

# Heavy baryon mass spectrum from Lattice QCD with 2+1 flavors

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# Outline

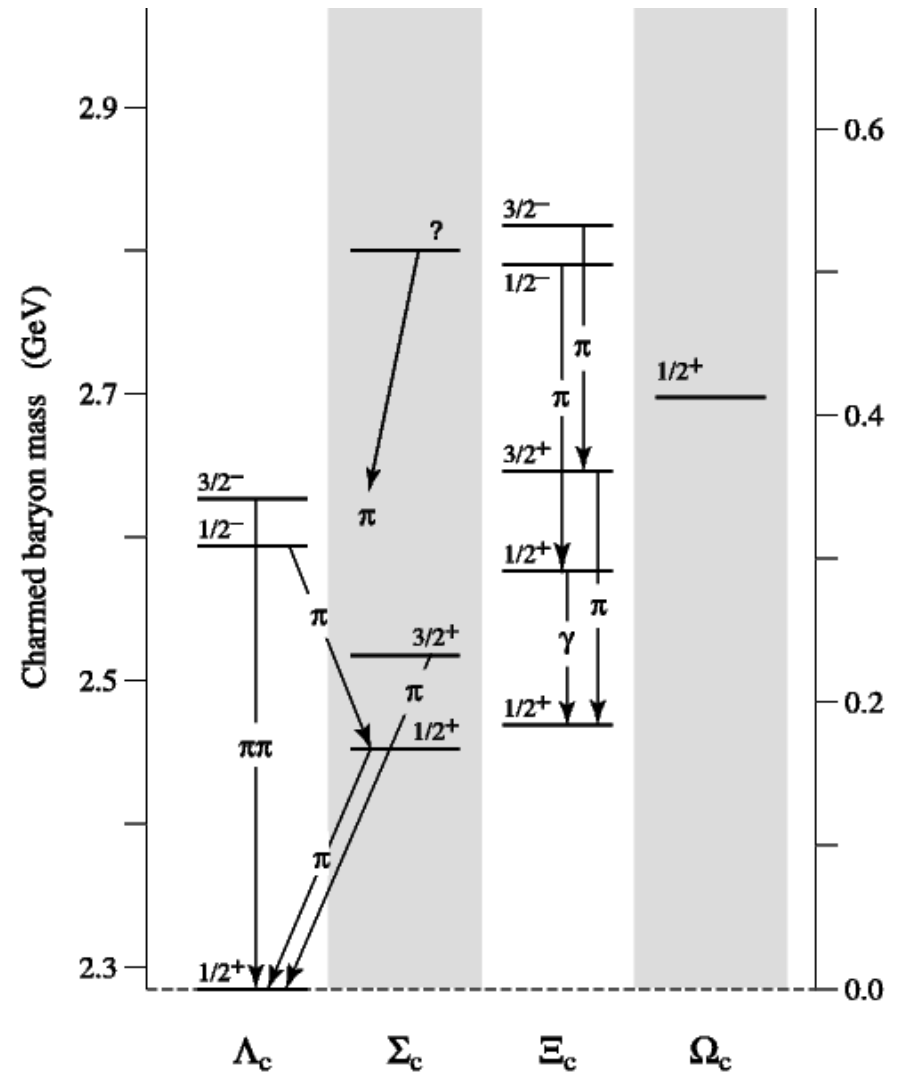
- Introduction
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## ● Introduction

- Singly charmed heavy baryons :

$$\Lambda_C, \Sigma_C, \Xi_C, \Xi'_C, \Omega_C$$

- Lattice QCD with 2+1 flavors



PDG, J. Phys. G 33, 1 (2006)

# ● Lattices and Propagators

## ● MILC coarse lattices

–  $20^3 \times 64$ ,  $a = 0.12$  fm

– 2 ensembles

•  $m_q = 0.01$      $m_s = 0.05$  : 385 confs

•  $m_q = 0.02$      $m_s = 0.05$  : 458 confs

## ● Propagators

– 9 different staggered light valence quarks

• 0.005 ~ 0.02

– 3 different staggered strange valence quarks

• 0.024, 0.03, 0.0415

– One valence clover heavy quark

•  $k = 0.122$  (Tuned for charm quark)

## ● Formalism

- **Operators** (K.C. Bowler et al., PRD 54, 3619 (1996))

$$O_5 = \varepsilon_{abc} (\psi_1^{aT} C \gamma_5 \psi_2^b) \Psi_H^c, \quad O_\mu = \varepsilon_{abc} (\psi_1^{aT} C \gamma_\mu \psi_2^b) \Psi_H^c$$

	J <sup>p</sup>	s <sup>π</sup>	Content	Baryon
O <sub>5</sub>	1/2 <sup>+</sup>	0 <sup>+</sup>	llc	Λ <sub>c</sub>
		0 <sup>+</sup>	lsc	Ξ <sub>c</sub>
O <sub>μ</sub>		1 <sup>+</sup>	llc	Σ <sub>c</sub>
		1 <sup>+</sup>	lsc	Ξ' <sub>c</sub>
		1 <sup>+</sup>	ssc	Ω <sub>c</sub>

- **Converting naive to staggered quark**

(M. Wingate et al. PRD67, 054505 (2003))

$$\begin{aligned} C(\vec{p}, t) &= \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \text{Tr}[\Gamma_{sc} G_{\Psi}(0; x) \Gamma_{sk}^+ G_H(x; 0)] \\ &= \sum_{\vec{x}} e^{i\vec{p}\cdot\vec{x}} \sum_{cc'} \text{tr}[\Gamma_{sc} \Omega^+(x) \Gamma_{sk}^+ G_H^{c'c}(x; 0)] G_{\chi}^{cc'}(0; x) \end{aligned}$$

$$G_{\psi}(x, y) = \Omega(x) \Omega^+(y) G_{\chi}(x, y)$$

$$\text{where } \Omega(x) = \prod_{\mu} (\gamma_{\mu})^{x_{\mu}/a}$$

- Two point function for heavy baryon

$$\begin{aligned}
 C_{\mu\nu}(\vec{p}, t) &= \sum_{\vec{x}} e^{-i\vec{p}\cdot\vec{x}} \left\langle O_{5\mu}(\vec{x}, t) \bar{O}_{5\nu}(\vec{0}, 0) \right\rangle \\
 &= \sum_{\vec{x}} e^{-i\vec{p}\cdot\vec{x}} \varepsilon_{abc} \varepsilon_{a'b'c'} \text{tr}[G_1^{aa'T}(x, 0) C \gamma_5 G_2^{bb'}(x, 0) C \gamma_5] G_{H\mu\nu}^{cc'}(x, 0)
 \end{aligned}$$

$$\begin{aligned}
 C_{\mu\nu}(\vec{p}, t) &= \sum_{\vec{x}} e^{-i\vec{p}\cdot\vec{x}} \varepsilon_{abc} \varepsilon_{a'b'c'} \text{tr}[\Omega^T(x) C \gamma_5 \Omega(x) C \gamma_5] \\
 &\quad \times G_{1\chi}^{aa'}(x, 0) G_{2\chi}^{bb'}(x, 0) G_{H\mu\nu}^{cc'}(x, 0)
 \end{aligned}$$

$$\begin{aligned}
 \text{tr}[\Omega^T(x) C \gamma_5 \Omega(x) C \gamma_5] &= \text{tr}[-1(-1)^{x_1+x_3} (-1)^{x_1+x_3}] \\
 &= -4
 \end{aligned}$$

Finally,

$$C_{\mu\nu}(\vec{p}, t) = \sum_{\vec{x}} e^{-i\vec{p}\cdot\vec{x}} (-4) \varepsilon_{abc} \varepsilon_{a'b'c'} G_{1\chi}^{aa'}(x, 0) G_{2\chi}^{bb'}(x, 0) G_{H\mu\nu}^{cc'}(x, 0)$$

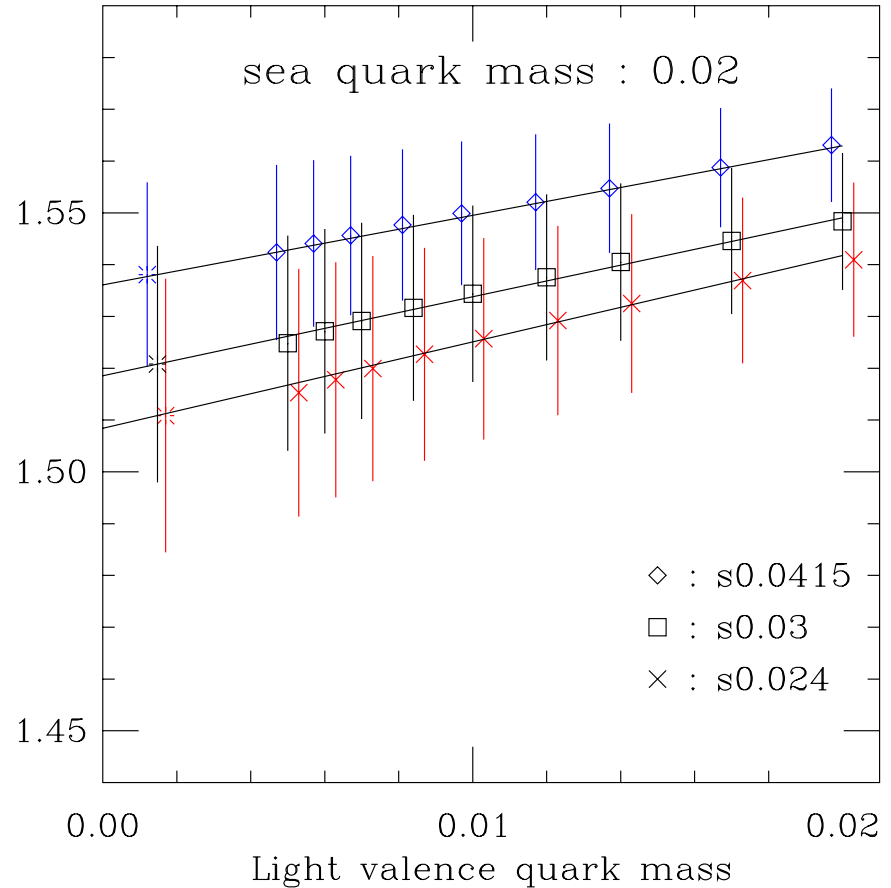
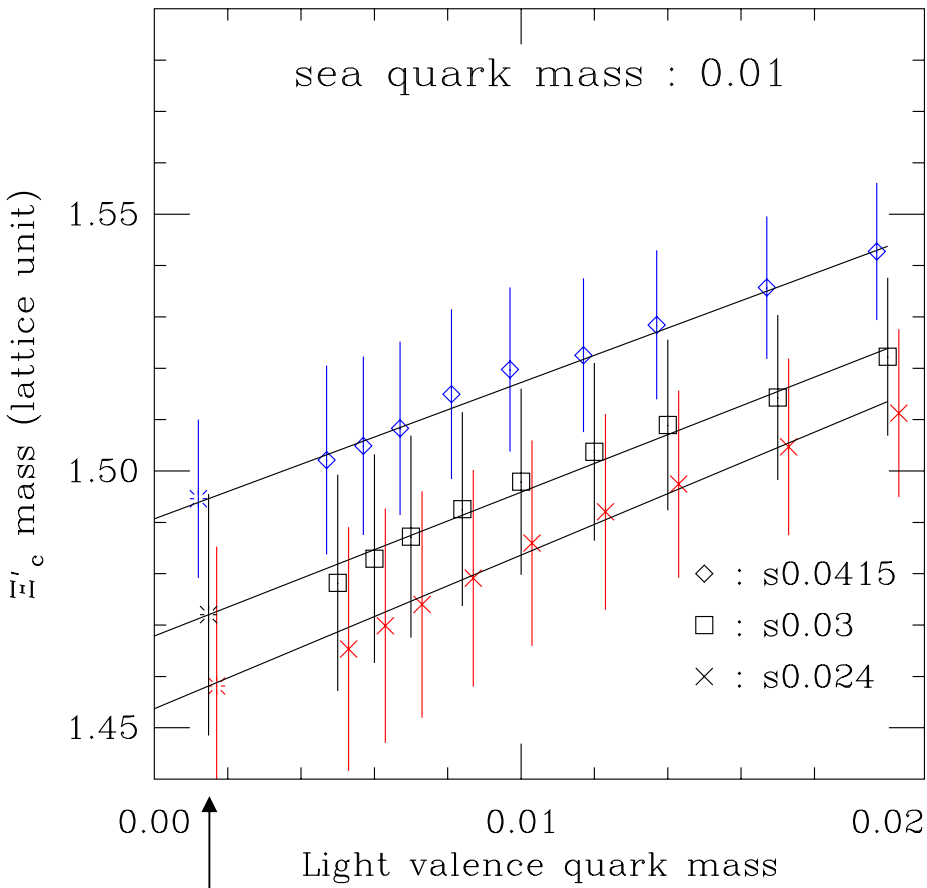
- Data analysis

- Fit model function

$$P(t) = Ae^{-mt} + Ae^{-m(T-t)} + (-1)^t \tilde{A}e^{-\tilde{m}t} + (-1)^t \tilde{A}e^{-\tilde{m}(T-t)} \\ + A^*e^{-m^*t} + A^*e^{-m^*(T-t)} + (-1)^t \tilde{A}^*e^{-\tilde{m}^*t} + (-1)^t \tilde{A}^*e^{-\tilde{m}^*(T-t)}$$

- Correlated least squares fit
- Error estimation
  - 1000 bootstrap samples
- Linear extrapolation

- Extrapolation of light valence quark mass

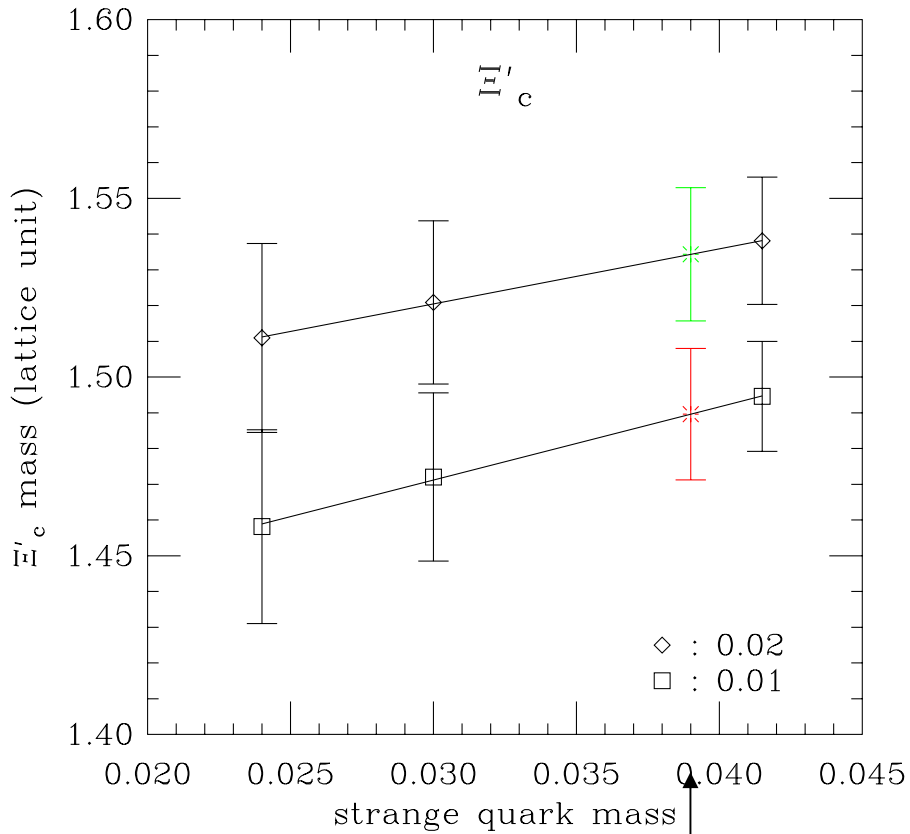


0.00148

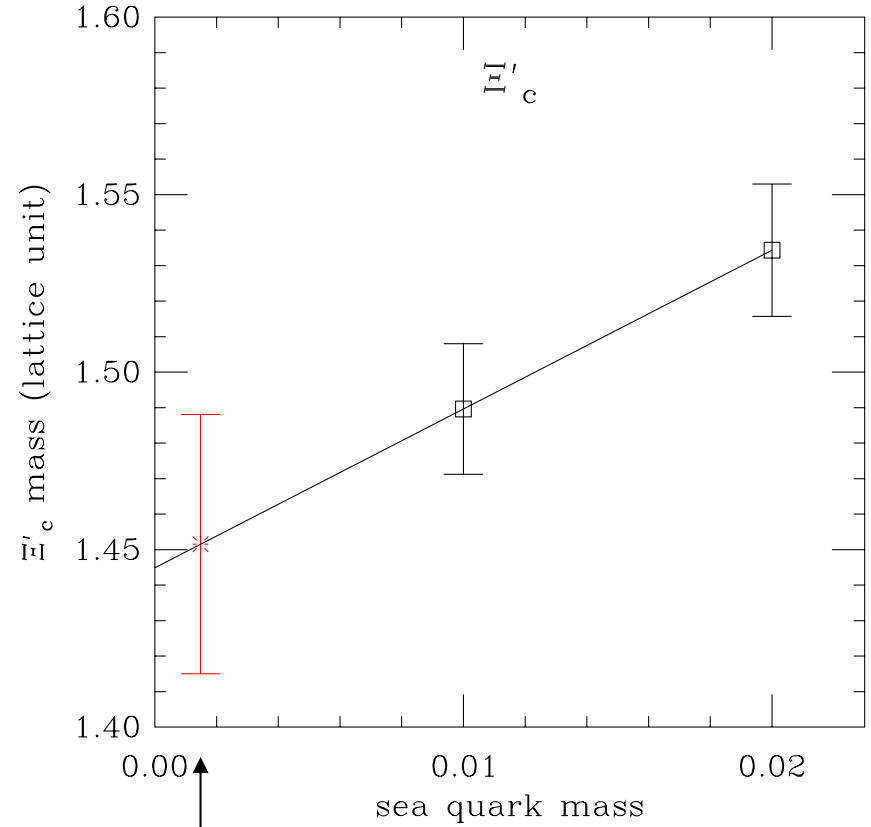
Confidence level ~ 40% in average

Real quark masses are quotations from MILC. PRD 70, 114501 (2004)

- Interpolation of Strange quark mass and extrapolation of Light sea quark mass

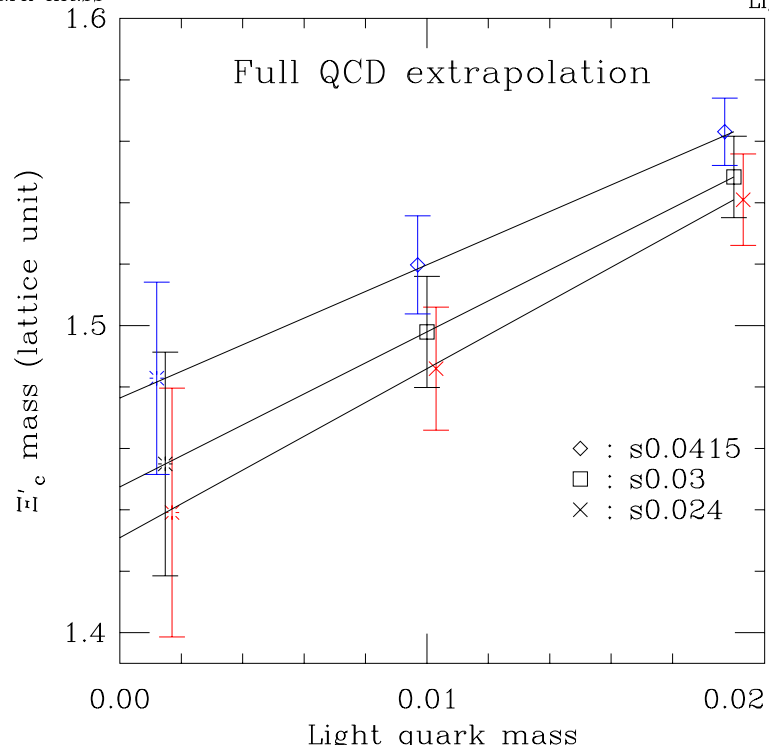
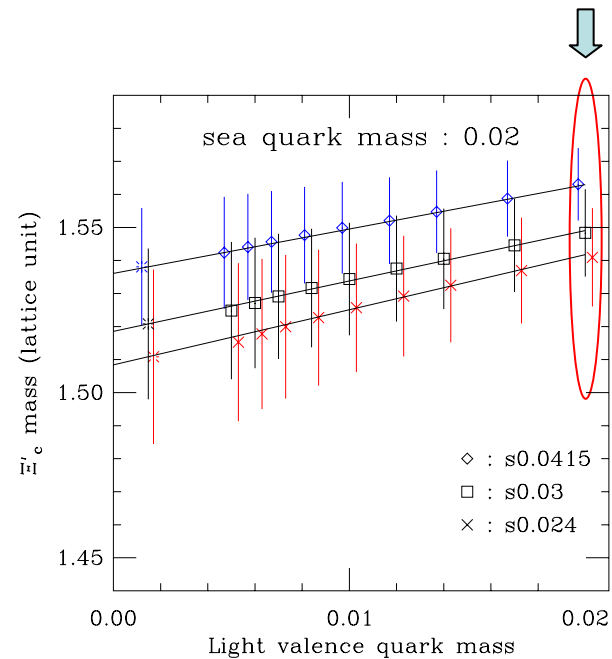
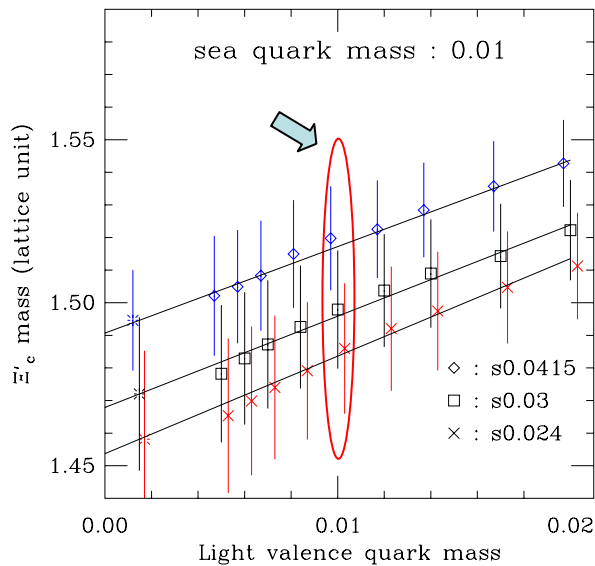


0.039

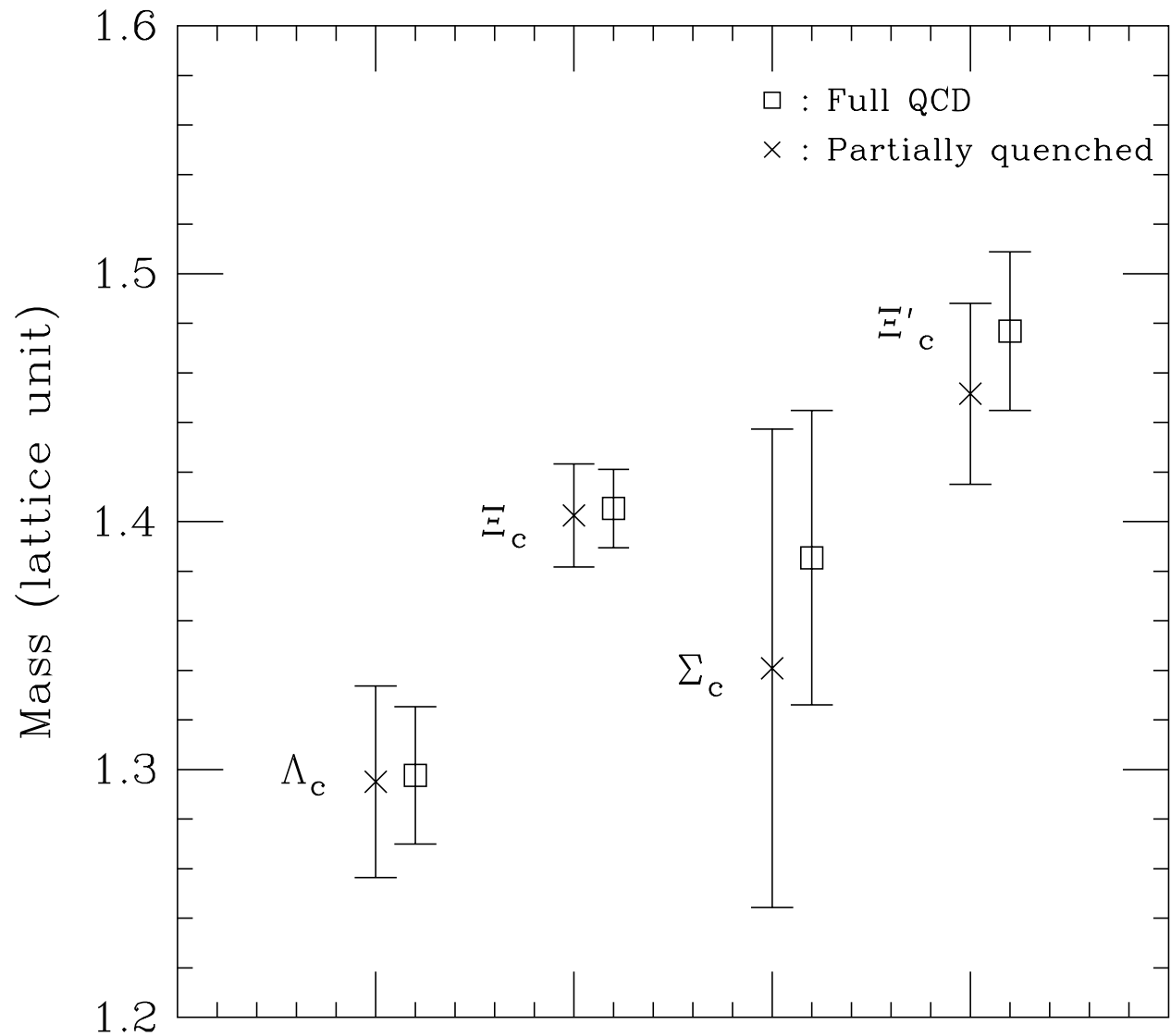


0.00148

# • Full QCD extrapolation

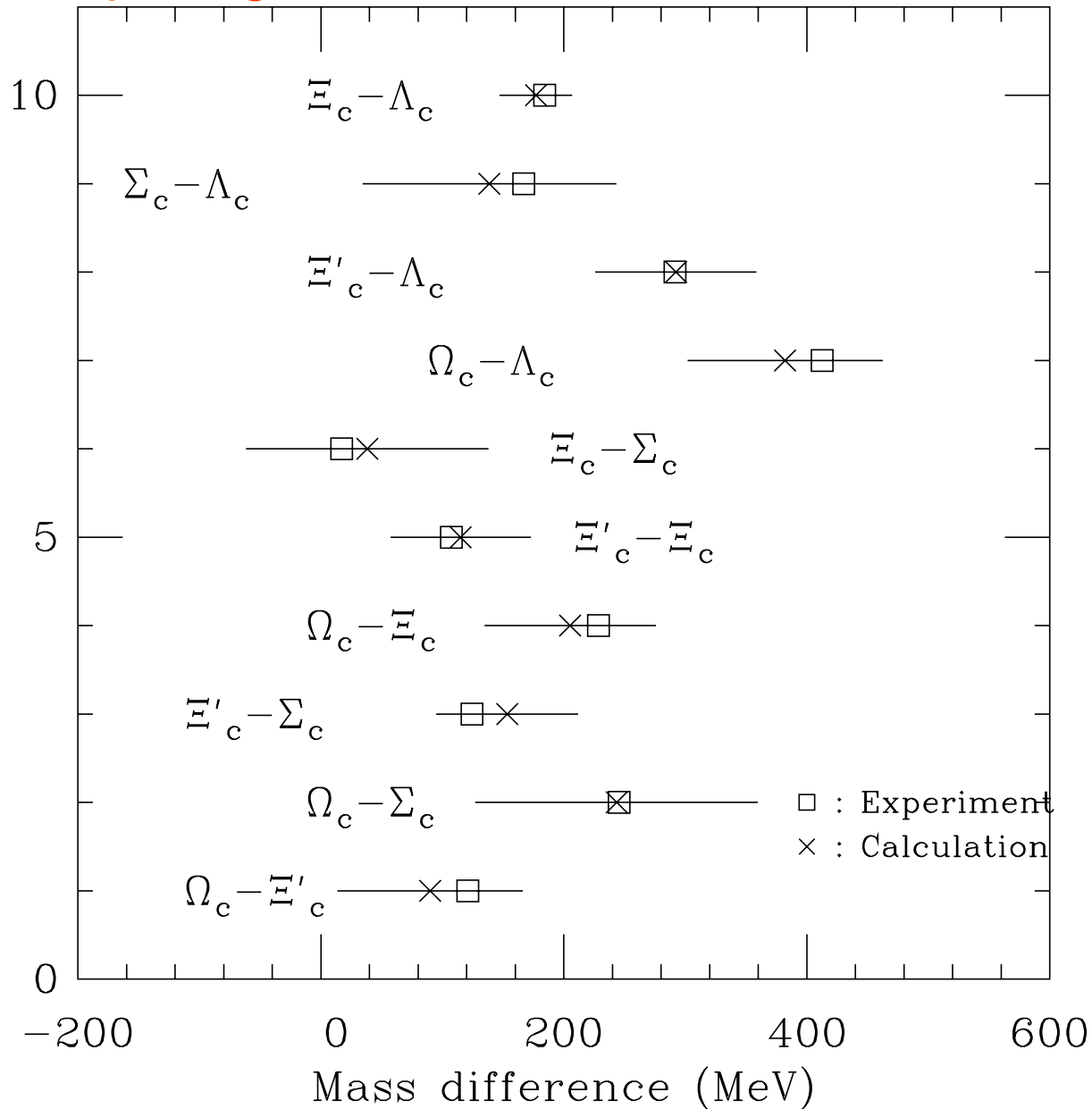


- **Full QCD** vs. **Partially quenched QCD**

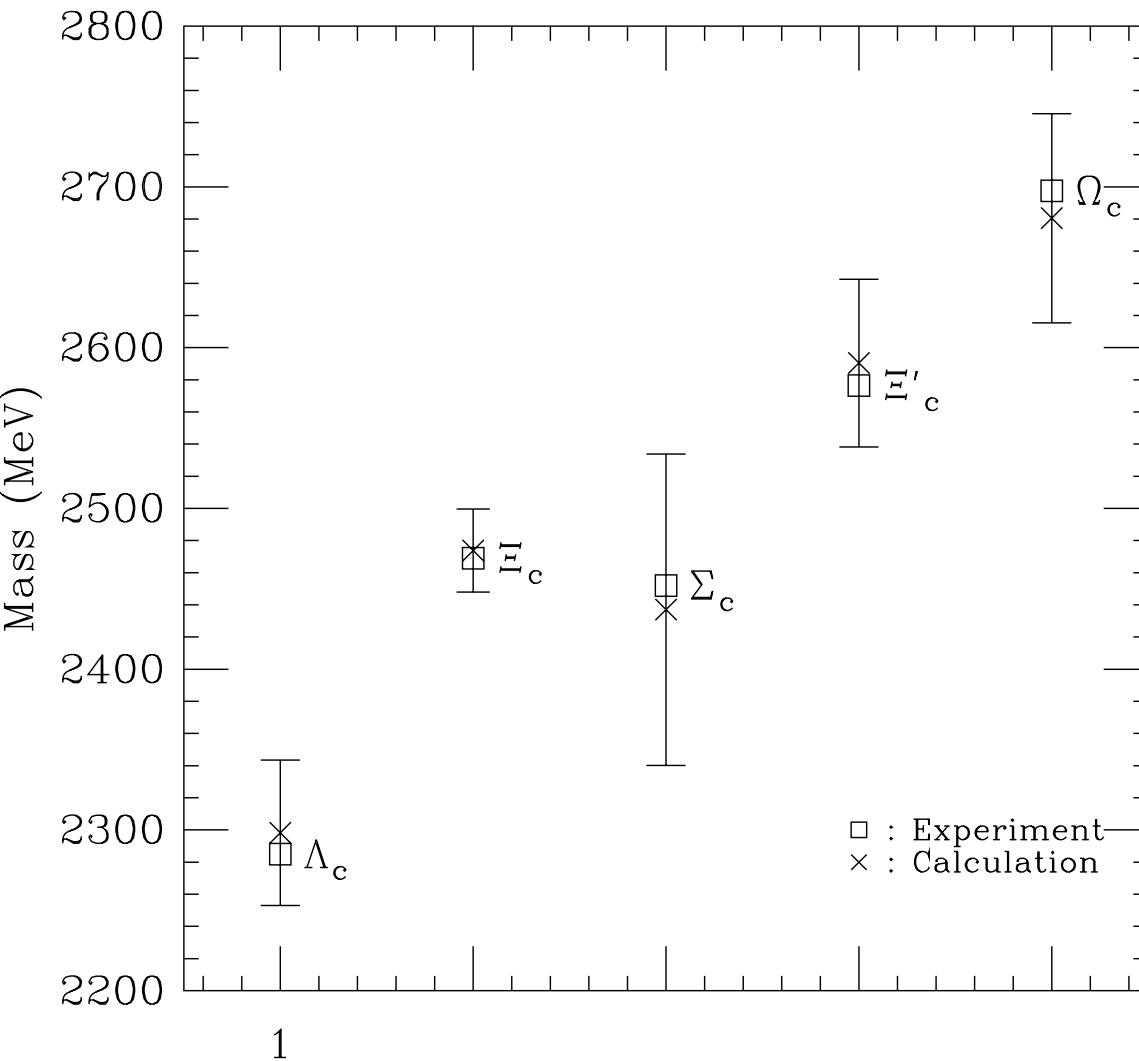


# ● Results

## ● Mass splitting



- Mass spectrum



$$\mathbf{M_{phy} = M_{cal} + \Delta}$$

$$\mathbf{M_{kin} = \frac{|\vec{p}|^2 - [M_{cal}(\vec{p}) - M_{cal}(0)]^2}{2[M_{cal}(\vec{p}) - M_{cal}(0)]}}$$

**Constant Mass Shift**

$$\mathbf{= Average (M_{exp} - M_{cal})}$$

## Future study

- Bottom quark in addition to charm quark
  - Canceling chiral effects
- Doubly charmed heavy baryon
- More about error analysis
- Increase statistics, other ensembles
- Excited states ( $3/2^+$ ,  $1/2^-$ ,  $3/2^-$ )