

# Light nuclei and nucleon form factors in $N_f = 2 + 1$ lattice QCD

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for PACS Collaboration

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## 1. Light nuclei

in collaboration with

K.-I. Ishikawa, Y. Kuramashi, and A. Ukawa for PACS Collaboration

Refs: PRD81:111504(R)(2010); PRD84:054506(2011); PRD86:074514(2012)

PRD92:014501(2015)

## 2. Nucleon form factors

in collaboration with

K.-I. Ishikawa, Y. Kuramashi, S. Sasaki and A. Ukawa

for PACS Collaboration

# Outline

- Introduction
- Simulation parameters
- Results of light nuclei
  - ${}^4\text{He}$  and  ${}^3\text{He}$  channels
  - NN channels
- Very preliminary result at  $m_\pi \sim 0.145$  GeV
  - Light nuclei binding energy
  - nucleon form factors
- Summary and future work

# Introduction

Binding force  $\left\{ \begin{array}{l} \text{protons and neutrons} \rightarrow \text{nuclei} \\ \text{quarks and gluons} \rightarrow \text{protons and neutrons} \end{array} \right.$   
both from fundamental strong interaction of quark and gluon  
well known, but hard to prove

Spectrum of proton and neutron (nucleons)

success of non-perturbative calculation of QCD  
degrees of freedom of quarks and gluons

quarks and gluons  $\rightarrow$  proton and neutron  $\rightarrow$  nucleus

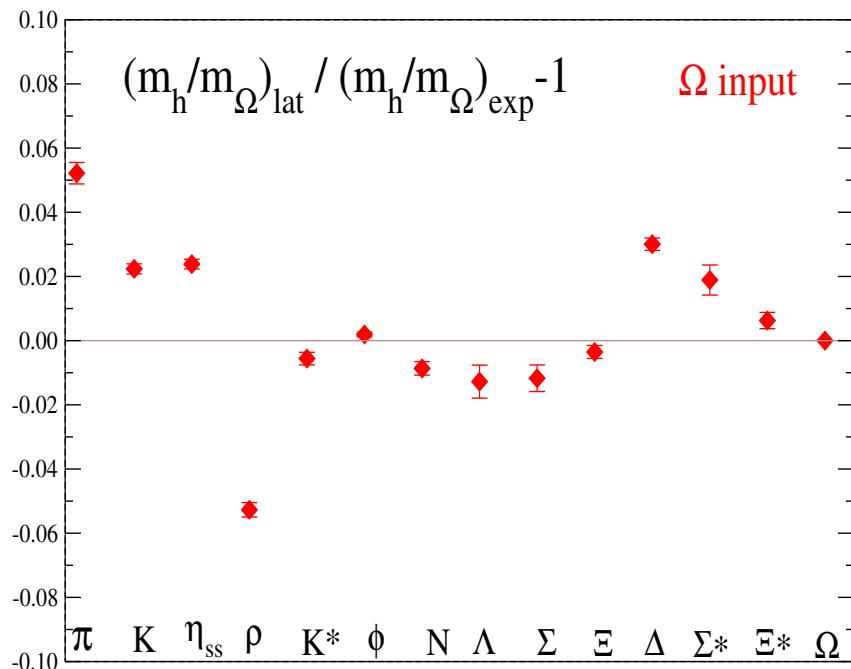
# Hadron spectrum in $N_f = 2 + 1$ QCD

Lattice 2015, Ukita for PACS Collaboration

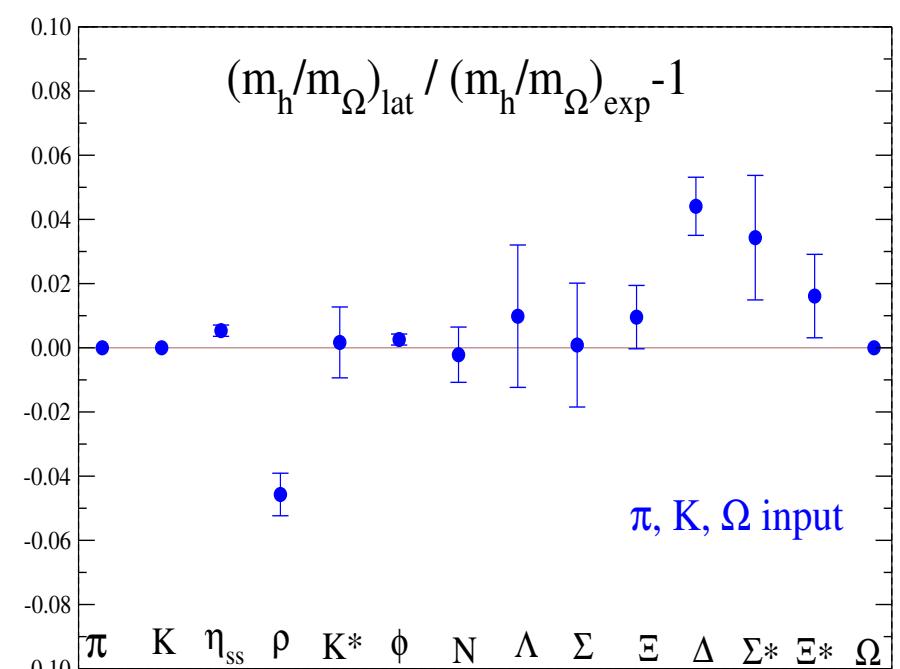
$m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

using reweighting  $m_{u,d}, m_s$  + extrapolation  $\rightarrow$  physical  $m_\pi$  and  $m_K$

$m_\pi \sim 0.145$  GeV



physical point



Stable hadron mass: well reproduced from lattice QCD

# Introduction

Binding force  $\left\{ \begin{array}{l} \text{protons and neutrons} \rightarrow \text{nuclei} \\ \text{quarks and gluons} \rightarrow \text{protons and neutrons} \end{array} \right.$   
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Spectrum of proton and neutron (nucleons)

success of non-perturbative calculation of QCD  
degrees of freedom of quarks and gluons

quark and gluon  $\rightarrow$  proton and neutron  $\rightarrow$  nucleus

goal: quantitatively understand property of nucleus from QCD

So far not many studies for multi-baryon bound states

$\rightarrow$  Can we reproduce known binding energy in light nuclei?

# Introduction

Binding force  $\left\{ \begin{array}{l} \text{protons and neutrons} \rightarrow \text{nuclei} \\ \text{quarks and gluons} \rightarrow \text{protons and neutrons} \end{array} \right.$   
both from fundamental strong interaction of quark and gluon  
well known, but hard to prove

Spectrum of proton and neutron (nucleons)

success of non-perturbative calculation of QCD  
degrees of freedom of quarks and gluons

2nd motivation: Nucleon form factors not well understood

quarks and gluons  $\rightarrow$  proton and neutron  $\rightarrow$  nucleus

goal: quantitatively understand property of nucleus from QCD

# Multi-baryon bound state from lattice QCD

Extend our exploratory  $N_f = 0$  study to  $N_f = 2 + 1$  calculation

## 1. ${}^4\text{He}$ and ${}^3\text{He}$

'10 PACS-CS  $N_f = 0$   $m_\pi = 0.8$  GeV PRD81:111504(R)(2010)

'12 HALQCD  $N_f = 3$   $m_\pi = 0.47$  GeV,  $m_\pi > 1$  GeV  ${}^4\text{He}$

'12 NPLQCD  $N_f = 3$   $m_\pi = 0.81$  GeV

'12 TY et al.  $N_f = 2 + 1$   $m_\pi = 0.51$  GeV PRD86:074514(2012)

'15 TY et al.  $N_f = 2 + 1$   $m_\pi = 0.30$  GeV PRD92:014501(2015)

## 2. H dibaryon in $\Lambda\Lambda$ channel ( $S=-2$ , $I=0$ )

'11, '12 NPLQCD  $N_f = 2 + 1$   $m_\pi = 0.39$  GeV,  $N_f = 3$   $m_\pi = 0.81$  GeV

'11, '12 HALQCD  $N_f = 3$   $m_\pi = 0.47\text{--}1.02$  GeV

'11 Luo et al.  $N_f = 0$   $m_\pi = 0.5\text{--}1.3$  GeV

## 3. NN

'11 PACS-CS  $N_f = 0$   $m_\pi = 0.8$  GeV PRD84:054506(2011)

'12 NPLQCD  $N_f = 2 + 1$   $m_\pi = 0.39$  GeV (Possibility)

'12 NPLQCD  $N_f = 3$   $m_\pi = 0.81$  GeV

'12 TY et al.  $N_f = 2 + 1$   $m_\pi = 0.51$  GeV PRD86:074514(2012)

'15 TY et al.  $N_f = 2 + 1$   $m_\pi = 0.30$  GeV PRD92:014501(2015)

Other states:  $\Xi\Xi$ , '12 NPLQCD; spin-2  $N\Omega$ ,  ${}^{16}\text{O}$  and  ${}^{40}\text{Ca}$ , '14 HALQCD

# Calculation method of multi-nucleon bound state

Traditional method for example  ${}^4\text{He}$  channel

$$\langle 0 | O_{{}^4\text{He}}(t) O_{{}^4\text{He}}^\dagger(0) | 0 \rangle = \sum_n \langle 0 | O_{{}^4\text{He}} | n \rangle \langle n | O_{{}^4\text{He}}^\dagger | 0 \rangle e^{-E_n t} \xrightarrow[t \gg 1]{} A_0 e^{-E_0 t}$$

Difficulties for multi-nucleon calculation

## 1. Statistical error

$$\text{Statistical error} \propto \exp \left( N_N \left[ m_N - \frac{3}{2} m_\pi \right] t \right)$$

## 2. Calculation cost

$$\begin{aligned} \text{Wick contraction for } {}^4\text{He} &= p^2 n^2 = (udu)^2 (dud)^2: 518400 \\ \text{proton} &= p = (udu): 2 \end{aligned}$$

## 3. Identification of bound state on finite volume

Finite volume effect of attractive scattering state

$$\Delta E_L = E_0 - N_N m_N = O(L^{-3}) < 0 \leftrightarrow \text{binding energy}$$

# Calculation method of multi-nucleon bound state

Traditional method for example  ${}^4\text{He}$  channel

$$\langle 0 | O_{{}^4\text{He}}(t) O_{{}^4\text{He}}^\dagger(0) | 0 \rangle = \sum_n \langle 0 | O_{{}^4\text{He}} | n \rangle \langle n | O_{{}^4\text{He}}^\dagger | 0 \rangle e^{-E_n t} \xrightarrow[t \gg 1]{} A_0 e^{-E_0 t}$$

Difficulties for multi-nucleon calculation

## 1. Statistical error

$$\text{Statistical error} \propto \exp \left( N_N \left[ m_N - \frac{3}{2} m_\pi \right] t \right)$$

→ heavy quark  $m_\pi = 0.8\text{--}0.3 \text{ GeV}$  + large # of measurements

## 2. Calculation cost PACS-CS PRD81:111504(R)(2010)

Wick contraction for  ${}^4\text{He} = p^2 n^2 = (udu)^2 (dud)^2$ : 518400 → 1107

→ reduction using  $p(n) \leftrightarrow p(n)$ ,  $p \leftrightarrow n$ ,  $u(d) \leftrightarrow u(d)$  in  $p(n)$   
+ block of 3 quark props(parallel) and contraction(workstation)  
c.f.) '12 Doi and Endres; Detmold and Orginos; '13 Günther et al.

## 3. Identification of bound state on finite volume

attractive scattering state  $\Delta E_L = E_0 - N_N m_N = O(L^{-3}) < 0$

'86, '91 Lüscher, '07 Beane et al.

→ Volume dependence of  $\Delta E_L \rightarrow \Delta E_\infty \neq 0 \rightarrow$  bound state

c.f.) Spectral weight: '04 Mathur et al., Anti-PBC '05 Ishii et al.

# Simulation parameters

$N_f = 2 + 1$  QCD

Iwasaki gauge action at  $\beta = 1.90$

$a^{-1} = 2.194$  GeV with  $m_\Omega = 1.6725$  GeV '10 PACS-CS

non-perturbative  $O(a)$ -improved Wilson fermion action

$m_\pi = 0.51$  GeV and  $m_N = 1.32$  GeV PRD86:074514(2012)

$m_\pi = 0.30$  GeV and  $m_N = 1.05$  GeV PRD92:014501(2015)

$m_s \sim$  physical strange quark mass

${}^4\text{He}$ ,  ${}^3\text{He}$ , NN( ${}^3\text{S}_1$  and  ${}^1\text{S}_0$ )

		$m_\pi = 0.5$ GeV		$m_\pi = 0.3$ GeV		$R$
$L$	$L$ [fm]	$N_{\text{conf}}$	$N_{\text{meas}}$	$N_{\text{conf}}$	$N_{\text{meas}}$	
32	2.9	200	192			
40	3.6	200	192			
48	4.3	200	192	400	1152	12
64	5.8	190	256	160	1536	5

$$R = (N_{\text{conf}} \cdot N_{\text{meas}})_{0.3\text{GeV}} / (N_{\text{conf}} \cdot N_{\text{meas}})_{0.5\text{GeV}}$$

Computational resources

PACS-CS, T2K-Tsukuba, HA-PACS, COMA at Univ. of Tsukuba

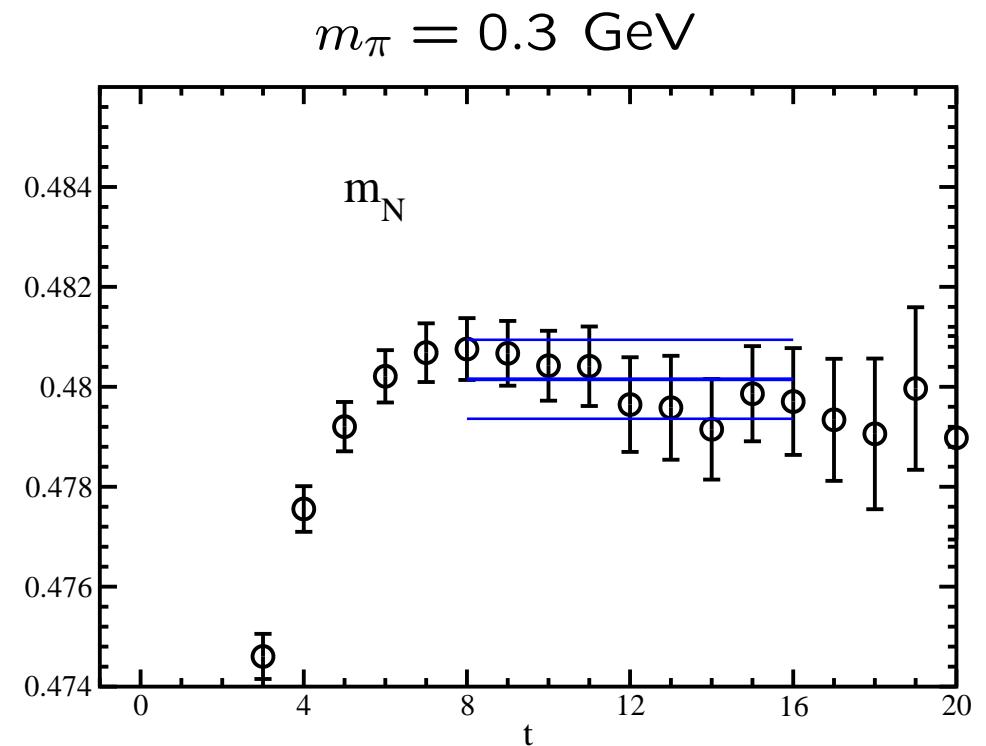
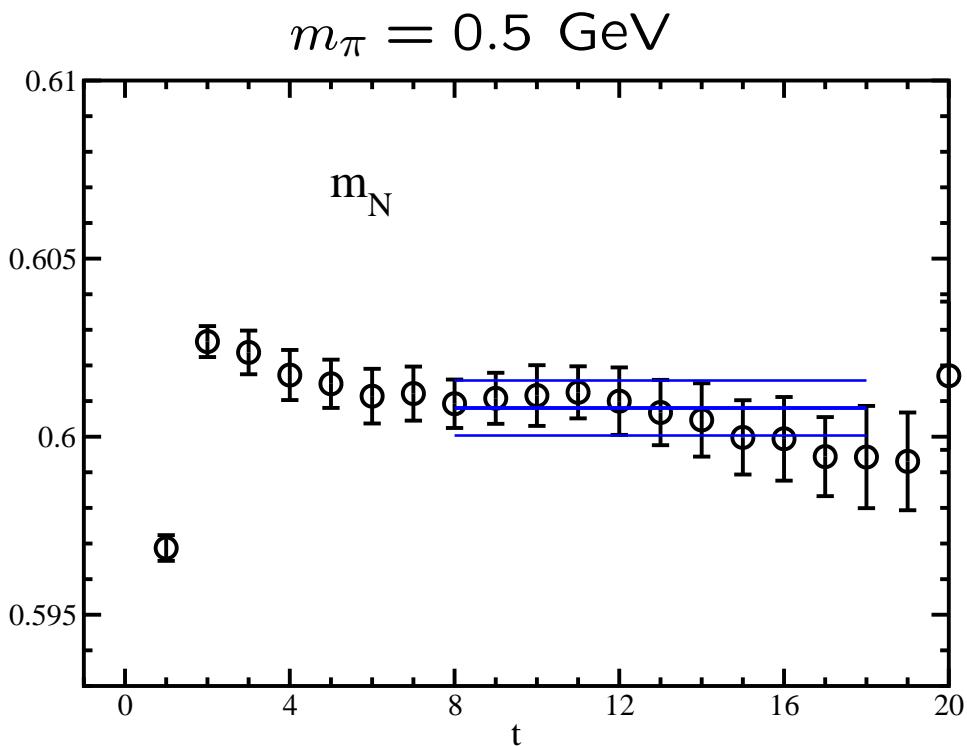
T2K-Tokyo and FX10 at Univ. of Tokyo, and K at AICS

Results at  $m_\pi = 0.5$  and  $0.3$  GeV

# Results

Effective mass of nucleon on  $L = 5.8$  fm

$$\text{Effective } m_N = \log \left( \frac{C_N(t)}{C_N(t+1)} \right)$$



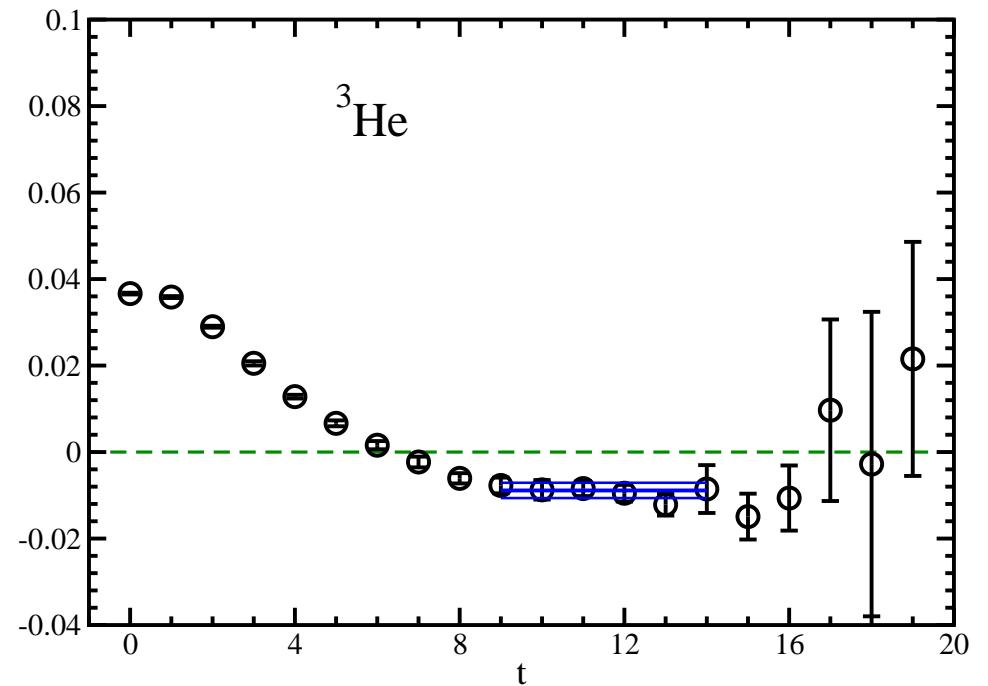
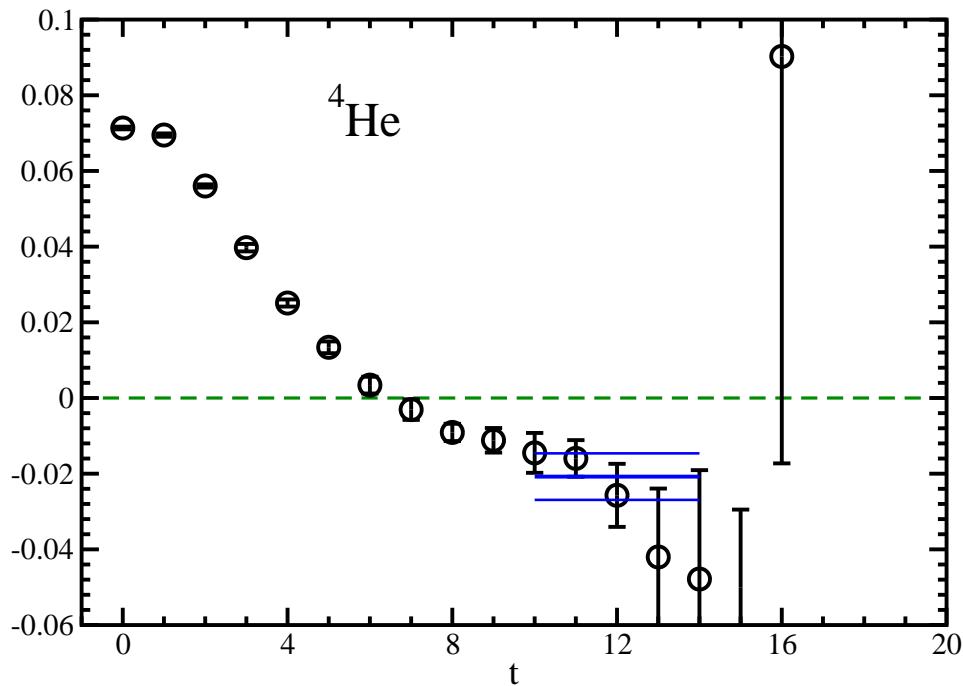
- Good plateau  $t \gtrsim 7$
- Statistical error  $< 0.2\%$

$\Delta E_L = E_0 - N_N m_N$  in  $^4\text{He}$  and  $^3\text{He}$  channels

at  $m_\pi = 0.5$  GeV on  $L = 5.8$  fm

TY et al., PRD86:074514(2012)

$$\Delta E_L = \log \left( \frac{R_{^4\text{He}}(t)}{R_{^4\text{He}}(t+1)} \right) \text{ with } R_{^4\text{He}}(t) = \frac{C_{^4\text{He}}(t)}{(C_N(t))^4}$$

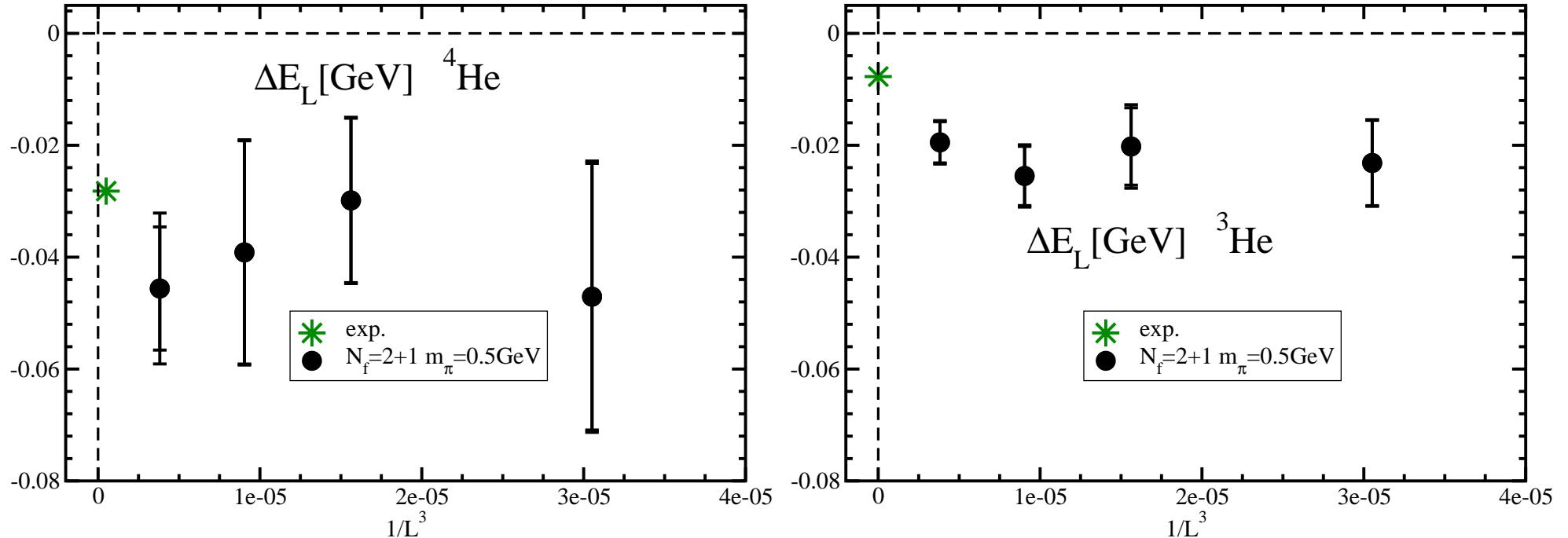


- Larger error in  ${}^4\text{He}$  channel
- Statistical error under control in  $t < 12$
- Negative  $\Delta E_L$  in both channels

${}^4\text{He}$  and  ${}^3\text{He}$  channels  $\Delta E_L = E_0 - N_N m_N$  at  $m_\pi = 0.5$  GeV

TY et al., PRD86:074514(2012)

### Identification of bound state from volume dependence of $\Delta E$

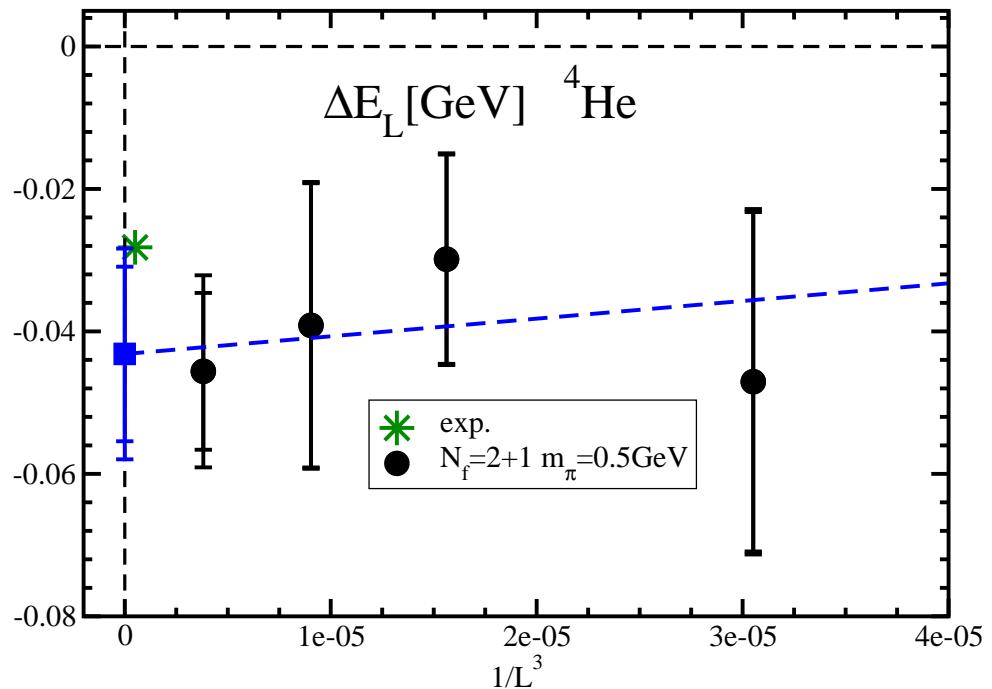


- $\Delta E_L < 0$  and mild volume dependence
- Infinite volume extrapolation with  $\Delta E_L = -\Delta E_{\text{bind}} + C/L^3$   
small difference with  $\exp(-cL)$  fit due to large error

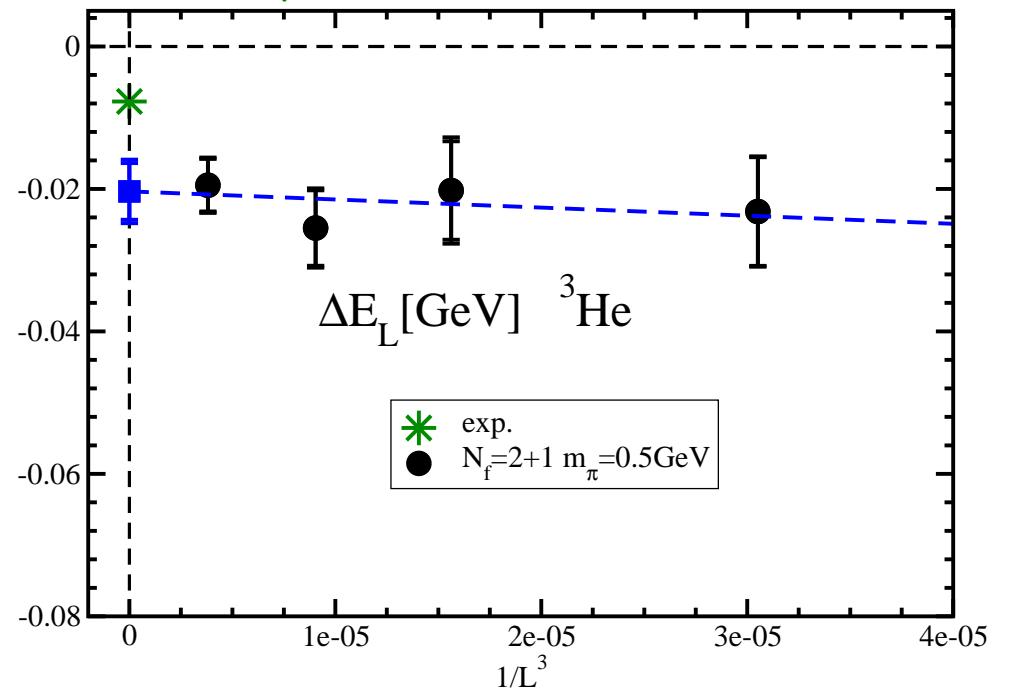
${}^4\text{He}$  and  ${}^3\text{He}$  channels  $\Delta E_L = E_0 - N_N m_N$  at  $m_\pi = 0.5$  GeV

TY et al., PRD86:074514(2012)

### Identification of bound state from volume dependence of $\Delta E$



$$\Delta E_{4\text{He}} = 43(12)(8) \text{ MeV}$$



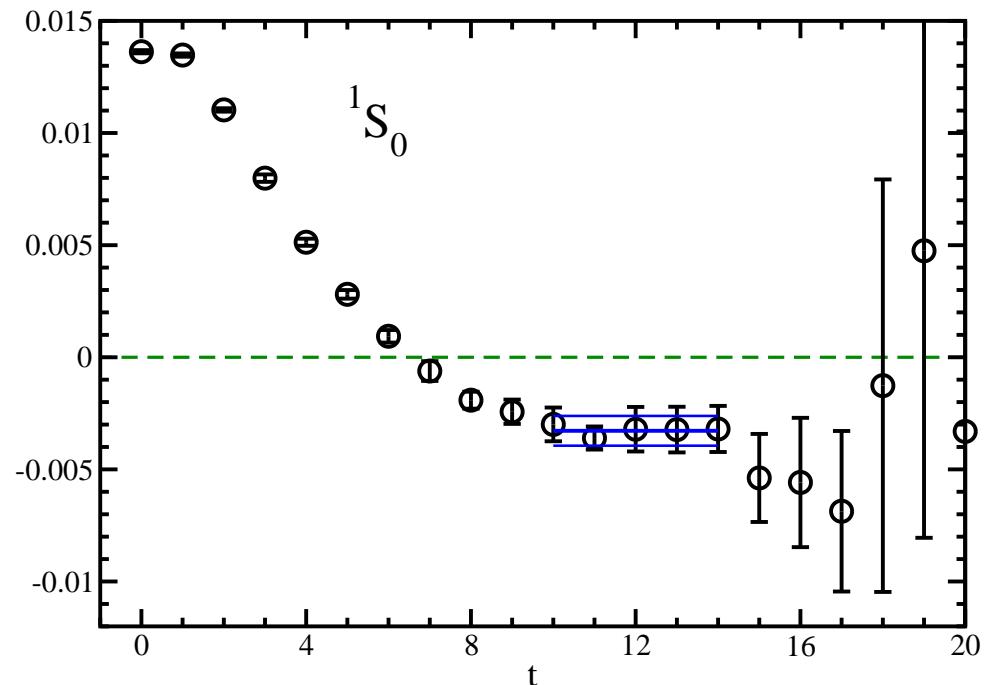
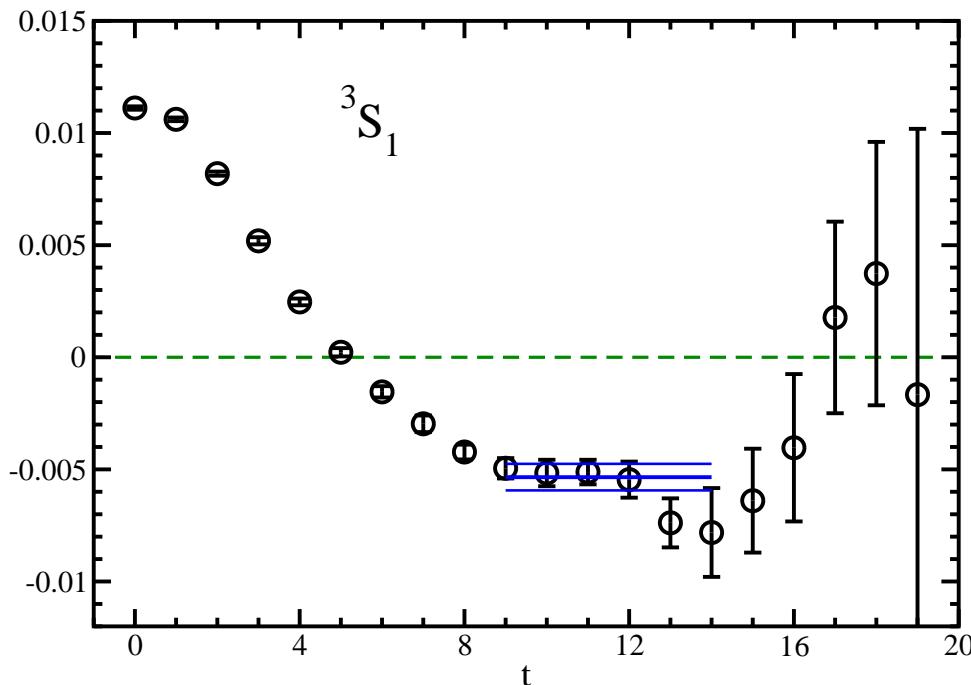
$$\Delta E_{3\text{He}} = 20.3(4.0)(2.0) \text{ MeV}$$

Observe bound state in both channels

# $\Delta E_L$ in 2-nucleon channels at $m_\pi = 0.5$ GeV on $L = 5.8$ fm

TY et al., PRD86:074514(2012)

$$\Delta E_L = \log \left( \frac{R_{\text{NN}}(t)}{R_{\text{NN}}(t+1)} \right) \text{ with } R_{\text{NN}}(t) = \frac{C_{\text{NN}}(t)}{(C_N(t))^2}$$

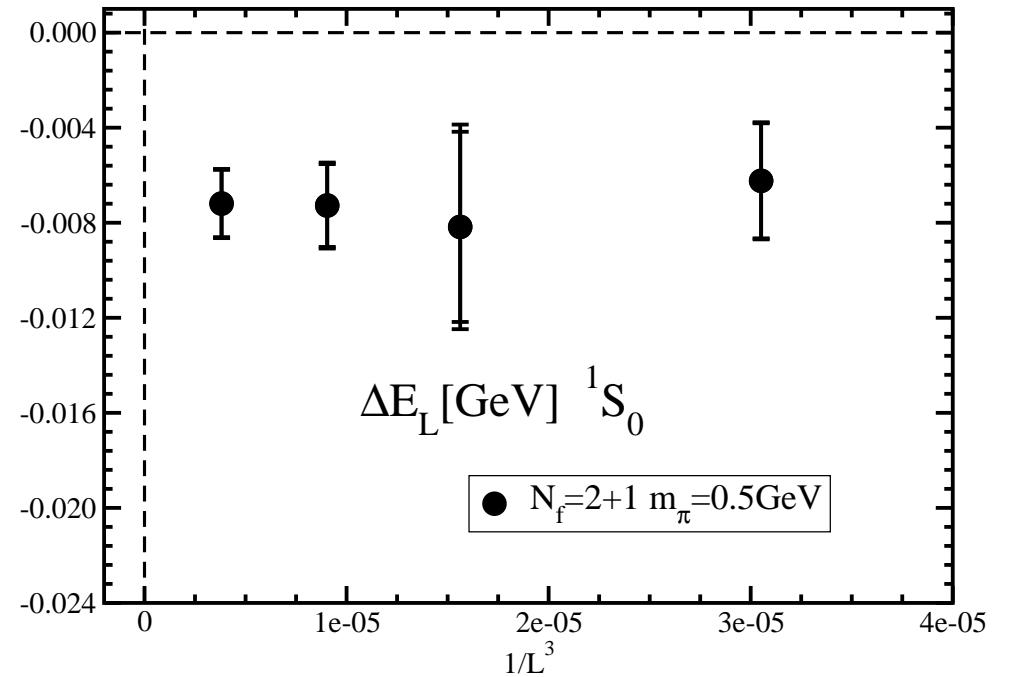
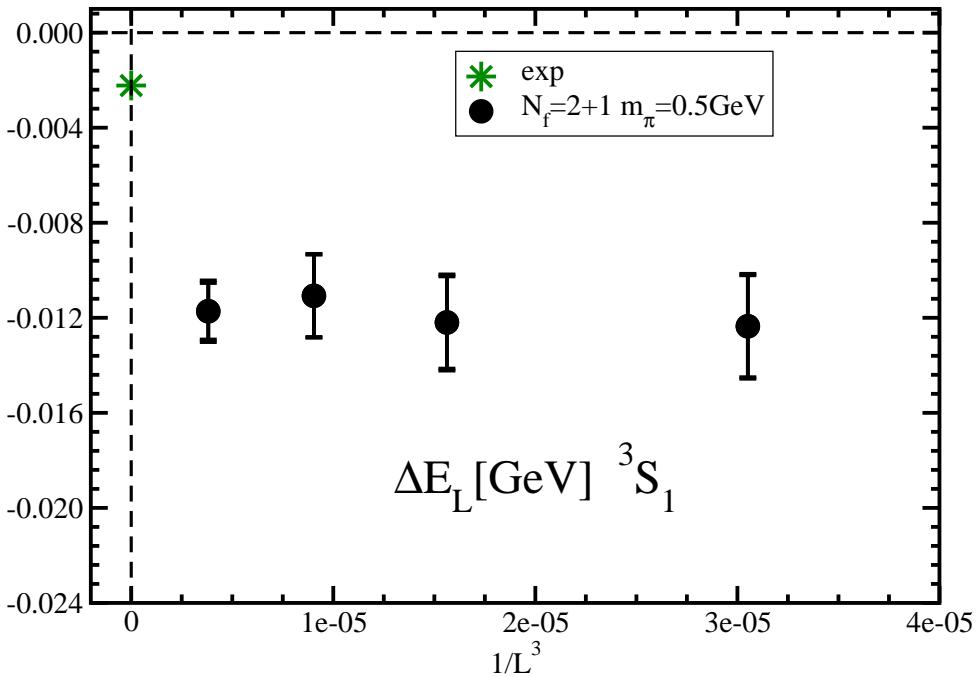


- Statistical error under control in  $t \leq 12$
- Smaller error than  $^4\text{He}$  and  $^3\text{He}$  channels
- Negative  $\Delta E_L$  in both channels

NN ( ${}^3S_1$  and  ${}^1S_0$ ) channels  $\Delta E_L = E_0 - 2m_N$  at  $m_\pi = 0.5$  GeV

TY *et al.*, PRD86:074514(2012)

### Identification of bound state from volume dependence of $\Delta E$



- Negative  $\Delta E_L$
- Infinite volume extrapolation of  $\Delta E_L$

'04 Beane *et al.*, '06 Sasaki & TY

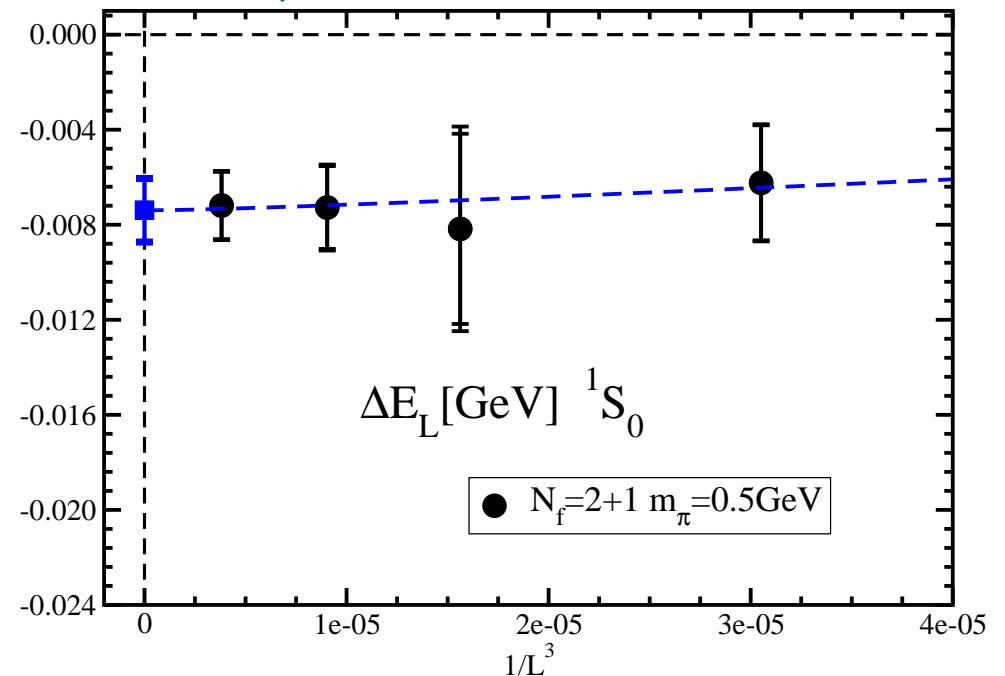
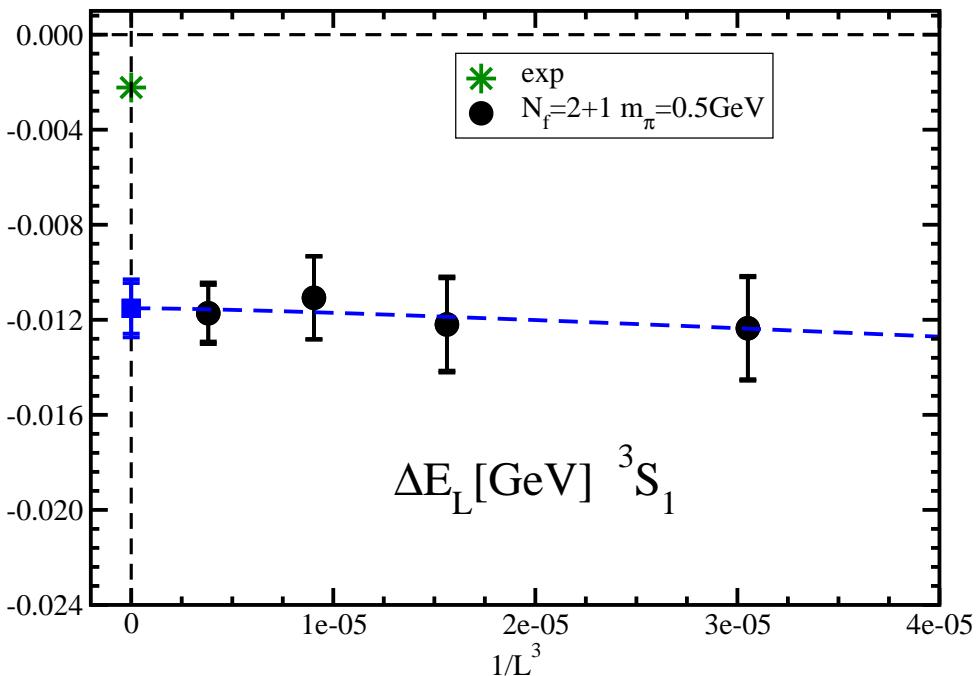
$$\Delta E_L = -\frac{\gamma^2}{m_N} \left\{ 1 + \frac{C_\gamma}{\gamma L} \sum'_{\vec{n}} \frac{\exp(-\gamma L \sqrt{\vec{n}^2})}{\sqrt{\vec{n}^2}} \right\}, \quad \Delta E_{\text{bind}} = \frac{\gamma^2}{m_N}$$

based on Lüscher's finite volume formula

NN ( ${}^3S_1$  and  ${}^1S_0$ ) channels  $\Delta E_L = E_0 - 2m_N$  at  $m_\pi = 0.5$  GeV

TY et al., PRD86:074514(2012)

### Identification of bound state from volume dependence of $\Delta E$

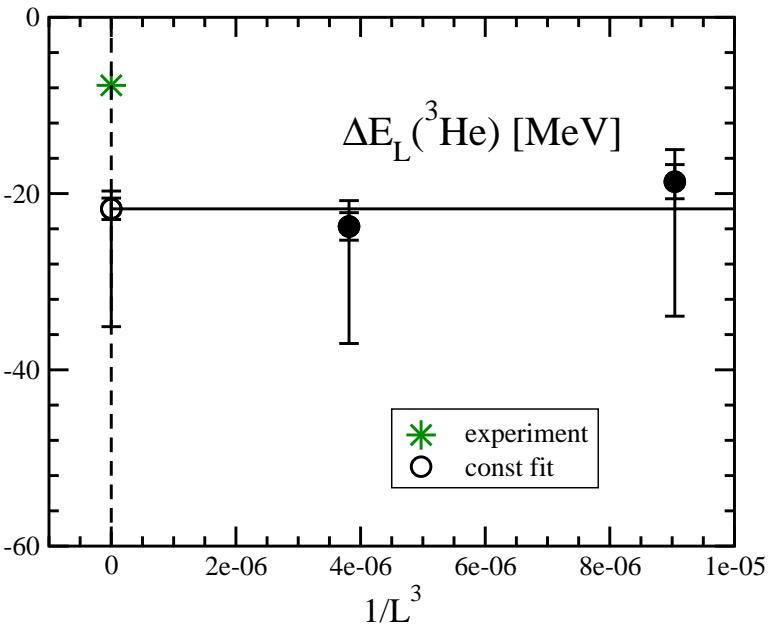
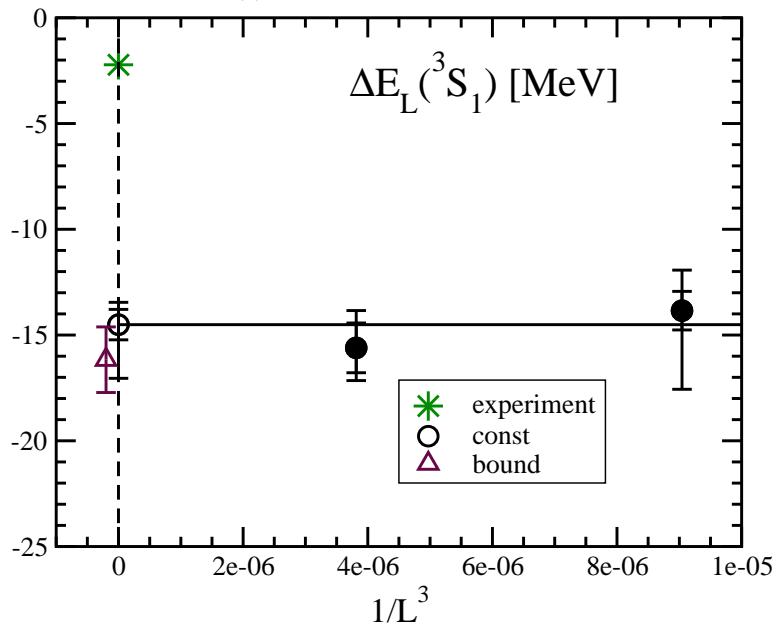


Bound state in both channels  $\leftarrow$  different from experiment

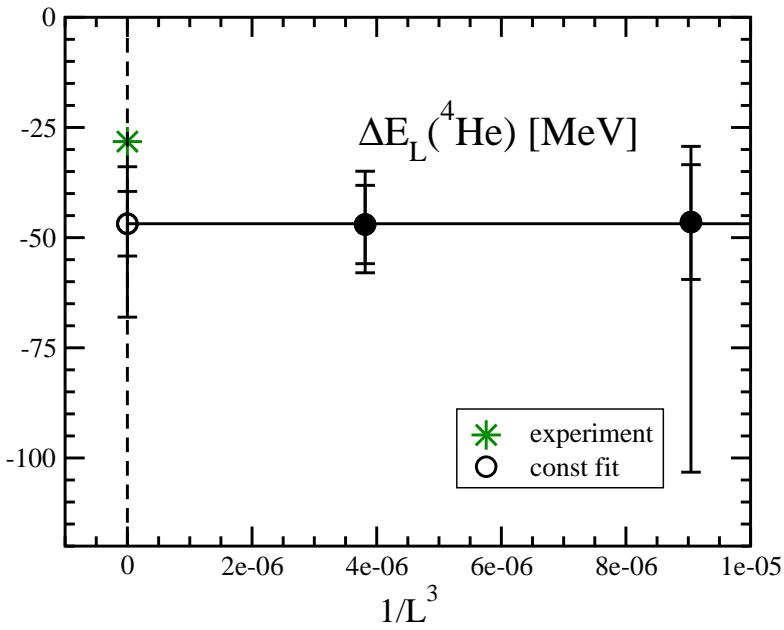
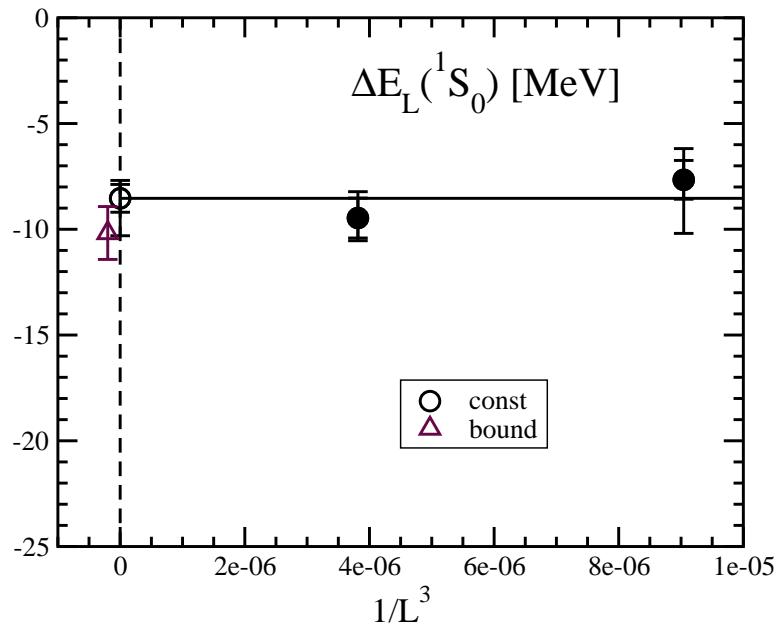
$$\Delta E_{3S_1} = 11.5(1.1)(0.6) \text{ MeV}$$

$$\Delta E_{1S_0} = 7.4(1.3)(0.6) \text{ MeV}$$

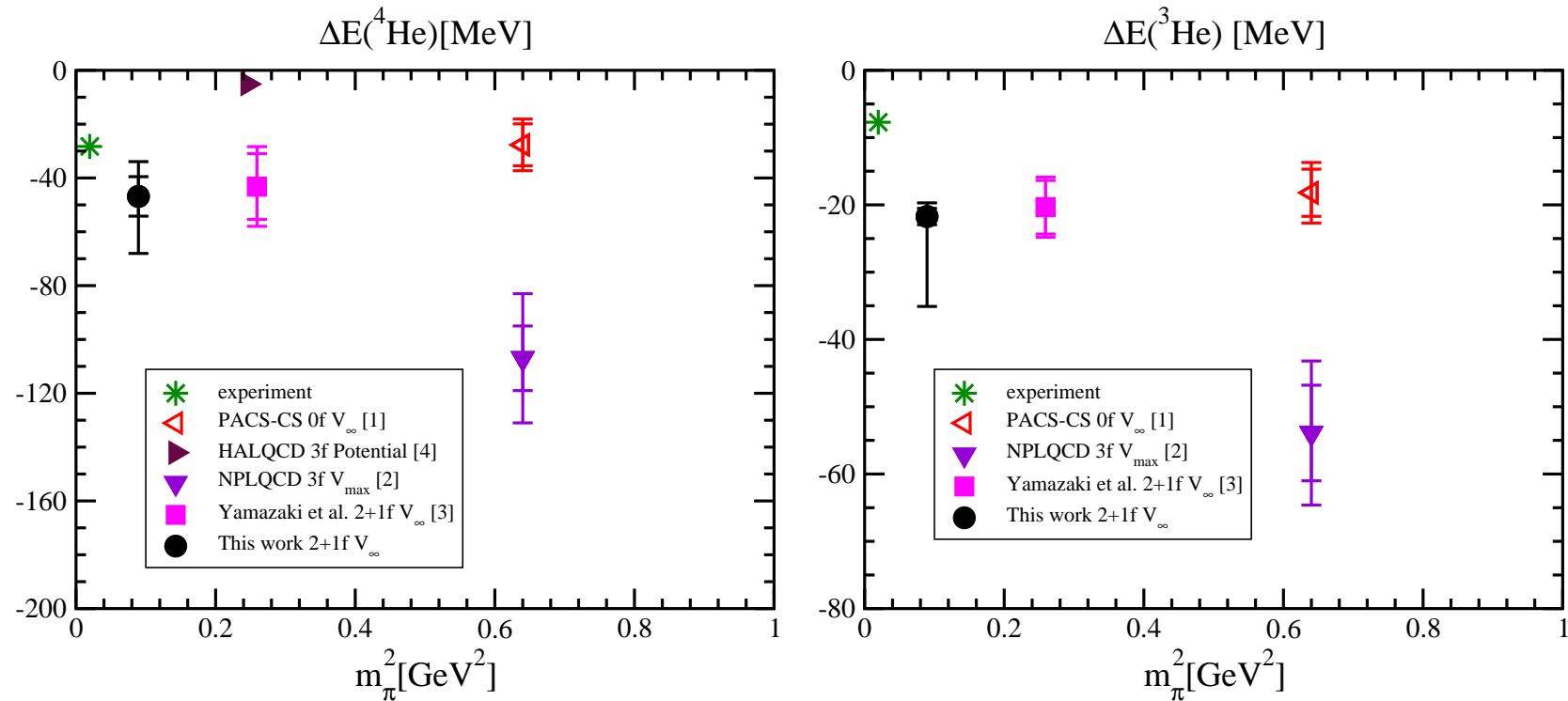
## Results at $m_\pi = 0.3$ GeV



TY et al., PRD92:014501(2015)



## Comparison of $^4\text{He}$ and $^3\text{He}$ channels

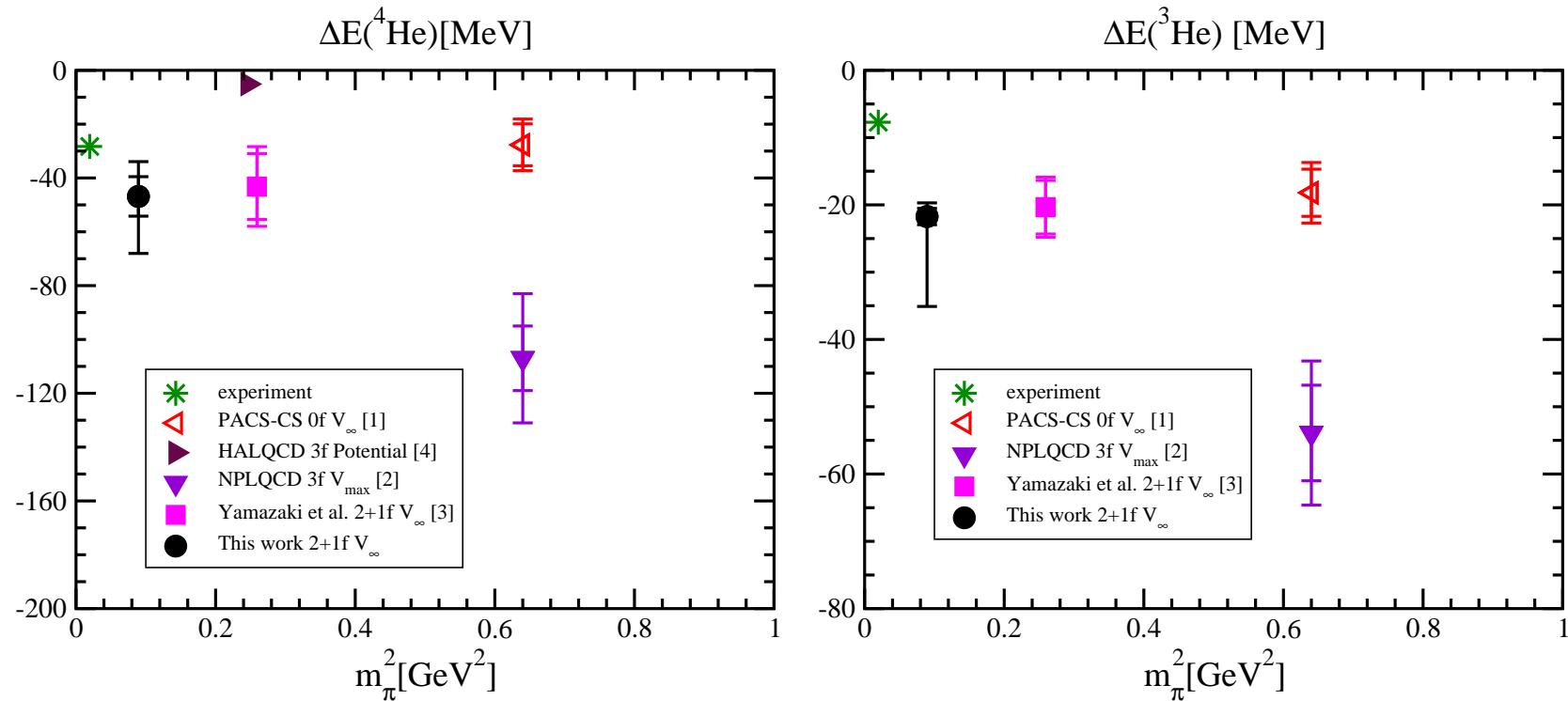


$L^3 \rightarrow \infty$  results only

Light nuclei likely formed in  $0.3 \text{ GeV} \leq m_\pi \leq 0.8 \text{ GeV}$

Same order of  $\Delta E$  to experiments

## Comparison of $^4\text{He}$ and $^3\text{He}$ channels



$L^3 \rightarrow \infty$  results only

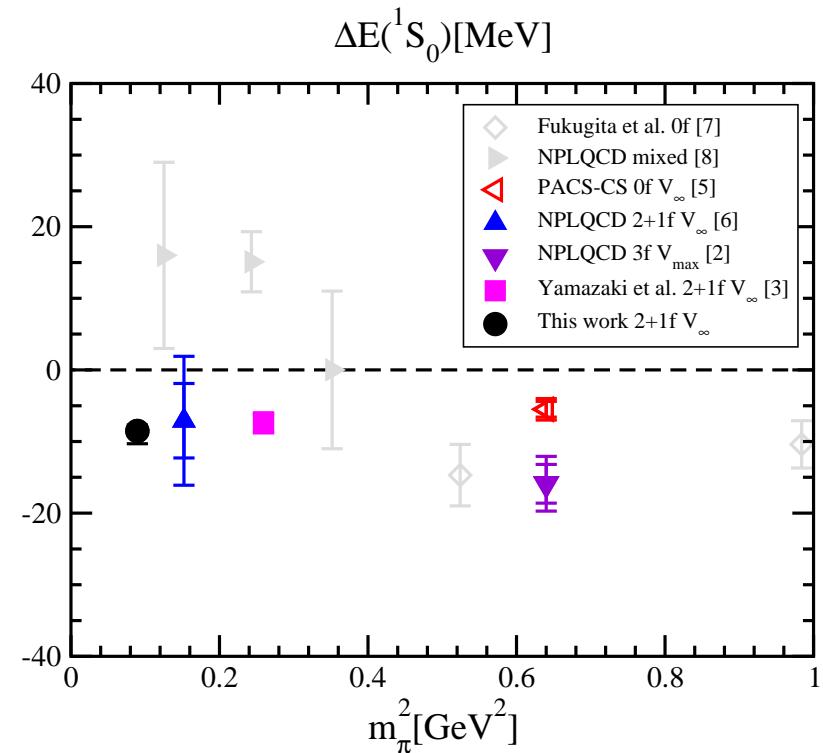
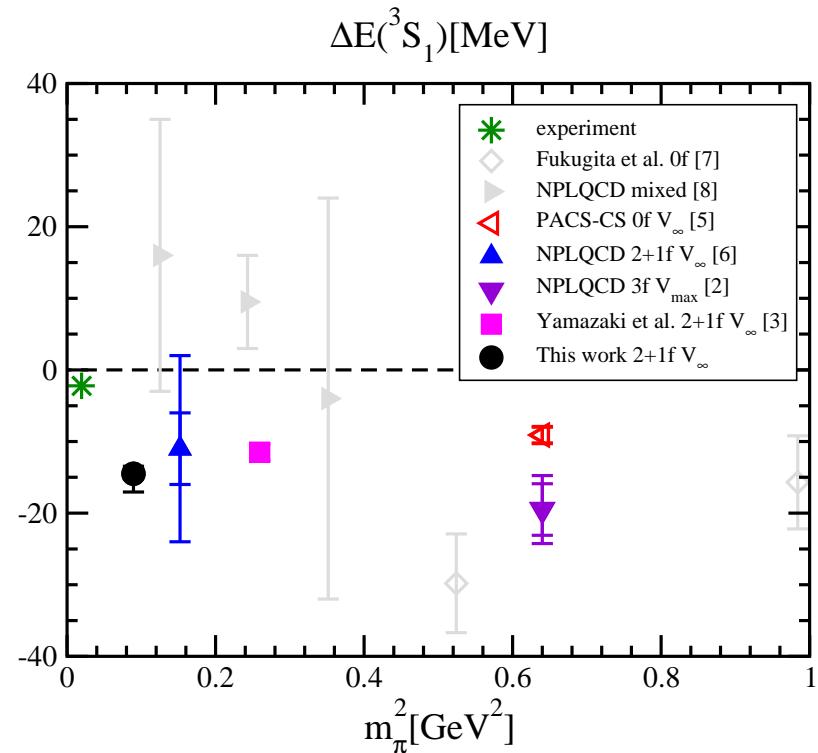
Light nuclei likely formed in  $0.3 \text{ GeV} \leq m_\pi \leq 0.8 \text{ GeV}$

Same order of  $\Delta E$  to experiments  $\rightarrow$  relatively easier than  $NN$   
large  $|\Delta E|$  makes less  $V$  dependence at physical  $m_\pi$

touchstone of quantitative understanding of nuclei from lattice QCD

Investigations of  $m_\pi$  dependence  $\rightarrow m_\pi \sim 0.145 \text{ GeV}$  on  $L \sim 8 \text{ fm}$

## Comparison of $NN$ channels

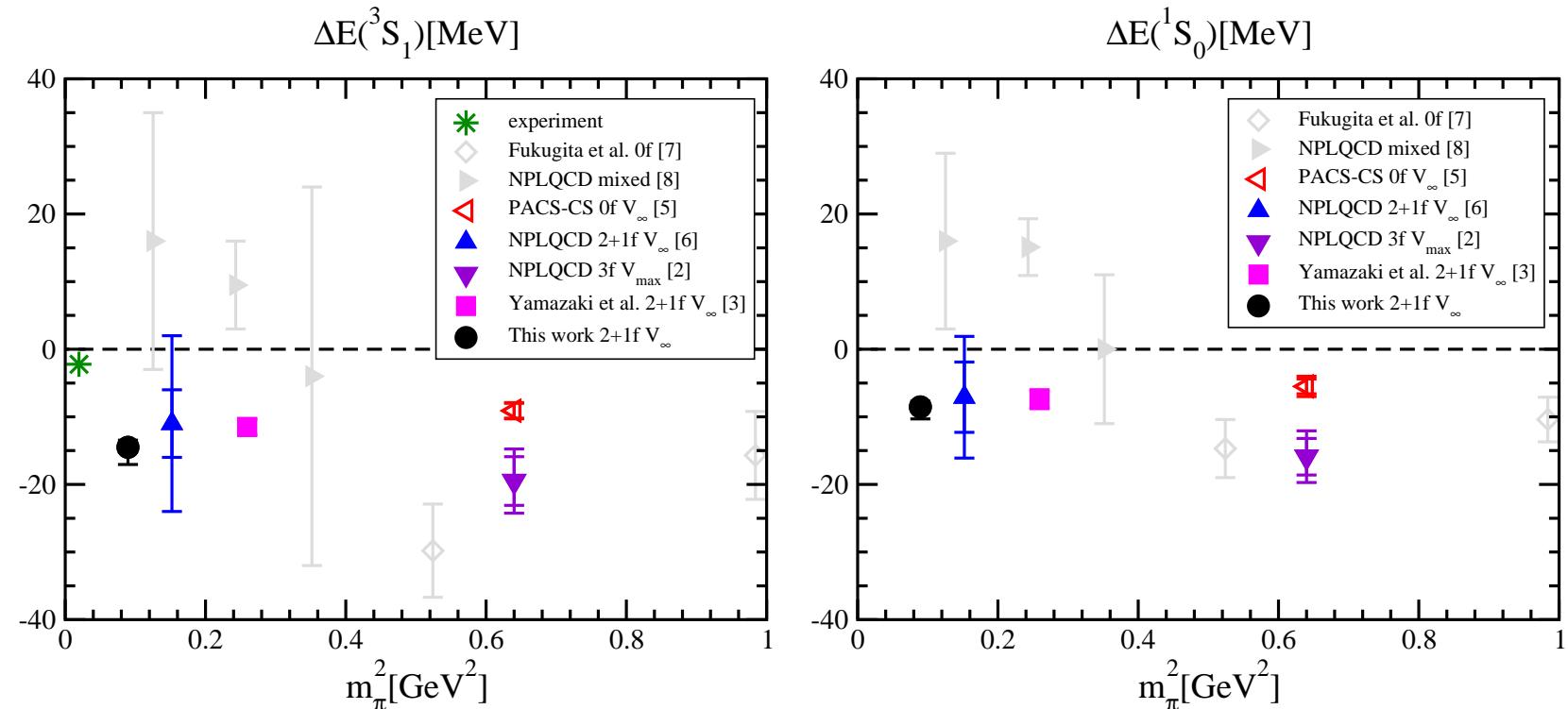


gray data: single volume calculation

$L^3 \rightarrow \infty$  data: existence of bound states in  $^3S_1$  and  $^1S_0$

inconsistent with experiment

## Comparison of $NN$ channels



gray data: single volume calculation

$L^3 \rightarrow \infty$  data: existence of bound states in  $^3S_1$  and  $^1S_0$

inconsistent with experiment

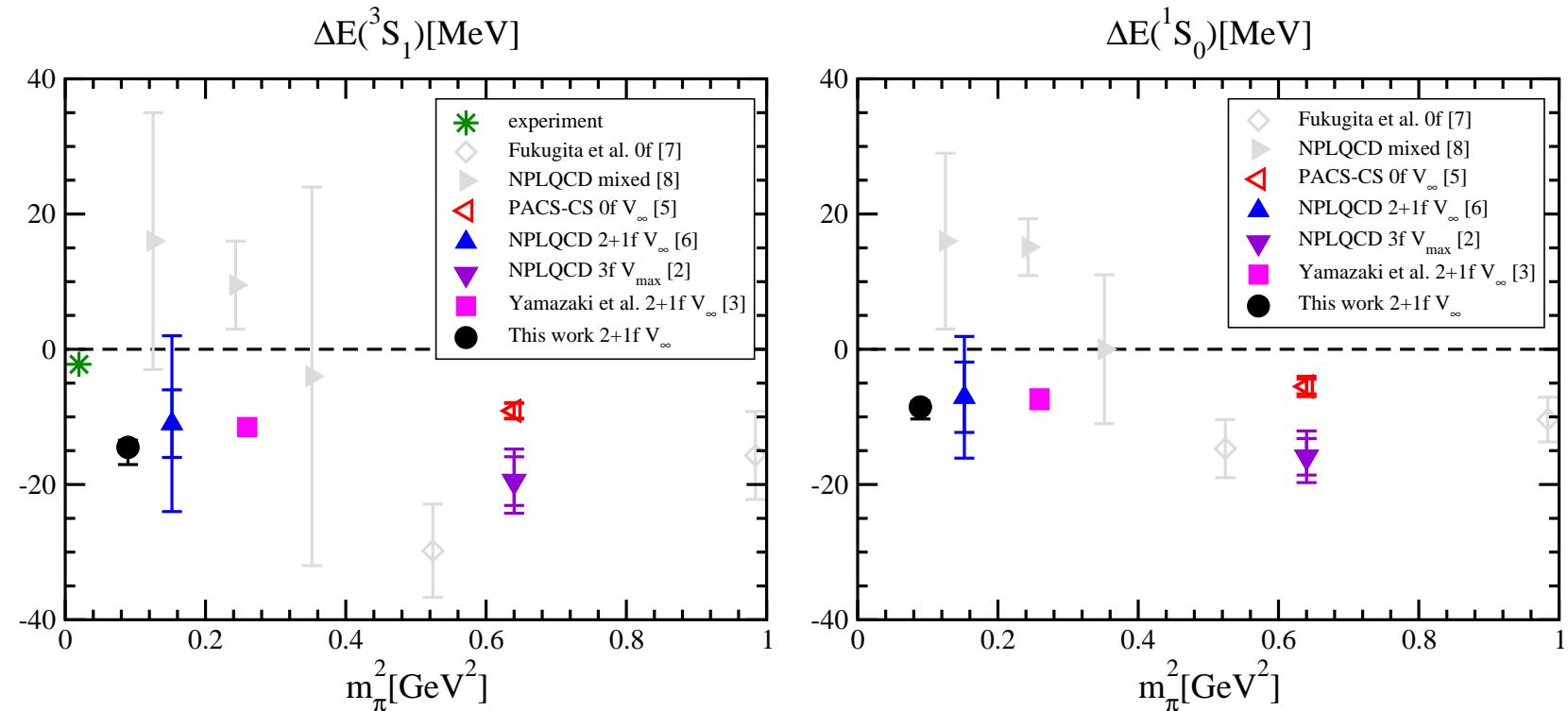
Lattice 2015

$N_f = 3$  at  $m_\pi = 0.8$  GeV by CalLat with sophisticated sources

$N_f = 2 + 1$   $m_\pi = 0.45$  GeV by NPLQCD

No bound state with wall source by HALQCD

## Comparison of $NN$ channels



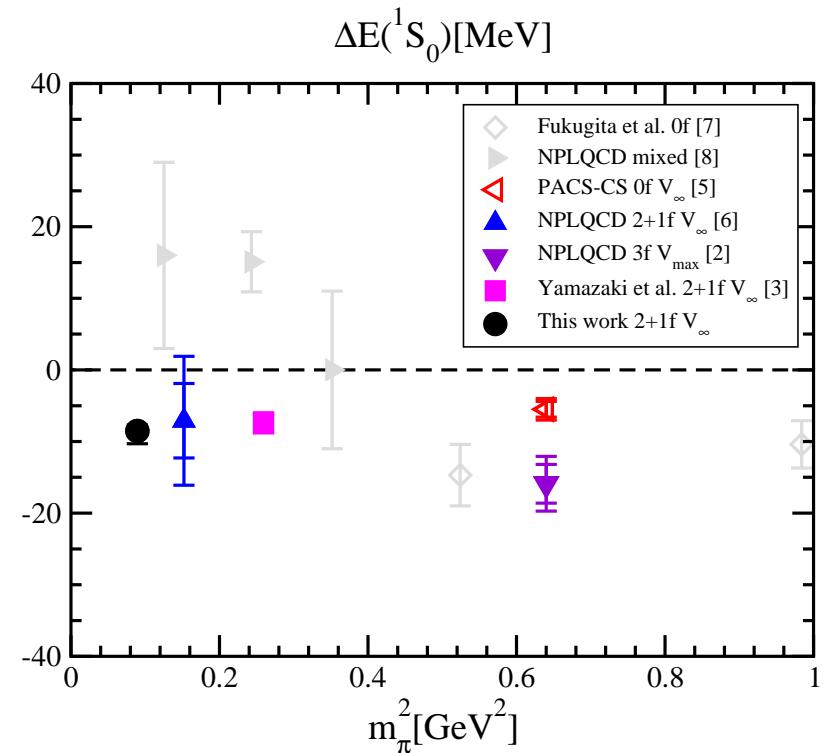
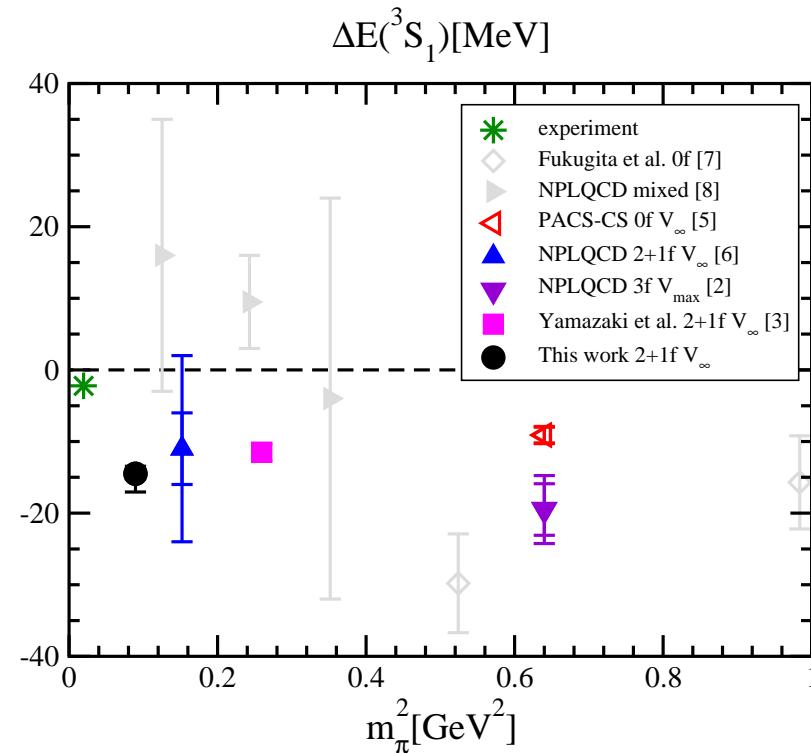
gray data: single volume calculation

$L^3 \rightarrow \infty$  data: **existence of bound states in  ${}^3S_1$  and  ${}^1S_0$**

inconsistent with experiment due to larger  $m_\pi$ (?)

Investigation of  $m_\pi$  dependence  $\rightarrow m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

## Comparison of $NN$ channels



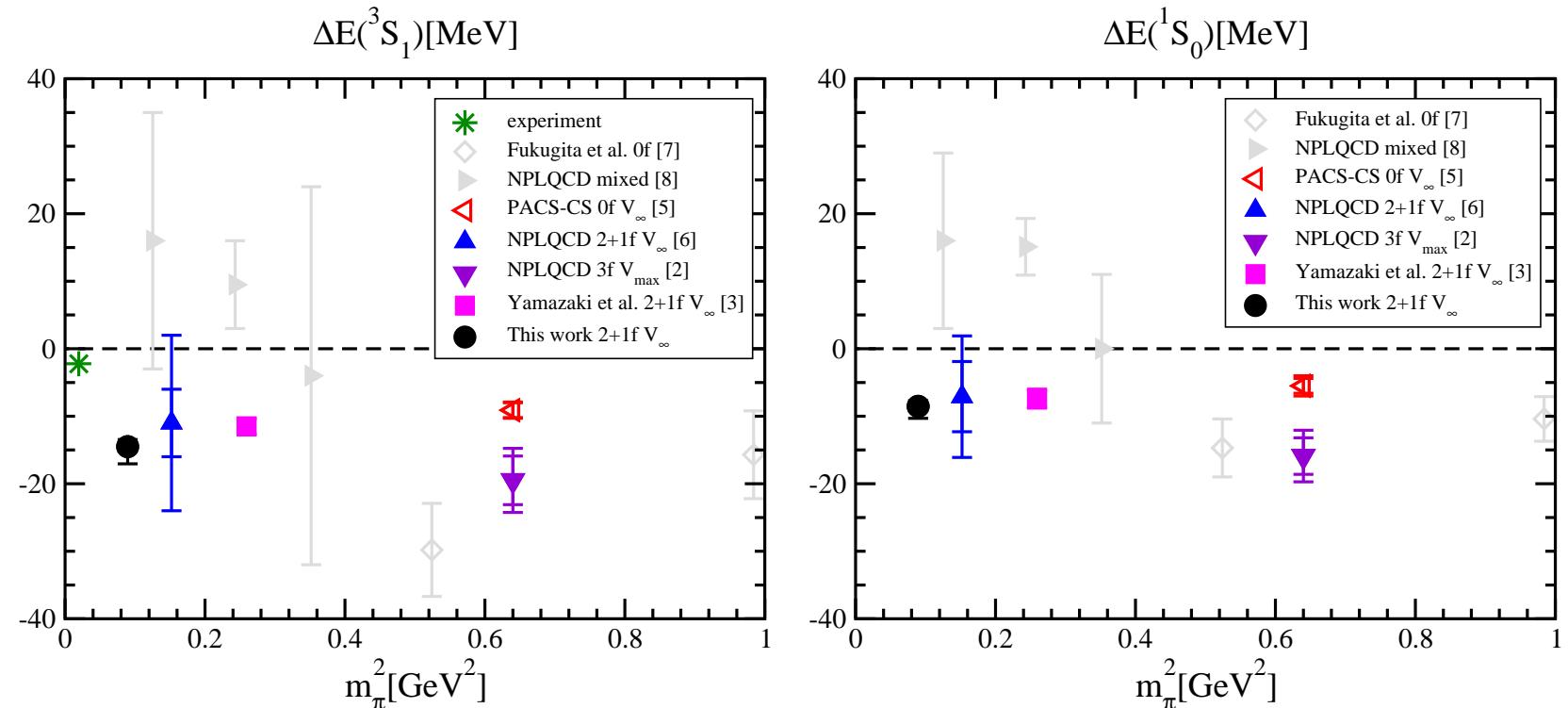
gray data: single volume calculation

Investigations of  $m_\pi$  dependence  $\rightarrow m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

Large finite volume effect expected even on  $L \sim 8$  fm

'86 Lüscher, '04 Beane et al., '14 Briceño et al.

## Comparison of $NN$ channels



gray data: single volume calculation

Investigations of  $m_\pi$  dependence  $\rightarrow m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

Large finite volume effect expected even on  $L \sim 8$  fm

$$^3S_1: \Delta E_{\text{exp}} = 2.2 \text{ MeV}$$

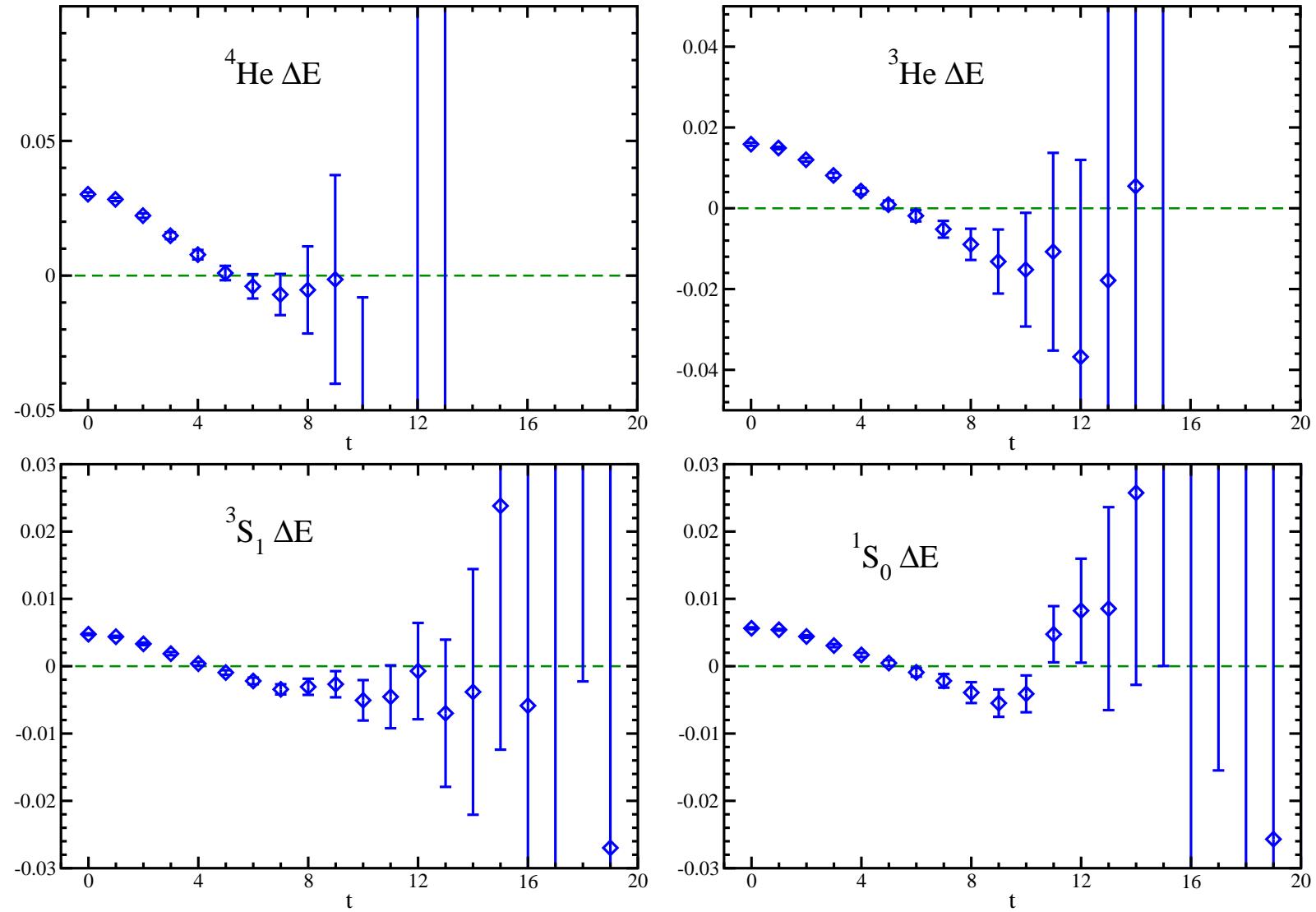
'86 Lüscher, '04 Beane et al., '14 Briceño et al.

$$\Delta E_L = -(\Delta E_{\text{exp}} + \mathcal{O}(\exp(-L\sqrt{m_N \Delta E_{\text{exp}}}))) \lesssim -4 \text{ MeV}$$

$$^1S_0: a_0^{\text{exp}} = 23.7 \text{ fm}$$

$$\Delta E_L = -\frac{4\pi a_0^{\text{exp}}}{m_N L^3} + \mathcal{O}(1/L^4) \lesssim -2 \text{ MeV}$$

Very preliminary results of  $\Delta E$  at  $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm



Computational resources

HA-PACS, COMA @Univ. of Tsukuba, K @AICS, FX100 @RIKEN

# Nucleon form factors at almost physical $m_\pi$

in collaboration with

K.-I. Ishikawa, Y. Kuramashi, S. Sasaki, and A. Ukawa  
for PACS Collaboration

Computational resources

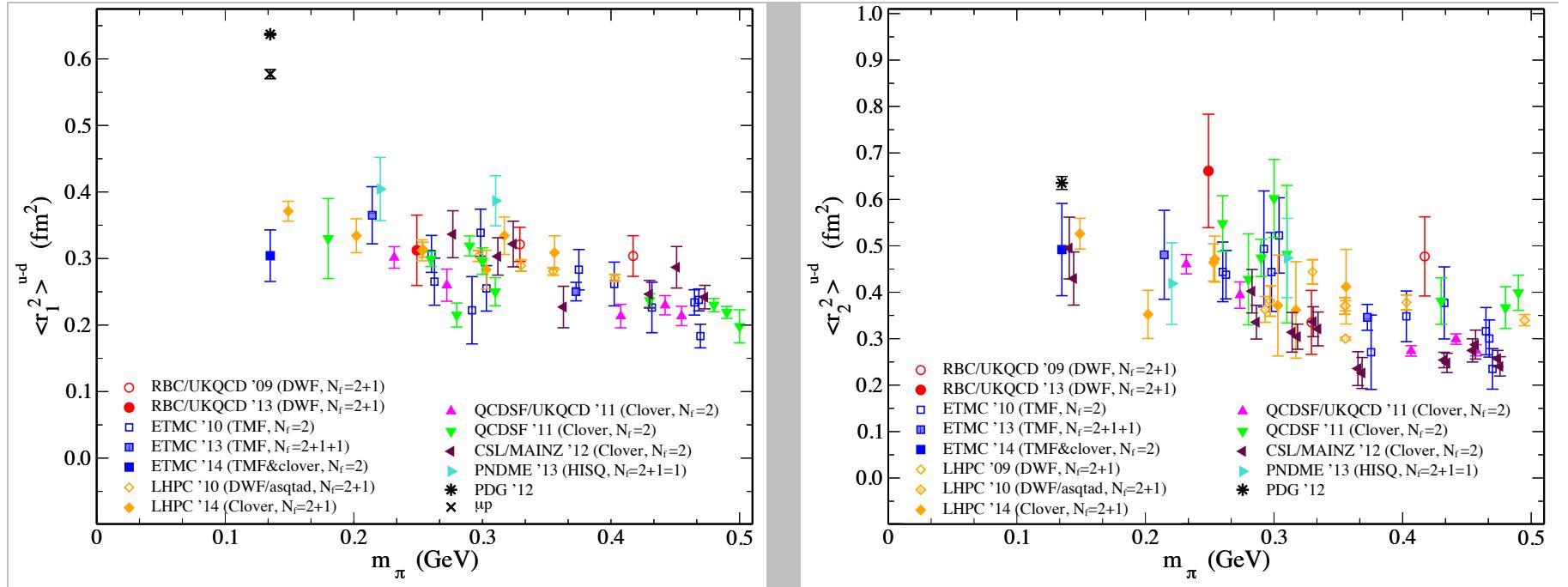
COMA @Univ. of Tsukuba, FX10 @Univ. of Tokyo,

K @AICS, FX100 @RIKEN, System E @Kyoto Univ.

# Example of large quark mass dependence near $m_\pi \rightarrow 0$

## Isovector radii from form factors $F_1$ and $F_2$

Constantinou, Lat14 plenary

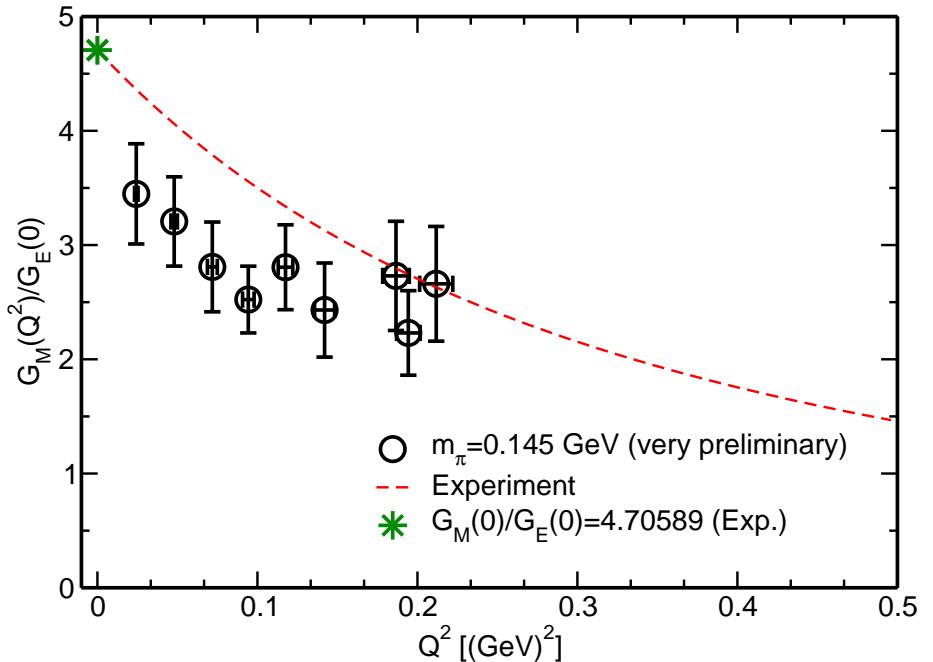
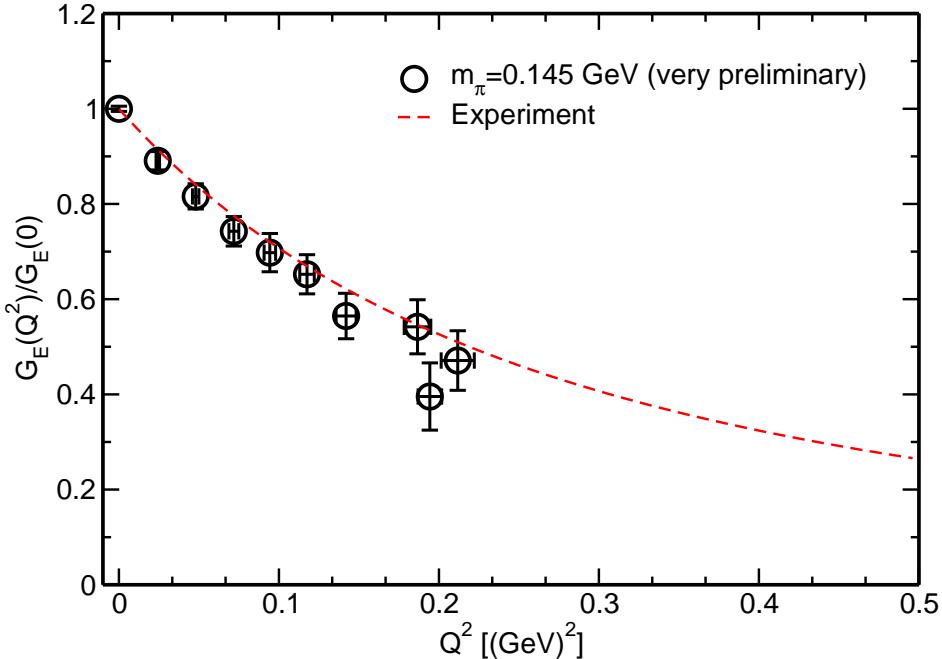


important for understanding of nucleus property  
 Can we reproduce experiment at physical  $m_\pi$ ?

c.f.) '14 LHP, '15 Capitani *et al.*, '15 ETM, see also James's Lat15 plenary

# Isovector electric and magnetic Sachs form factors

Very preliminary results at  $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm



Need much more statistics  
but encouraging signal in  $G_E$

Axial charge  $g_A = Z_A g_A^{\text{bare}}$

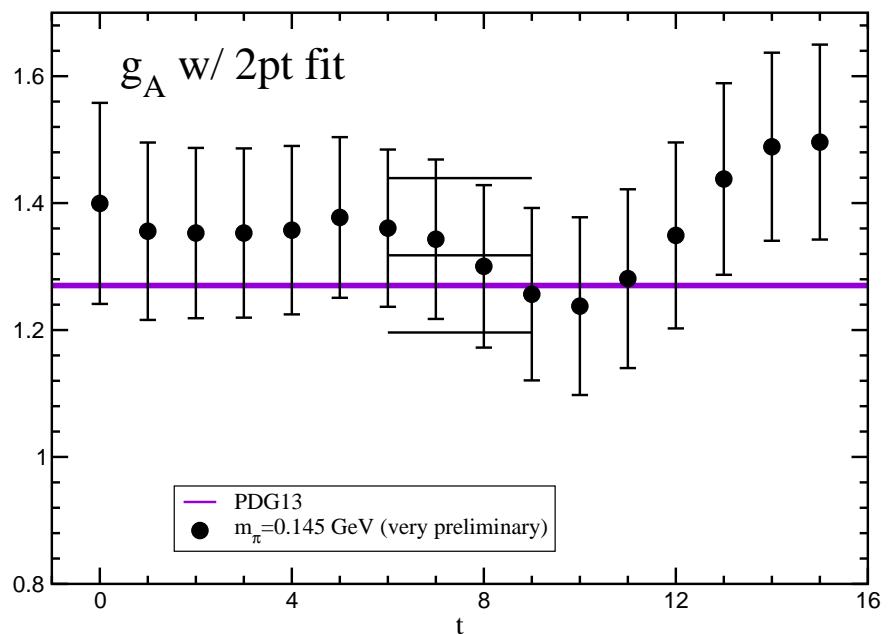
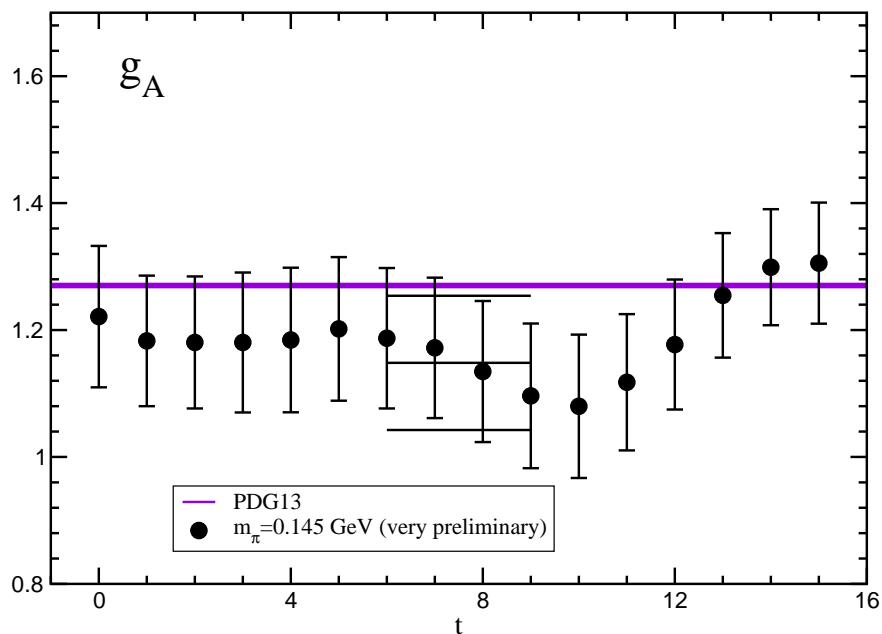
Very preliminary results at  $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

$Z_A \sim 0.965$  in SF scheme: consistent with  $Z_V = 1/G_E(0)$  within 1–2%

$$g_A^{\text{bare}} = C_{A_3}(t)/C_N(t_{\text{sink}})$$

$$g_A^{\text{bare}} = C_{A_3}(t)/(Z_N^2 \exp(-M_N t_{\text{sink}}))$$

$Z_N$  and  $M_N$  from fit of  $C_N(t)$



Discrepancy of two analyses → systematic error

roughly consistent with experiment,

but need much more statistics for stringent test

# Summary

$N_f = 2 + 1$  lattice QCD at  $m_\pi = 0.5$  and  $0.3$  GeV

- Volume dependence of  $\Delta E$

$\Delta E \neq 0$  of 0th state in infinite volume limit  
→ bound state in  ${}^4\text{He}$ ,  ${}^3\text{He}$ ,  ${}^3\text{S}_1$  and  ${}^1\text{S}_0$   
at  $m_\pi = 0.5$  and  $0.3$  GeV

- $\Delta E$  larger than experiment and small  $m_\pi$  dependence
- Bound state in  ${}^1\text{S}_0$  not observed in experiment

$N_f = 3$  at  $m_\pi = 0.8$  GeV by NPLQCD  
and CaILat with sophisticated sources (preliminary)

$N_f = 2 + 1$   $m_\pi = 0.45$  GeV by NPLQCD (preliminary)

No bound state in HALQCD method with wall source

## Need further investigations

e.g. systematic error from large  $m_\pi$  and finite lattice spacing

$N_f = 2 + 1$   $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

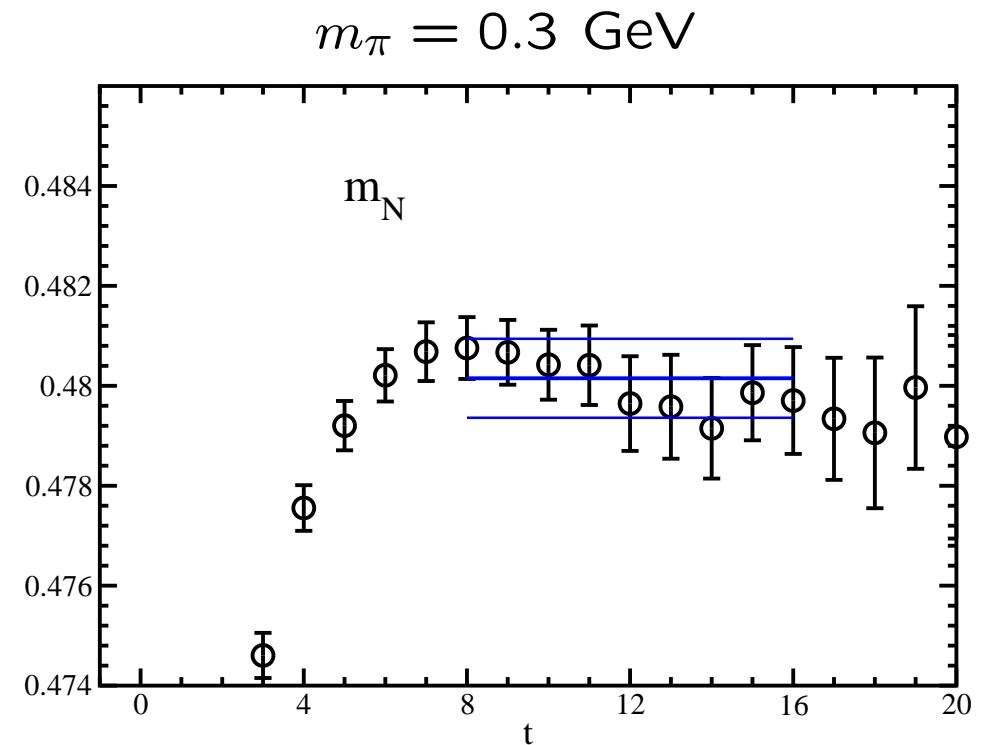
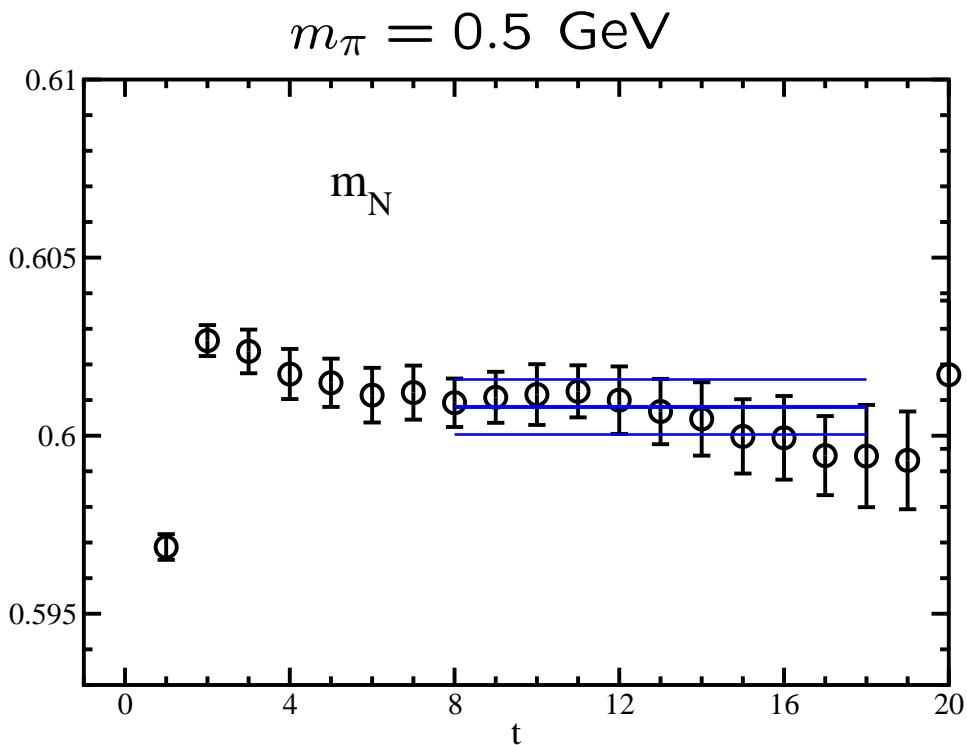
$\Delta E$  for nuclei and Isovector form factors of nucleon

Back up

# Results

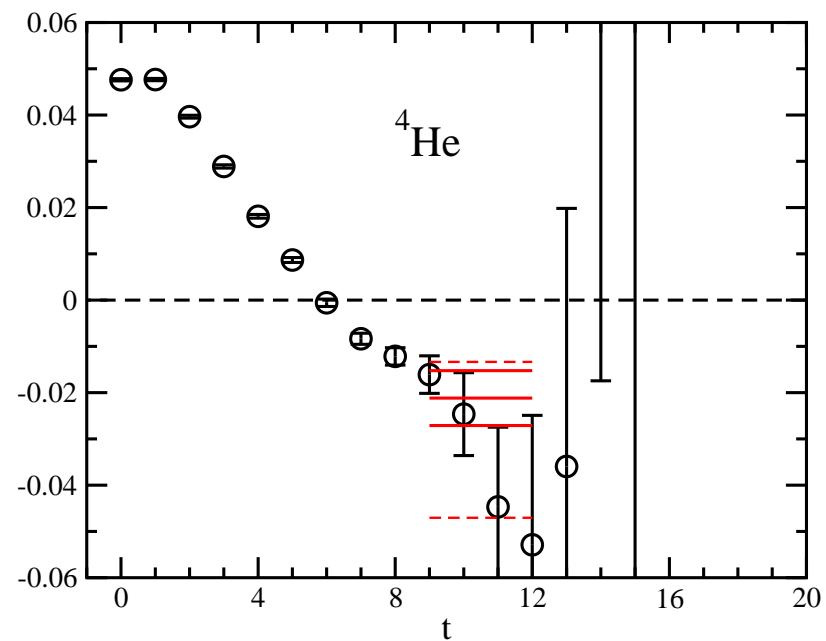
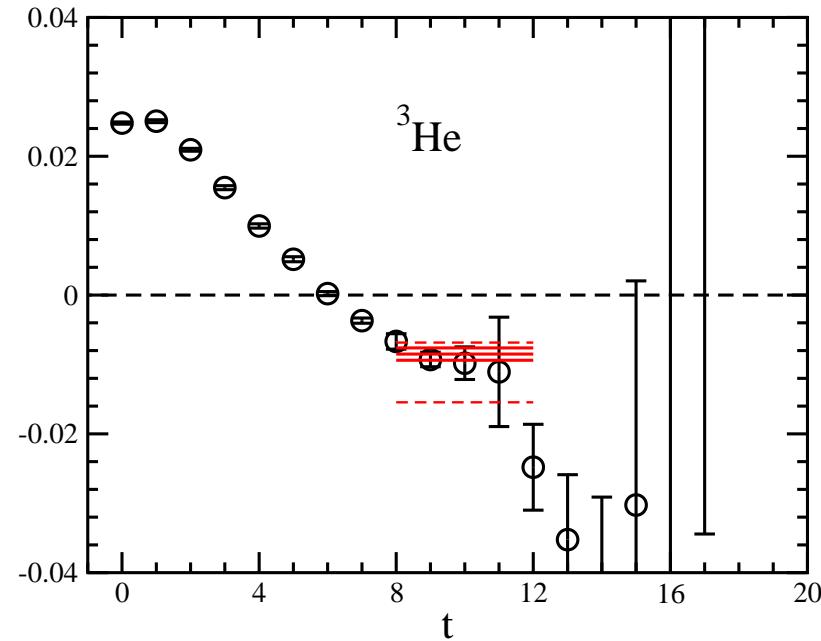
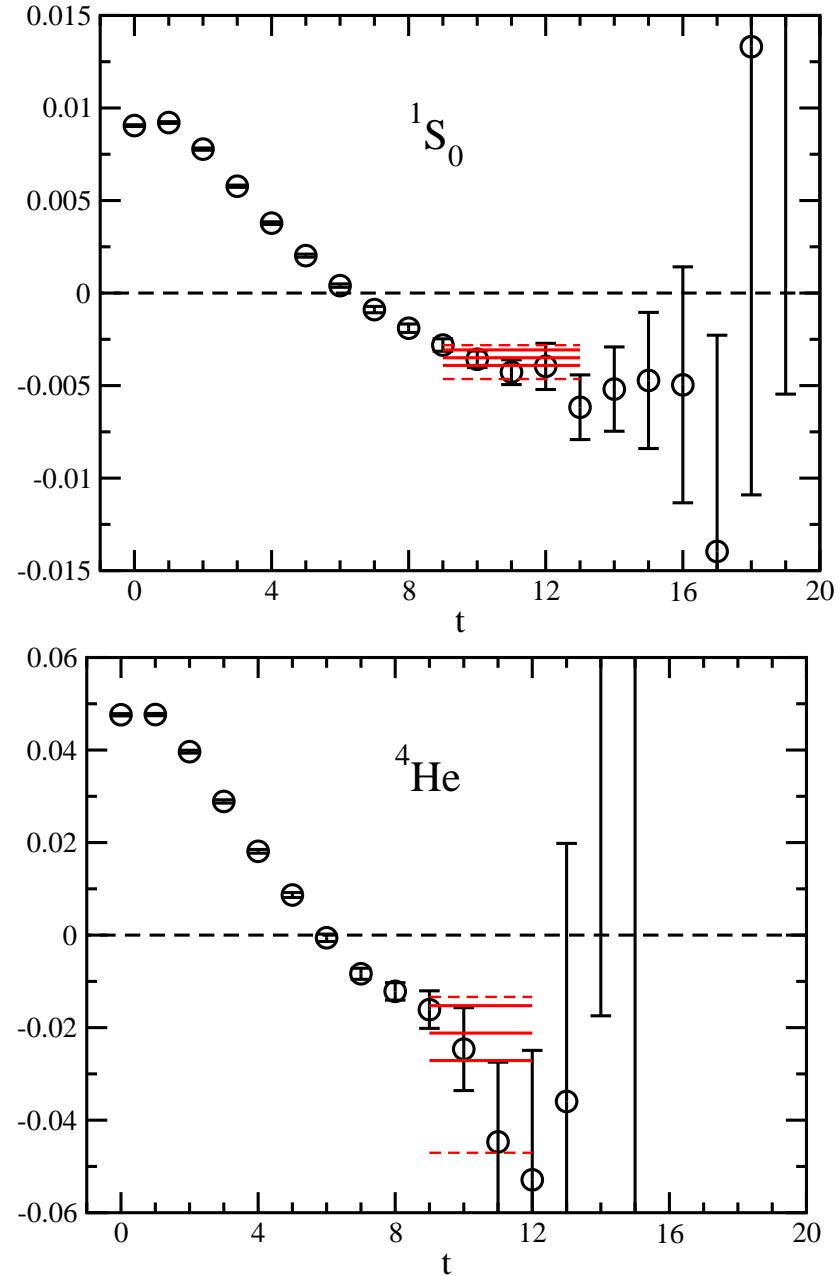
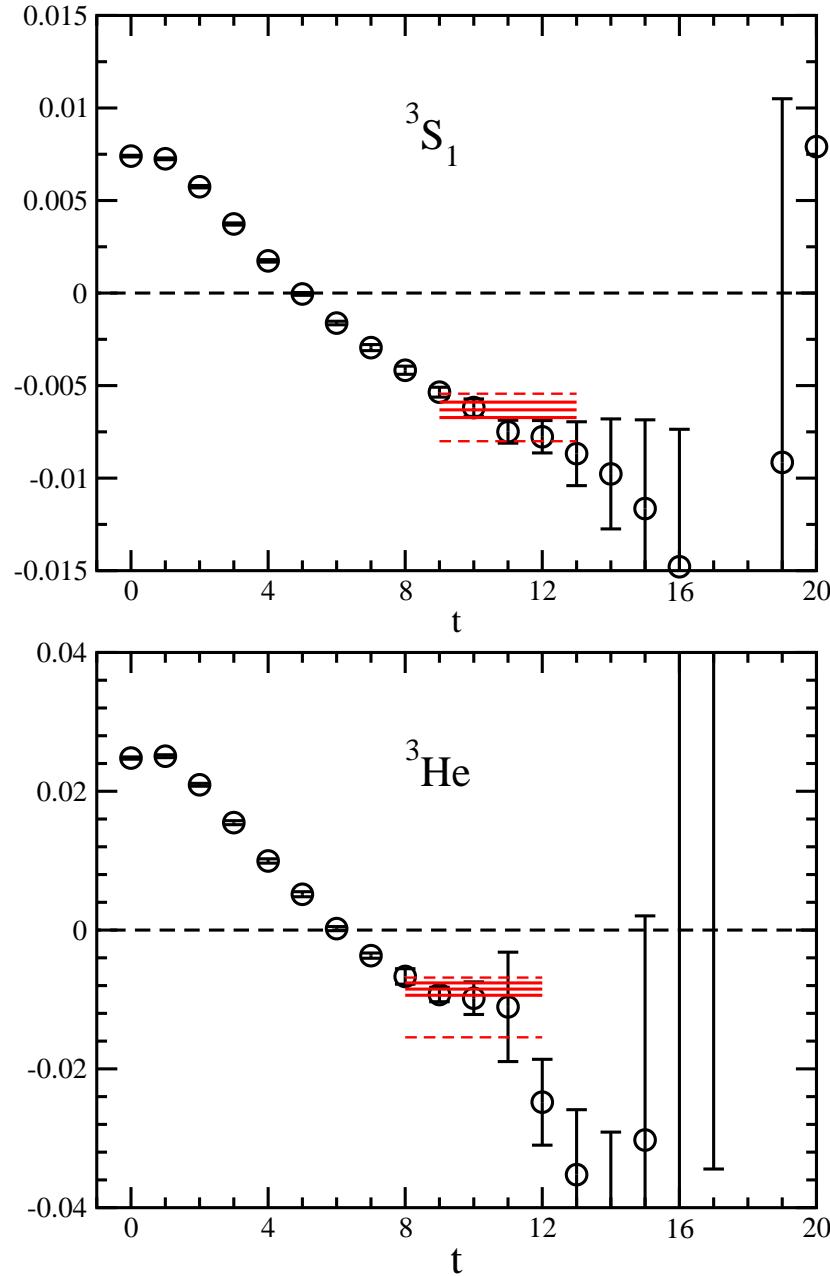
Effective mass of nucleon on  $L = 5.8$  fm

$$\text{Effective } m_N = \log \left( \frac{C_N(t)}{C_N(t+1)} \right)$$

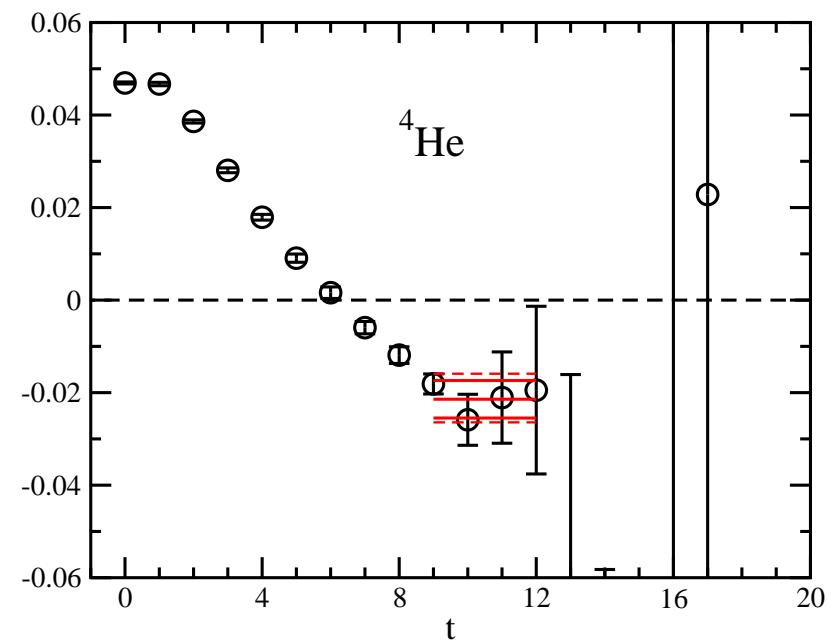
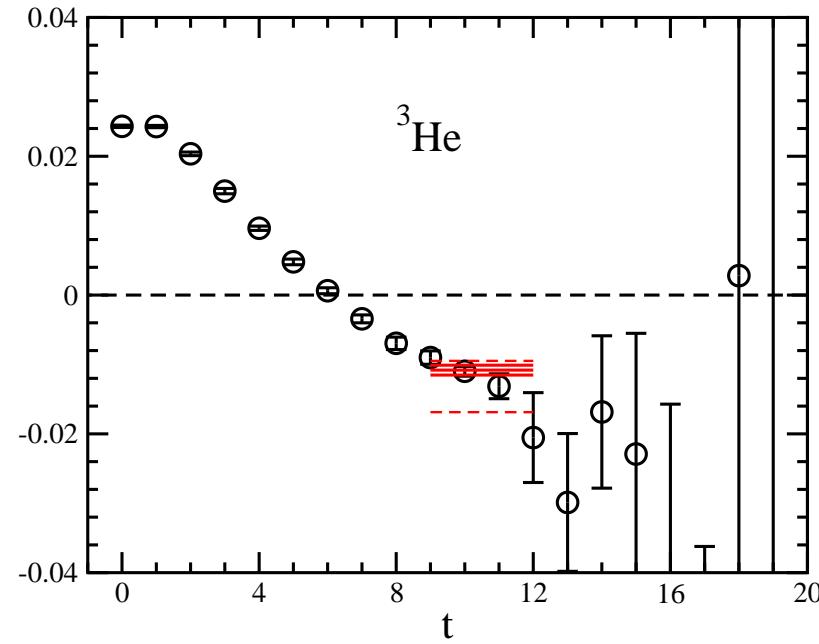
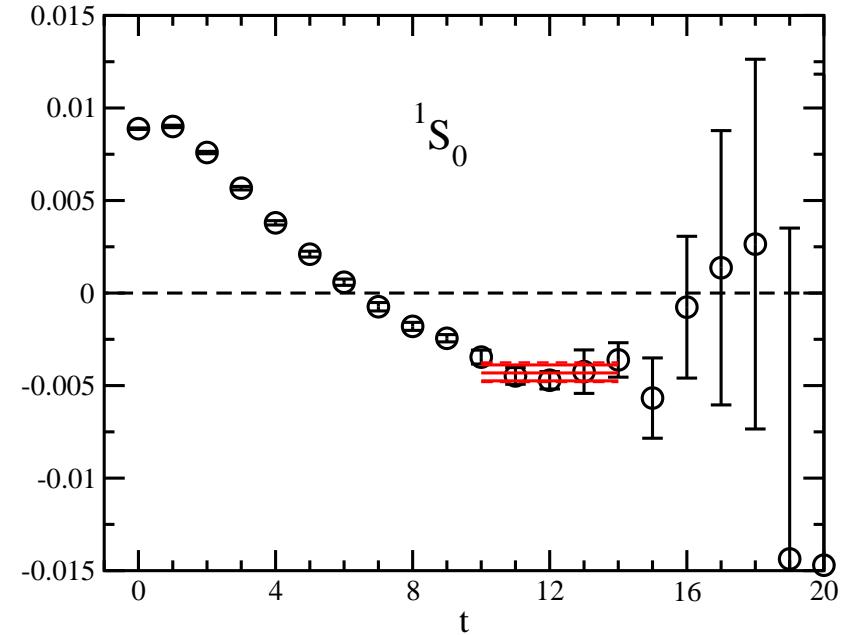
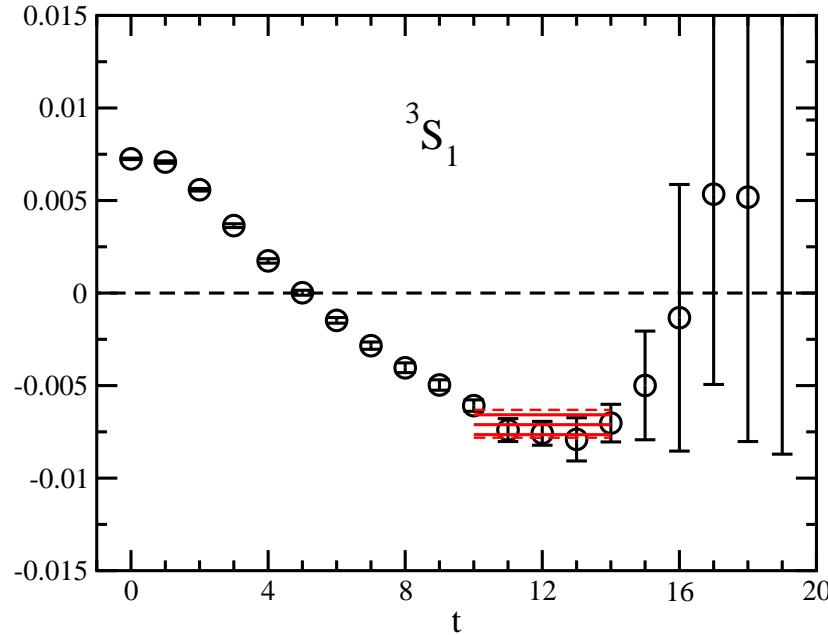


- Good plateau  $t \gtrsim 7$
- Statistical error  $< 0.2\%$

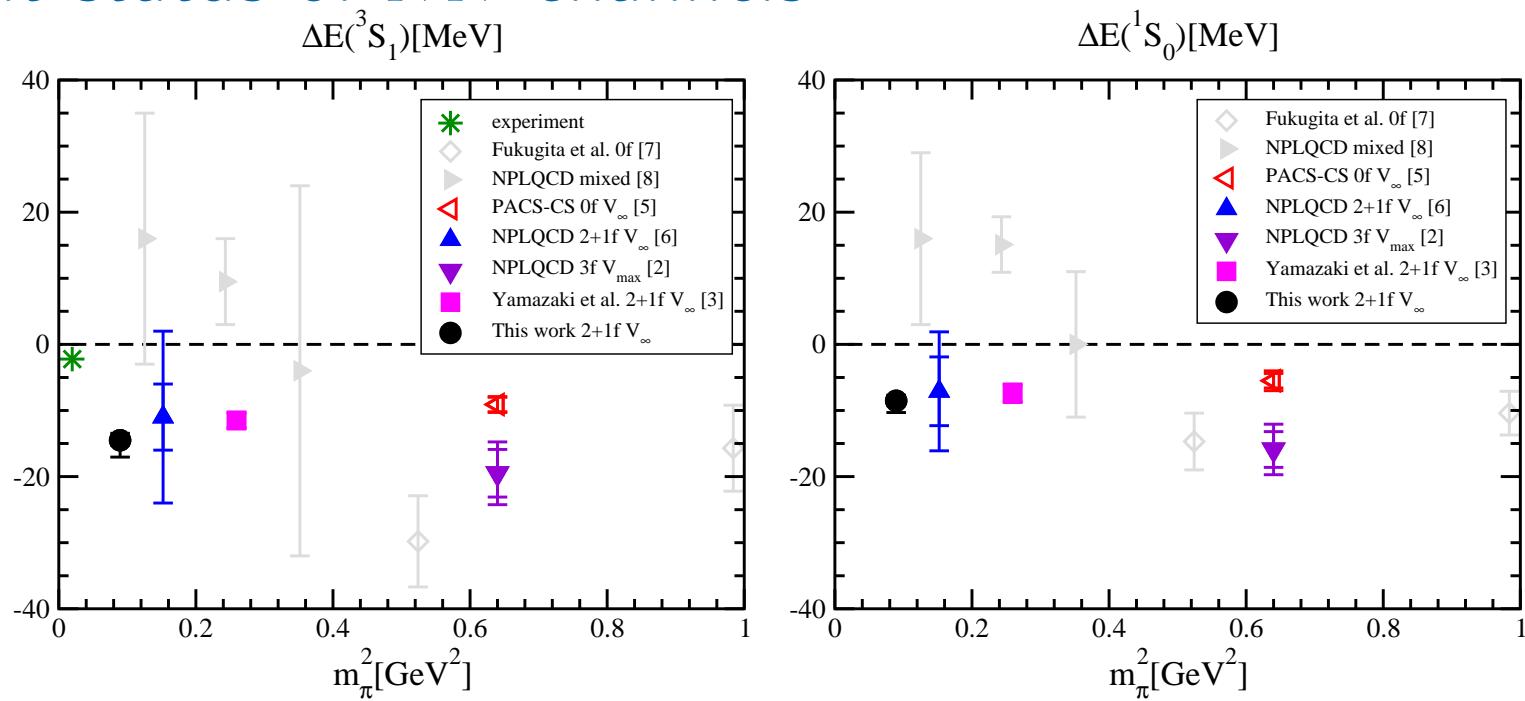
effective  $\Delta E_L$  @  $m_\pi = 0.3\text{GeV}$  on  $L = 48$   $N_f = 2 + 1$  TY et al.



effective  $\Delta E_L$  @  $m_\pi = 0.3\text{GeV}$  on  $L = 64$   $N_f = 2 + 1$  TY et al.



# Current status of $NN$ channels



$L^3 \rightarrow \infty$ : **existence of bound states in  ${}^3S_1$  and  ${}^1S_0$**   
**inconsistent with experiment due to larger  $m_\pi$ (?)**

$a_0 < 0$  at  $m_\pi = 0.8$  GeV  $\rightarrow$  **bound state in each channel**

c.f. Beane et al., PLB585:106(2004); Sasaki and TY, PRD74:114507(2006)

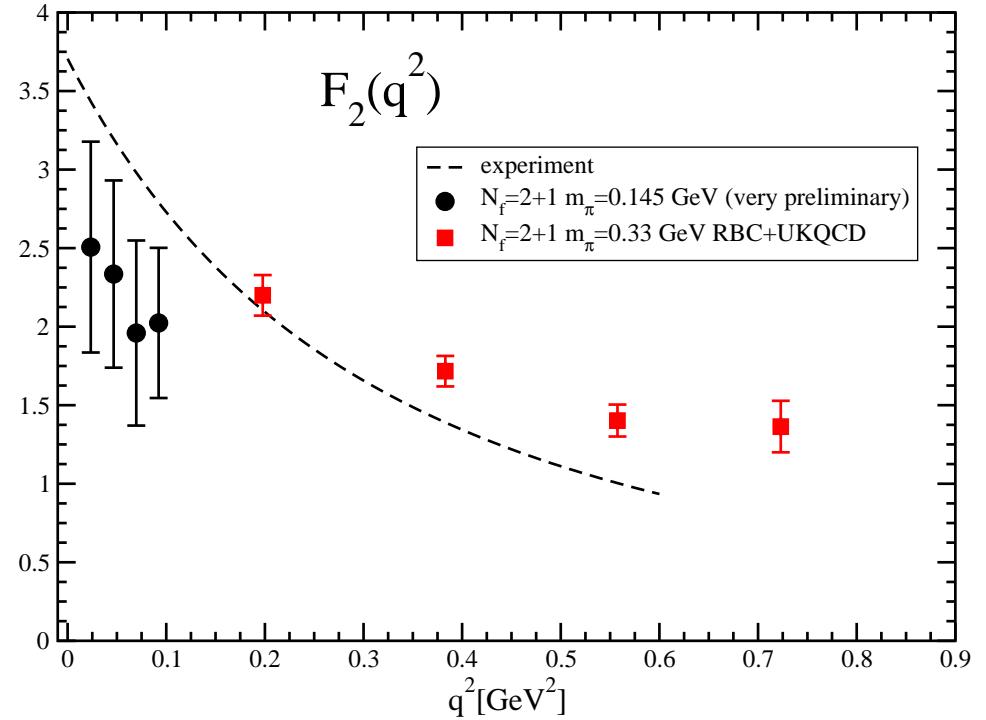
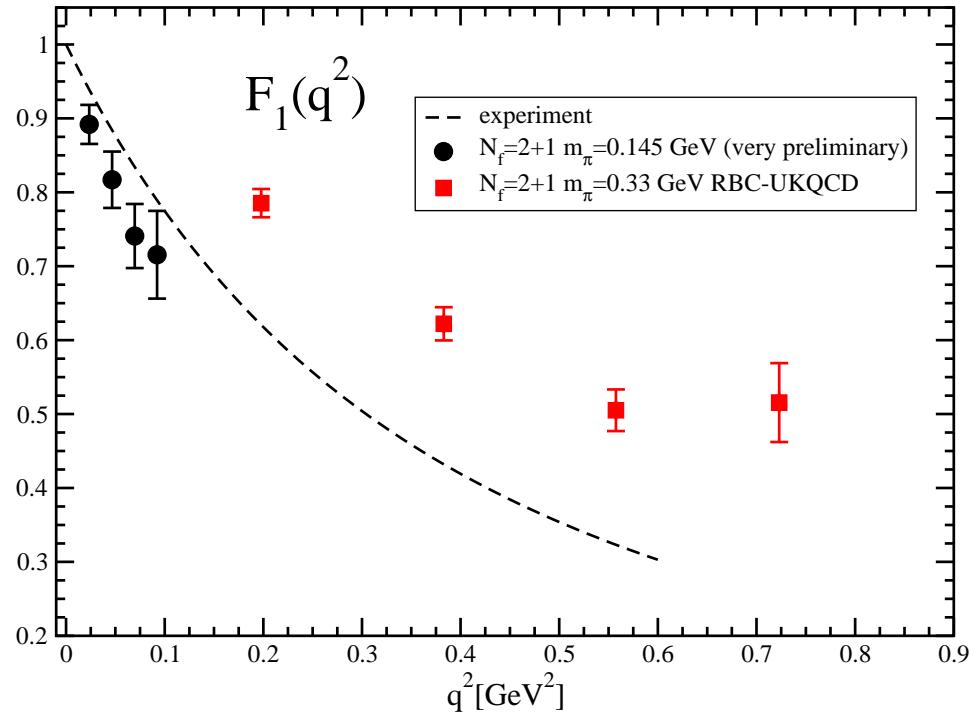
	PACS-CS, $N_f = 0^*$	NPLQCD, $N_f = 3$
$a_0^{^3S_1}$ [fm]	$-1.05(24) \begin{pmatrix} 5 \\ 65 \end{pmatrix}$	$-1.82 \begin{pmatrix} 14 \\ 13 \end{pmatrix} \begin{pmatrix} 17 \\ 12 \end{pmatrix}$
$a_0^{^1S_0}$ [fm]	$-1.62(24) \begin{pmatrix} 1 \\ 75 \end{pmatrix}$	$-2.33 \begin{pmatrix} 19 \\ 17 \end{pmatrix} \begin{pmatrix} 27 \\ 20 \end{pmatrix}$

\* from  $L = 6.1$  fm PACS-CS, PRD84:054506(2011)

NPLQCD, PRD87:034506(2013)

# Isovector Dirac and Pauli form factors

Very preliminary results at  $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm



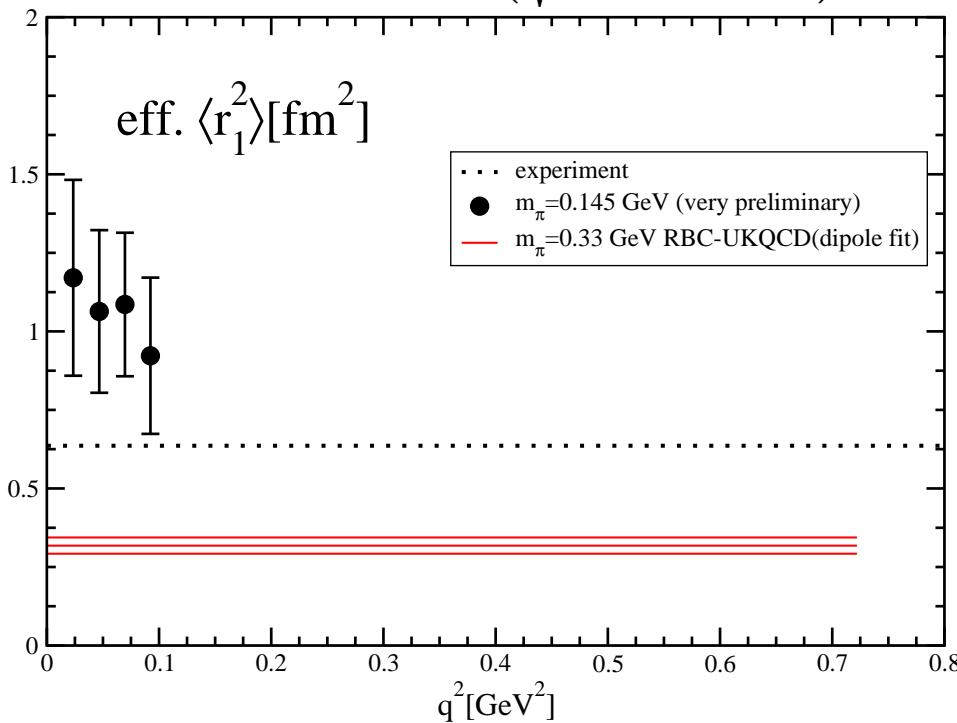
Need much more statistics

# Effective Dirac radius

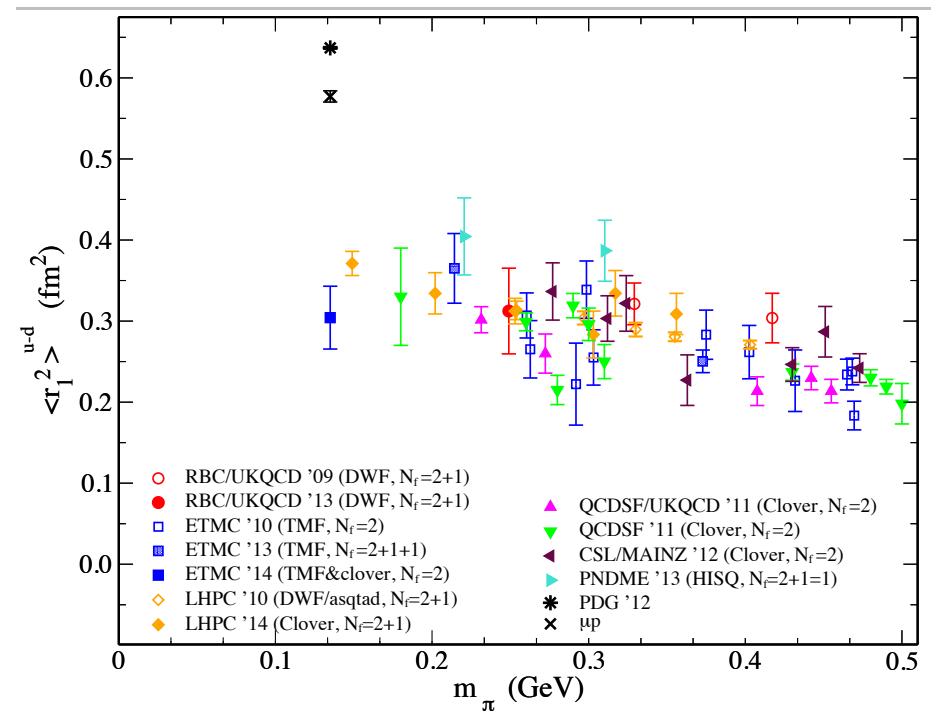
Very preliminary results at  $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm

$$F_1(q^2) = \left(1 + \frac{q^2}{12} \langle r_1^2 \rangle\right)^{-2}$$

$$\text{Eff. } \langle r_1^2 \rangle = \frac{12}{q^2} \left( \sqrt{\frac{1}{F_1(q^2)}} - 1 \right)$$



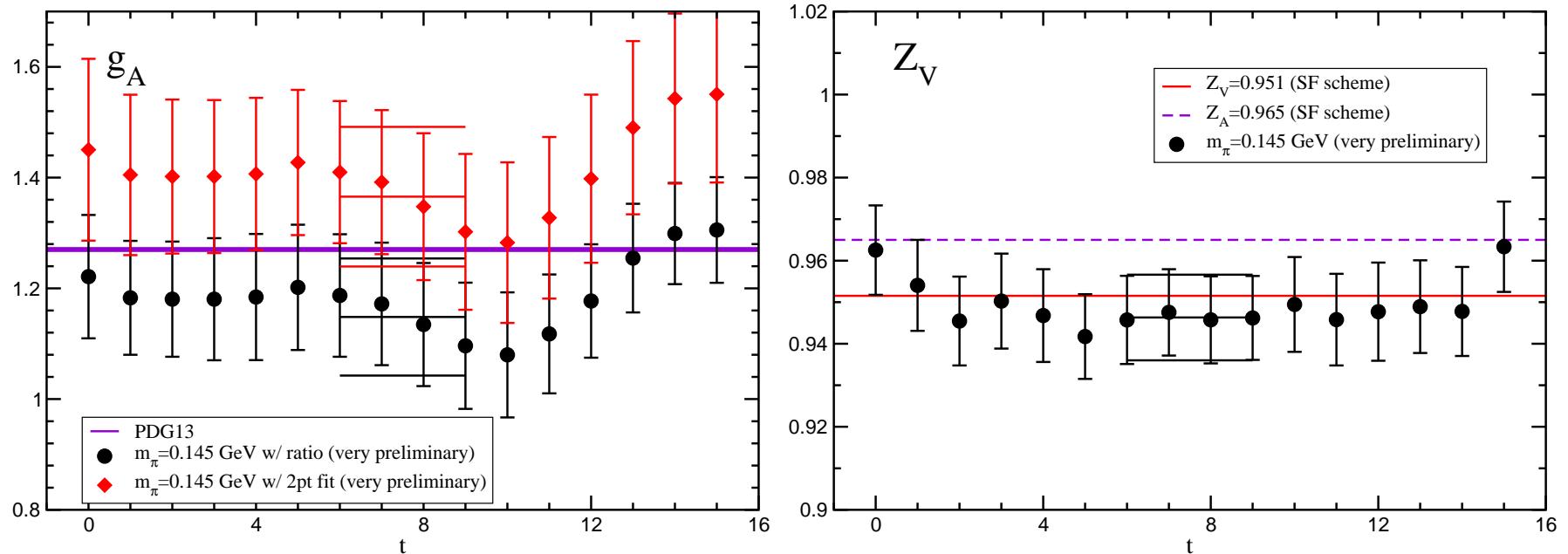
Constantinou, Lat14 plenary



Too large error to compare experiment and other results

Axial charge  $g_A = Z_A g_A^{\text{bare}}$

Very preliminary results at  $m_\pi \sim 0.145$  GeV on  $L \sim 8$  fm  
 $Z_A \sim 0.965$  in SF scheme: consistent with  $Z_V = 1/G_E(0)$  within 1–2%



Discrepancy of two analyses → systematic error

roughly consistent with experiment,

but need much more statistics for stringent test

# Simulation parameters

$N_f = 2 + 1$  QCD

Iwasaki gauge action

$a^{-1} \sim 2.35$  GeV with  $m_\Omega$

non-perturbative  $O(a)$ -improved Wilson fermion action

with stout smearing

$m_\pi \sim 0.145$  GeV and  $m_s \sim$  physical strange quark mass

1. Light nuclei: 205 conf  $\times$  192 meas/conf
2. Form factor: 56 conf  $\times$  64 meas/conf

Computational resources

HA-PACS, COMA @Univ. of Tsukuba, FX10 @Univ. of Tokyo,

K @AICS, FX100 @RIKEN, System E @Kyoto Univ.