Charmed baryon spectroscopy on the physical point in 2+1 flavor lattice QCD

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1 Introduction

Lattice QCD is required to be a guide for charmed baryons, because of the following reasons.

[To solve Ξ_{cc} problem]

- Only SELEX(2002,2005) found $\Xi_{cc} = 3519$ [MeV].
- BABAR, BELLE and FOCUS found no evidence for Ξ_{cc}.
  $\rightarrow$ Ξ_{cc} has been omitted from PDG.

[To give a prediction to forthcoming experiments]

- BES-III in operation.
- J-PARC in operation(damaged by the big earthquake in Japan, but has been restored now).
- PANDA is coming.

[Previous works in lattice full QCD]

- H.Na and S.A.Gottlieb(2006-2008) : staggered $N_f = 2+1$ sea + naive up, down and strange and Fermilab charm valence quarks
- L.Liu et al(2009) : staggered $N_f = 2+1$ sea + domain-wall up, down and strange and Fermilab charm valence quarks
- Briceno et al(2011) : staggered $N_f = 2+1+1$ sea + clover up, down and strange and relativistic charm valence quarks
- ETMC(2012) : twisted mass $N_f = 2$ sea + Osterwalder-Seiler strange and charm valence quarks
- This work : clover $N_f = 2+1$ sea + relativistic charm valence quarks
    - ◇ We need to control heavy quark contributions $O(m_{charm}a)$.
    - ◇ A mixed action breaks the unitarity and complicates the continuum extrapolation.
      → It is better to use the same quarks in sea and valence sectors.

2 Simulation setup

We perform $N_f = 2 + 1$ full QCD simulation for charmed baryons 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}

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

[Operators]

- We use the following relativistic operators for baryons, because the relativistic heavy quark is employed.

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

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

[Operators for baryons with $J = 3/2$]

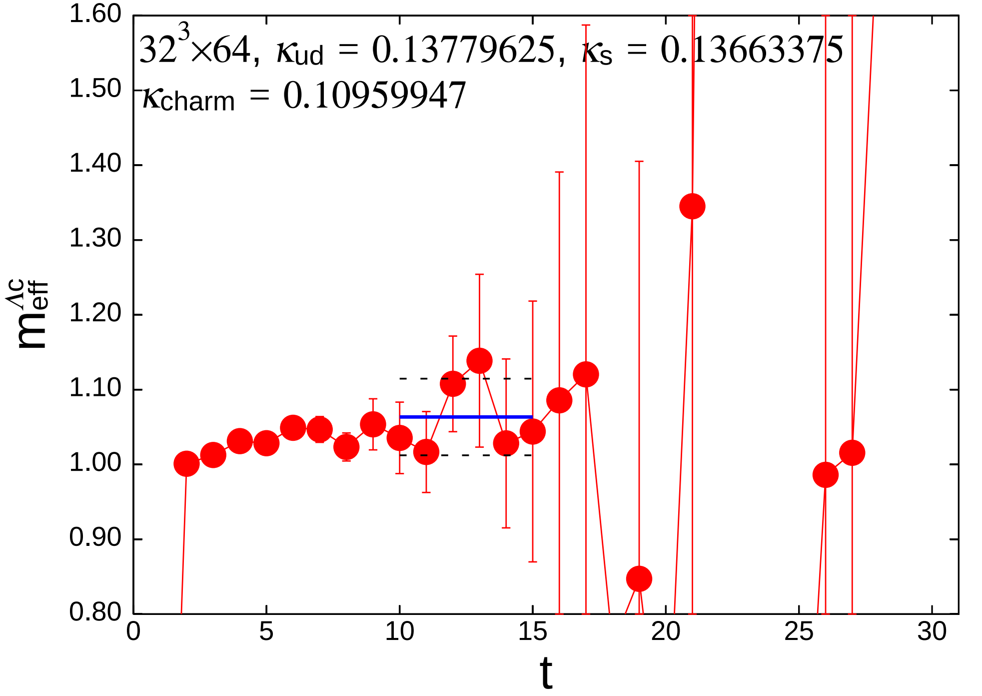
$$\begin{aligned} D_{3/2}^{fgh}(x) &= \epsilon^{abc}((q_f^a(x))^T C\Gamma_+ q_g^b(x))q_{h1}^c(x), \\ D_{1/2}^{fgh}(x) &= \epsilon^{abc}[((q_f^a(x))^T C\Gamma_0 q_g^b(x))q_{h1}^c(x) \\ &\quad -((q_f^a(x))^T C\Gamma_+ q_g^b(x))q_{h2}^c(x)]/3, \\ D_{-1/2}^{fgh}(x) &= \epsilon^{abc}[((q_f^a(x))^T C\Gamma_0 q_g^b(x))q_{h2}^c(x) \\ &\quad -((q_f^a(x))^T C\Gamma_- q_g^b(x))q_{h1}^c(x)]/3, \\ D_{-3/2}^{fgh}(x) &= \epsilon^{abc}((q_f^a(x))^T C\Gamma_- q_g^b(x))q_{h2}^c(x), \\ &\quad \Gamma_\pm = (\gamma_1 \mp \gamma_2)/2, \Gamma_0 = \gamma_3. \end{aligned}$$

3 Results

3.1 Singly charmed baryon

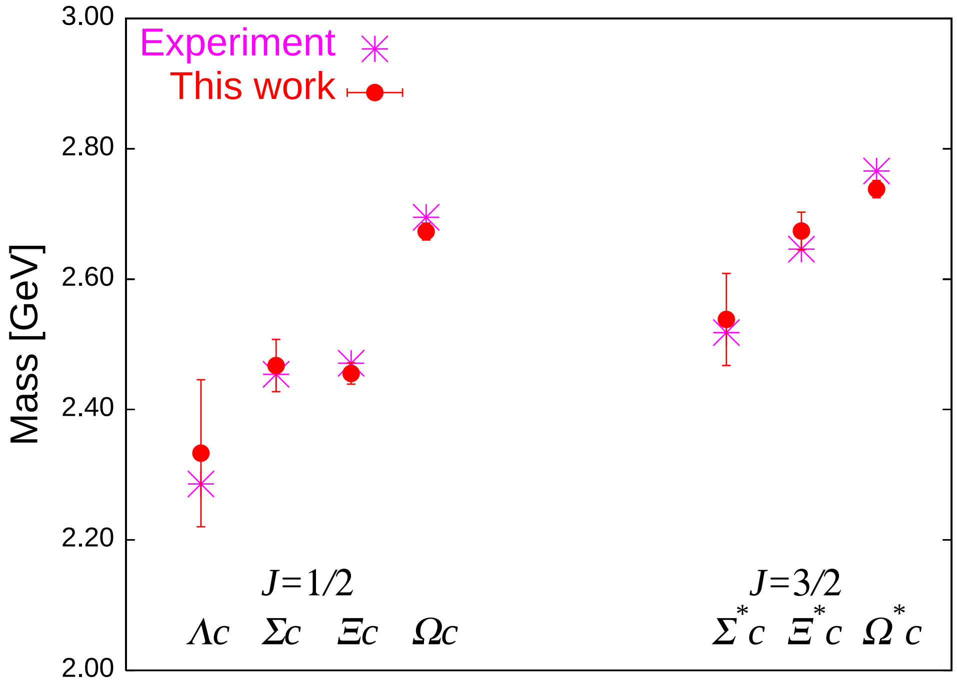
[Effective mass of Λ_c]

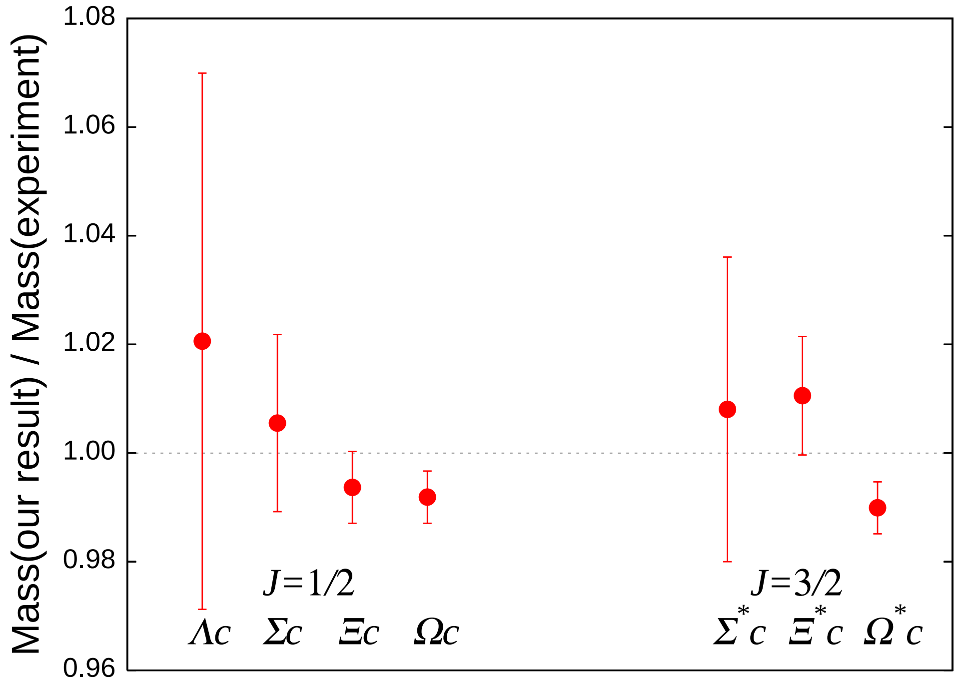
- Plateau is observed in $t = [10, 15]$.



[Mass spectrum of singly charmed baryons]

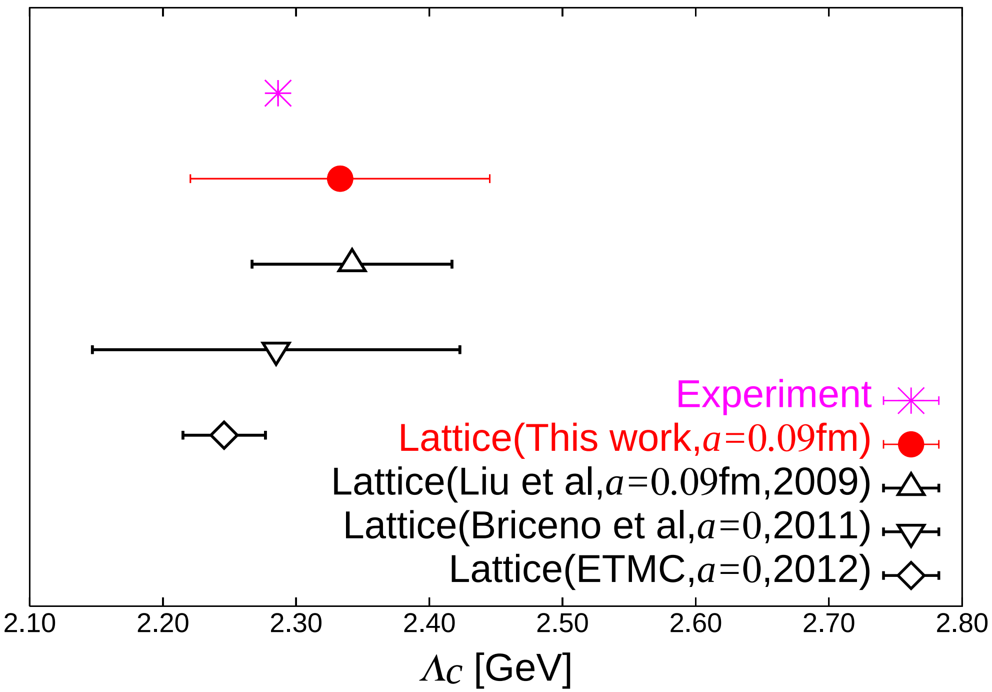
- Our results agree with experiments in 2σ level.
- (Σ_c decay is prohibited on our lattice.)





[Comparison of Λ_c with other lattice QCD simulations]

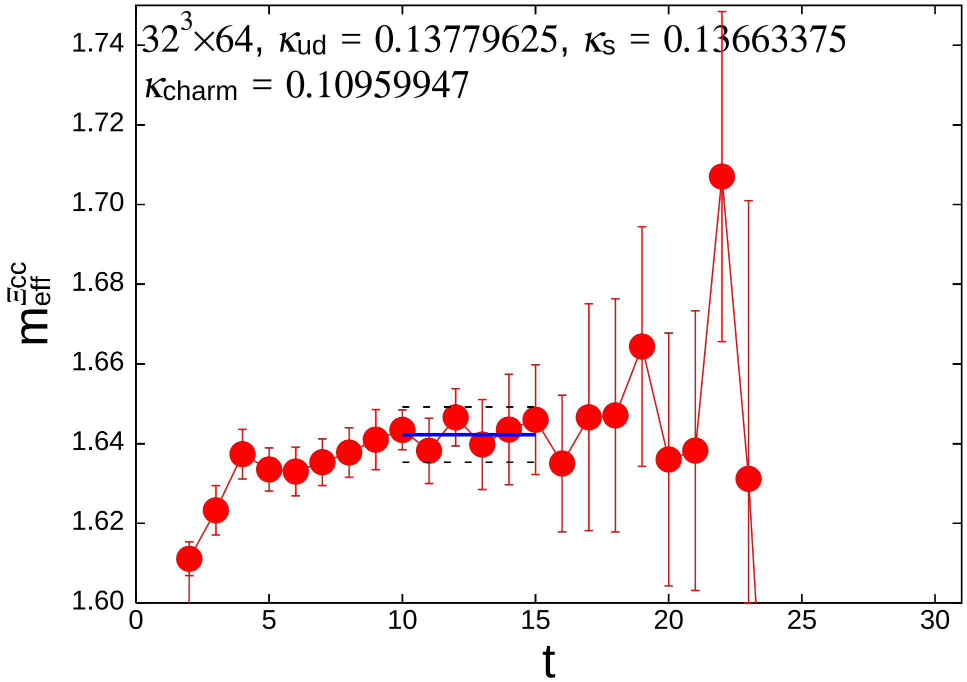
- Our result is consistent with others and experiments.



3.2 Doubly charmed baryon

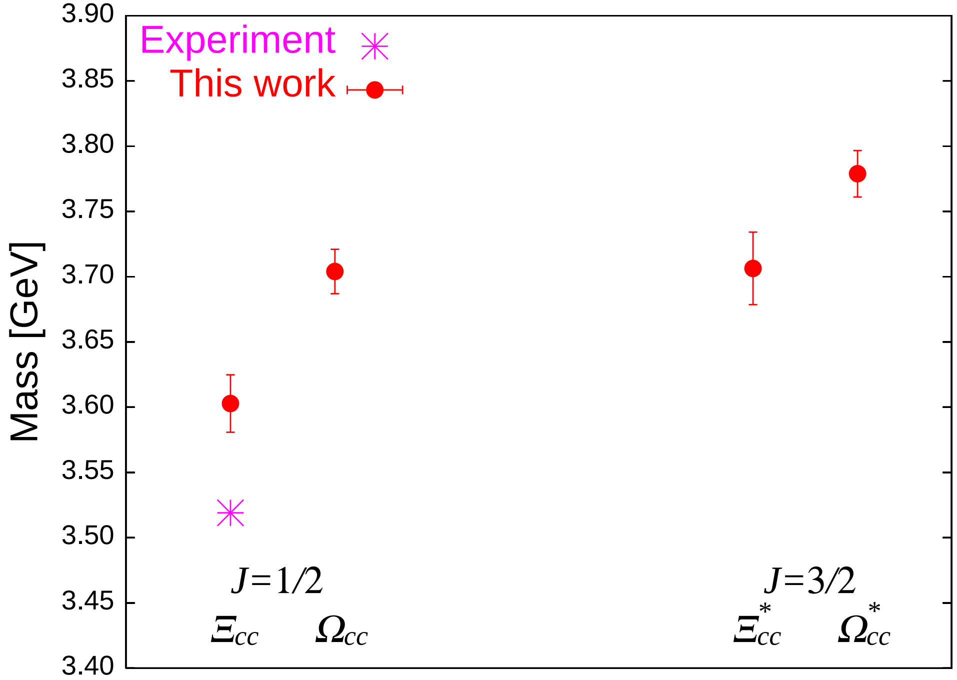
[Effective mass of Ξ_{cc}]

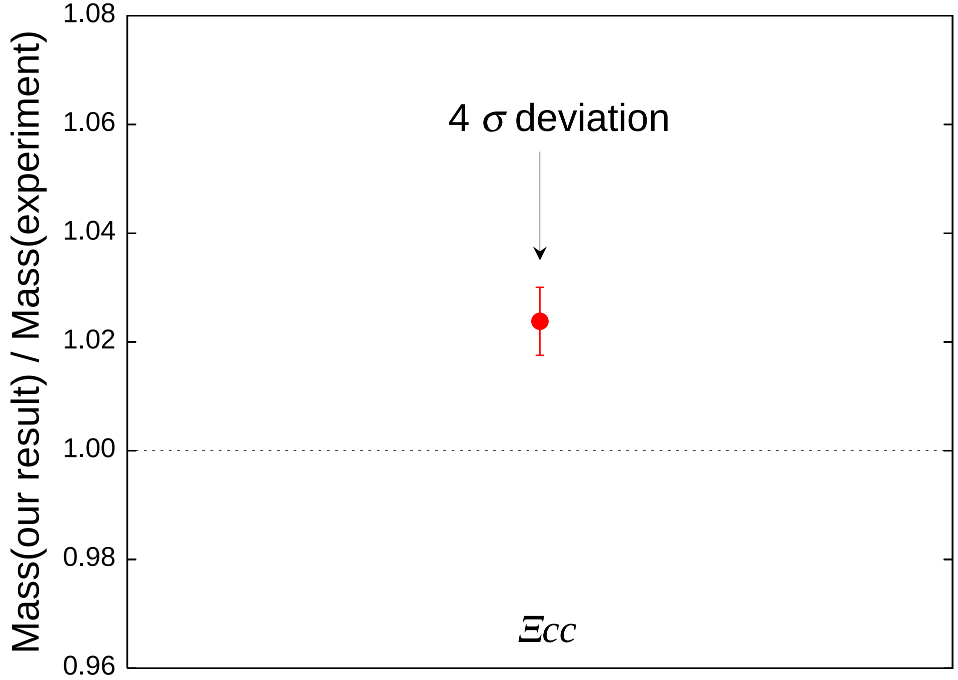
- Plateau is observed in $t = [10, 15]$.



[Mass spectrum of doubly charmed baryons]

- Our result does not agree with the experimental value of Ξ_{cc}.
- Experimental status of Ξ_{cc} has not been established yet.
    - ♢ Only SELEX(2002,2005) found $\Xi_{cc} = 3519$ [MeV].
    - ♢ BABAR, BELLE and FOCUS found no evidence for Ξ_{cc}.
      $\rightarrow$ Ξ_{cc} has been omitted from PDG.

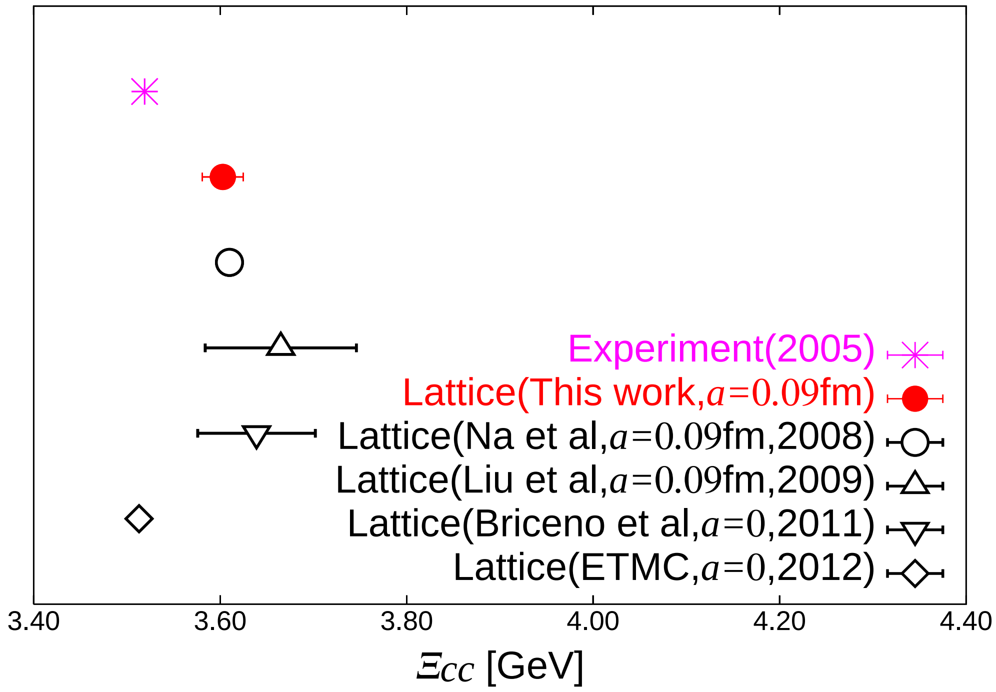




[Comparison of Ξ_{cc} with other lattice QCD simulations]

Our result is consistent with others, except for that of ETMC.

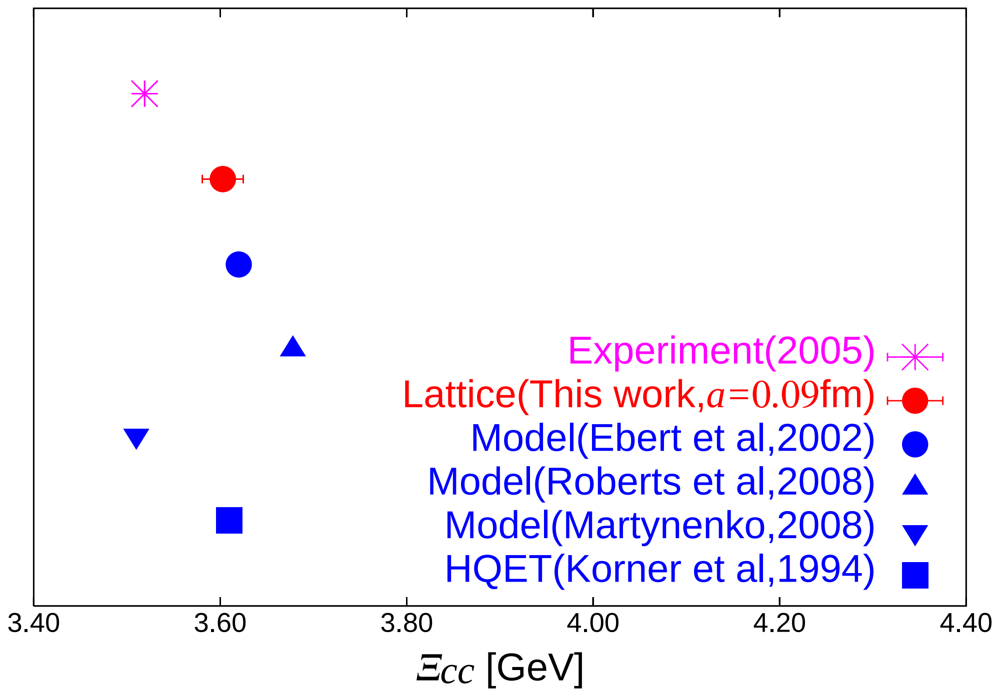
- Lattice simulations give Ξ_{cc} higher than the experiment by around 100 MeV, except for that of ETMC.
- Our result deviates from ETMC value by 3.3σ.
  $\leftarrow$ Continuum extrapolation is needed for a definite comparison.



[Comparison of Ξ_{cc} with models]

Typical model calculations are compared with our lattice result.

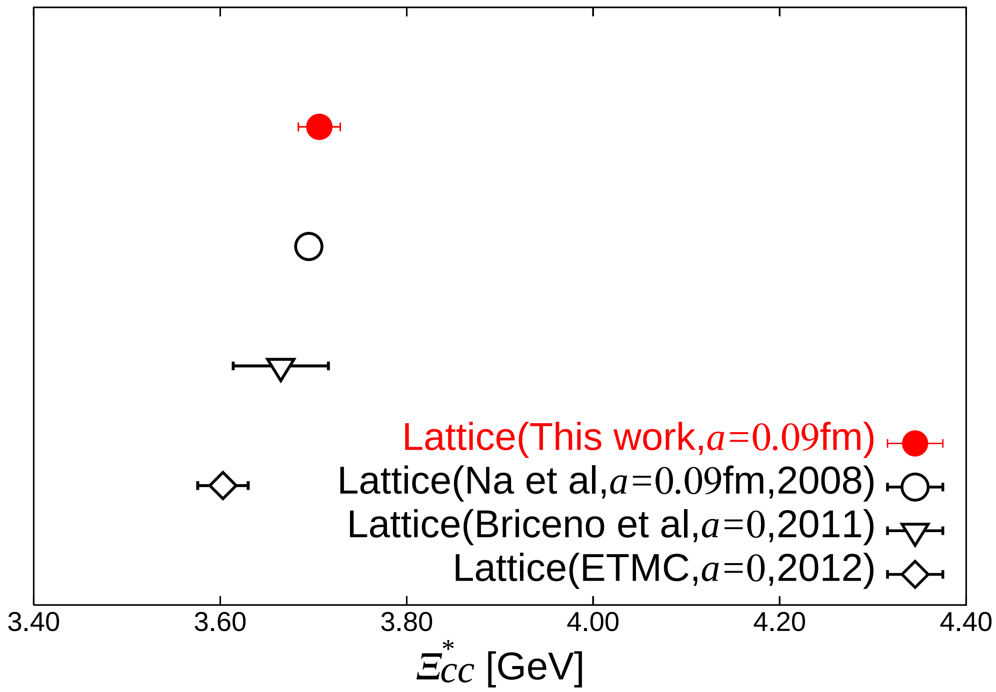
- For Ξ_{cc}, many models are close to our result.
- Many models and our result give Ξ_{cc} mass higher than SELEX experiment by around 100 MeV.



[Comparison of Ξ^*_{cc} with other lattice QCD simulations]

Our result is consistent with others, except for that of ETMC.

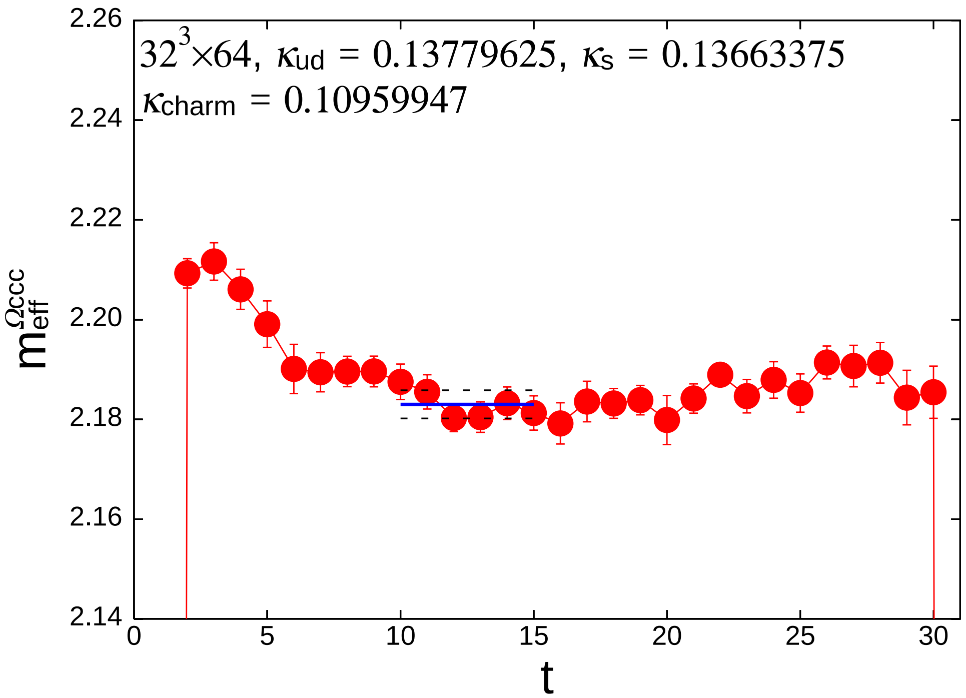
- Our result deviates from ETMC value by 3.8σ.
  $\leftarrow$ Continuum extrapolation is needed for a definite comparison.



3.3 Triply charmed baryon

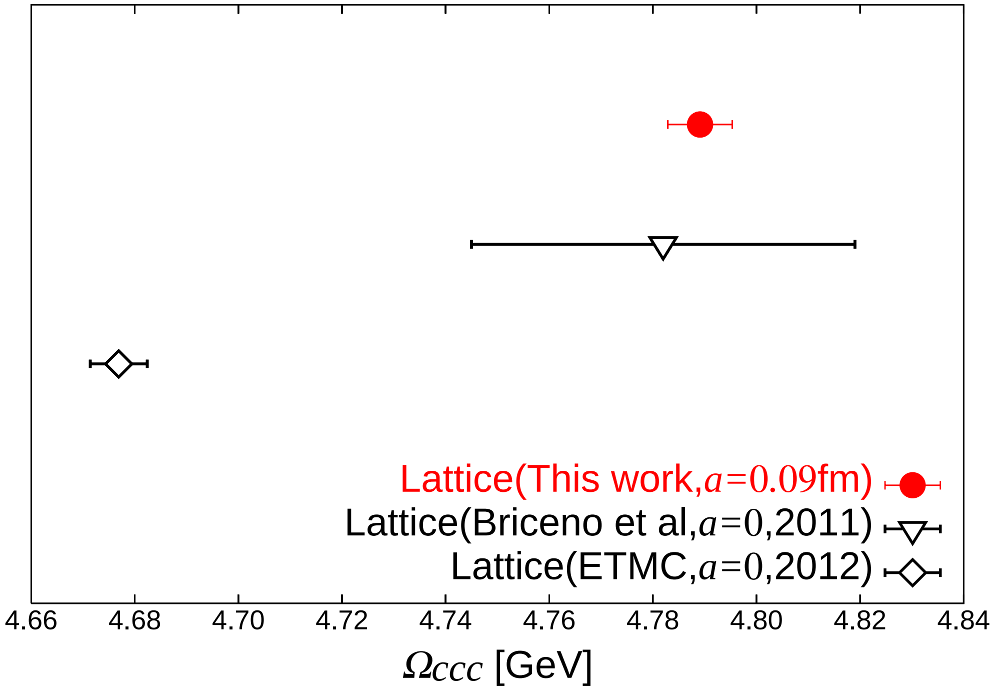
[Effective mass of Ω_{ccc}]

- Plateau is observed in $t = [10, 15]$.



[Comparison of Ω_{ccc} with other lattice QCD simulations]

- Our result agrees with the value by R.A.Briceno et al, 2011.
- Results of ours and R.A.Briceno et al, 2011 do not agree with ETMC, 2012 value.



4 Summary

We performed $N_f = 2 + 1$ full QCD simulation for the charmed baryons on the physical point at $a^{-1} = 2.2$ GeV.

- Our charmed baryon calculation reproduces experimental spectrum well, except for Ξ_{cc}.
  - ◇ Our data of Ξ_{cc} shows a significant deviation from the experimental value of SELEX group.
- Mass spectrum of doubly and triply charmed baryons are presented.
  - ◇ Our results are consistent with previous lattice QCD estimates, except for those by ETMC, 2012.

[Future works]

- We have to take a continuum limit.

[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