Lattice calculations for $n - \bar{n}$

Enrico Rinaldi

12/13/2018 - Particle Physics with Neutrons at the ESS, Nordita, Stockholm, Sweden

RIKEN BNL Research Center

Neutron-antineutron oscillations on the lattice

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Livermore, California 94550, USA
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[PoS, Lattice 2012, 128]

Neutron-Antineutron Oscillation Matrix Elements with Domain Wall Fermions at the Physical Point

Sergey Syritsyn[*a,b], **Michael Buchoff**[c,d], **Chris Schroeder**[c], **Joe Wasem**[c]
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[PoS, Lattice 2015, 132]

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[PoS, Lattice 2015, 132]

Neutron-antineutron oscillations from lattice QCD

Enrico Rinaldi,[1,2,*] Sergey Syritsyn,[1,3,†] Michael L. Wagman,[4,‡]
Michael I. Buchoff,[5] Chris Schroeder,[5] and Joseph Wasem[5]
[1] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
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[5] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

[arxiv:1809.00246]

Motivations

- Oscillations of neutral particles can teach us about new physics

K^0	B^0	ν	N
CP	CP	m_ν	?

- Neutron oscillations violate baryon number (B) and baryon-lepton (B-L) number: $|\Delta B| = 2$, $\Delta L = 0$

[Sakharov, JETP Lett. 5, 24 (1967)]

- Contrary to proton decay, scale of new physics is within reach and can explain baryogenesis

[Grojean et al., 1806.00011]

- Future experiments have the potential for a great increase in sensitivity to oscillations (<u>ESS</u> and DUNE)

[Frost, 1607.07271]
[many talks at this workshop!!] [Hewes, DOI:10.2172/1426674]

Synopsis of oscillations

$$\mathcal{M}_{\mathcal{B}} = \begin{pmatrix} m_n - \vec{\mu}_n \cdot \vec{B} - i\lambda/2 & \delta m \\ \delta m & m_n + \vec{\mu}_n \cdot \vec{B} - i\lambda/2 \end{pmatrix}$$

$$\langle n \,|\, \mathscr{M}_{\mathscr{B}} \,|\, \bar{n} \rangle = \delta m$$

Coupling between neutrons and anti-neutrons

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Energy difference ΔE

$$\langle n | \mathcal{M}_{\mathcal{B}} | \bar{n} \rangle = \delta m$$

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$$P(n(t) = \bar{n}) = \left(\frac{2\delta m}{\Delta E}\right)^2 \sin^2\left(\frac{\Delta E \cdot t}{2}\right) e^{-\lambda t}$$

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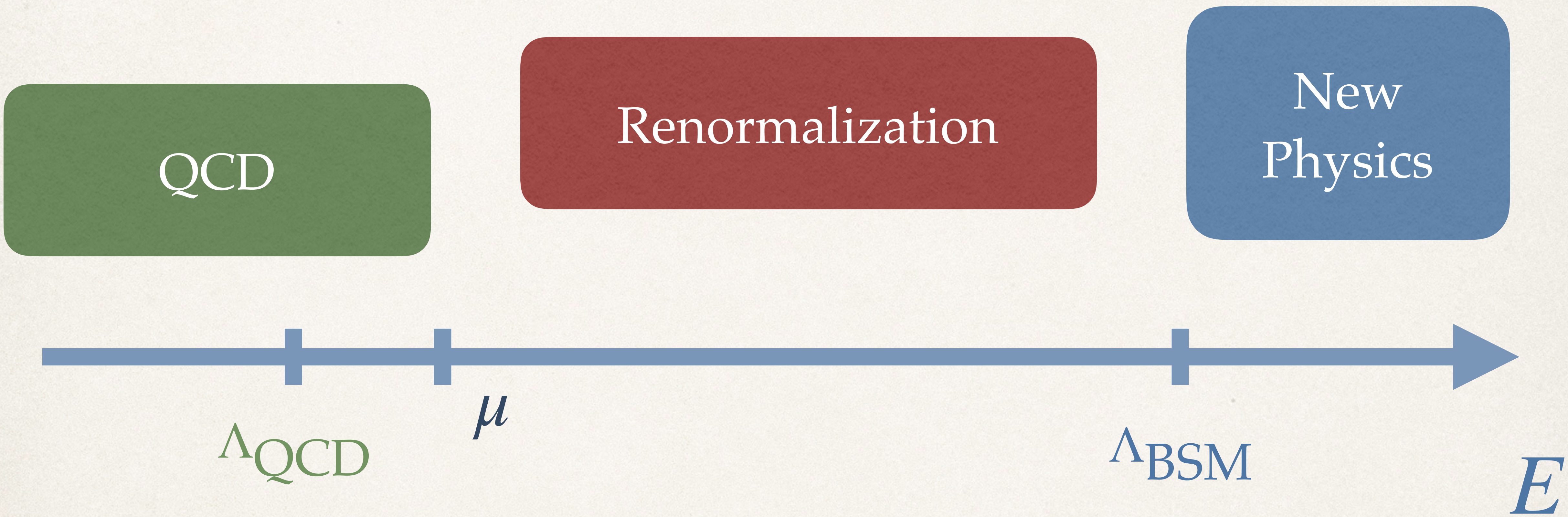
$$\tau_{n-\bar{n}} = \frac{1}{\delta m}$$

Effective field theory



Vast separation of scale between hadronic physics and new physics

New physics

- Relate the off-diagonal matrix element of the effective Hamiltonian to the microscopic operators

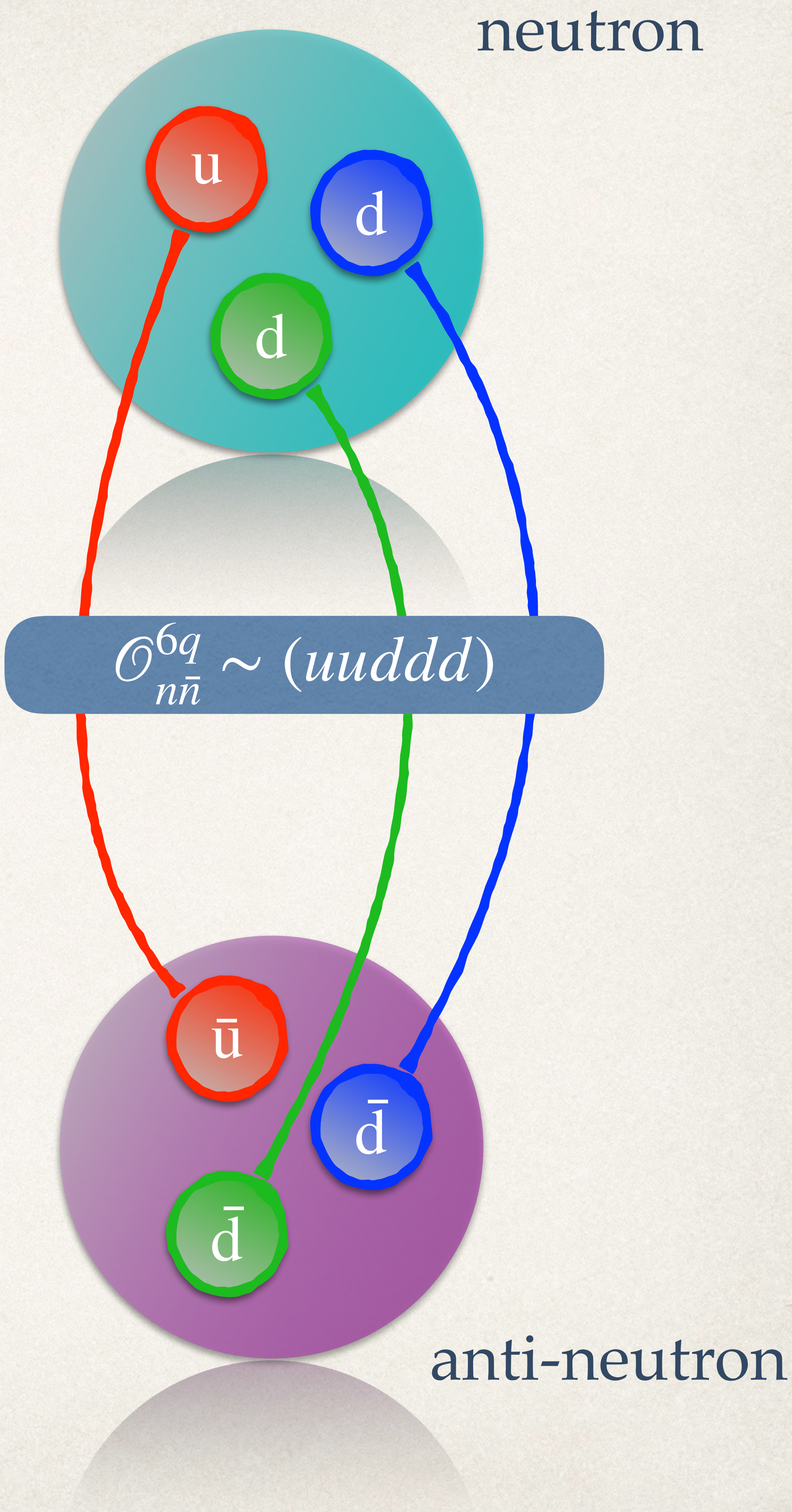
$$\langle n | \mathcal{H}_{\text{eff}} | \bar{n} \rangle = \frac{1}{\Lambda_{\text{BSM}}^5} \sum_i c_i \langle n | \mathcal{O}_i | \bar{n} \rangle$$

- The process is mediated by a effective 6-quark operators of dimension 9

$$\delta m = \langle n | \int \mathrm{d}^3\mathrm{x}\ \mathcal{H}_{\text{eff}} | \bar{\mathrm{n}} \rangle \sim \mathrm{c} \frac{\Lambda_{\text{QCD}}^6}{\Lambda_{\text{BSM}}^5}$$

- The mass scale for new physics is obtained roughly as $\Lambda_{\text{BSM}} \sim 100 - 1000$ TeV

[Phillips et al., 1410.1100]



Operators

[Rao & Shrock, Nucl. Phys. B 232, 143 (1984)]
[Caswell, et al., Phys.Lett. B122, 373 (1983)]
[Buchoff & Wagman, 1506.00647]
[Grojean et al., 1806.00011]
[Syritsyn et al., PoS, Lattice 2015, 132]

Color-singlet, Electrically-neutral, |ΔB|=2

Q_I	Ref. [7]	Ref. [3]	Ref. [8]	$(I, I_z)_R \otimes (I, I_z)_L$	$\gamma^{\mathcal{O}}$ (1-loop)
$-\frac{3}{4}Q_1$	$[(RRR)_{\mathbf{1}}]$	$3\mathcal{O}^3_{\{RR\}R}$	$12\mathcal{O}_1$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-2)$
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$-\frac{5}{4}Q_4$	$[(RRR)_{\mathbf{3}}]$	$\mathcal{O}^1_{R\{RR\}} + 4\mathcal{O}^2_{\{RR\}R}$	—	$(3,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-12)$
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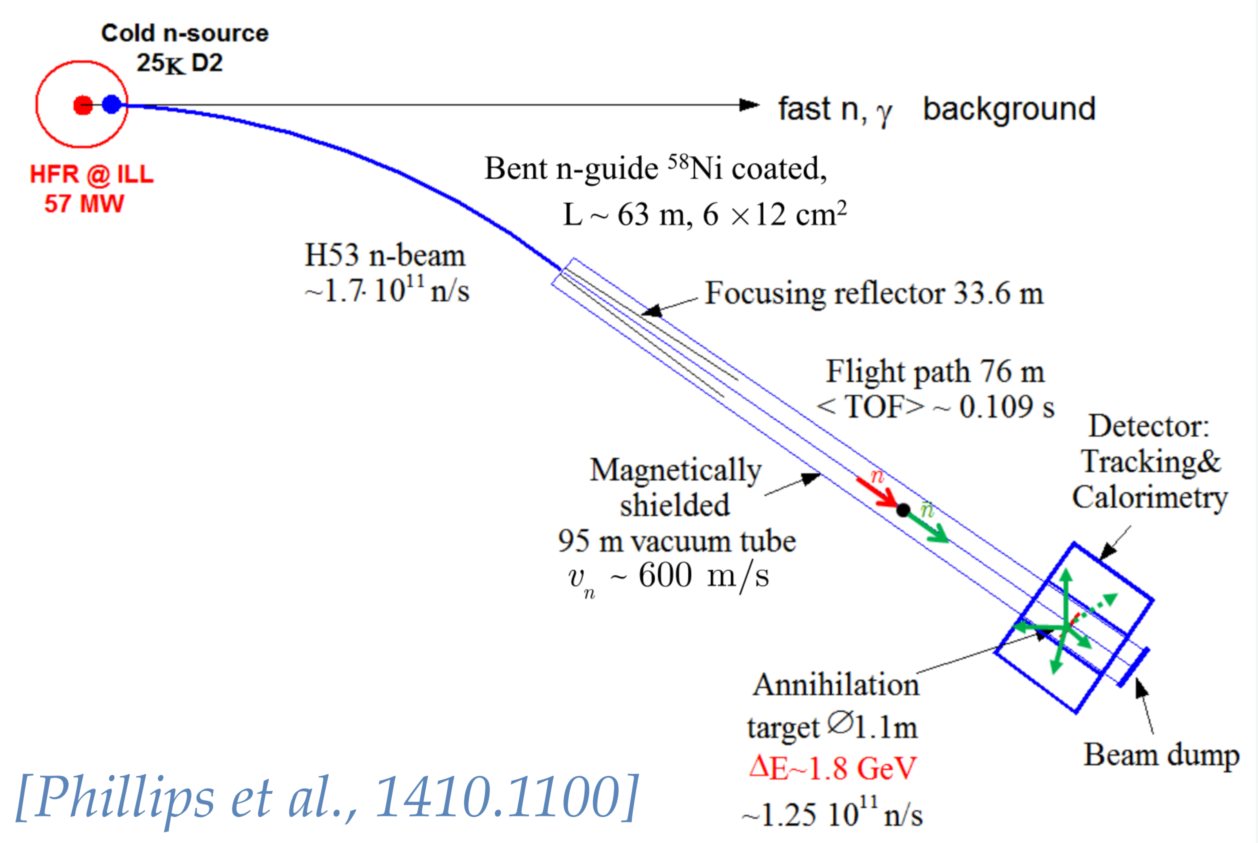
Experimental searches

- free neutrons: $\tau_{n-\bar{n}} = (\delta m)^{-1}$
  - prepare cold neutrons
  - free propagation in vacuum
  - detector to look for multiple pions after annihilation

- bound neutrons: $\tau_A \propto (\delta m)^{-2} \rightarrow R_A \tau^2_{n-\bar{n}}$
  - large amount of nuclei in underground detector
  - irreducible atmospheric neutrino background



[Phillips et al., 1410.1100]

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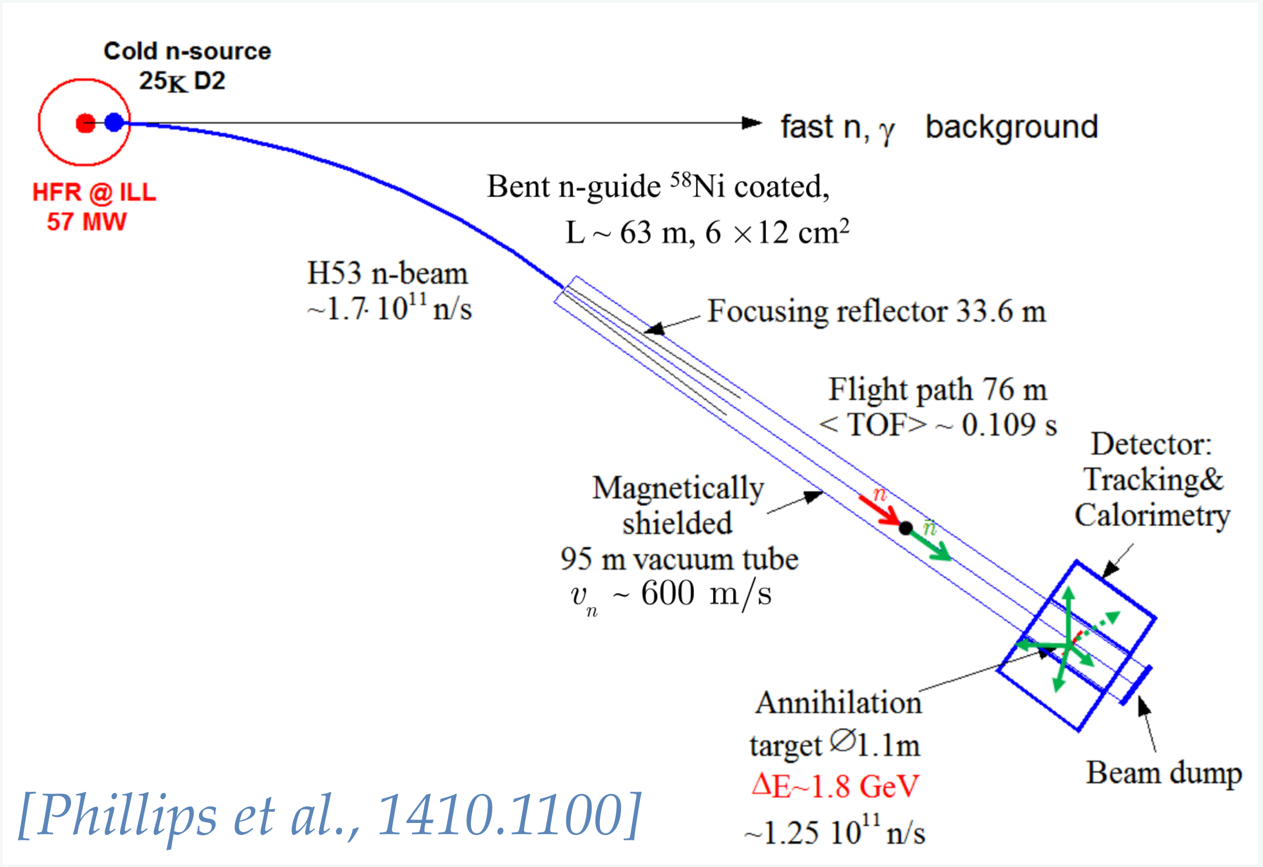

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almost background free

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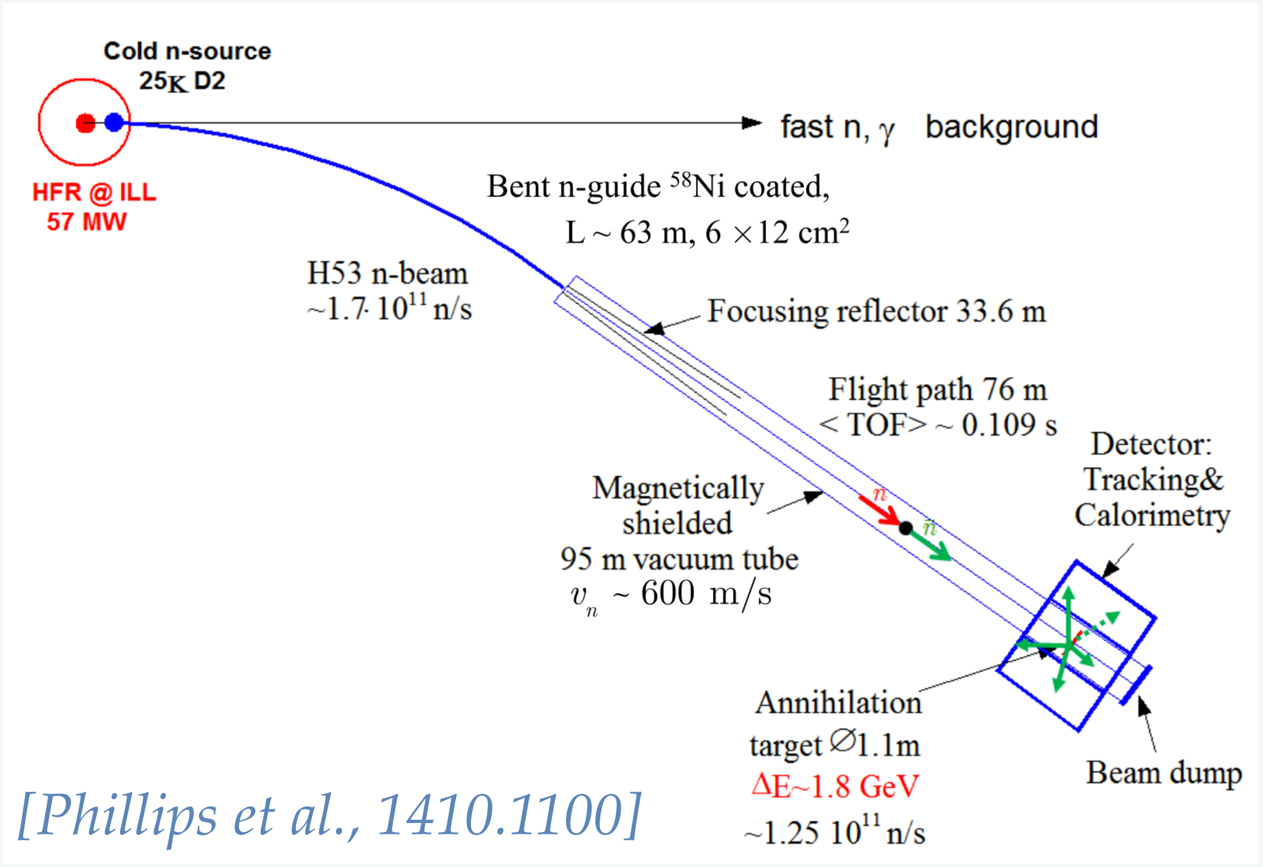

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sensitivity $\propto N_n (t^2_{\rm obs})$

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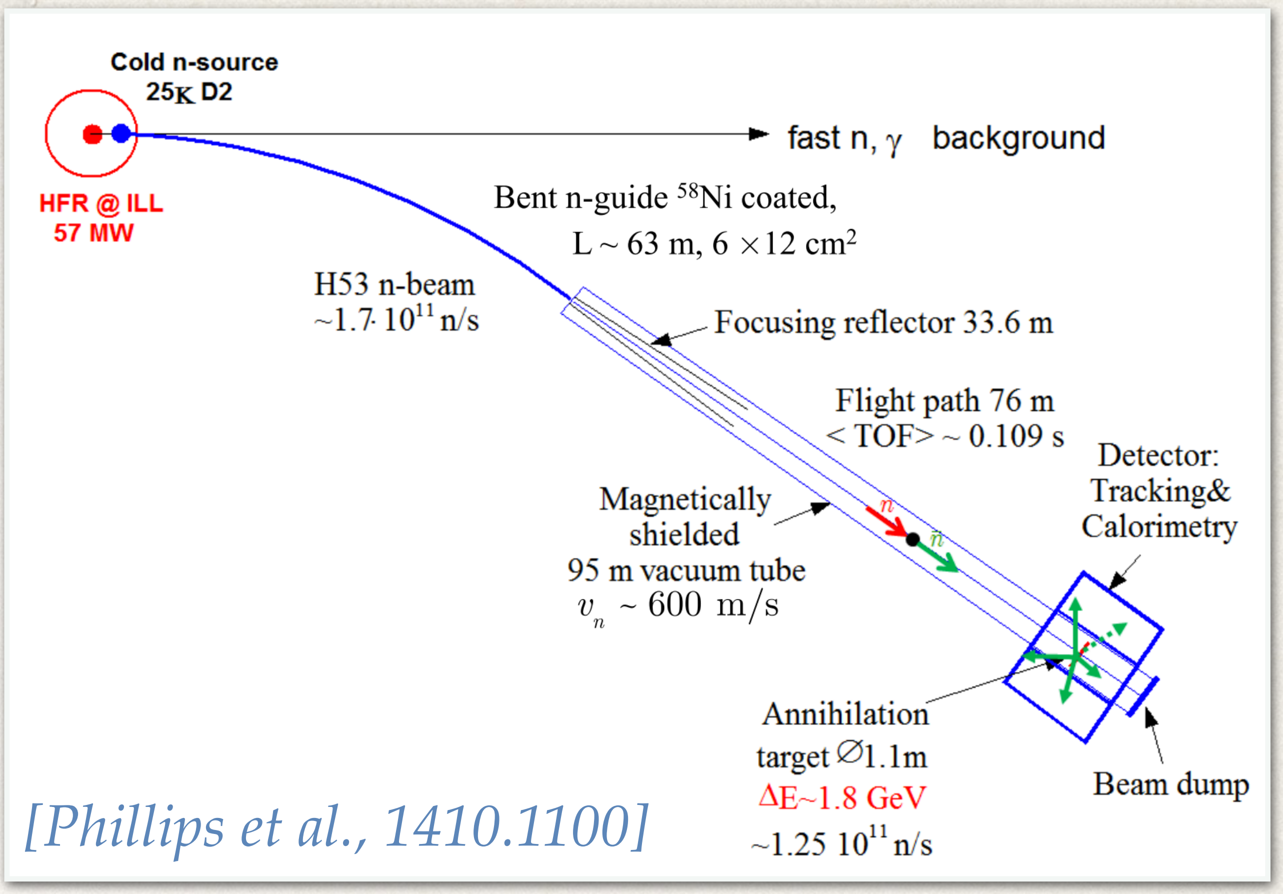

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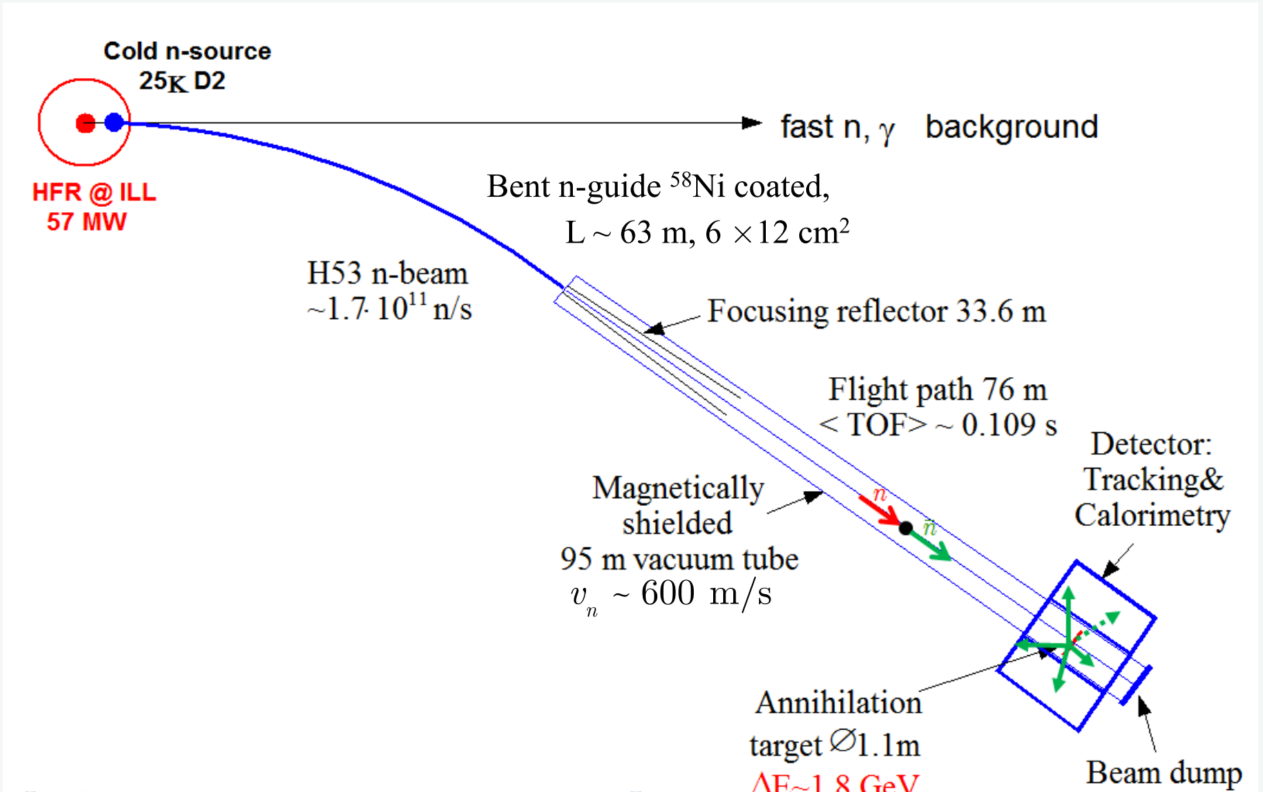
Nuclear suppression factor due to different nuclear potential

Experimental searches



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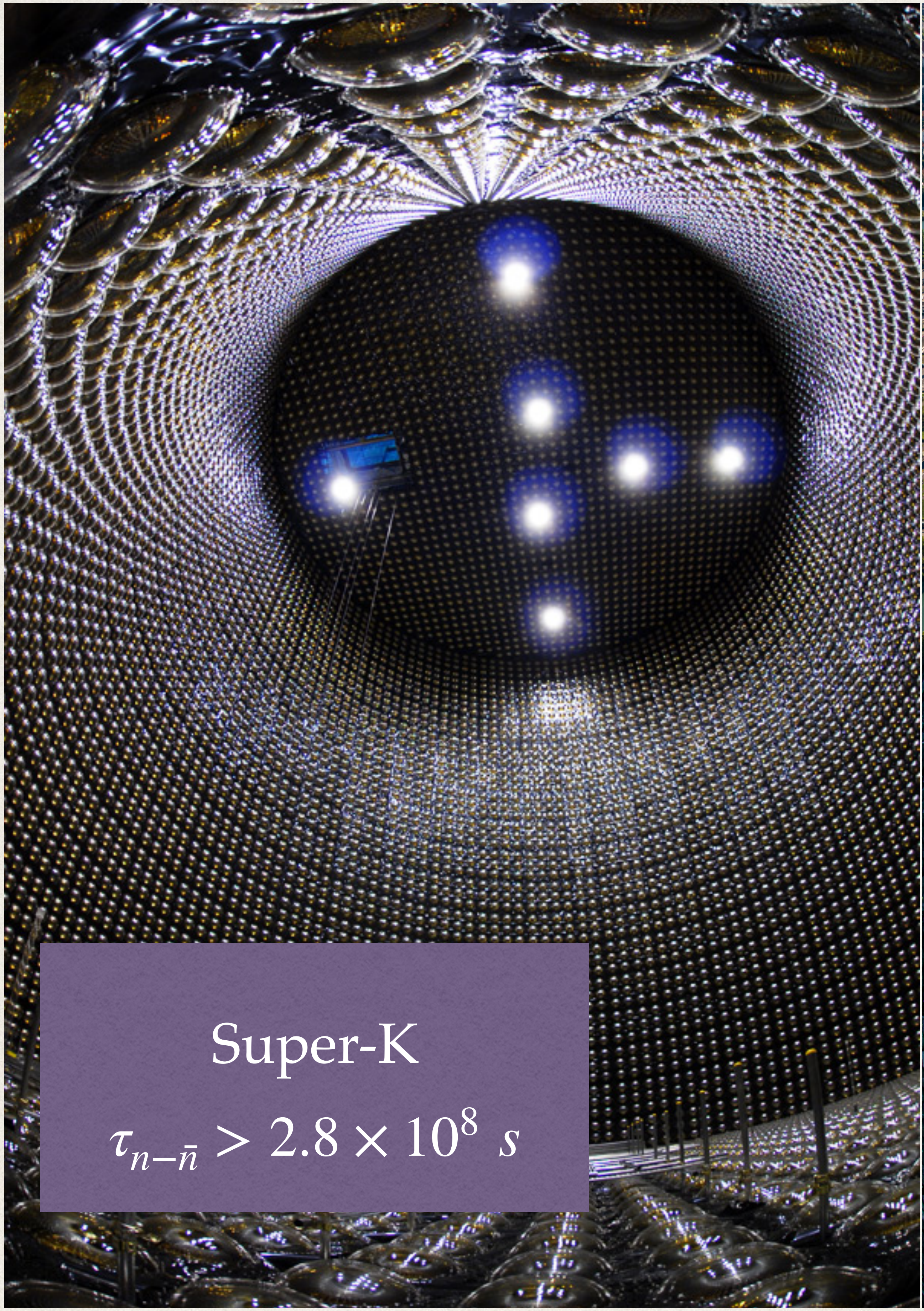
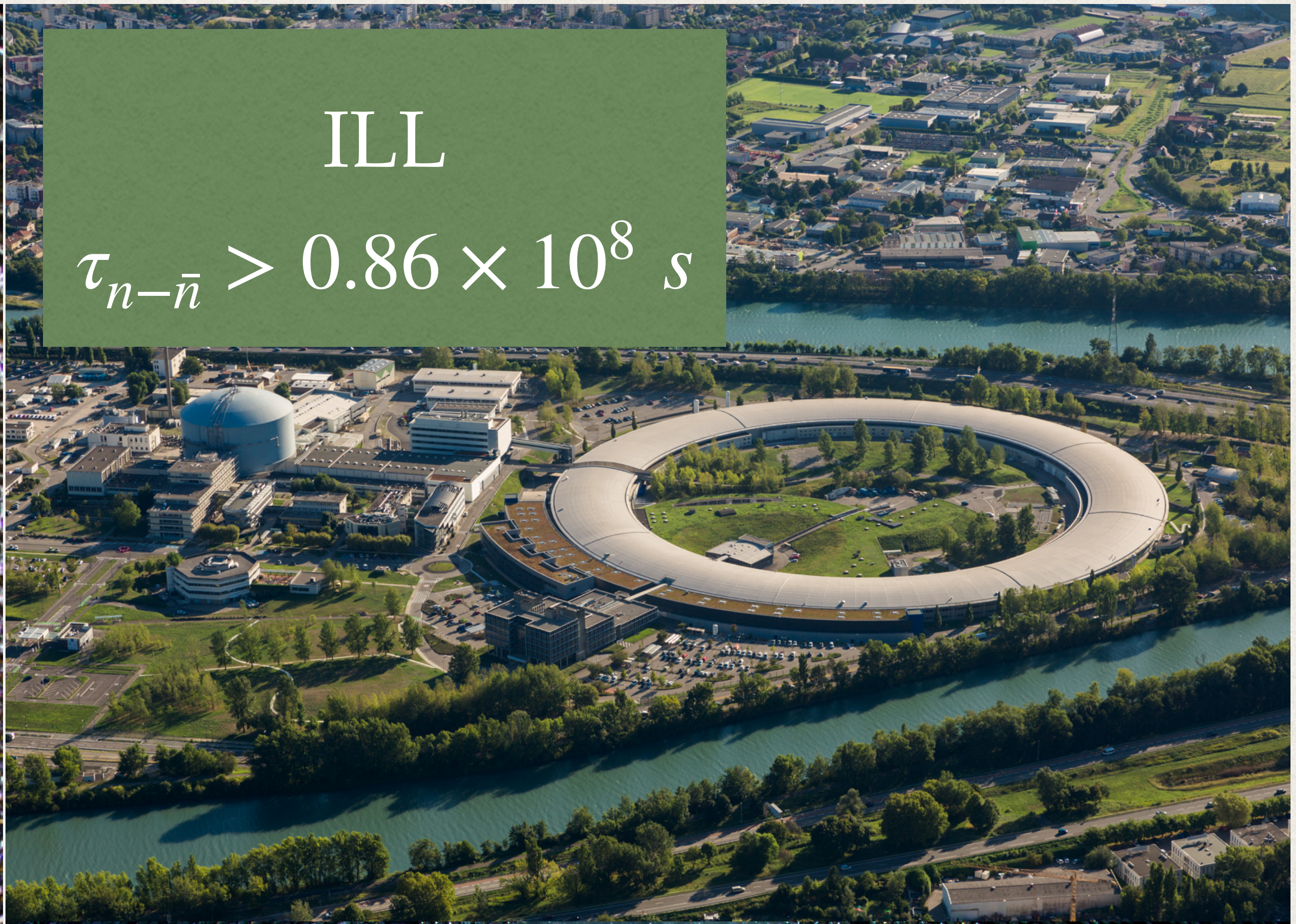
Nuclear suppression factor due to different nuclear potential

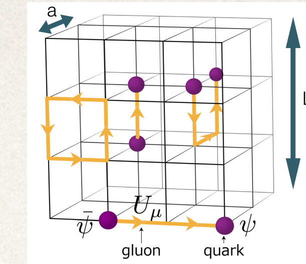
can be improved with particle tracking


Super-K
$\tau_{n-\bar{n}} > 2.8 \times 10^8\ s$

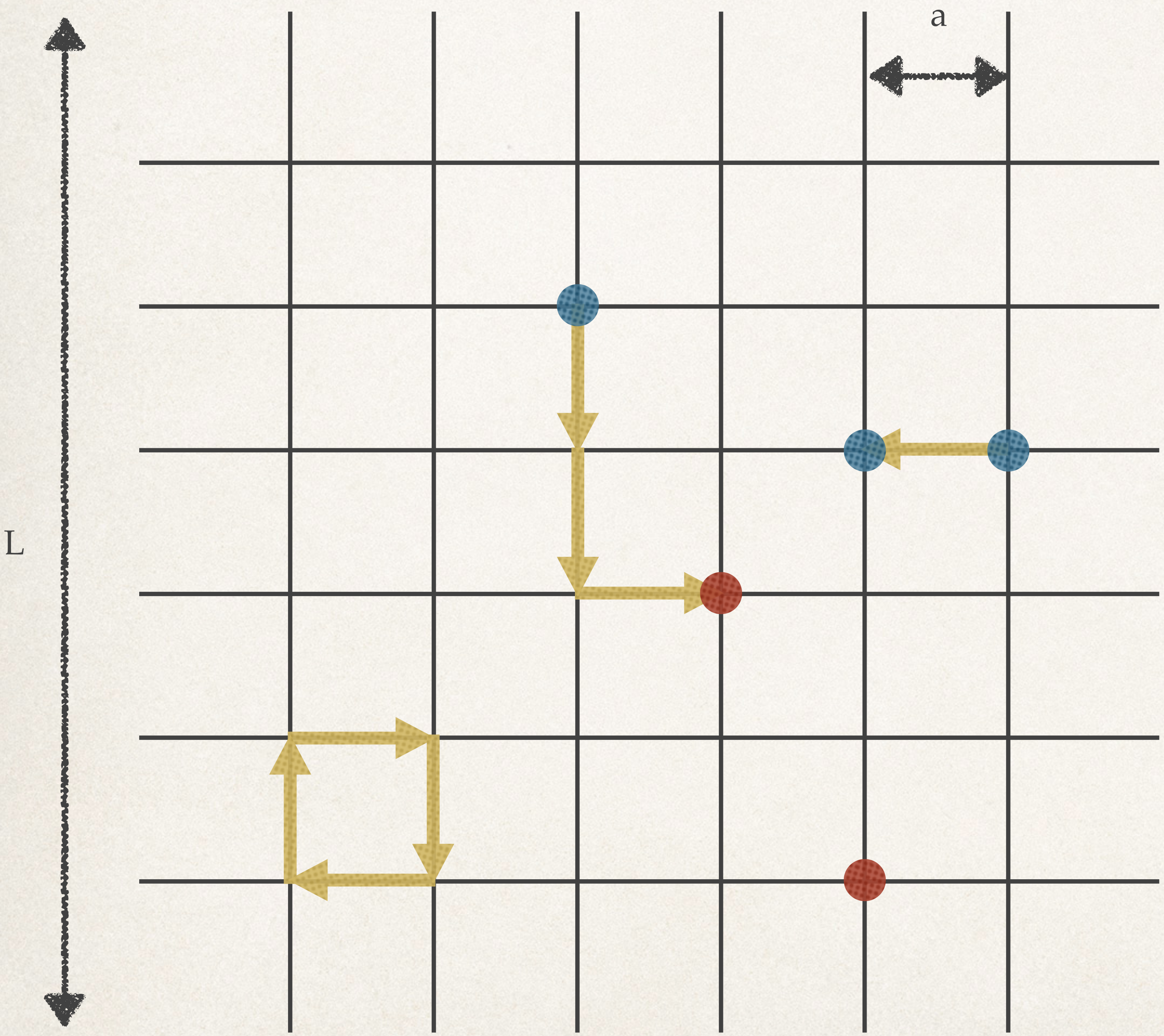

ILL
$\tau_{n-\bar{n}} > 0.86 \times 10^8\ s$


SNO
$\tau_{n-\bar{n}} > 1.2 \times 10^8\ s$

[KEK-Japan]

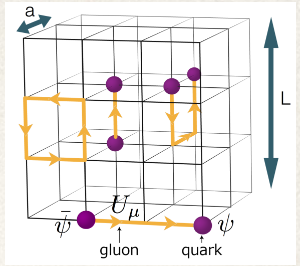


Lattice QCD - basics



- Discretize space and time
  - lattice spacing “a”
  - lattice size “L”
- Keep all d.o.f. of the theory
  - not a model!
  - no simplifications
- Amenable to numerical methods
  - Monte Carlo sampling
  - use supercomputers
- Precisely quantifiable and improvable errors
  - Systematic
  - Statistical

[KEK-Japan]



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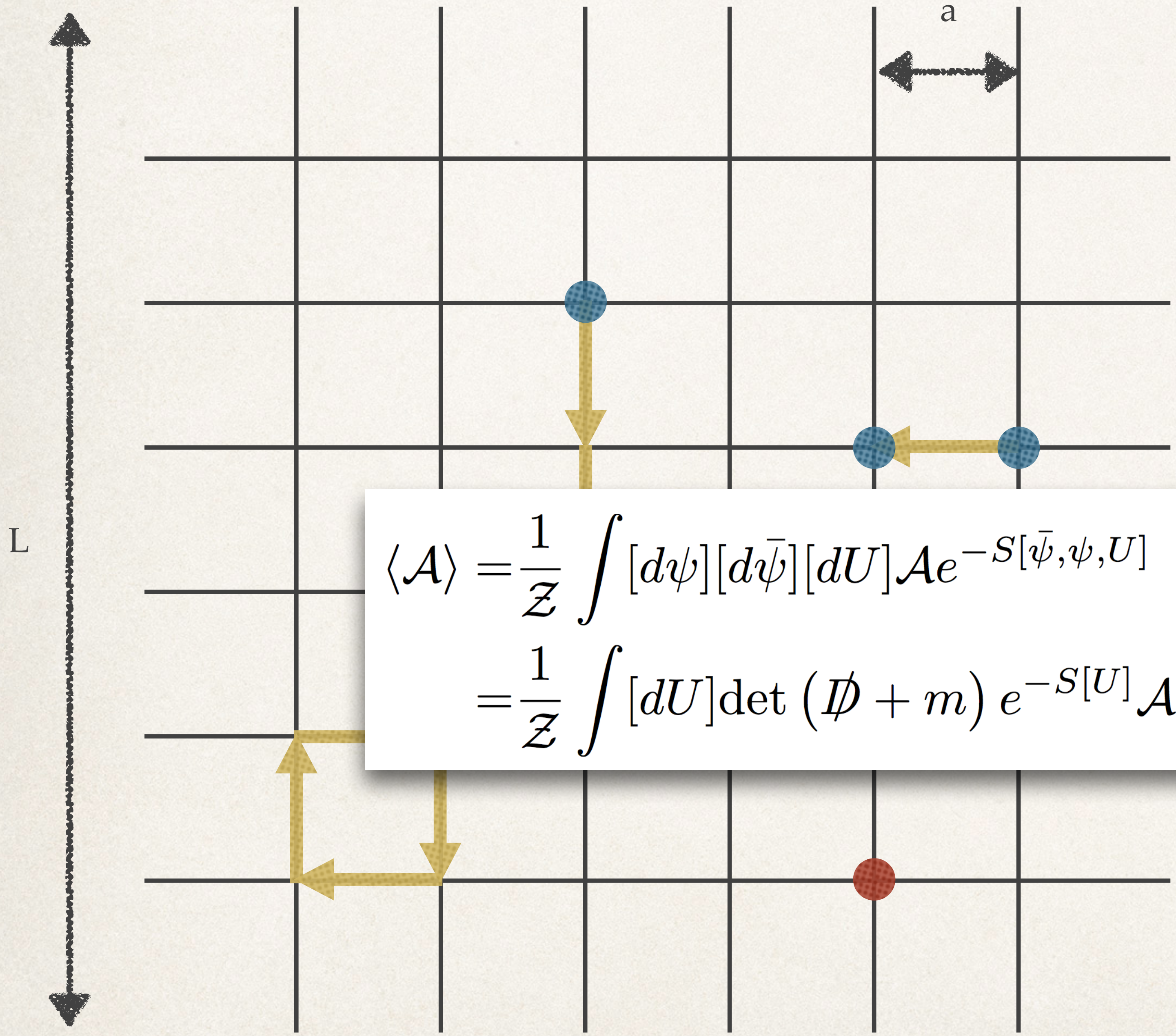

$$\langle \mathcal{A} \rangle = \frac{1}{\mathcal{Z}} \int [d\psi][d\bar{\psi}][dU] \mathcal{A} e^{-S[\bar{\psi},\psi,U]}$$
$$= \frac{1}{\mathcal{Z}} \int [dU] \det\left(\not{D} + m\right) e^{-S[U]} \mathcal{A}$$

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  - lattice spacing “a”
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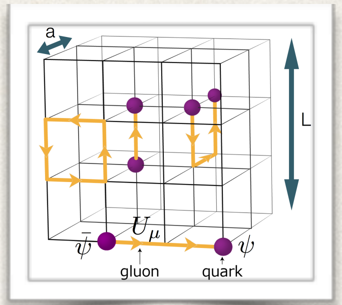
Lattice details

[KEK-Japan]

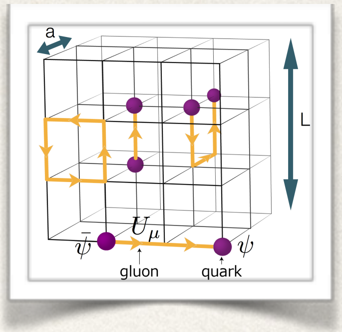


[RBC/UKQCD, 1411.7017]

- Configurations and propagators from RBC/UKQCD
  - Mobiüs Domain Wall fermions
  - Physical pion mass
  - 48^3x96 with a=0.114 fm
  - 30 independent configs.
  - Non-perturbative renorm.

Lattice details

[KEK-Japan]



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chiral

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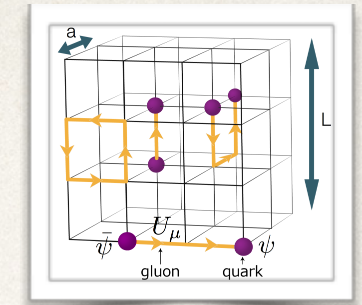

[RBC/UKQCD, 1411.7017]

- Configurations and propagators from RBC/UKQCD
  - Mobiüs Domain Wall fermions — chiral
  - Physical pion mass — no extrapolation
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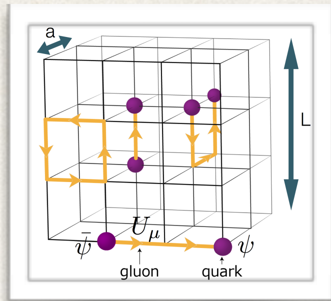
[KEK-Japan]



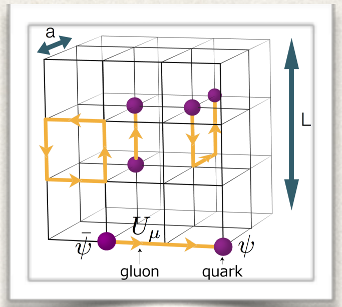
Lattice details

[RBC/UKQCD, 1411.7017]

- Configurations and propagators from RBC/UKQCD
  - Mobiüs Domain Wall fermions — chiral
  - Physical pion mass — no extrapolation
  - 48^3x96 with a=0.114 fm — large volume + small disc.
  - 30 independent configs.
  - Non-perturbative renorm.

Lattice details

[KEK-Japan]



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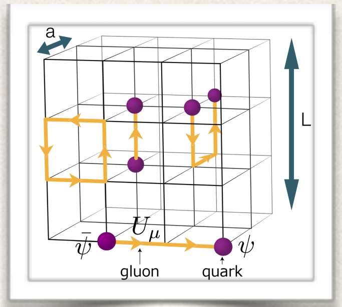
- Configurations and propagators from RBC/UKQCD
  - Mobiüs Domain Wall fermions — chiral
  - Physical pion mass — no extrapolation
  - 48^3x96 with a=0.114 fm — large volume + small disc.
  - 30 independent configs. — determines statistical err.
  - Non-perturbative renorm.

Lattice details

[KEK-Japan]



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  - Non-perturbative renorm. — small systematic err.

[Syritsyn et al., 1809.00246]

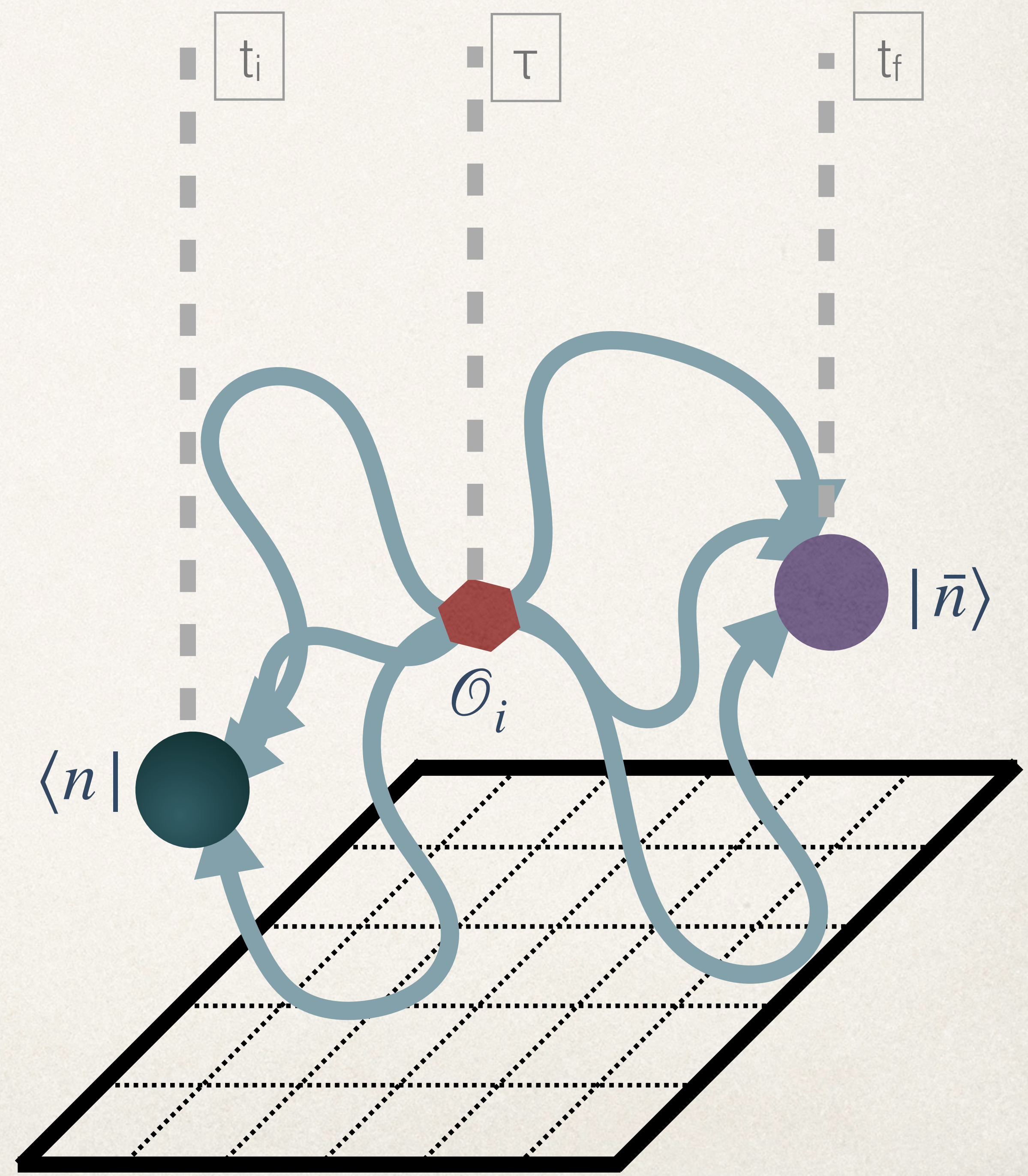
Methodology

- Calculate 3-point function of operator inserted at time τ
- Only 1 propagator (point-to-all) needed: fix source at $\tau = 0$
- All time separations accessible

  $t_f - \tau$ $\tau - t_i$
- Only point insertions, but point and gaussian smeared nucleons

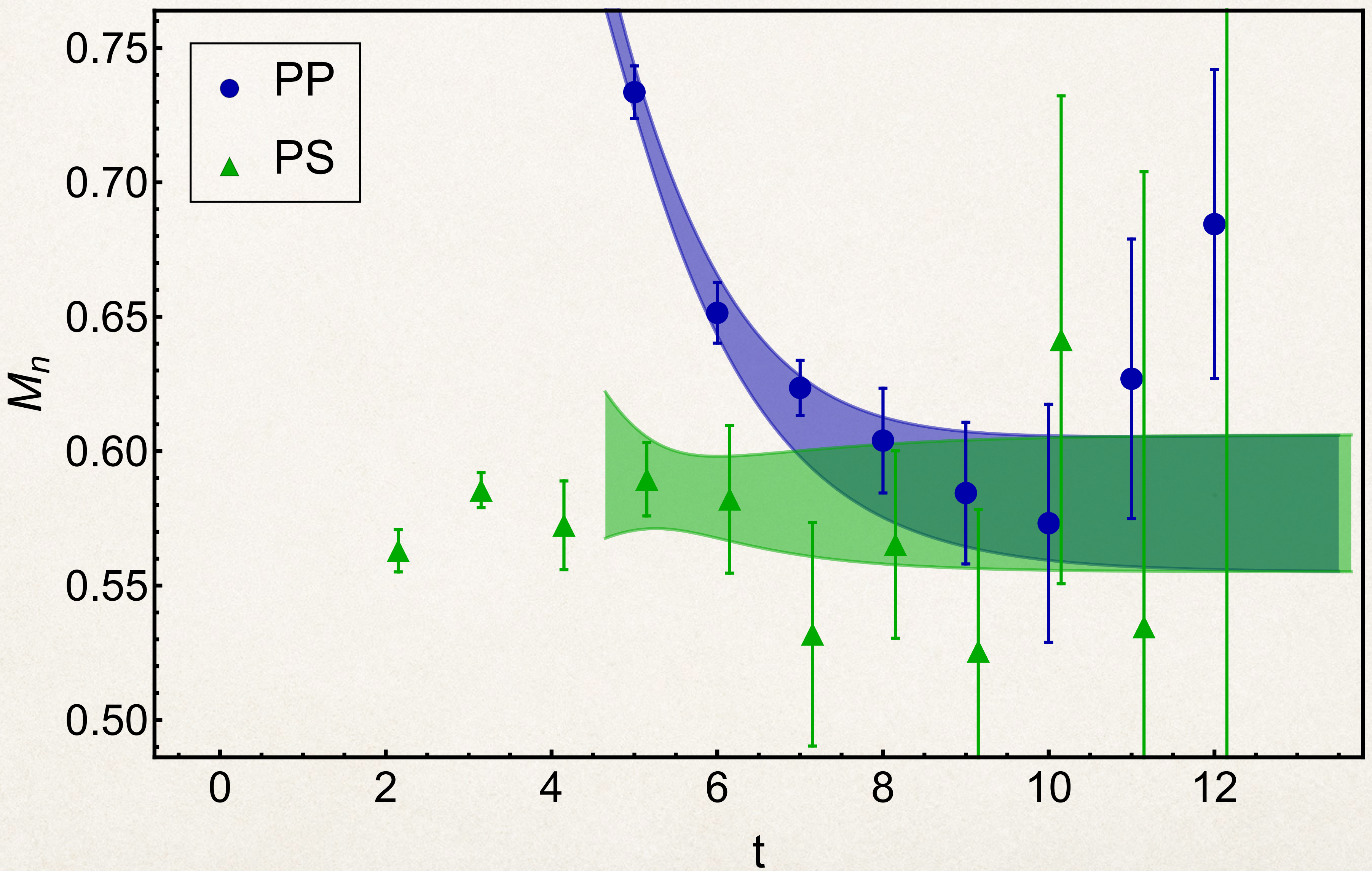
$C^{\text{2pt}}_{\text{PP,PS}}(t_f, t_i)$ $C^{\text{3pt}}_{\text{PP,PS,SP,SS}}(t_f, \tau, t_i)$

$$\langle 0 | N(t_f) \mathcal{O}_i(\tau) \bar{N}(t_i) | 0 \rangle$$

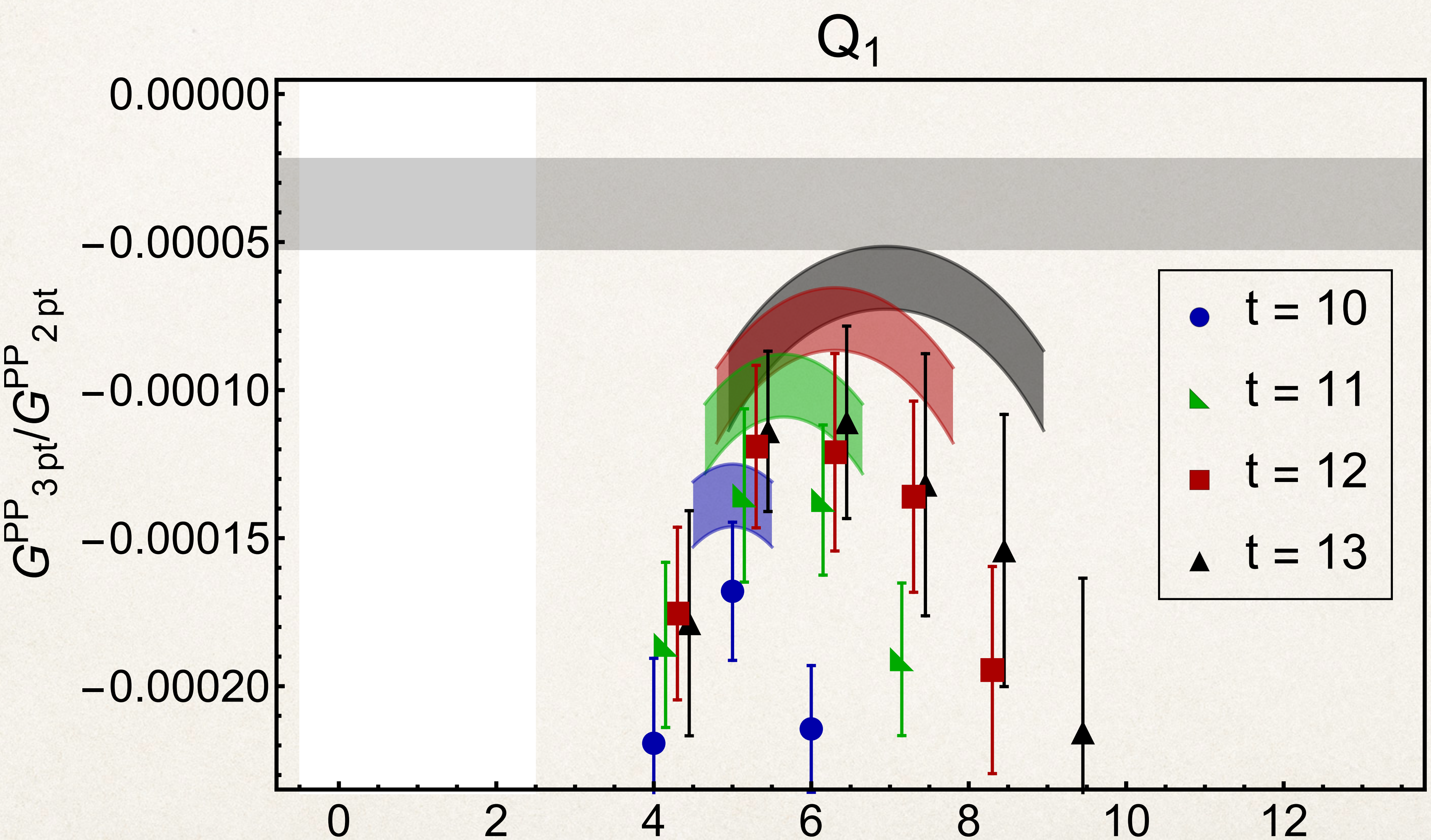


[Syritsyn et al, 1809.00246]

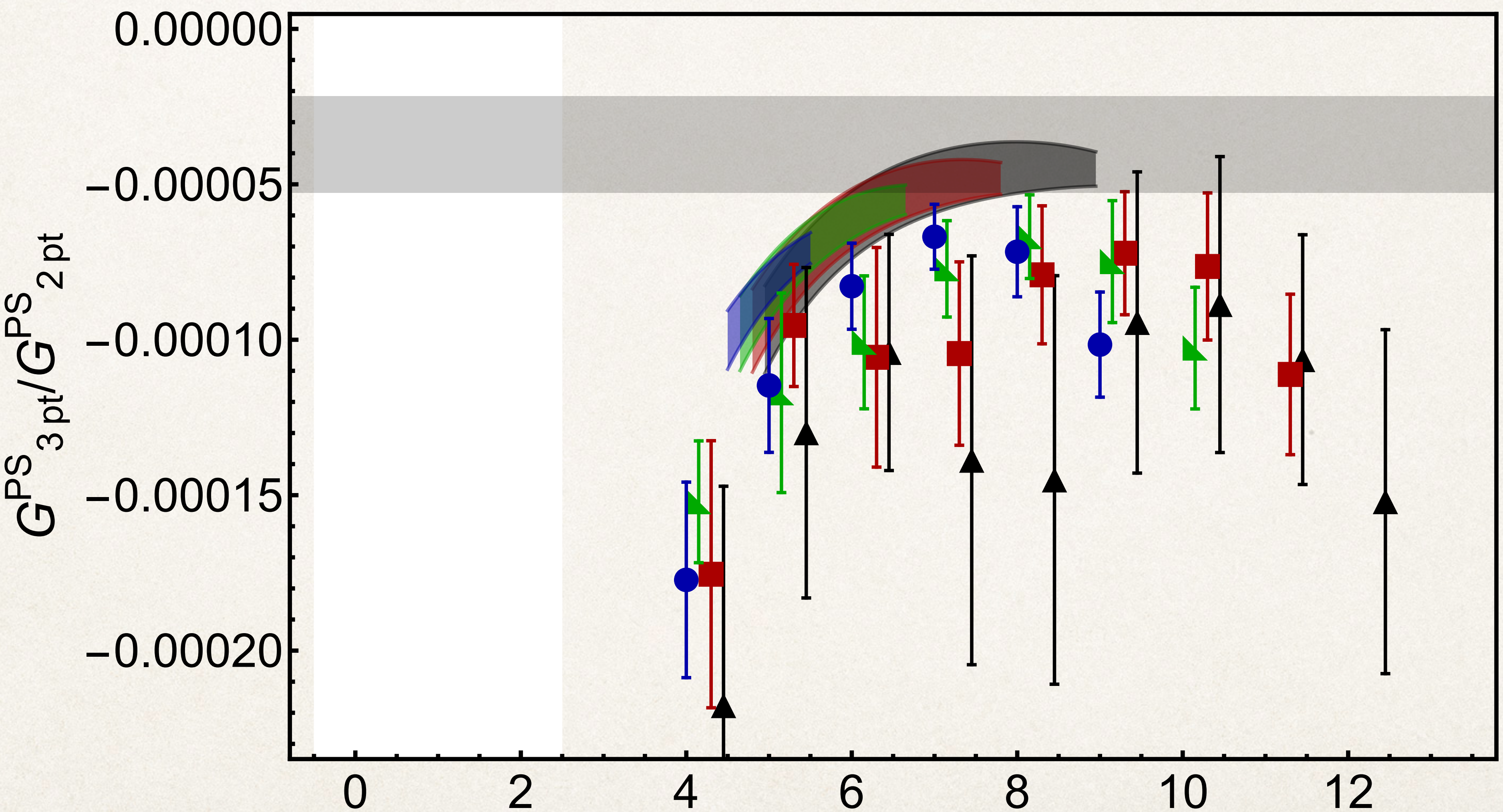
Fits



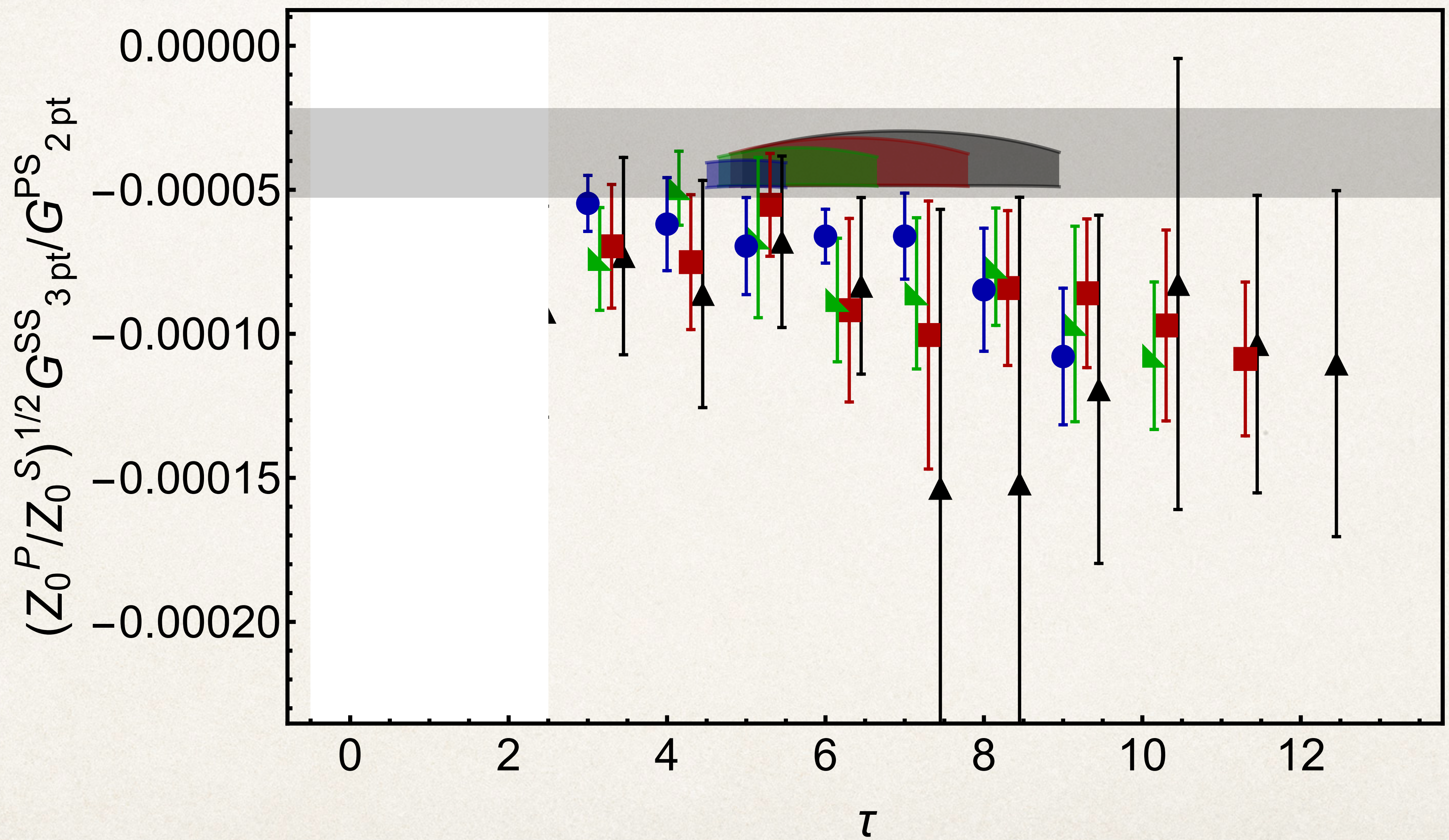
Fits


Q1
0.00000
−0.00005
−0.00010
−0.00015
−0.00020
G^PP_3pt/G^PP_2pt
0
2
4
6
8
10
12
t = 10
t = 11
t = 12
t = 13

Fits


0.00000
−0.00005
−0.00010
−0.00015
−0.00020
$G^{PS}{}_{3\,pt}/G^{PS}{}_{2\,pt}$
0
2
4
6
8
10
12

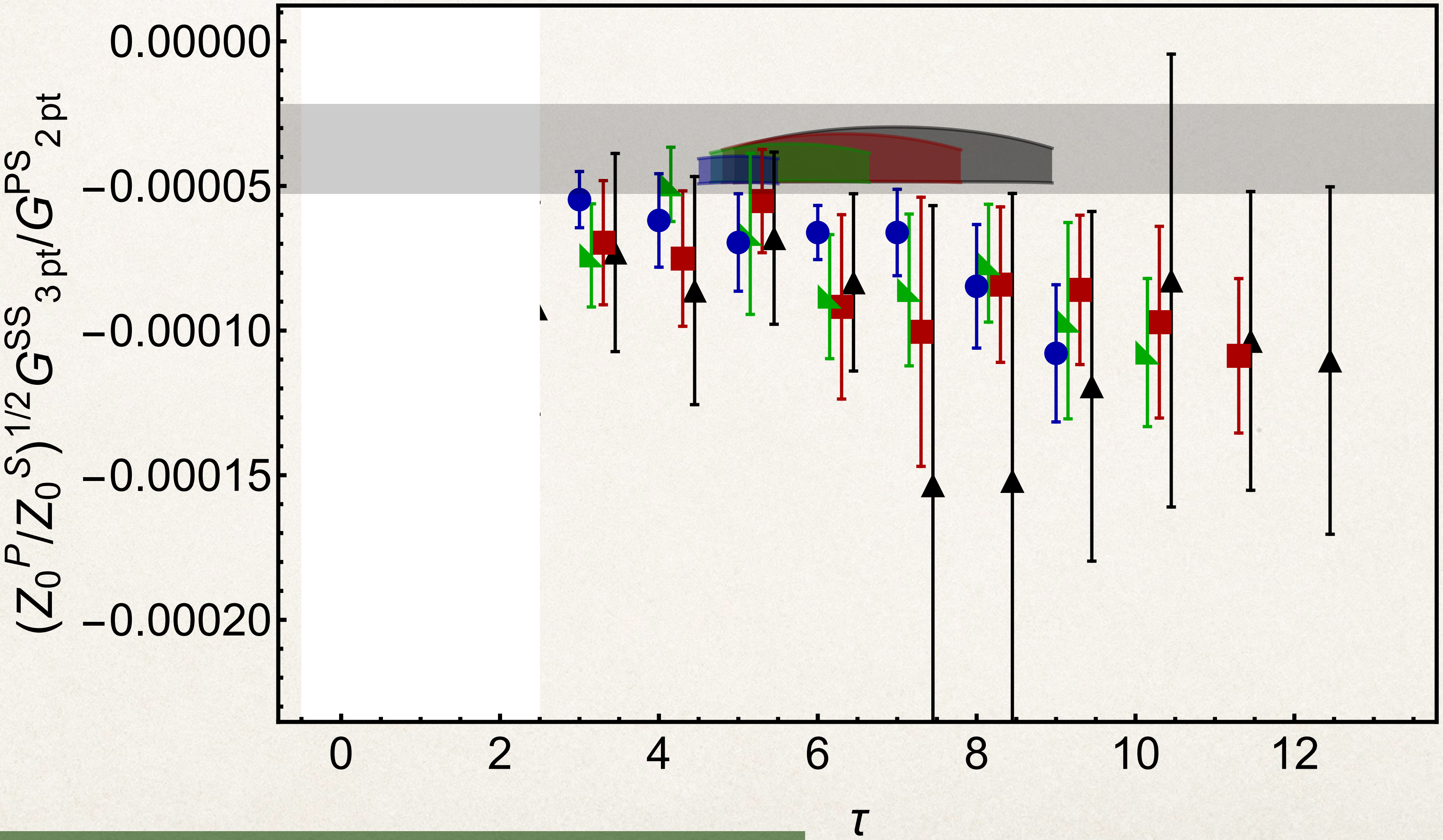
Fits



0.00000
−0.00005
−0.00010
−0.00015
−0.00020
$(Z_0{}^P/Z_0{}^S)^{1/2}G^{SS}{}_{3\,pt}/G^{PS}{}_{2\,pt}$
0
2
4
6
8
10
12
τ

[Syritsyn et al, 1809.00246]

Fits



good control over excited states

[Syritsyn et al, 1809.00246]

Results

$$\tau_{n\text{-}\bar{n}}^{-1} = \left| \sum_{I=1}^{5} C_I(\mu) \langle \bar{n} | Q_I(\mu) | n \rangle \right|$$

Operator	$\overline{\mathrm{MS}}$(2 GeV), 10^{-5} GeV^6	$\frac{\overline{\mathrm{MS}}\text{(2 GeV)}}{\text{MIT bag B}}$	Bare, 10^{-5} l.u.	χ^2/dof
Q_1	-44(19)	5.0	-3.7(1.6)	0.75
Q_2	140(40)	12.8	11.8(3.2)	0.69
Q_3	-79(23)	9.7	-6.6(1.9)	0.72
Q_5	-1.43(64)	2.1	-0.096(42)	0.73

[Syritsyn et al, 1809.00246]

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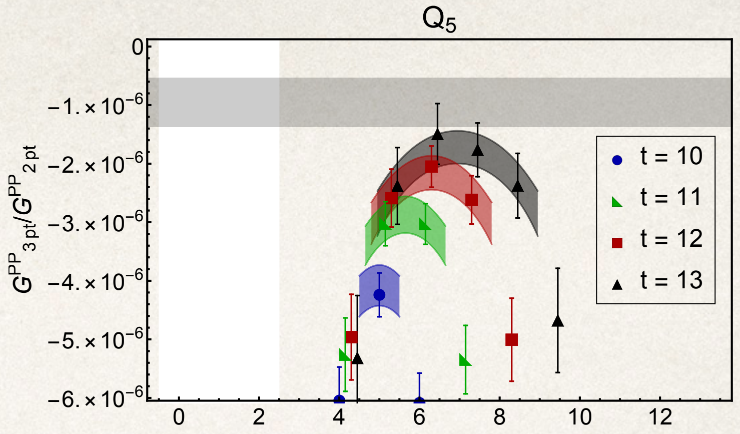
enhancement of ME wrt models up to 10x

Summary



- Improvement of the experimental limits on oscillations is expected in the next decade $\tau_{n-\bar{n}} > 10^{10}\ s$
  - Minimal EFT approaches connecting new physics to nuclear matrix elements exist and they need precision to compare to experiments *[Grojean et al., 1806.00011]*
- Fully non-perturbative estimates of nuclear ME are needed for translating experimental bounds to constraints on new physics models
  - LQCD calculations should now replace old and uncertain MIT bag model estimates for nuclear ME

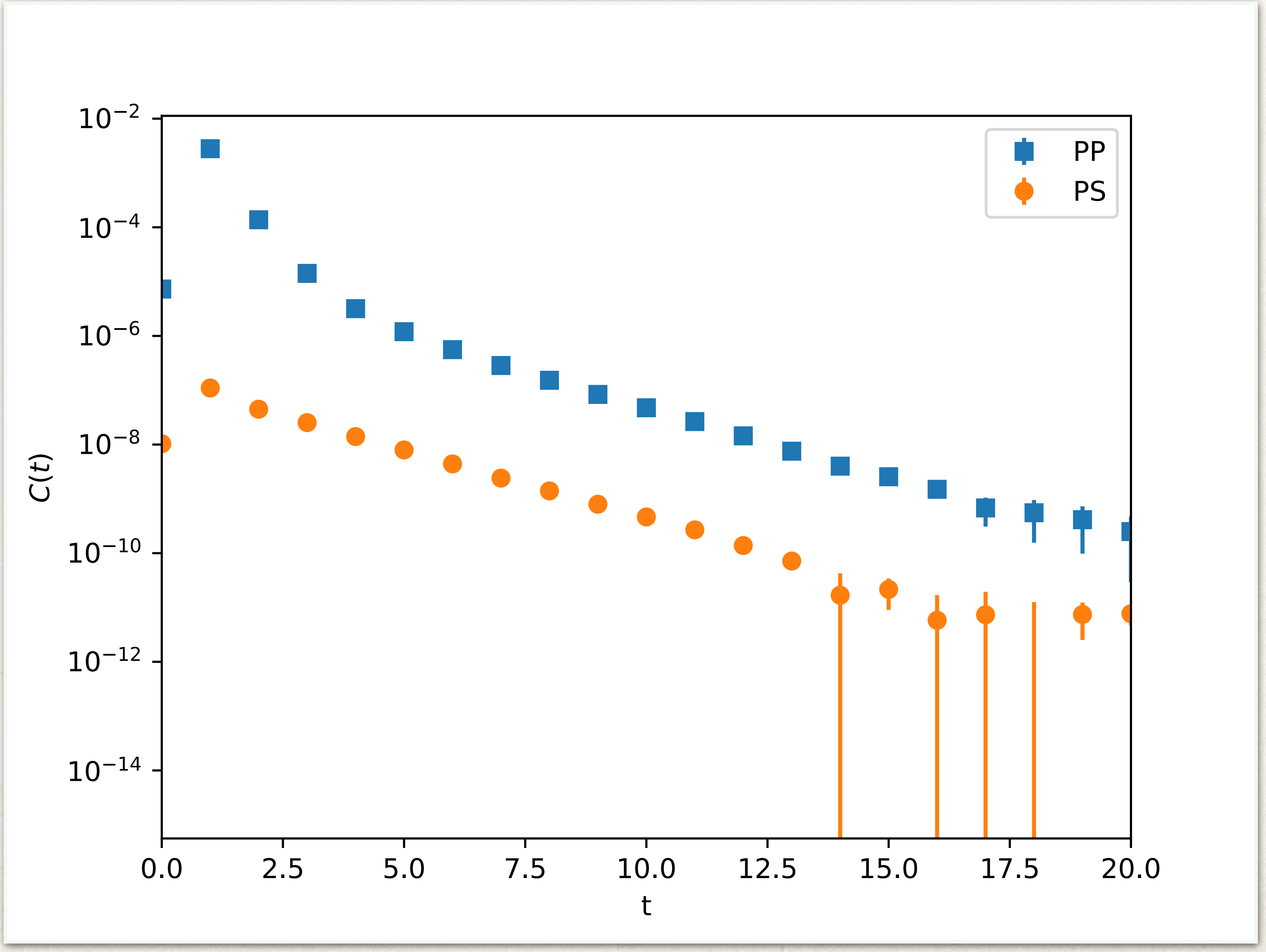
thank you

Part of this research was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and supported by the LLNL LDRD "Illuminating the Dark Universe with PetaFlops Supercomputing" 13-ERD-023.

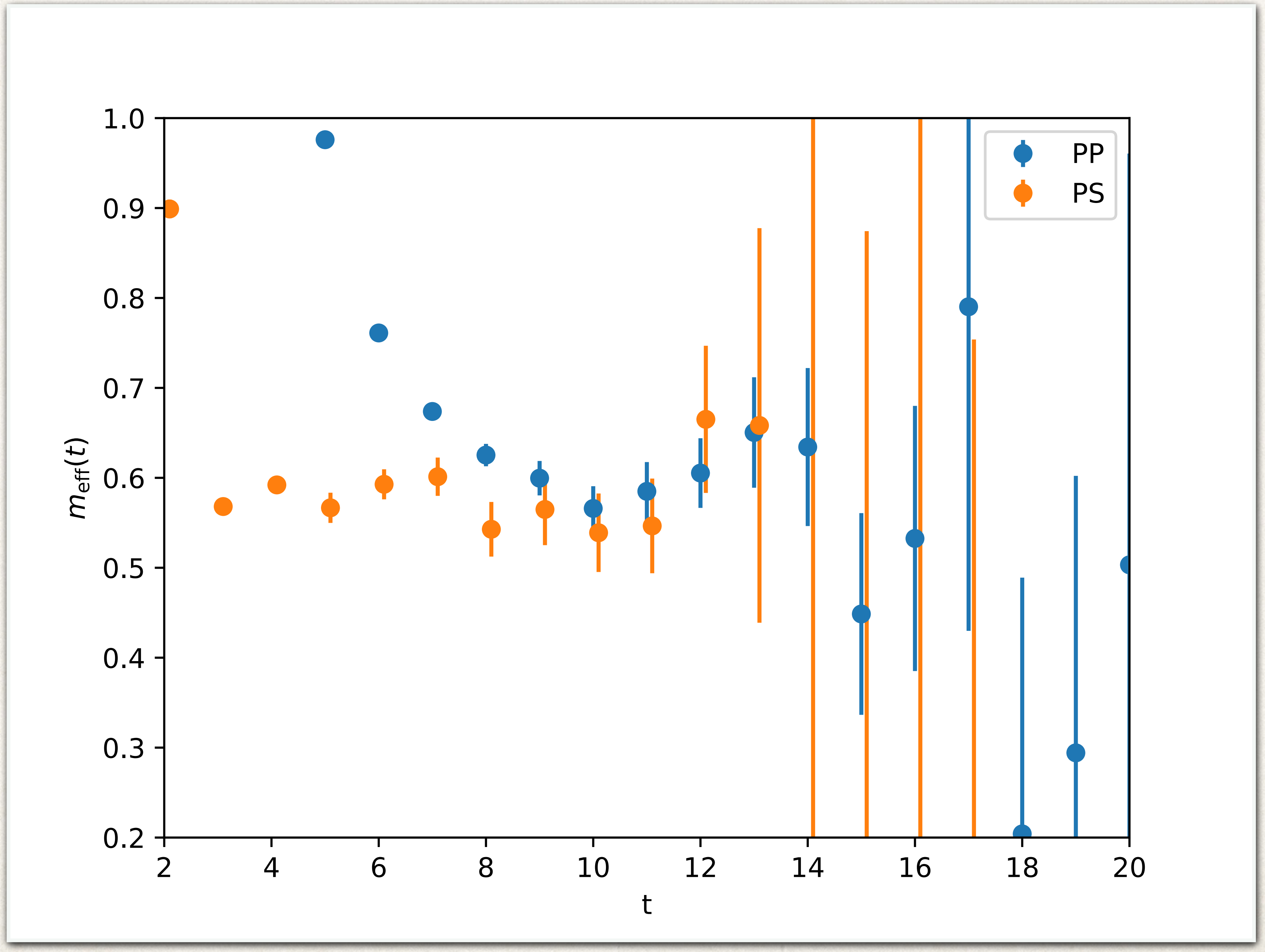
Computing support comes from the LLNL Institutional Computing Grand Challenge program and from the USQCD Collaboration, which is funded by the Office of Science of the US Department of Energy.

We are indebted to Norman Christ, Bob Mawhinney, Taku Izubuchi, Oliver Witzel, and the rest of the RBC/UKQCD collaboration for access to the physical point, domain-wall lattices and propagators used in this work

Signals: $C^{\mathrm{2pt}}_{\mathrm{PP,PS}}(t_f, t_i)$



Signals: $C^{\text{2pt}}_{\text{PP,PS}}(t_f, t_i)$



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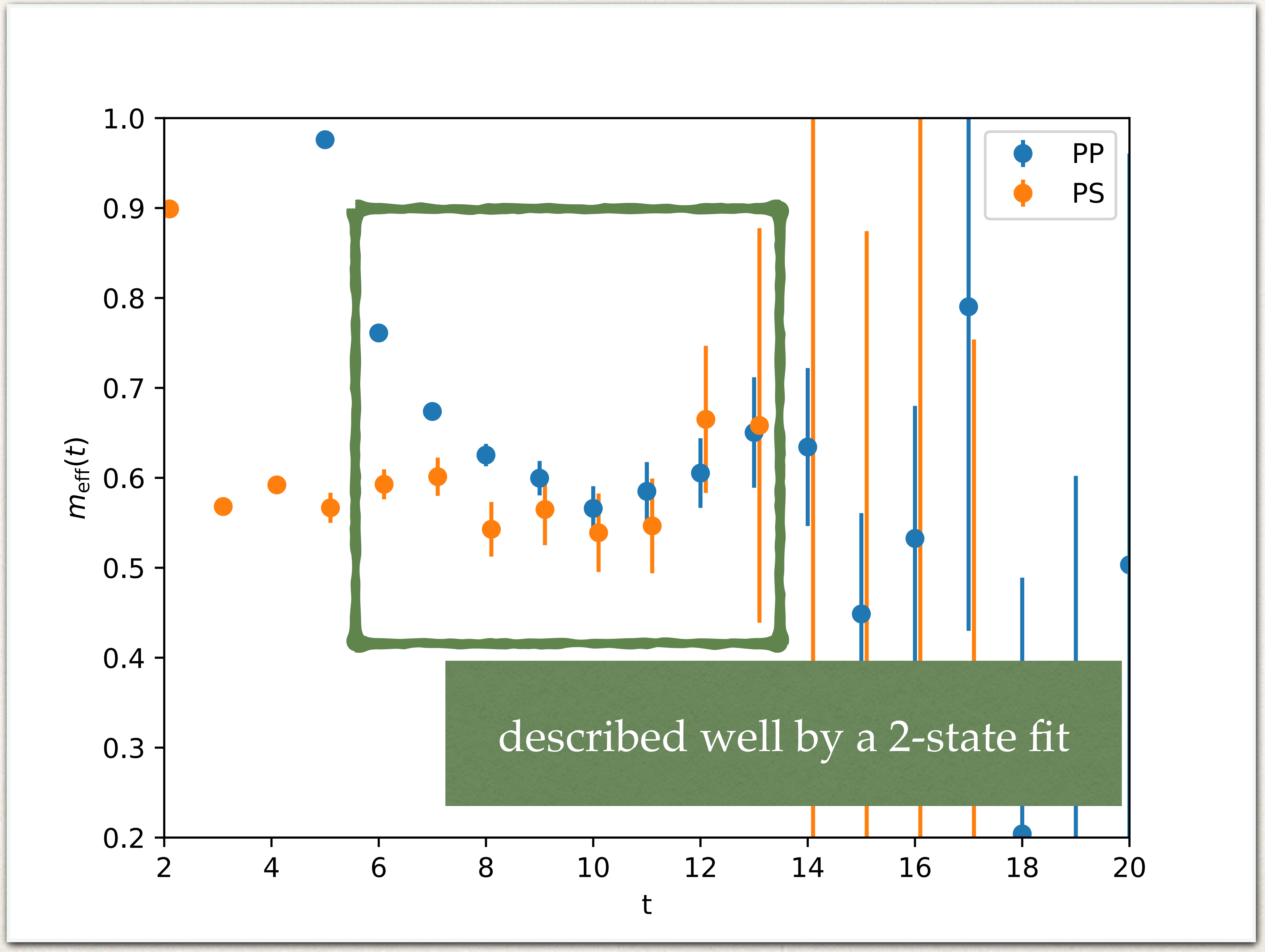
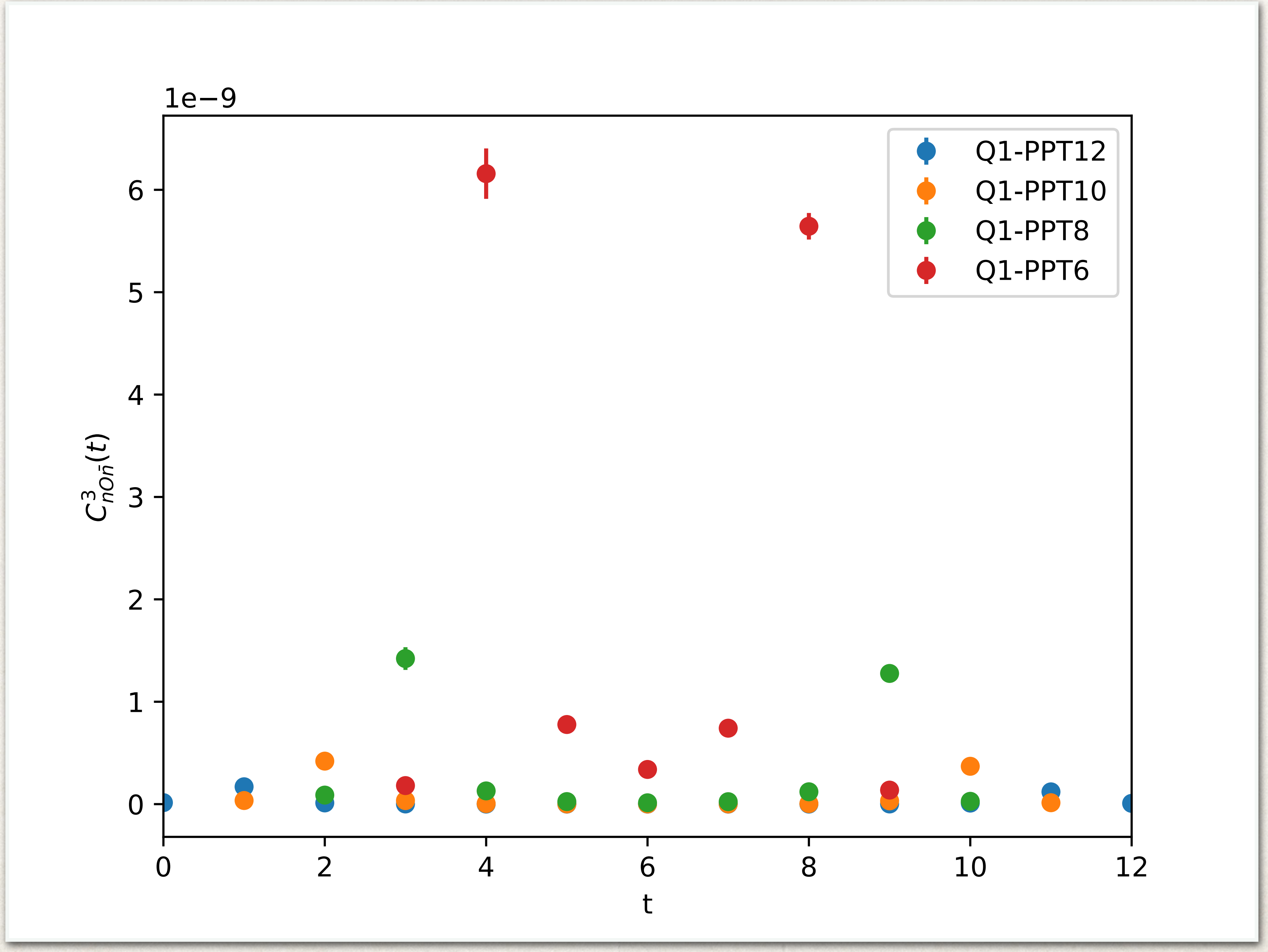
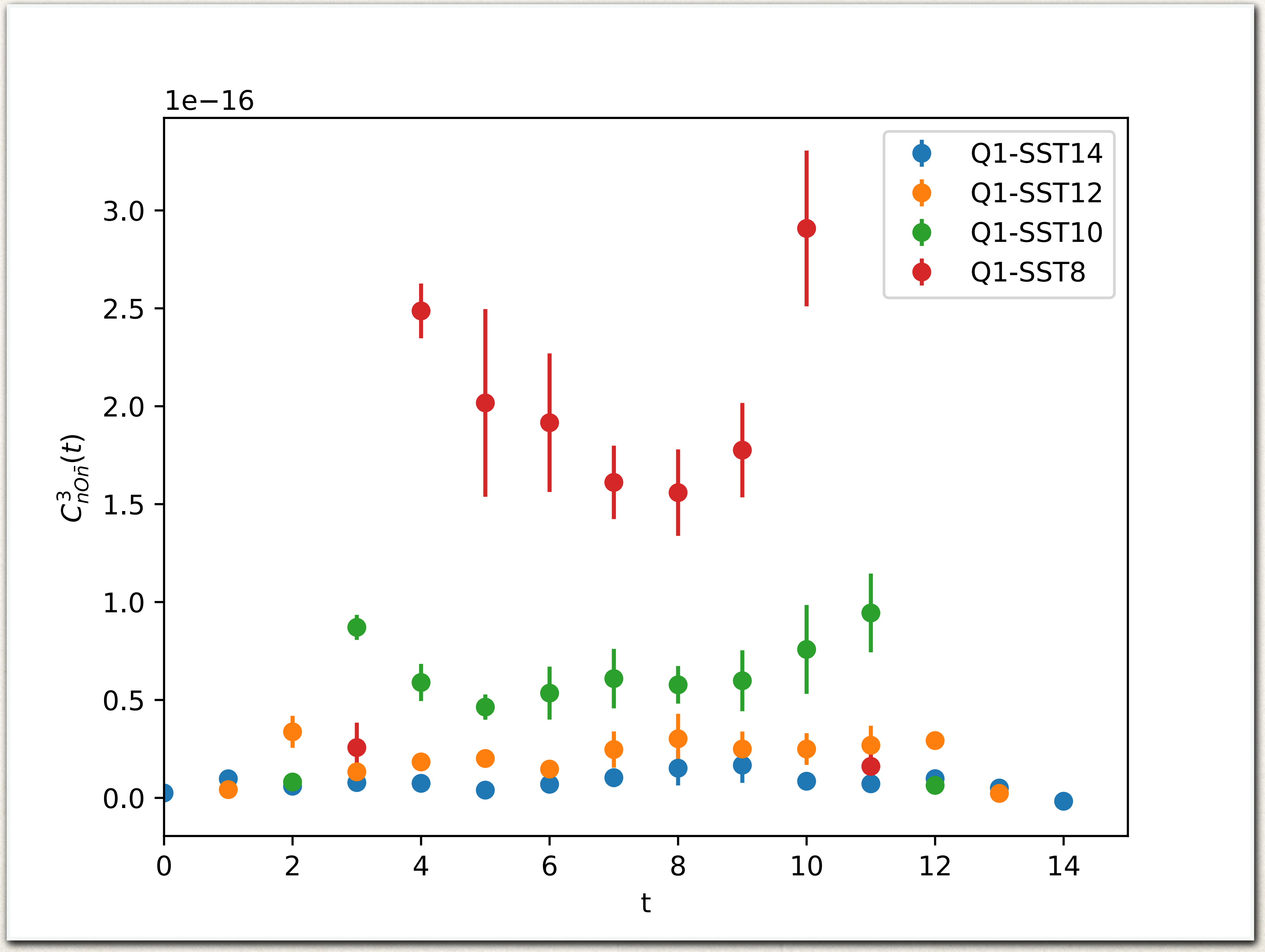


Signals: $C^{\mathrm{3pt}}_{\mathrm{PP,PS,SP,SS}}(t_f, \tau, t_i)$



Signals: $C^{3\text{pt}}_{\text{PP,PS,SP,SS}}(t_f, \tau, t_i)$



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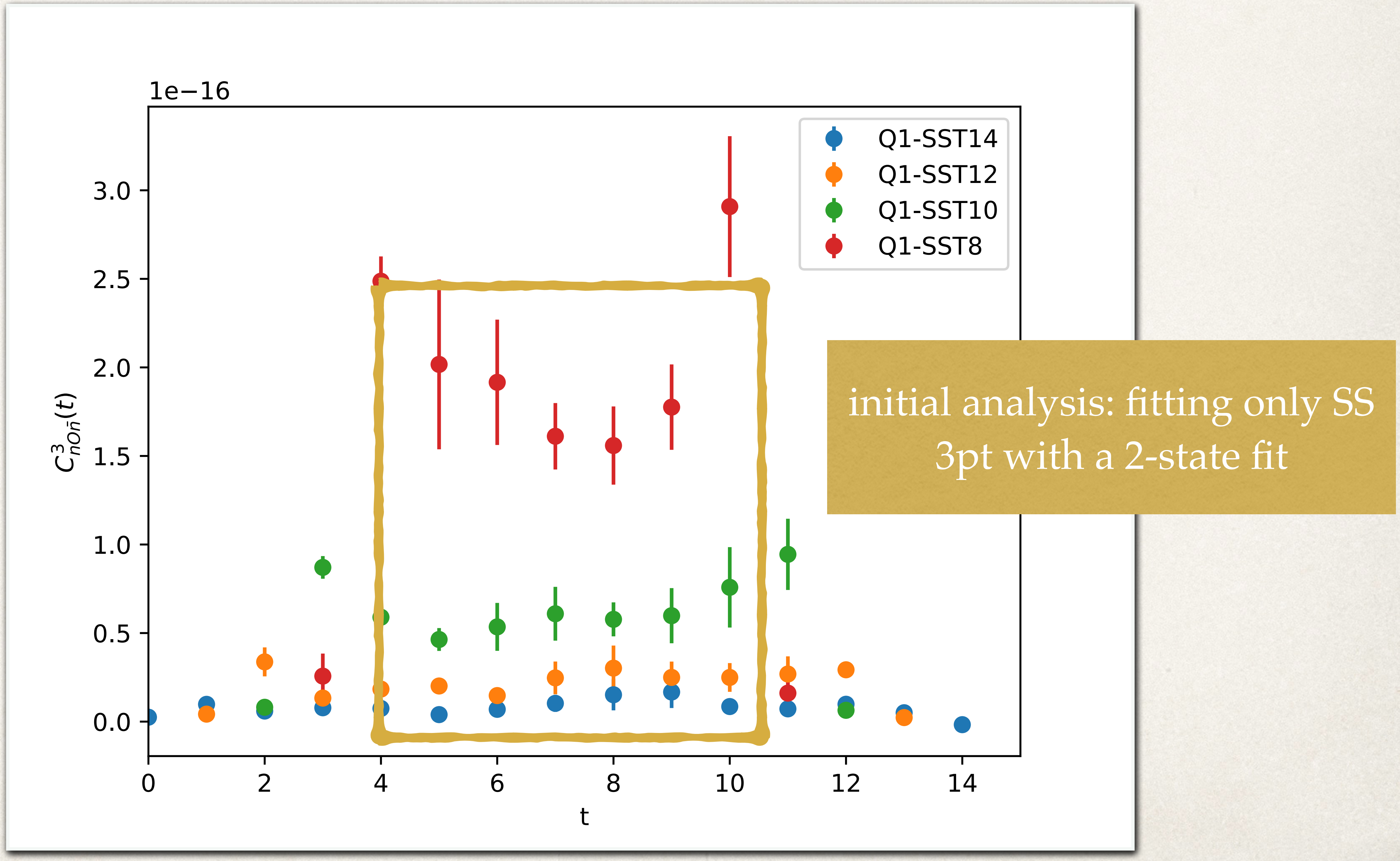


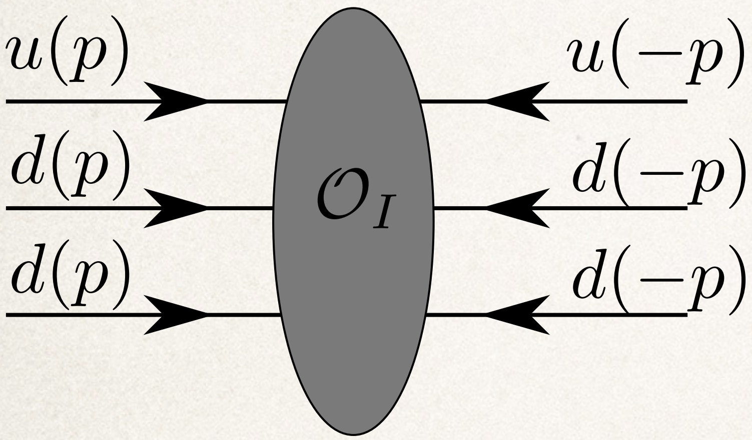
Fit functions

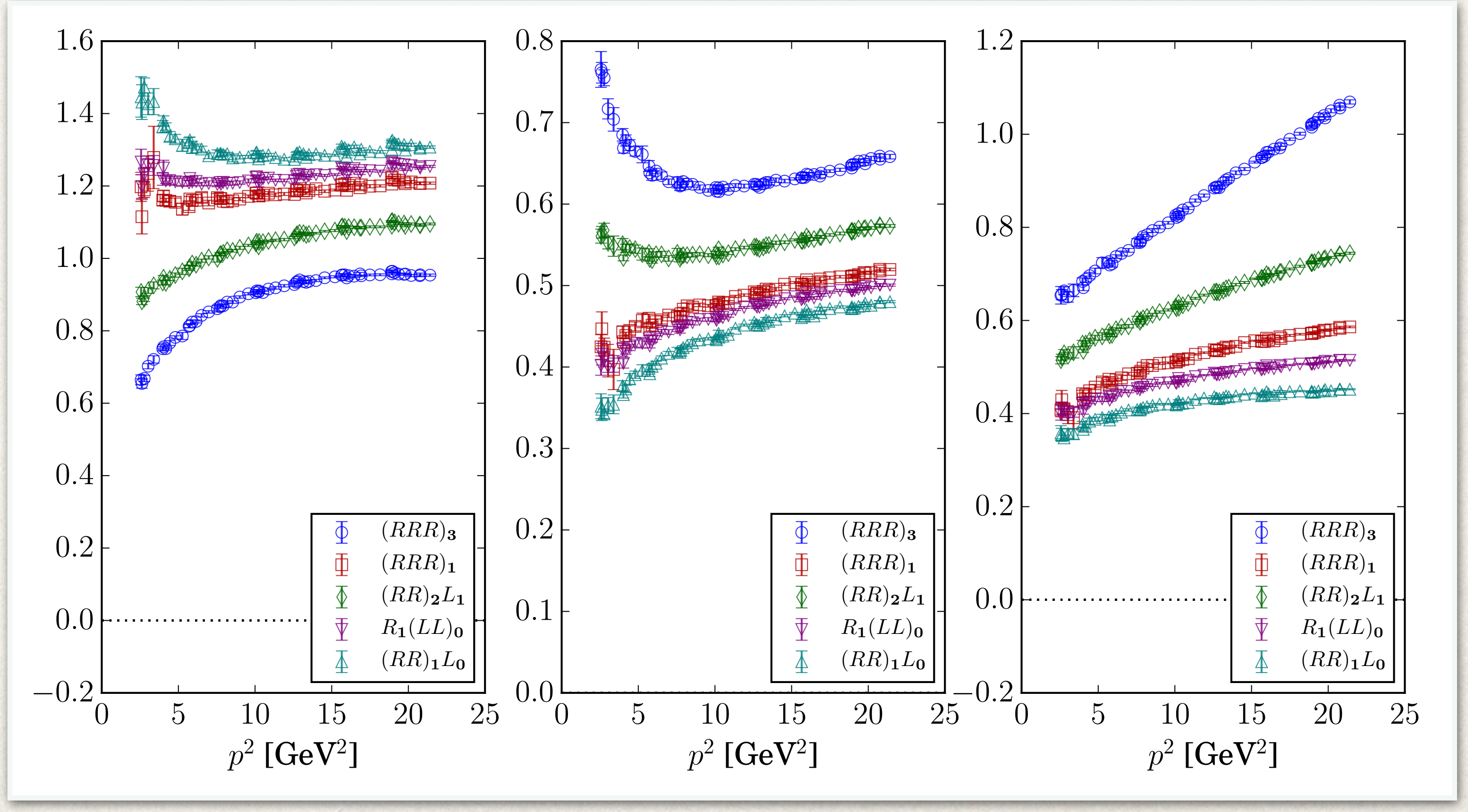
$$C^{2\mathrm{pt}}(t_f, t_i) = |\mathcal{A}_0|^2 e^{-M_0(t_f - t_i)} + |\mathcal{A}_1|^2 e^{-M_1(t_f - t_i)}$$

$$\begin{aligned}
C_\Gamma^{3\mathrm{pt}}(t_f, \tau, t_i) = \;& |\mathcal{A}_0|^2 \langle 0|\mathcal{O}_\Gamma|0\rangle e^{-M_0(t_f - t_i)} + \\
& |\mathcal{A}_1|^2 \langle 1|\mathcal{O}_\Gamma|1\rangle e^{-M_1(t_f - t_i)} + \\
& \mathcal{A}_0 \mathcal{A}_1^* \langle 0|\mathcal{O}_\Gamma|1\rangle e^{-M_0(\tau - t_i)} e^{-M_1(t_f - \tau)} + \\
& \mathcal{A}_0^* \mathcal{A}_1 \langle 1|\mathcal{O}_\Gamma|0\rangle e^{-M_1(\tau - t_i)} e^{-M_0(t_f - \tau)},
\end{aligned}$$

[Syritsyn et al., PoS, Lattice 2015, 132]
[Syritsyn et al, 1809.00246]

Renormalization





[Syritsyn et al., PoS, Lattice 2015, 132]
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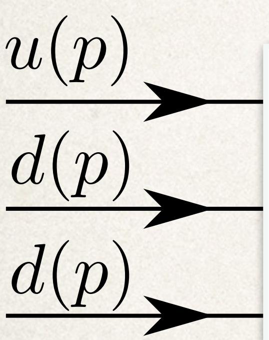
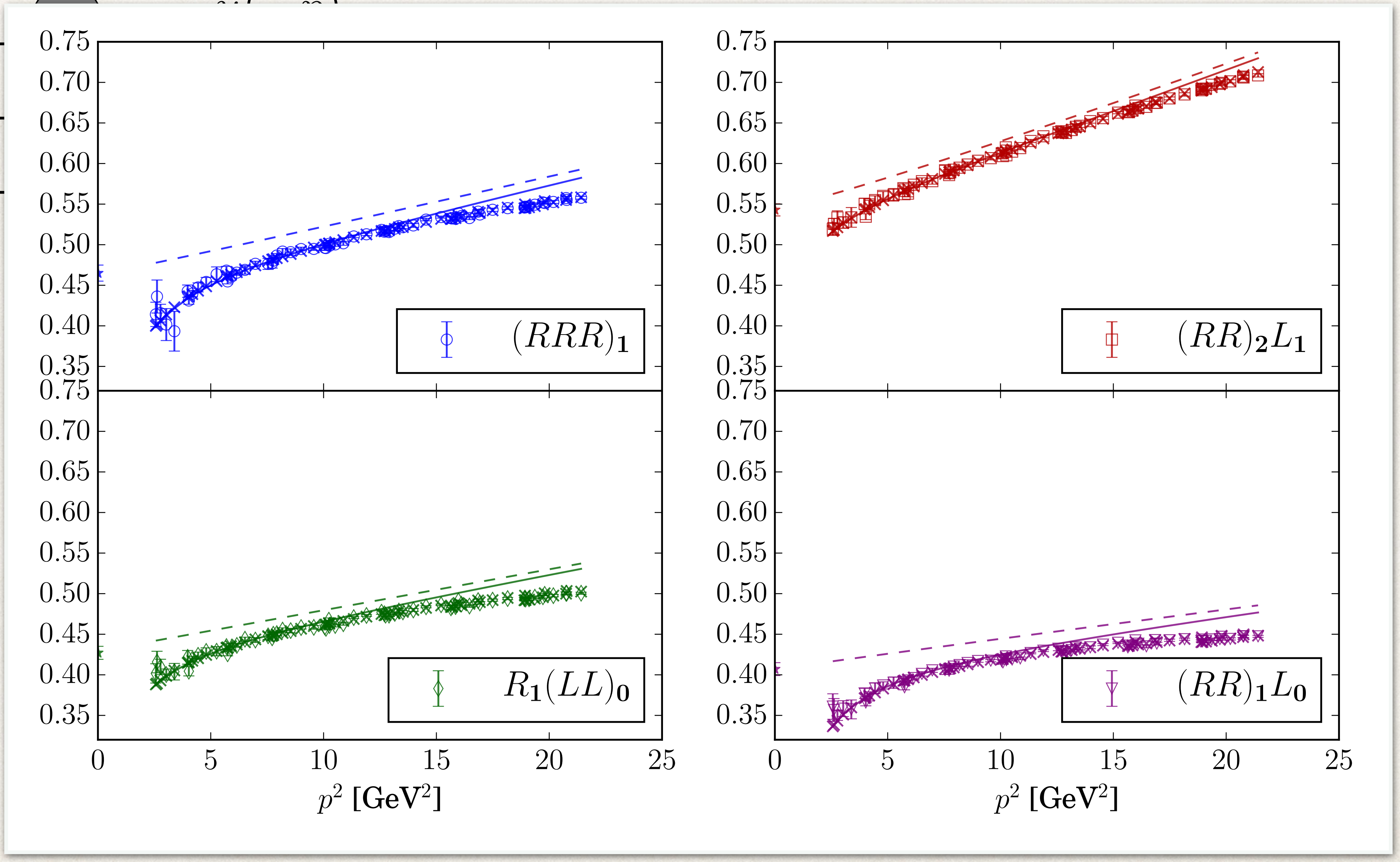
Renormalization





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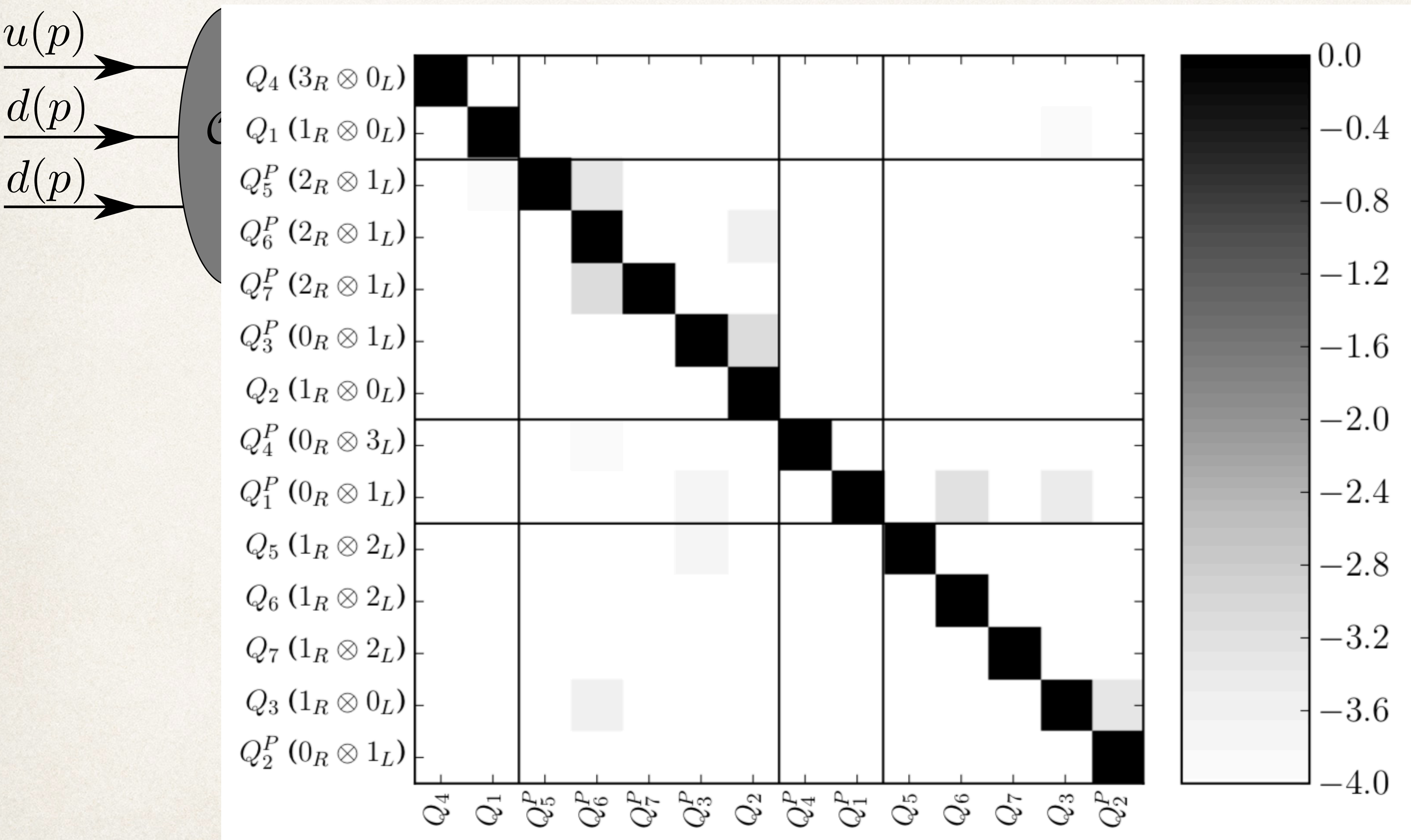

[Grojean et al., 1806.00011]