Charm quark physics from lattice QCD

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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 important for the standard model of elementary particles, because they are fundamental parameters which are difficult to be determined precisely due to $m_{charm} \sim \Lambda_{QCD}$. Lattice QCD is needed.
  $\leftarrow$ In addition, m_{charm} and V_{CKM} are also needed as inputs not only for the standard model but also for a new theory beyond the standard model.

- Exotic hadrons such as $Z^+(4430)$, made of $udc\bar{c}$!?, have been observed.



Kobayashi and Maskawa got the Nobel prize in 2008.

[Model and lattice QCD]

So far, many model studies have been performed.

- Correctness of a model must be always checked, because the result is model-dependent.
  $\leftarrow$ In addition to experiments, lattice QCD can judge a model.

- Since a lattice QCD simulation is expensive, a first trial must be performed by simple models. Then, we should improve models by experiments and lattice QCD.
  $\leftarrow$ Judgment on models by lattice QCD will be given later.

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

[Recent progress in lattice QCD]

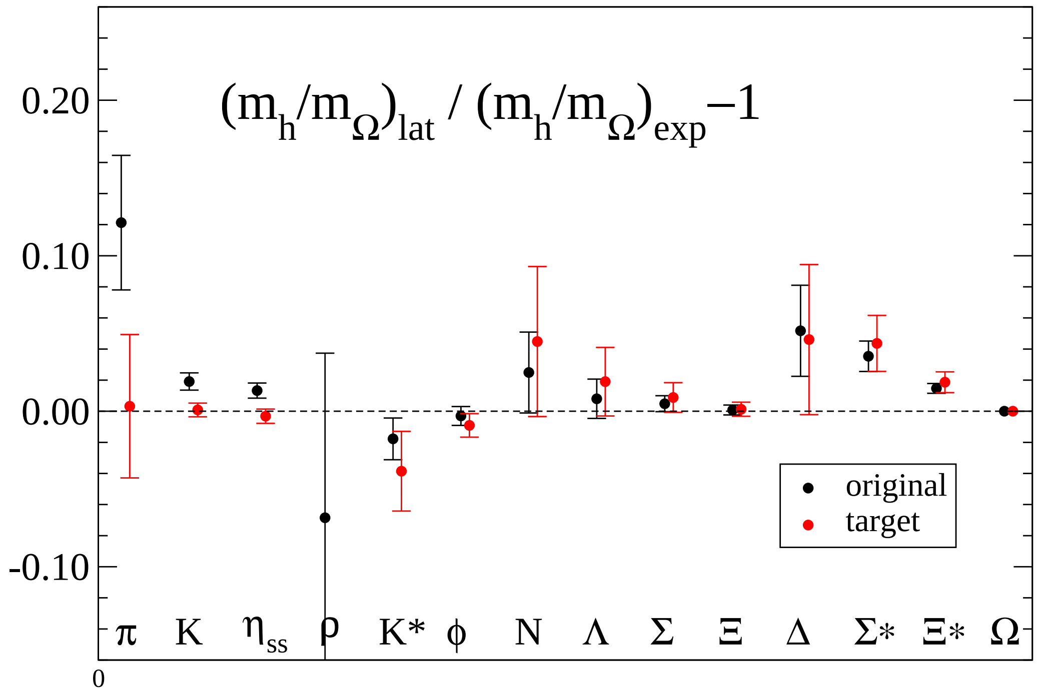
Simulations become realistic, thanks to the development of computers and algorithms.

- $N_f = 2 + 1$ full QCD simulation 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 by use of reweighting (i.e. $m_\pi = 135$ MeV).
  $\leftarrow$ So far, up-down quark masses are higher than their physical value, because of the computational cost.

[Recent progress in lattice QCD(continued)]

Light hadron spectrum has been reproduced within 5% accuracy.

$\rightarrow$ As a next step, we move on to the heavy quark system.



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

PACS-CS,2010

2 Simulation setup

We perform a $N_f = 2+1$ full QCD simulation of 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_π,m_K,m_Ω for m_{ud},m_s,a; $m(1S) \equiv \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ 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)

[Operators]

- We employ the following two quark operators for mesons.

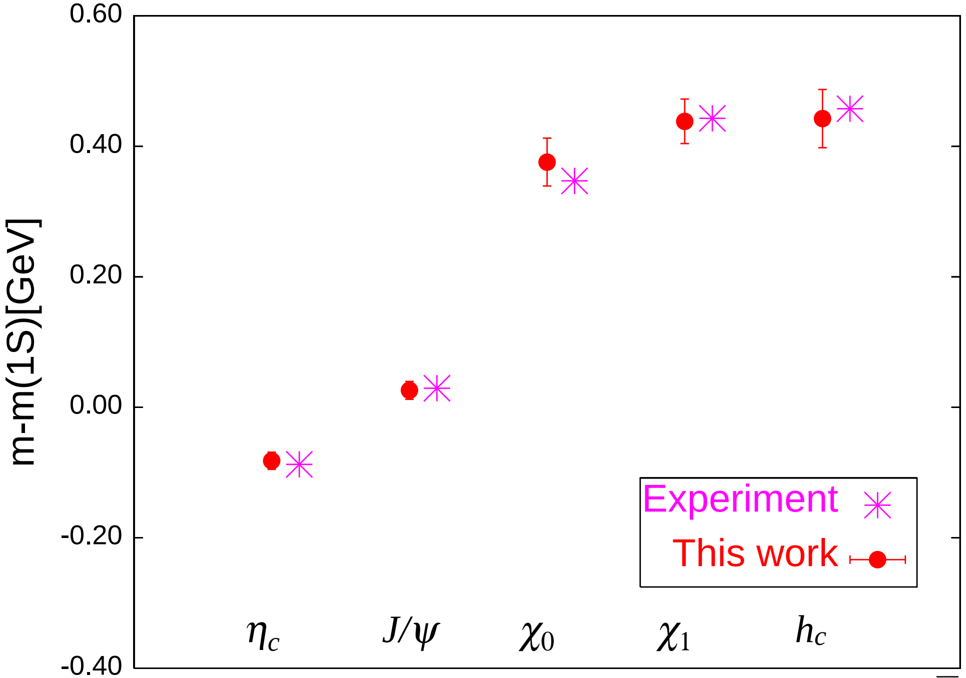
$$
\begin{aligned}
M_\Gamma^{fg}(x) &= \bar{q}_f(x)\Gamma q_g(x), \\
\Gamma &= I, \gamma_5, \gamma_\mu, i\gamma_\mu\gamma_5, i[\gamma_\mu, \gamma_\nu]/2, \\
f, g &: \text{labels for quark flavors.}
\end{aligned}
$$

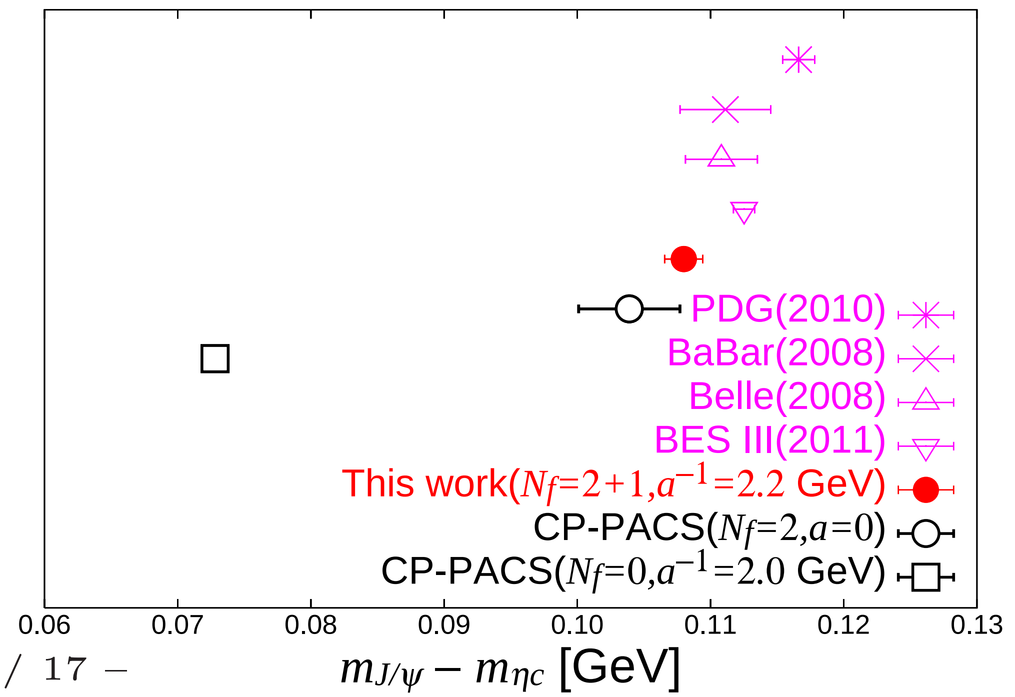
- Smearing function : $\Psi(r) = A\exp(-Br)$ at $r \neq 0$, $\Psi(0) = 1$.
  - ◇ $A = 1.2$, $B = 0.07$ for ud quark.
  - ◇ $A = 1.2$, $B = 0.18$ for strange quark.
  - ◇ $A = 1.2$, $B = 0.55$ for charm quark.

3 Results

3.1 Charmonium spectrum

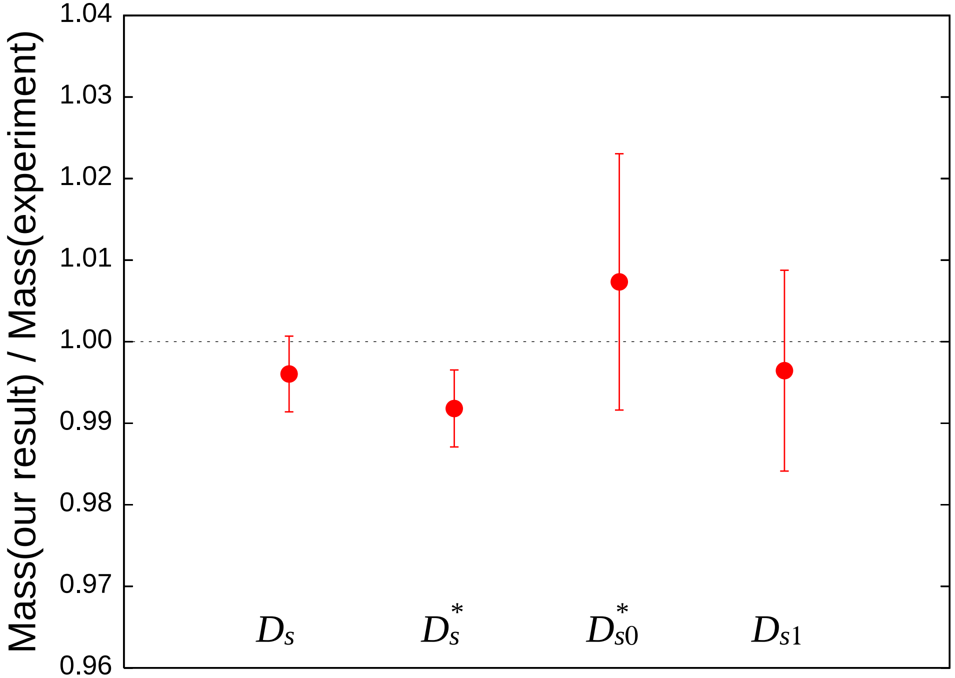
- Since $m(1S) \equiv \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ is used as an input for m_{charm}, differences from $m(1S)$ are predictions.
- Our results agree with experiments except for the hyperfine splitting.
- The hyperfine splitting is underestimated by 3σ from the experimental value of BES III(2011).
  $\rightarrow$ We have not evaluated the following systematic errors: scaling violations, dynamical charm quark effects, disconnected loop contributions.





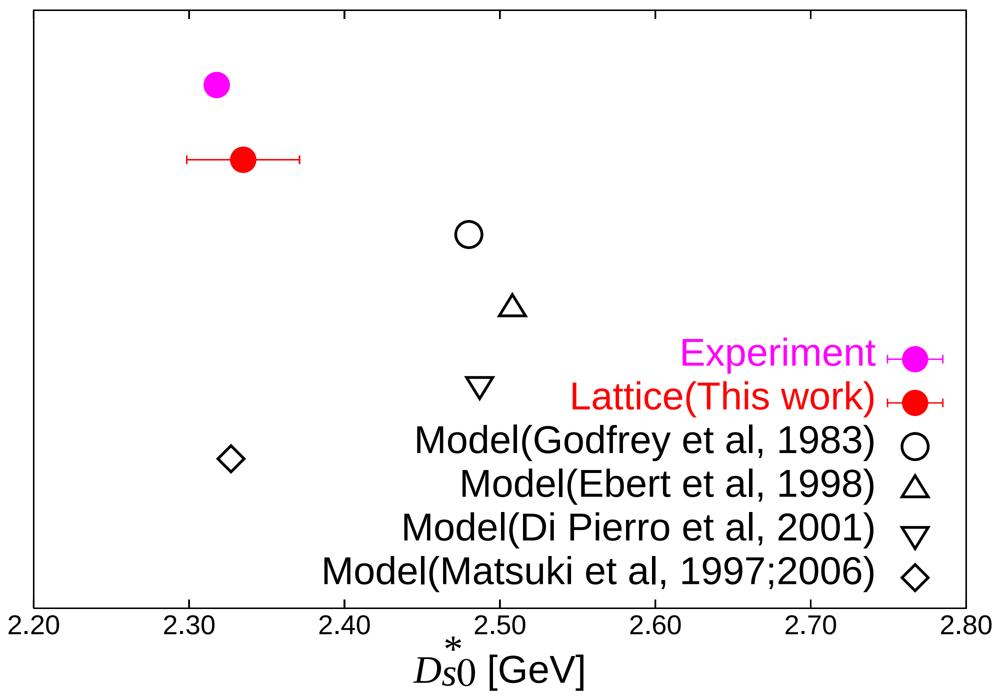
3.2 Charm-strange spectrum

- Our calculation reproduces the charm-strange spectrum in 2σ 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.)



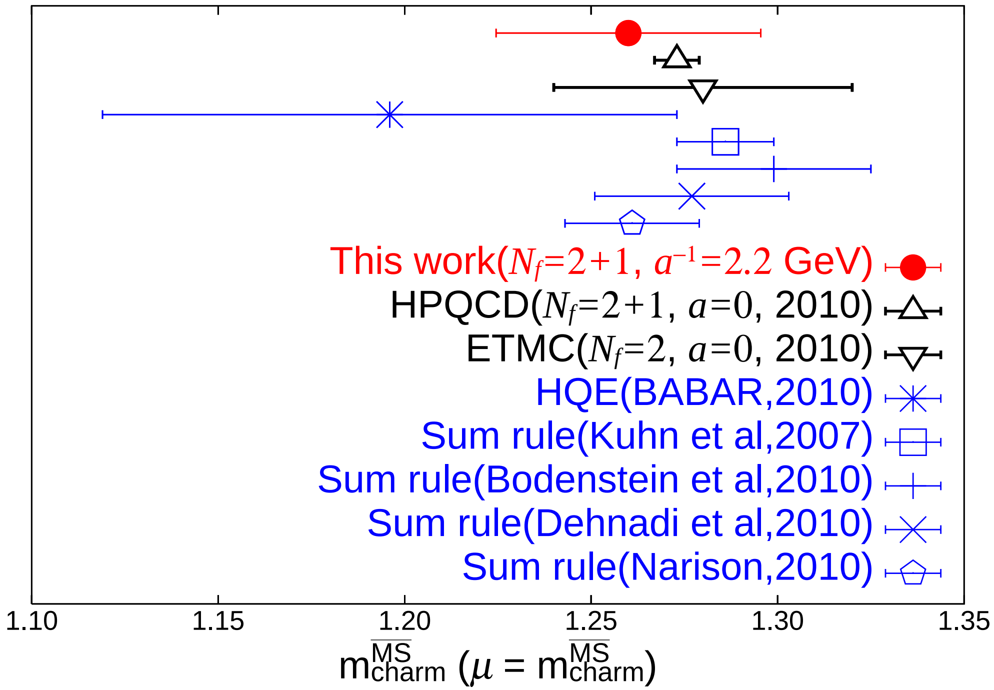
[Judgment on models by lattice QCD]

- For D_{s0}^*, many models are not good.
  $\leftarrow$ The standard potential model by Godfrey et al, 1983 fails to reproduce D_{s0}^* masses.
- A model by Matsuki et al, 1997;2006 is good.
- ($D_{s0}^*(2317)$ have been confirmed experimentally by BaBar, Belle, CLEO.)



3.3 Charm quark mass

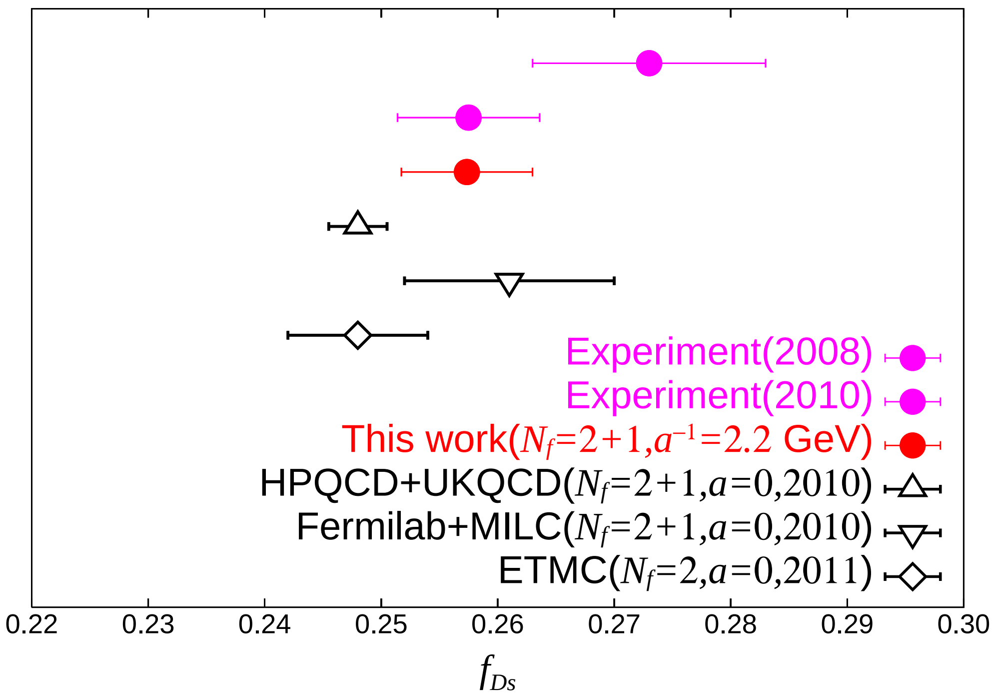
- Charm quark mass is determined from the axial Ward-Takahashi identity.
- Our result is consistent with other lattice and continuum calculations.
- Our systematic error is still large. The main source of our error is the non-perturbative renormalization factors.
  (The renormalization factor is calculated 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.)

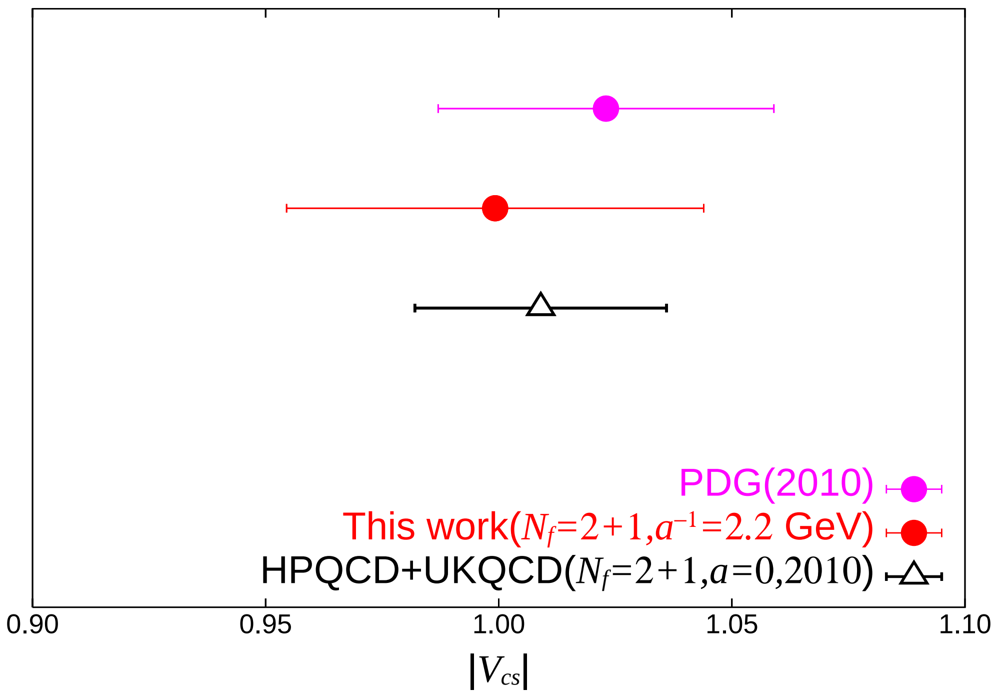


3.4 Decay constants and CKM matrix elements

- 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.

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

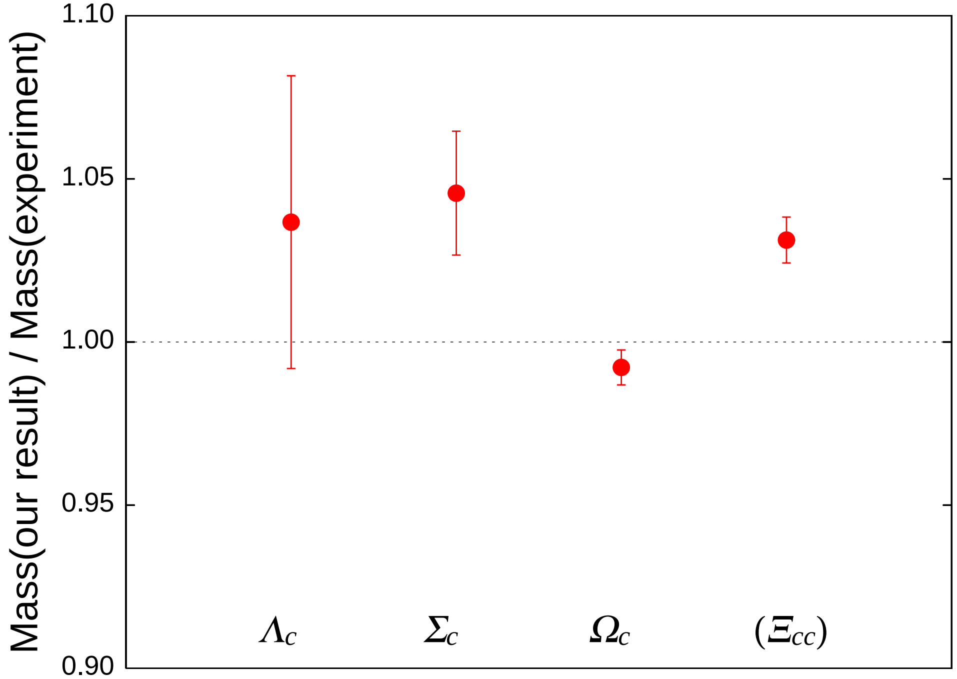




3.5 Charmed baryon – Preliminary –

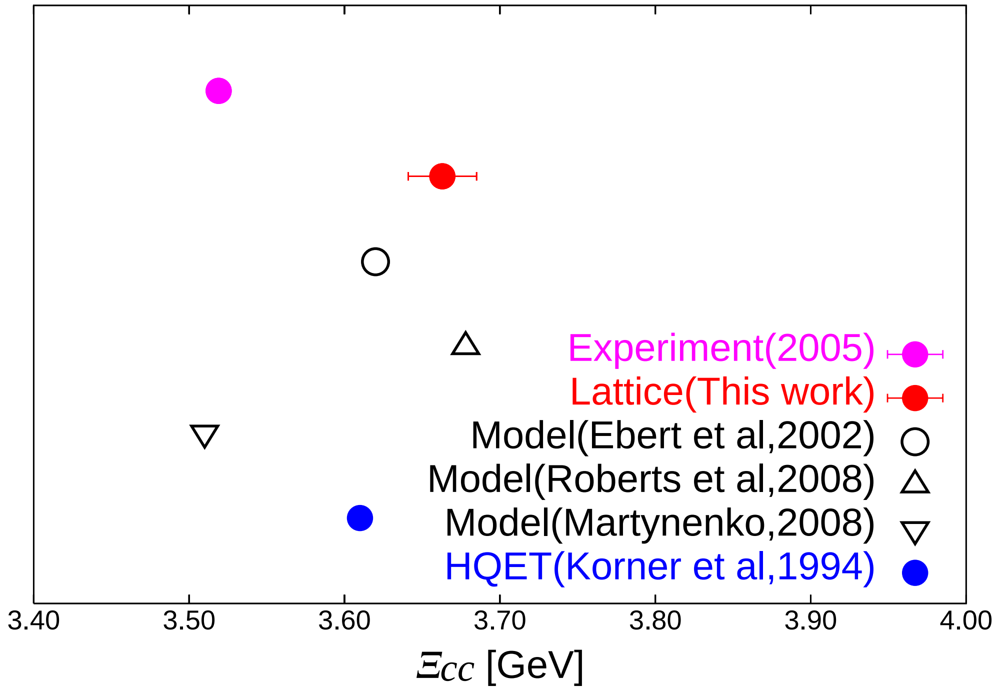
- Our results agree with experiments in 2σ level, except for Ξ_{cc}.
  - ◇ Only SELEX(2002,2005) found $\Xi_{cc} = 3519$ [MeV].
  - ◇ BABAR, BELLE and FOCUS found no evidence for Ξ_{cc}.
    $\rightarrow \Xi_{cc}$ has been omitted from PDG 2011.

- (Σ_c decay is prohibited on our lattice.)



[Judgment on models by lattice QCD] – Preliminary –

- For Ξ_{cc}, many models are not bad.
  $\leftarrow$ A model by Martynenko, 2008 seems to be wrong.
- SELEX experiment seems to be wrong.



4 Summary

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

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

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

- Our results for charm quark mass and CKM matrix elements are presented.
- Our calculation reproduces baryon mass spectrums of the ground states except for Ξ_{cc}.

  ◇ Our preliminary data of Ξ_{cc} shows a significant deviation from the experimental value of SELEX group.
  $\leftarrow$ SELEX value seems to be wrong.

[Future work]

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

[New computer]

- K-computer will be used for lattice QCD, which is the fastest computer in the world at present(Nov. 2011).
- Many lattice QCD theorists in Japan(including me) are working for this K-computer project.

Appendix