

Progress in Multibaryon spectroscopy

Evan Berkowitz

Institut für Kernphysik

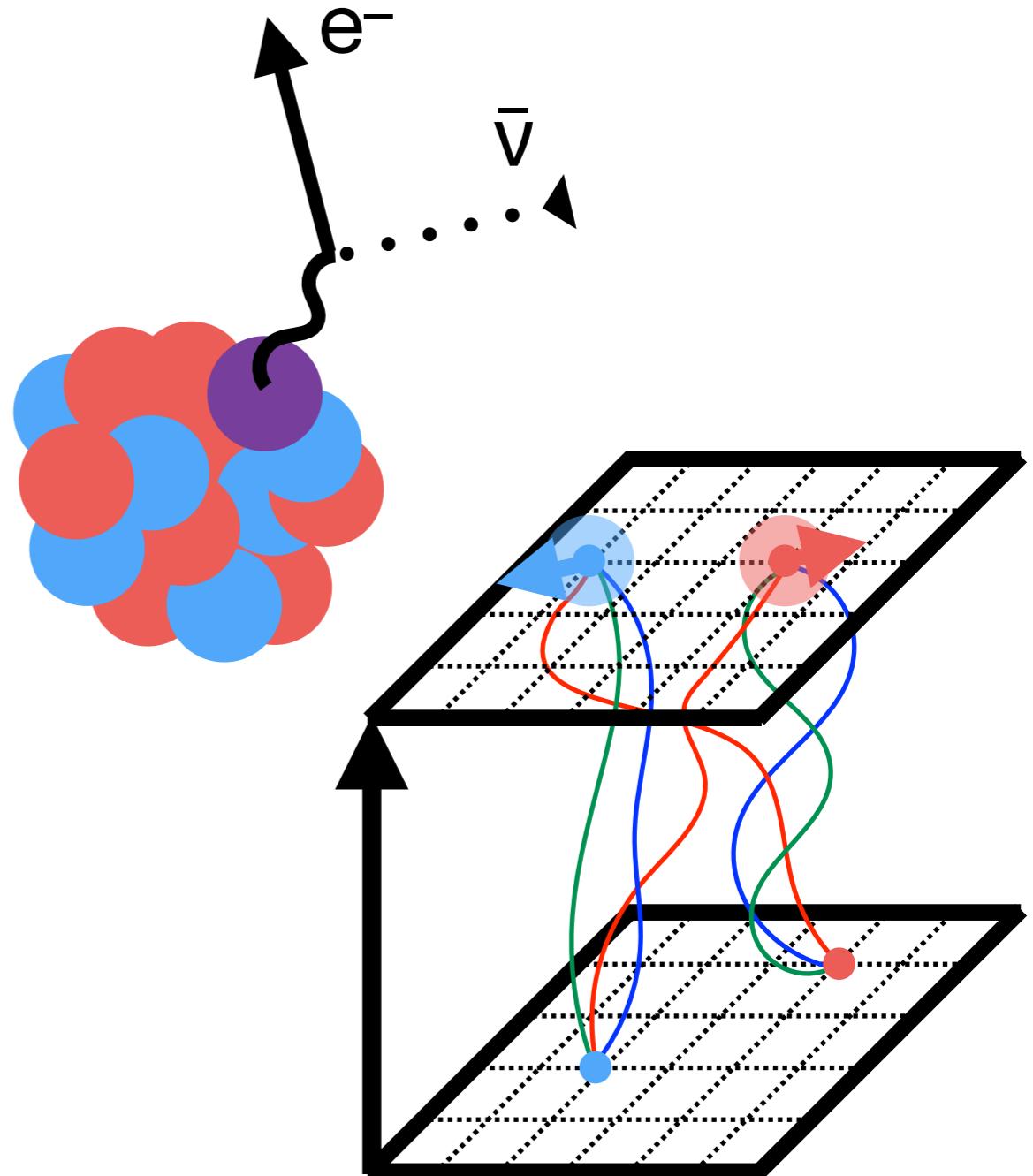
Institute for Advanced Simulation

Forschungszentrum Jülich

23 July 2018

LATTICE XXXVI

East Lansing, Michigan





Berkeley
LBL

David Brantley, Henry Monge Camacho, Chia
Cheng (Jason) Chang, Ken McElvain, André
Walker-Loud, Wick Haxton



RBRC

Enrico Rinaldi



U.S. DEPARTMENT OF
ENERGY

Office of
Science



U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING



SciDAC
Scientific Discovery
through
Advanced Computing



Jefferson Lab

JLab

Bálint Joó



LLNL

Arjun Gambhir
Pavlos Vranas

NERSC

NERSC

Thorsten Kurth



UNC

Amy Nicholson

NVIDIA.

NVIDIA

Kate Clark



Lüscher Formalism

Lüscher Commun.Math.Phys 104 and 105 (1986)
 Lüscher Nucl. Phys. B354 (1991) 531-578
 Wiese, Nucl. Phys. B Proceedings Supplements 9, 609 (1989)
 Lüscher Nucl. Phys. B 354 (1991) 531; Nucl. Phys B 364 (1991) 237
 Rummukainen and Gottlieb Nucl. Phys. B 450 (1995) 397-436
 + many others since

$$\det \left[(\mathcal{M}^\infty)^{-1} + \delta\mathcal{G}^V \right] = 0$$



 Physics of interest \leftarrow Lattice calculation

$$\det \left[(\mathcal{M}^\infty)^{-1} + \delta \mathcal{G}^V \right] = 0$$

Wednesday

| | | |
|----------|---|-------|
| Hoying | Pion-pion scattering with physical quark masses | 15:00 |
| Leskovec | Calculating the p radioactive decay width with LQCD | 15:20 |

Thursday

| | | |
|---------------|---|-------|
| Darvish | Scattering phase shift determinations from a two-scalar field theory and resonance parameters from QCD scattering | 08:30 |
| Brett | Kπ scattering and excited meson spectroscopy using the Stochastic LapH method | 08:50 |
| Pittler | Hadron-Hadron Interactions from N _f =2+1+1 Lattice QCD: π-K scattering length | 09:10 |
| Rendon Suzuki | Kπ scattering and the K*(892) resonance in 2+1 flavor QCD | 09:30 |
| Cheung | DK scattering and D _{s0} (2317) | 09:50 |
| Baroni | Finite volume matrix elements of two-body states | 10:10 |

$$\det \left[(\mathcal{M}^\infty)^{-1} + \delta \mathcal{G}^V \right] = 0$$

Thursday

| | | |
|---------|---|-------|
| Sharpe | Progress on relativistic three-particle quantization condition | 11:00 |
| Wang | Studies of I=0 and 2 pi-pi scattering with physical pion mass | 11:20 |
| Liu | Roper State from Overlap Fermion | 12:00 |
| Fallica | Coupling to Multihadron States with Chiral Fermions | 12:20 |
| Hanlon | Progress towards understanding the H-dibaryon from lattice QCD | 12:40 |

$$\det \left[(\mathcal{M}^\infty)^{-1} + \delta \mathcal{G}^V \right] = 0$$

Friday

Piemonte

Coupled channel scattering of vector and scalar charmonium resonances on the lattice

15:20

Skerbis

J/ ψ -nucleon scattering in P_c^+ pentaquark channels

15:40

Silvi

Towards the P-wave nucleon-pion scattering amplitude in the $\Delta(1232)$ channel: interpolating fields and spectra

16:30

Paul

Towards the P-wave nucleon-pion scattering amplitude in the $\Delta(1232)$ channel: Phase shift analysis

16:50

Wynen

Three neutrons from Lattice QCD

17:50

HAL QCD Potential Method

| | | | |
|----------|--|-------|-------|
| Yamazaki | Relations between scattering amplitude and Bethe-Salpeter wave function in QFT | Thurs | 11:20 |
| Namekawa | Scattering length from BS wave function inside the interaction range | Thurs | 11:40 |
| Iritani | HAL QCD method and Nucleon-Omega interaction with physical quark masses | Fri | 17:10 |
| Doi | Baryon interactions at physical quark masses in Lattice QCD | Fri | 17:30 |
| Sugiura | Charmonium-nucleon interactions from 2+1 flavor lattice QCD | Fri | 18:10 |

Other Strategies

| | | | |
|--------|---|-----|-------|
| Mai | 3-body quantization condition in unitary isobar formalism | Mon | 16:30 |
| Z. Guo | Confront the lattice finite-volume energy levels with chiral effective field theory | Tue | 14:40 |

A large and growing literature

The HALQCD Potential Method

- PRL 99 (2007) 022001
- Prog.Theor.Phys 123 (2010) 89-128
- Prog.Theor.Phys 124 (2010) 591-603
- Prog.Theor.Phys 125 (2011) 1225-1240
- PTEP 2012 01A105
- PLB 712 (2012) 437-441
- arXiv:1711.09344 (to appear in PRD)

Other/coupled channels:

- PLB673 (2009) 136-141
- Nucl. Phys. A928 (2014) 89-98
- PTEP 2015 071B01
- PRL 120 (2018) 212001
- Nucl. Phys. A 971 (2018) 113

Theory

- Proc.Jon.Acad.Ser. 87 (2011) 509-517
- PRD 87 (2013) 034512
- PRD 88 (2013) 014036

$\pi\pi$

- Kurth et al. JHEP 1312 (2013) 015
- PTEP 2018 043B04

Spin-Orbit / Derivative Expansion

- PLB 735 (2014) 19-24
- arXiv:1805.02365

More Than 2 Baryons

- Prog.Theor.Phys. 127 (2012) 723-738

Applications

- PRL 111 (2013) 112503
- PRC 91 (2015) 011001(R)

Tetraquarks

- PLB 729 (2014) 85-90
- PRL 117 (2016) 242001

and many others!

A large and growing literature

CaLLat PLB 765:285-292 (2017)

$m_\pi \sim 800$ MeV

NPLQCD PRD 87 (2013) 034506

Yamazaki et al. PRD 84 (2011) 054506

NPLQCD PRD 96 (2017) 114510

$m_\pi \sim 510$ MeV

Yamazaki et al. PRD 86 (2012) 074514

$m_\pi \sim 450$ MeV

NPLQCD PRD 92 (2015) 114512

$m_\pi \sim 300$ MeV

Yamazaki et al. PRD 92 (2015) 014501

H Dibaryon

NPLQCD Mod.Phys.Lett. A26 (2011)
2587-2595

NPLQCD Phys.Rev.Lett. 106 (2011) 162001

HALQCD PRL 106 (2011) 162002

HALQCD Nucl.Phys. A881 (2012) 28-43

Green et al. PoS(LATTICE2014)107

Junnarkar et al. PoS(LATTICE2015)082

Francis et al. 1805.03966

method of baryon blocks

Doi + Endres Comput. Phys. Commun 184
(2013) 117

Detmold + Orginos PRD 87 (2013) 114512

matrix elements + transitions

NPLQCD PRL 119 (2017) 062002

NPLQCD PRL 119 (2017) 062003

NPLQCD PRD 96 (2017) 054505

NPLQCD PRL 120 (2018) 152002

signal-to-noise

Parisi Phys. Rept. 103 203 (1984)

Lepage, Boulder ASI 1989:97-120 (1989)

NPLQCD PRD 79 (2009) 114502

NPLQCD PRD 80 (2009) 074501

NPLQCD PRD 81 (2010) 054505

NPLQCD Prog.Part.Nucl.Phys. 66 (2011)
1-40

NPLQCD PRD 96 (2017) 114508

DWF on MILC

NPLQCD PRL 97 (2006) 012001

Mirage Plateaus and Sanity Checks

HALQCD JHEP 1610 (2016) 101

HALQCD PRD 96 (2017) 034521

NPLQCD arXiv:1705.09239

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Doi + Endres Comput. Phys. Commun 184
(2013) 117

Detmold + Orginos PRD 87 (2013) 114512

matrix elements + transitions

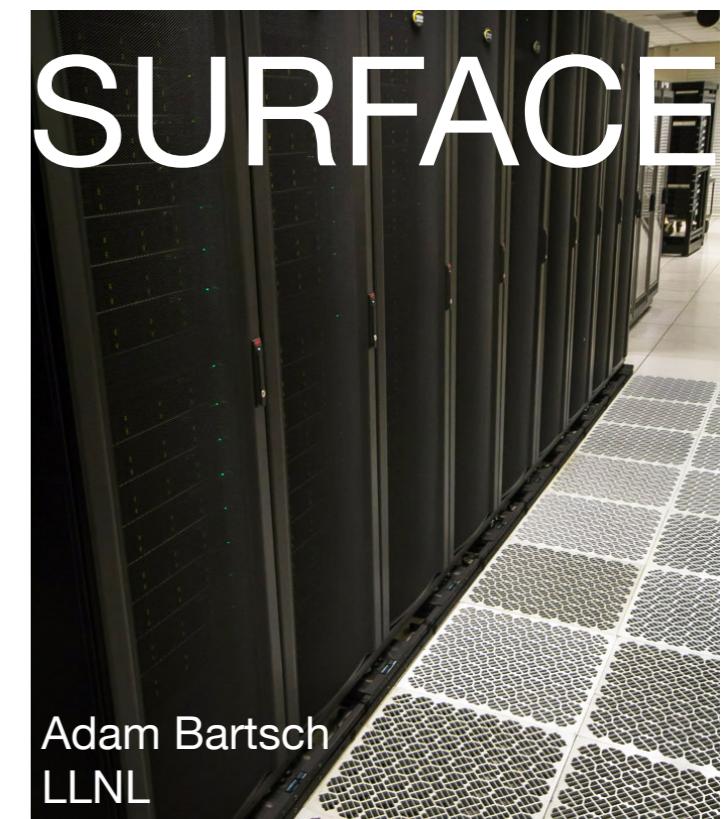
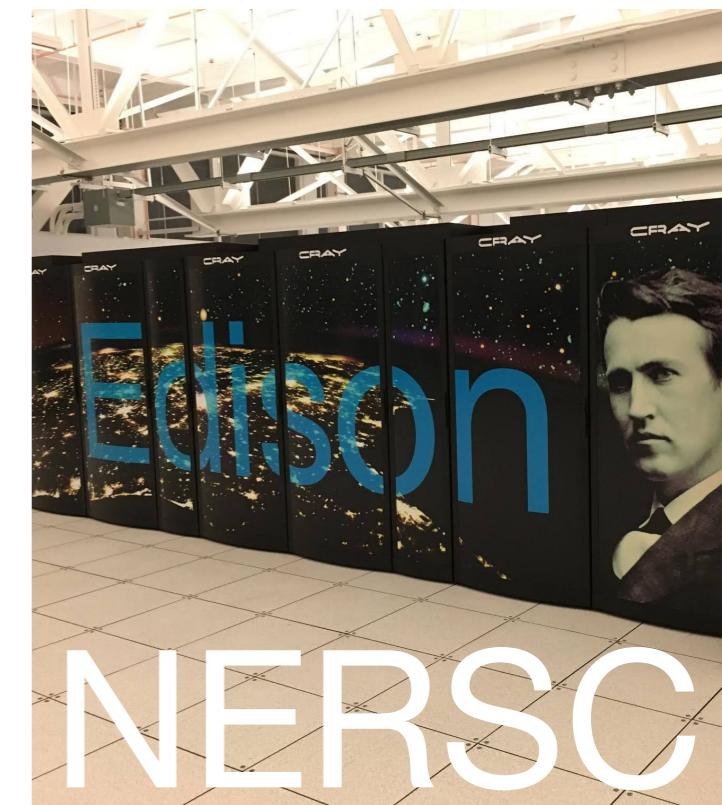
NPLQCD PRL 111 (2013) 161601
Detmold
NPLQCD PRL 111 (2013) 161602
Weak Decays + MEs
NPLQCD PRD 93 (2016) 054502
Tuesday 14:40
NPLQCD PRL 120 (2018) 152002

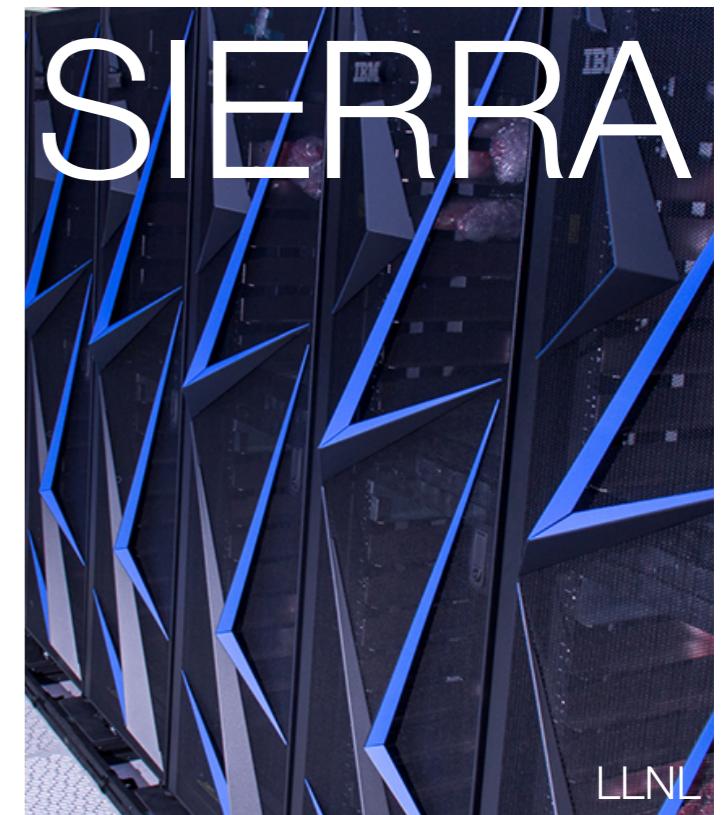
signal-to-noise

Parisi Phys. Rep^t 102 202 (1984)
Lepage, Boulde
NPLQCD PRD 77 (2008) 054502
NPLQCD PRD 81 (2010) 054505
NPLQCD Prog.Part.Nucl.Phys. 66 (2011)
1-40
NPLQCD PRD 96 (2017) 114508

DWF on MILC

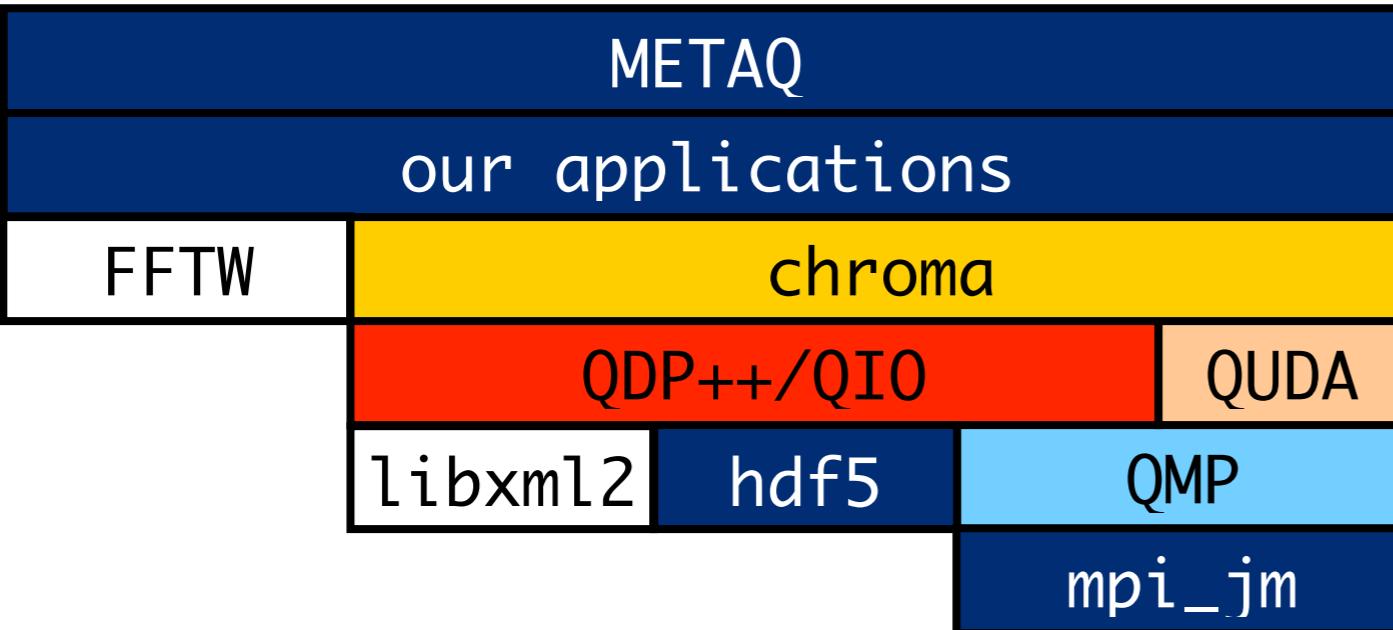
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Mirage Plateaus and Sanity Checks
HALQCD JHEP 1610 (2016) 101
HALQCD PRD 96 (2017) 034521
NPLQCD arXiv:1705.09239





LASSEN





| Software | References |
|---------------|---|
| METAQ | Berkowitz arXiv:1702.06122 github.com/evanberkowitz/metaq Berkowitz et al. EPJ (LATTICE2017) 175 09007 (2018) |
| chroma | Edwards and Joo (SciDAC, LHPC and UKQCD Collaborations) Nucl. Phys. |
| QDP++ | Proc. Suppl 140, 832 (2005) |
| QUADA | Clark et al. Comput. Phys. Commun. 181 1517 (2010) Babich et al. Supercomputing 11, 70 |
| hdf5 in QDP++ | Kurth et al PoS LATTICE2014 045 (2015) |
| qmp | Chen, Edwards, and Watson et al. https://github.com/usqcd-software/qmp |
| mpi_jm | Berkowitz et al. EPJ (LATTICE2017) 175 09007 (2018) McElvain et al. https://github.com/kenmcelvain/mpi_jm/ |

Wagner
Plenary
Saturday 09:45

mpi_jm

Lin
Plenary
Saturday 09:00

| | | | | | | | |
|---|---|---|---|----|----|----|----|
| m | m | m | m | m | m | m | m |
| s | | | | | | | |
| m | m | m | m | m | m | m | m |
| | | | | | | | |
| m | m | m | m | m | m | m | m |
| A | A | A | A | BD | BD | BD | BD |
| m | m | m | m | m | m | m | m |
| A | A | A | A | CD | CD | CD | CD |

m: master

s: scheduler

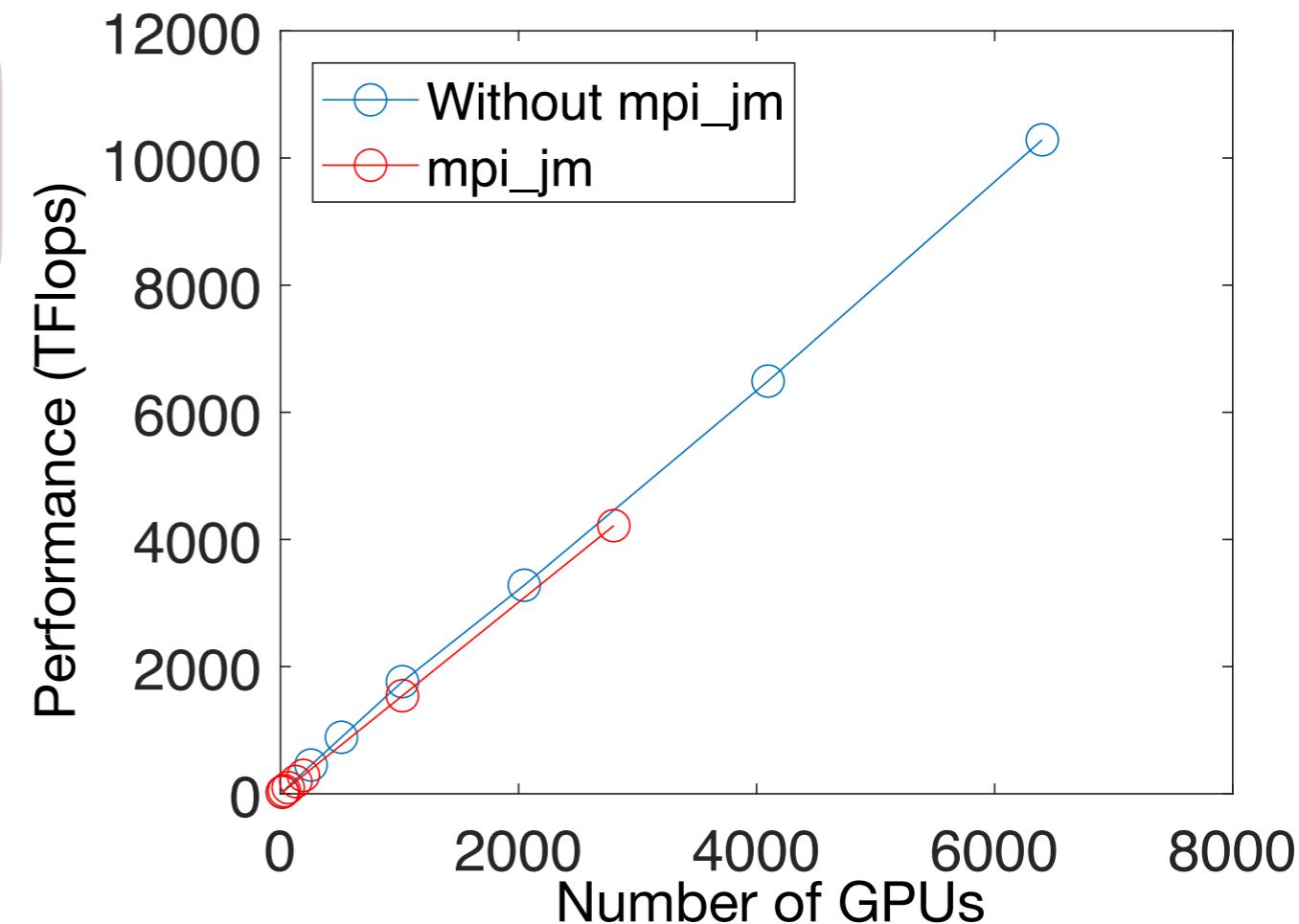
A: whole block

B: 4 nodes' GPUs

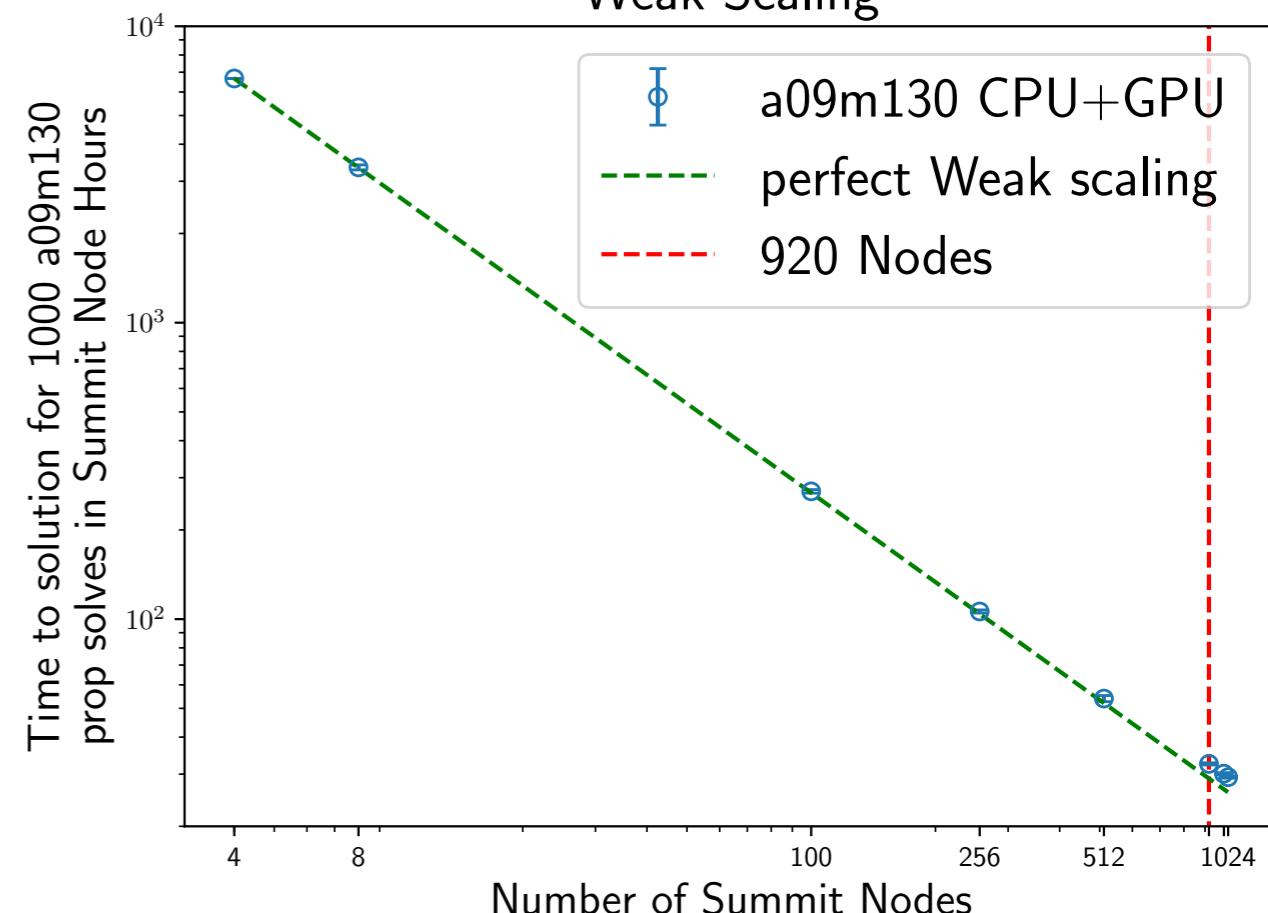
C: 4 nodes' GPUs

D: 8 nodes' CPUs

Weak Scaling on Sierra



Weak Scaling



Lüscher Formalism

Lüscher Commun.Math.Phys 104 and 105 (1986)
 Lüscher Nucl. Phys. B354 (1991) 531-578
 Wiese, Nucl. Phys. B Proceedings Supplements 9, 609 (1989)
 Lüscher Nucl. Phys. B 354 (1991) 531; Nucl. Phys B 364 (1991) 237
 Rummukainen and Gottlieb Nucl. Phys. B 450 (1995) 397-436
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 Physics of interest \leftarrow Lattice calculation

Two-Nucleon Spectrum

- Spectrum given by effective mass of (schematic) NN correlator:

$$\langle \Omega | \mathcal{O}_{\Lambda' \mu', Im_I}^{[J' \ell' S']} (t) \bar{\mathcal{O}}_{\Lambda \mu, Im_I}^{[J \ell S]} (0) | \Omega \rangle$$

$\delta \mathcal{G}^V$

- Box breaks rotational symmetry \rightarrow spectrum falls into irreps of O_H , not $SO(3)$.

| Isospin 0 | | Isospin 1 | |
|----------------|-----------------------------------|----------------|--|
| Partial wave | Irreps | Partial wave | Irreps |
| 1P_1 | T_1^- | 1S_0 | A_1^+ |
| $^3S_1, ^3D_1$ | T_1^+ | 3P_0 | A_1^- |
| 3D_2 | $E^+ \oplus T_2^+$ | 3P_1 | T_1^- |
| 3D_3 | $A_2^+ \oplus T_1^+ \oplus T_2^+$ | $^3P_2, ^3F_2$ | $E^- \oplus T_2^-$ |
| 1F_3 | $A_2^- \oplus T_1^- \oplus T_2^-$ | 1D_2 | $E^+ \oplus T_2^+$ |
| | | 3F_3 | $A_2^- \oplus T_1^- \oplus T_2^-$ |
| | | 3F_4 | $A_1^- \oplus E^- \oplus T_1^- \oplus T_2^-$ |

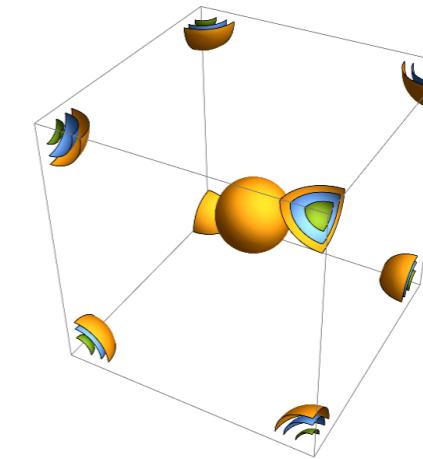
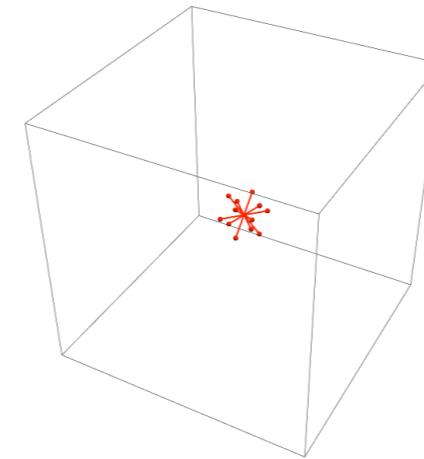
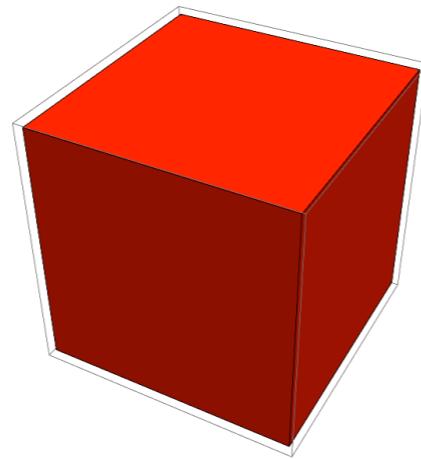
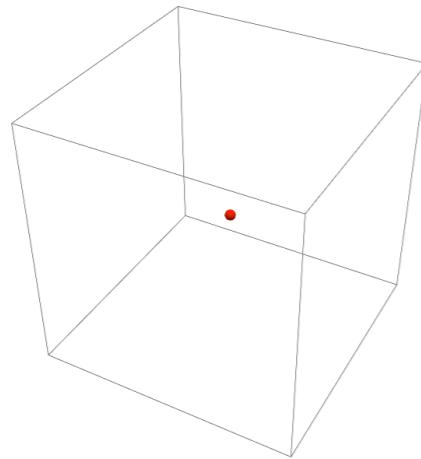
Non-interacting States

Luu & Savage 1101.3347 (arXiv version is better!)

- Project to eigenstates of a noninteracting theory in a box.
- Full volume information → exactly project to any desired irrep

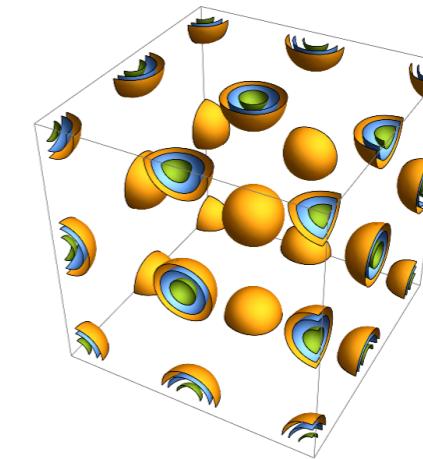
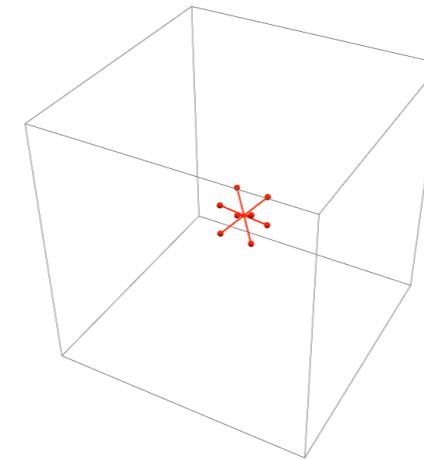
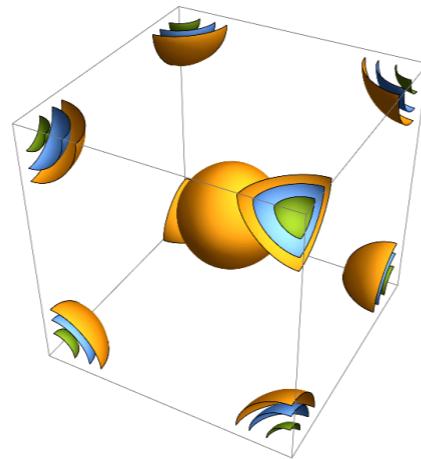
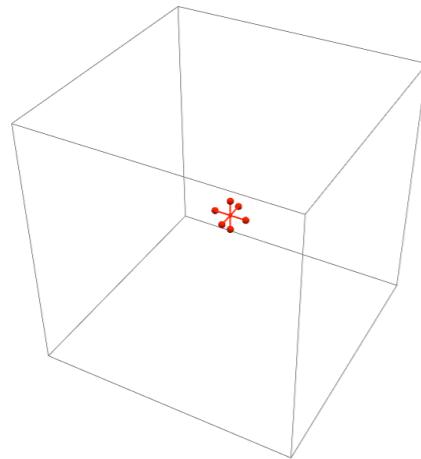
A_1^+

$n^2=0$



$n^2=2$

$n^2=1$



$n^2=3$

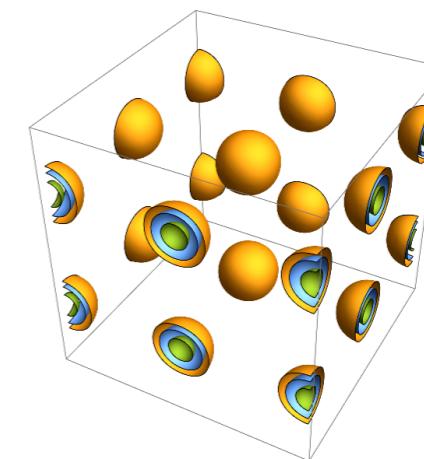
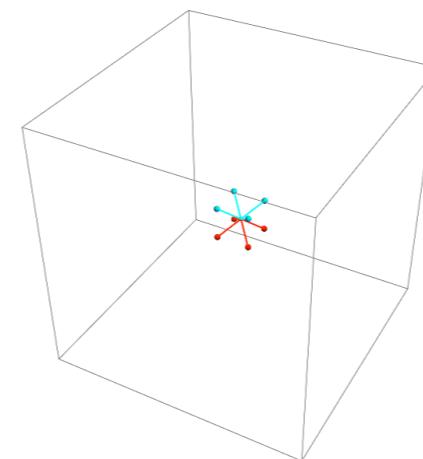
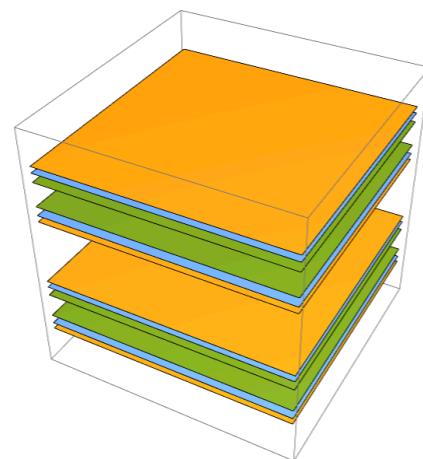
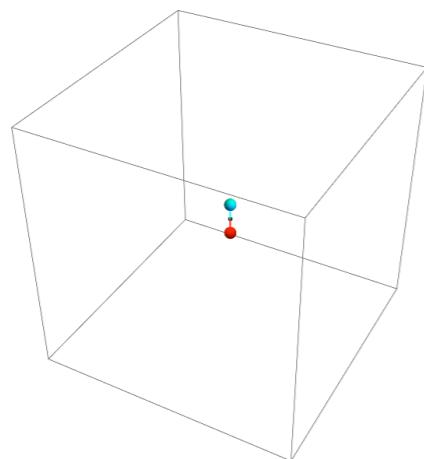
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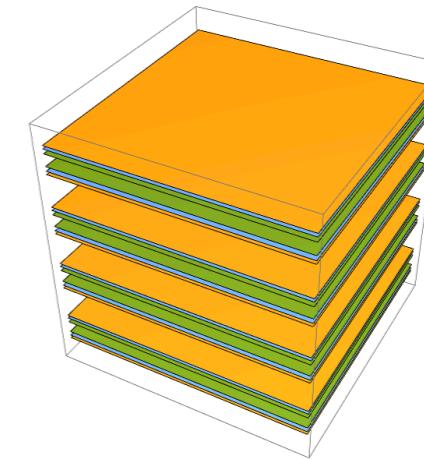
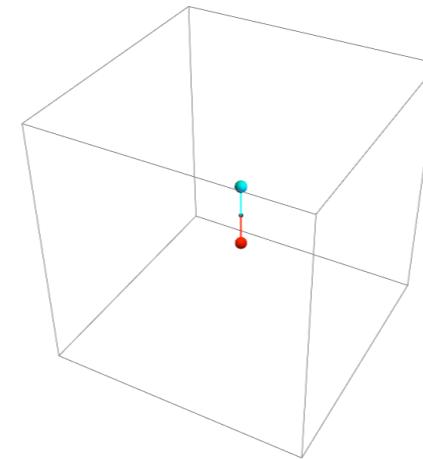
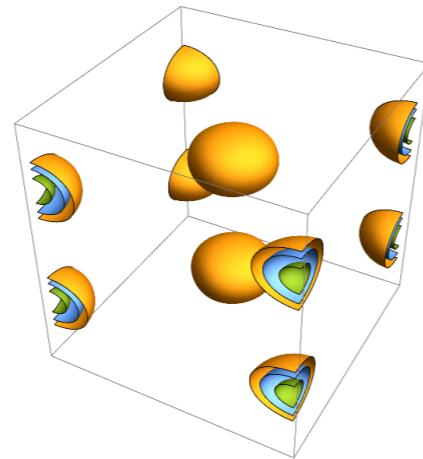
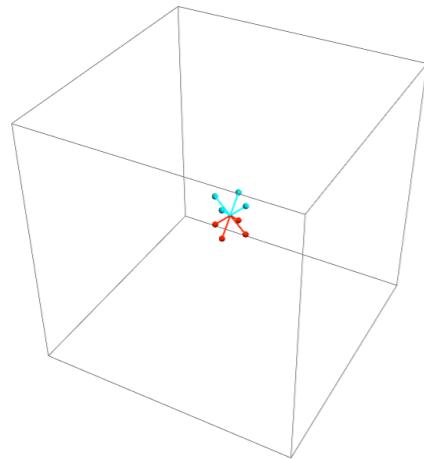
T_1^-

$n^2=1$



$n^2=3$

$n^2=2$

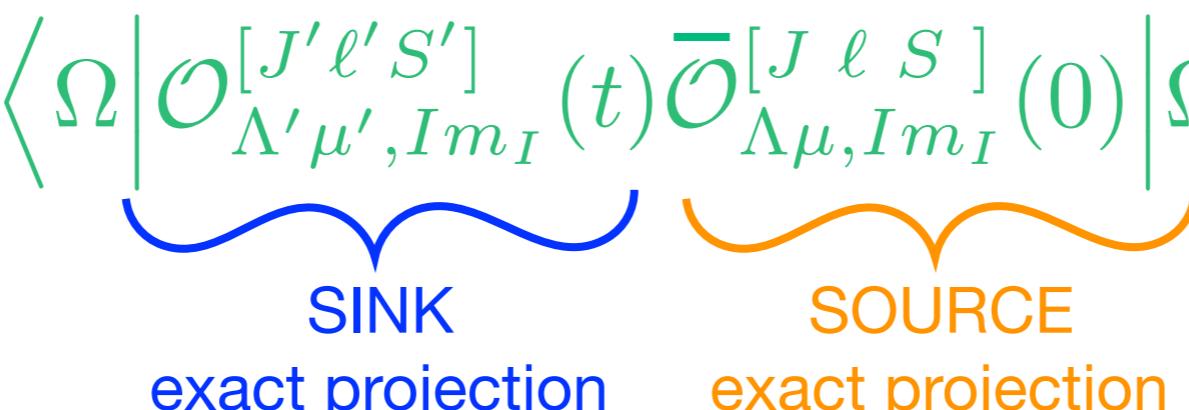


$n^2=4$

Two-Nucleon Spectrum

- Spectrum given by effective mass of (schematic) NN correlator:

$$\left\langle \Omega \left| \mathcal{O}_{\Lambda' \mu', Im_I}^{[J' \ell' S']} (t) \bar{\mathcal{O}}_{\Lambda \mu, Im_I}^{[J \ell S]} (0) \right| \Omega \right\rangle$$


SINK
exact projection SOURCE
exact projection

$$\delta G^V$$

Two-Nucleon Spectrum

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SINK
 exact projection
 SOURCE
 exact projection

δG^V

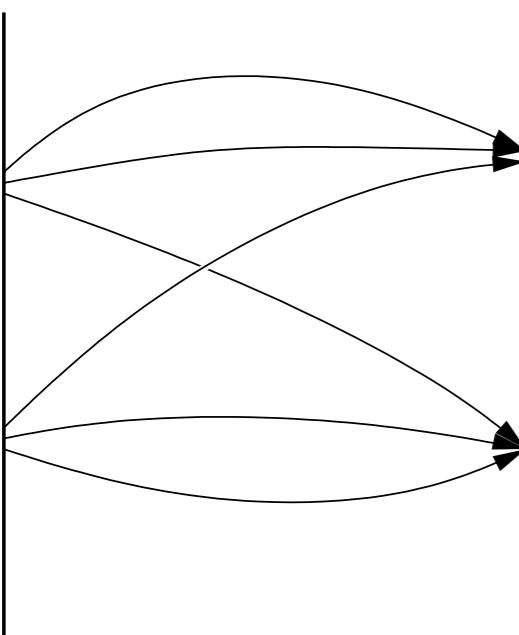


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SINK
 exact projection
 SOURCE
 exact projection



Francis et al. 1805.03966
 H binding energy = 19 ± 10 MeV
 $m_\pi \sim 960$ MeV SU(3)-symmetric
 via distillation



Two-Nucleon Spectrum

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SINK
 exact projection

SOURCE
 ?

δG^V

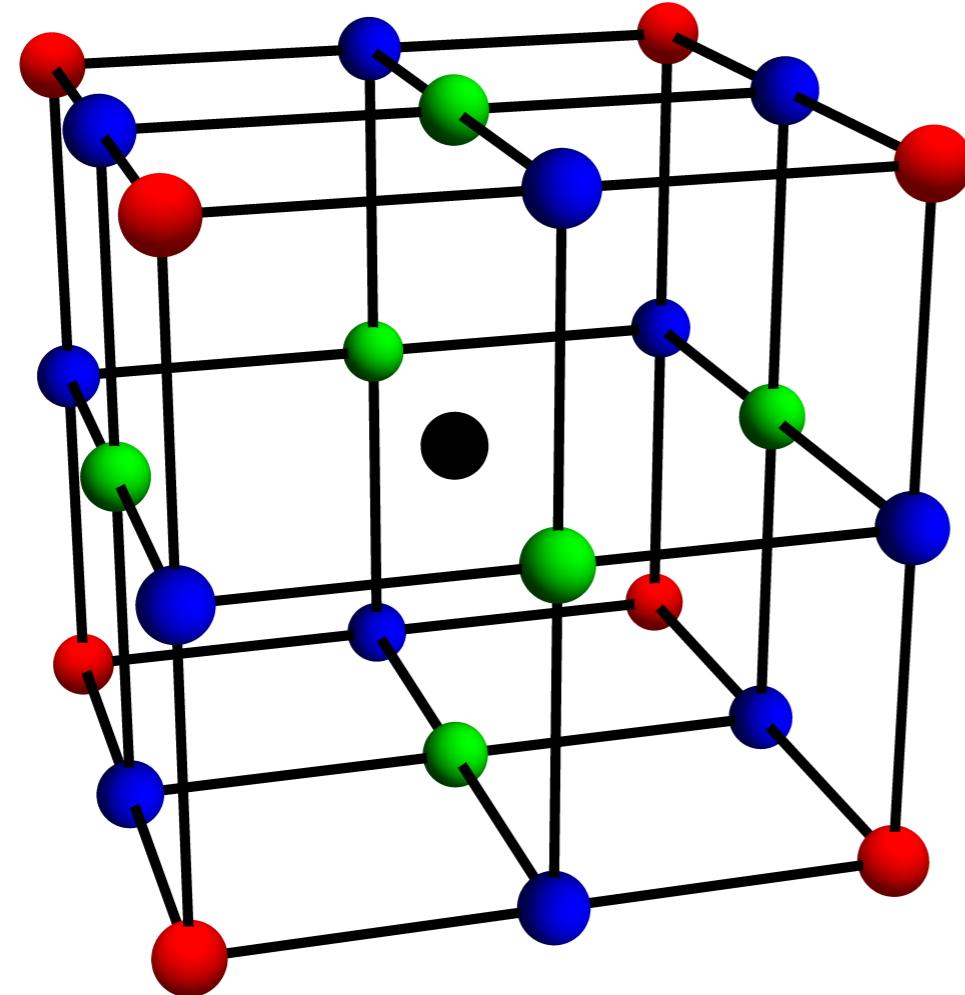
Schemes to avoid all-to-all
 source displacements
 single-baryon improvement



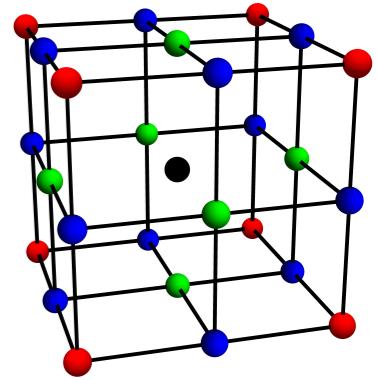
Spatially Displaced Two-Nucleon Operators

Source Overlap

- Exact projection source-side costs $\sim(\text{volume})^2$
- Pick displacements



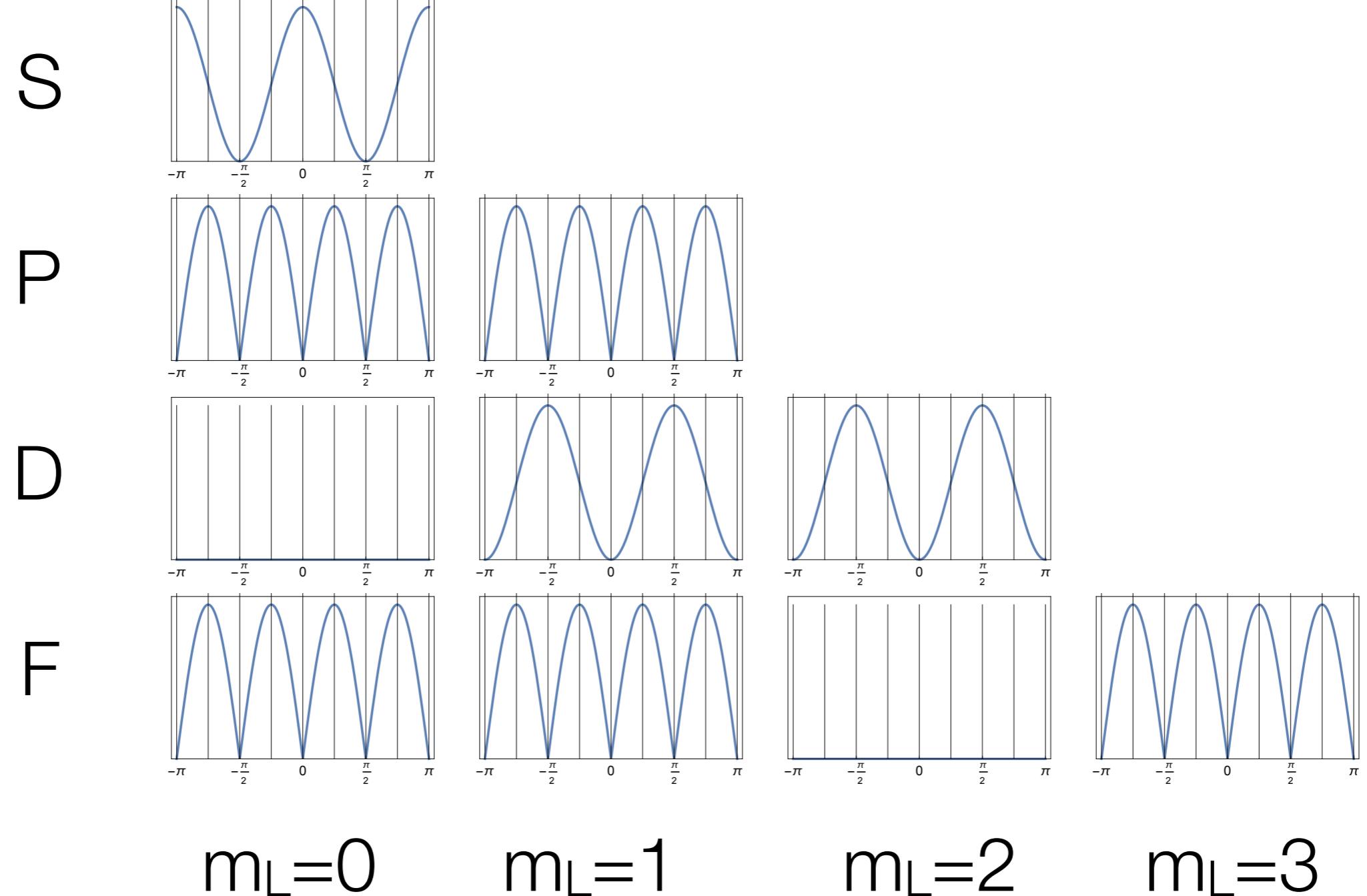
| name | $\Delta x \sim$ | # solves |
|--------|-----------------|----------|
| local | (0, 0, 0) | 1 |
| face | (0, 0, 1) | 6 |
| edge | (0, 1, 1) | 12 |
| corner | (1, 1, 1) | 8 |
| | (0, 1, 2) | 24 |
| | (1, 1, 2) | 24 |
| | (1, 2, 3) | 48 |

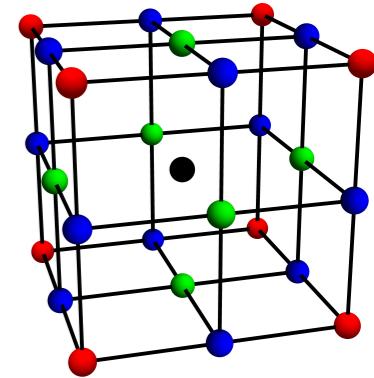


Source Overlap

Luu & Savage 1101.3347 (arXiv version is better!)

Project Luu & Savage momentum sources to **corner** as a function of $\pi\Delta x/L$

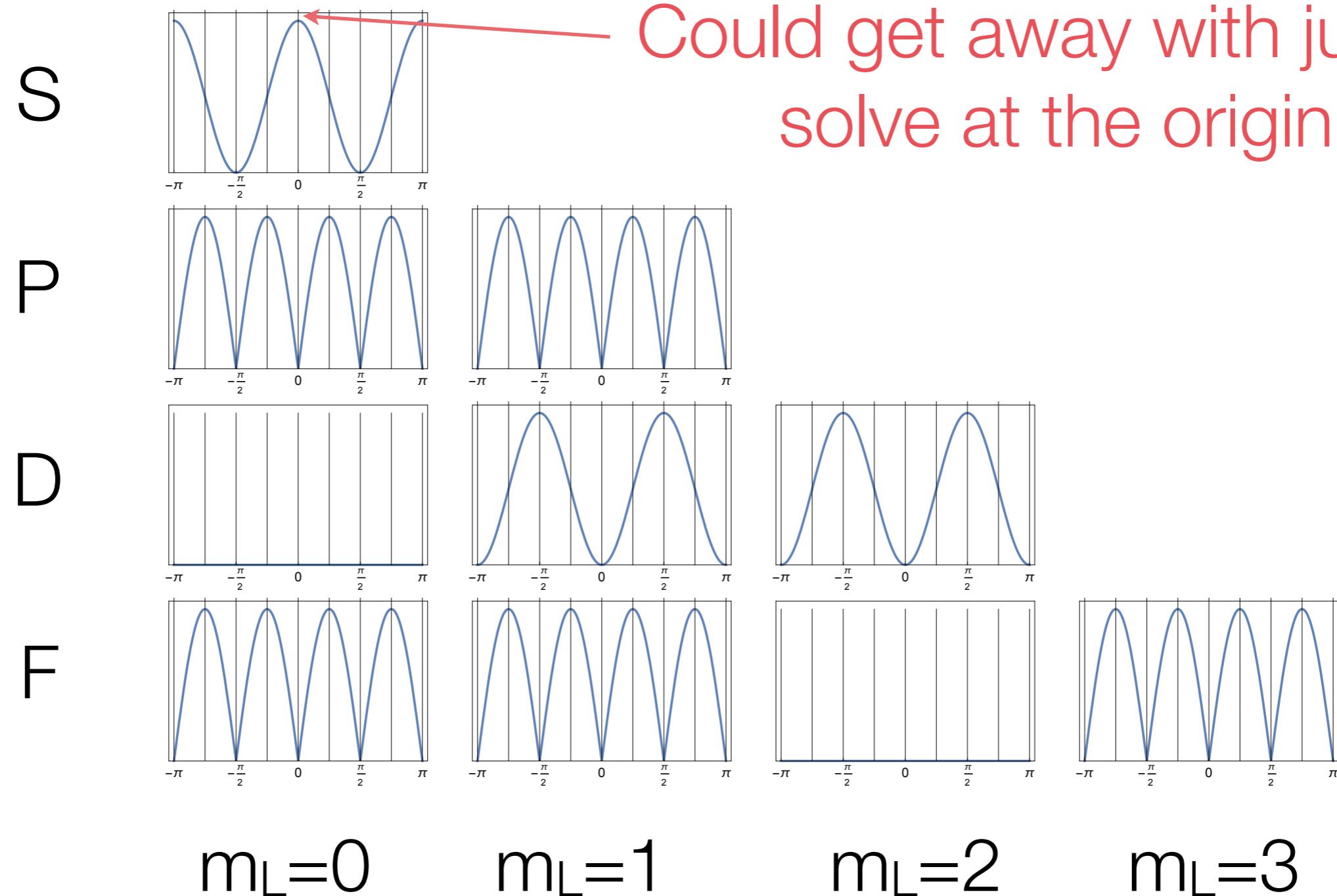


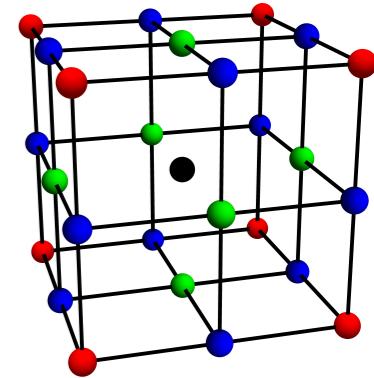


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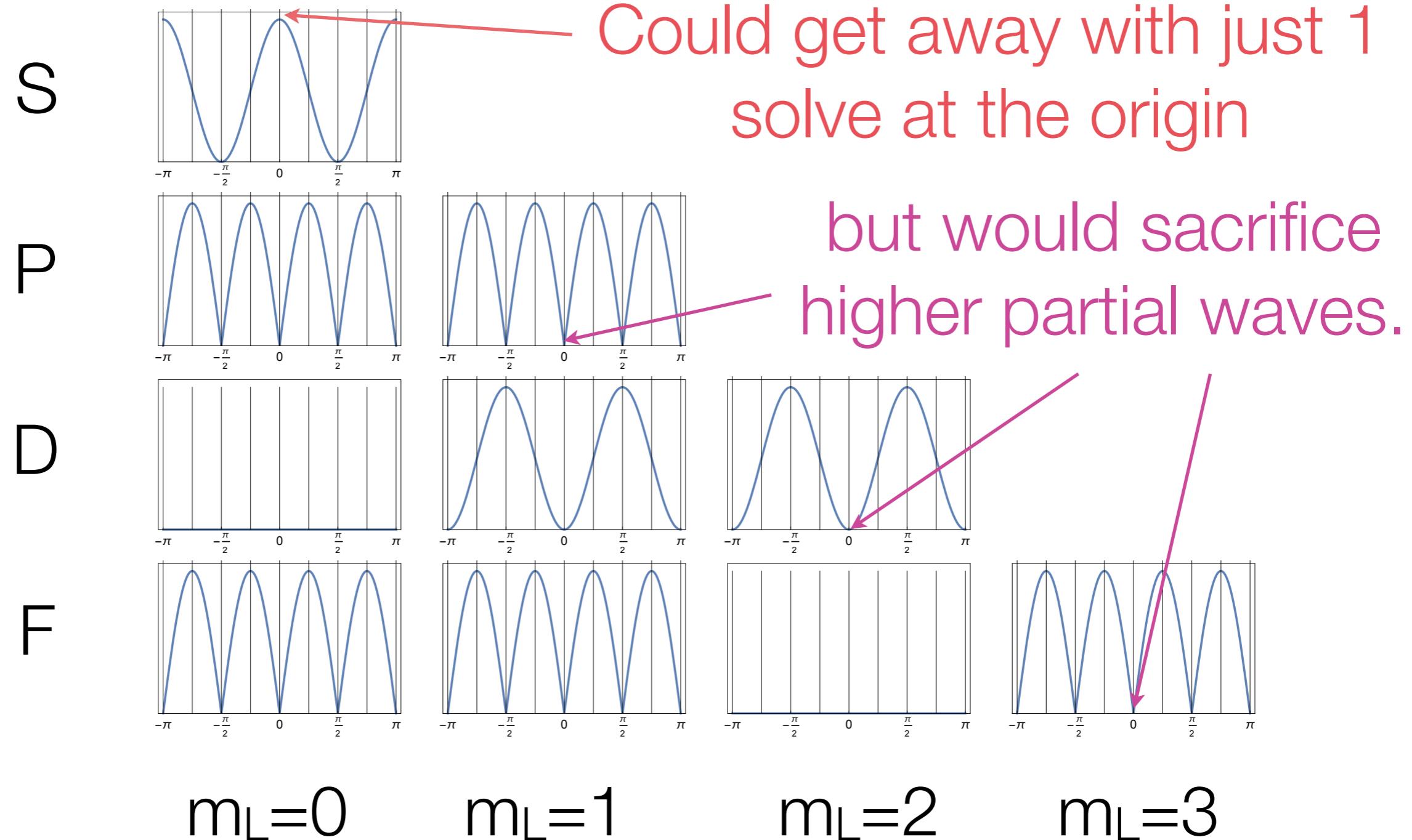


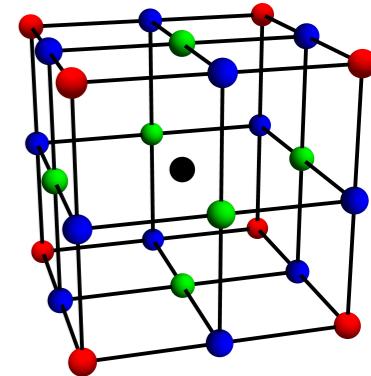


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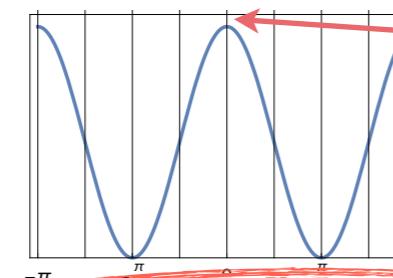


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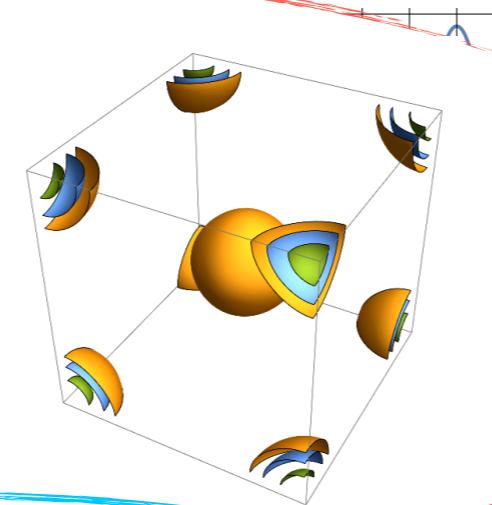
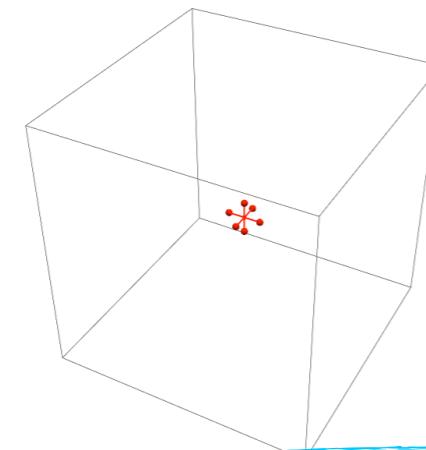
Project Luu & Savage momentum sources to corner as a function of $\pi\Delta x/L$

S



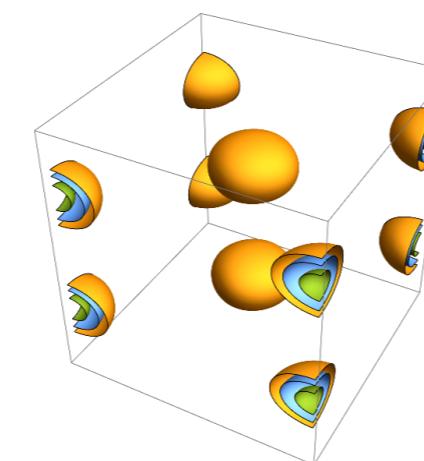
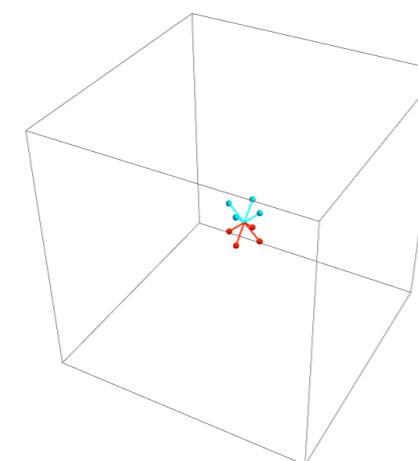
Could get away with just 1
solve at the origin

A_1^+
 $n^2=1$

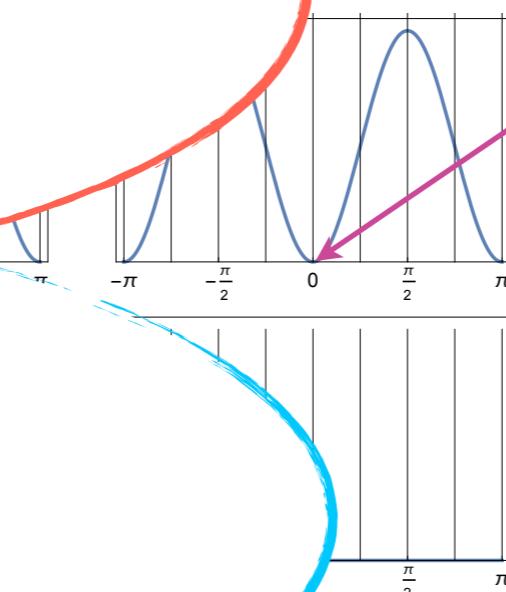


but would sacrifice
higher partial waves.

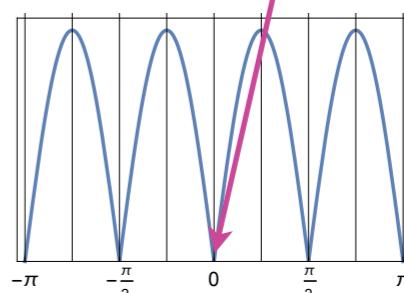
T_{1^-}
 $n^2=2$

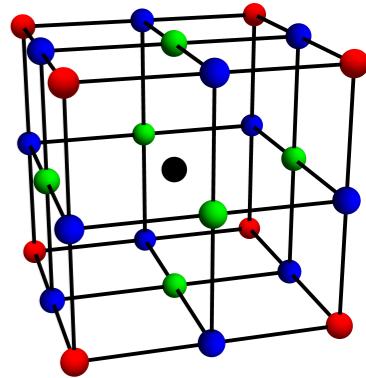


$m_L=2$



$m_L=3$

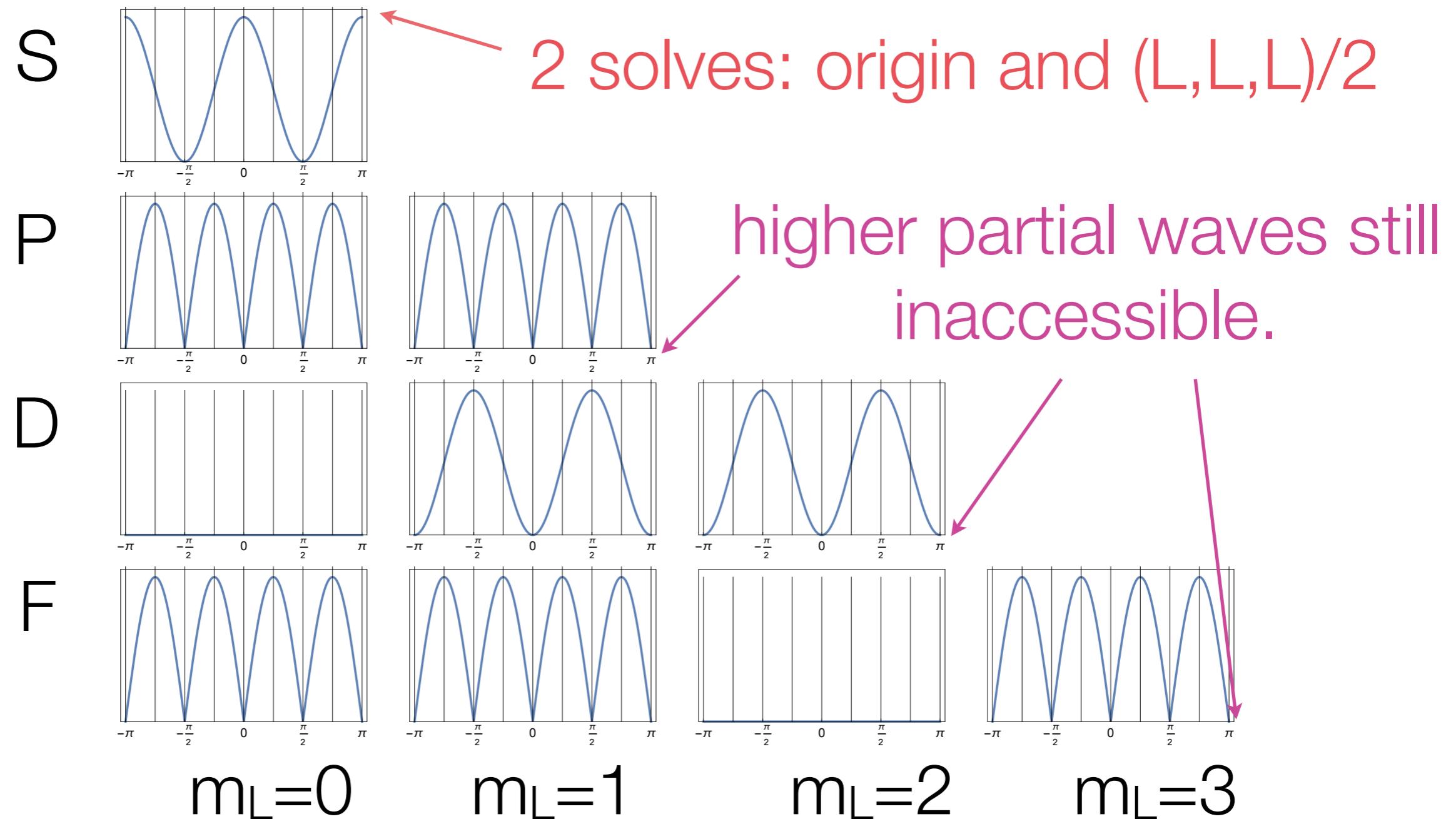




Source Overlap

Luu & Savage 1101.3347 (arXiv version is better!)

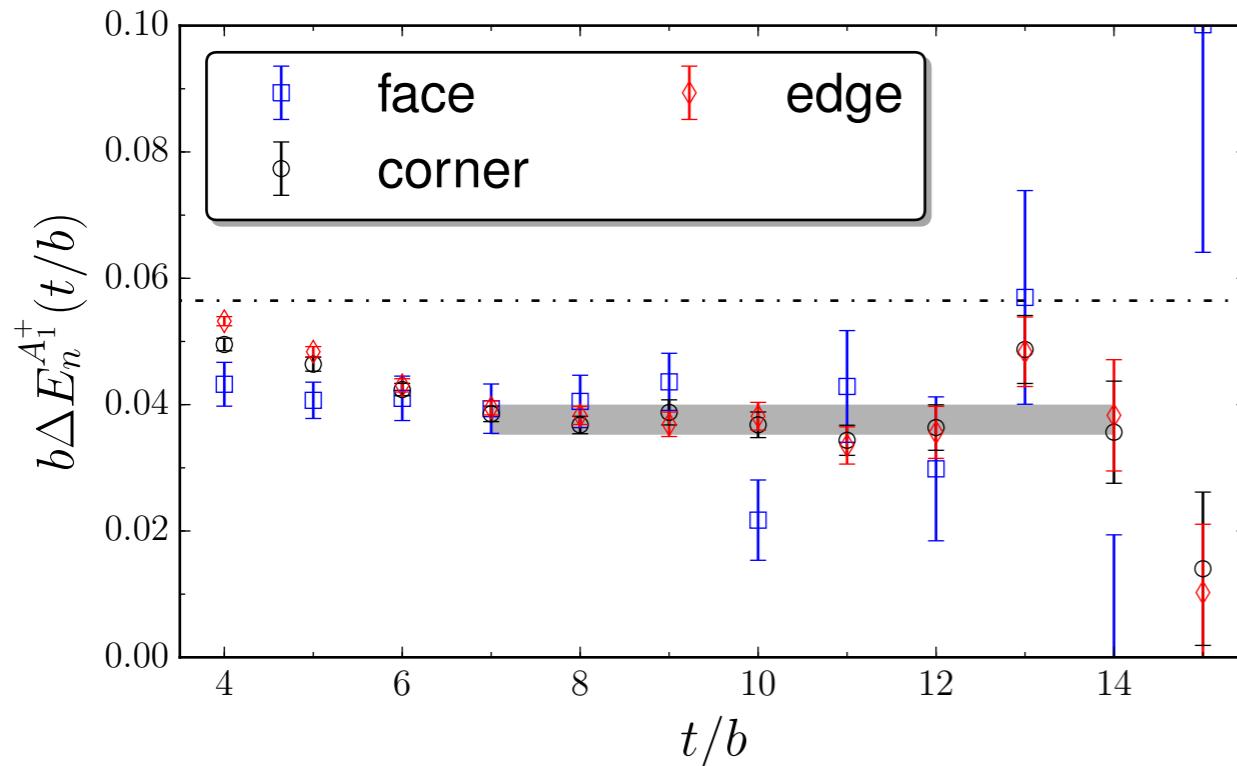
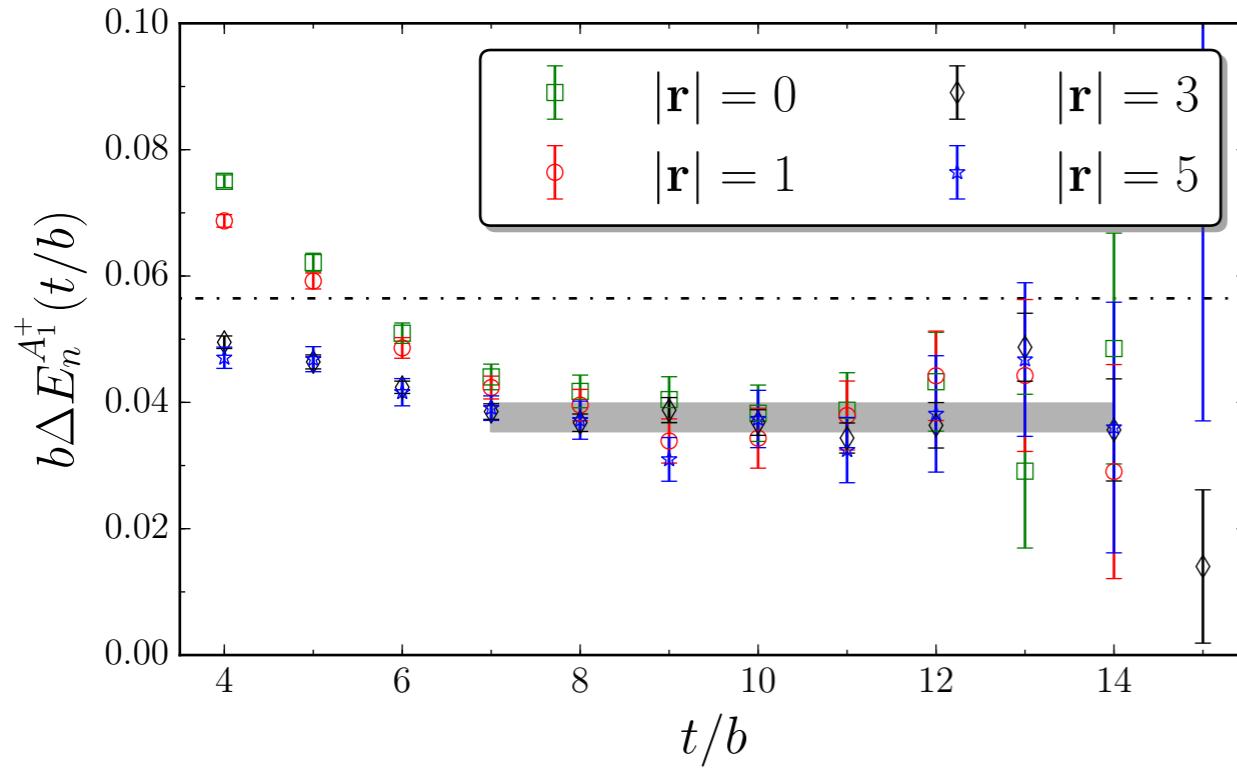
Project Luu & Savage momentum sources to corner as a function of $\pi\Delta x/L$



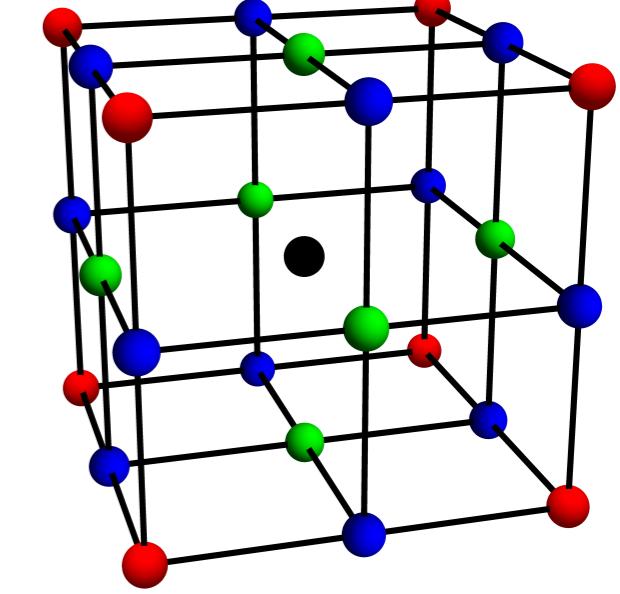
Different Sources Agree

CaLLat PLB 765:285-292 (2017)

WM/JLab cfgs.
 $m_\pi \sim 800$ MeV
 $b \sim 0.145$ fm



$L=24$
 $A_1^+ n^2=1$

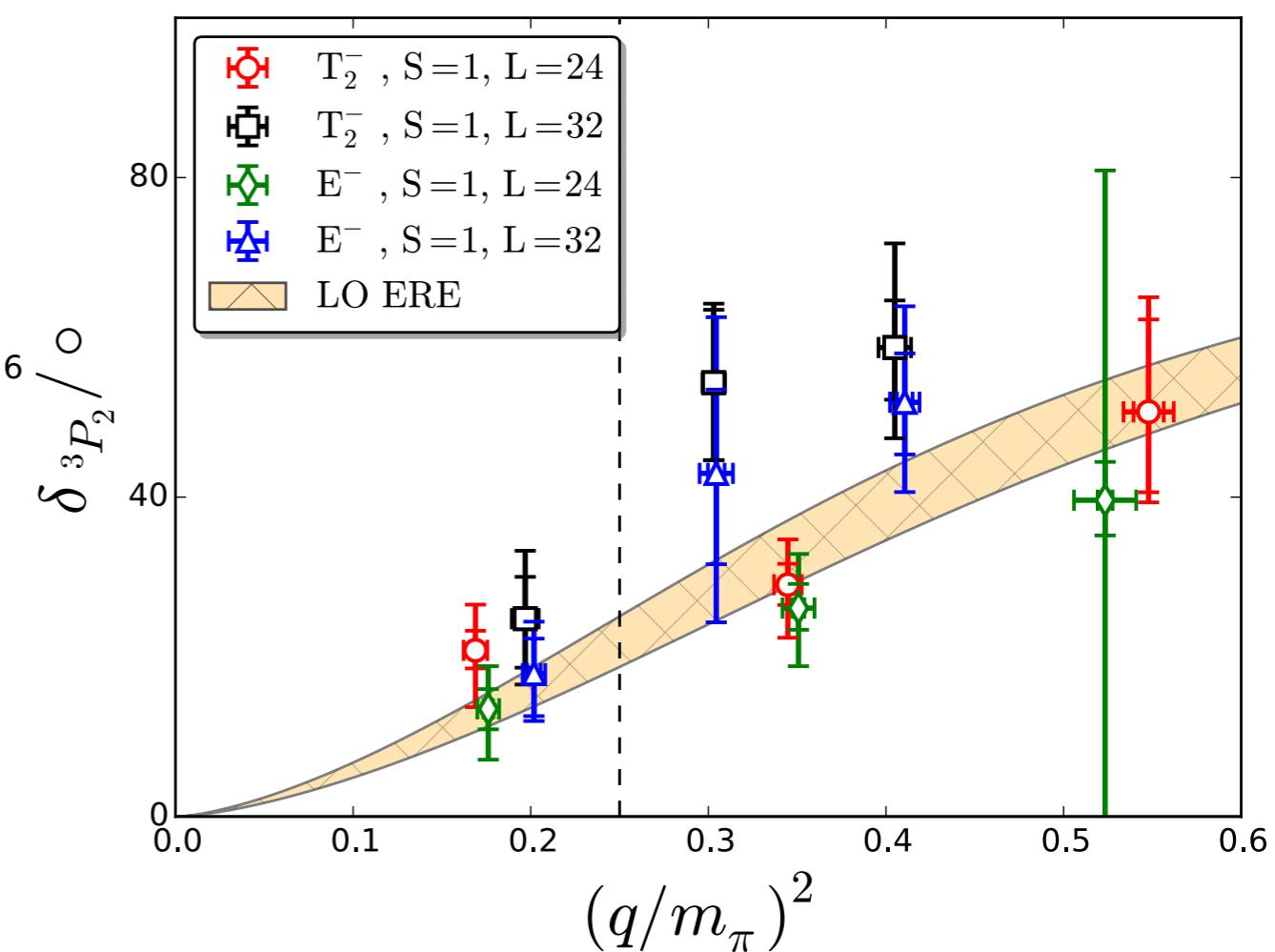
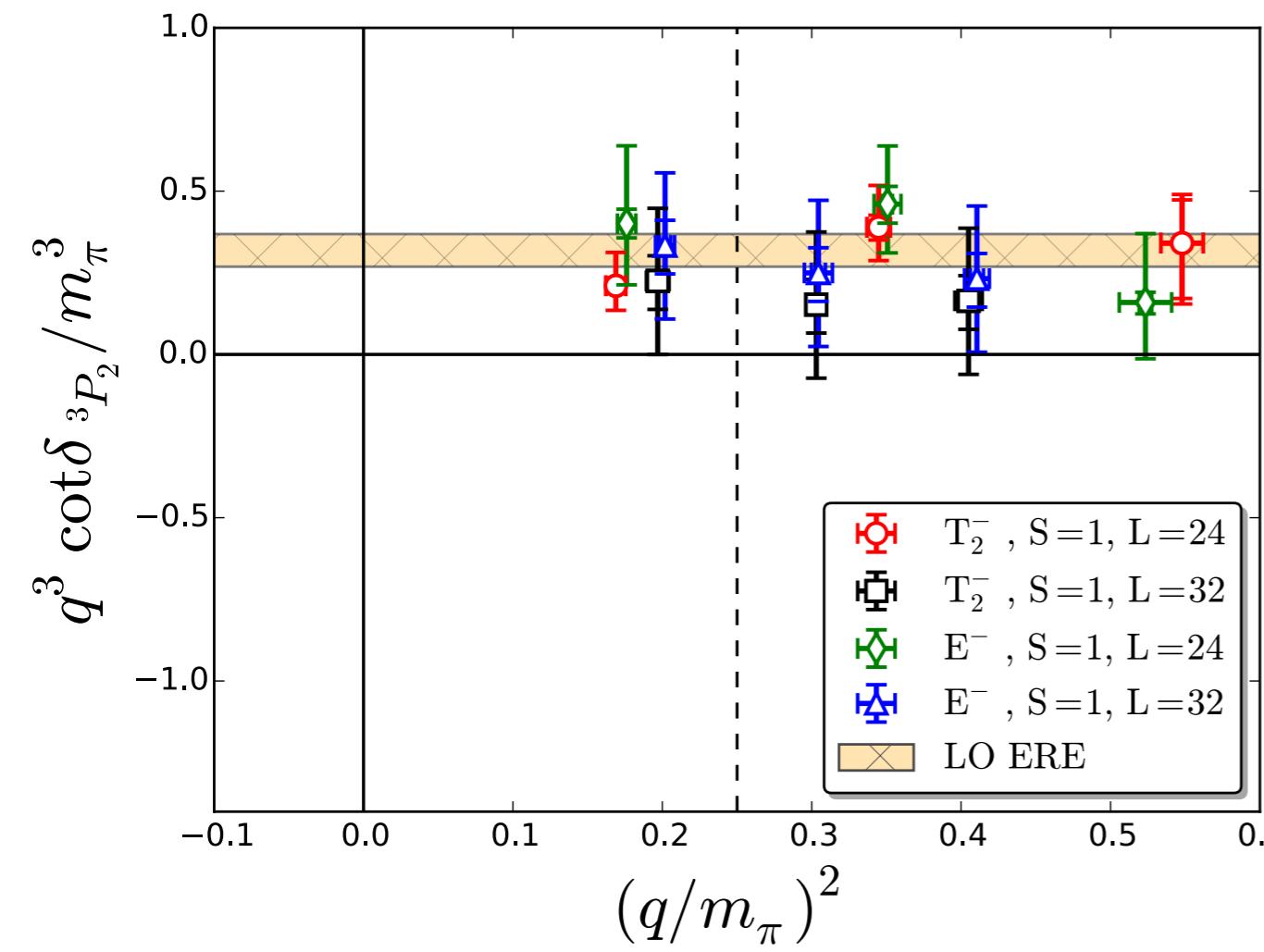


| name | $\Delta x \sim$ | # solve |
|--------|-----------------|---------|
| local | (0, 0, 0) | 1 |
| face | (0, 0, 1) | 6 |
| edge | (0, 1, 1) | 12 |
| corner | (1, 1, 1) | 8 |

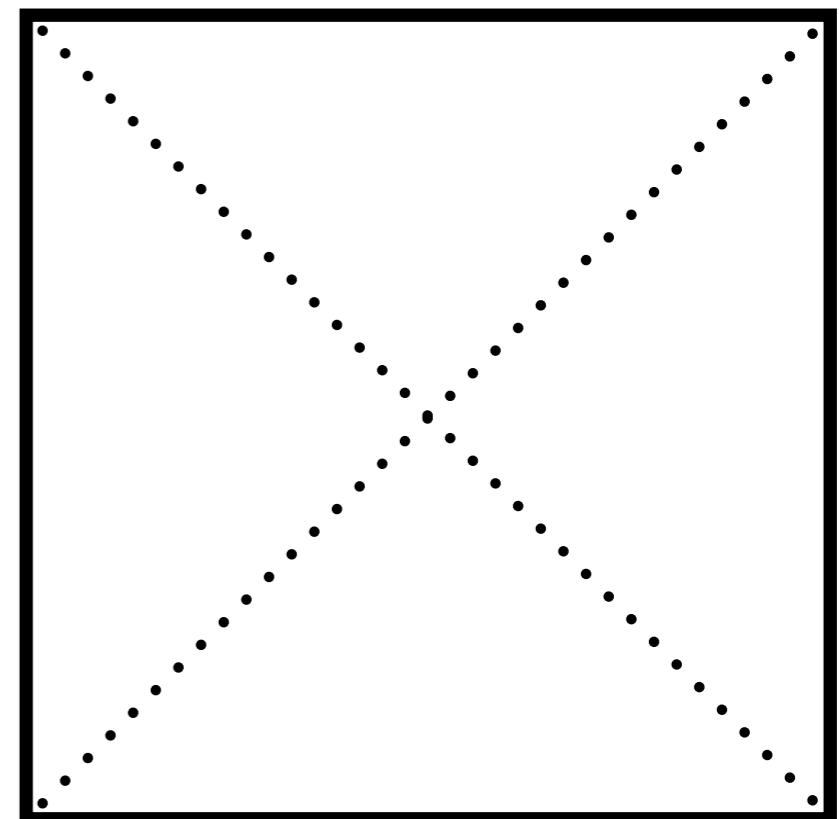
I=1 P-wave

CalLat PLB 765:285-292 (2017)

WM/JLab cfgs.
 $m_\pi \sim 800$ MeV
 $b \sim 0.145$ fm

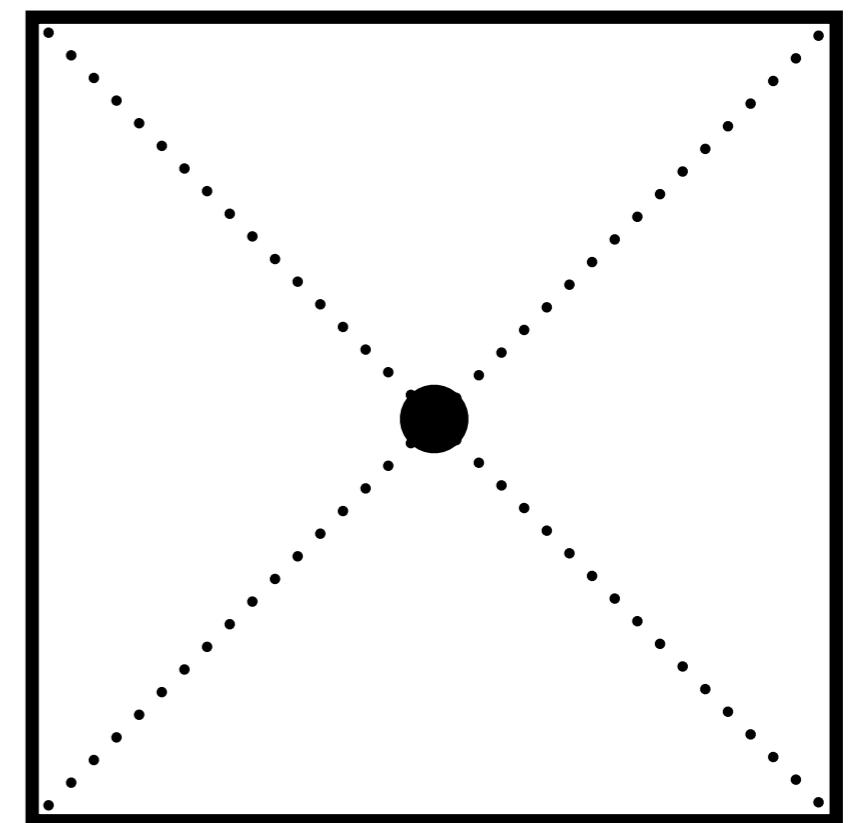


Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

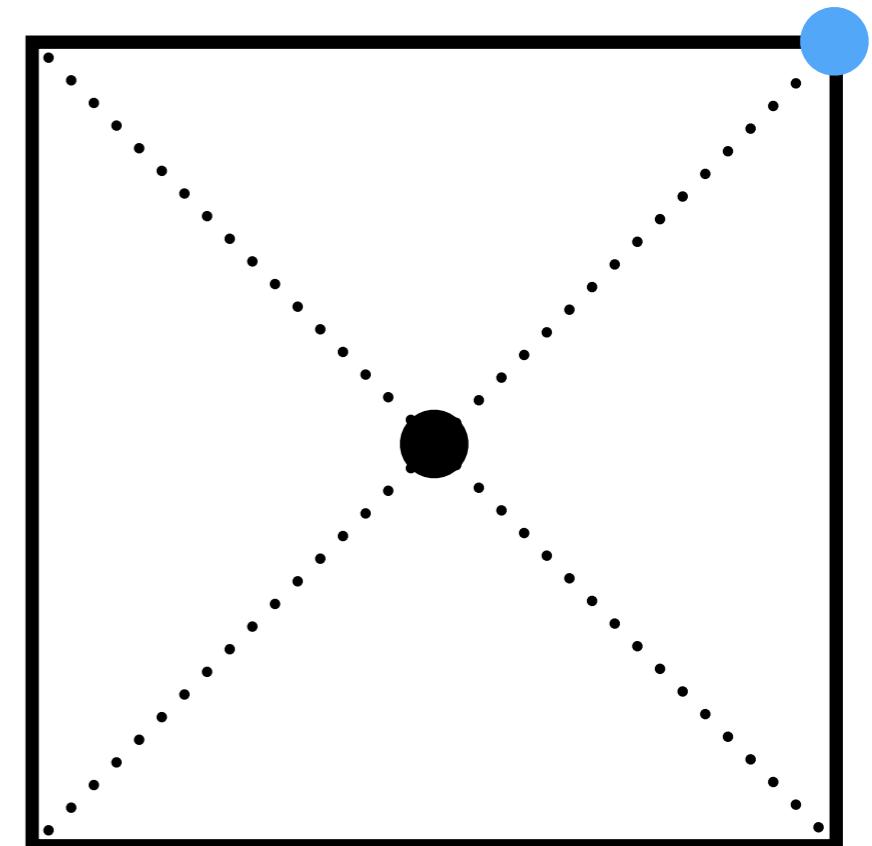
$O = (0,0,0)$



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$\mathbf{O} = (0,0,0)$$

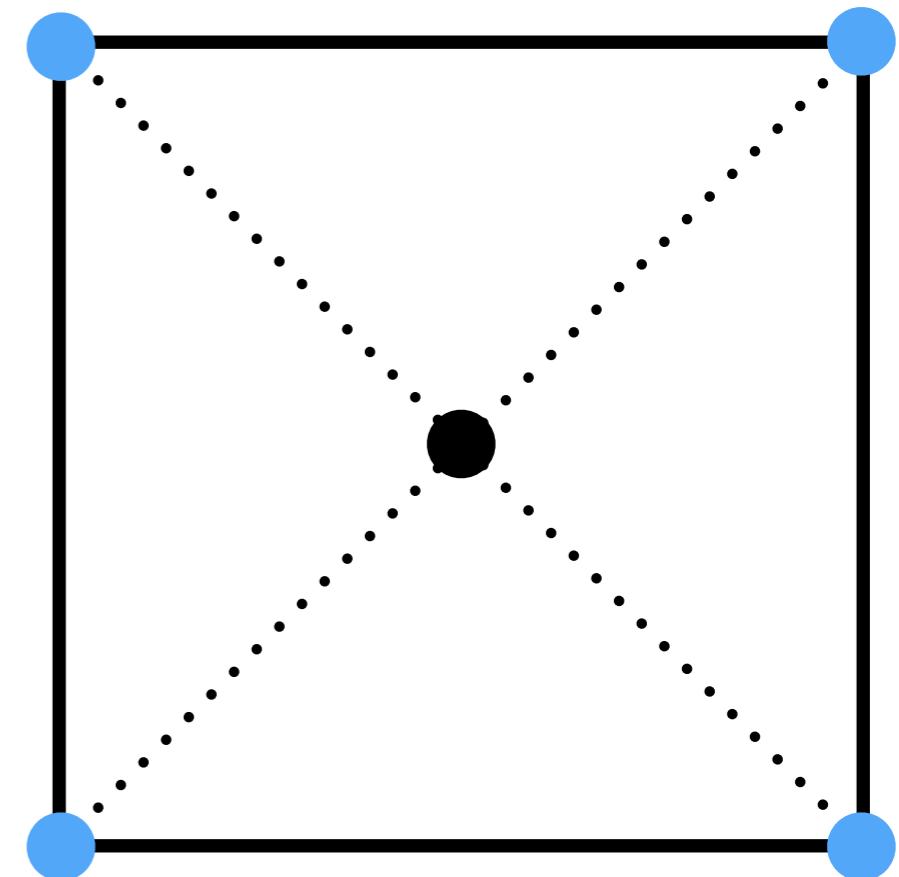
$$\mathbf{A} = (\mathbf{L}, \mathbf{L}, \mathbf{L})/2$$



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$\mathbf{O} = (0,0,0)$$

$$\mathbf{A} = (\mathbf{L},\mathbf{L},\mathbf{L})/2$$

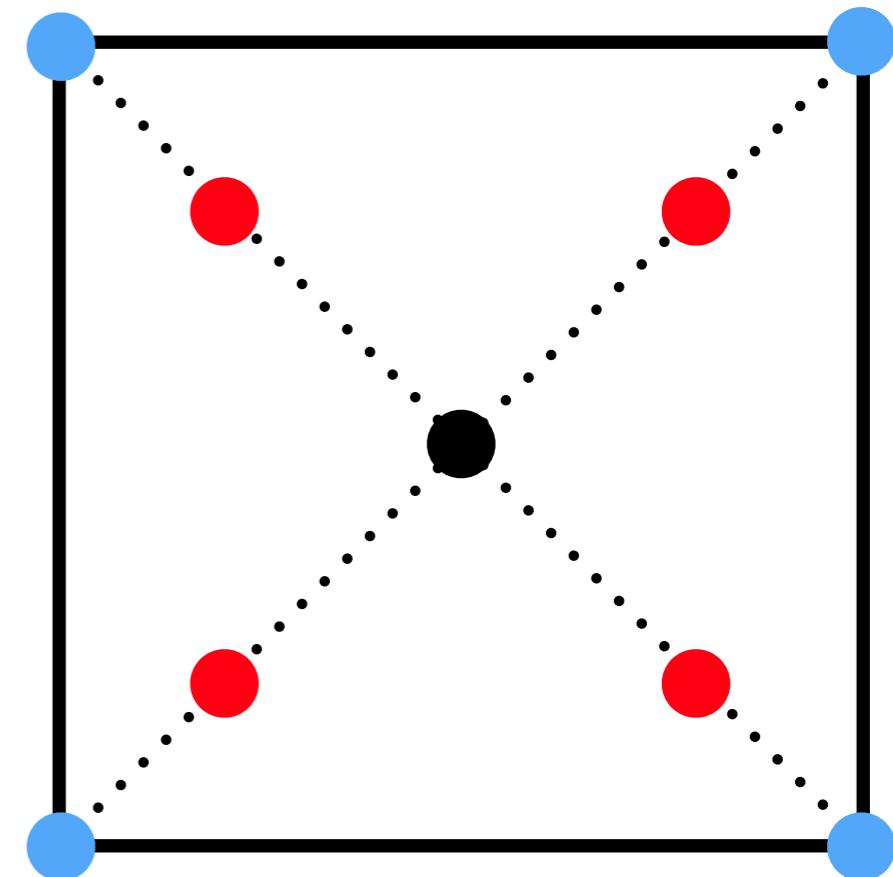


Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$\mathbf{O} = (0,0,0)$$

$$\mathbf{A} = (\mathbf{L}, \mathbf{L}, \mathbf{L})/2$$

$$\mathbf{C} = (\pm 1, \pm 1, \pm 1) \Delta x$$



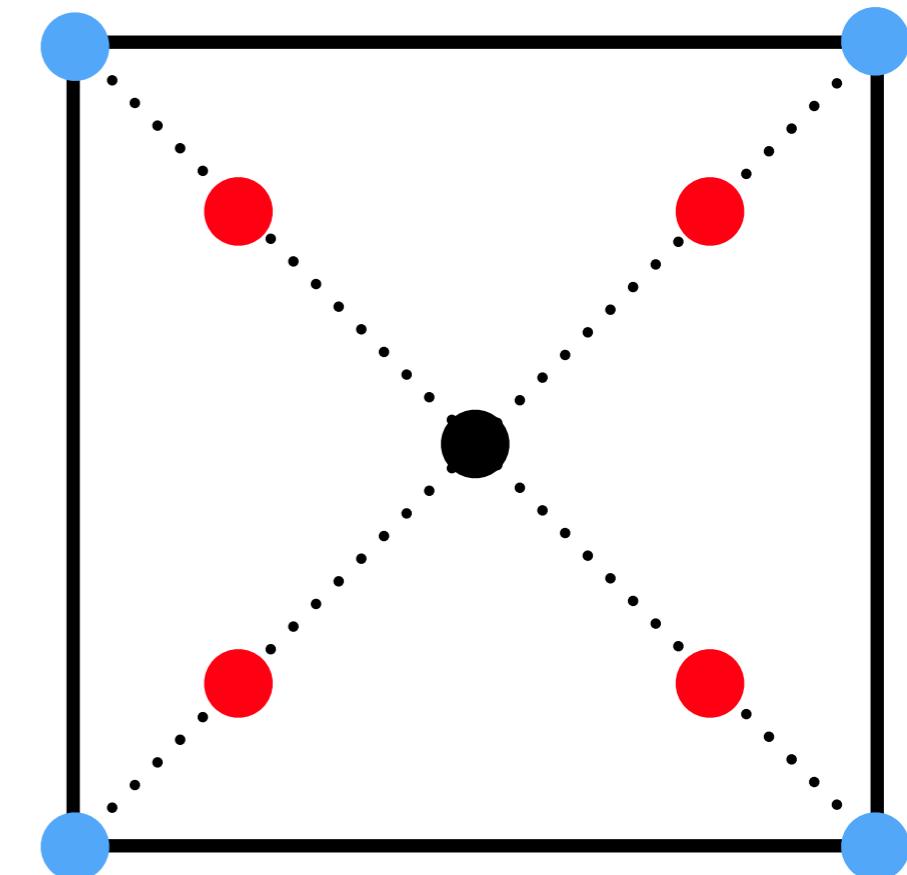
Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$\mathbf{O} = (0,0,0)$$

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10 local sources



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

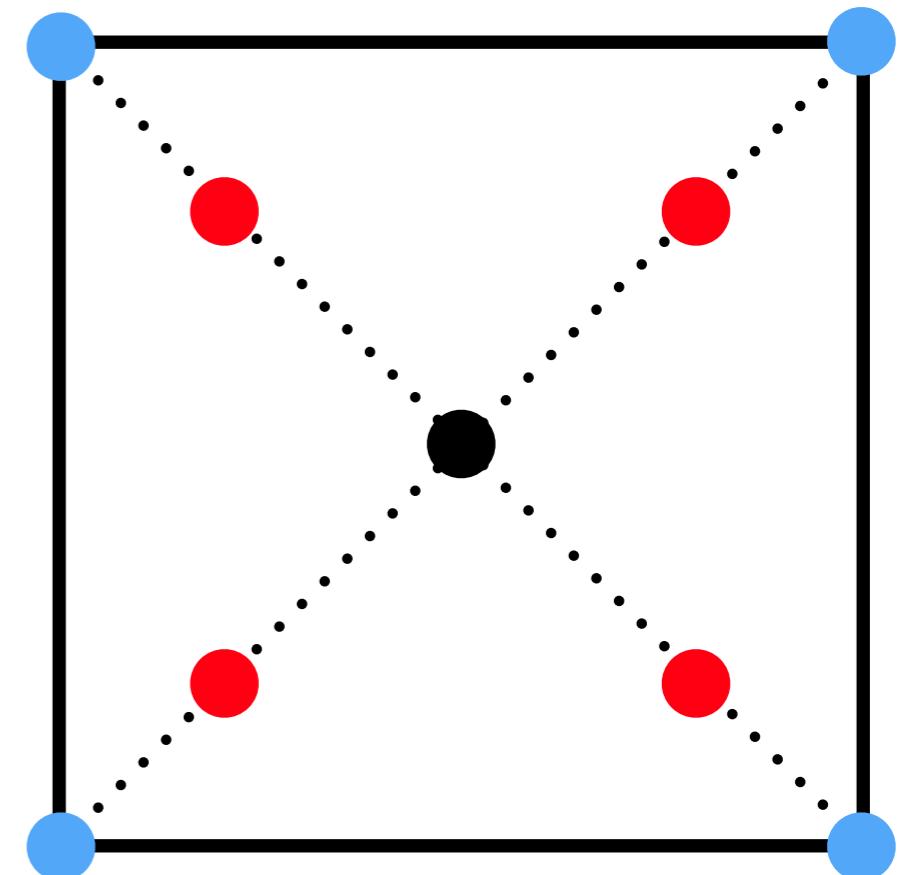
$$O = (0,0,0)$$

$$A = (L,L,L)/2$$

$$C = (\pm 1, \pm 1, \pm 1) \Delta x$$

10 local sources

OA maximally displaced



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$O = (0,0,0)$$

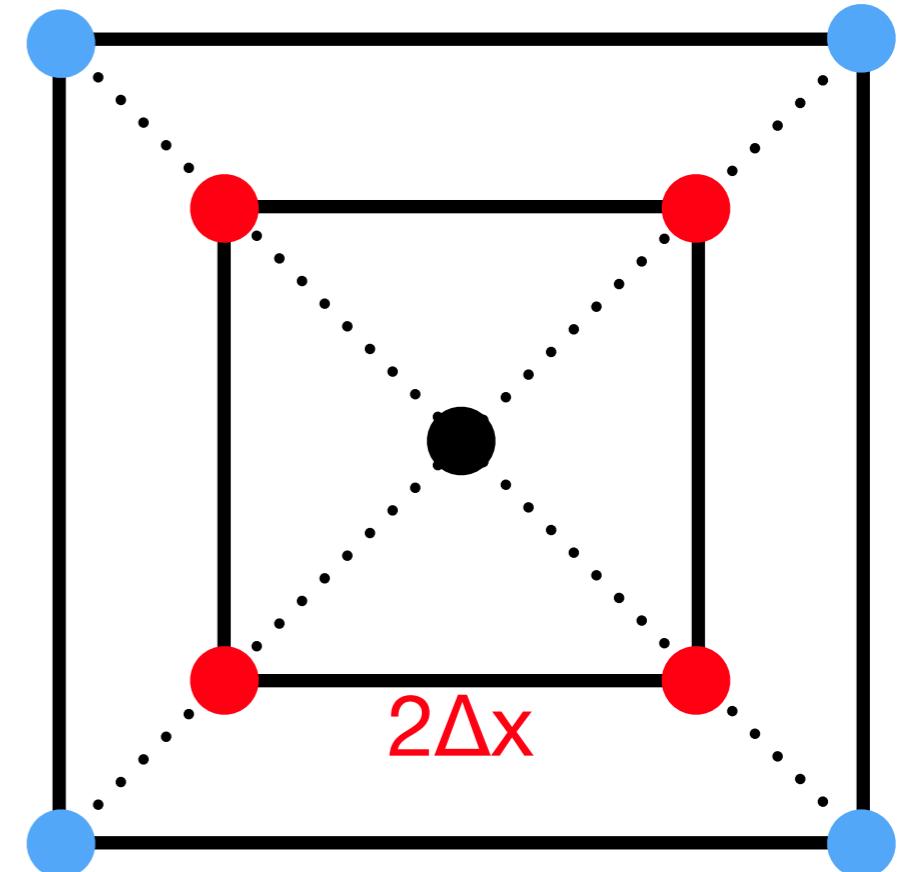
$$A = (L,L,L)/2$$

$$C = (\pm 1, \pm 1, \pm 1) \Delta x$$

10 local sources

OA maximally displaced

OC corner(Δx) around O



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$O = (0,0,0)$$

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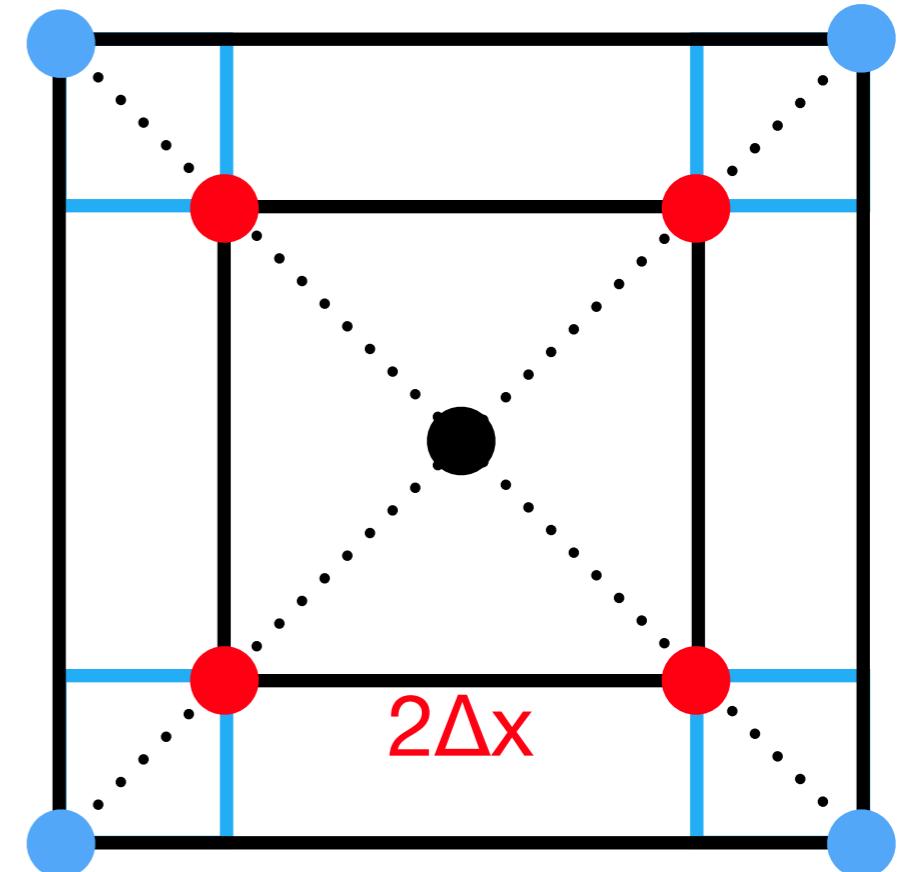
$$C = (\pm 1, \pm 1, \pm 1) \Delta x$$

10 local sources

OA maximally displaced

OC corner(Δx) around O

AC corner($L/2 - \Delta x$) around A



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$O = (0,0,0)$$

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$$C = (\pm 1, \pm 1, \pm 1) \Delta x$$

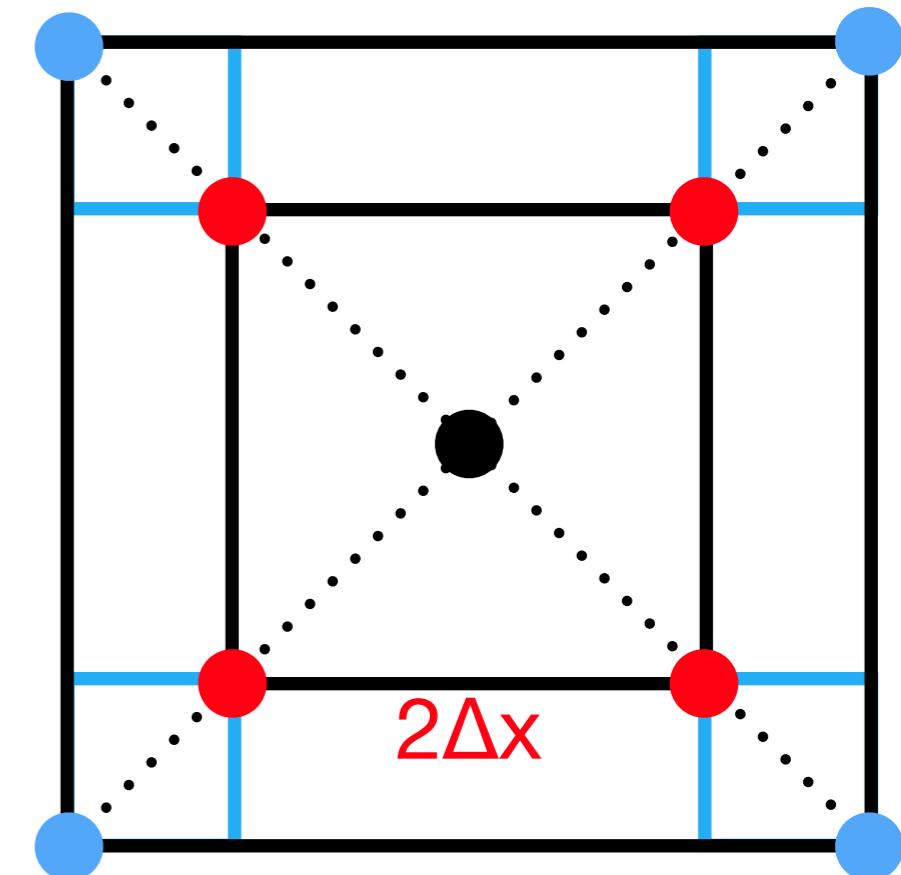
10 local sources

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+ additional combinations of
just C sources



Solid Geometry on the 3-Torus for Fun and Profit: Propagator Reuse

$$\mathbf{O} = (0,0,0)$$

$$\mathbf{A} = (\mathbf{L}, \mathbf{L}, \mathbf{L})/2$$

$$\mathbf{C} = (\pm 1, \pm 1, \pm 1) \Delta x$$

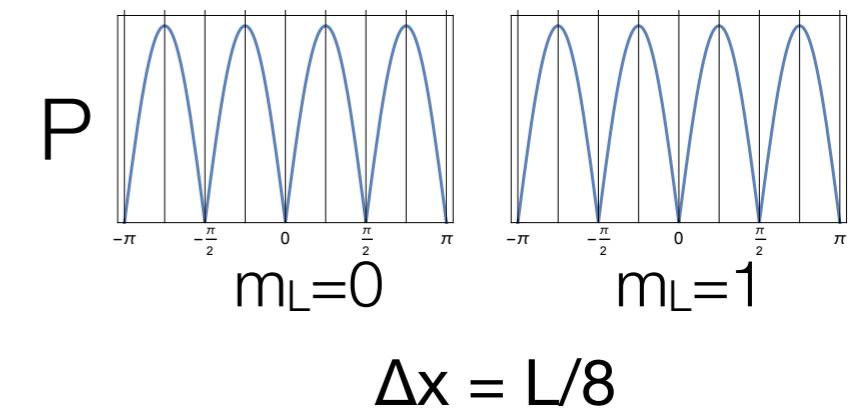
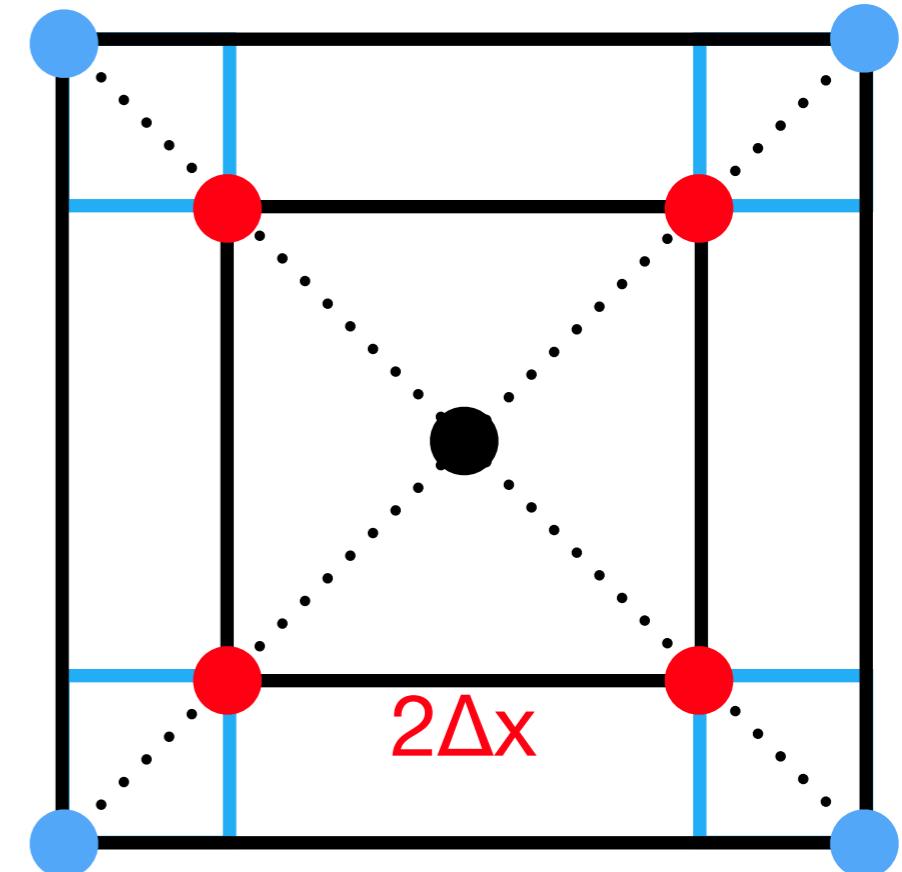
10 local sources

\mathbf{OA} maximally displaced

\mathbf{OC} corner(Δx) around \mathbf{O}

\mathbf{AC} corner($\mathbf{L}/2 - \Delta x$) around \mathbf{A}

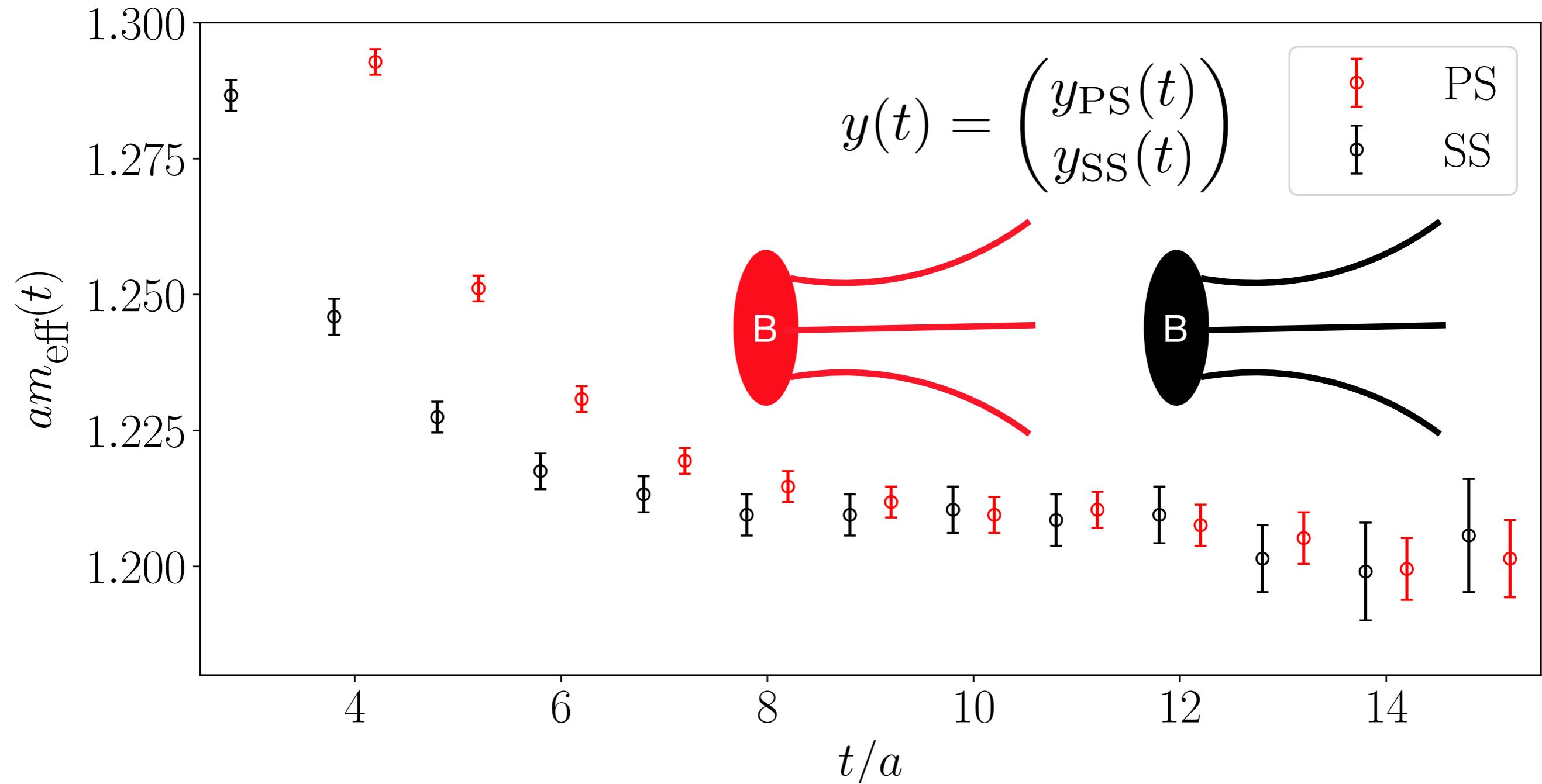
+ additional combinations of
just \mathbf{C} sources



Single-Nucleon Improvements

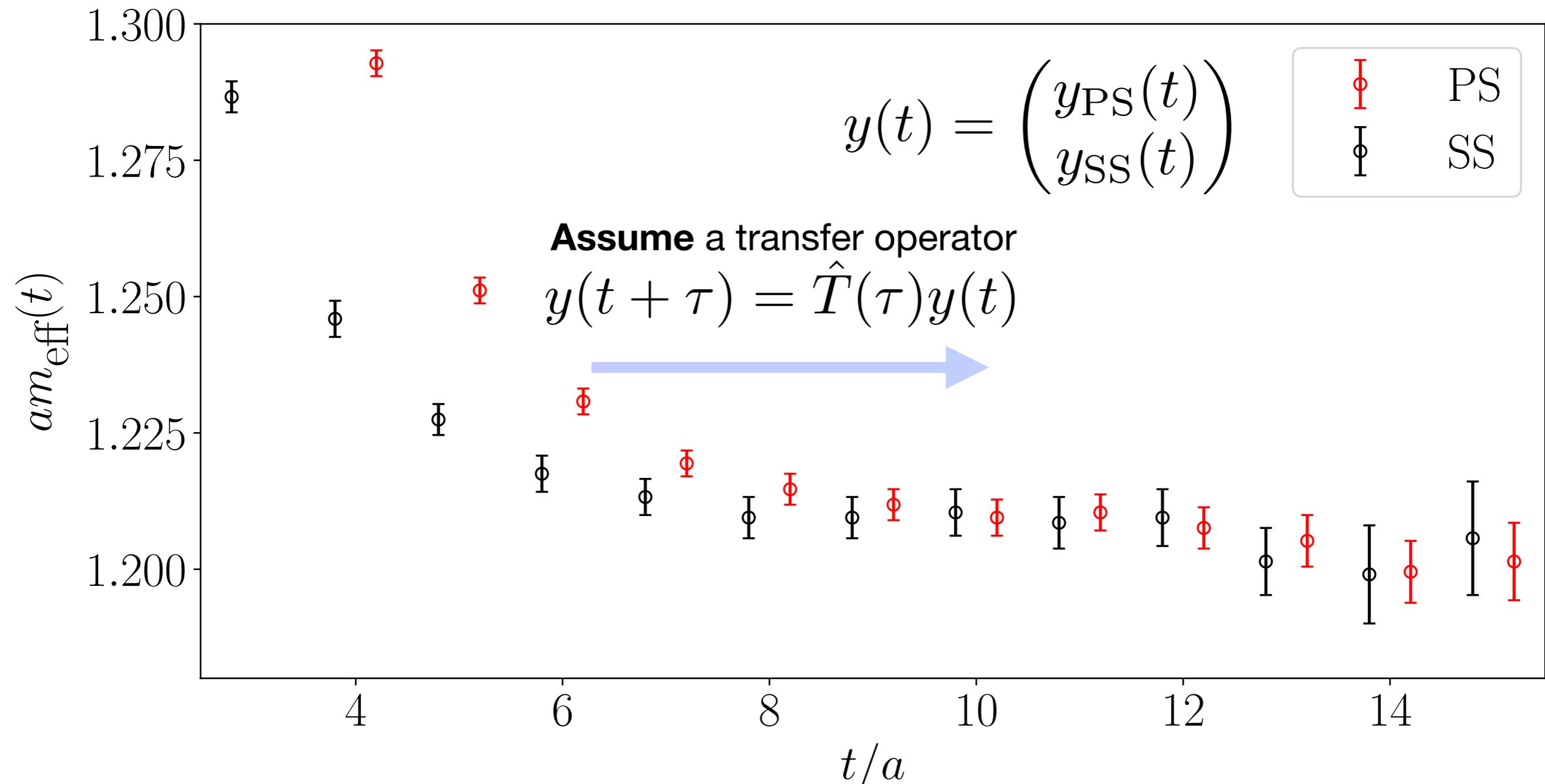
Calm Baryons via Matrix Prony

EPJ Web Conf. 175 (2018) 01016 EB et al.



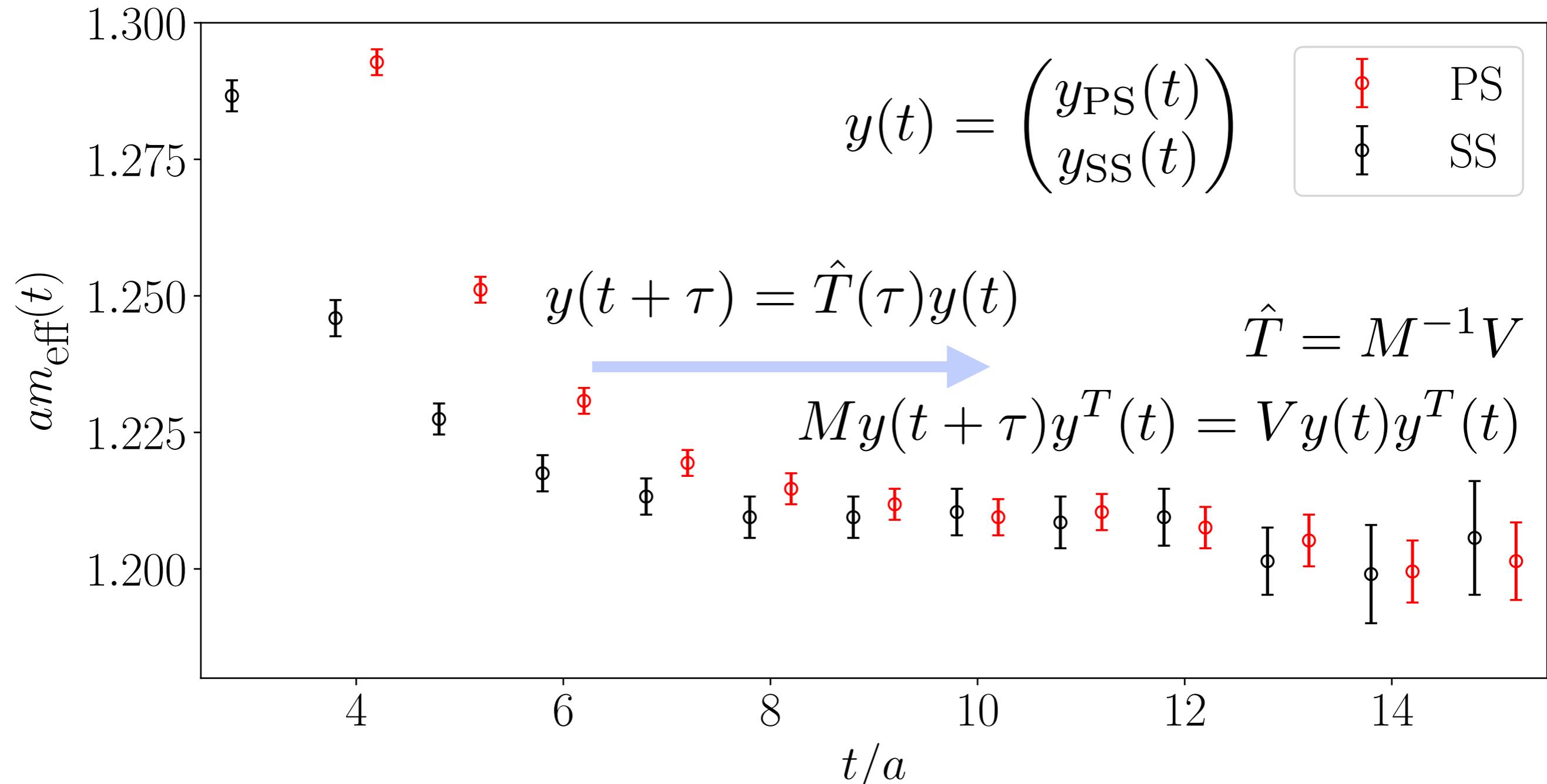
Calm Baryons via Matrix Prony

EPJ Web Conf. 175 (2018) 01016 EB et al.



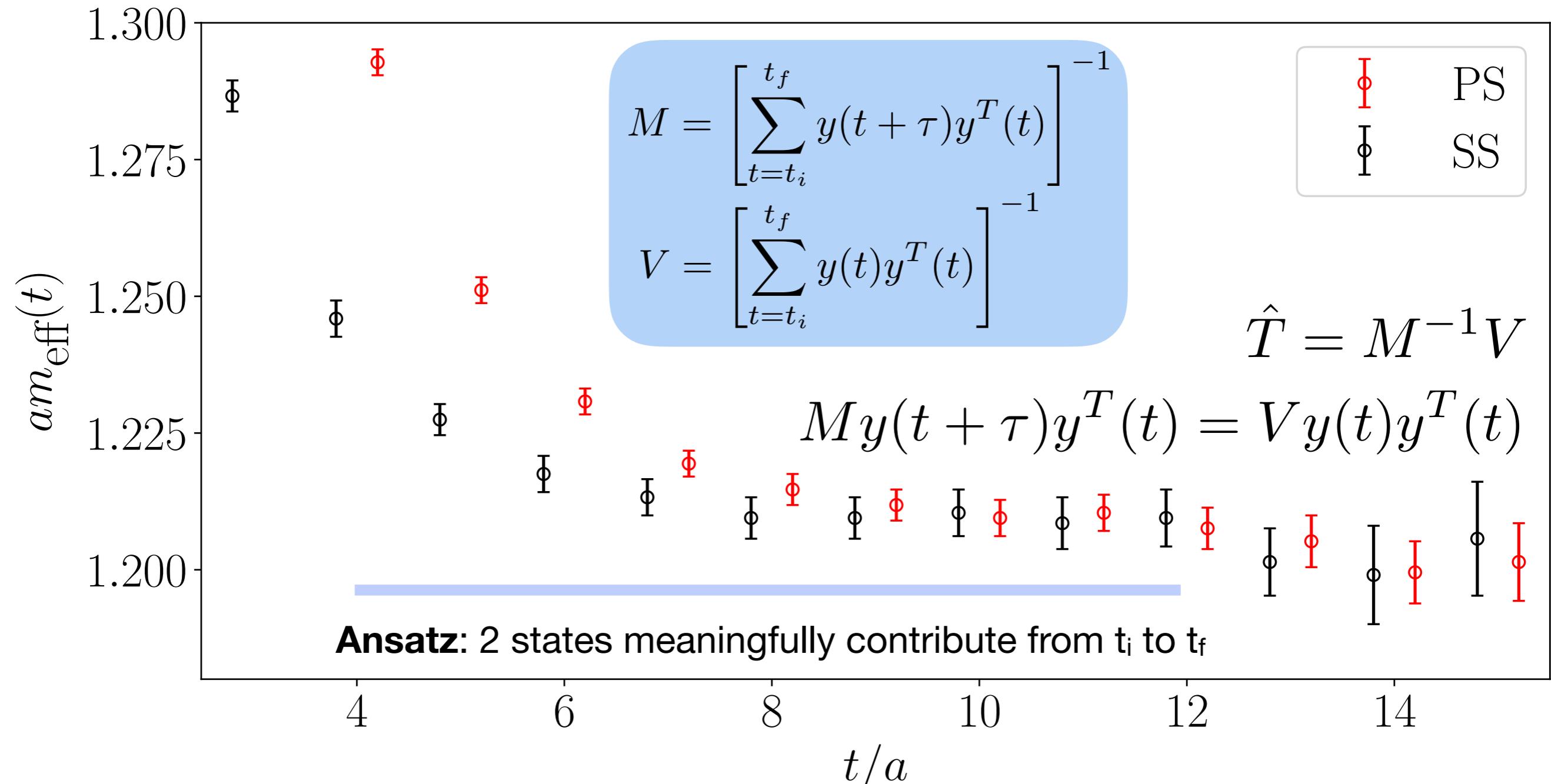
Calm Baryons via Matrix Prony

EPJ Web Conf. 175 (2018) 01016 EB et al.



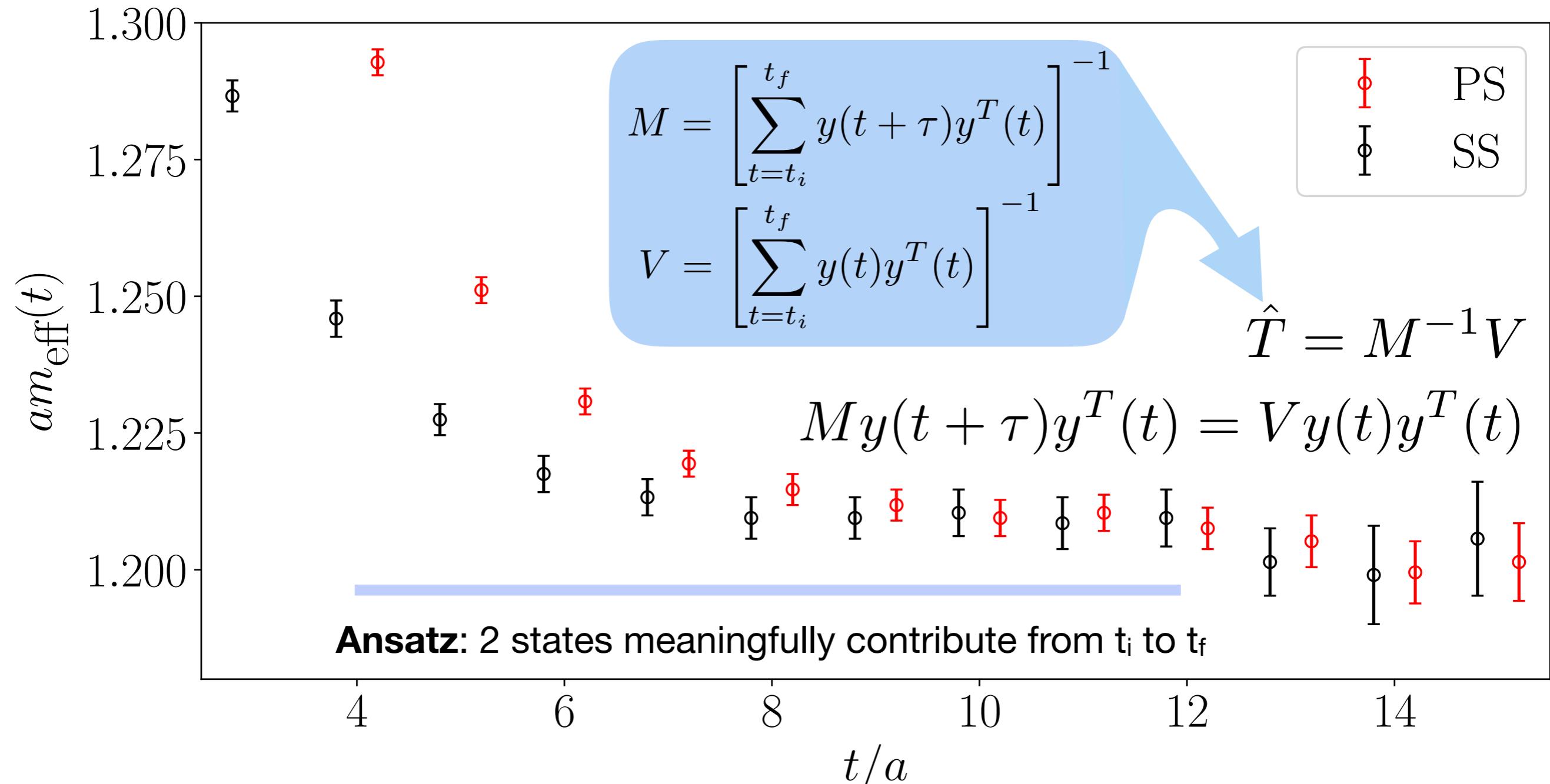
Calm Baryons via Matrix Prony

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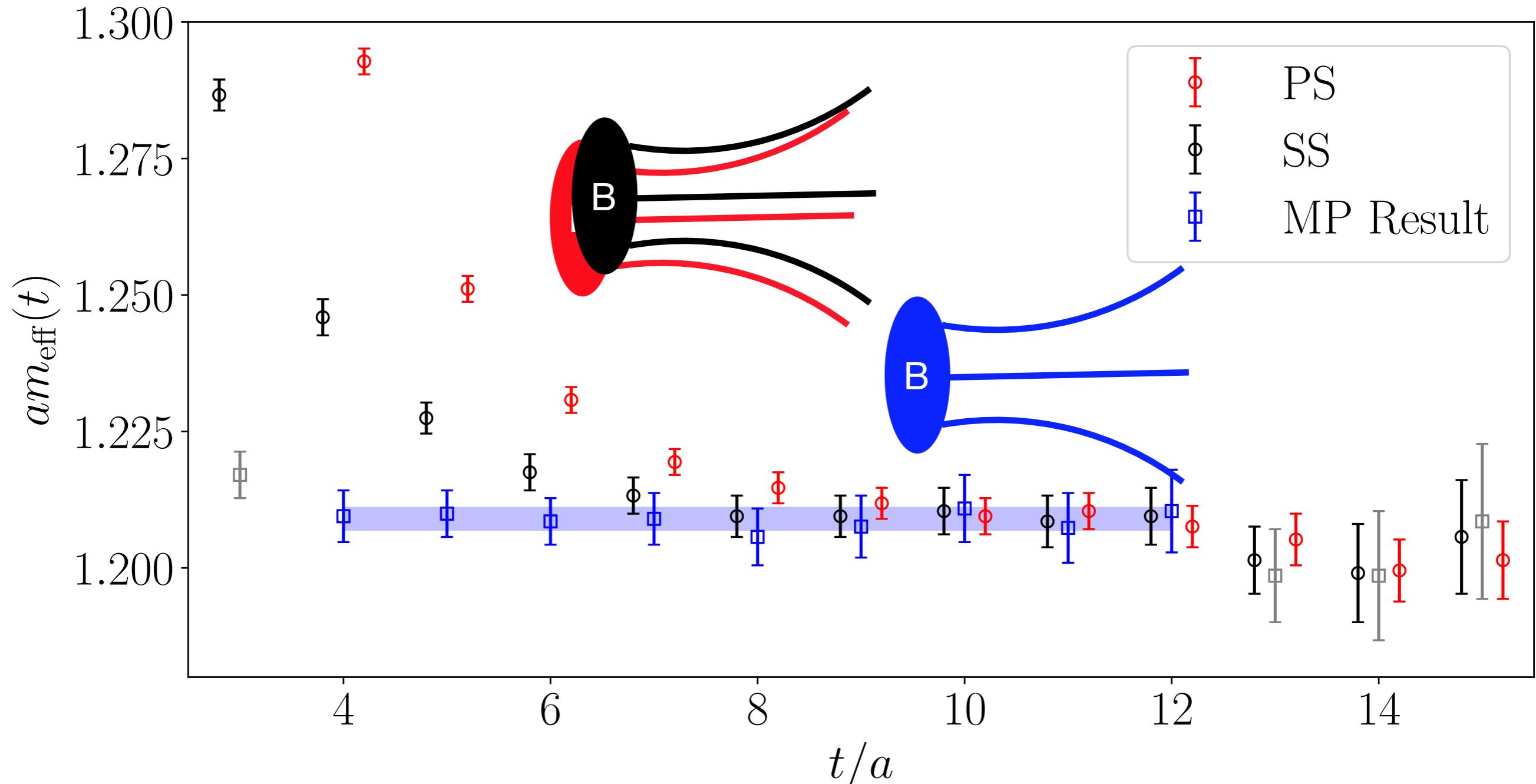
Calm Baryons via Matrix Prony

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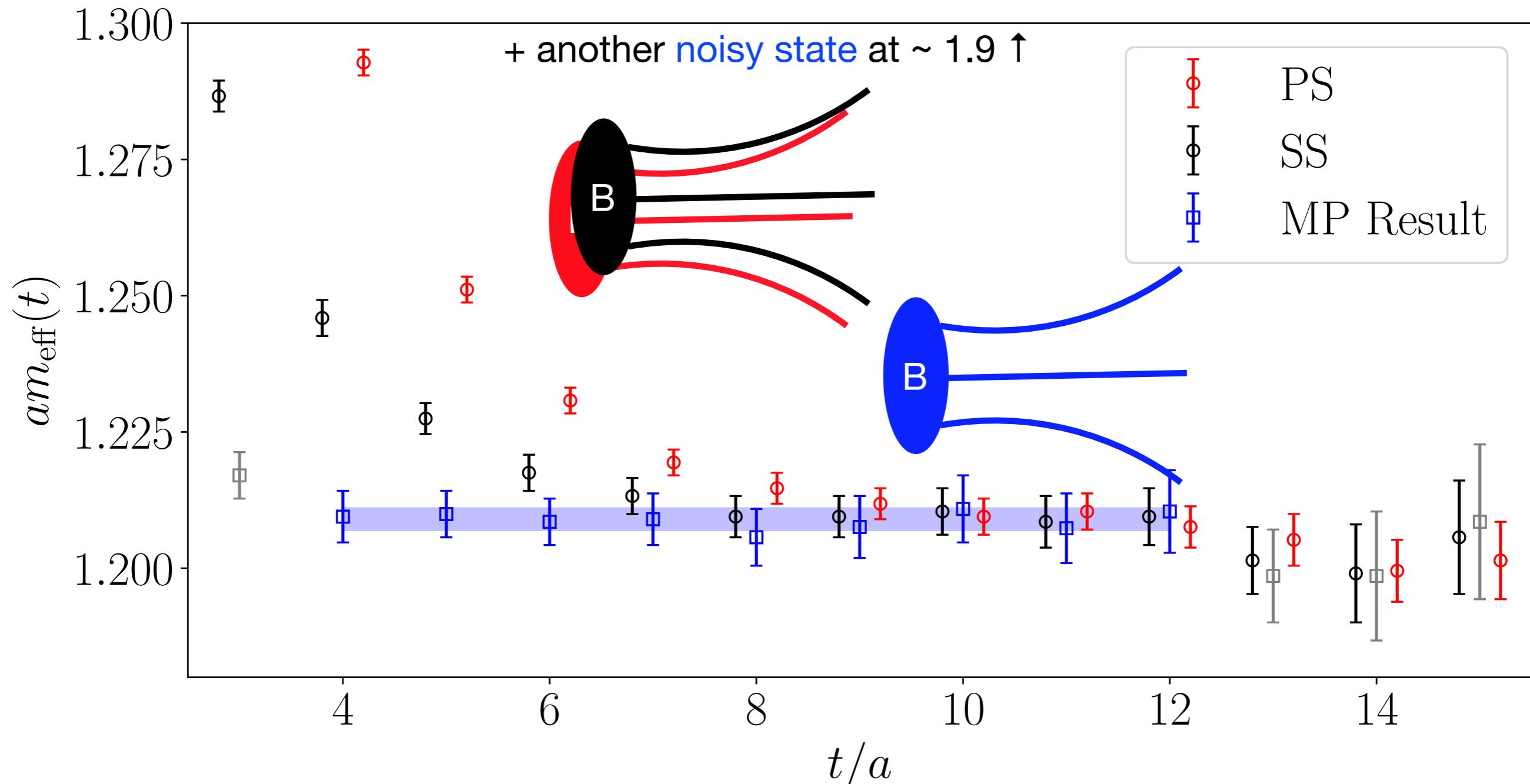
Calm Baryons via Matrix Prony

EPJ Web Conf. 175 (2018) 01016 EB et al.



Calm Baryons via Matrix Prony

EPJ Web Conf. 175 (2018) 01016 EB et al.

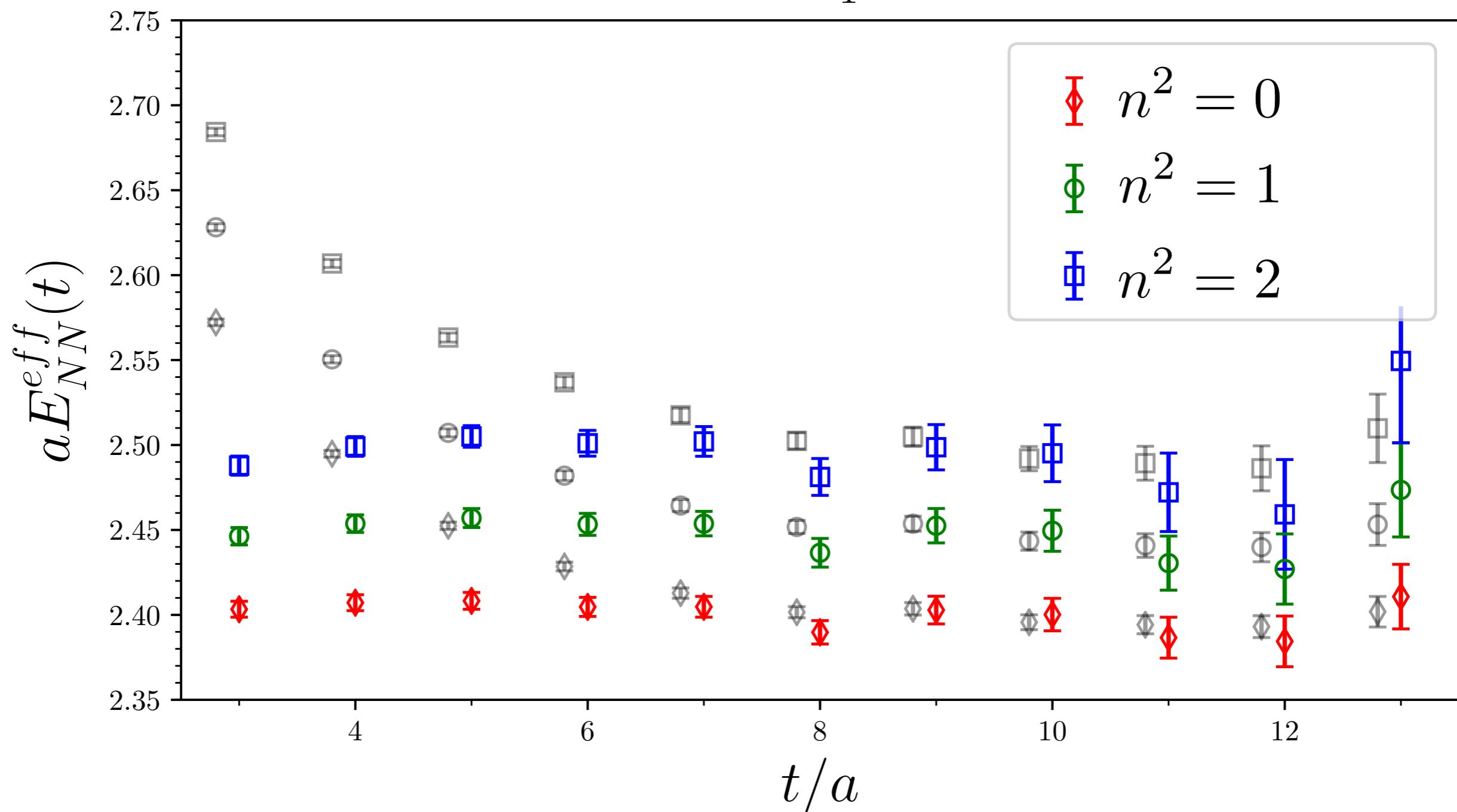


NN with Calm Baryons

EPJ Web Conf. 175 (2018) 01016 EB et al.

WM/JLab cfgs.
 $m_\pi \sim 800$ MeV
 $b \sim 0.145$ fm

$$NN : A_1^+ : {}^1S_0$$

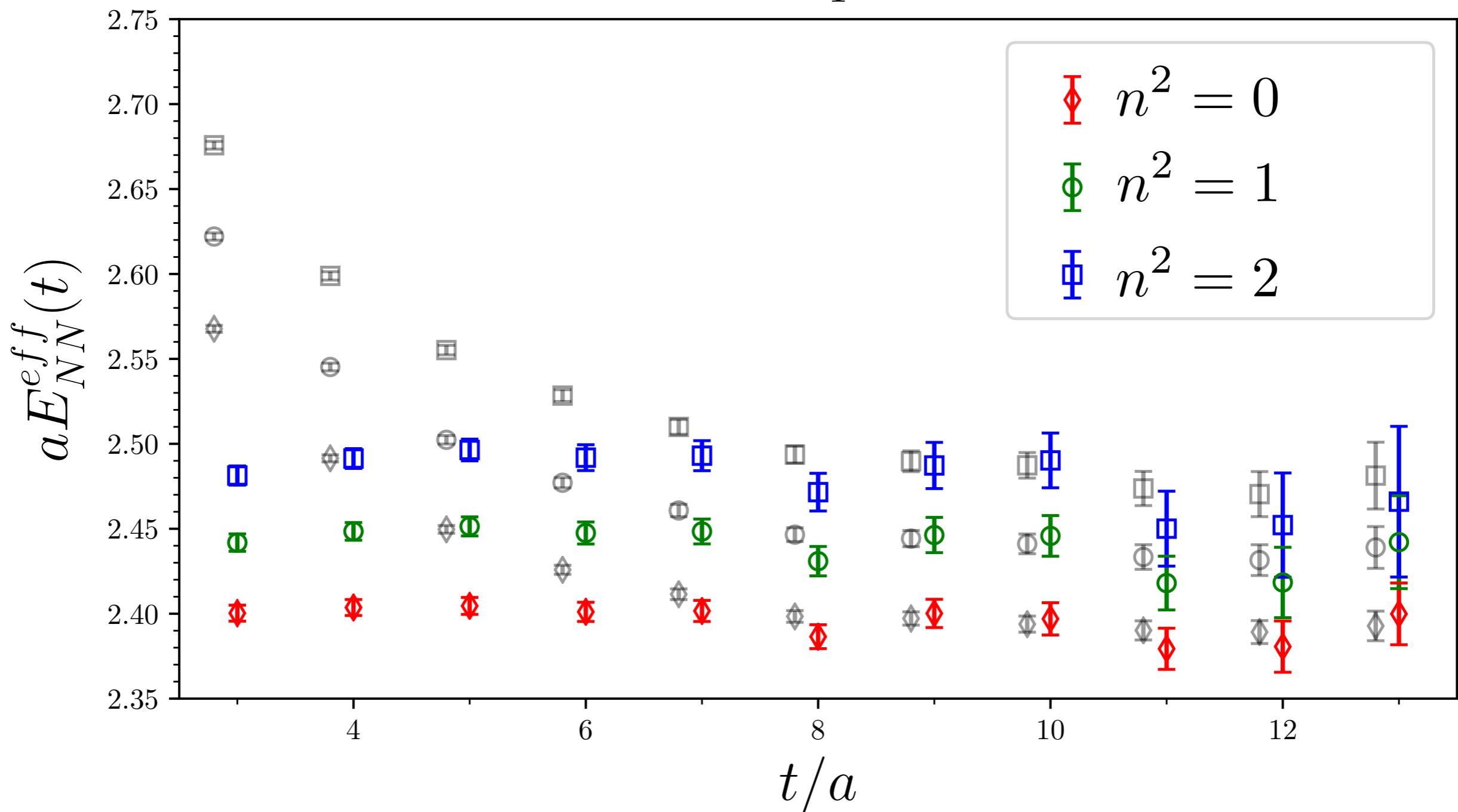


NN with Calm Baryons

EPJ Web Conf. 175 (2018) 01016 EB et al.

WM/JLab cfgs.
 $m_\pi \sim 800$ MeV
 $b \sim 0.145$ fm

$$NN : T_1^+ : {}^3S_1$$



Preliminary NN Results at $m_\pi \sim 350$ MeV

Möbius Domain Wall on HISQ

CaLat PRD96 (2017) 054513

- For g_A we used MILC ensembles of $N_f=2+1+1$ HISQ

Follana et al. PRD 75 (2007) 054502

Bazavov et al. PRD82 (2010) 074501, PRD87 (2013) 054505

- DWF on asqtad quite successful

Renner et al. [LHPC] NPPS 140 (2005) 255-260

LHPC; NPLQCD; Aubin, Laiho, Van de Water; ...

- Well-developed mixed-action EFT

Bar, Bernard, Rupak, Shoresh; Tiburzi; Chen, O'Connell, Van de Water, Walker-Loud; ...

- We generated 10 000 thermalized $24^3 \times 64$ $m_\pi \sim 350$ MeV, $a \sim 0.12$ fm HISQ configurations ($m_\pi L = 5.1$)

milc

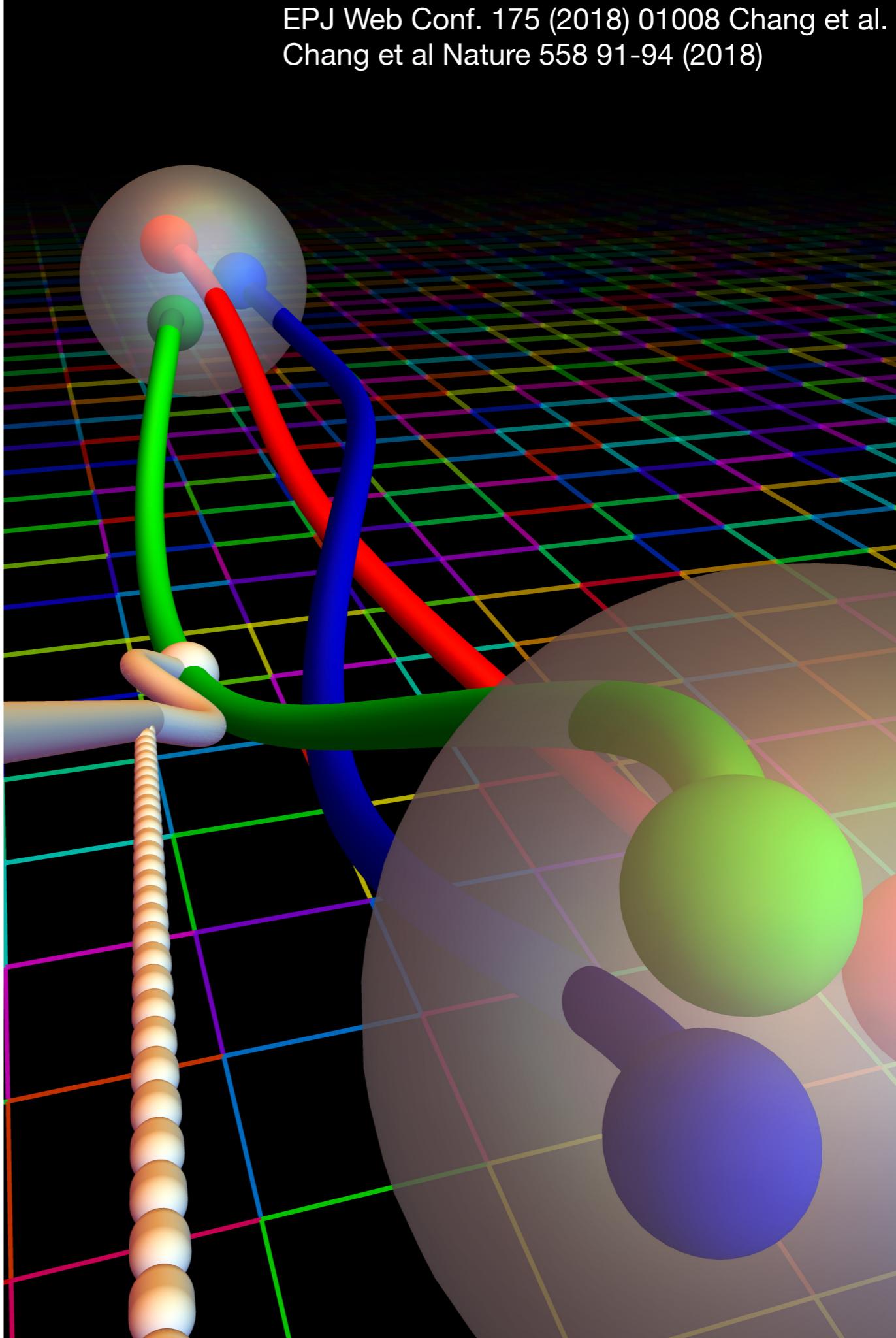
- Fantastic GPU MDWF solver in QUDA

Kim and Izubuchi PoS(LATTICE2013)033

and substantial subsequent enhancements

- (So far) one measurement each.

This means 10 solves on a single time slice!



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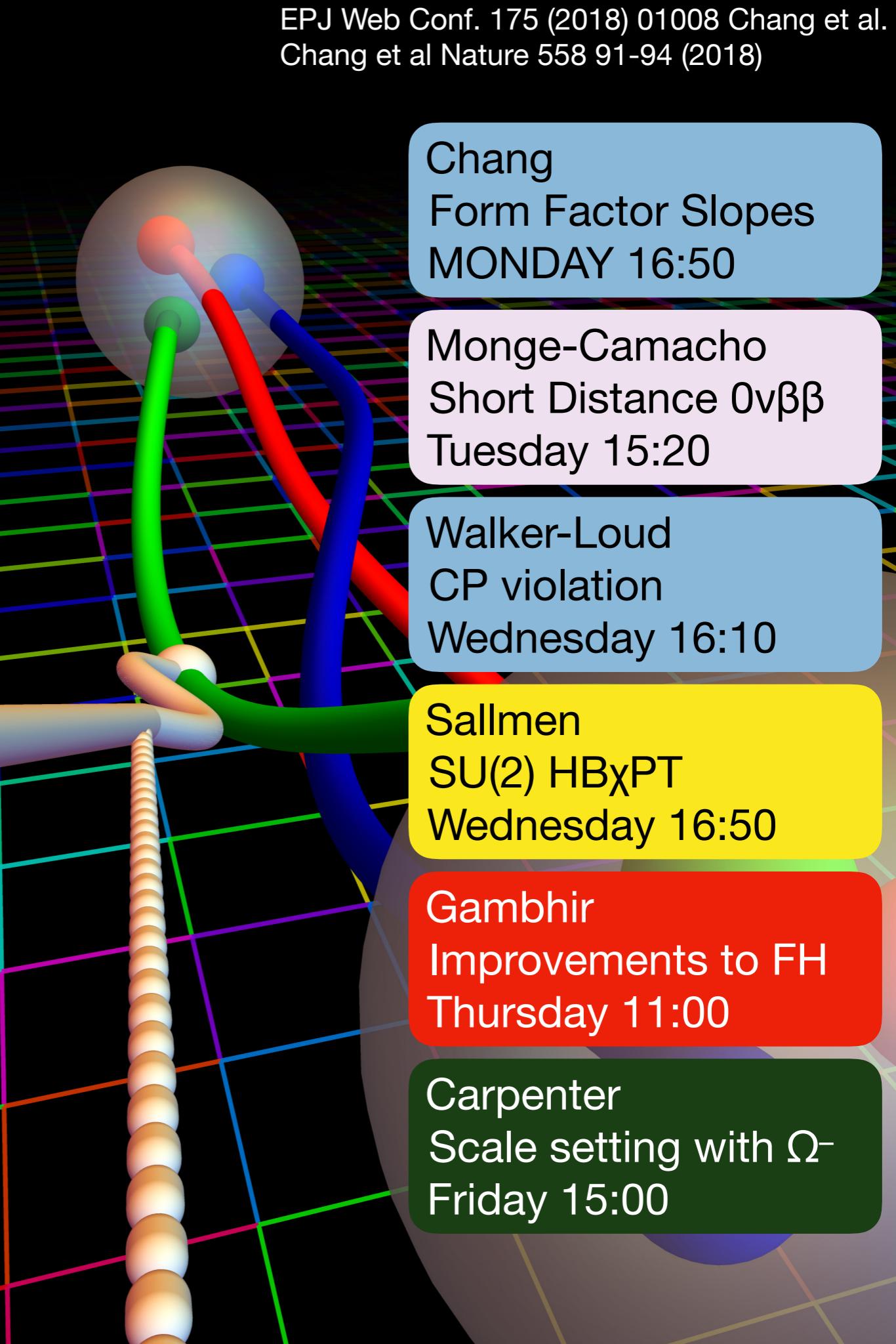
Follana et al. PRD 75 (2007) 054502
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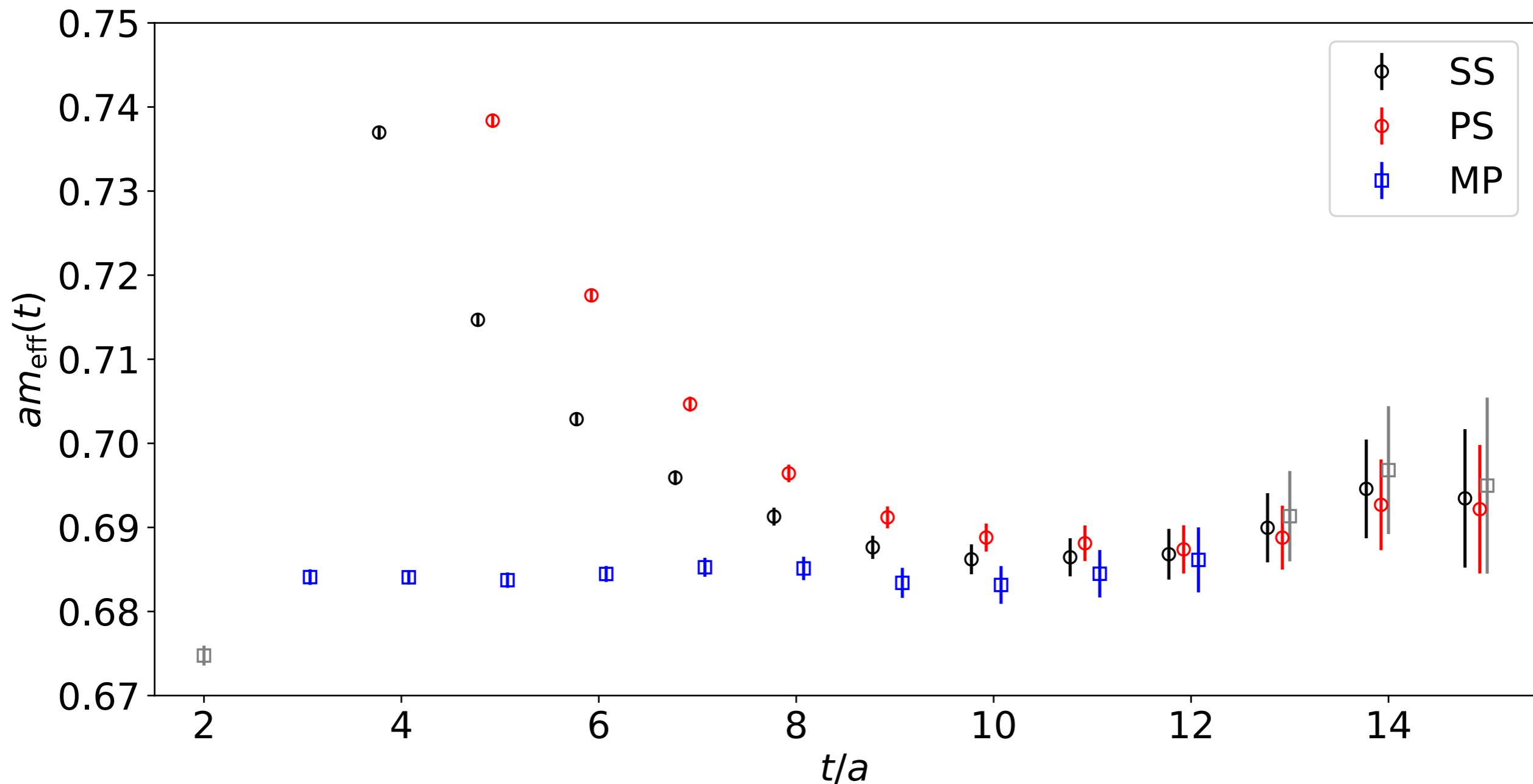
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MDWF on HISQ
a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$

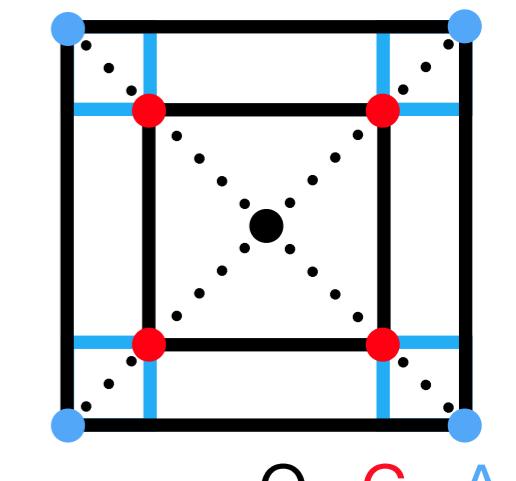
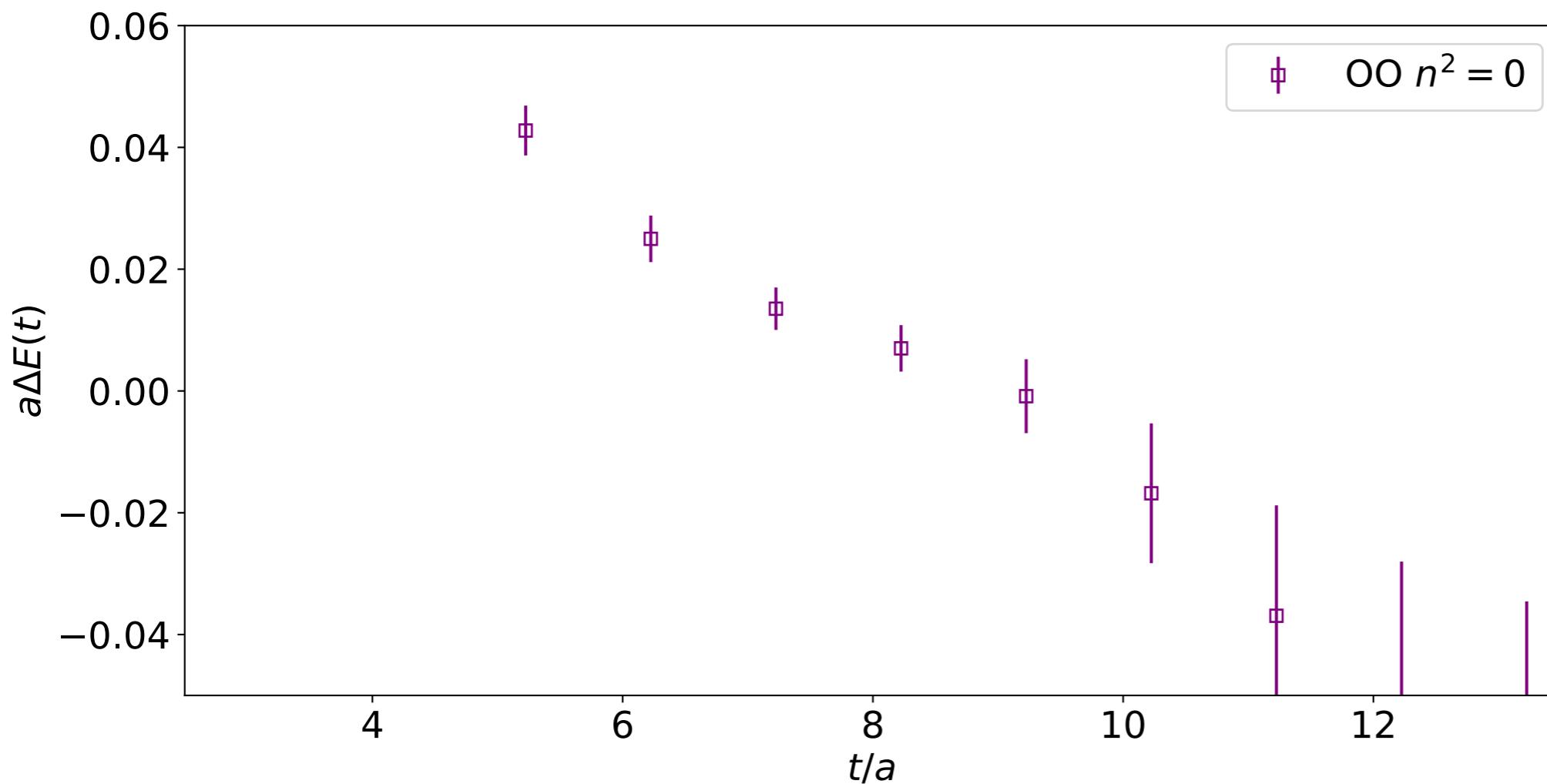
Calm Nucleon



Source Study

$I=1 A_1^+ n^2=0 ({}^1S_0 \text{ Dineutron})$

MDWF on HISQ
a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$

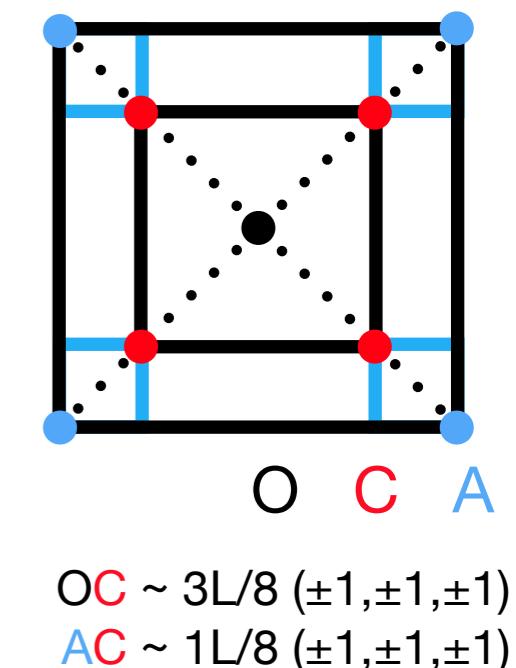
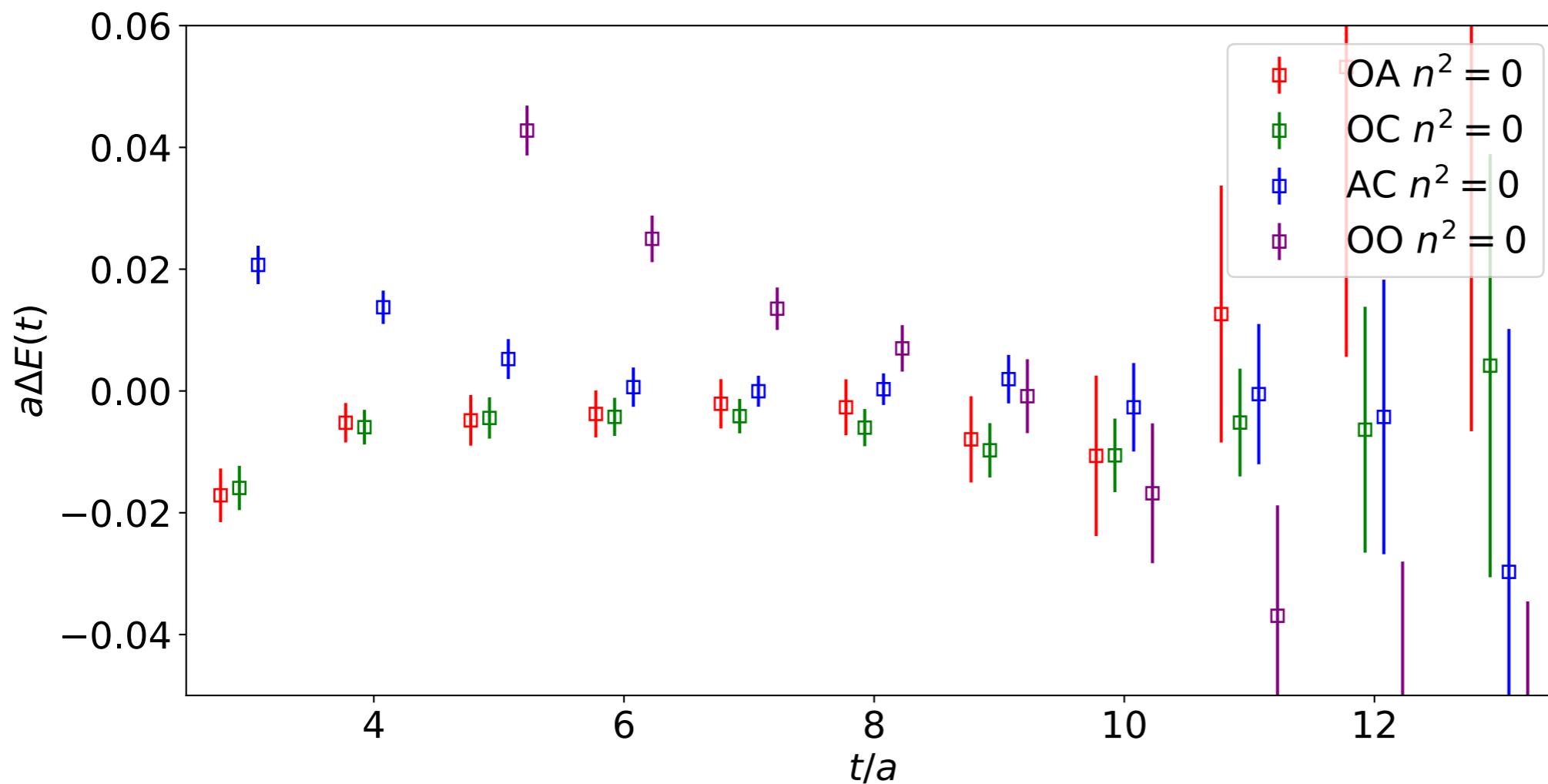


OC $\sim 3L/8 (\pm 1, \pm 1, \pm 1)$
AC $\sim 1L/8 (\pm 1, \pm 1, \pm 1)$

Source Study

$I=1 A_1^+ n^2=0 ({}^1S_0 \text{ Dineutron})$

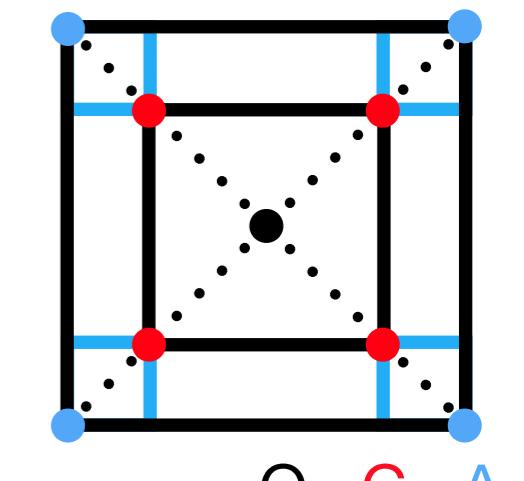
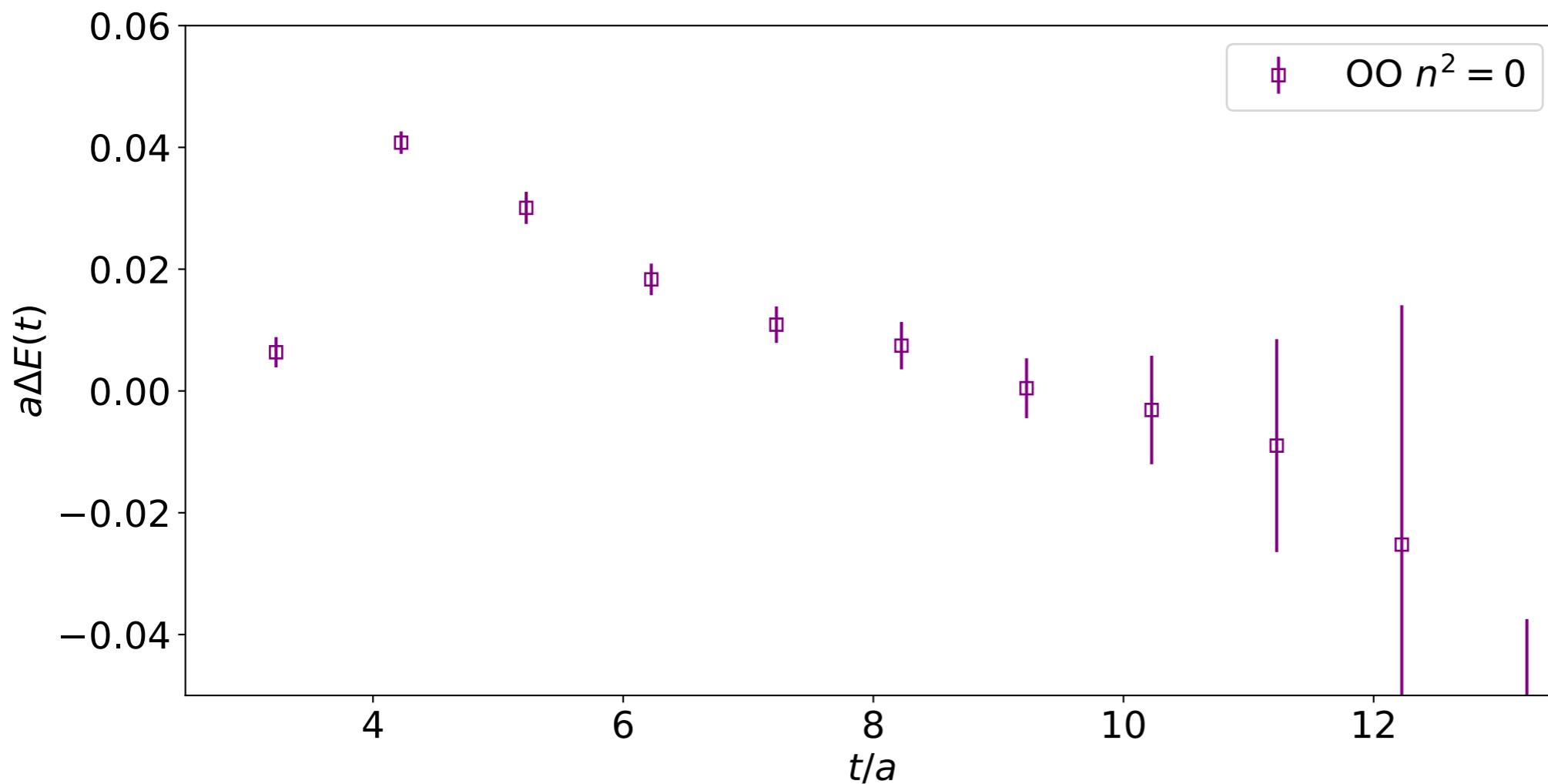
MDWF on HISQ
a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$



Source Study

$I=0 T_1^+ n^2=0$ (3S_1 Deuteron)

MDWF on HISQ
 a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$

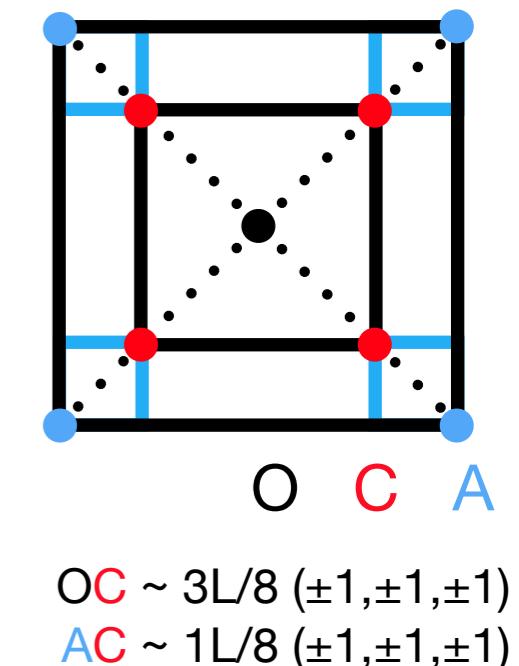
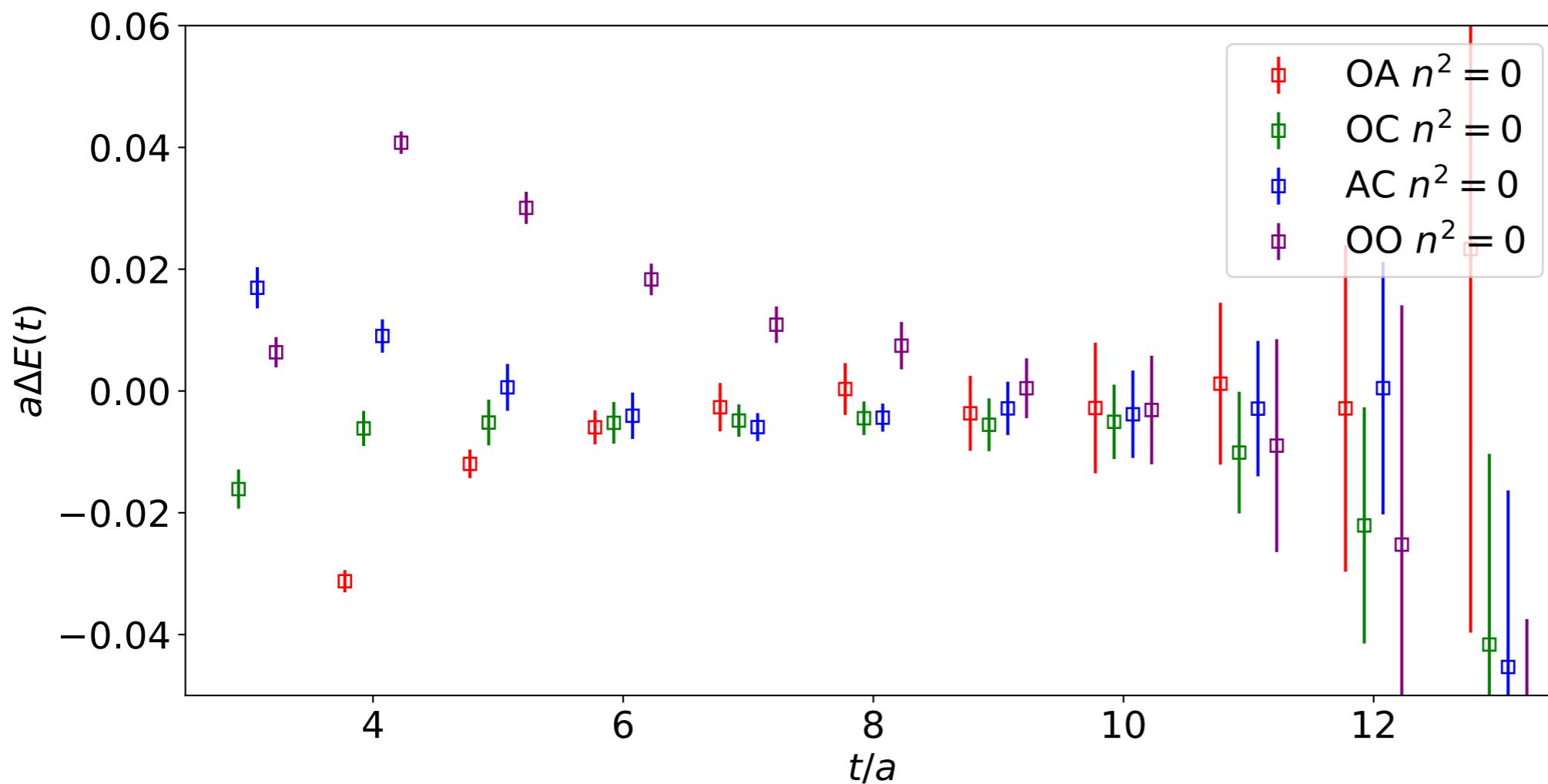


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Source Study

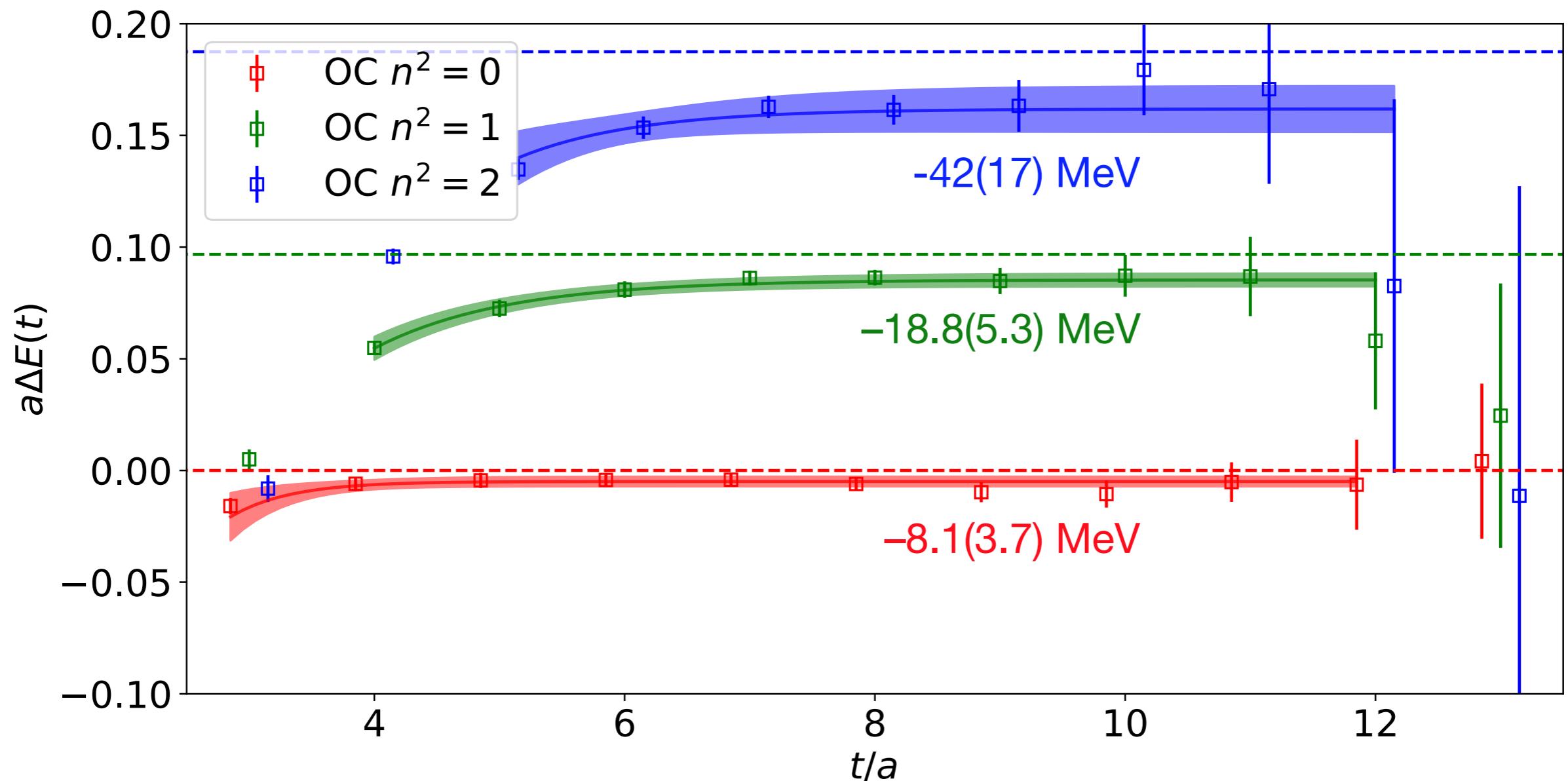
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MDWF on HISQ
 a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$



I=1 1S_0 Dineutron

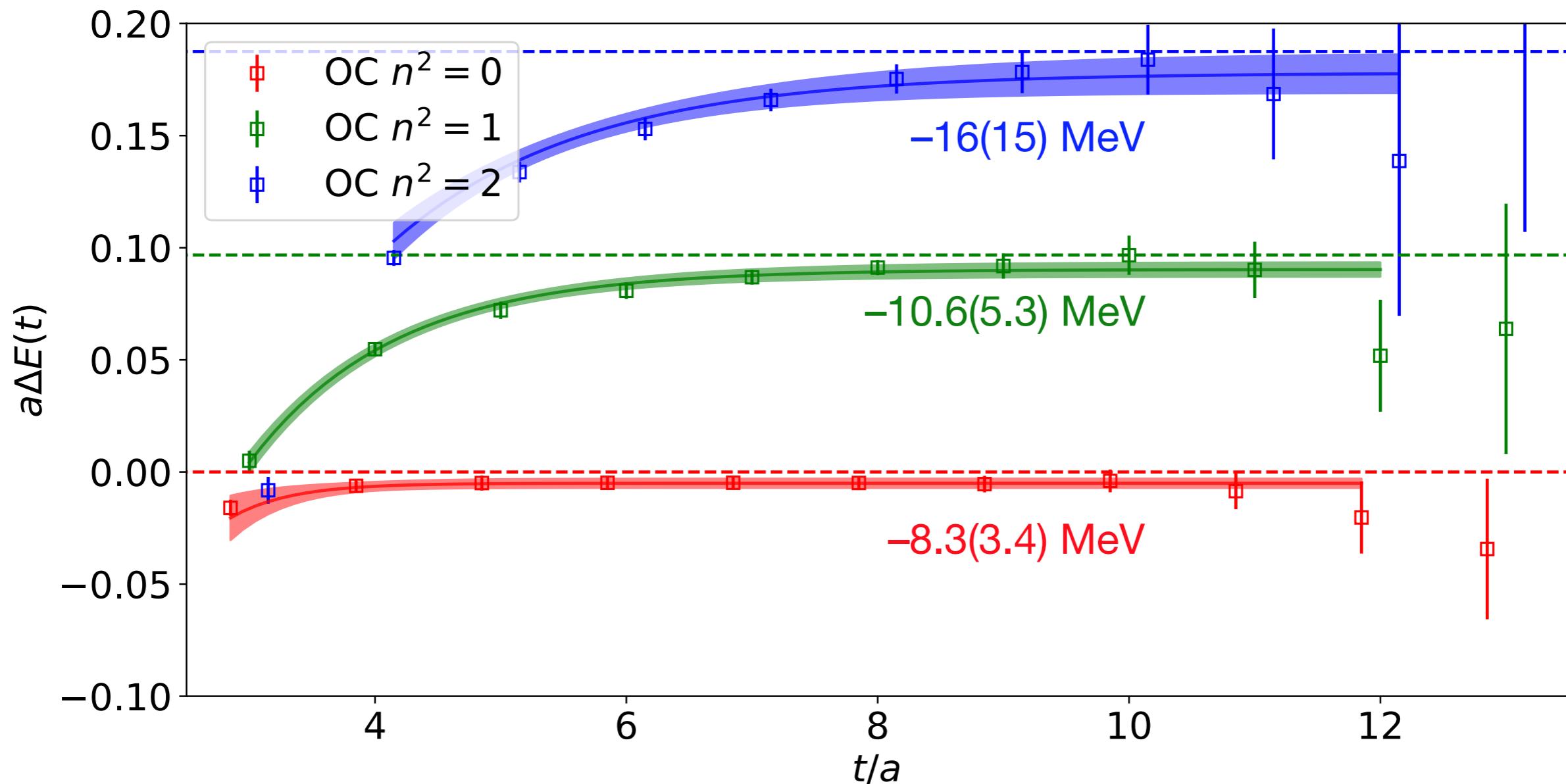
MDWF on HISQ
a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$



Dineutron binding energies at nearby m_π :
 Yamazaki *et al.* $m_\pi \sim 300$ MeV $8.5(0.7)(^{+1.6}_{-0.5})$ MeV
 NPLQCD $m_\pi \sim 450$ MeV $12.5(^{+3.0}_{-5.0})$ MeV

I=0 3S_1 Deuteron

MDWF on HISQ
a12m350
 $24^3 \times 64$
 $m_\pi L = 5.1$



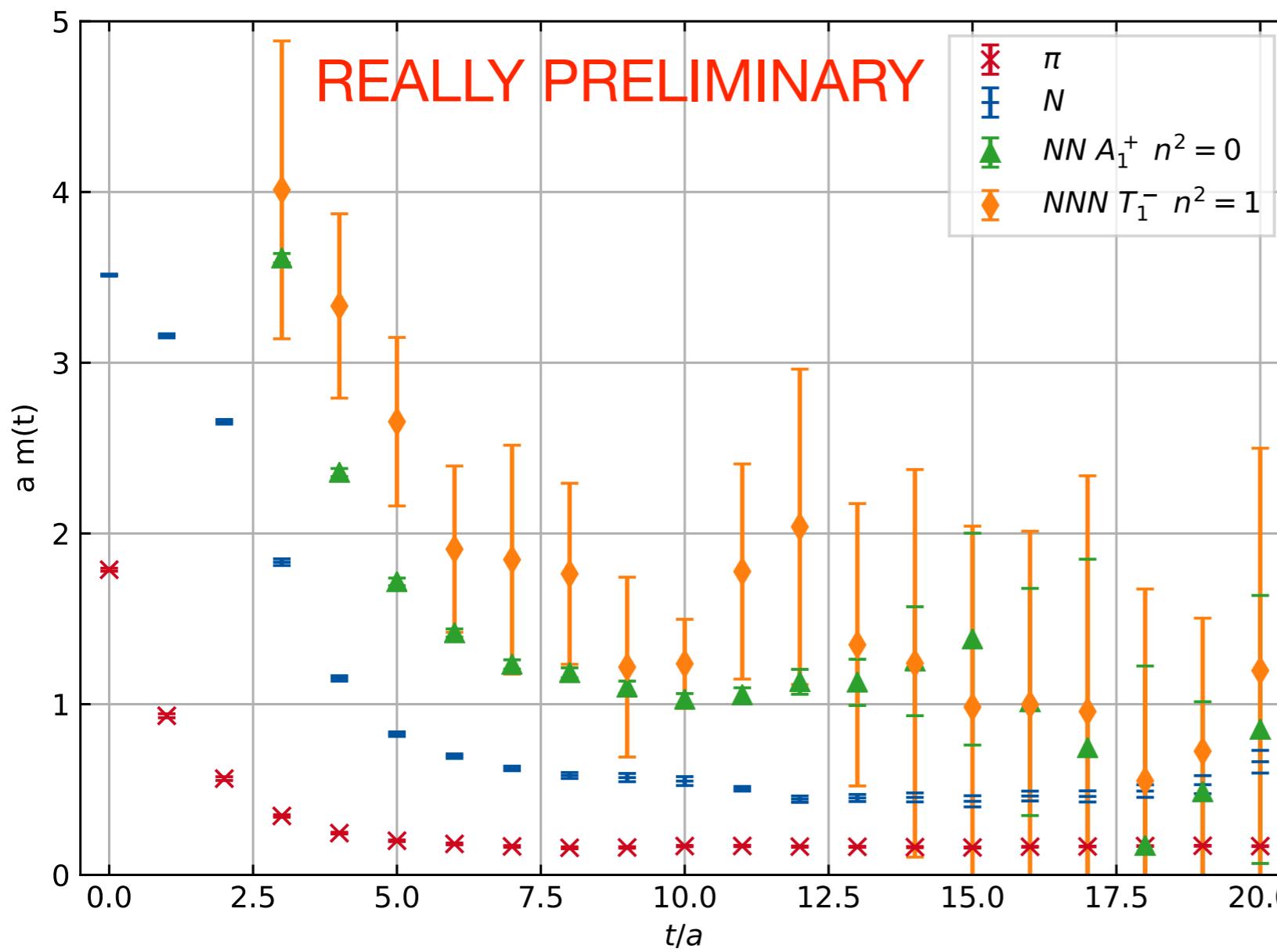
Deuteron binding energies at nearby m_π :
 Yamazaki *et al.* $m_\pi \sim 300$ MeV $14.5(0.7)(^{+2.4}_{-0.8})$ MeV
 NPLQCD $m_\pi \sim 450$ MeV $14.4(^{+3.2}_{-2.6})$ MeV

Outlook

Three Neutrons In A Box

Jan-Lukas Wynen, EB, Tom Luu, Andrea Schindler, John Bulava

Jan-Lukas Wynen
Hadron Spectroscopy
Friday 17:50



CLS H107
RQCD PRD 94 (2016) 074501
 $m_\pi \sim 368$ MeV
 $a \sim 0.09$ fm
 483×96
175 measurements

PoS(LATTICE 2008)246 Luu
PoS(LATTICE 2013)221 Hansen and Sharpe
PoS(LATTICE 2014)088 Sharpe and Hansen
PoS(LATTICE 2015)008 Hansen
PoS(LATTICE 2016)115 Sharpe, Briceño, Hansen

Maxim Mai
Hadron Spectroscopy
Tuesday 16:30

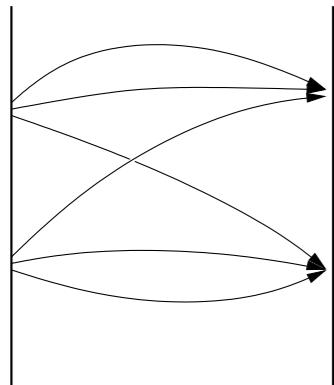
Stephen Sharpe
Hadron Spectroscopy
Thursday 11:00

Future Methods

Variational Methods

Distillation

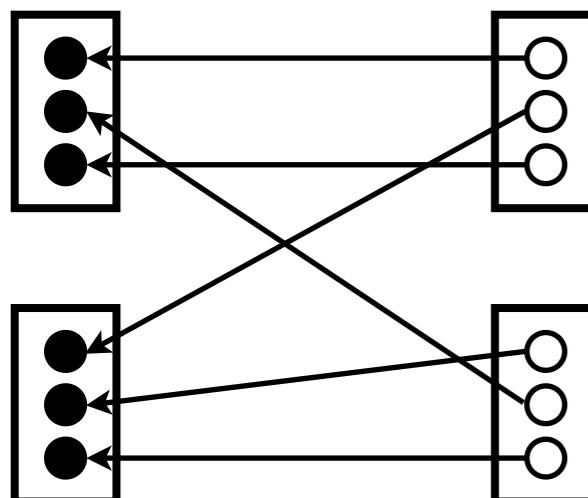
Peardon *et al.* PRD 80 (2009) 054506



Francis *et al.* 1805.03966
H binding energy = 19 ± 10 MeV
 $m_\pi \sim 960$ MeV SU(3)-symmetric

Stochastic LapH

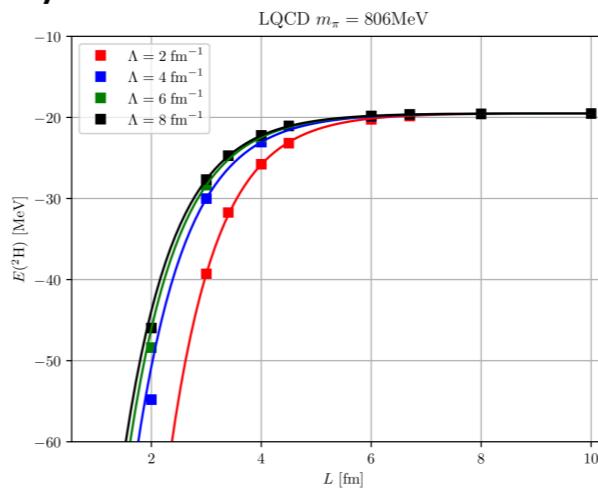
Morningstar *et al.* PRD 83 (2011) 114505



Andersen, Bulava, Hörz,
Morningstar, CalLat

Finite Volume Matching

π EFT in Finite Volume



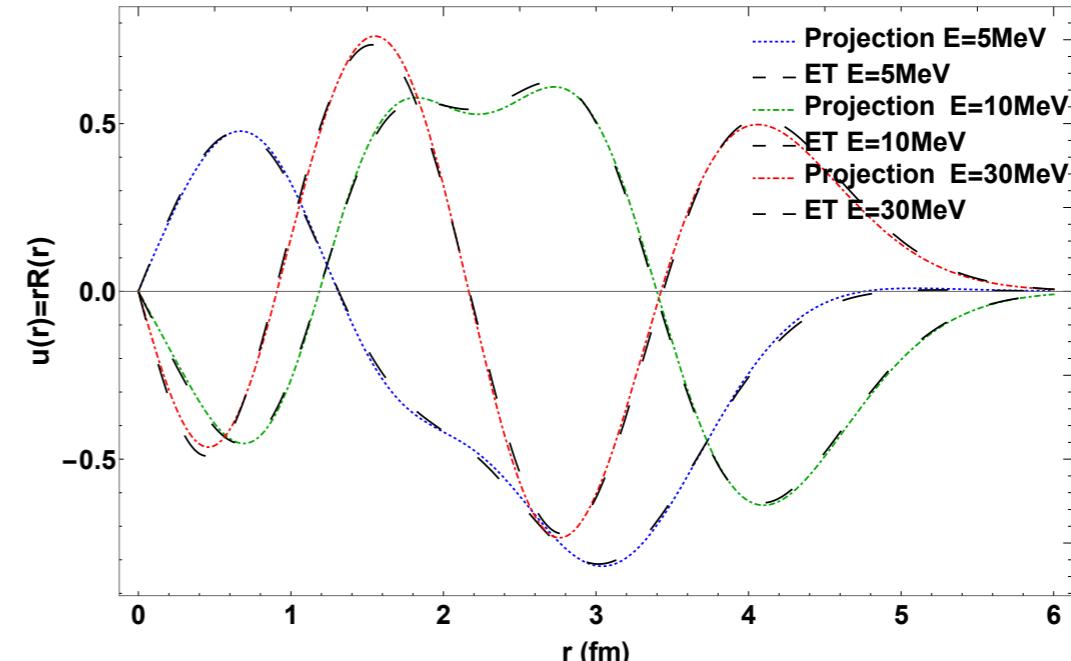
Barnea Few Body 22 (2018)
EFT for Lattice Nuclei
Barnea, Eliyahu, Bazak (forthcoming)

Z. Guo
xEFT in FV
Tuesday 14:40

Harmonic-Oscillator Basis Effective Theory

McElvain and Haxton 1607.06863

McElvain APS April 2017 62 1 BAPS.2017.APR.C13.5





Berkeley
LBL



RBRC

Enrico Rinaldi

Rinaldi
NN Oscillations
MONDAY 14:00

ARTMENT OF
ERGY | Office of
Science

U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA
SciDAC
Scientific Discovery
through
Advanced Computing

OLCF
OAK RIDGE LEADERSHIP COMPUTING FACILITY

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Kate Clark

Clark
QUADA on Summit
Wednesday 16:10

Calullat

Backup Slides

MDWF on HISQ

Our Lattice QCD Action

Möbius Domain Wall Fermion on HISQ sea

CalLat PRD96 (2017) 054513

| HISQ gauge configuration parameters | | | | | | | valence parameters | | | | | | | |
|-------------------------------------|------------------|------------------|------------------|-----------|---------------------------|-------------------|--------------------|---------|--------|-------|-------|----------------------|-----------------------|------------------|
| abbr. | N_{cfg} | volume | $\sim a$ [fm] | m_l/m_s | $\sim m_{\pi_5}$ [MeV] | $\sim m_{\pi_5}L$ | N_{src} | L_5/a | aM_5 | b_5 | c_5 | $am_l^{\text{val.}}$ | σ_{smr} | N_{smr} |
| a15m400 | 1000 | $16^3 \times 48$ | 0.15 | 0.334 | 400 | 4.8 | 8 | 12 | 1.3 | 1.5 | 0.5 | 0.0278 | 3.0 | 30 |
| a15m350 | 1000 | $16^3 \times 48$ | 0.15 | 0.255 | 350 | 4.2 | 16 | 12 | 1.3 | 1.5 | 0.5 | 0.0206 | 3.0 | 30 |
| a15m310 | 1960 | $16^3 \times 48$ | 0.15 | 0.2 | 310 | 3.8 | 24 | 12 | 1.3 | 1.5 | 0.5 | 0.01580 | 4.2 | 60 |
| a15m220 | 1000 | $24^3 \times 48$ | 0.15 | 0.1 | 220 | 4.0 | 12 | 16 | 1.3 | 1.75 | 0.75 | 0.00712 | 4.5 | 60 |
| a15m130 | 1000 | $32^3 \times 48$ | 0.15 | 0.036 | 130 | 3.2 | 5 | 24 | 1.3 | 2.25 | 1.25 | 0.00216 | 4.5 | 60 |
| a12m400 | 1000 | $24^3 \times 64$ | 0.12 | 0.334 | 400 | 5.8 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.02190 | 3.0 | 30 |
| a12m350 | 1000 | $24^3 \times 64$ | 0.12 | 0.255 | 350 | 5.1 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01660 | 3.0 | 30 |
| a12m310 | 1053 | $24^3 \times 64$ | 0.12 | 0.2 | 310 | 4.5 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01260 | 3.0 | 30 |
| a12m220S | 1000 | $24^3 \times 64$ | 0.12 | 0.1 | 220 | 3.2 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220 | 1000 | $32^3 \times 64$ | 0.12 | 0.1 | 220 | 4.3 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220L | 1000 | $40^3 \times 64$ | 0.12 | 0.1 | 220 | 5.4 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m130 | 1000 | $48^3 \times 64$ | 0.12 | 0.036 | 130 | 3.9 | 3 | 20 | 1.2 | 2.0 | 1.0 | 0.00195 | 7.0 | 150 |
| a09m400 | 1201 | $32^3 \times 64$ | 0.09 | 0.335 | 400 | 5.8 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0160 | 3.5 | 45 |
| a09m350 | 1201 | $32^3 \times 64$ | 0.09 | 0.255 | 350 | 5.1 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0121 | 3.5 | 45 |
| a09m310 | 784 | $32^3 \times 96$ | 0.09 | 0.2 | 310 | 4.5 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.00951 | 7.5 | 167 |
| a09m220 | 1001 | $48^3 \times 96$ | 0.09 | 0.1 | 220 | 4.7 | 6 | 8 | 1.1 | 1.25 | 0.25 | 0.00449 | 8.0 | 150 |

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|-------------------------------------|------------------|------------------|------------------|-----------|---------------------------|-------------------|--------------------|---------|--------|-------|-------|----------------------|-----------------------|------------------|
| abbr. | N_{cfg} | volume | $\sim a$ [fm] | m_l/m_s | $\sim m_{\pi_5}$ [MeV] | $\sim m_{\pi_5}L$ | N_{src} | L_5/a | aM_5 | b_5 | c_5 | $am_l^{\text{val.}}$ | σ_{smr} | N_{smr} |
| a15m400 | 1000 | $16^3 \times 48$ | 0.15 | 0.334 | 400 | 4.8 | 8 | 12 | 1.3 | 1.5 | 0.5 | 0.0278 | 3.0 | 30 |
| a15m350 | 1000 | $16^3 \times 48$ | 0.15 | 0.255 | 350 | 4.2 | 16 | 12 | 1.3 | 1.5 | 0.5 | 0.0206 | 3.0 | 30 |
| a15m310 | 1960 | $16^3 \times 48$ | 0.15 | 0.2 | 310 | 3.8 | 24 | 12 | 1.3 | 1.5 | 0.5 | 0.01580 | 4.2 | 60 |
| a15m220 | 1000 | $24^3 \times 48$ | 0.15 | 0.1 | 220 | 4.0 | 12 | 16 | 1.3 | 1.75 | 0.75 | 0.00712 | 4.5 | 60 |
| a15m130 | 1000 | $32^3 \times 48$ | 0.15 | 0.036 | 130 | 3.2 | 5 | 24 | 1.3 | 2.25 | 1.25 | 0.00216 | 4.5 | 60 |
| a12m400 | 1000 | $24^3 \times 64$ | 0.12 | 0.334 | 400 | 5.8 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.02190 | 3.0 | 30 |
| a12m350 | 1000 | $24^3 \times 64$ | 0.12 | 0.255 | 350 | 5.1 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01660 | 3.0 | 30 |
| a12m310 | 1053 | $24^3 \times 64$ | 0.12 | 0.2 | 310 | 4.5 | 8 | 8 | 1.2 | 1.25 | 0.25 | 0.01260 | 3.0 | 30 |
| a12m220S | 1000 | $24^3 \times 64$ | 0.12 | 0.1 | 220 | 3.2 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220 | 1000 | $32^3 \times 64$ | 0.12 | 0.1 | 220 | 4.3 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m220L | 1000 | $40^3 \times 64$ | 0.12 | 0.1 | 220 | 5.4 | 4 | 12 | 1.2 | 1.5 | 0.5 | 0.00600 | 6.0 | 90 |
| a12m130 | 1000 | $48^3 \times 64$ | 0.12 | 0.036 | 130 | 3.9 | 3 | 20 | 1.2 | 2.0 | 1.0 | 0.00195 | 7.0 | 150 |
| a09m400 | 1201 | $32^3 \times 64$ | 0.09 | 0.335 | 400 | 5.8 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0160 | 3.5 | 45 |
| a09m350 | 1201 | $32^3 \times 64$ | 0.09 | 0.255 | 350 | 5.1 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.0121 | 3.5 | 45 |
| a09m310 | 784 | $32^3 \times 96$ | 0.09 | 0.2 | 310 | 4.5 | 8 | 6 | 1.1 | 1.25 | 0.25 | 0.00951 | 7.5 | 167 |
| a09m220 | 1001 | $48^3 \times 96$ | 0.09 | 0.1 | 220 | 4.7 | 6 | 8 | 1.1 | 1.25 | 0.25 | 0.00449 | 8.0 | 150 |

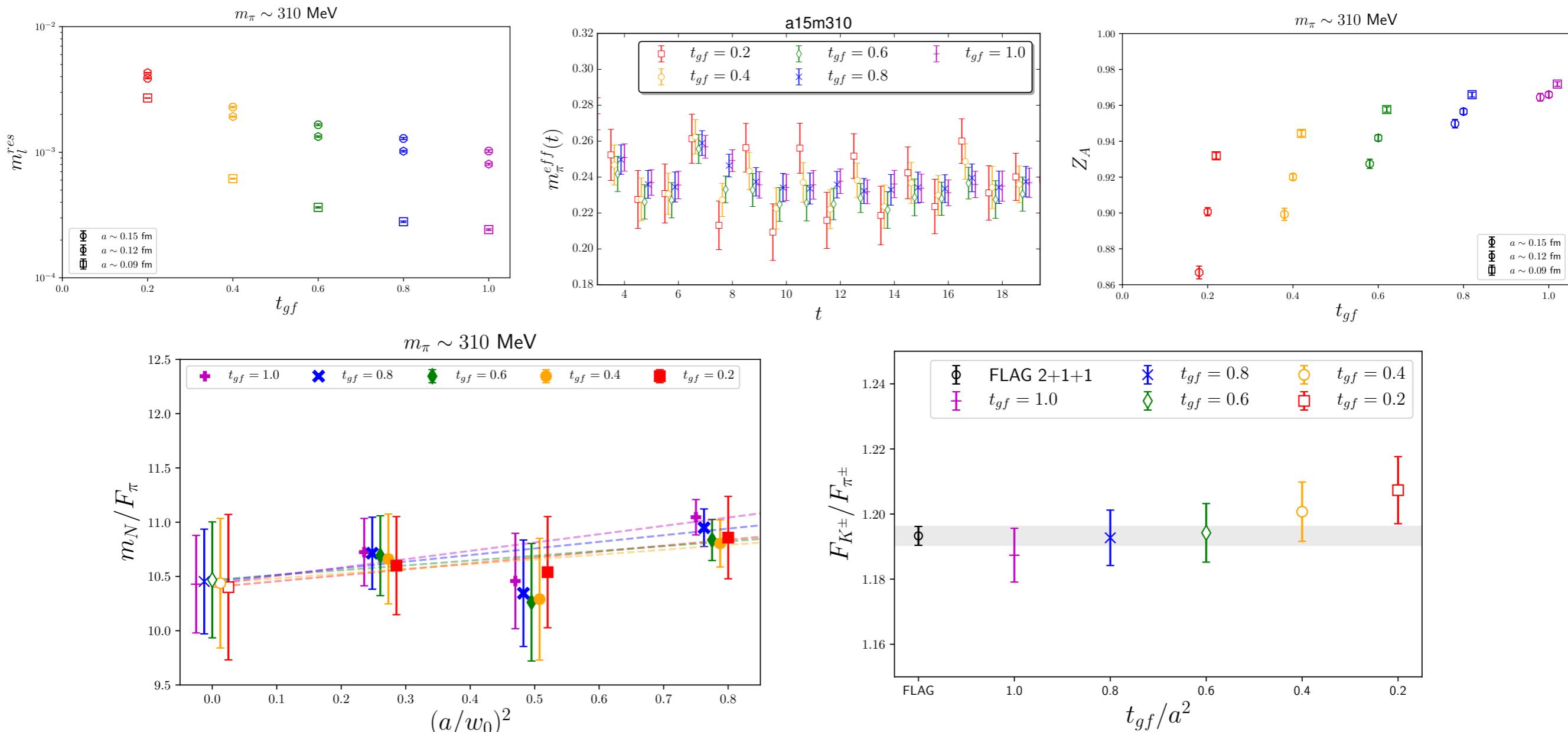
additional HISQ ensembles generated @ LLNL
available to interested parties

Our Lattice QCD Action

Möbius Domain Wall Fermion on HISQ sea

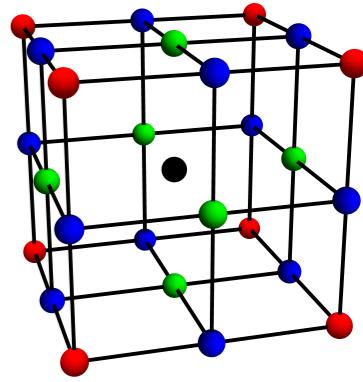
CaLat PRD96 (2017) 054513

Gradient Flow smearing of HISQ cfgs more effective at reducing residual chiral symmetry breaking than the HYP smearing used in DWF on asqtad
 $m_{\text{res}} < 0.1 m_l$ on all ensembles for small-to-moderate L_5 and $M_5 \leq 1.3$

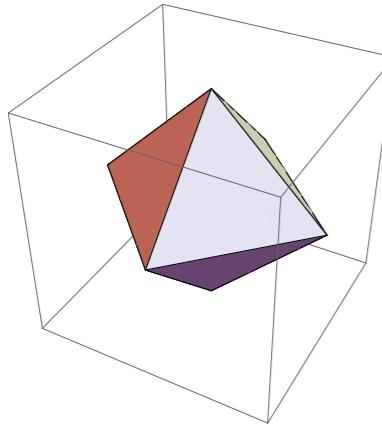


Source Geometry

Sources

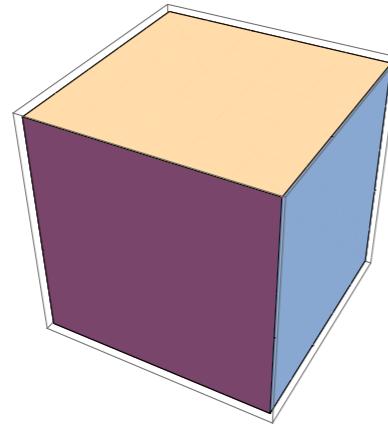


Octahedron
Vertices: 6



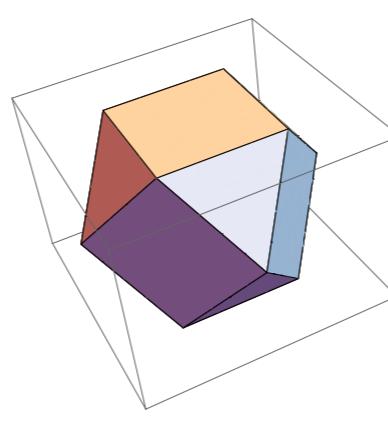
(0,0,1)

Cube
Vertices: 8



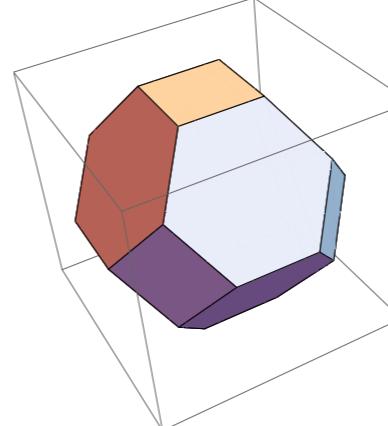
(1,1,1)

Cuboctahedron
Vertices: 12



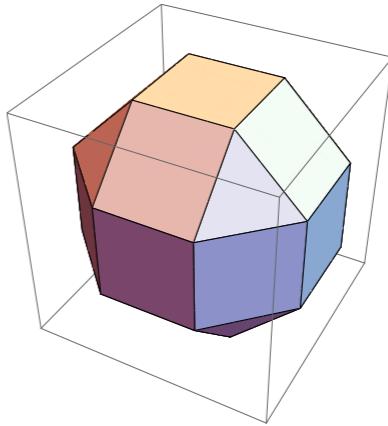
(0,1,1)

TruncatedOctahedron
Vertices: 24



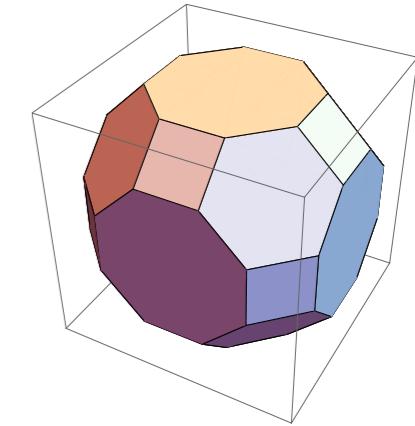
(0,1,2)

SmallRhombicuboctahedron
Vertices: 24



(1,1,2)

GreatRhombicuboctahedron
Vertices: 48

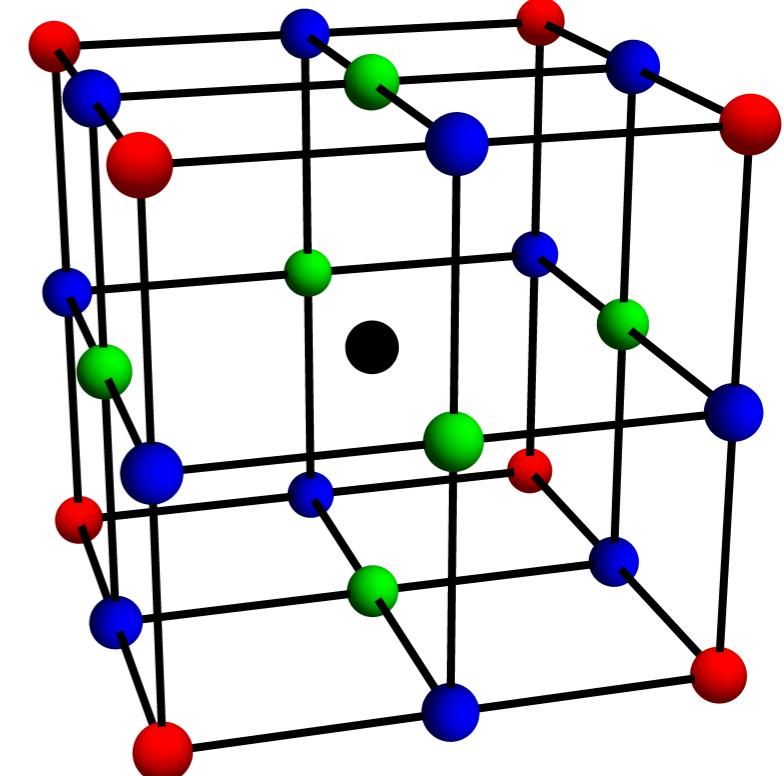


| name | solid | count |
|---------------|---------------------------|-------|
| local | point | 1 |
| face | octahedron | 6 |
| edge | cuboctahedron | 12 |
| corner | cube | 8 |
| knight's move | truncated octahedron | 24 |
| | small rhombicuboctahedron | 24 |
| | great rhombicuboctahedron | 48 |

States

Courtesy of Amy Nicholson and Raul Briceño

| | I=1 | | | | | I=0 | | | | |
|---------|---------|---------|---------|---------|-------|---------|---------|---------|---------|---------|
| | 1S_0 | | | | | 1D_2 | | | | |
| $n^2 S$ | A_1^+ | A_2^+ | T_1^+ | T_2^+ | E^+ | A_1^- | A_2^- | T_1^- | T_2^- | E^- |
| 0 | 1 | - | - | - | - | - | - | - | - | - |
| 1 | 1 | - | - | - | e | - | - | 1 | - | - |
| 2 0 | 1 | - | - | 1 | e | - | - | 1 | e | - |
| 3 | 1 | - | - | 1 | - | - | 1 | 1 | - | - |
| 4 | 1 | - | - | - | e | - | - | 1 | - | - |
| | | | | | | | | | | |
| 0 | - | - | 1 | - | - | - | - | - | - | - |
| 1 | - | - | 2 | 1 | - | 1 | - | 1 | 1 | 1 |
| 2 1 | - | 1 | 3 | 2 | 1 | 1 | e | 2 | 2 | 1 |
| 3 | - | 1 | 2 | 1 | 1 | 1 | - | 1 | 1 | 2 |
| 4 | - | - | 2 | 1 | - | 1 | - | 1 | 1 | 1 |
| | | | | | | | | | | |
| | 3D_3 | 3S_1 | 3D_2 | 3D_2 | | 3P_0 | 3F_3 | 3P_1 | 3P_2 | 3P_2 |
| | | 3D_1 | 3D_3 | | | 3F_4 | | 3F_3 | 3F_2 | 3F_2 |
| | | 3D_3 | | | | | | 3F_4 | 3F_3 | 3F_4 |
| | | | | | | | | | 3F_4 | |
| | | | | | | | | | | |
| | I=0 | | | | | I=1 | | | | |



e: edges only