Neutron-Antineutron Oscillations on the Lattice

N

$\overline{N}$

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Why should we care?

- Other particle/antiparticle mixings occur

$$K^0 \leftrightarrow \overline{K^0}$$
$$B^0 \leftrightarrow \overline{B^0}$$

- Expect baryon number number to be broken

  - Baryon-antibaryon asymmetry

$$\Delta B = 1 \text{ (Proton Decay)}$$
$$\Delta B = 2 \text{ } (N\overline{N} \text{ Oscillations})$$

- Natural in GUT theories with Majorana neutrinos

  - Usual sphaleron process: $\Delta(B-L) = 0$

Mohapatra, Marshak 1980

$\nu = \overline{\nu} \;\Rightarrow \Delta L = 2$ $\qquad$ $B - L = 0 \;\Rightarrow \Delta B = 2$

Basic Idea

- BSM physics leads to off-diagonal mixing

$$H = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix} = \begin{pmatrix} E + V & \delta m \\ \delta m & E - V \end{pmatrix}$$

$$V = 0 \;\Rightarrow \text{Free System}$$

- Transition Probability

$$P_{n \to \bar{n}}(t) = \frac{\delta m^2}{\delta m^2 + V^2} \sin^2 \left[\sqrt{\delta m^2 + V^2}\; t \right] \qquad \tau_{n\bar{n}} = \frac{1}{\delta m}$$

Restricting GUTs

Examples:

TeV-scale seesaw mechanism for neutrino masses in $SU(2)_L \times SU(2)_R \times SU(4)_c$	$10^{10} - 10^{11}$ sec	Babu, Bhupal Dev, Mohapatra (2009)
SO(10) seesaw mechanism with adequate baryogenisis	$10^{9} - 10^{12}$ sec	Babu, Mohapatra (2012)
Extra-dimensional particles above 45 TeV	$> 10^{8}$ sec	Nussinov, Shrock (2002)

- Estimates for ruling out large classes of GUTs

$$\tau_{n\bar{n}} > 10^{10} - 10^{11} \text{ sec}$$

Experimental prospects

Many neutrons → Many neutrons + antineutron → Annihilation

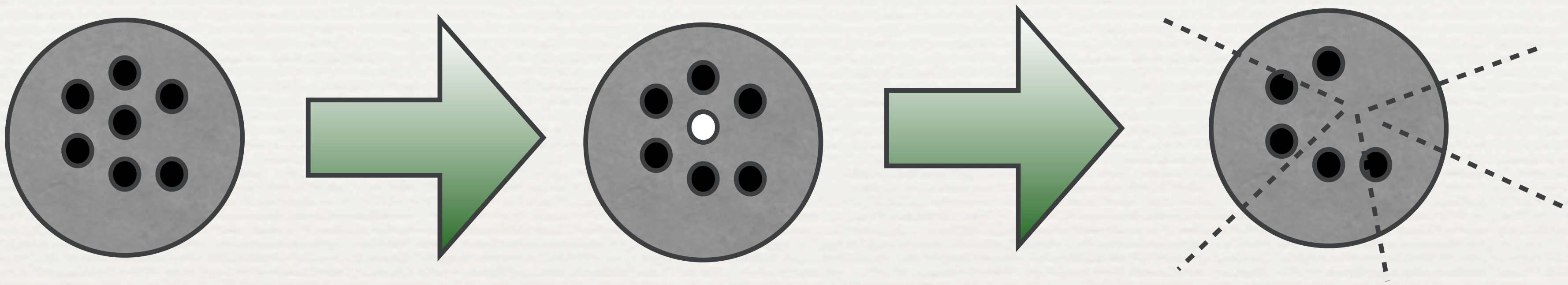
- Neutron-antineutron annihilation signals

Primary channel $n\bar{n} \to 5\pi$ ("Zero background" signal)

- Two Types of experimental searches

Experimental progress

1. Neutron-antineutron annihilation in nuclei



Straight-forward question:
Why have we not annihilated yet?

Crude Answer: Limited time neutron is "free" in nuclei

$$P \sim \frac{1}{\tau_{Nucl}} \sim \frac{1}{\Delta t}\left(\frac{\Delta t}{\tau_{n\overline{n}}}\right)^2$$

Friedman, Gal 2008

-Nuclear suppression: $\tau_{\mathrm{Nucl}} = (3 \times 10^{22})\dfrac{\tau_{n\overline{n}}^2}{\mathrm{sec}}$

Super-K bounds (2011) $\tau_{n\overline{n}} > 3.5 \times 10^{8}$ sec

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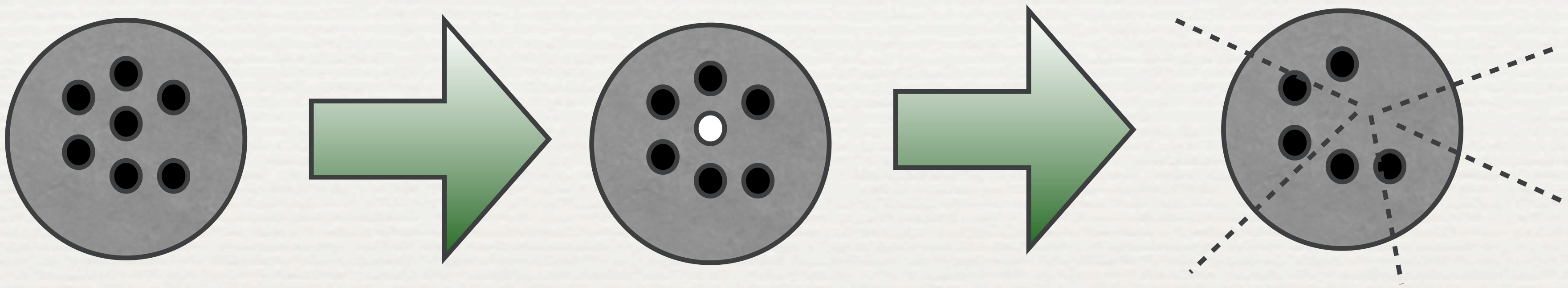

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Friedman, Gal 2008

-Nuclear suppression: $\tau_{\mathrm{Nucl}} = \boxed{(3 \times 10^{22})} \frac{\tau^2_{n\overline{n}}}{\mathrm{sec}}$ Model estimate

Super-K bounds (2011) $\tau_{n\overline{n}} > 3.5 \times 10^8$ sec

Experimental progress

2. Free, Cold neutron annihilation with target

Designed to:

1. Maximize number of neutrons
2. Minimize energy of neutrons
3. Maximize time of flight
4. Minimize External Magnetic Field

Minimize external potential → Most model-independent measurement

ILL bound (1993) $\tau_{n\bar{n}} > 0.86 \times 10^8$ sec

Experimental prospects

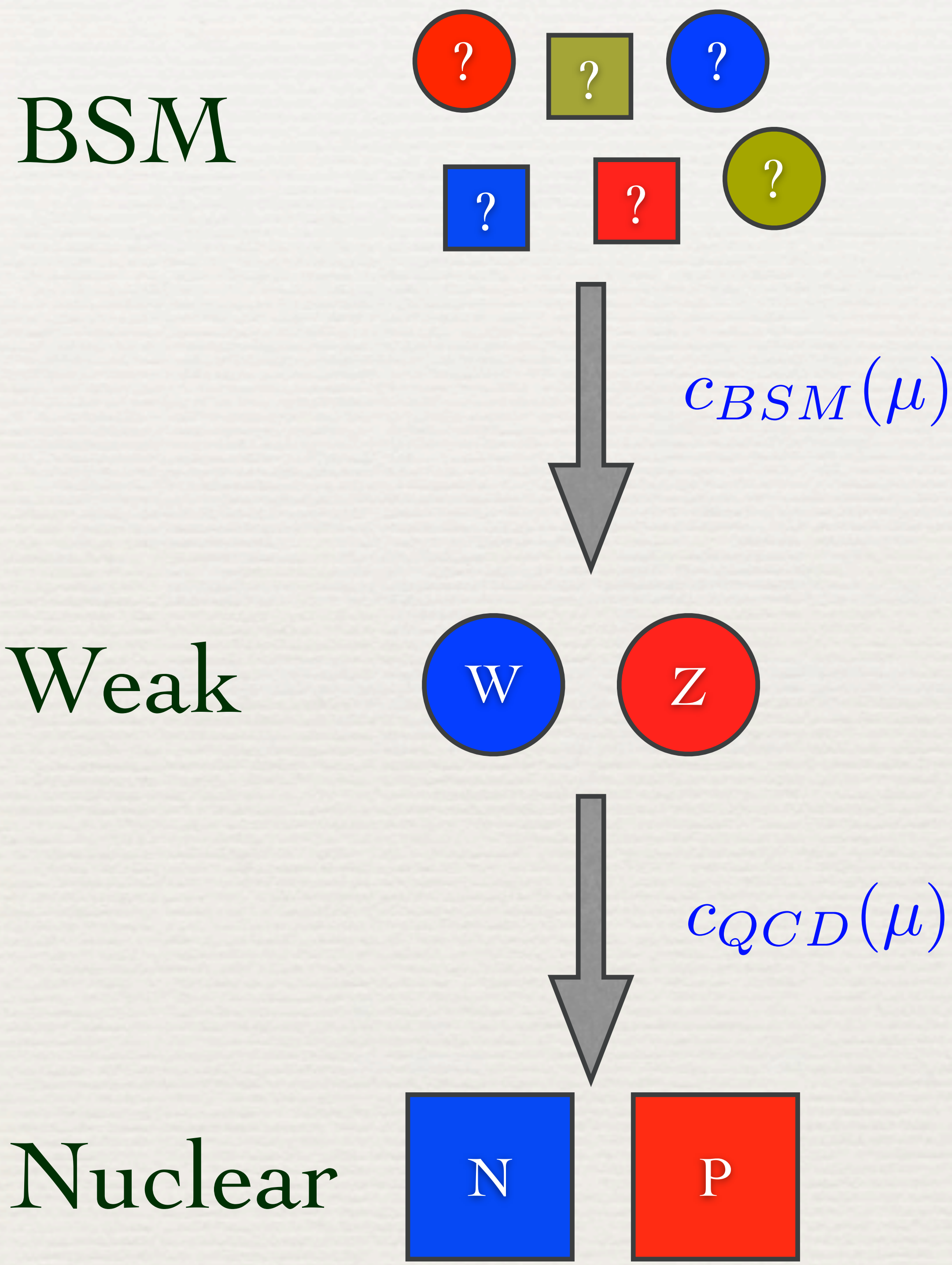
- Cost Estimates (Project X meeting, June 2012)

$$\tau_{n\bar{n}} \gtrsim 3 \times 10^9 \text{ sec:} \qquad \sim \$10 \text{ million}$$

$$\tau_{n\bar{n}} \gtrsim 1 \times 10^{11} \text{ sec:} \qquad \gtrsim \$200 \text{ million}$$

Bottom line: Lattice allows for rigorous, first-principle understanding of QCD input

Origin of Oscillations



- Running of BSM interaction to nuclear scale

$$\frac{1}{\tau_{n\overline{n}}} = \delta m = c_{BSM}(\mu) c_{QCD}(\mu) \langle \overline{n} | \mathcal{O} | n \rangle$$

Where Lattice Can Help

- Is BSM running non-perturbative?
  - Model-dependent (assume pert. models for now)
- Is QCD running non-perturbative?
  - Should be calculated (pert. running reasonable)
- What is neutron-antineutron matrix element?
  - Inherently non-perturbative question
- What is effect in nuclei?
  - Very interesting, VERY hard question

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Six-quark Operators

Rao, Shrock (1982)

Three pairs of quarks:

1. $u^T C u$ or $u^T C d$ or $d^T C d$

2. $u_L^T C d_L$ or $u_R^T C d_R$

3. $$\Gamma^s_{ijklmn} = \epsilon_{mik}\epsilon_{njl} + \epsilon_{nik}\epsilon_{mjl} + \epsilon_{mjk}\epsilon_{nil} + \epsilon_{njk}\epsilon_{mil}$$

$$\Gamma^a_{ijklmn} = \epsilon_{mij}\epsilon_{nkl} + \epsilon_{nij}\epsilon_{mkl}$$

Six-quark Operators

Rao, Shrock (1982)

$$\chi_i = L, R$$

1. $$\mathcal{O}^1_{\chi_1\chi_2\chi_3} = (u^T_{i\chi_1} C u_{j\chi_1})(d^T_{k\chi_2} C d_{l\chi_2})(d^T_{m\chi_3} C d_{n\chi_3})\Gamma^s_{ijklmn}$$

2. $$\mathcal{O}^2_{\chi_1\chi_2\chi_3} = (u^T_{i\chi_1} C d_{j\chi_1})(u^T_{k\chi_2} C d_{l\chi_2})(d^T_{m\chi_3} C d_{n\chi_3})\Gamma^s_{ijklmn}$$

3. $$\mathcal{O}^3_{\chi_1\chi_2\chi_3} = (u^T_{i\chi_1} C d_{j\chi_1})(u^T_{k\chi_2} C d_{l\chi_2})(d^T_{m\chi_3} C d_{n\chi_3})\Gamma^a_{ijklmn}$$

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$$\mathcal{O}^1_{\chi_1 LR} = \mathcal{O}^1_{\chi_1 RL}$$

$$\chi_i = L, R \qquad \mathcal{O}^{2,3}_{LR\chi_3} = \mathcal{O}^{2,3}_{RL\chi_3}$$

1. $\mathcal{O}^1_{\chi_1\chi_2\chi_3} = (u^T_{i\chi_1} C u_{j\chi_1})(d^T_{k\chi_2} C d_{l\chi_2})(d^T_{m\chi_3} C d_{n\chi_3})\Gamma^s_{ijklmn}$

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18 Independent Operators

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Caswell, Milutinovic, Sejanovic (1983)

18 Independent Operators $\rightarrow$ 14 Indep. Operators

Six-quark Operators

Rao, Shrock (1982)

If invariant under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

Restricts operators to:

-All combination of right-handed singlets

$$\mathcal{P}_1 = (u^T_{iR} C u_{jR})(d^T_{kR} C d_{lR})(d^T_{mR} C d_{nR})\Gamma^s_{ijklmn} = \mathcal{O}^1_{RRR}$$

$$\mathcal{P}_2 = (u^T_{iR} C d_{jR})(u^T_{kR} C d_{lR})(d^T_{mR} C d_{nR})\Gamma^s_{ijklmn} = \mathcal{O}^2_{RRR}$$

$$\mathcal{P}_3 = (u^T_{iR} C d_{jR})(u^T_{kR} C d_{lR})(d^T_{mR} C d_{nR})\Gamma^a_{ijklmn} = \mathcal{O}^3_{RRR}$$

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If invariant under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

Restricts operators to:

-All combination of right-handed singlets

-Flavor anti-symmetric combinations of left-handed doublets

$$\mathcal{P}_4 = ([q_{iL}^T]^w C[q_{jL}]^x)(u_{kR}^T C d_{lR})(d_{mR}^T C d_{nR})\Gamma^a_{ijklmn}\epsilon^{wx} = 2\mathcal{O}^3_{LRR}$$

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$$\mathcal{P}_4 = ([q_{iL}^T]^w C [q_{jL}]^x)(u_{kR}^T C d_{lR})(d_{mR}^T C d_{nR}) \Gamma^a_{ijklmn} \epsilon^{wx} = 2\mathcal{O}^3_{LRR}$$

$$\mathcal{P}_5 = ([q_{iL}^T]^w C [q_{jL}]^x)([q_{kL}^T]^y C [q_{lR})]^z)(d_{mR}^T C d_{nR}) \Gamma^a_{ijklmn} \epsilon^{wx} \epsilon^{yz} = 4\mathcal{O}^3_{LLR}$$

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Restricts operators to:

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$$\mathcal{P}_6 = ([q^T_{iL}]^w C[q_{jL}]^x)([q^T_{kL}]^y C[q_{lR})]^z)(d^T_{mR} C d_{nR})\Gamma^s_{ijklmn}(\epsilon^{wy}\epsilon^{xz} + \epsilon^{xy}\epsilon^{wz})$$
$$= 4(\mathcal{O}^1_{LLR} - \mathcal{O}^2_{LLR})$$

Six-quark Operators

Rao, Shrock (1982)

If invariant under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

(Six Operators)

$$\mathcal{P}_1 = \mathcal{O}^1_{RRR}$$
$$\mathcal{P}_2 = \mathcal{O}^2_{RRR}$$
$$\mathcal{P}_3 = \mathcal{O}^3_{RRR}$$
$$\mathcal{P}_4 = 2\mathcal{O}^3_{LRR}$$
$$\mathcal{P}_5 = 4\mathcal{O}^3_{LLR}$$
$$\mathcal{P}_6 = 4(\mathcal{O}^1_{LLR} - \mathcal{O}^2_{LLR})$$

- Matrix elements cannot be calculated perturbatively

Six-quark Operators

Rao, Shrock (1982)

If invariant under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

(Six Operators)

(Four Operators)

Caswell, Milutinovic, Sejanovic (1983)

$$\mathcal{P}_6 = -3\mathcal{P}_5$$

$$\mathcal{P}_2 - \mathcal{P}_1 = 3\mathcal{P}_3$$

$$\mathcal{P}_1 = \mathcal{O}^1_{RRR}$$

$$\mathcal{P}_2 = \mathcal{O}^2_{RRR}$$

$$\mathcal{P}_3 = \mathcal{O}^3_{RRR}$$

$$\mathcal{P}_4 = 2\mathcal{O}^3_{LRR}$$

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If invariant under $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$:

(Six Operators)

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(Four Operators)

$$\boxed{\mathcal{P}_2} = \mathcal{O}^2_{RRR}$$

$$\mathcal{P}_3 = \mathcal{O}^3_{RRR}$$

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Current Understanding of Matrix Elements

MIT bag Model: (Rao, Shrock 1982)

- Model dependent estimation
- Results roughly consistent with DA
- No QCD input

Lattice Motivation:

- Numerical QCD calculation
- Quantification of uncertainties
- Pinpoint target sensitivity for experiment
- Large enhancements/suppressions?

Lattice Calculation

Correlation Functions via path integral:

$$C_{\mathcal{O}} = \langle \mathcal{O} \rangle = \int d[U]\ \mathcal{O}\ \det(D_{lat}(U)) e^{-S_G(U)}$$

$$C_{NN}(t) = \langle \overline{N}(t) N(0) \rangle \to |\langle N | n \rangle|^2 e^{-m_n t}$$

$$C_{\overline{NN}}(t) = \langle N(t) \overline{N}(0) \rangle \to |\langle \overline{N} | \overline{n} \rangle|^2 e^{-m_n t}$$

$$C_{\overline{N}\mathcal{O}N}(t_1, t_2) = \langle N(t_1) \mathcal{O}(0) \overline{N}(t_2) \rangle \to \langle \overline{N} | \overline{n} \rangle \langle N | n \rangle e^{-m_n(t_1+t_2)} \langle n | \mathcal{O} | \overline{n} \rangle$$

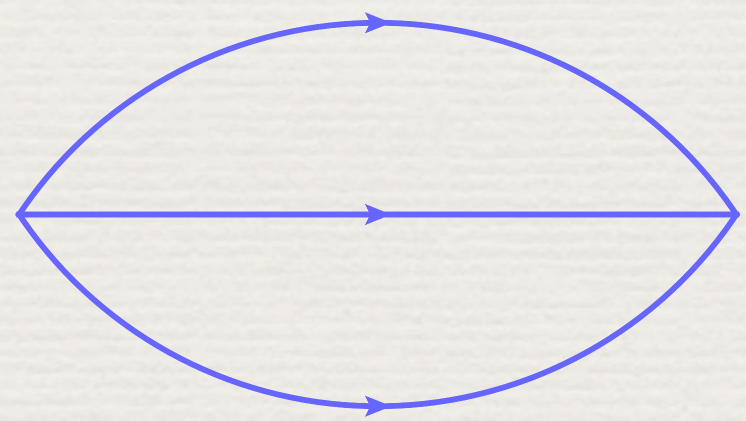
$$\mathcal{R} = \frac{C_{\overline{N}\mathcal{O}N}(t_1, t_2)}{C_{\overline{NN}}(t_1+t_2)} \left[\frac{C_{NN}(t_1) C_{\overline{NN}}(t_2) C_{\overline{NN}}(t_1+t_2)}{C_{\overline{NN}}(t_1) C_{NN}(t_2) C_{NN}(t_1+t_2)} \right]^{\frac{1}{2}} \to \langle \overline{n} | \mathcal{O} | n \rangle$$

Lattice Contractions

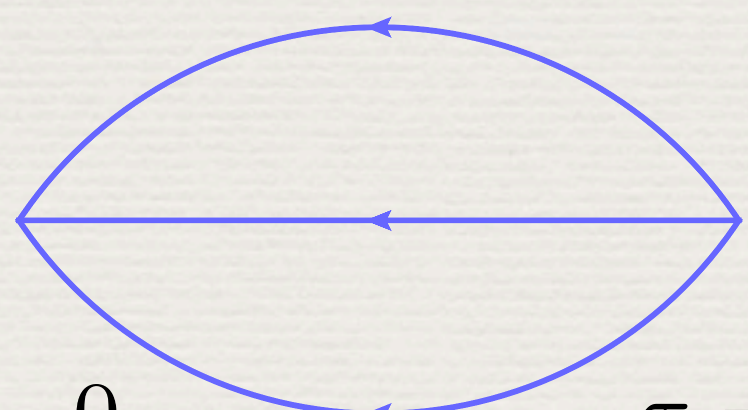
Propagator Contractions:

$$\overline{q}_{i'}^{\alpha'}(y)\; q_i^{\alpha}(x) = S_{i'i}^{\alpha'\alpha}(y,x) \qquad\qquad S^{\dagger} = \gamma_5 S \gamma_5$$

$C_{NN}(t)$



$C_{\overline{NN}}(t)$

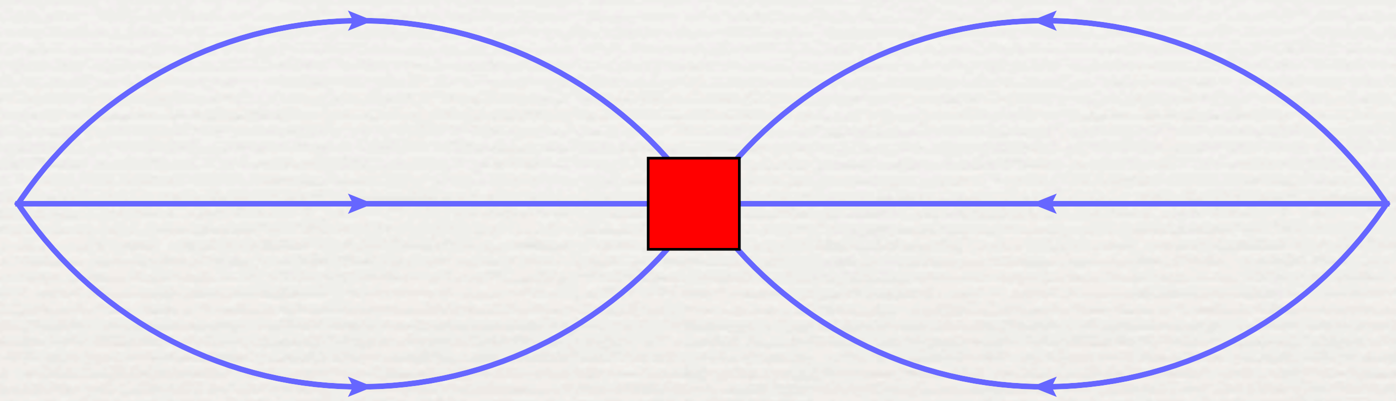


$\tau = 0$ $\qquad\qquad$ $\tau = t$

Lattice Contractions

$\tau = -t_1$ $\quad\quad$ $\tau = 0$ $\quad\quad$ $\tau = t_2$

$C_{\overline{N}\mathcal{O}N}(t_1, t_2)$



No
Dis.
Diagrams

1 Propagator $\Rightarrow$ Two measurement ALL time insertion

Lattice Contractions

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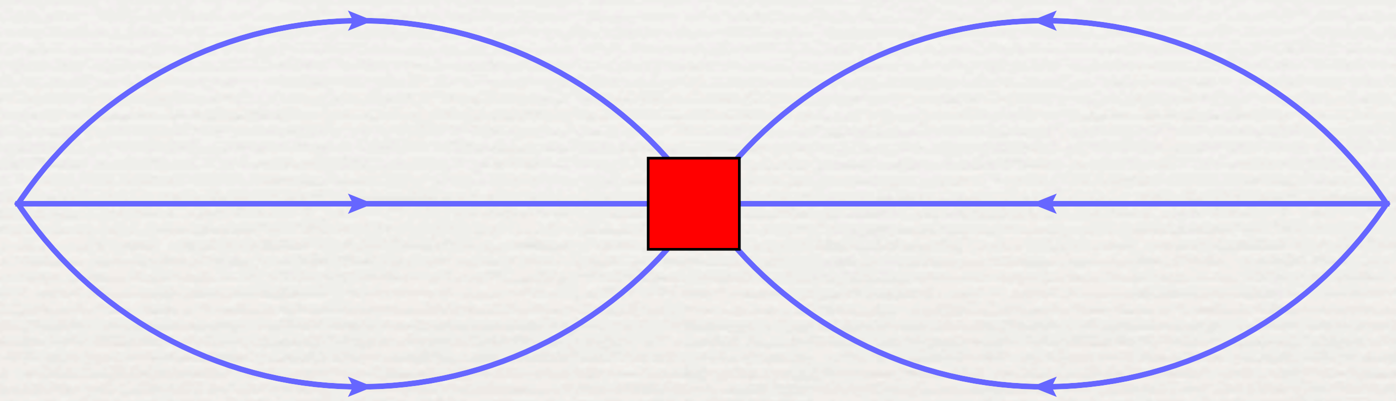
$C_{\overline{N}\mathcal{O}N}(t_1, t_2)$



No Dis. Diagrams

1 Propagator

Two measurement
ALL time insertion

$\tau = 0$

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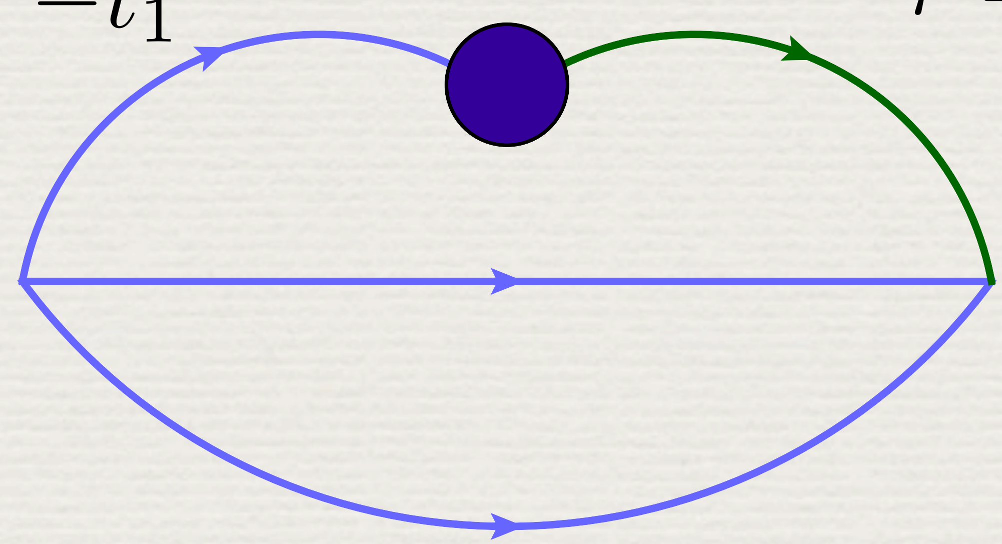


Typical
3-point

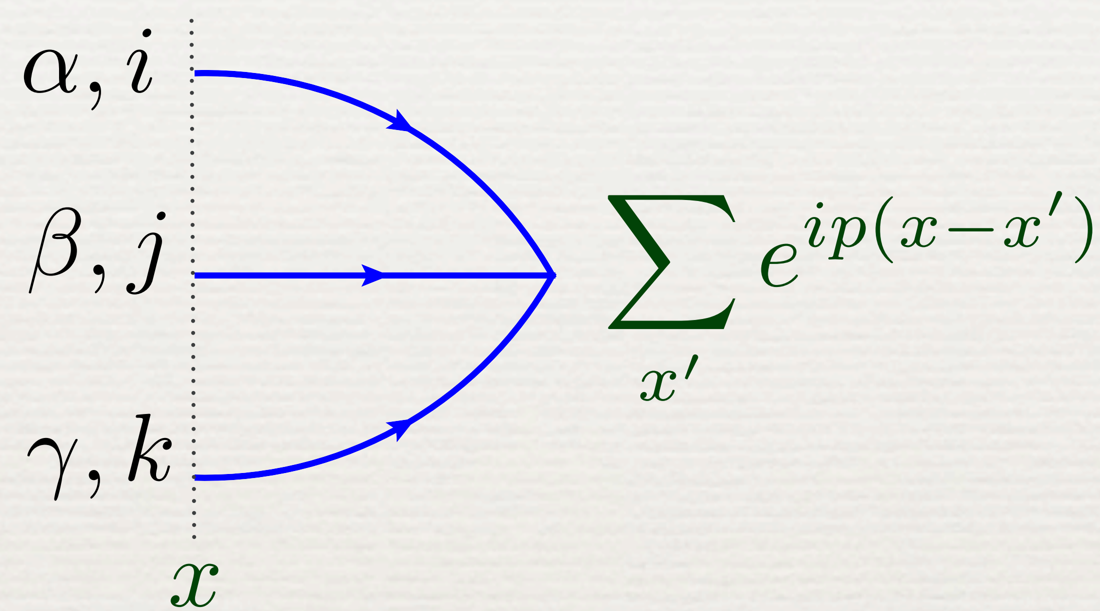
Often Dis. Diagrams

2 Propagators

One measurements
One time insertion

Neutron Blocks

Construct sink-contracted neutron blocks:



Project onto lattice irrep G_1^+

$12 \times 12 \times N_t$ Object $\longrightarrow$ N_s^3 times smaller than prop

Neutron Blocks

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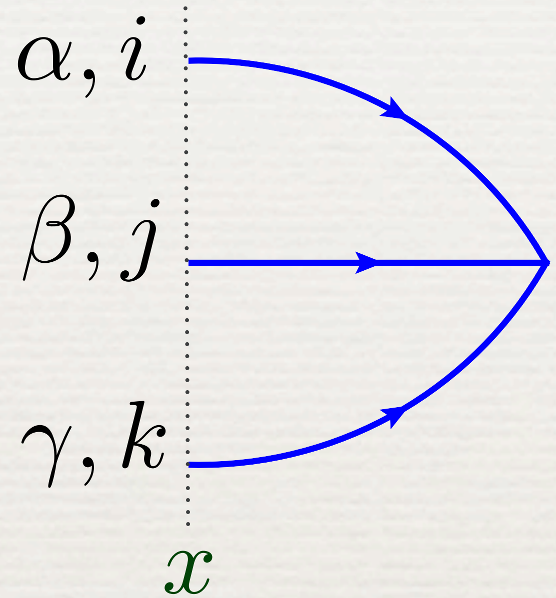
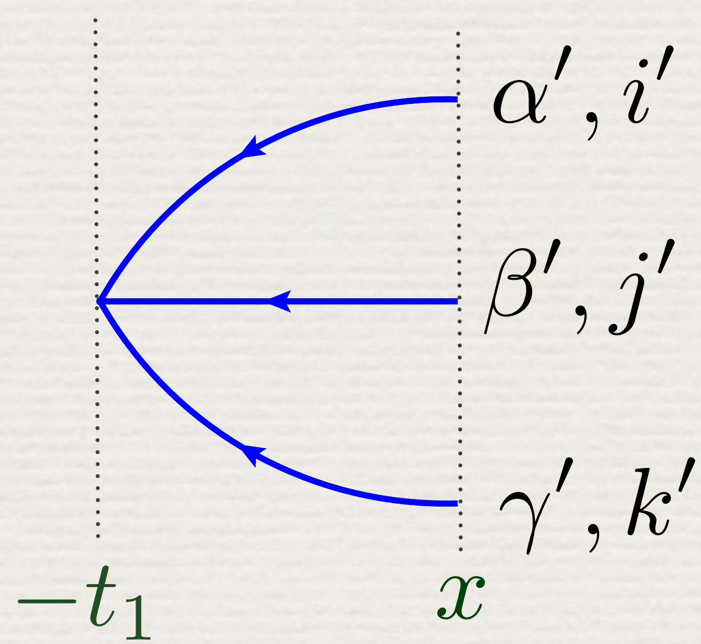


$$\sum_{x'} e^{ip(x-x')}$$

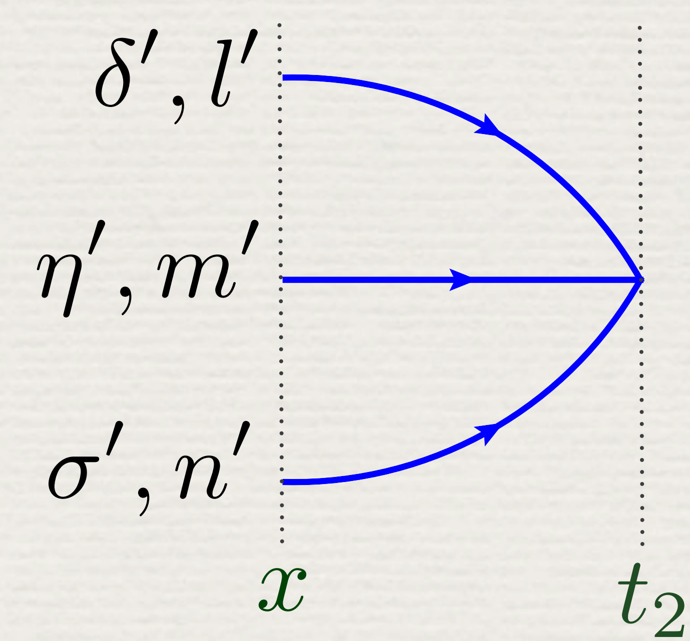
Project onto lattice irrep G_1^+

$12 \times 12 \times N_t$ Object → N_s^3 times smaller than prop

12 Indep. Contractions



$$\mathcal{O}_{ijklmn}^{\alpha,\beta,\gamma,\delta,\eta,\sigma}$$



Executive Summary

- Advantages of Neutron-Antineutron calculations

  For same cost:

  More Statistics

  All Operator Insertions

  No Quark Loop or Disconnected Diagrams

- Disadvantages of Neutron-Antineutron calculations

  More Propagator Multiplications → Potentially Worse Signal

Lattice Details

Original Calculation

- $32^3 \times 256$ anisotrpoic clover-Wilson lattices
- $m_\pi \sim 390$ MeV
- $a_t \sim 0.04$ fm, $a_s \sim 0.125$ fm
- $L \sim 4$ fm
- 159 configurations (every 4th trajectory)
- 7268 propagators (Gaussian smeared sources)

Problems:

Operator Smearing

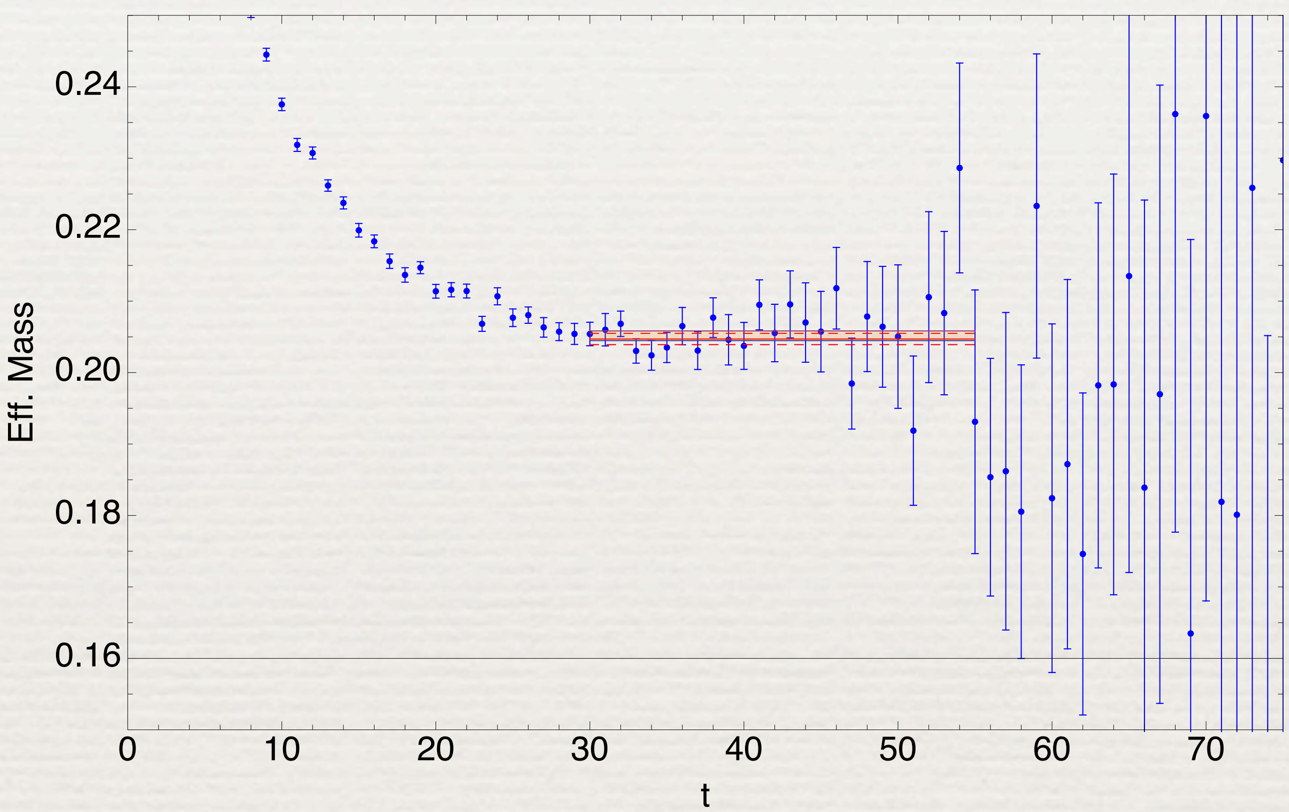
Insufficient statistics

- $20^3 \times 256$ anisotrpoic clover-Wilson lattices
- $m_\pi \sim 390$ MeV
- $a_t \sim 0.04$ fm, $a_s \sim 0.125$ fm
- $L \sim 4$ fm
- 875 configurations (every 5th trajectory) Aim: 1149
- 62,548 propagators Aim: 100,000

Nucleon Effective Mass

Eff. Mass

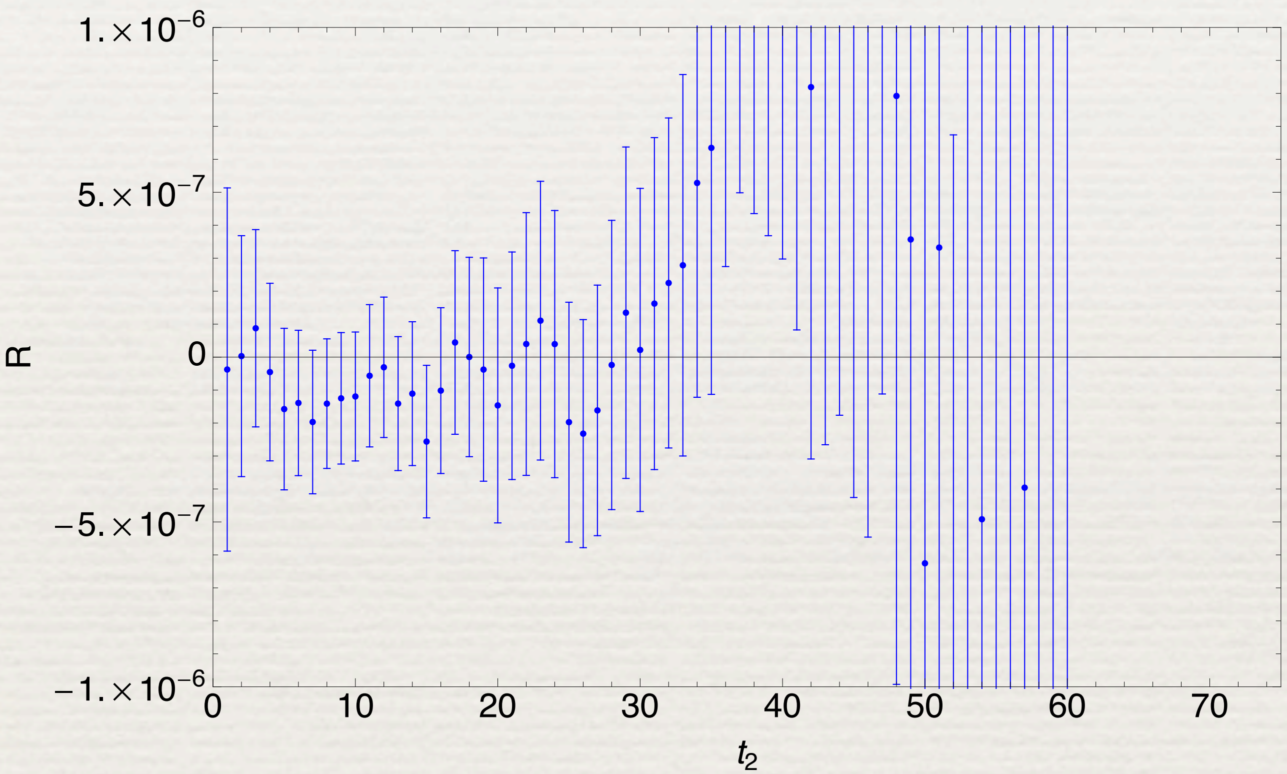
$$\frac{C_{NN}(t+1)}{C_{NN}(t)} \to m_n$$



$$a_t M_N = 0.20470(\pm 0.00079)(+0.00113)(-0.00022)$$

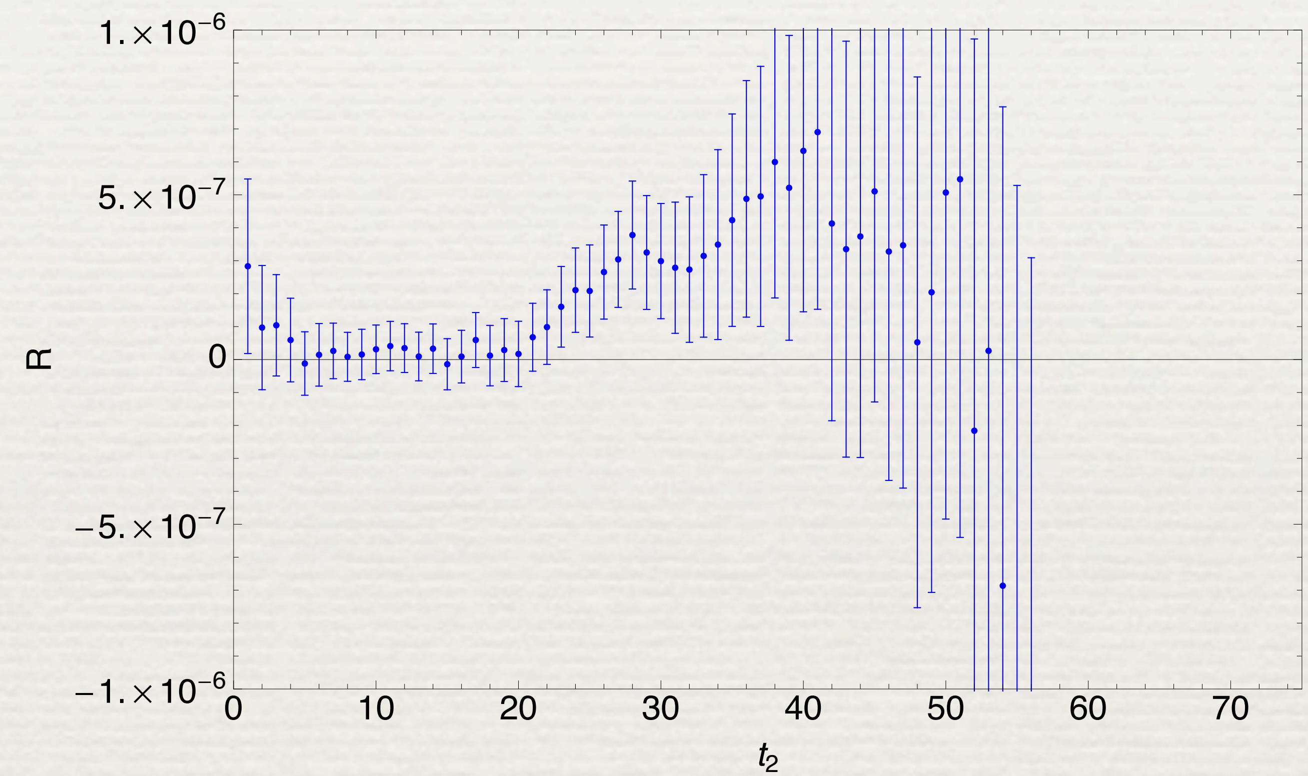
N-NBar Matrix Element

$t_1 = 15$



~10,000 Measurements

$t_1 = 15$

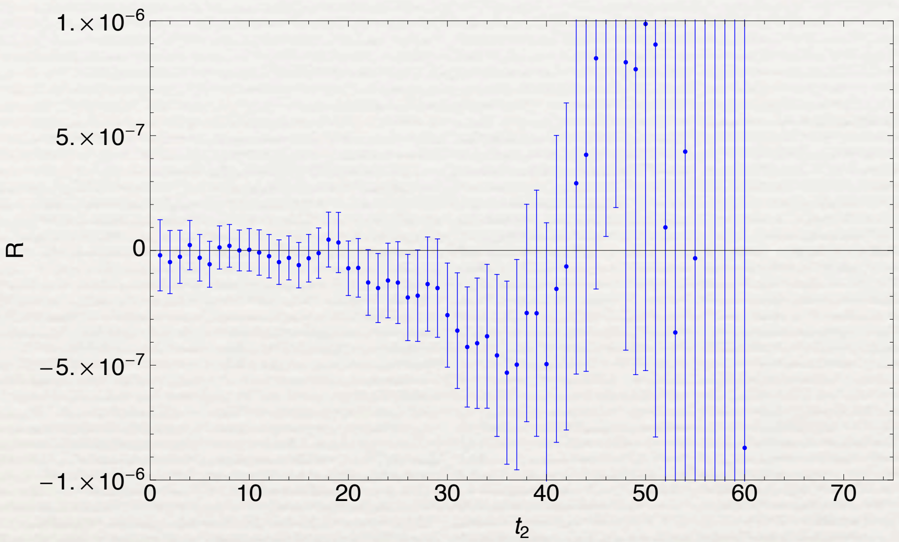


~60,000 Measurements

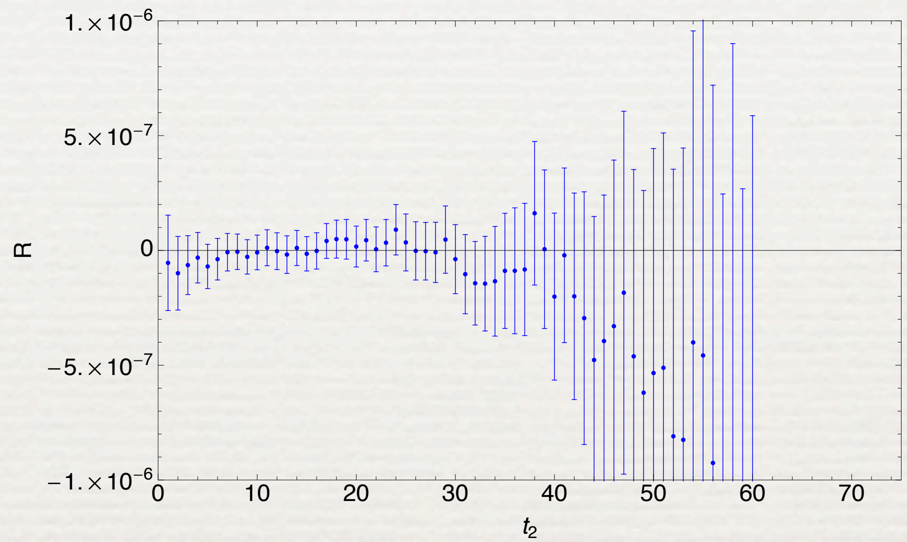
$$\mathcal{R} \to \langle \overline{n} | \mathcal{O} | n \rangle$$

N-NBar Matrix Element

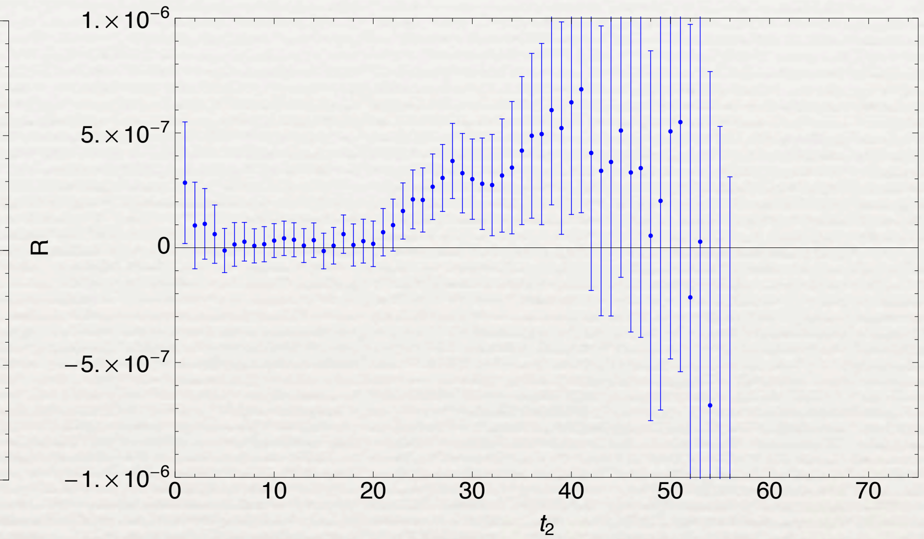
$t_1 = 5$



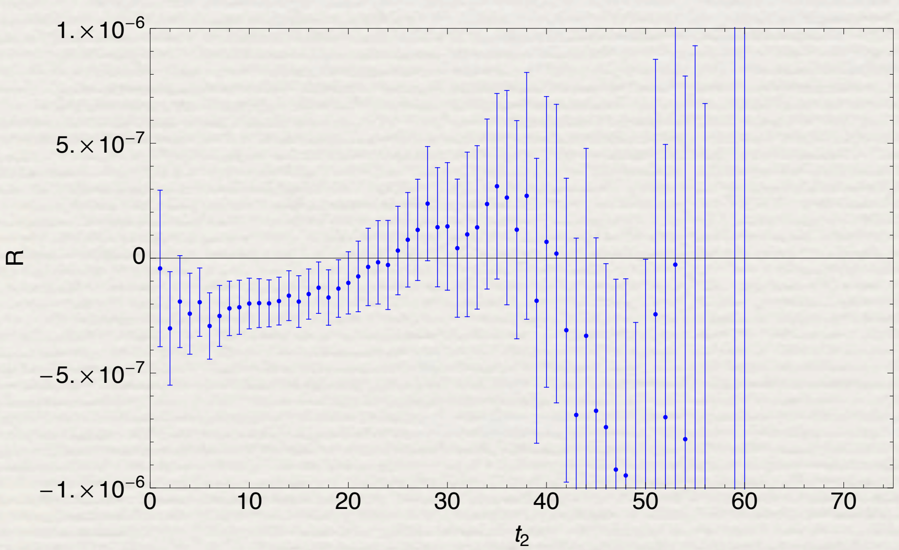
$t_1 = 10$



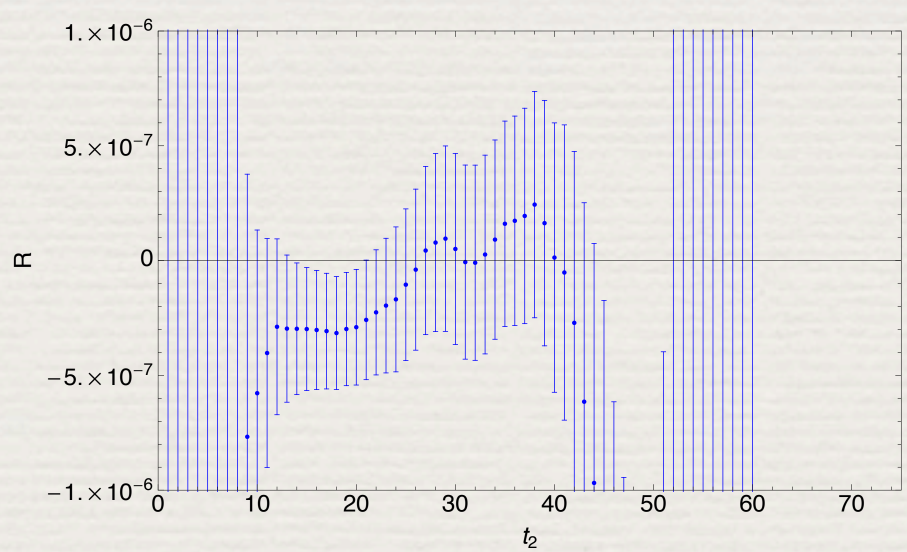
$t_1 = 15$



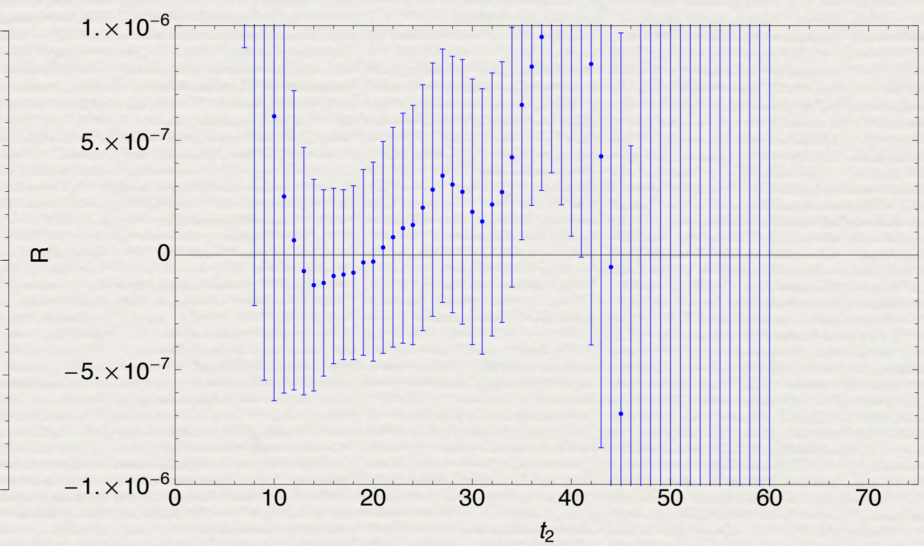
$t_1 = 20$



$t_1 = 25$



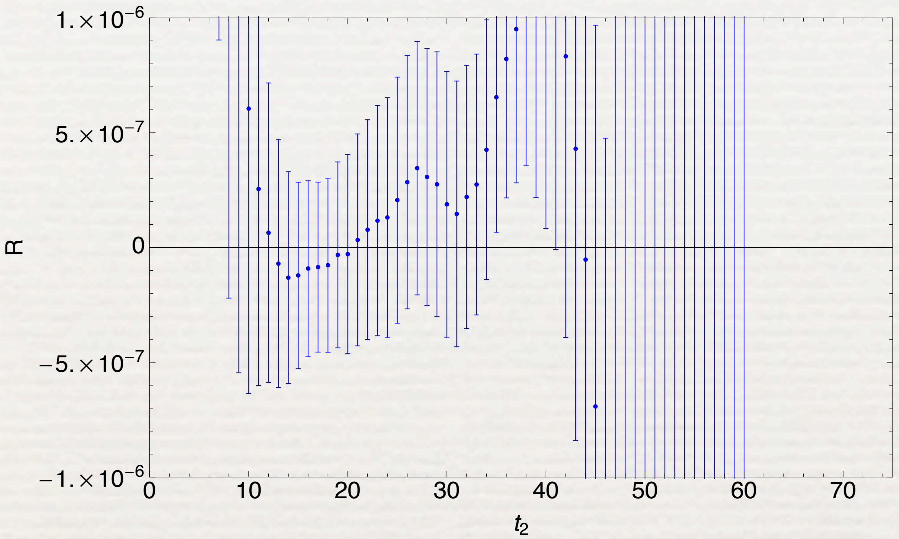
$t_1 = 30$



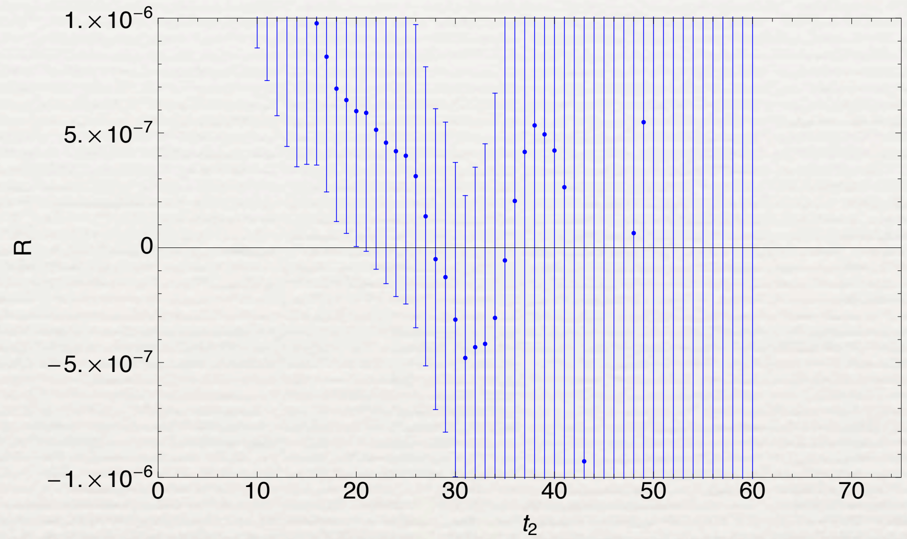
$$\mathcal{R} \to \langle \overline{n} | \mathcal{O} | n \rangle$$

N-NBar Matrix Element

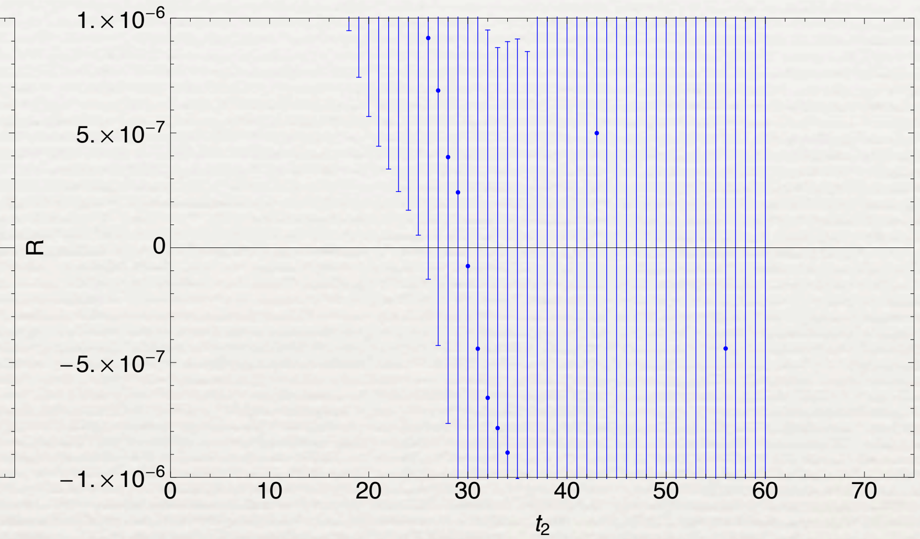
$t_1 = 30$



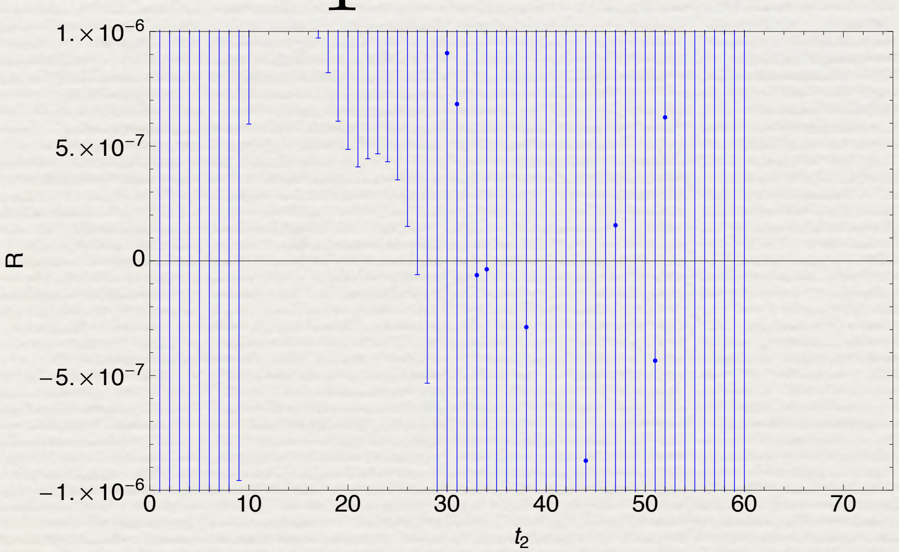
$t_1 = 35$



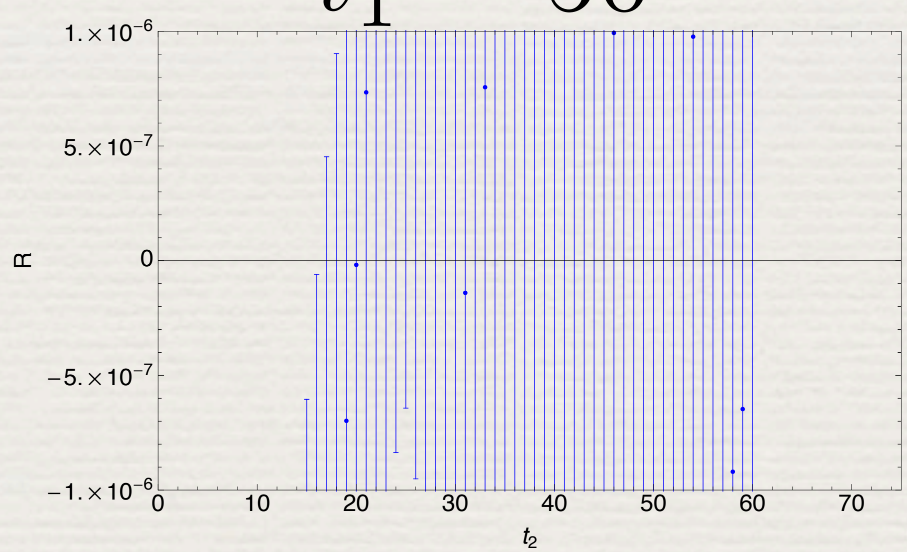
$t_1 = 40$



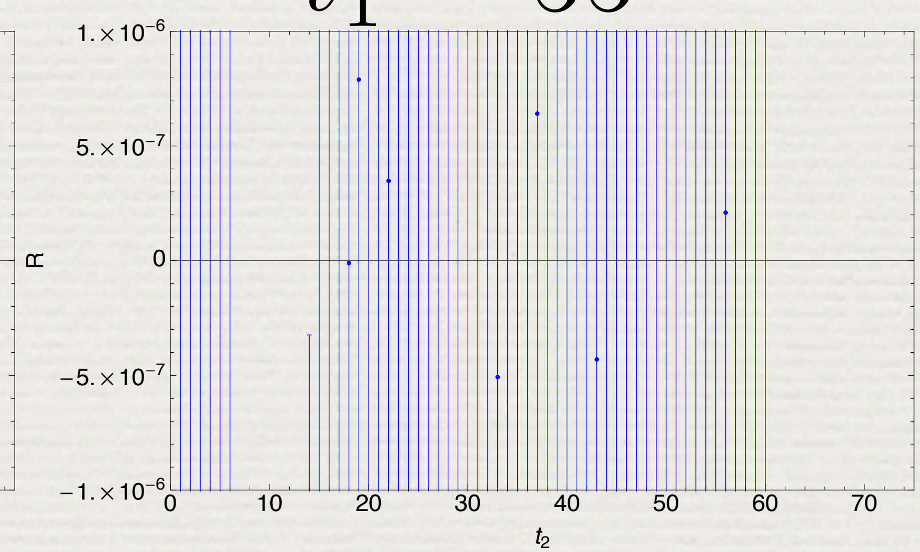
$t_1 = 45$



$t_1 = 50$



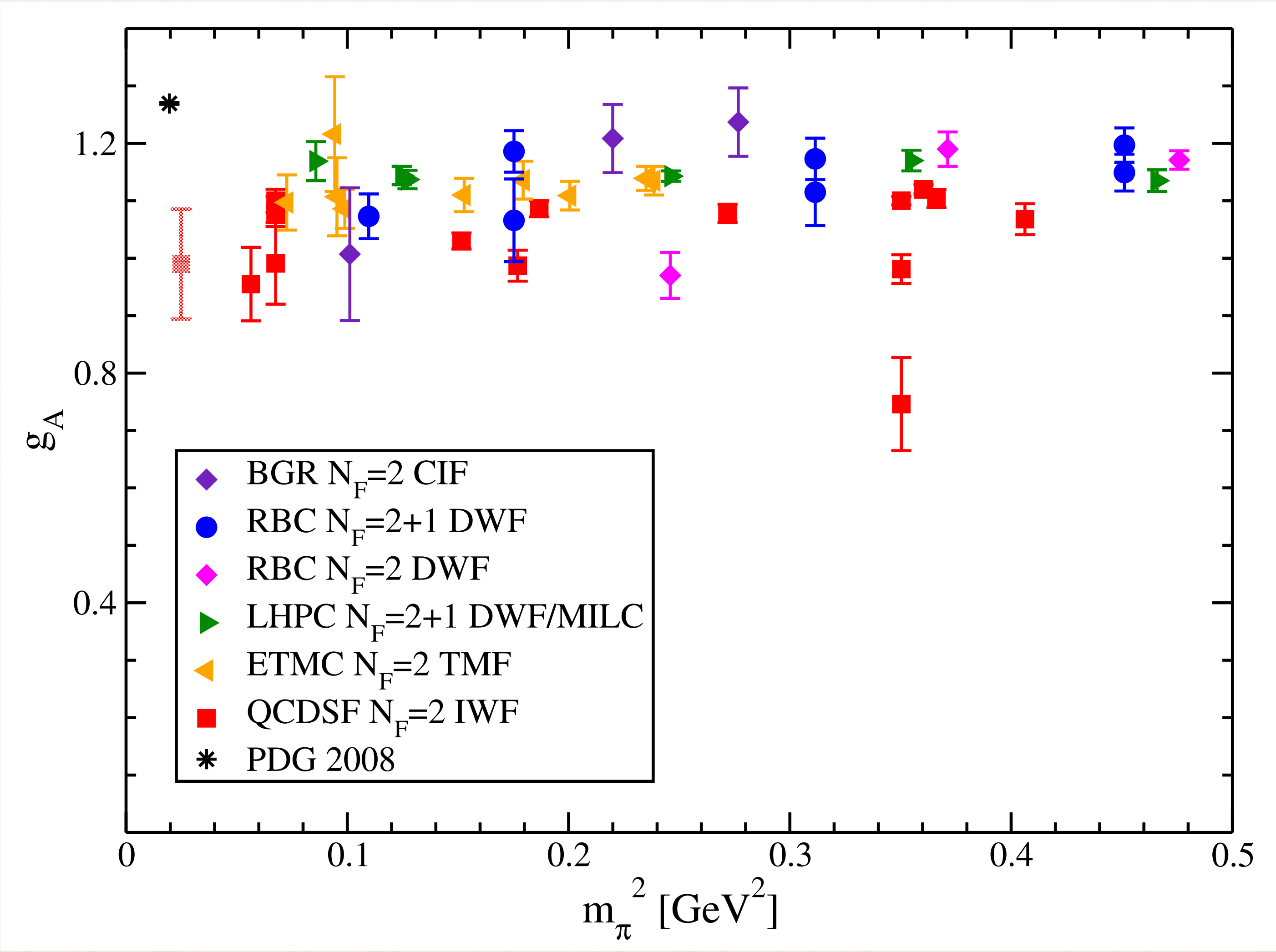
$t_1 = 55$



$$\mathcal{R} \to \langle \overline{n} | \mathcal{O} | n \rangle$$

Possible Systematics Studies

Hosts of systematics can plague nucleon three-point functions



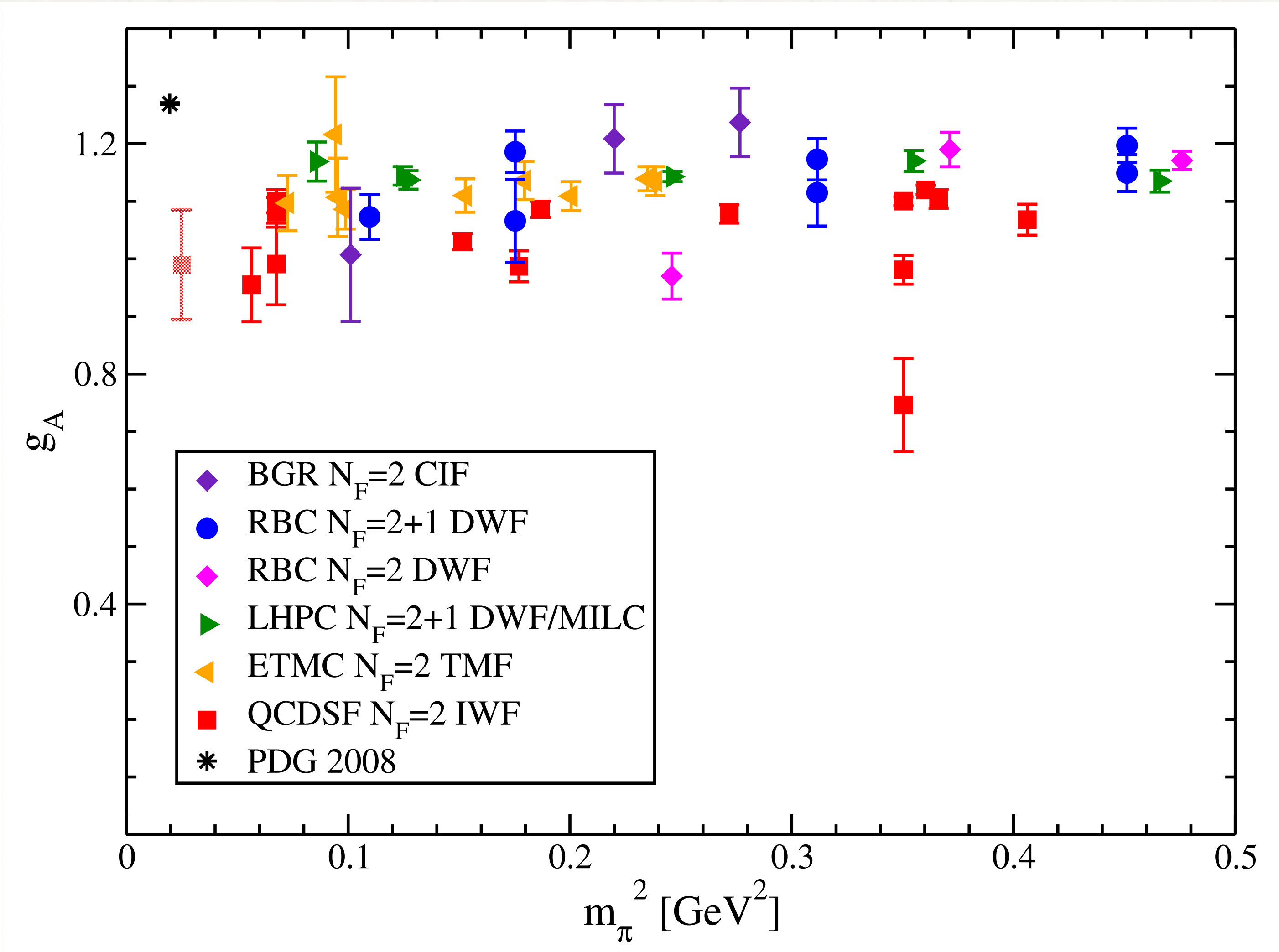
1) Volume Effects
2) Excited State Effects
3) Renormalization
4) Signal-to-noise
5) Statistics

Renner,
arXiv:1002.0925

Neutron-antineutron calculations
can be a testing ground!!

Possible Systematics Studies

Hosts of systematics can plague nucleon three-point functions



1) Volume Effects
2) Excited State Effects
3) Renormalization
4) Signal-to-noise
5) Statistics

Renner, arXiv:1002.0925

Neutron-antineutron calculations can be a testing ground!!

Variety of Three-point analyses

Examined here:

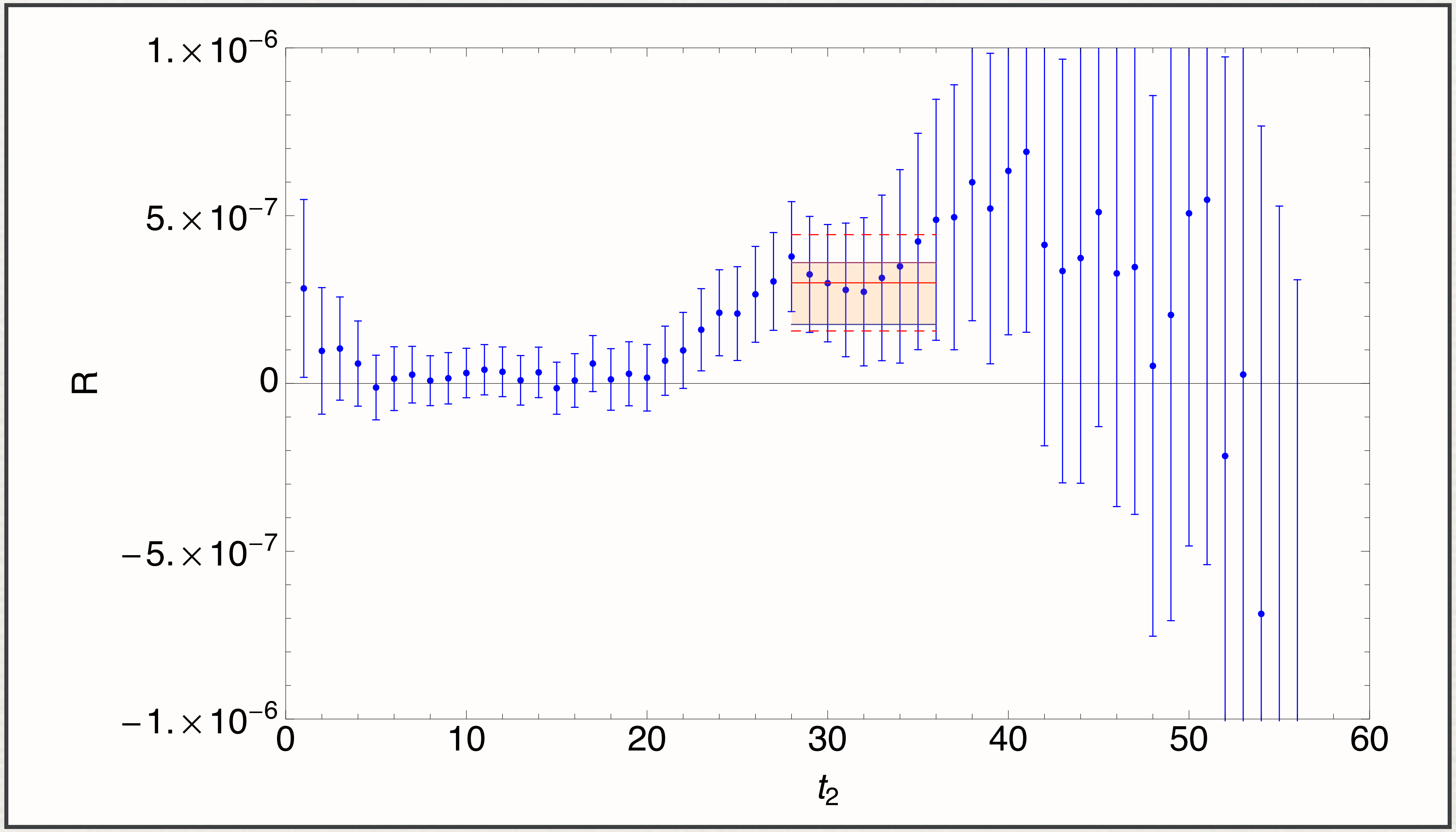
1) Single source-operator separation
2) Center-line Fit
3) 2D Center-line Fit (source-op & op-sink)
4) Summation Method

To be explored:

1) Three-point matrix-Prony
2) Folding
3) Other Suggestions?

One Separation Fit

$$t_1 = 15$$

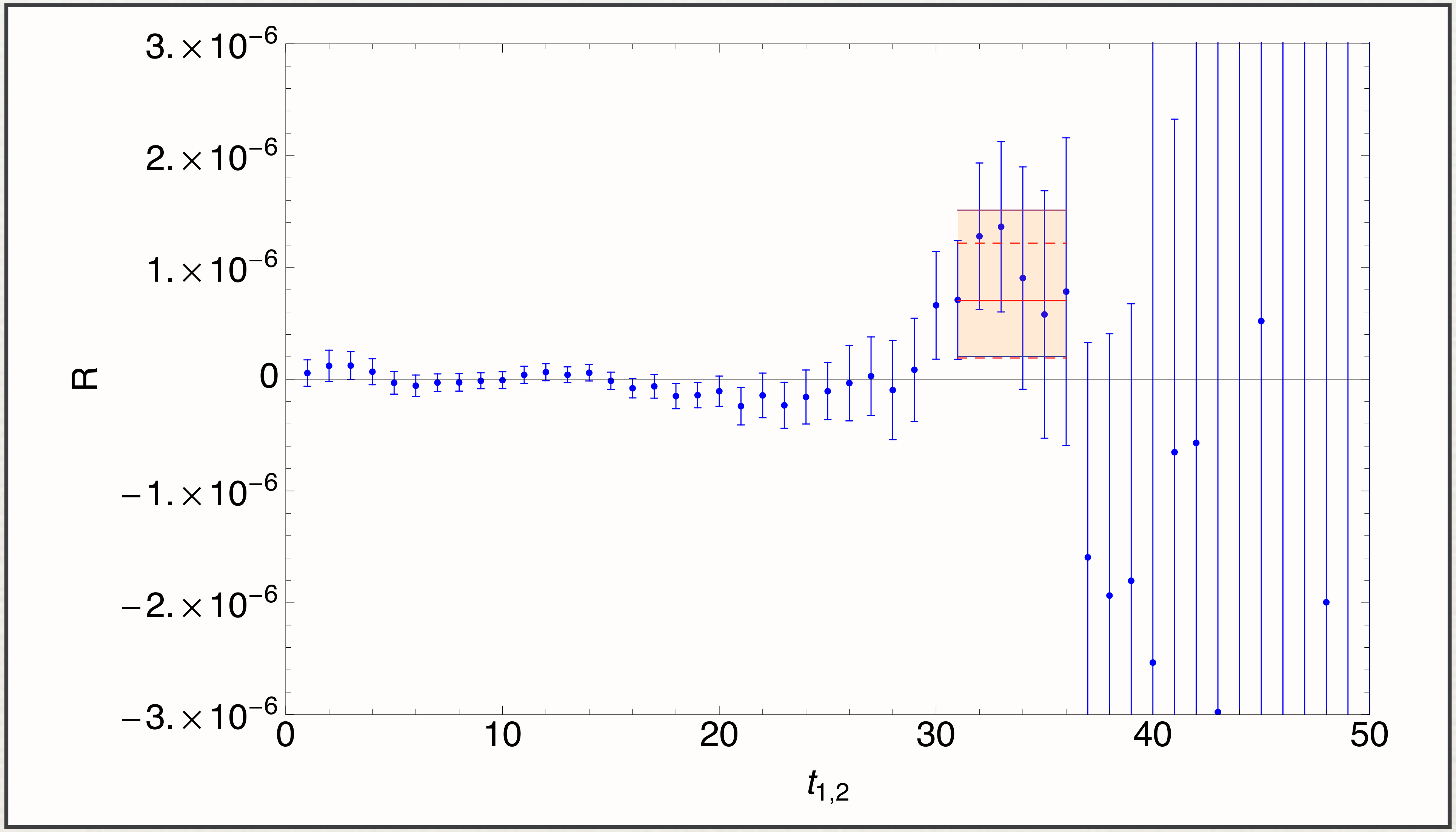


$$a_s^6 \langle N | \mathcal{O}^1_{RRR} | \overline{N} \rangle = (3.00 \pm 1.44^{+0.60}_{-1.24}) \times 10^{-7}$$

$$\chi^2/\mathrm{dof} = 0.859$$

Center-line Fit

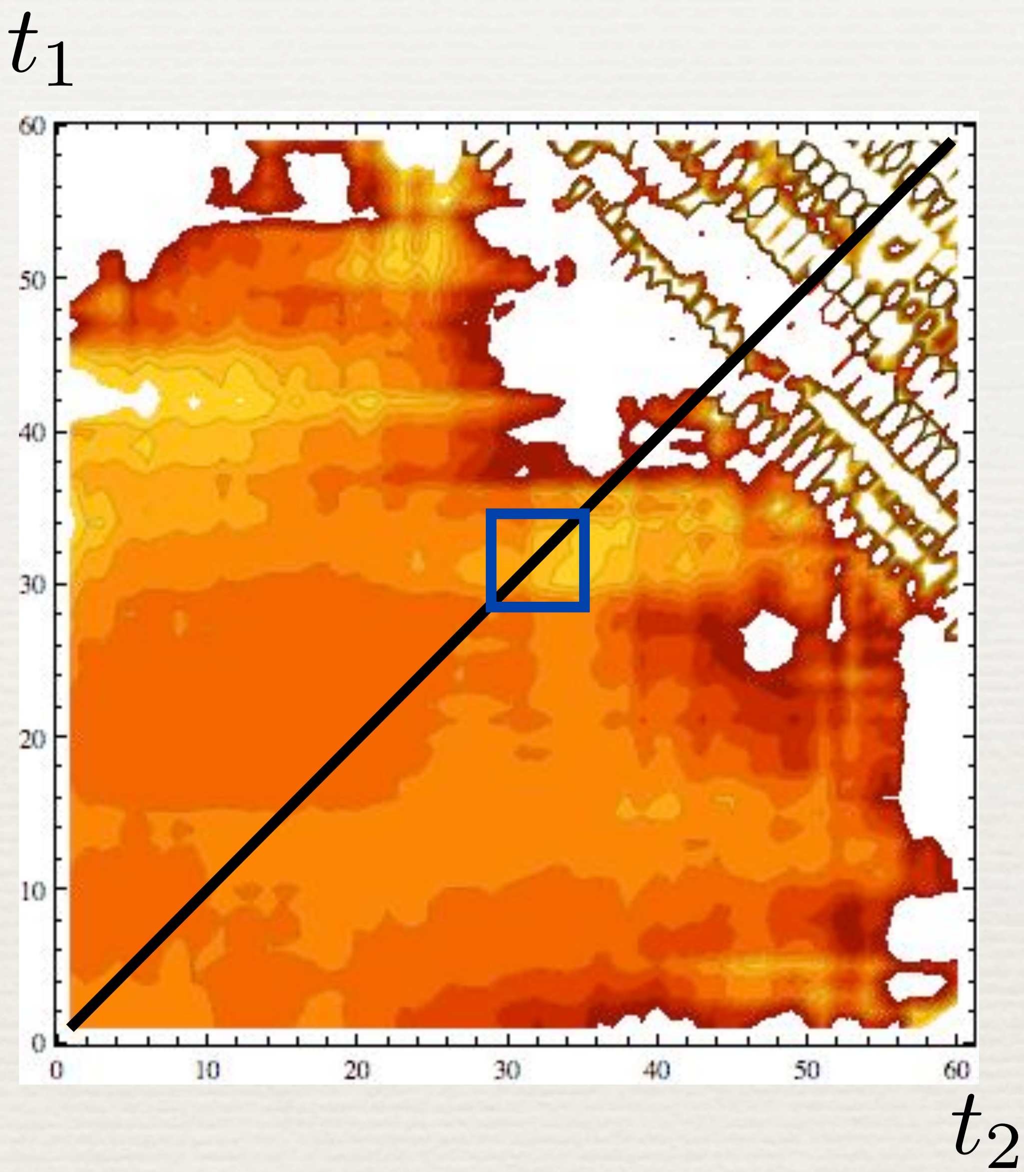
$$t_{1,2} = t_1 = t_2$$

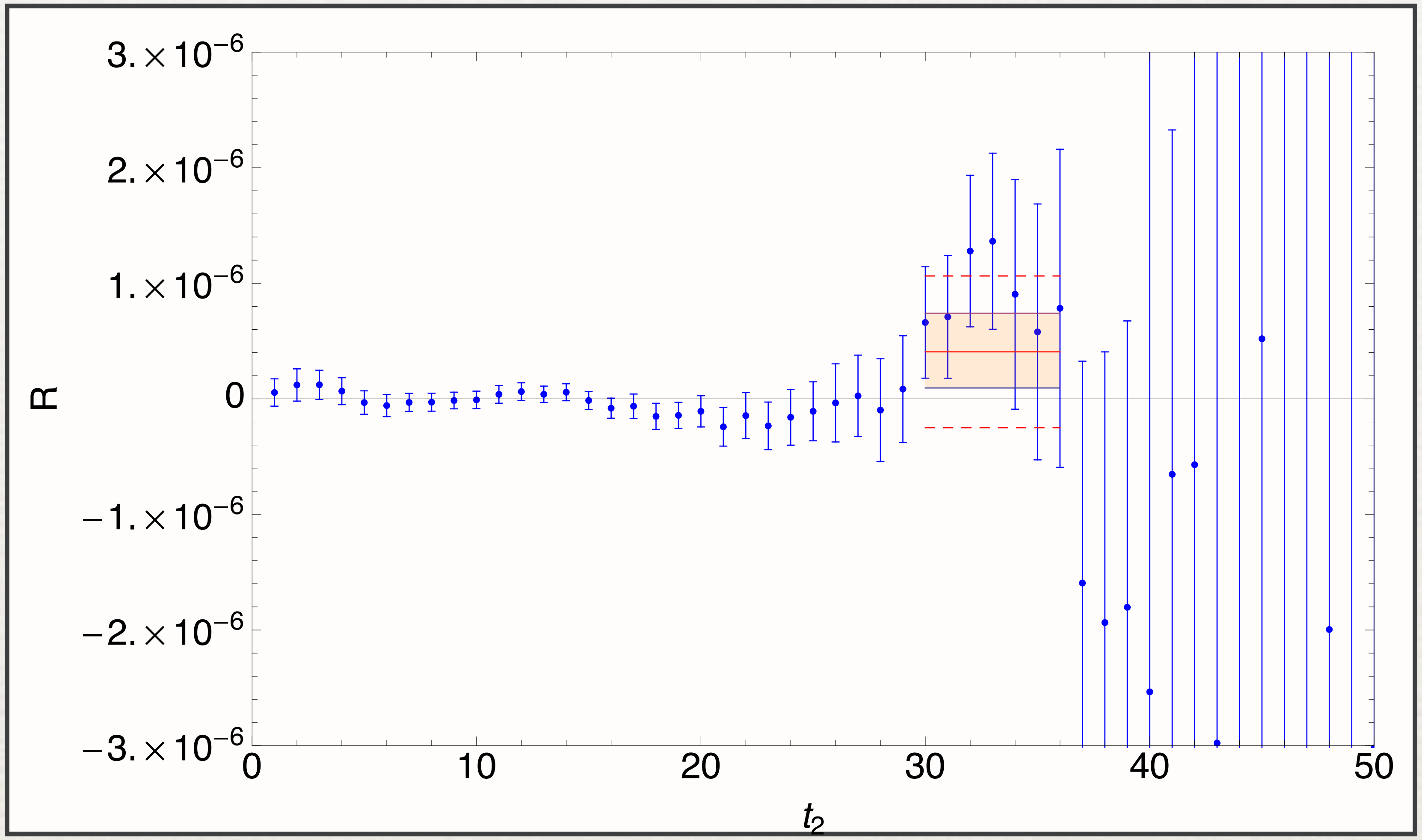


$$a_s^6 \langle N | \mathcal{O}^1_{RRR} | \overline{N} \rangle = (7.03 \pm 5.13^{+8.09}_{-5.00}) \times 10^{-7}$$

$$\chi^2/\mathrm{dof} = 0.834$$

2D Center Line Fit





$30 \leq t_1 \leq 36$

$30 \leq t_2 \leq 36$

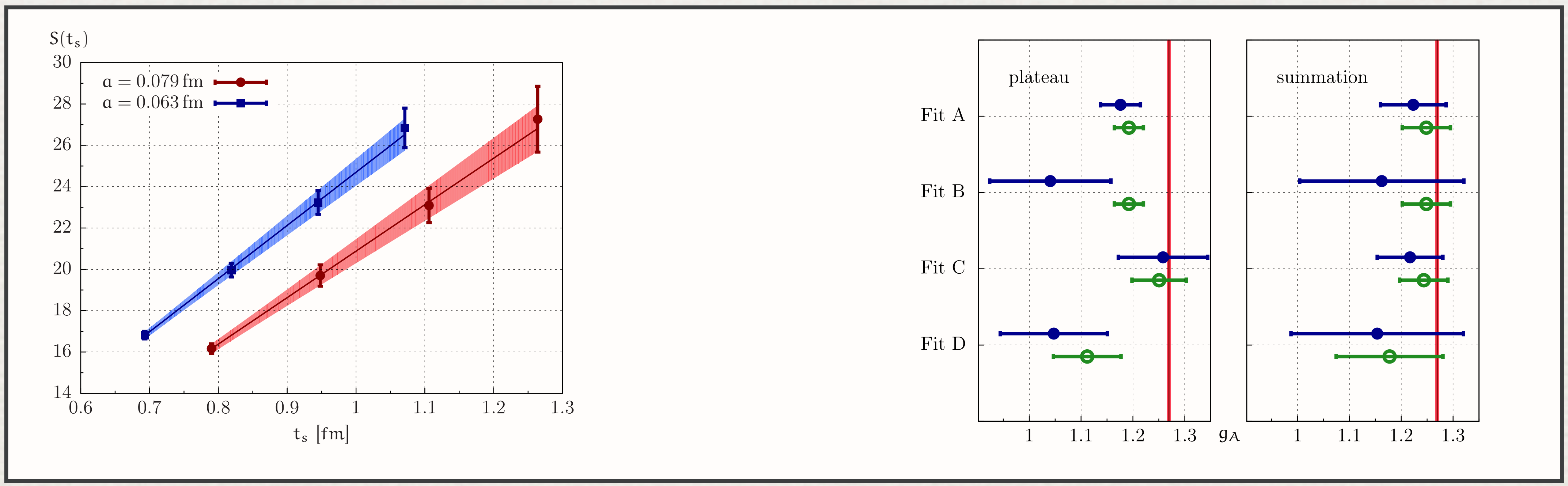
$$a_s^6 \langle N | \mathcal{O}^1_{RRR} | \overline{N} \rangle = (4.07 \pm 6.57^{+3.34}_{-3.13}) \times 10^{-7}$$

$$\chi^2/\mathrm{dof} = 1.32$$

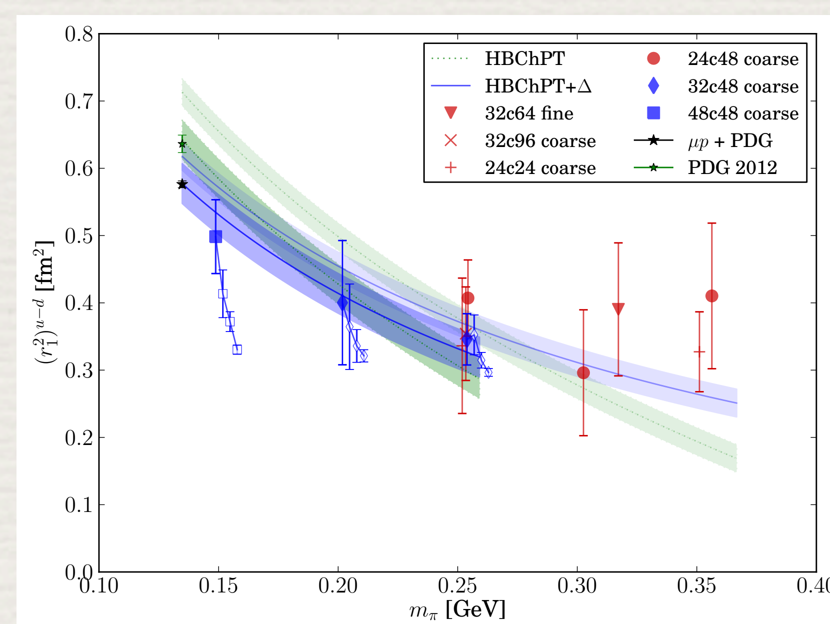
Summation Method

$$S(t_s) = \sum_{t=0}^{t_s} \mathcal{R}(t, t_s - t) \xrightarrow{t_s \gg 0} c + t_s \langle N|\mathcal{O}|\overline{N}\rangle$$

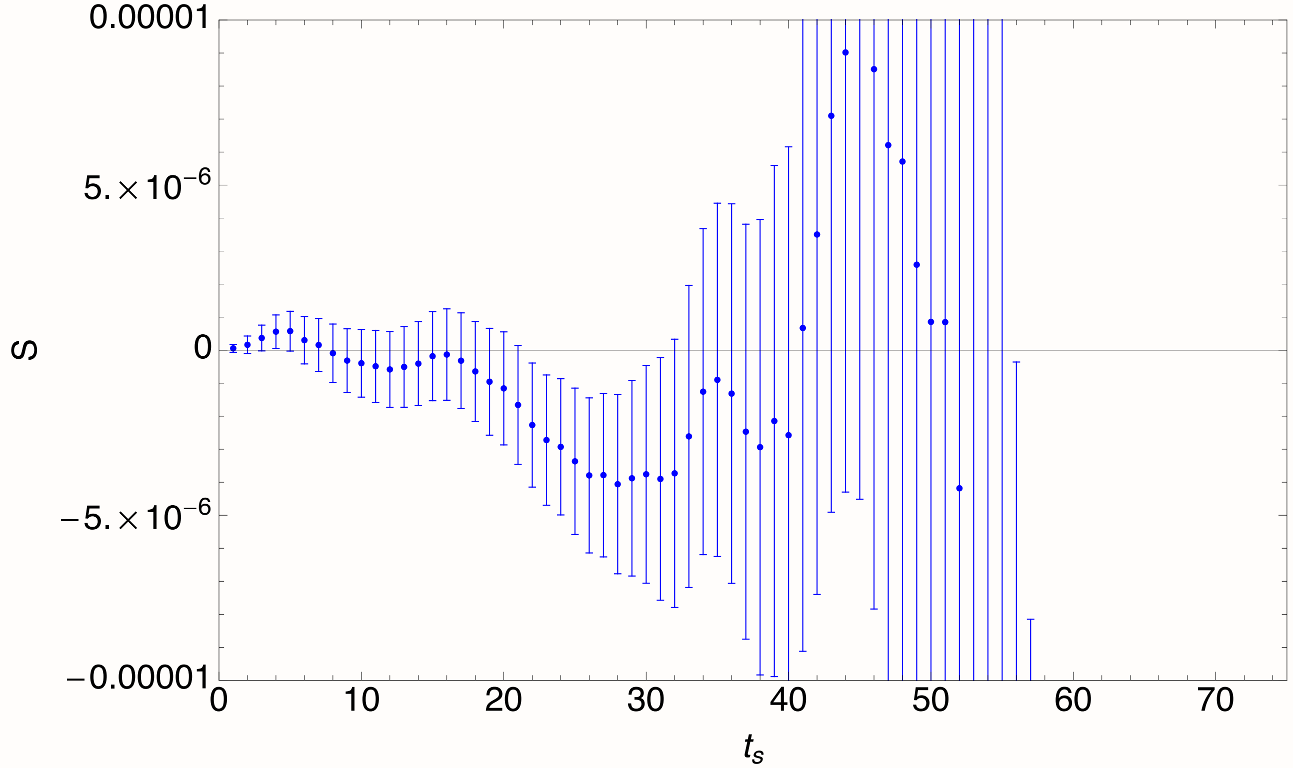
Capitani et al., 2012, arXiv:1205.0180



Green et al., 2012, arXiv:1205.0180

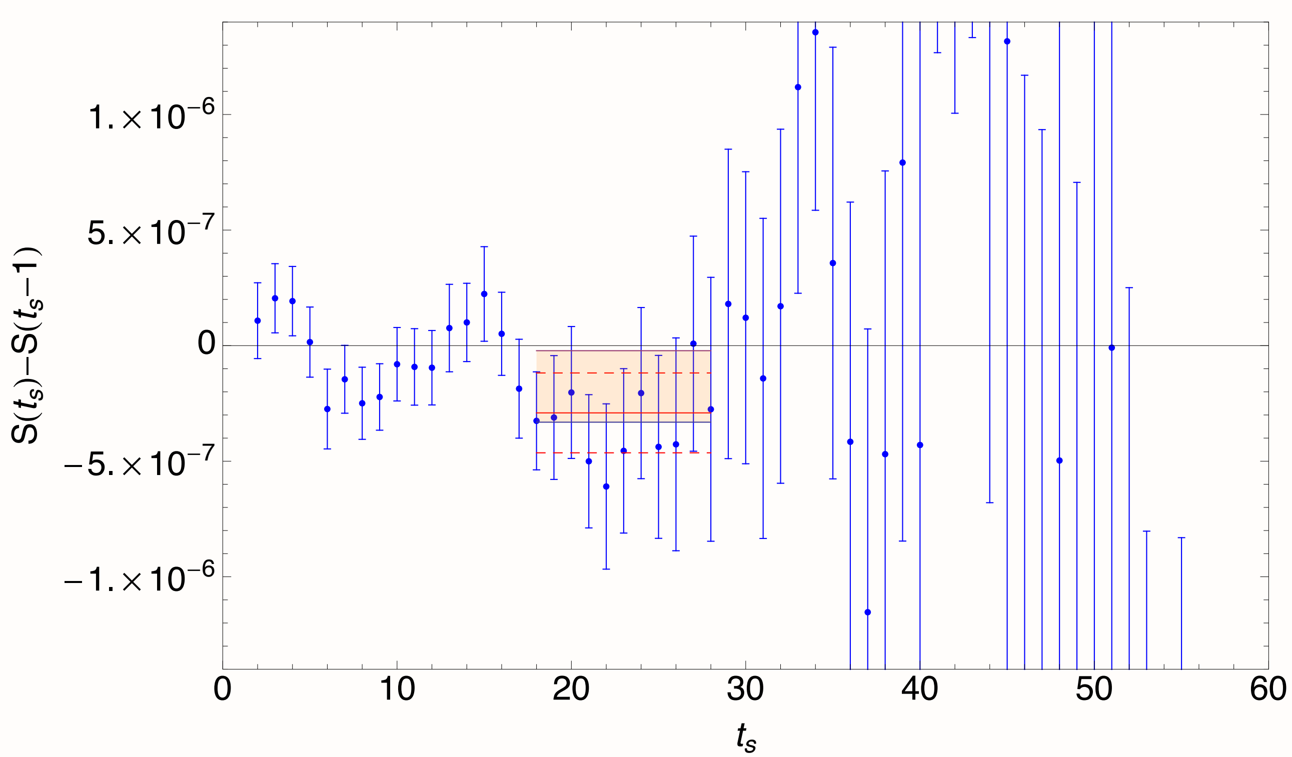


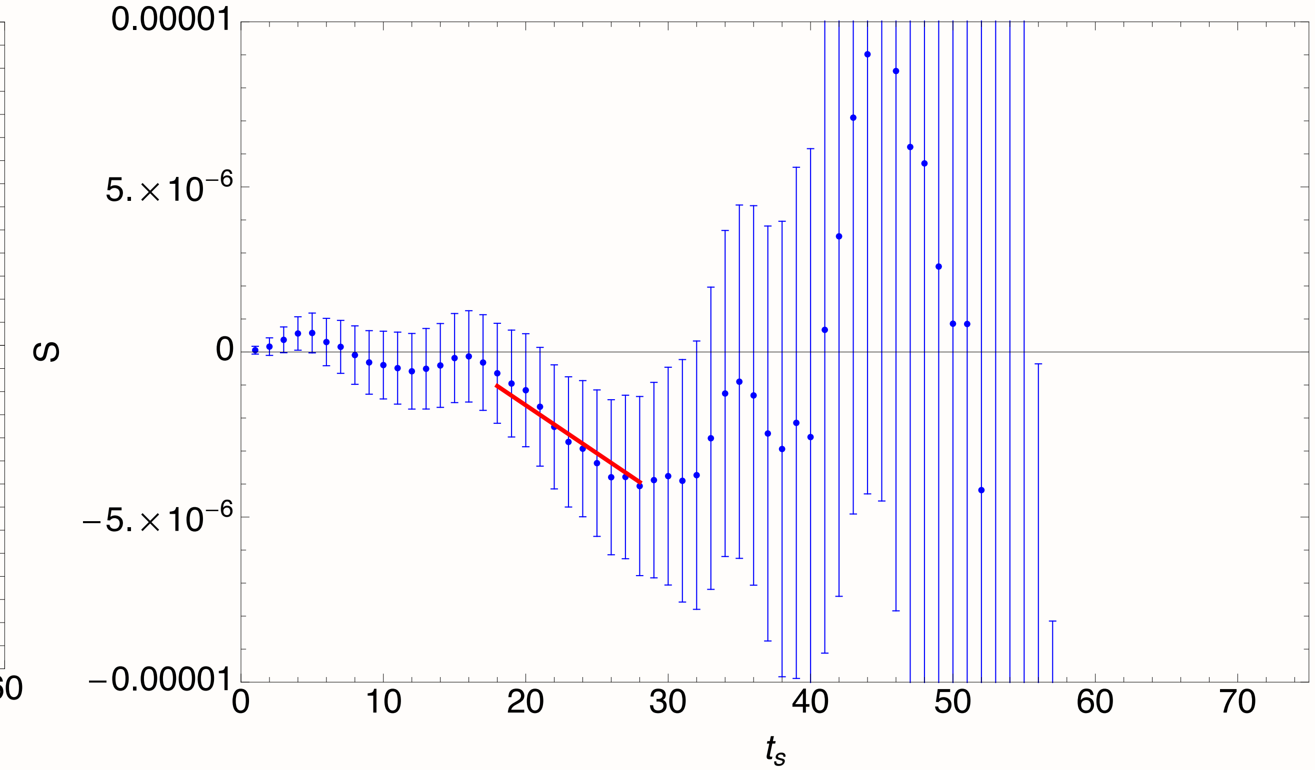
Summation Method



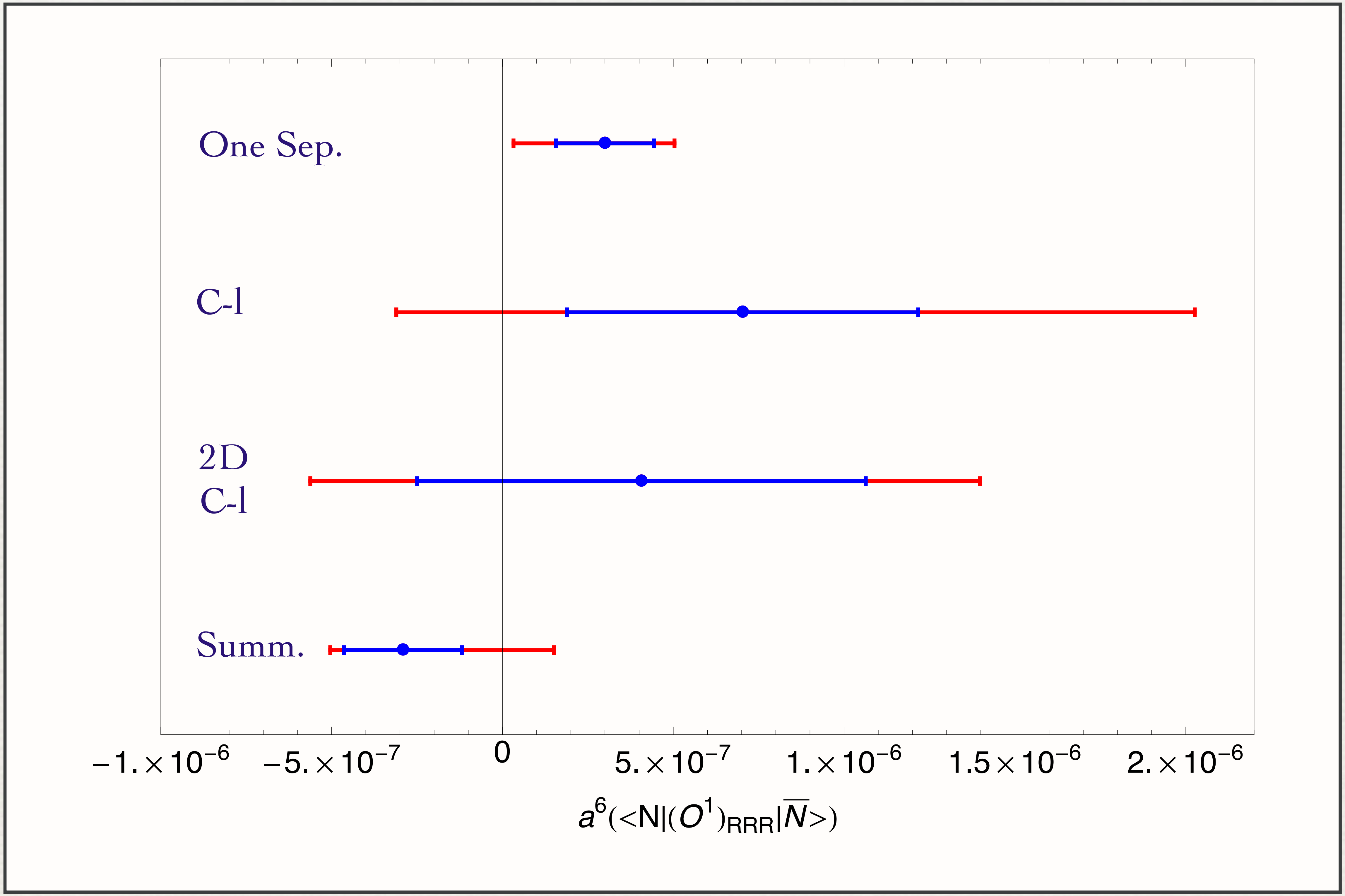
$$a_s^6\langle N|\mathcal{O}^1_{RRR}|\overline{N}\rangle =$$
$$(-2.91 \pm 1.73^{+2.69}_{-0.40}) \times 10^{-7}$$

$$\chi^2/\mathrm{dof} = 0.792$$

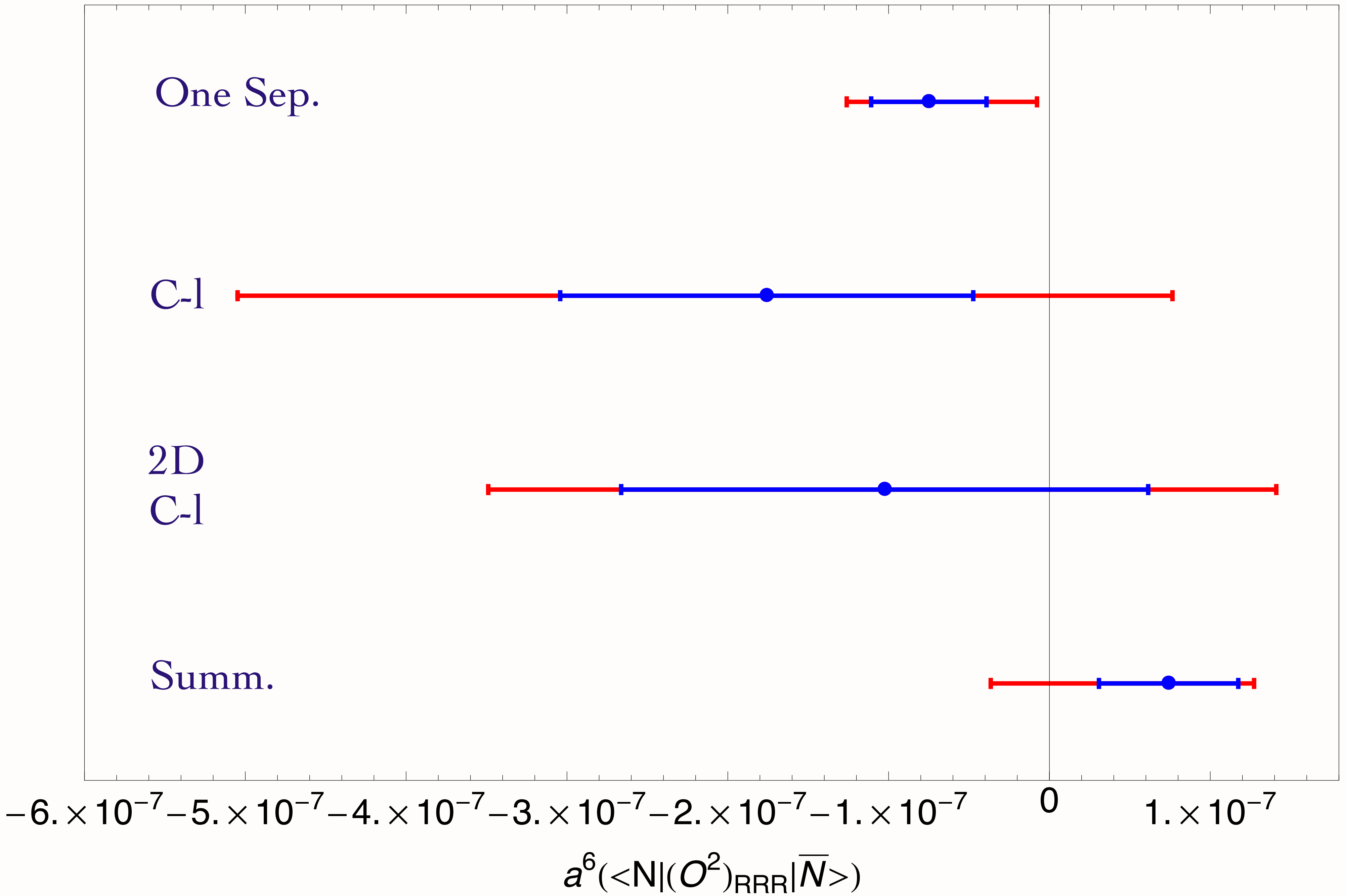




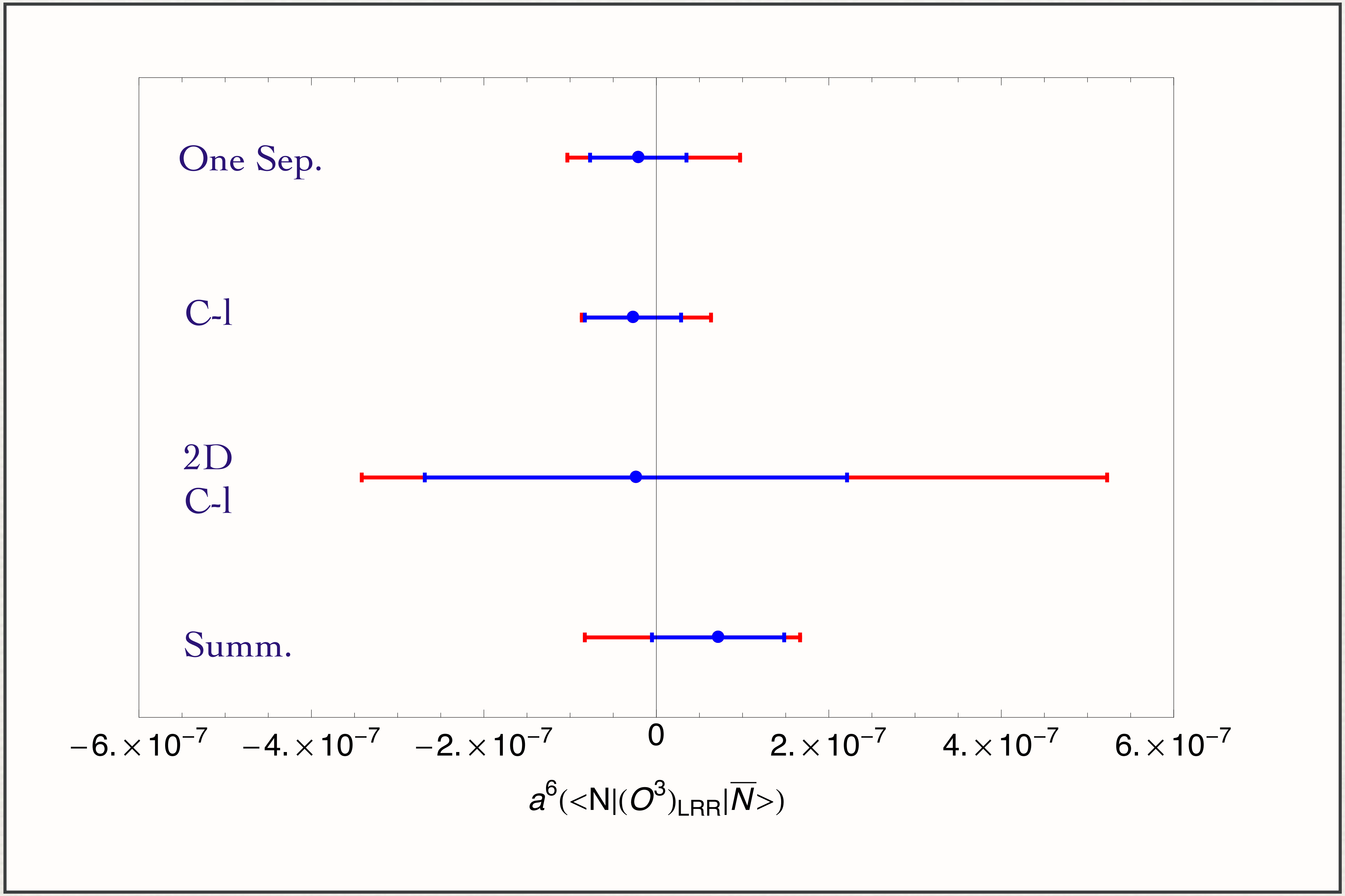
All results for $\mathcal{O}^1_{RRR}$



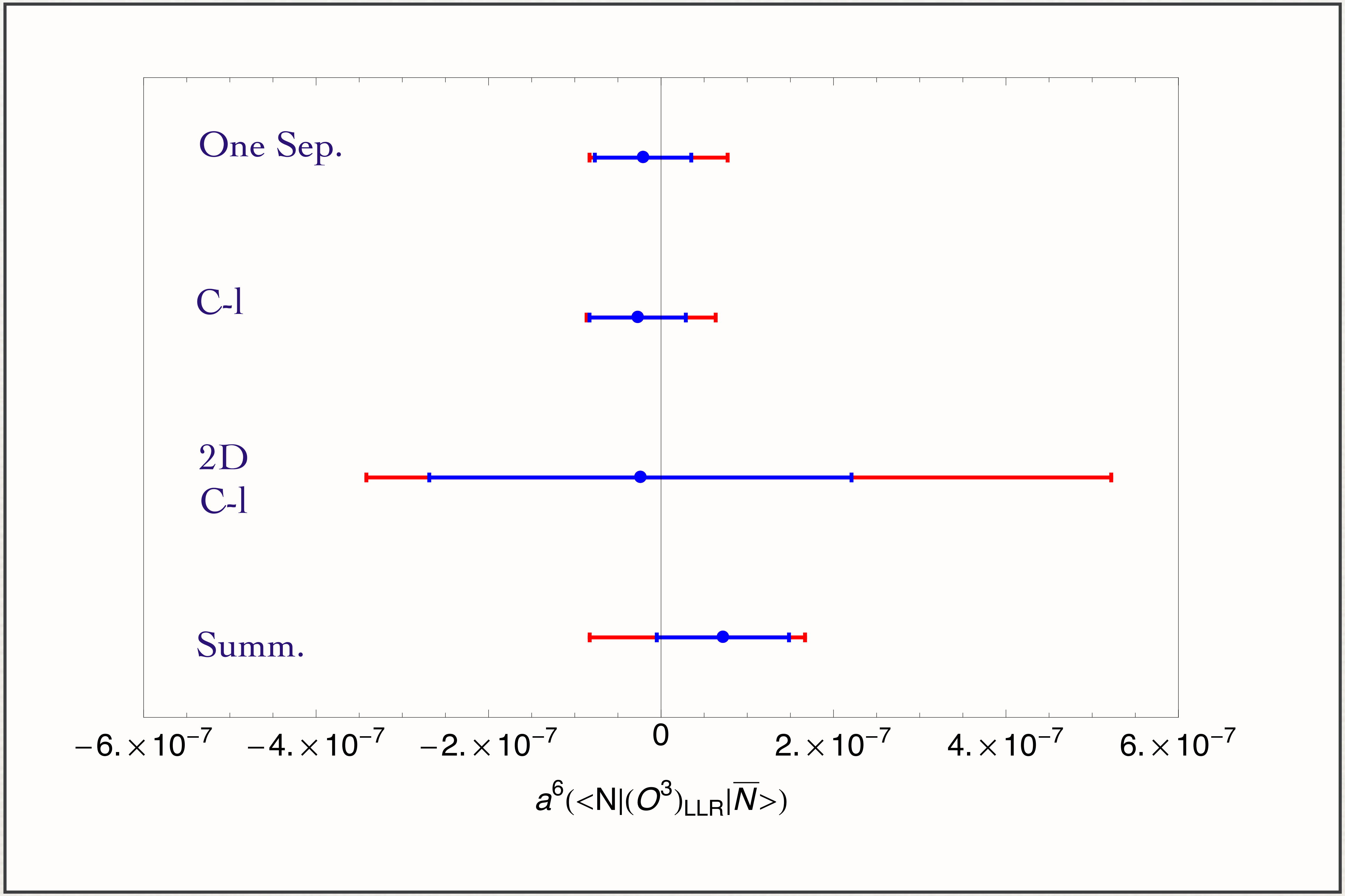
All results for $\mathcal{O}^2_{RRR}$



All results for $\mathcal{O}^3_{LRR}$



All results for $\mathcal{O}^3_{LLR}$



Preliminary Results

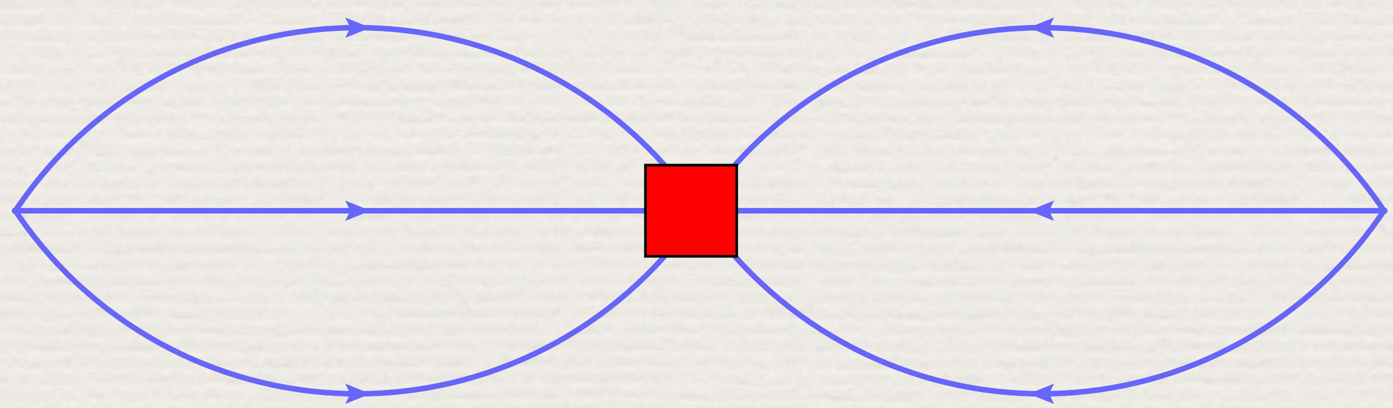
	Lattice (Bare)	MIT Bag Model
$\langle \overline{n} \vert \mathcal{P}_1 \vert n \rangle$	$0.81 \pm 1.30^{+0.66}_{-0.62}$	-6.56
$\langle \overline{n} \vert \mathcal{P}_2 \vert n \rangle$	$-0.21 \pm 0.32^{+0.15}_{-0.16}$	1.64
$\langle \overline{n} \vert \mathcal{P}_4 \vert n \rangle$	$-0.10 \pm 0.96^{+1.20}_{-0.28}$	-6.36
$\langle \overline{n} \vert \mathcal{P}_5 \vert n \rangle$	$-0.20 \pm 1.92^{+2.40}_{-0.54}$	9.64
	$\times 10^{-5}\ \mathrm{GeV}^6$	$\times 10^{-5}\ \mathrm{GeV}^6$

Still multiple important lattice systematics

Systematic Effects

- Unphysical Pion Mass
  - No chiral extrapolation (yet...)
  - Near physical point enhancements?

$n\bar{n}$: $\tau = -t_1$ $\tau = 0$ $\tau = t_2$



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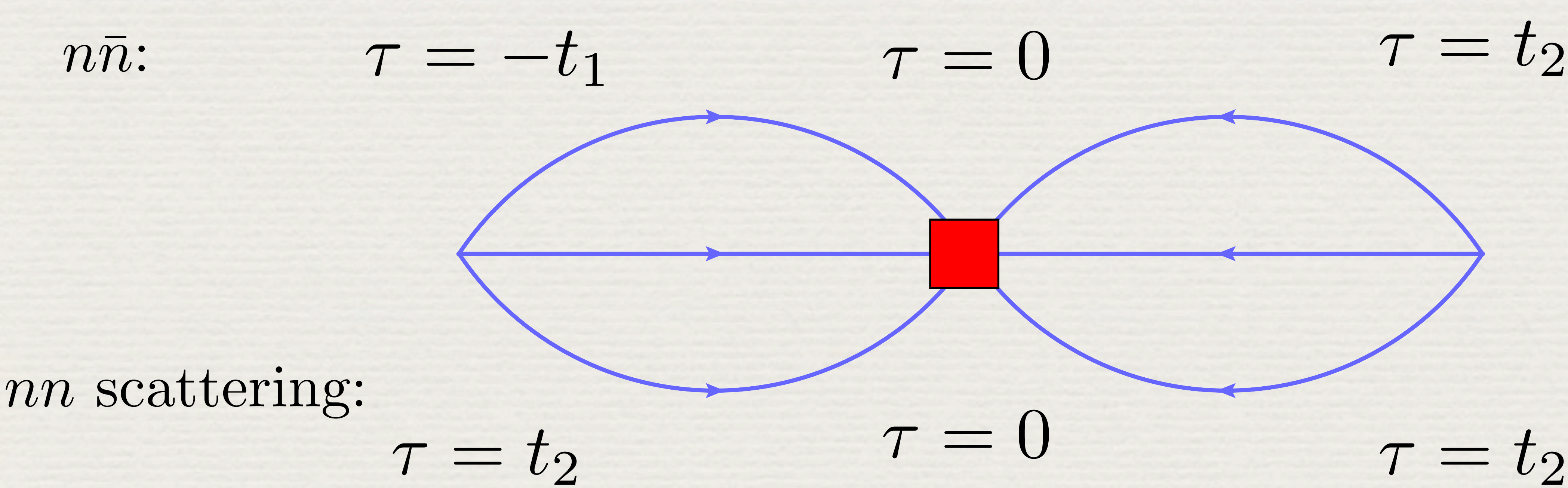

Other Systematic Effects

- Renormalization/discretization effects

  - Most violent case should not occur

    No lower dimensional $\Delta B = 2$ operator

  - Perturbative and non-perturbative renomalization needed

Six-quark operator $\Rightarrow$ Potentially larger Z-factor

Future Outlook

Currently in progress:

- Independent analysis checks
- Lattice Renormalization
- Systematic way to separate excited states & noise from ground state signal

Near Future:

- More Statistics
- Chiral Extrapolation

Future Outlook

Feasible in the next few years:

- Physical Point Calculation
- Chiral Fermion Calculation
- Construct Variational Basis
- Low-mode/all-mode averaging
- Separate wall sources?

Final word

Intriguing prospects for Neutron-antineutron oscillations!

Physically:

-Can unveil new physics or provide stringent constraints

-Proposed experiments can finally probe region of interest

Lattice:

-Can rigorously pinpoint bounds from various GUT theories

-At the same time, calculations can help address systematic effects for nucleon three-point functions

This research was supported by the LLNL LDRD "Unlocking the Universe with High Performance Computing" 10-ERD-033 and by the LLNL Multiprogrammatic and Institutional Computing program through the Tier 1 Grand Challenge award that has provided us with the large amounts of necessary computing