Nuclear matrix elements for baryogenesis

Enrico Rinaldi

2019/04/26 - Frontiers in Lattice QCD, YITP, Kyoto, Japan

RIKEN BNL Research Center

Nuclear matrix elements for baryogenesis

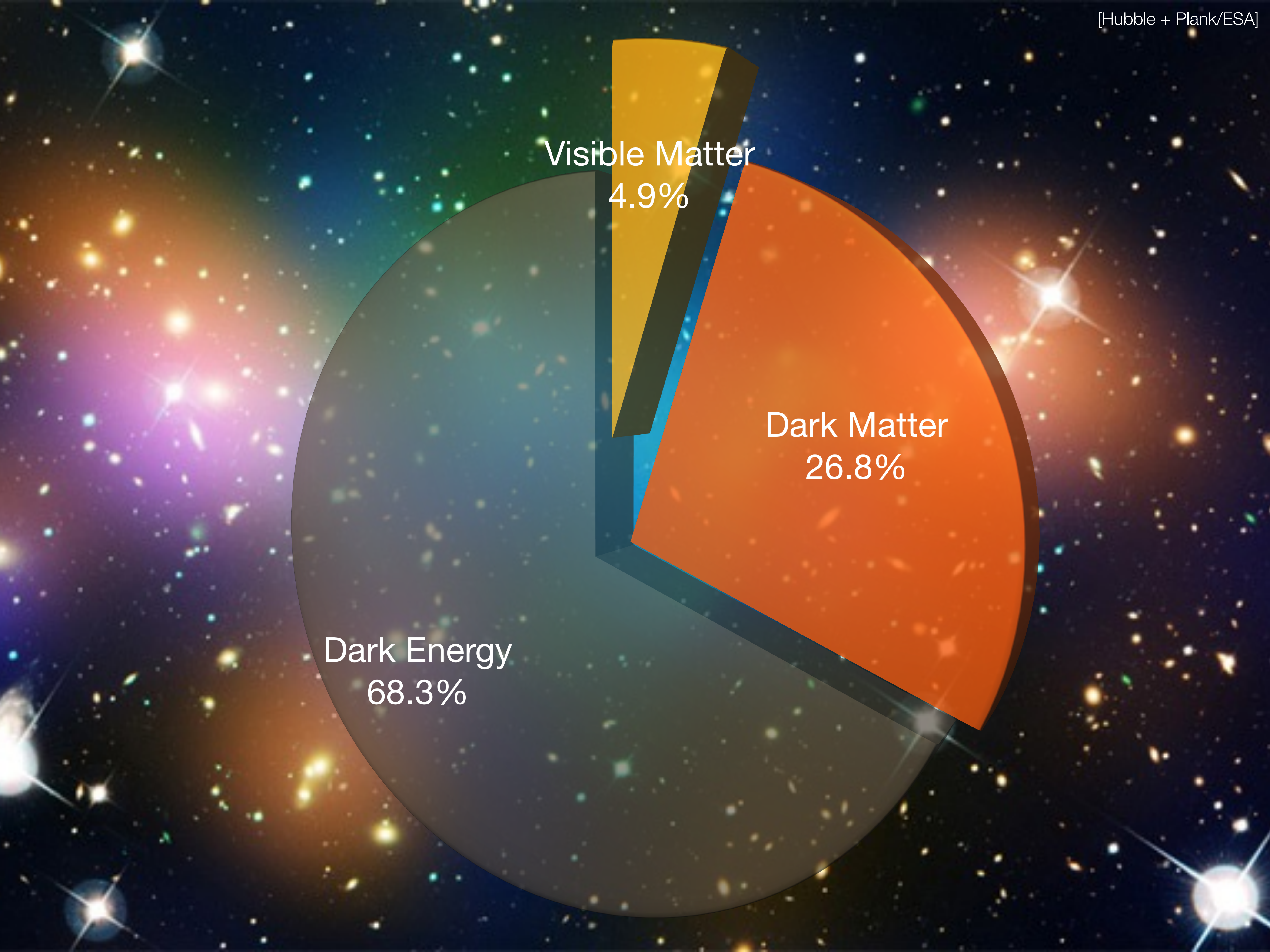
Enrico Rinaldi

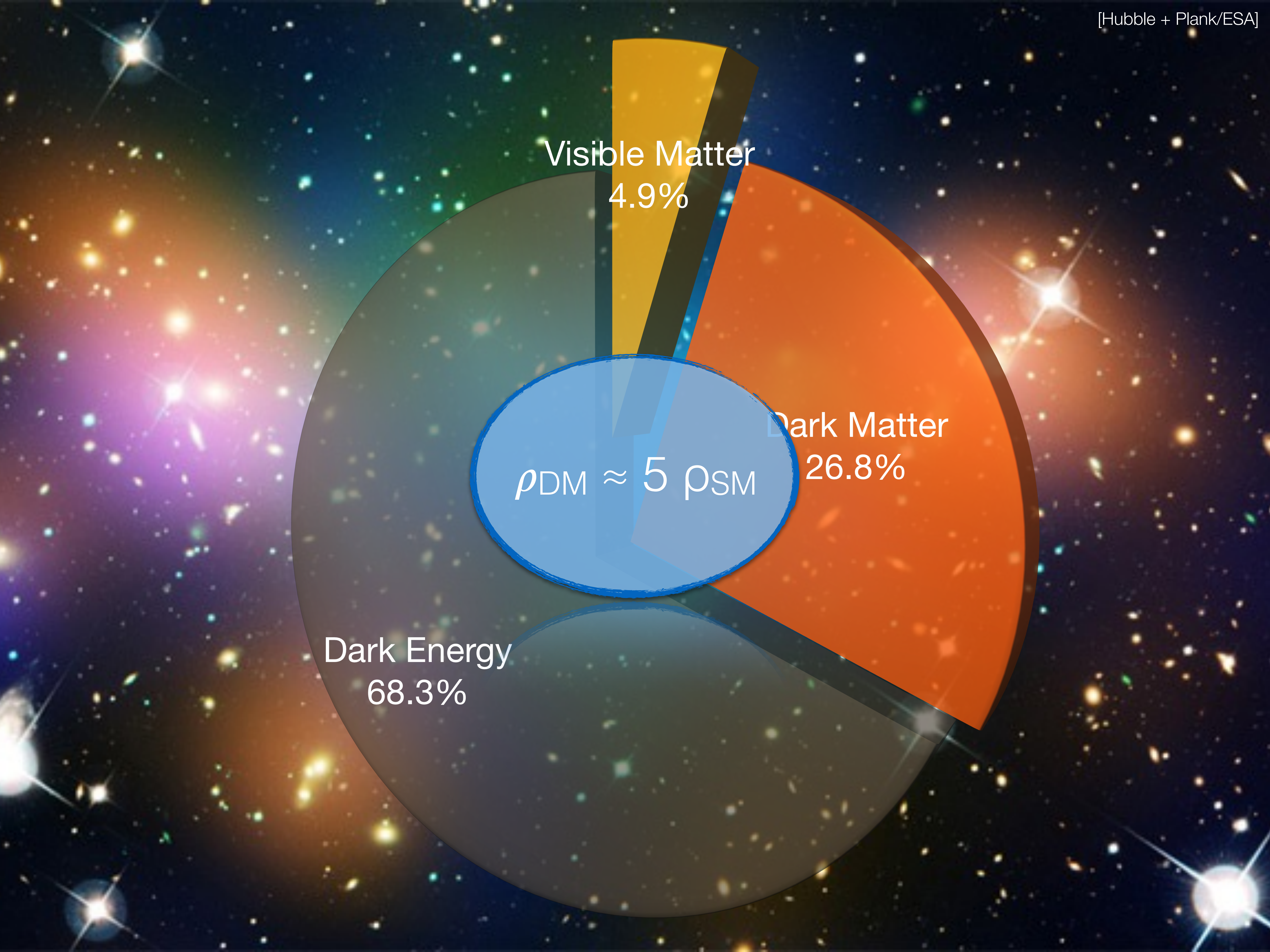
2019/04/26 - Frontiers in Lattice QCD, YITP, Kyoto, Japan

RIKEN NiSHiNA CENTER


[Hubble + Plank/ESA]


[Hubble + Plank/ESA]
Visible Matter
4.9%


[Hubble + Plank/ESA]
Visible Matter
4.9%
Dark Matter
26.8%
Dark Energy
68.3%


[Hubble + Plank/ESA]
Visible Matter
4.9%
Dark Matter
26.8%
Dark Energy
68.3%
$\rho_{DM} \approx 5\ \rho_{SM}$

The origin of matter

The origin of matter

- One of the unsolved problem in particle physics! Why is there a matter-antimatter asymmetry?

The origin of matter

- One of the unsolved problem in particle physics! Why is there a matter-antimatter asymmetry?
- Baryogenesis ➔ how to produce more “matter” than antimatter

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

The origin of matter

- One of the unsolved problem in particle physics! Why is there a matter-antimatter asymmetry?
- Baryogenesis ➔ how to produce more “matter” than antimatter
- *Sakharov conditions* (necessary):
    1. Baryon number violation
    2. C and CP symmetry violation
    3. Out-of-equilibrium interactions

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

The origin of matter

- One of the unsolved problem in particle physics! Why is there a matter-antimatter asymmetry?
- Baryogenesis ➔ how to produce more “matter” than antimatter
- *Sakharov conditions* (necessary):
  1. Baryon number violation
  2. C and CP symmetry violation
  3. Out-of-equilibrium interactions

The Standard Model can produce baryogenesis, but it is not enough.

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

The origin of matter

- One of the unsolved problem in particle physics! Why is there a matter-antimatter asymmetry?
- Baryogenesis ➔ ” than antimatter
- *Sakharov conditi*

1. Baryon number violation
2. C and CP symmetry violation
3. Out-of-equilibrium interactions

search for baryon-violating interactions: new physics!

The Standard Model can produce baryogenesis, but it is not enough.

Neutron-antineutron oscillations

Neutron-antineutron oscillations

- Oscillations of neutral particles can teach us about new physics!

K^0	B^0	ν	N
CP	CP	m_ν	?

Neutron-antineutron oscillations

- 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)]

Neutron-antineutron oscillations

- 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]

Neutron-antineutron oscillations

- 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]

Neutron-antineutron oscillations on the lattice

Michael I. Buchoff[*†], **Chris Schroeder, Joseph Wasem**
Physical Sciences Directorate, Lawrence Livermore National Laboratory
Livermore, California 94550, USA
E-mail: buchoff1@llnl.gov

[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]
[a] *RIKEN/BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[b] *Jefferson Laboratory, 12000 Jefferson Ave, Newport News, VA 23606, USA*
[c] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[d] *Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA*
E-mail: ssyritsyn@quark.phy.bnl.gov

[PoS, Lattice 2015, 132]

Neutron-antineutron oscillations on the lattice

Michael I. Buchoff[*†], **Chris Schroeder, Joseph Wasem**
Physical Sciences Directorate, Lawrence Livermore National Laboratory
Livermore, California 94550, USA
E-mail: buchoff1@llnl.gov

[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]
[a] *RIKEN/BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[b] *Jefferson Laboratory, 12000 Jefferson Ave, Newport News, VA 23606, USA*
[c] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[d] *Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA*
E-mail: ssyritsyn@quark.phy.bnl.gov

[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*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[5] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

[arxiv:1809.00246]

Neutron-antineutron oscillations on the lattice

Michael I. Buchoff[*†‡], **Chris Schroeder, Joseph Wasem**
Physical Sciences Directorate, Lawrence Livermore National Laboratory
Livermore, California 94550, USA
E-mail: buchoff1@llnl.gov

[PoS, Lattice 2012, 128]

Lattice QCD determination of neutron-antineutron matrix elements with physical quark masses

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*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[5] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

[c] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[d] *Institute for Nuclear Theory, Box 351550, Seattle, WA 98195-1550, USA*
E-mail: ssyritsyn@quark.phy.bnl.gov

[arxiv:1901.07519]

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*
[2] *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Department of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[5] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*

[arxiv:1809.00246]

NEWS!

Open Access

Access by Kyoto University

Neutron-Antineutron Oscillations from Lattice QCD

Enrico Rinaldi, Sergey Syritsyn, Michael L. Wagman, Michael I. Buchoff, Chris Schroeder, and Joseph Wasem
Phys. Rev. Lett. **122**, 162001 – Published 22 April 2019

Open Access

Access by Kyoto University

Lattice QCD determination of neutron-antineutron matrix elements with physical quark masses

Enrico Rinaldi, Sergey Syritsyn, Michael L. Wagman, Michael I. Buchoff, Chris Schroeder, and Joseph Wasem
Phys. Rev. D **99**, 074510 – Published 22 April 2019

[Phillips et al., 1410.1100]
[Babu et al., 1310.8593]

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

[Phillips et al., 1410.1100]
[Babu et al., 1310.8593]

Synopsis of oscillations

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

Energy difference ΔE

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

Coupling between neutrons and anti-neutrons

[Phillips et al., 1410.1100]
[Babu et al., 1310.8593]

Synopsis of oscillations

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

Energy difference ΔE

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

Coupling between neutrons and anti-neutrons

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

[Phillips et al., 1410.1100]
[Babu et al., 1310.8593]

Synopsis of oscillations

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

Energy difference ΔE

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

Coupling between neutrons and anti-neutrons

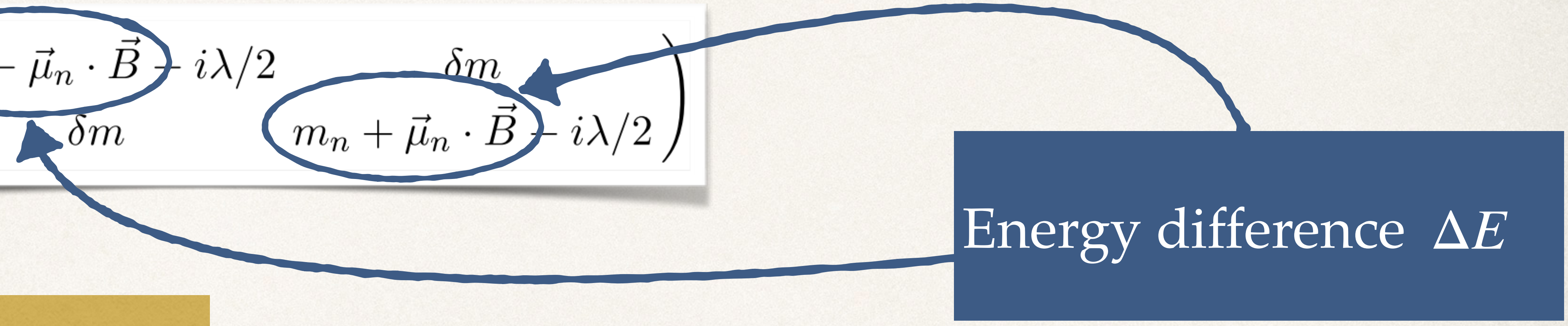
$$P(n(t) = \bar{n}) = \left(\frac{2\delta m}{\Delta E} \right)^2 \sin^2 \left(\frac{\Delta E \cdot t}{2} \right) e^{-\lambda t}$$

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

[Phillips et al., 1410.1100]
[Babu et al., 1310.8593]

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

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

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

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

[Phillips et al., 1410.1100]
[Babu et al., 1310.8593]

Synopsis of oscillations

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

Energy difference ΔE

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

Coupling between neutrons and anti-neutrons

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

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

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

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

New physics

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

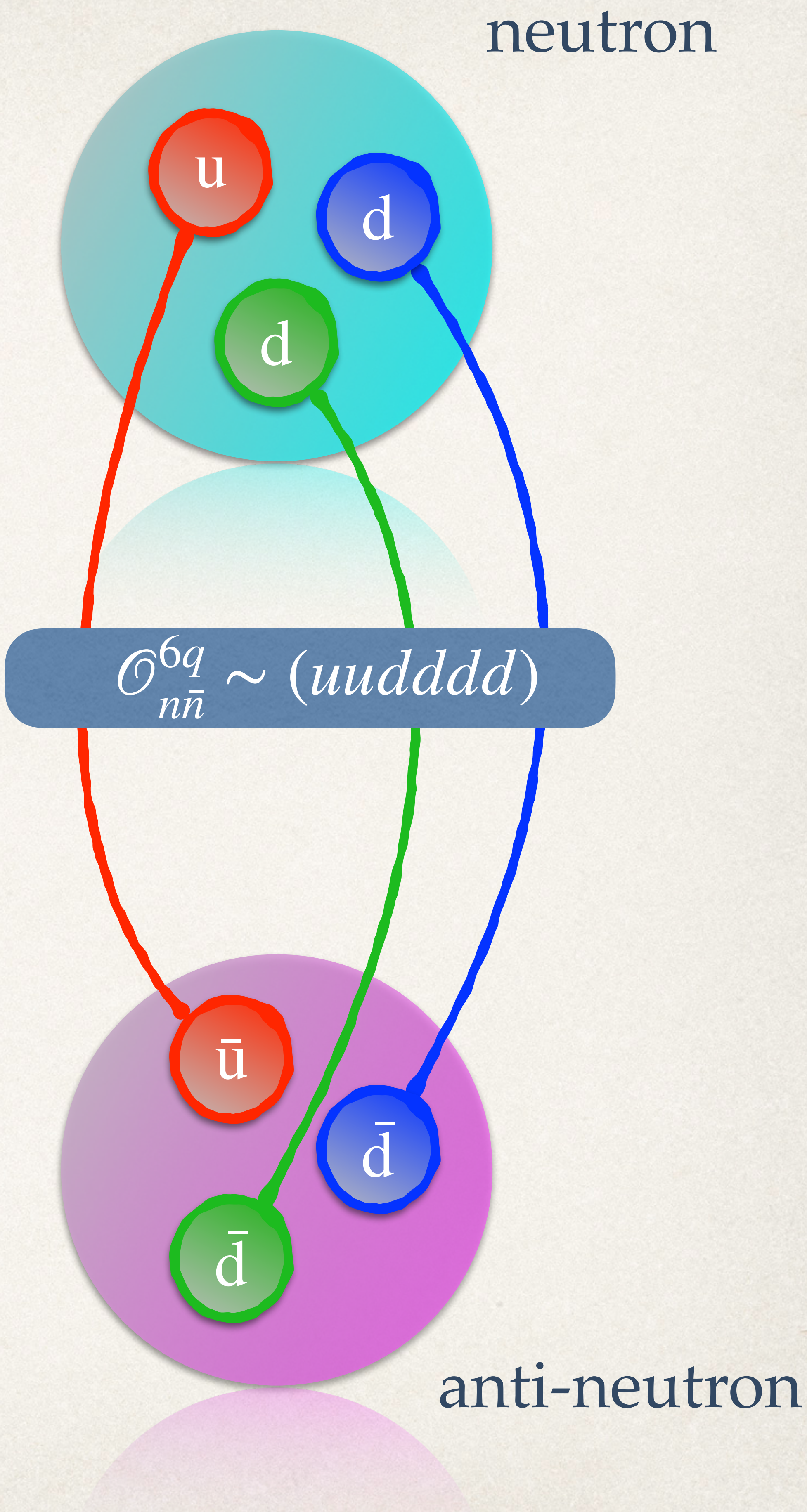
$$\langle n | \mathscr{H}_{\text{eff}} | \bar{n} \rangle = \frac{1}{\Lambda_{\text{BSM}}^5} \sum_i c_i \langle n | \mathscr{O}_i | \bar{n} \rangle$$

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

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

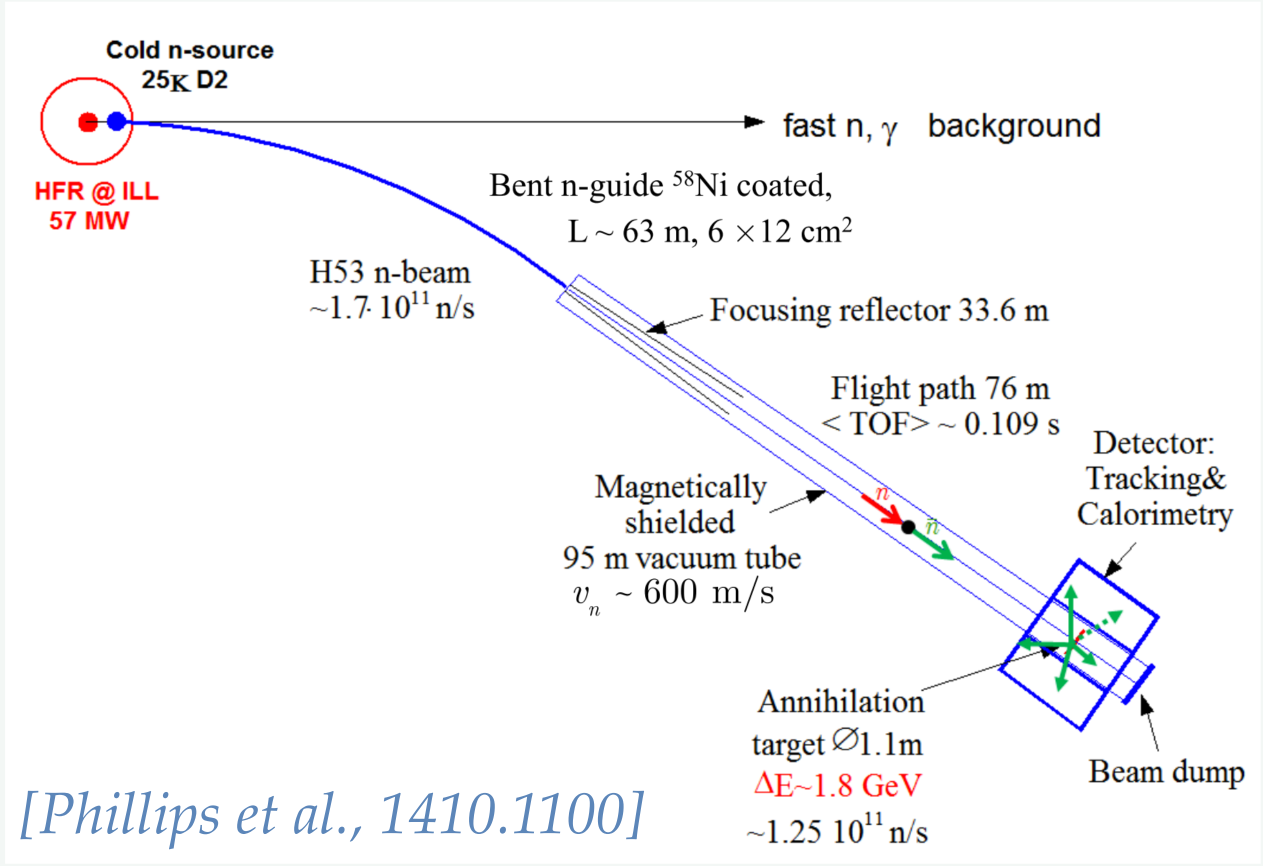
- The mass scale for new physics is obtained roughly as $\Lambda_{\text{BSM}} \sim 100 - 1000$ TeV

[Phillips et al., 1410.1100]



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

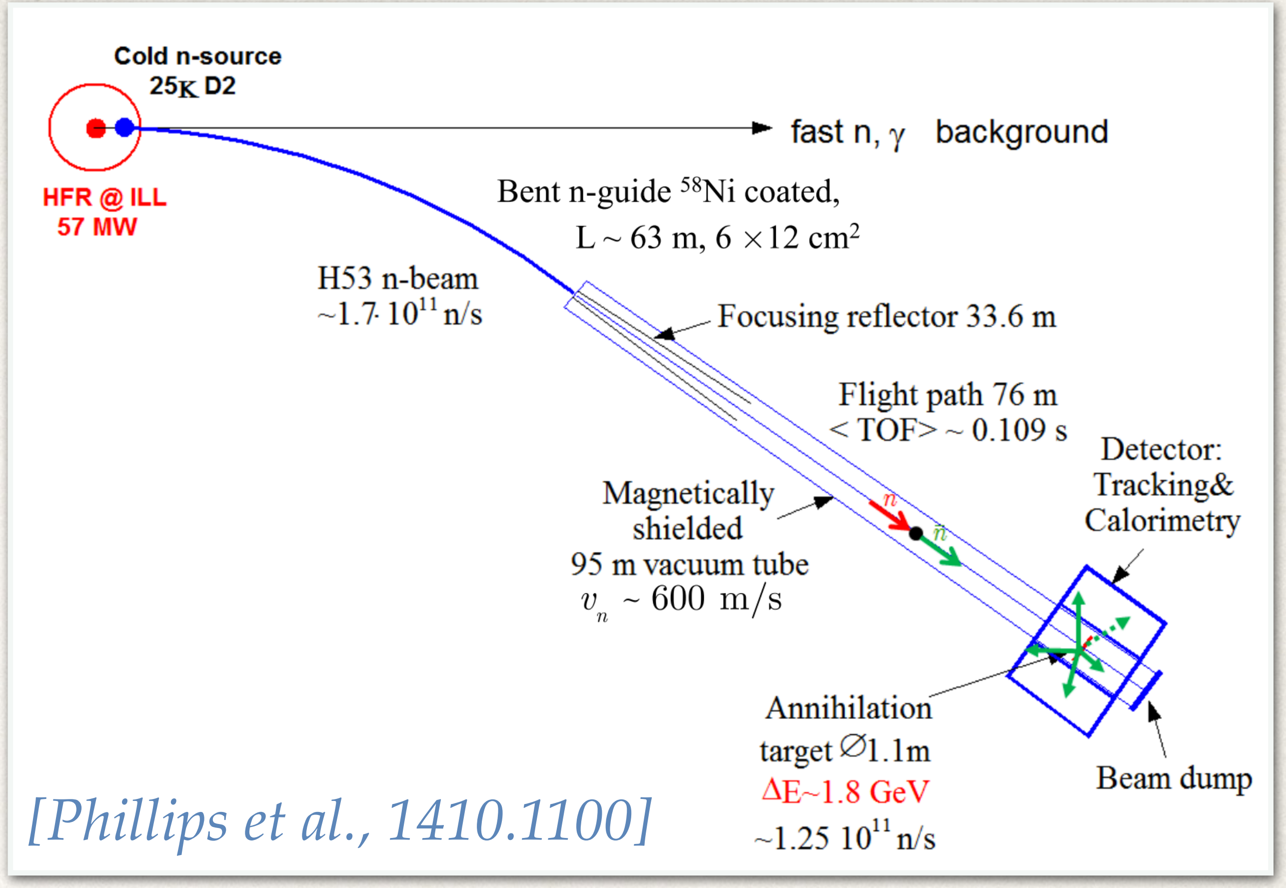


[Phillips et al., 1410.1100]

- **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

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

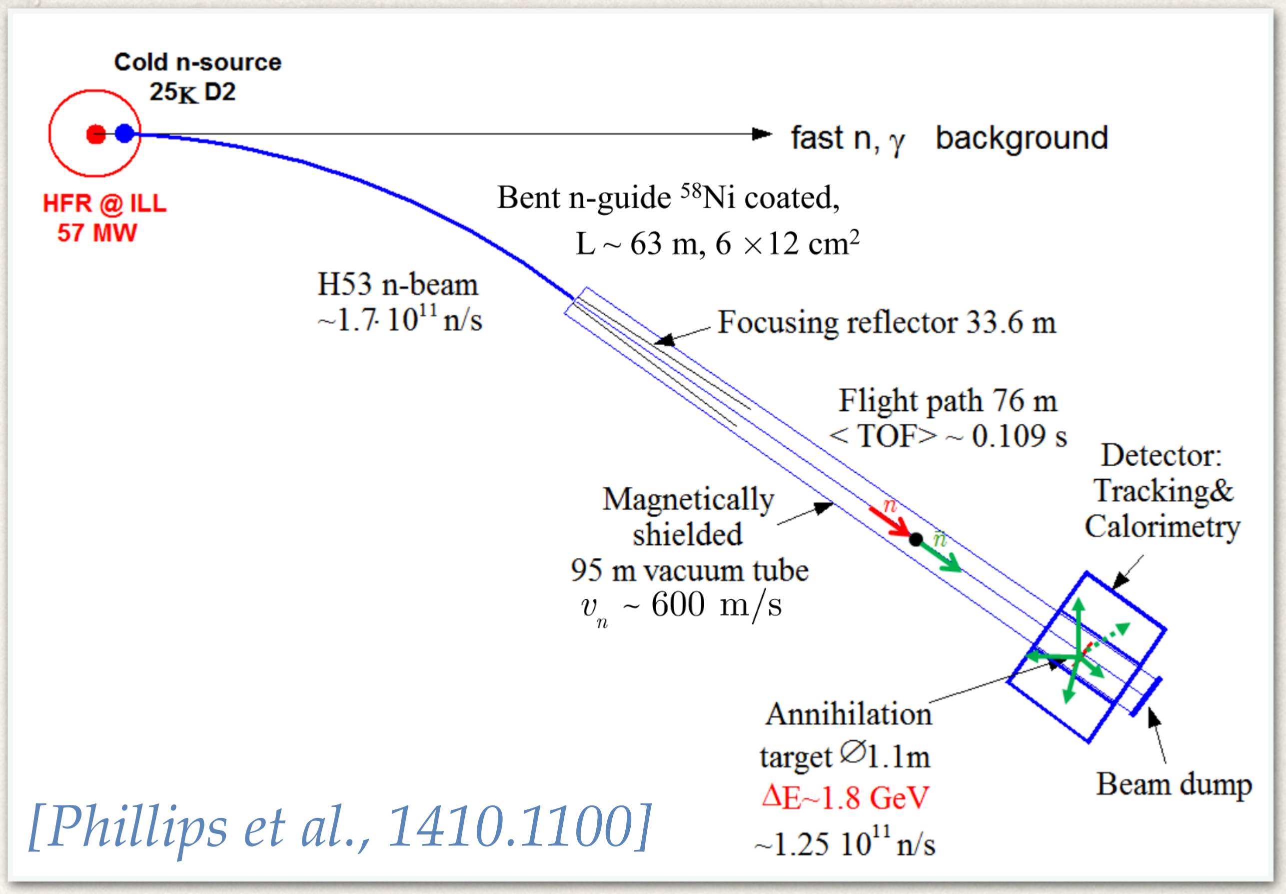


[Phillips et al., 1410.1100]

← almost background free

- **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

Experimental searches



[Phillips et al., 1410.1100]

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

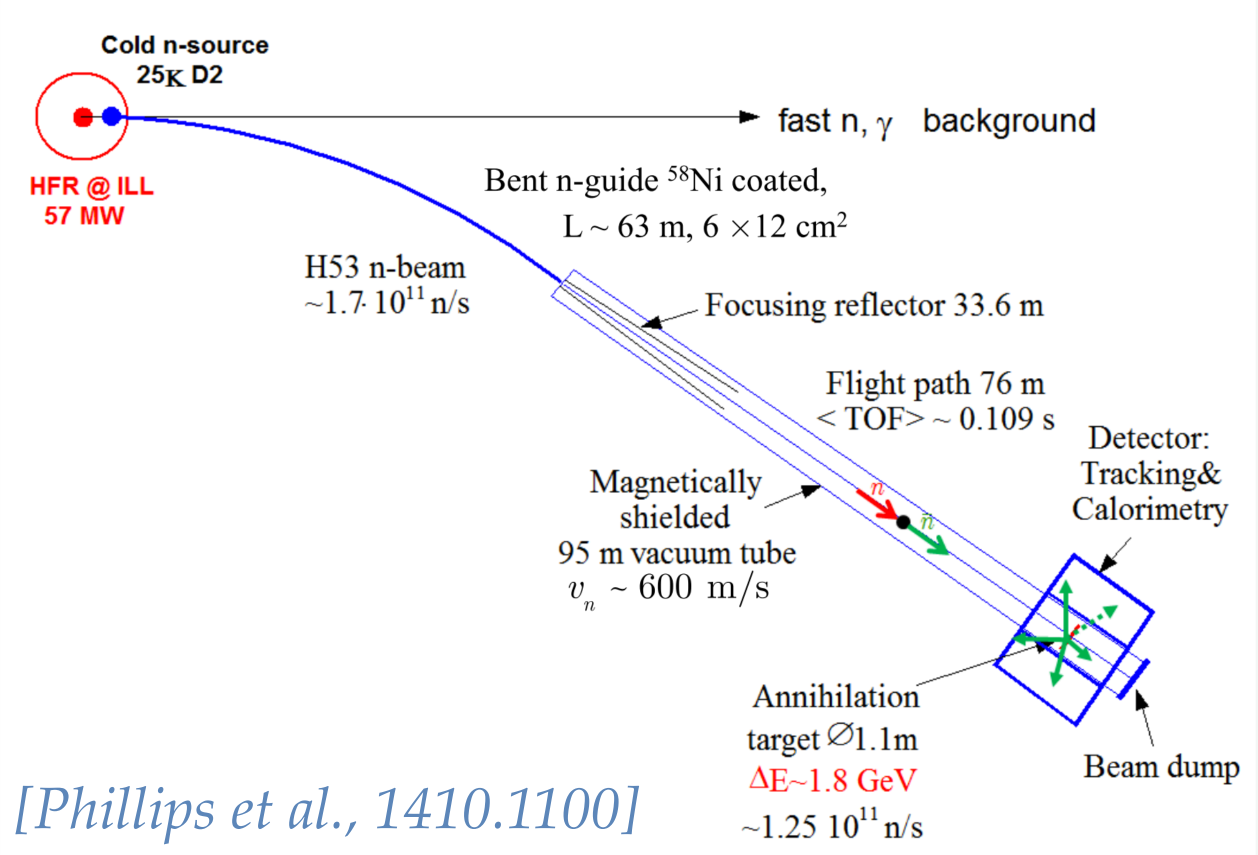
← almost background free

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

- **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

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



[Phillips et al., 1410.1100]

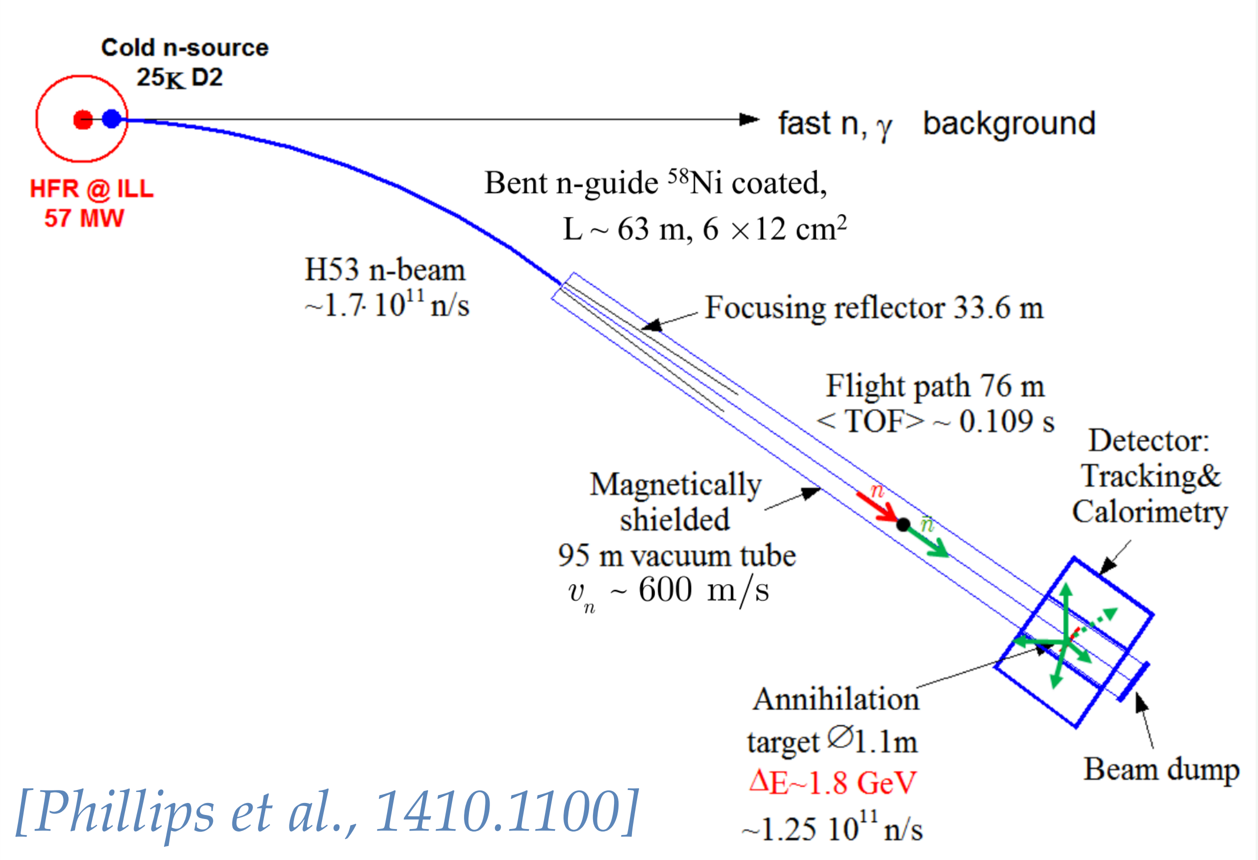
almost background free

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

- **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

Nuclear suppression factor due to different nuclear potential

Experimental searches



[Phillips et al., 1410.1100]

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

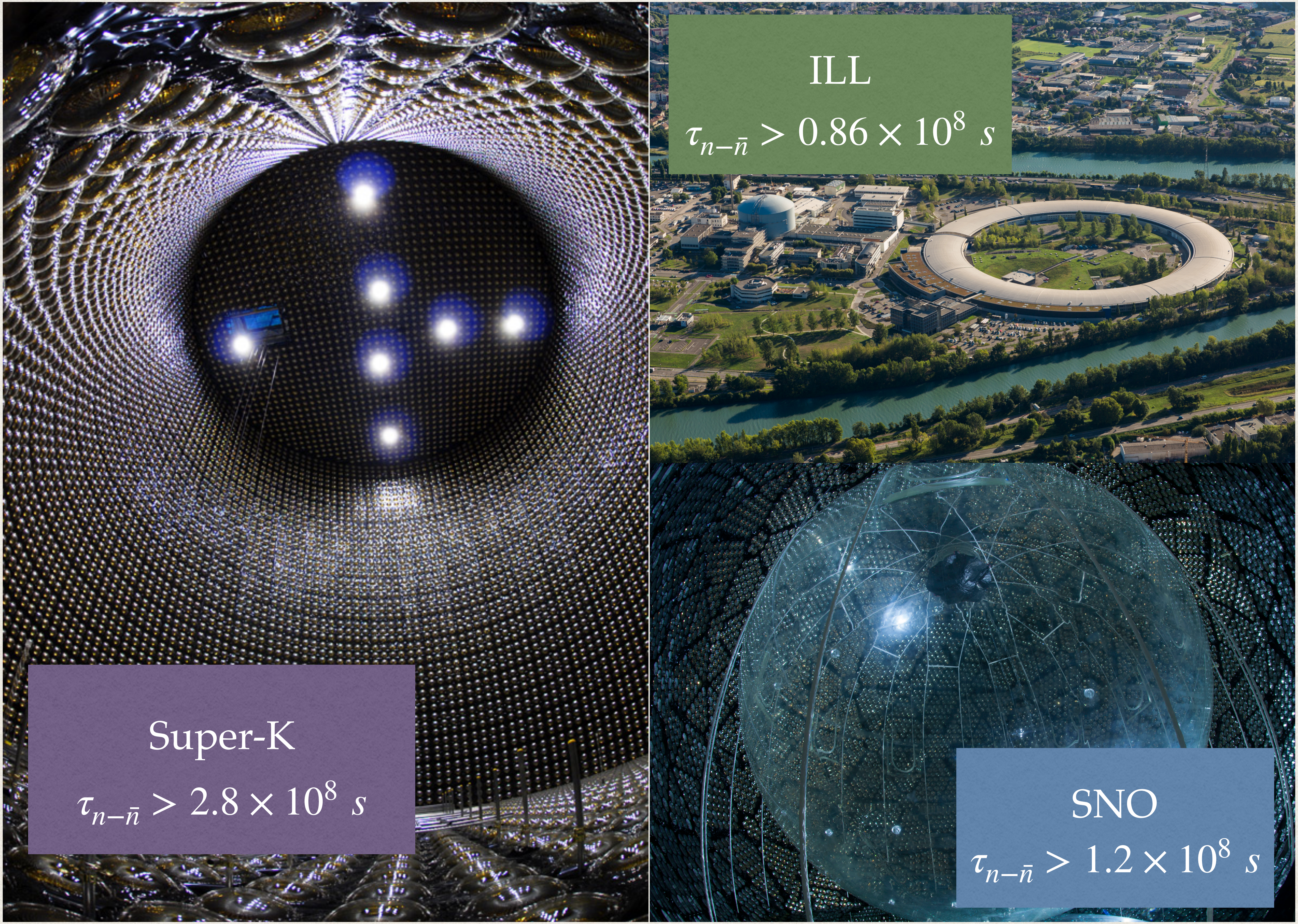
almost background free

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

- **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

Nuclear suppression factor due to different nuclear potential

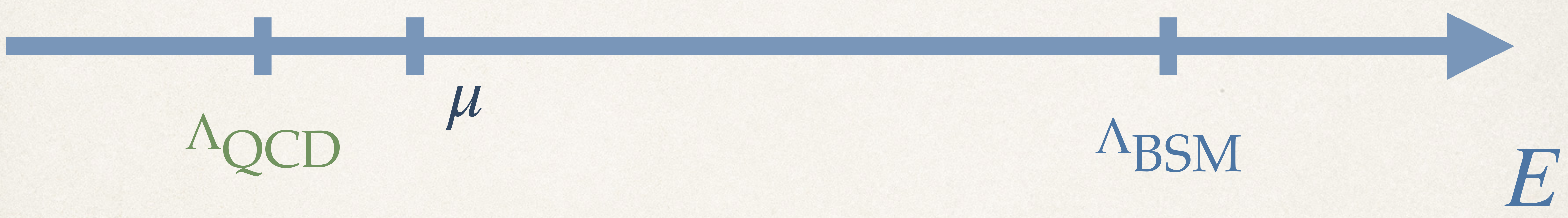
can be improved with particle tracking


ILL
$\tau_{n-\bar{n}} > 0.86 \times 10^8 \ s$
Super-K
$\tau_{n-\bar{n}} > 2.8 \times 10^8 \ s$
SNO
$\tau_{n-\bar{n}} > 1.2 \times 10^8 \ s$

Aside: nuclear models

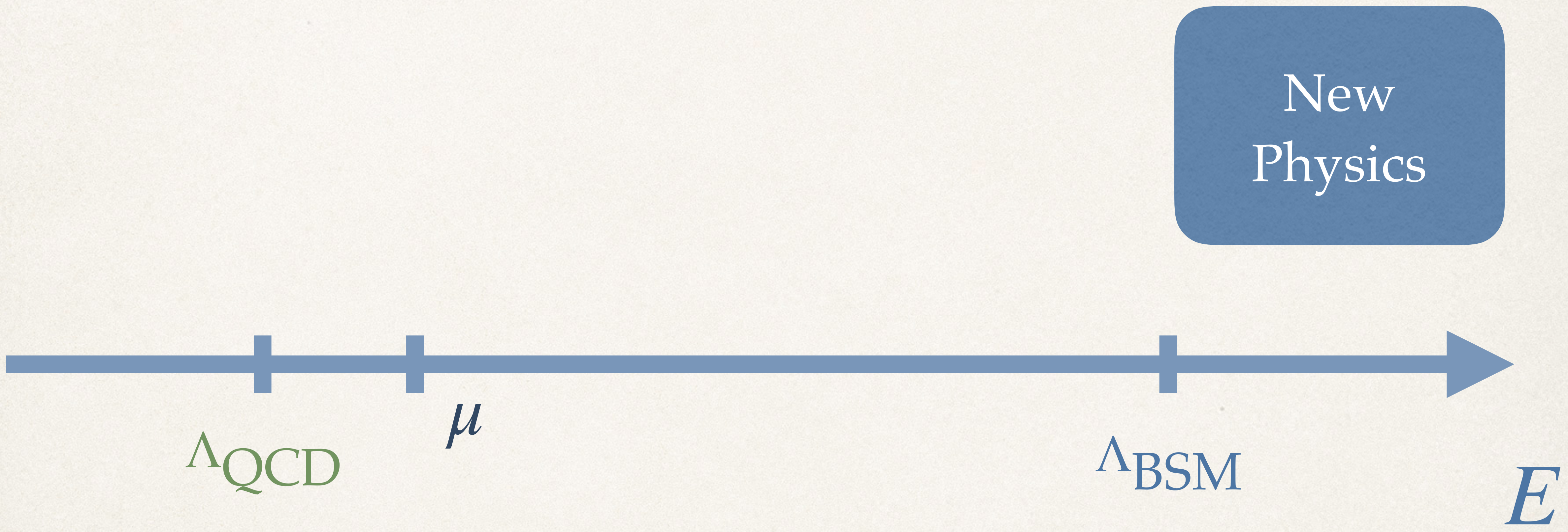
- The most stringent bounds arise from experiments where the neutrons are affected by the nuclear potential
- Important to understand the medium effects $\tau_A \propto (\delta m)^{-2} \;\rightarrow\; R_A \tau_{n-\bar{n}}^2$
- E.g. deuteron (SNO experiment): $\tau_A = 1.18 - 1.48 \times 10^{31}$ yr
  - Model 1: $1.23 - 1.37 \times 10^8\ s$ *[C. B. Dover et al. Phys. Rev. D 27, 1090 (1983)]*
  - Model 2: $1.2 - 1.4 \times 10^8\ s$ *[E. Friedman and A. Gal, Phys. Rev. D 78, 016002 (2008)]*
  - EFT: $1.6 \times 10^8\ s$ *[F. Oosterhof et al. (2019), arXiv:1902.05342]*

Effective field theory



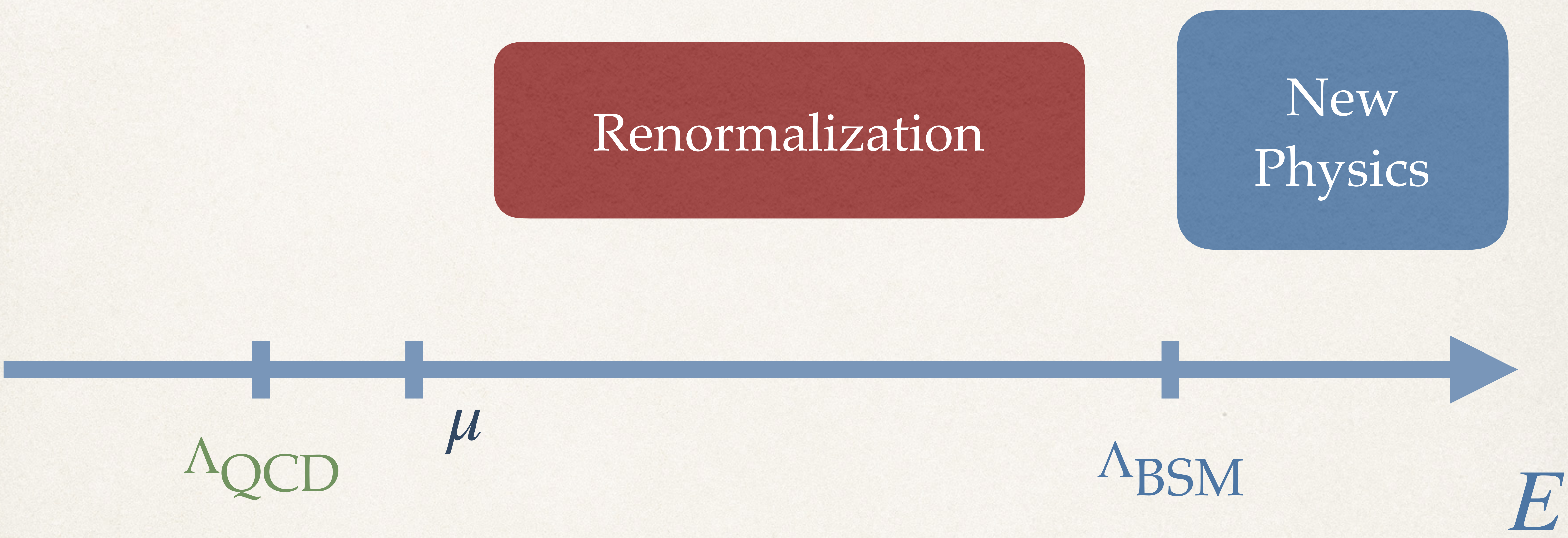
Vast separation of scale between hadronic physics and new physics

Effective field theory



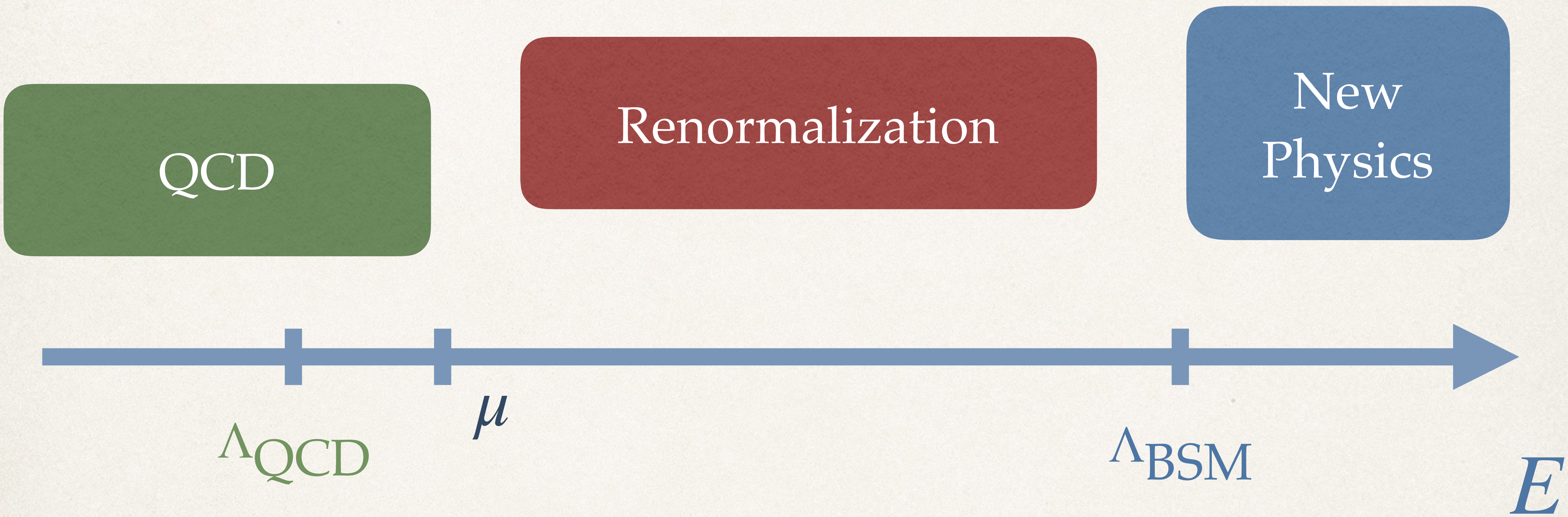
Vast separation of scale between hadronic physics and new physics

Effective field theory



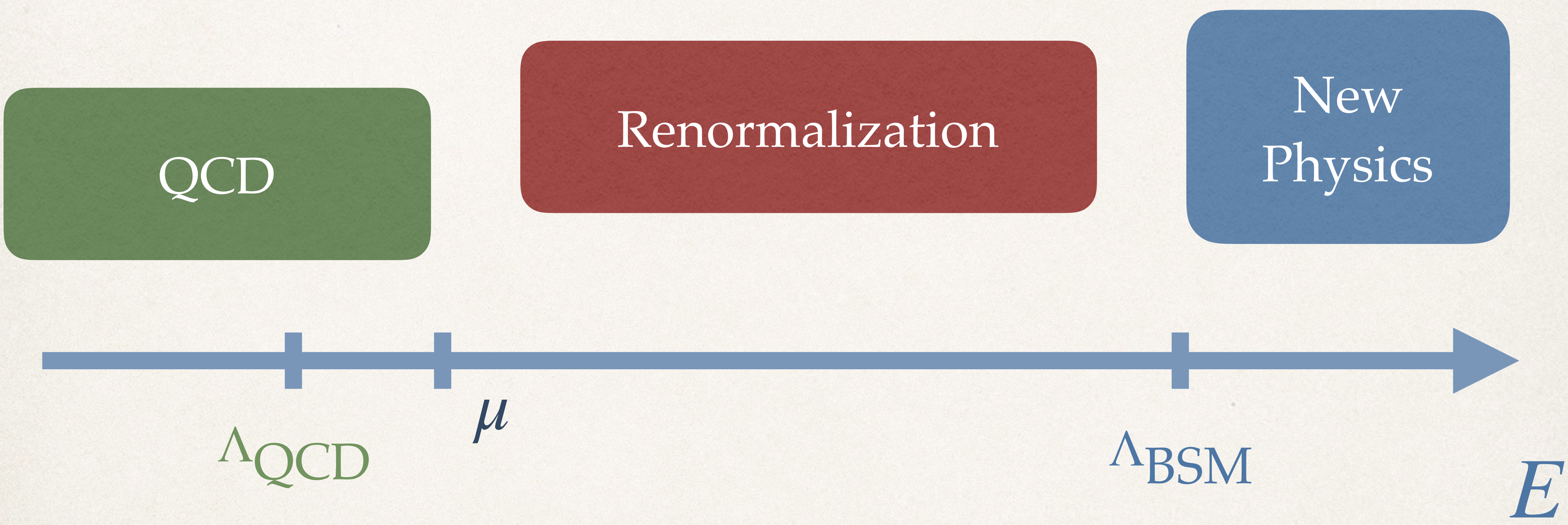
Vast separation of scale between hadronic physics and new physics

Effective field theory



Vast separation of scale between hadronic physics and new physics

Effective field theory



$$\mathscr{L}_{n\bar{n}} = \sum_{I=1}^{N} C_I(\mu) Q_I(\mu)$$

Vast separation of scale between hadronic physics and new physics

[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]

Operators

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)
$-\frac{3}{4}Q_1$	$[(RRR)_{\mathbf{1}}]$	$3\mathcal{O}^3_{\{RR\}R}$	$12\mathcal{O}_1$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-2)$
$-\frac{3}{4}Q_2$	$[(RR)_{\mathbf{1}}L_{\mathbf{0}}]$	$3\mathcal{O}^3_{\{LR\}R}$	$6\mathcal{O}_2$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(+2)$
$-\frac{3}{4}Q_3$	$[R_{\mathbf{1}}(LL)_{\mathbf{0}}]$	$3\mathcal{O}^3_{\{LL\}R}$	$12\mathcal{O}_3$	$(1,-1)_R \otimes (0,0)_L$	0
$-\frac{5}{4}Q_4$	$[(RRR)_{\mathbf{3}}]$	$\mathcal{O}^1_{R\{RR\}} + 4\mathcal{O}^2_{\{RR\}R}$	—	$(3,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-12)$
$-Q_5^{\mathcal{P}}$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(1)}$	$\mathcal{O}^1_{L\{RR\}}$	$-4\mathcal{O}_4^{\mathcal{P}}$	$(2,-2)_R \otimes (1,1)_L$	$(\alpha_S/4\pi)(-6)$
$\frac{1}{4}Q_6^{\mathcal{P}}$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(2)}$	$\mathcal{O}^2_{\{LR\}R}$	$-2\mathcal{O}_5^{\mathcal{P}}$	$(2,-1)_R \otimes (1,0)_L$	$(\alpha_S/4\pi)(-6)$
$\frac{3}{4}Q_7^{\mathcal{P}}$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(3)}$	$\mathcal{O}^1_{R\{RL\}} + 2\mathcal{O}^2_{\{RR\}L}$	$-4\mathcal{O}_6^{\mathcal{P}}$	$(2,0)_R \otimes (1,-1)_L$	$(\alpha_S/4\pi)(-6)$

Chiral basis: 14 operators. 7 ind. due to P-symmetry

[Syritsyn et al., 1901.07519]

[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]

Operators

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)
$-\frac{3}{4}Q_1$	$[(RRR)_{\mathbf{1}}]$	$3\mathcal{O}^3_{\{RR\}R}$	$12\mathcal{O}_1$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-2)$
$-\frac{3}{4}Q_2$	$[(RR)_{\mathbf{1}}L_{\mathbf{0}}]$	$3\mathcal{O}^3_{\{LR\}R}$	$6\mathcal{O}_2$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(+2)$
$-\frac{3}{4}Q_3$	$[R_{\mathbf{1}}(LL)_{\mathbf{0}}]$	$3\mathcal{O}^3_{\{LL\}R}$	$12\mathcal{O}_3$	$(1,-1)_R \otimes (0,0)_L$	0
$-\frac{5}{4}Q_4$	$[(RRR)_{\mathbf{3}}]$	$\mathcal{O}^1_{R\{RR\}} + 4\mathcal{O}^2_{\{RR\}R}$	—	$(3,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-12)$
$-Q^{\mathcal{P}}_5$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(1)}$	$\mathcal{O}^1_{L\{RR\}}$	$-4\mathcal{O}^{\mathcal{P}}_4$	$(2,-2)_R \otimes (1,1)_L$	$(\alpha_S/4\pi)(-6)$
$\frac{1}{4}Q^{\mathcal{P}}_6$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(2)}$	$\mathcal{O}^2_{\{LR\}R}$	$-2\mathcal{O}^{\mathcal{P}}_5$	$(2,-1)_R \otimes (1,0)_L$	$(\alpha_S/4\pi)(-6)$
$\frac{3}{4}Q^{\mathcal{P}}_7$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(3)}$	$\mathcal{O}^1_{R\{RL\}} + 2\mathcal{O}^2_{\{RR\}L}$	$-4\mathcal{O}^{\mathcal{P}}_6$	$(2,0)_R \otimes (1,-1)_L$	$(\alpha_S/4\pi)(-6)$

Chiral basis: 14 operators. 7 ind. due to P-symmetry

[Syritsyn et al., 1901.07519]

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]

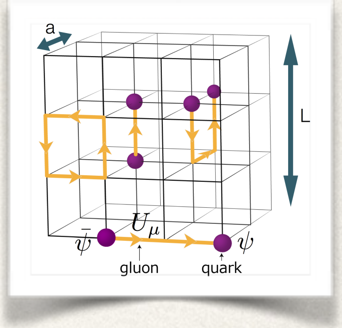
Color-singlet, Electrically-neutral, |ΔB|=2

Q_I	Ref. [7]	Ref. [3]	Ref. [8]	$(I, I_z)_R \otimes (I, I_z)_L$	$\gamma^{\mathcal{O}}$ (1-loop)
$-\frac{3}{4}Q_1$	$[(RRR)_{\mathbf{1}}]$	$3\mathcal{O}^3_{\{RR\}R}$	$12\mathcal{O}_1$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-2)$
$-\frac{3}{4}Q_2$	$[(RR)_{\mathbf{1}}L_{\mathbf{0}}]$	$3\mathcal{O}^3_{\{LR\}R}$	$6\mathcal{O}_2$	$(1,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(+2)$
$-\frac{3}{4}Q_3$	$[R_{\mathbf{1}}(LL)_{\mathbf{0}}]$	$3\mathcal{O}^3_{\{LL\}R}$	$12\mathcal{O}_3$	$(1,-1)_R \otimes (0,0)_L$	0
$-\frac{5}{4}Q_4$	$[(RRR)_{\mathbf{3}}]$	$\mathcal{O}^1_{R\{RR\}} + 4\mathcal{O}^2_{\{RR\}R}$	—	$(3,-1)_R \otimes (0,0)_L$	$(\alpha_S/4\pi)(-12)$
$-Q_5^{\mathcal{P}}$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(1)}$	$\mathcal{O}^1_{L\{RR\}}$	$-4\mathcal{O}_4^{\mathcal{P}}$	$(2,-2)_R \otimes (1,1)_L$	$(\alpha_S/4\pi)(-6)$
$\frac{1}{4}Q_6^{\mathcal{P}}$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(2)}$	$\mathcal{O}^2_{\{LR\}R}$	$-2\mathcal{O}_5^{\mathcal{P}}$	$(2,-1)_R \otimes (1,0)_L$	$(\alpha_S/4\pi)(-6)$
$\frac{3}{4}Q_7^{\mathcal{P}}$	$[(RR)_{\mathbf{2}}L_{\mathbf{1}}]_{(3)}$	$\mathcal{O}^1_{R\{RL\}} + 2\mathcal{O}^2_{\{RR\}L}$	$-4\mathcal{O}_6^{\mathcal{P}}$	$(2,0)_R \otimes (1,-1)_L$	$(\alpha_S/4\pi)(-6)$

Chiral basis: 14 operators. 7 ind. due to P-symmetry

[Syritsyn et al., 1901.07519]

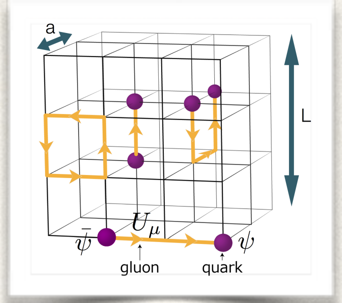
[KEK-Japan]



Lattice details

[RBC/UKQCD, 1411.7017]

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



[KEK-Japan]

Lattice details

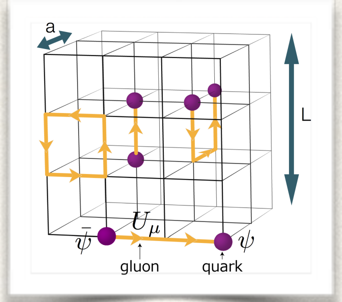
[RBC/UKQCD, 1411.7017]

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

chiral

Lattice details

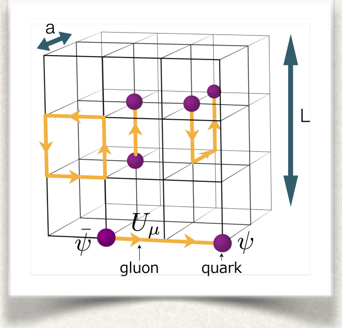
[KEK-Japan]



[RBC/UKQCD, 1411.7017]

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

[KEK-Japan]

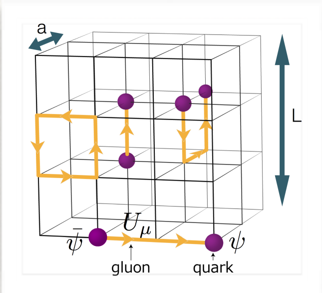


Lattice details

[RBC/UKQCD, 1411.7017]

- Configurations and propagators from RBC/UKQCD
  - Möbius 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.

[KEK-Japan]



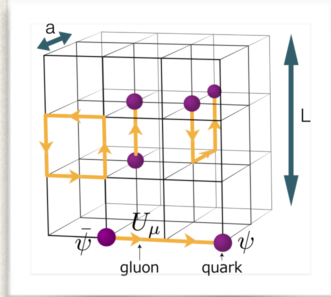
Lattice details

[RBC/UKQCD, 1411.7017]

- Configurations and propagators from RBC/UKQCD
  - Möbius 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]



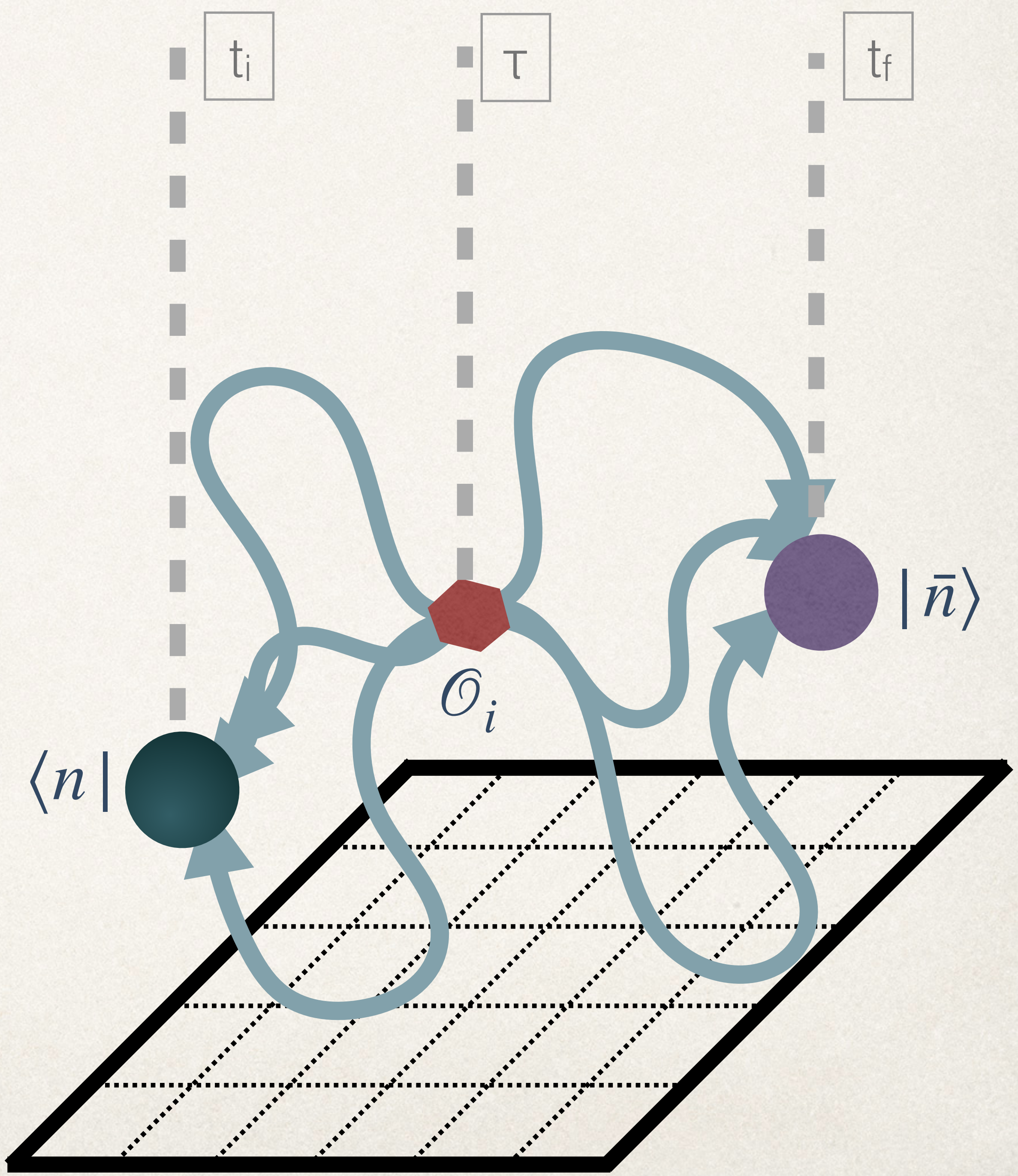
[RBC/UKQCD, 1411.7017]

- Configurations and propagators from RBC/UKQCD
  - Möbius 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. — small systematic err.

[Syritsyn et al., 1809.00246]
[Syritsyn et al., 1901.07519]

Methodology

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



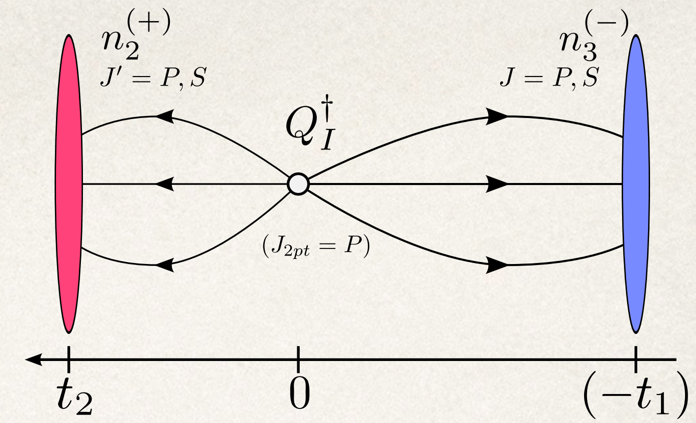
- Calculate 3-point function of operator inserted at time τ
- Only 1 propagator (point-to-all) needed: fix source at $\tau = 0$
- All time separations accessible

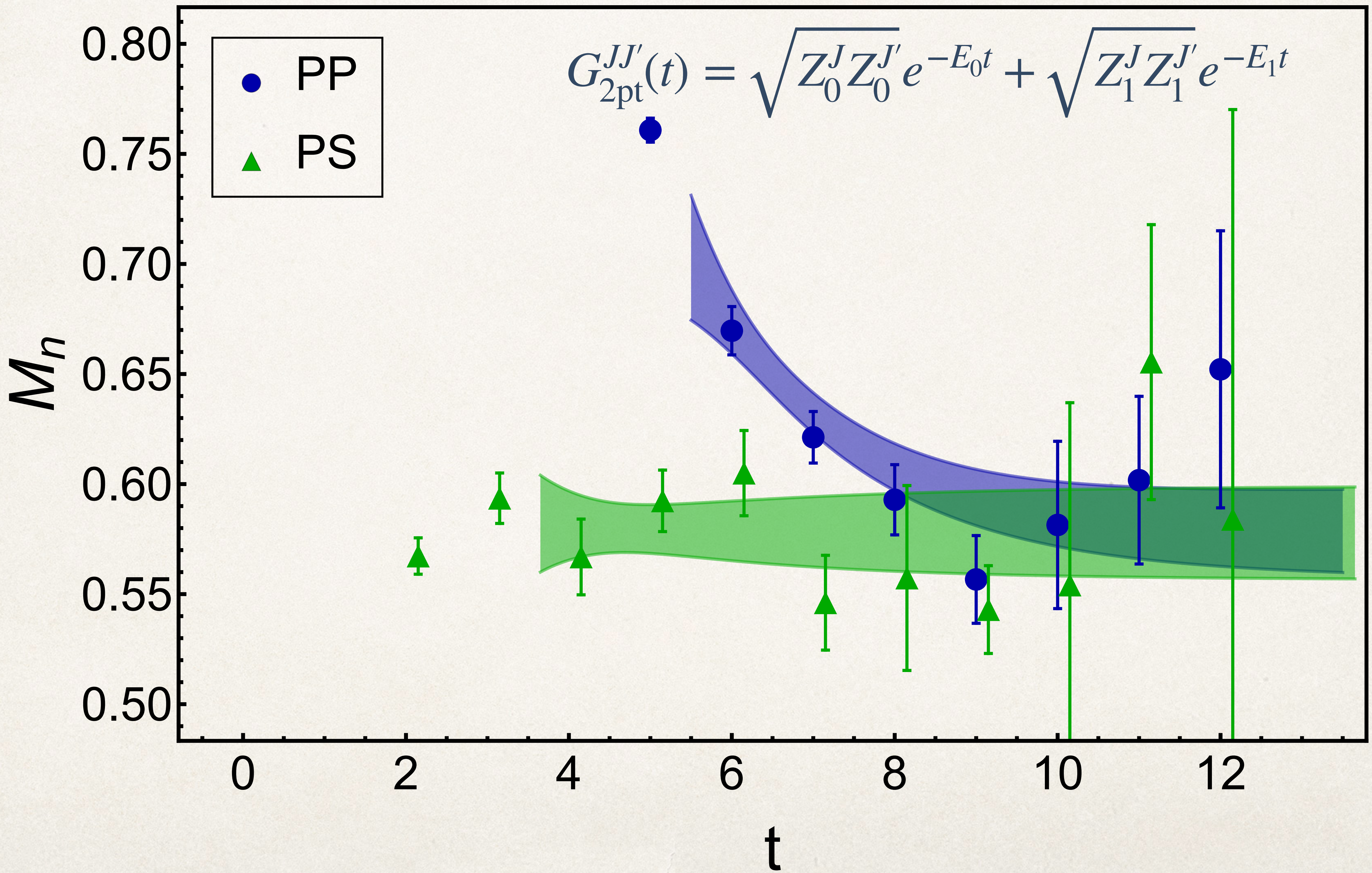
  $t_f - \tau$ $\tau - t_i$

- Only point insertions, but point and gaussian smeared nucleons

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

Nucleon mass

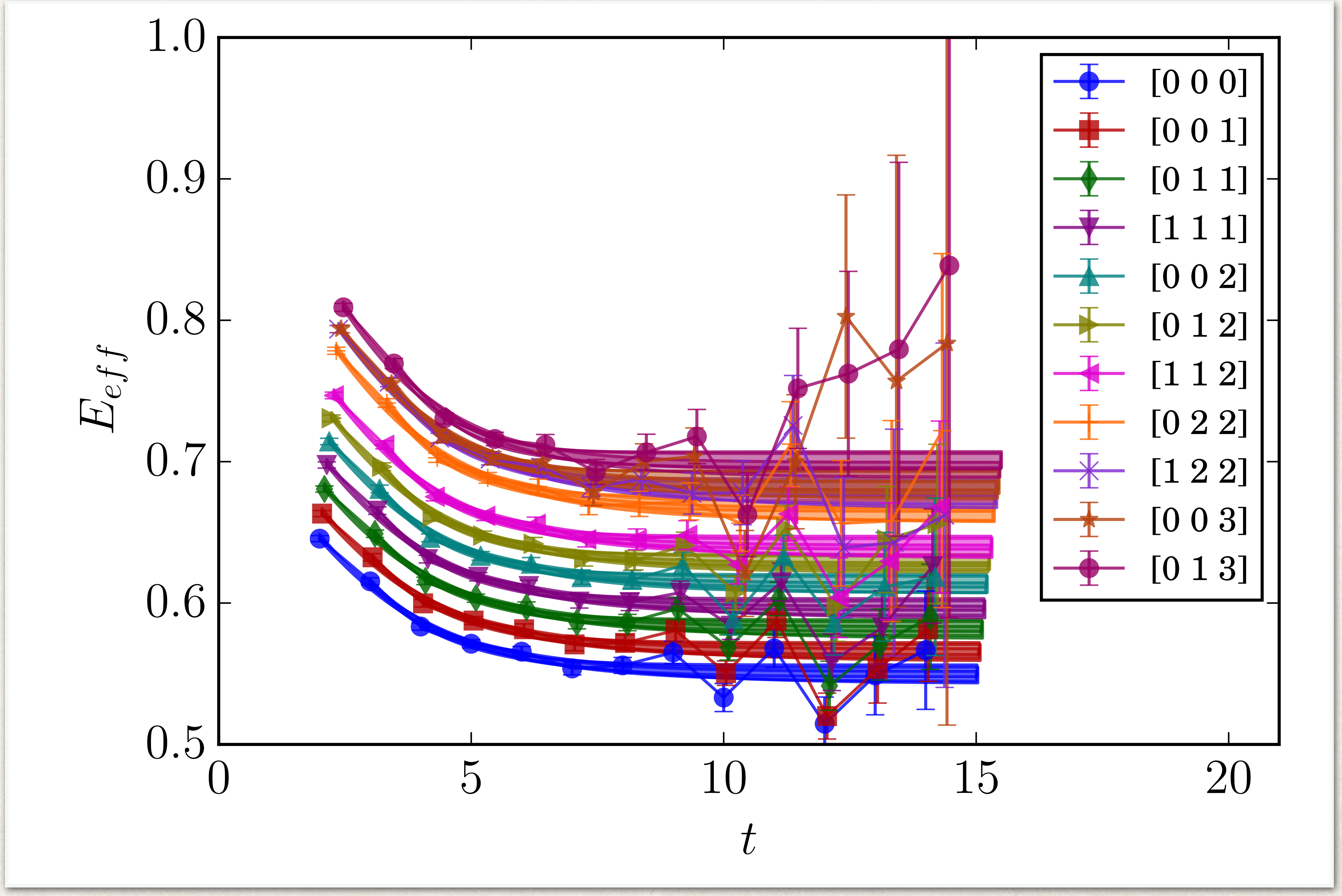




[Syritsyn, Izubuchi, Ohki, 1901.05455]

Nucleon mass

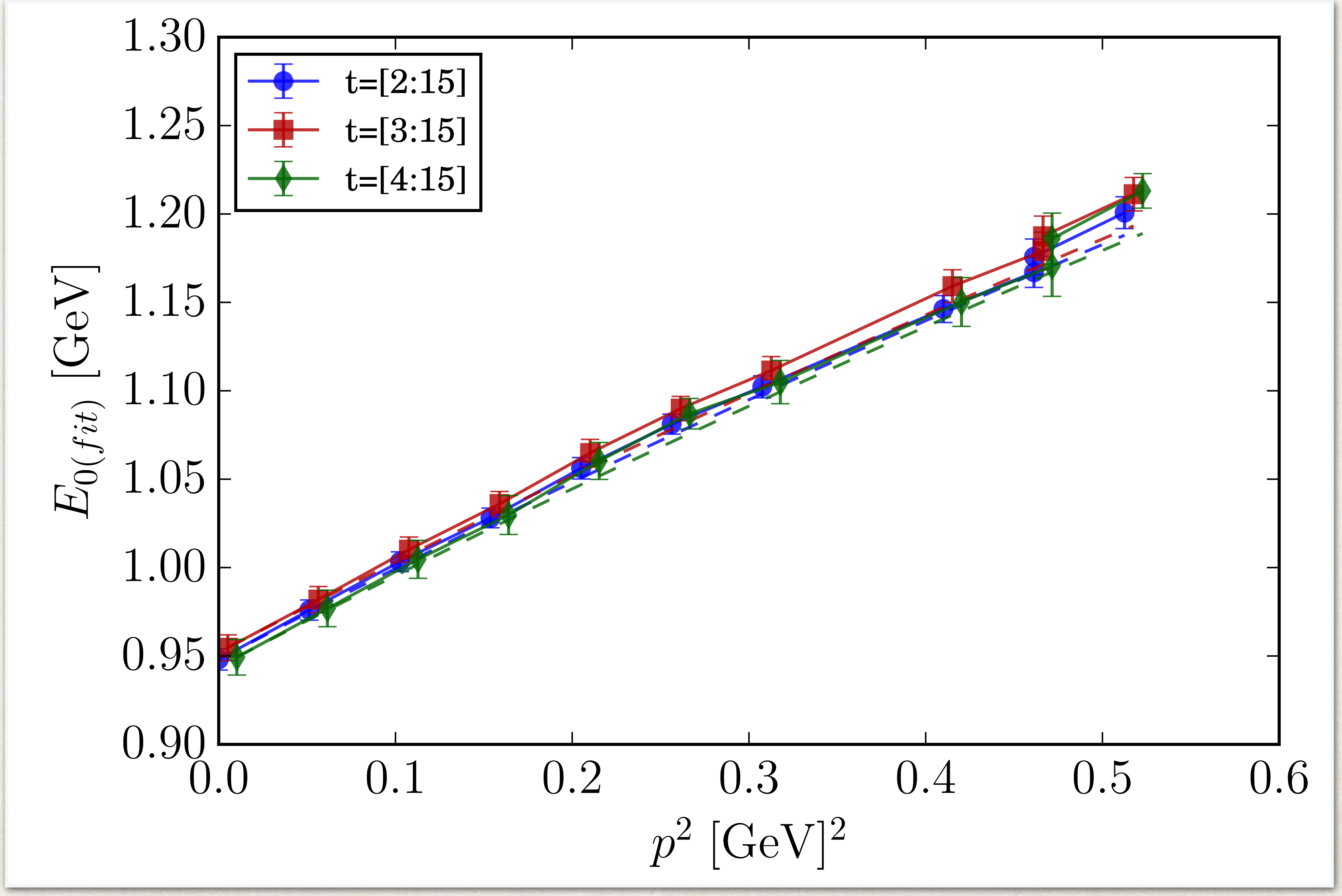
High statistics: 33280 samples



[Syritsyn, Izubuchi, Ohki, 1901.05455]

Nucleon mass

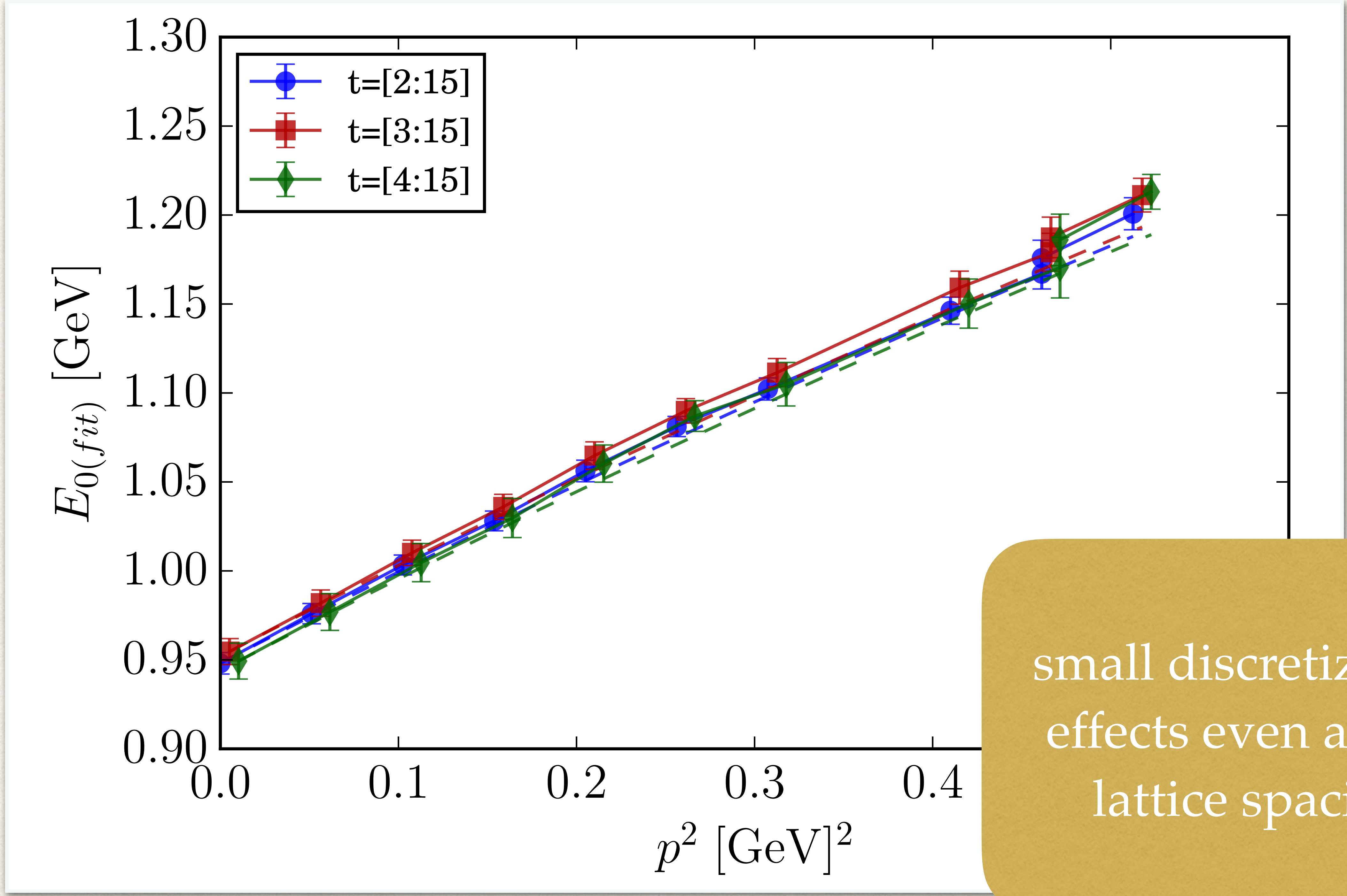
High statistics: 33280 samples



[Syritsyn, Izubuchi, Ohki, 1901.05455]

Nucleon mass

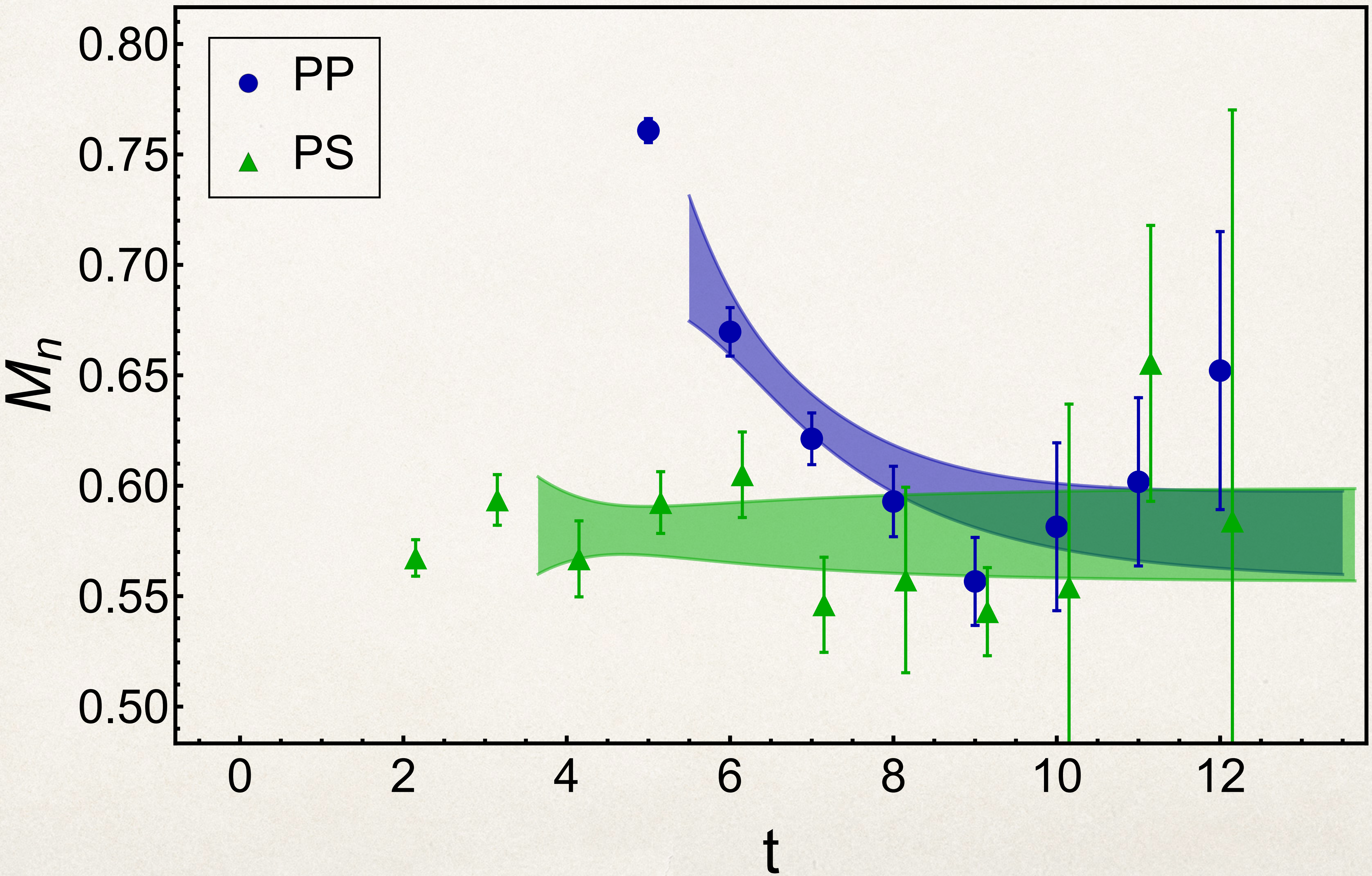
High statistics: 33280 samples



small discretization effects even at this lattice spacing

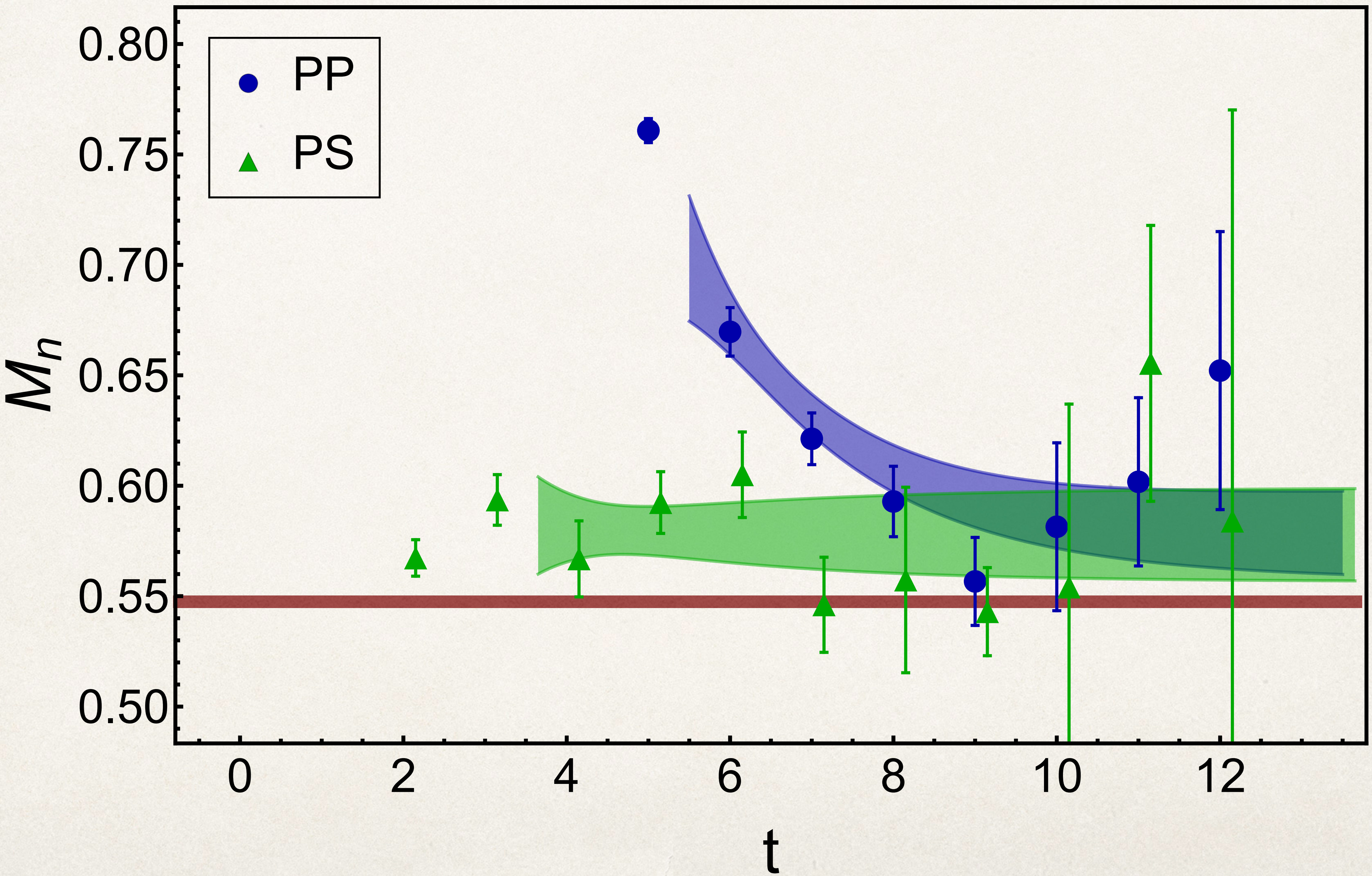
Nucleon mass

t_{PP}^{min}	t_{PS}^{min}	t^{max}	$N_{\rm dof}$	E_0	E_1	$\chi^2/N_{\rm dof}$	λ^*
6	4	13	12	0.578(23)	1.23(27)	0.50	0.14
6	6	13	10	0.556(22)	1.11(15)	0.42	0.15
6	5	13	11	0.560(24)	1.13(21)	0.40	0.14
5	5	13	12	0.566(20)	1.26(9)	0.40	0.13
7	5	13	13	0.554(69)	0.98(43)	0.42	0.15
Weighted Ave				0.565(24)(8)	1.21(15)(65)		



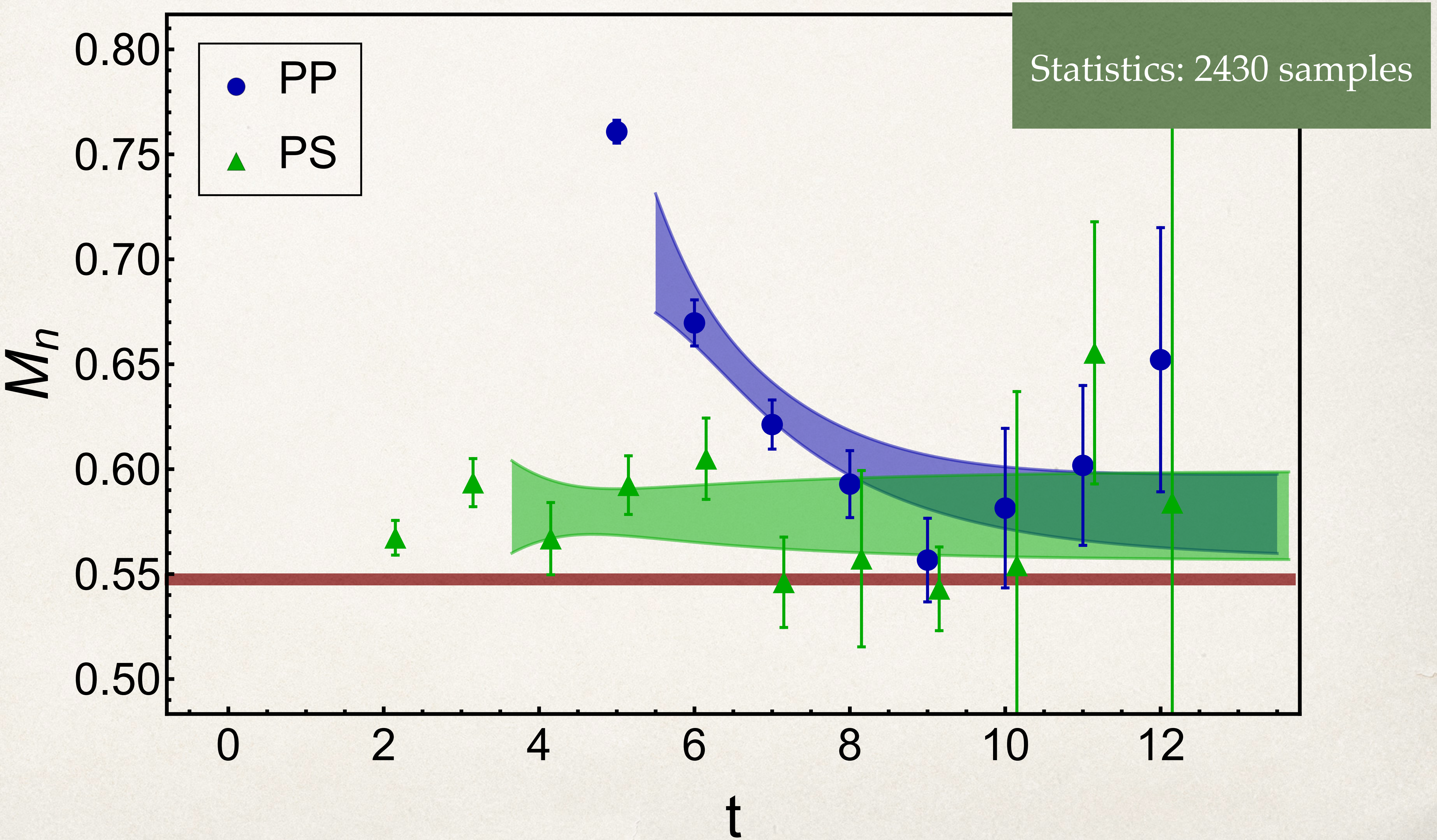
Nucleon mass

t_{PP}^{min}	t_{PS}^{min}	t^{max}	$N_{\rm dof}$	E_0	E_1	$\chi^2/N_{\rm dof}$	λ^*
6	4	13	12	0.578(23)	1.23(27)	0.50	0.14
6	6	13	10	0.556(22)	1.11(15)	0.42	0.15
6	5	13	11	0.560(24)	1.13(21)	0.40	0.14
5	5	13	12	0.566(20)	1.26(9)	0.40	0.13
7	5	13	13	0.554(69)	0.98(43)	0.42	0.15
Weighted Ave				0.565(24)(8)	1.21(15)(65)		



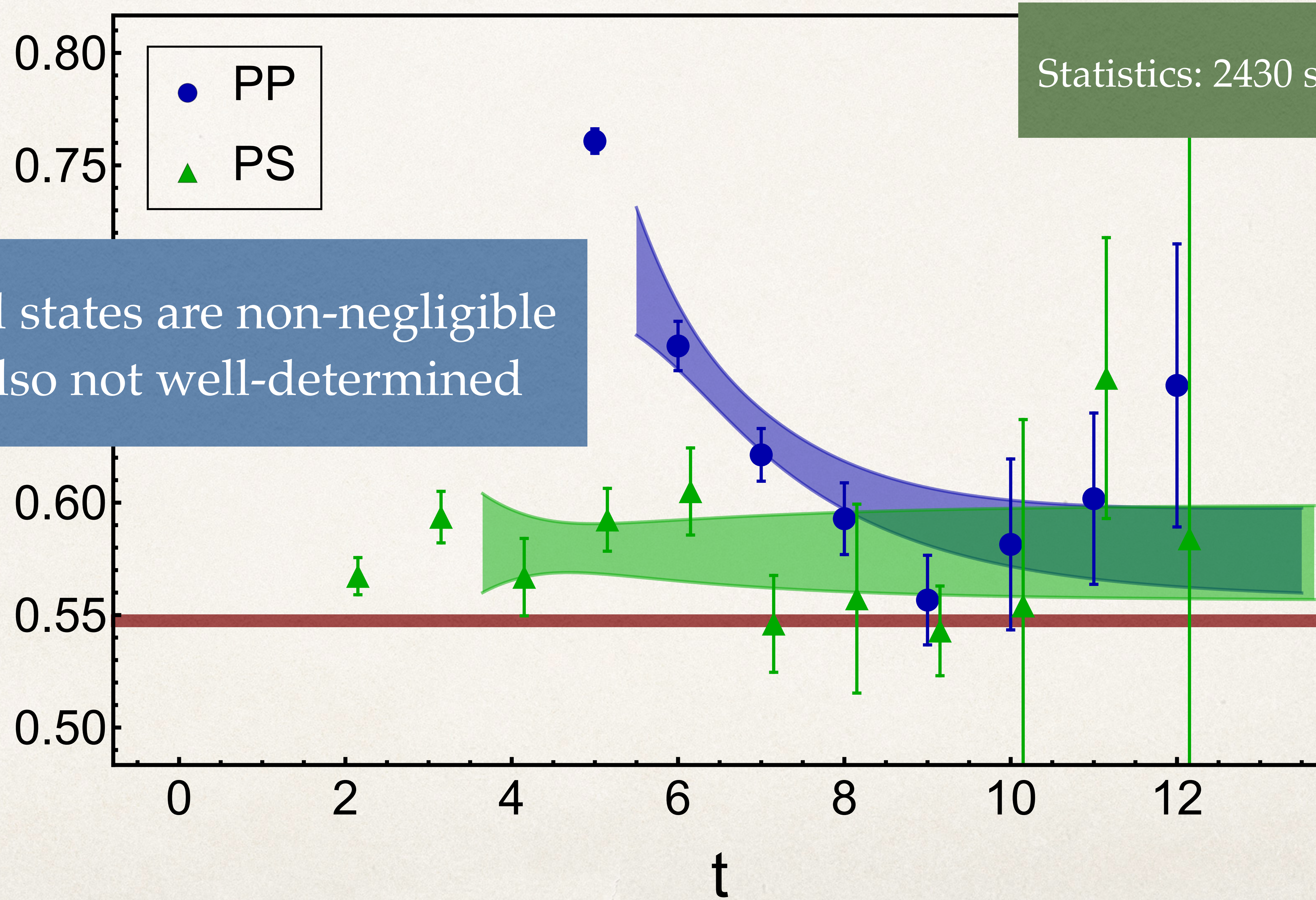
Nucleon mass

t_{PP}^{min}	t_{PS}^{min}	t^{max}	$N_{\rm dof}$	E_0	E_1	$\chi^2/N_{\rm dof}$	λ^*
6	4	13	12	0.578(23)	1.23(27)	0.50	0.14
6	6	13	10	0.556(22)	1.11(15)	0.42	0.15
6	5	13	11	0.560(24)	1.13(21)	0.40	0.14
5	5	13	12	0.566(20)	1.26(9)	0.40	0.13
7	5	13	13	0.554(69)	0.98(43)	0.42	0.15
Weighted Ave				0.565(24)(8)	1.21(15)(65)		



Nucleon mass

t_{PP}^{min}	t_{PS}^{min}	t^{max}	N_{dof}	E_0	E_1	χ^2/N_{dof}	λ^*
6	4	13	12	0.578(23)	1.23(27)	0.50	0.14
6	6	13	10	0.556(22)	1.11(15)	0.42	0.15
6	5	13	11	0.560(24)	1.13(21)	0.40	0.14
5	5	13	12	0.566(20)	1.26(9)	0.40	0.13
7	5	13	13	0.554(69)	0.98(43)	0.42	0.15
Weighted Ave				0.565(24)(8)	1.21(15)(65)		



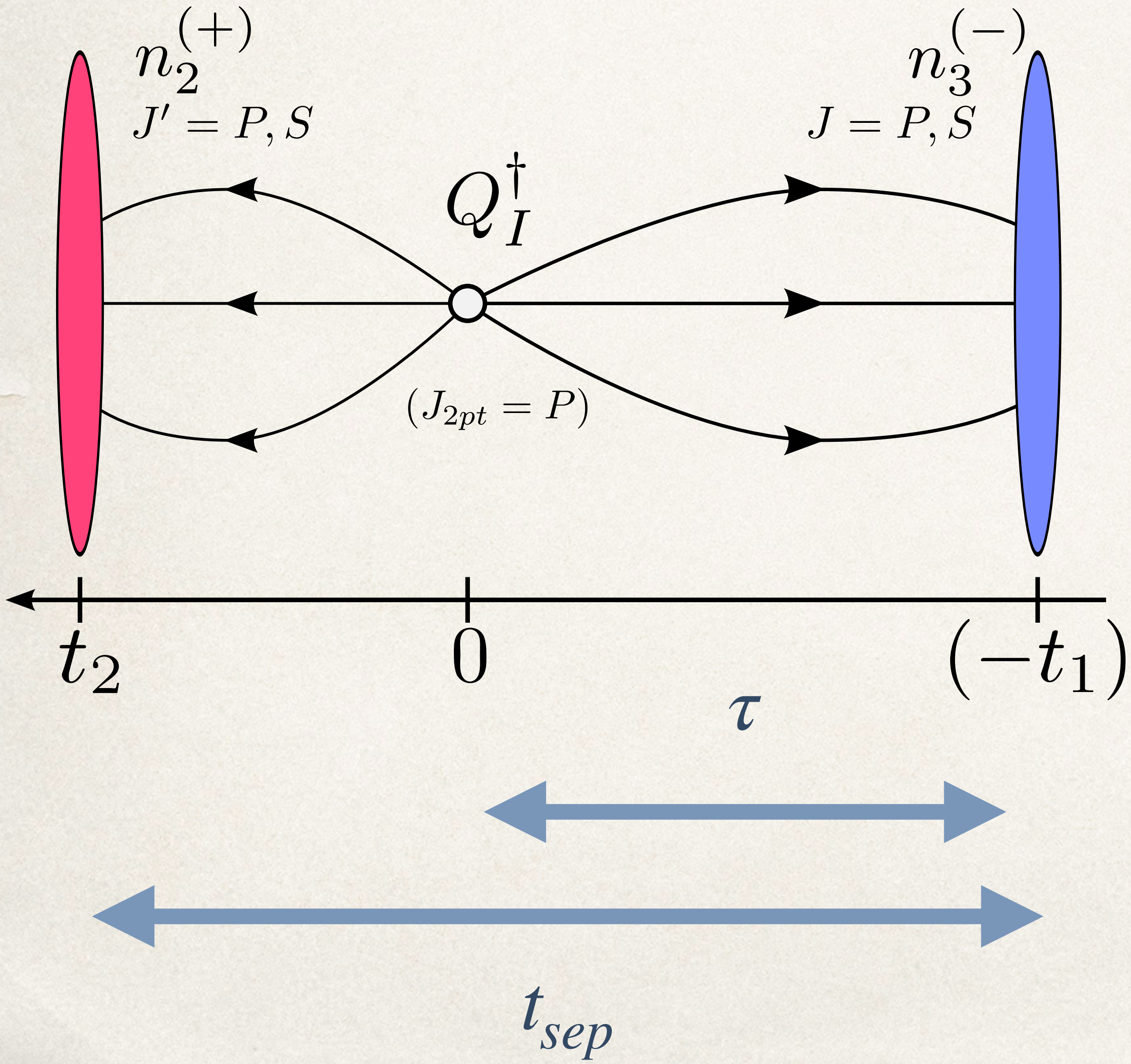
Statistics: 2430 samples

excited states are non-negligible
but also not well-determined

[Syritsyn et al., 1901.07519]

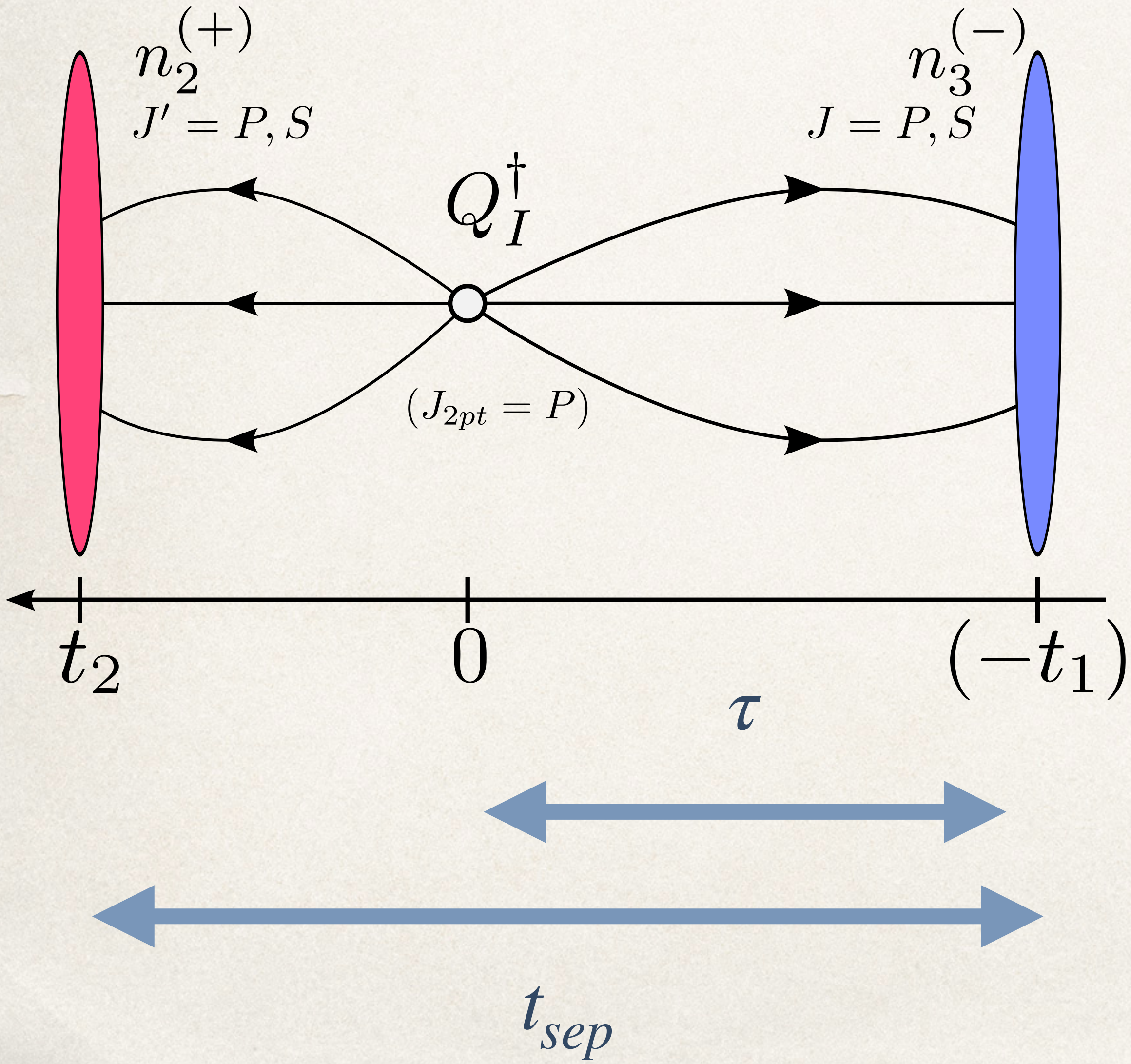
Extracting matrix elements

$$G^{JJ'}_{nQ_I^\dagger\bar{n}}(t_{sep},\tau) = \sqrt{Z_0^J Z_0^{J'}} e^{-E_0 t_{sep}} \mathscr{M}_I + e^{-E_0\tau - E_1(t_{sep}-\tau)} \mathscr{A}_I^{JJ'} + e^{-E_1\tau - E_0(t_{sep}-\tau)} \mathscr{A}_I^{J'J} + e^{-E_1 t_{sep}} \mathscr{B}_I^{JJ'}$$



Extracting matrix elements

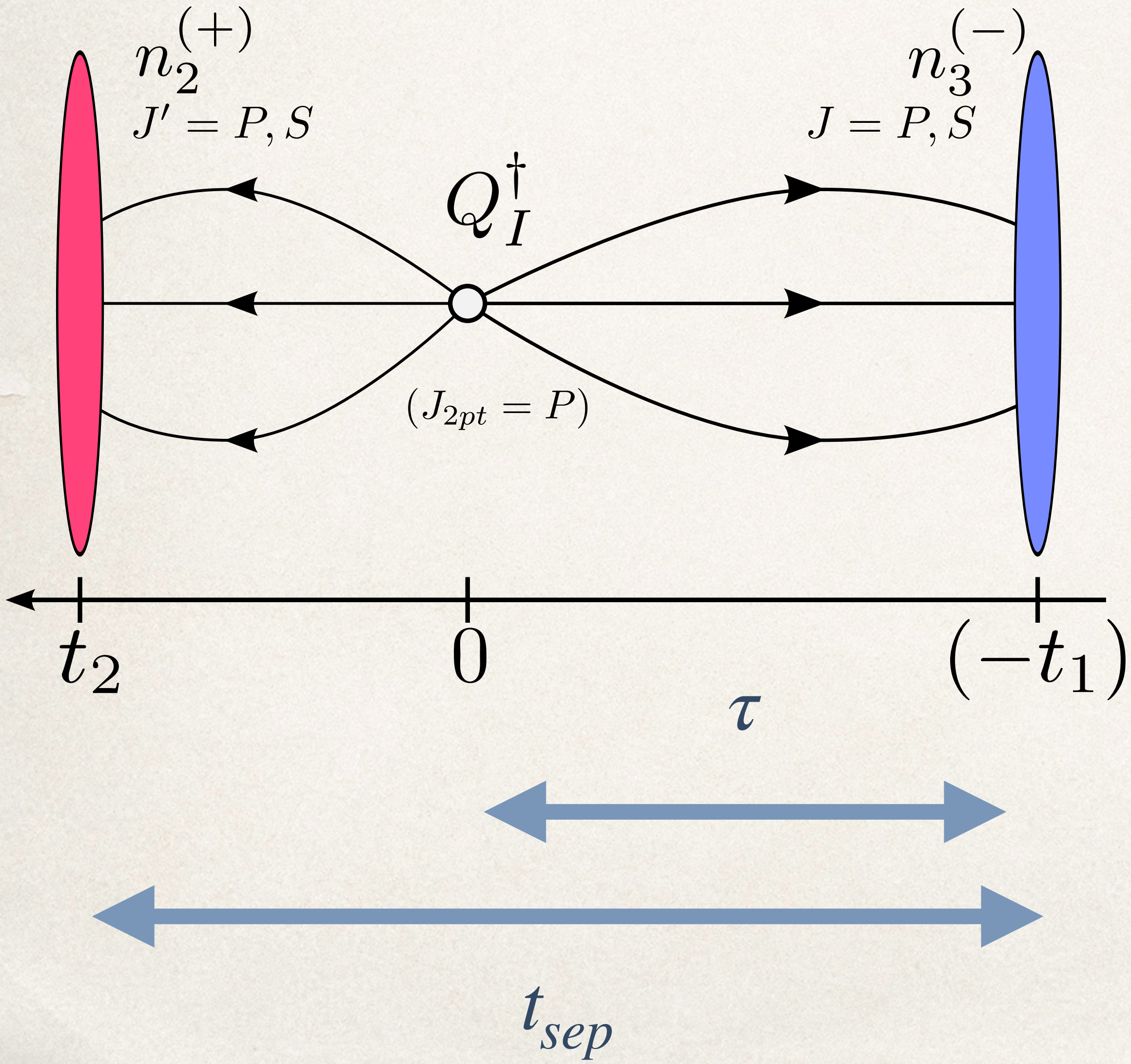
$$G^{JJ'}_{nQ_I^\dagger \bar{n}}(t_{sep}, \tau) = \sqrt{Z_0^J Z_0^{J'}} e^{-E_0 t_{sep}} \mathscr{M}_I + e^{-E_0\tau - E_1(t_{sep}-\tau)} \mathscr{A}_I^{JJ'} + e^{-E_1\tau - E_0(t_{sep}-\tau)} \mathscr{A}_I^{J'J} + e^{-E_1 t_{sep}} \mathscr{B}_I^{JJ'}$$



[Syritsyn et al., 1901.07519]

Extracting matrix elements

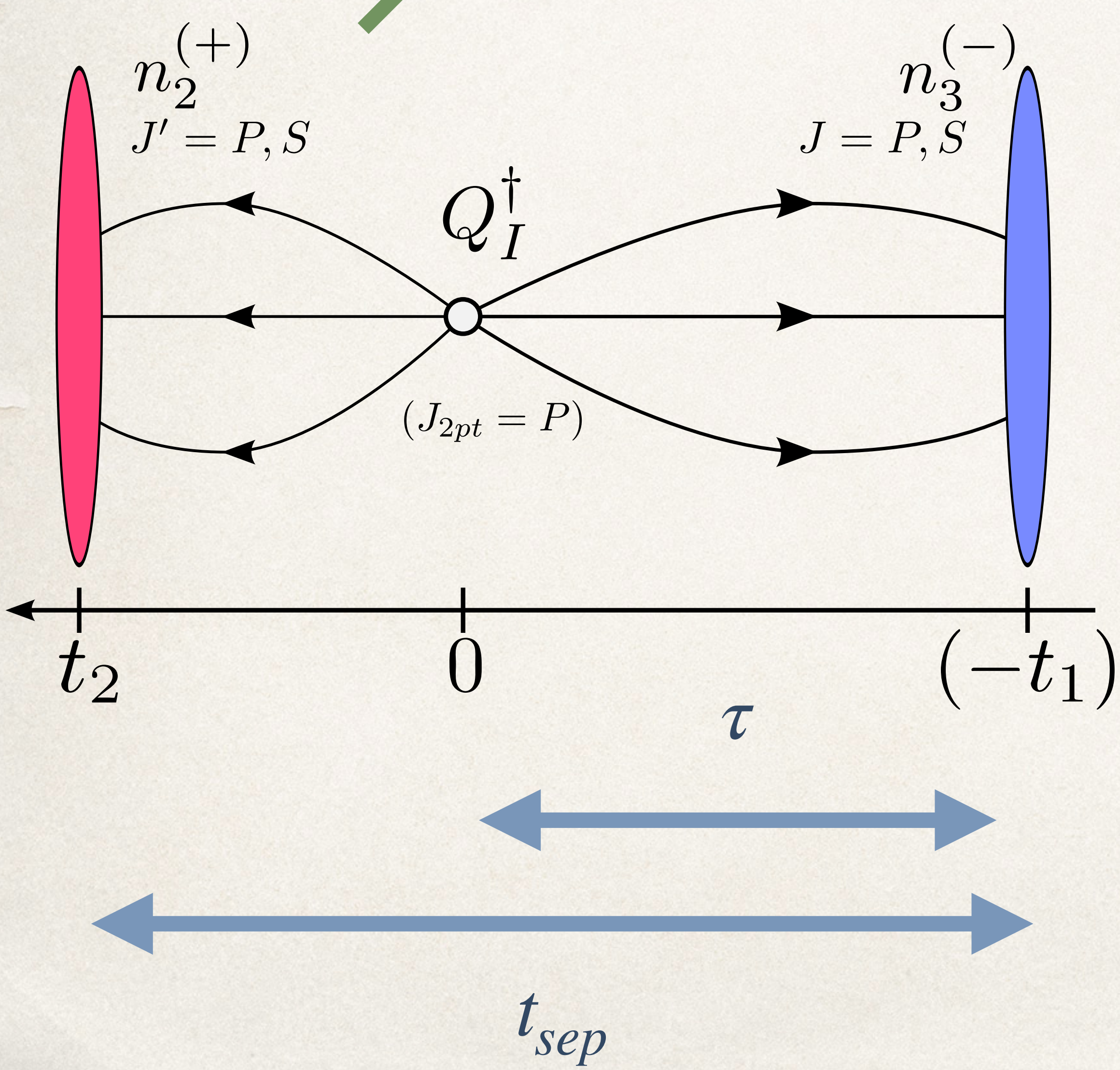
$$G^{JJ'}_{nQ_I^\dagger\bar{n}}(t_{sep},\tau) = \sqrt{Z_0^J Z_0^{J'}}\, e^{-E_0 t_{sep}}\mathscr{M}_I + e^{-E_0\tau - E_1(t_{sep}-\tau)}\mathscr{A}_I^{JJ'} + e^{-E_1\tau - E_0(t_{sep}-\tau)}\mathscr{A}_I^{J'J} + e^{-E_1 t_{sep}}\mathscr{B}_I^{JJ'}$$



[Syritsyn et al., 1901.07519]

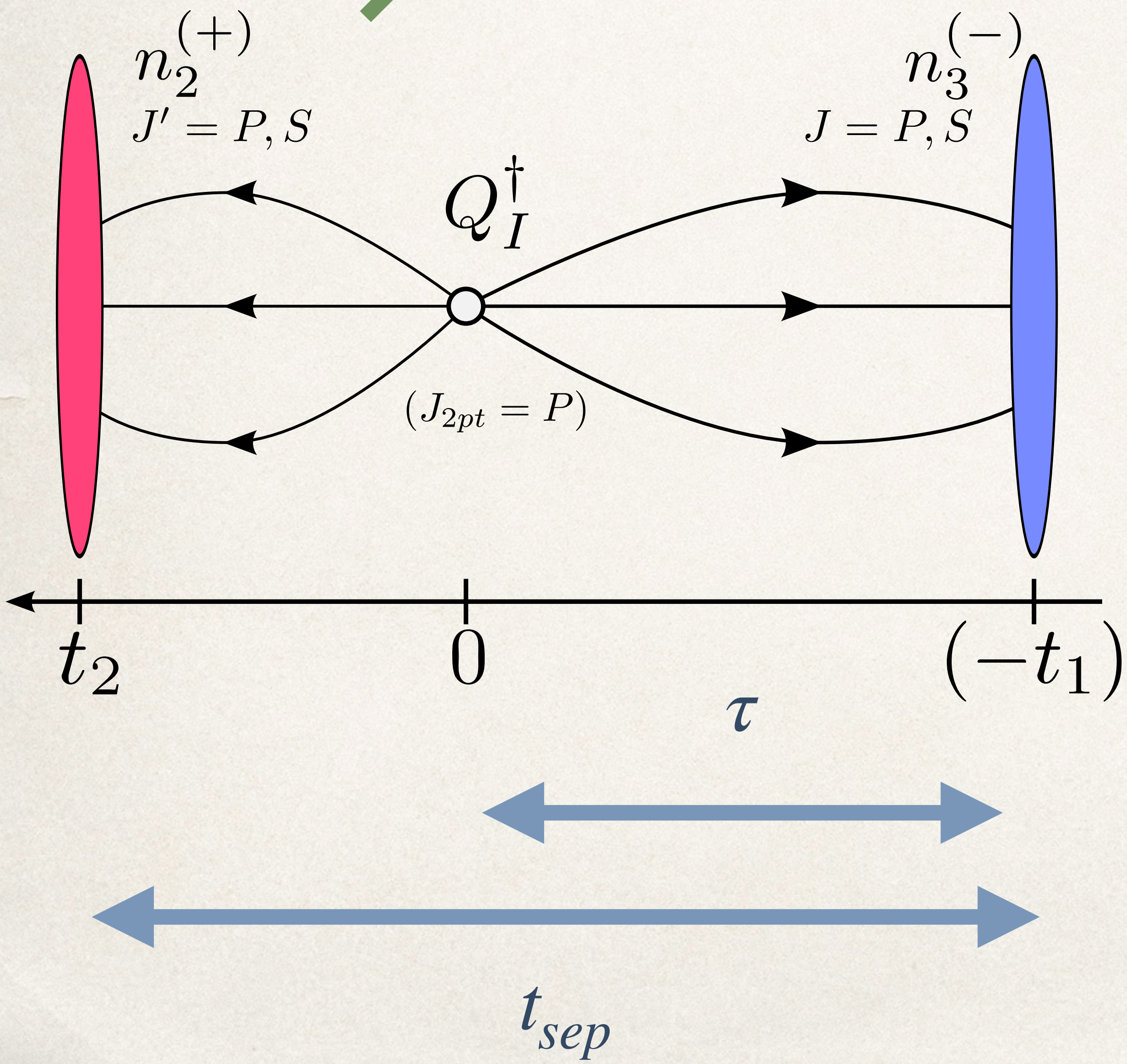
Extracting matrix elements

$$G^{JJ'}_{nQ_I^\dagger\bar{n}}(t_{sep},\tau) = \sqrt{Z_0^J Z_0^{J'}}\, e^{-E_0 t_{sep}} \mathscr{M}_I + e^{-E_0\tau - E_1(t_{sep}-\tau)} \mathscr{A}_I^{JJ'} + e^{-E_1\tau - E_0(t_{sep}-\tau)} \mathscr{A}_I^{J'J} + e^{-E_1 t_{sep}} \mathscr{B}_I^{JJ'}$$



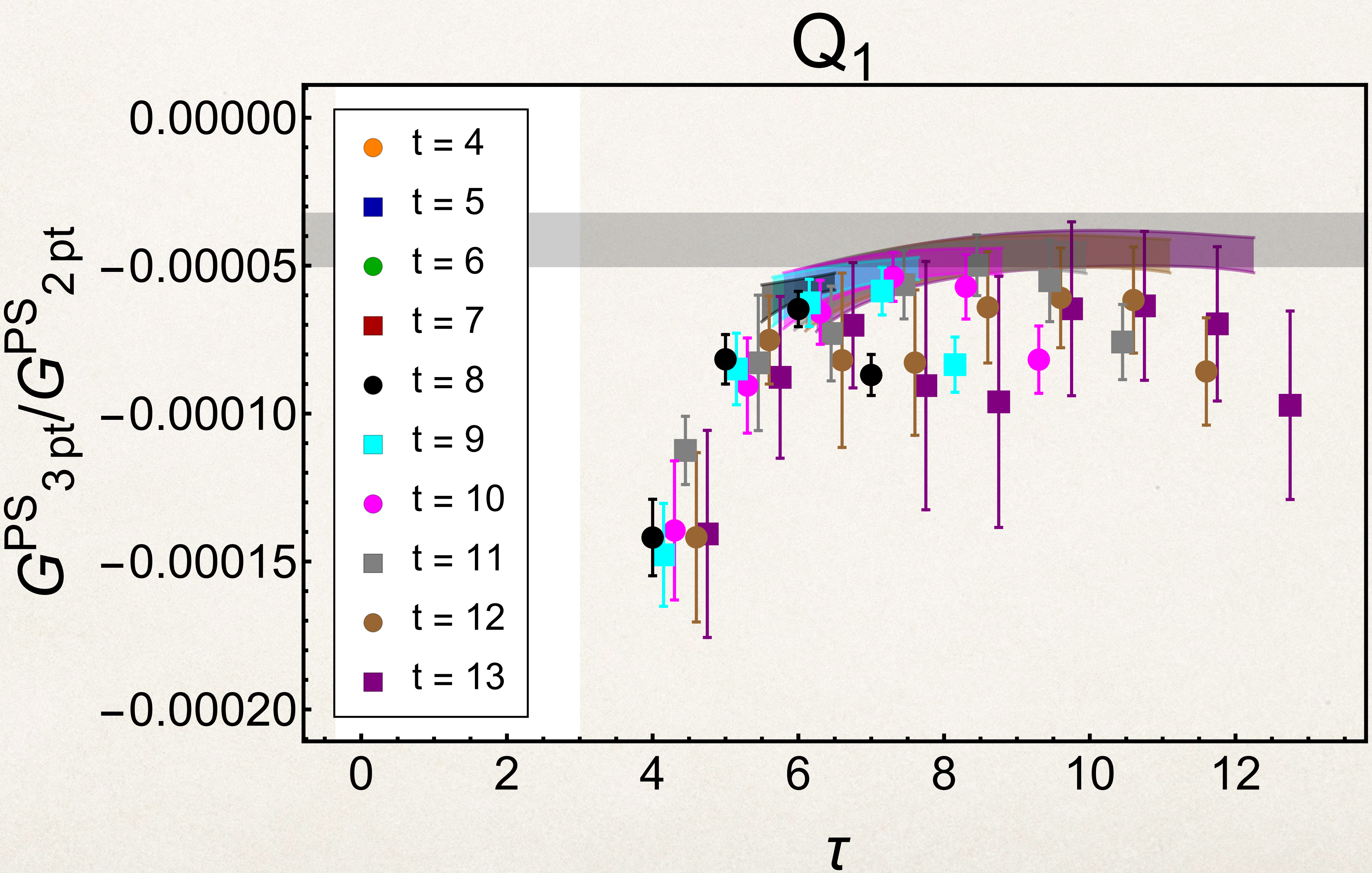
Extracting matrix elements

$$G^{JJ'}_{nQ_I^\dagger \bar{n}}(t_{sep}, \tau) = \sqrt{Z_0^J Z_0^{J'}}\, e^{-E_0 t_{sep}} \mathscr{M}_I + e^{-E_0\tau - E_1(t_{sep}-\tau)} \mathscr{A}_I^{JJ'} + e^{-E_1\tau - E_0(t_{sep}-\tau)} \mathscr{A}_I^{J'J} + e^{-E_1 t_{sep}} \mathscr{B}_I^{JJ'}$$



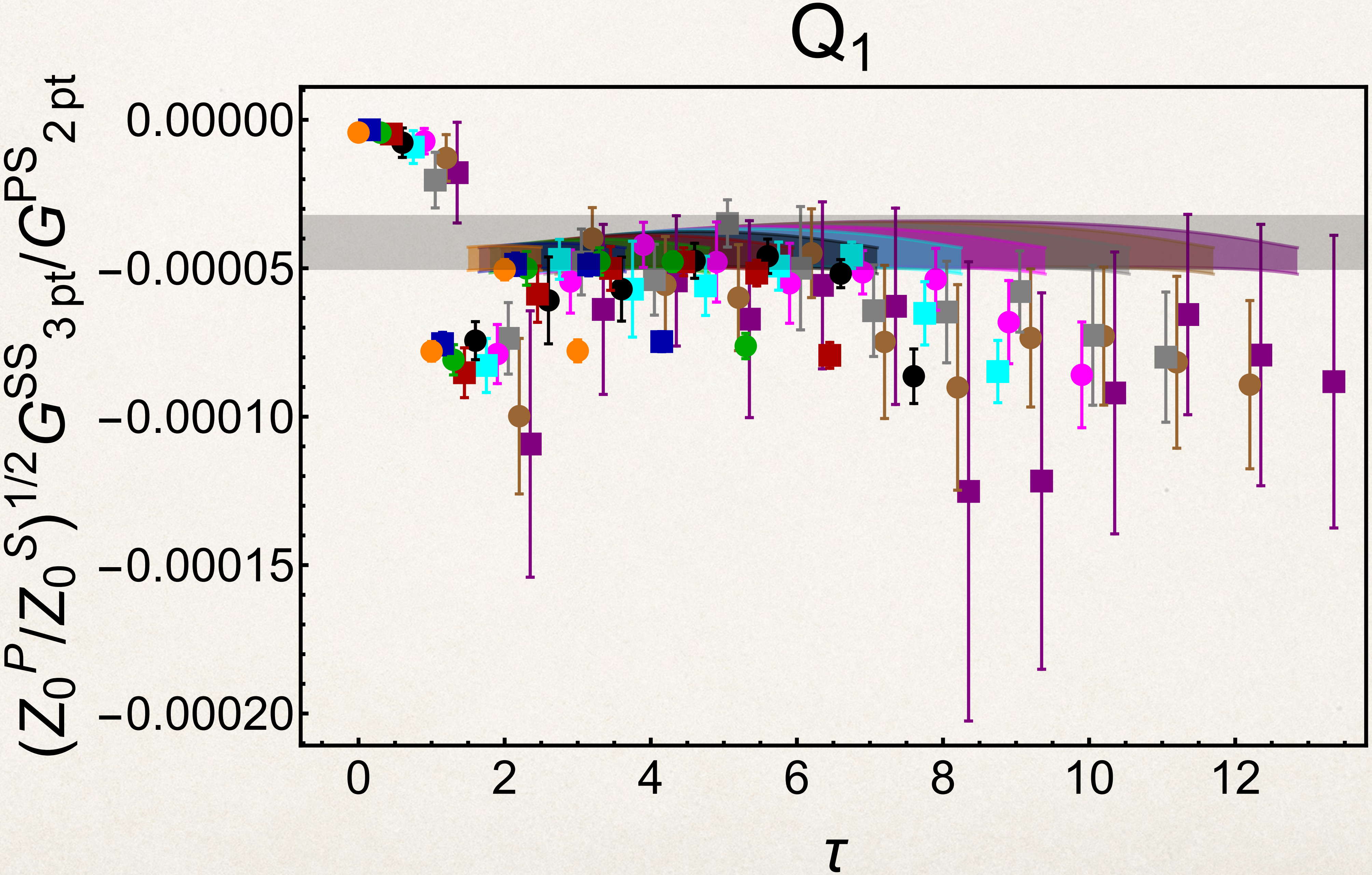
- Increase statistics by using symmetries of operators and states
- Reduce ill-defined covariance matrix by using "shrinkage"
- Inspect fit by looking at ratios

Some fits


Q1
0.00000
−0.00005
−0.00010
−0.00015
−0.00020
$G^{PS}_{3pt}/G^{PS}_{2pt}$
t = 4
t = 5
t = 6
t = 7
t = 8
t = 9
t = 10
t = 11
t = 12
t = 13
0
2
4
6
8
10
12
τ

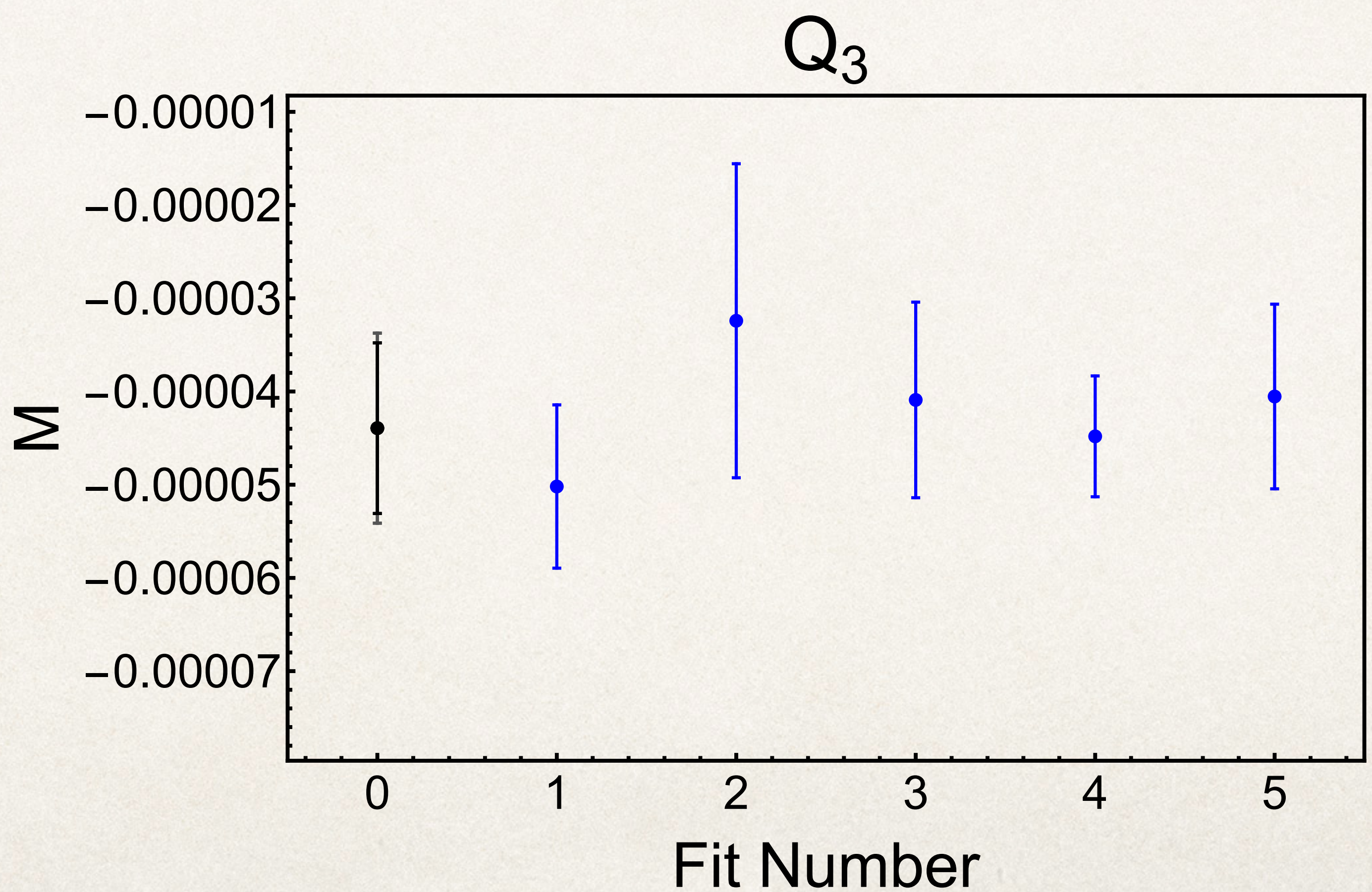
[Syritsyn et al., 1901.07519]

Some fits



Systematic errors

τ_P^{min}	τ_S^{min}	$t_{\rm sep}^{max}$	$N_{\rm dof}$	$\mathcal{M}_1^{\rm lat} \times 10^5$	$\chi^2/N_{\rm dof}$	λ^*	$\mathcal{M}_2^{\rm lat} \times 10^5$	$\chi^2/N_{\rm dof}$	λ^*	$\mathcal{M}_3^{\rm lat} \times 10^5$	$\chi^2/N_{\rm dof}$	λ^*	$\mathcal{M}_5^{\rm lat} \times 10^5$	$\chi^2/N_{\rm dof}$	λ^*
6	2	13	70	-4.13(0.92)	0.25	0.77	8.50(1.07)	0.40	0.35	-5.01(0.76)	0.44	0.32	-0.098(39)	0.62	0.53
6	4	13	25	-3.81(1.78)	0.44	0.72	6.46(2.15)	0.31	0.31	-3.21(1.25)	0.40	0.29	-0.063(45)	0.53	0.41
6	3	13	45	-3.85(1.07)	0.30	0.76	8.24(1.52)	0.34	0.31	-4.09(0.95)	0.47	0.30	-0.068(38)	0.54	0.50
5	3	13	51	-4.09(0.92)	0.28	0.75	8.61(1.06)	0.34	0.29	-4.50(0.67)	0.44	0.29	-0.077(22)	0.54	0.47
7	3	13	40	-3.87(1.13)	0.34	0.76	8.13(1.32)	0.37	0.32	-4.05(1.00)	0.50	0.31	-0.069(32)	0.55	0.53
Weighted Ave				-3.99(1.08)(0.13)			8.28(1.29)(0.54)			-4.37(0.86)(0.52)			-0.075(32)(10)		

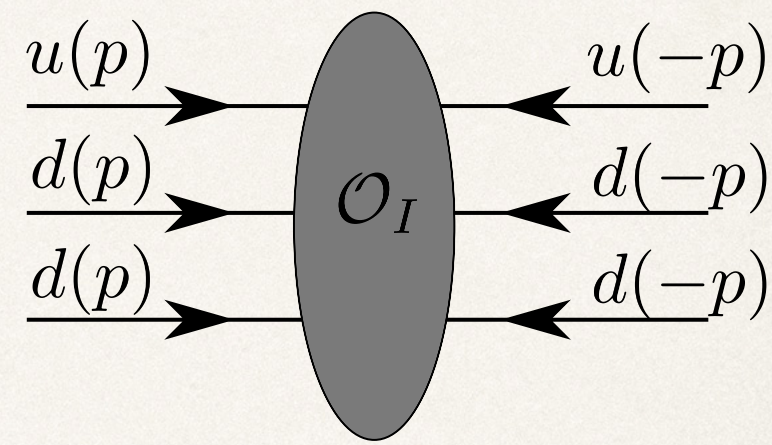


Non-perturbative renormalization

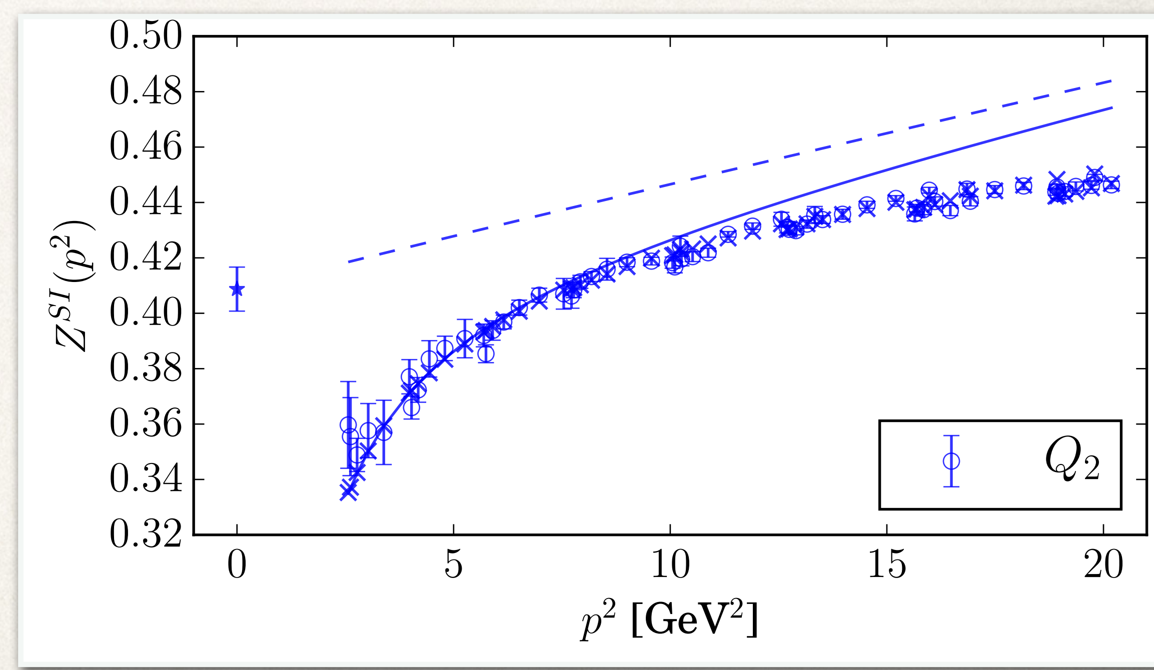
$$Q_I^R(\mu) = Z_{IJ}^{\text{lat}}(\mu, a) Q_J^{\text{lat}}(a)$$

- We use the RI-MOM scheme

$$Z_q^{-3}(p) Z_{IJ}^{\text{lat}}(p)\, \Lambda_J^{\{A_i\}}(p) = \Gamma_I^{\{A_i\}}$$



- Explicitly check for operator mixing

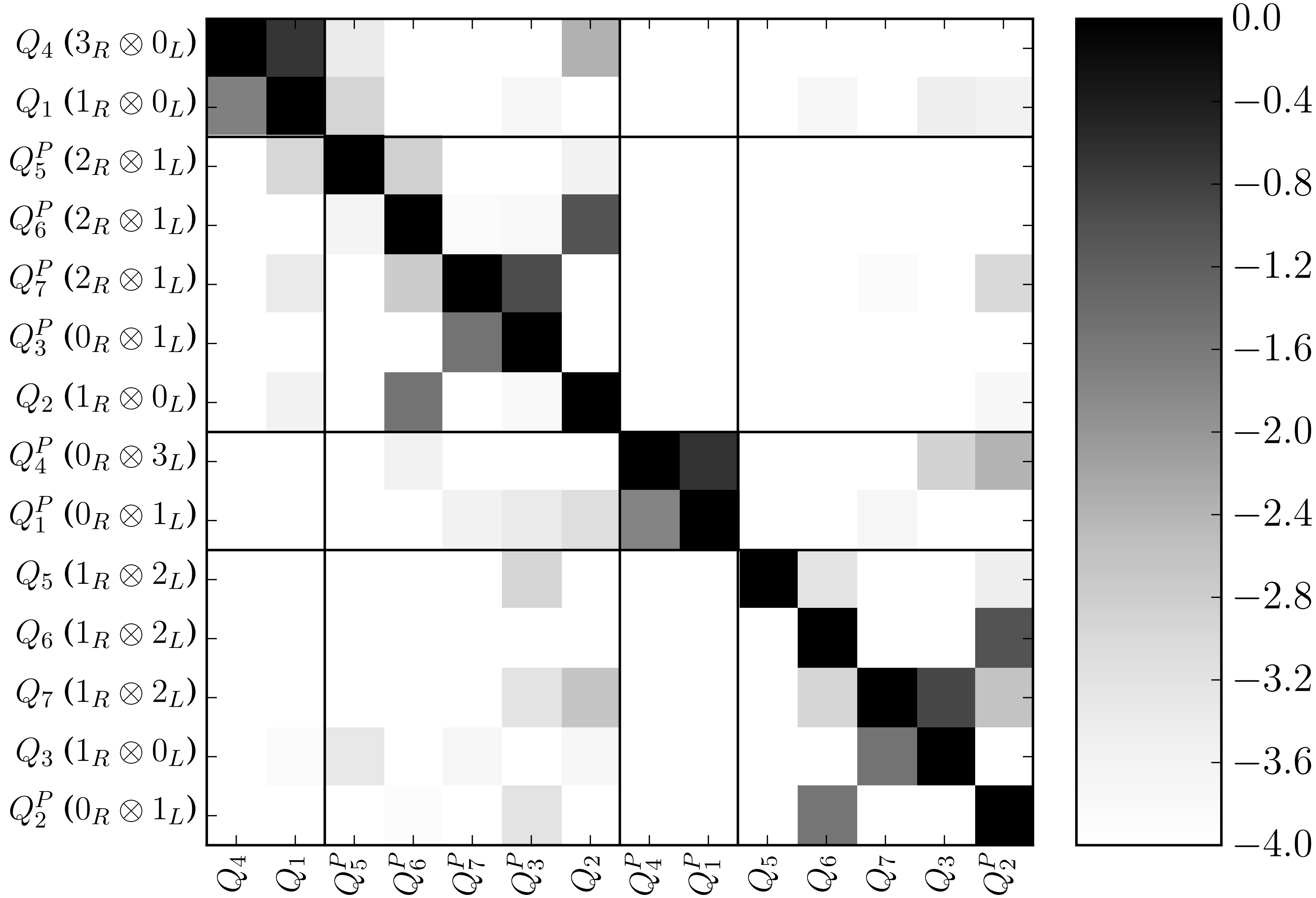


- Remove discretization artifacts

$$\Delta Z_I^{\text{disc}}(a^k p^i[k]) = A(ap)^2 + \left[B_1(ap)^2 + B_2(ap)^4\right] \frac{a^4 p^{[4]}}{(ap)^4}$$

Renormalization matrix

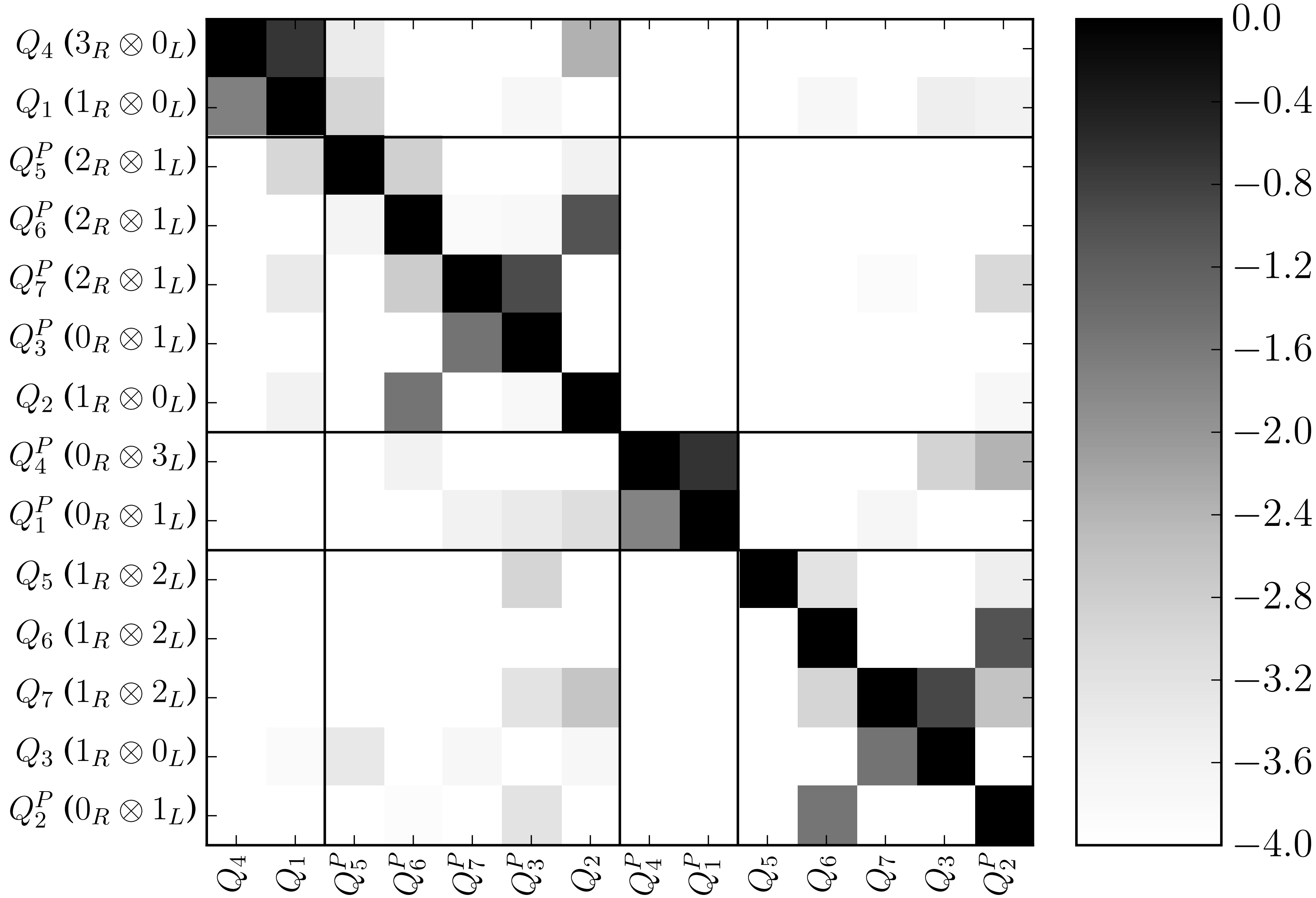
$$Q_I^R(\mu) = Z_{IJ}^{\text{lat}}(\mu, a) Q_J^{\text{lat}}(a)$$



one combination of momenta

[Syritsyn et al., 1901.07519]

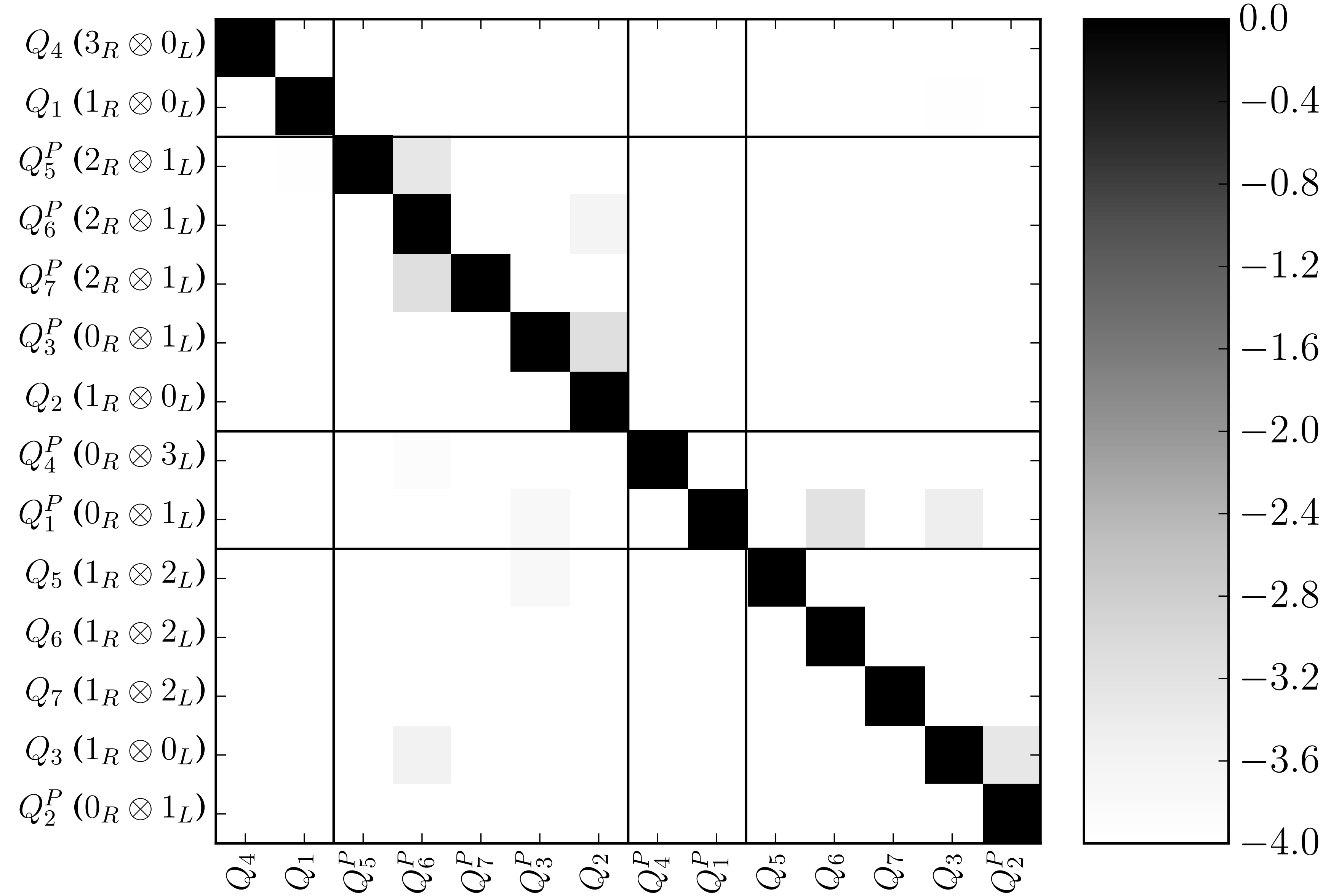
Renormalization matrix $X_{IJ} = \log\left(\frac{|Z_{IJ}|}{\sqrt{Z_{II} Z_{JJ}}}\right)$



one combination of momenta

[Syritsyn et al., 1901.07519]

Renormalization matrix $X_{IJ} = \log\left(\frac{|Z_{IJ}|}{\sqrt{Z_{II}Z_{JJ}}}\right)$



average over permutations of momenta

[Syritsyn et al., 1809.00246]
[Syritsyn et al., 1901.07519]

Final results

$$\tau^{-1}_{n\text{-}\bar{n}} = \Big| \sum_{I=1,2,3,5} \widehat{C}_I(\mu) \langle \bar{n}| Q_I(\mu) |n\rangle \Big|$$

Operator	$\mathcal{M}_I^{\overline{\rm MS}}$ (2 GeV)	$\mathcal{M}_I^{\overline{\rm MS}}$ (700 TeV)	$\frac{\mathcal{M}_I^{\overline{\rm MS}}}{\text{MIT bag A}}$ (2 GeV)	$\frac{\mathcal{M}_I^{\overline{\rm MS}}}{\text{MIT bag B}}$ (2 GeV)
Q_1	$-46(13)$	$-26(7)$	4.2	5.2
Q_2	95(17)	144(26)	7.5	8.7
Q_3	$-50(12)$	$-47(11)$	5.1	6.1
Q_5	$-1.06(48)$	$-0.23(10)$	-0.8	1.6

$$\tau^{-1}_{n\bar{n}} = \frac{10^{-9}\ \text{s}^{-1}}{(700\ \text{TeV})^{-5}} \Big| 4.2(1.1)\, \widehat{C}{}_1^{\overline{\rm MS}}(\mu) - 8.6(1.5)\, \widehat{C}{}_2^{\overline{\rm MS}}(\mu) + 4.5(1.1)\, \widehat{C}{}_3^{\overline{\rm MS}}(\mu) + 0.096(43)\, \widehat{C}{}_5^{\overline{\rm MS}}(\mu) \Big|_{\mu=2\ \text{GeV}}$$

[Syritsyn et al., 1809.00246]
[Syritsyn et al., 1901.07519]

Final results

$$\tau^{-1}_{n\text{-}\bar{n}} = \left| \sum_{I=1,2,3,5} \hat{C}_I(\mu) \langle \bar{n} | Q_I(\mu) | n \rangle \right|$$

Operator	$\mathcal{M}_I^{\overline{\mathrm{MS}}}$ (2 GeV)	$\mathcal{M}_I^{\overline{\mathrm{MS}}}$ (700 TeV)	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}}{\text{MIT bag A}}$ (2 GeV)	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}}{\text{MIT bag B}}$ (2 GeV)
Q_1	$-46(13)$	$-26(7)$	4.2	5.2
Q_2	$95(17)$	$144(26)$	7.5	8.7
Q_3	$-50(12)$	$-47(11)$	5.1	6.1
Q_5	$-1.06(48)$	$-0.23(10)$	-0.8	1.6

$$\tau^{-1}_{n\bar{n}} = \frac{10^{-9}\ \mathrm{s}^{-1}}{(700\ \mathrm{TeV})^{-5}} \left| 4.2(1.1)\, \widehat{C}_1^{\overline{\mathrm{MS}}}(\mu) - 8.6(1.5)\, \widehat{C}_2^{\overline{\mathrm{MS}}}(\mu) + 4.5(1.1)\, \widehat{C}_3^{\overline{\mathrm{MS}}}(\mu) + 0.096(43)\, \widehat{C}_5^{\overline{\mathrm{MS}}}(\mu) \right|_{\mu=2\ \mathrm{GeV}}$$

[Syritsyn et al., 1809.00246]
[Syritsyn et al., 1901.07519]

Final results

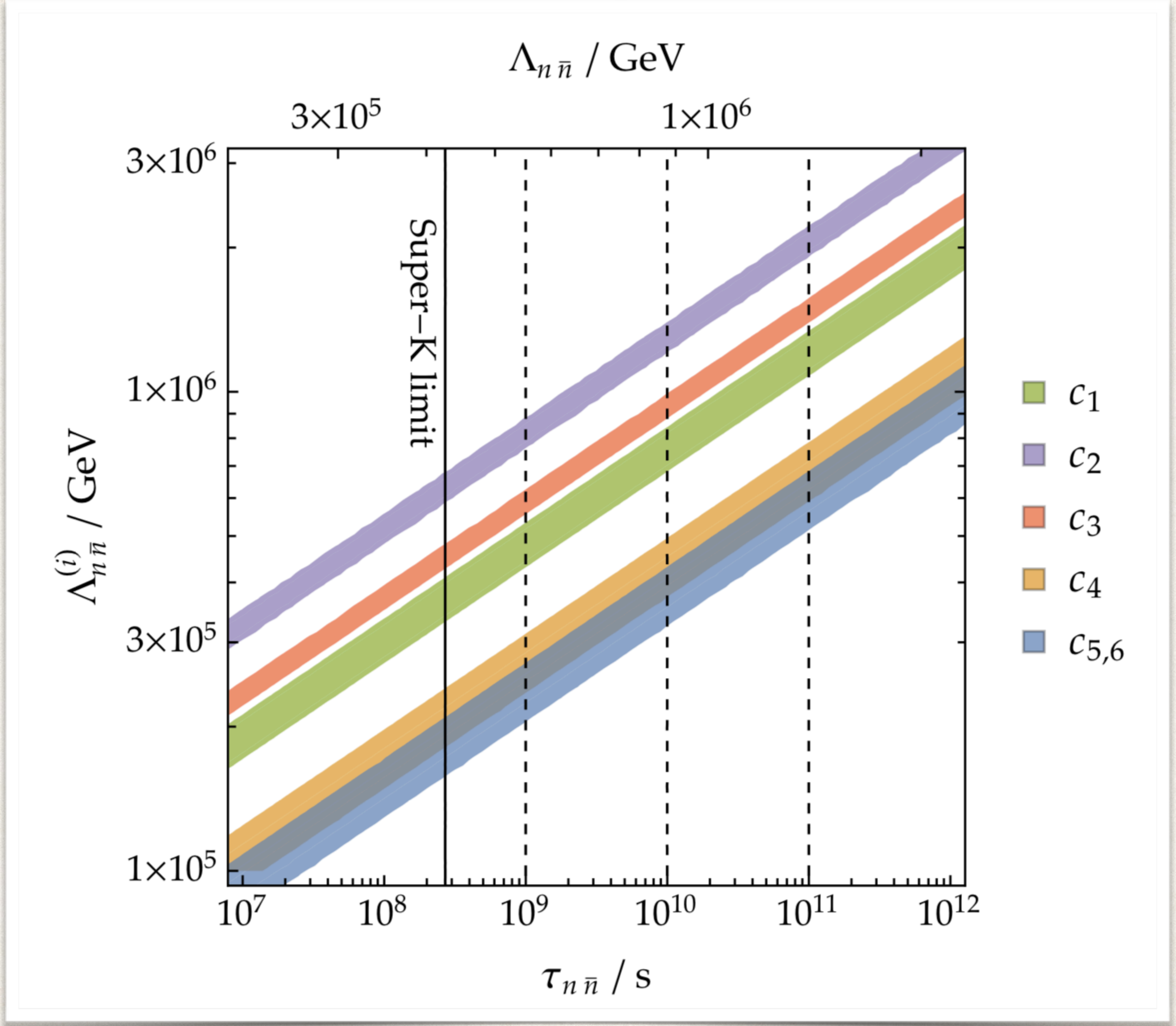
$$\tau_{n\text{-}\bar{n}}^{-1} = \left| \sum_{I=1,2,3,5} \hat{C}_I(\mu) \langle \bar{n} | Q_I(\mu) | n \rangle \right|$$

Operator	$\mathcal{M}_I^{\overline{\mathrm{MS}}}$ (2 GeV)	$\mathcal{M}_I^{\overline{\mathrm{MS}}}$ (700 TeV)	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}}{\text{MIT bag A}}$ (2 GeV)	$\frac{\mathcal{M}_I^{\overline{\mathrm{MS}}}}{\text{MIT bag B}}$ (2 GeV)
Q_1	$-46(13)$	$-26(7)$	4.2	5.2
Q_2	$95(17)$	$144(26)$	7.5	8.7
Q_3	$-50(12)$	$-47(11)$	5.1	6.1
Q_5	$-1.06(48)$	$-0.23(10)$	-0.8	1.6

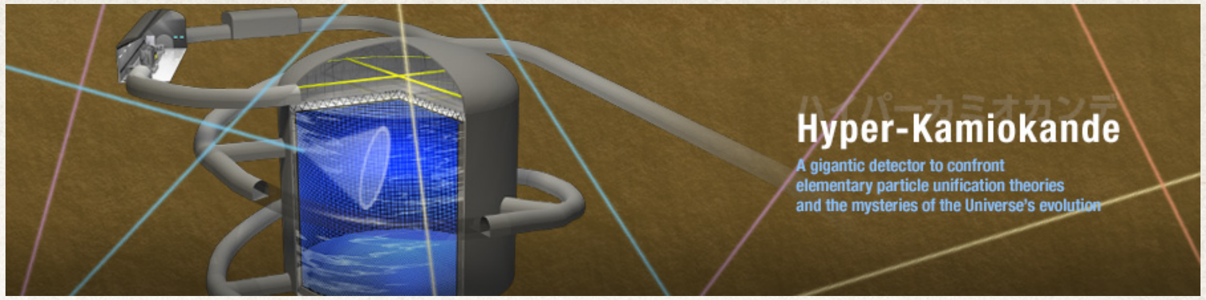
$$\tau_{n\bar{n}}^{-1} = \frac{10^{-9}\ \mathrm{s}^{-1}}{(700\ \mathrm{TeV})^{-5}} \left| 4.2(1.1)\, \widehat{C}_1^{\overline{\mathrm{MS}}}(\mu) - 8.6(1.5)\, \widehat{C}_2^{\overline{\mathrm{MS}}}(\mu) + 4.5(1.1)\, \widehat{C}_3^{\overline{\mathrm{MS}}}(\mu) + 0.096(43)\, \widehat{C}_5^{\overline{\mathrm{MS}}}(\mu) \right|_{\mu=2\ \mathrm{GeV}}$$

enhancement of ME wrt models up to ~10x

[Grojean et al., 1806.00011]



Summary



- Improvement of the experimental limits on oscillations is expected in the next decade (DUNE, Hyper-K, ESS): $\tau_{n-\bar{n}} > 10^{10}\ s$

  - 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 will now replace outdated 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