

→ As a next step, we move on to the heavy quark system.

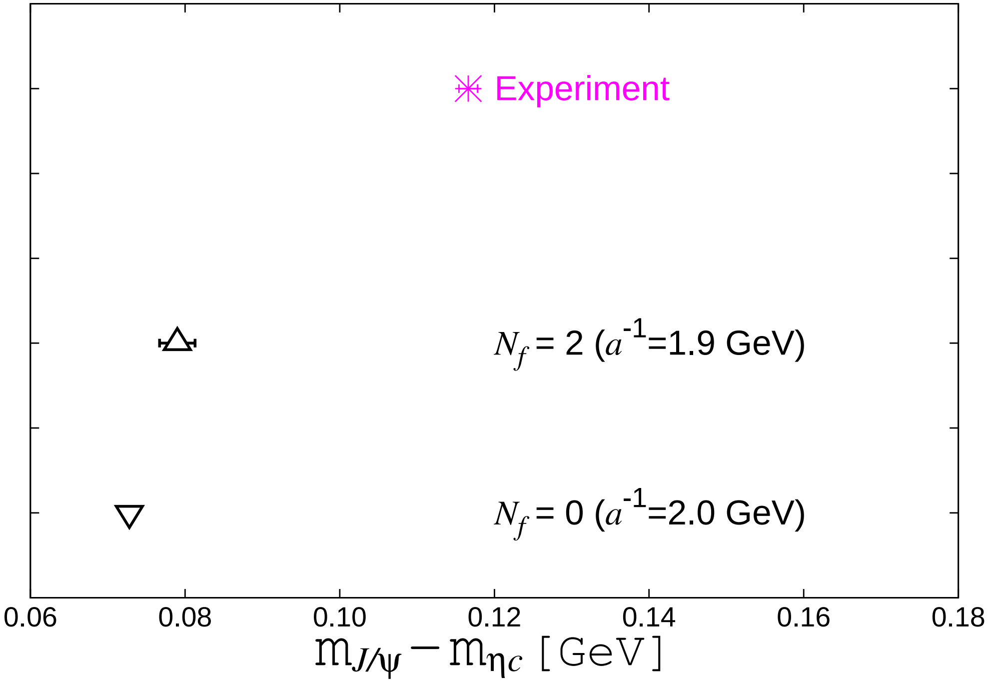


$N_f = 2 + 1, \ a^{-1} = 2.2$ GeV

PACS-CS,2010

[Problem of the heavy quark system on the lattice]

- So far, lattice QCD fails to explain the charmonium hyperfine splitting $m_{J/\psi} - m_{\eta_c}$.
  $\rightarrow$ We try to solve this problem using the $N_f = 2+1$ lattice QCD on the physical point.



2 Simulation setup

We perform a $N_f = 2+1$ full QCD simulation of the charm quark system on the physical point using a relativistic heavy quark formalism.

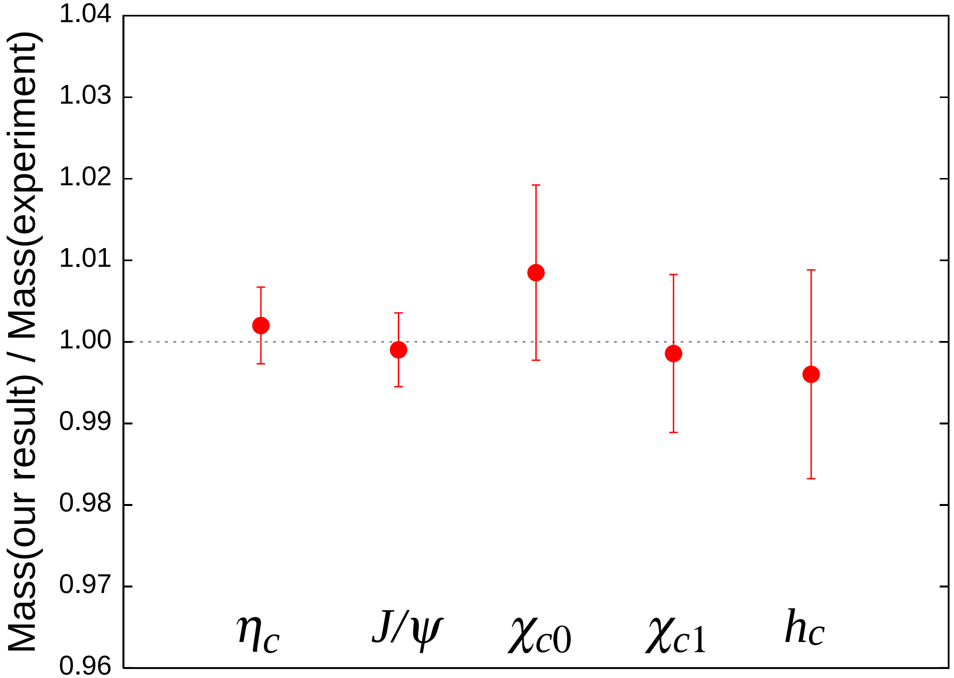
- Action : RG improved gauge + $O(a)$ improved Wilson fermion for light sea quarks + relativistic heavy quark for valence charm quark
- Lattice size : $32^3 \times 64$ ($L = 3$ fm, $a^{-1} = 2.2$ GeV ($\beta = 1.90$))
- Sea quark masses : on the physical point (i.e. $m_\pi = 135$ MeV)
- Inputs : m_π,m_K,m_Ω for m_{ud},m_s,a; $\overline{m}(1S) \equiv \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ for m_{charm}

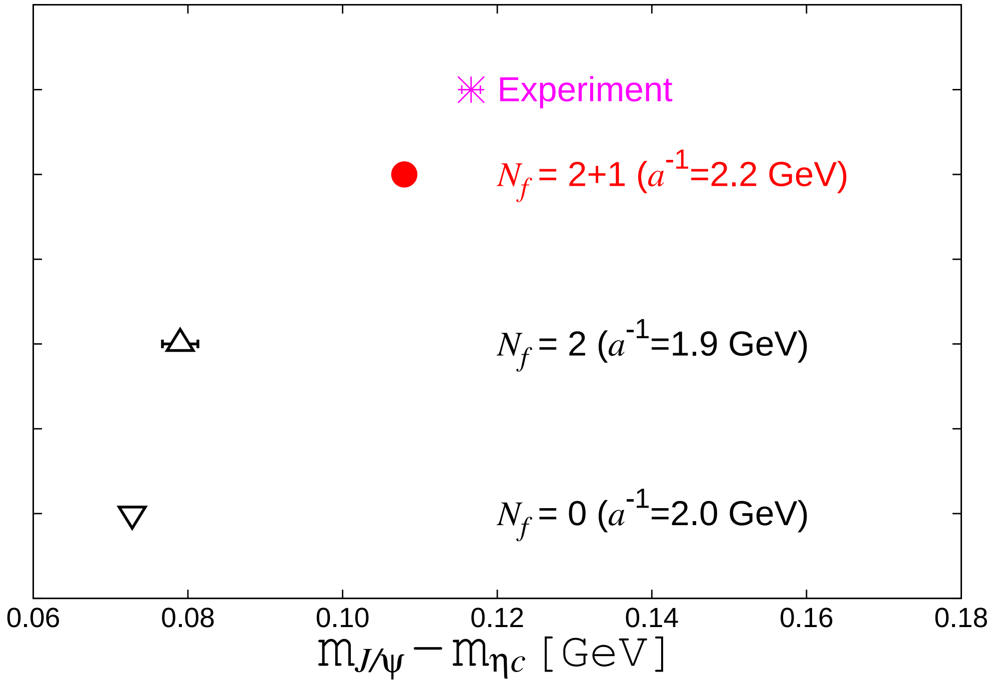
$m_{ud}^{\overline{\mathrm{MS}}}(\mu = 2\mathrm{GeV})$[MeV]	$m_s^{\overline{\mathrm{MS}}}(\mu = 2\mathrm{GeV})$[MeV]	N_{conf} (MD time)
3	93	80 (2000)

3 Results

3.1 Charmonium spectrum

- Charmonium spectrum is reproduced well except for the hyperfine splitting.
- The hyperfine splitting is slightly underestimated, but $N_f = 2 + 1$ result is much closer to the experiment than those of $N_f = 2, 0$.
  → Possible origins of the discrepancy are $O(a)$ effects in RHQ action, disconnected loop contributions, dynamical charm quark effects.

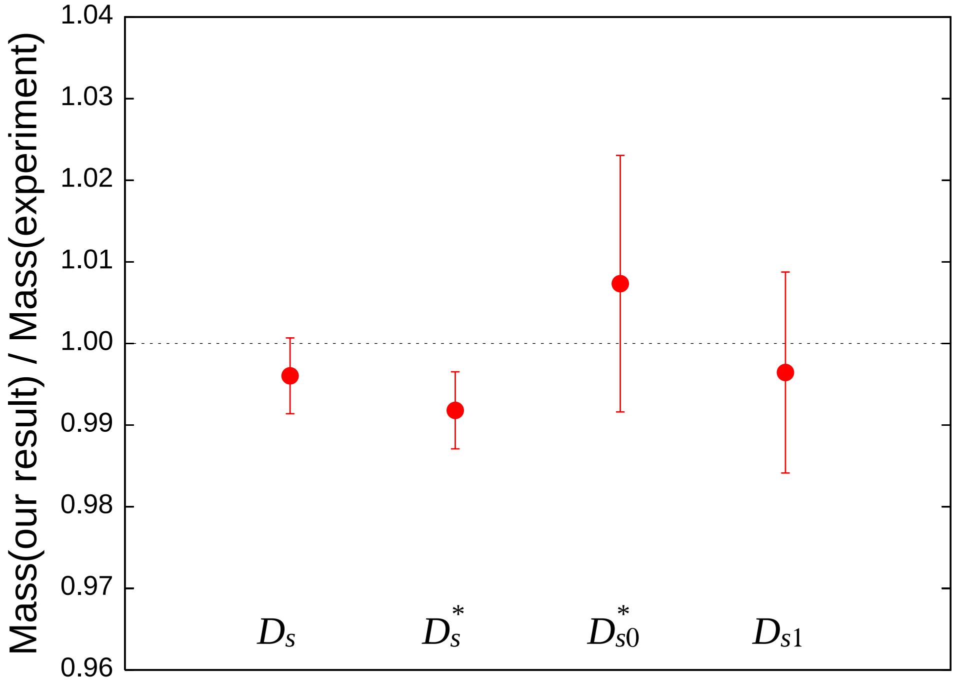




3.2 Charm-strange spectrum

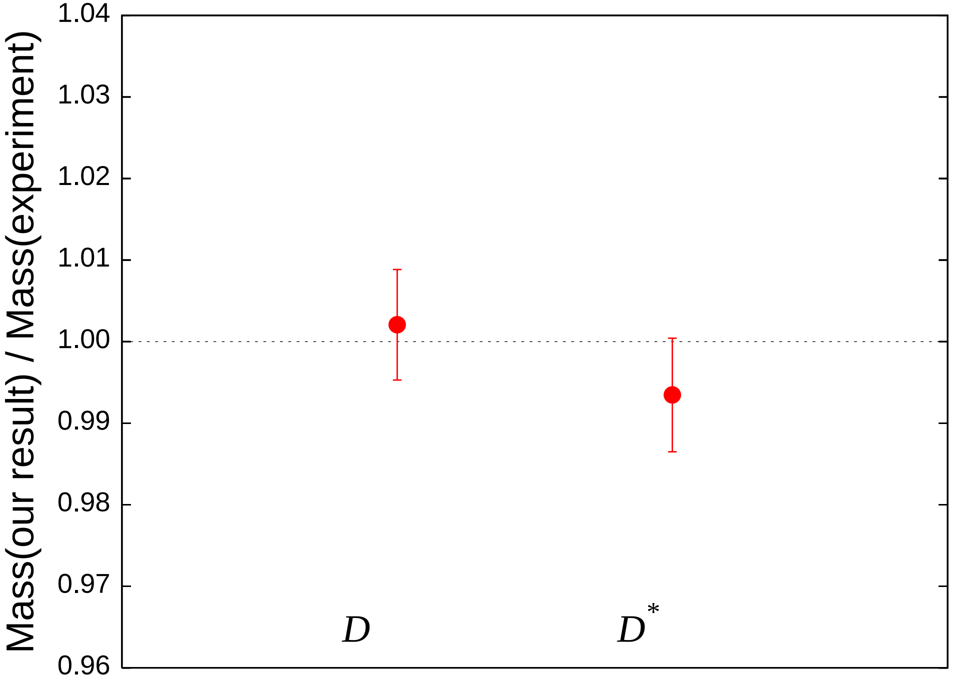
- Lattice QCD reproduces the charm-strange spectrum in 2 σ level, while the standard potential model fails to reproduce D^*_{s0} mass.
  cf. for model studies of $m_{D^*_{s0}}$, see Matsuki,et al,1997;2007.

- (D^*_{s0}, D_{s1} decays are prohibited in our $N_f = 2 + 1$ lattice QCD.)



3.3 Charm-ud spectrum

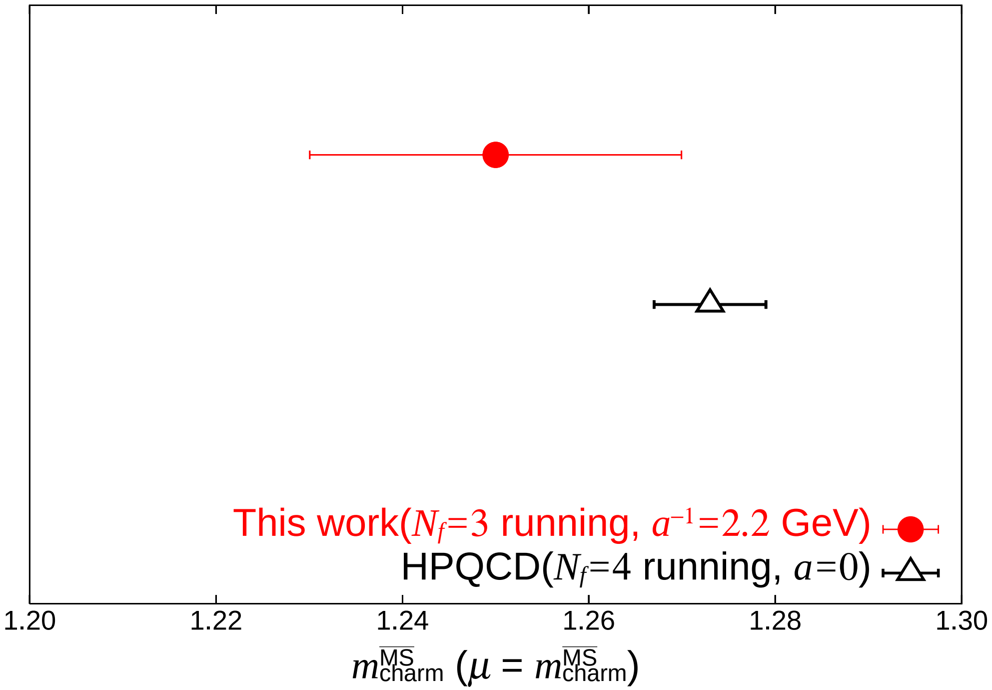
- Spectrum is reproduced by lattice QCD.
- (D^* decay is prohibited on our lattice of $L = 3$ fm with $a^{-1} = 2$ GeV.)
- (For unstable particles, D_0, D_1, more detailed analysis using Lüscher's formula is needed.)



3.4 Charm quark mass and CKM matrix elements

[Charm quark mass]

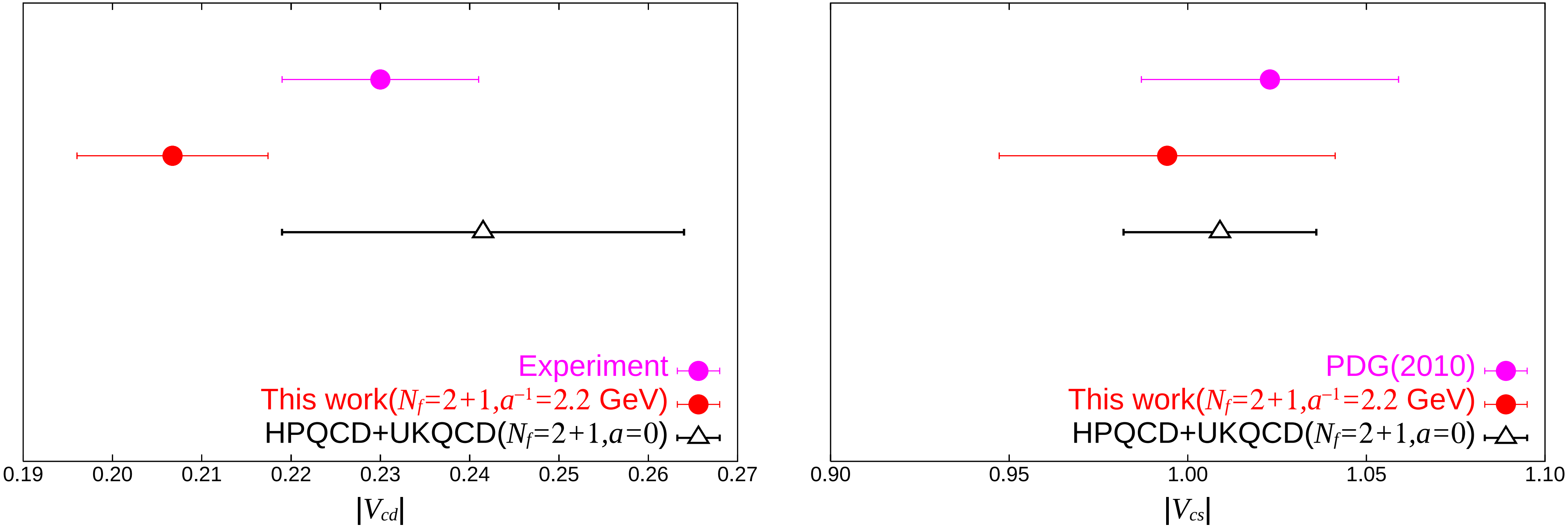
- Charm quark mass is determined from axial Ward-Takahashi identity.
- (The renormalization factor is calculated non-perturbatively at the massless point. The mass dependent part is calculated perturbatively.)
- (Charm quark mass is renormalized at $\mu = 1/a$, and evolved to $\mu = m^{\overline{\mathrm{MS}}}_{charm}$ using $N_f = 3$ four-loop beta function.)



[CKM matrix elements]

- CKM matrix elements $|V_{cd}|, |V_{cs}|$ are extracted from our decay constants of charmed and charmed-strange mesons combined with experimental values for the leptonic decay widths of charmed mesons.

$$\Gamma(D \to l\nu) = \frac{G_F^2}{8\pi} m_l^2 m_D f_D^2 \left(1 - \frac{m_l^2}{m_D^2}\right)^2 |V_{cd}|^2$$



4 Summary

We performed a $N_f = 2+1$ full QCD simulation of the charm quark system on the physical point at $a^{-1} = 2$ GeV.

- Lattice QCD reproduces mass spectrums of the ground states, except for hyperfine splittings.
    - ♢ Our data of the hyperfine splitting are slightly smaller than the experimental value.
      → Possible origins of the discrepancy are $O(a)$ effects in our relativistic heavy quark action, dynamical charm quark effects, and disconnected loop contributions.
- Charm quark mass and CKM matrix elements are determined.

[Future work]

- (Charmed baryon, doubly-charmed baryon, Ω_c have already calculated.)
- We are going to a finer lattice ($a^{-1} = 3$ GeV) to take a continuum limit.
- Excited states (such as $X(3872)$) separating $D\bar{D}$ contamination.

格子量子色力学によるエキゾチックハドロンの数値的研究

研究代表者：滑川　裕介（筑波大学　計算科学研究センター）

課題番号：22105501（平成22年度～23年度）

研究の目的・概要

本研究では、格子ＱＣＤシミュレーションを用いて、 エキゾチックハドロン候補である状態の性質解明を行う。 格子ＱＣＤ計算は第一原理計算であり、計算結果に模型のような依存性は無い。 実験結果に対し、ＱＣＤに基づく統一的な理解が可能である。

平成22年度：研究の進捗と成果

格子重クォーク作用中のパラメータ及び 繰り込み因子を非摂動論的に決定した。 これらの値は、格子上で重クォークを取り扱うために必要である。

決定したパラメータを使用し、チャームクォークを含むハドロンスペクトルを求めた。 我々の計算値は実験値を良く再現する。 標準的なポテンシャル模型では D_{s0}^* 中間子の質量が実験値と大きくずれる。 このため、D_{s0}^* 中間子を通常のクォーク２体系ではなく、 ４つのクォークから成るエキゾチック状態する模型が提唱されている。 一方、クォーク２体系の演算子を用いた我々の格子ＱＣＤ計算結果は 1% の精度で実験と無矛盾である。 D_{s0}^* 中間子は通常のクォーク２体系とみなせる。

上記に加え、チャームクォーク質量、CKM 行列要素を格子ＱＣＤを用いて決定した。 これらの値は、素粒子標準理論の確立に必要であるだけでなく、 標準理論を越える物理の検証にも不可欠であり、重要である。

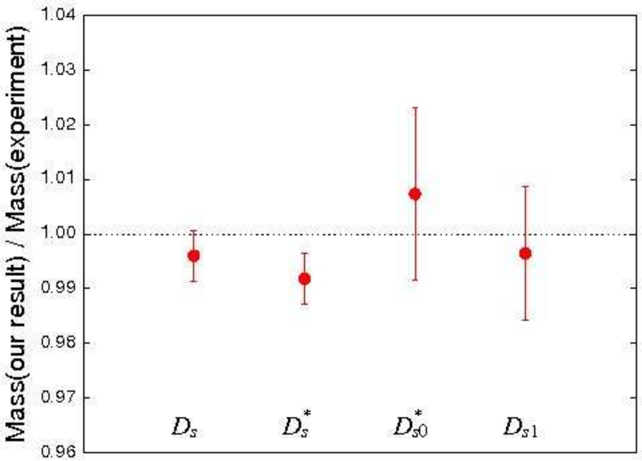


図1: charmed-strange meson mass spectrum

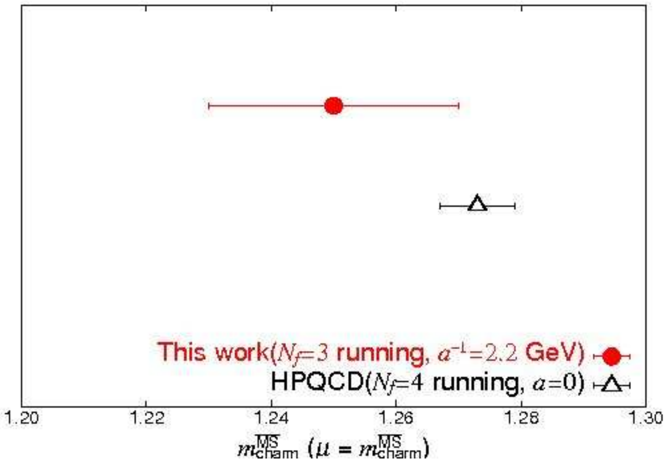


図2: charm quark mass

論文・紀要・会議録：

- "Non-perturbative renormalization of quark mass in $N_f = 2+1$ QCD with the Schroedinger functional scheme", PACS-CS Collaboration: S. Aoki et al, JHEP 1008 (2010) 101
- "Calculation of ρ meson decay width from the PACS-CS

Appendix

[Relativistic Heavy Quark(RHQ) Action]
We employ a RHQ action(Tsukuba-type) for heavy quarks. S.Aoki et al, 2001

- Since the charm quark is not too heavy, relativistic approach is needed.
- RHQ action can control heavy quarks on the lattice. It reduces $O((ma)^n, \forall n)$ to $O(\alpha_s^2 f(ma)(a\Lambda_{QCD}))$ where f is smooth around $ma = 0$.

◇ For r_s, $C_{SW}^{s,t}$, tadpole improved 1-loop values are used. S.Aoki et al, 2003
$C_{SW}^{s,t}$ are non-perturbatively improved at the massless point,
$C_{SW}^{s,t} = C_{SW}(NP, m = 0) - C_{SW}^{s,t}(PT, m = 0) + C_{SW}^{s,t}(PT, m \neq 0)$.

◇ ν is non-perturbatively tuned.

$$
\begin{aligned}
S_{RHQ} &= \sum_{x,y} \bar{q}(x) D(x,y) q(y), \\
D(x,y) &\equiv \delta_{x,y} - \kappa_{heavy} \Big\{ (1-\gamma_4) U_4(x) \delta_{x+4,y} + (1+\gamma_4) U_4^\dagger(x) \delta_{x,y+4} \\
&\quad + \sum_i \Big((r_s - \nu\gamma_i) U_i(x) \delta_{x+i,y} + (r_s + \nu\gamma_i) U_i^\dagger(x) \delta_{x,y+i} \Big) \Big\} \\
&\quad - \delta_{x,y} \kappa_{heavy} \Big\{ C_{SW}^s \sum_{i<j} \sigma_{ij} F_{ij} + C_{SW}^t \sum_i \sigma_{4i} F_{4i} \Big\}.
\end{aligned}
$$