Study of Finite Size Effect on Hadron Masses and Decay Constants with $(5.4\text{fm})^4$ and $(10.8\text{fm})^4$ Lattices at the Physical Point in 2+1 Flavor QCD

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Plan of talk

- PACS Collaboration Members
- Simulation Parameters for 2+1 Flavor QCD
- Quick Review of Results for Pseudoscalar Sector
- Results for Vector Meson and Baryon Sectors
  - Comparison btw 128^4 and 64^4
  - Ω baryon
  - Determination of Physical Point
- Summary

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Simulation Parameters for 2+1 Flavor QCD (1)

PACS,PRD99(2019)014504

128^4 lattice

- Wilson-clover quark action + Iwasaki gauge action
- Stout smearing with α=0.1 and N_{smear}=6
- NP C_{SW}=1.11 determined by SF
- β=1.82 $\Rightarrow$ $a^{-1}\sim$2.33 GeV
- Lattice size=128^4 $\Rightarrow$ $\sim(11\ \mathrm{fm})^4$
- Hopping parameters: (κ_{ud},κ_s)=(0.126117,0.1247902)

  $\Rightarrow m_\pi\approx$135 MeV, $m_\pi L\approx$7.5
- Simulation algorithm
  - $(HB)^2$DDHMC w/ active link for ud quarks,
  - RHMC w/ N_{RHMC}=8; [0:00025; 1:85] for s quark
  - Block size=16x16x8x64
  - HB parameters: (ρ_1,ρ_2)=(0.9997,0.9940)
  - Multi-time scale integrator: (N_0,N_1,N_2,N_3,N_4)=(8,2,2,2,22)
  - trajectory length: τ=1.0
  - Chronological inverter guess
  - Solver: mixed precision nested BiCGStab

Simulation Parameters for 2+1 Flavor QCD (2)

PACS,PRD99(2019)014504

64^4 lattice

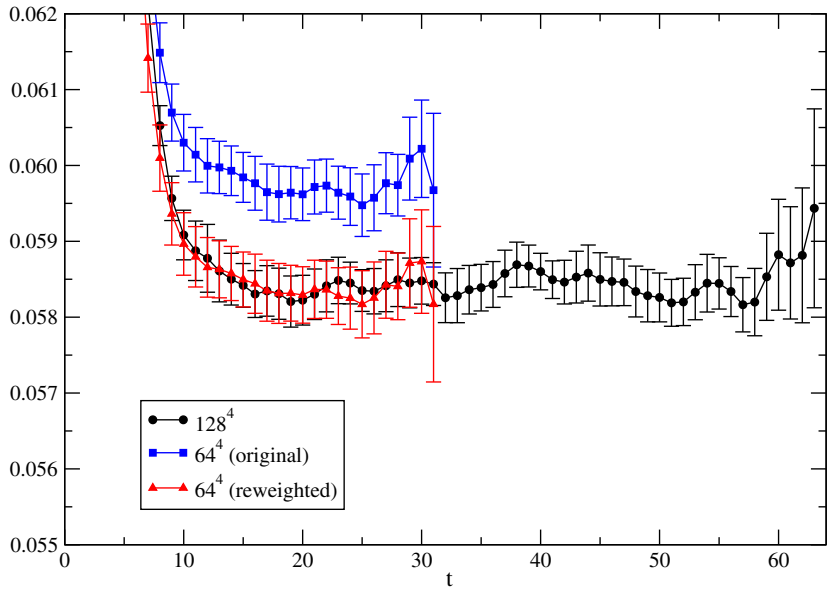
- Wilson-clover quark action + Iwasaki gauge action
- Stout smearing with α=0.1 and N_{smear}=6
- NP C_{SW}=1.11 determined by SF
- β=1.82 $\Rightarrow$ $a^{-1}\sim$2.33 GeV
- Lattice size=64^4 $\Rightarrow$ $\sim$(5.5 fm)^3 spatial volume
- Hopping parameters: (κ_{ud},κ_s)=(0.126117,0.1247902)

  $\Rightarrow$ $m_\pi\approx$138 MeV, $m_\pi L\approx$7.6
- Simulation algorithm
  - $(HB)^2$DDHMC w/ active link for ud quarks,
  - UVPHMC w/ N_{poly}=350 for s quark
  - Block size=8x8x16x32
  - HB parameters: (ρ_1,ρ_2)=(0.9997,0.9940)
  - Multi-time scale integrator: (N_0,N_1,N_2,N_3,N_4)=(8,2,2,2,12)
  - trajectory length: τ=1.0
  - Chronological inverter guess
  - Solver: mixed precision nested BiCGStab

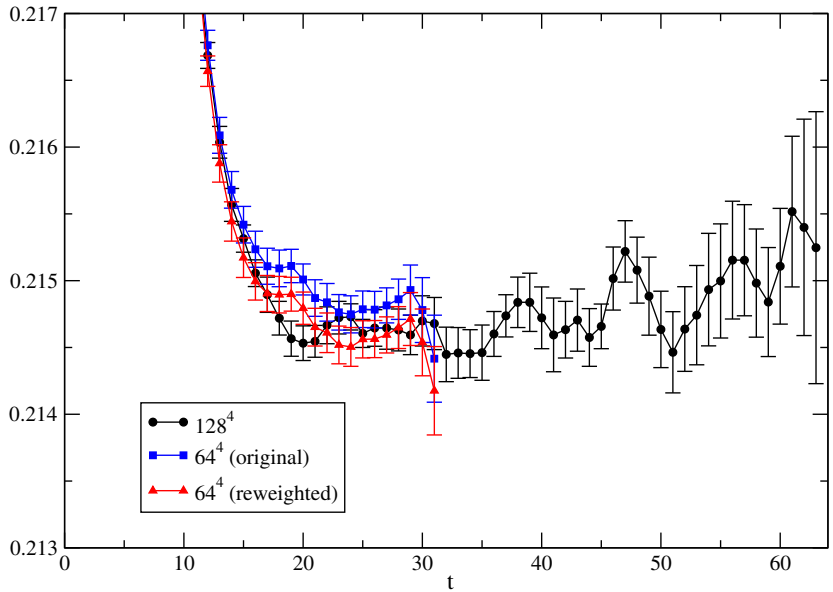
Finite Size Effect on PS Sector (1)

PACS,PRD99(2019)014504

π meson effective mass



K meson effective mass



Clear finite size effect on π meson mass

$m_\pi(L=64)$ is heavier than $m_\pi(L=128)$ by 2.1(8)%

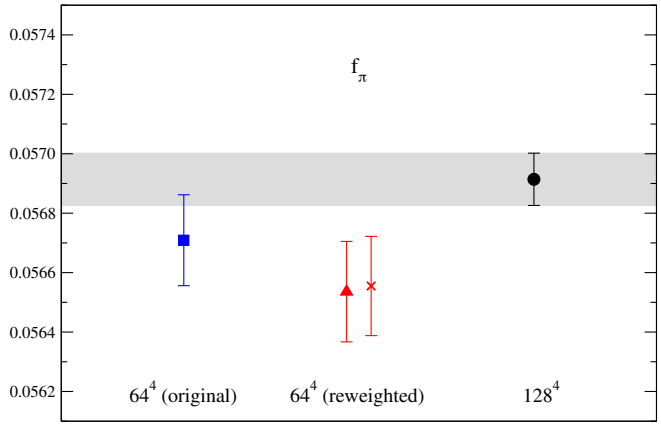
$m_{ud}(L=64)$ is heavier than $m_{ud}(L=128)$ by 4.8(1.6)%

It is hard to detect the finite size effect on K meson mass

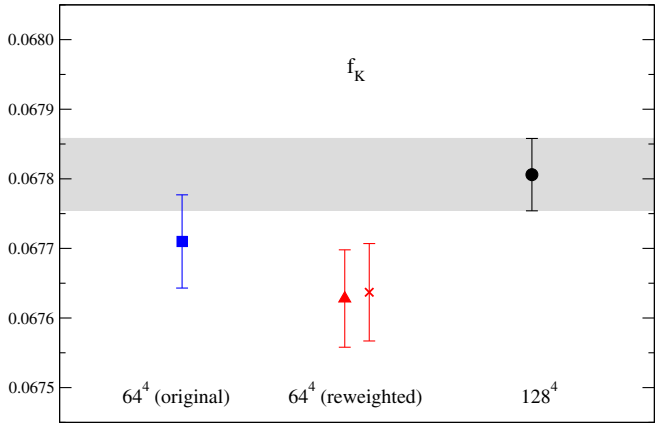
Finite Size Effect on PS Sector (2)

PACS,PRD99(2019)014504

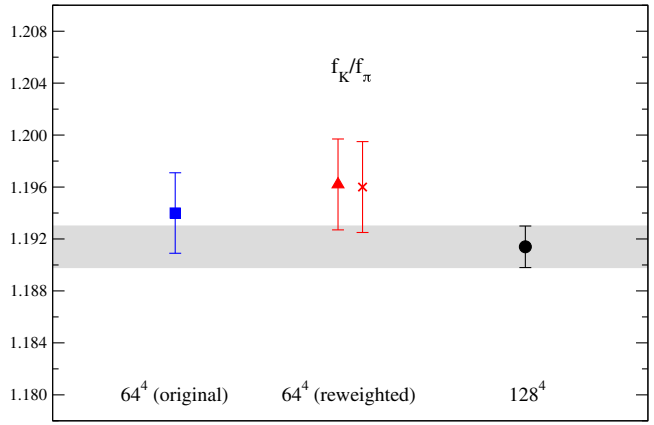
π meson decay const



K meson decay const



ratio



2σ difference after tuning $m_\pi(L=64)=m_\pi(L=128)$

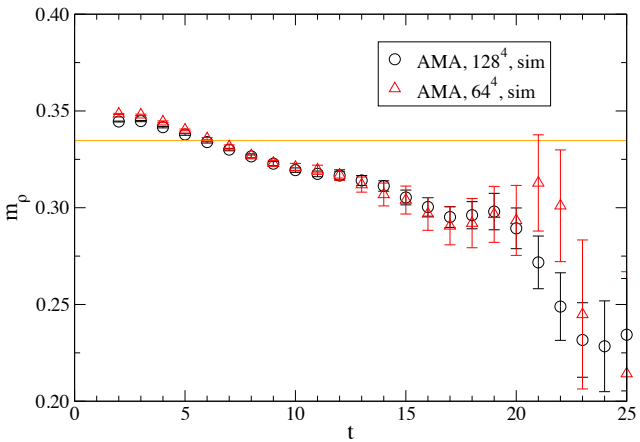
$f_\pi(L=64)$ is smaller than $f_\pi(L=128)$ by 0.66(33)%

$f_K(L=64)$ is smaller than $f_K(L=128)$ by 0.26(13)%

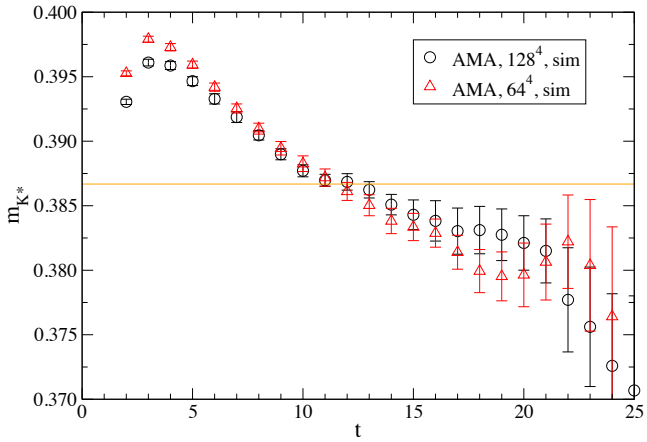
The deviation becomes smaller for f_K/f_π

Results for Vector Meson Sector

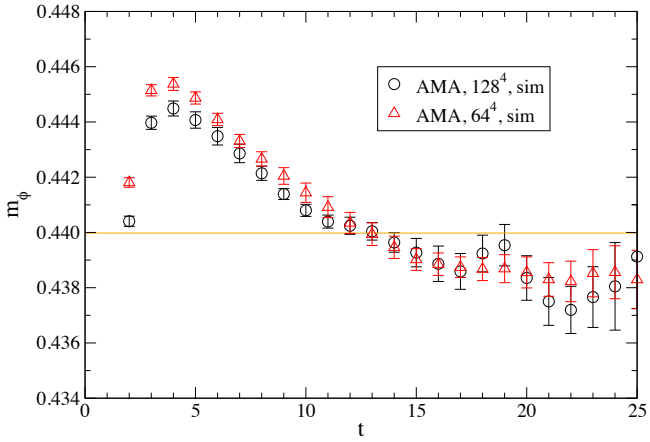
ρ meson



K* meson



ϕ meson



Measurements (128^4: 7679, 64^4: 25573) were carried out by AMA method

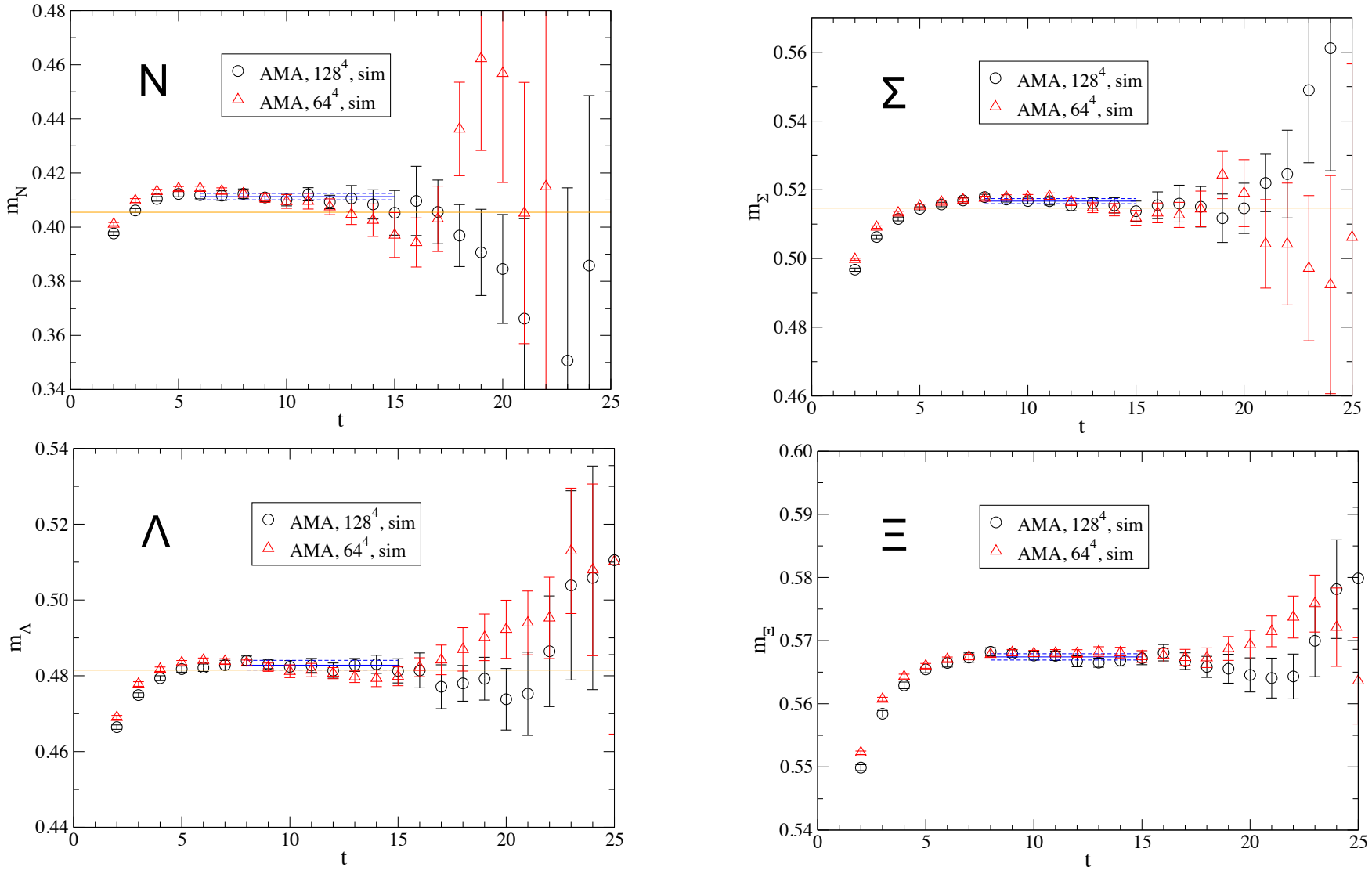
Finite size effects are negligible within error bars

No plateau is observed

Effective masses go below the experimental resonance value in the large time region

⇒ Need appropriate treatment to extract the energy levels

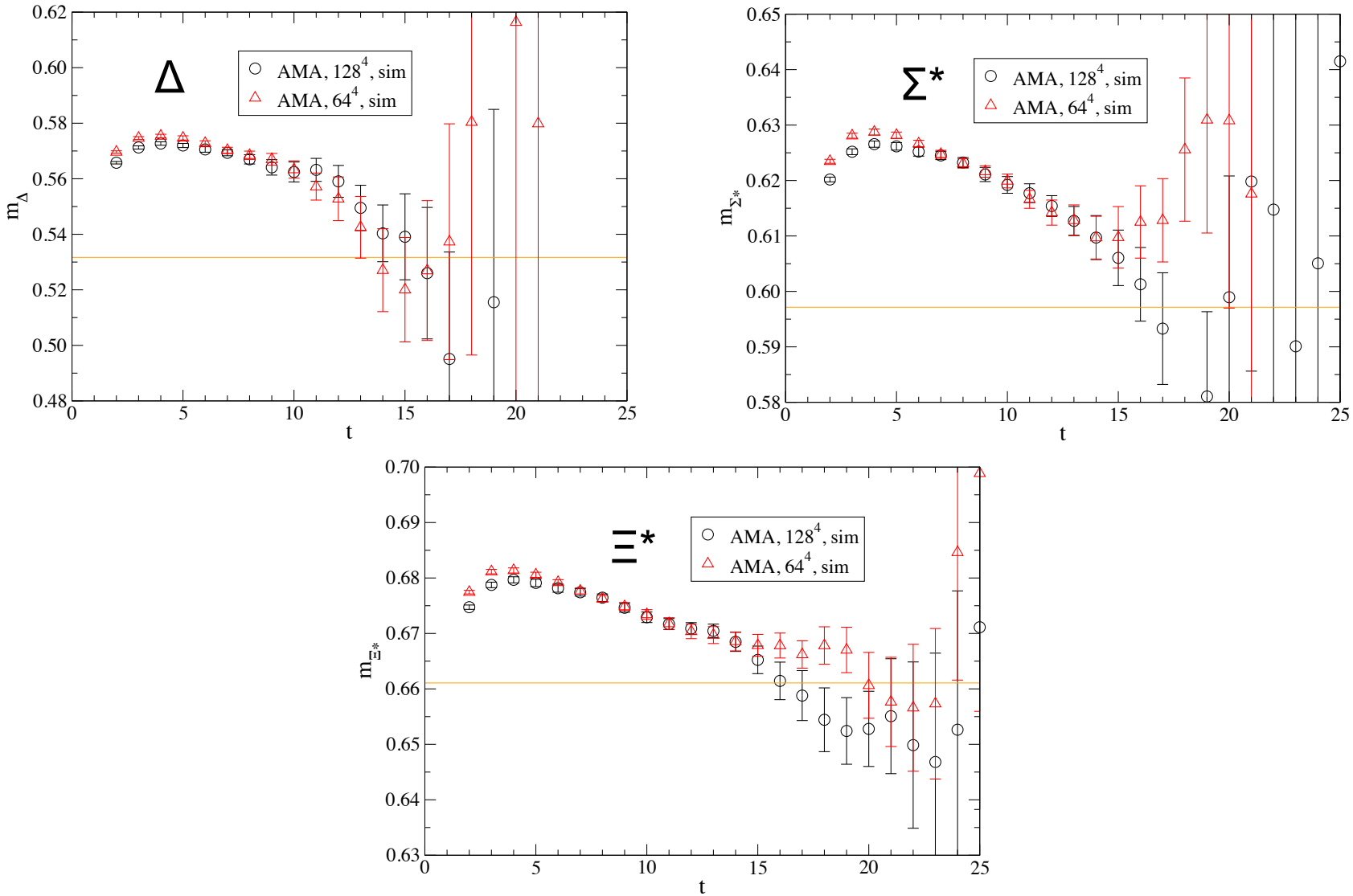
Results for Octet Baryon Sector



Finite size effects are negligible within error bars

Reasonable plateau regions are observed

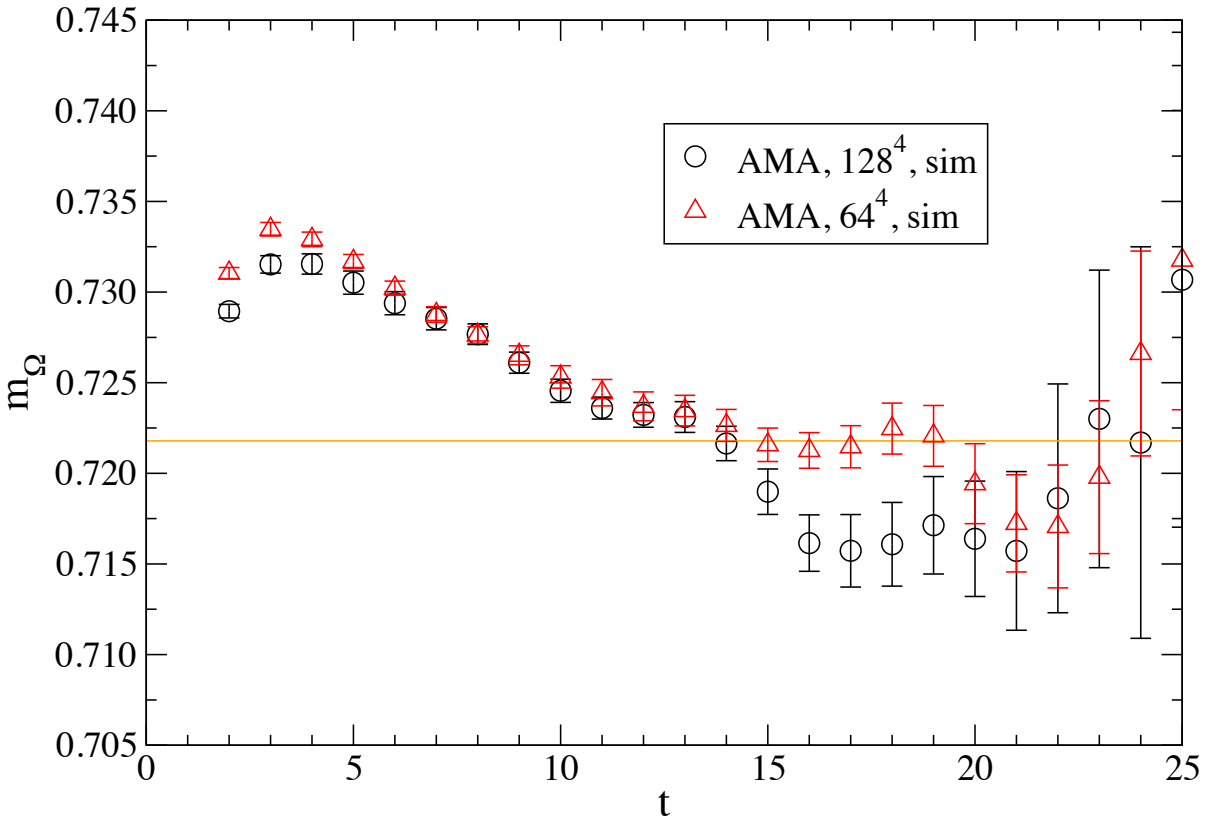
Results for Decuplet Baryon Sector



Finite size effects seem negligible

No plateau similar to vector mesons

Ω Baryon with AMA



Similar signal with other decuplet baryons

Plateau in the large time region t≳16?

Finite size effect in t≳16?

⇒ Need to check with high statistics employing a different source and a different solver algorithm

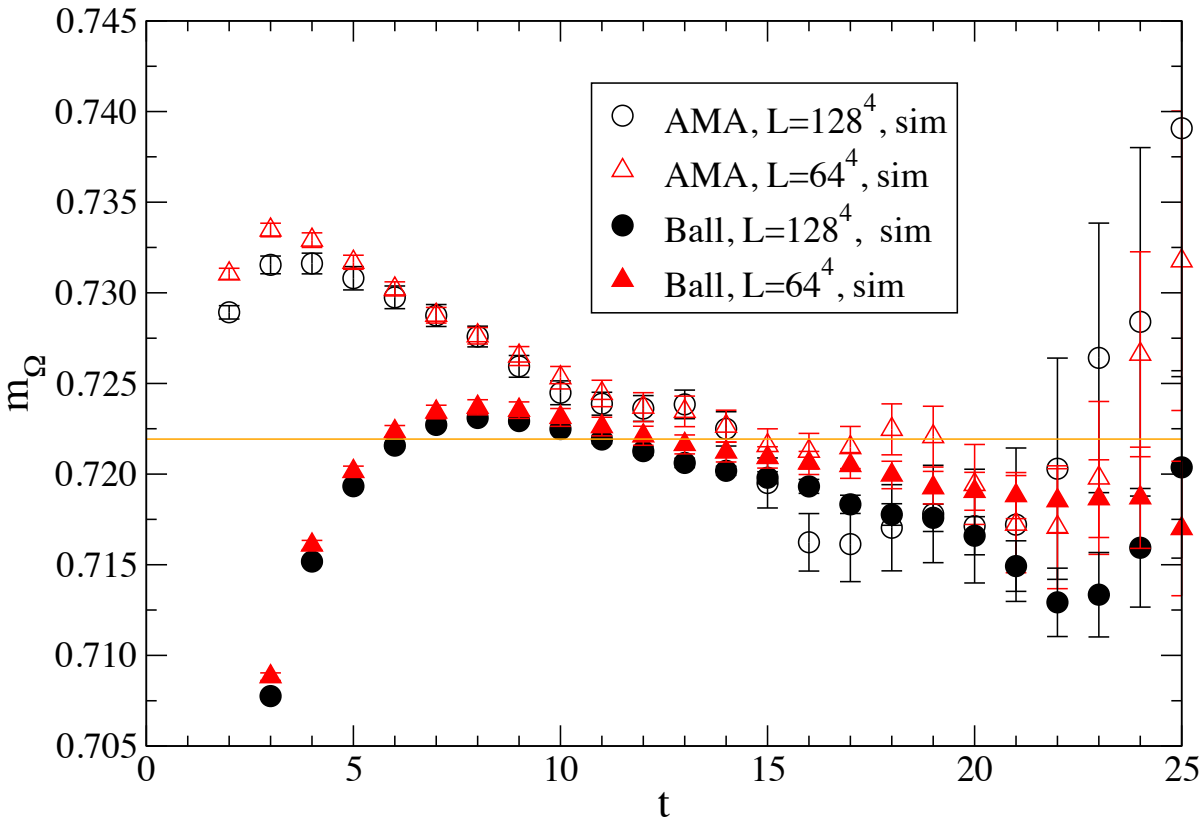
Precision measurement with BCC Ball Source

- Ball sources are filled in 3D spatial lattice with the body-centered-crystal (BCC) structure
- BCC Ball source is a variant of grid source

  Li et al., PRD82(2010)114501; PRD88(2013)014503
  Wu et al., J.Phys.G45(2018)125102
- $(n_{ball},r_{ball})=(128,13.9)$ for 128^4 lattice
- $(n_{ball},r_{ball})=(16,13.9)$ for 64^4 lattice
- Exponential smearing: $A\exp(-Br)$ w/ $(A=1.0,B=0.06)$

- Solver: mixed precision nested BiCGStab
- Strict tolerance $|Dx-b|/|b|<10^{-15}$
- No. measurements: 2560 for 128^4 and 25600 for 64^4

Ω Baryon with BCC Ball Source



Error bar is significantly reduced with bcc ball source method

No plateau before signal is lost beyond t≈20

⇒ impossible to extract Ω baryon mass with single exponential fit

Possible Mixing States on the Lattice

Johnson,PLB114(1982)147

Channel	^2O rep.	j	j'	nearby two-body state
π	A_1	0	4	
K	A_1	0	4	
ρ	G_1	1	3	$\pi\pi$
K^*	G_1	1	3	$K\pi$
ϕ	G_1	1	3	KK
N	T_1	1/2	7/2	
Λ	T_1	1/2	7/2	
Σ	T_1	1/2	7/2	
Ξ	T_1	1/2	7/2	
Δ	H	3/2	5/2	$N\pi$
Σ^*	H	3/2	5/2	$\Lambda\pi$
Ξ^*	H	3/2	5/2	$\Xi\pi$
Ω	H	3/2	5/2	ΞK

Possible contaminations to decuplet baryon (j=3/2):

higher spin states of j'=5/2

ΞK state ($m_\Xi+m_K-m_\Omega\approx140$MeV)

Determination of Physical Point on 128^4 lattice (1)

Physical inputs: m_π, m_K, m_Ξ

Taylor expansion around the simulation point in terms of m_{ud} and m_s

$$m_\pi^2 = m_\pi^2|_{\rm org} + \left.\frac{\partial m_\pi^2}{\partial m_{\rm ud}}\right|_{\rm org} (m_{\rm ud} - m_{\rm ud}|_{\rm org}) + \left.\frac{\partial m_\pi^2}{\partial m_{\rm s}}\right|_{\rm org} (m_{\rm s} - m_{\rm s}|_{\rm org}) \,,$$

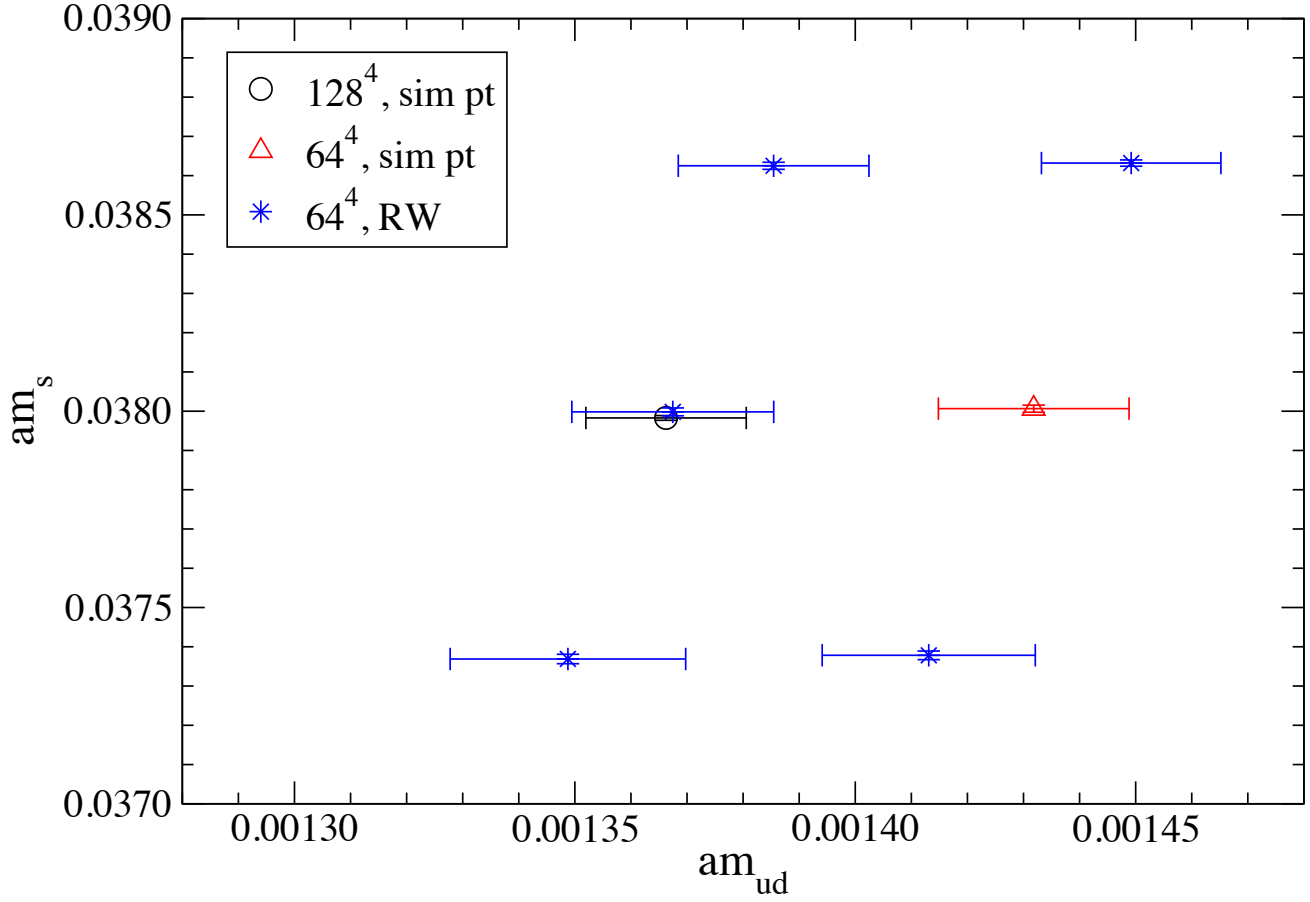
$$m_K^2 = m_K^2|_{\rm org} + \left.\frac{\partial m_K^2}{\partial m_{\rm ud}}\right|_{\rm org} (m_{\rm ud} - m_{\rm ud}|_{\rm org}) + \left.\frac{\partial m_K^2}{\partial m_{\rm s}}\right|_{\rm org} (m_{\rm s} - m_{\rm s}|_{\rm org}) \,,$$

$$m_\Xi = m_\Xi|_{\rm org} + \left.\frac{\partial m_\Xi}{\partial m_{\rm ud}}\right|_{\rm org} (m_{\rm ud} - m_{\rm ud}|_{\rm org}) + \left.\frac{\partial m_\Xi}{\partial m_{\rm s}}\right|_{\rm org} (m_{\rm s} - m_{\rm s}|_{\rm org}) \,.$$

Coefficients are determined from the reweighted results on 64^4 lattice

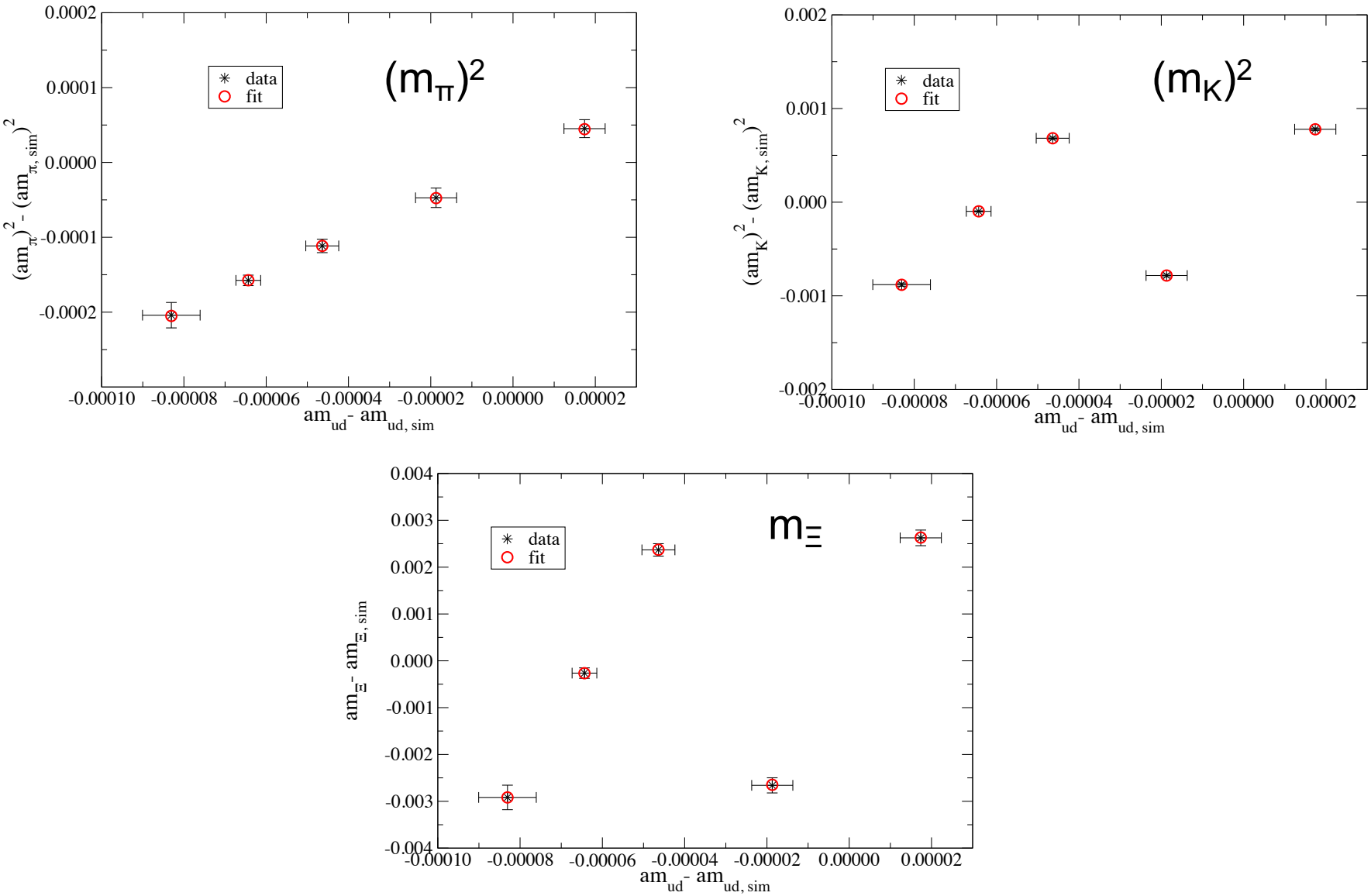
Determination of Physical Point on 128^4 lattice (2)

Reweighting point in $m_{ud} - m_s$ plane



Δm_{ud} : 4.4%, Δm_s : ±1.6%

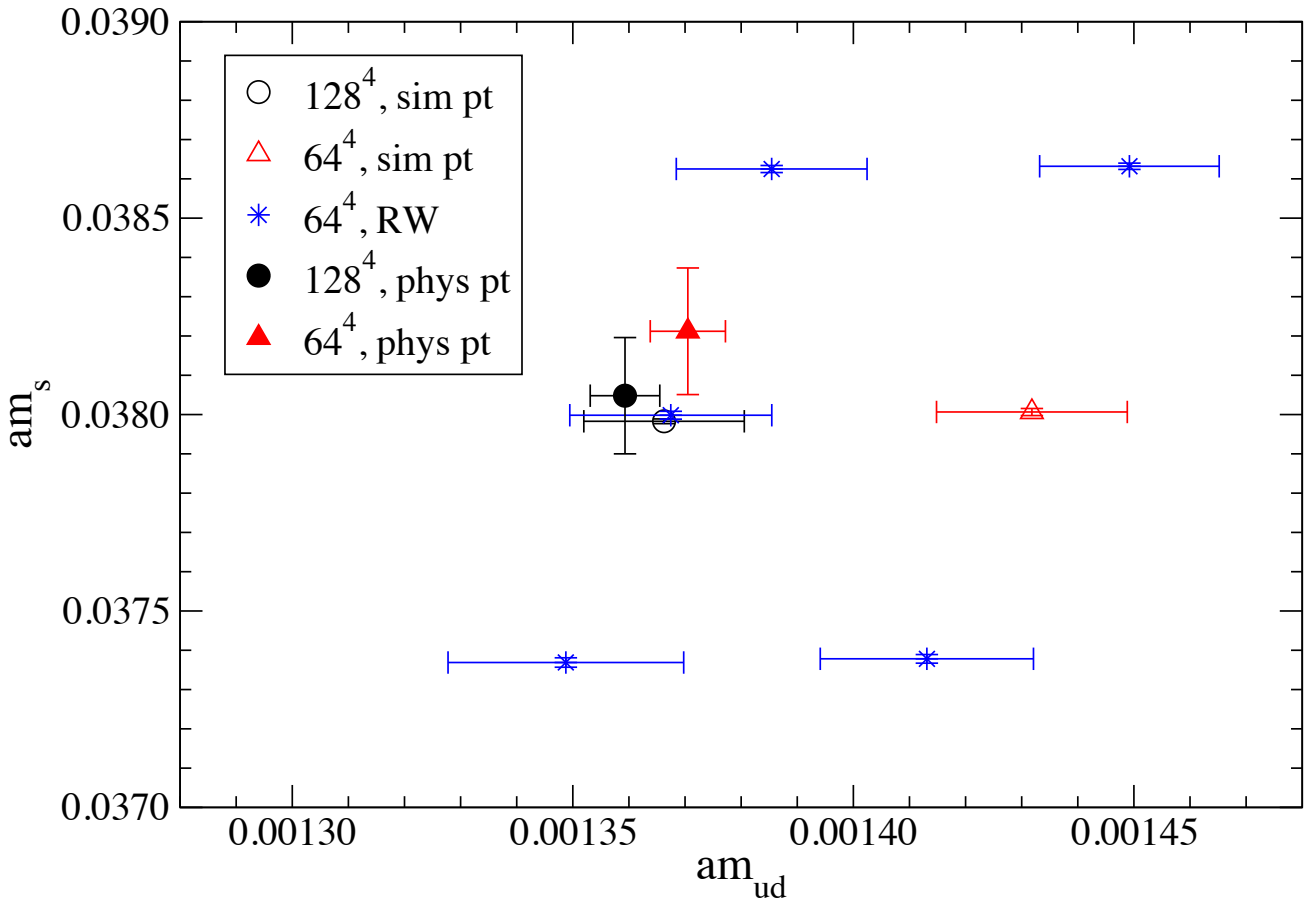
Determination of Physical Point on 128^4 lattice (3)



Reweighted data are well described by the linear expansion

Determination of Physical Point on 128^4 lattice (4)

Physical point in m_{ud} – m_s plane



Physical point is consistent with simulation point on 128^4 lattice

The sacle is determined to be 1/a=2.3162(44) GeV

Summary

<u>2+1 flavor QCD simulation at the physical point on 128^4 and 64^4 lattices</u>

- Clear finite size effect for PS meson sector
- Hard to detect finite size effects for vector meson and baryon sectors
- Ω baryon seems “unstable” on the lattice
- Simulation point was successfully tuned to the physical point

<u>Future plan</u>

- Investigation of cut-off effects with finer lattice
- Calculation of various physical quantities