# Charm quark physics from lattice QCD

arXiv:1104.4600,1111.0142

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# Contents

# 1 Introduction

[Charm quark system]
Charm quark system is charming for physicists.

- Charm quark mass and Cabibbo-Kobayashi-Maskawa(CKM) matrix elements are fundamental parameters of the standard model, which are hard to be determined by experiments.
  ← In addition, these parameters are also needed as inputs for a new theory beyond the standard model.
- Exotic hadrons such as $Z^+(4430)$, made of $udc\bar{c}$ !?, have been observed.
- Charmonium is a good probe for a hot and dense QCD matter.

  ◇ Charm quark system is hard to be studied analytically because of $m_{charm} \sim \Lambda_{QCD}$. Effective theories are not effective. Non-perturbative method is needed.

[Model and lattice QCD]

So far, many models have been used for study of charm quark system.

- Correctness of a model must be always checked, because the result is model-dependent.
  ← Experiment gives a check. In addition, precise lattice QCD calculations can judge a model now.

| | Model | Lattice |
|---|---|---|
| Result | Model-dependent | Model-independent |
| Input | Many parameters | $\alpha_s, m_{quark}$ (or hadron masses) |
| $\alpha_s, m_{quark}$ | Artificial | QCD running |
| Heavy quark | $1/M$ expansion | Full order |
| Cost | Low | High |

[Recent development of lattice QCD]

- Thanks to recent development of computers and algorithms, realistic lattice QCD simulations can be performed.
  → Pion mass in lattice simulations reaches the physical value.

| Year | Machine | Speed [TFlops] | $m_\pi$[MeV] |
|---|---|---|---|
| 1996-2005 | CP-PACS | 0.6 | 700 |
| 2006- | PACS-CS | 14 | 160 |
| 2008- | T2K(Tokyo,Tsukuba,Kyoto) | 235 | 135 |
| | Experiment | | 135 |



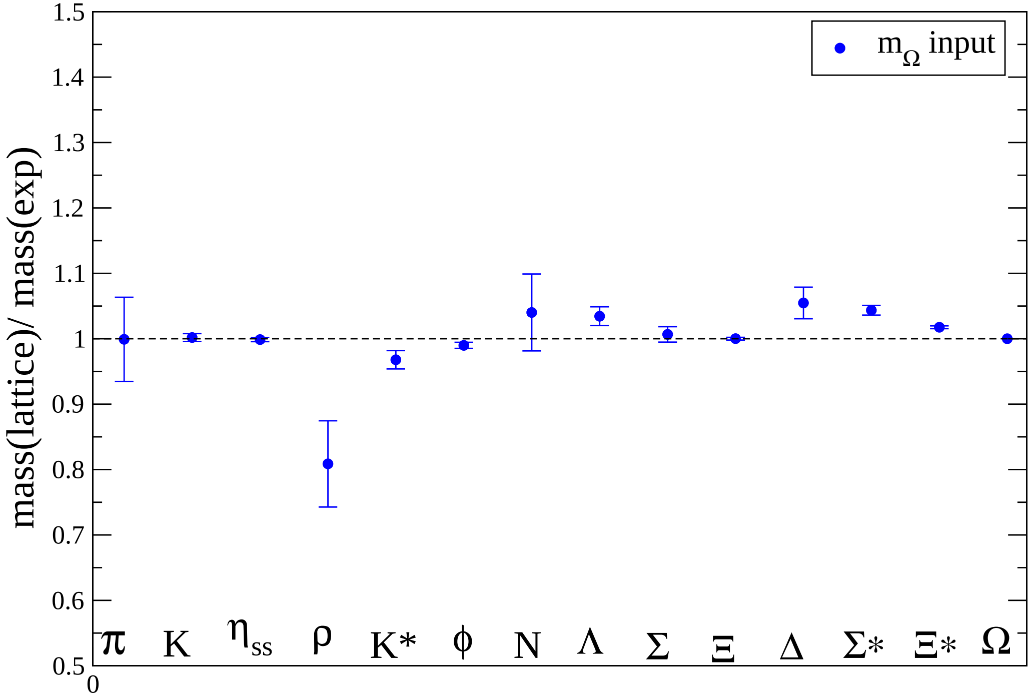
[Light hadron spectrum]

Two lattice groups have reached the physical point of dynamical $ud$, $s$ quarks.

Light hadron spectrum is reproduced in 5% accuracy. PACS-CS,2009; BMW,2010

$\rightarrow$ Based on this result, we move on to the heavy quark system.

- For unstable hadrons such as $\rho$, more detailed analysis using Lüscher's formula is needed.
- MILC has started $N_f = 2 + 1 + 1$ lattice QCD simulations around the physical point.




PACS-CS,2009

# 2 Simulation setup

We perform $N_f = 2+1$ full QCD simulation(including dynamical up,down and strange quarks) for the charm quark system on the physical point.

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

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

[Operators]

- We use the relativistic operators, because the relativistic heavy quark formulation is employed.
- We employ the two quark operators for mesons.
  $\leftarrow$ Only the quantum number is meaningful for the lattice field theory. Two- and four-quark operators give the same central value.

[Operators for mesons]

$$\begin{aligned} M_\Gamma^{fg}(x) &= \bar{q}_f(x)\Gamma q_g(x), \\ \Gamma &= I, \gamma_5, \gamma_\mu, i\gamma_\mu\gamma_5, i[\gamma_\mu, \gamma_\nu]/2, \\ f, g &: \text{labels for quark flavors.} \end{aligned}$$

[Operators for baryons with $J = 1/2$]

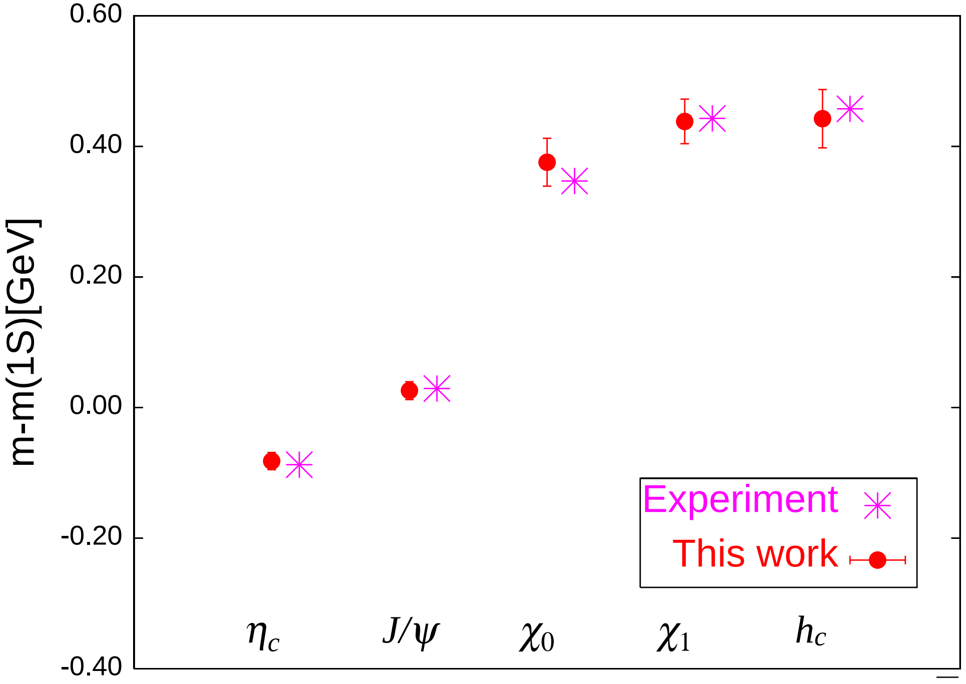
$$\begin{aligned} B_\alpha^{fgh}(x) &= \epsilon^{abc}((q_f^a(x))^T C\gamma_5 q_g^b(x))q_{h\alpha}^c(x), \\ & C = \gamma_4\gamma_2, \alpha = 1, 2. \end{aligned}$$

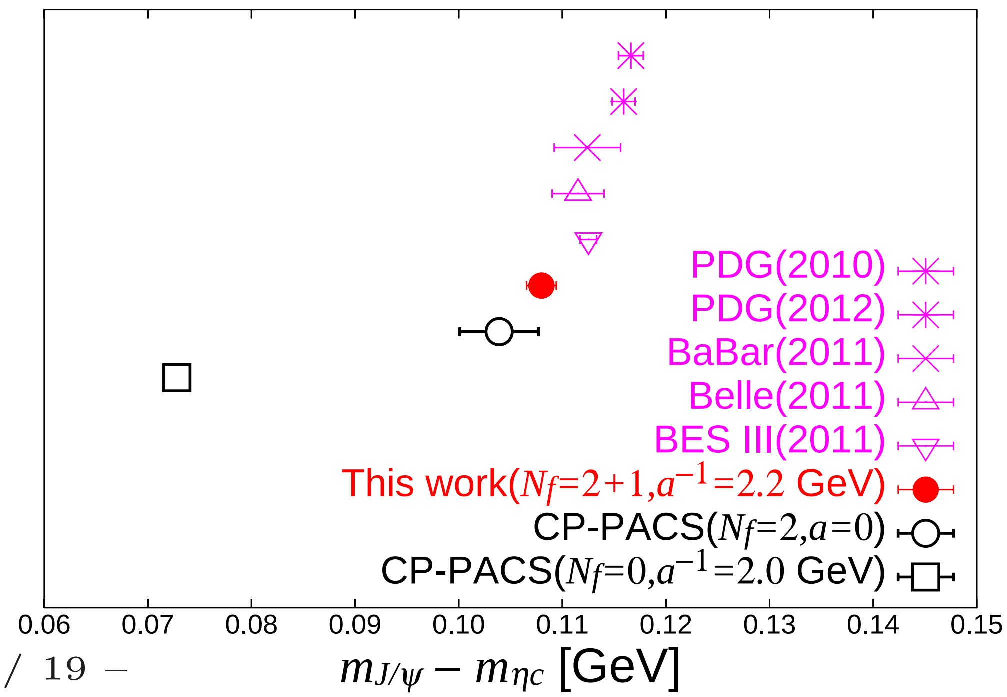
# 3 Results

## 3.1 Charmonium spectrum

- Since $m(1S) \equiv \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ is used as an input for $m_{charm}$, differences from $m(1S)$ are predictions.
- Our results agree with experiments except for the hyperfine splitting.
- Our hyperfine splitting deviates from BES III experiment(2011) by $3\sigma(4\%)$.

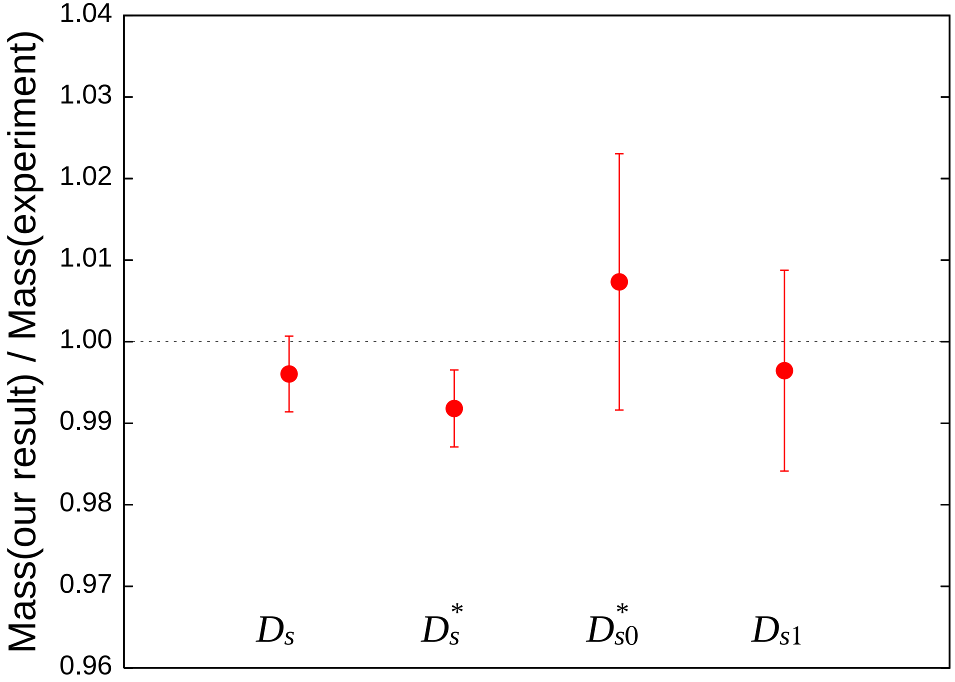
  $\rightarrow$ Our error does not include the following systematic errors: scaling violations, dynamical charm quark effects, disconnected loop contributions, QED effects.



## 3.2 Charm-strange spectrum

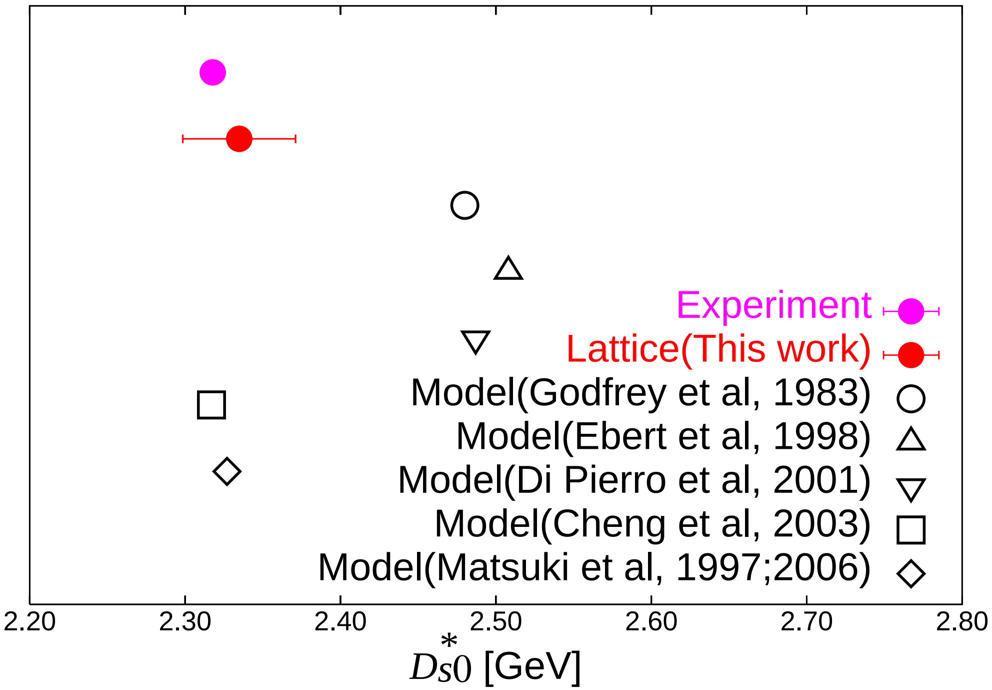
- Our calculation reproduces the charm-strange spectrum in $2\sigma$ level.
- Contaminations to $m_{D^*_{s0}}$, $m_{D_{s1}}$ from $DK$ scattering states can be considerably large, which have not been included yet.
- ($D^*_{s0}$, $D_{s1}$ decays are prohibited in our $N_f = 2 + 1$ lattice QCD.)



[Comparison of lattice QCD with non-lattice results]

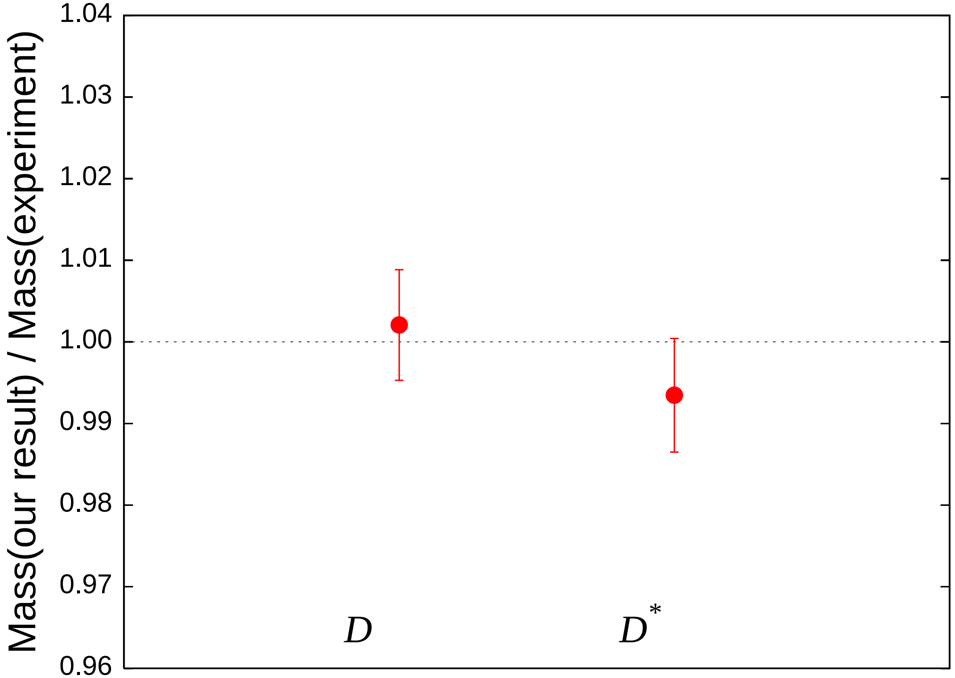
- Our lattice QCD result using two-quark interpolating operators reproduces the experimental value. No need for multi-quark picture.
- Many models are not good for $D^*_{s0}$.

  ← The standard potential model by Godfrey et al, 1983 fails to reproduce $D^*_{s0}$ masses.
- A tetra-quark model by Cheng et al,2003 can fit to experiment.
- A model by Matsuki et al, 1997;2006 is close to experiment.



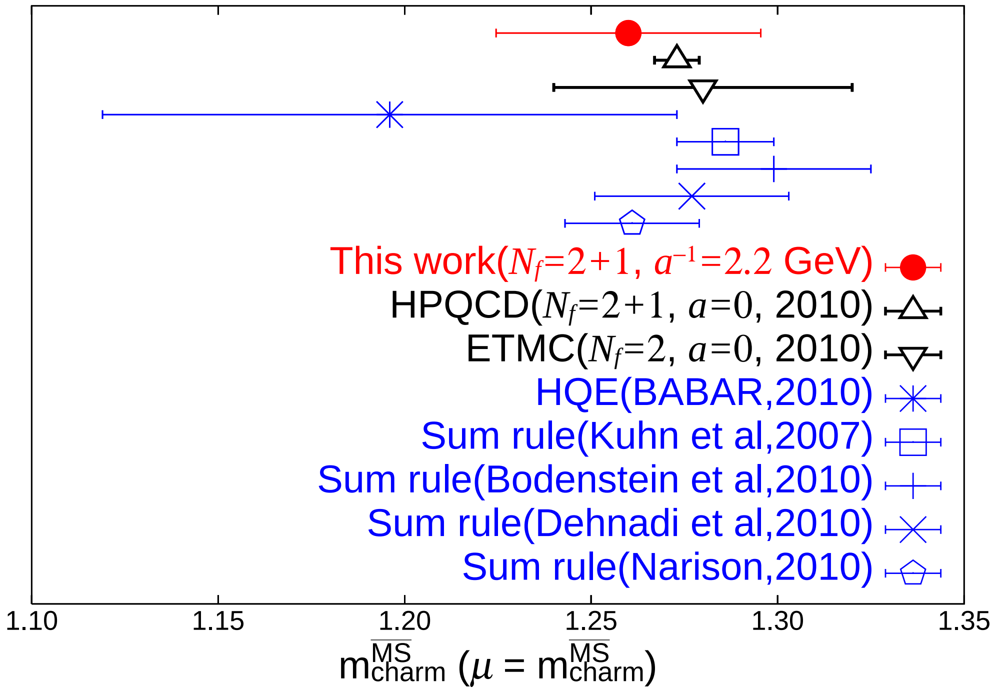
## 3.3 Charm-ud spectrum

- D meson mass spectrums are reproduced well.
- ($D^*$ decay is prohibited on our lattice of $L = 3$ fm with $a^{-1} = 2.2$ GeV.)
- (For unstable particles, $D_0$, $D_1$, more detailed analysis using Lüscher's formula is needed.)



## 3.4 Charm quark mass

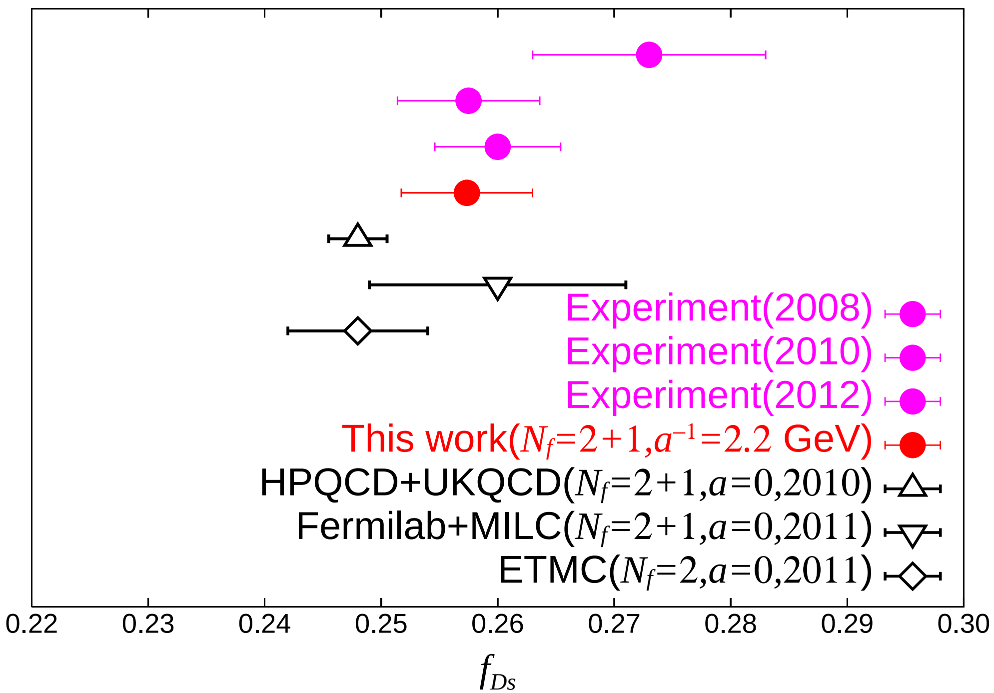
- Charm quark mass is determined from the axial Ward-Takahashi identity.
- Our result is consistent with other lattice and continuum calculations.
- Our systematic error is still large. The main source of our error is the non-perturbative renormalization factors.
  (The renormalization factor is calculated 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 $\mu = m_{charm}^{\overline{MS}}$ using $N_f = 4$ four-loop beta function.)

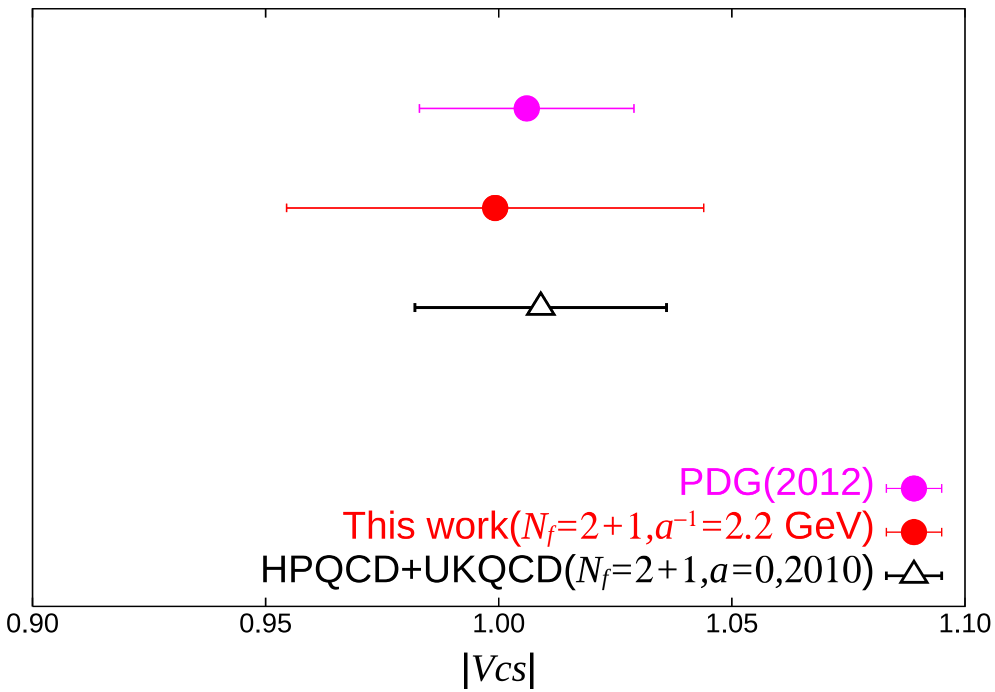


## 3.5 Decay constants and CKM matrix elements

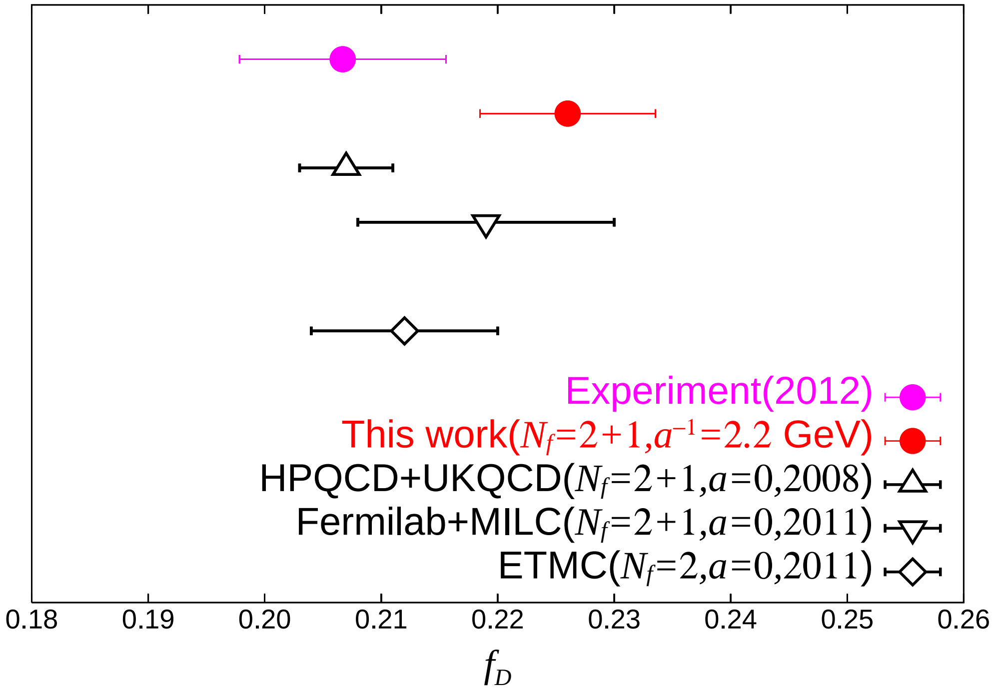
- Our $f_{D_s}$ agrees with the experimental value and other lattice QCD results.
- CKM matrix elements are extracted from our mass and pseudoscalar decay constant of charmed-strange meson combined with experimental values for the leptonic decay width of charmed-strange mesons.

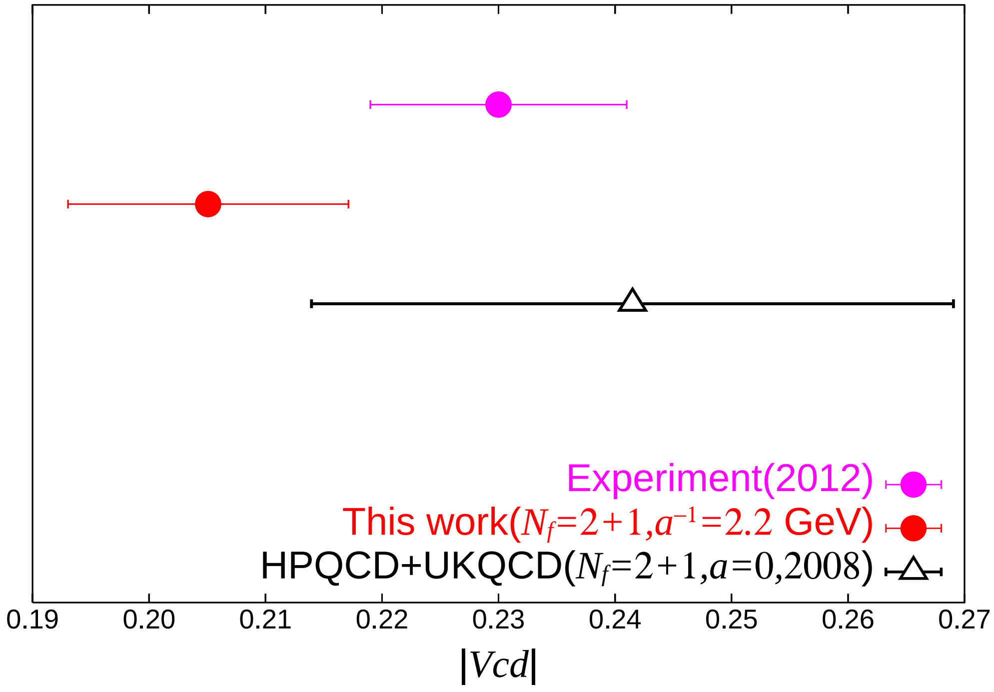
$$\Gamma(D_s \to l\nu) = \frac{G_F^2}{8\pi} m_l^2 m_{D_s} f_{D_s}^2 \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2 |V_{cs}|^2$$



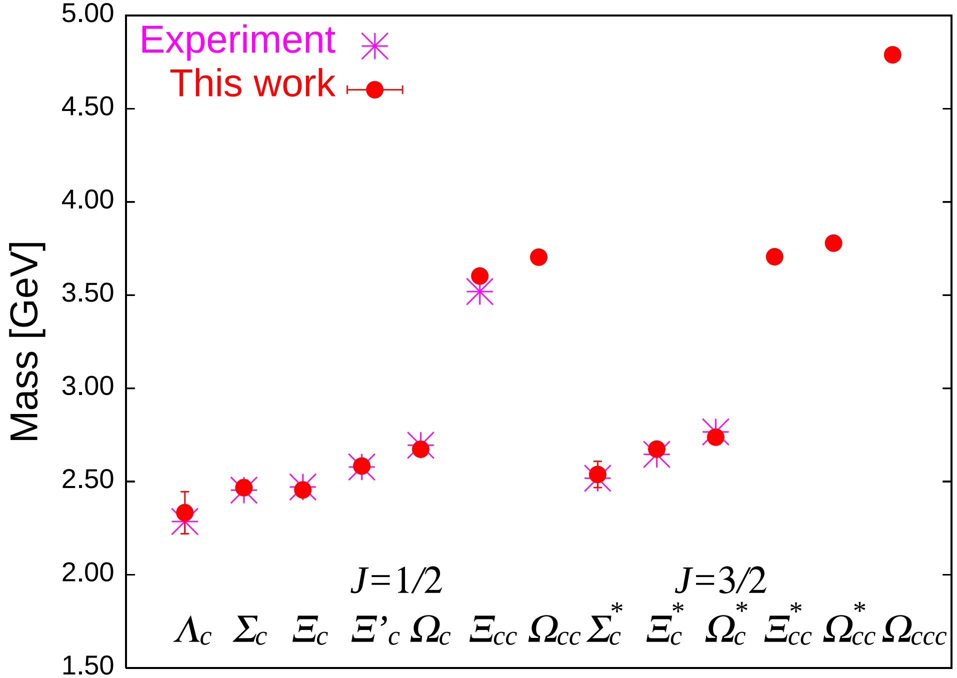
- Our $f_D$ is consistent with experiments and other results in $2\sigma$ level.
  $\leftarrow$ Our $f_D$ is $2.2\sigma$ higher than experiments, and $2.4\sigma$ higher than HPQCD and UKQCD value.
- Continuum extrapolation of our $f_D$ is needed for a definite comparison.
- $|V_{cd}|$ is consistent with the other result, because the experimental error of the leptonic decay width is large.

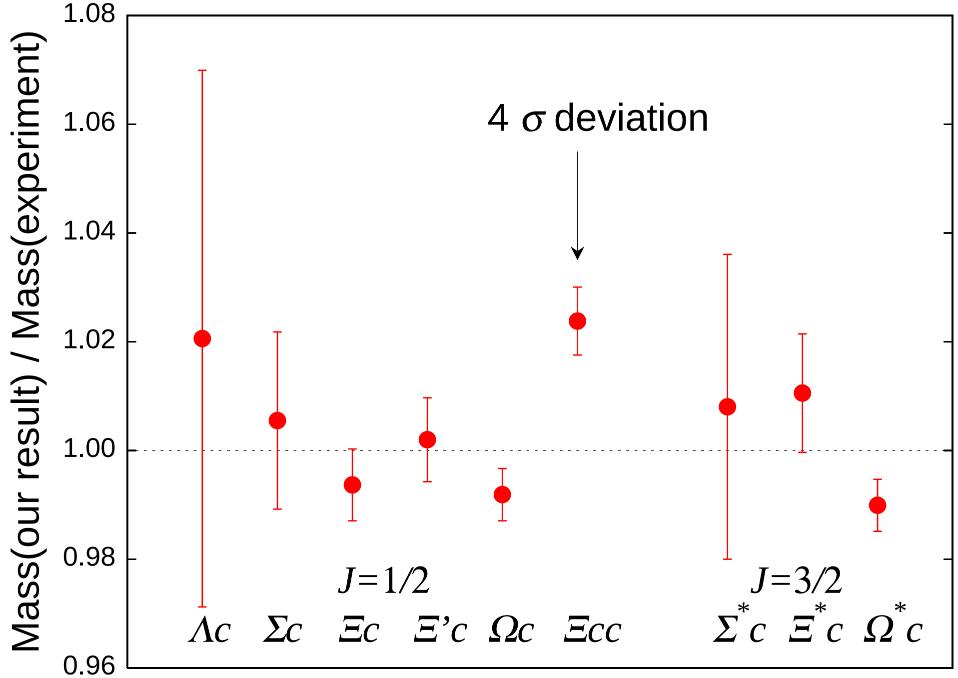


## 3.6 Charmed baryon

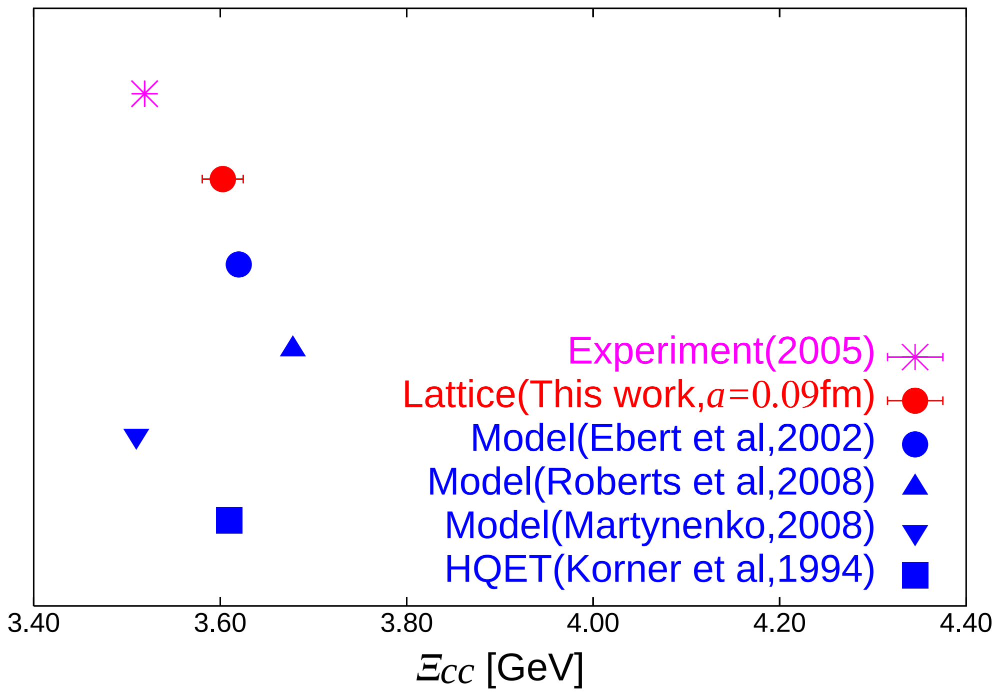
- Our results agree with experiments in $2\sigma$ level, except for $\Xi_{cc}$.
  - ◇ Only SELEX(2002,2005) found $\Xi_{cc} = 3519$ [MeV].
  - ◇ BABAR, BELLE and FOCUS found no evidence for $\Xi_{cc}$. $\rightarrow$ $\Xi_{cc}$ has been omitted from PDG.



[Comparison of lattice QCD with non-lattice results]
Typical model calculations are compared with our lattice result.

- For $\Xi_{cc}$, many models are close to our result.
- Many models and our result give $\Xi_{cc}$ mass higher than SELEX experiment by around 100 MeV.



# 4 Summary

We performed $N_f = 2+1$ full QCD simulation of the charm quark system on the physical point at $a^{-1} = 2.2$ GeV.

- Our calculation reproduces meson mass spectrums of the ground states except for hyperfine splittings.

  ◇ Our data of the charmonium hyperfine splitting is $3\sigma$ smaller than experiments.
  $\leftarrow$ Possible origins of the discrepancy are $O(a)$ effects in our relativistic heavy quark action, dynamical charm quark effects, disconnected loop contributions, QED effects.

- Our results for charm quark mass and CKM matrix elements are presented.
- Our calculation reproduces charmed baryon spectrum except for $\Xi_{cc}$.

  ◇ Our data of $\Xi_{cc}$ shows a significant deviation from the experimental value of SELEX group.

[Future works]

- We are going to a finer lattice ($a^{-1} = 3$ GeV) to take a continuum limit.
- Excited states of charmonium such as $X, Y, Z$, separating $D\bar{D}$ contamination.

[New computers]

| Machine | Speed [PFlops] |
|---|---|
| K-computer@RIKEN,AICS | 11 |
| BlueGene/Q@KEK | 1.3 |
| HA-PACS@Univ. of Tsukuba | 0.8 |
| PACS-CS@Univ. of Tsukuba | 0.01 |
| CP-PACS@Univ. of Tsukuba | 0.001 |


# Appendix