Neutron-antineutron oscillations

Enrico Rinaldi

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[PoS, Lattice 2012, 128]

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

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[PoS, Lattice 2015, 132]

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[PoS, Lattice 2015, 132]

Neutron-antineutron matrix elements from lattice QCD with physical pions

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[2] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[3] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
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[5] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[in preparation]

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 (ESS and DUNE)

[Frost, 1607.07271]
[Hewes, DOI:10.2172/1426674]

Synopsis of oscillations

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

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

Coupling between neutrons and anti-neutrons

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Energy difference ΔE

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

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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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↓ quasi-free limit $|\Delta E| t \ll 1$

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quasi-free limit $|\Delta E| t \ll 1$

$$P(n(t) = \bar{n}) = [(\delta m)\, t]^2 e^{-\lambda t} = (t/\tau_{n-\bar{n}})^2 e^{-\lambda t}$$

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$$P(n(t) = \bar{n}) = [(\delta m)\, t]^2\, e^{-\lambda t} = (t/\tau_{n-\bar{n}})^2\, e^{-\lambda t}$$

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

New physics

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

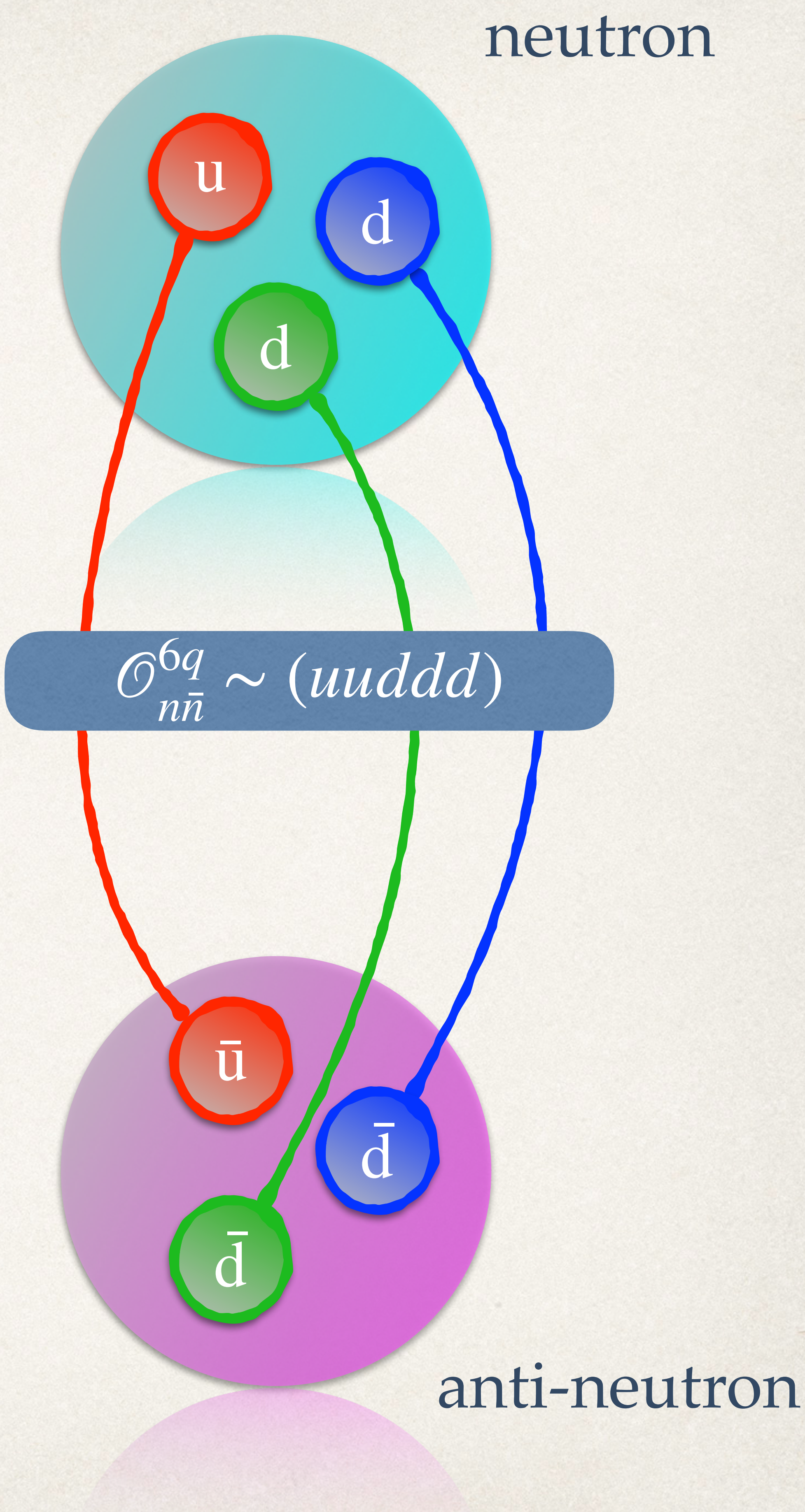
$$\langle n | \mathcal{H}_{\text{eff}} | \bar{n} \rangle = \frac{1}{\Lambda_{\text{BSM}}^5} \sum_i c_i \langle n | \mathcal{O}_i | \bar{n} \rangle$$

- The process is mediated by an effective 6-quark operator 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]



[Rao & Shrock, Nucl. Phys. B 232, 143 (1984)]
[Buchoff & Wagman, 1506.00647]

Operators

Chiral Basis	Fixed-Flavor Basis	Chiral Tensor Structure	Chiral Irrep
Q_1	$\mathcal{O}^3_{RRR}$	$\mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^+T^{AAS}$	$(\mathbf{1}_L,\mathbf{3}_R)$
Q_2	$\mathcal{O}^3_{LRR}$	$\mathcal{D}_L\mathcal{D}_R\mathcal{D}_R^+T^{AAS}$	$(\mathbf{1}_L,\mathbf{3}_R)$
Q_3	$\mathcal{O}^3_{LLR}$	$\mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^+T^{AAS}$	$(\mathbf{1}_L,\mathbf{3}_R)$
Q_4	$4/5\ \mathcal{O}^2_{RRR}+1/5\ \mathcal{O}^1_{RRR}$	$\mathcal{D}_R^{33+}T^{SSS}$	$(\mathbf{1}_L,\mathbf{7}_R)$
Q_5	$\mathcal{O}^1_{RLL}$	$\mathcal{D}_R^-\mathcal{D}_L^{++}T^{SSS}$	$(\mathbf{5}_L,\mathbf{3}_R)$
Q_6	$\mathcal{O}^2_{RLL}$	$\mathcal{D}_R^3\mathcal{D}_L^{3+}T^{SSS}$	$(\mathbf{5}_L,\mathbf{3}_R)$
Q_7	$2/3\ \mathcal{O}^2_{LLR}+1/3\ \mathcal{O}^1_{LLR}$	$\mathcal{D}_R^+\mathcal{D}_L^{33}T^{SSS}$	$(\mathbf{5}_L,\mathbf{3}_R)$
$\widetilde{Q}_1$	$1/3\ \mathcal{O}^2_{RRR}-1/3\ \mathcal{O}^1_{RRR}$	$\mathcal{D}_R\mathcal{D}_R\mathcal{D}_R^+T^{SSS}$	$(\mathbf{1}_L,\mathbf{3}_R)$
$\widetilde{Q}_3$	$1/3\ \mathcal{O}^2_{LLR}-1/3\ \mathcal{O}^1_{LLR}$	$\mathcal{D}_L\mathcal{D}_L\mathcal{D}_R^+T^{SSS}$	$(\mathbf{1}_L,\mathbf{3}_R)$

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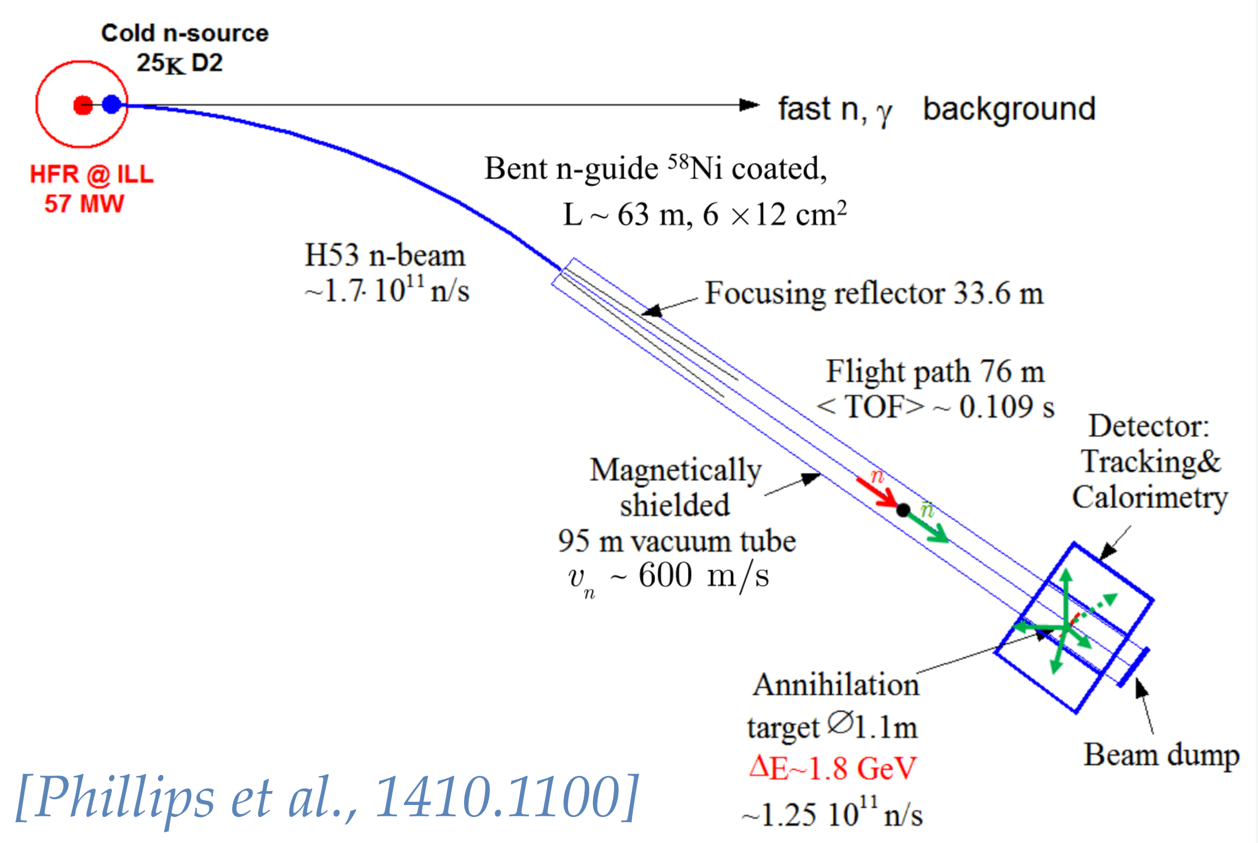
Experimental searches

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



[Phillips et al., 1410.1100]

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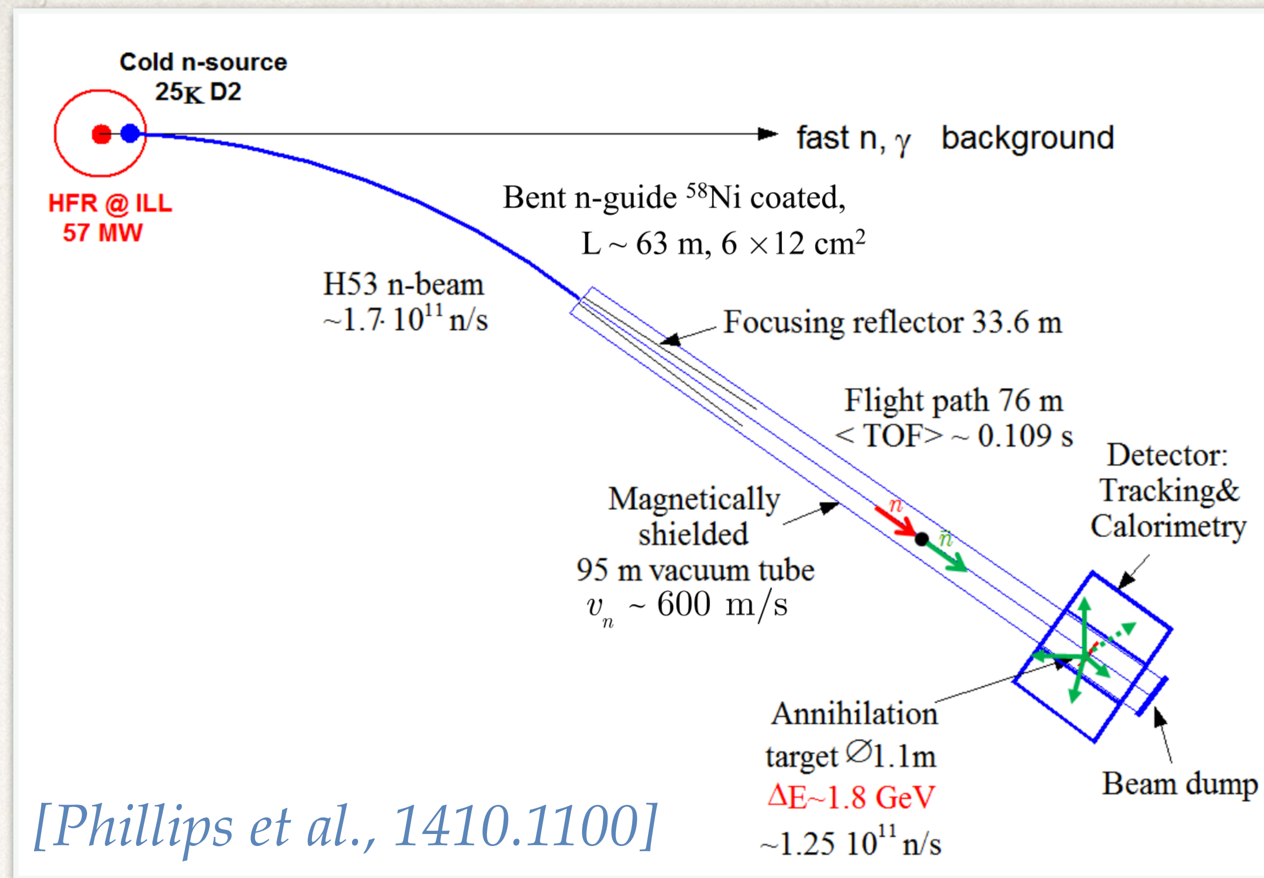

[Phillips et al., 1410.1100]

almost background free

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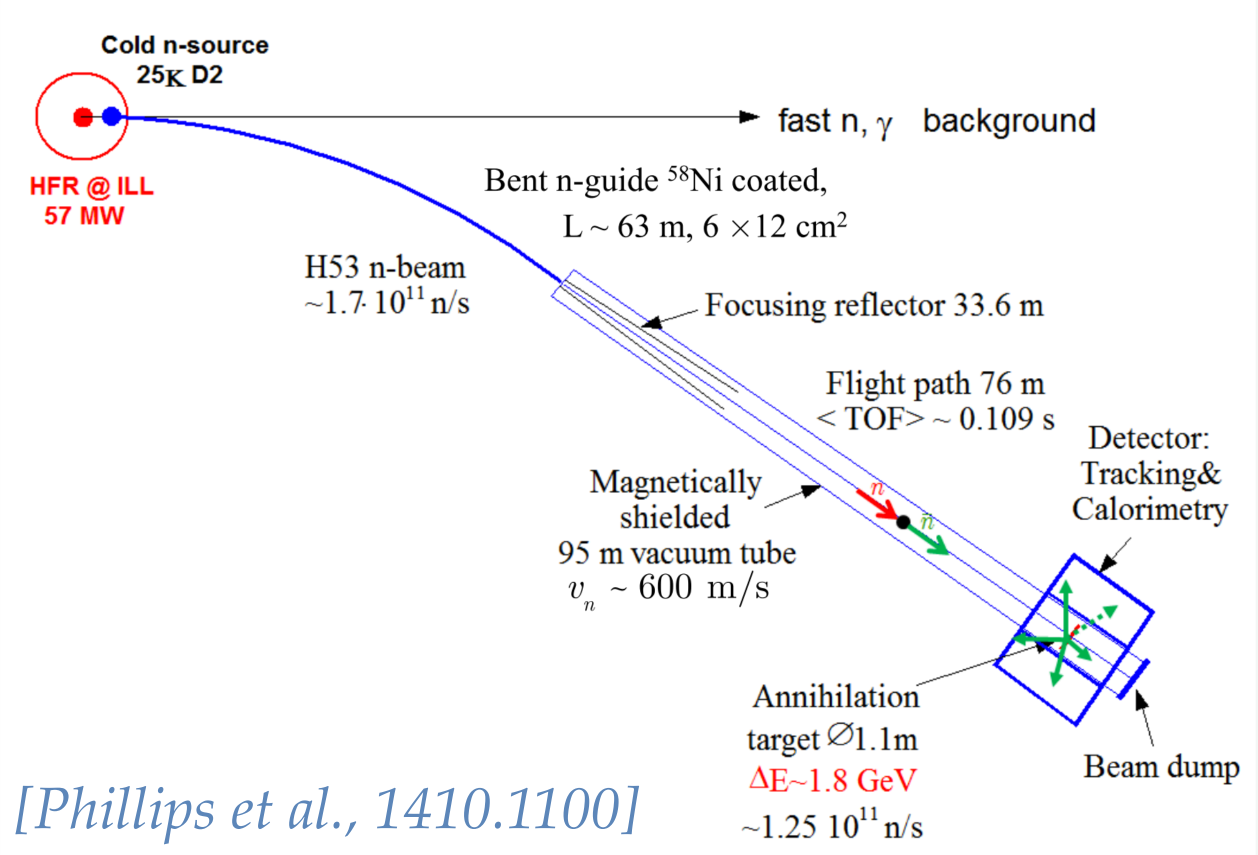

[Phillips et al., 1410.1100]

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

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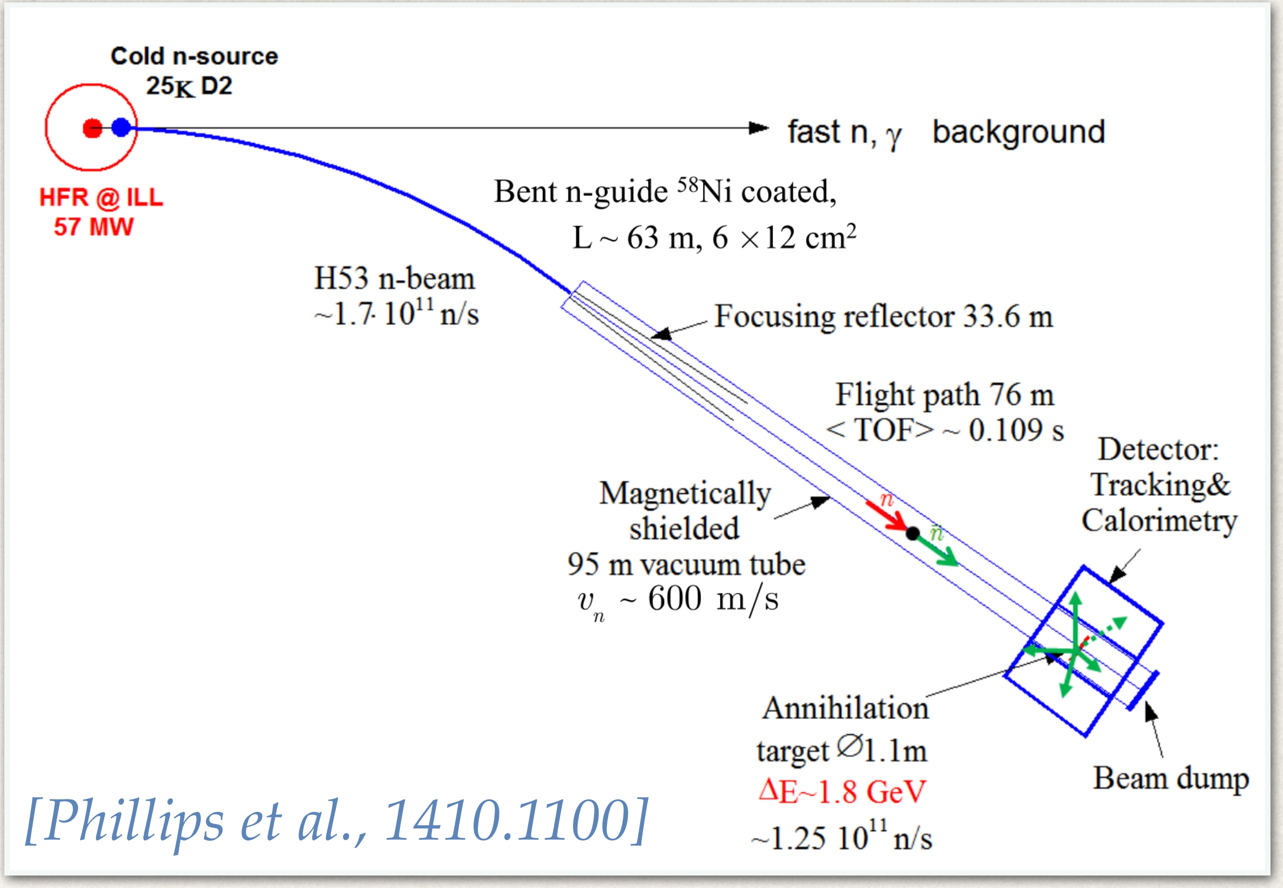

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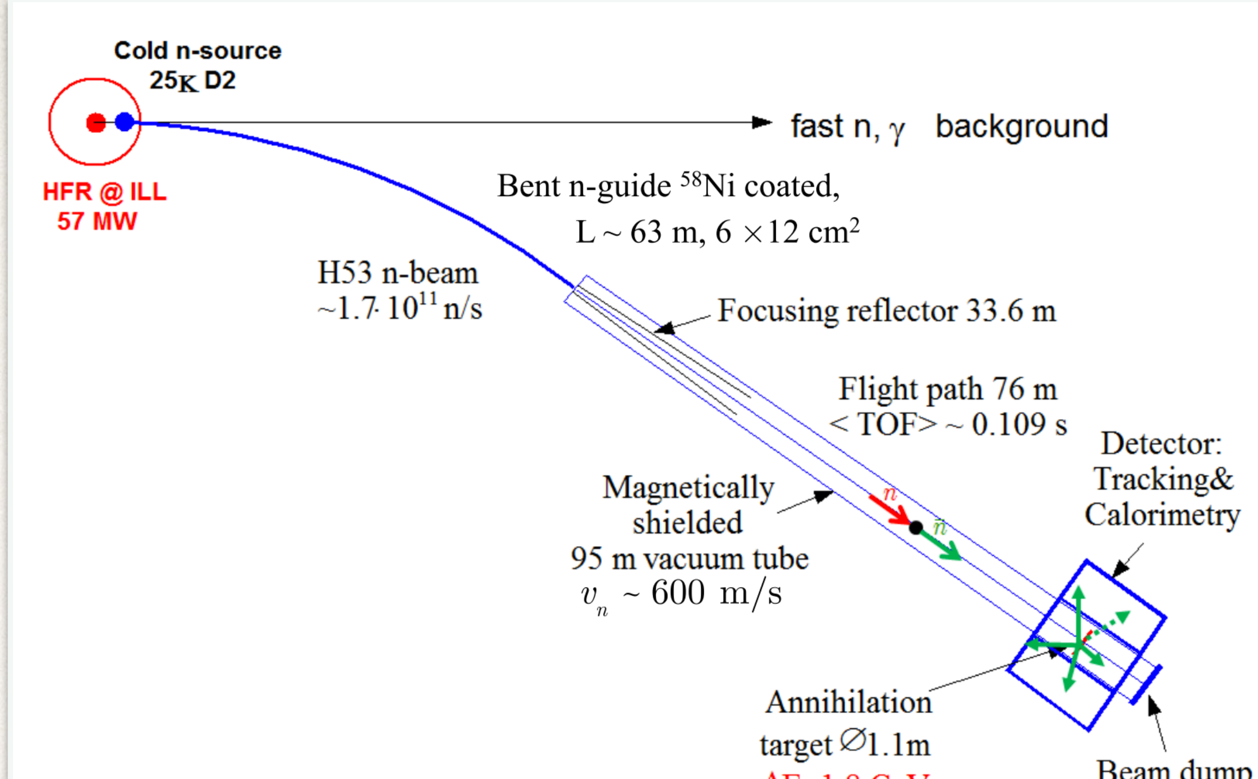
Nuclear suppression factor due to different nuclear potential

Experimental searches



[Phillips et al., 1410.1100]

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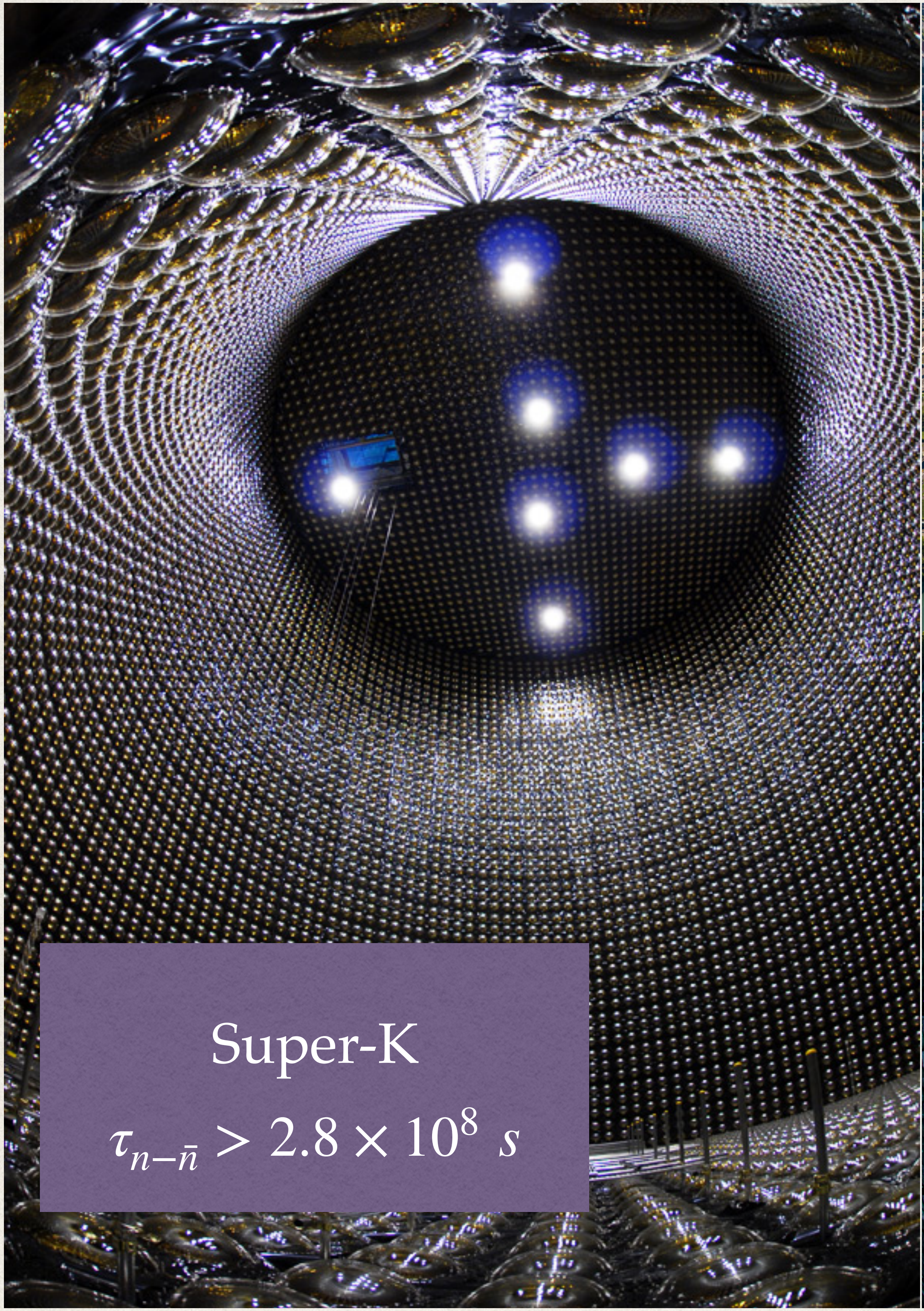
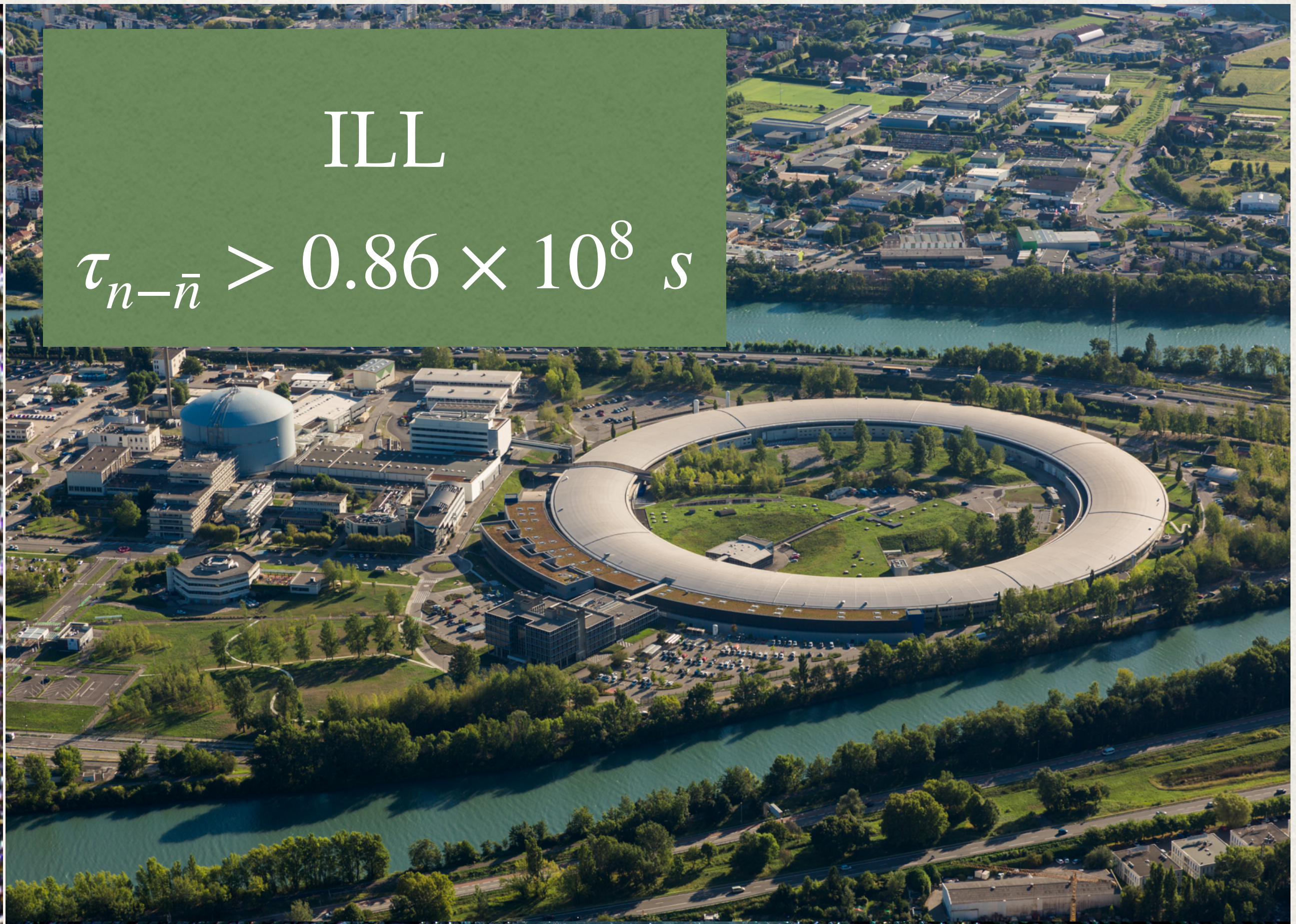
Nuclear suppression factor due to different nuclear potential

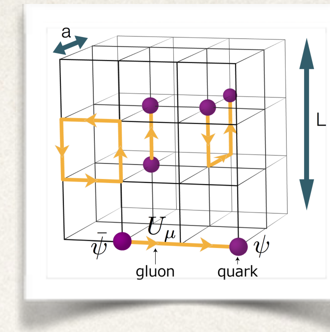
can be improved with particle tracking


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


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


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

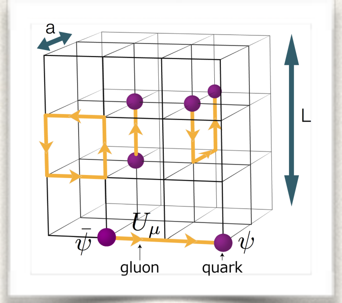
[KEK-Japan]



Lattice details

- Configurations and propagators from RBC/UKQCD
  [RBC/UKQCD, 1411.7017]
  - Mobiüs Domain Wall fermions
  - Physical pion mass
  - 48^3x96 with a=0.123 fm
  - 30 independent configs.

[KEK-Japan]



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    chiral
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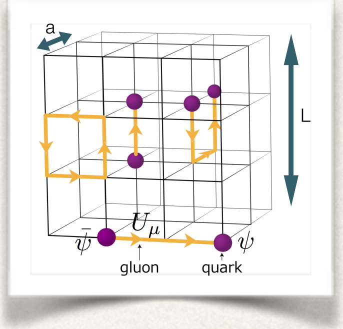
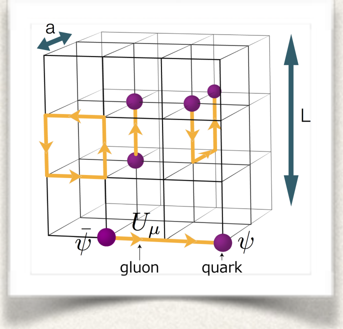
[KEK-Japan]



Lattice details

- Configurations and propagators from RBC/UKQCD
  [RBC/UKQCD, 1411.7017]
  - Mobiüs Domain Wall fermions — chiral
  - Physical pion mass — no extrapolation
  - 48^3x96 with a=0.123 fm
  - 30 independent configs.

[KEK-Japan]



Lattice details

- Configurations and propagators from RBC/UKQCD

  [RBC/UKQCD, 1411.7017]

  - Mobiüs Domain Wall fermions

    chiral

  - Physical pion mass

    no extrapolation

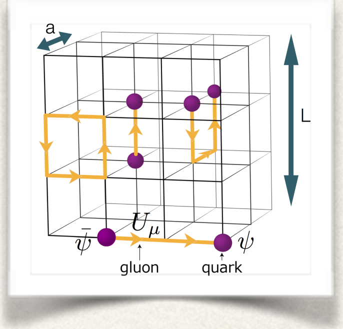
  - 48^3x96 with a=0.123 fm

    large volume

  - 30 independent configs.

Lattice details

[KEK-Japan]



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  - Physical pion mass
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chiral

no extrapolation

large volume

+AMA to increase stat.

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

Methodology

- Calculate 3-point function of operator inserted at time τ

- Only 1 propagator (point-to-all) needed: fix source at $\tau = 0$

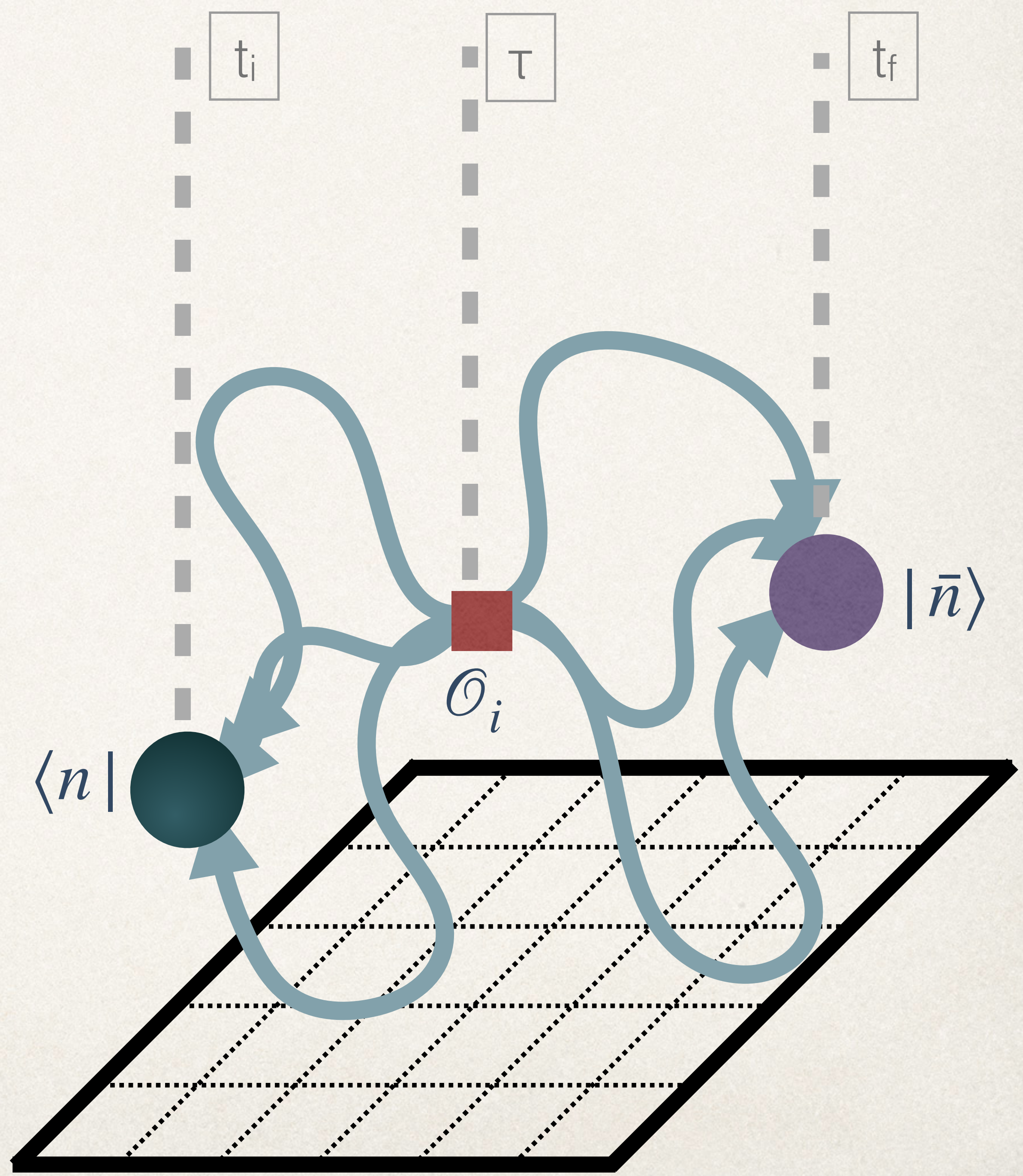
- All time separations accessible

  $t_f - \tau$ $\tau - t_i$

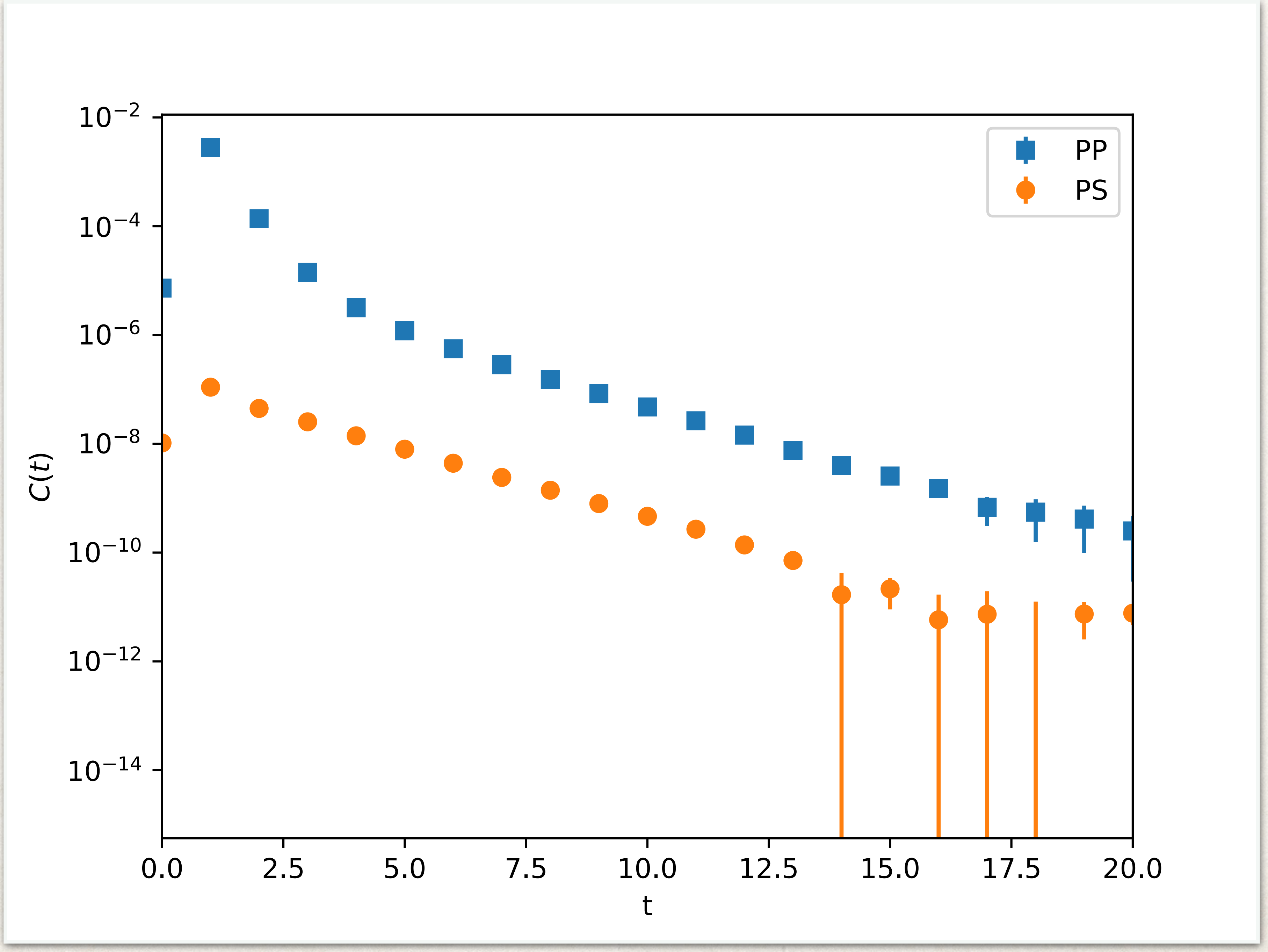
- Only point insertions, but point and gaussian smeared nucleons

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

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



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



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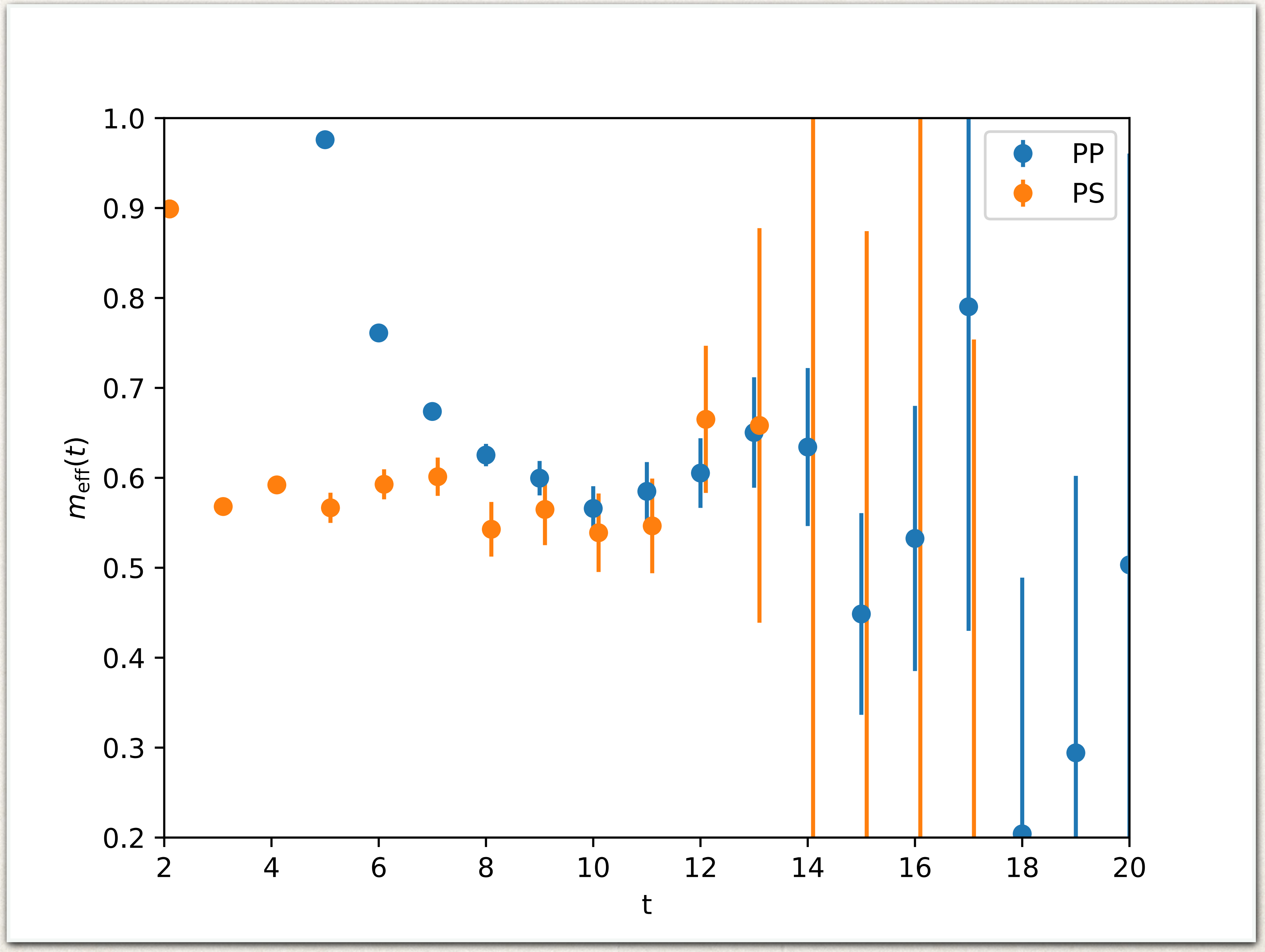
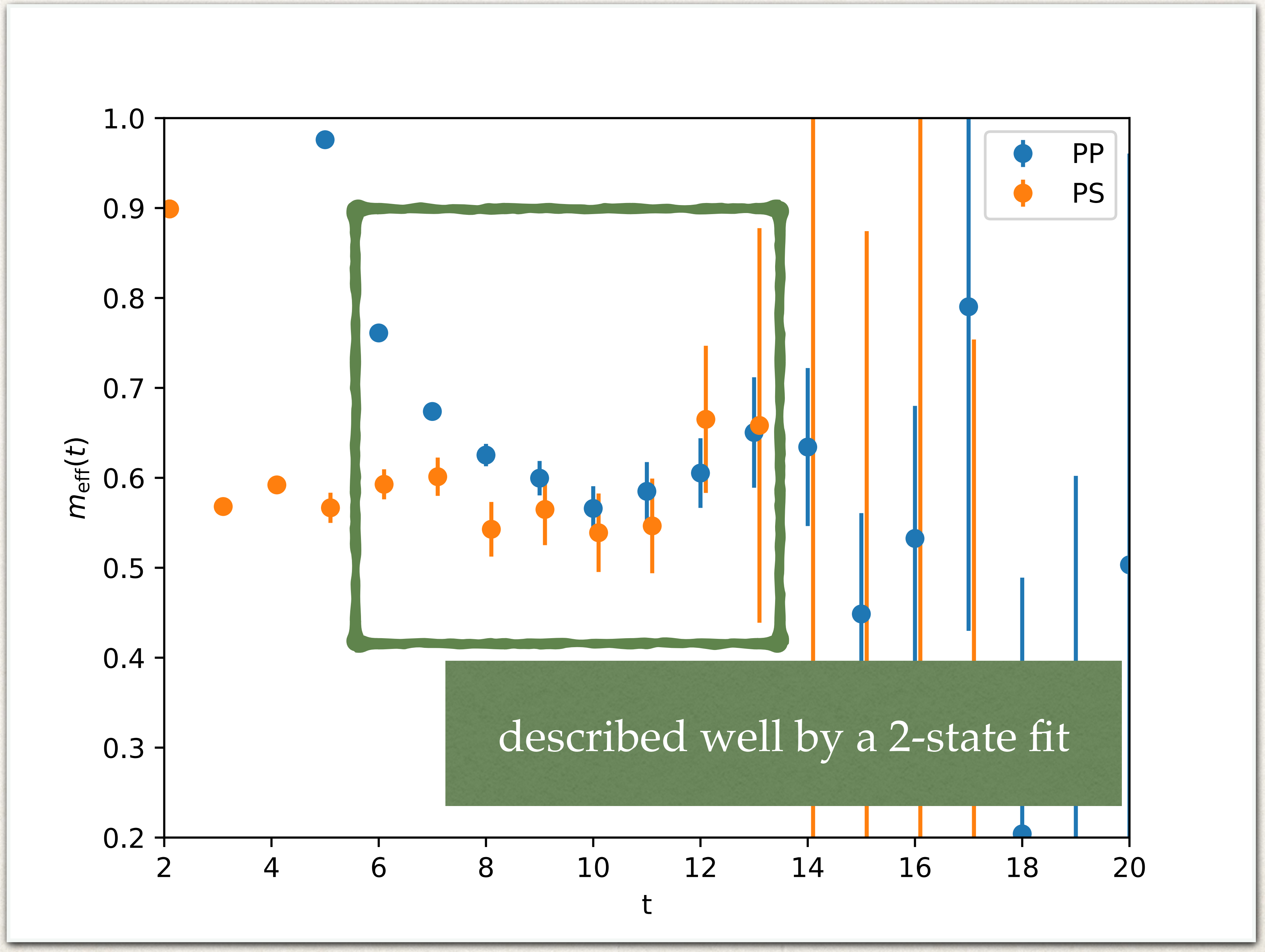
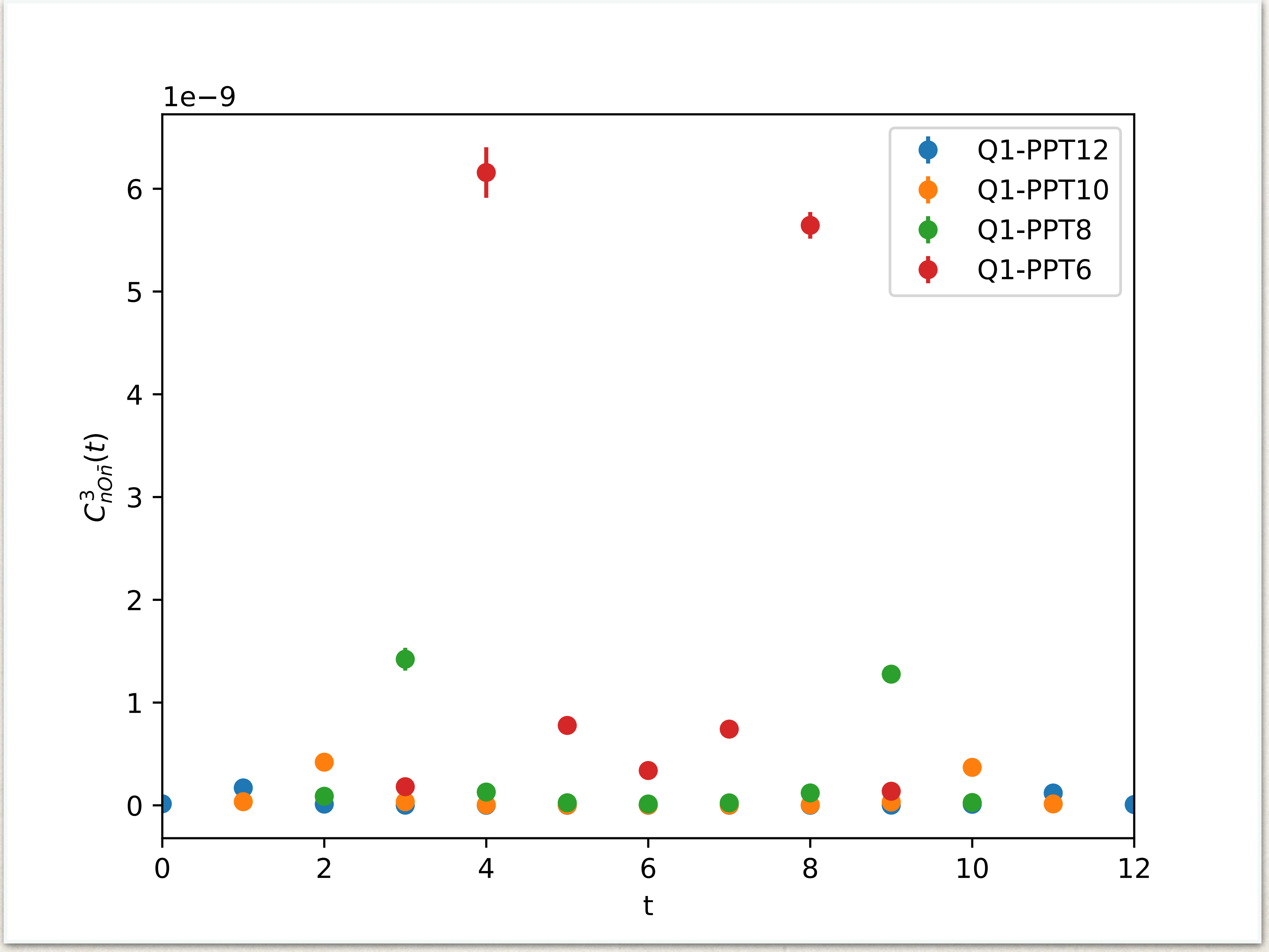


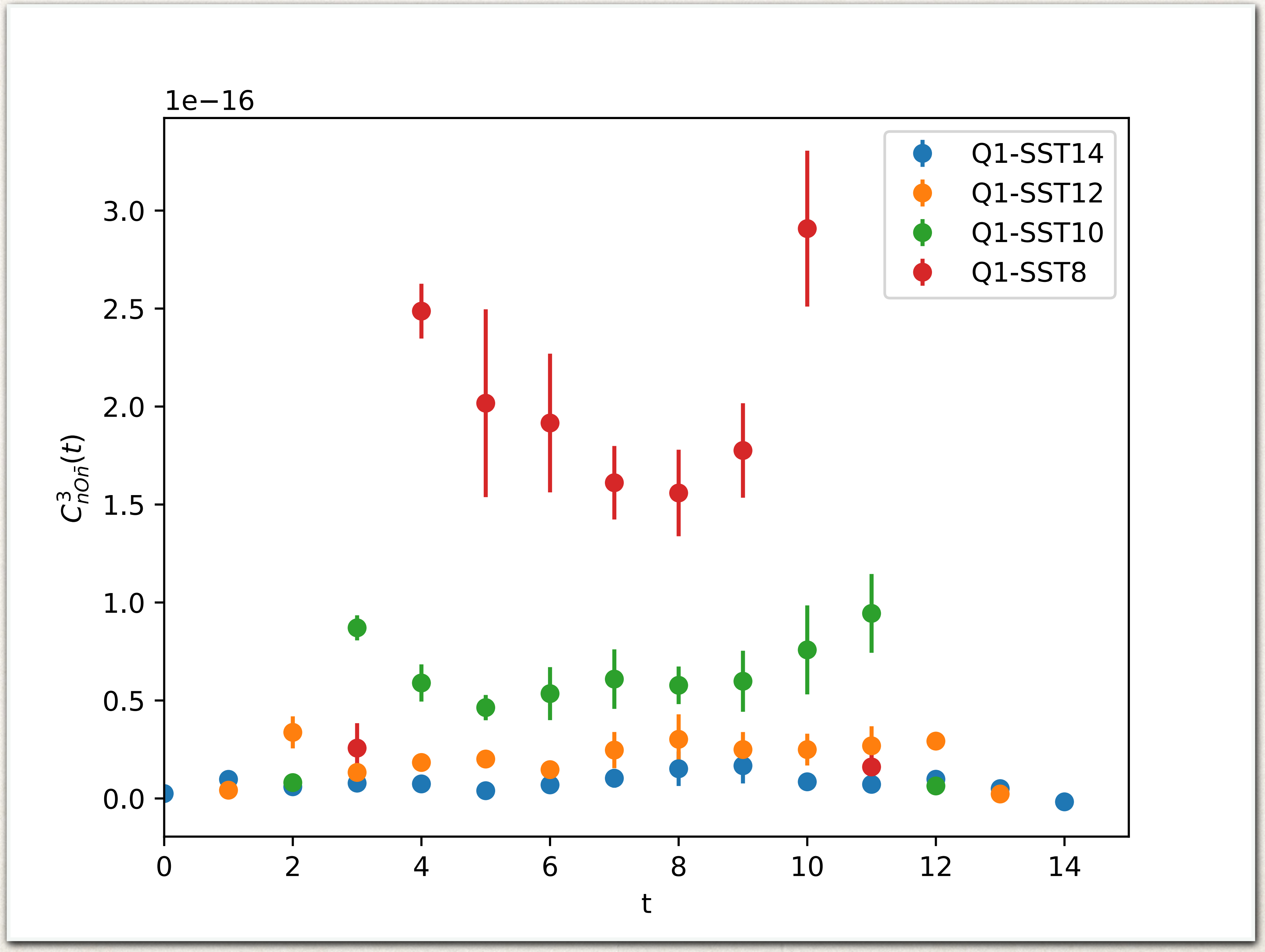
Signals: $C^{2\text{pt}}_{\text{PP,PS}}(t_f, t_i)$



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



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



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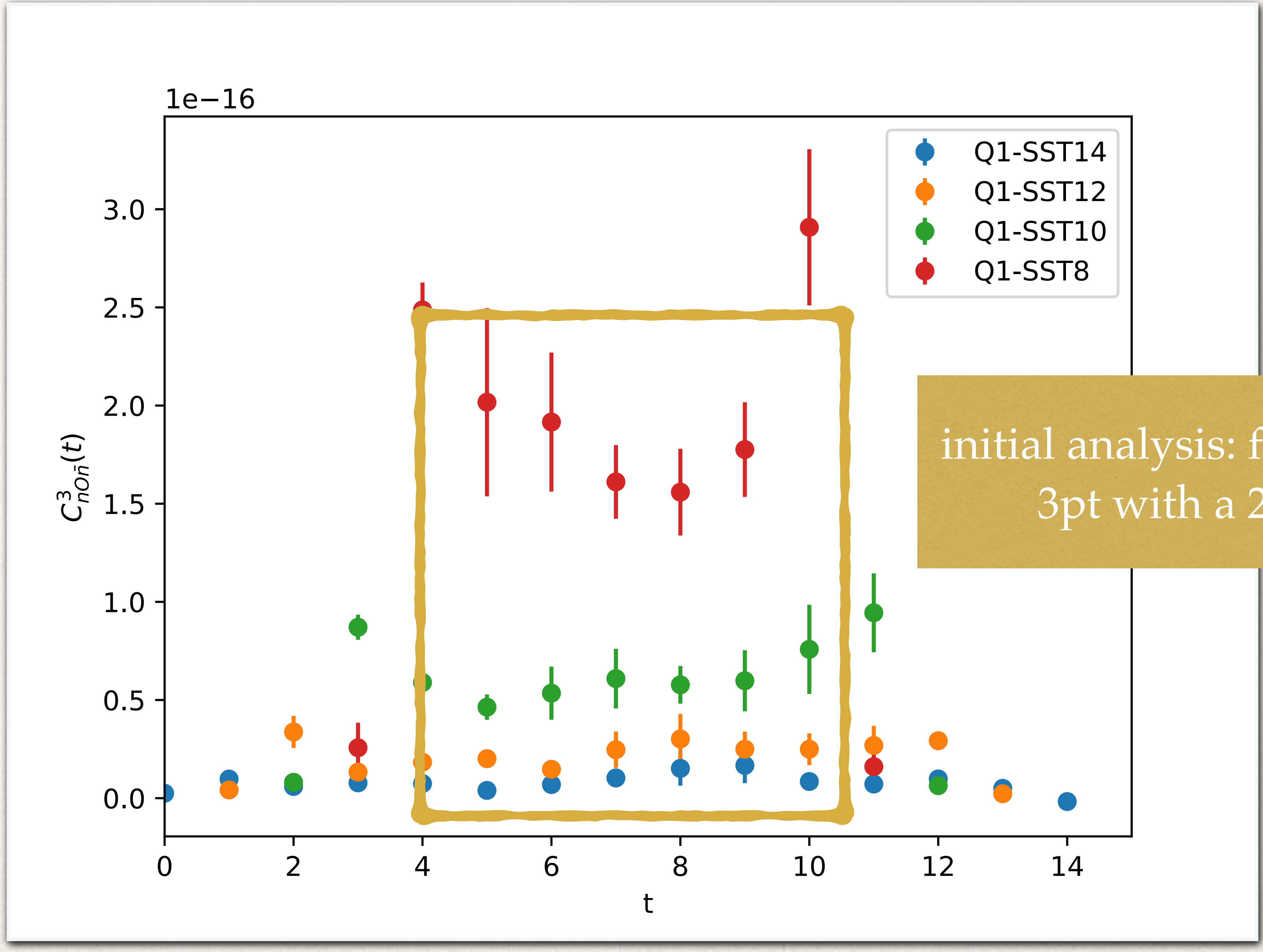


initial analysis: fitting only SS 3pt with a 2-state fit

Outlook

- Non-perturbative renormalization to scales above the hadronic world already exists

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

- perturbative renormalization to the scale of new physics already exists

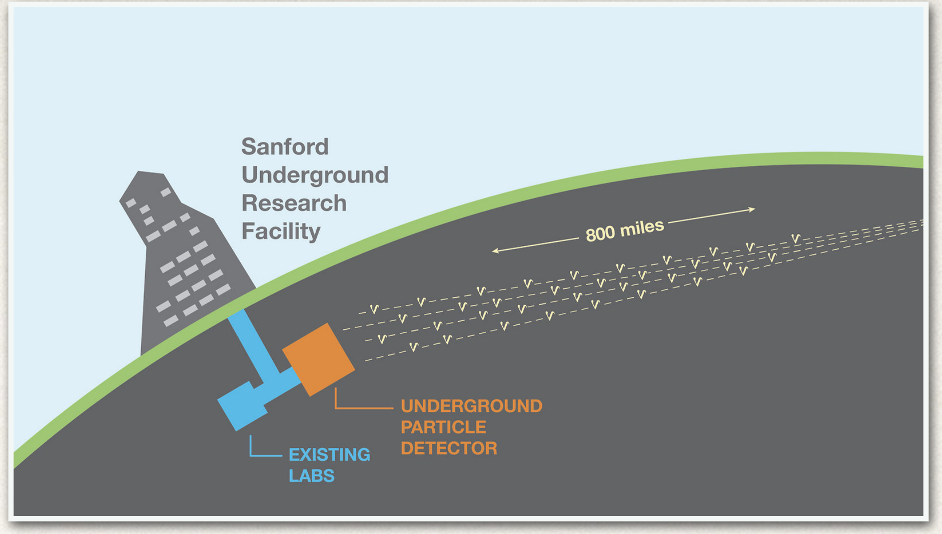
  [Buchoff & Wagman, 1506.00647]

- more statistics (configurations and propagators) already exists: can reduce errors below 20%

- excited state analysis almost finalized

  [Syritsyn et al, in preparation]

Summary



- Improvement of the experimental limits on oscillations is expected in the next decade $\tau_{n-\bar{n}} > 10^{10}\ s$
  - New EFT approaches connecting new physics to nuclear matrix elements are in progress: 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 are now replacing old and uncertain MIT bag model estimates for nuclear ME

thank you

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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

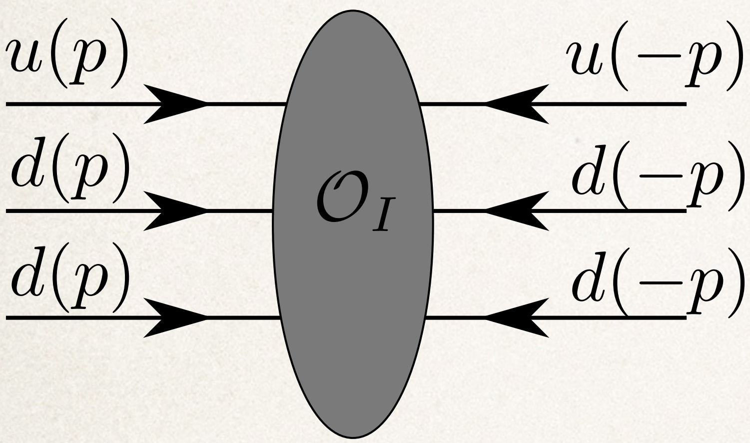
Fit functions

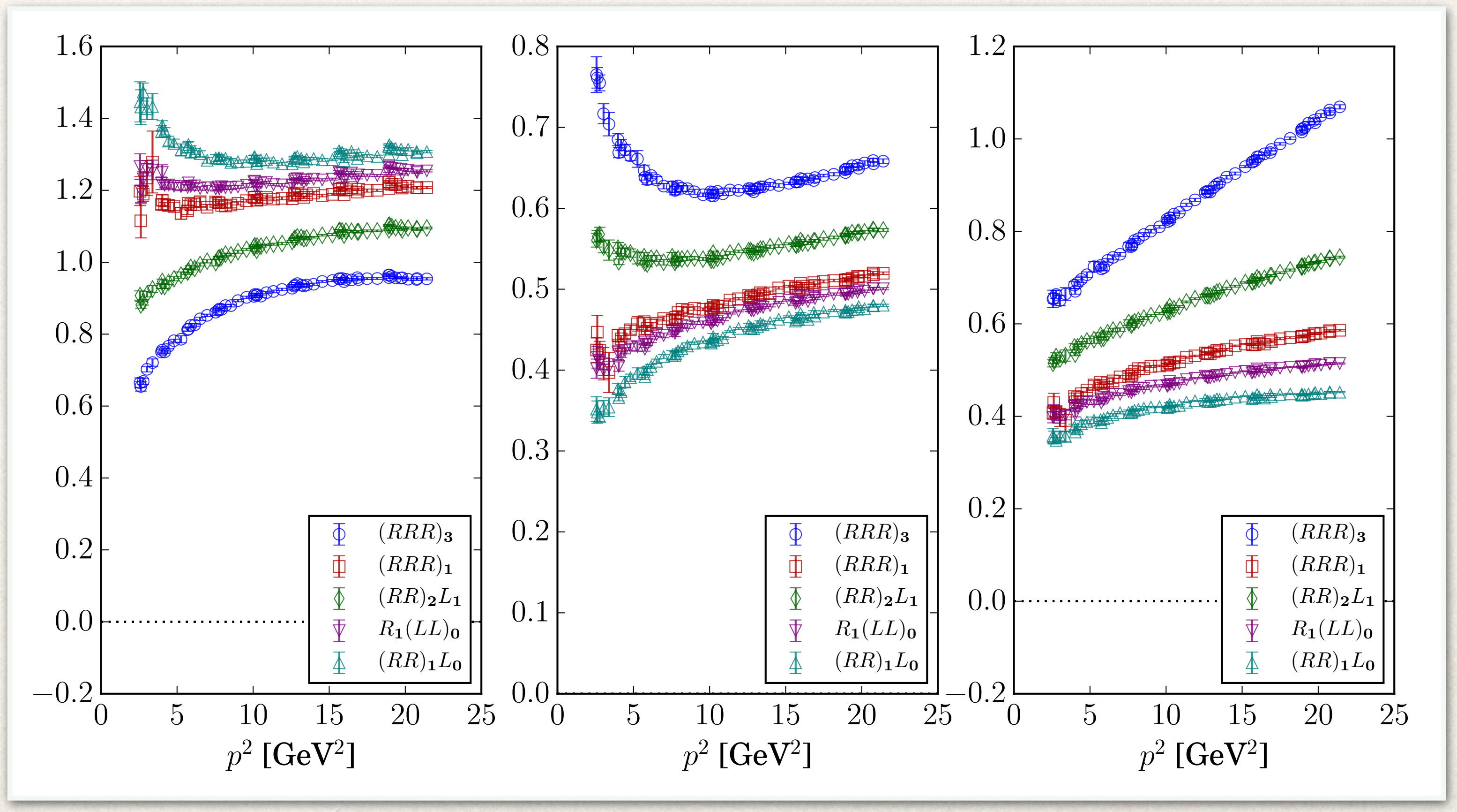
$$C^{2\mathrm{pt}}(t_f, t_i) = |\mathcal{A}_0|^2 e^{-M_0(t_f - t_i)} + |\mathcal{A}_1|^2 e^{-M_1(t_f - t_i)}$$

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

[Syritsyn et al., PoS, Lattice 2015, 132]
[Syritsyn et al, in preparation]

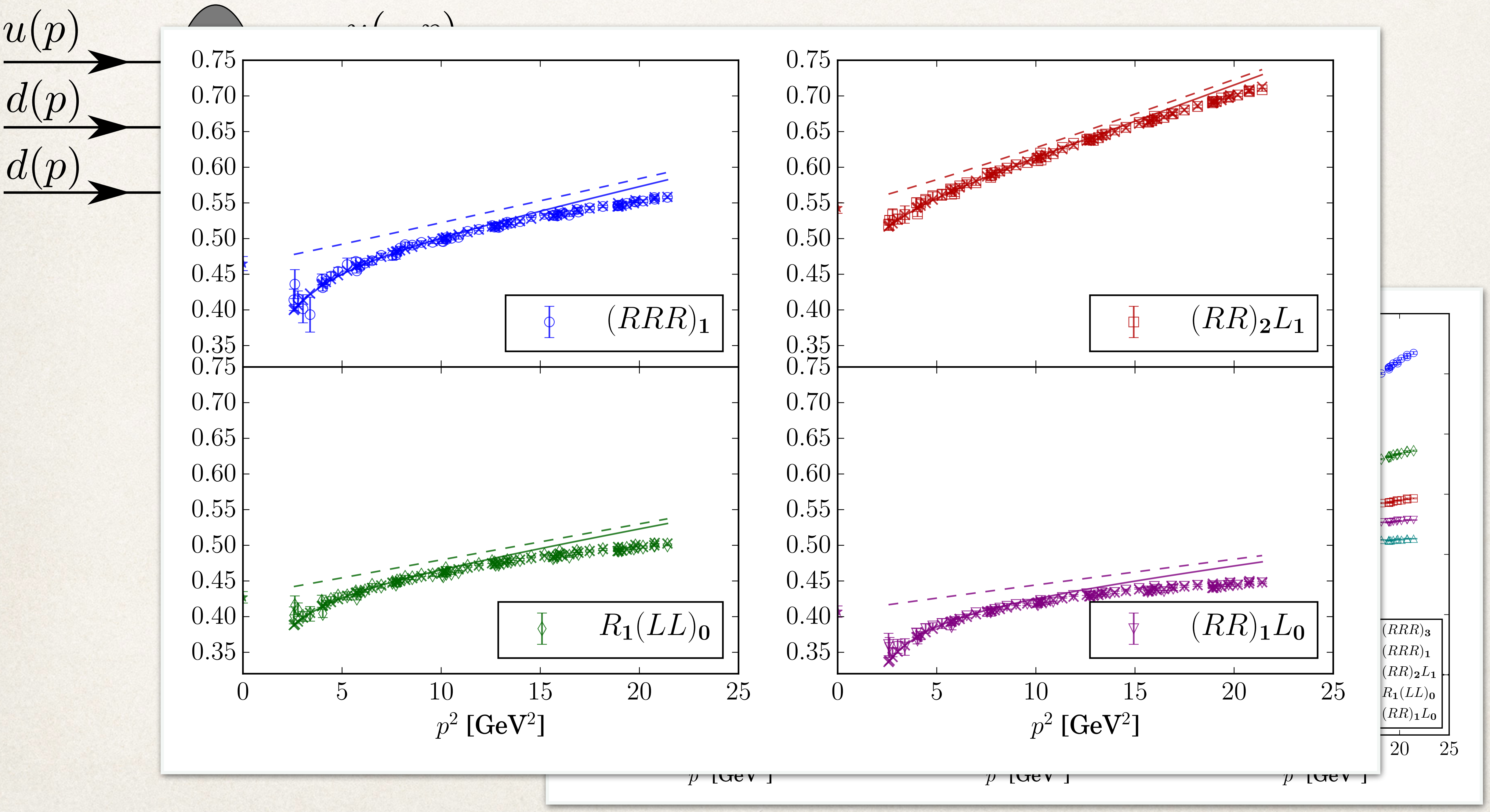
Renormalization





[Syritsyn et al., PoS, Lattice 2015, 132]
[Syritsyn et al, in preparation]

Renormalization



Preliminary results (do not quote)

Operator	Bare Matrix Element
Q_1	$1.19(42)(15) \times 10^{-5}$
Q_2	$-2.80(56)(31) \times 10^{-5}$
Q_3	$2.04(35)(26) \times 10^{-5}$
Q_6	$0.0366(105)(152) \times 10^{-5}$

Chiral Basis	RI-MOM, 2 GeV	$\overline{\text{MS}}$, 10 TeV	$\frac{\text{RI-MOM, 2 GeV}}{\text{MIT Bag 2}}$
Q_1	-60.5(7.5)	-33.1(4.1)	6.8
Q_2	88.8(10.2)	133(15.2)	8.1
Q_3	-58.7(5.4)	-53.7(4.9)	7.2
Q_4	0	0	-
Q_5	8.84 (1.04)	2.11(0.25)	3.2
Q_6	-2.12 (0.26)	-0.506(0.062)	3.2
Q_7	1.41 (0.17)	0.337(0.041)	3.2

[Syritsyn et al, in preparation]